

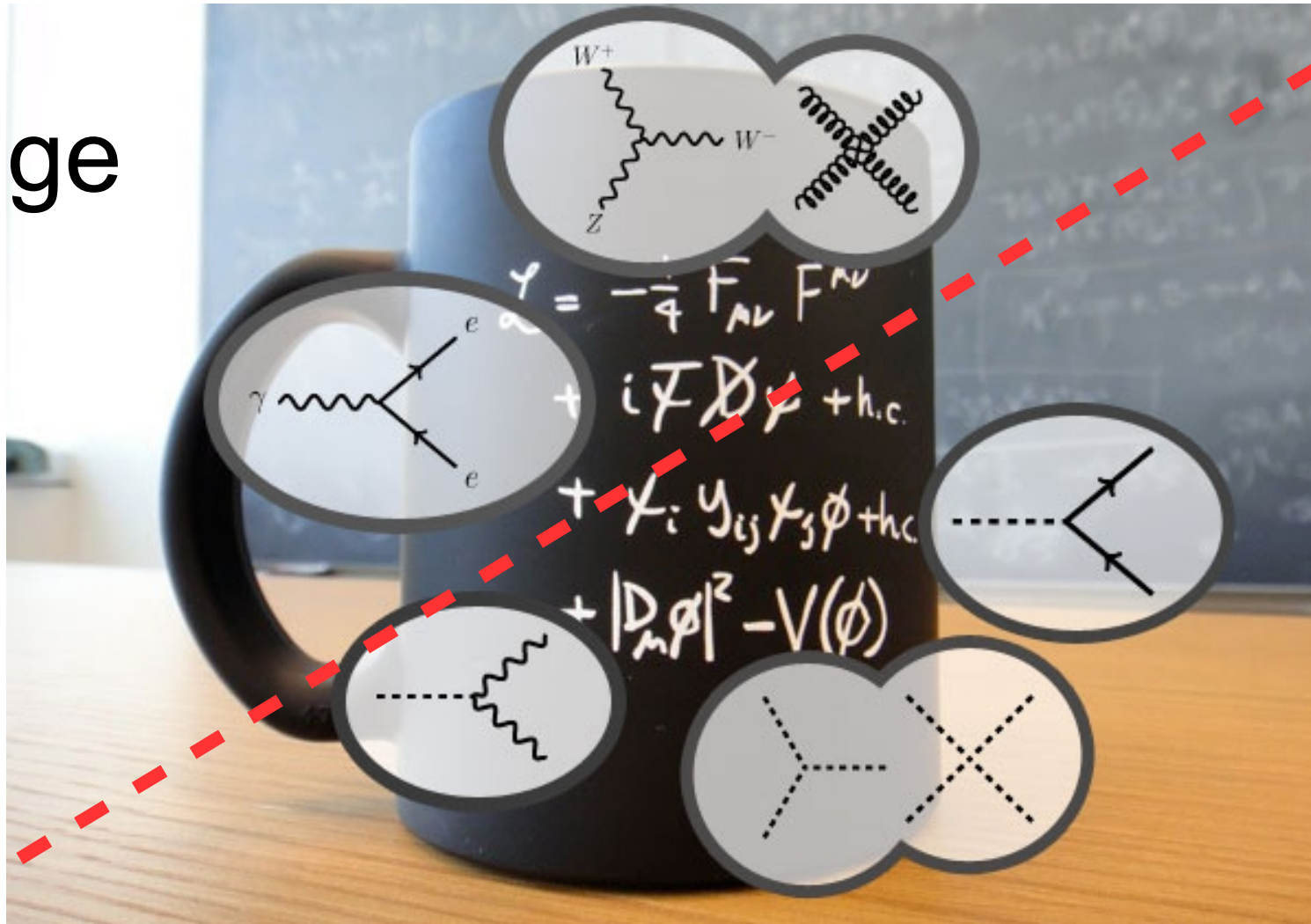


Physics at electron positron Higgs factories

Manqi Ruan

The Higgs field: one of the two pillars of the SM

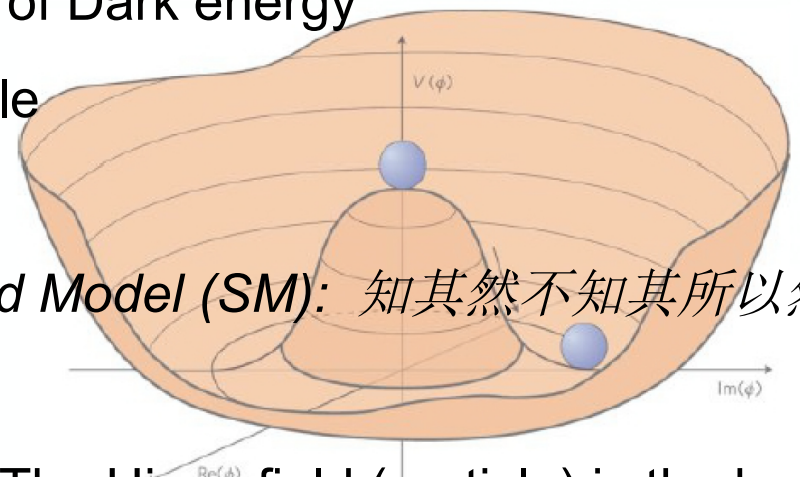
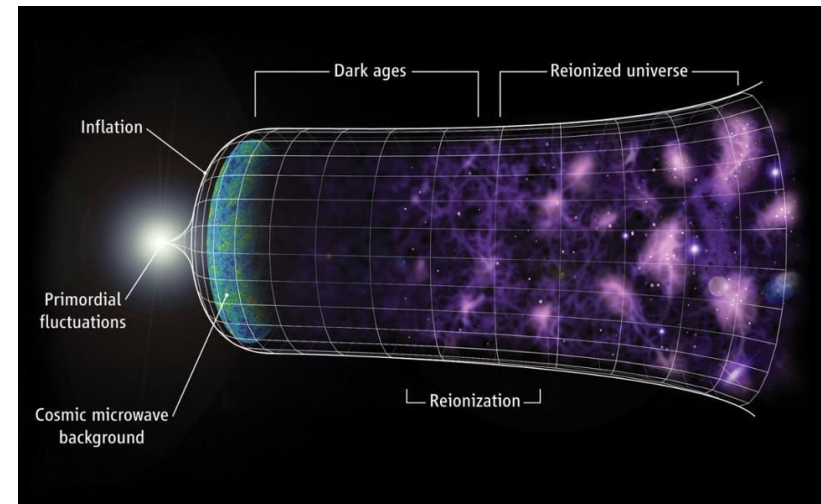
Gauge

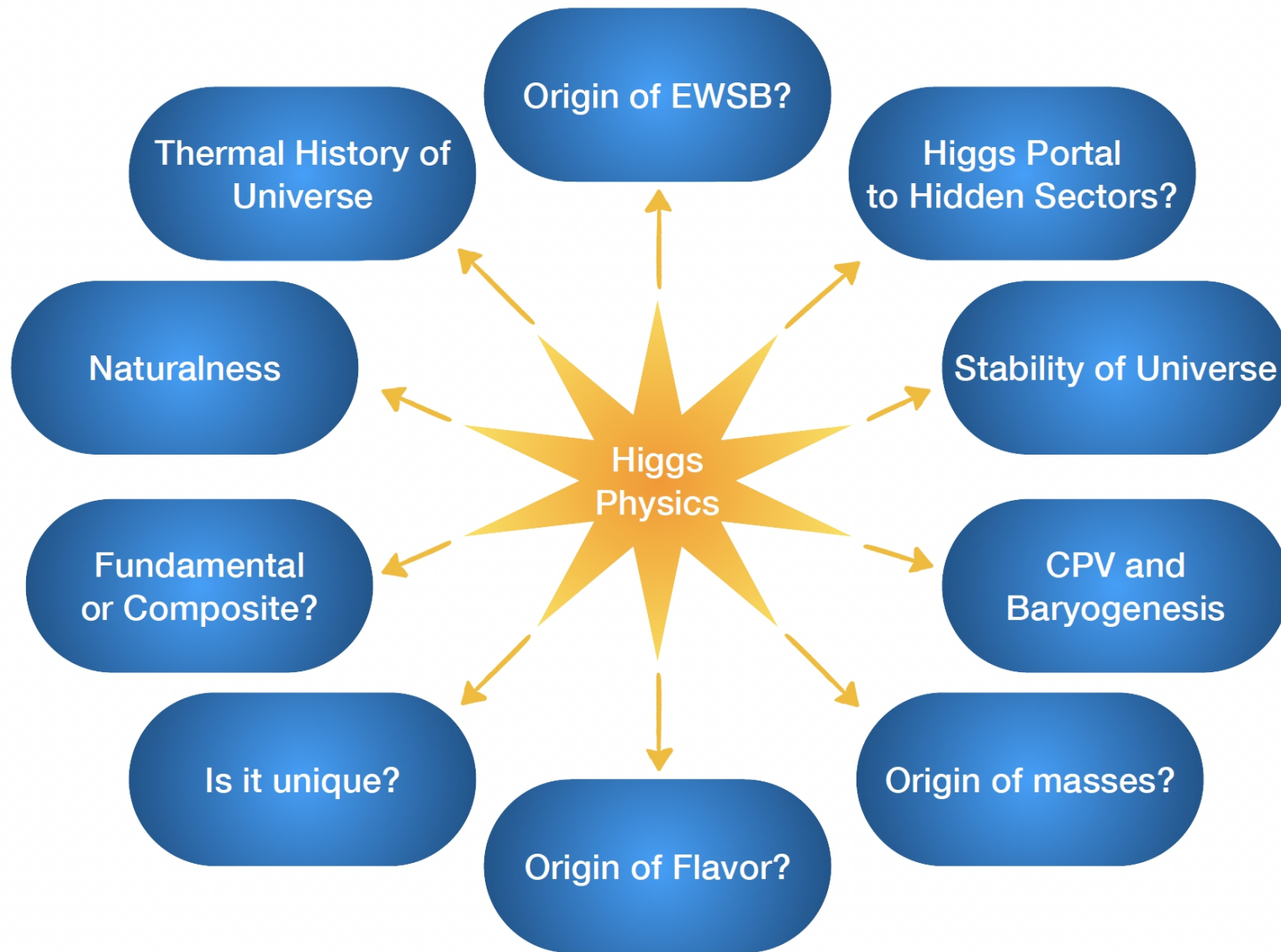


Higgs

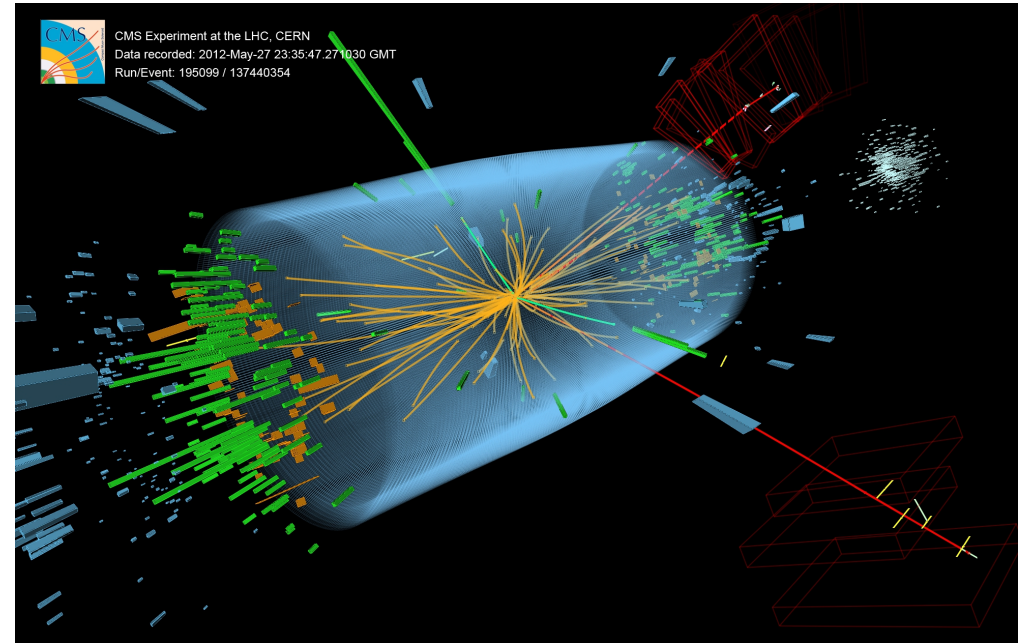
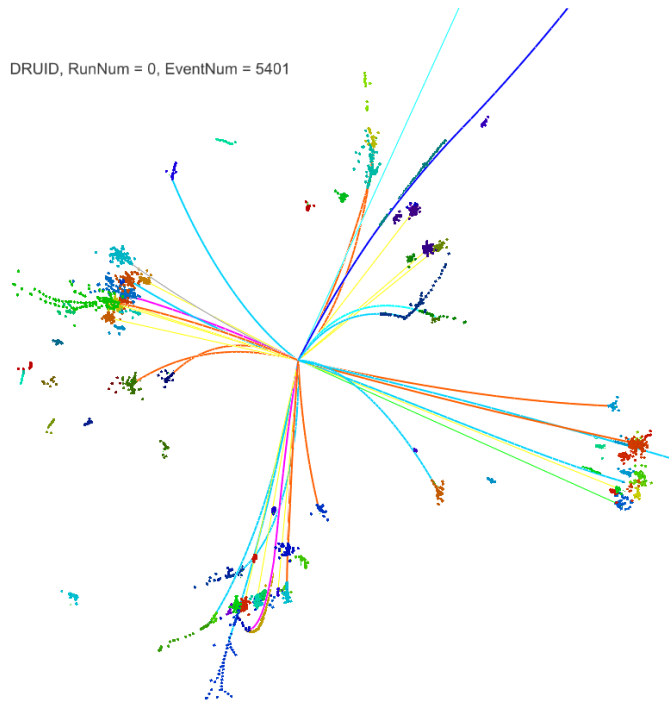
Mysteries of Particle & Universe

- Inflation
- **Mass** hierarchy
- Neutrino **mass** & Oscillation
- Matter anti-matter asymmetry
- Vacuum stabilities: depends on particle **mass**
- Origin of Dark matter and its/their **mass**, nature of Dark energy
- Naturalness: EW - Higgs **mass** V.S. Planck scale
- Flavor Structure: **mass** & flavor eigenstates
- *We don't know why Nature choose the Standard Model (SM): 知其然不知其所以然*
- Being the heart of the SM and the **mass** origin: The Higgs field (particle) is the key to understand these mysteries





Higgs measurement at e+e- & pp



	Yield	efficiency	Comments
LHC	Run 1: 10^6 Run 2/HL: 10^{7-8}	$\sim \mathcal{O}(10^{-3})$	High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to $g(\text{ttH})$, and even $g(\text{HHH})$
e+e- Higgs factory	10^6	$\sim \mathcal{O}(1)$	Clean environment & Absolute measurement, Percentage level accuracy of Higgs width & Couplings

Consensus on electron positron Higgs factory

clear consensus in HEP community

2013, 2016: *the CEPC is the best approach* and a major historical opportunity for the national development of accelerator-based high-energy physics program.

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

In April 2022, the International Committee for Future Accelerators (ICFA) “reconfirmed the international consensus on the importance of *a Higgs factory as the highest priority for realizing the scientific goals of particle physics*”, and expressed support for the above-mentioned Higgs factory proposals. Recently, the United States also proposed a new linear collider concept based on the cool copper collider (C3) technology [31].



Conclusion from Executive Summary

Given the **strong motivation** and existence of proven technology to build an e^+e^- **Higgs Factory in the next decade**, the **US should participate** in the construction of any facility that has firm commitment to go forward.

Sridhara Dasu (Wisconsin)

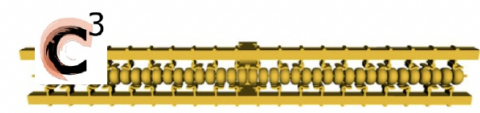
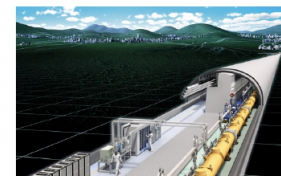
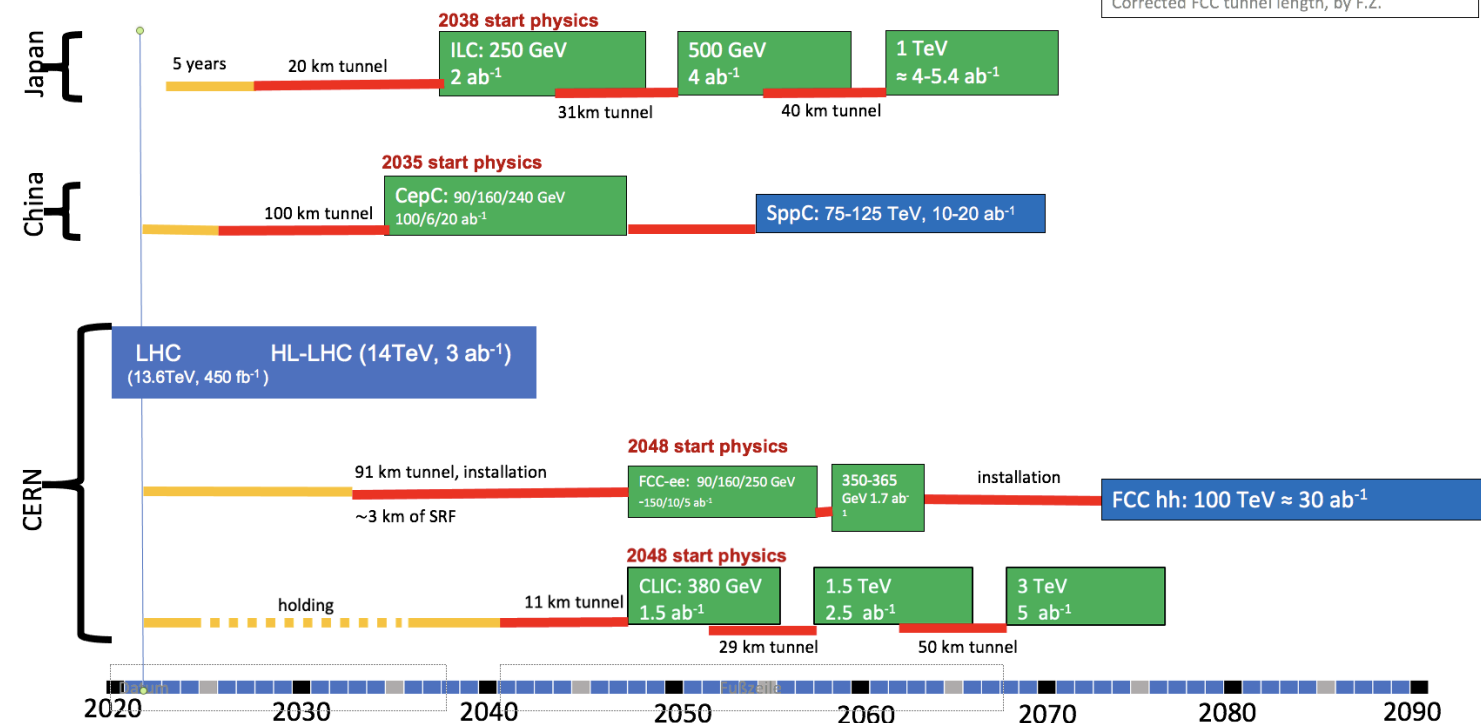
Multiple e^+e^- Higgs factory proposals

Indicative scenarios of future colliders [considered by ESG]

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

Original from ESG by Ursula Bassler
Updated July 25, 2022 by Meenakshi Narain
Corrected FCC tunnel length, by F.Z.



Statements from last ESPP relevant to ECFA

3. High-priority future initiatives

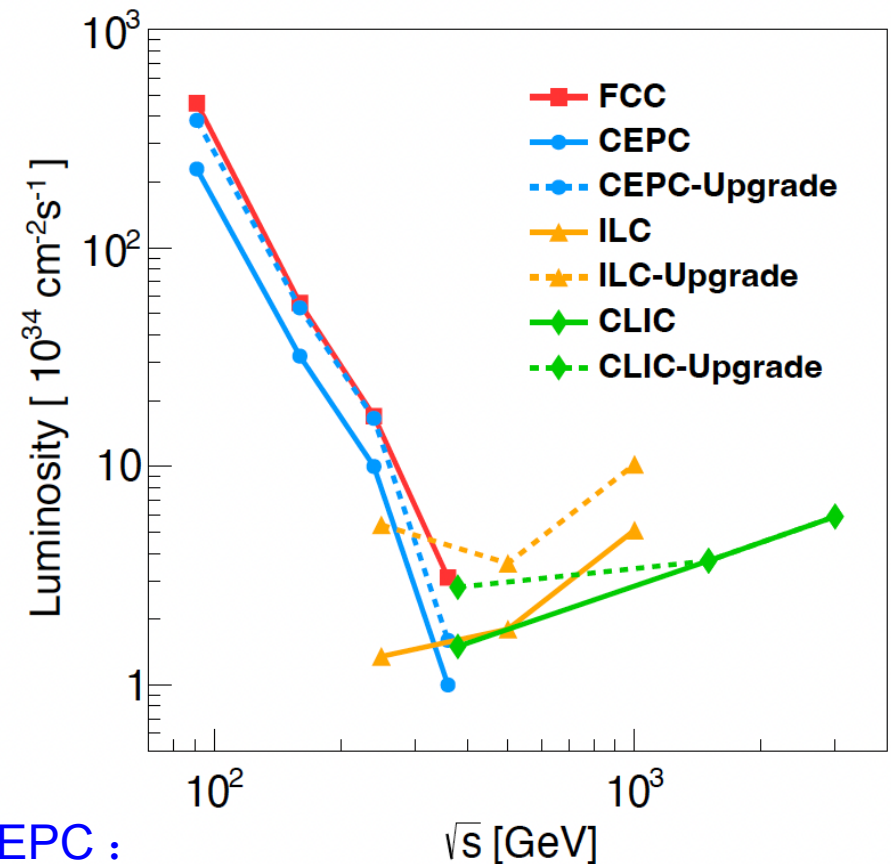
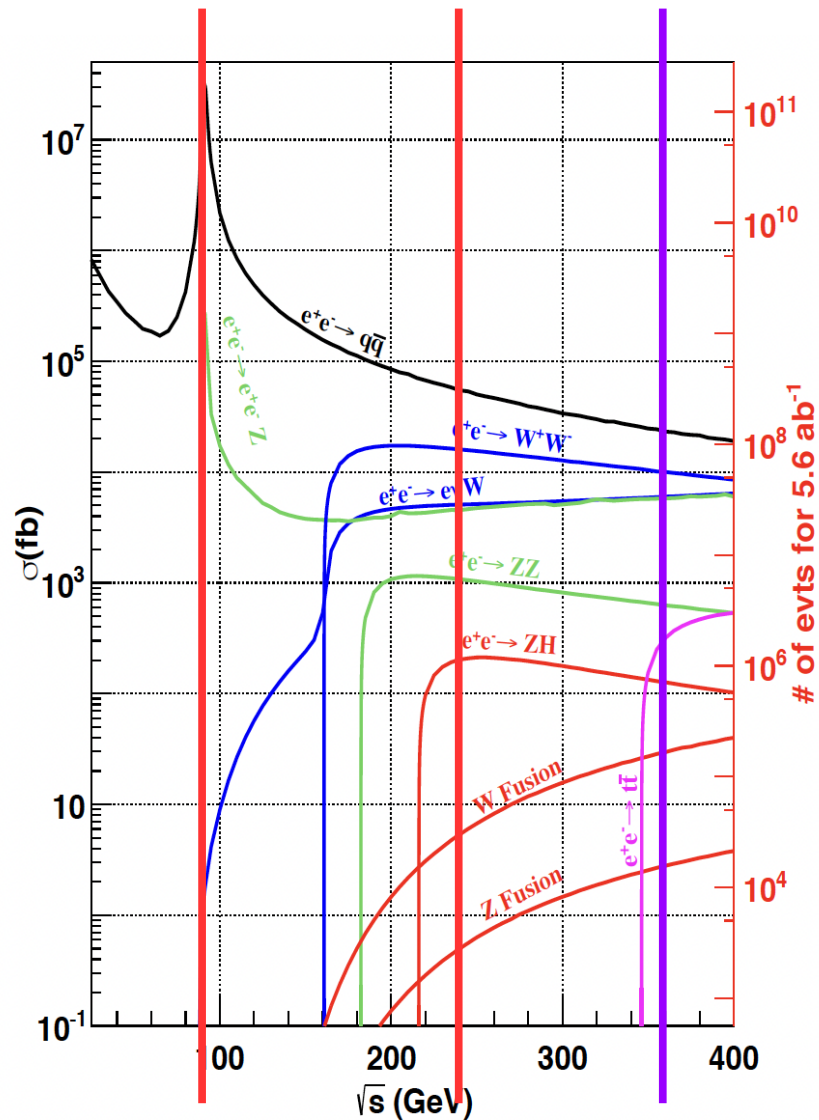
An **electron-positron Higgs factory** is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy**.

Accomplishing these compelling goals will require innovation and cutting-edge technology:

1/12/2023

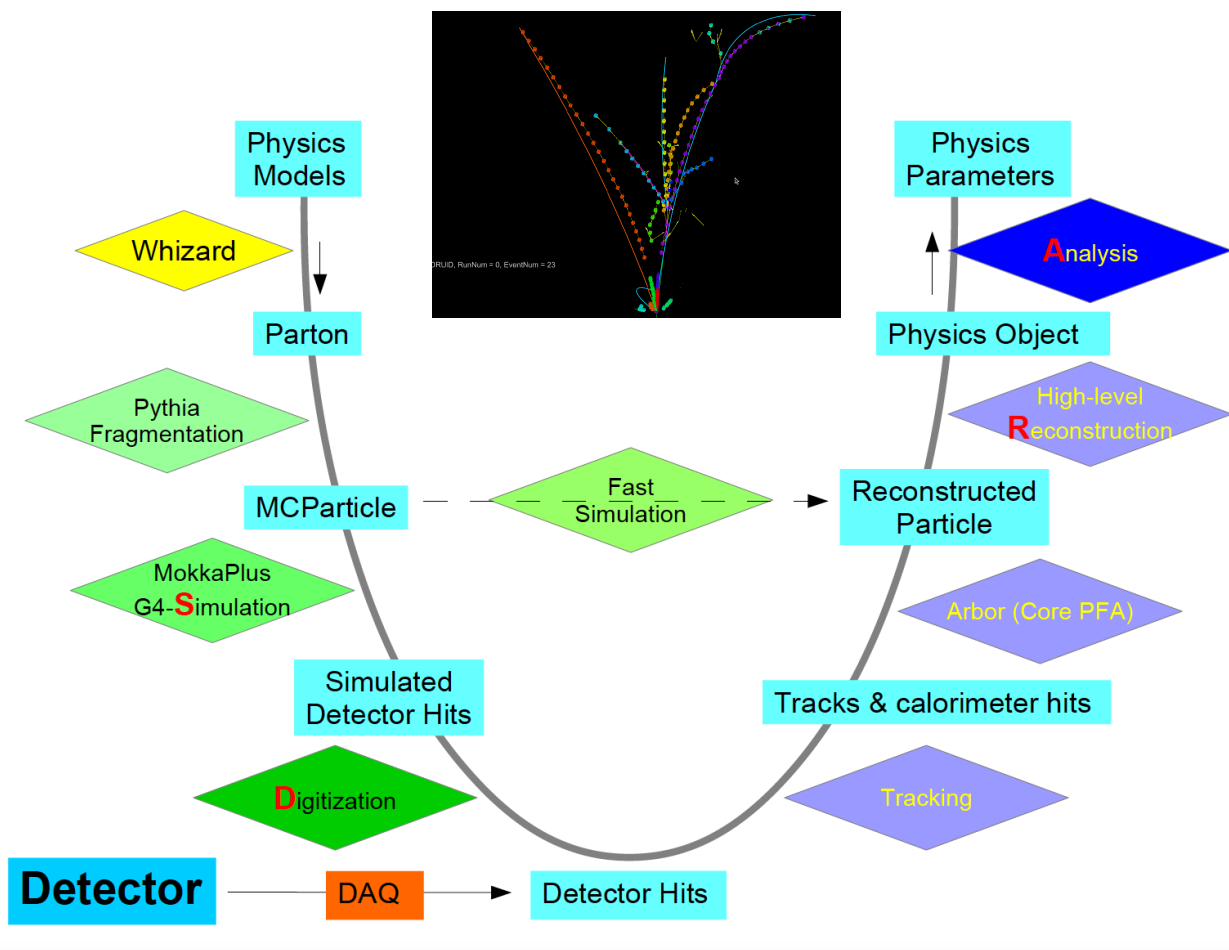
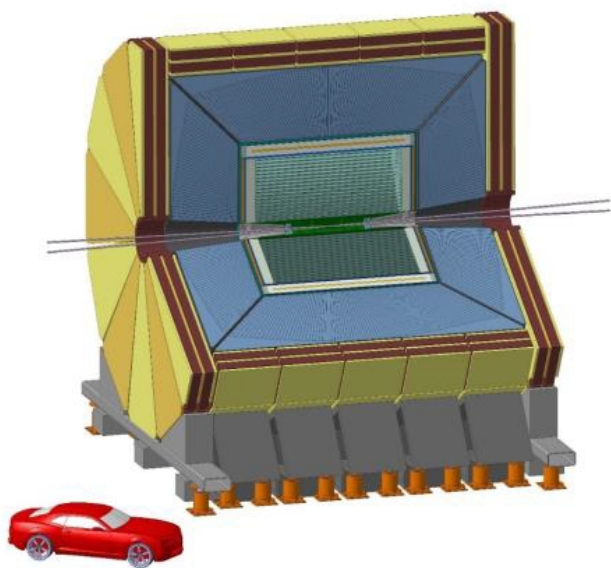
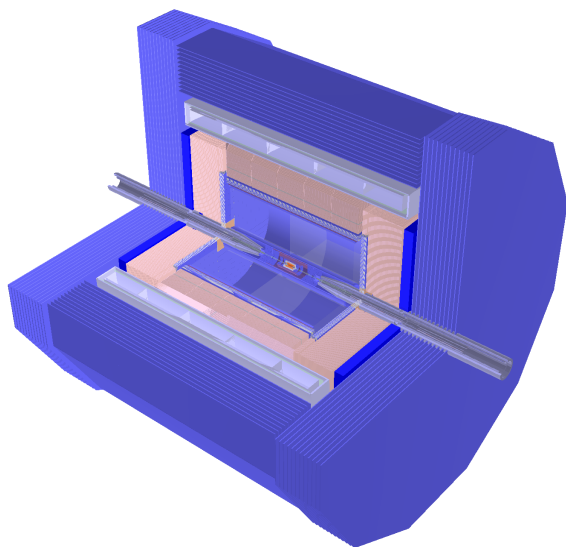
Higgs2023@IHEP

Yields \sim Xsec \times Lumi \times Time



- **CEPC :**
 - 4 Million Higgs (10 years)
 - \sim 1 Giga W (1 year) + 4 Tera Z (2 years)
 - Upgradable: Top factory (500 k ttbar)

Detector & Software



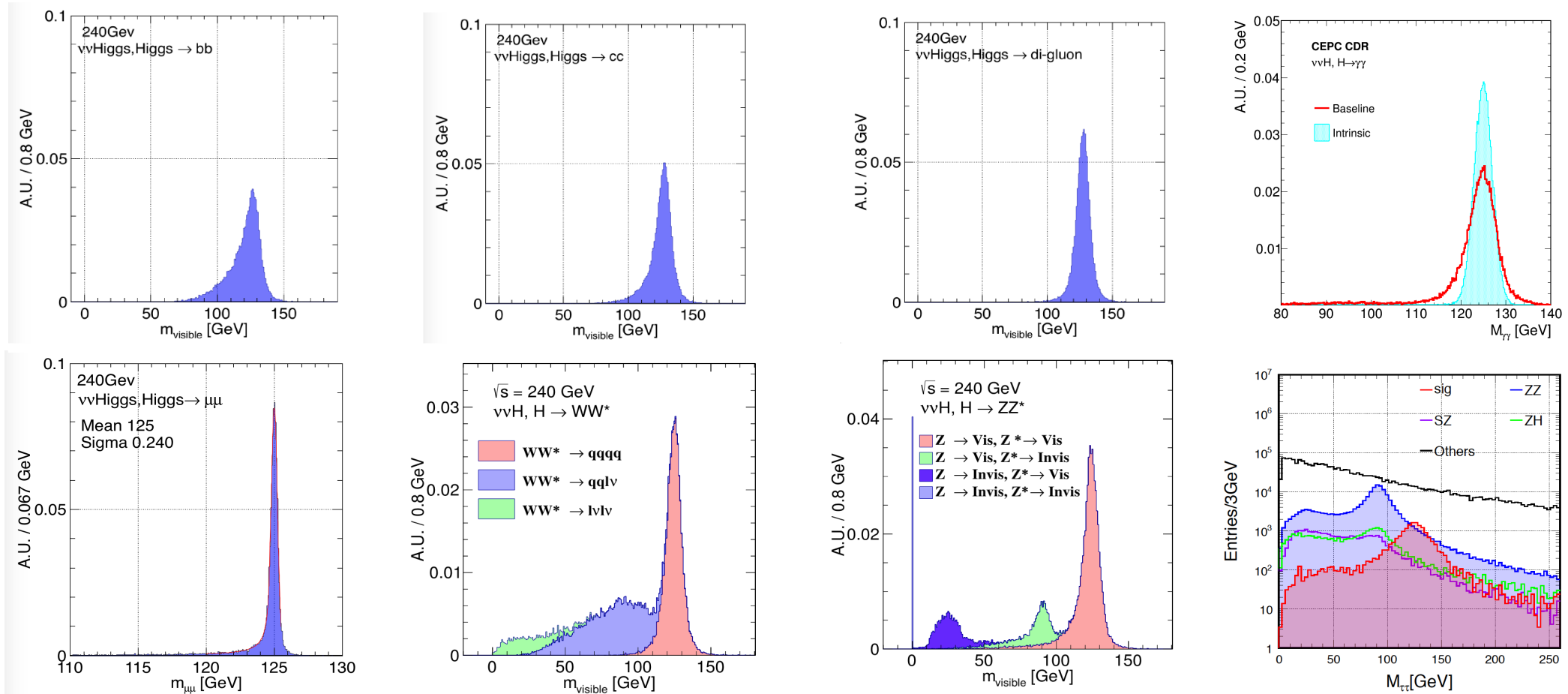
$Z \rightarrow 2 \text{ muon},$
 $H \rightarrow 2 b$
 $\sim 2\%$

$Z \rightarrow 2 \text{ jet},$
 $H \rightarrow 2 \text{ tau}$
 $\sim 5\%$

$ZH \rightarrow 4 \text{ jets}$
 $\sim 50\%$

$Z \rightarrow 2 \text{ muon}$
 $H \rightarrow WW^* \rightarrow eevv$
 $\sim 1\%$

Reconstructed Higgs Signatures



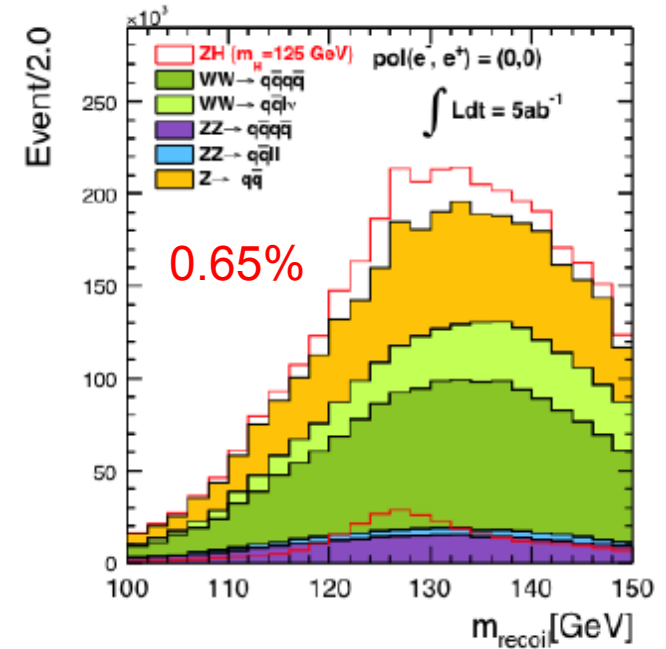
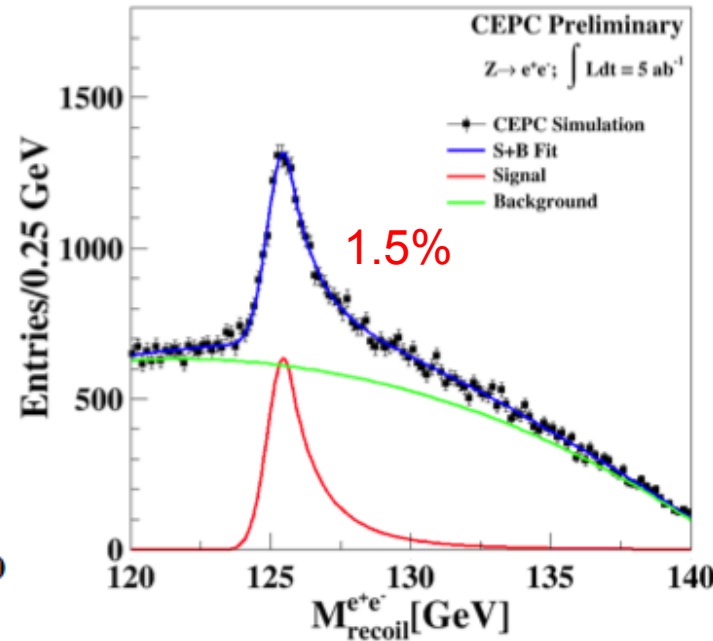
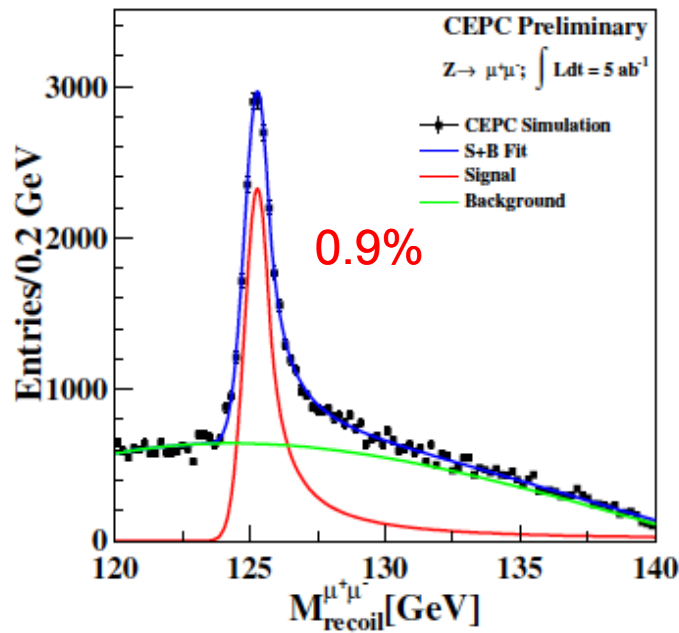
Clear Higgs Signature in all SM decay modes

Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

Right corner: di-tau mass distribution at qqH events using collinear approximation

Model-independent measurement of $\sigma(\text{ZH})$

Zhenxing Chen & Yacine Haddad



- Recoil mass method. Combined precision:
 $\delta\sigma(\text{ZH})/\sigma(\text{ZH}) = 0.5\%$ -
 $\delta g(\text{HZZ})/g(\text{HZZ}) = 0.25\%$
 With 1 Million Higgs bosons (5.6 iab)

$$\sigma_{Zh} = \left| \begin{array}{c} e \\ \text{---} \\ e \end{array} \right|^2 + 2 \text{Re} \left[\begin{array}{c} e \\ \text{---} \\ e \end{array} \right] \cdot \left(\begin{array}{c} e^+ \\ \text{---} \\ e^- \end{array} \right) + \begin{array}{c} e^+ \\ \text{---} \\ e^- \end{array} \right)$$

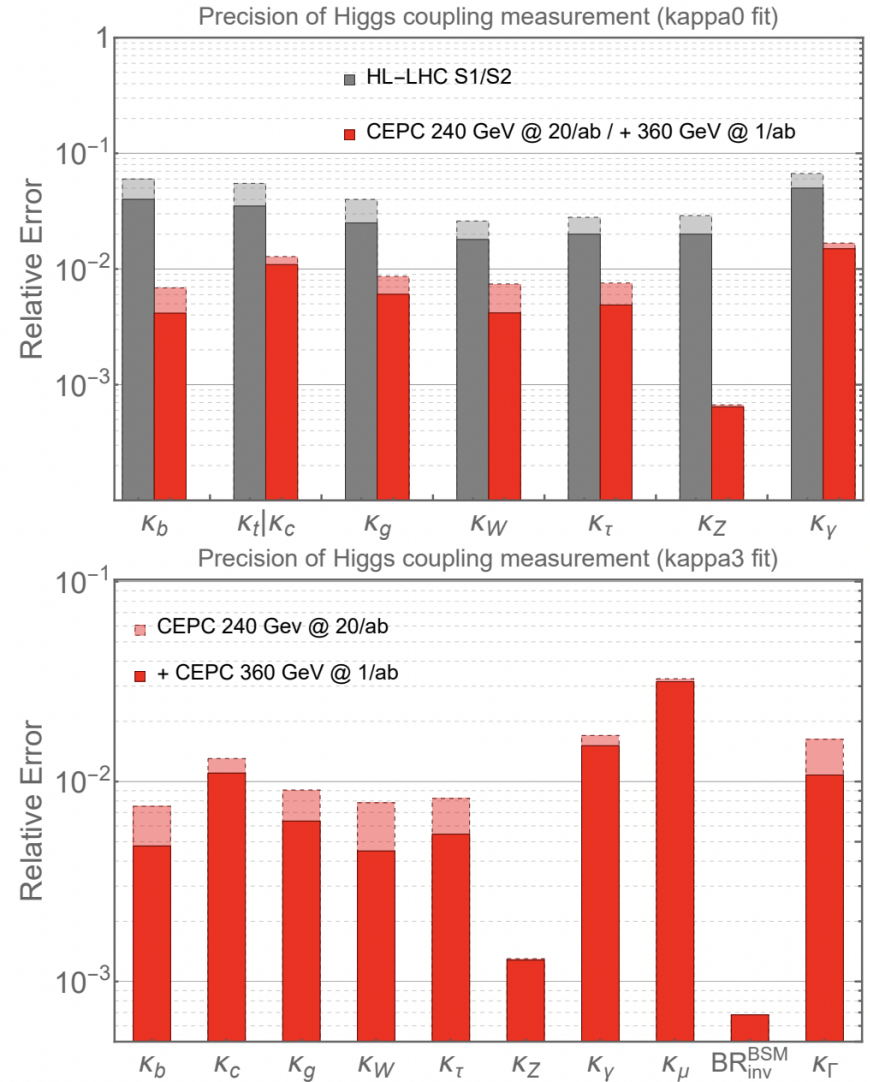
$$\delta_{\pi}^{240} = 100 (2\delta_Z + 0.014\delta_h) \%$$

- Indirect Access to $g(\text{HHH})$

• M. McCullough, 1312.3322

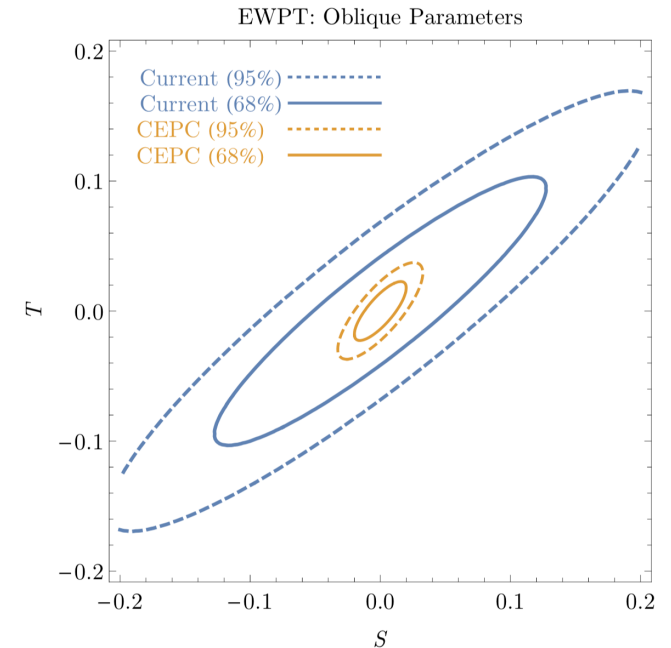
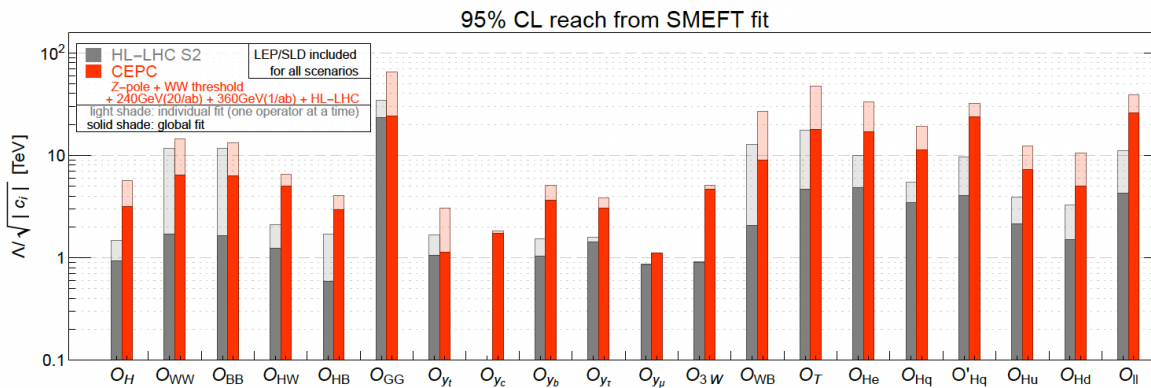
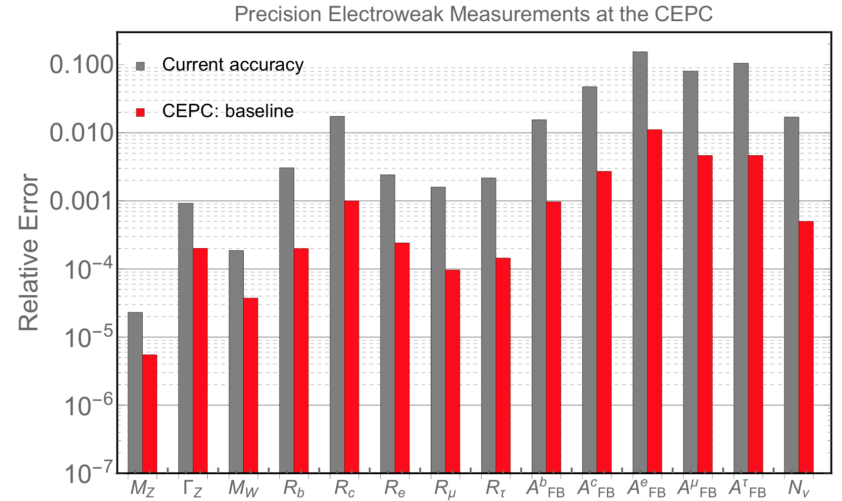
Physics reach via Higgs at CEPC

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	$\nu\nu\text{H}$	ZH	$\nu\nu\text{H}$	eeH
inclusive	0.26%		1.40%	\	\
$\text{H} \rightarrow \text{bb}$	0.14%	1.59%	0.90%	1.10%	4.30%
$\text{H} \rightarrow \text{cc}$	2.02%		8.80%	16%	20%
$\text{H} \rightarrow \text{gg}$	0.81%		3.40%	4.50%	12%
$\text{H} \rightarrow \text{WW}$	0.53%		2.80%	4.40%	6.50%
$\text{H} \rightarrow \text{ZZ}$	4.17%		20%	21%	
$\text{H} \rightarrow \tau\tau$	0.42%		2.10%	4.20%	7.50%
$\text{H} \rightarrow \gamma\gamma$	3.02%		11%	16%	
$\text{H} \rightarrow \mu\mu$	6.36%		41%	57%	
$\text{H} \rightarrow \text{Z}\gamma$	8.50%		35%		
$\text{Br}_{\text{upper}}(\text{H} \rightarrow \text{inv.})$	0.07%				
Γ_{H}	1.65%		1.10%		

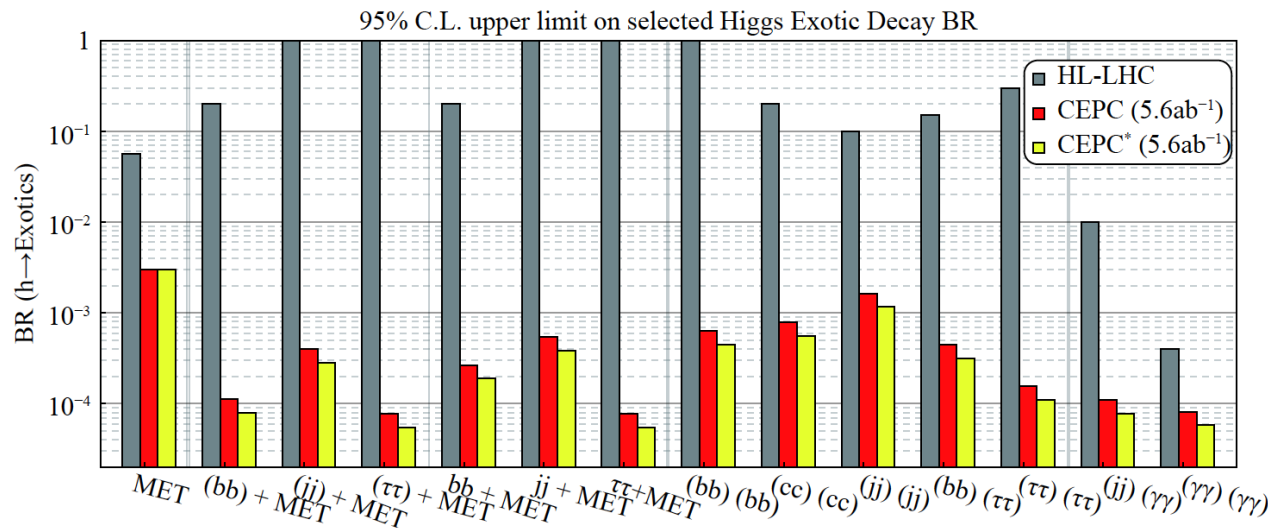
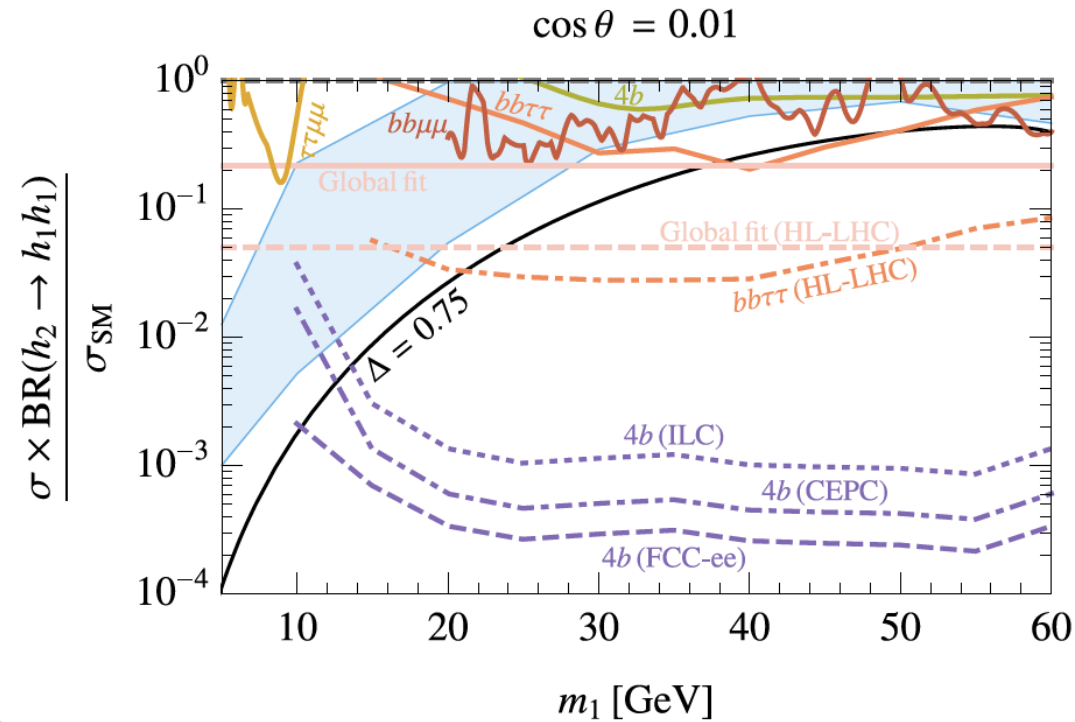
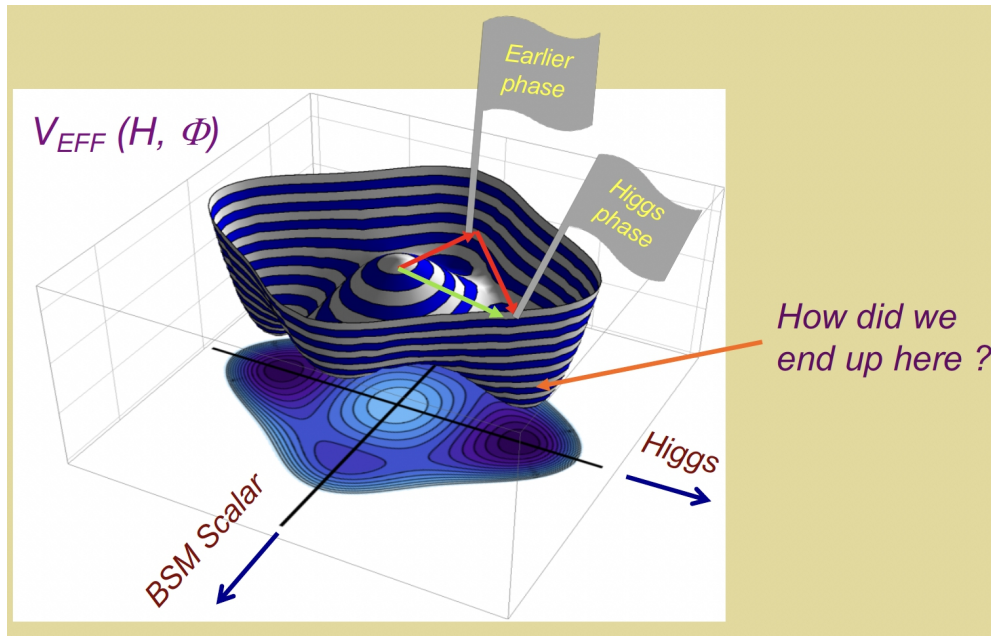


EW measurements & SMEFT

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta \Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	VW threshold	E_{beam}
$\Delta \Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV ^a	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z \rightarrow \tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z \rightarrow \mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z \rightarrow \tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta \sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	luminosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale



Phase Transition in early Universe



Origin of matter -

Synergy with GW detection...

Low mass Higgs bosons...

The Observation of a 95 GeV Scalar at future e^+e^- Colliders

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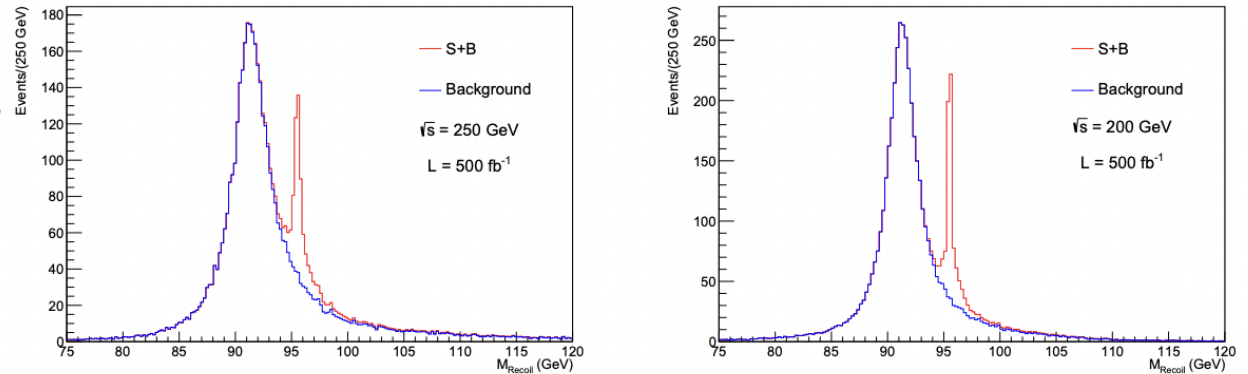


Figure 1. Recoil mass distribution for simulated $e^+e^- \rightarrow HZ \rightarrow H\mu^+\mu^-$ events with $m_S = 95, 5$ GeV and all relevant background events after a pre-selection described in this section for (a) $\sqrt{s} = 250$ GeV and (b) $\sqrt{s} = 200$ GeV both at integrated luminosity $\mathcal{L} = 500 \text{ fb}^{-1}$; measured with the CLIC_ILD detector concept. This is achieved by considering the BSM signal to be 10% SM Higgs-like.

...Preliminary...

- Assume signal $X_{\text{sec}} \sim 20 \text{ fb}$

- CEPC Higgs operation: $\sim 6 \text{ fb}^{-1}/\text{day} \sim 2 \text{ ab}^{-1}/\text{year}$

- Turn-key discovery

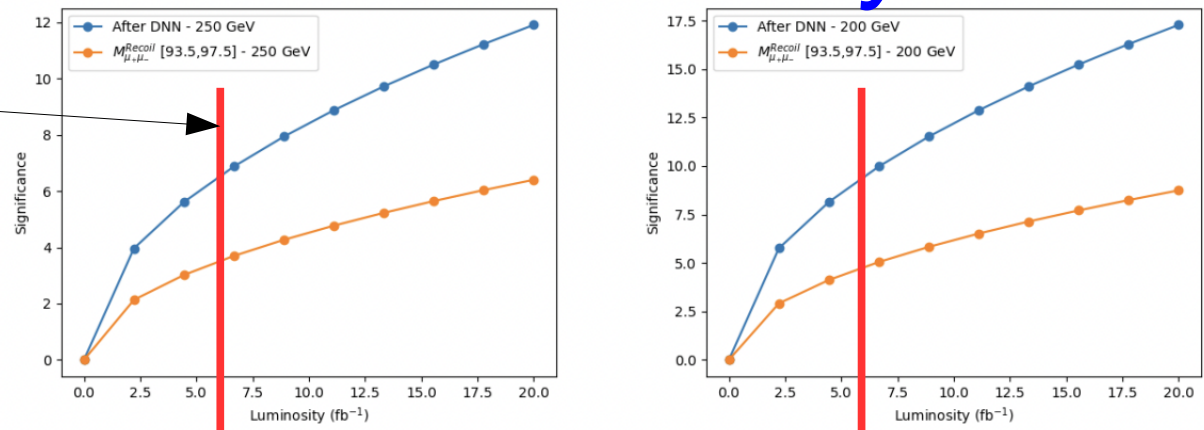


Figure 5. The signal significance as a function of Luminosity (\mathcal{L}) for (left) $\sqrt{s} = 250$ GeV before (Orange) and after DNN (Blue), (right) $\sqrt{s} = 200$ GeV before (Orange) and after DNN (Blue) respectively.

At FCC, ILC, CLIC, MuC...

High Energy Physics – Phenomenology

[Submitted on 16 Jun 2022 (v1), last revised 1 Dec 2022 (this version, v3)]

Global SMEFT Fits at Future Colliders

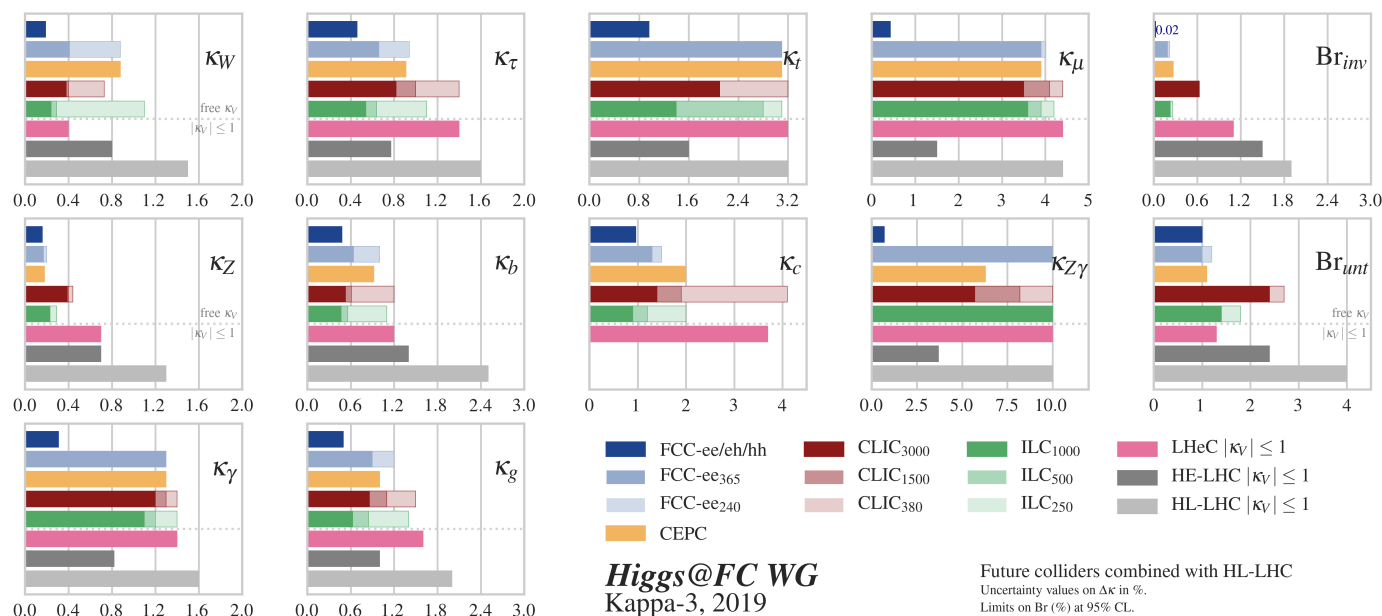
Jorge de Blas, Yong Du, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael E. Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou

Based on the framework of Standard Model Effective Field Theory, we performed a few global fits, each containing a subset of dimension-6 operators, for the measurements that are expected at future colliders. The fit for the Higgs and electroweak sector improves what has been done for the European Strategy Update in 2020 on both EFT treatments and experimental inputs. A new comprehensive fit is performed focusing on 4-fermion interactions at future colliders. Top-quark sector is studied in a dedicated fit which restricts the operators and measurements to be directly related to top-quark. A small subset of CP-violating operators involving bosonic fields alone are also investigated. Various running scenarios for future e+e- and Muon Colliders that are suggested in the Snowmass 2021 discussion are considered in the global fits. The outcomes from each fit are expressed in terms of either direct constraint on Wilson Coefficients or precision on Higgs and electroweak effective couplings.

Comments: Contributed Paper to Snowmass 2021. Minor updates from v2 on type correction in top-Yukawa coupling conversion and clarification on Higgs total width measurements at LHC

Subjects: High Energy Physics – Phenomenology

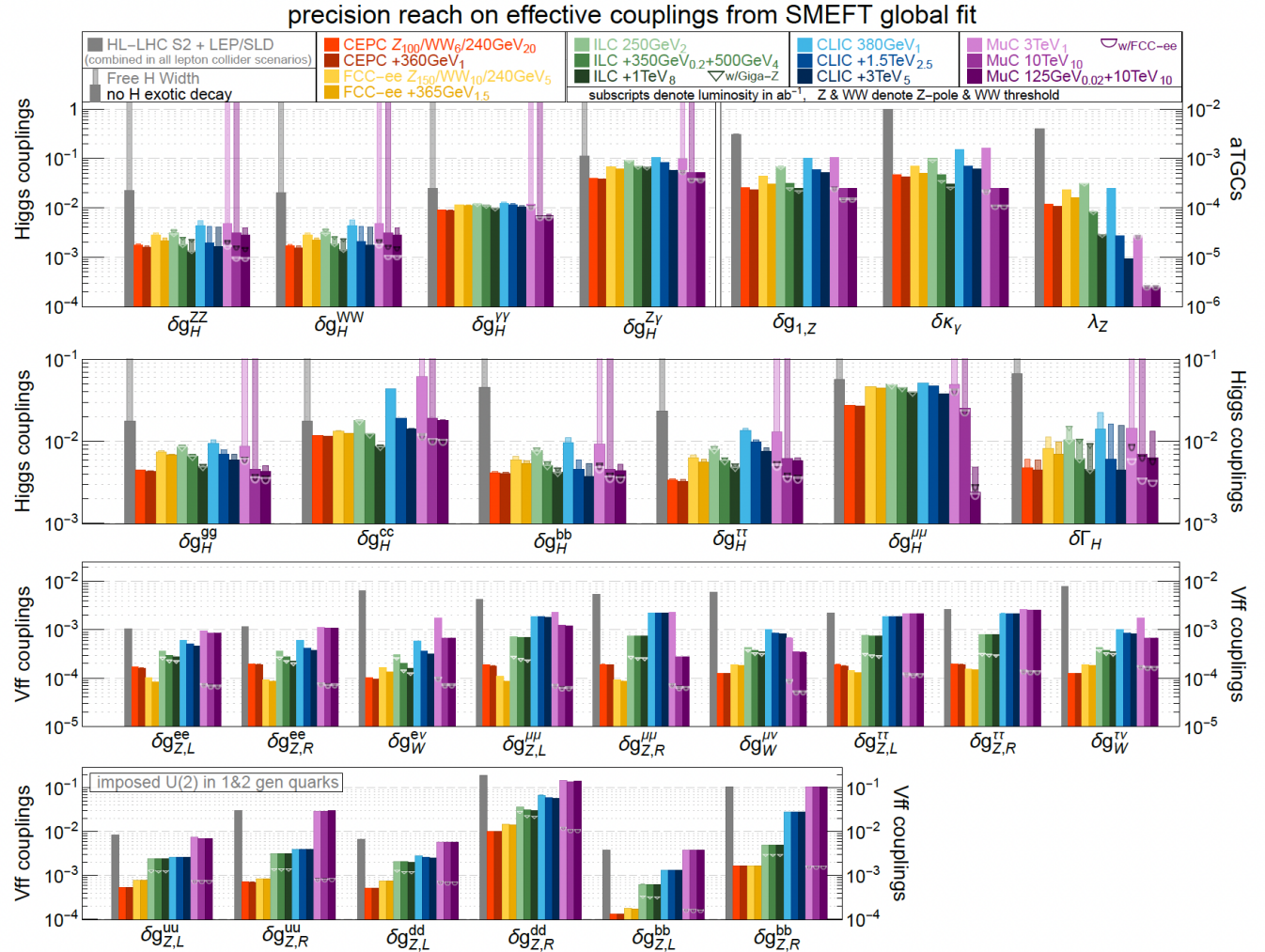
Cite as: arXiv:2206.08326 [hep-ph]
(or arXiv:2206.08326v3 [hep-ph] for this version)
<https://doi.org/10.48550/arXiv.2206.08326>



Polarization, sqrt(s), Luminosity & Access

Machine	Pol. (e^-, e^+)	Energy	Luminosity
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	$(\mp 80\%, \pm 30\%)$ $(\mp 80\%, \pm 20\%)$	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
		1 TeV	8 ab^{-1}
CLIC	$(\pm 80\%, 0\%)$	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC- ee	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

Table 2: Future collider scenarios considered in this



You can find more details in talks of Jiayin, Ivanka, etc

Flavor Physics White paper

Flavor Physics at CEPC: a General Perspective

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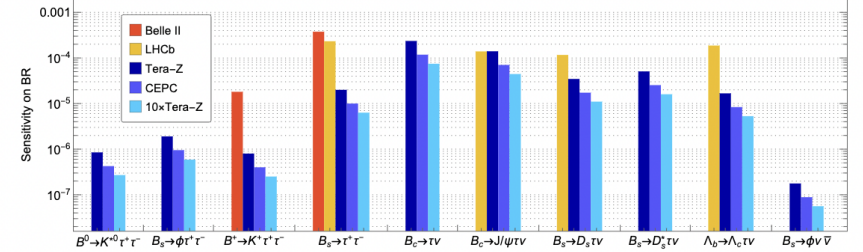


Figure 18: Projected sensitivities of measuring the $b \rightarrow s\tau\tau$ [70], $b \rightarrow s\nu\bar{\nu}$ [34] and $b \rightarrow c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities are generated by combining the analyses of $\tau^+ \rightarrow \pi^+ \pi^- \pi^0 \nu$ and $\tau \rightarrow \mu\nu\bar{\nu}$. This plot is adapted from [35].

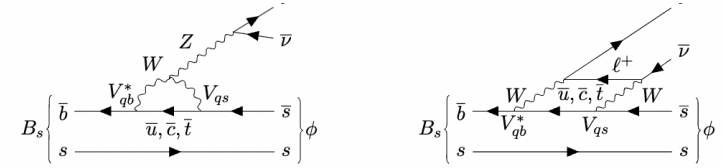


Figure 21: Illustrative Feynman diagrams for the $B_s \rightarrow \phi\nu\bar{\nu}$ transitions in the SM. **LEFT:** EW penguin diagram. **RIGHT:** EW box diagram.

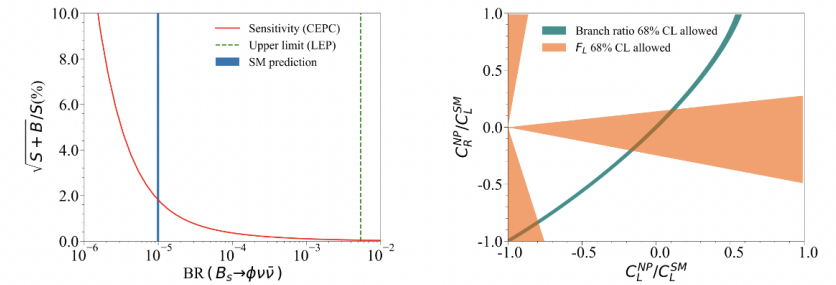


Figure 22: **LEFT:** Relative precision for measuring the signal strength of $B_s \rightarrow \phi\nu\bar{\nu}$ at Tera-Z, as a function of its BR. **RIGHT:** Constraints on the LEFT coefficients $C_L^{\text{NP}} \equiv C_L - C_L^{\text{SM}}$ and C_R with the measurements of the overall $B_s \rightarrow \phi\nu\bar{\nu}$ decay rate (green band) and the ϕ polarization F_L (orange regions). These plots are taken from [34].

~ 40 benchmarks

No.	Process	\sqrt{s} (GeV)	Parameter of interest	Observable	Current precision	CEPC Precision	Estimation method	Key detector performance	Relevant Section
1	$Z \rightarrow \mu\mu$	91.2	-	BR upper limit	-	$\lesssim 3 \times 10^{-11}$ [251]	Fast simulation	Tracker Missing energy	12
2	$B \rightarrow K^0(\rightarrow \mu\mu)$	91.2	-	BR upper limit	-	$\lesssim 10^{-10}$ [261]	Fast simulation	Tracker Vertex	12
3	$Z \rightarrow \pi^+\pi^-$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-10})$ [109]	Guestimate	Tracker PID	9
4	$Z \rightarrow \pi^+\pi^-\pi^0$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-9})$ [109]	Guestimate	Tracker PID ECAL	9
5	$b \rightarrow s\tau^+\tau^-$	91.2	-	BR upper limit	-	$B^0 \rightarrow K^{*0}\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \rightarrow \phi\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B^+ \rightarrow K^+\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \rightarrow \tau^+\tau^- \sim \mathcal{O}(10^{-5})$ [71]	Fast simulation	Tracker Vertex Jet origin ID	4
6	$Z \rightarrow \mu\gamma$	91.2	-	BR upper limit	$< 2.5 \times 10^{-5}$ [150]	$\mathcal{O}(10^{-9})$ [109]	Guestimate	Tracker PID ECAL	9
7	$Z \rightarrow J/\psi\gamma$	91.2	-	BR upper limit	$< 1.4 \times 10^{-6}$ [150]	$10^{-9} - 10^{-10}$ [109]	Guestimate	Tracker PID ECAL	9
8	$Z \rightarrow \tau\mu$	91.2	-	BR upper limit	$< 6.5 \times 10^{-6}$ [105-107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-6} [110]	Guestimate	E_{beam} Tracker PID	6
9	$Z \rightarrow \tau e$	91.2	-	BR upper limit	$< 5.0 \times 10^{-6}$ [105-107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-6} [110]	Guestimate	E_{beam} Tracker PID	6
10	$Z \rightarrow \mu e$	91.2	-	BR upper limit	$< 7.5 \times 10^{-7}$ [105-107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-6} [110]	Guestimate	E_{beam} Tracker PID	6
11	$\tau \rightarrow \mu\mu$	91.2	-	BR upper limit	$\lesssim 7 \times 10^{-4}$ [259]	$\lesssim 3 \times 10^{-6}$	Fast simulation	Tracker Missing energy	12
12	$\tau \rightarrow \mu\mu$	91.2	-	BR upper limit	$< 2.1 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID	8
13	$\tau \rightarrow e e e$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID	8
14	$\tau \rightarrow e\mu\mu$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID	8
15	$\tau \rightarrow \mu e e$	91.2	-	BR upper limit	$< 1.8 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID	8
16	$\tau \rightarrow \mu\gamma$	91.2	-	BR upper limit	$< 4.4 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID ECAL	8
17	$\tau \rightarrow e\gamma$	91.2	-	BR upper limit	$< 3.3 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guestimate	Tracker Lepton ID ECAL	8
18	$B_c \rightarrow \tau\nu$	91.2	$ V_{cb} $	$\sigma(\mu)/\mu$	BR $\lesssim 30\%$ [267]	$\mathcal{O}(1\%)$ [63]	Full simulation	Tracker Lepton ID Missing energy Jet origin ID	3
19	$B_s \rightarrow \phi\mu\bar{\mu}$	91.2	-	$\sigma(\mu)/\mu$	BR $< 5.4 \times 10^{-3}$ [150]	$\lesssim 2\%$ [35]	Full simulation	Tracker Vertex Missing energy PID	4
20		91.2		τ_c (s)	$\pm 5 \times 10^{-16}$ [150]	$\pm 1 \times 10^{-16}$ [108]	Guestimate	-	8
21		91.2		m_τ (MeV)	± 0.12 [150]	$\pm 0.004 \pm 0.1$ [108]	Guestimate	-	8
22	$\tau \rightarrow \nu\bar{\mu}\nu$	91.2	-	BR	$\pm 4 \times 10^{-4}$ [150]	$\pm 3 \times 10^{-5}$ [108]	Guestimate	Tracker Lepton ID Missing energy	8
23	$b \rightarrow c\bar{b}\nu$	91.2	-	R_{B_c}	$R_{B_c} = 0.71 \pm 0.17 \pm 0.18$ [268] $R_{B_c} = 0.242 \pm 0.076$ [269]	relative (stat. only) $R_{B_c} \lesssim 5\%$ $R_{B_c} \lesssim 0.4\%$ $R_{B_c} \sim 0.1\%$	[38] Fast simulation	Tracker Vertex	3
24	$B_s \rightarrow J/\psi\phi$	91.2	ϕ_ψ ($\sim -23^\circ$)	Γ_ψ , $\Delta\Gamma_\psi$	$\Gamma_\psi = 657.3 \pm 2.3 \text{ ns}^{-1}$ [150] $\Delta\Gamma_\psi = 65.7 \pm 4.3 \pm 3.7 \text{ ns}^{-1}$ [270] $\phi_\psi = -87 \pm 36 \pm 21 \text{ mrad}$ [270]	$\sigma(\Gamma_\psi) = 0.072 \text{ ns}^{-1}$ $\sigma(\Delta\Gamma_\psi) = 0.24 \text{ ns}^{-1}$ $\sigma(\phi_\psi) = 4.3 \text{ mrad}$	[45] Full simulation	Tracker Vertex Lifetime resolution Jet origin ID	5
25	$B^0 \rightarrow \pi^0\pi^0$	91.2	α	BR, A_{CP}	$BR^{B^0} = (1.59 \pm 0.26) \times 10^{-6}$ (16%) [150] $C_{CP}^{B^0} = -0.33 \pm 0.22$	$\sigma(BR)/BR^{B^0} = 0.45\%$ $\sigma(C_{CP}^{B^0}) = \pm (0.014-0.018)$	[31] Fast simulation	ECAL Jet origin ID	5
26	$B^0 \rightarrow \pi^+\pi^-$	91.2	α	BR	$BR^{B^0} = (5.5 \pm 0.4) \times 10^{-6}$ (7%) [150]	$\sigma(BR)/BR^{B^0} = 0.19\%$	[31] Fast simulation	Tracker Jet origin ID	5
27	$B^+ \rightarrow \pi^+\pi^0$	91.2	α	BR, A_{CP}	$BR^{B^+} = (5.12 \pm 0.19) \times 10^{-6}$ (4%) [150] $C_{CP}^{B^+} = -0.314 \pm 0.030$ $S_{CP}^{B^+} = -0.670 \pm 0.030$	$\sigma(BR)/BR^{B^+} = 0.18\%$ $\sigma(C_{CP}^{B^+}) = \pm (0.004-0.005)$ $\sigma(S_{CP}^{B^+}) = \pm (0.004-0.005)$	[31] Fast simulation	ECAL Tracker Vertex Jet origin ID	5
28	$H \rightarrow s\bar{s}$	240	-	BR upper limit	-	$0.02\% - 0.1\%$ [32]	Full simulation	Jet origin ID	10
29	$H \rightarrow d\bar{d}$	240	-	BR upper limit	-	$0.02\% - 0.1\%$ [32]	Full simulation	Jet origin ID	10
30	$H \rightarrow d\bar{s}$	240	-	BR upper limit	-	$0.02\% - 0.1\%$ [32]	Full simulation	Jet origin ID	10
31	$H \rightarrow u\bar{u}$	240	-	BR upper limit	-	$0.02\% - 0.1\%$ [32]	Full simulation	Jet origin ID	10
32	$H \rightarrow s\bar{s}$	240	-	BR upper limit	-	0.1% [32]	Full simulation	Jet origin ID	10
33	$H \rightarrow u\bar{u}$	240	-	BR upper limit	-	0.1% [32]	Full simulation	Jet origin ID	10
34	$H \rightarrow d\bar{d}$	240	-	BR upper limit	-	0.1% [32]	Full simulation	Jet origin ID	10
35	$e^+e^- \rightarrow t\bar{t}j$	240	-	FCNC constraint coefficients	two-fermion, LHC [199-203] four-fermion, LEP2 [204, 205]	1-2 orders of magnitude improvement compared to LEP2 [198]	Fast simulation	Tracker Missing energy Jet origin ID	10
36	$WW \rightarrow \mu\nu q\bar{q}$ $W^+W^- \rightarrow \tau^+\tau^-\mu\nu q\bar{q}$	240	$ V_{ts} $	$ V_{ts} $	$(38.9 \pm 0.53) \times 10^{-3}$ relative $\sim 1.4\%$ [9]	$\lesssim 0.5\%$ [193]	Full simulation	Jet origin ID	10

- Access to non-seen

- Orders of magnitudes improvements

- Multiple sqrt(s)

- Non-inclusive + long wishlist: to be addressed in phase II flavor WP study

$$b \rightarrow s\nu\nu$$

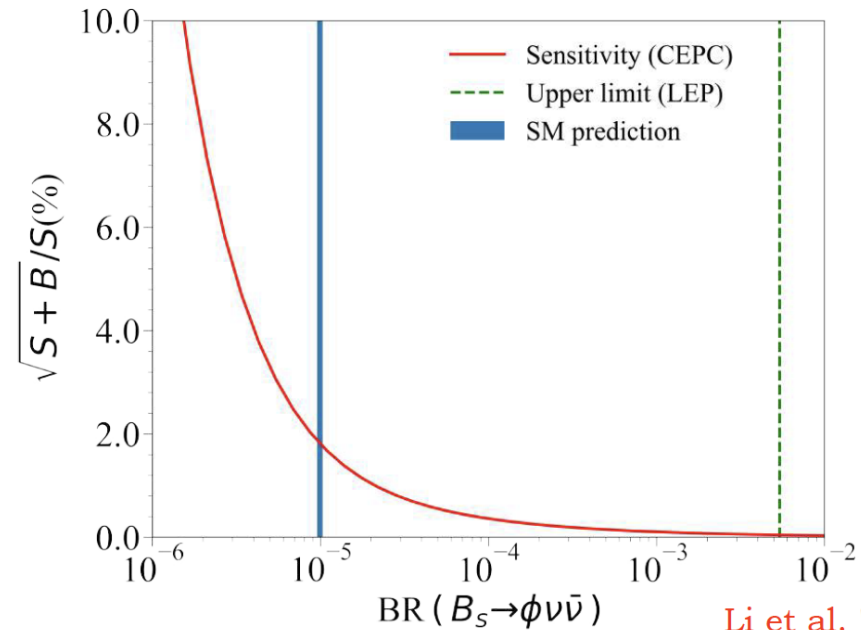
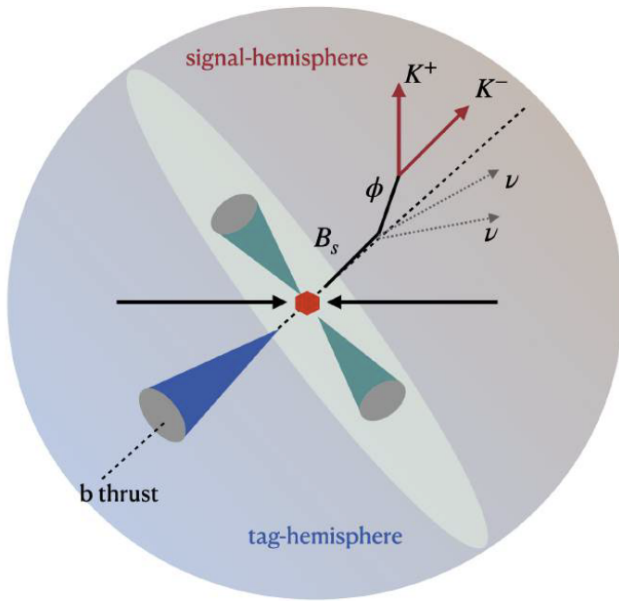
Li et al. '22

	Current Limit	Detector	SM Prediction
$\text{BR}(B^0 \rightarrow K^0 \nu \bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\text{BR}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\text{BR}(B^\pm \rightarrow K^\pm \nu \bar{\nu})$	$< 1.6 \times 10^{-5}$ [4]	BABAR	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$\text{BR}(B^\pm \rightarrow K^{*\pm} \nu \bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$\text{BR}(B_s \rightarrow \phi \nu \bar{\nu})$	$< 5.4 \times 10^{-3}$ [6]	DELPHI	$(9.93 \pm 0.72) \times 10^{-6}$

- Also these modes can be greatly enhanced by new physics responsible for the B anomalies

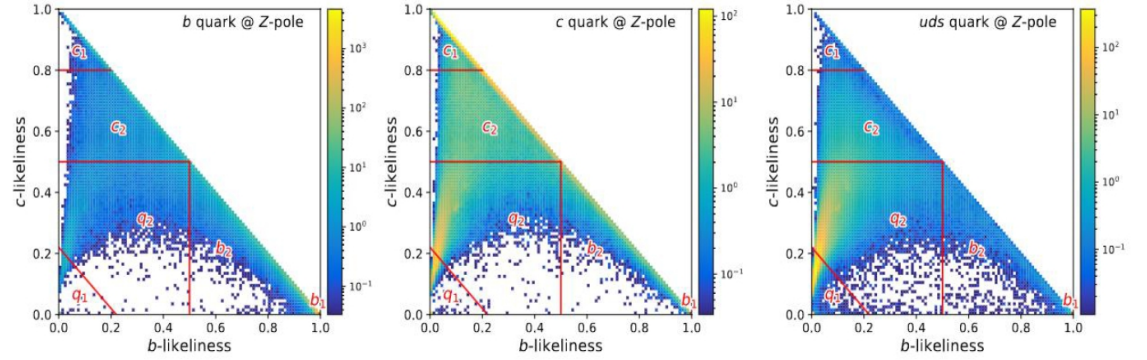
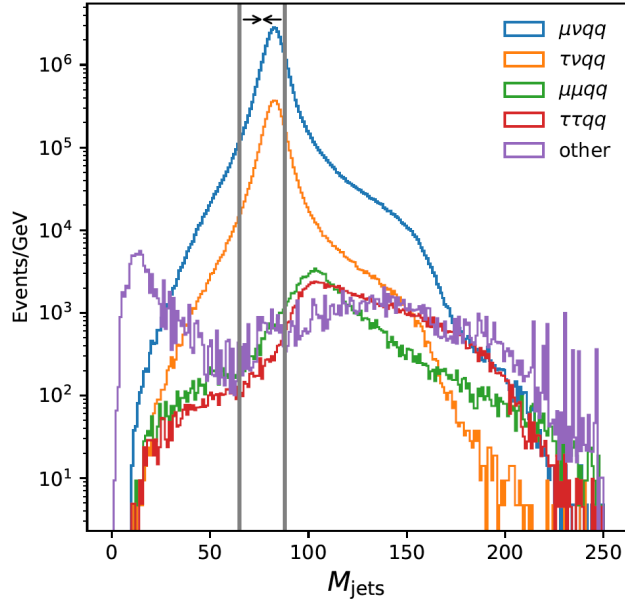
see e.g. [LC Crivellin Ota '15](#)

- A Tera Z can measure $B_s \rightarrow \phi \nu \bar{\nu}$ with a percent level precision:



Li et al. '22

Vcb from W decay



quark \ tag	b_1	b_2	c_1	c_2	q_1	q_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

	$\mu\nu W, W \rightarrow$				$\tau(\mu\nu)\nu_\tau W, W \rightarrow$				$\tau\nu_\tau qq, \tau \rightarrow$				$\tau\tau qq, \mu\mu qq$				Higgs	others
	cb	ub	$c(d/s)$	$u(d/s)$	cb	ub	$c(d/s)$	$u(d/s)$	$e2\nu$	$had.\nu_\tau$	$\tau\tau qq$	$\mu\mu qq$	$\tau\tau qq$	$\mu\mu qq$	$\tau\tau qq$	$\mu\mu qq$		
w/o selections	40.3K	363	24.2M	24.2M	7.73K	74	4.2M	4.2M	8.66M	31.4M	2.18M	4.47M	4.07M	2.06G				
$E_{L\mu} > 12\text{GeV}$	37.9K	330	22.6M	22.6M	5.59K	56	2.98M	2.97M	133K	687K	422K	2.82M	645K	186.3M				
$R_{L\mu} > 0.85$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M				
$\cos(\theta_{L\mu})$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M				
$q_{L\mu} \cos(\theta_{L\mu}) < 0.20$	32.8K	283	19.6M	19.6M	4.7K	42	2.57M	2.57M	1.26K	39.9K	156K	1.03M	183K	92.6M				
2nd isolation ℓ veto	32.8K	283	19.5M	19.6M	4.7K	42	2.57M	2.57M	1.26K	39.9K	154K	526K	138K	43.9M				
multiplicity ≥ 15	32.8K	283	19.5M	19.4M	4.7K	42	2.56M	2.55M	1.23K	39.6K	153K	522K	118K	185K				
Missing $P_T > 9.5\text{ GeV}/c$	31.5K	264	18.7M	18.6M	4.38K	37	2.4M	2.39M	1.18K	37.2K	136K	118K	92.6K	97.7K				
$M_{\text{jets}} > 65\text{ GeV}/c^2$	29.4K	254	18.1M	18.3M	4.15K	32	2.33M	2.35M	978	36.0K	132K	112K	85.3K	24.5K				
$M_{\text{jets}} < 88\text{ GeV}/c^2$	24.1K	193	14.3M	14.1M	3.49K	23	1.87M	1.85M	641	24.7K	5.62K	11.5K	6.76K	4.31K				
$M_{\text{jets, recoil}} < 115\text{ GeV}/c^2$	20.2K	184	13.0M	13.1M	2.96K	23	1.72M	1.73M	505	22.6K	3.57K	6.86K	536	3.02K				
$M_{L\mu S\mu} < 75\text{ GeV}/c^2$	19.6K	184	12.9M	13.0M	2.95K	23	1.72M	1.73M	505	22.6K	3.56K	5.78K	414	3.0K				
$M_{\ell\nu} > 12\text{ GeV}/c^2$	19.6K	184	12.9M	13.0M	2.7K	18	1.54M	1.55M	416	19.5K	2.08K	5.16K	390	1.81K				
$\epsilon_{\text{kin}} (\%)$	48.8	50.6	53.5	53.7	34.9	25.0	36.7	36.9	0.0	0.1	0.1	0.1	0.0	0.0				
	(0.7)	(8.1)	(0.0)	(0.0)	(1.5)	(12.5)	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)				
$b_1 c_{1,2}$	5.14K	4	2.79K	571	632	0	407	65	0	14	67	228	0	0				
	12.8	1.3	0.0	0.0	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
$\epsilon_{b_1 c_{1,2}} (\%)$	(0.4)	(1.3)	(0.0)	(0.0)	(0.7)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)				

- Purity $> 99.5\%$ at Eff. 50% for $\mu\nu qq$ and 34% for $\tau(\mu 2\nu)\nu qq$
- Main backgrounds include:
 - $W \rightarrow c(d/s)$
 - $\mu\mu qq$

Vcb could be measured to a relative uncertainty of 0.4% at CEPC Nominal Set up...

Summary of rare B decays

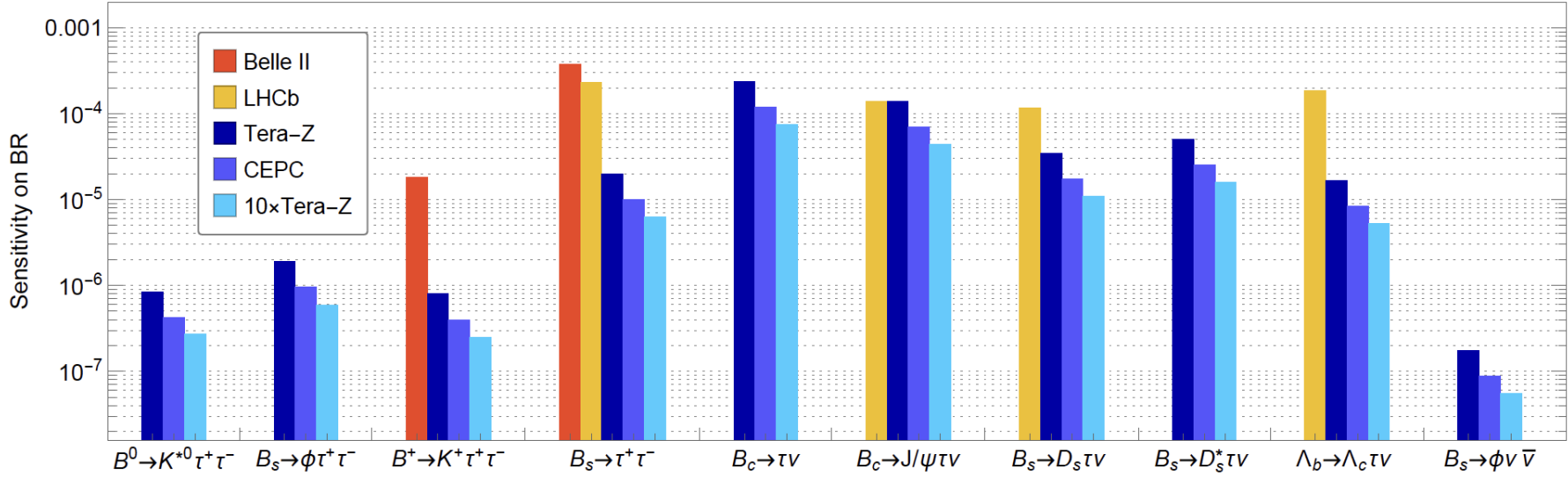


Figure 17: Projected sensitivities of measuring the $b \rightarrow s\tau\tau$ [71], $b \rightarrow s\nu\bar{\nu}$ [35] and $b \rightarrow c\tau\nu$ [37, 63] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 72] have also been provided as a reference. Note, the LHCb sensitivities are generated by combining the analyses of $\tau^+ \rightarrow \pi^+ \pi^- \pi^- (\pi^0) \nu$ and $\tau \rightarrow \mu \nu \bar{\nu}$. This plot is adapted from [37].

Ho et al. '22
CEPC flavour WP, in preparation

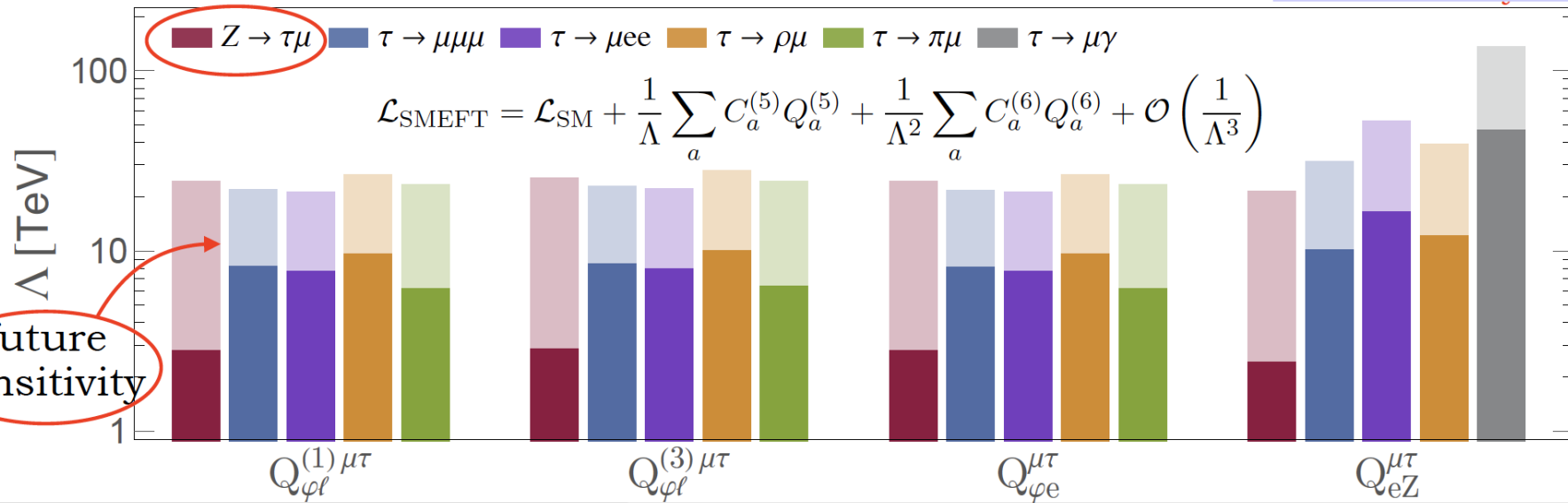
Lepton Flavour Violation in Z decays

Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee exp.
$\text{BR}(Z \rightarrow \mu e)$	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
$\text{BR}(Z \rightarrow \tau e)$	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
$\text{BR}(Z \rightarrow \tau \mu)$	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

←
M. Dam '18

- LHC searches limited by backgrounds (in particular $Z \rightarrow \tau\tau$):
max ~ 10 improvement can be expected at HL-LHC (3000/fb)
- A Tera Z can test LFV new physics searching for $Z \rightarrow \tau \ell$ at the level of what Belle II (50/ab) will do through LFV tau decays (or better)

LC Marcano Roy '21

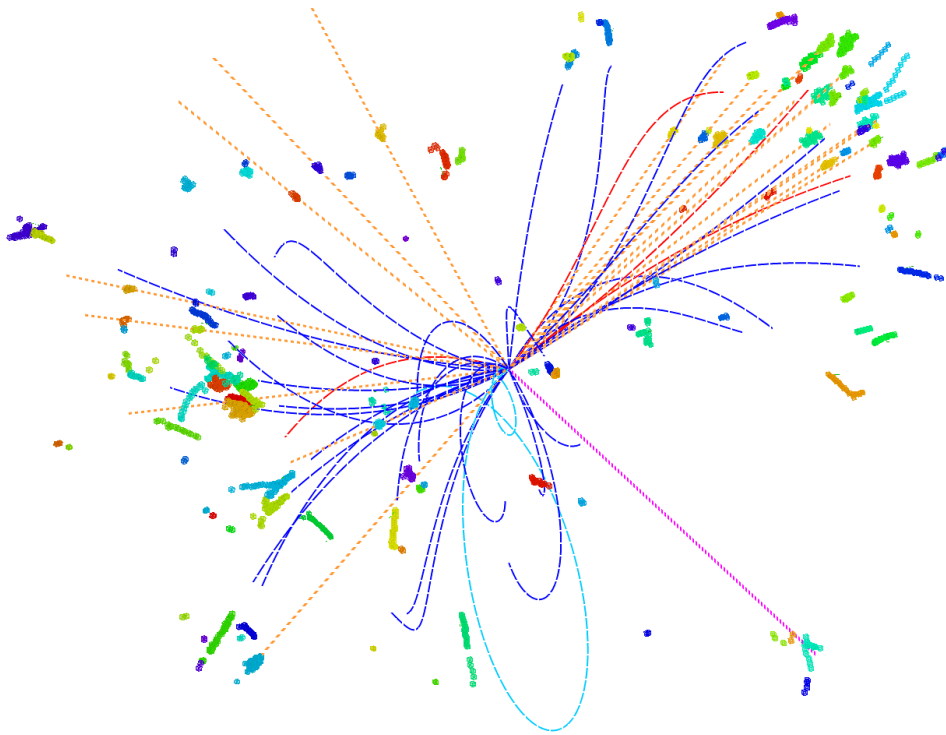


Extreme detector requirements

- Suited to the **collision environment**, especially beam background/MDI
- **Trigger-less equivalent**: Trigger system works as Trigger-less
- **Extremely stable**
- **Large acceptance**: polar angle, energy, time
- **PFA compatible (in SpaceTime)**: final state particle separation – pursue 1-1 correspondence
 - Physics Objects Identification: Isolated, inside jets & jets
 - Single particle objects: Leptons, photons, Charged hadron
 - Compositated objects: π^0 , K-short, Lambda, Phi, Tau, D/B hadron, ..., Jets
 - Improving the E/M resolution for compositated objects, especially jets
- **BMR (Boson Mass Resolution)**
 - < 4% for Higgs measurements, ~3% for NP tagging & Flavor Physics Measurements
- **Pid**: Pion & Kaon separation > 3σ
- **Jet origin identification**: Flavor Tagging, Charge Reconstruction, s-tagging...
- **Excellent intrinsic resolution** E/M/position: per mille level for track, percentage level for EM...

To be addressed by innovative detector design + key tech R&D

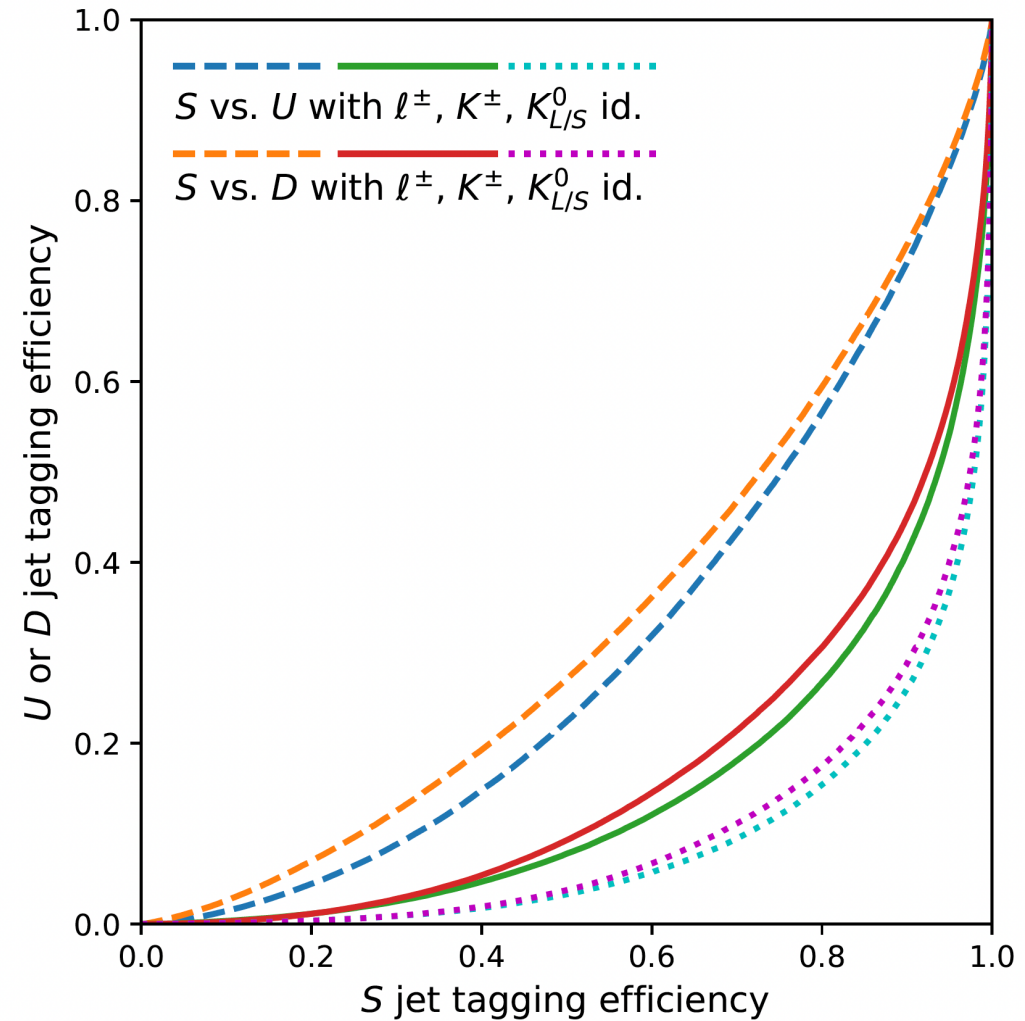
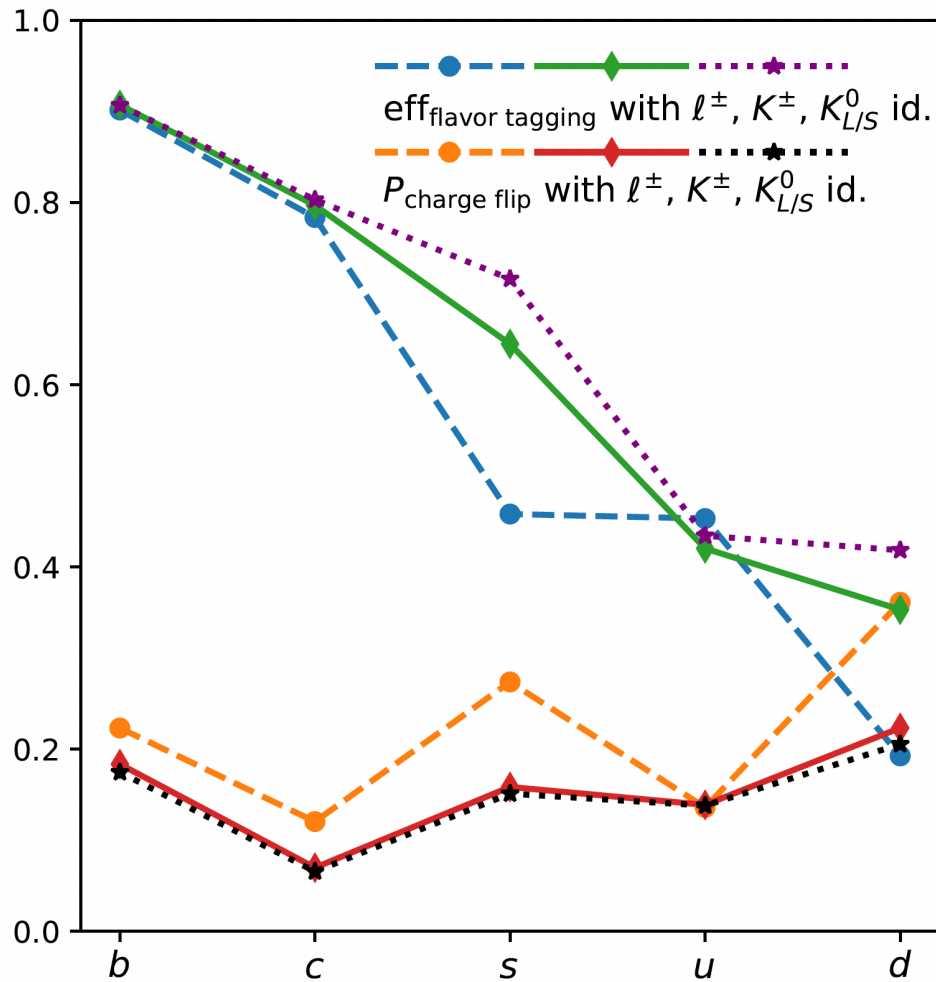
Jet Origin Identification



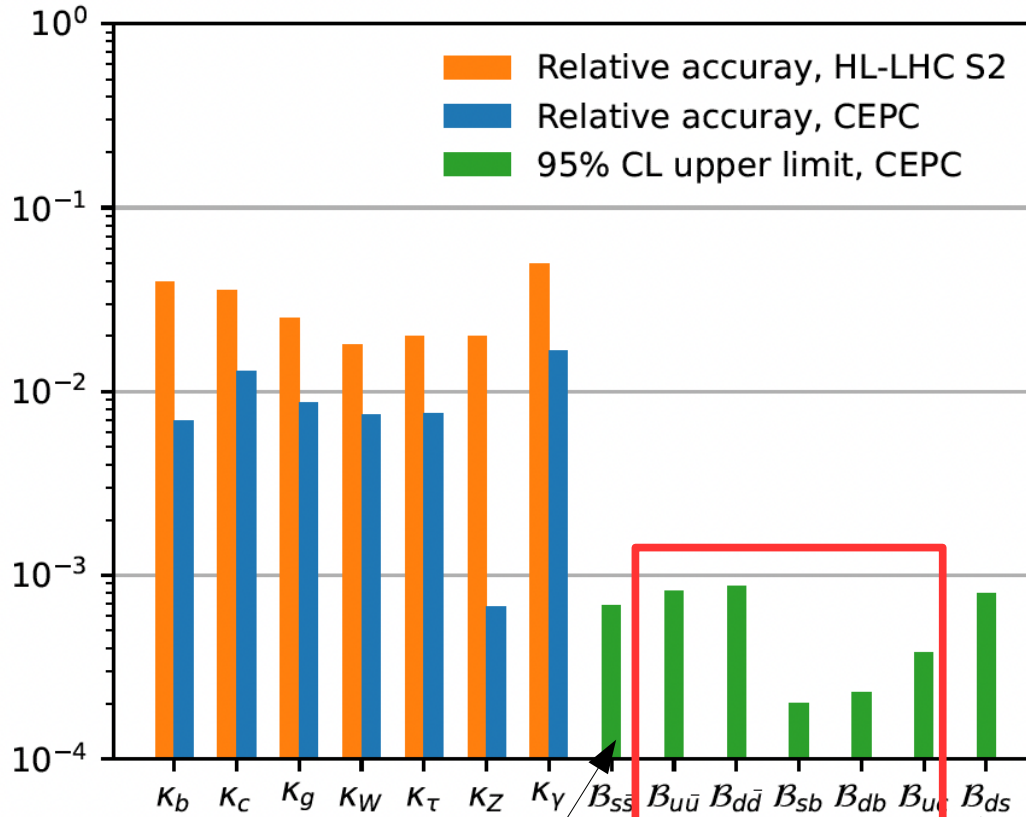
Truth	b	\bar{b}	c	\bar{c}	s	\bar{s}	u	\bar{u}	d	\bar{d}	G
	0.742	0.170	0.033	0.022	0.004	0.003	0.002	0.003	0.002	0.002	0.017
	0.172	0.739	0.022	0.032	0.003	0.004	0.003	0.002	0.002	0.002	0.018
	0.018	0.015	0.732	0.060	0.038	0.030	0.025	0.009	0.010	0.017	0.046
	0.016	0.018	0.056	0.734	0.030	0.037	0.010	0.024	0.018	0.009	0.047
	0.003	0.002	0.026	0.021	0.543	0.096	0.030	0.077	0.063	0.046	0.093
	0.002	0.003	0.021	0.025	0.097	0.547	0.079	0.026	0.048	0.060	0.091
	0.002	0.003	0.023	0.012	0.041	0.123	0.373	0.057	0.088	0.166	0.111
	0.003	0.002	0.014	0.022	0.122	0.041	0.064	0.356	0.183	0.079	0.113
	0.003	0.002	0.015	0.022	0.096	0.087	0.086	0.210	0.288	0.077	0.115
	0.002	0.003	0.023	0.013	0.088	0.099	0.222	0.079	0.086	0.272	0.112
	0.014	0.014	0.027	0.027	0.050	0.051	0.044	0.042	0.036	0.035	0.661
Prediction											

- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
 - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep Learning Tech.)**

Performance with different PID scenarios



Benchmark analyses using Jet origin ID



Improved by ~3 times

Improved by 1-2 orders of magnitudes

Presumably... firstly quantified

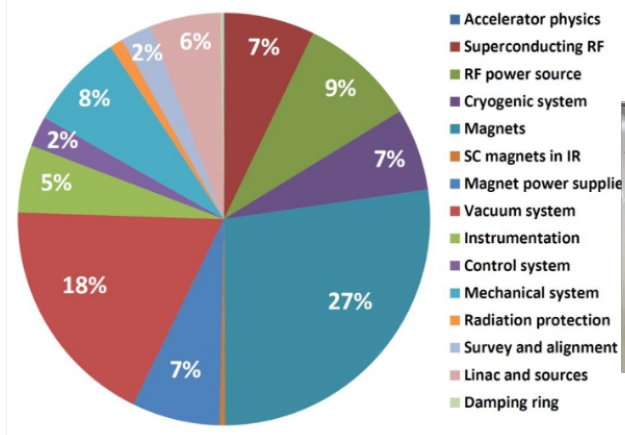
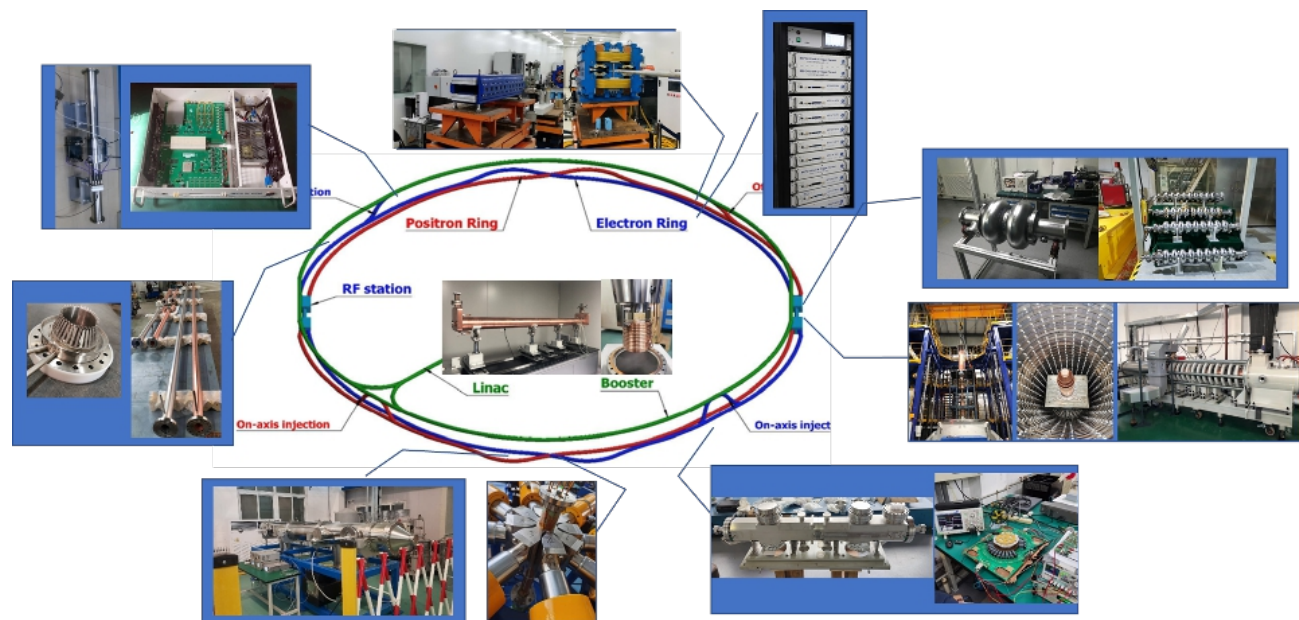
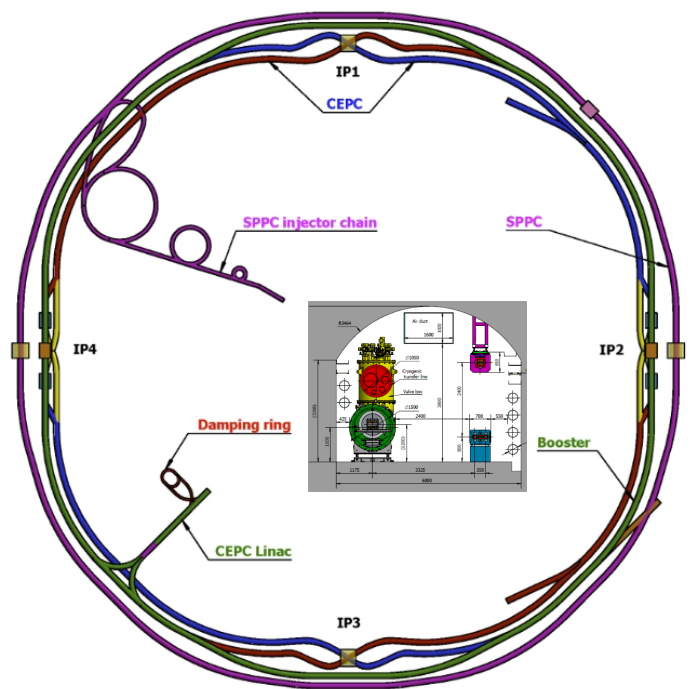
For $H \rightarrow b\bar{b}, c\bar{c}, g\bar{g}$: results in 20 – 40% improvement in relative accuracies (preliminary)...

TABLE I: Summary of background events of $H \rightarrow b\bar{b}/c\bar{c}/g\bar{g}$, Z , and W prior to flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL. Expectations are derived based on the background-only hypothesis.

	Bkg. (10^3)			Upper limit (10^{-3})					
	H	Z	W	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	sb	db	uc
$\nu\bar{\nu}H$	151	20	2.1	0.81	0.95	0.99	0.26	0.27	0.46
$\mu^+\mu^-H$	50	25	0	2.6	3.0	3.2	0.5	0.6	1.0
e^+e^-H	26	16	0	4.1	4.6	4.8	0.7	0.9	1.6
Comb.	-	-	-	0.75	0.91	0.95	0.22	0.23	0.39

- [28] J. Duarte-Campderros, G. Perez, M. Schlaffer, and A. Soffer. Probing the Higgs–strange-quark coupling at e^+e^- colliders using light-jet flavor tagging. *Phys. Rev. D*, 101(11):115005, 2020.
- [50] Alexander Albert et al. Strange quark as a probe for new physics in the Higgs sector. In *Snowmass 2021*, 3 2022.
- [59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.
- [60] Jorge De Blas, Gauthier Durieux, Christophe Grojean, Jiayin Gu, and Ayan Paul. On the future of Higgs, electroweak and diboson measurements at lepton colliders. *JHEP*, 12:117, 2019.

CEPC - Accelerator at 2023



650MHz SRF cavity



High efficiency klystron



Weak field dipole



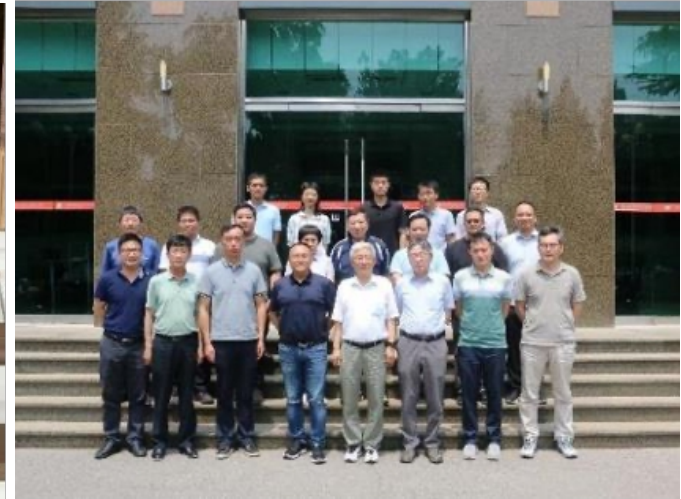
Reviews on Accelerator TDR, etc



Tech. Review June 2023



Cost. Review Sep 2023



Dom. Civil. Engineering Review



IAC endorsement Oct 2023

“After a site has been selected, the construction of CEPC could start in 2027/2028. The committee endorses this plan.”

Invite you to read the latest version of: CEPC TDR draft

This version is almost converged to the final one, but we will make the necessary adjustments and polishing later.

Sincerely inquire if you would **be willing to sign the TDR authorship**. If you agree to sign, please **fill in your information in TDR Authorship Collection page**.

We will also appreciate if you could kindly help to **invite people from your institutes or collaboration group to sign**.

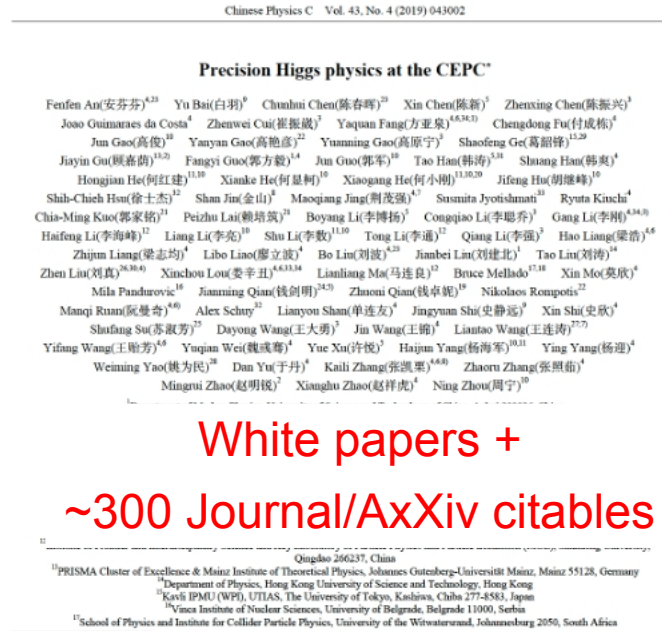
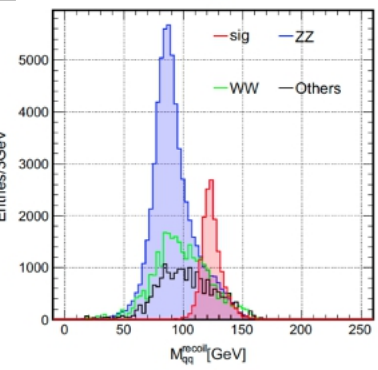
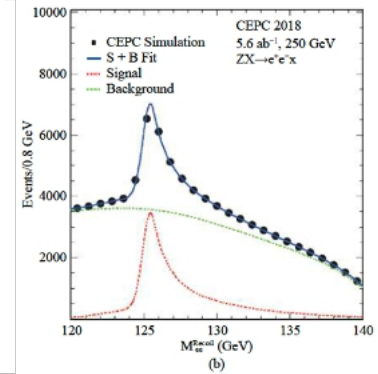
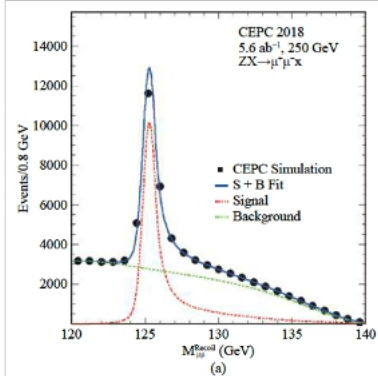
Your continuous support is essential

Summary

- Electron Positron Higgs factories: gigantic leap from LHC & current knowledge boundary
- Physics studies: science reach iterates with detector design/optimization studies
 - Community activated, many new ideas/results
 - International communication/collaboration is essential
 - CEPC Physics White papers in progressing
- Flavor Physics at Tera-Z: strong comparative advantages, access NP of 10 TeV+
 - Accesses to Un-seen, orders of magnitudes improvements, multiple center of mass energies...
- Extremely rich physics program results in stringent requirements on the detector performance, to be addressed
 - CEPC: Significant efforts towards the RDR (reference detector design TDR)
- New tools, especially AI, significantly alter the physics study/detector design
- 11 years of endeavor: Technologically ready to construct CEPC (TDR)
- Given the science merit of electron positron Higgs factories, we hope at least one of those facilities will be constructed soon

Backup

Physics study: 2023



White papers +
~300 Journal/AxXiv citables

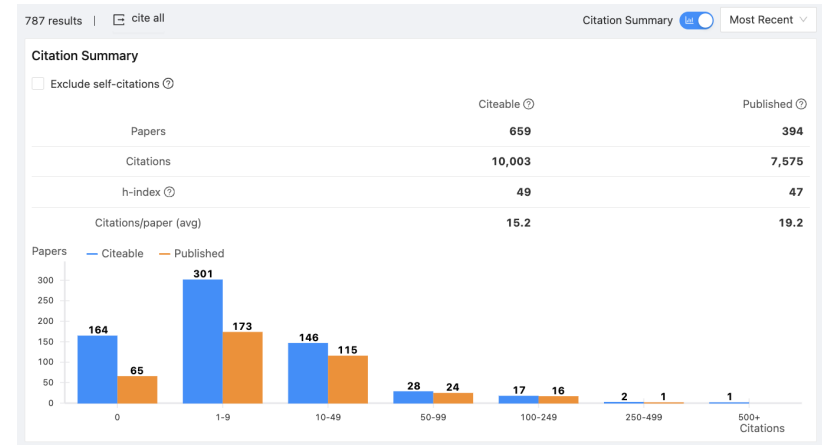


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab⁻¹. The HL-LHC projections of 3000 fb⁻¹ data are used for comparison. [2]

Observable	Higgs		W, Z and top		
	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \rightarrow bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \rightarrow cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \rightarrow gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \rightarrow WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \rightarrow ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \rightarrow \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \rightarrow \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \rightarrow \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \rightarrow Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
$B_{l\mu\mu}(H \rightarrow inv.)$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

Scientific Significance quantified by CEPC physics studies, via full simulation/phenomenology studies:

- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- ...

Higgs benchmark analyses

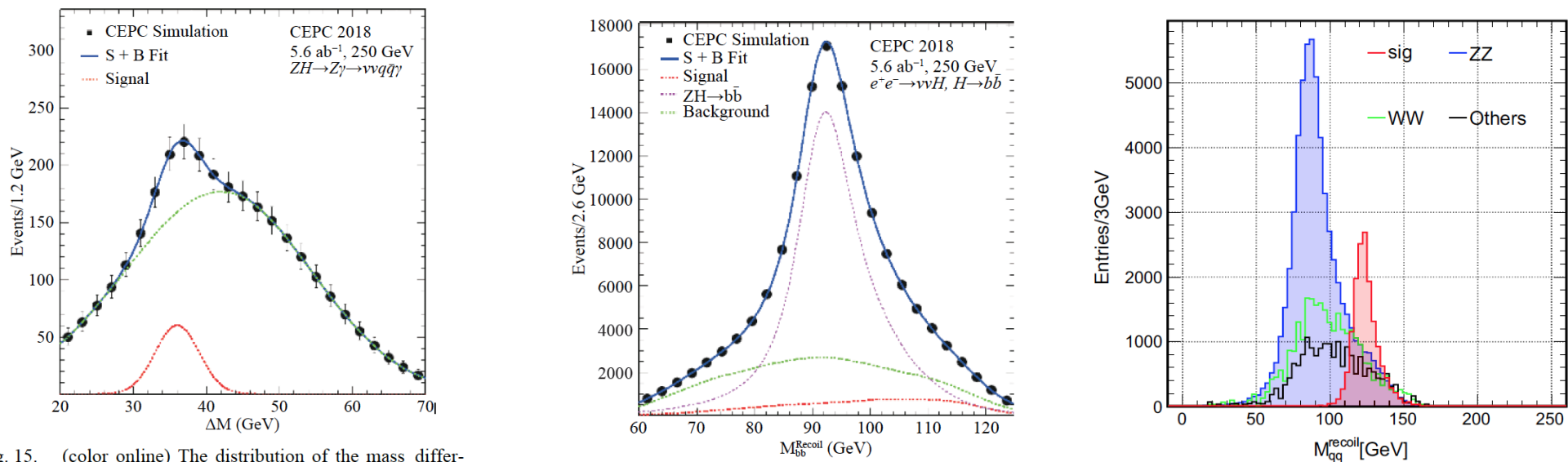
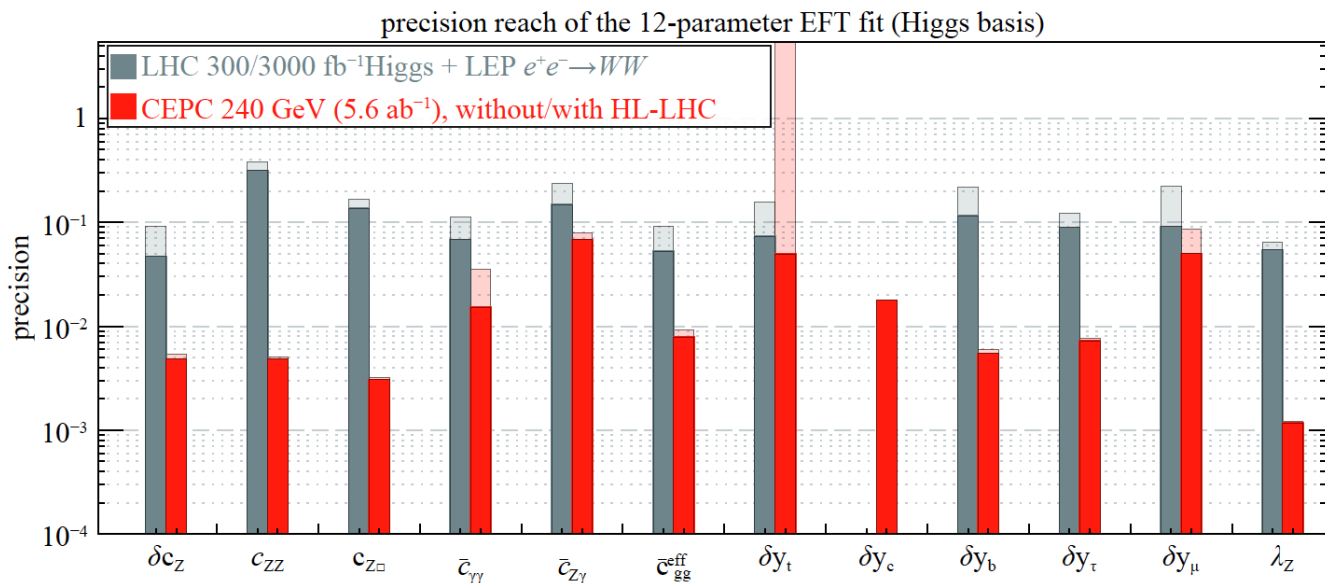
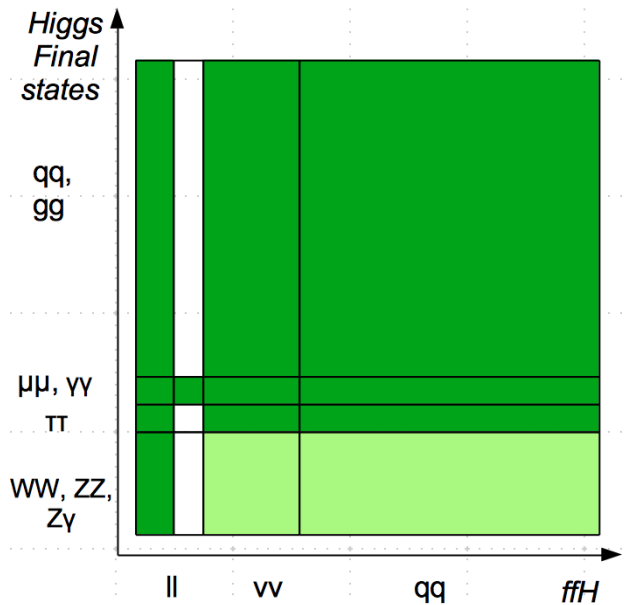
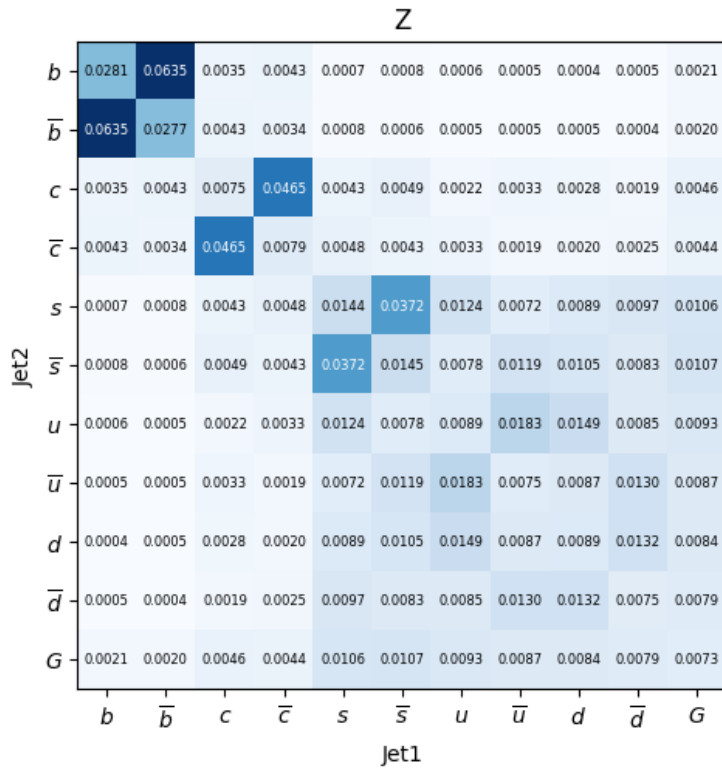


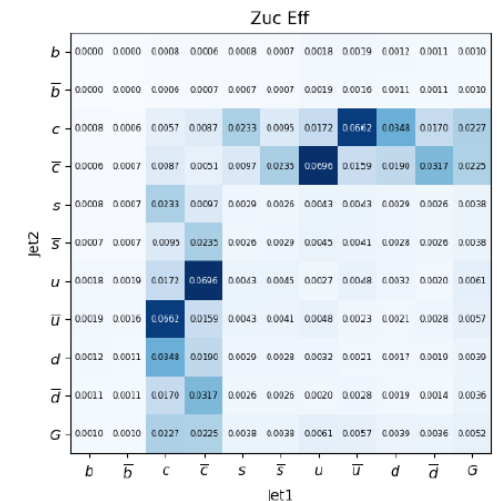
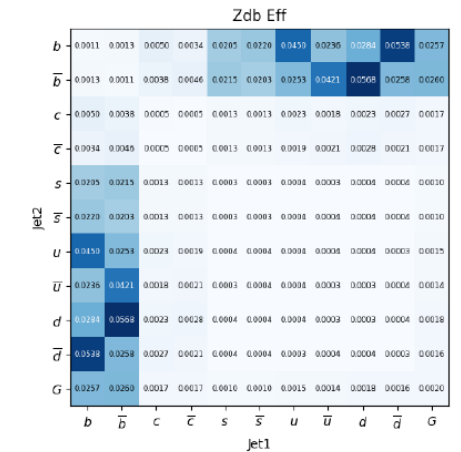
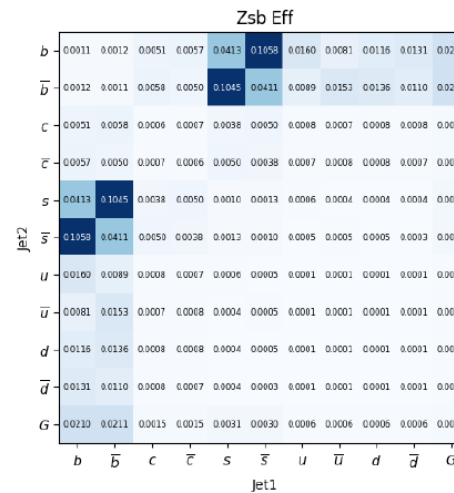
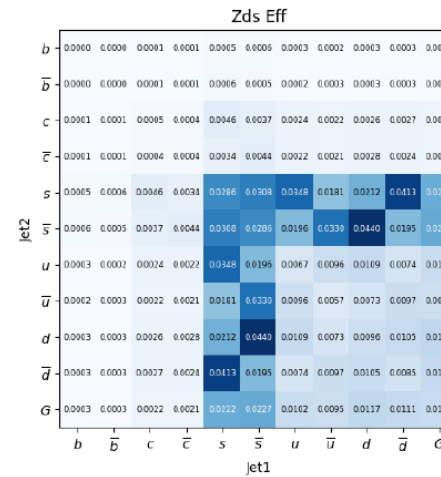
Fig. 15. (color online) The distribution of the mass differ-



Applied to Z FCNC (Preliminary)



	SM Br	95% Upper limit on Br (statistical only)
Z->bs	8.9E-8	2.3e-07
Z->bd	3.8E-9	2.5e-07
Z->cu	2.7E-20	6.3e-07
Z->sd	-	1.3e-06



- @ Tera Z using template fit
- **Calibration & Systematic control is critical**

Jet origin id: 11 categories

- vvH sample, with Higgs decays into different species of colored particle: 5 quark, 5 antiquark & gluon

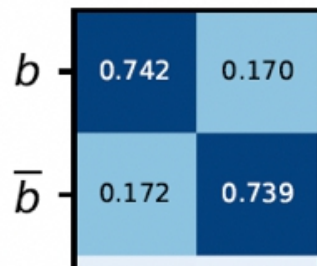
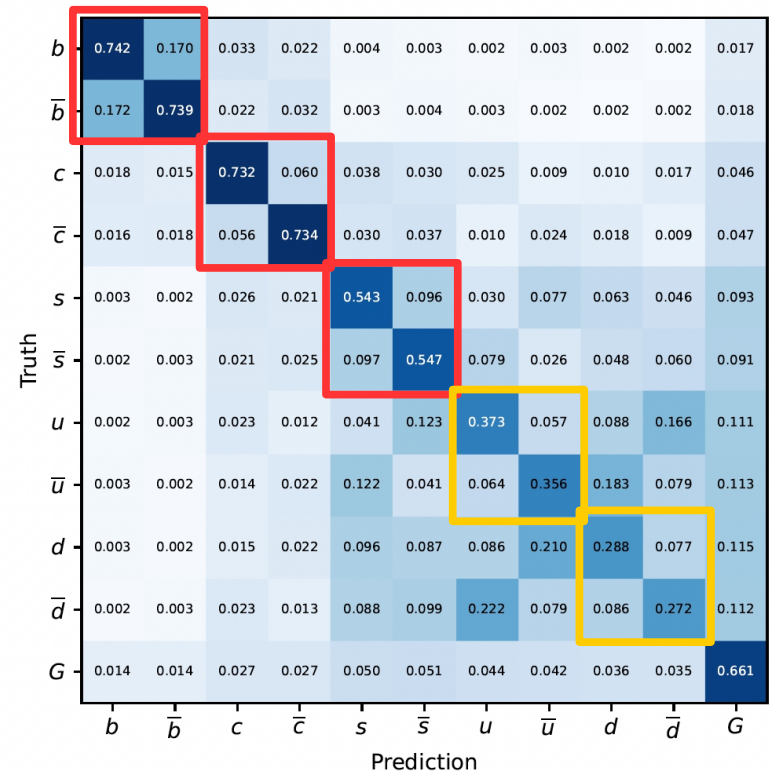
- **1 Million** of each type
- **60/20/20%** for training, validating, and testing, result corresponding to testing sample

- Pid: ideal Pid – three scenarios

- Lepton identification
- + Charged hadron identification
- + Neutral Kaons identification

- Patterns:

- ~ Diagonal at quark sector...
- $P(g \rightarrow q) < P(q \rightarrow g)$...
- Light jet id...



$$\text{Eff} = (0.74 + 0.17 + 0.74 + 0.17)/2 = 0.91$$

$$\text{Charge flip rate} = 0.17/0.91 = 0.19$$

A lot to scan!!

- A lot to be understood...
 - V.S. Scaling of Jet energy, Polar angle/eta,
 - V.S. Collision environment: beam background, # PU
 - V.S. Detector geometry: VTX configuration, acceptance, etc
 - V.S. Jet Clustering algorithm, interactions with jet finding & Color Singlet identification
 - V.S. Different hadronization & fragmentation modes...
 -
 - V.S. algorithm architecture
 - V.S. training & implementation procedure...