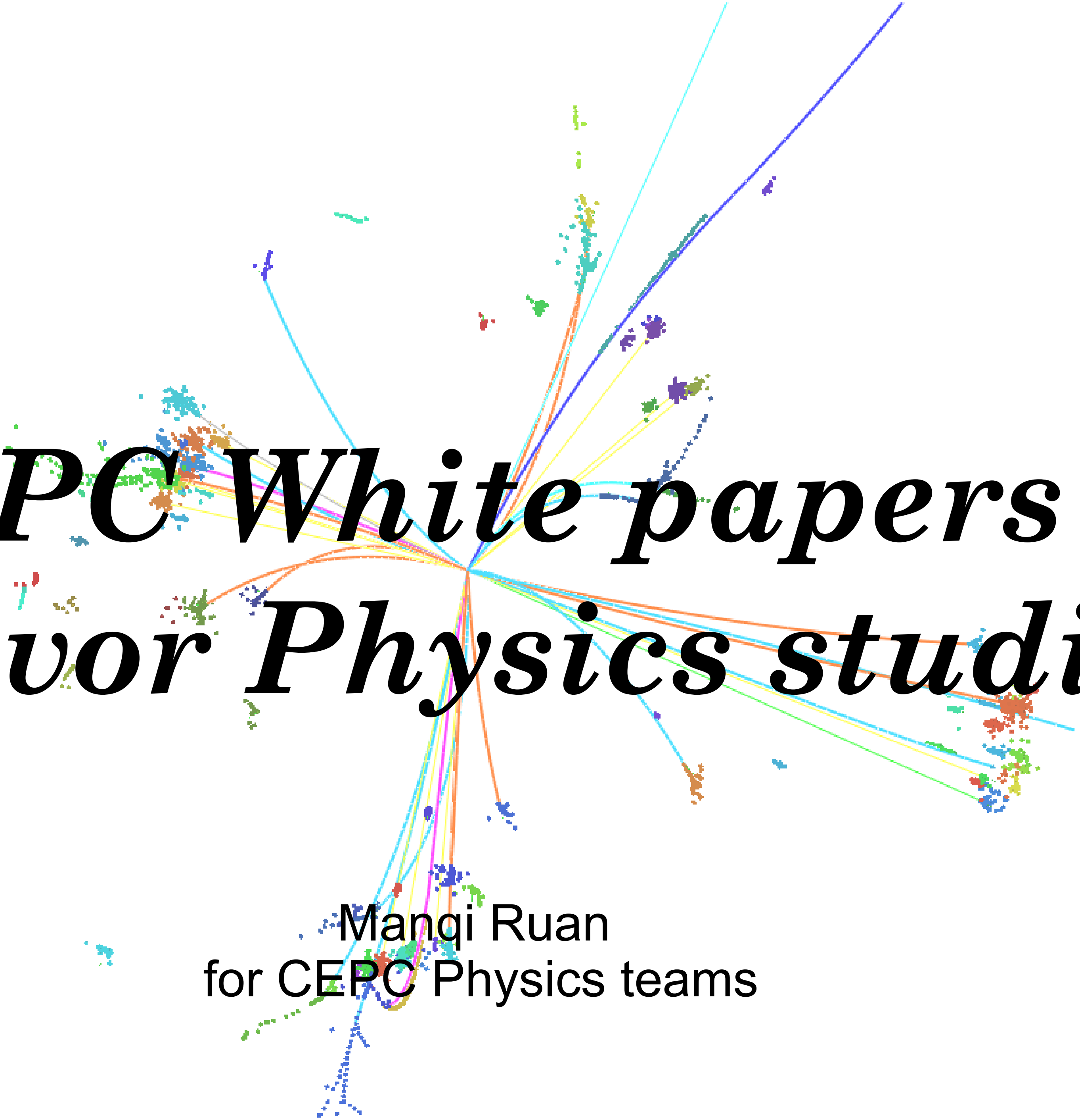
CEPC White papers & Flavor Physics studies

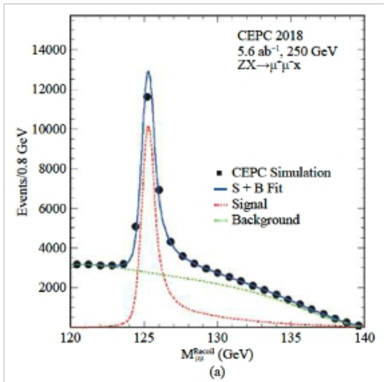


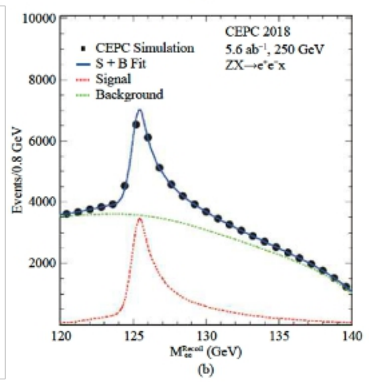
Manqi Ruan
for CEPC Physics teams

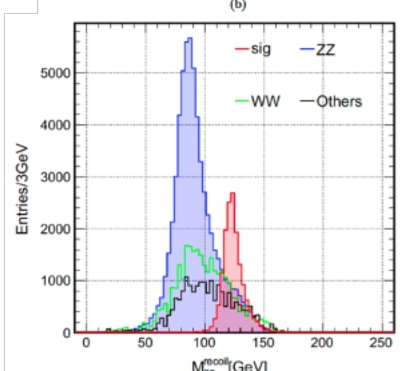
Objectives

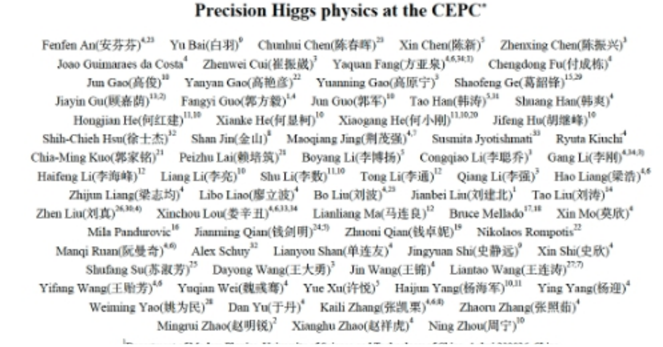
- To understand the physics landscape & science merits
  - Identify benchmarks & quantify reaches
  - Quantify the discovery power, especially NP Smoking guns
  - Added values compared to existing facilities
- To maximize the physics output
  - To iterate with detector/facility Design & optimization
  - To synergies with X-frontier facilities
- To stimulate new ideas/methods
- To actively participate international collaboration & participations
- To be in pace with the project application
- To communicate efficiently with general public & decision maker

Physics study: 2023








Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

White papers +

~300 Journal/AxXiv citables

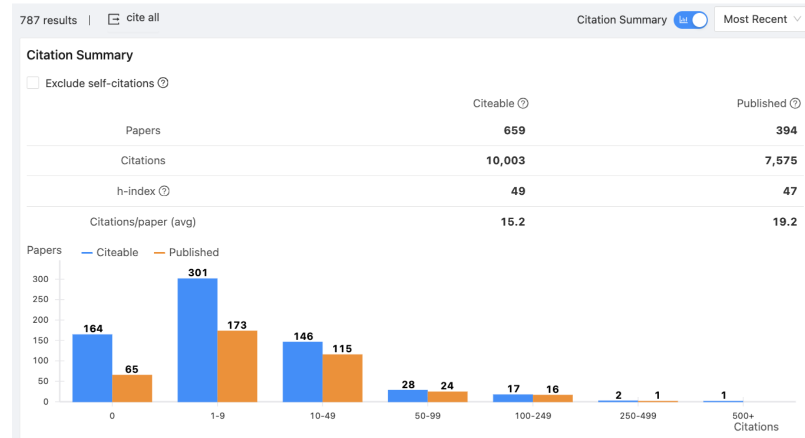


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

Higgs			W, Z and top		
Observable	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
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
$Bupper(H \to inv.)$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

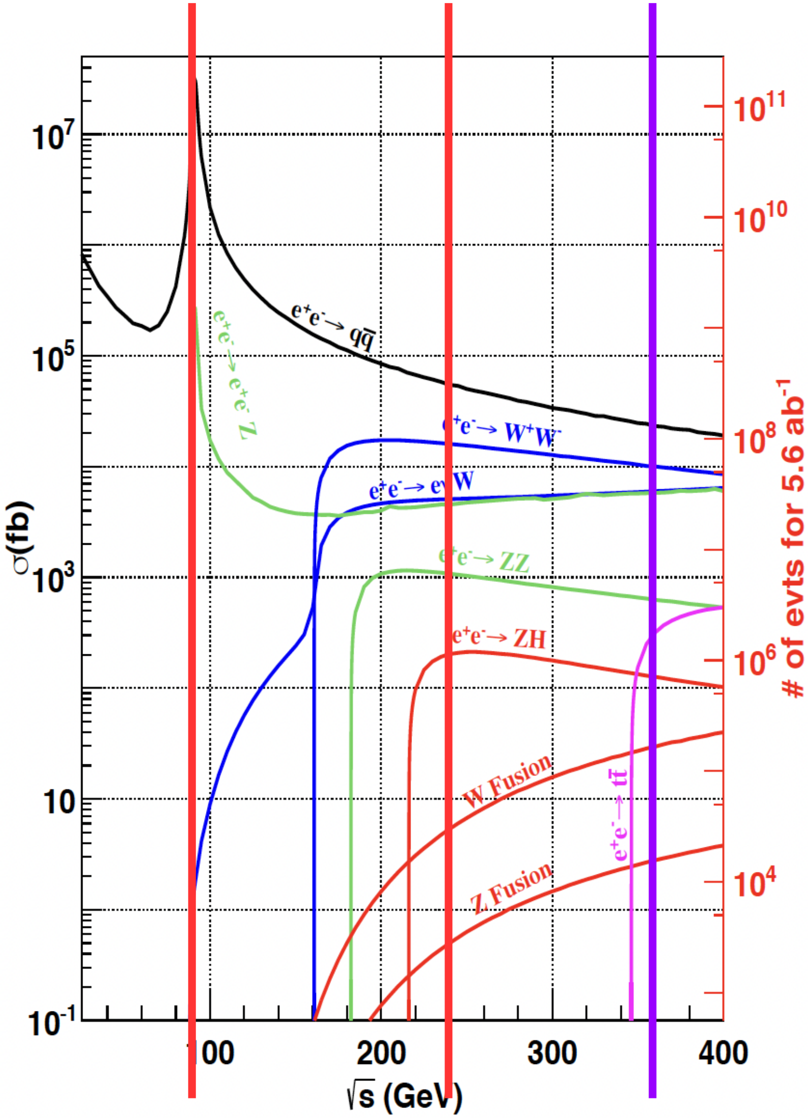
Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

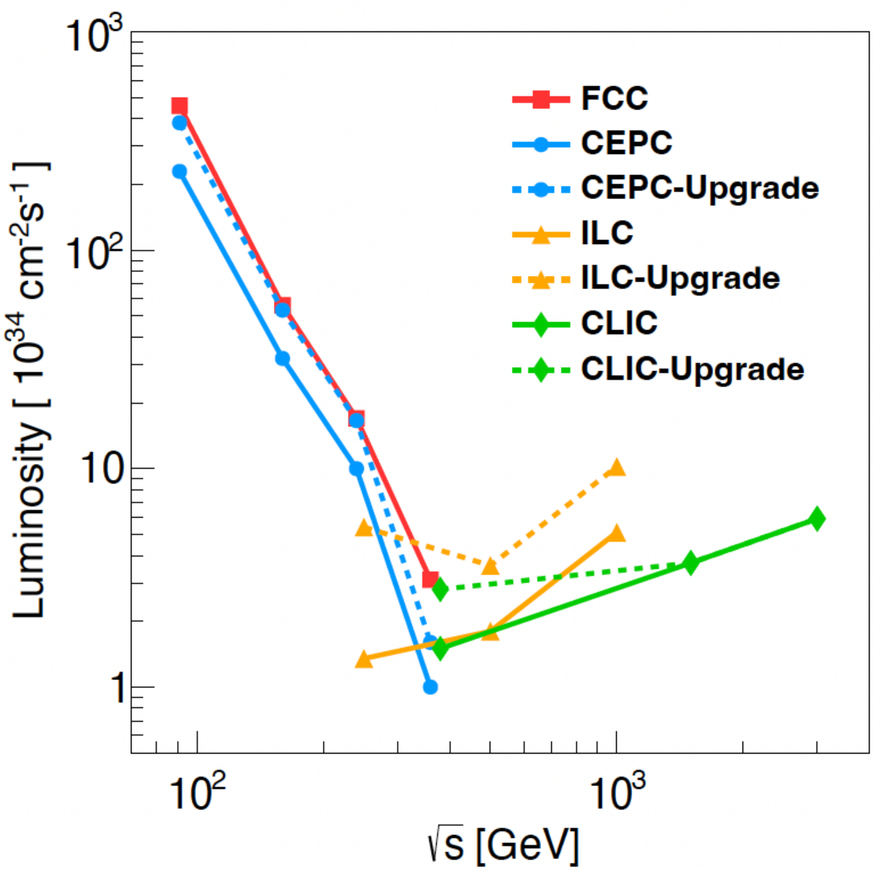
- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- …

White papers

- Higgs: published in 2019, updated in 2021 Snowmass WP
- Flavor:
  - Main editors: Lingfeng Li (Brown U), TaoLiu (HKUST), Fengkun Guo (ITP), Lorenzo Calibbi (Tianjing U), Qiangxin Li (CCNU), Qin Qin (Huazhong S&T), etc)
  - Phase-I: submit to ArXiv in a few weeks
  - Phase-II: to enhance the measurement with tautau events and CKM measurements
- EW: draft for internal review expected at beginning of 2024 – released at middle 2024
  - Main editors: Jiayin Gu (Fudan U), Zhijun Liang (IHEP)
- NP: same as EW White paper
  - Main editors: Jia Liu (PKU), Liantao Wang(Chicago U), Zhen Liu (Minnesota U), Xuai Zhuang (IHEP), Yu Gao (IHEP), etc
- QCD:
  - Main editors: Huaxing Zhu (PKU), Meng Xiao (ZJU), Jun Gao (SJTU), Zhao Li (IHEP), etc
  - Very rich physics: strong coupling constant measurement + Form Factor + Hadron Fragmentation + QCD Phase transition + accurate calculation + interplay to other measurements especially Flavor & Higgs...

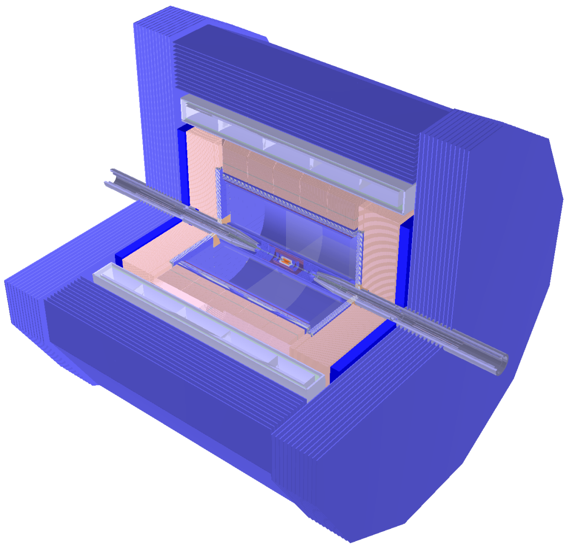
Yields ~ Xsec * Lumi * Time

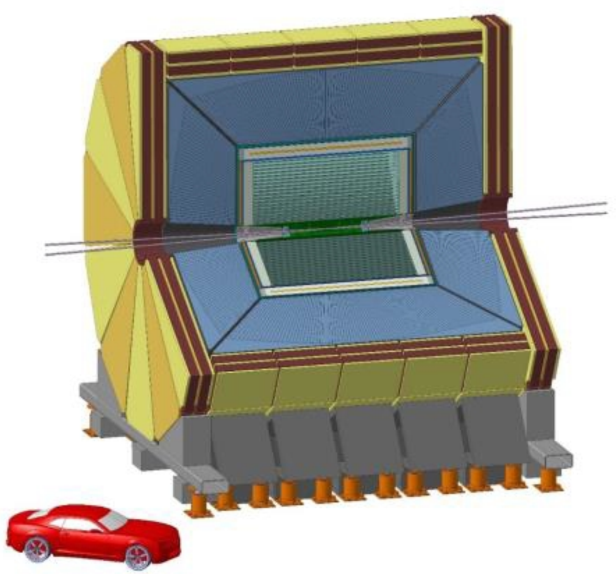


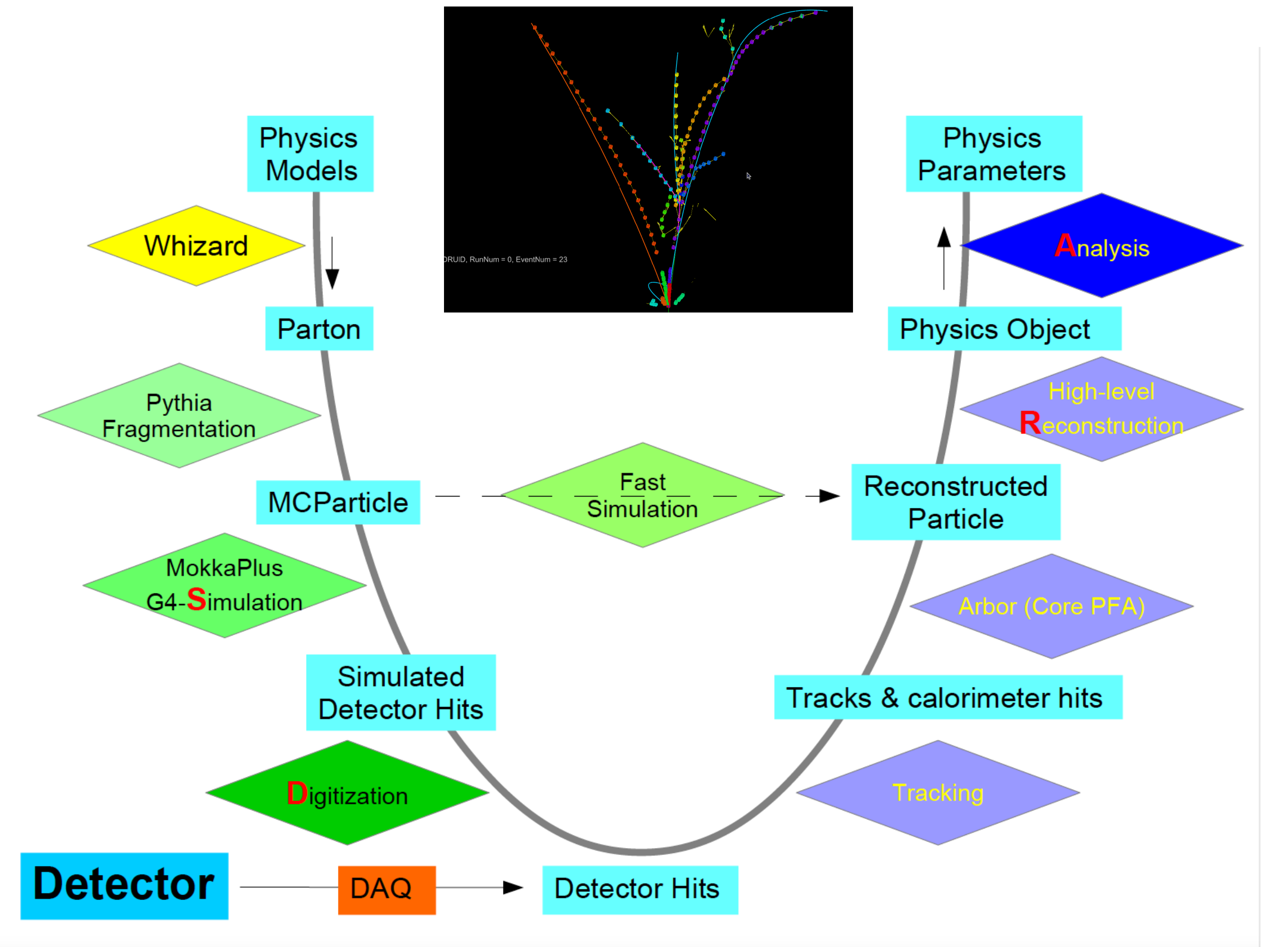


- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

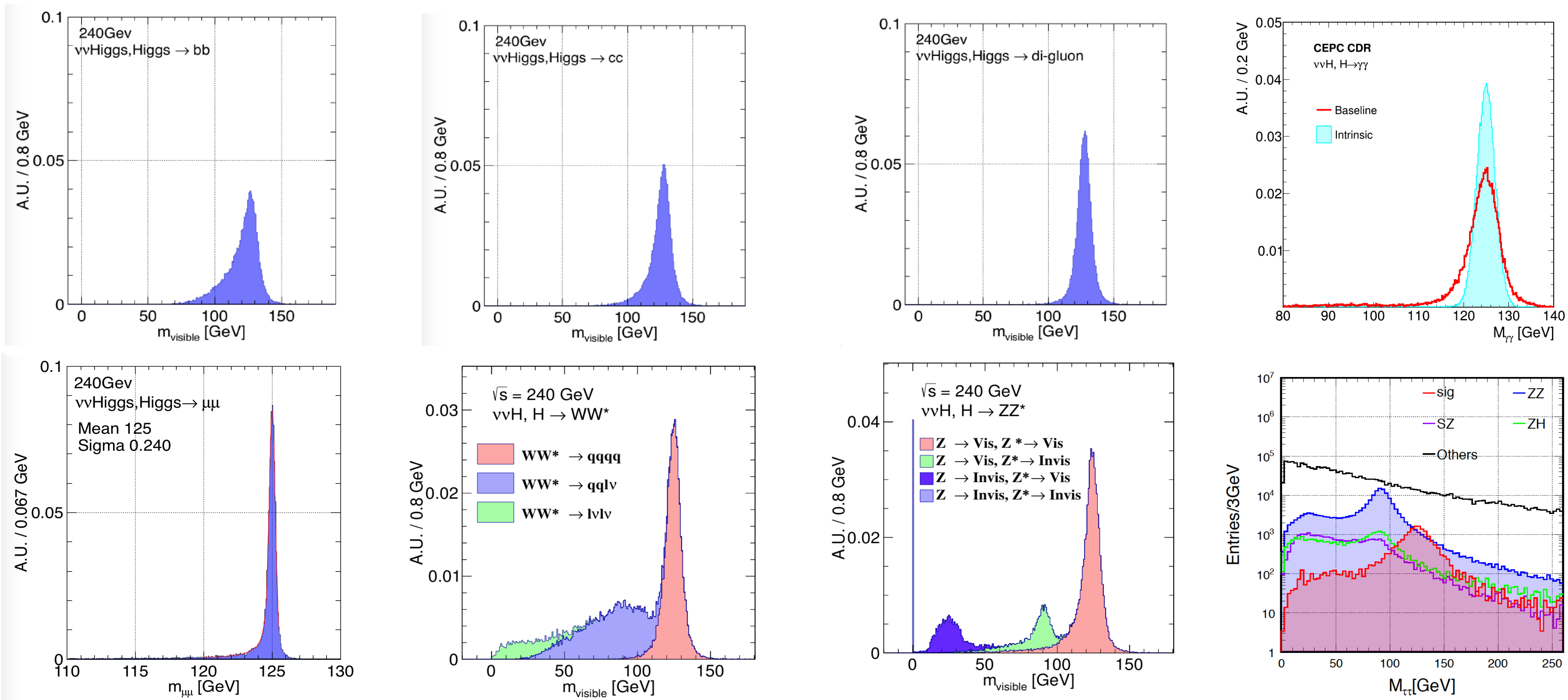
Detector & Software







Reconstructed Higgs Signatures



Clear Higgs Signature in all SM decay modes

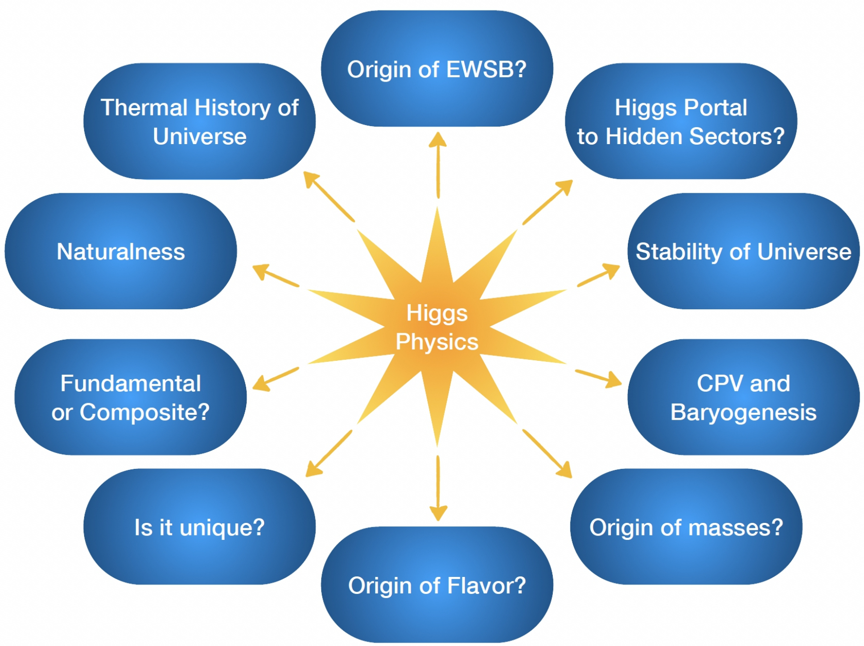
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

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

Higgs white paper

Mystery Higgs sector

Snowmass 2021 US Community Study
on the Future of Particle Physics



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Precision Higgs physics at the CEPC*

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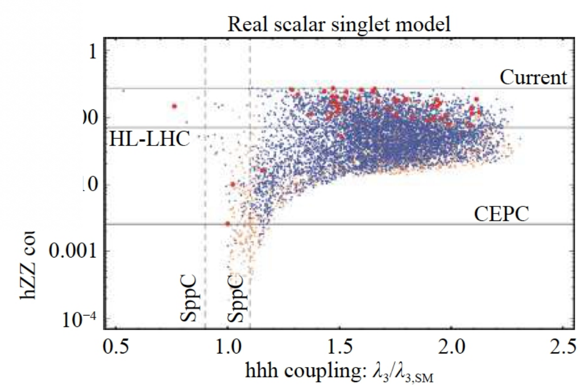

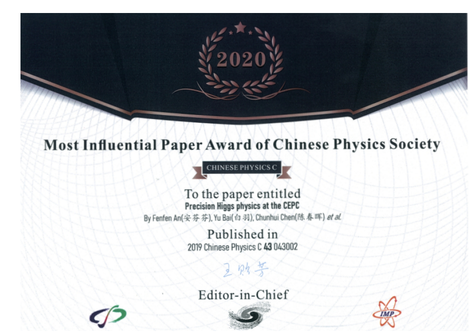

Snowmass White Paper

The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

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ABSTRACT

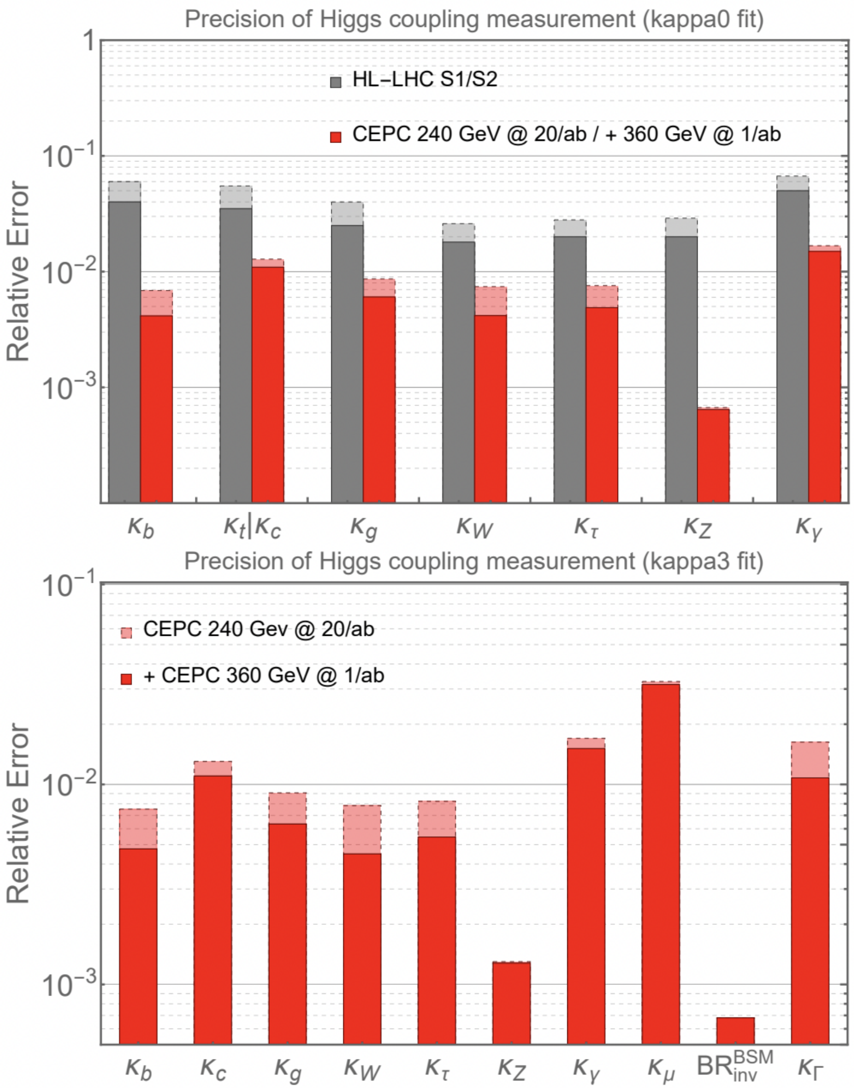
The Circular Electron Positron Collider (CEPC) is a large-scale collider facility that can serve as a factory of the Higgs, Z, and W bosons and is upgradable to run at the $t\bar{t}$ threshold. This document describes the latest CEPC nominal operation scenario and particle yields and updates the corresponding physics potential. A new detector concept is also briefly described. This submission is for consideration by the Snowmass process.

CONTENTS

- Summarize ~ 20 citables for CEPC Snowmass studies

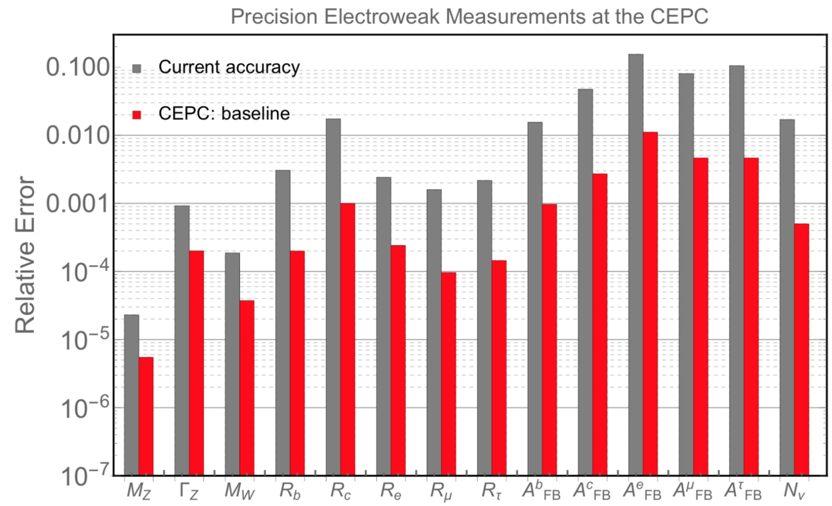
Physics reach via Higgs at CEPC

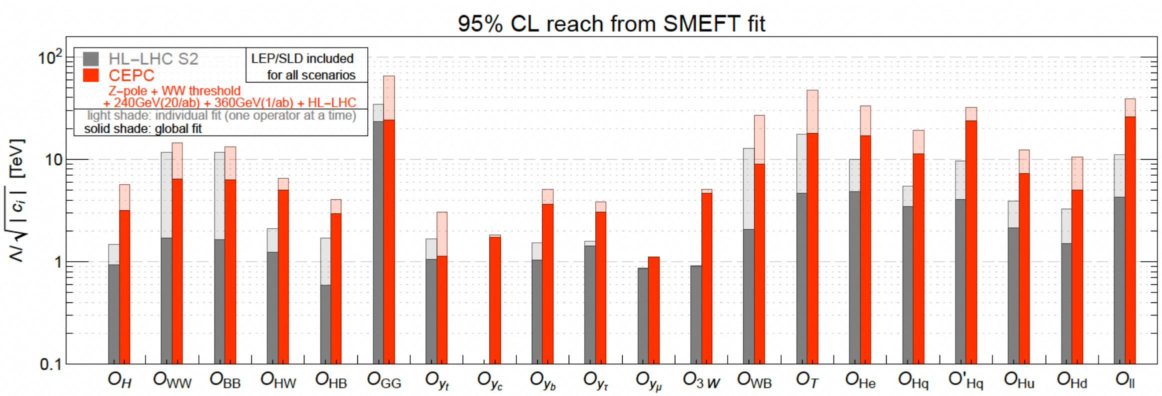
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**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

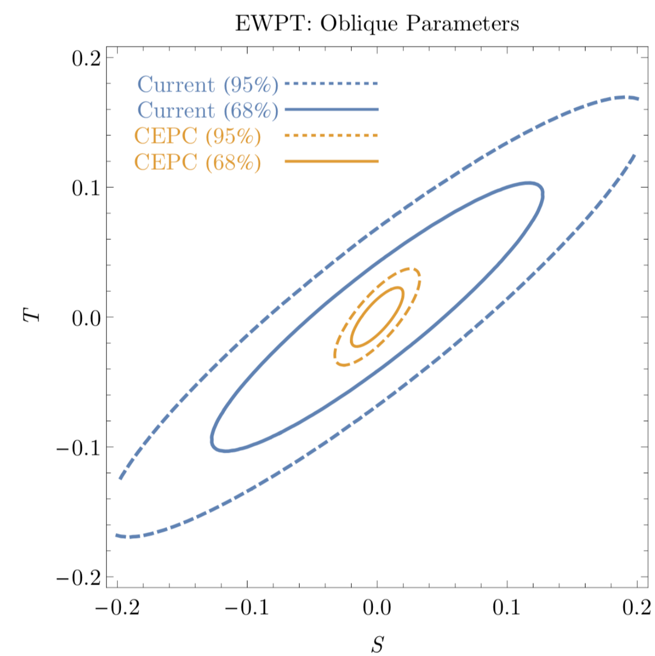


EW measurements & SMEFT

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)	WW 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 ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	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	lumiosity
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







New Physics White paper

5

The BSM Physics potential of the CEPC

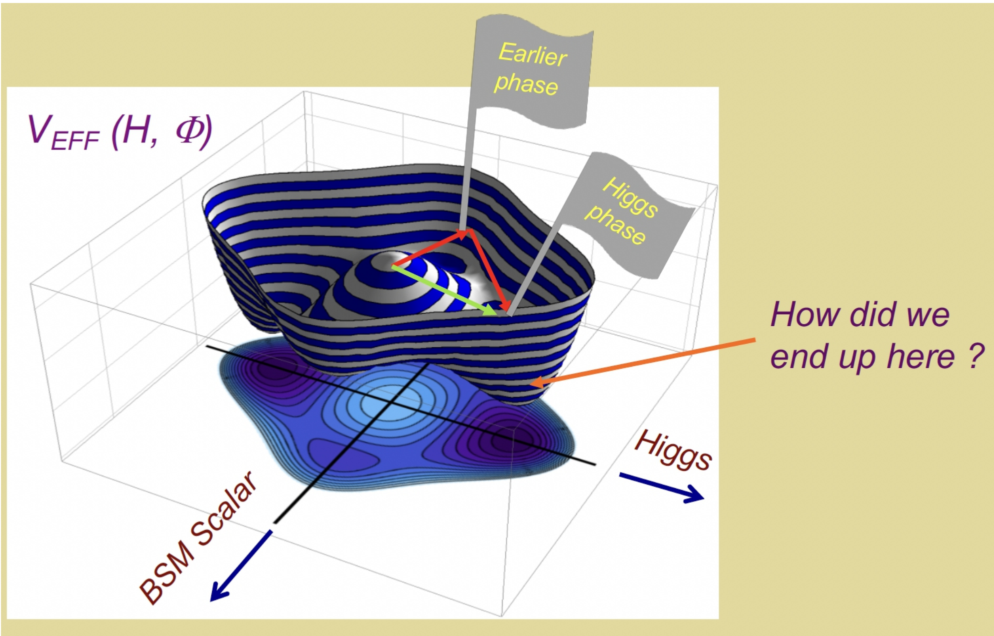
Prepared for the CEPC BSM white paper

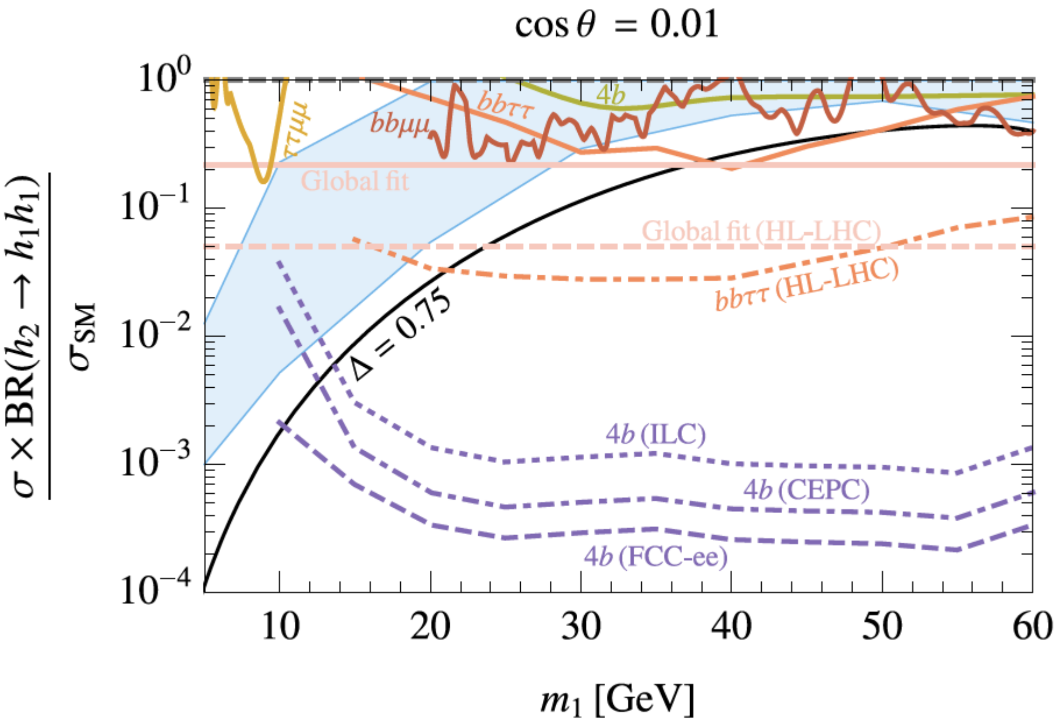
CEPC BSM Physics Study Group

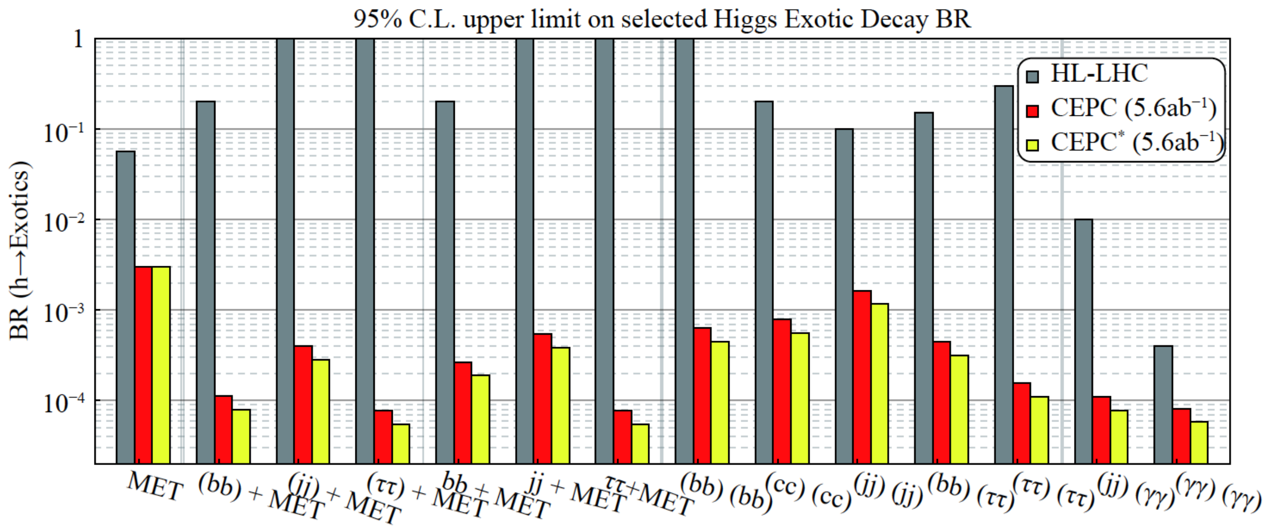
CONTRIBUTORS (TO BE UPDATED)

CONTENTS

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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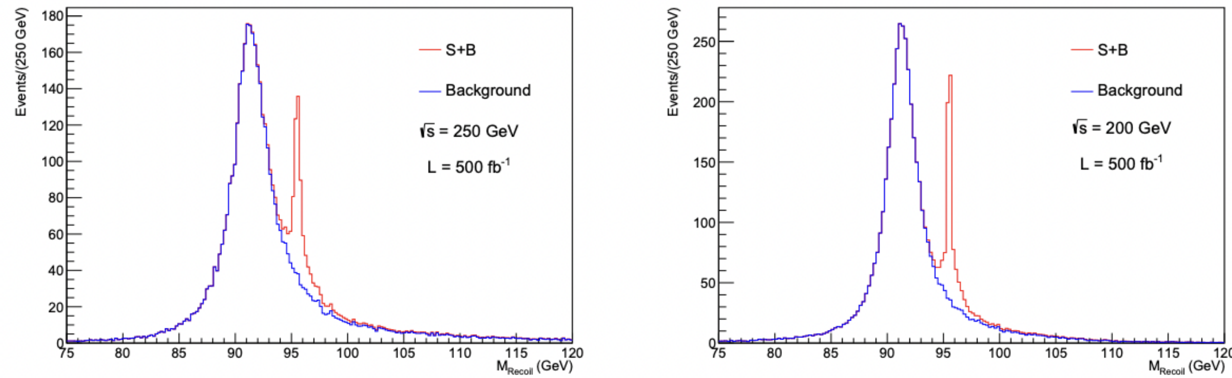


Figure 1. Recoil mass distribution for simulated $e^+e^- \to HZ \to H\mu^+\mu^-$ events with $m_S = 95,5$ GeV and all relevant background events after a pre-selection described in this section for (a) $\sqrt{S} = 250$ GeV and (b) $\sqrt{S} = 200$ GeV both at integrated luminosity $\mathscr{L} = 500$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

- *Assume signal Xsec ~ 20 fb*

...Preliminary...

- *CEPC Higgs operation: ~ 6 fb^{-1}/day ~ 2 ab^{-1}/year*
- *Turn-key discovery*

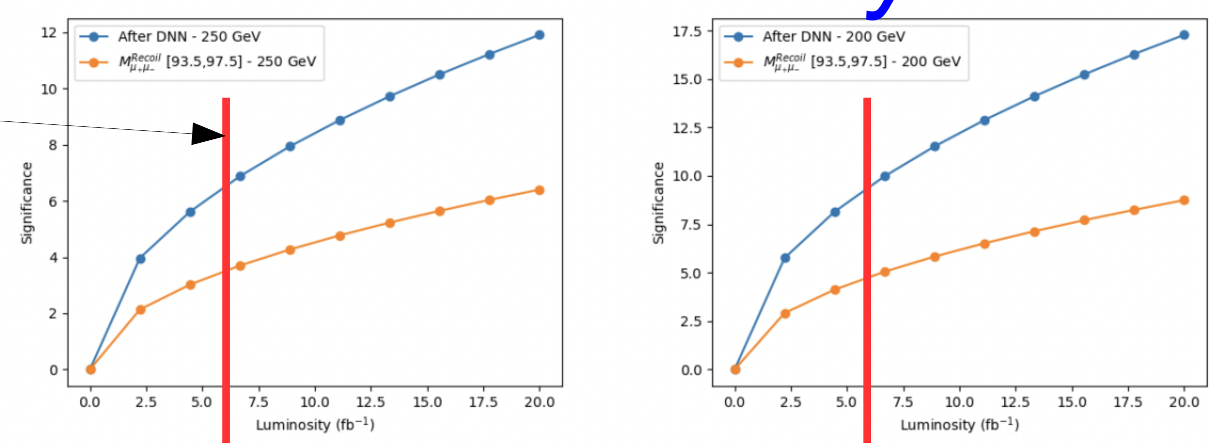


Figure 5. The signal significance as a function of Luminosity ($\mathscr{L}$) for (left) $\sqrt{s} = 250$ GeV before (Orange) and after DNN (Blue), (right) $\sqrt{s} = 200$ GeV before (Orange) and after DNN (Blue) respectively.

24/11/2023

Flavor Physics White paper

Flavor Physics at CEPC: a General Perspective

Contents

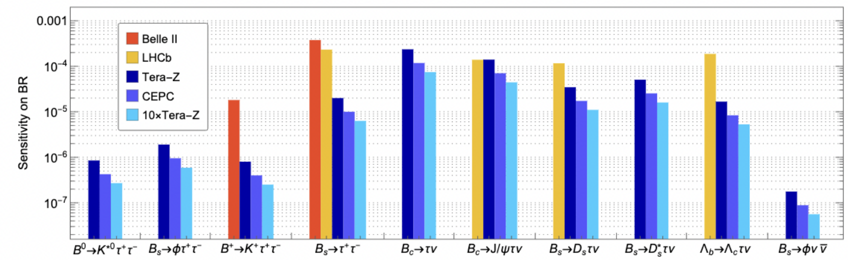


Figure 18: Projected sensitivities of measuring the $b\to s\tau\tau$ [70], $b\to s\nu\bar{\nu}$ [34] and $b\to c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities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

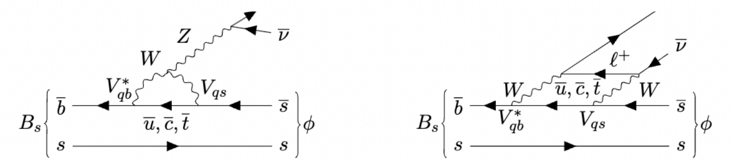


Figure 21: Illustrative Feynman diagrams for the $B_s\to\phi\nu\bar{\nu}$ transitions in the SM. **LEFT**: EW penguin diagram. **RIGHT**: EW box diagram.

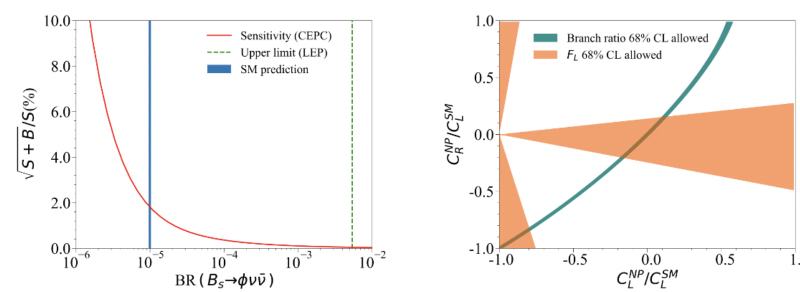


Figure 22: **LEFT**: Relative precision for measuring the signal strength of $B_s\to\phi\nu\bar{\nu}$ at Tera-Z, as a function of its BR. **RIGHT**: Constraints on the LEFT coefficients $C_L^{\rm NP}\equiv C_L-C_L^{\rm SM}$ and C_R with the measurements of the overall $B_s\to\phi\nu\bar{\nu}$ decay rate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

~ 20+ benchmarks + ... Access to NP at 10 TeV or higher

~ 40 benchmarks

No.	Process	$\sqrt{s}$ (GeV)	Parameter of interest	Observable	Current precision	CEPC Precision	Estimation method	Key detector performance	Relevant Section
1	$Z \to \mu\mu a$	91.2	-	BR upper limit	-	$\lesssim 3 \times 10^{-11}$ [251]	Fast simulation	Tracker Missing energy	12
2	$B \to K\hat{\pi}(\to \mu\mu)$	91.2	-	BR upper limit	-	$\lesssim 10^{-10}$ [261]	Fast simulation	Tracker Vertex	12
3	$Z \to \pi^+\pi^-$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-10})$ [109]	Guesstimate	Tracker PID	9
4	$Z \to \pi^+\pi^-\pi^0$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
5	$b \to s\tau^+\tau^-$	91.2	-	BR upper limit	-	$B^0 \to K^{*0}\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \to \phi\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B^+ \to K^+\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \to \tau^+\tau^-$ $\mathcal{O}(10^{-5})$ [71]	Fast simulation	Tracker Vertex Jet origin ID	4
6	$Z \to \rho\gamma$	91.2	-	BR upper limit	$< 2.5 \times 10^{-5}$ [150]	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
7	$Z \to J/\psi\gamma$	91.2	-	BR upper limit	$< 1.4 \times 10^{-6}$ [150]	$10^{-9} - 10^{-10}$ [109]	Guesstimate	Tracker PID ECAL	9
8	$Z \to \tau\mu$ $Z \to \tau e$ $Z \to \mu e$	91.2	-	BR upper limit	$< 6.5 \times 10^{-6}$ $< 5.0 \times 10^{-6}$ $< 7.5 \times 10^{-7}$ [105–107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-9} [110]	Guesstimate	E_{beam} Tracker PID	6
9	$\tau \to \mu a$	91.2	-	BR upper limit	$\lesssim 7 \times 10^{-4}$ [259]	$\lesssim$ 3–5 $\times 10^{-6}$	Fast simulation	Tracker Missing energy	12
10	$\tau \to \mu\mu\mu$ $\tau \to eee$ $\tau \to e\mu\mu$ $\tau \to \mu ee$	91.2	-	BR upper limit	$< 2.1 \times 10^{-8}$ $< 2.7 \times 10^{-8}$ $< 2.7 \times 10^{-8}$ $< 1.8 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
11	$\tau \to \mu\gamma$ $\tau \to e\gamma$	91.2	-	BR upper limit	$< 4.4 \times 10^{-8}$ $< 3.3 \times 10^{-8}$ [150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID ECAL	8
12	$B_c \to \tau\nu$	91.2	$\lvert V_{cb}\rvert$	$\sigma(\mu)/\mu$	BR$\lesssim$ 30% [267]	$\mathcal{O}(1\%)$ [63]	Full simulation	Tracker Lepton ID Missing energy Jet origin ID	3
13	$B_s \to \phi\nu\bar{\nu}$	91.2	-	$\sigma(\mu)/\mu$	BR $< 5.4 \times 10^{-3}$ [150]	$\lesssim 2\%$ [35]	Full simulation	Tracker Vertex Missing energy PID	4
14		91.2		τ_τ (s) lifetime	$\pm 5 \times 10^{-16}$ [150]	$\pm 1 \times 10^{-18}$ [108]	Guesstimate	-	8
15		91.2		m_τ (MeV)	± 0.12 [150]	$\pm 0.004 \pm 0.1$ [108]	Guesstimate	-	8
16	$\tau \to \ell\nu\bar{\nu}$	91.2	-	BR	$\pm 4 \times 10^{-4}$ [150]	$\pm 3 \times 10^{-5}$ [108]	Guesstimate	Tracker Lepton ID Missing energy	8
17	$b \to c\ell\nu$	91.2	-	R_{H_c}	$R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ [268] $R_{\Lambda_c} = 0.242 \pm 0.076$ [269]	relative (stat. only) $R_{J/\psi} \lesssim 5\%$ $R_{D_s^{(*)}} \lesssim 0.4\%$ $R_{\Lambda_c} \sim 0.1\%$ [38]	Fast simulation	Tracker Vertex	3
18	$B_s \to J/\psi\phi$	91.2	ϕ_s (= $-2\beta_s$)	Γ_s, $\Delta\Gamma_s$	$\Gamma_s = 657.3 \pm 2.3$ ns^{-1} [150] $\Delta\Gamma_s = 65.7 \pm 4.3 \pm 3.7$ ns^{-1} [270] $\phi_s = -87 \pm 36 \pm 21$ mrad [270]	$\sigma(\Gamma_s) = 0.072$ ns^{-1} $\sigma(\Delta\Gamma_s) = 0.24$ ns^{-1} $\sigma(\phi_s) = 4.3$ mrad [45]	Full simulation	Tracker Vertex Lifetime resolution Jet origin ID	5
19	$B^0 \to \pi^0\pi^0$ $B^0 \to \pi^+\pi^-$ $B^+ \to \pi^+\pi^0$	91.2	α	BR, A_{CP}	$BR^{00} = (1.59 \pm 0.26) \times 10^{-6}$ (16%) $BR^{+0} = (5.5 \pm 0.4) \times 10^{-6}$ (7%) $BR^{+-} = (5.12 \pm 0.19) \times 10^{-6}$ (4%) $C_{CP}^{00} = -0.33 \pm 0.22$ $C_{CP}^{+-} = -0.314 \pm 0.030$ $S_{CP}^{+-} = -0.670 \pm 0.030$ [150]	$\sigma(BR)/BR^{00} = 0.45\%$ $\sigma(BR)/BR^{+0} = 0.19\%$ $\sigma(BR)/BR^{+-} = 0.18\%$ $\sigma(a_{CP}^{00}) = \pm$ (0.014–0.018) $\sigma(C_{CP}^{+-}) = \pm$ (0.004–0.005) $\sigma(S_{CP}^{+-}) = \pm$ (0.004–0.005) [31]	Fast simulation	ECAL Tracker Vertex Jet origin ID	5
20	$H \to sb, sd, db, uc$	240	-	BR upper limit	-	0.02%—0.1% [32]	Full simulation	Jet origin ID	10
21	$H \to ss, uu, dd$	240	-	BR upper limit	-	0.1% [32]	Full simulation	Jet origin ID	10
22	$e^+e^- \to t(\bar{t})j$	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
23	$WW \to \mu\nu qq$ $WW \to \tau(\to \mu\nu\nu)\nu qq$	240	$\lvert V_{cb}\rvert$	$\lvert V_{cb}\rvert$	$(38.9 \pm 0.53) \times 10^{-3}$ relative $\sim 1.4\%$ [9]	$\lesssim 0.5\%$ [194]	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

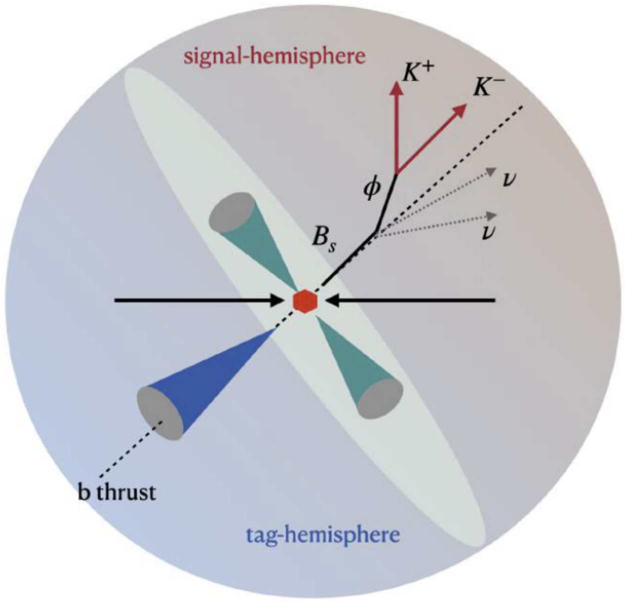
Accesses to the Non-Seen

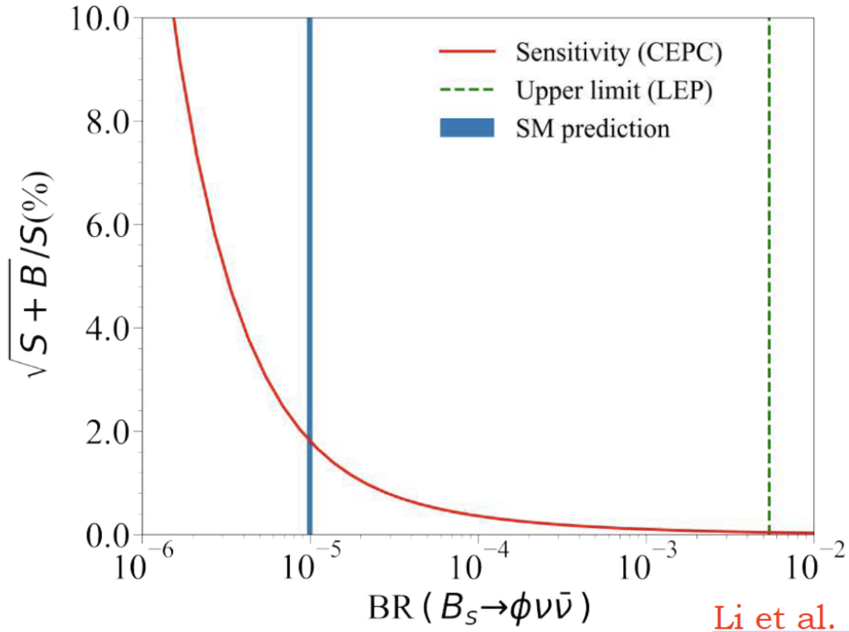
$b \to s\nu\nu$

Li et al. '22

	Current Limit	Detector	SM Prediction
$\mathrm{BR}(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$ [4]	BABAR	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$ [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 $B_s \to \phi\nu\nu$ with a percent level precision:



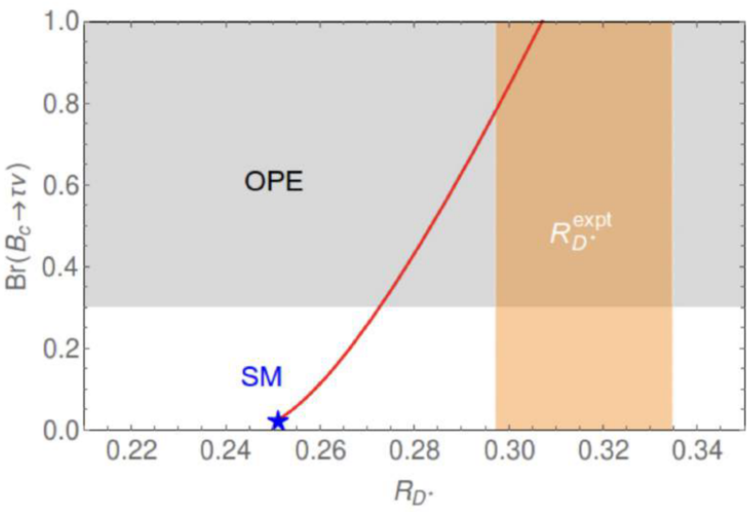


Li et al. '22

$B_c \to \tau\nu$

- Key observable to test the LFU anomalies in charged-current B decays

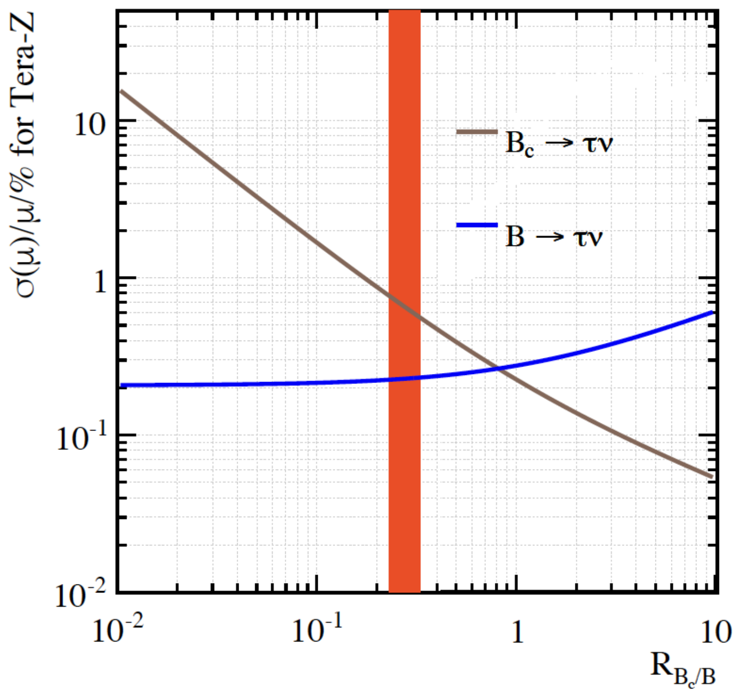
Alonso et al. '16



- SM prediction for the BR ~ 2%, beyond the reach of LHCb

- Tera Z could measure with percent level accuracy (thus providing also a percent level accurate measurement of V_{cb})

Zheng et al. '20



Summary of rare B decays

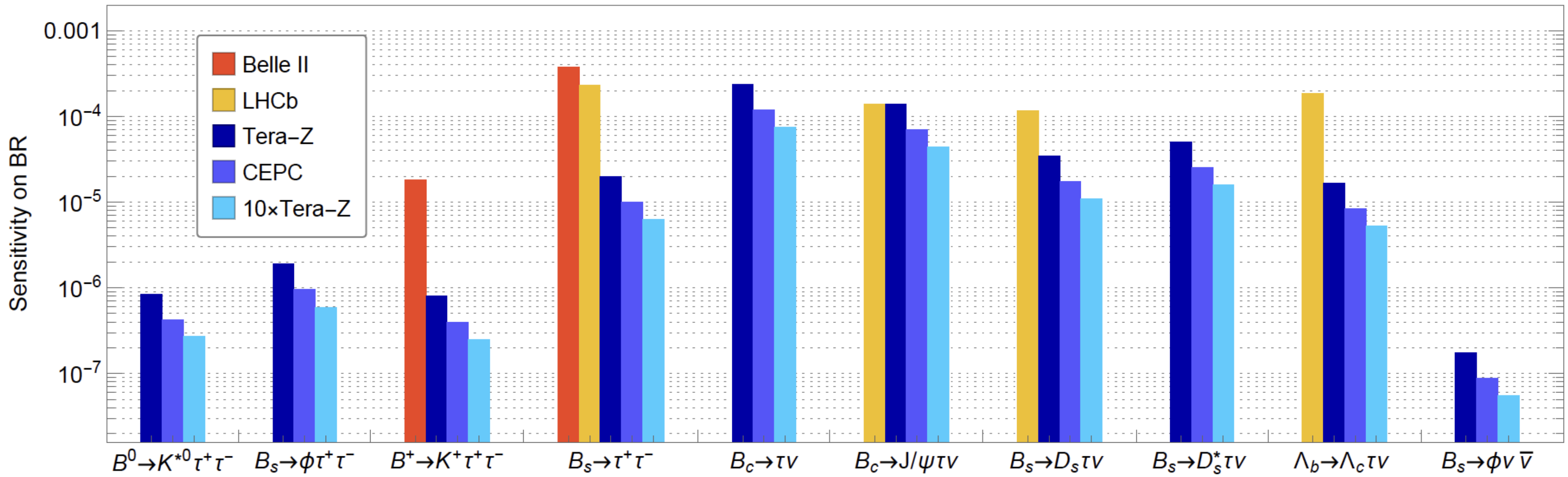


Figure 17: Projected sensitivities of measuring the $b \to s\tau\tau$ [71], $b \to s\nu\bar{\nu}$ [35] and $b \to c\tau\nu$ [37, 63] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 72] have also been provided as a reference. Note, the LHCb sensitivities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

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

Orders of magnitude improvements

Summary of the tau and Z prospects

Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^\pm \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited
$\mathrm{BR}(Z \to \tau\mu)$	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited
$\mathrm{BR}(Z \to \pi^+\pi^-)$			$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\mathrm{track}})$ limited, good PID
$\mathrm{BR}(Z \to \pi^+\pi^-\pi^0)$			$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$\mathrm{BR}(Z \to J/\psi\gamma)$	$< 1.4 \times 10^{-6}$		$10^{-9} - 10^{-10}$	$\ell\ell\gamma$+$\tau\tau\gamma$ bkg
$\mathrm{BR}(Z \to \rho\gamma)$	$< 2.5 \times 10^{-5}$		$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(p_{\mathrm{track}})$ limited

From the Snowmass report: The Physics potential of the CEPC

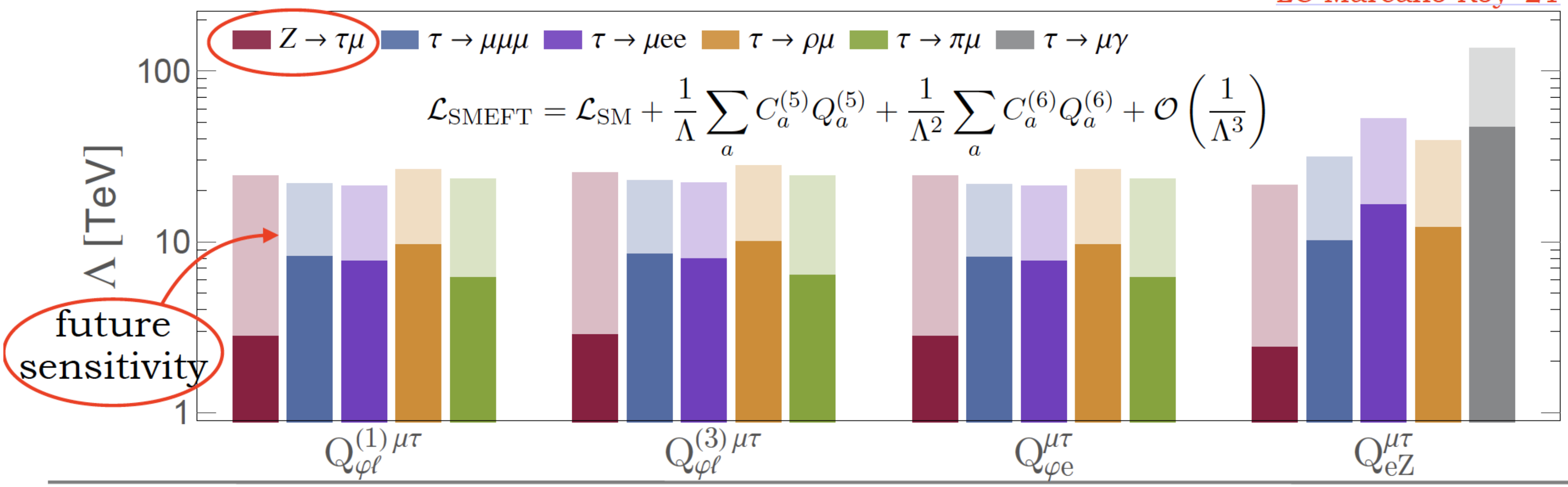
Lepton Flavour Violation in Z decays

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

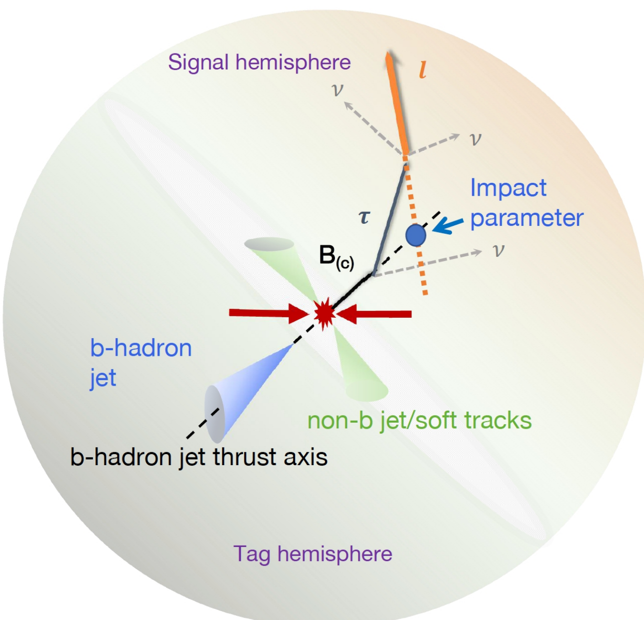
M. Dam '18

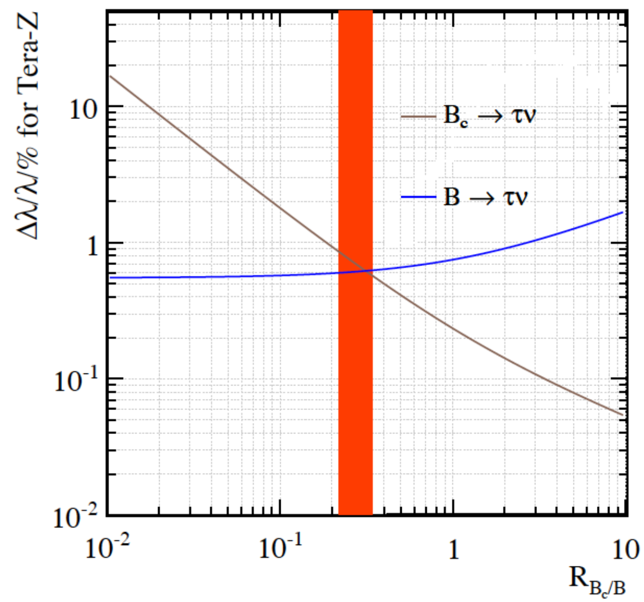
- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- A Tera Z can test LFV new physics searching for $Z \to \tau\,\ell$ at the level of what Belle II (50/ab) will do through LFV tau decays (or better)

LC Marcano Roy '21



Bc → τν





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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.

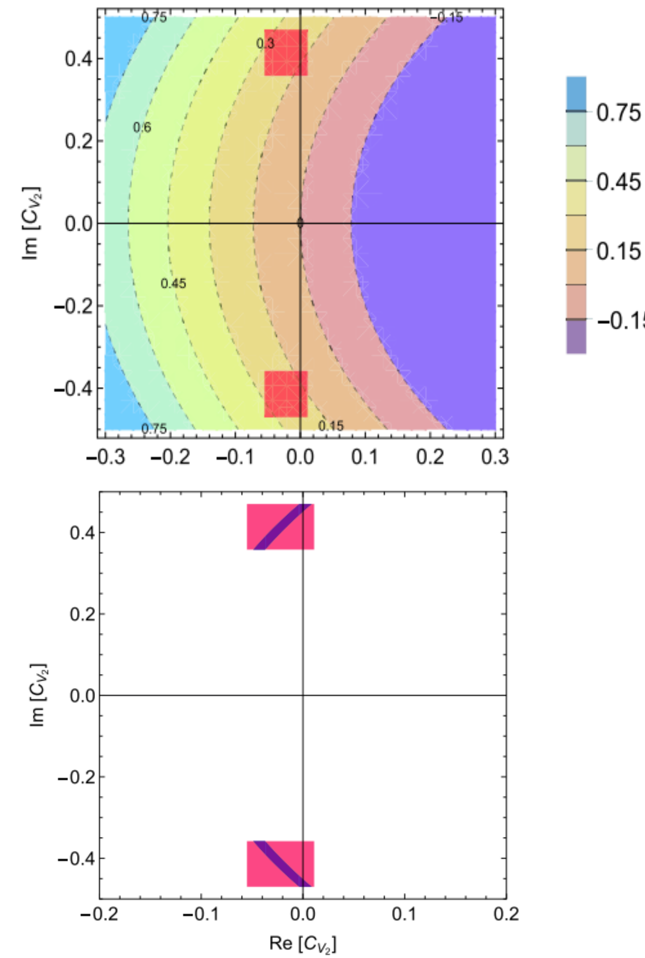
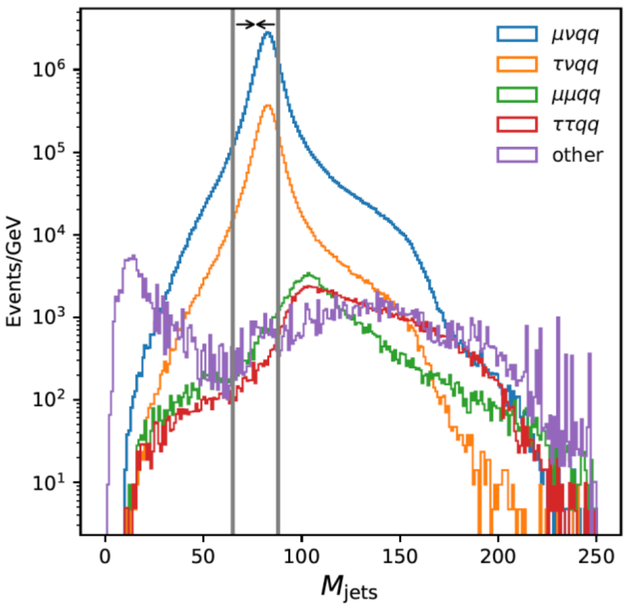
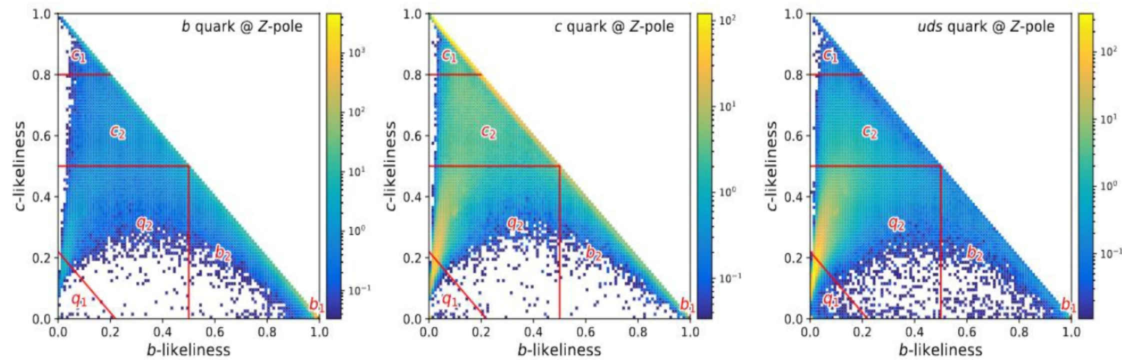


Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to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

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

	$\mu\nu W, W \to$				$\tau(\mu\nu)\nu_\tau W, W \to$				$\tau\nu_\tau qq, \tau \to$					
	cb	ub	$c(d/s)$	$u(d/s)$	cb	ub	$c(d/s)$	$u(d/s)$	$e2\nu$	had.ν_τ	$\tau\tau qq$	$\mu\mu qq$	Higgs	others
w/o slections	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
$E_{\text{L}\mu} > 12$GeV	37.9K	330	22.6M	22.6M	5.59K	56	2.98M	2.97M	133K	687K	422K	2.82M	645K	186.3M
$R_{\text{L}\mu} > 0.85$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M
$\cos(\theta_{\text{L}\mu})$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M
$q_{\text{L}\mu}\cos(\theta_{\text{L}\mu}) < 0.20$	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 $P_T > 9.5$ 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
$M_{\text{jets}} > 65$ 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
$M_{\text{jets}} < 88$ 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
$M_{\text{jets,recoil}} < 115$ 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
$M_{\text{L}\mu\text{S}\mu} < 75$ 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
$M_{\ell\nu} > 12$ 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
ϵ_{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)
$b_1c_{1,2}$	5.14K	4	2.79K	571	632	0	407	65	0	14	67	228	0	0
$\epsilon_{b_1c_{1,2}}$ (%)	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
	(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:
  - $W \to c(d/s)$
  - $\mu\mu qq$

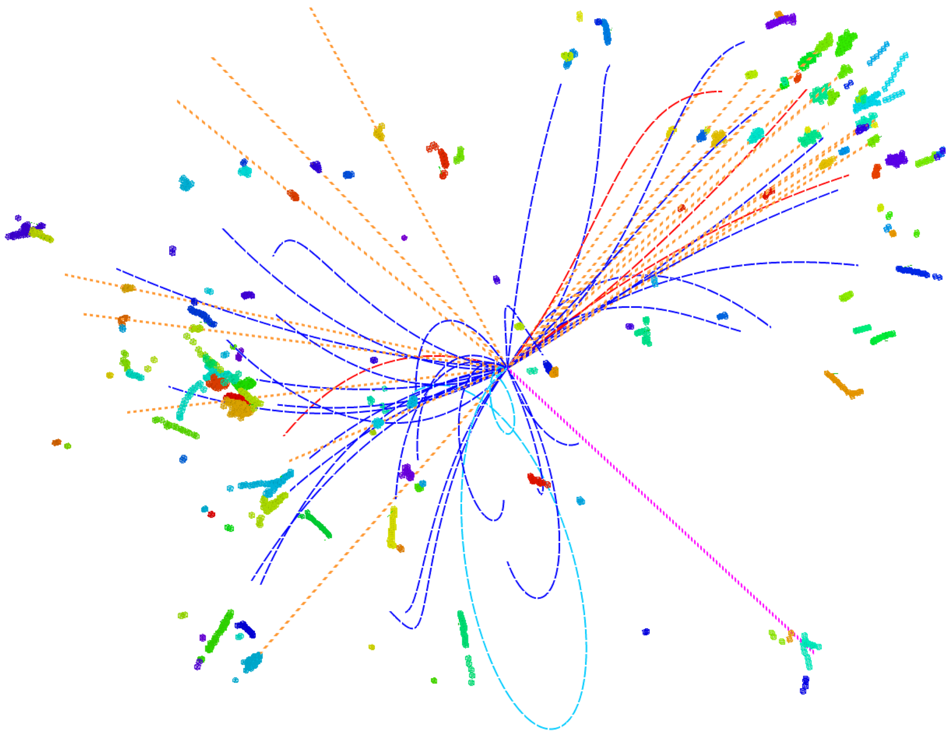
Vcb could be measured to a relative uncertainty of 0.4% at CEPC Nominal Set up...

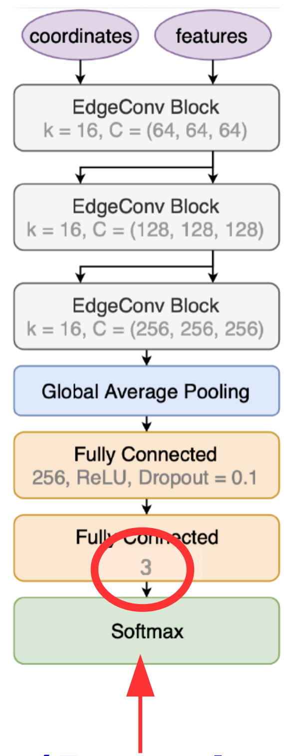
Extreme detector requirements

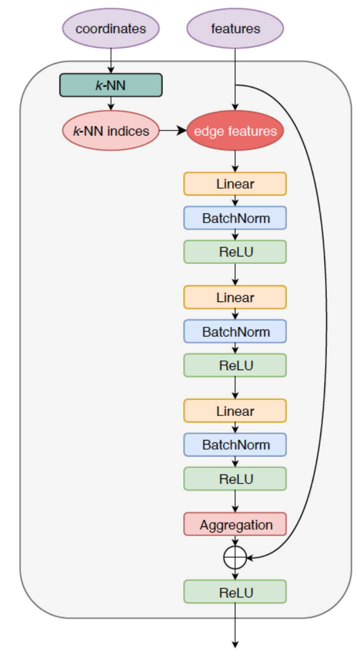
- Suited to the collision environment, especially beam background/MDI
- Trigger-less equivalent: Trigger system works as Trigger-less
- Extremely stable
- Large acceptance: polar angle, energy, time
- PFA compatible (in SpaceTime): final state particle separation – pursue 1-1 correspondence
  - Physics Objects Identification: Isolated, inside jets & jets
    - Single particle objects: Leptons, photons, Charged hadron
    - Composited objects: Pi-0, K-short, Lambda, Phi, Tau, D/B hadron, ..., Jets
  - Improving the E/M resolution for composited 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

Recent HL: Jet Origin Identification





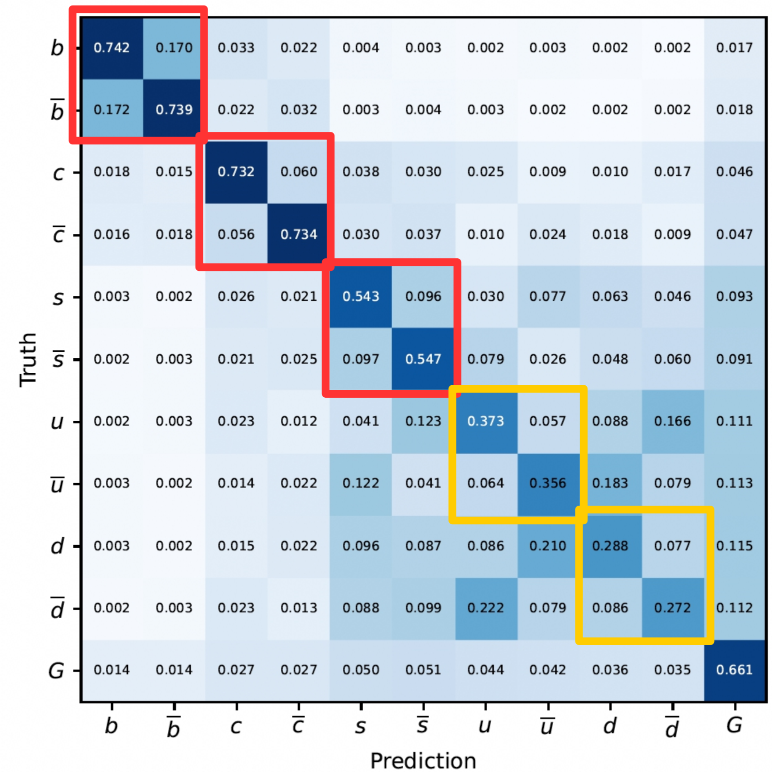


- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep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

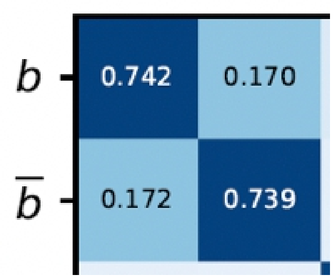
https://arxiv.org/abs/2310.03440
https://arxiv.org/abs/2309.13231

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



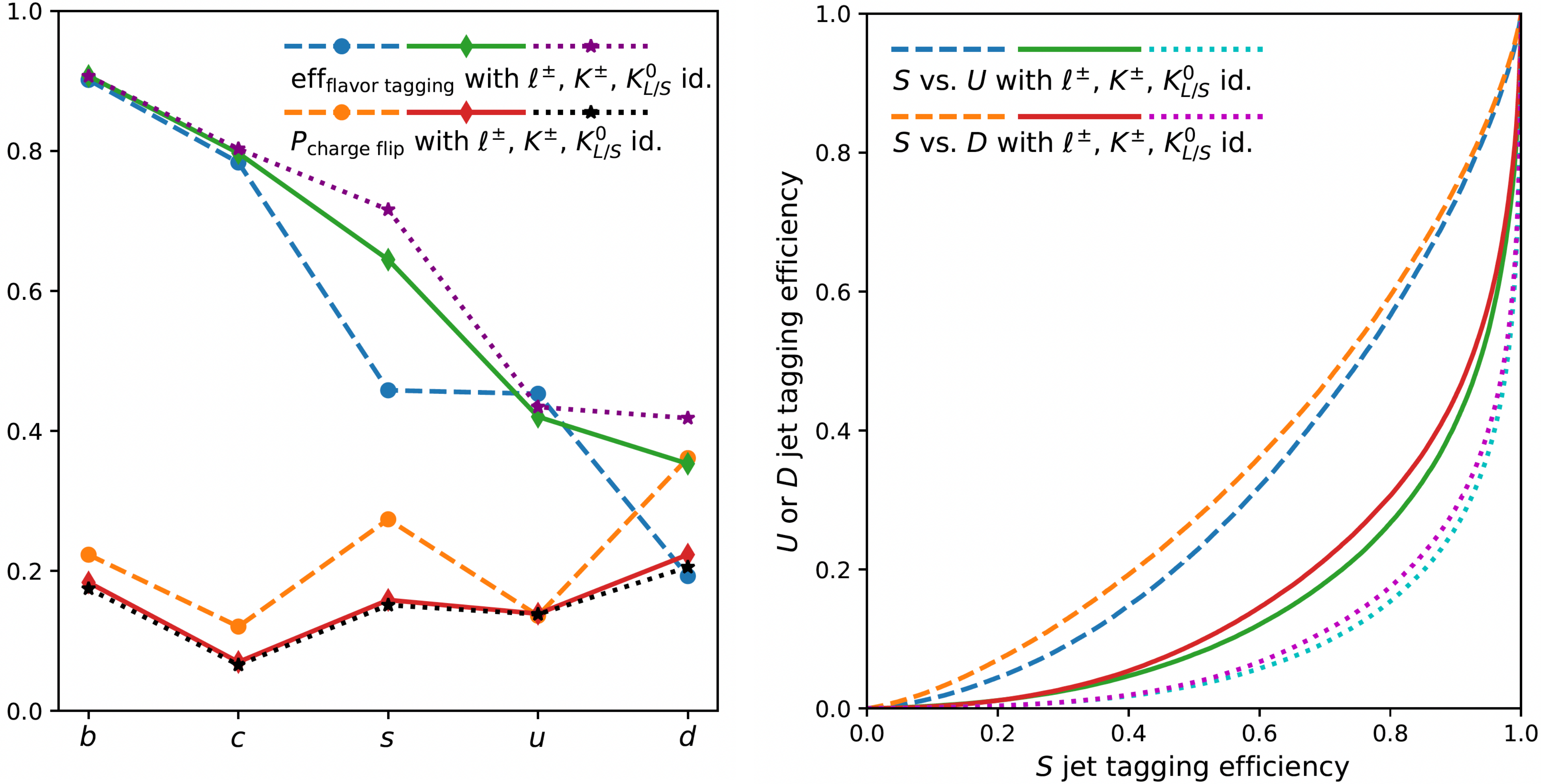
- Patterns:
  - ~ Diagonal at quark sector...
  - P(g→q) < P(q→g)...
  - Light jet id...



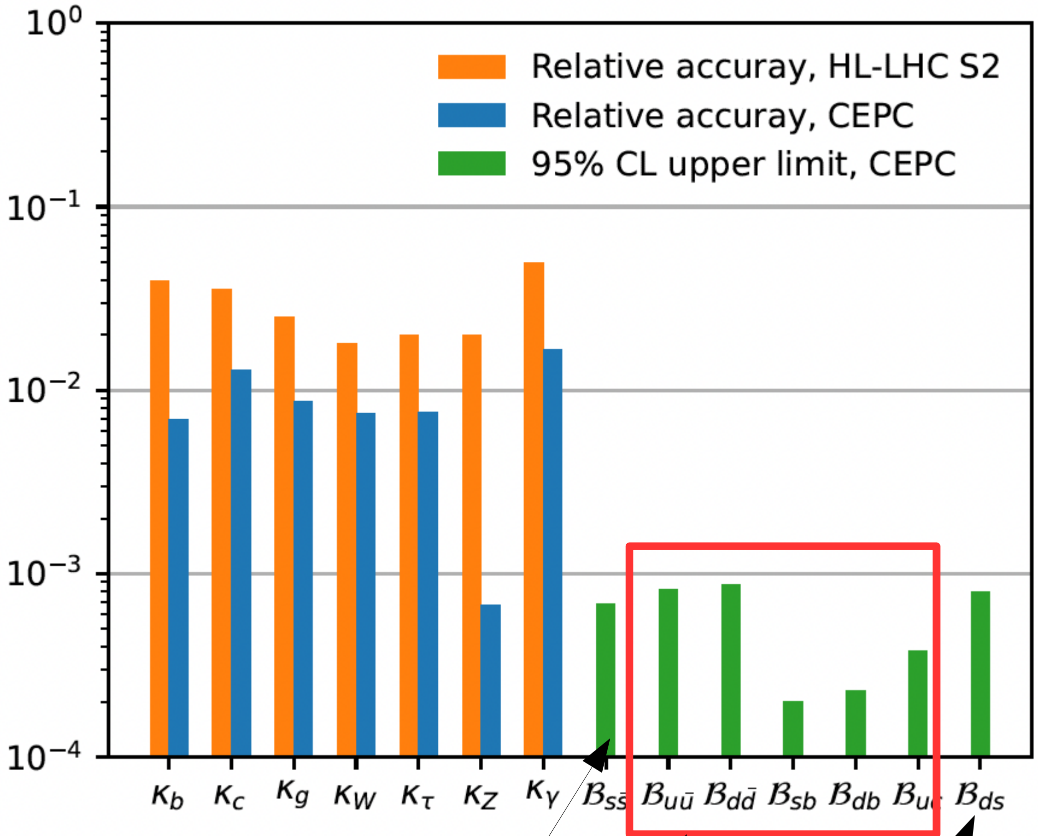
Eff = (0.74 + 0.17 + 0.74 + 0.17)/2 = 0.91

Charge flip rate = 0.17/0.91 = 0.19

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

TABLE I: Summary of background events of $H \to b\bar{b}/c\bar{c}/gg$, 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	ds
$\nu\bar{\nu}H$	151	20	2.1	0.81	0.95	0.99	0.26	0.27	0.46	0.93
$\mu^+\mu^-H$	50	25	0	2.6	3.0	3.2	0.5	0.6	1.0	3.0
e^+e^-H	26	16	0	4.1	4.6	4.8	0.7	0.9	1.6	4.3
Comb.	-	-	-	0.75	0.91	0.95	0.22	0.23	0.39	0.86

[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.

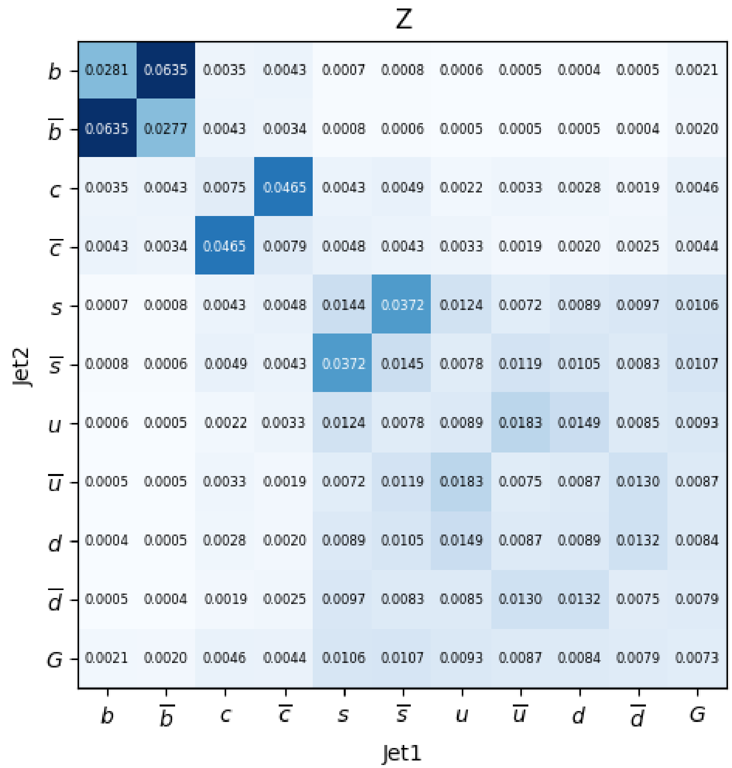
[50] Alexander Albert et al. Strange quark as a probe for new physics in the Higgs sector. In *Snowmass 2021*, 3 2022.

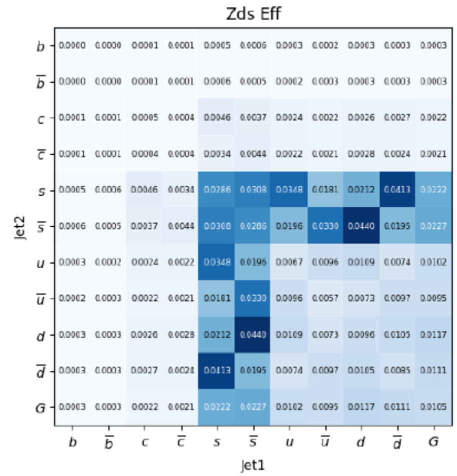
[59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.

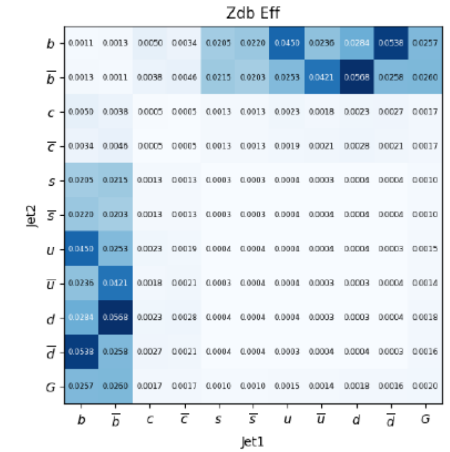
[60] Jorge De Blas, Gauthier Durieux, Christophe Grojean, Jiayin Gu, and Ayan Paul. On the future of Higgs, electroweak and diboson measurements at lepton colliders. *JHEP*, 12:117, 2019.

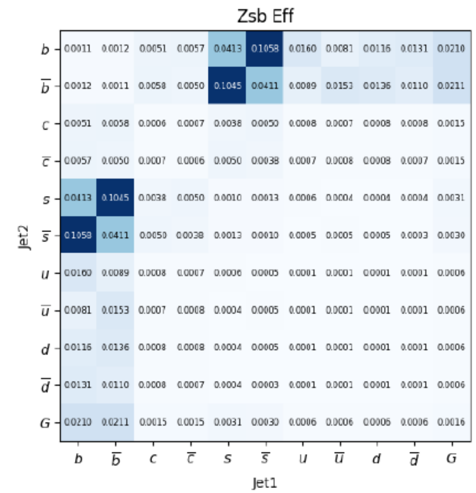
For H->bb, cc, gg: results in 20 – 40% improvement in relative accuracies (preliminary)...

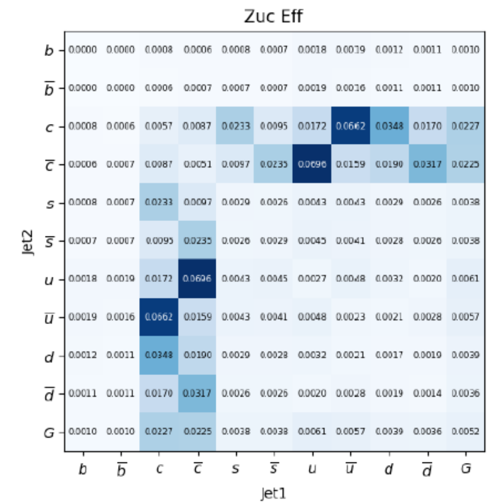
Applied to Z FCNC (Preliminary)











	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**

Seeking for signature & supports

CEPC Flavour Physics White Paper

Aug 14 – 31, 2023
Asia/Shanghai timezone

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- Overview
- Registration
- Surveys

Contact:

manqi.ruan@ihep.ac.cn
lingfeng_li@brown.edu
shanzhen.chen@ihep.a…

CEPC/FCC可产生数量在万亿级别的Z玻色子，千万级别的W粒子，百万级别的Higgs粒子，经升级后也可产生百万级别的顶夸克，而Z玻色子有70%的概率会衰变为一对正反夸克，以及3%的概率衰变到一对Tau轻子。因此，CEPC在味物理研究领域具有巨大的潜力。

为了量化CEPC在味物理上的科学潜力、明确其比较优势，并通过优化设计以最大化CEPC的科学产出，CEPC预研团队对CEPC上的味物理潜力进行了一系列研究。

2019年，CEPC研究小组提出撰写味物理白皮书的计划，以汇总上述关键信息；并于近期完成了一阶段的味物理白皮书（Phase-I）的初稿。目前的白皮书初稿覆盖了稀有b衰变、CP破坏、谱学研究等内容。

必须指出的是，味物理研究的范畴极为宽广，目前的白皮书中还有若干漏项，而CEPC加速器本身的各项参数也在逐步优化，将于今年（2023年）发布CEPC技术设计报告。CEPC上可进行的味物理研究领域中尚未被目前白皮书覆盖的内容，将通过未来的二阶段预研（Phase-II study）加以覆盖。

https://indico.ihep.ac.cn/event/20312/registrations/1629/

Summary

- Electron Positron Higgs factories: a gigantic boost from LHC
- CEPC physics studies: composed of physics reach/pheno and detector requirement optimization, aims at White papers to be released according to the project paces
  - Community activated, results in multiple new ideas/results
  - Good international communication/collaboration
  - Lots of raw material available, visionary summarization/interpretation is needed
- Flavor Physics at CEPC: strong comparative advantages, a windows to access NP of 10 TeV or even higher
  - Accesses to Un-seen, plus orders of magnitudes improvements
- Extremely rich physics program results in stringent requirements on the detector performance, to be addressed by intensive study on detector design, key tech R&D, and algorithms development
  - Significant efforts towards the RDR (reference detector design TDR)
- New tools, especially AI, could significantly alter the physics study/detector design.

Back up

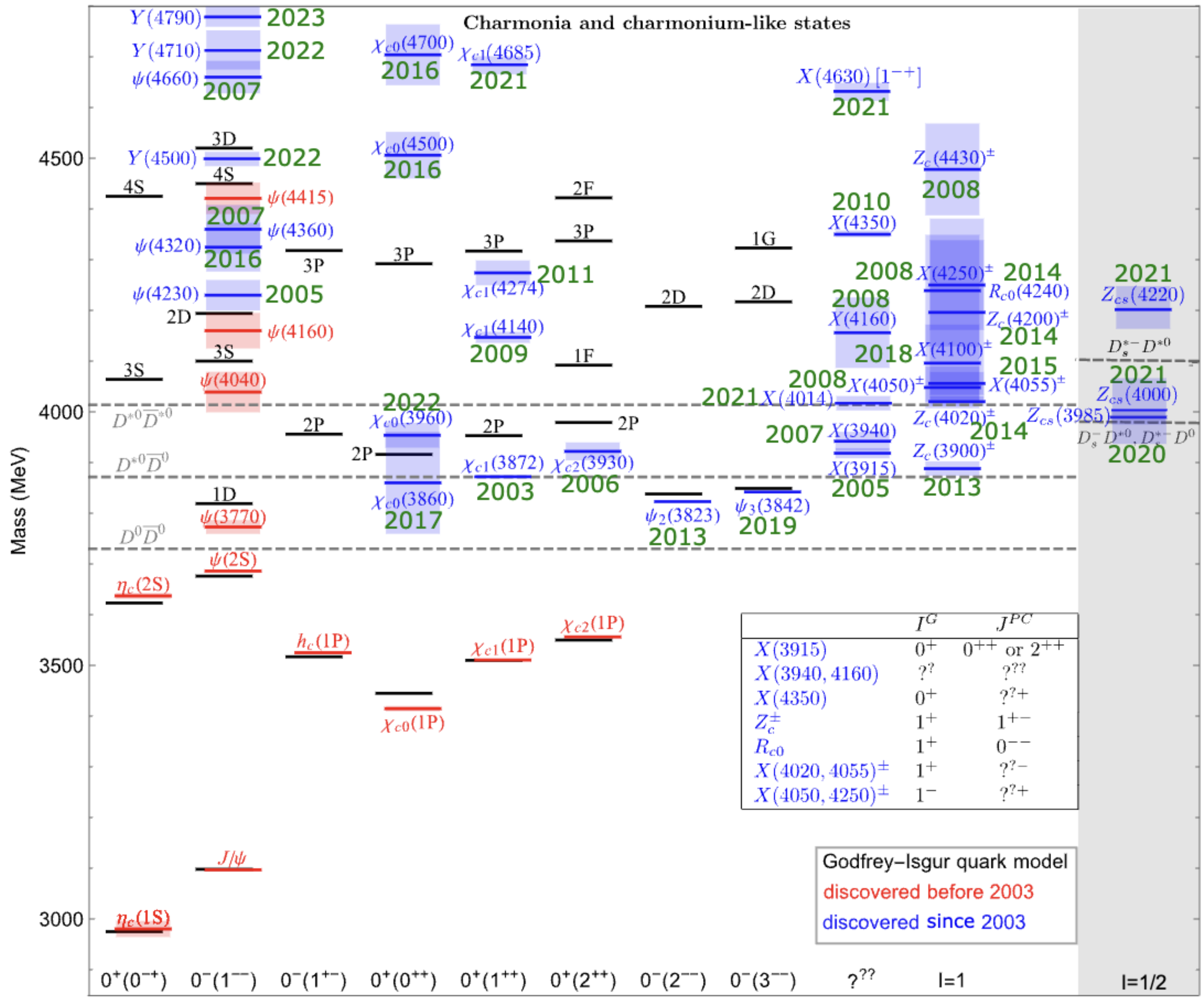
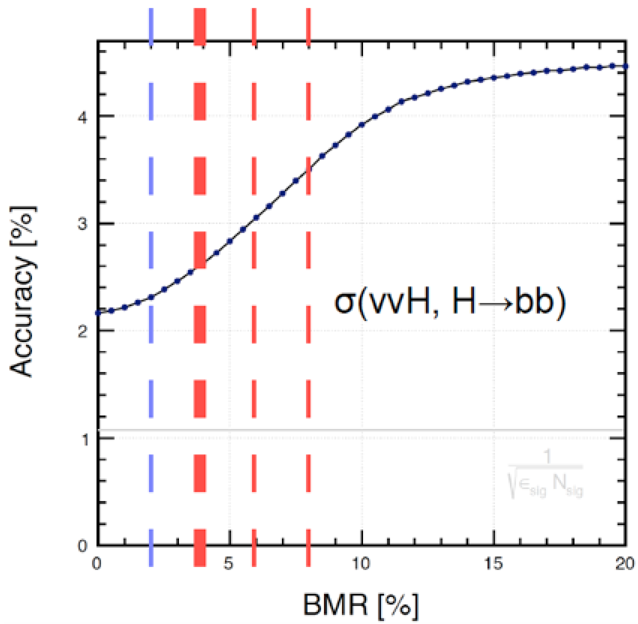
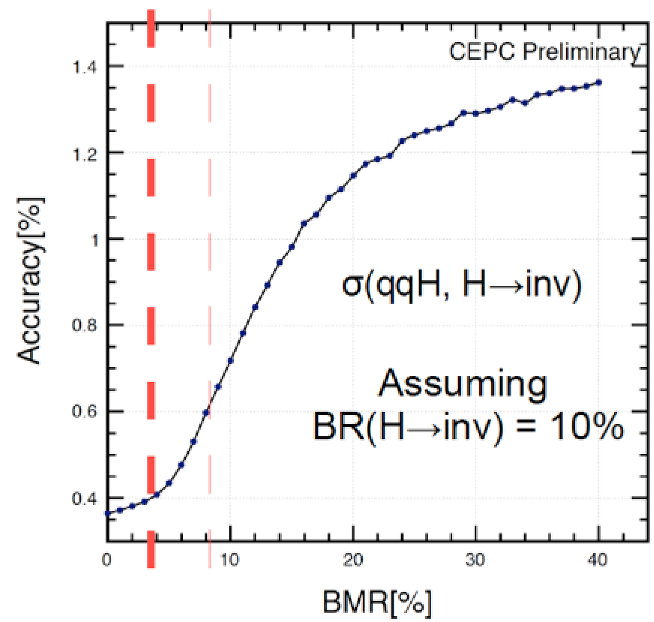
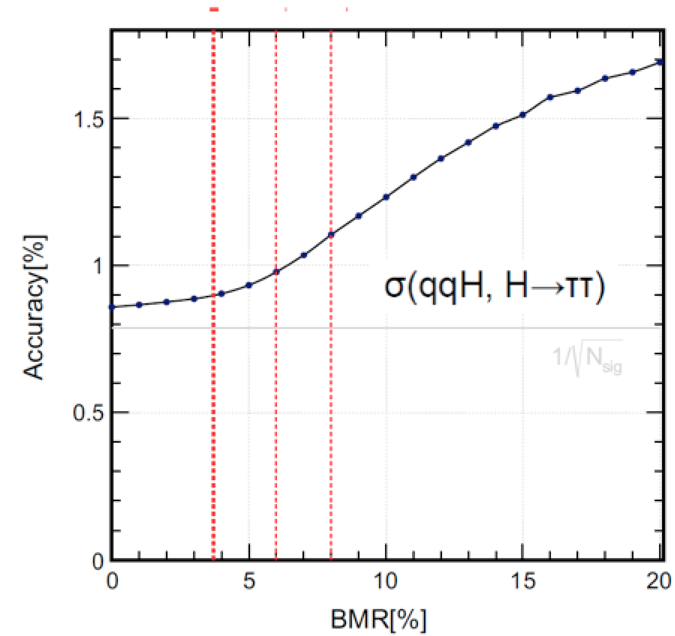


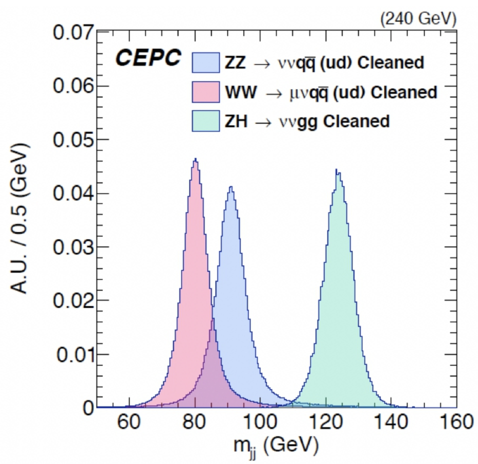
Figure 35: Spectrum of the charmonium and charmonium-like states. Black lines represent the masses in the Godfrey-Isgur quark model [215]. The red and blue lines represent the states observed experimentally before 2003 and since 2003, respectively. For the latter, the years when the states were observed are labeled in green. The height of each shadow indicates the width of the corresponding state. We also show a few two-body open-charm thresholds as dashed lines.

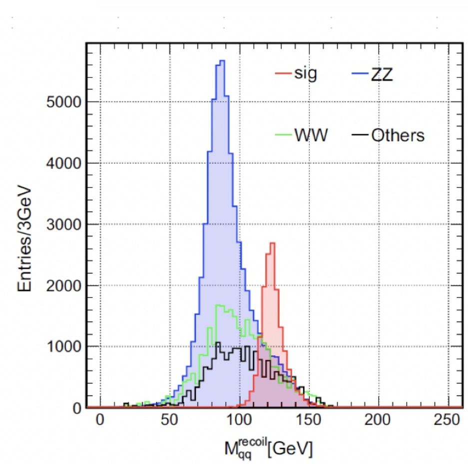
BMR < 4% for Higgs physics











	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(vvH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

Bs→Φvv

https://arxiv.org/pdf/2201.07374.pdf

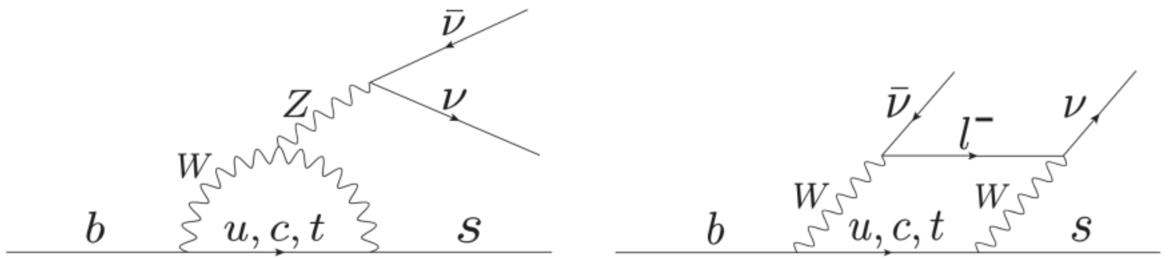
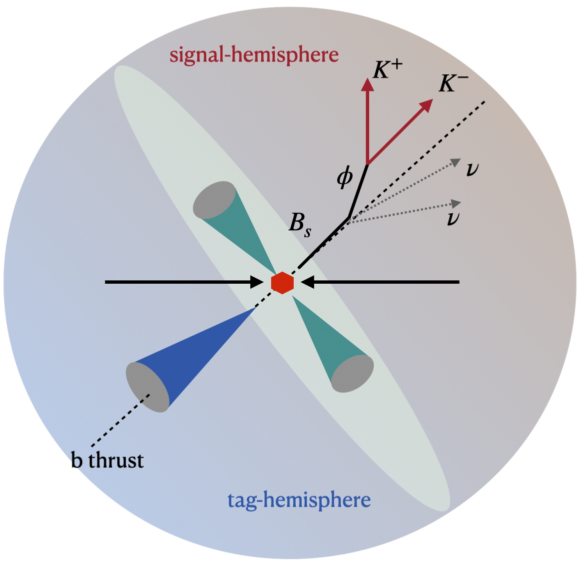
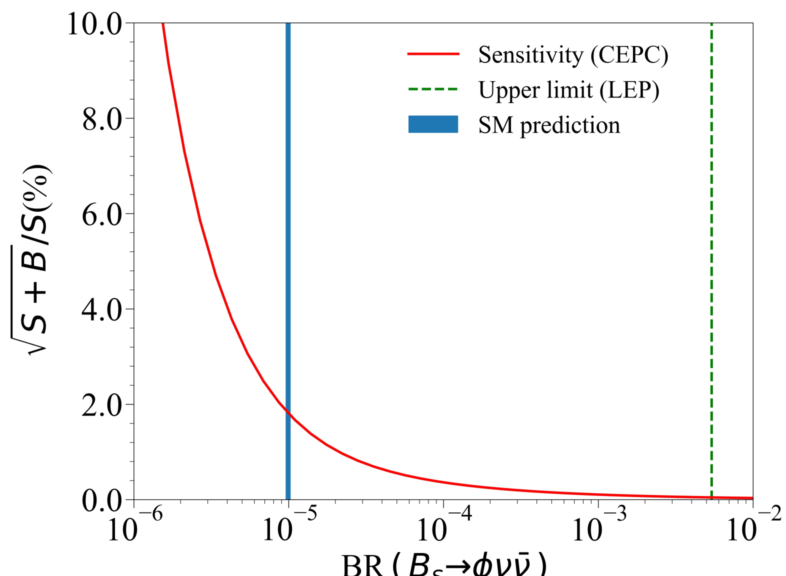


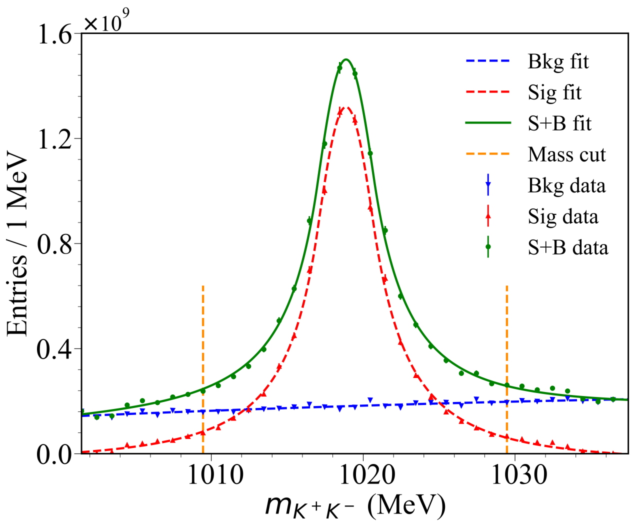
FIG. 1. The penguin and box diagrams of $b \to s\nu\bar{\nu}$ transition at the leading order.

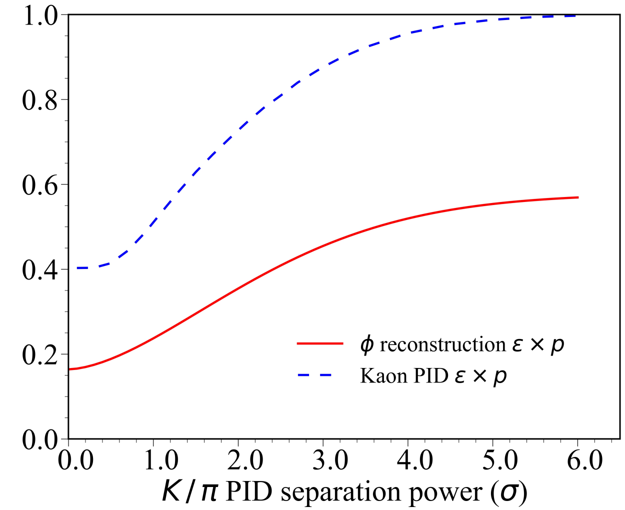


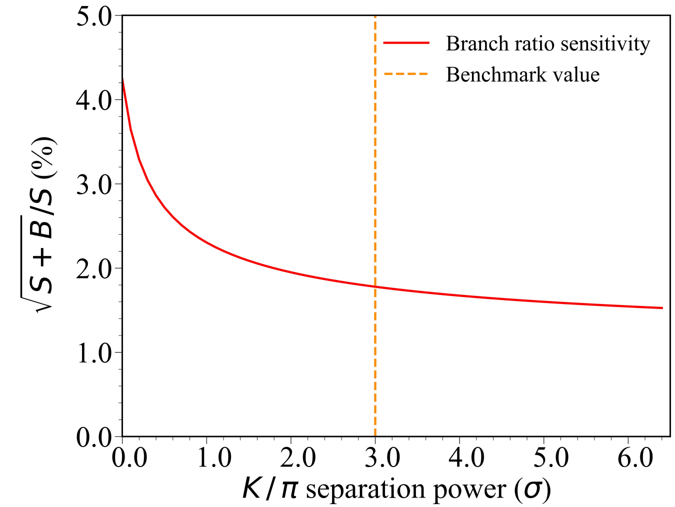
- Key ingredient to understand FCNC anomaly...
- Critical Physics Objects: Phi (and charged Kaon), 2nd VTX, Missing E/P, b-jet at opposite side
- Percentage level accuracy anticipated at Tera-Z

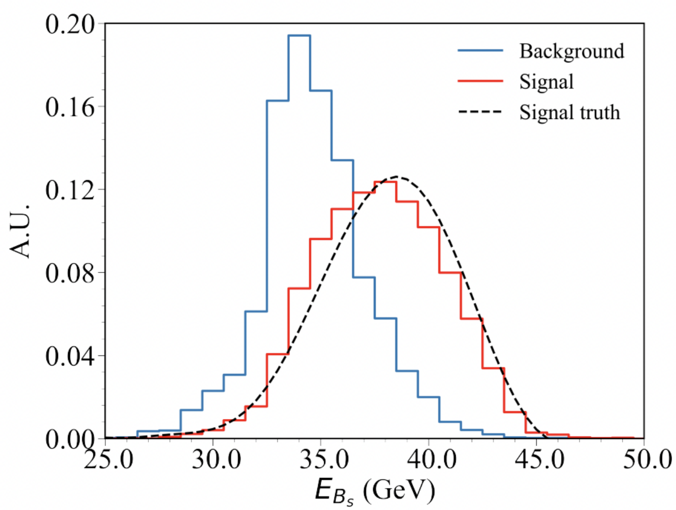


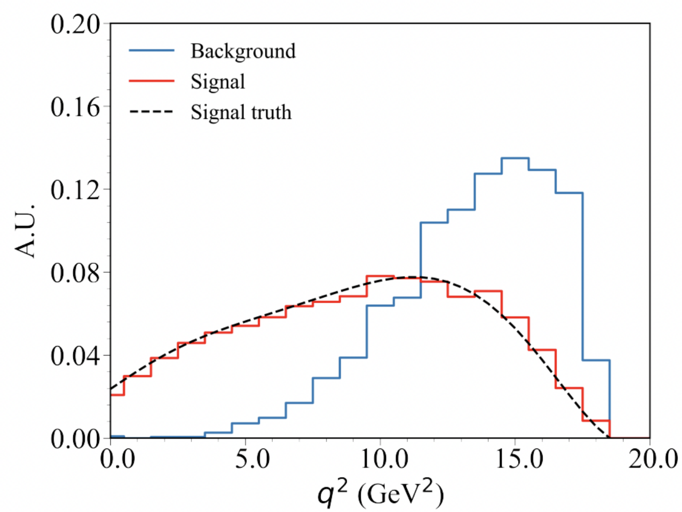
Requirements: Pid & MET











$$M_{\rm tag} = \sqrt{\left(\sum p_{\rm tag}^{\rm vis}\right)^2}\,,$$

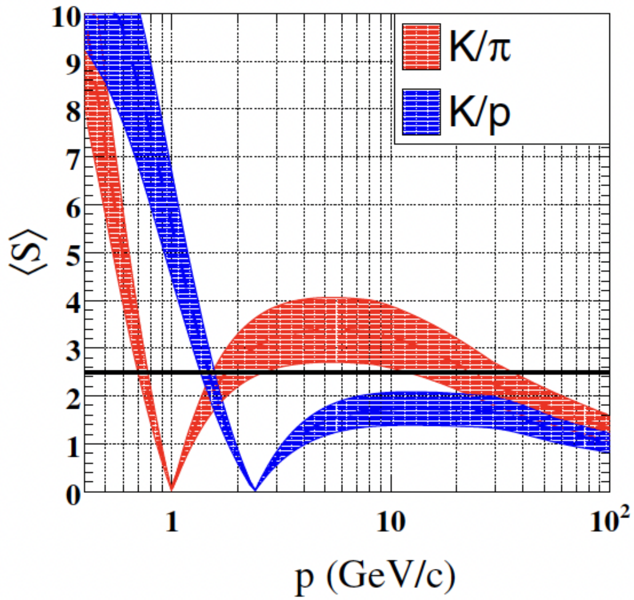
$$M_{\rm sig}^{(i)} = \sqrt{\left(\sum p_{\rm sig}^{\rm vis} + p_{B_s}^{(i-1)} - p_\phi\right)^2}\,,$$

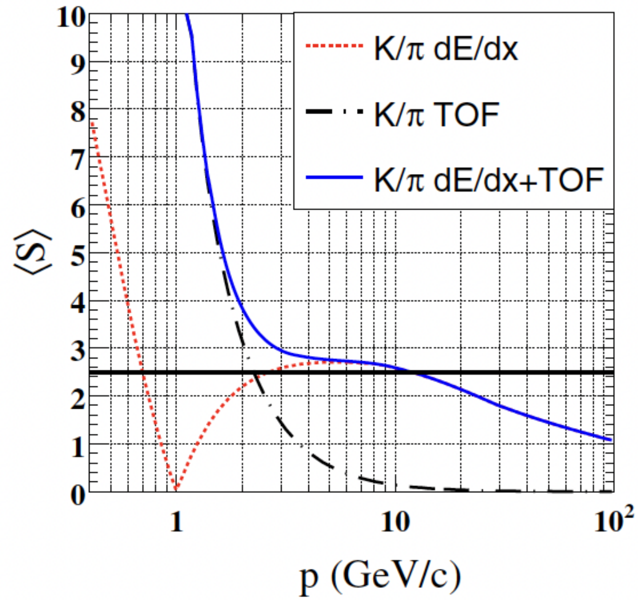
$$E_{B_s}^{(i)} = \frac{s + (M_{\rm sig}^{(i-1)})^2 - M_{\rm tag}^2}{2\sqrt{s}} - E_{\rm sig} + E_\phi\,,$$

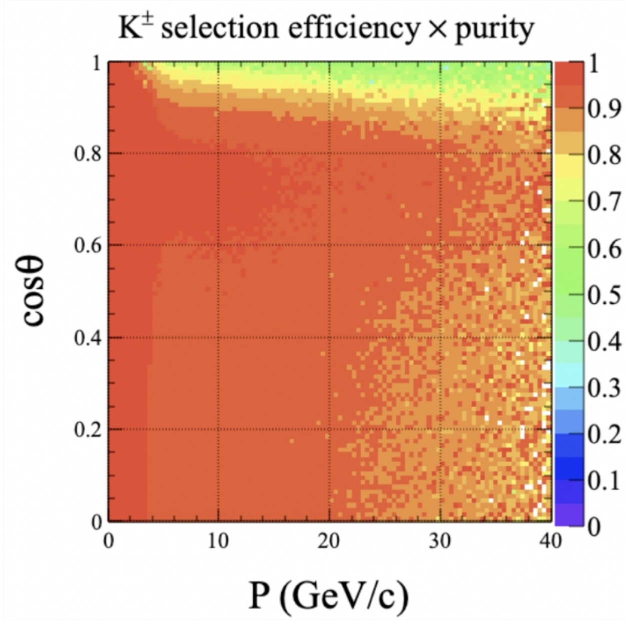
$$(q^2)^{(i)} = (p_{B_s}^{(i-1)} - p_\phi)^2\,,$$

3σ Pion-Kaon separation + Good missing Energy/Momentum (~ BMR) resolution

Tracker: Pid







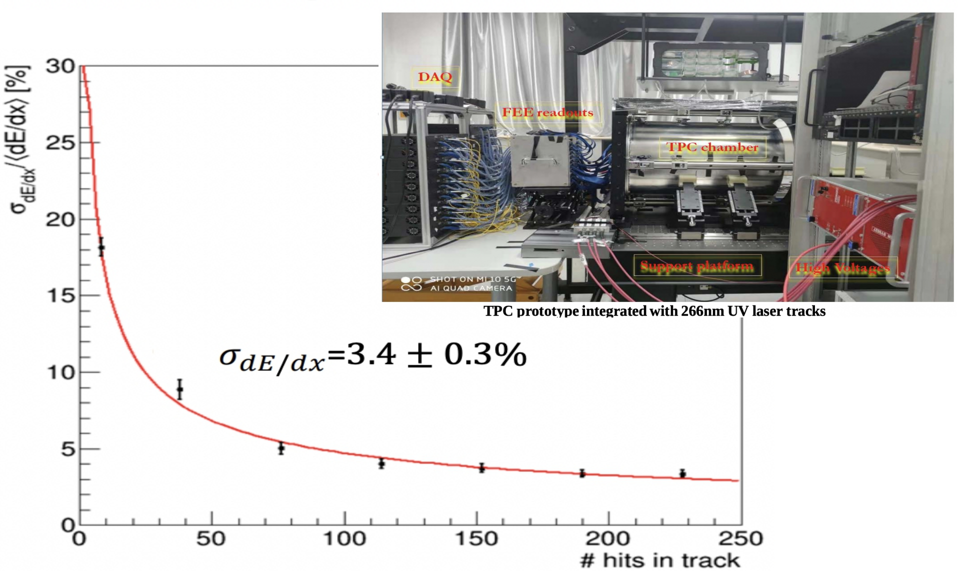


Table 3
The $K^{\pm}$ identification performance with different factors, $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$, with/without combination of TOF information at the Z-pole.

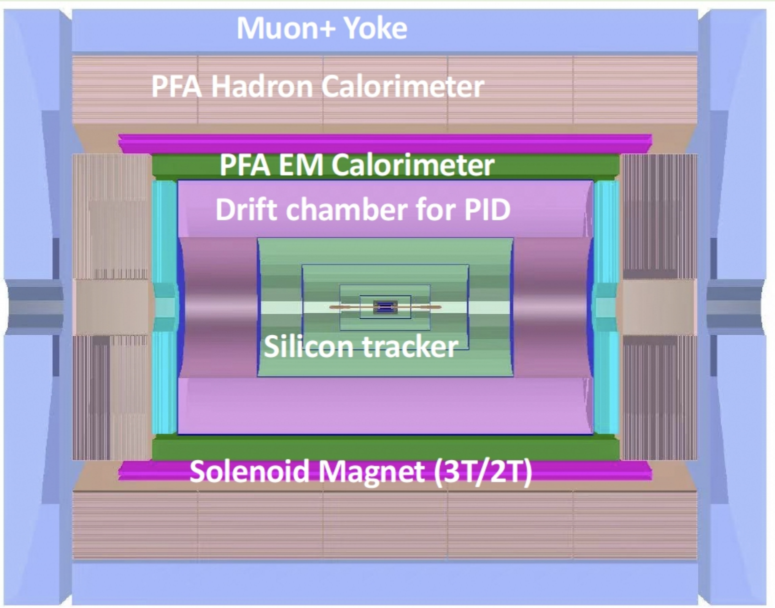
	Factor	1.	1.2	1.5	2.
dE/dx	ϵ_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ϵ_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

- Pid via dEdx or dNdx: **< 3%**
- Current TPC studies using laser reaches 3.4%
- 50 ps Timing on Calo. Clusters

Detector concept studies

Design of experimental facility and technical requirements

Detector

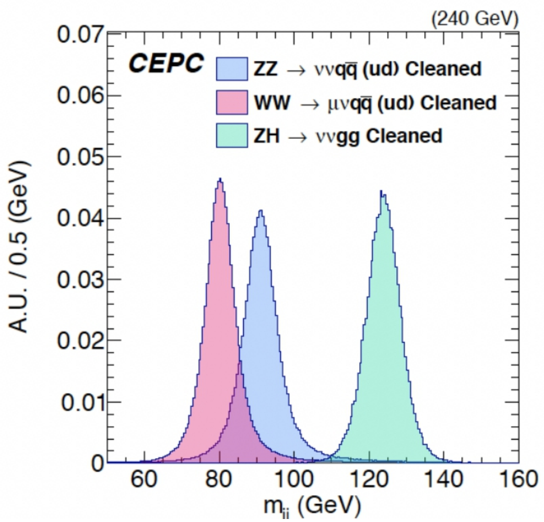


Requirements
boson mass resolution (BMR ~3%)

→

Challenges

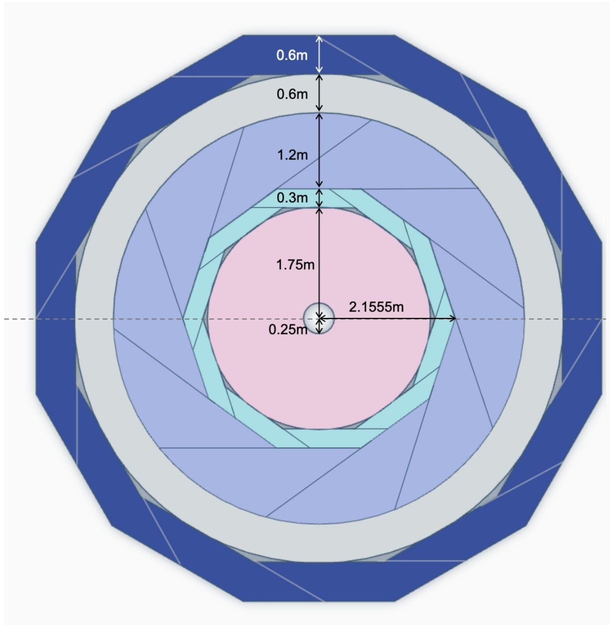
- Support Particle flow with
  - High granularity
  - High precision

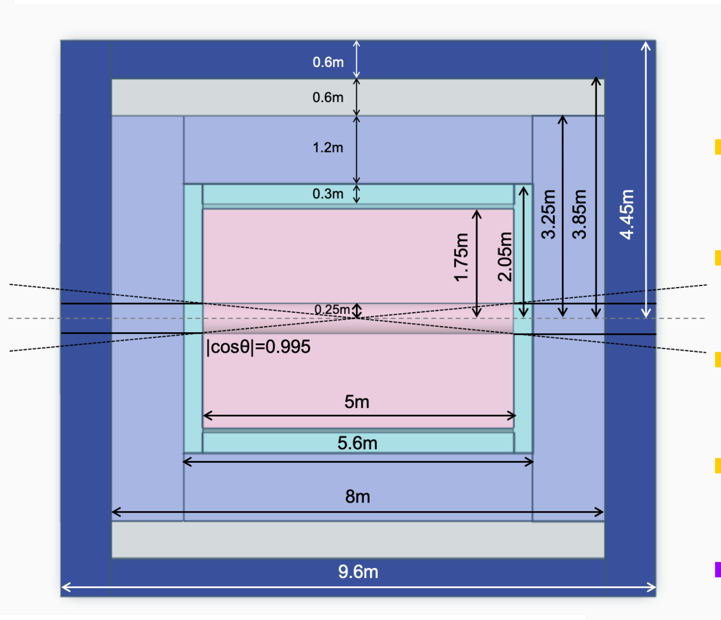


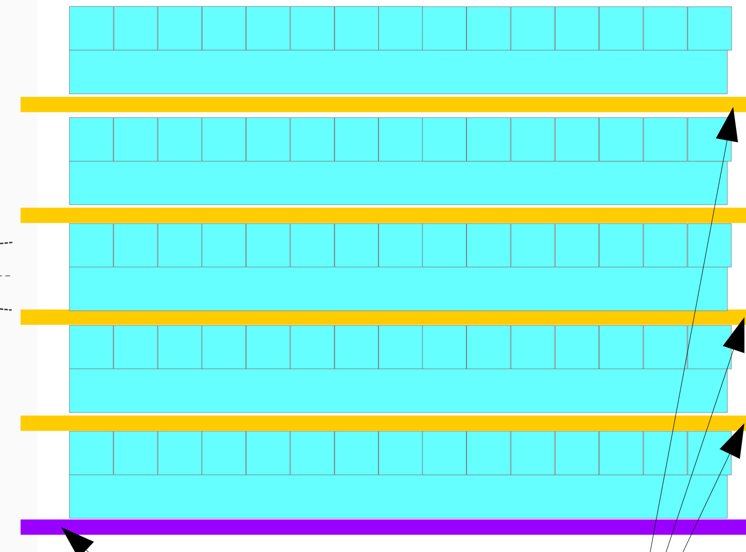
Novel detector design based on PFA calorimeter. Aim at improving BMR from 4% to 3%

Detector	Key parameter	World-class level	CEPC design
PFA based EM calorimeter	EM shower E resolution	~20%/√E	<3%/√E
PFA based Hadron calorimeter	Single hadron E resolution	~50%/√E	~40%/√E

Detector study: CHLOE design

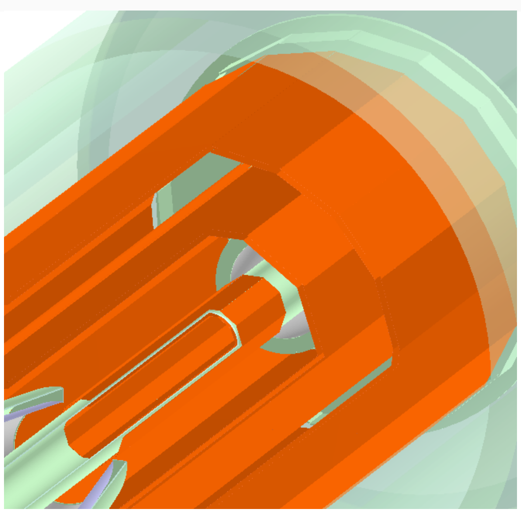


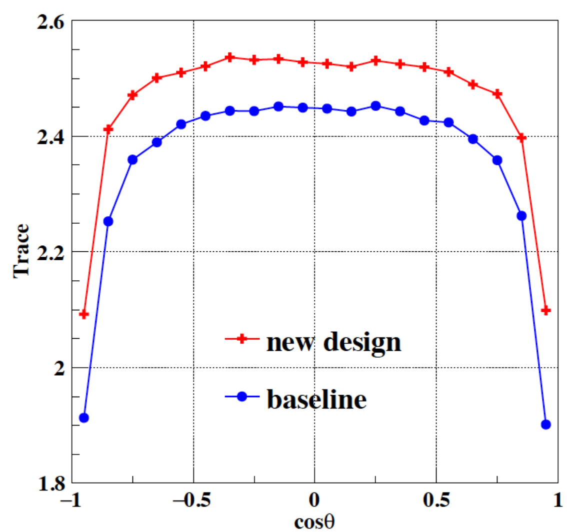




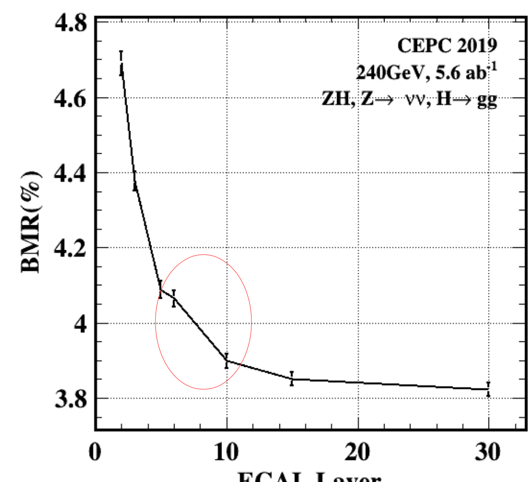
Silicon Tracker

Positioning - timing Layer with 1*1 cm granularity (Si or Alternative)

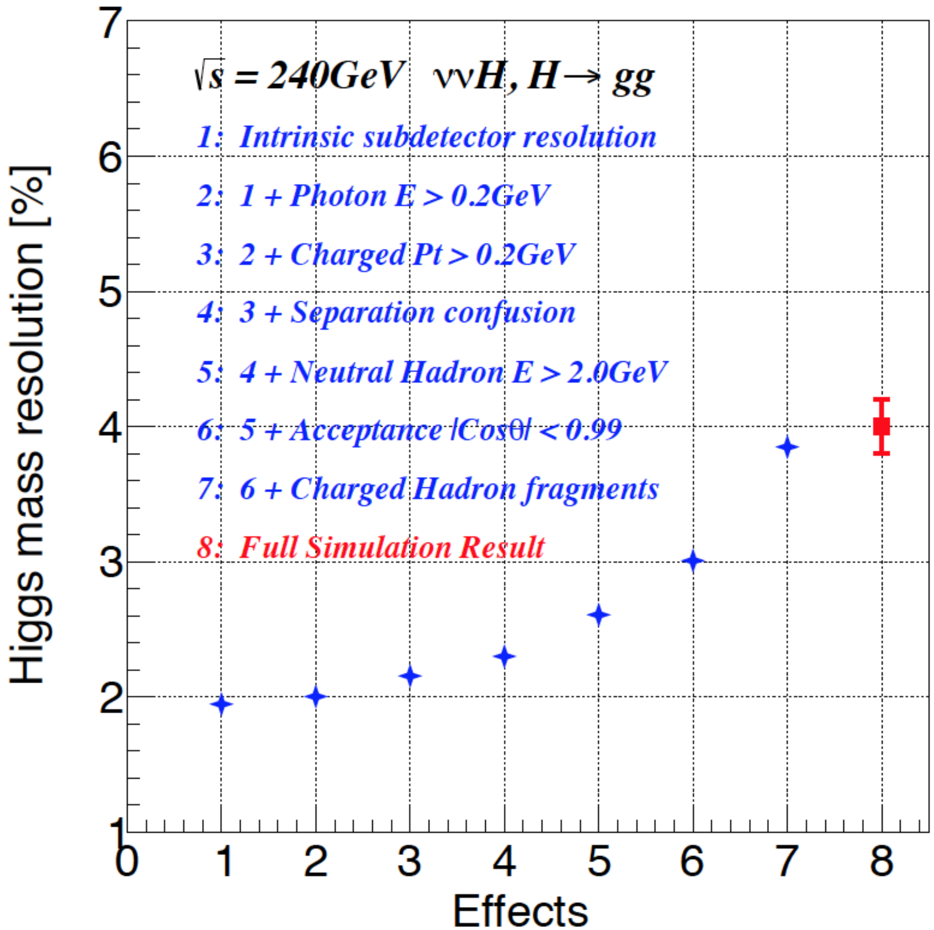




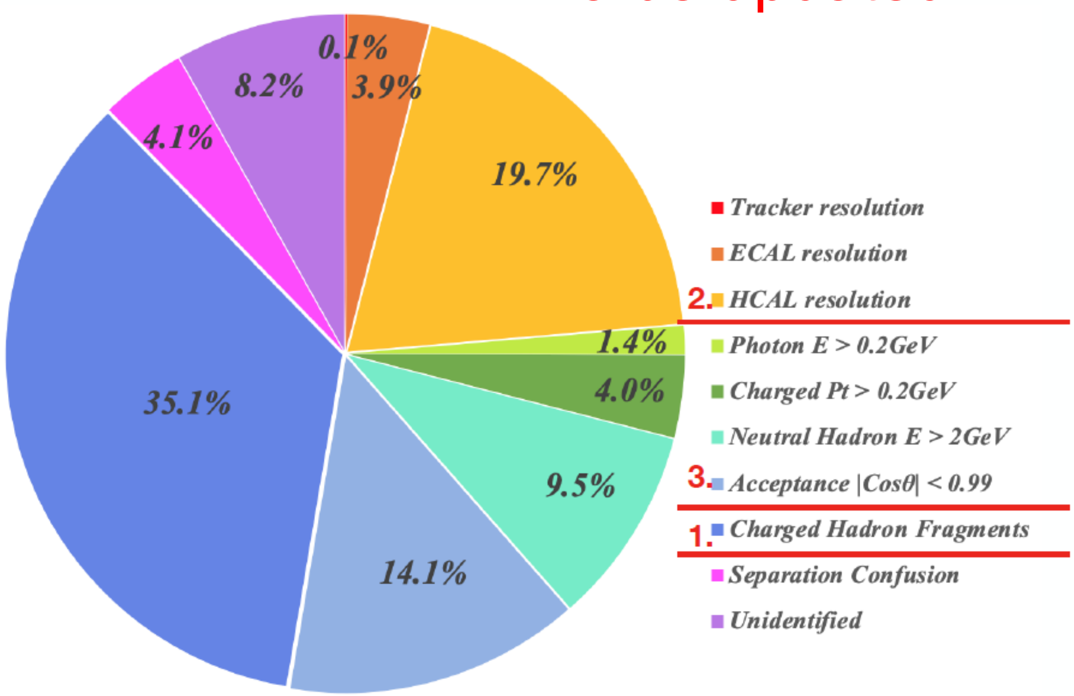
Vin (Vertex inside beam pipe): 20% imp. on Vcb measurements w.r.t. Baseline



PFA Fast simulation



To be updated!

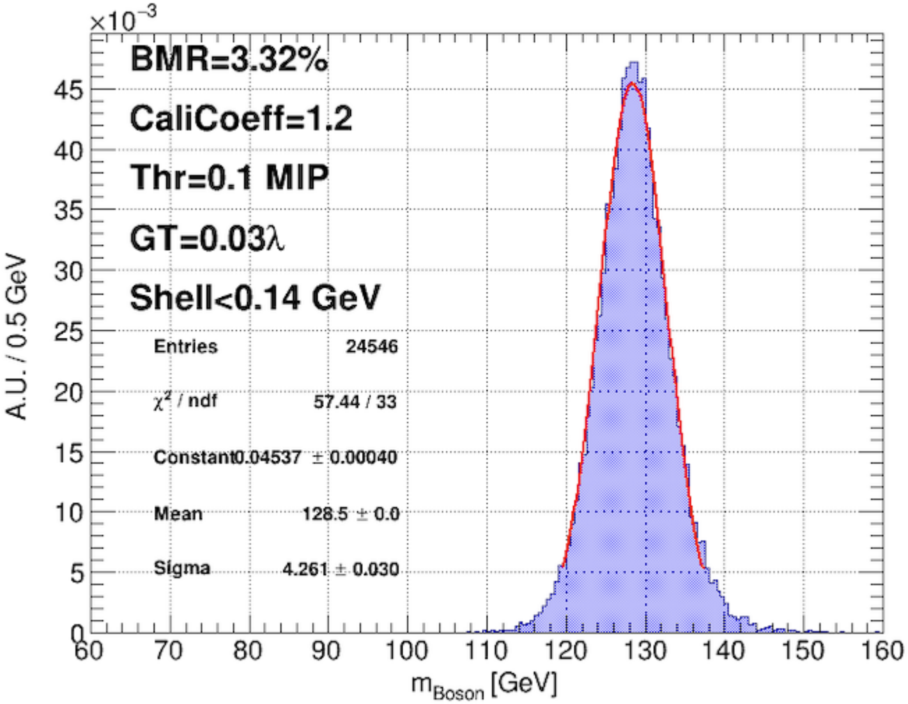


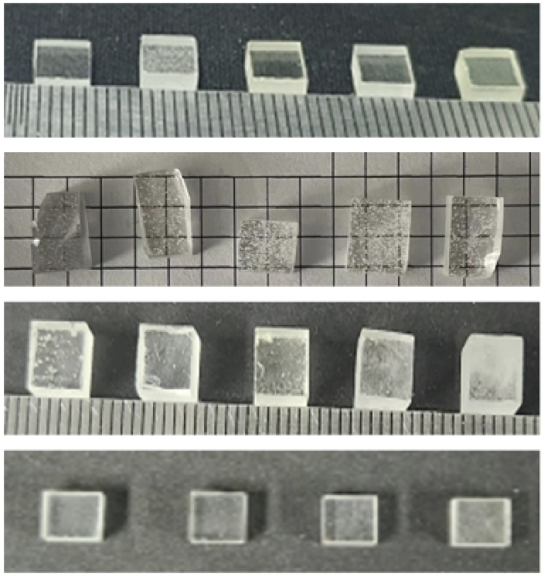
YX. Wang

Fast simulation reproduces the full simulation results, factorize/quantifies different impacts

BMR wi GSHCAL

P. Hu & YX. Wang





2021.11
Density ~4.5 g/cm^3

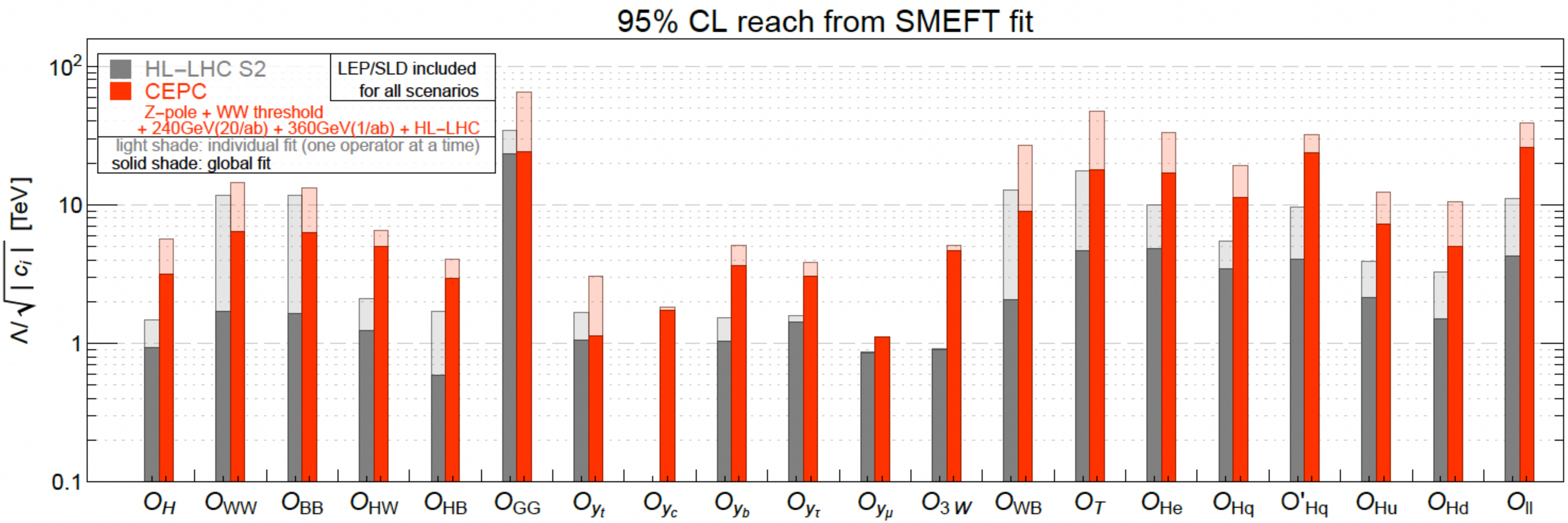
2021.11
Density ~4.0 g/cm^3

2022.06
Density ~6.0 g/cm^3

2023.02
Density ~6.0 g/cm^3

- Baseline + replace DHCAL to GSHCAL + Simple para. optimization
- ~ o(10)% improvement w.r.t. DHCAL

Physics reach via EFT



Challenges

- Physics: To be addressed by Physics studies & Summarized into White papers
  - Identify the Smoking gun for discovery -
  - Physics landscape & Synergies @ X-frontier (i.e., GW + Collider)
  - Interpretations
  - High precision calculation
- Accelerator: Engineering Design Report & Feasibility studied
  - Prototype & commissioning at integrated level (large scale test facility, test with beam load)
  - Integration & alignments
  - Civil Engineering
- Detector: Innovative detector design + A3 (AI Assistant Algorithms) + Key tech R&D
  - PFA oriented
  - Extremely stable
  - Trigger-less equivalent at Tera Z
  - Sub-detectors – state of art + pursue excellent intrinsic resolutions
- International collaboration!