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1.1 CEPC: the precision frontier

The discovery of a Higgs boson in 2012 by the ATLAS and CMS collaborations [1, 2] at the Large Hadron Collider (LHC) has opened a new era in particle physics. Subsequent measurements of the properties of this new particle have indicated compatibility with the predictions of the Standard Model (SM) [??????] [need updates]. While the SM has been remarkably successful in describing experimental phenomena, it is important to recognize that the SM is not a complete theory. In particular, the SM does not *predict* the parameters in the Higgs potential, such as the Higgs mass. The vast difference between the Planck scale and the weak scale remains a major mystery. In addition, there is not a complete understanding of the nature of the electroweak phase transition. The discovery of a spin zero Higgs boson, the first elementary particle of its kind, has only sharpened these questions, and their resolution will necessarily involve new physics beyond the SM. In this respect, the Higgs boson discovery marks the beginning of a new era of theoretical and experimental exploration.

The precision measurement of Higgs properties will be a critical component of any roadmap for high energy physics in the coming decades. In addition to motivating new physics beyond the SM, the Higgs provides a uniquely sensitive probe of new physics. In particular, new physics beyond the SM can lead to observable deviations in Higgs boson couplings relative to SM expectations. These deviations δ are generically of order

$$\delta = c \frac{v^2}{M_{\rm NP}^2} \,, \tag{1.1}$$

where v and $M_{\rm NP}$ are the vacuum expectation value of the Higgs field and the typical mass scale of new physics, respectively. The size of the proportionality constant c is

model-dependent, but it should not be much larger than O(1). The current and upcoming LHC runs will measure Higgs couplings to about the 5% level [3] [broken link], while direct searches at the LHC will test many new physics scenarios from a few hundreds of GeV to at least a TeV. Eq. (1.1) implies that probing new physics significantly *beyond* the LHC's reach requires measuring Higgs boson couplings with sub-percent-level accuracy. Achieving such a level of precision will require new facilities, for which a lepton collider operating as a Higgs factory is a natural candidate.

In this section we explore the physics potential of the CEPC, translating the potential precision of Higgs coupling measurements into implications for a variety of motivated scenarios for physics beyond the SM. Projections for the precision in Higgs coupling measurements and electroweak observables attainable by the CEPC are summarized below. The details of the analysis underpinning these projections are presented in Section [refer to the physics potential section].



Figure 1.1: Left: Higgs coupling extraction in the κ -framework. **Right:** Projection for the precision of the Z-pole measurements.

The CEPC will operate primarily at a center-of-mass energy of $\sqrt{s} \sim 240$ GeV. The main mode of Higgs production is through $e^+e^- \rightarrow Zh$ process, and with an integrated luminosity of 5 ab^{-1} , over one million Higgs bosons will be produced. At CEPC, in contrast to the LHC, Higgs boson candidate events can be identified through a technique known as the recoil mass method without tagging its decay products. This allows Higgs boson production to be disentangled from Higgs decay in a model-independent way. Moreover, the cleaner environment at a lepton collider allows much better exclusive measurement of Higgs boson properties. The resulting precision attainable by CEPC in measurements of Higgs couplings is shown in the left panel of Fig. 1.1 in terms of the κ framework.

Several aspects of the Higgs precision attainable at CEPC stand out. The CEPC will be able to measure the Higgs boson coupling to the Z boson with an accuracy of 0.25%[update], about a factor of 10 better than the reach of the High Luminosity upgrade of the LHC (HL-LHC). Such a precise measurement gives CEPC unprecedented reach into interesting new physics scenarios which are very difficult to probe at the LHC. The CEPC also has strong capability in detecting invisible decays of the Higgs boson. For example, with 5 ab⁻¹, it can improve the accuracy of the measurement of the Higgs invisible branching ratio to 0.14% [update]. In addition, it is expected to have excellent sensitivity to exotic decay channels which are swamped by backgrounds at the LHC. It is also important to stress that an e^+e^- Higgs factory can perform *model independent* measurement



precision reach of the 12-parameter EFT fit (D6 basis)

Figure 1.2: Upper panel: The reach of the Higgs measurement on the size of effective field theory operators, normalized as $c_i(\mathcal{O}_i/v^2)$. Lower panel: On the left, the CEPC limit on the oblique parameters in comparison with the current precision. On the right, 68% (dash-dot) and 95% (solid) contours from CEPC measurement.

of the Higgs boson width. This unique feature in turn allows for the determination of the Higgs boson couplings without assumptions about Higgs decay channels.

The CEPC is also designed to run at the Z pole and near the W^+W^- threshold (with about $10^7 W$ pairs). This enables a robust program of electroweak precision measurements to complement the Higgs precision program. The projected precision for a set of such observables is shown in on the right panel of Fig. 1.1. In comparison with the current precision, CEPC can improve by about one order of magnitude.

The combination of precision Higgs and electroweak measurements at CEPC is particularly powerful. This is most readily apparent in the potential for CEPC to constrain departures from the Standard Model parameterized in the language of effective field theory (EFT). The reach of CEPC Higgs measurements in constraining Wilson coefficients of select dimension-6 operators in the SM EFT is shown in Fig. 1.2, while the reach of CEPC electroweak precision measurements in terms of the so-called oblique parameters (likewise expressible in terms of Wilson coefficients of dimension-6 operators in the SM EFT) is shown in the lower panel of Fig. 1.2. The significant improvement of CEPC relative to both current and projected LHC measurements is apparent. Later in this sec-

tion, we will explore in detail the implications of the precision measurements at CEPC for important open questions of the Standard Model.

CEPC, running as both Higgs factory and Z-factory, will also probe interesting new physics, offer an excellent opportunity of studying flavor physics, allow precise QCD measurements. We will also elaborate on these later in this section. To set the stage, we briefly comment on the running scenarios assumed in the results presented in this section. While the plan for the Higgs factory has been fixed, the plan for the Z-factory run is still preliminary. The total number of Zs with different options ranging from 0.3×10^{12} (baseline) to up to 10^{12} Zs. To give an characterization of the full potential of the CEPC, we will use 10^{12} Zs (Tera Z) in our estimates.

1.2 Higgs and electroweak symmetry breaking

1.2.1 Naturalness

The appearance of large numerical hierarchies in fundamental theories has long been a source of discomfort, articulated in the modern era by Dirac [4] and subsequently refined in the context of quantum field theory by Wilson [5], Susskind [6], 't Hooft [7], and others. In the context of quantum field theory, dimensionless parameters of a quantum field theory are naturally expected to be O(1), while the dimensionful parameters are naturally the size of the fundamental scale at which the theory is defined. An exception arises when a symmetry is manifested in the limit that a parameter of the theory is taken to zero. In this case, it is "technically natural" for some parameters to remain smaller than others, in the sense that they are protected from large quantum corrections, though even in this case one is left to find an explanation for the dynamical origin of the small parameter. This notion of naturalness has been reinforced by the widespread successes of effective field theory and diverse realizations in both particle physics and condensed matter physics.

Famously, all of the observed parameters of the Standard Model satisfy the naturalness criterion in some form, with the exception of the Higgs mass parameter and the strong CP angle. The naturalness of these parameters remains an open question, and in each case a natural explanation entails a significant extension of the Standard Model. Of these, the naturalness of the weak scale is perhaps the most pressing, as it is drawn into sharp relief by the discovery of an apparently elementary Higgs boson at the LHC. Evidence for a natural explanation for the value of the weak scale has yet to appear, with null results across a suite of experimental searches imperiling many preferred candidates. But the LHC is not capable of decisively deciding the naturalness of the weak scale, providing strong motivation for colliders that complement LHC sensitivity to natural new physics.

The oft-cited quadratically divergent radiative corrections to the Higgs mass parameter,

$$\delta m_h^2 \sim \frac{3y_t^2}{8\pi^2} \Lambda^2 \,, \tag{1.2}$$

are not the naturalness problem in and of themselves, but rather an indication of the problem. Such divergences indicate that the Higgs mass parameter is precisely that – a parameter – and incalculable in the Standard Model. But the robust expectation is that the Higgs mass and other parameters of the Standard Model are fully calculable in a fundamental theory. In this case, the quadratically divergent contributions to the Higgs mass parameter in the Standard Model are replaced by finite contributions dictated by the fundamental theory. The Higgs mass in terms of underlying parameters will take the form

$$m_h^2 = a\Lambda_h^2 + b\frac{3y_t^2}{8\pi^2}\Lambda_h^2 + \dots$$
 (1.3)

where a, b, \ldots are dimensionless constants and Λ_h is an underlying mass scale of the fundamental theory. If the Higgs mass is *natural*, the parameters a and b will be O(1), up to possible manifestations of technical naturalness associated with symmetries in the underlying theory. In this case, one expects $m_h \sim \Lambda_h$, corresponding to the appearance of new physics near the weak scale. Alternately, $m_h \ll \Lambda_h$ points either to *fine-tuning* among fundamental parameters, or to a correlation between ultraviolet and infrared aspects of the theory with no known counterpart in effective field theory.

The most promising strategy for rendering the weak scale natural in a more fundamental theory is to extend the Standard Model to include additional symmetries that render the Higgs mass parameter technically natural. In four dimensions, the available symmetries are supersymmetry and global symmetry. In the former case, the fields of the Standard Model are extended into complete supersymmetric multiplets, and supersymmetry is softly broken to accommodate the non-degeneracy of Standard Model fields and their partners [8–10]. The Higgs is related to a fermionic partner, thereby rendering the Higgs mass technically natural by the same chiral symmetries that protect the fermion masses. In the latter case, the Higgs is a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry, with a mass parameter protected by the corresponding shift symmetries. The scale of global symmetry breaking in such theories must itself be rendered natural, leading to e.g. composite Higgs models [11] and little Higgs models [12] (for an excellent recent review, see [13]).

In both cases, these symmetries predict an abundance of new physics near the weak scale. Although this new physics may be searched for efficiently at the LHC, such searches typically leverage ancillary properties of the new physics unrelated to the naturalness of the weak scale. For example, searches for the scalar top partners predicted by supersymmetry typically leverage QCD quantum numbers of the stop and decay modes unrelated to the stop-Higgs coupling. The sensitivity of LHC searches to inessential features of the new physics makes them imperfect probes of electroweak naturalness.

In this respect, a Higgs factory provides the ideal context for probing natural new physics via precision Higgs couplings. The same couplings and diagrams that control the size of the Higgs mass in a natural theory generate radiative corrections to its couplings. As such, precision tests of Higgs properties directly probe natural physics in a way that is complementary to, and less subject to caveats than, direct searches at the LHC.

Signatures of natural new physics in precision Higgs measurements take a variety of forms. In most symmetry solutions, there are Higgs coupling deviations due to tree-level mixing with additional Higgs-like states. However, these tree-level deviations need not be the leading effect. Radiative corrections are also significant, due to both the size of Higgs couplings and the proximity of new particles to the weak scale. In theories where new physics associated with naturalness carries Standard Model quantum numbers, such as conventional supersymmetric and composite models, the most distinctive radiative corrections modify loop-induced Higgs couplings to gluons and photons. In addition, all symmetry solutions – whether or not they involve new states charged under the Standard Model – radiatively modify Higgs couplings through effective wavefunction renormaliza-

tion of the physical Higgs scalar, an effect that may be observed in loop-level corrections to tree-level Higgs couplings.

Although our discussion of naturalness has focused on symmetries, they are not the only mechanism for explaining the value of the weak scale. The most notable alternative is to lower the cutoff in Eq. (1.3), the avenue realized by technicolor [6, 14] and large [15, 16] or warped [17, 18] extra dimensions. However, these solutions typically do not predict a significant mass gap between the Higgs and additional degrees of freedom, making them more susceptible to LHC null results. More recent proposals, such as relaxation of the weak scale [19], can potentially lead to $m_h \ll \Lambda_h$ without fine-tuning, and remain interesting targets for exploration. Nonetheless, these alternatives still involve new particles coupling to the Higgs, and may leave their imprint on Higgs couplings or exotic decays.

Supersymmetry

Supersymmetric extensions of the Standard Model have the virtue of rendering the weak scale natural with an elementary Higgs scalar, consistent with properties observed thus far at the LHC. While searches for supersymmetric partner particles at the LHC have excluded large regions of the natural supersymmetric parameter space, significant blind spots remain that are best covered by precision Higgs coupling measurements.

Tree-level modifications to Higgs properties Supersymmetric extensions of the Standard Model necessitate more than one Higgs doublet. Mass mixing between the CP-even neutral Higgs scalars leads to tree-level deviations in Higgs properties. In the limit that the additional Higgs scalars are heavy and may be integrated out, this leads to dimension-six operators that shift Higgs couplings to fermions and dimension-eight operators that shift Higgs couplings to fermions and lepton sectors. Percent-level CEPC sensitivity to modifications of the Higgs coupling to bottom quark enables indirect tests of the MSSM Higgs sector to the TeV scale, as illustrated in Fig. 1.3. More broadly, CEPC sensitivity to tree-level effects in extended Higgs sectors such as the MSSM is studied comprehensively in [20]. However, due to the decoupling properties of the MSSM Higgs states may remain above the TeV scale without increasing the fine-tuning of the weak scale. In this respect, tree-level modifications to Higgs properties arising in supersymmetric theories represent a discovery opportunity but not an irreducible constraint.

Loop-level modifications to Higgs properties The plethora of new partner particles predicted by supersymmetric extensions of the Standard Model leads to a wealth of looplevel contributions to Higgs couplings. These contributions are typically largest in the stop sector, due to the large coupling to the Higgs required by supersymmetry, but may be significant for any of the partners of third-generation fermions. The most distinctive consequences are modifications to the loop-level Standard Model couplings of the Higgs to gluons and photons, though radiative corrections to tree-level couplings arise as well and may be used to cover blind spots arising in the loop-level couplings. The potential for CEPC to probe a suite of loop-level corrections to Higgs and electroweak observables in supersymmetric models is comprehensively studied in [23].

For simplicity, here we will focus on the loop-level consequences in the stop sector, corresponding to the scalar partners of both the right-handed and left-handed top quarks.



Figure 1.3: Potential coverage of the MSSM Higgs sector in the hMSSM limit [21] at CEPC is shown in blue. Sensitivity is driven largely by modifications of the Higgs coupling to bottom quarks. Projected HL-LHC coverage of the MSSM Higgs sector in the same limit due to direct searches for heavy Higgs states is shown in orange [22].

In the limit that the stops are significantly heavier than the Higgs, the correction to gluons and photons is proportional to

$$\frac{1}{4} \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right)$$
(1.4)

where $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ are the stop mass eigenstates and $X_t = A_t - \mu \cot \beta$ is the off-diagonal mixing parameter in the stop mass matrix. The mixing parameter is bounded from above by the avoidance of tachyonic stops, and from below by precision measurements of the Higgs coupling to gluons and photons. A robust bound may be placed on the stop sector whenever the minimum value exceeds the maximum value [24]. The strongest constraints arise in the degenerate limit when $m_{\tilde{t}_1} = m_{\tilde{t}_2}$, in which case CEPC is capable of probing stop masses close to the TeV scale; this is illustrated in the left panel of Fig. 1.4. However, the modification of Higgs couplings is highly sensitive to the mixing in the stop sector, and blind spots arise when the mixing leads to vanishing deviations in the Higgs coupling to gluons and photons [23, 25]. However, as illustrated in the right panel of Fig. 1.4, these blind spots may be covered by precision measurements of the Zh cross section, which is sensitive to loop-level corrections to the tree-level hZZ coupling that are generically nonzero in the gluon/photon blind spot [25].

Global symmetry

Global symmetry approaches to the weak scale cover a vast array of specific models and UV completions, but share the common features of an approximately elementary Standard Model-like Higgs mixing with heavier resonances and further influenced by the presence of light fermionic excitations.

Tree level In global symmetry solutions, the Higgs is a pNGB of a spontaneously broken global symmetry. This invariably implies tree-level corrections, which can be interpreted as arising from mixing between the Standard Model-like Higgs and heavy states associ-



Figure 1.4: Left: LHC and CEPC precision Higgs constraints in the $m_{\tilde{t}_1} - m_{\tilde{t}_2}$ plane from Higgs couplings to gluons and photons. **Right:** Coverage of blind spots including precision measurement of the Zh cross section. Figures adapted from [26].



Figure 1.5: Potential coverage of composite-type global symmetry models in terms of resonance mass m_{ρ} and coupling parameter g_{ρ_L} (left panel) or mixing parameter $\xi \equiv v^2/f^2$ (right panel) via direct searches at the LHC (blue and green shaded regions) and precision Higgs measurement constraints (red lines).

ated with the spontaneously broken global symmetry. This mixing is typically proportional to v^2/f^2 , where f is the decay constant associated with the broken global symmetry (see e.g. [27] for a comprehensive parameterization), although precise corrections may vary between Higgs couplings to fermions and gauge bosons depending on the model. As shown in Fig. 1.5, the precision attainable at CEPC probes this mixing to better than one part in one hundred, translating to an energy reach of several TeV. In the simplest composite realizations of global symmetries, bounds on v^2/f^2 translate directly into lower bounds on the tuning of the electroweak scale, but this tuning may be avoided in Little Higgs models and related constructions. The complementarity between precision measurements of Higgs couplings and direct searches at future colliders in probing global symmetry approaches to the hierarchy problem is explored in detail in e.g. [28].



Figure 1.6: Left: LHC and CEPC precision Higgs constraints in the $m_{T_1} - m_{T_2}$ plane from Higgs couplings to gluons and photons assuming equal couplings. **Right:** Coverage of blind spots including precision measurement of the Zh cross section. Figures adapted from [26].

Loop level Global symmetry approaches to naturalness likewise feature a plethora of new states near the weak scale, albeit with the same statistics as their Standard Model counterparts. While corrections to Higgs couplings from loops of these new particles are typically sub-dominant compared to tree-level corrections, they provide a more immutable test of naturalness. As with supersymmetry, the largest corrections are typically due to the fermionic top partner sector, due to the large coupling of these partners to the Higgs and their proximity to the weak scale. As such partners typically carry Standard Model quantum numbers, the most striking corrections are to the loop-level couplings of the Higgs to gluons and photons.

For the sake of definiteness, consider a theory involving two top partners T_1, T_2 whose couplings are dictated by the global symmetry protecting the Higgs mass. In this case corrections to the Higgs coupling to gluons and photons are proportional to [26]

$$-\left(\rho \frac{m_t^2}{m_{T_1}^2} + (1-\rho) \frac{m_t^2}{m_{T_2}^2}\right) \tag{1.5}$$

where ρ parameterizes the fraction of the quadratic divergence cancellation coming from the T_1 field, which is directly reflected in the modification of Higgs couplings. In the case of equal couplings, CEPC is capable of probing fermionic top partners above the TeV scale, as shown in the left panel of Fig. 1.6. Note that the existence of more than one fermionic top partner allows for the possibility of a blind spot to arise when $\rho >$ 1, which may be constrained by radiative corrections to the Zh cross section (shown in the left panel of Fig. 1.6) in analogy with the stop blind spot in supersymmetry. A comprehensive exploration of CEPC's potential to constrain radiative corrections to Higgs couplings arising in global symmetry solutions to the hierarchy problem may be found in [26].

Neutral naturalness

While it is entirely possible that the naturalness of the weak scale is explained by conventional symmetries that have thus far evaded LHC detection, LHC null results may indicate that the weak scale is stabilized by less conventional symmetries that do not lead



Figure 1.7: CEPC reach in the mass scale of neutral fermionic top partners due to tree-level mixing corrections to σ_{Zh} .

to partner particles carrying Standard Model quantum numbers. This form of "neutral naturalness" [29] can occur, for example, when only discrete symmetries are operative at the weak scale. To date both opposite-statistics and same-statistics examples of neutral naturalness have been constructed. The former case is exemplified by Folded Supersymmetry [30], which features new partner particles carrying electroweak quantum numbers but no irreducible tree-level corrections. The latter case is exemplified by the Twin Higgs [31], which features new partner particles entirely neutral under the Standard Model, as well as significant tree-level Higgs coupling deviations. Examples also exist of theories with entirely neutral scalar top partners [32] and electroweak-charged fermionic top partners [33], both of which share the tree-level modifications to Higgs couplings of the Twin Higgs.

The primary phenomenological consequences of neutral naturalness are (1) a significant weakening of direct search limits due to the paucity of states charged under the Standard Model, and (2) the reduction of loop-level corrections to loop-level Higgs couplings. However, these models still lead to distinctive patterns of Higgs coupling deviations that may be first revealed at a Higgs factory.

Tree level Many theories of neutral naturalness, most notably the Twin Higgs [31], feature significant tree-level mixing between the Standard Model-like Higgs and an additional CP even scalar state. Much as with conventional global symmetries, this leads to $O(v^2/f^2)$ deviations in Higgs couplings. In contrast to conventional global symmetries, however, these corrections are typically universal in the sense that they are the same for Higgs couplings to both vectors and fermions. Bounds on v^2/f^2 may be translated directly into bounds on the mass of the twin top partner, as shown in Fig. 1.7. In such cases, CEPC can probe multi-TeV scales and test the efficacy of neutral naturalness down to the percent level.

Loop level While all models of neutral naturalness feature loop-level corrections to Higgs properties, they are the leading effect in many opposite-statistics models such as folded supersymmetry. New partner particles in these models still carry electroweak quan-



Figure 1.8: Left: CEPC reach for color-neutral folded stops in Folded SUSY from Higgs couplings to photons, from [23]. **Right:** CEPC reach in the mass scale of neutral scalar top partners due to loop-level corrections to σ_{Zh} , adapted from [34].

tum numbers, leading to loop-level deviations in the Higgs coupling to photons, as shown in Fig. 1.8. This allows CEPC to place constraints on the mass scale of folded partner particles in the hundreds of GeV, probing tuning of the weak scale to the 20% level in these theories.

It is also possible that the weak scale is stabilized by scalar top partners entirely neutral under the Standard Model without accompanying tree-level Higgs coupling deviations. In this case, all of the distinctive direct search channels and corrections to loop-level Higgs couplings are absent. However, a precision measurement of the Zh cross section is still sensitive to the wavefunction renormalization of the physical Higgs scalar induced by loops of the scalar top partners [34]. In general, n_{ϕ} scalars ϕ_i coupling via the Higgs portal interaction $\sum_i \lambda_{\phi} |H|^2 |\phi_i|^2$ leads to a correction to the Zh cross section of the form

$$\delta\sigma_{Zh} = \frac{n_{\phi}|\lambda_{\phi}|^2}{8\pi^2} \frac{v^2}{m_h^2} \left[1 + \frac{1}{4\sqrt{\tau(\tau-1)}} \log\left(\frac{1-2\tau-2\sqrt{\tau(\tau-1)}}{1-2\tau+2\sqrt{\tau(\tau-1)}}\right) \right]$$
(1.6)

where $\tau = m_h^2/4m_{\phi}^2$. This leads to the sensitivity shown in Fig. 1.8, for which CEPC is able to place constraints in the hundreds of GeV on a scenario that is otherwise largely untestable at colliders.

Other solutions

Symmetries are not the only mechanism for explaining the origin of the weak scale, though other solutions may not be manifestly natural in the same way. However, even non-symmetry explanations for the value of the weak scale (excepting anthropic ones) generically entail some degree of coupling between new degrees of freedom and the Higgs itself. This typically leads to deviations in Higgs couplings, new exotic decay modes of the Higgs, or a combination thereof.

A compelling example of non-symmetry solutions is the relaxion [19], in which the value of the weak scale is set by the evolution of an axion-like particle across its potential in the early universe. The relaxion necessarily couples to the Higgs boson in order for its



Figure 1.9: Constraints on the relaxion mass m_{ϕ} and relaxion-Higgs mixing angle $\sin \theta$ from the non-Standard Model decay of the Higgs into relaxion pairs, adapted from [35]. Shaded regions indicate current exclusions from LEP and the LHC. Dashed blue lines indicate the reach of CEPC and future operation of the LHC in searches for untagged non-Standard Model decays of the Higgs, while the orange dashed line indicates the reach of CEPC in searches for $h \rightarrow \phi \phi \rightarrow 4b$. The green dashed line indicates the reach of CEPC's Z-pole run in searches for $e^+e^- \rightarrow Z\phi$.

evolution to influence the Higgs mass. This leads to a variety of signatures that may be tested via precision Higgs measurements [35, 36].

The most promising signature is that of new exotic Higgs decays, most notably into the relaxion itself. This signature arises in most relaxion models as a generic consequence of the backreaction of electroweak symmetry breaking onto the relaxion potential. The mixing angle between the Higgs and relaxion in these scenarios is parametrically of order

$$\sin\theta \approx \frac{\Lambda_{\rm br}^4}{vfm_b^2} \tag{1.7}$$

where $\Lambda_{\rm br}$ is the confinement scale inducing a potential for the relaxion (identifiable with $\Lambda_{\rm QCD}$ in the most minimal models) and f is the relaxion decay constant. This leads to the decay of the Higgs into pairs of relaxions ϕ , which in turn decay back into Standard Model states via Higg-relaxion mixing.

The CEPC can significantly constrain these scenarios through both direct searches for processes such as $h \rightarrow \phi \phi \rightarrow 4b$ and indirect limits on exotic Higgs decays coming from precision Higgs measurements, as shown in Fig. 1.9. This exemplifies the considerable power of CEPC in identifying natural explanations for the weak scale, even in the absence of additional symmetries, by virtue of its broad sensitivity to new particles interacting with the Higgs.

1.2.2 Electroweak phase transition

The discovery of the Higgs boson marks the culmination of a decades-long research program to understand the source of electroweak symmetry breaking (EWSB). We have known since the mid- 20^{th} century that this symmetry is not realized in nature and that the



Figure 1.10: An illustration of a continuous crossover (left) and a first order phase transition (right).

weak gauge bosons are massive. Now measurements at the Large Hadron Collider (LHC) have provided overwhelming evidence that EWSB results from the recently-discovered Higgs. With the Higgs boson discovery we have learned *why* the electroweak symmetry is broken in nature, but we still do not understand *how* it is broken dynamically — this is the question of the *electroweak phase transition*.

The nature of the electroweak phase transition (EWPT) is controlled by the properties and interactions of the Higgs boson. For instance the Higgs mass sets the temperature scale of the phase transition to be roughly $T \sim m_h \simeq 125$ GeV. The more detailed and interesting features of the phase transition depend also upon the interactions of the Higgs boson with itself, with other Standard Model particles, and with possible new physics. The nature of these interactions will not be determined very precisely at the LHC, where we have only just begun to study the Higgs. Rather, if we want to understand the nature of the electroweak phase transition, we require precision measurements of Higgs physics at a dedicated Higgs factory experiment like CEPC.

First order phase transition or continuous crossover?

Despite years of careful study at the LHC, we still have such a poor understanding of the Higgs that it is impossible to determine even the *order of the electroweak phase transition*. In general, these two scenarios are used to classify symmetry-breaking phase transitions:

- A *first order phase transition* proceeds through the nucleation of *bubbles* that grow, coalesce, and eventually fill the system.
- By contrast, a *continuous crossover* occurs smoothly throughout the system.

See also Fig. 1.10. If the phase transition is determined to be first order, there would be profound implications for early-universe cosmology and the origin of the matter-antimatter asymmetry. Moreover, determining the order of the EWPT is simply the first step in a much richer research program that deals with other aspects of the phase transition including its latent heat, bubble wall velocity, and plasma viscosity.

The Higgs potential

The order of the EWPT is intimately connected to the shape of the *Higgs potential energy* function. For each value of the Higgs field, ϕ , there is an associated potential energy density, $V(\phi)$. During the electroweak phase transition, the Higgs field passes from $\phi = 0$ where the electroweak symmetry is unbroken to $\phi = v \simeq 246 \text{ GeV}$ where the electroweak

symmetry is broken and the weak gauge bosons are massive. Thus the order of the phase transition is largely determined by the shape of $V(\phi)$ in the region $0 < \phi < v$.

For instance, if the Higgs potential has a barrier separating $\phi = 0$ from $\phi = v$, then electroweak symmetry breaking is accomplished through a first order phase transition with the associated bubble nucleation that we discussed above. If there is no barrier in $V(\phi)$, the transition may be either first order or a crossover depending on the structure of the *thermal effective potential*, $V_{\text{eff}}(\phi, T)$.

Currently we know almost nothing about the shape of the Higgs potential. This situation is illustrated in Fig. 1.11 and the following discussion. When we make measurements of the Higgs boson in the laboratory, we only probe small fluctuations of the potential around $\phi = v$. By measuring the strength of the weak interactions, $G_F = (\sqrt{2}v^2)^{-1} \simeq 1 \times 10^{-5} \text{ GeV}^{-2}$, we learn that the Higgs potential has a local minimum at $v \simeq 246 \text{ GeV}$. By measuring the Higgs boson's mass, we learn that the local curvature of the potential at its minimum is $(d^2V/d\phi^2)|_{\phi=v} = m_h^2 \simeq (125 \text{ GeV})^2$. This is the extent of what we know today about the Higgs potential. Even the third derivative, which is related to the Higgs boson's cubic self-coupling, is completely undetermined!

Measurements of the Higgs boson thus far are consistent with the predictions of the Standard Model of particle physics. The Standard Model asserts that the Higgs potential has the form

$$V(\phi) = \frac{1}{2}\mu^2 \phi^2 + \frac{1}{4}\lambda \phi^4 , \qquad (1.8)$$

which only depends on the two parameters μ^2 and λ . Taking $\lambda > 0$ and $\mu^2 < 0$ induces a vacuum expectation value (VEV) for the Higgs field and triggers electroweak symmetry breaking. At the minimum of the potential $v = \sqrt{-\mu^2/\lambda}$ gives the Higgs field VEV and $m_h^2 = -2\mu^2$ gives the Higgs boson's mass. Thus, having measured both $v \simeq 246$ GeV and $m_h \simeq 125$ GeV in the laboratory, the Standard Model completely predicts the shape of the Higgs potential. For these values of the Higgs mass and VEV, the electroweak phase transition is expected to proceed via a continuous crossover in the absence of additional physics beyond the Standard Model.

However the presence of new physics can dramatically change the shape of the Higgs potential without disrupting the measurements of v and m_h . For example, a simple generalization of Eq. (1.8) is to include a sextic term and write the Higgs potential as [37–39]

$$V(\phi) = \frac{1}{2}\mu^2 \phi^2 + \frac{1}{4}\lambda \phi^4 + \frac{1}{8\Lambda^2}\phi^6 .$$
 (1.9)

A potential of this form arises if new, heavy particles are coupled to the Higgs boson, and then Λ is related to the mass scale of the new particles. This potential has enough structure to support two local minima with a barrier between, which we see in Fig. 1.11 for the curve labeled "new physics (1)." The nature of the electroweak phase transition in this model is expected to be very different from the Standard Model due to the barrier [40– 42]. Alternatively the new physics can manifest through a non-analytic term in the Higgs potential, such as the one proposed by Coleman and Weinberg [43],

$$V(\phi) = \frac{1}{4}\lambda\phi^4 \log\frac{\phi^2}{\Lambda^2}.$$
(1.10)

Such a potential arises when new physics is coupled to the Higgs and leads to a strong running in the Higgs quartic self-coupling [44]. As shown by the curve labeled "new physics



Figure 1.11: The Higgs potential energy function. All we know about the shape of the Higgs potential is the local curvature at its minimum. These observations are consistent with the Standard Model, but they are also consistent with models containing new physics that can dramatically change the nature of the electroweak phase transition.

(2)" in Fig. 1.11, this potential is very flat near the origin allowing thermal corrections to induce a barrier and thus a first order phase transition.

Precision measurements of the Higgs boson's interactions with itself and other particles will probe the shape of the potential energy function and thereby provide much-needed experimental input to test the order of the electroweak phase transition.

Cosmological implications

Since we cannot reproduce the high-temperature conditions of the electroweak phase transition in the laboratory, the question of the EWPT has the most relevance for studies of the early universe. Most cosmologists expect that a thermal EWPT occurred soon after the Big Bang when the universe was filled with a very hot plasma. If the early universe EWPT was first order, it may have left behind interesting cosmological relics that could be accessible to observations today.

Gravitational Waves. During a first order electroweak phase transition, gravitational waves are produced from the collisions of bubbles, the decay of magnetohydrodynamic turbulence, and the damping of sound waves [45]. Today these gravitational waves would look like a stochastic and isotropic "noise" from all directions on the sky. As we see in Fig. 1.12 the predicted gravitational wave spectrum falls within reach of future spacebased interferometer experiments, including LISA, DECIGO, BBO, Taiji, and TianQin. The detection of these gravitational waves would provide direct evidence that the cosmological EWPT was a first-order one, but a future collider like CEPC is required to uncover the new physics that explains *why* the EWPT is first order.

Matter-Antimatter Asymmetry. A first order cosmological EWPT provides the right environment to explain the Universe's excess of matter over antimatter through the mechanism of *electroweak baryogenesis* [46]. This mechanism uses the fact that baryon number is



Figure 1.12: The spectrum of gravitational waves generated during a first order electroweak phase transition for the model described in Eq. (1.9). Colored curves show the predicted spectrum for different models as the scale of new physics, Λ , is varied. The figure is reproduced from Ref. [42].

violated in the Standard Model through reactions mediated by the electroweak sphaleron. Before the cosmological EWPT, the sphaleron efficiently converts matter into antimatter, but during the electroweak phase transition the sphaleron-mediated reactions are shut off. If this shutoff is sufficiently abrupt, then an excess of matter over antimatter can be generated. This requires that the electroweak phase transition is *strongly first order* in the sense that

$$\frac{v(T_{\rm pt})}{T_{\rm pt}} \gtrsim 1.0$$
 ("strongly first order" electroweak phase transition) (1.11)

where $v(T_{pt})$ is the value of the Higgs field inside of the bubbles during the phase transition at temperature T_{pt} .

Electroweak baryogenesis is not viable in the Standard Model, because the electroweak phase transition is a continuous crossover, $v(T_{\rm pt}) = 0$, and thus the observed excess of matter over antimatter is an irrefutable motivation for physics beyond the Standard Model. In general the new physics can take many forms, but in the context of electroweak baryogenesis, it is clear that the new physics must couple to the Higgs boson so that the sphaleron-suppression condition in Eq. (1.11) is satisfied. Therefore this condition directly quantifies the required departure from Standard Model physics.

New physics and the electroweak phase transition

The Standard Model predicts that the EWPT is a continuous crossover, but we have seen in the discussion of Fig. 1.11 that even minimal extensions of the Standard Model can drastically change the predictions for electroweak symmetry breaking. Thus for any model with new physics coupled to the Higgs, it is necessary to ask: What is the nature of the electroweak phase transition?

In the years before the LHC started running, much of the work was focused on the *light stop scenario* of the Minimal Supersymmetric Standard Model (MSSM) [47, 48]. Early LHC data determined that this scenario is ruled out [49, 50], because the light stops,

which are colored and charged particles with spin-0, should have been easy to produce and detect at the LHC. However, if the new scalar particles were not charged or colored, the electroweak phase transition could still be first order while evading collider constraints; to leading order, the electroweak phase transition only cares about couplings with the Higgs, not quantum numbers [51]. Therefore in order to assess the unique power of CEPC to test new physics that leads to a first order electroweak phase transition, it is useful to consider models with uncharged and uncolored particles, which are very difficult to probe at the LHC.

A viable model with a first order EWPT is found in even the most minimal extension of the Standard Model with a real, scalar singlet field S [52–54]. The relevant Lagrangian is written as

$$\mathscr{L} = (D_{\mu}H)^{\dagger} (D^{\mu}H) + \frac{1}{2} (\partial_{\mu}S) (\partial^{\mu}S) - \mu_{H}^{2} H^{\dagger}H - \lambda_{H} (H^{\dagger}H)^{2} - \frac{\mu_{S}^{2}}{2} S^{2} - \frac{a_{S}}{3} S^{3} - \frac{\lambda_{S}}{4} S^{4} - \lambda_{HS} H^{\dagger}HS^{2} - 2a_{HS} H^{\dagger}HS$$
(1.12)

where H(x) denotes the Higgs doublet field. The last two operators in Eq. (1.12) correspond to the so-called Higgs portal interactions. The Higgs field acquires a vacuum expectation value, $\langle H \rangle = (0, v/\sqrt{2})$ that breaks the electroweak symmetry. In general the singlet field may acquire a vacuum expectation value, $\langle S \rangle = v_S$, and it can mix with the Higgs boson, which is parametrized by an angle θ . The spectrum of this theory contains two scalars with masses $m_h \simeq 125 \text{ GeV}$ and m_S .

It is also interesting to consider the model that is obtained by imposing a \mathbb{Z}_2 symmetry on Eq. (1.12). This symmetry transformation, $S(x) \to -S(x)$, enforces $a_{HS} = a_S = 0$, and it is conventional to also assume that $v_S = 0$.

The singlet extension of the Standard Model allows for a first order electroweak phase transition in a variety of ways [51]. If the singlet particle is heavy, $m_S \gg m_h$, then it can be integrated out of the theory generating an effective potential for the Higgs field. In the regime where the a_S and λ_S terms are negligible and $\mu_S^2 \gg \lambda_{HS}v^2$, the Higgs potential takes the form

$$V(\phi) = \frac{1}{2}\mu_H^2 \phi^2 + \frac{1}{4} \left(\lambda_H - \frac{2a_{HS}^2}{\mu_S^2}\right) \phi^4 + \frac{\lambda_{HS} a_{HS}^2}{2m_S^4} \phi^6 , \qquad (1.13)$$

which has the same structure as the one that we encountered in Eq. (1.9). The two potentials are matched by taking $\Lambda^2 = m_S^4/(4\lambda_{HS}a_{HS}^2)$. For smaller Λ the shape of the Higgs potential begins to deviate more from the Standard Model prediction, and the phase transition becomes first order. This example illustrates the intuition that models with a first order electroweak phase transition require new, light particles with a large coupling to the Higgs boson. If the singlet particle is so light that we are not justified to integrate it out $(m_S \sim m_h)$ the analysis above is inapplicable, but the phase transition can still be made first order due to the presence of large loop corrections to the Higgs potential [44], large thermal corrections, and/or a multi-step phase transition [55]. Some of these scenarios are illustrated in the left panel of Fig. 1.13 for the Z₂-symmetric singlet extension.

In general the presence of new particles coupled to the Higgs boson modifies how strongly the Higgs couples to itself and to the other Standard Model particles. It is precisely the goal of Higgs factory experiments, like CEPC, to measure these couplings with high precision. Therefore, if the electroweak phase transition is first order, we expect that the measurements of these couplings must deviate from their Standard Model predictions.



Figure 1.13: Parameter space of the real scalar singlet model with \mathbb{Z}_2 symmetry. **Left:** Regions of parameter space that lead to a first order electroweak phase transition that proceeds in one or two steps. The orange curves show the strength of the electroweak phase transition, $v(T_c)/T_c$, in the one-step region. **Right:** Purple curves show the fractional change to the Zh production cross section relative to the SM prediction in percent; these values are $2 \delta g_{hZZ}$ using the notation in the text (1.14). The figures are taken from Ref. [56]. (Also see Ref. [57].)

The coupling that will be measured most precisely at CEPC and future lepton colliders is the Higgs-Z-Z coupling. We can parametrize deviations in this parameter away from the Standard Model prediction with the variable

$$\delta g_{hZZ} \equiv \frac{1}{2} \left(\frac{\sigma(e^+e^- \to hZ)}{\sigma_{\rm SM}(e^+e^- \to hZ)} - 1 \right) \Big|_{s=(250 \text{ GeV})^2} = \frac{g_{hZZ}}{g_{hZZ,\rm SM}} - 1 \Big|_{s=(250 \text{ GeV})^2}.$$
(1.14)

In the singlet extension model, the strength of the hZZ coupling is suppressed compared to the SM prediction. The leading-order suppression arises from the Higgs-singlet mixing, and the sub-leading effect arises from Higgs wavefunction renormalization [34] and the Higgs triple self-coupling [58]. Combining these effects, the fractional suppression is written as [56, 59]

$$\delta g_{hZZ} = (\cos \theta - 1) - 2 \frac{|a_{HS} + \lambda_{HS} v_S|^2}{16\pi^2} I_B(m_h^2; m_h^2, m_S^2)$$
(1.15)
$$- \frac{|\lambda_{HS}|^2 v^2}{16\pi^2} I_B(m_h^2; m_S^2, m_S^2) + 0.006 \left(\frac{\lambda_3}{\lambda_{3,\text{SM}}} - 1\right)$$

where θ is the Higgs-singlet mixing angle, and I_B is a loop function. The Higgs triple selfcoupling λ_3 also deviates from the Standard Model prediction due to the Higgs-singlet mixing. Then the self-coupling is predicted to be [60]

$$\lambda_3 = (6\lambda_H v) \cos^3 \theta + (6a_{HS} + 6\lambda_{HS} v_S) \sin \theta \cos^2 \theta + (6\lambda_{HS} v) \sin^2 \theta \cos \theta + (2a_S + 6\lambda_S v_S) \sin^3 \theta .$$
(1.16)

In the Standard Model we have $\lambda_3 = \lambda_{3,\text{SM}} \equiv 3m_h^2/v \simeq 191 \text{ GeV}$. If the singlet is light, $m_S < m_h/2$, then the Higgs boson acquires an exotic decay channel, $h \to SS$, which



Figure 1.14: Collider observables in the real scalar singlet model. Points in theory space with a first order phase transition are shown in orange, points with a strongly first order phase transition are shown in blue, and points with a strongly first order phase transition that also produces detectable gravitational waves are shown in red. The figure is reproduced from Ref. [59].

may be invisible depending on the stability of S. The rate for this decay is

$$\Gamma(h \to SS) = \frac{\lambda_{211}^2}{32\pi m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}}$$
(1.17)

where

$$\lambda_{211} = (2a_{HS} + 2\lambda_{HS}v_S)\cos^3\theta + (4\lambda_{HS}v - 6\lambda_Hv)\sin\theta\cos^2\theta + (6\lambda_Sv_S + 2a_S - 4\lambda_{HS}v_S - 4a_{HS})\sin^2\theta\cos\theta + (-2\lambda_{HS}v)\sin^3\theta$$
(1.18)

is the effective tri-linear coupling of the mass eigenstates. Measurements of the Higgs boson at the LHC already strongly constrain the invisible decay channel, which requires $\lambda_{211} \ll 1$ or $m_S > m_h/2$.

The complementarity between a first order electroweak phase transition and precision Higgs observables is shown in Fig. 1.14 for the singlet extension of the Standard Model. Orange points correspond to models with a first order phase transition, $v(T_{\rm pt})/T_{\rm pt} \neq 0$. Blue points correspond to models with a strongly first order phase transition, $v(T_{\rm pt})/T_{\rm pt} \gtrsim$ 1, which is a necessary requirement for electroweak baryogenesis (1.11). Red points correspond to models with a very strongly first order phase transition that can potentially be probed by the space-based gravitational wave interferometer telescope LISA.

Figure 1.14 shows that the models with a first order phase transition (all colored points) also generally predict large deviations in the hZZ coupling. For the models with a strongly first order phase transition (blue and red points) the effect on g_{hZZ} is large enough to be tested by CEPC. Additionally, most of the parameter points also predict a large enhancement to the Higgs trilinear self-coupling that can be probed by a future 100 TeV hadron collider experiment, like the proposed SppC. The funnel region of orange points at $\lambda_3/\lambda_{3,SM} \approx 1$ corresponds to a "blind spot" where the Higgs-singlet mixing vanishes. Thus, apart from the blind spot, *the reach of CEPC is sufficient to probe a first order electroweak phase transition across the entire parameter space*.



Figure 1.15: A correlation between the cubic self-coupling of the SM-like scalar boson and the critical temperature of the first order electroweak phase transition. To connect with the notation in the text, $g_{111} \rightarrow \lambda_3/(6 \text{ GeV})$ and $T_c \rightarrow T_{\text{pt}}/\text{GeV}$. The figure is reproduced from Ref. [60].

The blind spot mentioned above corresponds to two scenarios. The Higgs-singlet mixing could vanish, because of an accidental cancellation between a_{HS} and $\lambda_{HS}v_S$. This corresponds to an artificially fine-tuned parameter space, that is not theoretically appealing. Alternatively, the mixing vanishes identically in the \mathbb{Z}_2 symmetric limit of the singlet extension. In this case, the relevant parameter space is shown in Fig. 1.13. The right panel shows the predicted deviation in the hZZ coupling away from the Standard Model expectation, which is comfortably within reach of CEPC's projected sensitivity.

Another representation of the parameter space appears in Fig. 1.15, which shows a correlation between the phase transition temperature and the Higgs cubic self-coupling. For a similar analysis see also Ref. [61], but note that this article was published before the Higgs mass was determined.

Among all possible new physics that renders the electroweak phase transition to be first order, we focus on the singlet extension here, because it is the most challenging to test with collider experiments. To illustrate this point, one can allow the new scalar particles to carry an electric charge (similar to a two-Higgs doublet model). An analysis of this model has been performed in Ref. [59], and the results are shown in Fig. 1.16. The CEPC has enough sensitivity to test the entire interesting parameter space, and much of the space will also be tested by measurements at the LHC.

What will we learn from CEPC?

The CEPC will probe the Higgs boson with unprecedented precision. While the LHC has taught us that the Higgs is responsible for electroweak symmetry breaking, measurements at CEPC provide a unique opportunity to learn *how* electroweak symmetry breaking occurs. The nature of the electroweak phase transition is a question that we cannot settle using only measurements at the LHC and its upgrades. Simple and compelling extensions of the Standard Model can have a dramatic effect on the nature of the electroweak phase transition, while remaining completely inaccessible to the LHC. However, the presence of new particles coupled to the Higgs boson must affect the way that the Higgs boson



Figure 1.16: A model in which the new scalar particles are charged and uncolored. Such a model can be tested by CEPC, but it is already strongly constrained by the LHC's measurement of the Higgs diphoton decay width. The figure is reproduced from Ref. [59].

couples to itself and to other Standard Model particles, such as the Z-boson. Therefore precision measurements of the Higgs couplings are precisely what's required to expose the new physics. In particular, the strength of the hZZ coupling, which will be measured at the 0.1% level by CEPC, is an excellent litmus test for a first order electroweak phase transition.

1.3 Exploring new physics

Exotic new physics could interact with the Standard Model in multiple ways that could be tested at CEPC. Here we summarize and classify different possible scenarios, which are discussed in more detail in the following sections:

- 1. Exotic particles carry Standard Model charges. The classic example in the dark matter context is dark matter in electroweak multiplets: although dark matter must be neutral, it could be part of an SU(2) multiplet that also contains charged particles. Because CEPC is primarily a machine for Higgs and electroweak physics, this is a natural case to consider.
- Renormalizable Standard Model portals: if there are no new particles with Standard Model gauge interactions and no new gauge groups that the Standard Model particles are charged under, exotic particles in the hidden (dark) sectors can still interact with the Standard Model via the gauge-singlet operators H[†]H ("Higgs portal") [62–69], B_{μν} ("hypercharge portal" or kinetic mixing) [70–76], and HL ("neutrino portal") [77–83].
- 3. Portals with additional Standard Model sector physics or new gauge groups that the Standard Model is charged under: if some exotic particle itself carries no Standard Model gauge charges, it may nonetheless interact with the Standard Model via unknown new particles with Standard Model charges. For instance, the existence of a

second Higgs doublet that couples dominantly to leptons can make models of "leptophilic" dark matter possible. The second possibility is that there exists some new gauge group, e.g. U(1)', that (some) Standard Model particles are charged under. Then there is a renormalizable coupling between the new gauge boson and the current made of the Standard Model particles. If the new gauge group is anomalous with the Standard Model particle content, there could also be a Wess-Zumino type interaction between the Z and the new gauge boson [84–93].

4. Effective theory and high dimensional operators: this approach is agnostic to which of the above three scenarios we consider. The theory only contains certain light exotic particles and the Standard Model. The other new physics that generates the coupling between them is not identified and is only encoded in Wilson coefficients. Examples include an axion-like particle (ALP) interacting with the Z boson or photon through dimension-five operators [94–106] and magnetic inelastic dark matter and Rayleigh dark matter models [107–111], in which the dark sector interacts with Z via even higher dimensional operators.

These different scenarios may result in modifications to precision Higgs and Z observables or to exotic Higgs and Z decays. The first type of signal has been discussed in Chapter 2. In sections 1.3.1 and 1.3.2, we will discuss the potential of CEPC for measuring exotic Higgs and Z decays. Then in section 1.3.3, we will focus on the implications for dark matter and dark sectors. In sections 1.3.4 and 1.3.5, we will discuss the potential of measuring exotic physics connected to neutrino and flavor physics.

1.3.1 Exotic Higgs boson decays

Higgs boson can be an important portal to new physics beyond the Standard Model. Such new physics could manifest itself through Higgs exotic decays if some of the degrees of freedom are light. The Higgs boson BSM decays have a rich variety of possibilities. Two-body Higgs decays into BSM particles $H \rightarrow X_1X_2$, where the BSM particles X_i are allowed to subsequently decay further, are considered here. These decay modes are classified into four cases, schematically shown in Fig. 1.17. These processes are well-motivated by BSM models such as singlet extensions of the SM, two-Higgs-doublet-models, SUSY models, Higgs portals, gauge extensions of the SM, and so on [112–114].



Figure 1.17: The topologies of the SM-like Higgs exotic decays.

For CEPC running at the center of mass energy 240 GeV, the most important Higgs production mechanism is Z-Higgs associated production $e^+e^- \rightarrow Z^* \rightarrow ZH$. The Z boson with visible decays enables Higgs tagging using the "recoil mass" technique. A cut around the peak of the recoil mass spectrum would remove the majority of the SM background. Further selection and tagging on the Higgs decay product can hence achieve

Decay	95% C.L. limit on Br			
Mode	LHC	HL-LHC	CEPC	
$E_{\rm T}^{\rm miss}$	0.23	0.056	0.014	
$(b\bar{b}) + E_{\rm T}^{\rm miss}$	_	[0.2]	1×10^{-4}	
$(jj) + E_{\mathrm{T}}^{\mathrm{miss}}$	_	-	4×10^{-4}	
$(\tau^+\tau^-) + E_{\rm T}^{\rm miss}$	_	[1]	8×10^{-5}	
$b\bar{b} + E_{\rm T}^{\rm miss}$	_	[0.2]	2×10^{-4}	
$jj + E_{\mathrm{T}}^{\mathrm{miss}}$	_	-	5×10^{-4}	
$\tau^+ \tau^- + E_{\rm T}^{\rm miss}$	_	_	8×10^{-5}	
$(bar{b})(bar{b})$	1.7	(0.2)	6×10^{-4}	
(car c)(car c)	_	(0.2)	8×10^{-4}	
(jj)(jj)	_	[0.1]	2×10^{-3}	
$(b\bar{b})(\tau^+\tau^-)$	[0.1]	[0.15]	4×10^{-4}	
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]	$[0.2 \sim 0.4]$	2×10^{-4}	
$(jj)(\gamma\gamma)$	_	[0.01]	1×10^{-4}	
$(\gamma\gamma)(\gamma\gamma)$	$[7 \times 10^{-3}]$	4×10^{-4}	8×10^{-5}	

Table 1.1: The current and projected limits on Higgs exotic decay modes for the (HL-)LHC and CEPC with 5 ab^{-1} integrated luminosity, based upon results from Ref. [114]. The projections for the HL-LHC are collected in the third column, where the limits for 100 fb⁻¹ and 300 fb⁻¹ alone are shown in parentheses and square brackets, respectively.



Figure 1.18: The 95% C.L. upper limit on selected Higgs exotic decay branching fractions at HL-LHC and CEPC, based on Ref. [114]. The benchmark parameter choices are the same as in Table 1.1. The red bars correspond to the results using only leptonic decays of the spectator Z-boson. The yellow bars further include extrapolation with the inclusion of the hadronic decays of the spectator Z-boson. Several vertical lines are drawn in this figure to divide different types of Higgs exotic decays.

high signal efficiency, and the major background would be from the Higgs SM decays. The details of these analysis can be found in Ref. [114].

The set of Higgs exotic decays with their projected LHC constraints and limits from the CEPC with 5 ab^{-1} integrated luminosity are summarized in Table 1.1. For the LHC constraints, both the current limits and projected limits on these exotic decay channels from various references are tabulated. The comparison are performed for particular benchmark points to demonstrate the qualitative difference between the (HL-)LHC and CEPC.

The exotic Higgs decay channels summarized in Table 1.1 and the corresponding Fig. 1.19 are among the most difficult modes to constrain at the LHC and exemplify the considerable sensitivity of the CEPC. The red bars in Fig. 1.19 correspond to a recoil mass analysis that only uses leptonic decays of the Z-boson that is produced in association with the Higgs boson. The inclusion of hadronic decays of the Z-boson provides around ten times more statistics and would lead to substantially improved reach. Based upon the study of Higgs decays $H \rightarrow WW^*$, ZZ^* and invisibles, hadronically decaying Z-bosons are conservatively assumed to provide a limit comparable to the limit from leptonic Z-bosons, and hence improve the limits by around 40% when combined. These extrapolated results are shown in yellow bars in Fig. 1.18.

In comparison with the HL-LHC, the improved coverage of Higgs exotic branching fractions is significant, varying from one to four orders of magnitude for the channels under consideration. For the Higgs exotic decays into hadronic final states plus missing energy, $b\bar{b} + E_{\rm T}^{\rm miss}$, $jj + E_{\rm T}^{\rm miss}$ and $\tau^+\tau^- + E_{\rm T}^{\rm miss}$, CEPC improves on the HL-LHC sensitivity for these channels by three to four orders of magnitude. These significant improvements benefit from low QCD backgrounds and the Higgs tagging from recoil mass reconstruction at CEPC. As for the Higgs exotic decays without missing energy, the comparative improvements vary between two to three orders of magnitude, as LHC performance in these channels is improved by reconstruction of the Higgs mass from visible final state particles and reduced QCD backgrounds in events with leptons and photons.

1.3.2 Exotic Z boson decays

The CEPC's Z-pole run will offer unique possibilities to test new physics that allows the Z boson to decay through new, exotic channels. Fig. 1.19 summarizes the sensitivity of CEPC to exotic Z decays, and it compares CEPC's sensitivity to that of the highluminosity LHC (HL-LHC) and a proposed Tera Z upgrade. Exotic Z decay channels are classified by final states, the number of intermediate resonances, and different topologies. The final states considered here include $Z \to E + \gamma, E + \gamma\gamma, E + \ell^+\ell^-, E + JJ$, (JJ)(JJ) and $\gamma\gamma\gamma$. Each pair of photons, charged leptons, or jets can form a resonance, denoted with (). All six categories of final states are represented in Fig. 1.19; several representative decay topologies are chosen for each category and correspondingly labeled on the bar-chart. For CEPC and Tera Z, the sensitivity reach for exotic Z decay branching ratios (BR) are plotted as blue and red bars. These projections include kinematic cuts, namely general p_T and angular cuts on reconstructed objects, as well as an appropriate invariant mass cut if there is a resonance in the pair of particles (including dark matter particles). The cuts are optimized for each topology by checking the kinematic variable distributions. The sensitivity reach for the HL-LHC at 13 TeV with $\mathcal{L} = 3 \text{ ab}^{-1}$ has been computed in a similar way. Details of the simulation can be found in Ref. [115].

The sensitivity to final states with missing energy reaches branching ratios of 10^{-6} to $10^{-9.5}$ for CEPC and 10^{-7} to $10^{-11.5}$ for Tera Z. For each topology, the light blue and red shaded regions indicate the range from varying the model parameters, like mediator or dark matter mass. The light color regions with dashed boundary show the optimal sensitivity, while the dark color regions with solid boundary show the pessimistic benchmark of the model. In all the channels, future Z factories improve the sensitivity by several orders of magnitude above those of the HL-LHC.



Figure 1.19: The sensitivity reach in the Z branching ratio for various exotic Z decay topologies at CEPC (10^{10} Z), a possible extension to Tera Z (10^{12} Z), and the high luminosity LHC at 13 TeV with $\mathcal{L} = 3 \text{ ab}^{-1}$. Adapted from Ref. [115].

In general, CEPC has several advantages compared to a hadron collider like the HL-LHC. First, an e^+e^- collider has a much cleaner environment compared to a hadron collider with a huge QCD background. Second, in the Drell-Yan production of a Z boson at a hadron collider, the decay products tends to be soft because the Z boson mass is small compared to the beam energy, which makes them hard to detect at the HL-LHC. Therefore, it is natural that CEPC has better sensitivity compared to the HL-LHC and provides a better opportunity to investigate dark sector physics through exotic Z decays.

Two specific benchmark scenarios demonstrate the significant power of exotic Z decays to probe different dark (hidden) sectors [115]. (Further discussion of a variety of exotic Z decays appears in [116].) The first model contains fermionic dark matter interacting with a singlet real scalar S, which mixes with the Standard Model Higgs. The possible exotic Z decay channel in this case is $Z \to \tilde{s}Z^* \to (\bar{\chi}\chi) + \ell^+\ell^-$, where \tilde{s} is the light scalar mass eigenstate (mostly the dark Higgs S) and χ is the fermionic dark matter. The second model is an axion-like particle a coupling to the Standard Model U(1)_Y gauge field B_{μ} . Then the exotic Z decay is $Z \to a\gamma \to (\gamma\gamma)\gamma$. The final state is 3γ and in the case that m_a is too small to separate the two photons, the final state is 2γ . The sensitivity of exotic Z decays (as well as other possible probes) to key parameters in these two models is summarized in Fig. 1.20.

Projections for CEPC and Tera Z reach in the first model are are shown in the left panel of Fig. 1.20. There are two free parameters, namely the Higgs mixing angle $\sin \alpha$ and dark Higgs mass $m_{\tilde{s}}$. The other two parameters related to dark matter are fixed. One is the dark matter mass, fixed close to half of $m_{\tilde{s}}$, which only affects the dark matter relic abundance but not other limits. The other one is the Yukawa coupling between dark matter χ and the dark Higgs \tilde{s} , which is taken to be $y_{\chi} = 0.1$ for illustrative purposes. Limits are projected for the exotic Z decay process $Z \to \ell^+ \ell^- \tilde{s} \to \ell^+ \ell^- (\bar{\chi}\chi)$, which has been labeled as an orange solid line for CEPC (10^{10} Z) option and a red dot-dashed line for the



Figure 1.20: The reach for rare Z decays at CEPC in two benchmark scenarios, adapted from Ref. [115]. Left: the sensitivity to the dark Higgs mixing angle $\sin \alpha$ at CEPC $(10^{10} Z)$ and at a Tera Z option $(10^{12} Z)$ in a Higgs portal dark matter model, using the process $Z \to \ell^+ \ell^- \tilde{s} \to \ell^+ \ell^- (\bar{\chi}\chi)$. Right: the sensitivity to the coupling Λ_{aBB} for an axion-like particle (ALP) model as a function of the ALP mass m_a , where B is the hypercharge gauge field. The signal process is $Z \to \gamma a$, where a can decay to a pair of photons (3γ) , be detected as one photon due to high boost (2γ) , or be detected as missing energy due to its long lifetime $(\gamma \not E)$.

Tera Z (10^{12} Z) option, and compared with the LEP result with an integrated luminosity 114 pb^{-1} [117] labeled as "LEP-Zs-inv".

The dark Higgs in this benchmark scenario can also be constrained by the modification of SM Higgs couplings proportional to the mixing angle $\sin \alpha$, independent of the scalar mass \tilde{s} . The global fit to Higgs data at the LHC 7 TeV and 8 TeV runs can constrain the single scaling factor to Higgs interactions, giving $\sin \alpha < 0.33$ [118]; this is labeled as " \tilde{h} current global fit (LHC)". The HL-LHC can extend this reach to $\sin \alpha < 0.28 \ (0.20)$ using 300 fb^{-1} (3 ab^{-1}) luminosity [119]. At CEPC, the precision measurement of the Higgs bremsstrahlung cross-section $\sigma(Zh)$ can reach the accuracy of O(0.3% - 0.7%)expected from $5-10 \text{ ab}^{-1}$ [120–122], which can probe the scalar mixing down to 0.055-0.084 [123]; this is labeled as " $\delta\sigma(Zh)$ ". In addition, there are constraints coming from the invisible decay of the SM Higgs. The current LHC limits from the Run I combination of ATLAS and CMS data constrains $BR(h \rightarrow inv) < 0.23$ at 95% C.L. [124, 125]. Following the h invisible decay branching ratio in the Higgs portal dark matter model, the limit on the mixing angle $\sin \alpha$ is labeled as "BR^{\tilde{h}}_{inv} < 0.23". We also add the HL-LHC (3 ab⁻¹) and future e^+e^- collider projections on invisible Higgs search, which lead to 95% C.L. limits $BR_{inv}^{\tilde{h}} \lesssim 0.08 \sim 0.16$ [126, 127] and $BR_{inv}^{\tilde{h}} \lesssim 0.003$ [121, 128] at ILC and CEPC. There are also constraints based on dark matter assumptions. The dark matter relic abundance [129] is satisfied on the dashed gray line, while the direct detection limits on spin-independent cross-sections (XENON1T [130], LUX [131], PANDAX-II [132], and CRESST-II [133]) exclude the region within the dashed green line.

Projections for CEPC and Tera Z reach in the second model are illustrated in the right panel of Fig. 1.20, focusing on the exotic Z decay $Z \rightarrow \gamma a$ followed by $a \rightarrow \gamma \gamma$. In the 3γ signal, the ALP mass is heavy enough that the two photons are well separated and

detectable. When the mass of the ALP is below O(1) GeV, the boost of the axion makes the two photons from the axion decay close enough together that they cannot be resolved, leading to signals in the 2γ search channel. The current constraints on the two cases are given by LEP and LHC photon searches. In Fig. 1.20, the LEP I [134] constraint uses an inclusive diphoton search $e^+e^- \rightarrow 2\gamma + X$ covering the small mass region. In the higher mass region, the boost of the axion decreases and the 3γ channel is considered. The LEP II (OPAL) constraints have 2γ and 3γ data [135], which are employed to put bounds on the process $e^+e^- \rightarrow \gamma/Z^* \rightarrow a\gamma \rightarrow 2\gamma + \gamma$. ATLAS 3γ and $Z \rightarrow 3\gamma$ [136, 137] searches can be translated to an ALP bound, as derived in [138]. There is also the possibility that the ALP decays outside of the detector, which is relevant for a $E + \gamma$ search. In this case the strongest bound comes from the LEP L3 collaboration with 137 pb^{-1} data at the Z pole [139], which constrains the branching ratio of the exotic decay $Z \to \gamma E$ down to 1.1×10^{-6} if the photon energy is greater than ~ 30 GeV. It directly excludes $\Lambda_{aBB} < 4.3 \times 10^4 \text{ GeV}$ for $Z \to \not E + \gamma$ decay, and is labeled as "L3 ($\not E \gamma$)" in the right panel of Fig. 1.20. The sensitivity curves are plotted as an orange solid line for CEPC ($10^{10} Z$) and a red dot-dashed line for a Tera $Z(10^{12} Z)$ option, demonstrating the significant reach of CEPC and Tera Z in this scenario.

These comparisons show that searches for exotic Z decays at CEPC (and a possible Tera Z extension) can provide the leading sensitivity to a range of motivated extensions of the Standard Model, substantially exceeding the reach of dark matter direct detection experiments, current limits from collider searches, and estimated sensitivities of the high luminosity run of the LHC (HL-LHC).

1.3.3 Dark matter and hidden sectors

Observations tell us that the majority of matter in the universe is dark matter (DM). Because the abundance of dark matter in the universe is within an order of magnitude of the abundance of ordinary matter, it is natural to suspect that dark matter and ordinary matter should be related in some way. A variety of models, including the classic thermal relic weakly interacting massive particle (WIMP), attempt to explain the abundance of dark matter in terms of its interactions with ordinary matter. In some models, there is a richer "dark sector" consisting not only of dark matter itself but of new force-carrying particles that can mediate self-interactions between dark matter particles or interactions of dark matter with ordinary matter.

Different classes of possibilities for how dark matter interacts with the Standard Model have been summarized in Sec. 1.3. Below we discuss each of these possibilities in turn. This categorization of studies may be useful in the future for identifying DM scenarios at CEPC that have not yet been fully studied.

There are major efforts underway to search for dark matter via direct detection, indirect detection, and searches at the LHC and lower-energy-but-high-luminosity collider and fixed-target experiments. It is possible that one of these experiments will discover a dark matter signal before CEPC operates. Even in that case, CEPC can play a crucial role in discovering the *nature* of the dark matter particle. Direct detection, for example, may tell us a spin-independent scattering rate, but without knowledge of the local dark matter density or whether the particle we are seeing constitutes all of the dark matter or is just a component, limited knowledge of particle physics would be gleaned from the discovery. The role of CEPC in such a case could be to tell us that dark matter interacts directly with

the Higgs boson or weak gauge bosons, for instance. Below we will emphasize both cases in which CEPC can *measure* dark matter properties and supplement other experiments and cases in which CEPC could play the crucial role in *discovering* a DM signal for the first time.

Dark matter in electroweak multiplets

The CEPC's strength is electroweak physics, both through precision measurements of properties of the W and Z bosons and through its primary role as a Higgs factory. Studies of CEPC's capabilities for detecting new electroweak physics include Refs. [20, 23, 40, 140–146]. Hence, the most natural place to begin is with CEPC searches for dark matter particles that are in electroweak multiplets (e.g. doublets or triplets of $SU(2)_L$) or mixtures of electroweak multiplets (including admixtures of a singlet). Studies on this topic include Refs. [147–152].

One question is whether other, dedicated dark matter experiments will cover the full parameter space of dark matter in electroweak multiplets. Dark matter direct detection experiments, like the currently-operating Xenon1T [130] and PandaX [153], are currently probing much of the parameter space for spin-independent dark matter scattering on nucleons mediated by Higgs exchange. The current bound on the DM-nucleon cross section of a few times 10^{-46} cm² corresponds to an $h\chi\chi$ coupling in the Lagrangian with coefficient of order 10^{-2} . Future experiments like DARWIN [154] will potentially push the search down to the neutrino floor, corresponding to $h\chi\chi$ couplings of order 10^{-3} . This will probe a large swath of the parameter space for electroweak dark matter.

As noted above, CEPC could help to measure DM properties even if a direct detection experiment makes the discovery first. Still more interesting are possibilities in which electroweak DM could be *missed* by direct detection experiments but seen by CEPC. There are two main scenarios to consider where this could happen. The first is if DM is a nearly pure electroweak multiplet, such as a pseudo-Dirac higgsino. Such particles have very small interactions with the Higgs, so their direct detection rate is loop-suppressed and at about the level of the neutrino floor [155]. These particles would also be very difficult to detect at the LHC [156]. Indirect detection may constrain them, but at low mass their thermal abundance is low, and even a significant non-thermal abundance may fall below current constraints [157, 158]. A second possibility is that DM lies in a mixed electroweak multiplet with couplings to the Higgs, but the coupling of the lightest mass eigenstate has a small coupling to the Higgs, either accidentally or due to an approximate symmetry. This is referred to as a *blind spot* for direct detection [159, 160]. For instance, a mostlywino dark matter particle in a supersymmetric theory has vanishing tree-level coupling to the Higgs boson if $M_2 = -\mu \sin(2\beta)$. In some cases, a spin-independent blind spot may be covered by spin-dependent scattering. Blind spots might also be uncovered by collider searches [161].

Robust blind spots for both spin-dependent and spin-independent scattering arise in some theories due to approximate *parity* or *custodial* symmetries. In the MSSM, this occurs for higgsino dark matter at $\tan \beta = 1$ and $\operatorname{sign}(\mu M_{1,2}) < 0$. In closely related theories, these blind spots have been understood to result from custodial symmetries [148]. These robust direct detection blind spots are excellent opportunities for CEPC to play a role in dark matter physics, so let us explain the physics in somewhat more detail. They arise for pseudo-Dirac DM, i.e. theories with a Dirac mass term of the form $\mu \chi_1 \chi_2$ which can be written as a sum of two Majorana mass terms, $\mu(\chi_+\chi_+ - \chi_-\chi_-)$ where $\chi_{\pm} =$

 $(\chi_1 \pm \chi_2)/\sqrt{2}$. In such a theory the Z boson couples off-diagonally, $Z_{\mu}(\chi_{+}^{\dagger}\overline{\sigma}^{\mu}\chi_{-} + h.c.)$. Mixing or higher-dimension operators can split the mass eigenstates, but in the custodially symmetric limit, the eigenstates remain χ_{+} and χ_{-} rather than mixtures thereof. There is a parity symmetry under which χ_{+} and the Z are odd but χ_{-} and h are even, which forbids an $h\chi_{+}\chi_{+}$ coupling. Hence when χ_{+} is the lighter mass eigenstate, both spin-dependent and spin-independent scattering are turned off.

A number of studies have been carried out on two particular models of electroweak dark matter, the doublet-singlet and doublet-triplet models (e.g. [162–164]). The doublet-singlet model introduces a singlet fermion S (with zero hypercharge) with Majorana mass $-(m_S/2)SS$ and two electroweak doublet Weyl fermions $D_{1,2}$ with opposite hypercharges $\pm 1/2$ and Dirac mass $-m_D\epsilon_{ij}D_1^iD_2^j$, together with mixing through the SM Higgs:

$$y_1 H S D_1 - y_2 H^{\dagger} S D_2 + \text{h.c.}$$
 (1.19)

The doublet-triplet model introduces the same doublet fields as well as an SU(2) triplet with zero hypercharge, T, with a Majorana mass $-(m_T/2)T^iT^i$ and mixing with the doublet through the Higgs:

$$y_1(H\sigma^i D_1)T^i - y_2(H^{\dagger}\sigma^i D_2)T^i + \text{h.c.}$$
 (1.20)

Both of these models have blind spots for both spin-independent *and* spin-dependent direct detection in the pseudo-Dirac case when $m_D < m_{S,T}$ (all mass parameters taken to be positive) and $y_1 = y_2$. An explicit rewriting of the Lagrangian that makes a custodial symmetry manifest in this limit has been given in [148]. This blind spot can also be understood in terms of a parity symmetry at the point $y_1 = y_2$ along the lines explained in the previous paragraph.

In the SUSY context we can identify the fields S, D, and T with the bino, higgsino, and wino. In this case the couplings y_1 and y_2 are equivalent to $g^{(\prime)} \cos \beta$ and $g^{(\prime)} \sin \beta$ in the doublet-triplet (doublet-singlet) case. These relatively small couplings tend to lead to small signals at CEPC. However, it is also interesting to consider extensions of the MSSM with an *additional* doublet and singlet that mix to serve as dark matter. Such theories can help to explain why the observed Higgs mass is heavier than expected in the simplest SUSY theories [165], which offers a motivation for considering the larger values of $y_{1,2}$ that could be probed at CEPC.

Precision electroweak physics at the Z pole is most sensitive to the S and T parameters. Although these operators appear in studying the propagators of gauge fields, they originate from new physics that couples to the Higgs. For instance, in the basis of Ref. [166], the S parameter is related to the operators $H^{\dagger}\sigma^{i}HW_{\mu\nu}^{i}B^{\mu\nu}$, $(H^{\dagger}\sigma^{i}\overrightarrow{D}_{\mu}H)D^{\nu}W_{\mu\nu}^{i}$, and $(H^{\dagger}\overrightarrow{D}_{\mu}H)\partial^{\nu}B_{\mu\nu}$; the T parameter, to $(H^{\dagger}\overrightarrow{D}_{\mu}H)^{2}$. These operators are generated in the doublet–singlet or doublet–triplet model because the fermions mix by coupling to the Higgs boson. On the other hand, for a pure electroweak multiplet like the pseudo-Dirac higgsino, Higgs couplings are very small and S and T are suppressed. The T parameter is also suppressed in models with a good approximate custodial symmetry. In such theories, other electroweak precision observables like the W and Y operators $(D^{\mu}W_{\mu\nu}^{i})^{2}$ or $(\partial^{\mu}B_{\mu\nu})^{2}$ may be relatively important, though they are generated with small coefficients and are harder to probe. In this case, observables at 240 GeV from processes like $e^{+}e^{-} \rightarrow \mu^{+}\mu^{-}$ [167] or $e^{+}e^{-} \rightarrow W^{+}W^{-}$ [149, 168] may be more effective probes of electroweak dark matter than Z-pole observables.



Figure 1.21: Left: The CEPC electroweak precision (S, T) fit probe of the doublet-triplet model at the custodially symmetric point $y_1 = y_2 = 1$, taken directly from Figure 5a of Ref. [148]. When the dark matter particle is mostly triplet $(m_D \gg m_T)$, spin-independent direct detection is a powerful probe (shaded green region). When the dark matter particle is mostly doublet, the tree-level direct detection rate vanishes but CEPC's measurement of the *S* parameter becomes a powerful probe (dashed contours). **Right:** CEPC's sensitivity to the same model via the Higgsstrahlung cross section $\sigma(Zh)$, taken directly from Figure 11b of Ref. [151]. We see that in a large part of parameter space with $m_T \gg m_D$, where the direct detection rate is low due to custodial symmetry, there are observable (percent-level or higher) deviations in the *Zh* cross section.

The doublet-singlet and doublet-triplet models at CEPC have been discussed in Ref. [148], which focuses on the S and T parameters (and also discusses a quadruplet-triplet model with similar properties).¹ They have shown that CEPC can probe a large region of parameter space where the dark matter mass is below 200 GeV, and certain regions of parameter space with even larger masses. In particular, the S parameter allows a probe of the custodially symmetric region that is hidden from direct detection. We show some results from this paper in the left-hand panel of Figure 1.21. A related study in Ref. [151] considers effects of doublet-singlet and doublet-triplet dark matter on Higgs observables, including the Zh cross section, the $h \rightarrow \gamma \gamma$ decay rate, and the Higgs invisible width. Away from the custodially symmetric point in the doublet-singlet model, when $y_1 = 0.5$ and $y_2 = 1.5$, CEPC's measurement of the total Zh cross section probes the lightest neutralino mass up to 200 GeV. For $y_1 = y_2 = 1$, with custodial symmetry, deviations are smaller and m_D is probed only up to about 125 GeV. In the doublet-triplet case, the region of parameter space bounded by the Zh measurement is illustrated in the right-hand panel of Figure 1.21. Aspects of a slightly different doublet-singlet model, with the singlet taken to be a Dirac fermion, have also been discussed in Ref. [147]. They focus on the region with mostly singlet DM, in which case the doublet may be thought of as allowing a completion of a "Higgs portal" model. In this case, the most important constraints come from the T parameter. They also present results for a wider range of doublet and singlet masses including cases where dark matter is mostly doublet.

¹Earlier papers discussing electroweak and Higgs constraints on similar models include [169–173].


Figure 1.22: These figures, which are adapted from Ref. [174], show constraints on nonthermal neutralino dark matter and invisible Higgs decays. **Left:** The spin-independent WIMP-nucleon cross-section vs $M_{\tilde{\chi}_1^0}$ for all points allowed by collider and relic density constraints. The color code characterizes the value of Br($h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$), while black points have Br($h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$) < 0.4%. The solid blue line shows the current limit from LUX-2016 [175], and the dashed blue line shows the reach for Xenon1T [176] and Xenon-nT [176]. **Right:** The Higgs to invisible branching ratio Br($h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$) vs. the LSP mass $M_{\tilde{\chi}_1^0}$. The grey (colored) points distinguish the points allowed before (after) the Higgs signal strength constraints. Blue, green, yellow, red points are allowed by the current limits on SI WIMP-nucleon cross-section from Xenon1T, LUX-2016, LUX-2013, and Xenon-100. From top to bottom, the black-dashed line represents the reach of the LHC with 300 fb⁻¹, the LHC with 3000 fb⁻¹, and CEPC.

In the case in which DM resides in a nearly pure electroweak multiplet, the S and T parameters and the $h \rightarrow \gamma \gamma$ rate are no longer useful probes. For the case of nearly pure higgsinos, Ref. [149] has studied the prospects of an $e^+e^- \rightarrow W^+W^-$ measurement at CEPC as a constraint. This measurement is sensitive not only to corrections to the photon and Z propagators but to loop corrections to the triple gauge coupling vertex. Ref. [149] claims that a 0.1% precision measurement of $e^+e^- \rightarrow W^+W^-$ at CEPC could probe higgsino dark matter up to about 210 GeV. However, the scatter plot in Figure 1 of that reference suggests that many models with even heavier higgsinos will be accessible. A more detailed future exploration of the parameter space probed by the W^+W^- measurement would be useful. The rate of $e^+e^- \rightarrow \mu^+\mu^-$ at 240 GeV can also be a sensitive probe of deviations in the propagators of photons and Z bosons; in particular, for new physics contributing to the W and Y parameters but not to S and T, it may be superior to electroweak precision studies on the Z pole thanks to the larger center-of-mass energy. A detailed study of this probe of electroweak physics has been carried out in Ref. [167]. Their conclusion is that if systematic uncertainties can be controlled to achieve a 0.1%precision on the rate, pseudo-Dirac higgsinos may be excluded up to a mass of about 200 GeV. This is encouraging, since pseudo-Dirac doublets are among the most difficult electroweak particles to probe in any experiment. In particular, the LHC is not expected to reach far above 200 GeV (though this will depend in part on how well systematic uncertainties can be understood). The results of Ref. [167] may not apply directly to CEPC due to their assumptions about beam polarization, so a further dedicated CEPC study of this process is warranted.

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Another interesting possibility is that of light singlet dark matter mixing with heavier electroweak-charged particles. A particular example arises for mostly-bino dark matter in the MSSM [174], $\tilde{\chi}_1^0$, which could have a non-thermal relic abundance. Because the bino is a pure singlet, it couples to the Standard Model only through small mixing parameters and is difficult to detect directly. However, in some cases it can be detected through the invisible width of the Higgs boson. The parameter space probed by dark matter direct detection and CEPC is shown in the right panel of Fig. 1.22. This figure illustrates that CEPC could probe the region allowed by the current direct detection with a sensitivity to Br $(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \gtrsim 0.24\%$.

Standard Model portals

If the dark matter does not reside in an electroweak multiplet, it may still interact with the SM particles through gauge-invariant "portal" operators. The portal operators include

$$H^{\dagger}H$$
, $B^{\mu\nu}$, and HL , (1.21)

where H is the SM Higgs doublet, $B^{\mu\nu}$ is the hypercharge field strength tensor, and L is a SM lepton doublet. These three portals are usually referred to as the Higgs portal, the kinetic mixing (or hypercharge) portal, and the lepton (neutrino) portal. These simple portal dark matter scenarios predict rich phenomenology and a plethora of experimental signatures. They have been established as well-defined dark matter benchmarks and experimental targets, in addition to the traditional electroweak WIMP scenario.

The CEPC, along with all the powerful direct and indirect probes it could provide, could potentially play an important role in detecting and testing these SM portals to dark matter. Below we will present estimates of the CEPC potential for the Higgs and kinetic mixing portals based on the studies in the existing literature. The neutrino portal is discussed further in Sec. 1.3.4.

In a simple example of the Higgs portal model, the dark matter (DM) is assumed to be either a real scalar (S) or a Majorana fermion (χ), with the following interaction terms to the Higgs field [177, 178] (maybe cite more)

$$\mathcal{L} = -H^{\dagger}H\left(\frac{\lambda_{\rm DM}}{4}S^2 + \bar{\chi}\frac{y_{\rm DM} + iy_{\rm DM}^P\gamma_5}{\sqrt{2}v}\chi\right).$$
(1.22)

The couplings between a single Higgs particle and the dark matter fields are thus given by

$$\mathcal{L} = -\frac{\lambda_{\rm DM} v}{4} h S^2 - \frac{y_{\rm DM}}{\sqrt{2}} h \bar{\chi} \chi - \frac{i y_{\rm DM}^P}{\sqrt{2}} h \bar{\chi} \gamma_5 \chi \,. \tag{1.23}$$

For dark matter masses smaller than $m_h/2$, the decay channel $h \rightarrow SS/\bar{\chi}\chi$ is open, which produces the signal of Higgs invisible decays. As shown in ... (refer to Higgs section), the CEPC could reach a sensitivity of 0.31% (at 95% CL) on the branching ratio of Higgs invisible decays.² This provides very strong probing powers on Higgs portal models with a dark matter mass below $m_h/2$, which can be competitive with the reaches of current and future direct detection experiments. To illustrate this, we make a comparison between

² Here we only include the Higgs invisible decay to BSM particles. If the SM decay $h \rightarrow ZZ \rightarrow \nu \bar{\nu} \nu \bar{\nu}$ is also included, the bound on the Higgs invisible branching ratio becomes 0.42% instead. See ... (refer to Higgs section) for more details.



Figure 1.23: The *mass-coupling* plane for the Higgs portal models of Eq. (1.23) with a scalar DM (left), a Majorana fermion DM with a scalar coupling y_{DM} (middle) and a Majorana fermion DM with a pseudo-scalar coupling y_{DM}^P (right). The orange region is excluded by the invisible Higgs decay measurements at the CEPC, which constrains the branching ratio to be below 0.31% at 95% CL. The blue region is excluded by the most recent result from XENON1T [179]. The cyan dotted curve corresponds to the discovery limit set by the coherent-neutrino-scattering background, adapted from Ref. [180].

the reach of the CEPC and the one from the most recent result of XENON1T [179] in the *mass-coupling* plane for both the scalar DM and the Majorana fermion one. For the fermion DM, we consider two separate scenarios, one with a purely scalar coupling (y_{DM}) and the other with a purely pseudo-scalar coupling (y_{DM}^P) , as shown in Eq. (1.23). We also assume that the correct relic abundance is achieved regardless of the model parameters. The results are shown in Fig. 1.23. For the three scenarios in consideration, the CEPC bound on the Higgs invisible branching ratio, 0.31%, corresponds to a sensitivity on the Higgs-DM coupling of around 10^{-3} for DM mass smaller than $m_h/2$. For the scalar DM and Majorana fermion DM with coupling y_{DM} , this clearly surpasses the reach of XENON1T in this mass region. Even for future direct detection experiments, the reach could not go beyond the so-called "neutrino floor" (shown by the cyan dotted curve) due to the coherent-neutrino-scattering background [180], while the CEPC could still probe a significant part of the region below the neutrino discovery limit in the region $m_{
m DM} \lesssim$ 10 GeV. The pseudo-scalar coupling $y_{\rm DM}^P$ only produces spin-dependent WIMP-nucleon interaction which is suppressed by the transferred momentum. The constraints on the fermion DM with $y_{\rm DM}^P$ from direct detection experiments are thus much weaker, while the reach of the CEPC still remains strong. The CEPC's sensitivity to fermionic Higgs portal dark matter through exotic Z boson decays has been discussed in Sec. 1.3.2.

In Fig. 1.24, the CEPC reaches of the Higgs portal models for the scalar DM and the fermion DM (y_{DM}) are converted to the sensitivities on the spin-independent WIMPnucleon cross-section in these models, and compared to the ones of direct detection experiments. In addition to the Xenon1T, the sensitivities of other experiments are also presented, including LUX (2017) [131] and PandaX-II (2017) [153], as well as future projections of PandaX4T with 5.6 $t \times yr$ data [181], XENONnT with 20 $t \times yr$ data [176], LUX-ZEPLIN (LZ) with 15.6 $t \times yr$ data [182] and a xenon experiment with 200 $t \times yr$ data [183] that corresponds to either DARWIN [154] or PandaX-30T. The current and future reaches of the LHC Higgs invisible decay measurements are also shown. The current bound, BR(h \rightarrow inv) < 24% at 95% CL, comes from the CMS analysis in Ref. [184]. The projection by the ATLAS collaboration on the reach of BR(h \rightarrow inv) at the HL-LHC



Figure 1.24: The sensitivity on the spin-independent WIMP-nucleon cross-section of current and future direct detection experiments, in comparison with the reaches of the Higgs invisible decay measurements at the LHC and CEPC in the Higgs portal models. The direct detection limits are shown in solid lines, which include the most recent limits from LUX (2017) [131], PandaX-II (2017) [153], XENON1T [179] and future projections for PandaX4T [181], XENONNT [176], LZ [182] and a 200 $t \times yr$ xenon experiment [183]. For the Higgs portal models, the dark matter is assumed to be either a scalar or a Majorana fermion with a scalar coupling. The red dotted curves show the limits from CEPC which corresponds to a invisible Higgs branching ratio of BR(h \rightarrow inv) < 0.31% at the 95% CL. The gray dotted curves correspond to BR(h \rightarrow inv) < 3.5%, the projected reach at HL-LHC from Ref. [186]. The cyan dashed curve corresponds to the discovery limit set by the coherent-neutrino-scattering background, adapted from Ref. [180].

is around 10% [185]. A study in Ref. [186] suggests that the reach could be improved to 3.5% with multivariate techniques. Both the current bound (24%) and the optimistic projection (3.5%) are plotted in Fig. 1.24, which cover the possible range that the (HL-)LHC could reach in the future. Finally, the cyan dashed curve corresponds to the projected discovery limit from Ref. [180]. The region below this curve is inaccessible by direct detection experiments due to the coherent-neutrino-scattering background.

We see in Fig. 1.24 that the sensitivity of the Higgs invisible decay measurements for the scalar DM and the Majorana fermion DM have different dependences on the mass. This is due to the following two reasons: first, the Higgs portal interaction of the scalar DM is a dimension-four operator, while the fermion one is of dimension five, which results in different mass dependences of the WIMP-nucleon cross-section; second, the Higgs decay rates are also different for the two cases, with $\Gamma(h \rightarrow SS) \propto (1 - 4m_S^2/m_h^2)^{1/2}$ and $\Gamma(h \rightarrow \bar{\chi}\chi) \propto (1 - 4m_\chi^2/m_h^2)^{3/2}$, a result of the *s* (*p*)-wave nature of the scalar (fermion). Nevertheless, for both scenarios, it is clear that the Higgs invisible decay measurements provides the strongest limit in the mass region below ~ 10 GeV. Not only that the direct detections become less efficient in this region due to the mass threshold, the "neutrino floor" is also higher in this region, which sets the limit for the reach of direct detections

regardless of the size and length of the experiment. For dark matter masses in the region $10 \text{ GeV} \leq m_{\text{DM}} < m_h/2$, the sensitivities of the Higgs invisible decay measurements are somewhat comparable with the ones from direct detection experiments. In particular, for the fermion DM the CEPC still has sensitivity in regions not covered by PandaX4T, XENONnT or LZ. On the other hand, a $200 t \times yr$ xenon experiment would fully surpass the reach of the CEPC in this region.

(check if the following paragraph is correct) As mentioned earlier, the interaction term between the Higgs and the fermion DM in Eq. 1.22 is of dimension five. Such a nonrenormalizable operator indicates that the theory is only an effective one, and needs to be UV completed at a higher scale. More specifically, this operator can be generated by integrating out a heavy mediator that connects the Higgs and the fermion DM. The validity of the effective theory thus requires the mediator to be heavier than the scale of the interaction. For direct detection experiments, the momentum exchange is in the nonrelativistic regime, and is at the MeV level. For the Higgs decay, the interaction scale is at the order of the Higgs mass. Our results for the fermion DM are thus only valid if the mediator is at least heavier than the Higgs boson.

Next, let us consider the kinetic mixing portal scenario, in which the hidden sector containing the dark matter is charged under a broken dark Abelian gauge symmetry, $U(1)_D$. The $U(1)_D$ could mix with the SM hypercharge $U(1)_Y$ through the operator

$$\frac{1}{2} \frac{\epsilon}{\cos \theta} Z_{D\mu\nu} B^{\mu\nu}, \qquad (1.24)$$

where ϵ is the (dimensionless) kinetic mixing parameter and θ is the weak mixing angle. The heavy gauge boson associated with U(1)_D, often called the dark photon, could be searched for at a lepton collider in quite a few ways. First, the dark photon introduces two effects in the fit of precision electroweak observables: a shift in the Z mass observable and a shift of the Z couplings to SM fermions. The Z-pole program at CEPC could improve the sensitivity to electroweak observables by a factor of 10 compared to LEP and push the reach of ϵ down to $\sim 10^{-3}$ for $m_{Z_D} < 90$ GeV [187]. A more powerful way is to search for dark photons directly through the radiative return processes such as $e^+e^- \rightarrow \gamma Z_D \rightarrow \gamma \mu^+\mu^-$. The search can be implemented by simply counting the number of events in the dimuon invariant mass spectrum in both the Z-pole and Higgs programs at CEPC. The direct searches probe $\epsilon \subset (3 \times 10^{-4} - 10^{-3})$ depending on m_{Z_D} in the entire mass range up to 250 GeV that could be covered by CEPC [188], as illustrated in Fig. 1.25. Another possible direct probe is the rare Z decay: $Z \rightarrow h_D Z_D \rightarrow Z_D Z_D Z_D$, where h_D is the dark Higgs. The reach of this search has been discussed in Sec. 1.3.2.

In the remainder of this subsection we will discuss a case study of a model with two renormalizable Standard Model-dark sector couplings, the Double Dark Portal model of Ref. [123]. This model rests on the observation that one possible origin for the mass of a U(1)_D dark gauge boson is through the VEV of a dark Higgs scalar Φ carrying U(1)_D charge. The U(1)_D gauge boson kinetically mixes with the photon (with mixing parameter ϵ) while the dark Higgs Φ mixes with the Higgs through a $\lambda_{HP} |\Phi|^2 |H|^2$ quartic potential. A dark fermion χ with Dirac mass m_{χ} carrying U(1)_D dark charge can play the role of dark matter. We denote the two scalar mass eigenstates of this model by H_0 (mostly Higgs) and S (mostly Φ) with mixing angle α . We denote the vector mass eigenstates by \tilde{Z}_{μ} (mostly the SM Z boson) and \tilde{K}_{μ} (mostly the dark photon). Both of the renormalizable



Figure 1.25: This figure illustrates CEPC's capacity to probe dark photons via radiative return. The red-solid and blue-dashed lines show the 95% C.L. projected sensitivity to the (hypercharge) mixing parameter, ϵ , as a function of the dark photon's mass, $m_{Z'}$. The red curve corresponds to $\sqrt{s} = 90 \text{ GeV}$ and $\mathcal{L} = 0.5 \text{ ab}^{-1}$ while the blue curve shows 250 GeV and 5 ab^{-1} . The figure is adapted from Refs. [187, 188].

Parameter		Signal process	Back	ground (pb)	Signal region
		$\tilde{Z} \to \bar{\ell}\ell, \tilde{K} \to \bar{\chi}\chi$	$\bar{\ell}\ell\bar{\nu}\nu$	0.929	$N_{\ell} \ge 2, m_{\ell\ell} - m_Z < 10 \text{ GeV},$
	ĨŔ	$\tilde{Z} \to \bar{\ell}\ell \ \tilde{K} \to \bar{\ell}\ell$	ĒPĒP	0.055	$\frac{ m_{\rm recoil} - m_{\tilde{K}} < 2.5 {\rm GeV}}{N_{\ell} \ge 4, m_{\ell\ell} - m_Z < 10 {\rm GeV},}$
		2 7, 11 7	0000	01000	and $ m_{\ell\ell} - m_{\tilde{K}} < 2.5 \mathrm{GeV}$
	ÃŔ	\tilde{K} inclusive decay	$\gamma \bar{f} f$	23.14	$N_{\gamma} \geq 1$, and
ε			100		$ E_{\gamma} - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}}) < 2.5 \mathrm{GeV}$
		$\tilde{K} \to \bar{\ell} \ell$	$\gamma \bar{\ell} \ell$	12.67	$N_{\gamma} \ge 1, N_{\ell} \ge 2, E_{\gamma} - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}}) < 2.5 \text{ GeV},$
					and $ m_{\ell\ell} - m_{\tilde{K}} < 5 \mathrm{GeV}$
		$\tilde{K} \to \bar{\chi} \chi$	$\gamma \bar{\nu} \nu$	3.45	$N_{\gamma} \ge 1, E_{\gamma} - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}}) < 2.5 \text{ GeV},$
					and $\not\!$
	$ ilde{Z}H_0$	$H_0 \rightarrow \tilde{K}\tilde{Z}$ with	$\bar{\ell}\bar{\ell}\ell\ell\bar{\nu}\nu$	1.8×10^{-5}	$N_{\ell} \ge 4, m_{\ell\ell} - m_Z < 10 \text{GeV},$
		$\tilde{K} \to \bar{\chi}\chi, \tilde{Z} \to \bar{\ell}\ell$			and $ m_{ m recoil} - m_{ ilde{K}} < 2.5~{ m GeV}$
sin a	$\tilde{Z}S$	$\tilde{Z} \to \bar{\ell}\ell$	$\bar{\ell}\ell\bar{\nu}\nu$	0.87	$N_{\ell} \ge 2, m_{\ell\ell} - m_Z < 10 \text{ GeV},$
$\sin \alpha$		$S \to \tilde{K}\tilde{K} \to 4\chi$			and $ m_{ m recoil}-m_S < 2.5~{ m GeV}$

Table 1.2: Double Dark Portal model: summary of the different vector + scalar and vector + vector production modes studied, along with the most salient cuts to identify the individual signals. All background processes include up to one additional photon to account for initial and final state radiation. Background rates are given for $\sqrt{s} = 250 \text{ GeV}$, and visible particles are required to satisfy preselection cuts given in the main text of [123].

portal couplings lead to attractive discovery prospects at CEPC from a variety of channels summarized in Tab. 1.2.

This model contains several couplings allowing transitions from the Standard Model to the dark sector, proportional to an insertion of a mixing parameter. Vertices proportional to α include H_0SS ; H_0H_0S ; $\tilde{K}_{\mu}\tilde{K}^{\mu}H_0$; and $\tilde{Z}_{\mu}\tilde{Z}^{\mu}S$. Vertices proportional to ϵ include $\tilde{Z}_{\mu}\tilde{K}^{\mu}S$ and $\tilde{Z}_{\mu}\tilde{K}^{\mu}H_0$. If $4m_{\chi} < 2m_{\tilde{K}} < m_S$, then both the dark photon \tilde{K} and dark Higgs S will dominantly decay invisibly, with visible branching ratios suppressed by



Figure 1.26: This figure shows the reach of CEPC to test the Double Dark Portal model [123] through invisible decay of the SM-like Higgs boson. Left and center: Rates for the invisible branching fraction of the 125 GeV Higgs in the sin α vs. ϵ plane, setting $m_S = 50$ GeV, $m_K = 20$ GeV, and $g_D = e$ (left) and 0.01 (center). Right: Exclusion regions in the sin α vs. m_K plane from the search for an invisible decay of the 125 GeV Higgs by ATLAS and CMS giving BR_{inv} < 0.23 [124, 125], and the projected reach from a future e^+e^- machine giving BR_{inv} < 0.005 [119–121, 189].

 $e^2\epsilon^2/g_D^2$ and $\tan^2 \alpha/g_D^2$ respectively. Hence, the Double Dark Portal model contains invisible Higgs decay modes $H_0 \to SS \to 4\tilde{K} \to 8\chi$ and $H_0 \to 2\tilde{K} \to 4\chi$, in addition to the possible exotic decay $H_0 \to \tilde{Z}\tilde{K}$ which is either partially visible or invisible depending on the \tilde{Z} decay channel. A precision measurement of the invisible branching fractions of the Higgs boson can significantly constrain the model, as summarized in Fig. 1.26. Precision observation of the Higgsstrahlung rate with O(0.3% - 0.7%) accuracy [120–122] will constrain the scalar mixing angle at the level $\sin \alpha \leq 0.055 - 0.084$.

Direct searches for dark sector particles are possible in the channels $\tilde{Z}H_0$, $\tilde{Z}S$, $\gamma \tilde{K}$ and $\tilde{Z}\tilde{K}$. The sensitivity of CEPC searches for these signals and comparisons to existing constraints from BaBar, LEP, and LHC are summarized in Fig. 1.27. The $\tilde{Z}\tilde{K}$ final state can be searched for using the recoil mass in events containing $Z \to \ell^+ \ell^-$. The radiative return process $e^+e^- \to \gamma \tilde{K}$ allows a search for events with a monochromatic photon together with $\tilde{K} \to \bar{\chi}\chi, \ell^+\ell^-$. The left panel of Fig. 1.27 shows that searches with invisible \tilde{K} are more effective than those with $\tilde{K} \to \ell^+\ell^-$, due to the larger branching fraction. The figure also shows that a search for $H_0 \to \tilde{Z}\tilde{K}(\to \bar{\chi}\chi)$ is less effective. Finally, the right-hand panel of Fig. 1.27 shows the reach of a search for the S-strahlung process $e^+e^- \to \tilde{Z}S$ in the mixing angle $\sin \alpha$. This search is exactly analogous to the previous search at LEP-II for a purely invisible decaying Higgs [117]. Improved sensitivity could be obtained by varying the \sqrt{s} of the collider to maximize the $\sigma(e^+e^- \to \tilde{Z}S)$ rate for the test S mass (see also Ref. [190]).

Portals with additional SM-sector physics

While the renormalizable SM portals are simple, they are not the only possibilities. Portals between the dark and visible sectors could be formed by additional particles with Standard Model gauge charges. These can offer interesting variations on the renormalizable portal. One example of such a portal is the leptonic Higgs portal [194]. This model includes an elementary scalar, S, which only couples to the SM leptons, $g_\ell S \bar{l} l$.³ Note that

 $^{^{3}}$ A variant of the model with S dominantly coupling to the muon and proton with tiny couplings to the electron and neutron might explain the proton radius puzzle and the muon anomalous magnetic moment discrepancy.



Figure 1.27: This figure shows the reach of CEPC to test the Double Dark Portal model [123] through searches for dark-sector particles. **Left:** Projected exclusion regions in the ϵ vs. m_K plane from multiple complementary searches of \tilde{K} production. Solid lines enclose expected exclusion regions with $\mathcal{L} = 5 \text{ ab}^{-1}$ of $\sqrt{s} = 250 \text{ GeV } e^+e^-$ machine data. Dashed lines indicate existing limits from the LEP $e^-e^+ \rightarrow \ell^-\ell^+$ contact operator search, the LEP electroweak precision tests (LEP-EWPT), the BaBar \tilde{K} invisible decay search (BaBar), and the LHC Drell-Yan constraints (LHC-DY). The 3 ab⁻¹ HL-LHC projection for Drell-Yan constraints is also shown as a solid line. Note that m_K is approximately the $m_{\tilde{K}}$ mass eigenvalue. **Right:** Exclusion reach from the $\tilde{Z}S$, $\tilde{Z} \rightarrow \ell^+\ell^-$ search in the recoil mass distribution for invisible S decays in the sin α vs. m_S plane using 5 ab⁻¹ of $e^+e^$ data at $\sqrt{s} = 250 \text{ GeV}$ or 500 GeV. We also show comparisons to the current fit, sin $\alpha < 0.33$ [118], future LHC projections of 0.28 (0.20) using 300 fb⁻¹ (3 ab⁻¹) luminosity [119], and precision $\delta\sigma(Zh)$ measurements constraining 0.084 (0.055) using 5 ab⁻¹ (10 ab⁻¹) [120–122]. We plot the excluded region from LEP searches for invisible low mass Higgs in the ZS channel in cyan [117, 191–193].

this operator is not SM gauge invariant and has to be UV completed. One possible simple UV completion is to couple a SM singlet to two Higgs doublets with one of the doublets only coupling to leptons and the other one only coupling to quarks. At a lepton collider, assuming that the couplings g_{ℓ} are proportional to the corresponding lepton mass, S could be produced in association with τ leptons, $e^+e^- \rightarrow \tau^+\tau^- + (S \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-)$. Current beam dump and lepton colliders only probe m_S to a few GeV. CEPC could be capable of extending the sensitivity to much heavier S up to $m_S \sim 250$ GeV. In the particular lepton-specific two Higgs doublet UV completion, the mixing between the singlet S and the higgs boson h leads to exotic Higgs decays such as $h \rightarrow SS \rightarrow 4\tau, 2\mu 2\tau$. For the 4τ final state, CEPC could test a branching fraction as small as 10^{-4} at 95% C.L., improving the sensitivity by three orders of magnitude compared to even the HL-LHC [195]! This is translated to a factor of 30 improvement in testing the coupling g_{ℓ} , fixing all the other parameters. Another similar possibility is a leptonic portal arising from some gauge bosons coupling to SM lepton-flavor currents [196].

In general, the dark matter portal models could give rise to exotic Higgs decays. A thorough review of the models leading to exotic Higgs decays and the status of LHC searches can be found in Ref. [112]. Supersymmetric exotic decays of the Higgs boson have been studied in Refs. [195, 197]. The potential of detecting exotic Higgs decays in 14 different final states at CEPC has been presented in Ref. [195]. In every final state,

we expect at least one order of magnitude improvement in sensitivity compared to the HL-LHC and in quite a few channels, we expect 3-4 orders of magnitude improvement at CEPC. More details are discussed in Sec. 1.3.1.

A characteristic feature of many models that go beyond renormalizable portals is the possibility of new sources of flavor violation. For example, nonrenormalizable (dipole moment) operators could allow one SM fermion to decay to a dark photon and another SM fermion of different flavor, e.g. $\mu^{\pm} \rightarrow e^{\pm}\gamma_d$ or $t \rightarrow c\gamma_d$ [198]. Renormalizable completions of such models introduce new "messenger" particles that interact with the SM gauge groups and the dark photon. The induced flavor-violating decays could be searched for at CEPC.

Another possibility that could be tested at CEPC is flavor-violating dark matter in which dark matter couples dominantly to muons [199]. The dark multiplet contains a scalar and a vector-like fermion and couples to the muon through a Yukawa interaction. The neutral component of the scalar serves as the dark matter candidate. The interaction generates a loop correction to the $\gamma \mu^+ \mu^-$ and $Z \mu^+ \mu^-$ couplings that could be measured as deviations in the cross section of $e^+e^- \rightarrow \mu^+\mu^-$. Choosing the Yukawa coupling to be O(1), means that a 2% precision measurement of the cross section can probe dark matter mass within 20 GeV around 120 GeV. Related models include flavored dark matter [200, 201], in which the dark matter particle carries flavor quantum numbers and has renormalizable contact interactions with the SM fields. In particular, electron-flavored dark matter could be produced copiously at a lepton collider associated with a photon if its mass is below ~ 120 GeV.

Effective theory

So far, our discussion of dark matter has been organized based on details of the model. However, one could also take a portal-agnostic or "model-independent" approach, simply searching for a generic signal like a single photon plus missing energy [202]. This could arise if DM is part of an electroweak multiplet, due to loops of the charged $SU(2)_L$ partners of dark matter and W bosons. It could also arise if completely new charged particles, independent of DM, exist and couple to DM. Results could be expressed simply in terms of effective operators, without committing to a particular UV completion. A variety of studies of such signals at e^+e^- colliders have been carried out, e.g. [203–206].

In an effective theory approach, such signals arise from dimension-7 effective operators coupling fermionic dark matter to pairs of SM gauge bosons. The operators that can be efficiently constrained by searches at CEPC are

$$\mathcal{L}_{\rm S} \supset \frac{1}{\Lambda_{\gamma\gamma}^3} \bar{\chi} \chi A^{\mu\nu} A_{\mu\nu} + \frac{1}{\Lambda_{\gamma Z}^3} \bar{\chi} \chi A^{\mu\nu} Z_{\mu\nu},$$

$$\mathcal{L}_{\rm P} \supset \frac{1}{\Lambda_{\gamma\gamma}^3} \bar{\chi} i \gamma_5 \chi A^{\mu\nu} \widetilde{A}_{\mu\nu} + \frac{1}{\Lambda_{\gamma Z}^3} \bar{\chi} i \gamma_5 \chi A^{\mu\nu} \widetilde{Z}_{\mu\nu}, \qquad (1.25)$$

where the field strengths $A_{\mu\nu}$ and $Z_{\mu\nu}$ and their duals $\tilde{A}_{\mu\nu}$ and $\tilde{Z}_{\mu\nu}$ couple to the scalar (S) and the pseudoscalar (P) fermionic dark matter bilinears. The Λ factors in the coefficients represent the approximate mass scale of new physics (up to loop factors). Similar operators can also be written for the SU(2)_L gauge fields, but the WW couplings may not be as efficiently probed by e^+e^- collisions at the Z pole.

The diphoton operator dominates processes with low momentum transfer because the photon is massless. It is much more stringently constrained by direct detection than its



Figure 1.28: This figure shows CEPC's capacity to test whether dark matter couples to the SM photon and/or Z boson [through the operators in Eq. (1.25)]. From left to right, the three panels correspond to pure $\Lambda_{\gamma Z}$ interaction, pure $\Lambda_{\gamma \gamma}$ interaction, and $\Lambda_{\gamma Z} = \Lambda_{\gamma \gamma}$ interaction. The various curves show CEPC's 3σ projected sensitivity to the dark matter mass, m_{χ} , and the energy scale of new physics, Λ . The black, gray, and blue lines refer to $\sqrt{s} = 91.2 \text{ GeV}$ with 2.5 ab⁻¹, 91.2 GeV with 25 fb⁻¹, and 240 GeV with 5 ab⁻¹, respectively. The photon is required to have $|\eta| < 3$ and a $p_T > 25$ (35) GeV for 91.2 (240) GeV collision energy to optimize the sensitivity for a low m_{χ} . The solid lines are for a scalar operator and the dashed lines for the pseudoscalar case. The figure is adapted from Ref. [207].

DM- γZ and DM-ZZ counterparts. For DM lighter than half of m_Z , indirect detection using diffuse gamma rays is also more sensitive to the diphoton operator. Collider searches, on the other hand, can more effectively probe Z couplings. The high-luminosity Z-pole run at CEPC offers a unique opportunity to test the DM couplings to the Z boson. For a light DM mass, the resonantly produced $\bar{\chi}\chi\gamma$ system is best searched for in the channel of monophoton + missing energy.

Ref. [207] studies the proposed Z-pole runs' prospective limits on effective DM- γZ and $\gamma \gamma$ couplings in the monophoton channel. The major SM background, $e^+e^- \rightarrow \bar{\nu}\nu\gamma$, can be effectively controlled by optimizing the cut on the single photon's p_T . The corresponding constraints on Λ are illustrated in Figs. 1.28 and 1.29. The best sensitivity is obtained for light dark matter mass. In case only one operator is considered, the projected sensitivity for $\Lambda_{\gamma Z}$ is 360 GeV, 540 GeV for 25 fb⁻¹ (giga Z) and 2.5 ab⁻¹ (tera Z) luminosities at the Z pole. In comparison, $\Lambda_{\gamma\gamma}$ is best probed at higher energy runs, and a limit of 360 GeV is obtained for a 5 ab⁻¹ run at 240 GeV center-of-mass energy. In general, both $\Lambda_{\gamma Z}$ and $\Lambda_{\gamma\gamma}$ would be present and their relative size is model dependent.

Fig. 1.29 further shows the direct and indirect detection limits together with CEPC's constraint in the $\Lambda_{\gamma\gamma} - \Lambda_{\gamma Z}$ plane. For direct detection, we adopt the calculation of the spin-independent scattering rate via the scalar operator from Ref. [110, 212], which takes into account the diphoton exchange that dominates over γZ contributions. We choose benchmark DM masses at 4 and 10 GeV that are accessible to major nuclear recoil experiments. For indirect detection, we show the 95% C.L. constraint from the gamma ray line search at Fermi-LAT [211]. The nonrelativistic DM annihilation cross section into two photons ($\bar{\chi}\chi \to \gamma\gamma$) is dominated by $\Lambda_{\gamma\gamma}$ for m_{χ} below $m_Z/2$. The $\Lambda_{\gamma Z}$ dependence only emerges in a tiny correction as part of the $\bar{\chi}\chi \to \gamma(\gamma^*/Z^* \to \bar{f}f)$ process, and can be ignored at the DM masses shown.

The channel of monophoton + missing energy would also be sensitive to effective interactions between dark matter and electrons. In this case, the photon arises from initial state radiation. The related dimension-6 operators are

$$\mathcal{L}_{\chi e} = \frac{1}{\Lambda^2} \bar{\chi} \Gamma_{\chi} \chi \bar{e} \Gamma_e e, \qquad (1.26)$$



Figure 1.29: This figure shows CEPC's capacity to test whether dark matter couples to the SM photon and/or Z boson [through the operators in Eq. (1.25)]. The left (right) panel shows a DM mass of $m_{\chi} = 4 \,(10)$ GeV. The CEPC sensitivity is shown by the black, gray, and blue curves, which are defined in the caption of Fig. 1.28. The brown line denotes the ILC 3σ sensitivity with an integrated luminosity of 500 fb⁻¹ at $\sqrt{s} = 500$ GeV with cuts $10^{\circ} < \theta_{\gamma} < 170^{\circ}$ and $p_T(\gamma) > 90$ GeV. Constraints from dark matter direct detection experiments are shown in red for SuperCDMS [208], orange for CDEX [209], pink for CDMSlite [210], and green for XENON1T [130], LUX [131], and PandaX [153] (which are in close proximity to each other). The purple-dashed line denotes the Fermi-LAT bound from the R3 region [211]. Note that the XENON1T/LUX/PandaX limit only appears in the $m_{\chi} = 10$ GeV case. The figure is adapted from Ref. [207].



Figure 1.30: CEPC 3σ reach for several effective interactions between dark matter and electrons in the channel of monophoton + missing energy with integrated luminosities of 100 fb^{-1} and 1 ab^{-1} .

where $\Gamma_{\chi}, \Gamma_e \in \{1, \gamma_5, \gamma^{\mu}, \gamma^{\mu}\gamma_5, \sigma^{\mu\nu}\}$. The CEPC reach at 250 GeV center of mass energy are demonstrated in the $m_{\chi} - \Lambda$ plane in Fig. 1.30. For low masses, limits of ~ 1.4 TeV on Λ could be achieved with an integrated luminosity of 1 ab⁻¹.

An analogous approach is to search for a signal in the channel of mono-Z + missing energy. This channel is sensitive to effective operators like

$$\mathcal{L}_{\chi Z} = \frac{1}{\Lambda^3} \bar{\chi} \chi Z^{\mu\nu} Z_{\mu\nu}. \tag{1.27}$$

Z bosons can be reconstructed by either two jets or two opposite-sign same-flavor leptons. Fig. 1.31 shows the CEPC reach in the $m_{\chi} - \Lambda$ plane at 250 GeV center of mass energy. It is expected that the hadronic modes would provide a better sensitivity than the leptonic modes.



Figure 1.31: CEPC 3σ reaches for the effective operator $\mathcal{L}_{\chi Z}$ in the channel of mono-Z + missing energy, adapted from [206]. Both the hadronic $(jj + \not E)$ and the leptonic $(\ell \ell + \not E)$ modes are presented with integrated luminosities of 100 fb⁻¹ and 1 ab⁻¹.

Miscellaneous

Merge these references into the neutrino section once it's complete?

Batell/McCullough "natural neutrinos" (does this belong here or in a different section?) [213]

Lepton flavor violation from neutral scalar at CEPC [214] should be cited somewhere, maybe not here

Summary and outlook

1.3.4 Neutrino connection

Neutrino mass models

The CEPC is an excellent tool to study the physics of neutrino mass generation as a portal to unknown new physics during both, the 240 GeV and the Z-pole runs. It can therefore be used as a discovery machine for new physics that evades the detection at hadronic colliders, including feebly coupled "hidden sector" extensions of the SM that can address fundamental questions in particle physics and cosmology.

The experimental observation of neutrino flavor oscillations [215, 216] indicates that neutrinos have a nonzero mass. Global fits to neutrino oscillation experiments (cf. e.g. [217, 218]) allow to fix two neutrino mass square differences as well as all mixing angles in the Pontecorvo-Maki-Nakagawa-Sakata matrix V_{ν} (assuming it to be unitary), while the absolute neutrino mass scale is constrained from cosmology to be in the sub-eV range, cf. e.g. [219]. The data immediately poses the questions why the neutrinos are so much lighter than all other fermions, and why the elements of the neutrino mass mixing matrix are so different from the quark mixing matrix.

Since the Standard Model (SM) of particle physics cannot account for the nonzero neutrino masses in a renormalizable way, the neutrino oscillations provide compelling evidence from the laboratory for physics beyond the SM. While the origin of mass for the charged third generation SM fermions is well established by the Higgs boson measurements, the origin of mass for the neutrinos is unknown and calls for a more fundamental theory of nature, into which the SM is embedded. Moreover, neutrinos may be Majorana fermions [220], fundamentally different from their charged fermion counterparts with experimentally verifiable consequences related to violation of lepton number,

discoverable at colliders [221]. Lepton-number violation may also be connected to an open question in cosmology, the *baryon asymmetry of the universe* (BAU), i.e., the tiny excess $\sim 10^{-10}$ [129] of matter over antimatter.

Under the assumption that the New Physics scale Λ associated with the mass of the lightest new particle involved in the generation of neutrino masses is much larger than the typical energy $E_{\nu} \sim \text{MeV}$ in neutrino oscillation experiments,⁴ the neutrino oscillations can be described in the framework of Effective Field Theory (EFT). The relevant operators $\mathcal{O}_i^{[n]}$ have mass dimension n > 4, are suppressed by powers of Λ^{n-4} , and have Wilson coefficients $c_i^{[n]}$ that are matrices in flavor space. In this framework the smallness of the neutrino masses can be a consequence of any combination of the following reasons:

- High-Scale Seesaw Mechanism: Large values of Λ automatically lead to small m_i. The three tree level implementations of the idea [224] are known as: Type-I Seesaw [77, 78, 225–228], SM plus right-handed neutrinos N; Type-II Seesaw [228–232], SM plus scalar SU(2)_L triplet Δ_L; and Type-III Seesaw [233], SM plus fermionic SU(2)_L triplet field Σ_L.
- II) Small numbers: The $\mathcal{O}_i^{[n]}$ can remain small (for all values of Λ , including those accessible to CEPC) if the Wilson coefficients $c_i^{[n]}$ are small. In particular, if the neutrinos are Dirac particles their masses can be generated by the Higgs mechanism in exactly the same way as all other fermion masses with tiny Yukawa couplings. Tiny constants can be avoided e.g. when the neutrino interactions are created dynamically due to the spontaneous breaking of a flavor symmetry by flavons [234], or when the $\mathcal{O}_i^{[n]}$ are created radiatively, cf. e.g. [235–239].
- III) Low-Scale Seesaw Mechanism: A low scale Λ and O(1) couplings between the SM and the new particles can be realized when symmetries give rise to cancellations in the neutrino mass matrix. For instance the B L symmetry of the SM can keep the $\mathcal{O}_i^{[n]}$ small for Λ below the TeV scale [240–242]. Specific models that implement this idea include the inverse [243–245] and linear [246, 247] seesaw, the Neutrino Minimal Standard Model [248, 249] and scale invariant models [250].

Here the terms "high scale" and "low scale" scenarios should be understood with respect to the CEPC collision energy; for values of Λ far above 240 GeV the EFT treatment introduced here to describe neutrino oscillation experiments can also be applied to CEPC phenomenology, while lower values imply that the new particles can be found at CEPC and have to be described dynamically.

The original setting for the seesaw mechanism were grand unified theories, based on SO(10) [226], and SU(5) [225], as well as the minimal Left-Right (LR) symmetric model [77, 78] and flavor/family symmetries [227]. The large scale of grand unification typically sets the mass scale Λ related to neutrino physics beyond the direct reach of colliders, however parts of multiplets may lie much below the GUT scale. For example, the minimal SU(5) model with the addition of 24_F on top of the original Georgi-Glashow model, needs a light fermionic triplet in order for gauge couplings to unify [251, 252], motivating Type III Seesaw searches at the TeV scales. Other well known examples are

⁴Scenarios with $\Lambda < E_{\nu}$ are in principle feasible, cf. e.g. Refs. [222, 223] and references therein, but strongly constrained by the success of the high level of consistency in global fits to neutrino oscillation data that assume only three light neutrinos [217, 218].

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for instance B - L symmetry, additional "neutrinophilic" Higgs doublets, and flavor symmetries. Such neutrino mass physics generally predicts the existence of new particles, which could at least in principle be discovered and studied at CEPC.

Lepton number violation

If neutrinos are Majorana particles, the mechanism that generates their mass can mediate lepton-number violating (LNV) processes at colliders if the scale Λ is below or near the collision energy [221].

Type I Seesaw: Observing the violation of lepton number from heavy neutrino mass eigenstates (N_i) in the process $e^+e^- \rightarrow N\nu$ at lepton colliders is possible in principle due to the different kinematics of LNV and LNC processes as was demonstrated for the ILC [253]. In particular for heavy neutrino N_i masses $M_i > m_Z$, the process $e^+e^- \rightarrow \nu \ell j j$ is a promising signature at lepton colliders [254–256] and has been studied specifically for CEPC [257].

The subleading production process for heavy neutrinos at lepton colliders $e^+e^- \rightarrow N\ell^{\pm}W^{\mp}$ allows for same sign dileptons for $N \rightarrow \ell^{\pm}W^{(*)}$ and $W \rightarrow$ hadrons [256].

The observation of the interesting "inverse neutrinoless double β decay" [258], would require same sign lepton collisions [259]. It is worth pointing out, that LNV in the Type I Seesaw mechanism is suppressed by the smallness of the light neutrino masses [241, 242]. It has been proposed that the suppression of LNV may be alleviated by the process of heavy neutrino-antineutrino oscillations, which occurs for heavy neutrinos with masses below the W boson's mass, m_W , and with $U^2 < O(10^{-5})$ [260–262].

Signals in Type II Seesaw: The triplet scalar multiplet Δ_L in the Type II Seesaw contains three complex fields: the neutral CP-even and CP-odd states, singly charged and the doubly charged components. The appealing feature of the model is the direct connection between neutrino masses and mixing parameters [263, 264] and the Majorana Yukawa matrix $M_{\nu} = Y_{\Delta} \langle \Delta_L \rangle$, which may lead to charged lepton flavor violating signals [265].

Collider phenomenology of this setup is set by the final state that mainly depends on the triplet's vacuum expectation value (VEV) [266] and the mass splittings of its components [267]. If the masses are degenerate, the dominant decay mode is to leptons if the triplet VEV is small $\leq 10^{-4}$ GeV. This decay mode tests the flavor structure of the neutrino mass matrix and leads to significant flavor-dependent bounds up to 870 GeV at the LHC [268]. For the triplet VEV above $\geq 10^{-4}$ GeV, the states decay to pairs of gauge bosons. A relatively small mass splitting, allowed by the EW precision tests, triggers cascade decay modes [267], which produce soft hadronic and multi-lepton final states [269]. Signal in the WW lead to weak lower bounds at the LHC, $m_{\Delta_L^{++}} \geq 90$ GeV [270] or less, depending on the lepton's flavor. Similarly, the cascade decays [267, 271] are not easy to look for in hadronic colliders [272]; however, they may be observable in cleaner lepton collisions [273].

At lepton colliders, the triplet components can be produced pair-wise through $e^+e^- \rightarrow S\overline{S}$ where $S = \Delta_L^0$, Δ_L^{\pm} , $\Delta_L^{\pm\pm}$ or in single production in association with two same-sign leptons $e^+e^- \rightarrow \Delta_L^{\pm\pm}\ell^{\mp}\ell^{\mp}$, see [274, 275]. Another possible production mode is via vector-boson fusion $e^+e^- \rightarrow \ell \ell' S S'$, where $\ell, \ell' = e^{\pm}, \nu$, as discussed in [276].

The doubly charged scalar bosons $\Delta_L^{\pm\pm}$ can couple to the electrons and positrons directly and contribute to Bhabha scattering in the *t*-channel [274, 277]. Running the lep-

ton colliders with same-sign beams may strongly enhance the production of the doubly charged components in the *s*-channel [274, 278], see [279] for more recent work.

Exotic Higgs decays with same-sign leptons: The mixing of the SM Higgs doublet with the $SU(2)_R$ triplet Higgs that gives Majorana mass to right-handed neutrinos in the Left-Right Symmetric Model (LRSM) [280–283] may lead to LNV decays of $h \rightarrow NN$ [284]. The subsequent (and possibly displaced) decay of $N \rightarrow \ell^{\pm} j j$ can lead to a $\Delta L = 2$ LNV and potentially charged lepton flavor violating final state with two same sign-leptons and up to four jets. Due to the soft final states and displacement, such searches may be challenging at the LHC; however lepton colliders are much more suitable to detect such signals due to the absence of triggers and lower QCD backgrounds.

The presence of the mixing also allows for an enhanced production of the $SU(2)_R$ triplet $pp \rightarrow \Delta_R^0 \rightarrow NN$ at the LHC [285] with varying kinematics, depending on its mass. Moreover, one may be able observe a truly exotic Higgs decay with $h \rightarrow \Delta_R^0 \Delta_R^0 \rightarrow 4N$, where lepton number can be broken to up to four units [285]. The production at lepton colliders may proceed through the Higgs mixing $e^+e^- \rightarrow Z\Delta_R^0 \rightarrow NNZ$ for $\sqrt{s} \leq 100 \text{ GeV}$ and in the vector boson fusion (VBF) channel that produces the $NN\nu\bar{\nu}$ final state with lepton number violation and missing energy [285]. At $\sqrt{s} = 240 \text{ GeV}$ and $\mathcal{L} = 5$ ab, one may expect from a few 100 to more than 5000 NNZ events, depending on the masses of triplets and heavy neutrinos, as well as the Higgs-triplet mixing. Such events are essentially background free at lepton colliders because of the LNV final state, Z tagging, and characteristic displacement. Similarly, the quadruple production of N's can proceed through Higgs-triplet triple vertex with the potential of observing $O(10^4)$ events with the branching ratio of Higgs to $\Delta_R^0 \Delta_R^0$ at the 1% level.

Charged lepton flavor violation

Neutrino oscillations violate lepton flavor, which is transferred to the charged leptons via perturbation theory, such that the violation of the charged lepton flavor (cLFV) is a prediction [286].

Mixed flavor leptonic Higgs or Z **boson decays:** Observables at high energy that can measure cLFV are exotic decays of the Z boson into two charged leptons of different flavor, $Z \rightarrow e^{\pm}\mu^{\mp}, e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$ [287, 288]. Also the decays of the Higgs boson into two charged leptons of different flavor are possible [289, 290]. The processes $h \rightarrow e^{\pm}\mu^{\mp}, e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$ are lepton flavor violating Higgs decays that can be measured at CEPC for branching ratios as small as 1.2×10^{-5} to 1.6×10^{-4} [291].

Lepton universality violation in W **boson decays:** The branching ratios of the W bosons should be identical for the three different leptons⁵, which is due to the lepton universality in the SM. Another probe of lepton universality is given by the decays of the τ lepton. Mixing of the active neutrinos with neutral fermions from the Type I or III Seesaw can lead to violations of lepton universality, cf. e.g. [293]. Charged scalar particles can affect the measurement of lepton-universality observables from W boson branching ratios [294].

⁵Current LEP data features a branching $Br(W \to \tau \nu)$ that is larger than $Br(W \to \ell_{e,\mu}\nu)$ by $\sim 2\sigma$ [292].



Figure 1.32: The CEPC's ability to probe charged lepton-flavor violation (cLFV) is illustrated here as a sensitivity to the cLFV couplings, $h_{\alpha\beta}$ ($\alpha \neq \beta$), and the mass of a new, electrically-neutral scalar particle, m_H . Searches for $e^+e^- \rightarrow \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp}H$ (left) and $e^+e^- \rightarrow \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp}$ (right) at CEPC with $\sqrt{s} = 240 \text{ GeV}$ and $\mathcal{L} = 5 \text{ ab}^{-1}$ lead to projected sensitivities shown by the red curves (assuming 10 cLFV signal events). In the left panel the shaded regions are excluded by electron and muon g - 2, but the green band could explain the $(g - 2)_{\mu}$ discrepancy at the 2σ level. In the right panel the shaded regions are excluded by rare τ lepton decays, $\tau \rightarrow eee$ and $\tau \rightarrow ee\mu$. See the text and Ref. [214] for more details.

Mixed flavor final states with and without resonance: An observable cLFV process at lepton colliders is given by $e^+e^- \rightarrow \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp}$ (+*H*). These processes receive contributions from electrically neutral scalars, for instance from neutrinophillic Two Higgs Doublet models, Type II-based Seesaw models, B - L, or left-right symmetry. A dedicated study of such cLFV processes involving neutral scalars can be found in Ref. [214]. The most stringent constraints and the CEPC prospects in both the on-shell and off-shell modes are collected in Fig. 1.32.

Higgs boson properties

Anomalous Higgs boson production: For $M_i > m_h$ additional Higgs bosons can be produced from heavy neutrino decays in processes $e^+e^- \rightarrow Z^* \rightarrow N\nu \rightarrow H\nu\nu$. This can yield an enhancement of the SM mono-Higgs channel of up to $\sim 2\%$ when applying "standard" filters [295, 296]. The CEPC sensitivity via additional Higgs bosons from dedicated analyses is shown by the yellow line in Fig. 1.33.

Heavy neutrinos can also contribute significantly to the process $e^+e^- \rightarrow HWW$ [297]. The heavy charged leptons from the Type III Seesaw are expected to modify the Higgs potential [298, 299] and can lead to significant contributions to the process $e^+e^- \rightarrow HH$ [300].

In B - L and L - R symmetric models the additional neutral scalar particles may reduce the standard Higgs boson production cross section due to their mixing. In the minimal LRSM model at TeV scales, Higgs couplings, such as the triple Higgs vertex can be dominated by loops [285, 301] of charged triplets and heavy neutrinos, leading to several 10% or even O(1) corrections of the *hhh* vertex with respect to the SM, if the neutral triplet-Higgs mixing is at a 10% level.

Invisible Higgs boson decays: The N_i can leave measurable imprints in precision measurements of the Higgs boson branching ratios. In Type I Seesaw for N_i with $M < m_h$ the Higgs boson can decay into a light and a heavy neutrino mass eigenstate, which can account for up to 30% of the Higgs decays [302] without violating present constraints [303].



Figure 1.33: The CEPC's ability to probe heavy sterile neutrinos is expressed as a projected sensitivity on the active-sterile mixing angle, Θ , and the sterile neutrino mass scale, M. The blue (solid and dashed) line denotes electroweak precision measurements [293, 302, 311, 312]. The purple line denotes displaced vertex searches [313] at the Z-pole run with an integrated luminosity of 10 ab⁻¹. The yellow and red lines stem from the measurements of Higgs production [295, 296] and decay [302] for an integrated luminosity of 5 ab⁻¹ at $\sqrt{s} = 240$ GeV.

The sensitivity from searches via Higgs branching ratio measurements, considering the precision from Ref. [122], are shown by the red line in Fig. 1.33.

Leptonic Higgs decays with cLFV or LNV: As mentioned previously, cLFV decays also add loop-induced additional channels to the total Higgs decay width, and processes where the Higgs couples to two N_i can give rise to exotic LNV decay channels.

Higgs decays into two N_i : In B - L and L - R symmetric models, additional neutral scalars can mix with the Higgs boson. This can give rise to additional decay channels into two N_i , which can be observable, depending on their masses and lifetimes. Such signatures were studied in the context of LRSM [284, 285] and B - L models [304, 305].

Anomalous diphoton decays: In the Type II Seesaw the additional scalar particles couple directly to the Higgs boson, such that the singly and doubly charged components contribute to its loop-induced coupling to the photon [267, 306–308]. Also Type III Seesaw contains additional charged particles that can contribute to the Higgs-to-diphoton branching ratio, see e.g. [309]. In the LRSM, the doubly charged component of the SU(2)_R triplet couples rather strongly to the SM Higgs, leading to an O(100 GeV) lower bound on its mass [301].

Modified Higgs self couplings: In Type I Seesaw the N_i with masses M_i of a few TeV can modify the trilinear Higgs self-coupling up to 30 percent [310]. One would expect this modification also for the low-scale Type III Seesaw [298, 299].

Modifications of electroweak precision observables

Neutrino mass physics can modify the theory predictions for the electroweak precision observables, which may be observable even if the new mass scale is above the CEPC center-of-mass energy. These can either occur due to virtual exchange of the new particles (which may be represented by higher dimensional operators in an EFT approach [314,

315]) or due to the production of new particles that mix with SM particles (e.g. with the active neutrinos or the SM Higgs boson).

In the context of the Type I Seesaw mechanism the mixings $\theta_{ai} = vY_{ai}/M_i$ of n_s heavy right handed neutrinos with the SM neutrinos leads to an effective violation of unitarity in the 3 × 3 mixing matrix V_{ν} , which is a submatrix of the $(3 + n_s) \times (3 + n_s)$ leptonic mixing matrix \mathcal{U} [293, 316–318]. This affects all the electroweak precision observables. Such tests are mostly independent of the heavy neutrino masses M_i , and they test different combinations of the active-sterile mixing parameters [293, 302, 311, 312]. We show the corresponding possible sensitivity of CEPC by solid and dashed blue lines in Fig. 1.33, considering a total integrated luminosity of 0.1 ab^{-1} . In addition to the modified precision observables, one also expects violations of lepton universality and (apparent) violations of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix [293, 303, 319–322].

In the context of Type II Seesaw, the electroweak precision observables are affected both by the triplet VEV, as well as by the mass splittings [267] that enter the oblique Tparameter. In the minimal LRSM, this splitting is predicted to be large and leads to a lower bound on the entire $SU(2)_L$ triplet multiplet [301].

Displaced secondary vertices

Single displaced vertex in Type I Seesaw: For masses below the W bosons's mass, m_W , the lifetime of N_i scales as $\tau_{N_i} \propto |\sum_a |\theta_{ai}|^2|^{-2}G_F^{-2}M_i^{-5}$ and their decays give rise to a visibly displaced secondary vertex in a large part of the allowed parameter space. Displaced vertex signatures have been studied in detail for the case of the Type I Seesaw, and the CEPC specific results from Refs. [262, 313] are shown in Fig. 1.33 by the purple line. It is worth noting that with a longer Z-pole run the sensitivity for $M_i < m_Z$ can be significantly increased, cf. Fig. 1.34. The sensitivity of a standard detector could be increased with additional detectors of the MATHUSLA [323, 324] or FASER [325] type.

Long lived neutral scalars: Due to mixing with the Higgs boson, the electrically neutral scalars in gauged $U(1)_{B-L}$ [326] or the neutral scalar from $SU(2)_R$ [327] can decay via the SM Yukawa couplings into the SM fermions. For masses in the GeV range, the resulting proper lifetimes can easily be O(1 cm), such that their decays give rise to displaced secondary vertices.

Multiple displaced vertices: Pair production of N in exotic Higgs decays may lead to two displaced vertices, each containing a lepton and two jets at parton level, as pointed out in the context of LRSM [284, 285] and models with B - L symmetry [304, 305]. Rare exotic decays of the SM-like Higgs boson to a pair of triplets with subsequent decay to 4Ns leads to up to four displaced vertices with rather soft final states, which lepton colliders may be much more suited for than the LHC.

The associated production of the scalar triplet at $e^+e^- \rightarrow Z^* \rightarrow Z\Delta^0_R$ leads to two displaced vertices when $\Delta^0_R \rightarrow NN$, while Z decay gives additional prompt leptons/jets or missing energy.

Extra gauge bosons

Extended theoretical frameworks generally predict more and stronger signals from heavy neutrinos. In particular the gauged B - L symmetry, which contains an extra Z' gauge

Inverted Ordering



Normal Ordering

Figure 1.34: This figure illustrates CEPC's capacity to test models of leptogenesis. The parameter space for a minimal Type I Seesaw model with $n_s = 2$ is shown; the two sterile neutrino masses, M_1 and M_2 , are combined to form $\overline{M} = (M_1 + M_2)/2$ (with $|M_2 - M_1|/(M_2 + M_1) < 0.1$), and θ represents the active-sterile mixing angle. Models in the parameter space below the blue line are consistent with the observed baryon asymmetry of the universe through leptogenesis. Models above the orange lines are tested by CEPC at $\sqrt{s} = 240$ GeV, which is expected to observe at least four displaced vertex events. Models above the purple lines are probed by CEPC at the Z pole. The grey areas are ruled out by the DELPHI experiment [328, 329] (top) and current neutrino oscillation data (bottom). The figure is based on Ref. [262]. Note that for $n_s = 3$ heavy neutrinos, the "leptogenesis" upper bound is expected to be much higher [330] and practically identical to the DELPHI constraint, so that CEPC at 240 GeV can enter the cosmologically interesting parameter region for both hierarchies.

boson, may give rise to a modified rate for the processes $e^+e^- \rightarrow \ell^+\ell^-$ at lepton colliders [331–333].

The Left-Right symmetric model contains the parity-symmetric W_R and Z_{LR} charged and neutral gauge bosons. The charged bosons are strongly constrained by B and Kmeson mixing and CP-odd observables, cf. e.g. [334], as well as the neutron electric dipole moment constraints [335], with current bounds in the 3 TeV range. The neutral gauge boson Z_{LR} is typically heavier in minimal LR models.

In many instances, the LHC searches are catching up with flavor limits. In particular the 'golden channel' $pp \rightarrow W_R \rightarrow \ell N$ [336] features a dynamic parameter space [337] that ranges from prompt N production to merged neutrino jets [338–340], displaced vertices [341, 342] and a single prompt lepton with missing energy, where current bounds range up to 5 TeV, see [342] for the complete coverage of parameter space of W_R and N masses.

Additional gauge bosons can give rise to additional production mechanisms for N_i that are not suppressed by small Yukawa couplings, but possibly by the large gauge boson masses or their small couplings to the SM, cf. e.g. [304].

Monte Carlo Tools for seesaws at CEPC

The aforementioned seesaw scenarios have been implemented in various FeynRules [343–345]-based model files that are compatible with the general purpose event generators Herwig [346], MadGraph5_aMC@NLO [347], Sherpa [348], and Whizard [349]. In particular, publicly available Universal FeynRules Object (UFO) [350] libraries are avail-

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able for models of heavy neutrinos [351], including those with extra gauge bosons [340, 352–355]; models with triplet scalars [354, 356, 357], including the Higgs gluon fusion and Higgs-triplet mixing [358], as well as models with triplet leptons [359–362].

Leptogenesis

Leptogenesis refers to the idea that a matter-antimatter asymmetry is initially generated in the lepton sector [363] and then transferred into a baryon asymmetry via sphaleron processes [364]. Leptogenesis provides an explanation for the observed *baryon asymmetry of the universe* (BAU), i.e., the tiny excess $\eta_B \sim 10^{-10}$ [129] of matter over antimatter in the early universe over that formed the origin of the baryonic matter in the universe after mutual annihilation of all other particles and antiparticles, cf. e.g. [365]. Thus leptogenesis connects one of the deepest mysteries in cosmology to the properties of neutrinos.

Motivation. Global fits to present neutrino oscillation data prefer charge-parity (*CP*) violation in the leptonic sector at the 2 to 2.5σ level, cf. [217, 218]. This *CP* violation in the leptonic sector may be related [366] to the observed BAU.

For Λ above the collision energies at CEPC, it is impossible to discover the new particles responsible for the generation of the BAU, but observing a combination of LNV and cLFV signatures at scales accessible to CEPC could still rule out such "high scale leptogenesis" scenarios because particles with LNV interactions near the electroweak scale could wash out baryon asymmetries that were produced at high scales [367, 368].

If, in contrast, Λ is within reach of CEPC, one can directly probe the mechanism of leptogenesis by studying the properties of the new particles [369]. One of the best studied scenarios that accommodates leptogenesis is based on the low-scale Type I Seesaw model. The Yukawa couplings Y_{ai} that couple the right-handed neutrinos N_i to the Higgs and the left-handed neutrinos ν_{La} in general are complex and are a potential source of CP violation. Hence, the N_i may be the common origin on neutrino masses and baryonic matter in the universe.

If the mass range M_i is around or below the collider-accessible TeV scale, leptogenesis can proceed in two different ways. For M_i above the electroweak scale, the BAU can be generated during the freeze-out and decay of the N_i [370] ("freeze-out scenario"). For masses below the electroweak scale the BAU can be generated in *CP*-violating oscillations [249, 371] and Higgs decays [372] during the N_i production ("freeze-in scenario"). The latter effectively also describes leptogenesis in the *Neutrino Minimal Standard Model* (ν MSM) [248, 249], a complete model where a third heavy neutrino composes the Dark Matter [79, 80] and does not contribute significantly to neutrino mass generation and leptogenesis due to strong observational constraints [373]. Due to its minimality, part of the relevant parameter space of this model is in principle fully testable at colliders [374, 375], and significant fractions of the parameter space can be probed with CEPC [262]. For M_i below the electroweak scale, this analysis could be done with an accuracy on the percent level at the Z pole with 10 ab⁻¹ [262].

Lepton-number violation. Lepton number violation is a crucial ingredient of any leptogenesis scenario. Typical signatures at CEPC may involve same sign dilepton final states, either in prompt or displaced decays. An observation of such processes in all three SM flavors or a combination of LNV in some channel and different cLFV signatures could potentially falsify high scale leptogenesis scenarios [367, 368]. Many low scale models rely on an approximate lepton-number conservation to explain the smallness of the neutrino masses in the regime of coupling constants that is accessible to CEPC [240–242], which parametrically suppresses the rate of LNV processes in prompt decays. For particles with quasi-degenerate masses and comparable lifetimes, as they e.g. appear in resonant leptogenesis scenarios of the ν MSM, it has been proposed that this suppression may be overcome by the long time that they have to undergo coherent oscillations within the detector [260, 261, 376]. Since the amount of lepton number violation is proportional to the mass splitting, indirect measurements may be possible from a comparison of the rates for lepton number violating and conserving processes [260, 376] or by observing heavy neutrino-antineutrino oscillations in the detector [261] in displaced vertex searches at CEPC [262]. The reach of such searches at CEPC in the minimal seesaw model is shown in Fig. 1.34, cf. also Fig. 1.33.

Lepton-flavor violation. Measurements of cLFV are crucial to test high scale leptogenesis models at CEPC, because an efficient washout of the asymmetries in all flavors at temperatures above the electroweak scale is crucial to rule out such scenarios as the origin of the BAU [368].

Low scale leptogenesis scenarios typically rely on flavor effects and therefore tend to make predictions for the rates of cLFV. In the minimal Type I Seesaw with $n_s = 2$ (or the ν MSM), leptogenesis significantly restricts the flavor mixing pattern of heavy neutrinos N_i with experimentally accessible mixing angles [375]. The accuracy on the percent level at which the flavor mixing pattern can be probed in displaced vertex searches with 10 ab^{-1} at the Z pole are sufficient to probe large fractions of the parameter region for which heavy neutrinos can be discovered.

Displaced decays from long lived heavy neutrinos. For heavy neutrino masses below the electroweak scale, where leptogenesis proceeds in the "freeze in" manner, the N_i couplings should be comparably small to avoid a complete washout of the BAU in the early universe ($|\theta_{ai}|^2 < 10^{-8} \times (10 \text{ GeV}/M_i)$ [377], where larger values can be allowed due to strong hierarchies in their couplings to individual SM flavors [330]). Hence, most of the parameter space of active-sterile neutrino mixing and masses that is compatible with low scale leptogenesis in this scenario gives rise to long lifetimes of the heavy neutrino mass eigenstates, which can be found with high sensitivity via displaced vertex searches at CEPC. The reach of such searches at CEPC is compared to the parameter region where leptogenesis is feasible in the minimal seesaw model in Fig. 1.34.

1.3.5 Extended Higgs sector

In many extensions of BSM scenarios, the Higgs boson is imbedded in an extended Higgs sector. Searching for new Higgs bosons is an important experimental target with a high priority. One of the most straightforward and well-motivated extensions is the two-Higgs-doublet model (2HDM) [378], in which there are five massive spin-zero states in the spectrum (h, H^0, A^0, H^{\pm}) after electroweak symmetry breaking. Extensive searches for BSM Higgs bosons have been carried out, especially at the LHC [22, 379–389]. Unfortunately, no signal has been observed so far. The null results imply that either the non-SM Higgs bosons are much heavier and essentially decoupled from the SM, or the lightest CP-even Higgs boson mimicks the SM Higgs by accident or symmetry while non-SM Higgs bosons

are light as well [390–392]. In either case, it would be challenging to observe those states directly in experiments.

Complementary to the direct searches, precision measurements of the SM parameters and Higgs properties could also provide useful probes of new physics. High-precision measurements at future Higgs factories with about 10^6 Higgses, and Z-pole measurements with $10^{10} - 10^{12}$ Z bosons [140, 393–396] would hopefully shed light on new physics associated with the electroweak sector such as an extended Higgs sector. There is a plethora of articles in the literature on the effects of the heavy Higgs states on the SM Higgs couplings, e.g. [20, 378, 397–405]. Identifying the light CP-even Higgs h to be the experimentally observed 125 GeV Higgs, the couplings of h to the SM fermions and gauge bosons receive two contributions: tree-level values, which are controlled by the mixing angles α of the two CP-even Higgses and $\tan \beta$, ratios of the vacuum expectation values of two Higgs doublets, $\tan \beta = v_1/v_2$, and loop corrections from heavy Higgses running in the loop. Of particular interest is the "alignment limit" with $\cos(\beta - \alpha) = 0$, in which the light CP-even Higgs couplings are identical to the SM ones at the tree-level, regardless of the other scalars' masses. Loop corrections, however, could lead to deviations of the couplings of h to the other SM particles, even in the alignment limit.

First let's consider tree-level corrections. The allowed region at 95% C.L. in the $\cos(\beta - \alpha)$ vs. $\tan \beta$ plane for various types of 2HDM (depending on how the two Higgs doublets are coupled to the quarks and leptons) are shown in Fig. 1.35 with tree-level only effects. This is obtained via a global fit to the Higgs rate measurements at the LHC as well as CEPC, assuming that no deviation to the SM values is observed at future measurements. From the figure, one can see that $\cos(\beta - \alpha)$ in all four types is tightly constrained at both small and large values of $\tan \beta$, except for Type-I, in which constraints are relaxed at large $\tan \beta$ due to suppressed Yukawa couplings.

To fully explore the Higgs factory potential, both the tree-level deviation and loop corrections to the SM Higgs couplings need to be taken into account. Fig. 1.36 shows the global fit results to all CEPC Higgs rate measurements in the Type-II 2HDM parameter space, including both tree level and loop corrections. Degenerate heavy Higgs masses $m_A = m_H = m_{H^{\pm}} = m_{\Phi}$ are assumed so that the Z-pole precision constraints are automatically satisfied. The left panel is in the $\cos(\beta - \alpha)$ vs. $\tan \beta$ plane with regions enclosed by curves allowed if no deviation from the SM prediction is observed. Black, red, blue, and green curves are for $\sqrt{\lambda v^2} = \sqrt{m_{\Phi}^2 - m_{12}^2/s_{\beta}c_{\beta}} = 0$, 100, 200, and 300 GeV, respectively. The global fit result with tree-level only corrections is shown by dashed black lines for comparison. $|\cos(\beta - \alpha)|$ is typically constrained to be less than about 0.008 for $\tan \beta \sim 1$. For smaller or larger values of $\tan \beta$, the allowed range of $\cos(\beta - \alpha)$ is significantly reduced. Loop effects from the heavy Higgses tilt the allowed $\cos(\beta - \alpha)$ towards negative values, especially when $\tan \beta$ is large.

The right panel of Fig. 1.36 shows the allowed region at 95% C.L. in the m_{Φ} vs. $\tan \beta$ plane, with $\cos(\beta - \alpha) = -0.005$ (green), 0 (blue), and 0.005 (red). In the alignment limit with $\cos(\beta - \alpha) = 0$, the mass of the heavy Higgses $m_{\Phi} > 500$ GeV is still allowed when $\tan \beta \leq 10$. Once deviating away from the alignment limit, the constraints on the heavy Higgs mass get tighter. The reach in the heavy Higgs mass and couplings at future Higgs factories can be complementary to the direct search limits at the LHC [22, 379–389], especially at intermediate values of $\tan \beta$.

Going beyond the degenerate mass case, both the Higgs and Z-pole precision measurements are sensitive to the mass splitting between the charged and neutral Higgsses,



Figure 1.35: This figure shows the CEPC's capacity to test for new physics in the Higgs sector and its dramatic improvement over existing and projected limits from the LHC. Shaded regions show the viable parameter space assuming that the future measurements agree with SM predictions. The panels show the four types of two-Higgs-doublet models (2HDM). The special "arm" regions for the Type-II, L, and F 2HDMs are the wrong-sign Yukawa regions. Plots are taken from Ref. [20].

as well as the splitting between the neutral ones. Fig. 1.37 shows the allowed region of $\Delta m_A = m_A - m_H$ and $\Delta m_C = m_{H^{\pm}} - m_H$ at 95% C.L., for different choices of $\cos(\beta - \alpha)$. The Higgs and Z-pole precision constraints are presented separately in the left panel while the combined constraints are shown in the right panel, with $m_H = 600 \text{ GeV}$ and $\sqrt{\lambda v^2} = 300 \text{ GeV}$. For the Higgs precision fit, in the alignment limit, Δm_A and Δm_C are bounded to be around 0 within a few hundred GeV. Δm_A is constrained to be positive when $\cos(\beta - \alpha)$ takes a (small) positive value, and negative when $\cos(\beta - \alpha)$ is negative. The Z-pole precision measurements constrain either $\Delta m_C \sim 0$ or $\Delta m_C \sim \Delta m_A$, equivalent to $m_{H^{\pm}} \sim m_{H,A}$. In the small range of $\cos(\beta - \alpha)$ allowed by the current LHC Higgs precision measurements, the change of the Z-pole constraints due to different choices of $\cos(\beta - \alpha)$ is negligible. Combining both the Higgs and Z-pole precisions (right panel), the allowed $\Delta m_{A,C}$ is further constrained to be in a smaller region. From the plots, one can see that Z-pole measurements and Higgs measurements are complementary in constraining the heavy Higgs mass splittings.



Figure 1.36: The constraining power of the CEPC precision measurements are illustrated here using the Type-II 2HDM parameter space. Assuming that no deviation from SM predictions are observed, the allowed regions of parameter space (at 95% C.L.) are enclosed by the curves with the same style. These curves are calculated by a fit including both the tree-level and the loop correction to the SM Higgs couplings. Left: The left panel is in the $\cos(\beta - \alpha)$ vs. $\tan\beta$ plane, with $m_A = m_H = m_{H^{\pm}} = m_{\Phi} = 600 \text{ GeV}$. The parameter $\sqrt{\lambda v^2}$ is set to be 0 (black solid), 100 (red solid), 200 (blue solid), and 300 GeV (green solid). The global fit result with tree-level only correction is represented by the dashed black lines for comparison. **Right:** The right panel is in the m_{Φ} vs. $\tan\beta$ plane with $\sqrt{\lambda v^2} = 300 \text{ GeV}$. The values of $\cos(\beta - \alpha)$ are chosen to be -0.005 (green), 0 (blue), and 0.005 (red). The stars represent the corresponding best fit points. These plots are taken from Ref. [405]. Could the left panel be modified to add the unit GeV for different choices of $\sqrt{\lambda v^2}$?

1.4 QCD precision measurement

As a fundamental force in nature, the strong force is responsible for the generation of the proton's mass. The discovery in the 1970's of Quantum Chromodynamics (QCD) as a correct theory for describing the strong force marks a great achievement in the history of human civilization. Despite forty years of intense study and much progress, QCD remains the least understood quantum field theory of nature, particularly in its non-perturbative domain. Even at high energy where the strong force becomes weak due to the property of asymptotic freedom, it is still challenging to obtain a quantitative description of QCD phenomena. For example, the "fine structure constant" of QCD, α_s , is eight order of magnitude less constrained than the fine structure constant of Quantum Electrodynamics (QED); QCD is currently the least constrained fundamental force of nature, including gravity. Improving the precision in our understanding of QCD has direct impact to our understanding of nature, ranging from the production and decay of the Higgs boson, the partonic structure of proton, and the stability of the Standard Model vacuum.

QCD can be studied at lepton, lepton-hadron, and hadron colliders. Traditionally hadron colliders, such as the Large Hadron Collider (LHC), have been described as QCD machines, because both the initial state and the final state at these colliders are intimately connected to QCD. However, the strongly-interacting nature of the initial state adds additional complications to the description of hard scattering, including the need for the detailed knowledge of Parton Distribution Functions (PDFs), as well as the re-



Figure 1.37: Allowed regions of $\Delta m_A = m_A - m_H$ and $\Delta m_C = m_{H^{\pm}} - m_H$ at 95% C.L., for different choices of $\cos(\beta - \alpha)$. Left: Higgs precisions constraints for $\cos(\beta - \alpha) = 0.007$ (solid red), 0 (solid blue), and -0.007 (solid green) and Z-pole constraints (dashed blue). Note that the Z-pole constraints are the same for $\cos(\beta - \alpha) = 0.007$, 0, and -0.007. Right: constraints from combining both the Higgs and Z pole measurements for $\cos(\beta - \alpha) = 0.007$ (solid red), 0 (solid blue), and -0.007 (solid green). Plots are taken from Ref. [405]. Add GeV to $m_H = 600$.

moval/subtraction of the effects from multiple scattering or underlying events. These complications are absent at a lepton collider, making it an ideal environment for studying QCD at the highest precision. In the past lepton colliders have played an important role in the study of QCD, from the direct observation of gluon jets to the precise extraction of α_s . Compared with LEP, the largest e^+e^- collider ever built, CEPC has substantial improvement in statistics and systematics, therefore allowing QCD to be studied at unprecedented precision. The increase in collision energy will also allow for the exploration of QCD phenomena at previously unaccessible territory at a lepton collider. Besides those well-known problems from the LEP era, many new directions in QCD and jet physics have been opened since the LHC era due increasing attention to the study of jet structure, either as a way to disentangle new physics from QCD backgrounds, or as a probe of QCD dynamics. CEPC will be an ideal machine to address many of these questions at high precision, due to the absence of complications from multiple scattering and underlying events.

Combined with the remarkable progress in QCD theory, ranging from new methods for efficient calculation of cross sections, to the development of effective field theory for collider processes, to new ideas for simulating scattering processes on the lattice, it is expected that CEPC will mark a new chapter in QCD research.

1.4.1 Precision α_s determination

The strong coupling constant α_s is perhaps the most important parameter in QCD. It enters the perturbative predictions of QCD on every observable, in particular cross sections for scattering processes involving hadronic final states at CEPC. A precision determination of

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 α_s at CEPC with unprecedented experimental uncertainties will be an important contribution to the world's effort to determine α_s . At a lepton collider, α_s can be measured in a number ways. The represented ones include hadronic Z decay, hadronic τ decay, QCD jet rates, and QCD event shape measurements. A summary of α_s determination from these observables using LEP data can be found in Ref. [292].

A distinct feature of CEPC compared with previous lepton colliders is the increase in center-of-mass energy, Q. The measurements which can benefit from increased energy are event shape observables, for which non-perturbative corrections typically scale as $c\Lambda_{\rm QCD}/Q$, where c is an O(1) parameter that can not be calculated from first principle with our current understanding of QCD. There exist two different approaches in the modeling of non-perturbative hadronization effects for event shapes. One approach is based on corrections for non-perturbative hadronization effects using QCD inspired Monte Carlo tools [406–410], and the other is based on analytic modeling of the non-perturbative shape function [411–415]. Neither of the two treatments can be regarded as fully satisfactory. In the Monte Carlo approach, there is mismatch in the parton level definition of a Monte Carlo simulation and the fixed order calculation. In the analytic power correction approach, the associated systematics have not been fully verified. Therefore, by going to higher center-of-mass energy, the impact of hardonization effects can be reduced, and the uncertainties associated with them can also be reduced.

As an example of α_s determination from the event shape observables using analytic power correction, we quote the recent determination based on the C parameter from Ref. [415],

$$\alpha_s(m_Z) = 0.1123 \pm 0.0002_{\rm exp} \pm 0.0007_{\rm hadr} \pm 0.0014_{\rm pert} , \qquad (1.28)$$

where hadronization effects and perturbative uncertainties are the main source of uncertainties contributing to α_s determination. While the perturbative uncertainties can be expected to be reduced further in the coming years, given the remarkable progress in the calculation of higher order corrections and in the resummation of large logarithms, the reduction of hadronization uncertainty is likely coming from an increase of center-of-mass energy.

Currently, for thrust [412, 416], C parameter [414, 415], and heavy-jet-mass distribution [417], the best theoretical predictions are at the level of N³LL resummation matched to NNLO in fixed order perturbation theory. A notable recent progress is the calculation of Energy-Energy Correlation (EEC) at NNLO. EEC is an event shape observable which exhibits the so-called rapidity divergence, and leads to additional logarithms to be resummed, compared with thrust and others. Very recently, a determination of α_s using NNLL resummation matched to NNLO, and Monte Carlo for the modeling of power corrections, has been done, with the result [418] being

$$\alpha_s(m_Z) = 0.11750 \pm 0.00018_{\rm exp} \pm 0.00102_{\rm hadr} \pm 0.00257_{\rm ren} \pm 0.00078_{\rm res} , \quad (1.29)$$

where hadronization effects are important source of uncertainties. Since the analysis in Ref. [418] only uses data at or below the Z pole, it is expected that future data from CEPC at 250 GeV can significantly reduce the hadronization uncertainty. Additional scale and resummation uncertainties can also be reduced in the future by incorporating N³LL resummation [419].



Figure 1.38: Left: This plot shows the four-jet production cross section at CEPC ($\sqrt{s} = 250 \text{ GeV}$) with the Durham jet algorithm as a function of the resolution parameter y_{cut} . Right: This plot shows the scale variation and expected statistical uncertainties for the same cross sections normalized to their central values.

1.4.2 Jets rates at CEPC

Another distinct feature of CEPC compared with LEP is its unprecedented luminosity, in particular above the Z pole. The higher luminosity opens the door for the precision study of multi-jet production at an e^+e^- collider.

As an example, we show in Fig. 1.38 the four-jet production cross sections at CEPC $(\sqrt{s} = 250 \text{ GeV})$ with the Durham jet algorithm as a function of the resolution parameter y_{cut} , calculated using NLOjet++ [420]. The cross sections are at the level of a few pb to tens of pb for the range of y_{cut} considered. The colored bands represent the scale variations calculated by varying the renormalization scale from $\sqrt{s}/2$ to $2\sqrt{s}$. The NLO predictions show a smaller scale variation as compared to the LO ones. The cross sections diverge for small resolution parameter where further QCD resummations are needed to stabilize the theoretical predictions. The right panel shows the projected statistical uncertainties assuming an integrated luminosity of 1 and 5 ab^{-1} . The statistical uncertainties are at the level of one per mille or better for y_{cut} below 10^{-2} due to the large luminosity. The scale uncertainties of the NLO predictions are large in comparison and about 10%, which can be reduced with QCD resummation [420]. The n-jet rate has been employed to measure the strong coupling constant α_s at LEP [421]. The four-jet cross sections are proportional to α_s^2 at leading order, thus the statistical uncertainties in the measurement of α_s are estimated to be well below one per mille. On the other hand, the theoretical uncertainties will play a dominant role and need further investigation. Currently, NNLO predictions for e^+e^- to three jets are available [422–426]. Along this line there has been remarkable progress in the calculation of two-loop amplitudes with five external particles [427, 428] and its associated integrals [429, 430]. Although there is still substantial work to be done, an NNLO calculation for four jet production can be expected in the future. There has also been progress in resumming the large logarithms in jet rates. A Monte Carlo approach for resummation has been proposed and used to resum the large logarithms in two-jet rates in Ref. [431], which can achieve resummation at NNLL level. It would be very interesting to extend this approach to three and four jet rates.



Figure 1.39: This figure shows the normalized light-jet-mass distribution both at Z-pole (left) and at 250 GeV (right). Green curves are NLL results without NGLs, and red bands are full NLL results with scale uncertainties.

1.4.3 Non-global logarithms

Besides the precision extraction of α_s from jetty final states, there has also be significant interest in understanding some novel aspects of QCD dynamics from jet processes at a lepton collider. An important example is the study on Non-global logarithms (NGL) [432, 433].

Non-global logarithms are significant obstacles in the study of soft physics at high energy colliders (jet physics, energy flow measurements, hadronization, and so on). Therefore it is important to develop a theoretical framework to understand their structure. NGLs were first pointed out by Dasgupta and Salam in Ref. [432], where they developed a Monte-Carlo algorithm to resum leading-logarithmic(LL) NGLs in the large N_c limit. After that work, based on strong energy ordering limit Banfi, Marchesini and Smye derived an integral-differential evolution equation that can also resum LL NGLs [433]. Since then, there has been a great effort to improve the theoretical predictions [434–439], including the sub-leading N_c effects [440–442] and some fixed-order calculations [443, 444].

Recently, there have been several developments in this field [445–453]. One example is the effective field theory developed in Ref. [447]; this reference was the first to write down the factorization formula for non-global observables and to give an any-order renormalization group evolution equation for NGLs.

As an electron-positron collider, CEPC will provide new opportunities, which can precisely measure NGLs in many observables. Fig. 1.39 shows the normalized light-jet-mass distribution both at Z-pole (left) and at 250 GeV (right). Green curves are NLL results without NGLs, and red bands are full NLL results with scale uncertainties. Obviously, after including NGLs theoretical predictions are reduced significantly, and this reduction is especially magnificent at 250 GeV. Therefore CEPC will give us the first opportunity to measure NGLs.

1.4.4 QCD event shapes and light quark Yukawa coupling

The SM Higgs boson decays dominantly to various hadronic final states with a total branching fraction of more than 80%. These hadronic decays provide a new source for QCD studies at CEPC (in its Higgs factory mode). In particular Higgs decays produce a unique color-neutral digluon state. Tab. 1.3 summarizes the estimated number of events

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
$N_{\rm event}$	6140	41170	2070	6780	930	14

Table 1.3: This table shows branching ratios (BR) for decays of the SM Higgs boson in different hadronic channels [455] and the number of expected events (N_{event}) for ZH production at CEPC ($\sqrt{s} = 250 \text{ GeV}$ and $\mathcal{L} = 5 \text{ ab}^{-1}$) with the corresponding hadronic Higgs decay. In this table, H represents the Higgs boson, h represents any of the quarks except the top quark, and q are light quarks.

for different hadronic decay modes of the Higgs boson; the table assumes that the tagged Z boson decays into electrons or muons, and it takes $\mathcal{L} \sim \text{fb}^{-1}$ and $\sqrt{s} = 250 \text{ GeV}$.

At CEPC the traditional hadronic event shapes, e.g., thrust distribution, can be well measured due to the high statistics. At a lepton collider one can reconstruct the kinematics fully and then boost all final states back to the rest frame of the decaying Higgs boson. On the theory side those distributions can be calculated with high precision by QCD resummation matched with fixed-order results. There exist uncertainties from nonperturbative QCD effects, e.g. hadronization modeling, which are usually estimated by Monte Carlo event generators. The left panel of Fig. 1.40 shows the normalized distribution of the variable thrust for several different hadronic decay channels of the Higgs boson, including gg, $q\bar{q}$, $b\bar{b}$, and $W(q\bar{q})W^*(q\bar{q})$ [454]. The distribution peaks at $\tau \sim 0.02$ for the light-quark decay channel. The peak shifts to $\tau \sim 0.05$ for the gluon channel, corresponding to a scaling of roughly C_A/C_F . The distribution is much broader for the gluon case due to the stronger QCD radiation. The distribution for the $b\bar{b}$ channel is very close to the $q\bar{q}$ case, except at very small τ , where the mass and hadronization effects become important. For the WW^* channel there already exist four quarks at leading order and the distribution is concentrated in the large- τ region.

Different shapes of the thrust distribution from diquark and digluon final states motivates the idea of using global event shapes to probe the Yukawa couplings of light quarks [454], namely strange, up and down quarks. The provided discrimination can largely reduce background due to Higgs boson decays into two gluons while backgrounds from Higgs boson decays into heavy quarks can be suppressed with the usual heavy-flavor tagging algorithms. It is a great challenge to probe the light-quark Yukawa couplings since they are very small and the expected number of events with CEPC's full luminosity is only 14 as shown in Tab. 1.3. The expected exclusion limits on decay branching ratios of Higgs boson to light quarks are shown in the right plot of Fig. 1.40, indicated by intersections with the vertical line and normalized to the branching ratio to digluon. The results can be translated into an upper limit of 0.48% on the decay branching ratios or 5 times of its value in standard model for Yukawa coupling of strange quark.

1.5 Flavor Physics with the Z factory of CEPC

A high luminosity Z factory that produces 10^{12} Z bosons provides unique opportunities for various flavor measurements. In particular, the decay of 10^{12} Z bosons will result in approximately 10^{11} b hadrons, which is almost two orders of magnitude larger than the number of B mesons produced at the B factories BaBar and Belle and comparable to the number of B mesons expected at Belle II. As the B factories are running mainly



Figure 1.40: Left: This plot shows the normalized distributions of thrust in hadronic Higgs decay, in $e^+e^- \rightarrow q\bar{q}$ with a CMS energy of 125 GeV and in $e^+e^- \rightarrow Zq\bar{q}$ with a CMS energy of 250 GeV. **Right:** This plot shows CEPC's capacity to probe the Higgs boson's decay into light quarks. The green and yellow bands show the expected 95% C.L. exclusion limit on r = BR(qq)/BR(jj) as a function of the total cross section of the Higgs boson decay to jj normalized to the SM value.

on the $\Upsilon(4S)$ resonance, they mostly produce B^0 and B^{\pm} mesons; they also produce B_s mesons but in much smaller numbers from shorter runs on $\Upsilon(5S)$. A machine running on the Z-pole on the other hand will not only produce a large number of B_s mesons, but also a large sample of b baryons. In Tab. 1.4 we compare the expected numbers of produced b-hadrons corresponding to 10^{12} Z-boson decays to those produced with the 50 ab^{-1} run on $\Upsilon(4S)$ and the 5 ab^{-1} run on $\Upsilon(5S)$ of Belle II. For the tera-Z we also list number of produced charmed hadrons and tau leptons (we use the known Z branching fractions $BR(Z \to b\bar{b}) = (15.12 \pm 0.05)\%$, $BR(Z \to c\bar{c}) = (12.03 \pm 0.21)\%$, and $BR(Z \to \tau^+\tau^-) = (3.3696 \pm 0.0083)\%$ [292] and the b and c hadronization fractions at the Z pole from Refs. [456–458]). Using the large sample of produced b/c hadrons and taus, the tera-Z factory of CEPC will be able to access many rare decays of these particles, many with a precision beyond any of the ongoing or planned experiments. In addition, the $10^{12} Z$ bosons would also allow measurements of flavor violating Z decays with an unprecedented precision.

A future circular electron-positron collider does not only benefit from its large statistics. Compared to LHCb, an electron-positron collider offers a much cleaner environment and, therefore, generally smaller background levels. Compared to the Belle II flavor factory, running at the Z-pole leads to a much larger boost of the b hadrons and their decay products, which is in particularly useful in constraining decays with missing energy, e.g., decays with neutrinos in the final state.

In section 1.5.1 we discuss the prospects of measuring a number of rare *b*-hadron decays at the tera-*Z* factory of CEPC: we cover leptonic decays, semi-leptonic decays, and decays with missing energy. Particular emphasis is laid on rare decays to final states with tau leptons, in which the sensitivity of the tera-*Z* program of CEPC will be unparalleled. We also comment on possible implications of the current hints for lepton-flavor-universality violation in rare *B* decays, that have been observed by LHCb. A discussion of tau decays follows in section 1.5.2, where we discuss the prospects of CEPC to significantly improve lepton universality tests in leptonic tau decays as well as its prospects for mea-

Particle	@ Tera-Z	@ Belle II	
b hadrons			
B^+	6×10^{10}	3×10^{10}	$(50 \operatorname{ab}^{-1} \operatorname{on} \Upsilon(4S))$
B^0	6×10^{10}	3×10^{10}	$(50 \operatorname{ab}^{-1} \operatorname{on} \Upsilon(4S))$
B_s	2×10^{10}	3×10^8	$(5 \operatorname{ab}^{-1} \operatorname{on} \Upsilon(5S))$
b baryons	1×10^{10}		
Λ_b	1×10^{10}		
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
$ au^+$	3×10^{10}	5×10^{10}	$(50 \operatorname{ab}^{-1} \operatorname{on} \Upsilon(4S))$

Table 1.4: Collection of expected number of particles produced at a tera-Z factory from 10^{12} Z-boson decays. We have used the hadronization fractions (neglecting p_T dependences) from Refs. [456, 457] (see also Ref. [458]). For the decays relevant to this study we also show the corresponding number of particles produced by the full 50 ab^{-1} on $\Upsilon(4S)$ and 5 ab^{-1} on $\Upsilon(5S)$ runs at Belle II.

suring rare, lepton-flavor violating tau decays. Flavor violating Z decays are discussed in section 1.5.3.

1.5.1 Rare *B* decays

1.5.1.1 Leptonic decays $B^0 \rightarrow \ell^+ \ell^-$ and $B_s \rightarrow \ell^+ \ell^-$

The purely leptonic $B_s \rightarrow \ell^+ \ell^-$ and $B^0 \rightarrow \ell^+ \ell^-$ decays are strongly suppressed in the Standard Model and therefore highly sensitive to new-physics contributions. Their branching ratios are known with high precision in the Standard Model [459]

$$BR(B_s \to e^+ e^-)_{SM} = (8.54 \pm 0.55) \times 10^{-14} , \qquad (1.30)$$

$$BR(B^0 \to e^+ e^-)_{SM} = (2.48 \pm 0.21) \times 10^{-15} , \qquad (1.31)$$

$$BR(B_s \to \mu^+ \mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} , \qquad (1.32)$$

$$\mathbf{BR}(B^0 \to \mu^+ \mu^-)_{\mathbf{SM}} = (1.06 \pm 0.09) \times 10^{-10} , \qquad (1.33)$$

$$BR(B_s \to \tau^+ \tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7} , \qquad (1.34)$$

$$BR(B^0 \to \tau^+ \tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8} .$$
 (1.35)

Presently, LHCb has provided the most sensitive measurement of the $\mu^+\mu^-$ decays with a precision at the level of 10^{-9} [460]. The current most stringent bound on the $e^+e^$ modes is still coming from CDF [461]. With 50 fb⁻¹ of data, LHCb is expected to reach sensitivities of approximately 10^{-10} in the muonic modes and few× 10^{-10} in the electronic modes [462].

To estimate the sensitivity of a tera-Z factory for the decays to electrons and muons we rescale the existing bound from the L3 collaboration [463] from the full LEP-I data sam-

ple, which corresponds to approximately 3×10^5 , and $9 \times 10^4 B^0$'s, and B_s 's, respectively. A naive rescaling of these bounds accounting for the number of B^0 's and B_s 's produced at a tera-Z factory gives:

$$BR(B_s \to e^+e^-)_{tera-Z} \lesssim 4 \times 10^{-10}$$
, (1.36)

$$BR(B^0 \to e^+ e^-)_{tera-Z} \lesssim 8 \times 10^{-11}$$
, (1.37)

$$BR(B_s \to \mu^+ \mu^-)_{tera-Z} \lesssim 3 \times 10^{-10}$$
, (1.38)

$$BR(B^0 \to \mu^+ \mu^-)_{\text{tera-}Z} \lesssim 7 \times 10^{-11} \,. \tag{1.39}$$

Note, that this linear scaling with the number of B mesons assumes that backgrounds can be kept under control also at the CEPC. The comparison with the projections from LHCb [462] shows that LHCb with 50 fb^{-1} will likely outperform the tera-Z factory by a factor of few for the muonic modes. For the electronic modes the tera-Z factory may be able to compete with LHCb.

The rare B decays to the $\tau^+\tau^-$ final state are experimentally still a largely uncharted territory. The existing bound from BaBar [464], BR $(B^0 \rightarrow \tau^+\tau^-) < 4.1 \times 10^{-3}$, is orders of magnitude away from the corresponding SM prediction. Measurements of the $\tau^+\tau^-$ final states are highly challenging at LHCb. The current sensitivities are at the level of few×10⁻³ [465] and could improve down to few×10⁻⁴ [462]. Also Belle II will likely only reach sensitivities at the level of 10^{-4} for $B^0 \rightarrow \tau^+\tau^-$ [466]. The decays $B^0 \rightarrow \tau^+\tau^-$ and $B_s \rightarrow \tau^+\tau^-$ are thus prime examples of processes to which a circular electron–positron collider running at the Z pole is uniquely sensitive. As no dedicated study exists at them moment for the sensitivity of tera-Z factory to these decays, we estimate it by comparing Belle II's relative sensitivity between the $B^0 \rightarrow \mu^+\mu^-$ and the $B^0 \rightarrow \tau^+\tau^-$ modes. The corresponding rough estimates read

$$BR(B^0 \to \tau^+ \tau^-)_{\text{tera-}Z} < 4 \times 10^{-6} , \qquad (1.40)$$

$$BR(B_s \to \tau^+ \tau^-)_{\text{tera-}Z} < 2 \times 10^{-5} .$$
 (1.41)

These estimates do not account for the higher boost of the decay products in a Z factory. We thus expected them to be conservative, i.e., CEPC's sensitivity may be even higher. We thus find that CEPC's tera-Z factory will provide the by far most stringent measurements of the $B_s \rightarrow \tau^+ \tau^-$ and $B^0 \rightarrow \tau^+ \tau^-$ decays, improving the expected sensitivities at LHCb and Belle II by more than an order of magnitude.

1.5.1.2 Semileptonic decays $b \rightarrow s(d)\ell^+\ell^-$

Semileptonic FCNC decays of *b*-mesons are not as theoretically clean as the $B_{s,d} \rightarrow \ell^+ \ell^-$ decays. They are, however, *i*) less rare within the SM, which makes them experimentally more accessible, and *ii*) three-body or four-body decays resulting in multiple observables for a given mode, e.g., invariant-mass and angular distribution observables, *CP* asymmetries, etc.

In recent years, the exclusive decays $B \to K^{(*)}e^+e^-$ and $B \to K^{(*)}\mu^+\mu^-$ have attracted a lot of attention due to the large number of LHCb measurements and in particular due to some persistent $\approx 2-3\sigma$ tensions between data and SM expectations in related observables, i.e., $R_{K^{(*)}}$ [467, 468] theoretically clean observables that tests for lepton-flavoruniversality violation, and the angular observable P'_5 [469]. The tensions are present in LHCb's Run-1 data set of 3 fb^{-1} , with Run-2 results yet to be announced. We expect significant progress as LHCb collects a data set of 50 fb^{-1} . Belle II will also probe these exclusive modes. Its 50 ab^{-1} run on $\Upsilon(4S)$ will provide measurements of these modes with a precision not much lower that LHCb with its full data set [466]. As the number of B^0 and B^+ mesons produced at the tera-Z factory and at Belle II are approximately the same, we ultimately expect a similar precision at the two machines. In this respect, the CEPC's measurements of these modes will be invaluable, especially if the tensions in the exclusive $B \to K^{(*)}e^+e^-$ and $B \to K^{(*)}\mu^-\mu^+$ persist in the full data set of LHCb. In such a case, the CEPC's program will provide a new data set and will be able to independently confirm the existence of new-physics effects in the electronic and muonic decays.

Both Belle II and CEPC will also be able to access the inclusive decays $B \to X_s e^+ e^$ and $B \to X_s \mu^+ \mu^-$ with comparable precision. Hadronic uncertainties are under better control in the inclusive modes and their measurements will complement the studies of the exclusive decays mentioned above.

Contrary to the ee and $\mu\mu$ modes, little experimental information exists on the semitauonic modes $b \to s(d)\tau^+\tau^-$ so far. The only existing bound from BaBar [470], BR($B \to$ $K\tau^+\tau^-) < 3.3 \times 10^{-3}$, is approximately four orders of magnitude above the SM prediction and it is not clear whether LHCb will be able to improve the sensitivity substantially. The first major improvements are thus expected at Belle II. For instance, its 50 ab^{-1} run will probe the branching ratio of $B^+ \to K^+ \tau^+ \tau^-$ at the level of 2×10^{-5} [466]. A dedicated study is required to quantitatively assess the full potential of the tera-Z factory, which is expected to outperform Belle II in modes as the ones in question, in which missing energy from the tau decays is present in the event. A study for the FCC-ee program that investigates the $B^0 \to K^* \tau^+ \tau^-$ decay [471], finds that approximately a thousand cleanly reconstructed events are expected from 10^{13} Z's. We thus expect approximately hundred events at the tera-Z factory probing the SM branching ratio of $\sim 10^{-7}$ with a statistical uncertainty of 10%. We see that, similarly to the $B_q \to \tau^- \tau^+$ mode, also here the tera-Z factory will provide the by far most accurate measurements. With hundred events even a partial angular analysis might be possible. Additionally, the large number of B_s mesons and Λ_b baryons produced at the tera-Z factory will facilitate the first measurements of the corresponding decays, $B_s \to \phi \tau^+ \tau^-$, and $\Lambda_b \to \Lambda \tau^+ \tau^-$ at a similar level of precision. The measurements of the semi-tauonic decay will also open the path towards measurements of lepton-flavor-universality violation involving not only electrons and muons, but also taus, which will be of particular interest if the present tensions in the muon-electron data persist.

1.5.1.3 Decays with missing energy $b \rightarrow s(d)\nu\bar{\nu}$

The rare FCNC decays $B \to K^{(*)}\nu\bar{\nu}$ are widely recognized as important flavor probes, as they are not affected by non-factorizable corrections and thus theoretically cleaner compared to $b \to s\ell\ell$ transitions. The SM predictions for the branching ratios of these decays read [472]

$$BR(B^+ \to K^+ \nu \bar{\nu})_{SM} = (4.68 \pm 0.64) \times 10^{-6}, \qquad (1.42)$$

$$BR(B^0 \to K^0 \nu \bar{\nu})_{SM} = (2.17 \pm 0.30) \times 10^{-6}, \qquad (1.43)$$

$$\mathbf{BR}(B^+ \to K^{*+} \nu \bar{\nu})_{\mathrm{SM}} = (10.22 \pm 1.19) \times 10^{-6}, \qquad (1.44)$$

$$BR(B^0 \to K^{*0} \nu \bar{\nu})_{SM} = (9.48 \pm 1.10) \times 10^{-6}, \qquad (1.45)$$

with uncertainties in the theoretical predictions of roughly 10%, dominated by parametric and form-factor uncertainties. The accuracy of these predictions in combination with the fact that these modes have not yet been observed (current bounds are typically an order magnitude away from the SM predictions, e.g., see Ref. [473]), is the reason why these modes are prime candidates for disentangling small new-physics contributions. Since the neutrinos are never tagged in the experiments, such modes are not only relevant for searches for heavy new physics, but can also provide the leading constraints in models with light, long-lived particles with small flavor-violating couplings, e.g., the "axiflavon" [474].

With its full, 50 ab⁻¹ dataset run on $\Upsilon(4S)$, Belle II is expected to probe for the first time deviations from the SM predictions at a level of approximately 17% [475]. The dominant uncertainties in such measurements are expected to be due to statistics. The related decays based on the $b \to d\nu\bar{\nu}$ transition, i.e., $B \to \pi\nu\bar{\nu}$ and $B \to \rho\nu\bar{\nu}$, are further suppressed in the SM by a factor of approximately 30. Limits at a level of 10^{-6} are expected at Belle II.

Given that the number of B^0 and B^+ particles produced with 50 ab^{-1} at Belle II are roughly the same at a tera-Z factory, we expect similar statistical uncertainties there. Therefore, at the very least, the tera-Z factory will probe the SM predictions of $B \rightarrow K^{(*)}\nu\bar{\nu}$, $B \rightarrow \pi\nu\bar{\nu}$, and $B \rightarrow \rho\nu\bar{\nu}$ at the same level as Belle II. However, this estimate does not take into account the favourable kinematic environment of a tera-Z factory. The larger, with respect to Belle II, boost of the B mesons in a collider running on the Z pole persists on the neutrino system. This leads to a robuster measurement of missing energy, which is instrumental for the searches of these decays. While a dedicated study would be needed to quantitatively assess this advantage, it may well be the case that this will be enough to tilt the balance in favour of the tera-Z factory.

As illustrated in Tab. 1.4 the tera-Z factory will produce two orders of magnitude more $B_s^{(*)}$ mesons than a 5,ab⁻¹ run of Belle II on $\Upsilon(5S)$. Also, approximately 10^{10} b baryons will be produced at the tera-Z factory, whereas none can be produced at Belle II without (not planned) dedicated runs. The tera-Z factory will thus for the first time have access to decay modes of B_s mesons and Λ_b baryons, like $B_s \to \phi \nu \bar{\nu}$ and $\Lambda_b \to \Lambda \nu \bar{\nu}$. Given the large statistical sample, we expect the tera-Z factory to probe these branchings fractions at a level similar to the related B_0 and B^+ modes, i.e., branching fractions of approximately 10^{-6} .

More than one higher-dimensional operator of the five-flavor effective theory can induce these decays. By probing multiple members of this whole family of decays, the measurements of the tera-Z-factory will probe more than a single linear combination of operators. For instance, the combination of the information from the pseudoscalar to pseudoscalar transitions ($B \to K \nu \bar{\nu}$), the pseudoscalar to vector transitions ($B \to K^* \nu \bar{\nu}$ and $B_s \to \phi \nu \bar{\nu}$), as well as the fermion to fermion transition ($\Lambda_b \to \Lambda \nu \bar{\nu}$) could be a way to disentangle possible new-physics contributions from right-handed currents.

1.5.1.4 Probing new physics with $b \rightarrow s(d) \tau^+ \tau^-$ decays

There are many new-physics scenarios, e.g., models with extended Higgs sectors, or extended gauge sectors, or scenarios with leptoquarks, that could give rise to sizable effects in leptonic or semi-leptonic $\tau^+\tau^-$ modes, without violating constraints from the $e^+e^$ and/or $\mu^+\mu^-$ channels. Model independently, tau specific new physics in rare *B* decays can be encoded in an effective Lagrangian

$$\mathcal{L}_{\rm NP} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{tq}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i O_i + C_i' O_i' \right), \quad q = s, d , \qquad (1.46)$$

with the operators

$$O_{7} = (\bar{q}\sigma_{\mu\nu}P_{R}b)F^{\mu\nu}, \qquad O_{7}' = (\bar{q}\sigma_{\mu\nu}P_{L}b)F^{\mu\nu},
O_{9} = (\bar{q}\gamma_{\mu}P_{L}b)(\bar{\tau}\gamma^{\mu}\tau), \qquad O_{9}' = (\bar{q}\gamma_{\mu}P_{R}b)(\bar{\tau}\gamma^{\mu}\tau),
O_{10} = (\bar{q}\gamma_{\mu}P_{L}b)(\bar{\tau}\gamma^{\mu}\gamma_{5}\tau), \qquad O_{10}' = (\bar{q}\gamma_{\mu}P_{R}b)(\bar{\tau}\gamma^{\mu}\gamma_{5}\tau),
O_{S} = (\bar{q}P_{R}b)(\bar{\tau}P_{L}\tau), \qquad O_{S}' = (\bar{q}P_{L}b)(\bar{\tau}P_{R}\tau).$$

Constraining all possible $\tau^+\tau^-$ operators requires measurements of both the leptonic and semi-leptonic modes, as they have different blind directions in the parameter space of Wilson coefficients [476, 477]. Note, that also the decays with neutrinos, $b \to q\nu\bar{\nu}$, can constrain the operator-combinations that contain a left-handed tau current $O_9 - O_{10}$ and $O'_9 - O'_{10}$, due to $SU(2)_L$ invariance. On the other hand, the neutrino modes are blind to the orthogonal directions $O_9 + O_{10}$ and $O'_9 + O'_{10}$, which contain right-handed tau currents.

There are various new-physics models that can lead to non-standard effects in $b \rightarrow (d, s)\tau^+\tau^-$ decays. Interestingly, several models that address the LHCb anomalies in the $B \rightarrow K^*\mu^+\mu^-$ angular distribution or the hints for lepton-flavor-universality violation in $R_{K^{(*)}}$ [467, 468] or $R_{D^{(*)}}$ [478] predict characteristic non-standard effects in $b \rightarrow s\tau^+\tau^-$ transitions.

The model proposed in Ref. [479] is based on gauging the difference of muon- and tau-number, $L_{\mu} - L_{\tau}$. Given the current anomalies in $b \to s\mu^+\mu^-$, the model predicts that all semi-leptonic $b \to s\mu^+\mu^-$ decays are suppressed by approximately 25% [480]. The $L_{\mu} - L_{\tau}$ symmetry implies that all semi-leptonic $b \to s\tau^+\tau^-$ decays are instead enhanced by a similar amount. However, the $B_s \to \tau^+\tau^-$ decay remains SM-like in the $L_{\mu} - L_{\tau}$ framework.

In the new-physics scenarios originally introduced in Refs. [481–483], the current *B*-physics anomalies are addressed by non-standard left-handed currents involving mainly the 3rd generation of quarks and leptons. In such scenarios, enhancements of $B_s \rightarrow \tau^+ \tau^-$ and $b \rightarrow s\tau^+\tau^-$ rates by an order of magnitude compared to the SM predictions are possible. Left-handed currents also imply a strong correlation between $b \rightarrow s\tau^+\tau^-$ and $b \rightarrow s\nu\bar{\nu}$ decays, as well as enhanced $b \rightarrow s\nu\bar{\nu}$ rates. On the other hand, enhancements of $b \rightarrow s\tau^+\tau^-$ rates that are independent of $b \rightarrow s\nu\bar{\nu}$ are possible in models with right-handed lepton currents. In such scenarios the current experimental bounds can in principle be saturated.

1.5.2 Tau decays

From Tab. 1.4 we see that at the tera-Z factory of CEPC we can expect approximately $3 \times 10^{10} \tau^+ \tau^-$ pairs produced from Z decays. This is comparable to the expected number of taus produced at Belle II, i.e., roughly 5×10^{10} . This suggests that the sensitivities to lepton-flavor violating decays of taus at CEPC can be similar to the sensitivities expected at Belle II. The large boost of taus from the Z decays is expected to allow CEPC to measure the standard leptonic branching ratios of the tau and to test lepton universality in $\tau \to \ell \nu \bar{\nu}$ with unprecedented precision.

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1.5.2.1 Lepton universality in $\tau \rightarrow \ell \nu \bar{\nu}$

The best measurements of the leptonic branching ratios of the tau, $BR(\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\mu})$ and $BR(\tau \rightarrow e\nu_{\tau} \bar{\nu}_{e})$, still come from LEP [292]. The most precise individual results are from Aleph [484] and read $BR(\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\mu}) = (17.319 \pm 0.070 \pm 0.032)\%$ and $BR(\tau \rightarrow e\nu_{\tau} \bar{\nu}_{e}) = (17.837 \pm 0.072 \pm 0.036)\%$, where the first uncertainty is due to statistics and the second due to systematics. One can see that the measurements were statistics limited with systematic uncertainties at the level of approximately 2 permille. This implies that the larger statistics of a tera-Z program at the CEPC will result in the world best measurement of these branching ratios with uncertainties at the permille level or even much better. Indeed, it is very likely that the much larger number of τ pairs will also allow the experiments to gain a much better control of systematic uncertainties. Assuming that systematics can be reduced by an order of magnitude (which requires exquisite control of the electron and muon efficiencies), the leptonic tau branching ratios could be measured at CEPC with a relative uncertainty of 10^{-4} . Dedicated studies are required to establish the precise sensitivity of CEPC.

The leptonic branching ratios of the tau can in principle be predicted with very high precision in the SM [485]. The SM precision is limited by the uncertainty in the measured tau lifetime, τ_{τ} . The most precise tau lifetime determination comes currently from Belle [486] and has an uncertainty of approximately 2 permille. Given the much higher statistics expected at Belle II, future measurements may be able to improve the precision of τ_{τ} by up to an order of magnitude. We expect that CEPC could reach a precision for τ_{τ} similar to Belle II. The precise relation between the τ lifetime and the leptonic branching ratios in the SM, combined with future precise determinations of BR($\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\mu}$) and BR($\tau \rightarrow e \nu_{\tau} \bar{\nu}_{e}$) at CEPC would allow to scrutinize the weak interactions in tau decays with an unprecedented precision.

Additional information can be extracted from measurements of kinematic distributions in tau decays and the determination of the tau decay parameters (also known as Michel parameters) [292], which are highly sensitive to the structure (spin and chirality) of the current that mediates tau decays. CEPC can be expected to substantially improve the existing (LEP) and expected (Belle II) measurements of tau decay parameters.

In addition to measurements of the absolute leptonic branching ratios and their kinematic distributions, it is of particular interest to look at the lepton-flavor universality ratio

$$R_{\tau} = \frac{\mathbf{BR}(\tau \to \mu \nu_{\tau} \bar{\nu}_{\mu})}{\mathbf{BR}(\tau \to e \nu_{\tau} \bar{\nu}_{e})} \,. \tag{1.47}$$

This ratio is independent of the tau lifetime and can be predicted with extremely high precision in the SM, $R_{\tau}^{\text{SM}} = 0.972559 \pm 0.000005$ [485]. The currently most precise direct measurement of this ratio comes from BaBar and has an uncertainty of approximately 4 permille, $R_{\tau}^{\text{BaBar}} = 0.9796 \pm 0.0016 \pm 0.0036$ [487]. A measurement of R_{τ} with an uncertainty of 10^{-4} may be possible at CEPC (cf. discussion above about the expected precision in the absolute branching ratios).

Most new-physics models that explain the current hints for lepton-flavor universality violation in *B* decays, $R_{K^{(*)}}$ [467, 468] and $R_{D^{(*)}}$ [478] also lead to lepton-flavor universality violation in $\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\mu}$ vs. $\tau \rightarrow e \nu_{\tau} \bar{\nu}_{e}$ [488, 489]. Typical new-physics effects are at the level of a few permille and should be well within the reach of CEPC. Therefore,
more accurate measurements of R_{τ} would be invaluable to scrutinize many motivated new-physics scenarios.

1.5.2.2 Lepton-flavor violating τ decays

In the SM without neutrino masses, lepton flavor is conserved and lepton-flavor violating tau decays are completely absent. While non-zero neutrino masses in principle lead to lepton-flavor violating tau decays, branching ratios like $\tau \rightarrow \mu \gamma$ are predicted at the level of 10^{-45} . However, in models of new physics such branching ratios could be enhanced by many orders of magnitude and could be in reach of experimental searches. In this sense, any observation of lepton-flavor violating tau decays would be an unambiguous sign of physics beyond the SM.

Lepton-flavor violating tau decays have been searched for in a multitude of channels at the *B* factories BaBar and Belle. Among them are the radiative modes $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$, purely leptonic modes like $\tau \rightarrow 3\mu$, $\tau \rightarrow 3e$, $\tau \rightarrow \mu ee$, etc., as well as many hadronic modes like $\tau \rightarrow \mu\pi^0$, $\tau \rightarrow e\pi^0$, $\tau \rightarrow \mu K$, etc. Most of these decays have been constrained at the level of 10^{-8} [456]. Thanks to its increase in statistics, Belle II is expected to improve the sensitivities to the lepton-flavor violating tau decays by at least one order of magnitude or even more in very clean modes like $\tau \rightarrow 3\mu$.

The clean signature of three muons allows LHCb to search for the decay $\tau \to 3\mu$ with high sensitivity. The current limit, which has been obtained with 3 fb^{-1} of the combined 7 TeV and 8 TeV data, reads BR $(\tau \to 3\mu)_{\text{LHCb}} < 4.6 \times 10^{-8}$ [490] and is competitive with the existing bounds from BaBar and Belle. In the high-luminosity phase of LHC, LHCb will likely improve this bound by one order of magnitude down to few times 10^{-9} .

Given the comparable numbers of taus that will be produced at Belle II and that could be expected from the tera-Z factory at CEPC, we expect similar sensitivities to these decays at both machines. While dedicated studies would need to be performed to ascertain that backgrounds would be under control at CEPC, we expect CEPC's sensitivities to lepton-flavor violating tau decays across the board at the level of 10^{-9} or better.

1.5.3 Flavor violating Z decays

Rare decays of the Z boson that violate quark flavor, $Z \to qq'$, are absent in the SM at tree level and therefore strongly suppressed. The largest branching ratio in the SM is expected to be $Z \to bs$ and can be estimated as $BR(Z \to bs) \sim \left|\frac{g^2}{16\pi^2}V_{tb}V_{ts}^*\right|^2 \times BR(Z \to bb) \sim 10^{-9}$. Even with the statistics expected from $10^{12} Z$ bosons, a measurement of the SM rate would be extremely challenging as the $Z \to bs$ events will be buried under an enormous background from $Z \to q\bar{q}$ and $Z \to b\bar{b}$ decays. New physics can induce effective quark-flavor violating Z couplings, but such effects are typically constrained by rare meson decays and meson-mixing observables. Rates of $Z \to qq'$ that are far above SM expectations are therefore unlikely.

Lepton-flavor violating decays are completely absent in the SM without neutrino masses. Including neutrino masses, $Z \rightarrow \ell \ell'$ decays can in principle arise but the branching ratios are suppressed by the tiny neutrino masses and predicted to be in the ballpark of $10^{-50} - 10^{-60}$. However, new physics could enhance these branching ratios by many orders of magnitude.

Searches at LEP established the following upper bounds using few×10⁶ Z bosons [491–493]: BR($Z \rightarrow \mu e$) < 1.7 × 10⁻⁶, BR($Z \rightarrow \tau e$) < 9.8 × 10⁻⁶, and BR($Z \rightarrow \tau \mu$) <

 1.2×10^{-5} . Due to the huge numbers of Z bosons produced at the LHC, searches at ATLAS and CMS for the clean $Z \to \mu e$ decay have recently set limits at the level of few× 10^{-7} [494, 495]. Searches for the final states with taus are more challenging at the LHC. The current ATLAS limits for $Z \to \tau e$ and $Z \to \tau \mu$ are at the level of few× 10^{-5} [496]. With the high statistics that are be expected from the future LHC runs, it is conceivable that the bounds on lepton-flavor violating Z decays will improve by an order of magnitude or more.

Assuming that the sensitivities at the tera-Z factory of CEPC can be scaled from the LEP bounds with the square root of the number of produced Z bosons we find that with $10^{12} Z$ bosons

$$BR(Z \to \mu e)_{CEPC} \lesssim 3 \times 10^{-9}, \qquad (1.48)$$

$$BR(Z \to \tau e)_{CEPC} \lesssim 2 \times 10^{-8}, \qquad (1.49)$$

$$BR(Z \to \tau \mu)_{CEPC} \lesssim 2 \times 10^{-8} \,. \tag{1.50}$$

This is a substantial improvement compared to existing and expected bounds. A more realistic analysis, including explicit background studies from e.g. $Z \rightarrow \tau \tau$ would need to be performed to provide a more precise estimate of the sensitivities [497]. Nevertheless, the above estimates indicate promising sensitivities to new-physics models that induce lepton-flavor violating Z decays, as for example extensions of the SM with heavy sterile neutrinos [287].

1.5.4 Summary

A CEPC that produces $10^{12} Z$ bosons provides large statistics samples of b and c hadrons as well as tau leptons in a clean experimental environment. This results to unique opportunities for various flavor measurements that are unparalleled in current or any other future machine. For example, the observation of the rare tauonic decays $B \to K^* \tau^+ \tau^$ and $B_s \to \phi \tau^+ \tau^-$ at the SM rate could be achieved at CEPC, whereas the SM rates of such tauonic decays are not in reach of neither LHCb nor Belle II. It appears that sufficient statistics could be accumulated such that even an angular analysis of $B \to K^{(*)} \tau^+ \tau^-$ may be possible. CEPC should also achieve the world's best sensitivity to the related tauonic decay modes $B_s \to \tau^+ \tau^-$ and $B \to K \tau^+ \tau^-$ at a level of 10^{-5} . New physics in the rare tauonic decays is particularly well motivated given the current hints for lepton-flavor universality violation in $R_{K^{(*)}}$ and $R_{D^{(*)}}$. A future circular electron–positron collider is also the only machine that would allow measurements of the rare FCNC decays of B_s mesons and Λ_b baryons to neutrinos, i.e., $B_s \to \phi \nu \bar{\nu}$ and $\Lambda_b \to \Lambda \nu \bar{\nu}$, with sensitivities of $\sim 10^{-6}$, thus complementing the sensitivity of Belle II to $B \to K^{(*)} \nu \bar{\nu}$.

A tera-Z factory of CEPC will also likely reach sensitivities to lepton-flavor violation in tau decays at a level of 10^{-9} , which is comparable to the sensitivities expected at Belle II. The leptonic decays of taus, $\tau \rightarrow \mu\nu\nu$ and $\tau \rightarrow e\nu\nu$ would be measured at CEPC with unprecedented precision, providing extremely sensitive tests of the weak interaction in tau decays. Furthermore, it may be possible to test lepton universality in $\tau \rightarrow \ell\nu\nu$ at the level of 10^{-4} . Many new-physics explanations of the observed anomalies in $R_{K^{(*)}}$ and $R_{D^{(*)}}$ predict violation of lepton-flavor universality in tau decays at the permille level and could, therefore, be scrutinized at CEPC. Finally, the CEPC measurements would improve the bounds on lepton-flavor violating Z decays by orders of magnitude compared to the current best bounds from LEP, down to a level of 10^{-8} and better.

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathbf{BR}(B_s \to \tau \tau)$	5.2×10^{-3} (LHCb)	$\sim 5 \times 10^{-4}$ (LHCb)	$\sim 10^{-5}$
${\rm BR}(B\to K^*\tau\tau)$	_	$\sim 10^{-5}$ (Belle II)	$\sim 10^{-8}$
$\mathbf{BR}(B_s \to \phi \nu \bar{\nu})$	_	_	$\sim 10^{-6}$
$\mathbf{BR}(\Lambda_b \to \Lambda \nu \bar{\nu})$	_	_	$\sim 10^{-6}$
${\rm BR}(\tau \to \mu \gamma)$	4.5×10^{-8} (Belle)	$\sim 10^{-9}$ (Belle II)	$\sim 10^{-9}$
$\frac{\mathrm{BR}(\tau \rightarrow \mu \nu \bar{\nu})}{\mathrm{BR}(\tau \rightarrow e \nu \bar{\nu})}$	3.9×10^{-3} (BaBar)	$\sim 10^{-3}$ (Belle II)	$\sim 10^{-4}$
$\mathrm{BR}(Z\to \mu e)$	1.7×10^{-6} (LEP)	$\sim 10^{-8} (\text{ATLAS/CMS})$	$\sim 10^{-9}$
$\mathrm{BR}(Z\to\tau e)$	9.8×10^{-6} (LEP)	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8}$
${\rm BR}(Z\to\tau\mu)$	1.2×10^{-5} (LEP)	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8}$

Table 1.5: Order of magnitude estimates of the sensitivity to a number of key observables for which the tera-*Z* factory at CEPC has unique capabilities. The expected future sensitivities assume luminosities of 50 fb^{-1} at LHCb, 50 ab^{-1} at Belle II, and 3 ab^{-1} at ATLAS and CMS. For the tera-*Z* factory of CEPC we have assumed the production of $10^{12} Z$ bosons.

Tab. 1.5, we summarize a number of key observables. All listed sensitivities are rough estimates only and need to be followed up by dedicated sensitivity studies that carefully take into account detection efficiencies, background systematics, etc.

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