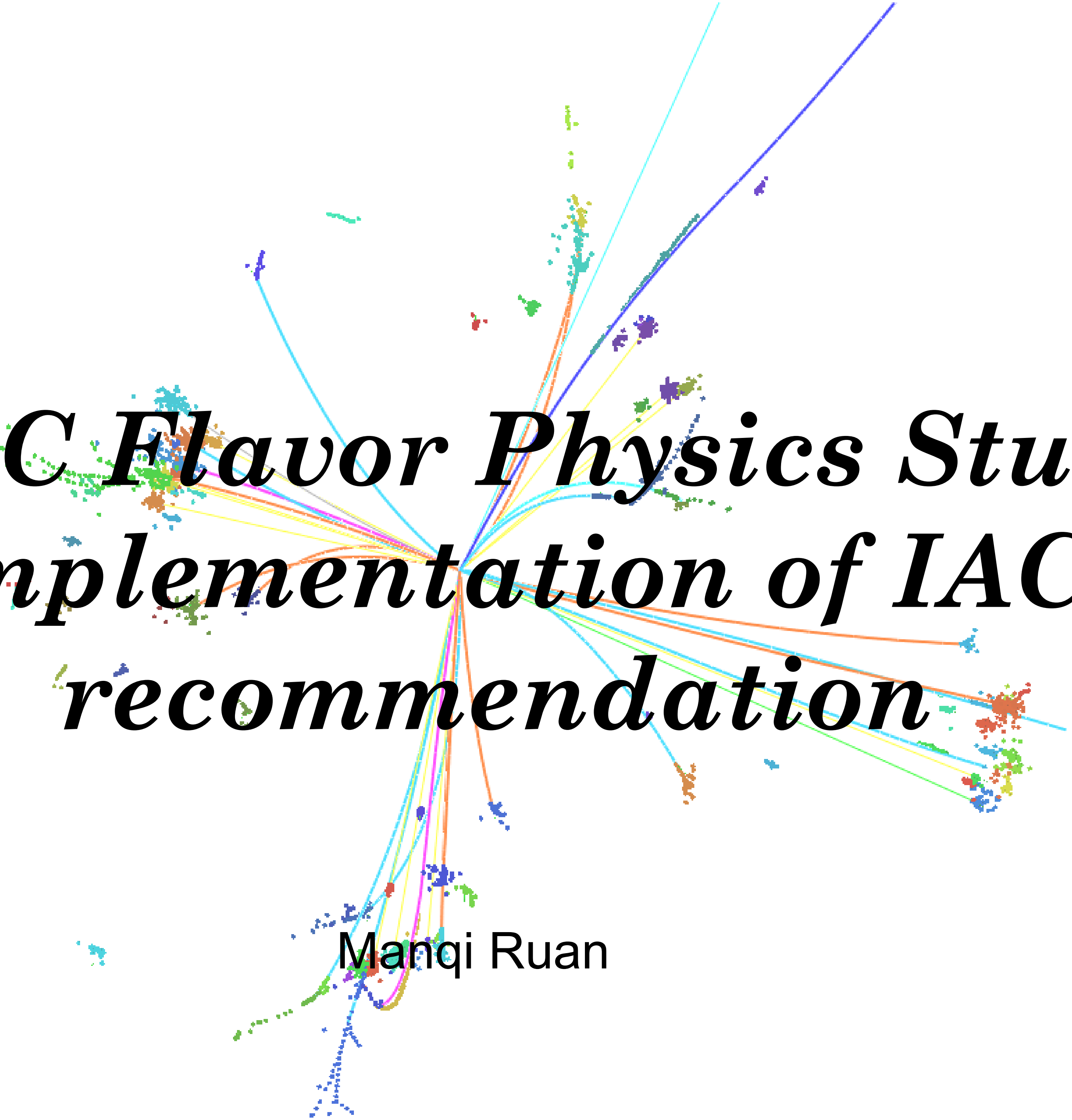
CEPC Flavor Physics Study: Implementation of IAC recommendation



Manqi Ruan

IAC Report - Recommendations

Detector R&D and Physics Studies

***Recommendation 13**: Assess the CEPC physics potential of the 360 GeV stage in full, including a demonstration that the accelerator design optimally fits the physics objectives at this stage.* Even if the 360 GeV stage is still far away in time, it is an important element to the attractiveness of CEPC as a whole. Not emphasizing it strongly in the presentation of the CEPC program may discourage potential partners.

***Recommendation 14**: Assess the CEPC physics potential for the high luminosity Z factory stage.* In particular it is important to fully develop the flavor physics program for this stage, from the perspective of weak interactions (e.g., precision measurements and rare and forbidden decays in the SM and in BSM scenarios), as well as from the perspective of strong interactions (e.g., in the area of exotic hadrons, where unique studies of doubly heavy or fully heavy tetraquarks, also including b quarks, would be possible).

Action Item: Continue to expand the team working on flavor physics and strong interactions

Promote engagement from university physicists

From IAC report 2019

Other recommended detector and physics studies:

Recommendation 16:

- *Perform detailed simulation studies to better understand the physics needs from the detector at the various CEPC energy stages; draw consequences about the corresponding detector performance requirements (e.g. photon resolution, jet resolution, added value of PID) and study how this influences the detector design.*
- *Study the physics case for performing flavor physics including the tau lepton at the Z-peak. Draw conclusions on a possible impact on the detector design.*
- *Given that time-of-flight detectors with a time resolution in the 30-50 ps are becoming available, study their potential added value for a CEPC detector by assessing a few key physics benchmarks.*
- *Assess the added value of dE/dx capabilities in the tracker.*
- *Assess the added value of the muon detector system. As a result, define the number of muon detection layers to include, together with their required performance.*

- Key words: Requirement, and Flavor

Action & related studies

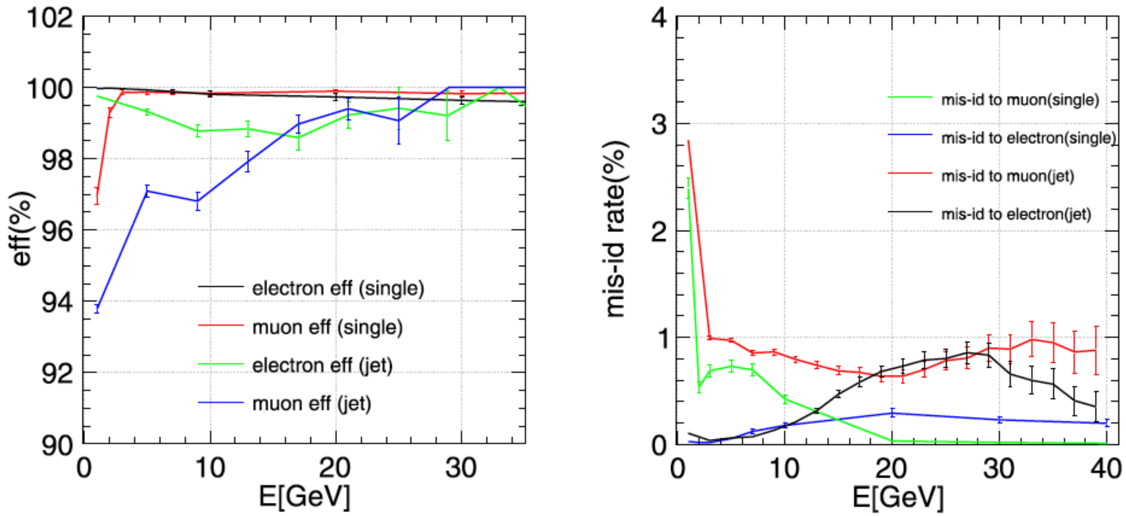
- Performance analysis at Full simulation,
  - and modeling at Fast simulation
- Physics analyses
- Physics white paper + Snowmass activities

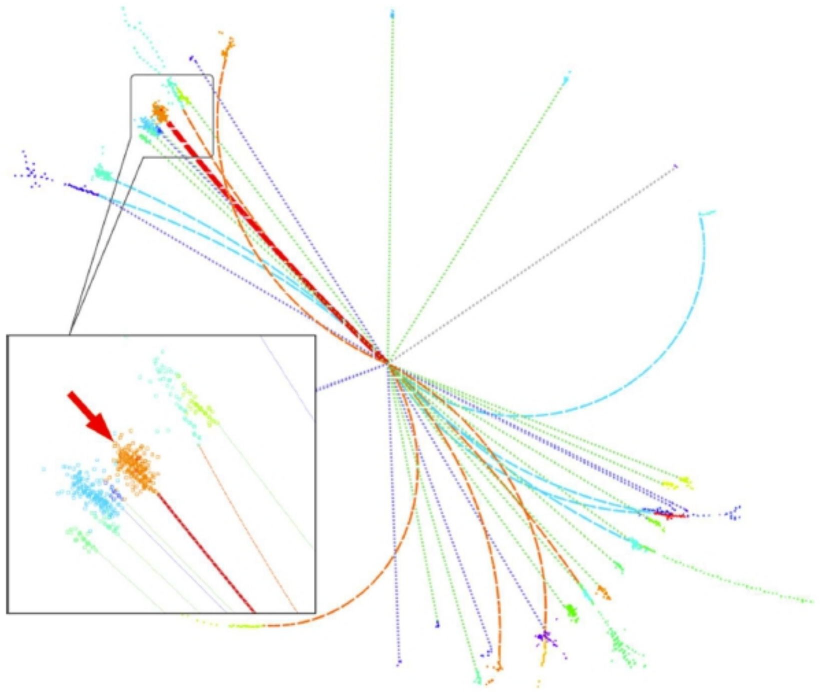
Baseline Detector-Reconstruction Performance

- Acceptance: |cos(θ)| < 099
- Tracks:
  - Pt threshold, ~ 100 MeV
  - δp/p ~ o(0.1%)
- Photons:
  - Energy threshold, ~ 100 MeV
  - δE/E: 3 – 15%/sqrt(E)
- Pi-Kaon separation requirement: 3-sigma
- Pi-0: rec. eff*purity @ Z→qq > 60 or 80% @ 5GeV, corresponding to EM resolution of 15%/sqrt(E) or 3%/sqrt(E)
- B-tagging: eff*purity @ Z→qq: 70%
- C-tagging: eff*purity @ Z→qq: 40%
- Jet charge: eff*$(1-2\omega)^2$ ~ 15%/30% @ Z→bb/cc
- Leptons:
  - Isolated: eff*purity @ ZH ~ 99% (E > 5 GeV)
  - Inside jet: eff*purity @ Z→qq ~ 90% (energy > 3 GeV)
- Tau: eff*purity @ WW→tauvqq: 70%, mis id from jet fragments ~ o(1%)
- Reconstruction of simple combinations: Ks/Lambda/D with all tracks @ Z→qq: 60/75 – 80/85%
- BMR: 3.7%
- Missing Energy: Consistent with BMR.

Physics objects

2021 JINST 16 P06013: Jet lepton





Pi-0: CEPC Note 2021

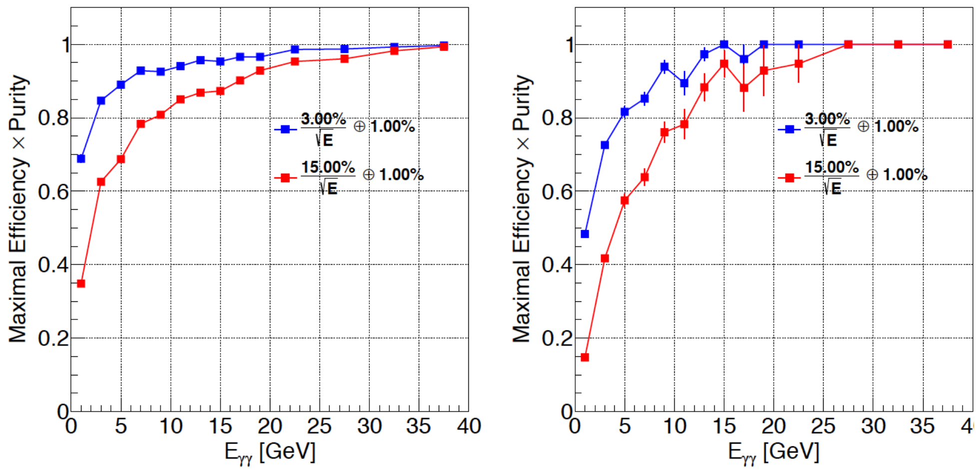
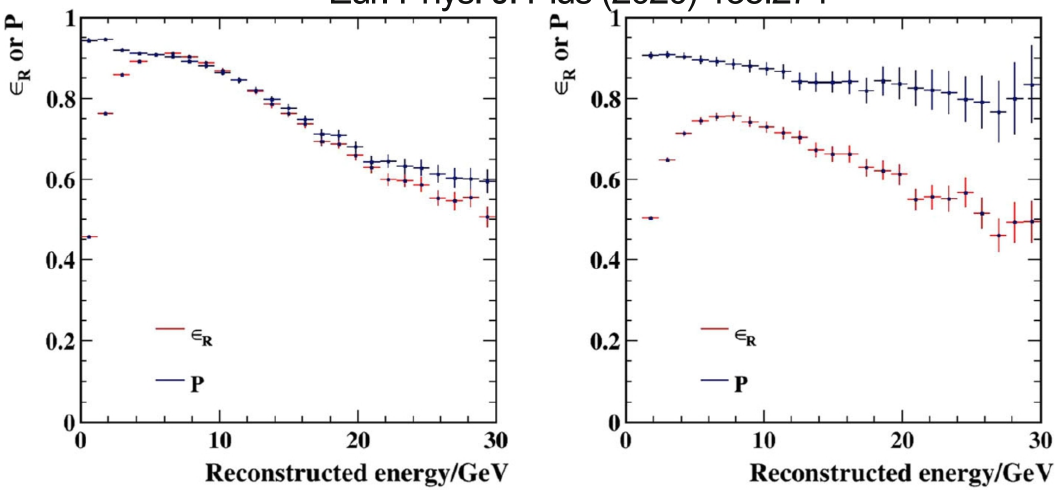


Figure 13: Energy differential maximal $\epsilon \times p$ for $Z \to \tau^+\tau^-$ (left) and $Z \to q\bar{q}$ (right).

Eur. Phys. J. Plus (2020) 135:274

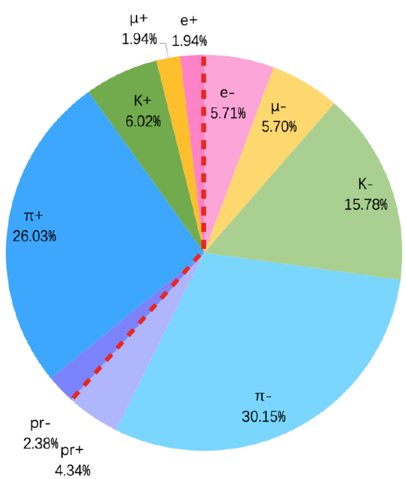


(a) K_S^0 (b) Λ

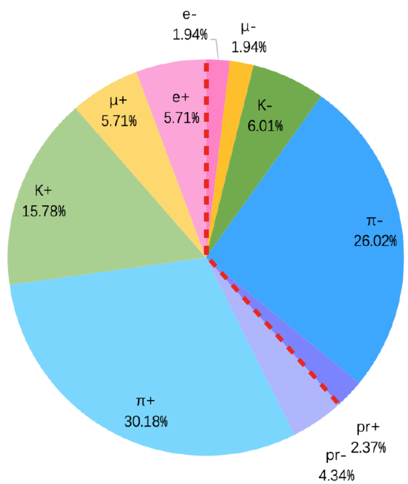
Fig. 9 Energy dependence of ϵ_R and P

Jet charge

$Z \to b\bar{b}$ **Percent of final charged leading particles of b jet and $\bar{b}$ jet**



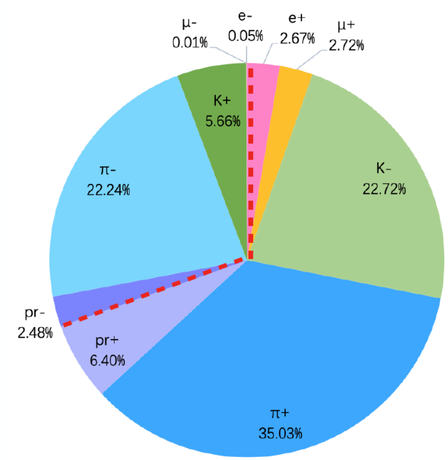
b jet



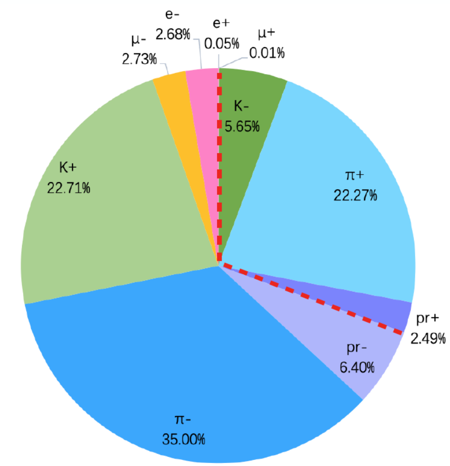
$\bar{b}$ jet

☞ *The distribution of each charged particle of two jets is asymmetry*

$Z \to c\bar{c}$ **Percent of final charged leading particles of c jet and $\bar{c}$ jet**



c jet



$\bar{c}$ jet

☞ *The distribution of each charged particle of two jets is asymmetry*

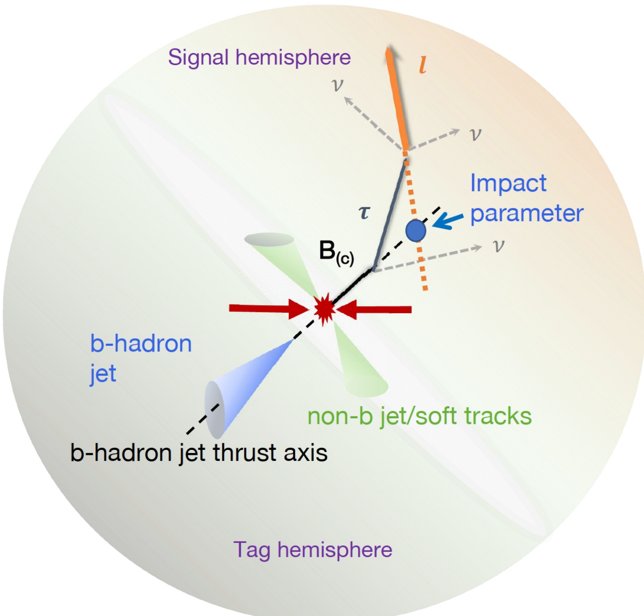
percent bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar	others	all
B^0bar	17.360%	17.350%	3.369%	0.022%	2.759%	0.688%	41.548%
B^-	17.350%	17.359%	3.364%	0.022%	2.765%	0.689%	41.550%
B_s^0bar	3.355%	3.362%	0.652%	0.004%	0.545%	0.144%	8.062%
B_c^-	0.022%	0.022%	0.004%	0.00003%	0.004%	0.001%	0.052%
Λ_b	2.762%	2.762%	0.543%	0.004%	0.451%	0.121%	6.644%
others	0.653%	0.655%	0.136%	0.001%	0.119%	0.579%	2.144%
all	41.503%	41.511%	8.068%	0.053%	6.641%	2.225%	100%

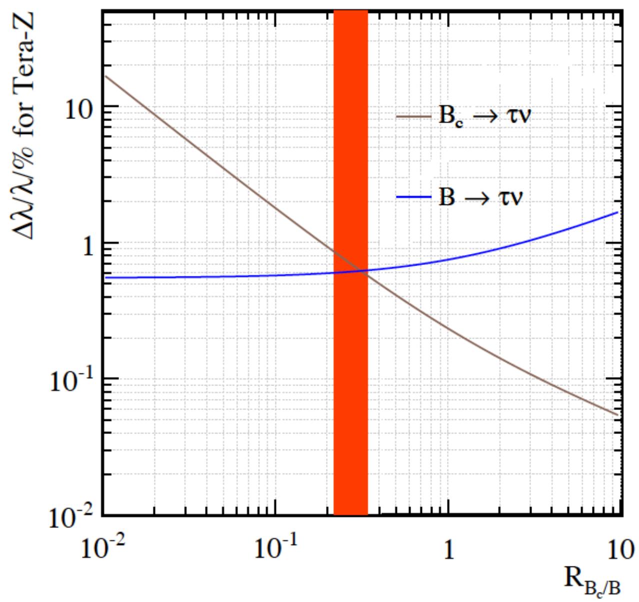
... we understand how the jet charge information eventually incarnated into Leading final state particles...

Physics benchmarks

- Propositions at Snowmass
  - Exclusive Z decay: draft ready - validating Bkgrd estimation
  - CP measurement via Bs→Jpsi + Φ: Accuracy comparable to LHCb – strong motivation to go beyond Tera Z. draft in preparation
  - Bs→Φvv: percentage level accuracy anticipated, draft in preparation
  - Bc→Tauv: 1 order of magnitude better than current accuracy. Published
- Other analyses
  - B0/Bs→2 pi0; ~ 1 order of magnitude better than Belle II, dependence on detector performance quantified. result ready, draft in preparation
  - LFV: Published. Comparable to FCC studies (Mogens Dam)
  - Many pheno-analyses such as b→stautau, R(J/psi), etc.

Bc→Tauv





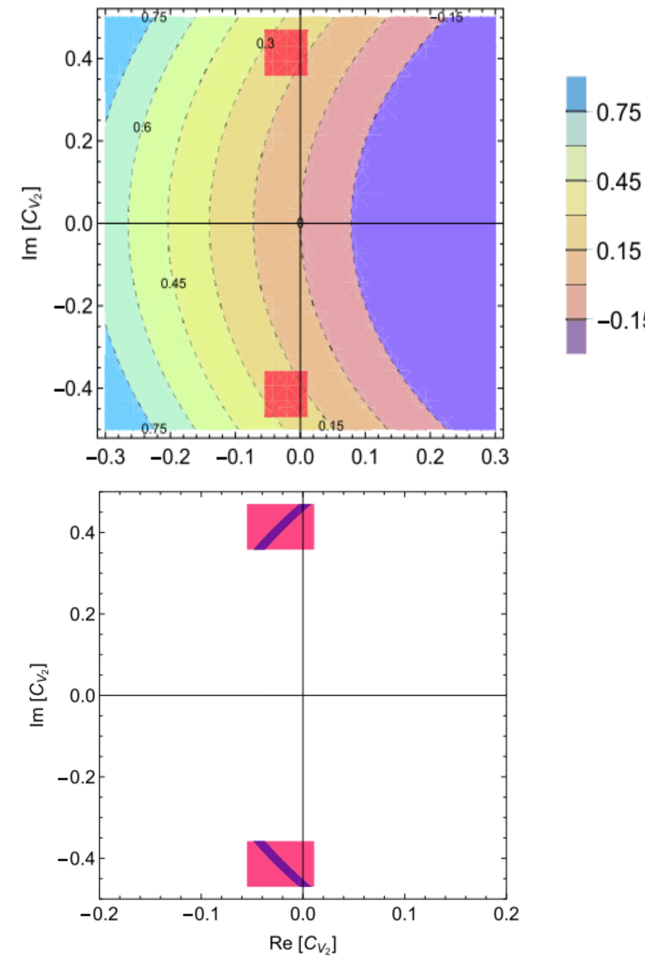


Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to 1%, the allowed region for C_{V_2} shrinks to the dark-blue regions.

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Analysis of $B_c \to \tau\nu_\tau$ at CEPC*

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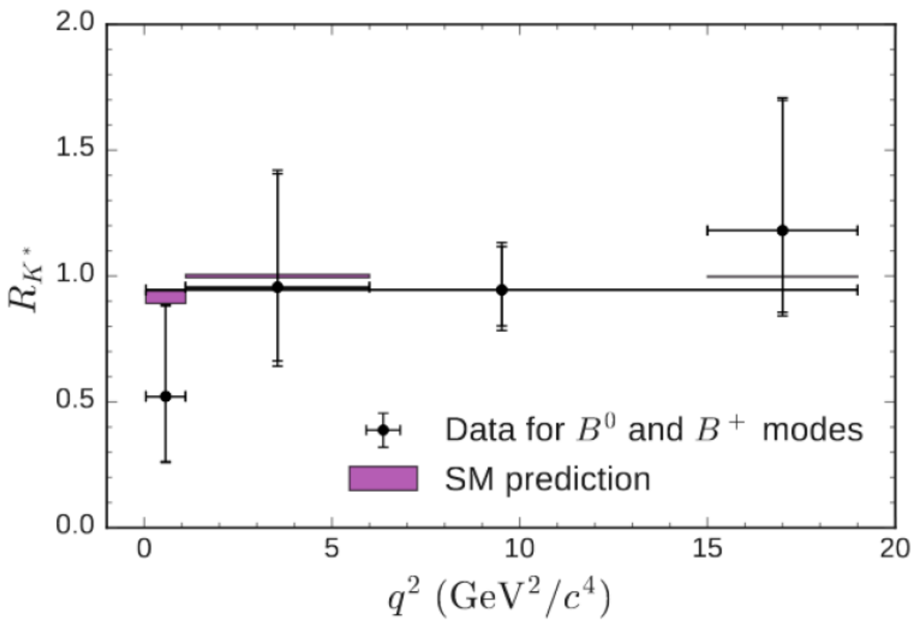
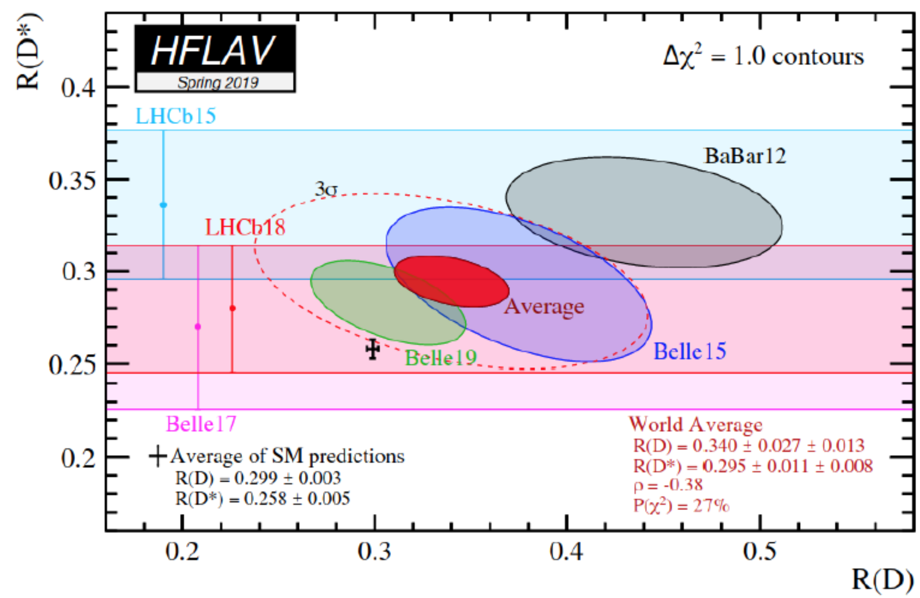
Abstract: Precise determination of the $B_c \to \tau\nu_\tau$ branching ratio provides an advantageous opportunity for understanding the electroweak structure of the Standard Model, measuring the CKM matrix element $|V_{cb}|$, and probing new physics models. In this paper, we discuss the potential of measuring the process $B_c \to \tau\nu_\tau$ with τ decaying leptonically at the proposed Circular Electron Positron Collider (CEPC). We conclude that during the Z pole operation, the channel signal can achieve five-σ significance with $\sim 10^9$ Z decays, and the signal strength accuracies for $B_c \to \tau\nu_\tau$ can reach around 1% level at the nominal CEPC Z pole statistics of one trillion Z decays, assuming the total $B_c \to \tau\nu_\tau$ yield is 3.6×10^6. Our theoretical analysis indicates the accuracy could provide a strong constraint on the general effective Hamiltonian for the $b \to c\tau\nu$ transition. If the total B_c yield can be determined to $O(1\%)$ level of accuracy in the future, these results also imply $|V_{cb}|$ could be measured up to $O(1\%)$ level of accuracy.

Taifan, etc, Published by CPC.
Collaborate with Wei Wang, et.al.

B Anomalies Indicating LFUV

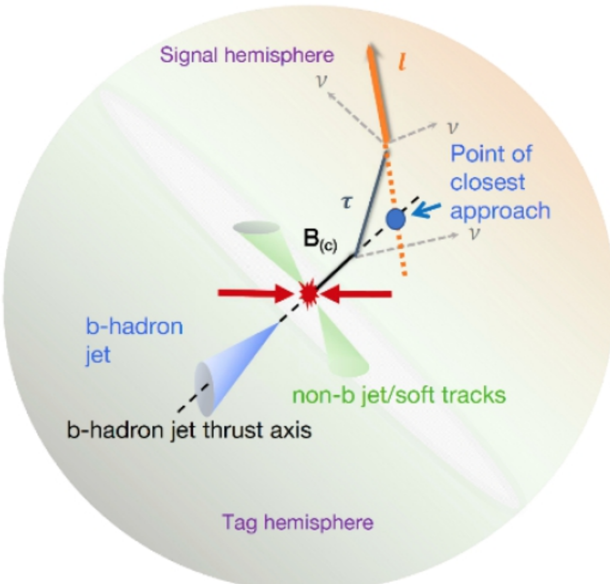




	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28	

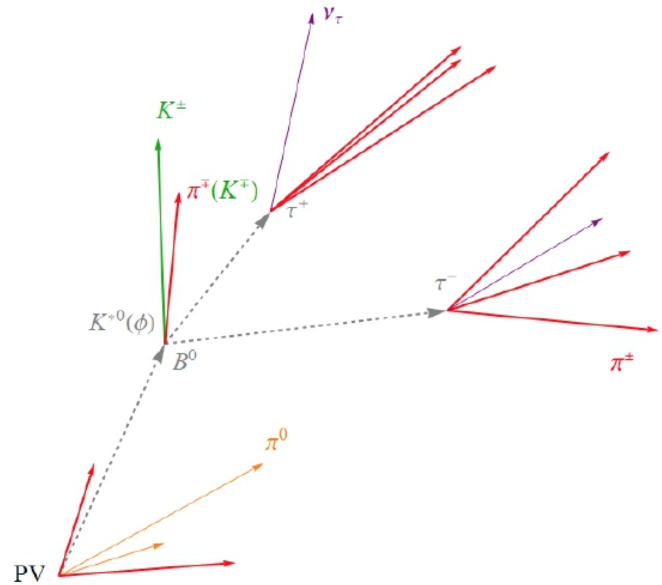
[Tanabashi et al., 2018][Altmannshofer et al., 2018].

Current Progress in LFU Tests



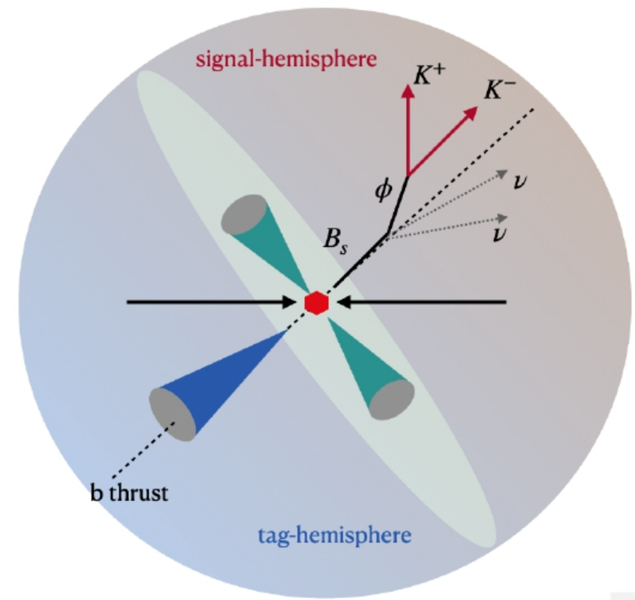
Charged current $B_c \to \tau\nu$ decays [Zheng et al., 2020b].

Absolute precision $\sim 10^{-4}$.



Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

Absolute precision $\lesssim 10^{-6}$: $\sim 10^3 - 10^4$ improvement from current limits.

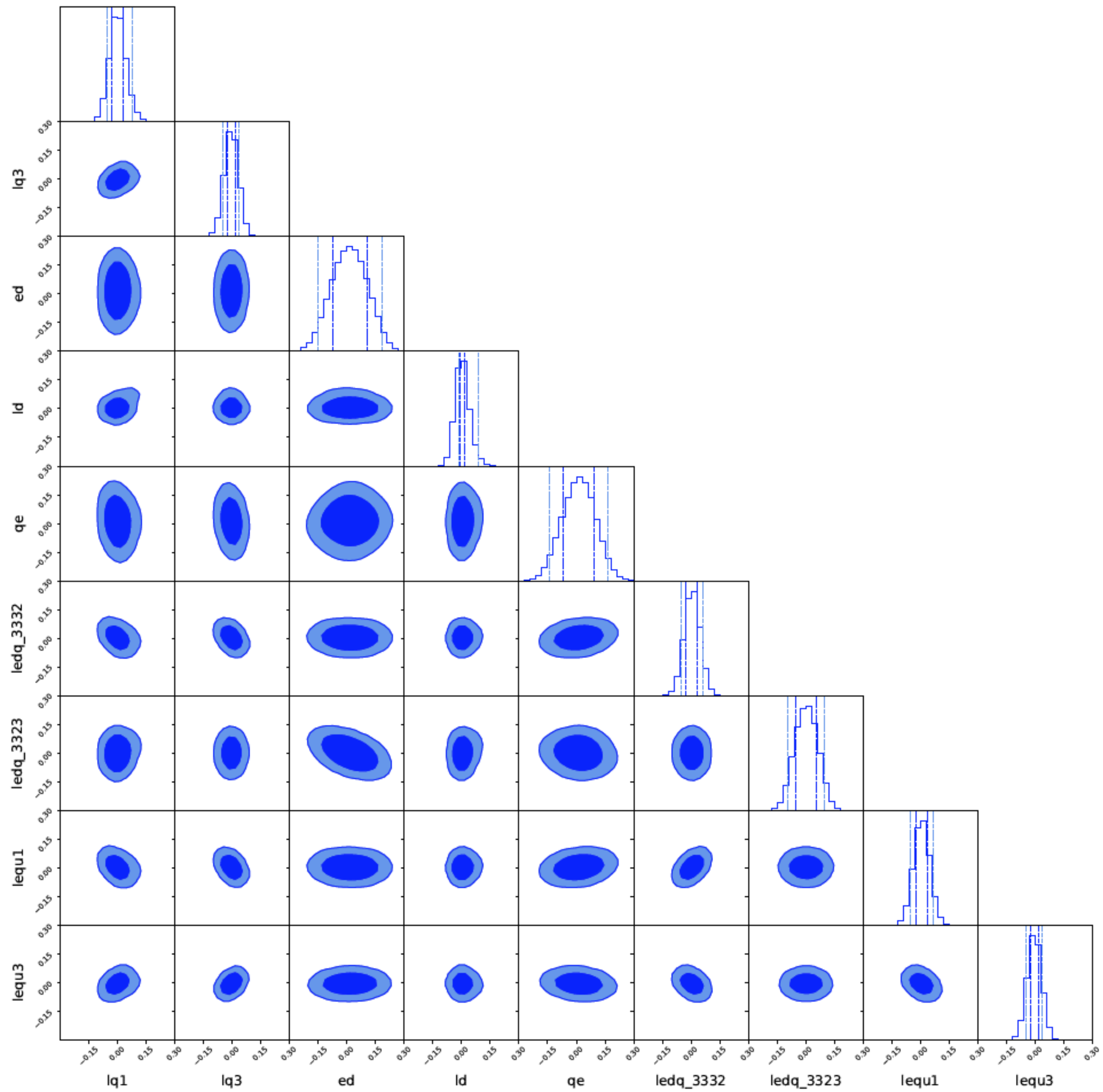


Neutral current $B_s \to \phi\nu\bar{\nu}$ decay [In preparation]

Absolute precision $\sim 10^{-7}$.

Unique opportunities at the Z-pole

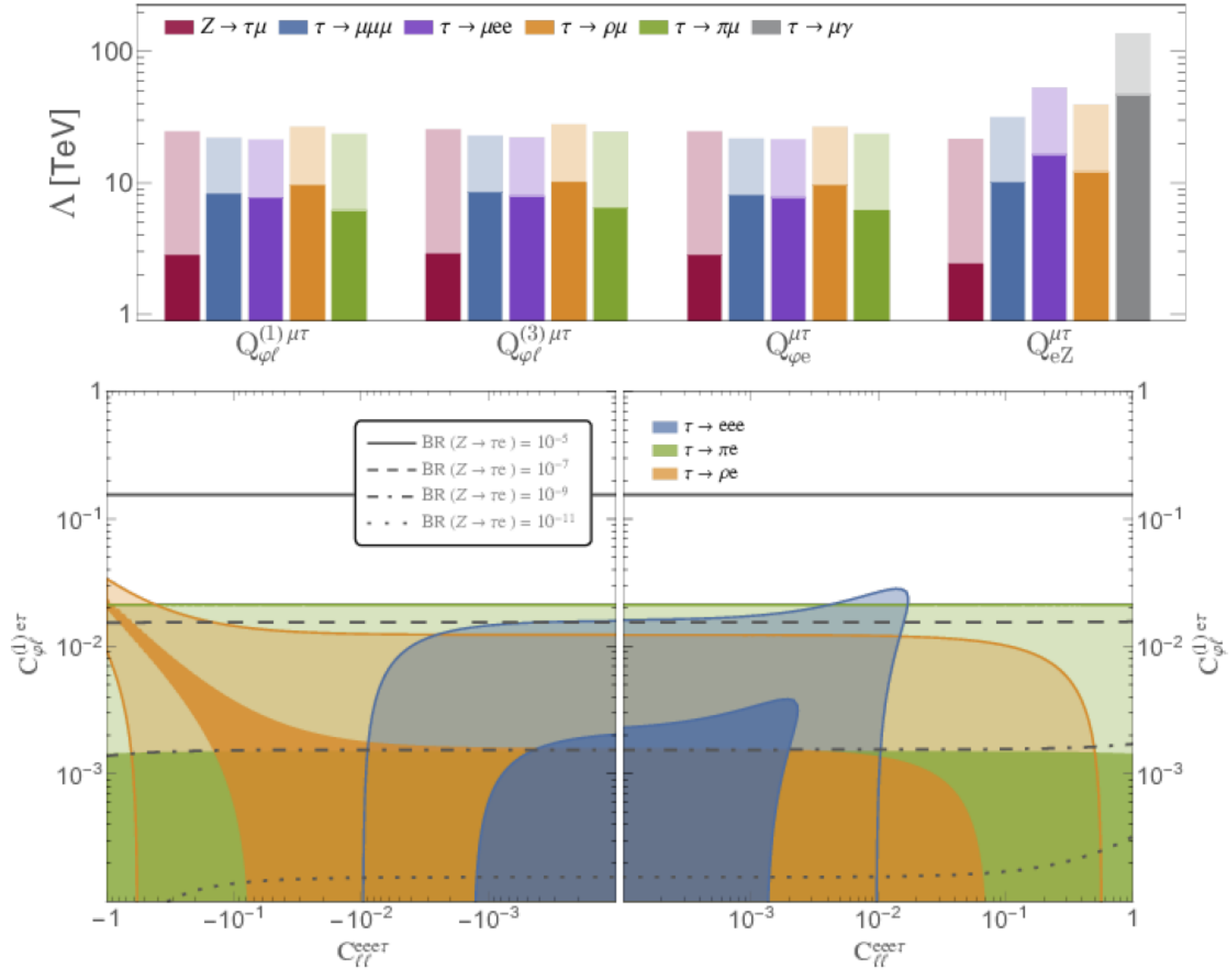
Current Progress in LFU Tests (II)



Preliminary: 9 effective channels:($R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, R_{Λ_c}, $B_c \to \tau\nu$, $B \to K\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $B^0 \to K\tau\tau$, $B^+ \to K^+\tau\tau$, $B_s \to \tau\tau$...)

Dim-6 SMEFT basis at NP scale Λ=3 TeV.

Lepton Flavor Violation (II)



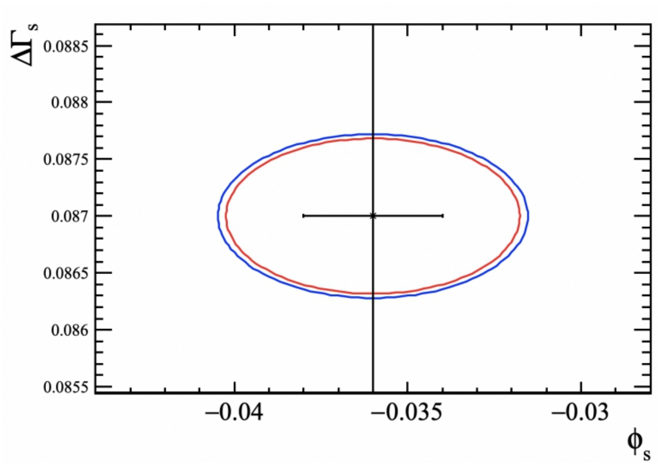
[Calibbi et al., 2021]

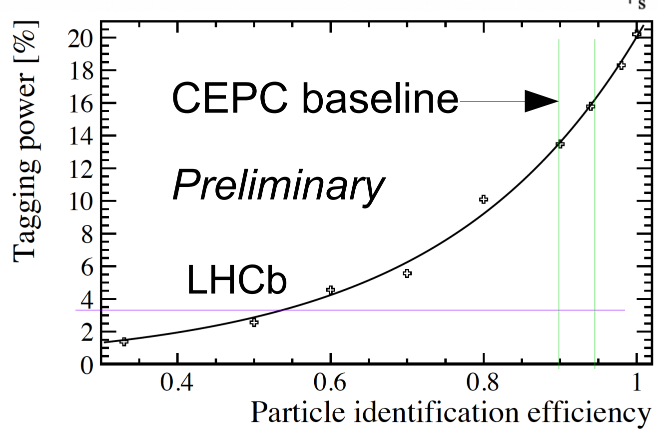
CP measurement with Bs→J/psi Phi

$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H, \phi_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$

SM: small CPV phase ϕ_s

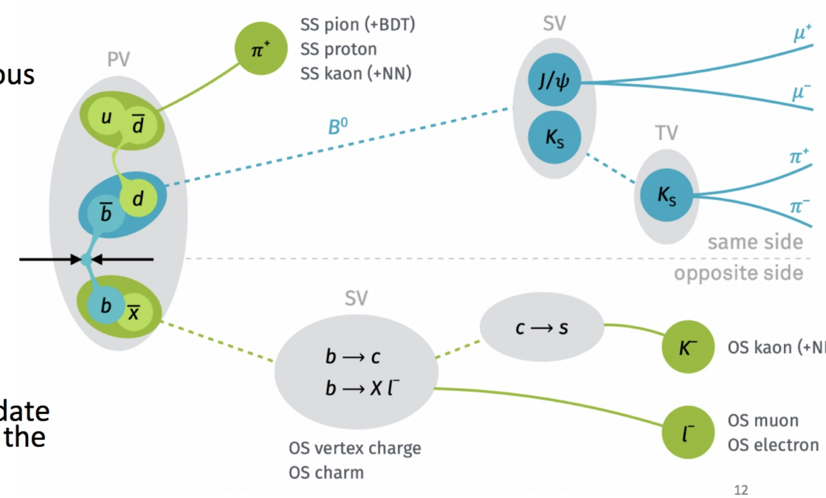
Contributions from physics beyond the SM could lead to much larger values of ϕ_s.





Flavour tagging power

- LHCb: 3~4%
- CEPC: 15% (Previous estimation)
- B factory: ~30%



- For Bs:
  - OS lepton
  - OS kaon
  - SS kaon
- A naïve algorithm developed to validate the robustness of the estimation

- With a decent Pid, the effective tagging power on jet Charge can be 5-6 times better than LHCb, which can compensate the statistic difference between LHCb & CEPC.
- Strong motivation to higher Luminosity at Z pole

White paper

Contents

1 Introduction

2 Description of CEPC facility

The Circular Electron Positron Collider (CEPC) is a double-ring e^+e^- collider with a 100 km circumference and two interaction points (IP) designed to precisely measure the Higgs boson and related particles. The CEPC Conceptual Design Report [1] includes exquisite details of the CEPC detector system. It operates at $\sqrt{s} \sim 240$ - 250 GeV for Higgs Factory,

factory mode can measure the BR with a $\mathcal{O}(10^{-4})$ precision. The CEPC study [23] uses full simulation and $\tau^\pm \to \ell^\pm \nu\bar{\nu}$ decay, while the FCC-*ee* based study [24] but uses fast simulation and $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu$ decays. A work in preparation [cite] studies R_{D_s}, $R_{D_s^*}$, $R_{J/\psi}$, and R_{Λ_c} in the general Tera-Z context and the fast simulation template of the CEPC. The results from these studies are promising. The relative uncertainty (stat. only) of $R_{J/\psi}$ may reach $\lesssim 3\%$ with 10^{12} Z produced. The numbers are $\sim 0.5\%$ for $R_{D_s^{(*)}}$, and $\sim 0.2\%$ R_{Λ_c} [cite]. Their S/B are of $\gtrsim 1$, ensuring robustness against background uncertainties. Although complete projections of these semileptonic observables are yet available for Belle II and LHCb, we can still compare them with the projected $\sigma(R_{D^{(*)}}) \sim 2(1)\%$ (stat.) at Belle II [2], $\sigma(R_{J/\psi}) \gtrsim 3\%$ (stat.+syst), and $\sigma(R_{\Lambda_c}) \sim 2.5\%$ (stat.+syst) after LHCb upgrade II [25]. It is clear that the potential of semileptonic measurements at CEPC is stronger than other experiments.

However, there are still many open topics in this field to be explored. For example, R_D and R_{D^*} and relevant differential measurements seems necessary. It may need specific work using full simulation, as data from other experiments keeps accumulating at Belle II [26] and LHCb [27]. The competition will be inevitable. The measurement of higher D-meson resonances like $B \to D^{**}\ell(\tau)\nu$ decays [28], providing further new observables sensitive to new physics, complementary to the ones mentioned above. The multi-body decays of $D^{**} = D_0^*(2300), D_1(2420), D_1(2430)^0, D_2^*(2460)$ may limit the relevant sensitivities at Belle II. Additionally, the searches for remaining baryonic decays such as R_{Ξ_c} from Ξ_b decay are viable. R One may further extend the trend to search for the inclusive $b \to X_c\ell(\tau)\nu$ decay rates at CEPC, but it could be challenging. Moreover, the searches of exclusive $b \to u\ell\nu$ decays are viable at CEPC, as long as the hadronic u final state like $\pi^\pm$ and ρ^0 can be well reconstructed. Finally, if the systematic uncertainty from lepton mis-ID is under control, the LFU tests between the first two generations, *e.g.*, $\frac{\mathrm{BR}(b\to c+\mu\nu)}{\mathrm{BR}(b\to c+e\nu)}$ become relevant. We may soon deliver the estimated limit once the performance study is done. Finally, from the time-dependent asymmetry of semileptonic $B_{d,s}$ decays we can extract the valuable CPV from $B_{d,s} - \bar{B}_{d,s}$ mixing, namely $\mathcal{A}_{\mathrm{SL}}^{[}$ and $\mathcal{A}_{\mathrm{SL}}^{f}$, contributing to the global picture of the phase β and β_s [29]. The current experimental uncertainty $\sim \mathcal{O}(10^{-3})$ [30] is still far from the SM prediction ($\mathcal{O}(10^{-4})$ for $\mathcal{A}_{\mathrm{SL}}^{d}$ and $\mathcal{O}(10^{-5})$ for $\mathcal{A}_{\mathrm{SL}}^{s}$) [31]. It will be interesting to validate the suggested precision of $\mathcal{O}(10^{-5})$ at the FCC-*ee* [21] and $\mathcal{O}(10^{-4})$ at the future LHCb [25].

4 Rare/Penguin and Forbidden b Decays

FCNC $b \to s$ and $b \to d$ decays are forbidden at the tree-level in the SM. These decays are induced by EW penguin or box diagrams in the SM at the one-loop level, making them rare processes in general. Rich phenomena thus emerge as physics at the EW scale meets QCD, ideal for testing SM at high precision. Moreover, as the SM rates are suppressed by the off-diagonal CKM matrix elements and the loop factor, these FCNC modes are also sensitive to small new physics contributions. At the CEPC's Z-pole run, the high luminosity ensures large signal statistics even if the target mode has a typically small BR $\lesssim 10^{-5}$.

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4.1 Dileptonic Modes

The CEPC full potential for dileptonic decays of b is still under evaluation. For light leptons, the event reconstruction is relatively straightforward, limited by statistics, lepton identification systematics, and the reconstruction of the hadronic decay products. In contrast, for di-τ modes, the missing momentum from neutrino makes the event reconstruction challenging. The background level also increases due to the large number of D mesons produced by Z and inclusive b-hadron decays. Fortunately, the advanced detector system and the clean environment make the di-τ mode one of the most valuable targets at the CEPC. The sensitivity and discovery potential will be orders of magnitude higher than those at other flavor physics experiments.

The sensitivity of several exclusive $b \to s\tau^+\tau^-$ decays are evaluated using $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu$ decays [32, 33]. The sensitivity are estimated together with the typical background level, reaching $\mathcal{O}(10^{-5})$ for the two-body $B_s \to \tau^+\tau^-$ mode and $\mathcal{O}(10^{-7})$ for other three-body modes. For the baseline CEPC luminosity, such sensitivities can $O(1)$ deviations from the SM. The SM rates of $b \to s\tau^+\tau^-$ will be directly measured if the luminosity is comparable to that of FCC-*ee*. It is noteworthy that these CEPC upper limits are 1-2 orders of magnitude smaller than the Belle II and LHCb upgrade two ones [2, 25], making them one of the flagships of CEPC flavor physics. A further study using full simulation might be available in the future (see also [34]). For light dilepton decays, a fast simulation study on $B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ measurements (see [34] for more details). The preliminary result indicates the measurement of BR$(B_s \to \mu^+\mu^-)$ is statistic limited, reaching $\mathcal{O}(10^{-10})$. On the other hand, BR$B^0 \to \mu^+\mu^-$ measurement is strongly affected by the $B^0 \to \pi^+\pi^-$ background with $\pi - \mu$ mis-ID.

Other than above studies that are published or in preparation, several valuable analyses to be done. The evaluation of $R_{K^{(*)}}$ potential at the CEPC is yet done. There will be multiple final states like K^+ or $K^*(892)^0 \to K^\pm\pi^\mp$ available at the CEPC. The lepton-ID induced systematics will be the bottleneck of the projection. However, the excellent electron-ID from the future detector will provide some advantage against the LHCb. Other similar topics include R_{pK} [35], R_ϕ [36], $R_{f_2'}$ [36] (potentially large deviations from the SM!), and R_Λ coming from heavier b-hadron decays. The latter may require a new analysis framework as the Λ lifetime is large. In addition, $b \to u\ell^+\ell^-$ searches may share similar systematic uncertainty sources with $b \to s\ell^+\ell^-$ decays, complimentary to LHCb measurements[1]. For di-τ modes, it is worth probing the possibility of differential measurements like the forward-backward asymmetry and the τ polarimetry, which further improves the constraint on new physics [32]. Other channels such as $\Lambda_b \to \Lambda\tau^+\tau^-$ are also noteworthy.

4.2 Neutrino Modes

FCNC $b \to s/d\nu\bar{\nu}$ decays are similar to dileptonic modes. They are thus important for testing the SM. Also, they can provide the possibility of extracting the elements of the CKM matrix and search for the origin of the CP violations. Because they are not affected by the non-factorizable corrections and no photonic penguin contributions, there will be

[1] There are ~ 900 LHCb events yields for $B^+ \to \pi^+e^+e^-$ at by the end of HL-LHC era [25]

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Facts & interpretation...

Many Thanks to Lingfeng & HKUST

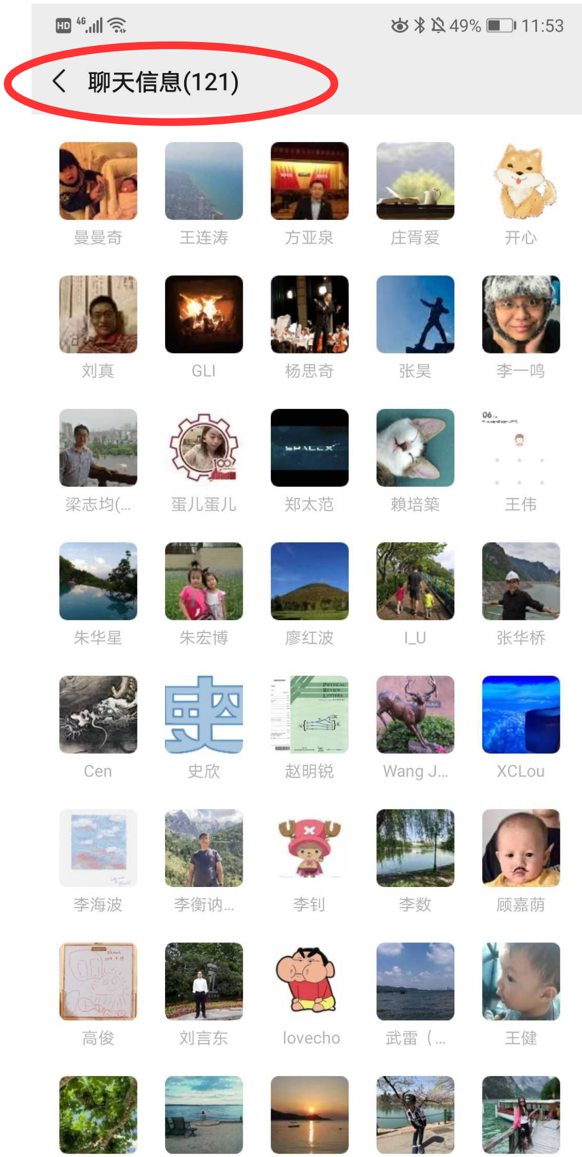
Summary

- With intensive & continuous studies, flavor physics is much better understood now... well aligned with IAC recommendations.
- Good understanding on detector requirement & performance via Full simulation studies.
- Precisions estimated for ~ o(10) physics benchmarks, many boost the current/estimated precisions by 1 order of magnitude.
- First to explore the flavor physics measurement via Hadronic final states (B0/Bs->2 pi0, Bs->J/psi+Phi) at future Higgs/Z factories
- Talent Young people emerges during those activities

- However, the funding support is not ideal & need to be addressed

Back up

CEPC @ Snowmass



title	ID	author	link	
Study of electroweak phase transition in exotic Higgs decays with CEPC Detector simulation	229-v1	Michael Ramsey-Musolf	URL	
Exclusive Z decays	226-v1	Qin Qin	URL	
Measurement of the leptonic effective weak mixing angle at CEPC	233-v1	Siqi Yang	URL	★
Heavy Neutrino search in Lepton-Rich Higgs Boson Rare Decays	244-v1	Yu Gao	URL	★
Higgs boson CP properties at CEPC	227-v1	Xin Shi	URL	
Measurement of branching fractions of Higgs hadronic decays	228-v1	Yanping Huang	URL	
Feasibility study of CP-violating Phase phi_s measurement via Bs->J/PsiPhi channel at CEPC	230-v1	Mingrui Zhao	URL	★
Probing top quark FCNC couplings tqr, tqZ at future e+e- collider	231-v1	Peiwen Wu	URL	
Searching for $B_s \to \phi\nu\nu$ and other b->dvv processes at CEPC	232-v1	Yanyun Duan	URL	★
Probing new physics with the measurements of e+e- -> W+W- at CEPC with optimal observables	234-v1	Jiayin Gu	URL	
NNLO electroweak correction to Higgs and Z associated production at future Higgs factory	235-v1	Zhao Li	URL	
SUSY global fits with future colliders using GAMBIT	237-v1	Peter Athron	URL	
Probing Supersymmetry and Dark Matter at the CEPC, FCCee, and ILC	238-v1	Waqas Ahmed	URL	
Search for t + j + MET signals from dark matter models at future e+e- collider	239-v1	Peiwen Wu	URL	
Search for Asymmetric Dark Matter model at CEPC by displaced lepton jets	240-v1	Mengchao Zhang	URL	
Dark Matter via Higgs portal at CEPC	241-v1	Tianjun Li	URL	
Lepton portal dark matter, gravitational waves and collider phenomenology	242-v1	Jia Liu	URL	★
CEPC Detectors Letter of Intent	245-v1	Jianchun Wang	URL	

Conclusion-2020

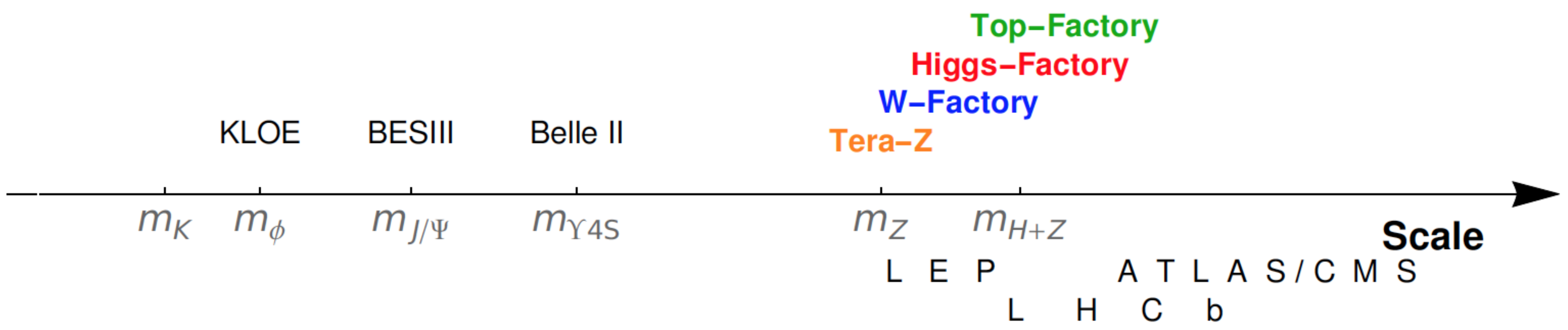
- The IAC recommendation is highly consistent with current CEPC simulation efforts: requirements, performance, analysis, and flavor physics
- Plan to address the IAC recommendation by the CEPC flavor physics white paper and corresponding documents. Performance – accuracy plots analogy to the BMR – Higgs accuracy plots shall be included.
- CEPC flavor simulation/analyses need to combine different methods:
  - Performance via Full Simulation and Analysis relies on Fast Simulation.
  - Proper modeling of the identification & reducible background contamination
- Significant progress on the flavor physics simulation
  - Good progress/coverage in Performance & object reconstruction
  - Multiple benchmark channels proposed, and half are covered by existing analysis

Flavor Physics at CEPC

Z Factory $\supseteq$ Flavor Factory

Particle-ID $\supseteq$ Flavor-ID!

Channel	Belle II	LHCb	Giga-Z	CEPC (Tera-Z)
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}
c, $\bar{c}$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^8	2.4×10^{11}
τ^+, τ^-	9×10^{10}	-	7.4×10^7	7.4×10^{10}



VS. B Factories

- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement