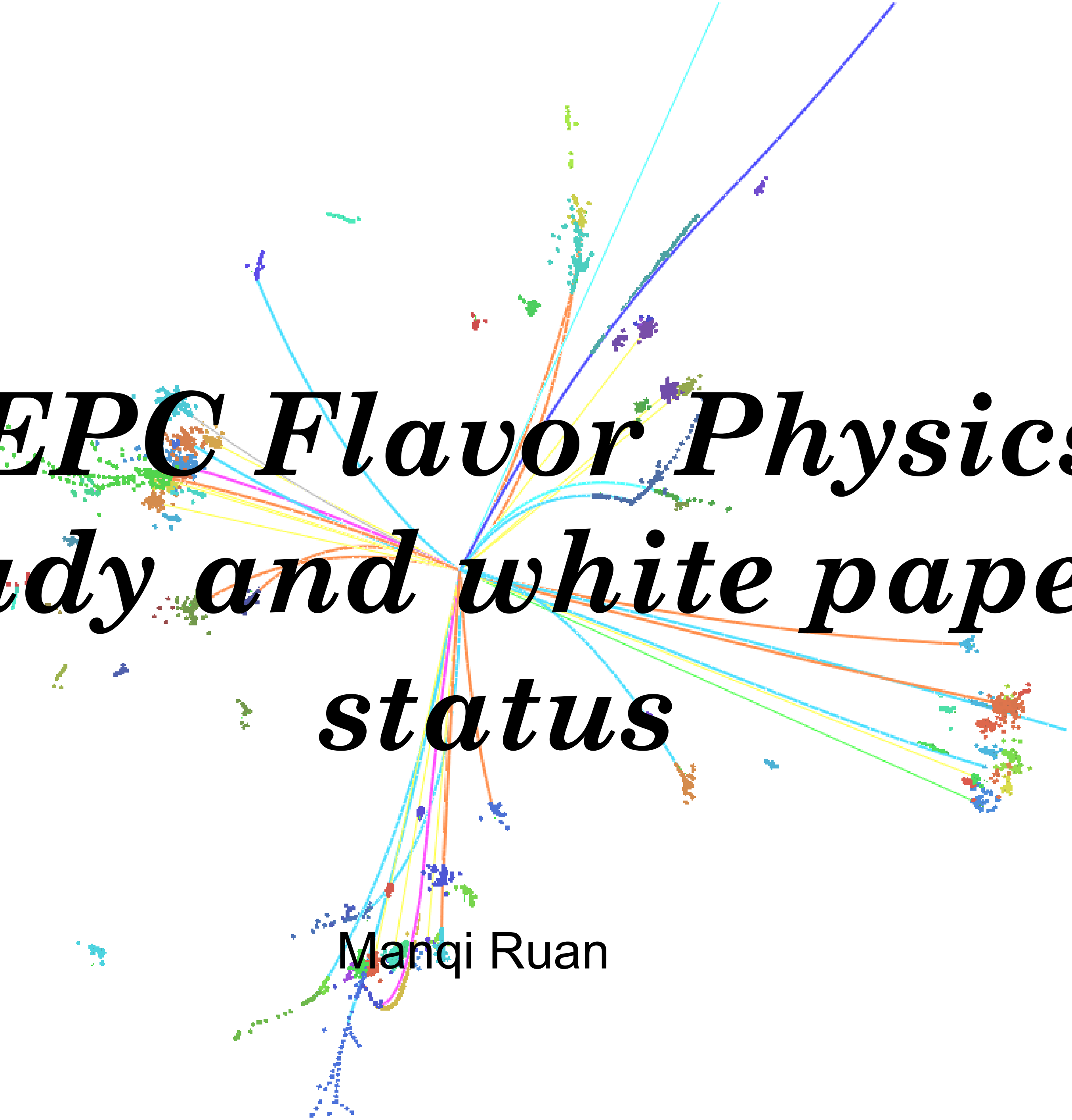
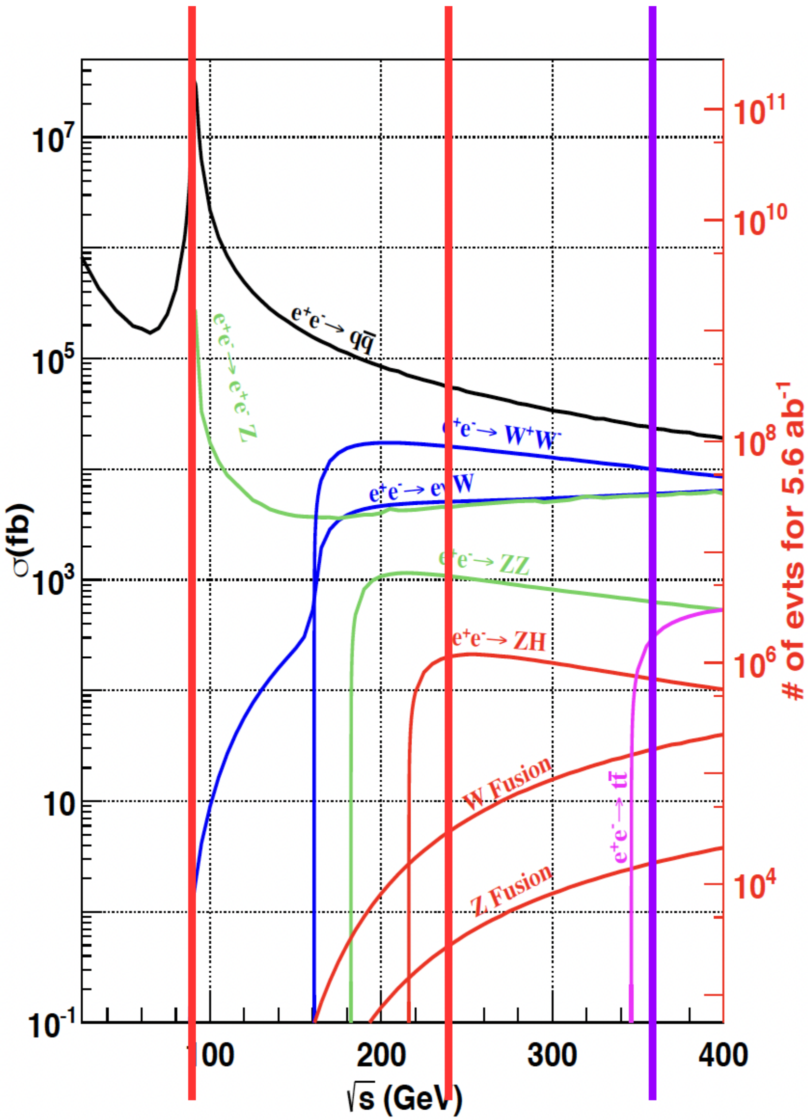
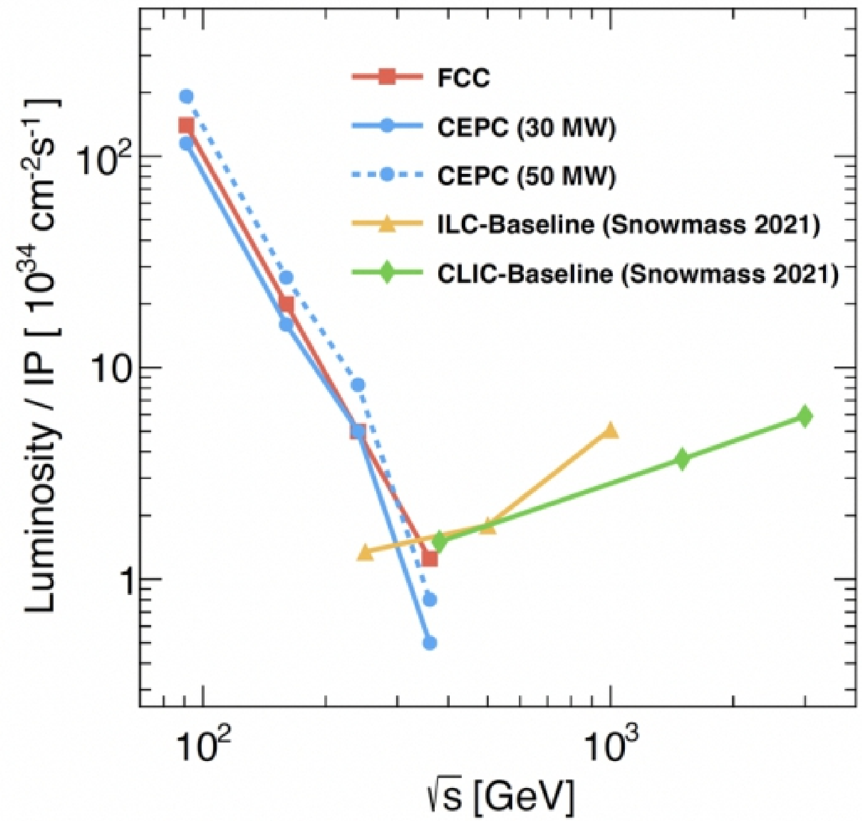
CEPC Flavor Physics study and white paper status



Manqi Ruan

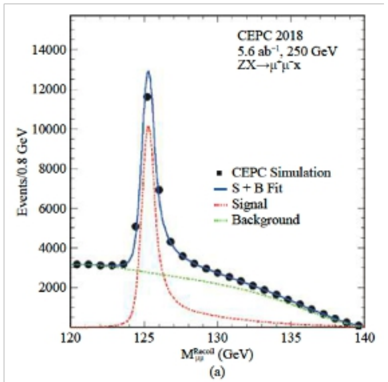
Yields ~ Xsec * Lumi * Time

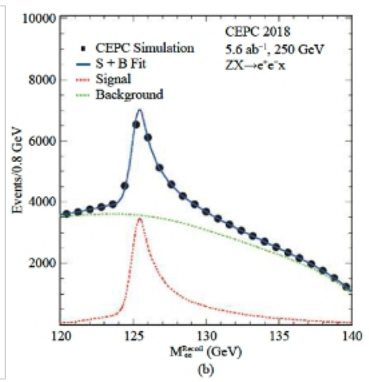


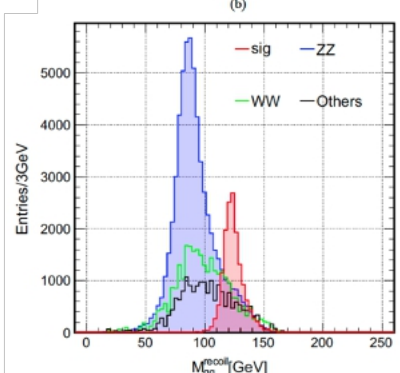


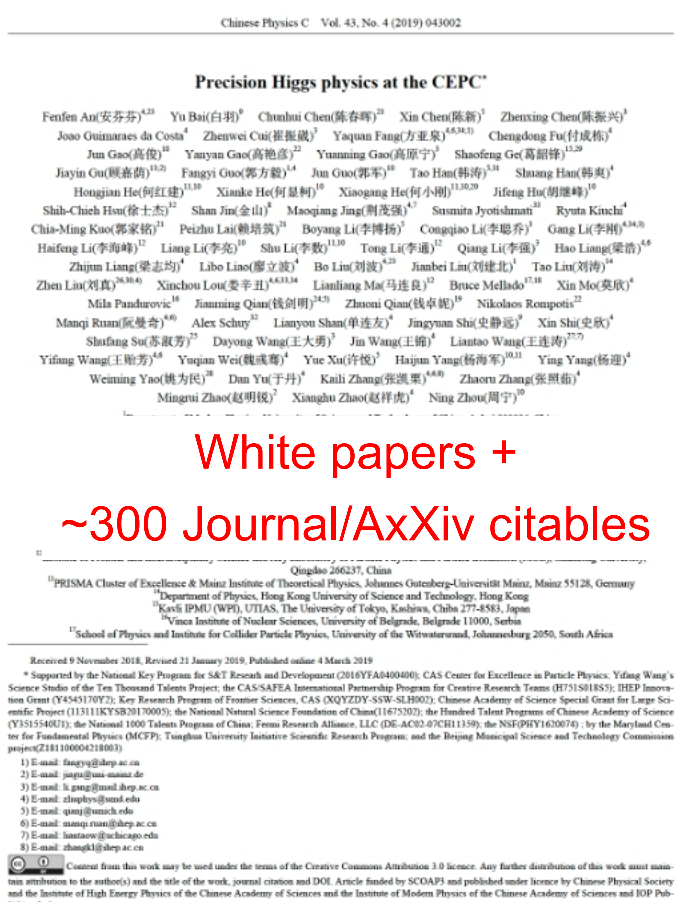
- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

CEPC Physics study









White papers +

~300 Journal/AxXiv citables

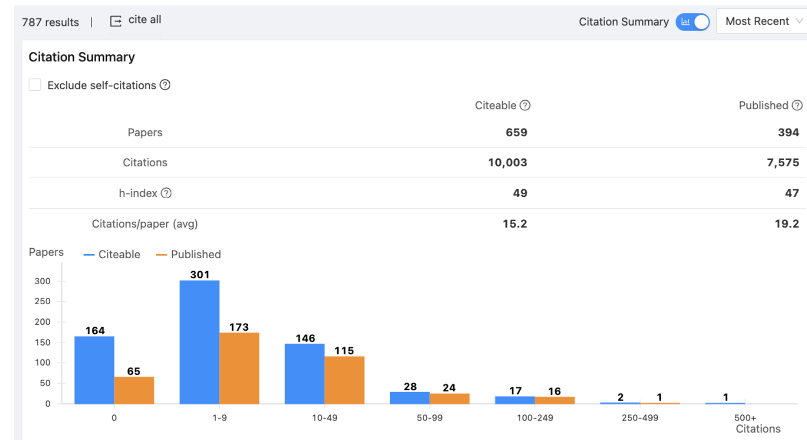


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

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.
- …

Flavor Physics

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10}	3×10^{13}	4.8×10^{11}
$B^\pm$	-	5.7×10^{10}	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^8 (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	-	1×10^{11}	7.2×10^8
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$	1.2×10^8	4.8×10^{10}	1.4×10^{15}	8.3×10^{11}
$D^\pm$	1.2×10^8	4.8×10^{10}	6×10^{14}	4.9×10^{11}
$D_s^\pm$	1×10^7	1.6×10^{10}	2×10^{14}	1.8×10^{11}
$\Lambda_c^\pm$	0.3×10^7	1.6×10^{10}	2×10^{14}	6.2×10^{10}
$\tau^+\tau^-$	3.6×10^8	4.5×10^{10}		1.2×10^{11}

Flavor Physics @ Z pole

- Extremely rich physics & strong competition from Belle-II & LHCb
- Comparative advantages of a Tera-Z
  - V.S. BelleII, Access to particles heavier than Bs, large boost
  - V.S. LHCb, much lower yields (2 orders of magnitudes) Better Acceptance, better reconstruction of neutral final state (photon, missing energy, and even Klong, neutron) and Jet Charge – Jet Origin

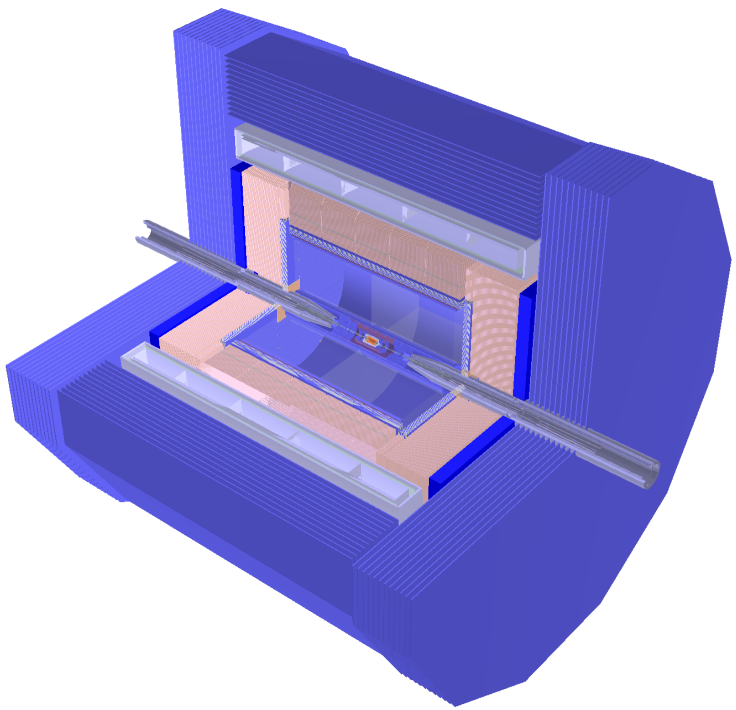
Contents

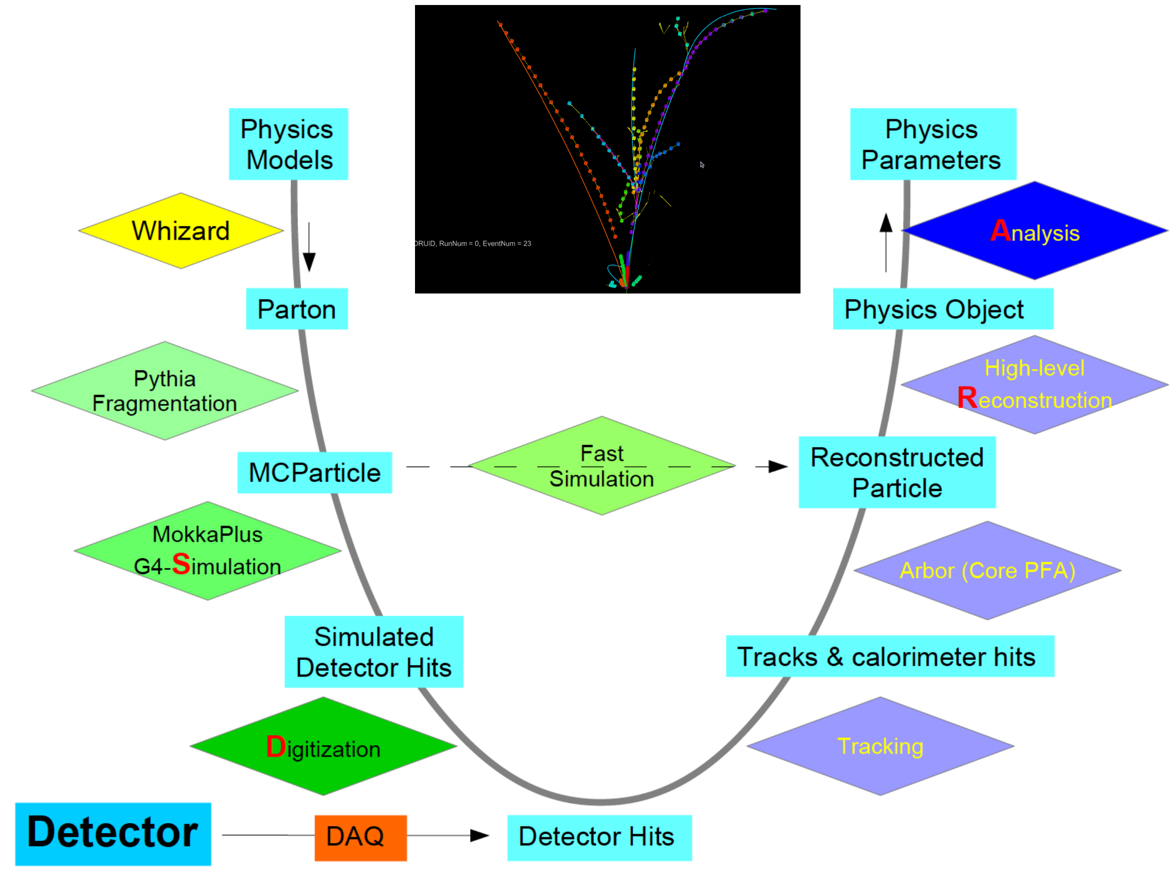
~ 40 benchmarks

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

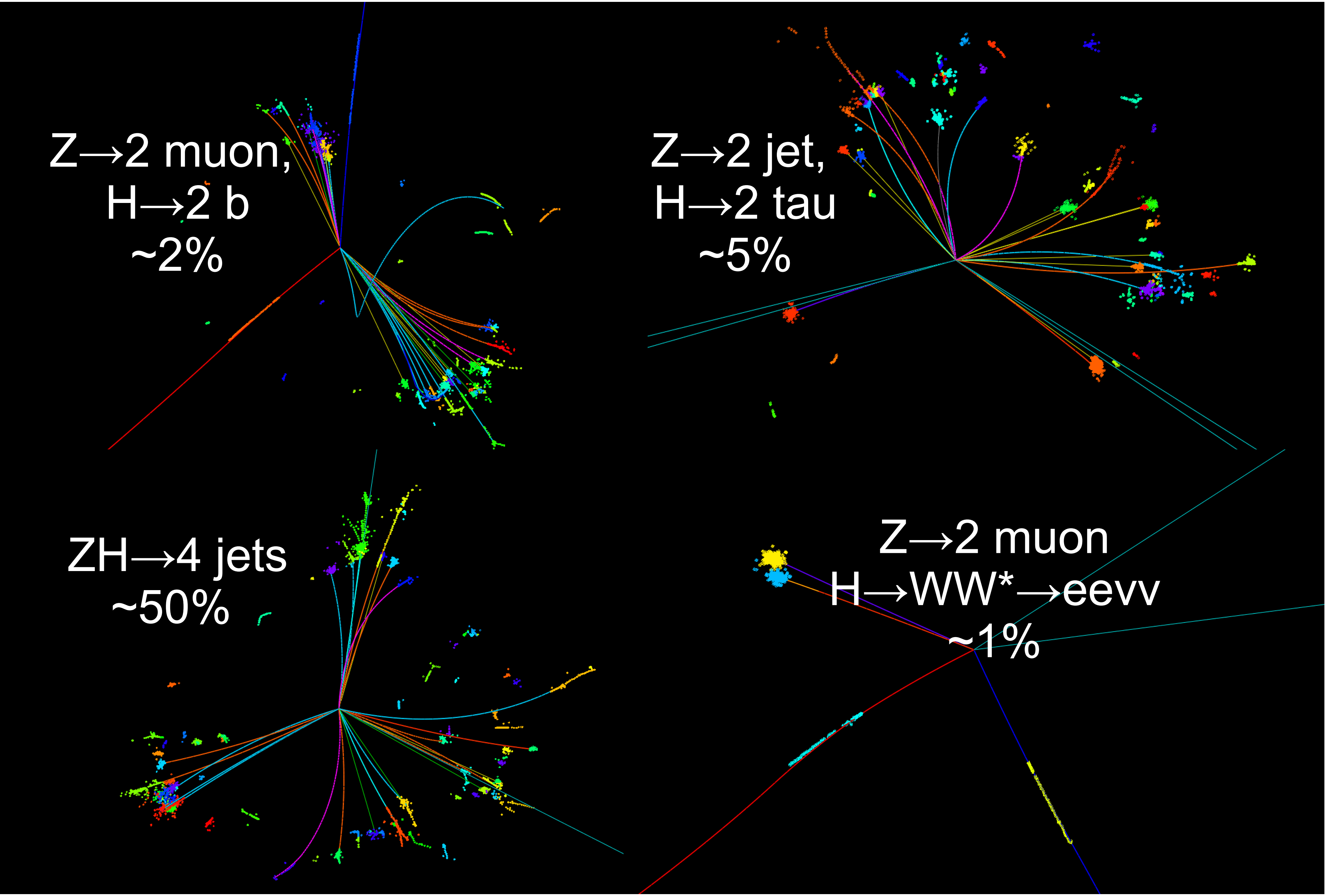
- Access to non-seen
- Orders of magnitudes improvements
- Multiple sqrt(s)
- Non-inclusive + long wishlist -> to be addressed in phase II flavor WP study

Detector & Reconstruction

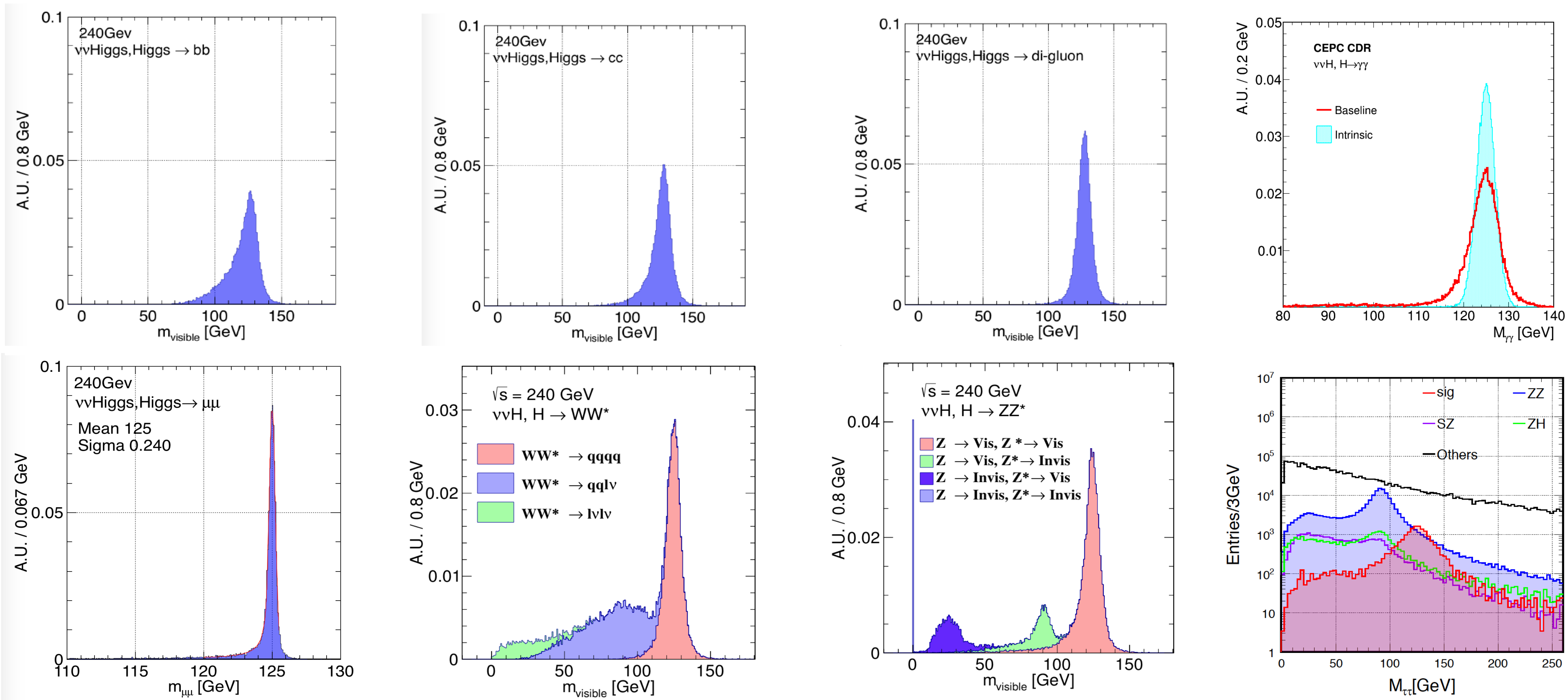




Part of the benchmark evaluated with detector performance in pace ref-TDR R&D


Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~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

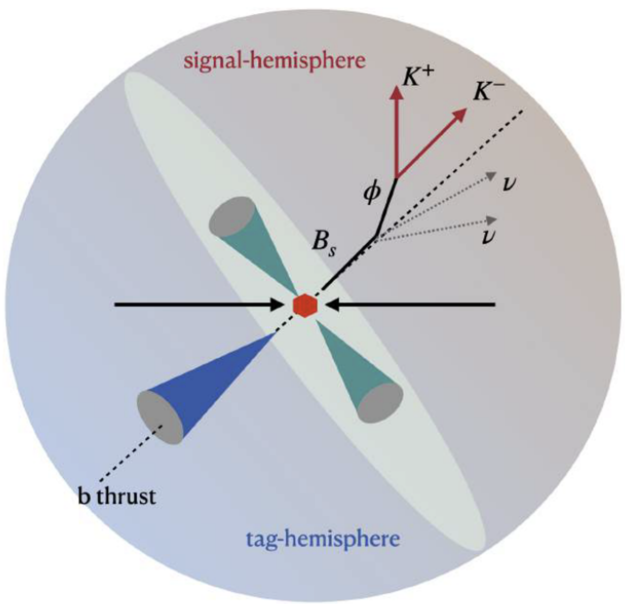
Accesses to the Non-Seen

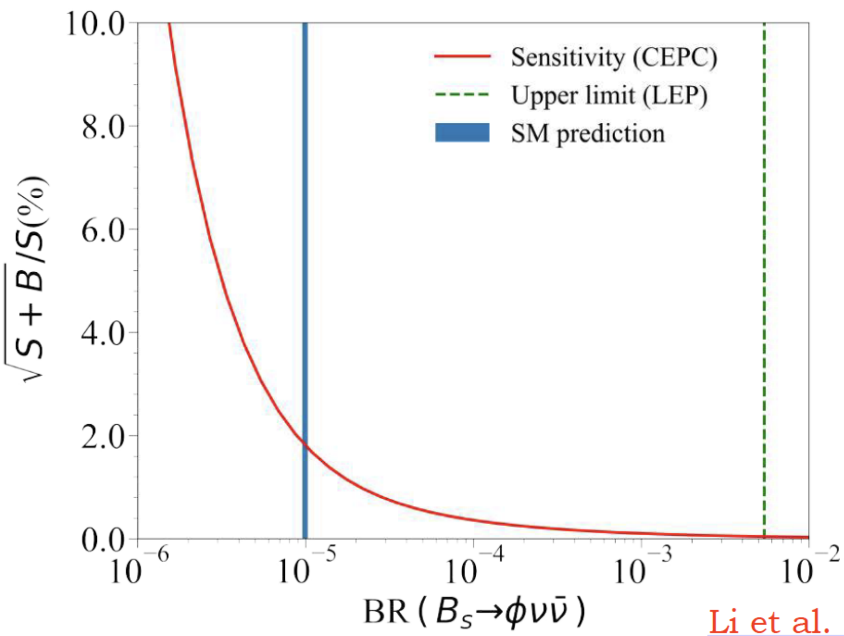
$b \to s\nu\nu$

Li et al. '22

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



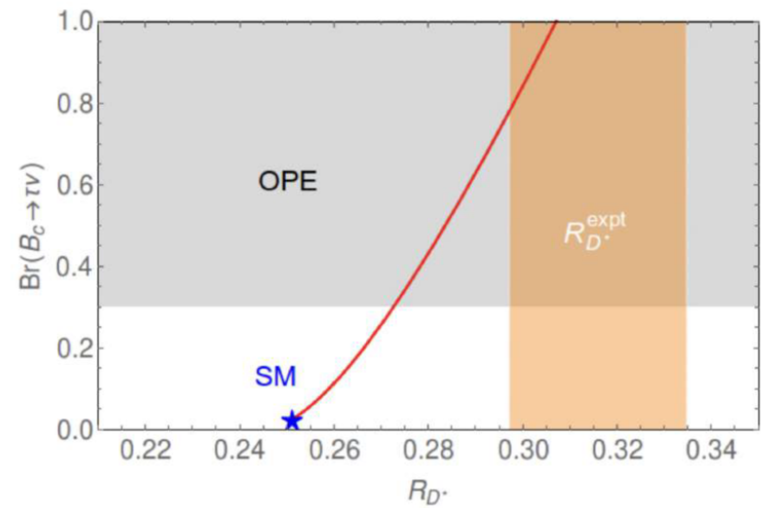


Li et al. '22

$B_c \to \tau\nu$

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

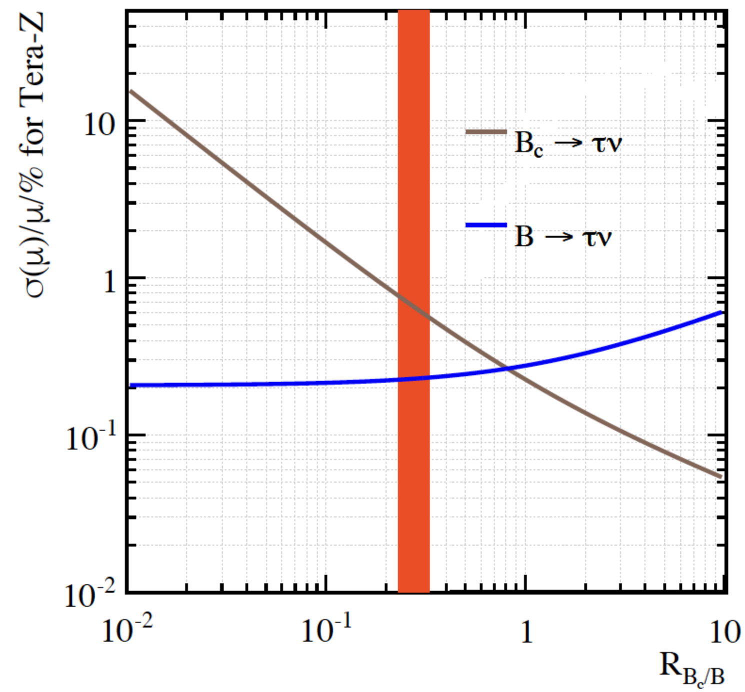
Alonso et al. '16



- 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



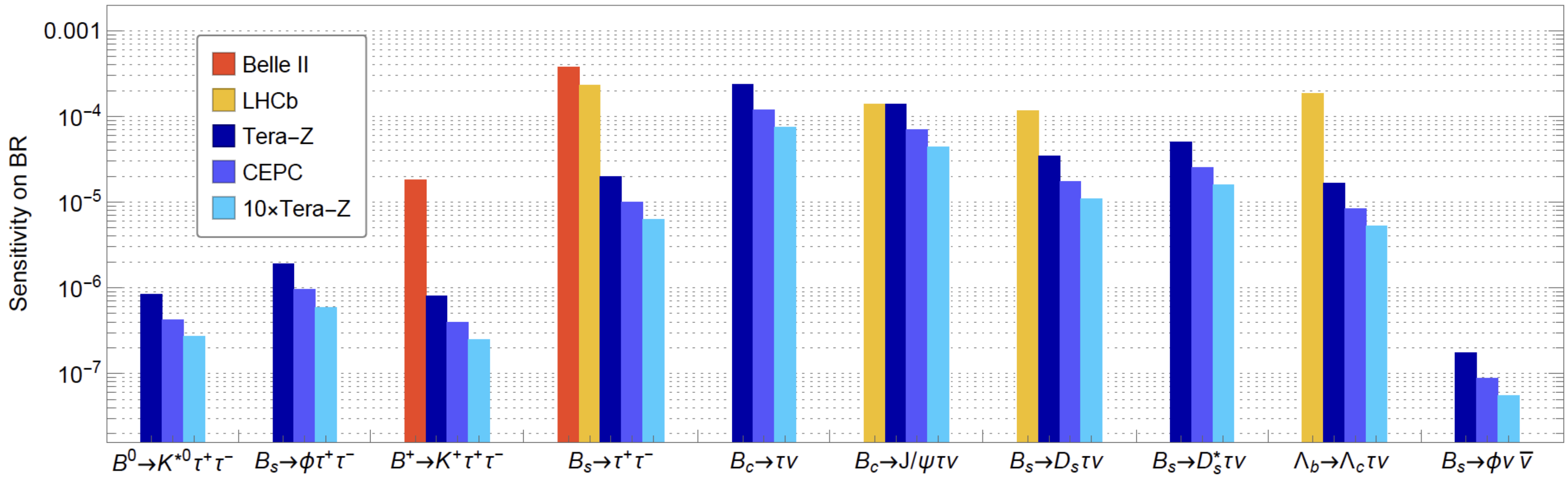


Figure 17: Projected sensitivities of measuring the $b \to s\tau\tau$ [71], $b \to s\nu\bar{\nu}$ [35] and $b \to c\tau\nu$ [37, 63] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 72] have also been provided as a reference. Note, the LHCb sensitivities 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

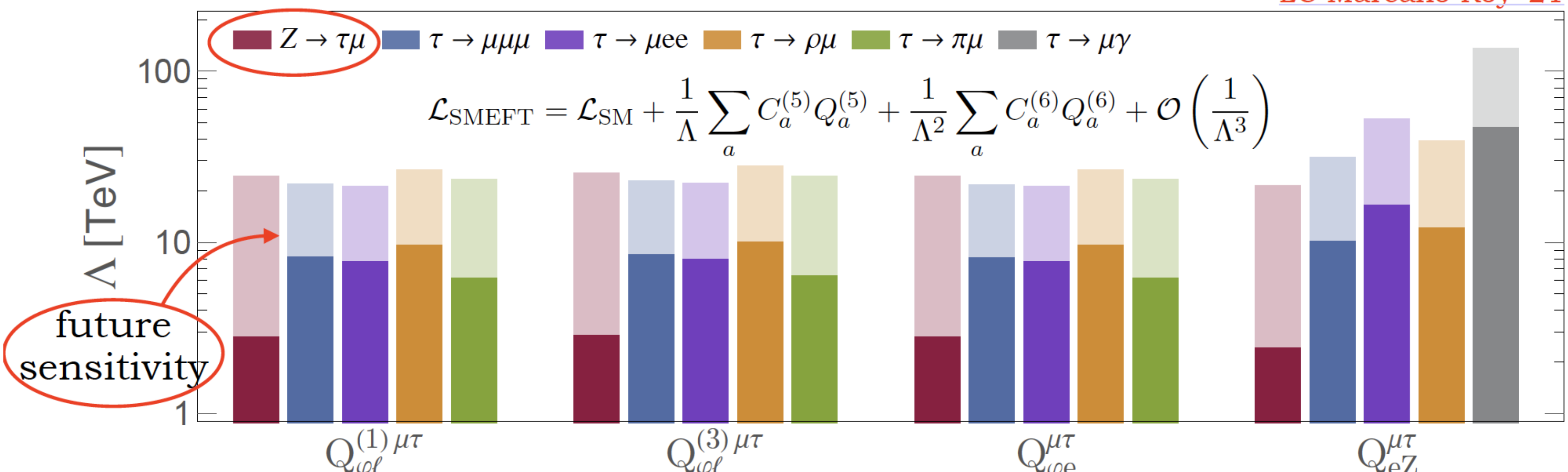
Lepton Flavour Violation in Z decays

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}

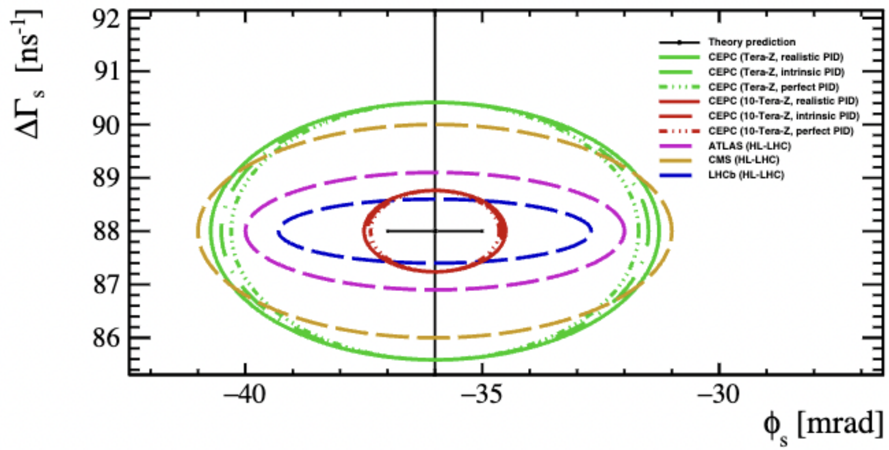
M. Dam '18

- 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



Bs→Jpsi/Phi : Xcheck with LHCb



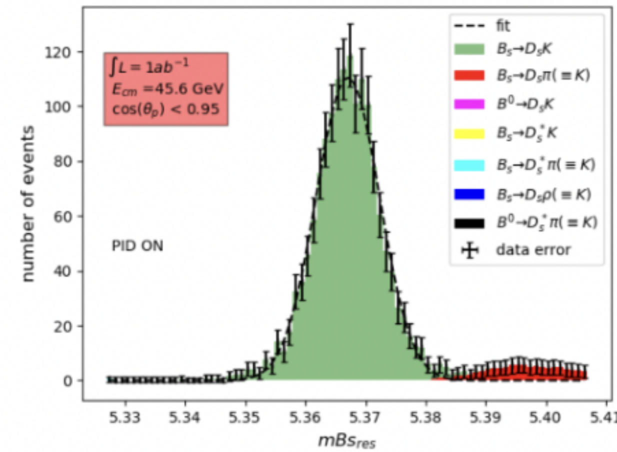


Figure 22: **LEFT:** Projected sensitivities (68% confidence level (C.L.)) of measuring the parameters $\Delta\Gamma_s$ and $\phi_s = -2\beta_s$ at the CEPC [56], through the time-dependent CP violation in the decay $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$. **RIGHT:** B_s^0 mass reconstruction in the decays $B_s^0 \to D_s^{\pm}(\to \phi\pi^{\pm} \to K^+K^-\pi^{\pm})K^{\mp}$ at the Z pole of FCC-ee [126].

Table 1 Parameters table of factors to calculate the precision of ϕ_s, Γ_s and $\Delta\Gamma_s$. The terms with $*$ means that the factor is insensitive to the resolution of Γ_s and $\Delta\Gamma_s$

	LHCb (HL-LHC)	CEPC (Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance × efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavor tagging*	4.7%	17.3%	3.7
Time resolution* $(\exp(-\frac{1}{2}\Delta m_s^2\sigma_t^2)^2)$	0.52	1	1.92
σ_t (fs)*	45	4.7	
Scaling factor ξ	0.0015	0.0021	1.4
$\sigma(\phi_s)$	3.3 mrad	4.6 mrad	

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Regular Article - Theoretical Physics

Prospect for measurement of the CP-violating phase ϕ_s in the $B_s \to J/\psi\phi$ channel at a future Z factory

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[1] Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[3] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Significantly enhanced using Jet origin id tech.

Lepton Flavor Universality

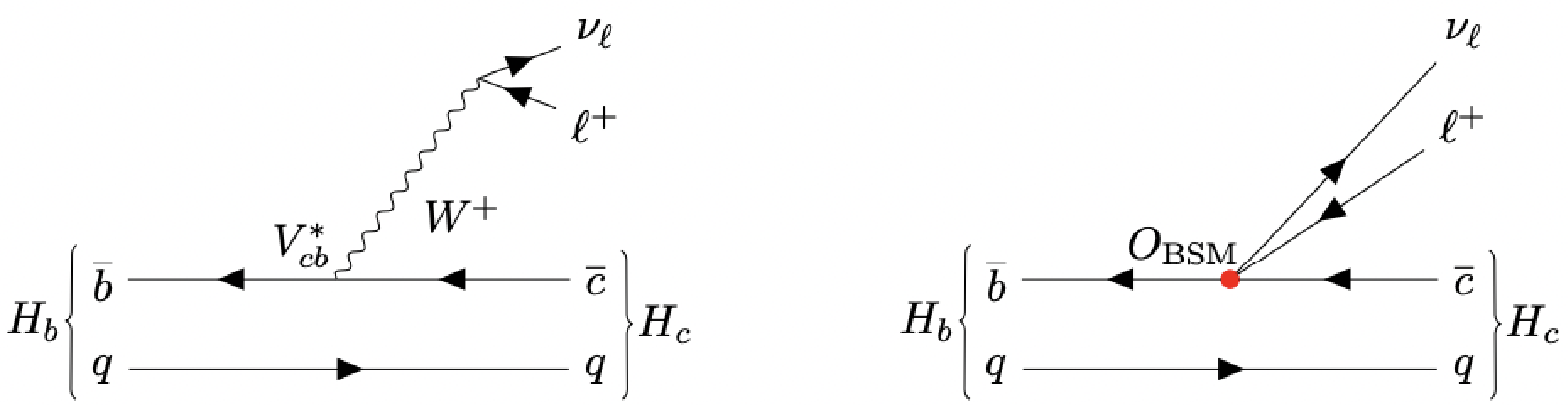


Figure 13: Illustrative Feynman diagrams for the transition $H_b \to H_c \ell^+ \nu_\ell$. **LEFT**: SM example. **RIGHT**: BSM example.

R_{H_c}	SM Value	Tera-Z	4×Tera-Z	10×Tera-Z
$R_{J/\psi}$	0.289	4.3×10^{-2}	2.1×10^{-2}	1.4×10^{-2}
R_{D_s}	0.393	4.1×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
$R_{D_s^*}$	0.303	3.3×10^{-3}	1.6×10^{-3}	1.0×10^{-3}
R_{Λ_c}	0.334	9.8×10^{-4}	4.9×10^{-4}	3.1×10^{-4}

Lepton Flavor Violation

Measurement	Current	HL-LHC	FCC	CEPC prelim.
$\mathrm{BR}(Z \to \tau\mu)$	$< 6.5 \times 10^{-6}$	1.4×10^{-6}	10^{-9}	10^{-9}
$\mathrm{BR}(Z \to \tau e)$	$< 5.0 \times 10^{-6}$	1.1×10^{-6}	10^{-9}	
$\mathrm{BR}(Z \to \mu e)$	$< 2.62 \times 10^{-7}$	5.7×10^{-8}	$10^{-8} - 10^{-10}$	10^{-9}

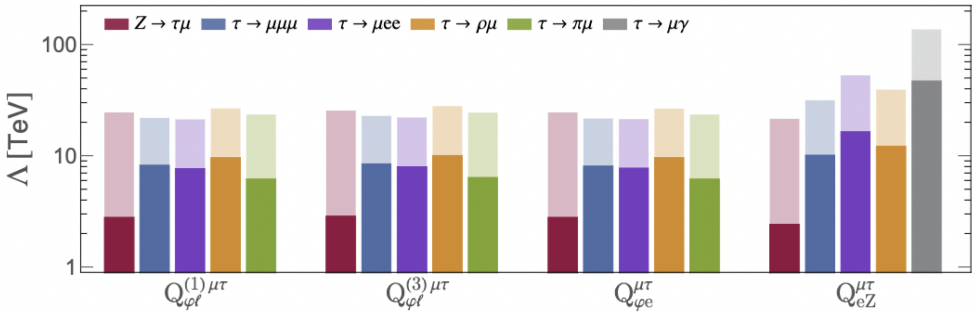


Figure 28: Sensitivity reach for probing the NP scale of the LFV operators in Eq. (8.1) and Eq. (8.2). Here the current bounds (dark-colored bars) are set by ATLAS [206] ($Z \to \tau\mu$) and B factories [149] (LFV τ decays), and the projected sensitivities (light-colored bars) are based on searches for $Z \to \tau\mu$ at the CEPC Z pole run with 100 ab^{-1} and $\tau \to \mu$ transitions at Belle II with 50 ab^{-1} [8], see Tables 7 and 8. The Wilson coefficients have been set equal to one uniformly. This plot is taken from Ref. [202]

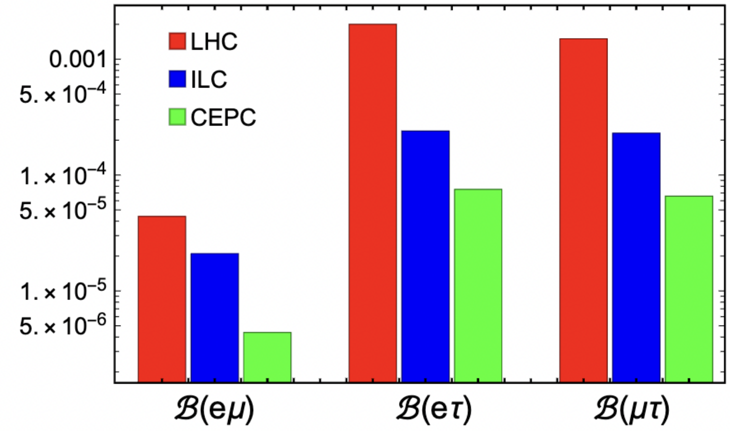
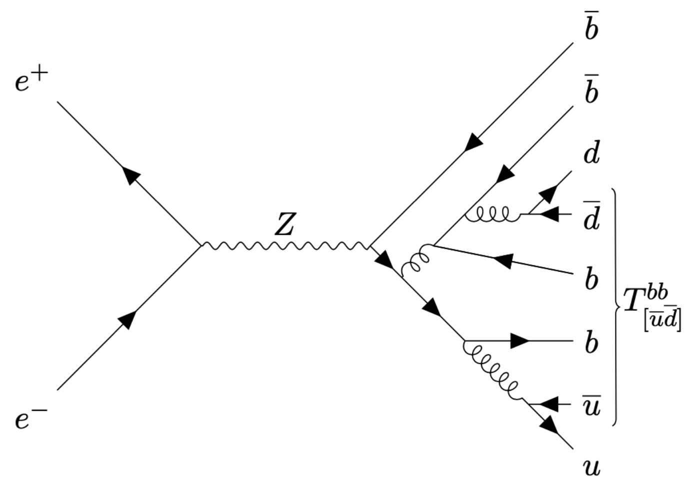
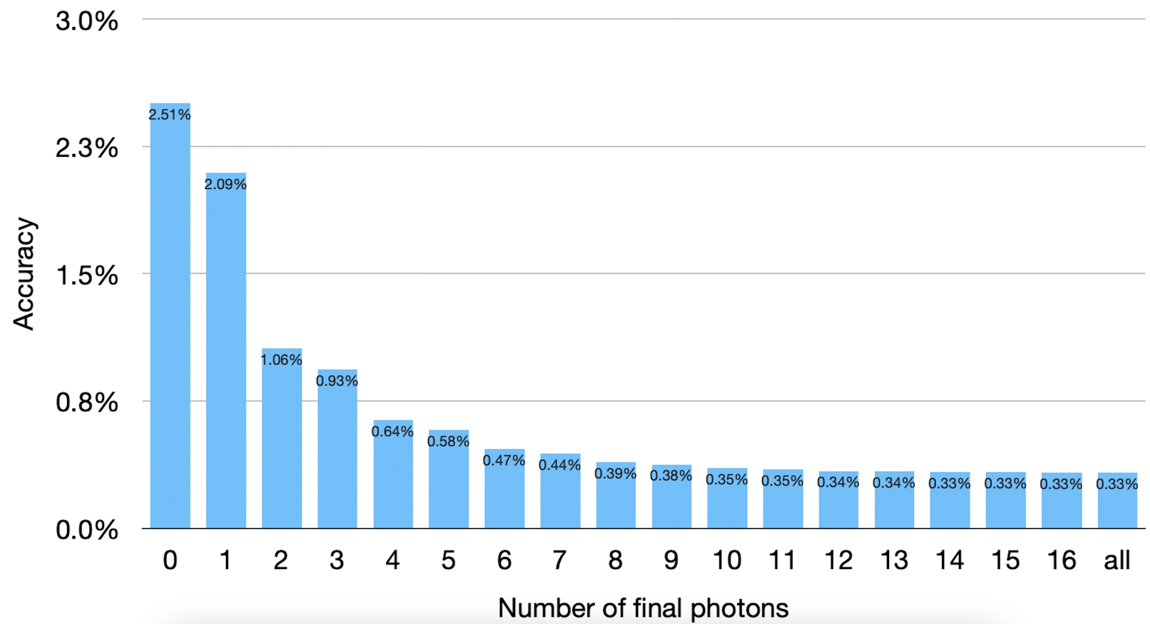
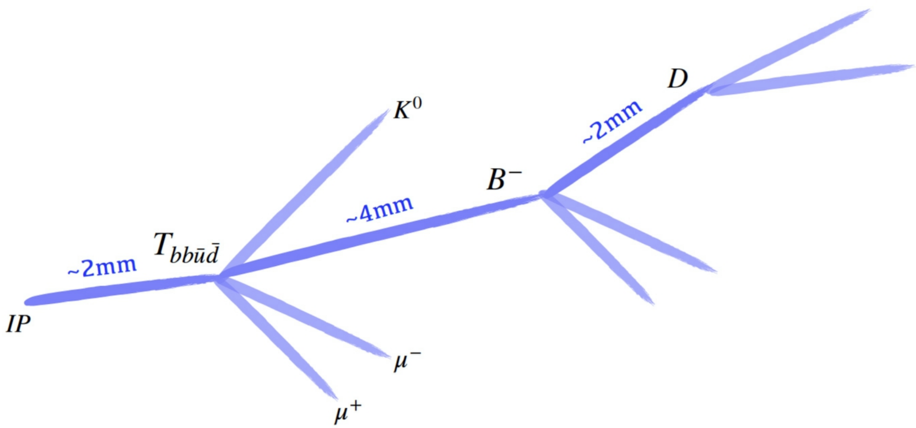


Figure 33: Anticipated upper limits on LFV Higgs decays at CEPC, ILC, and LHC. Figure updated from [231].

Spectroscope: T(bbud)



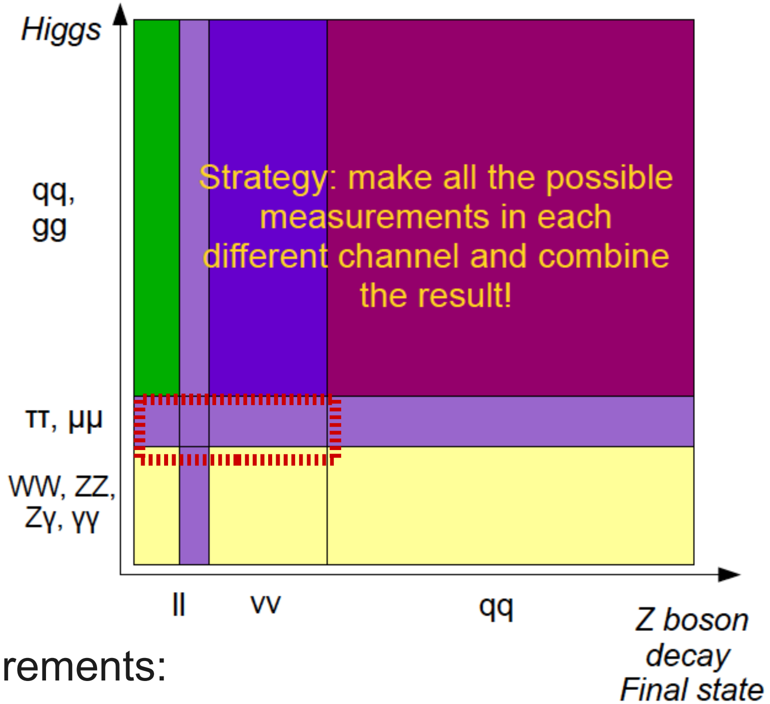




Simplified assumptions and parton-level simulations were employed to deduce the inclusive decay rates: $\mathrm{BR}(Z \to X + T^{cc}_{[\bar{q}\bar{q}']}) \sim \mathcal{O}(10^{-6})$, $\mathrm{BR}(Z \to X + \Xi_{cc}) \sim 5 \times 10^{-5}$, and $\mathrm{BR}(Z \to X + \Omega_{cc}) \sim 1 \times 10^{-5}$ at the Z pole [296]. Additionally, $\mathrm{BR}(Z \to X + T^{bb}_{[\bar{q}\bar{q}']}) \sim \mathcal{O}(10^{-6})$ was also calculated [297]. It's worth noting that $T^{bb}_{[\bar{q}\bar{q}']}$ could have a mass lower than the sum of B and B^* meson mass, thus it could only decay via weak interaction - as

Performance requirements

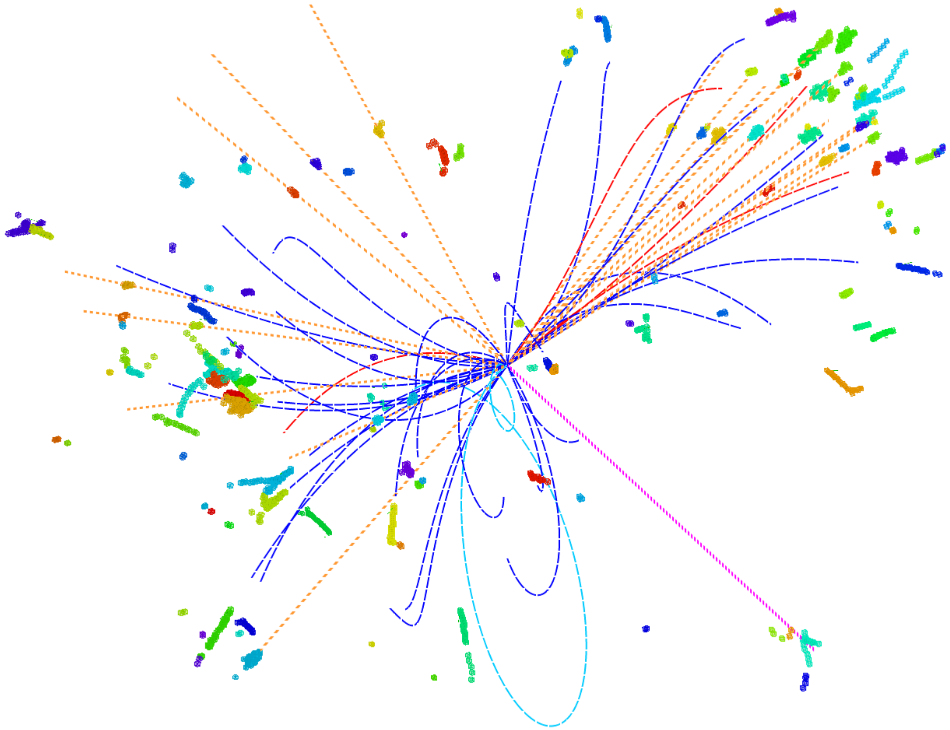
- To reconstruct all kinds of Physics Object
  - Identification & Measurements
  - Objects:
    - Lepton, Photons, Kaon,
    - pi-0, Tau, Lambda, Kshort,
    - Heavy flavor hadrons,
    - **Jets**
    - Missing energy/momentum
    - Exotics...
- Massive Four in Standard Model:
  - Z & W: ~ 70% goes to a pair of jets
  - Higgs: ~90% final state with jets (ZH events)
  - Top: t → W + b



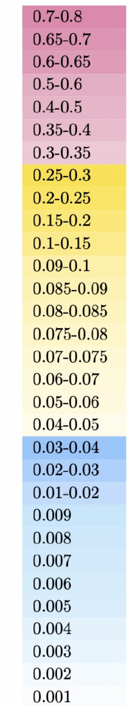
- Requirements:
  - **1-1 correspondence**

    Excellent pattern. Reco. & Object id - **PID**
  - Larger acceptance, Excellent intrinsic resolutions, Extremely stable...
- Be addressed by detector design, technology, and reconstruction algorithm

Jet origin id

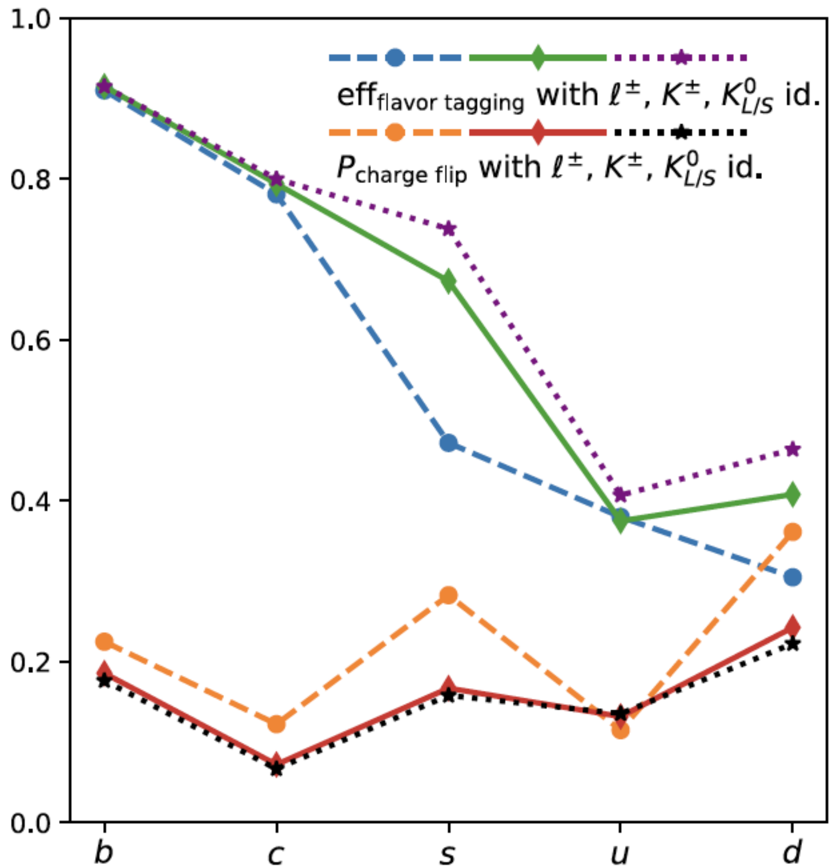


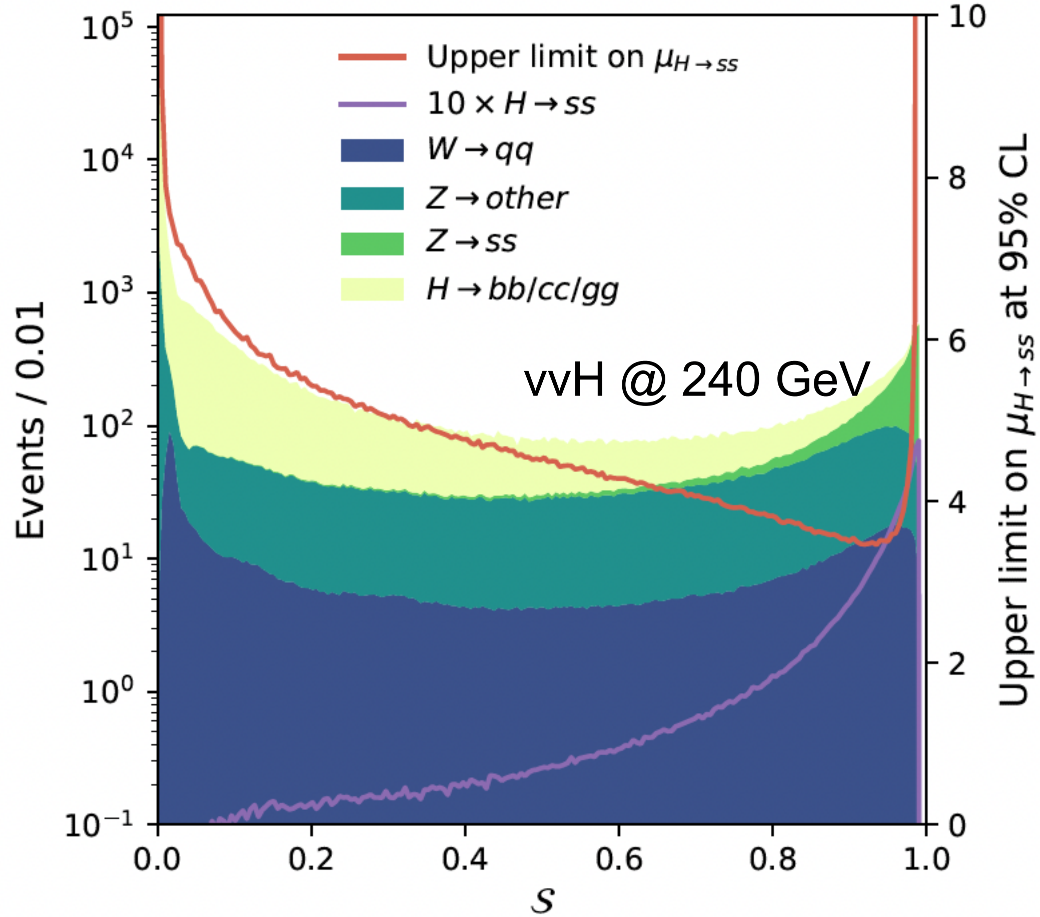
True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.738	0.167	0.034	0.026	0.005	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.167	0.737	0.026	0.034	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.015	0.740	0.057	0.037	0.032	0.026	0.010	0.009	0.017	0.043
$\bar{c}$	0.015	0.015	0.055	0.741	0.032	0.037	0.010	0.026	0.016	0.010	0.043
s	0.003	0.003	0.020	0.018	0.541	0.104	0.030	0.082	0.062	0.045	0.092
$\bar{s}$	0.002	0.003	0.018	0.021	0.101	0.543	0.085	0.028	0.044	0.062	0.092
u	0.002	0.003	0.019	0.012	0.044	0.132	0.375	0.057	0.079	0.168	0.109
$\bar{u}$	0.003	0.002	0.011	0.020	0.132	0.043	0.062	0.368	0.166	0.084	0.108
d	0.003	0.003	0.012	0.020	0.111	0.093	0.083	0.223	0.261	0.080	0.110
$\bar{d}$	0.003	0.003	0.020	0.013	0.093	0.113	0.226	0.079	0.076	0.265	0.110
G	0.015	0.014	0.025	0.025	0.053	0.053	0.043	0.044	0.033	0.035	0.661



- **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.)**
- 1 Million samples each, 60/20/20% for training, validation & test

Performance with different PID scenarios & H→ss measurements



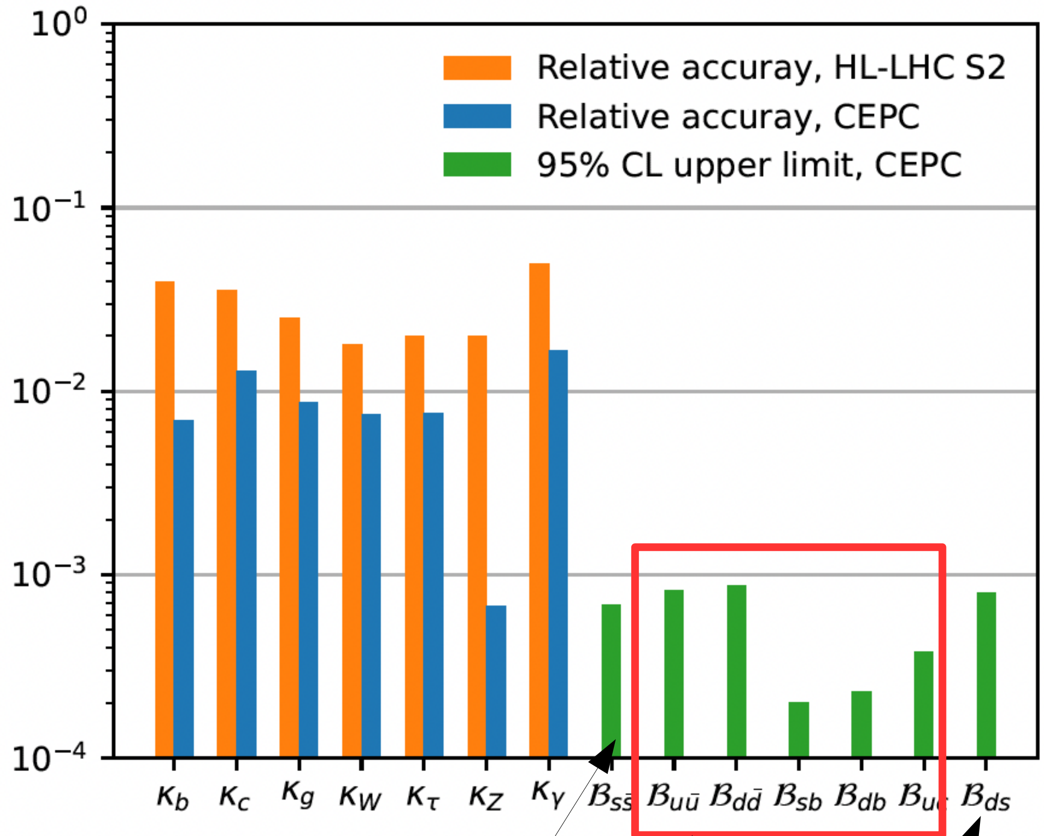


Flavor tagging: type that maximize {L_q + L_q_bar, L_g}

If quark jet: jet charge ~ compare {L_q, L_q_bar}

Remark: current jet flavor tagging efficiency & jet charge flip rates are projections of the 11-dim arrays produced by Jet origin id

Benchmark analyses: Higgs rare/FCNC



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.

...In principle...

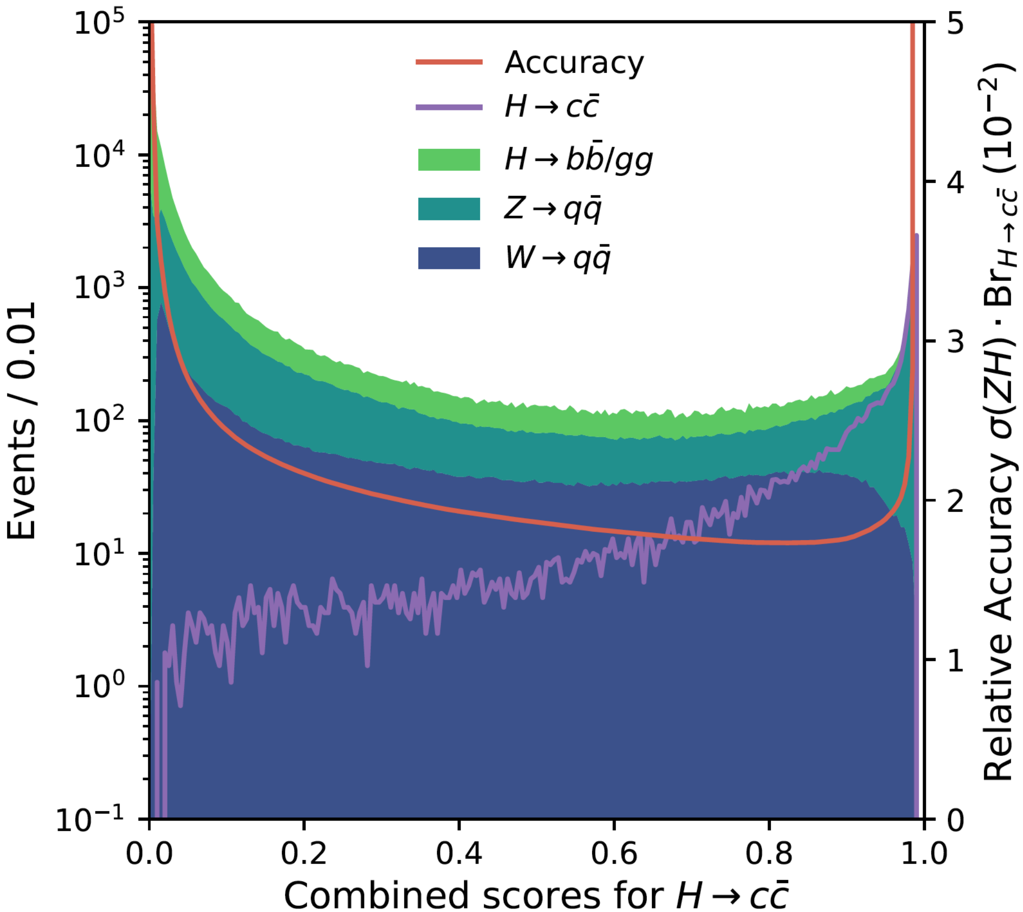
Z boson FCNC

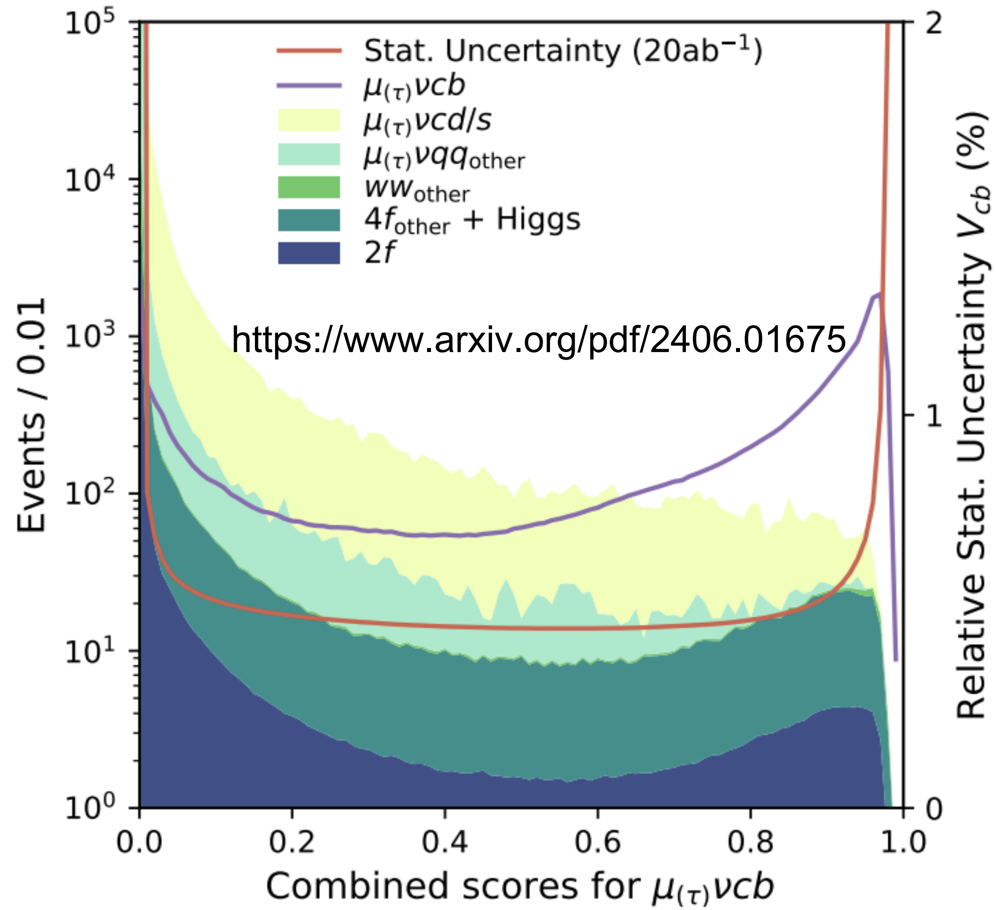
- Without considering other process other than Z
  - 1 Tera Z boson
- Confusion matrix based
  - Using 11x11 confusion matrix as template, extract signal strength of FCNC
  - Re-use confusion matrix of Higgs boson (No much difference according study of Yongfeng)
  - may not be statistically optimal
- No kinematic cut. No polar angle factors considered

	Z Br by SM (Flavor violating Higgs and Z decays at FCC-ee)	95% Upper limit on Br (statistics only)
Z->bs	4.2E-8	2.3e-07
Z->bd	1.8E-9	2.5e-07
Z->cu	1.4E-18	6.3e-07
Z->sd	-	1.3e-06

But surly the Calibration etc need breakthrough method...

Recent update at more benchmarks

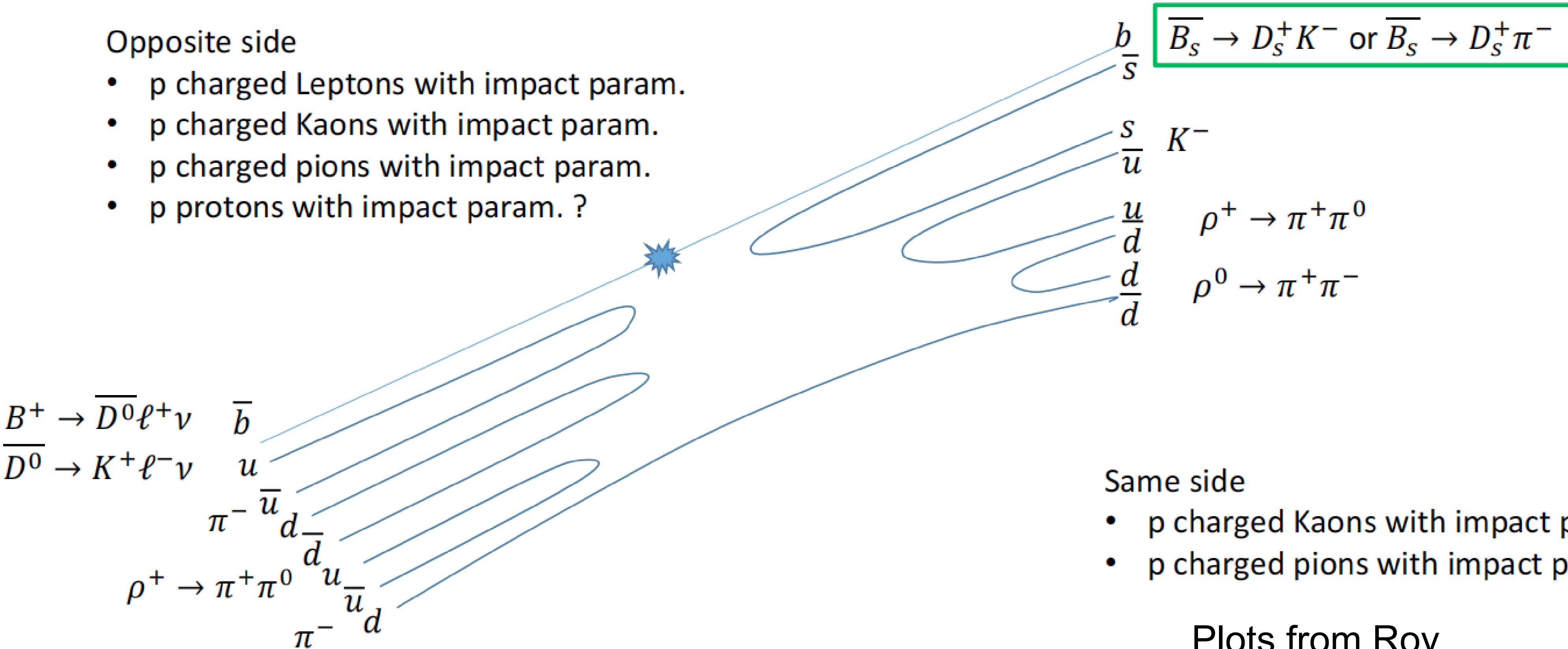




- From Jet Flavor Tagging to Jet Origin ID:
  - vvH, H→cc: 3% → 1.7% (**Preliminary**)
  - Vcb: 0.75% → 0.45% (muvqq channel. evqq: 0.6%, combined 0.4%)

B-charge flip rate: Bs oscillations

Opposite side
- p charged Leptons with impact param.
- p charged Kaons with impact param.
- p charged pions with impact param.
- p protons with impact param. ?

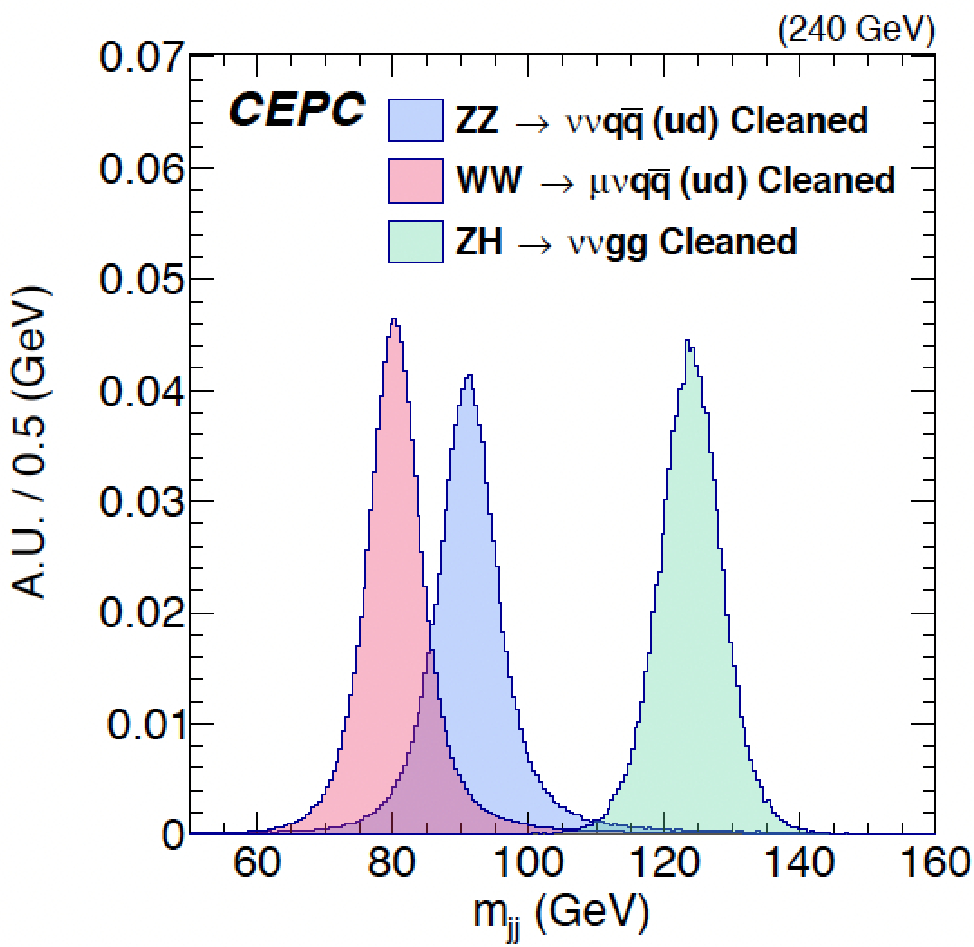


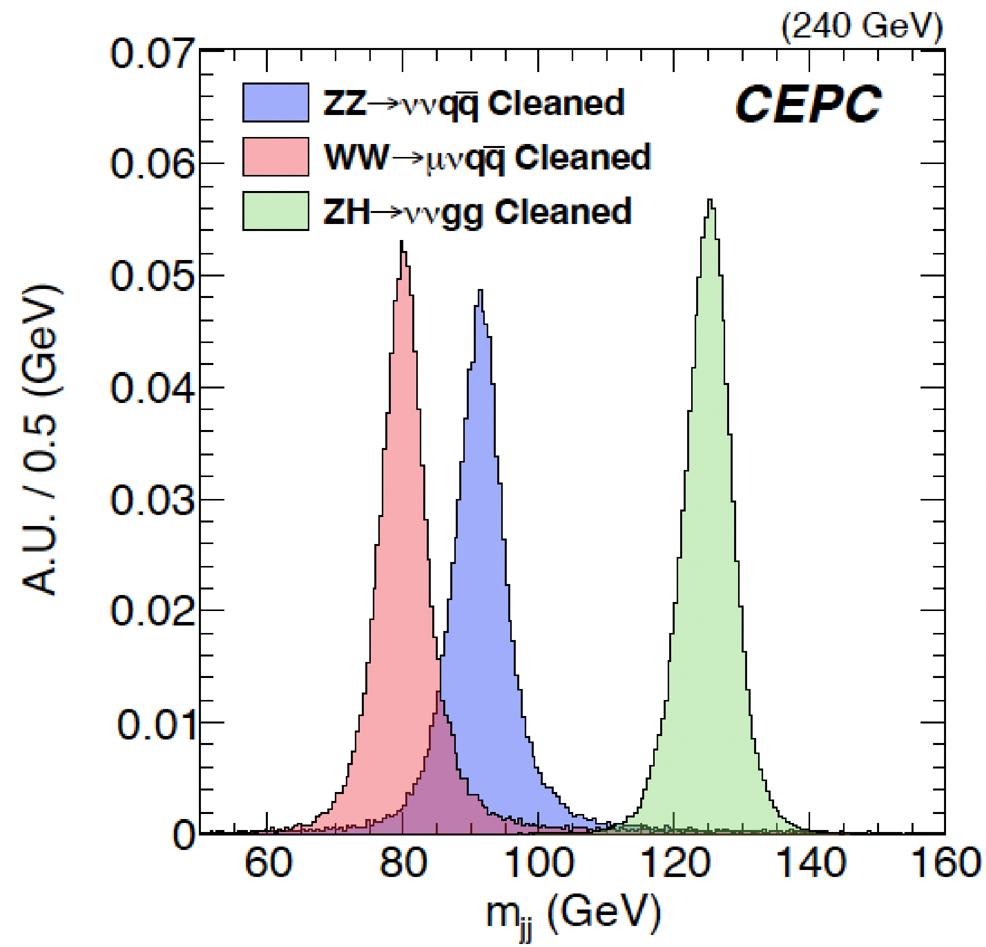
Same side
- p charged Kaons with impact param.
- p charged pions with impact param.

Plots from Roy

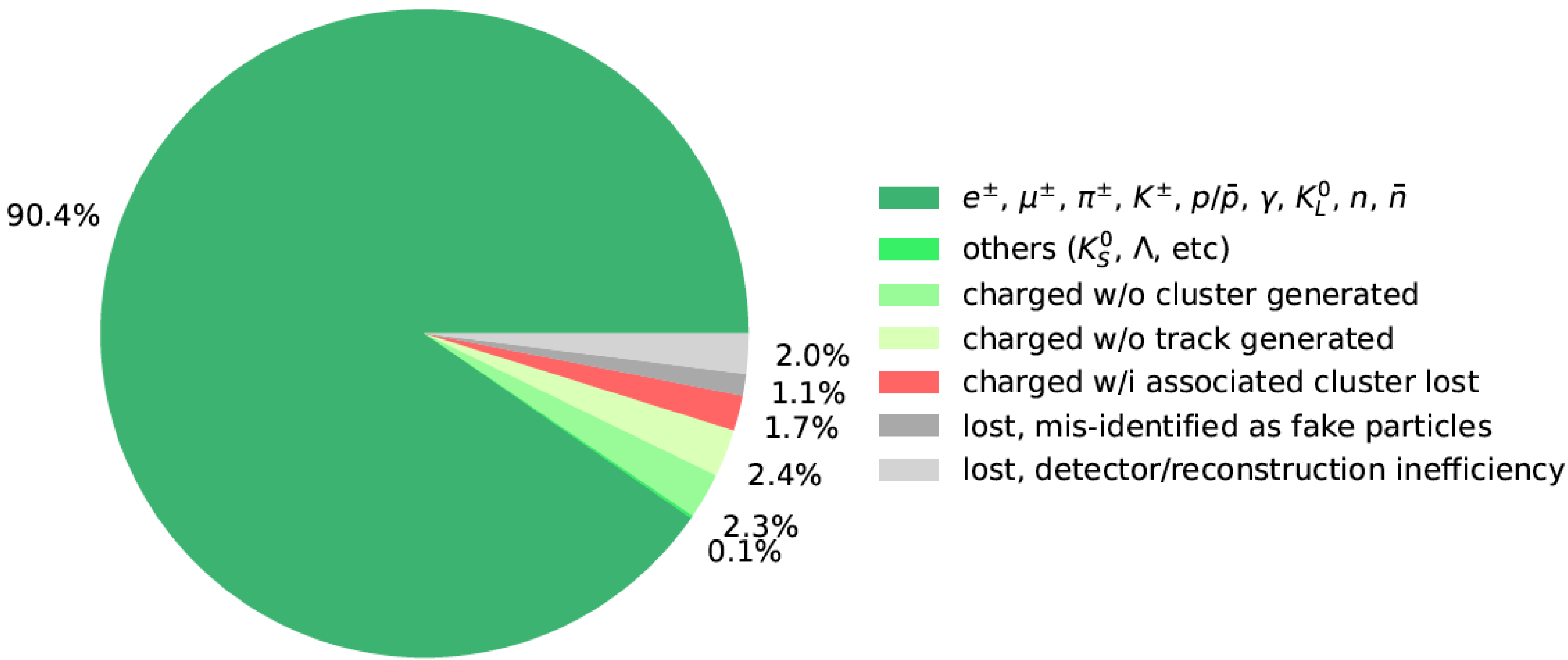
- See Mingrui's talk for more details

BMR of 2.75% reached





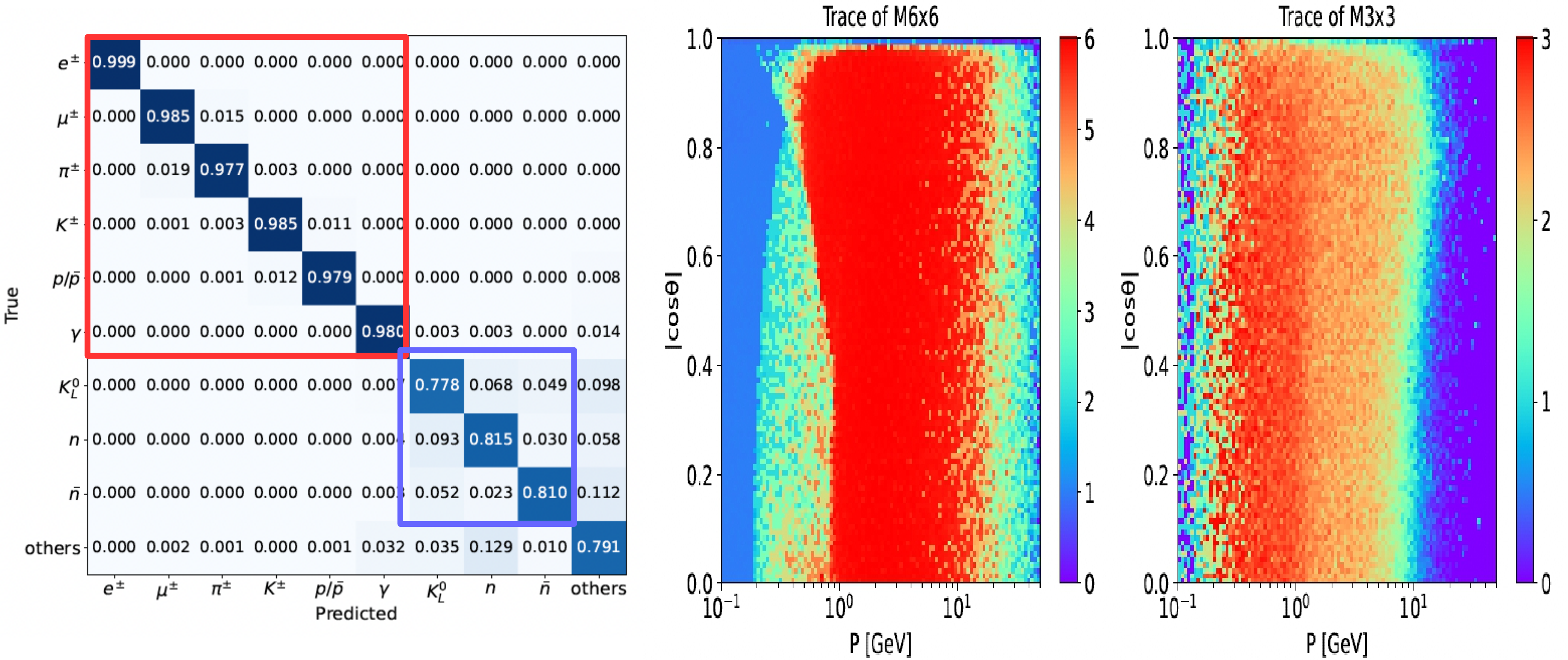
Visible particle: mapping composition



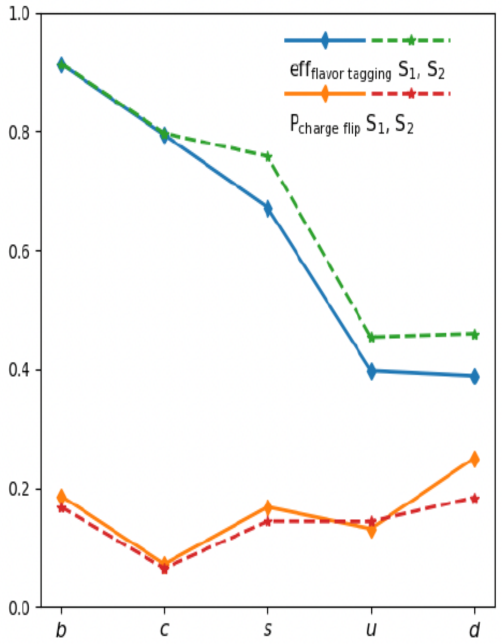
~95% of the visible energy are mapped to reco-particle with 1-1 correspondency.

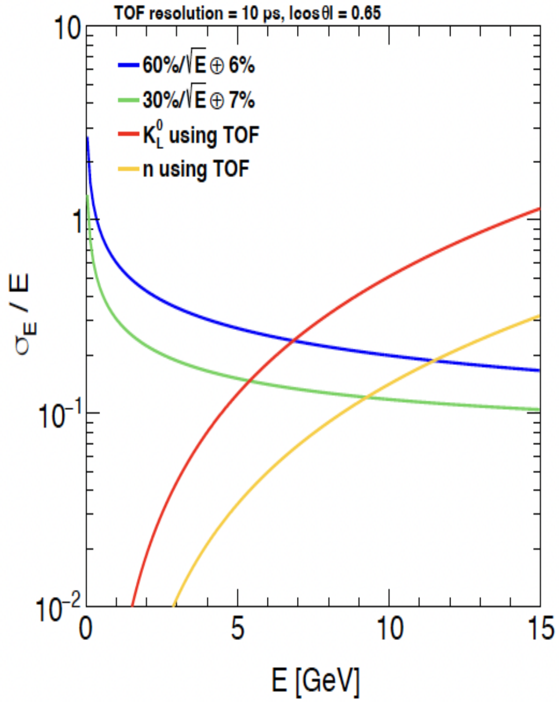
~90% are well reconstructed: has the right composition of clusters & tracks.

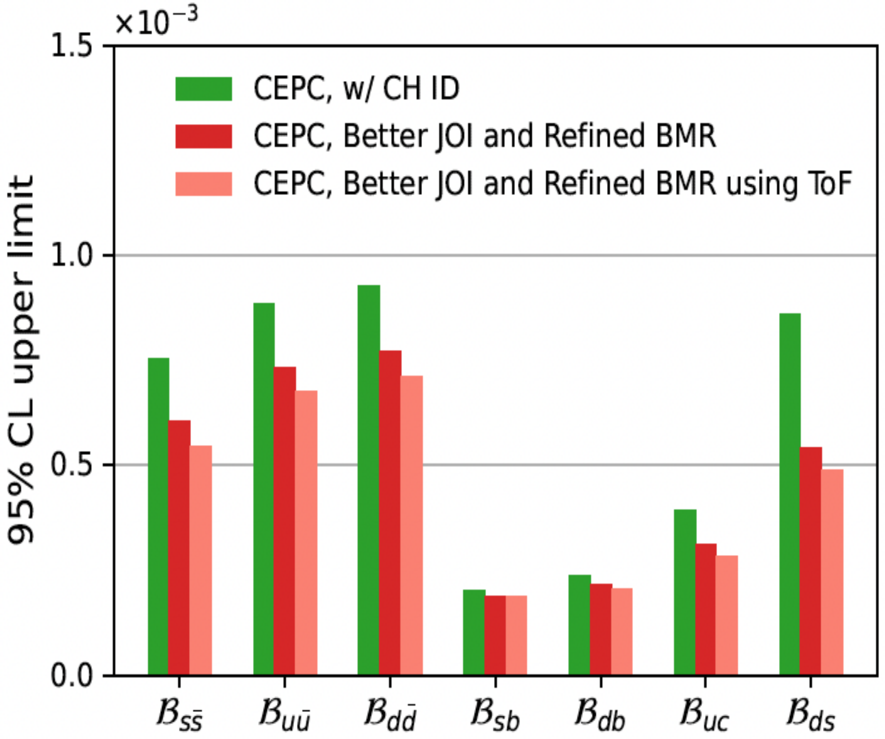
Identification of 'well reconstructed' particles

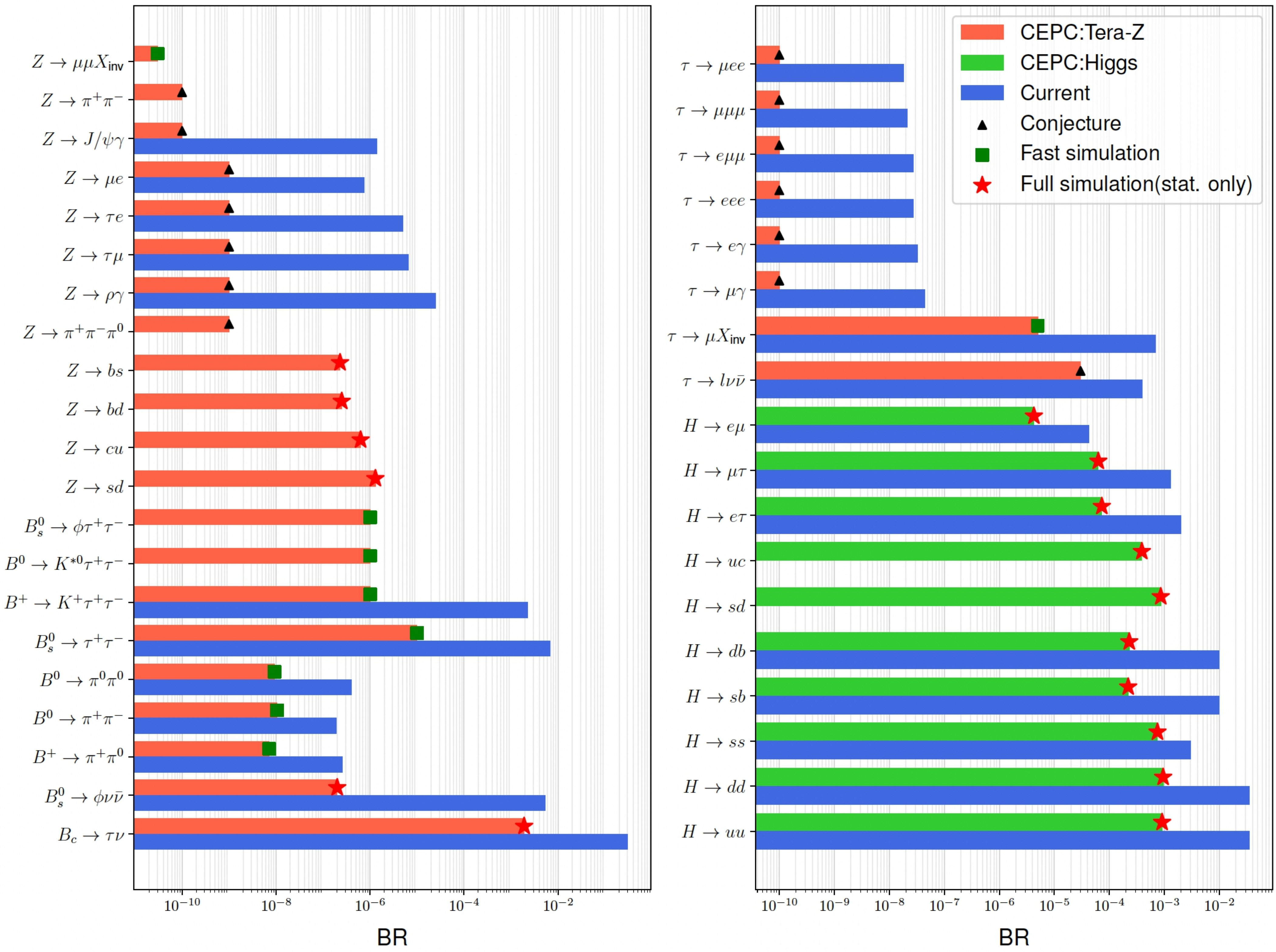


Impact on benchmark physics...









$Z \to \mu\mu X_{\rm inv}$
$Z \to \pi^+\pi^-$
$Z \to J/\psi\gamma$
$Z \to \mu e$
$Z \to \tau e$
$Z \to \tau\mu$
$Z \to \rho\gamma$
$Z \to \pi^+\pi^-\pi^0$
$Z \to bs$
$Z \to bd$
$Z \to cu$
$Z \to sd$
$B_s^0 \to \phi\tau^+\tau^-$
$B^0 \to K^{*0}\tau^+\tau^-$
$B^+ \to K^+\tau^+\tau^-$
$B_s^0 \to \tau^+\tau^-$
$B^0 \to \pi^0\pi^0$
$B^0 \to \pi^+\pi^-$
$B^+ \to \pi^+\pi^0$
$B_s^0 \to \phi\nu\bar{\nu}$
$B_c \to \tau\nu$
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2}
BR
$\tau \to \mu ee$
$\tau \to \mu\mu\mu$
$\tau \to e\mu\mu$
$\tau \to eee$
$\tau \to e\gamma$
$\tau \to \mu\gamma$
$\tau \to \mu X_{\rm inv}$
$\tau \to l\nu\bar{\nu}$
$H \to e\mu$
$H \to \mu\tau$
$H \to e\tau$
$H \to uc$
$H \to sd$
$H \to db$
$H \to sb$
$H \to ss$
$H \to dd$
$H \to uu$
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
BR
CEPC:Tera-Z
CEPC:Higgs
Current
Conjecture
Fast simulation
Full simulation(stat. only)

Summary

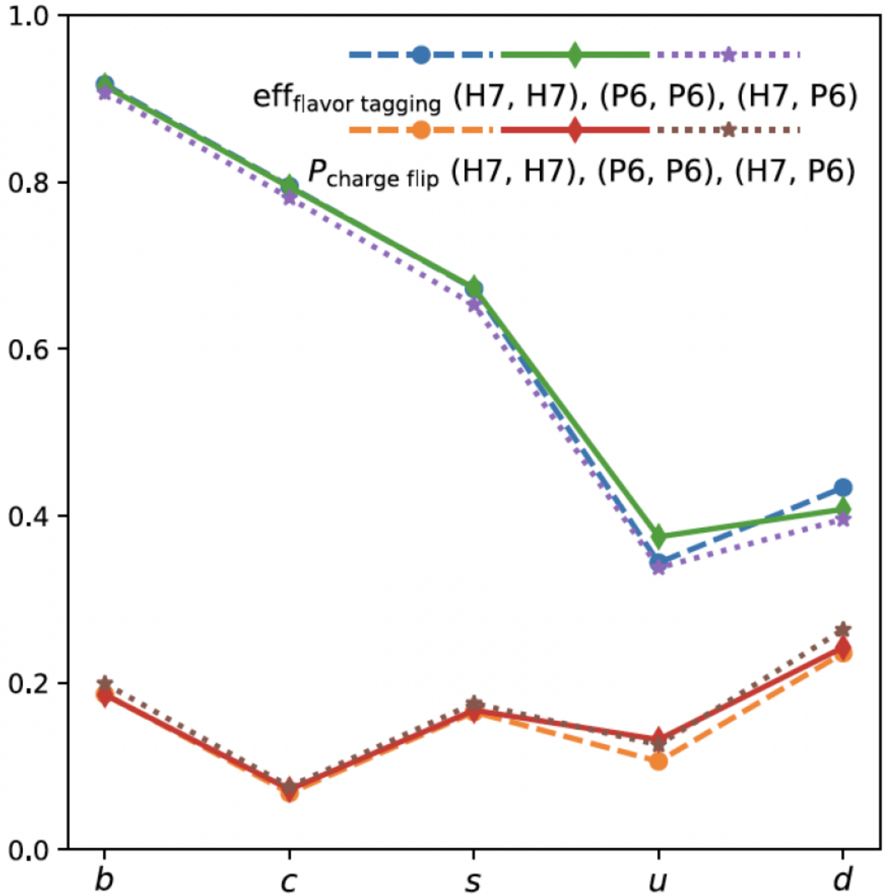
- Electron Positron Higgs factories: a gigantic boost from LHC
- CEPC physics studies: composed of physics reach/pheno and detector requirement optimization, aims at White papers to be released according to the project paces
  - Community activated, results in multiple new ideas/results
  - Good international 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 Reference detector design TDR)
- New tools, especially AI, could significantly alter the physics study/detector design.

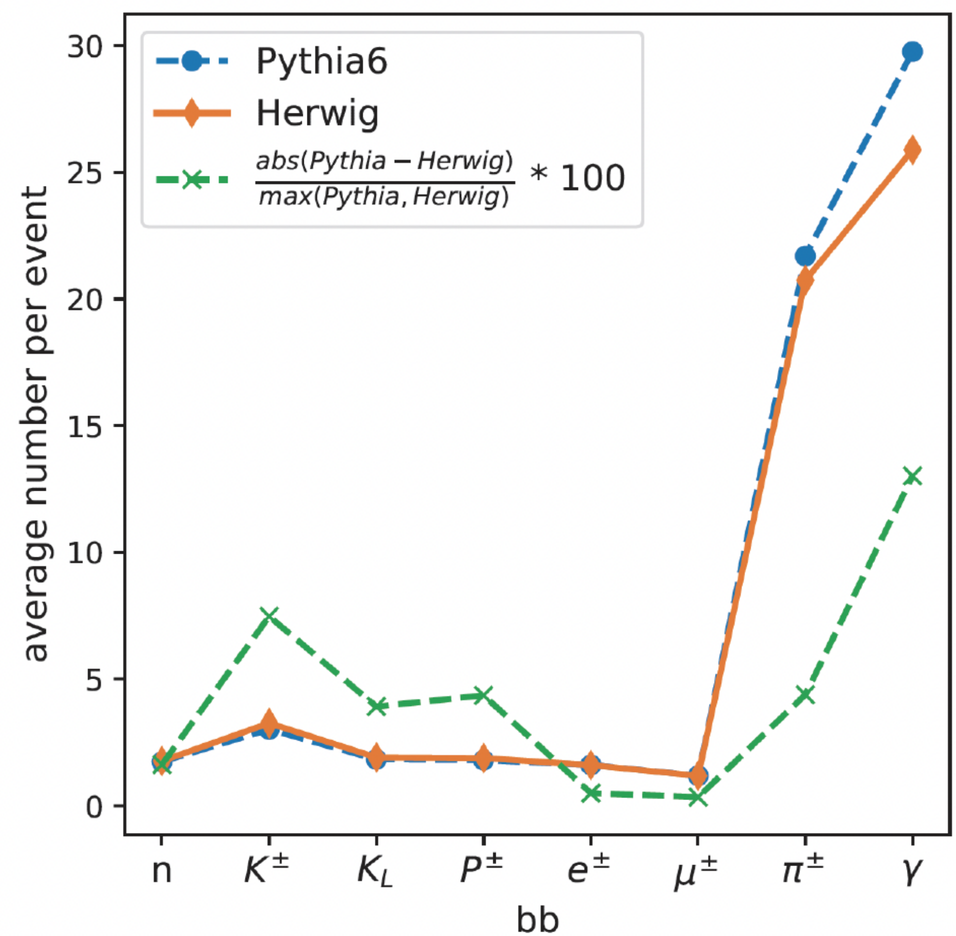
Summary

- White paper draft available at:
  - https://indico.ihep.ac.cn/event/20312/attachments/71044/105872/CEPC_Flavor_White_Paper_24th_Oct_2024_.pdf

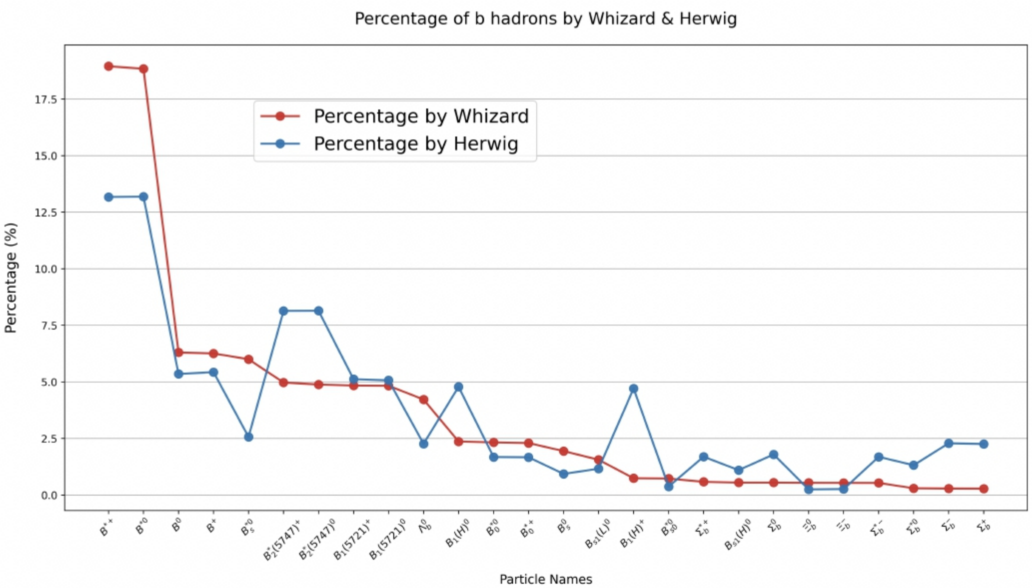
Back up

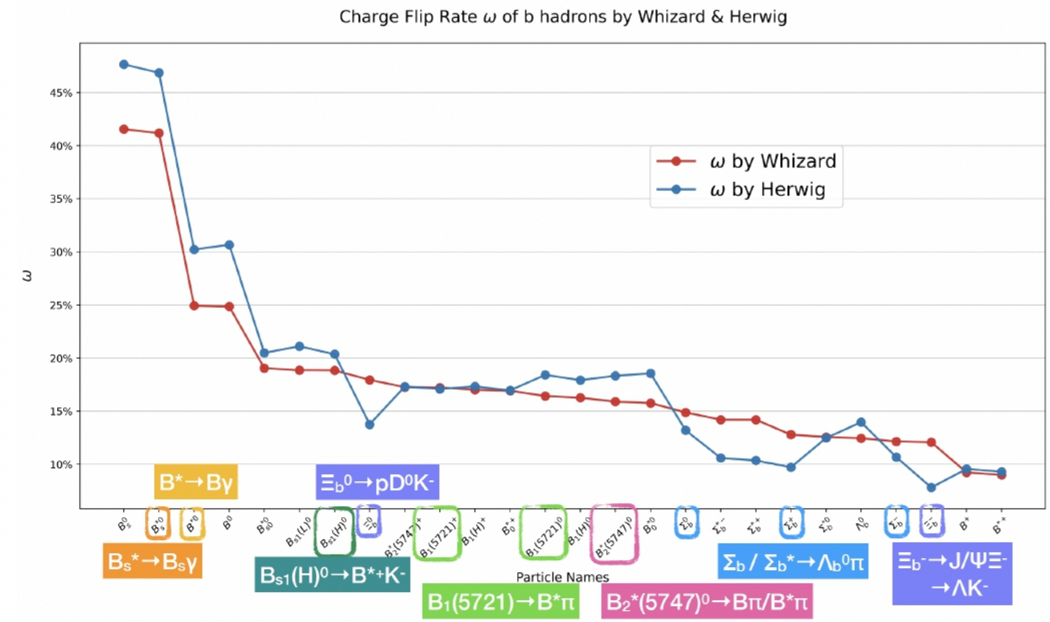
V.S. Hadronization models

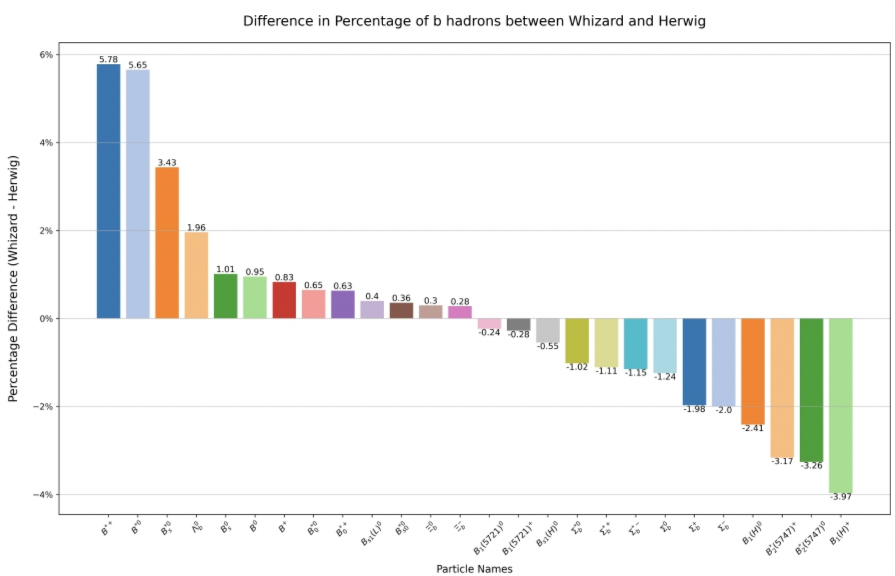


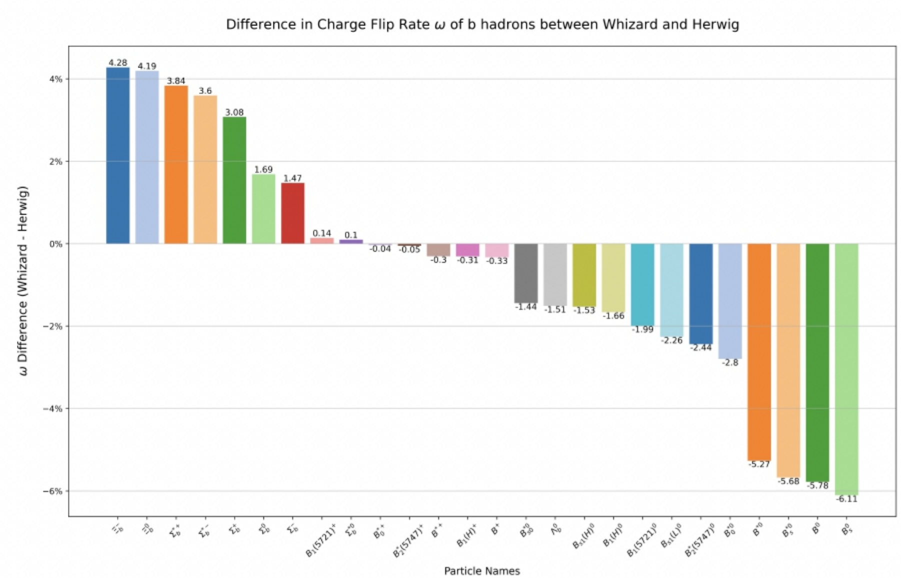


b-jet: leading b-hadrons & flip rates

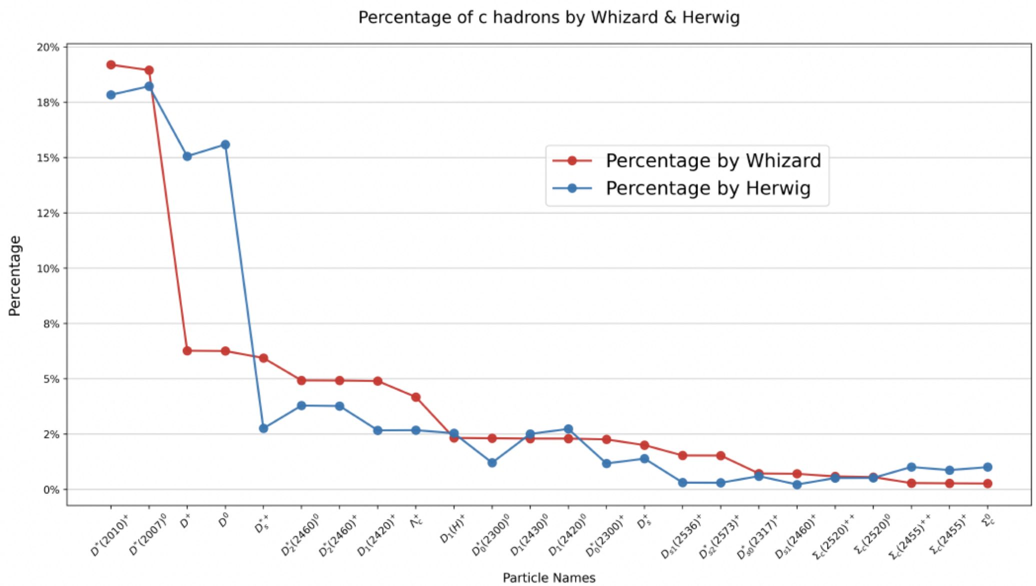


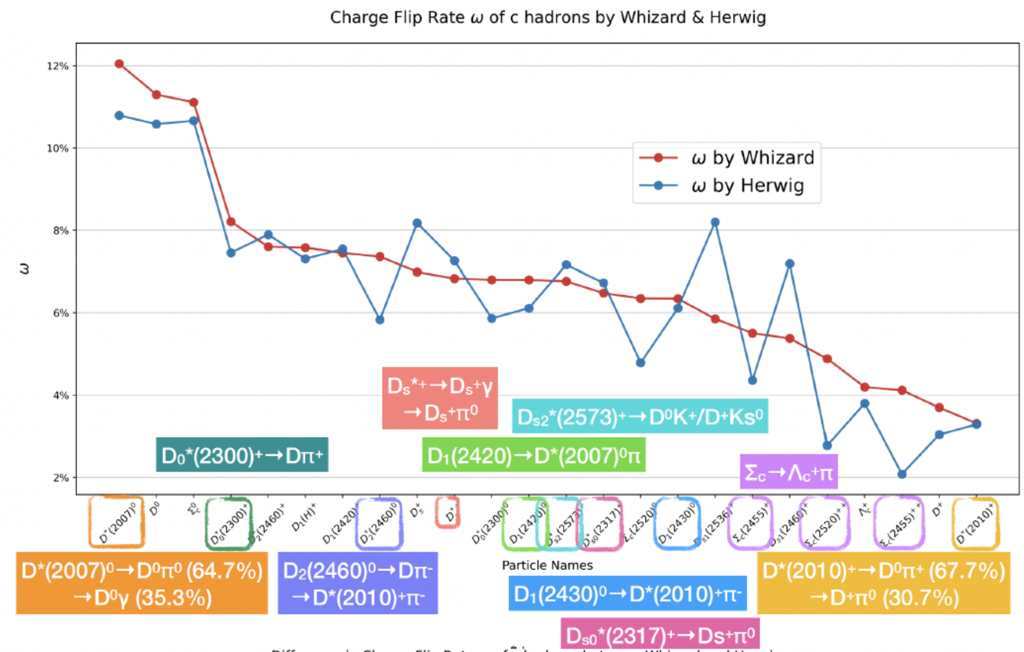


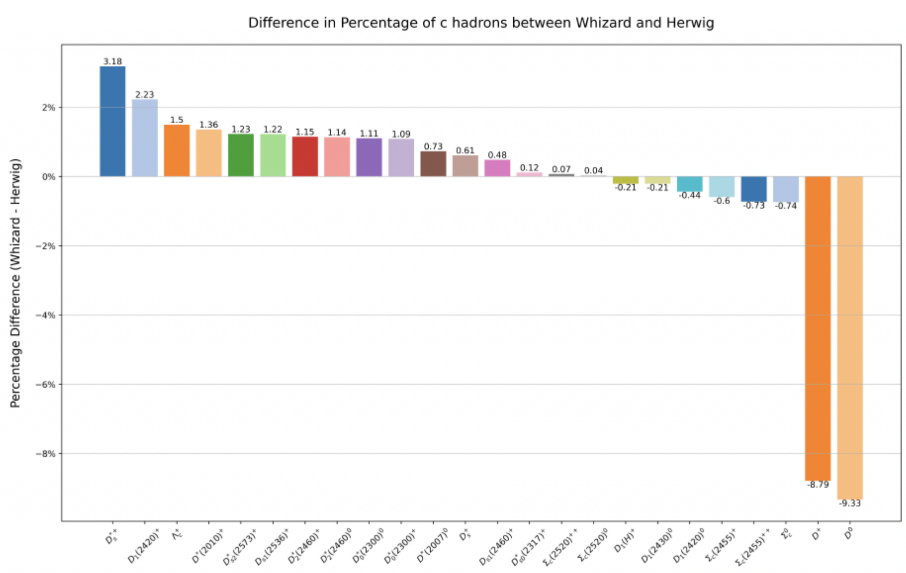


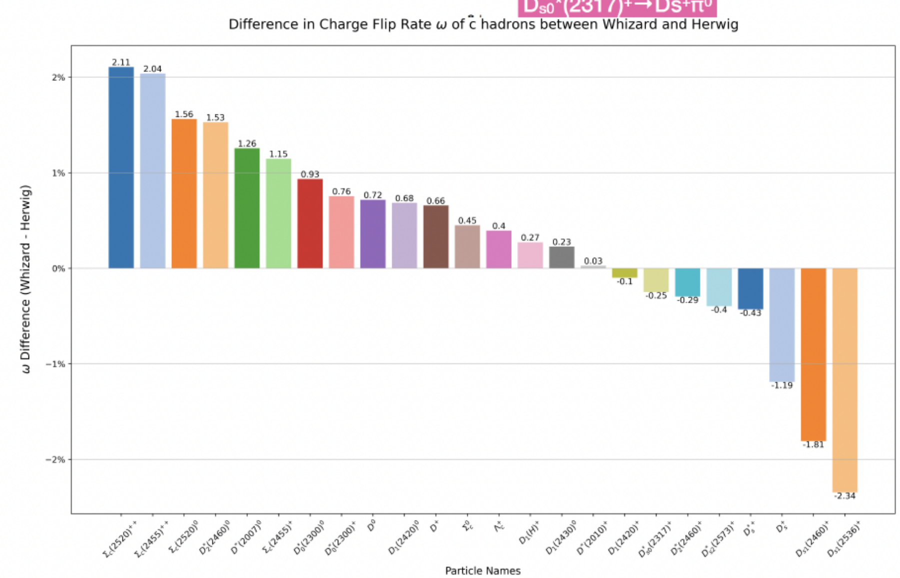


c-jet: leading c-hadrons & flip rates

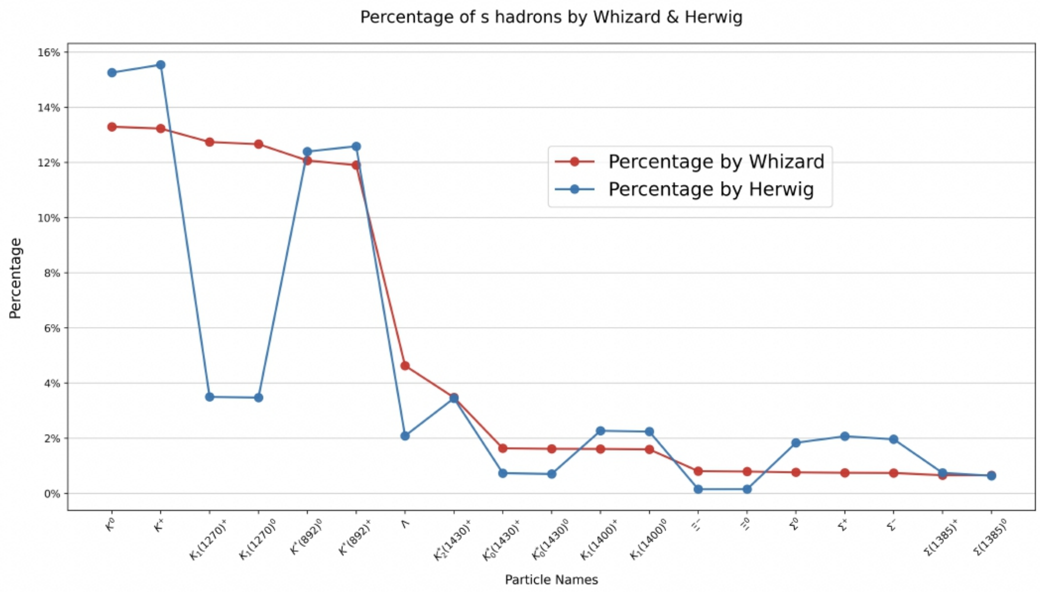


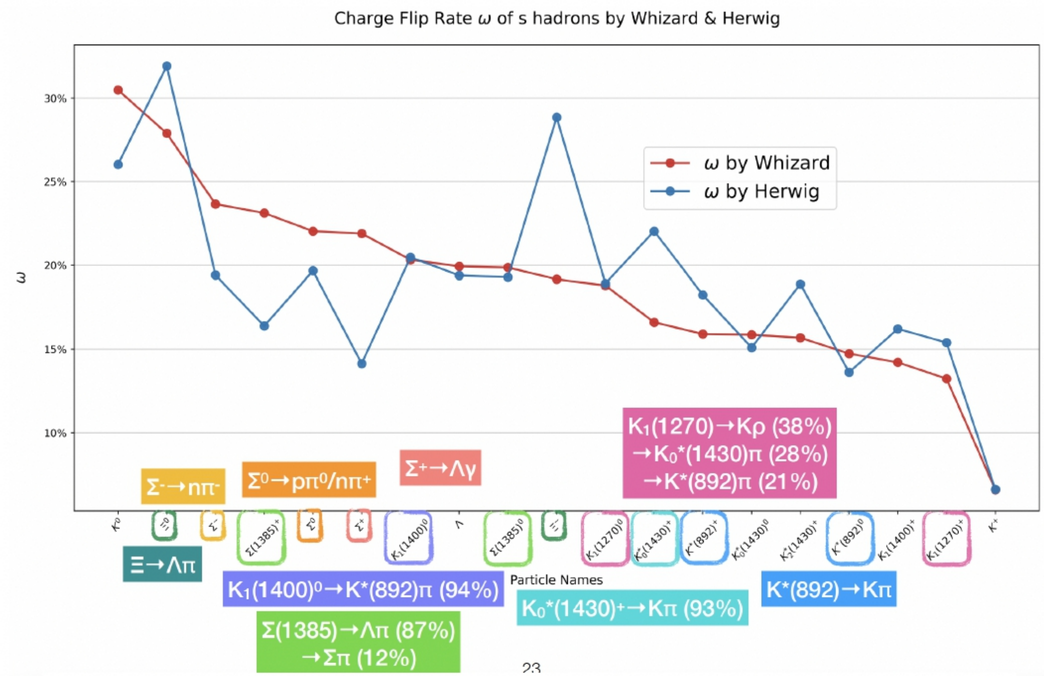


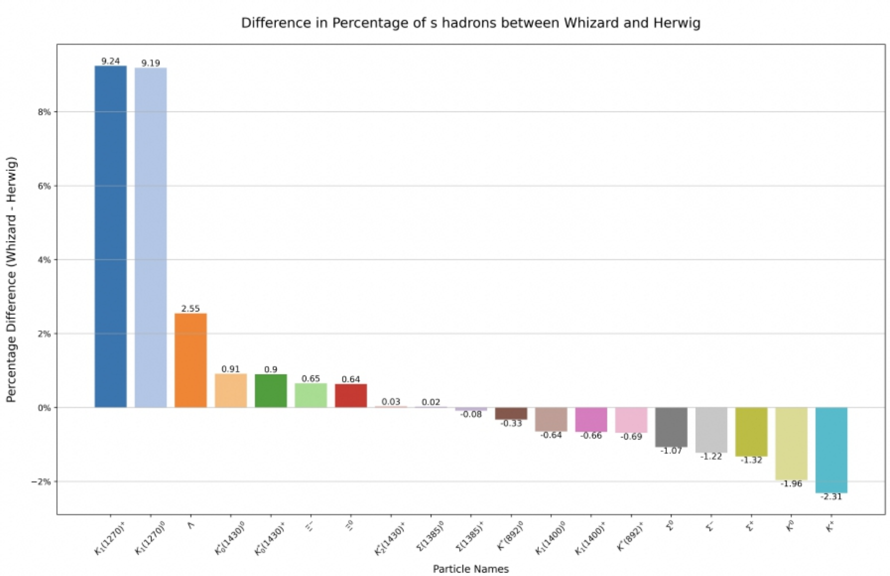


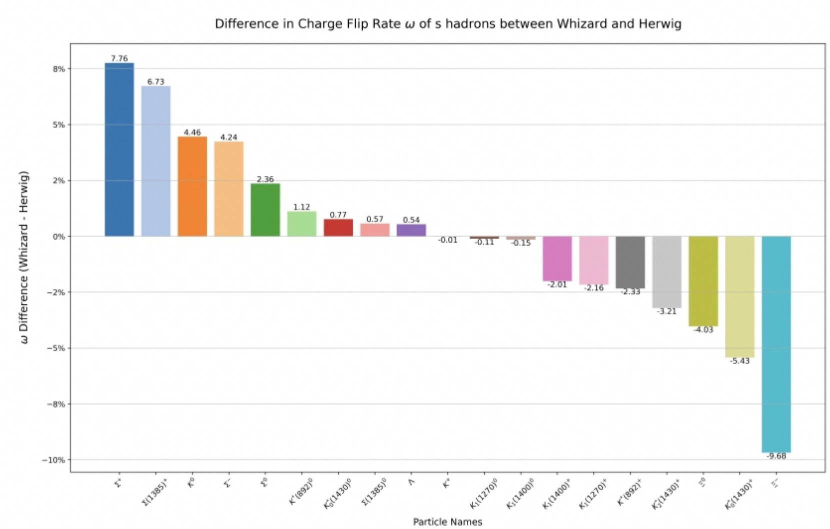


s-jet: leading s-hadrons & flip rates

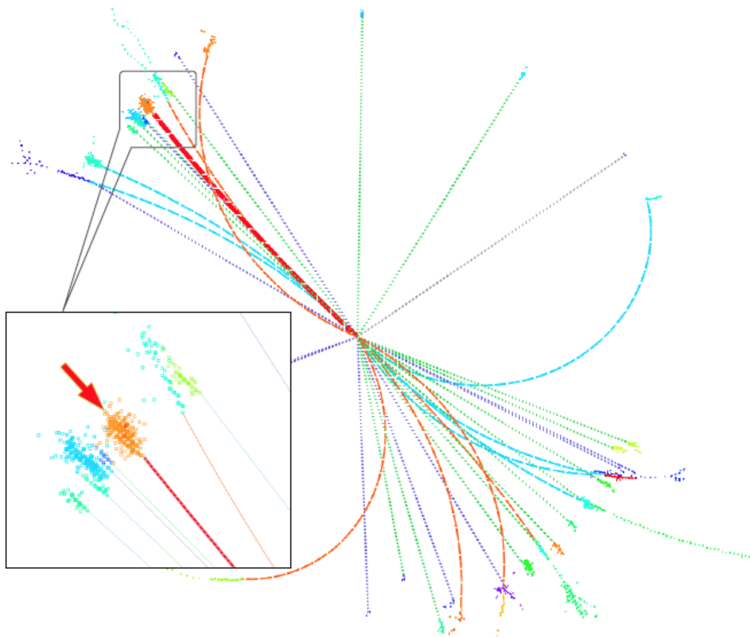


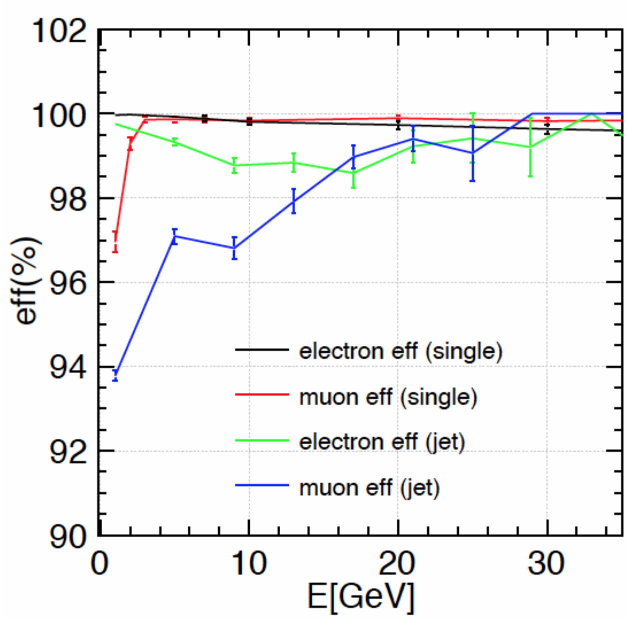


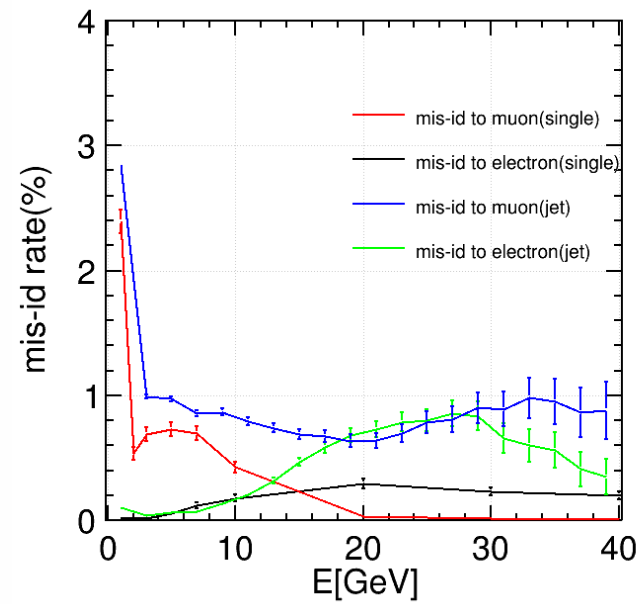




Lepton: inside jet



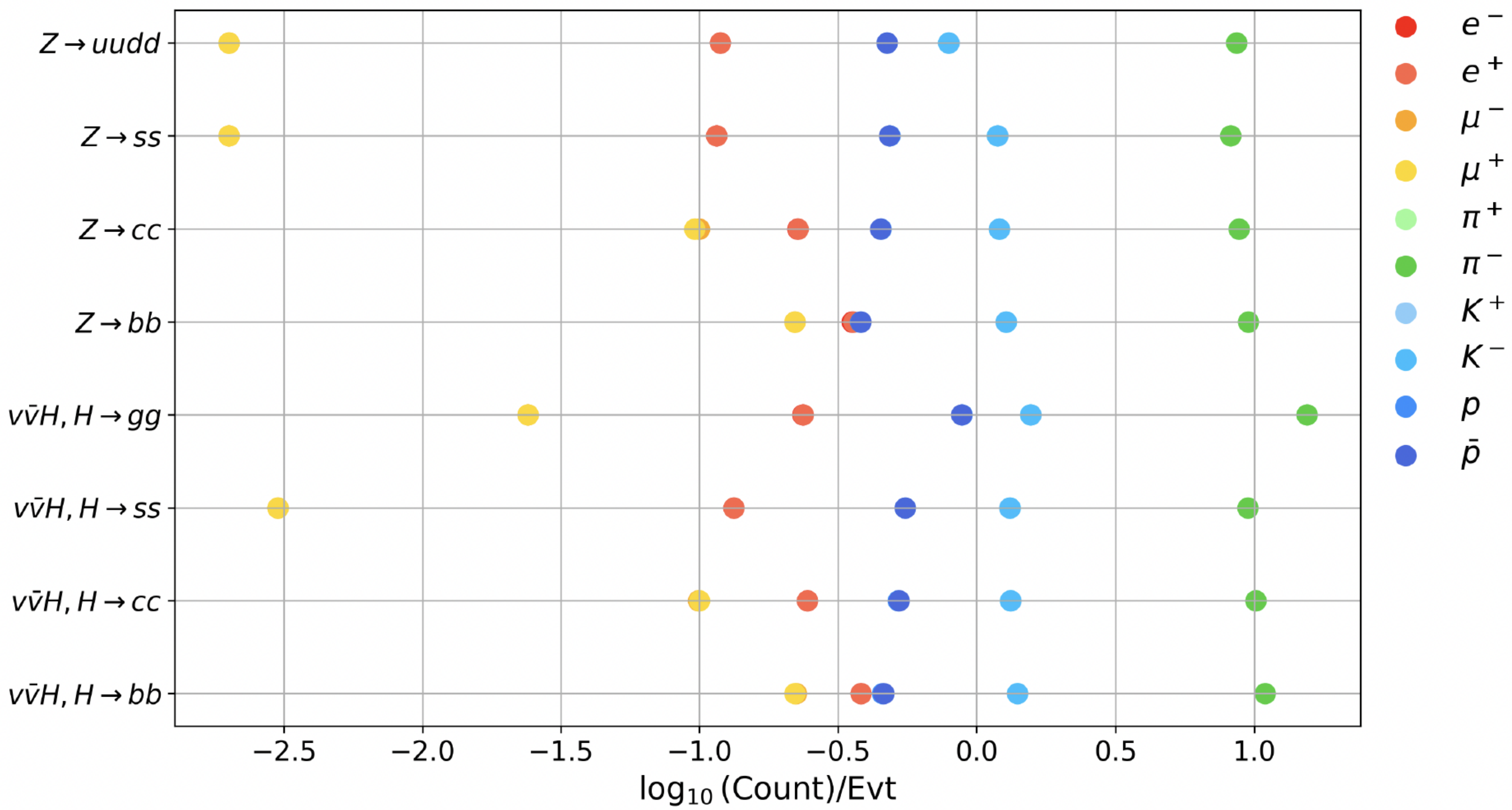




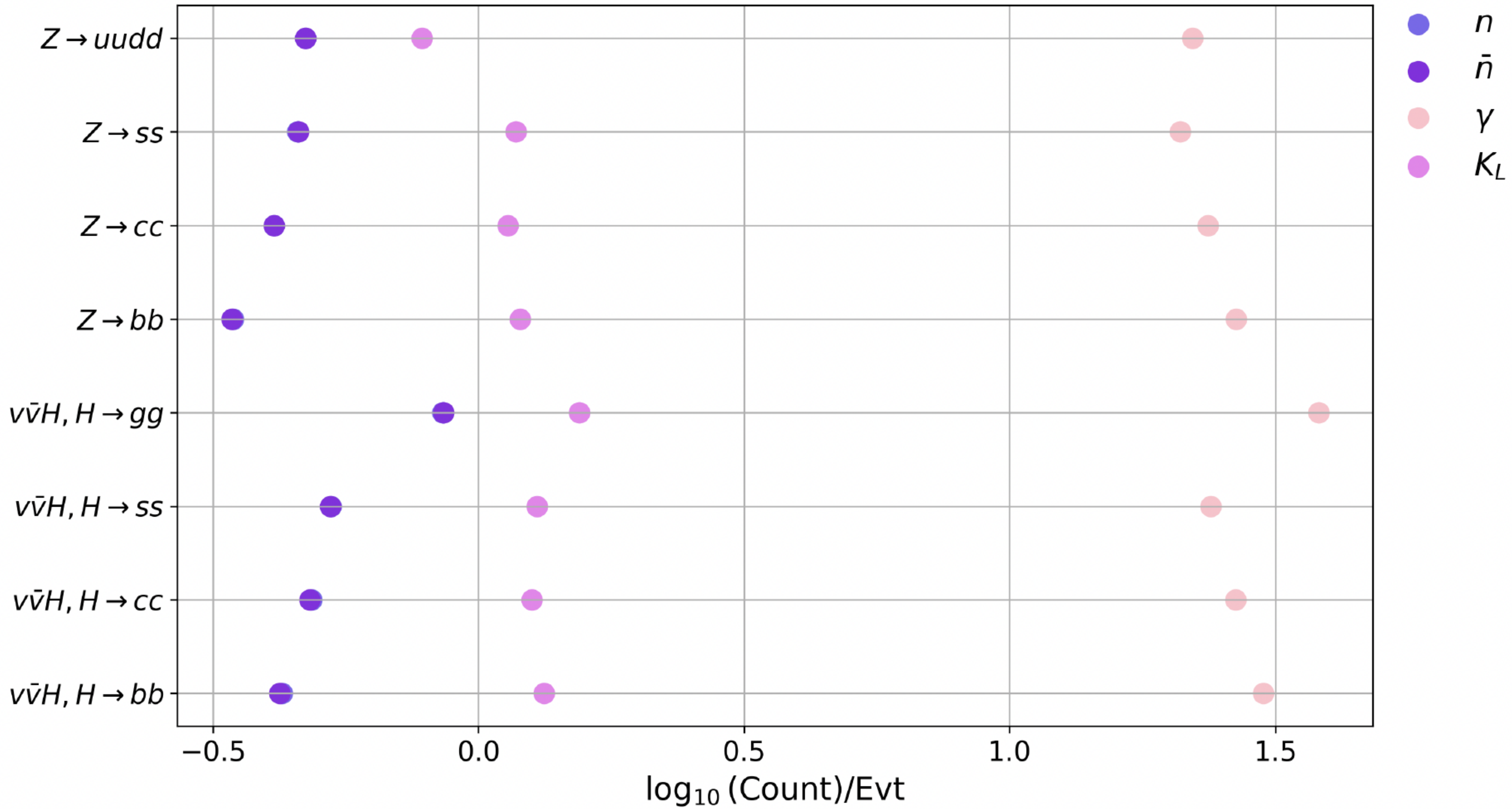
Compared the single particle sample, the jet lepton (at Z->bb sample at sqrt = 91.2 GeV) Performance will be slightly degraded – Due to the limited clustering performance (splitting & containimation).

At the same working point, the efficiency can be reduced by up to 3%; while mis-id rate increases up to 1%. Marginal Impact on Flavor Physics measurements as Bc->tauv.

However, to identify Genius Lepton and those coming from photon conversion & hadron decay, Is still a demanding task...



$Z \to uudd$
$Z \to ss$
$Z \to cc$
$Z \to bb$
$\nu\bar{\nu}H, H \to gg$
$\nu\bar{\nu}H, H \to ss$
$\nu\bar{\nu}H, H \to cc$
$\nu\bar{\nu}H, H \to bb$
−2.5 −2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0
$\log_{10}$ (Count)/Evt
e^-
e^+
μ^-
μ^+
π^+
π^-
K^+
K^-
p
$\bar{p}$


$Z \to uudd$
$Z \to ss$
$Z \to cc$
$Z \to bb$
$v\bar{v}H, H \to gg$
$v\bar{v}H, H \to ss$
$v\bar{v}H, H \to cc$
$v\bar{v}H, H \to bb$
−0.5
0.0
0.5
1.0
1.5
$\log_{10}$ (Count)/Evt
n
$\bar{n}$
γ
K_L

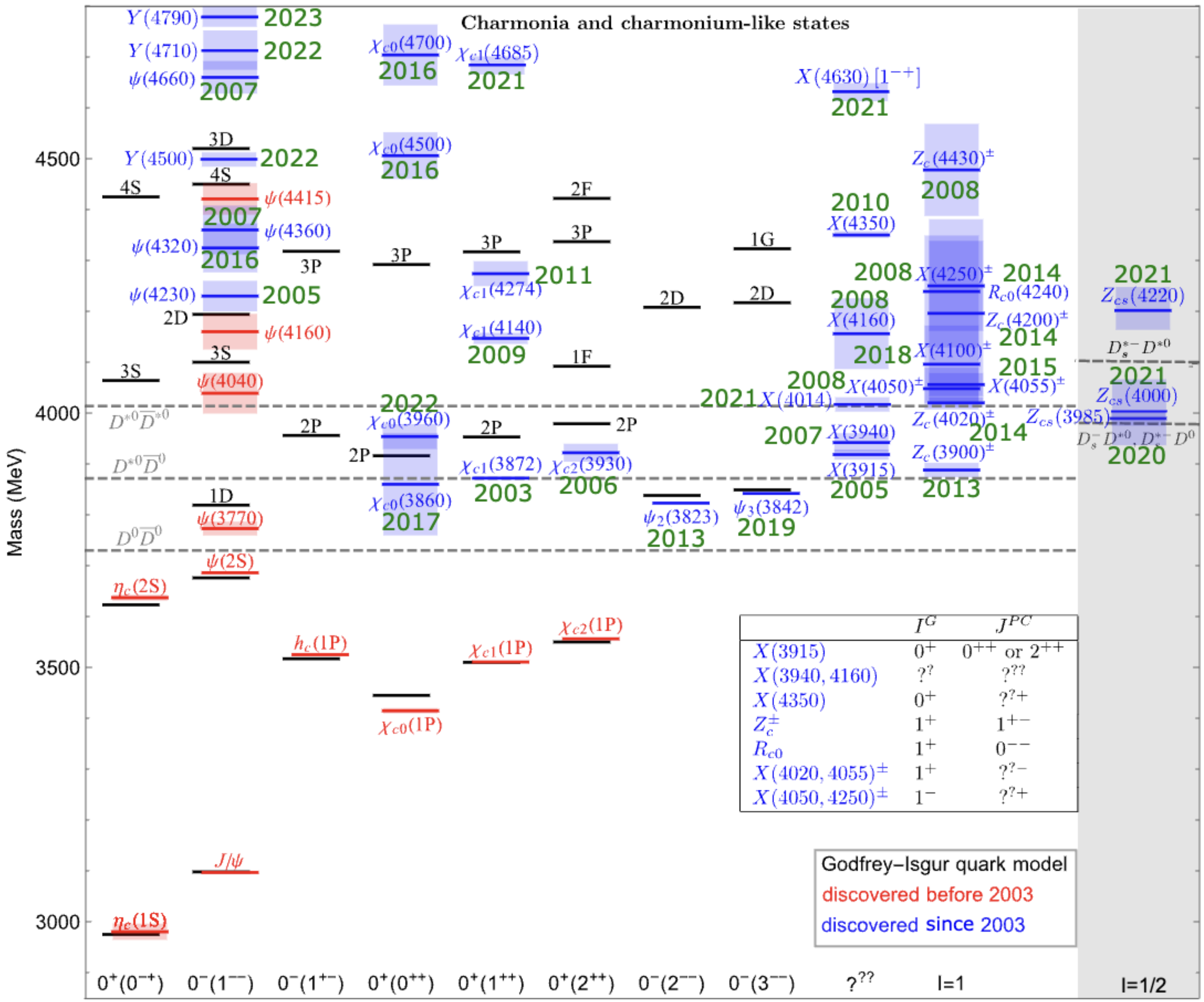
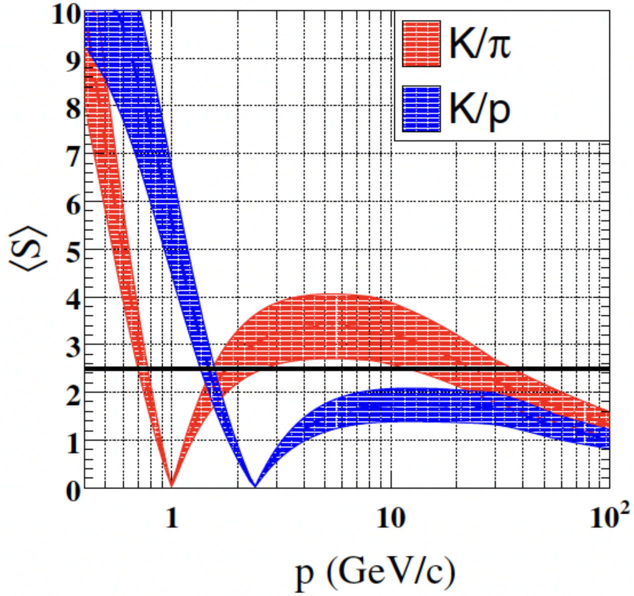
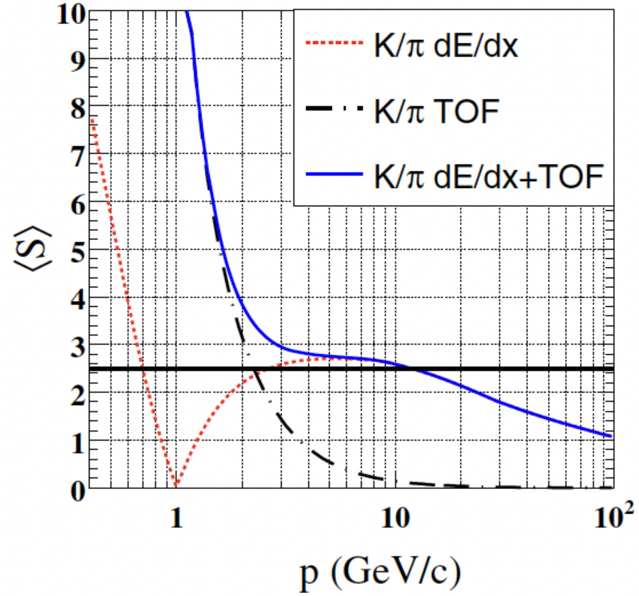
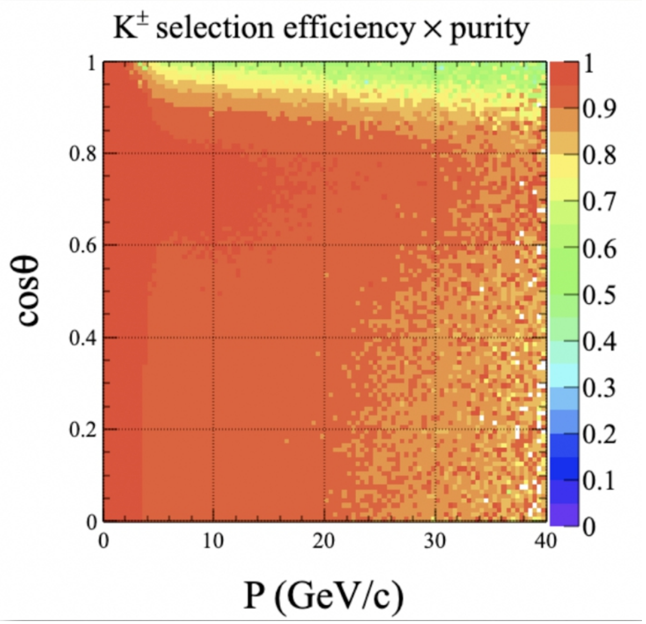


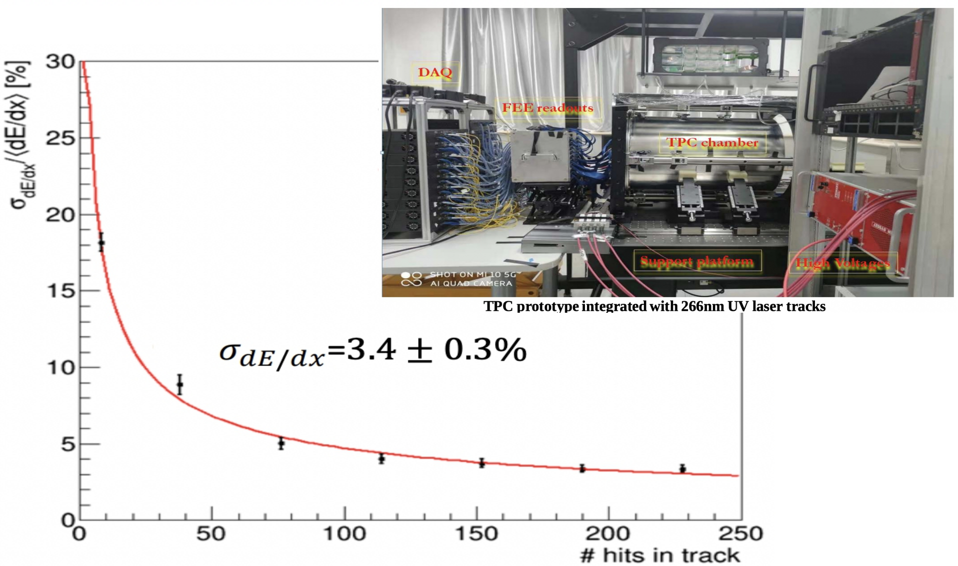
Figure 35: Spectrum of the charmonium and charmonium-like states. Black lines represent the masses in the Godfrey-Isgur quark model [215]. The red and blue lines represent the states observed experimentally before 2003 and since 2003, respectively. For the latter, the years when the states were observed 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.

Tracker: Pid









TPC prototype integrated with 266nm UV laser tracks

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

$B_s/B^0 \to 2$ pi0/eta

Preliminary...

$$A_{CP}\ (or\ C^{00}_{\pi\pi}) = \frac{\Gamma(B^0 \to \pi^0\pi^0) - \Gamma(\bar{B}^0 \to \pi^0\pi^0)}{\Gamma(B^0 \to \pi^0\pi^0) + \Gamma(\bar{B}^0 \to \pi^0\pi^0)}$$

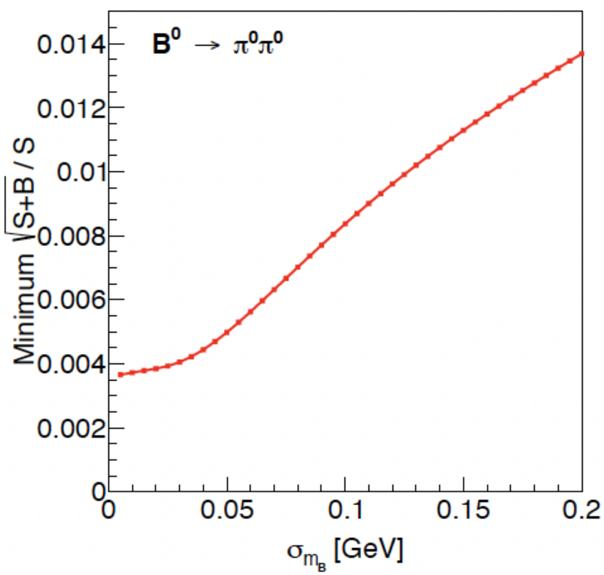
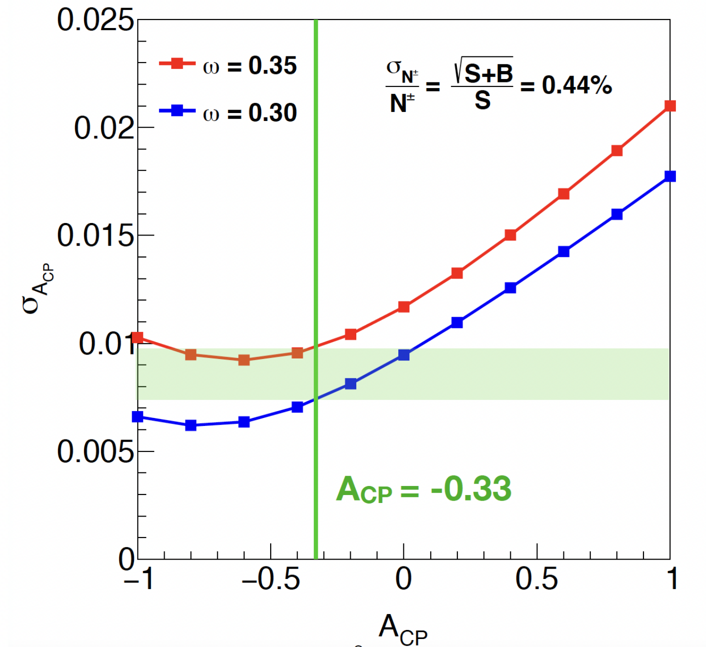
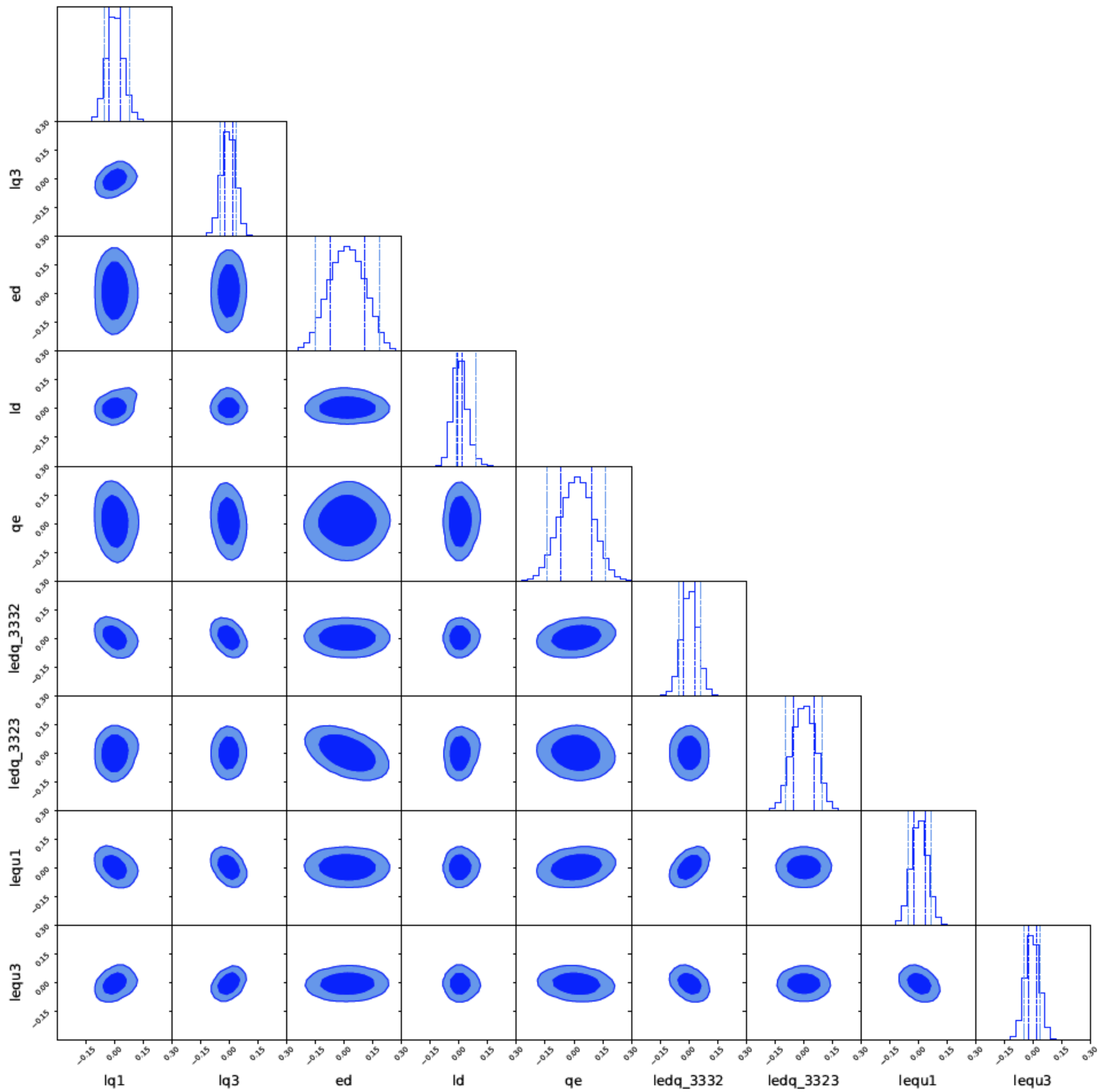


Figure 12: Accuracy of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) versus B mass resolution.



- Provide sub percentage level accuracies on B0->2 pi0, 40/5 times than current world average & Belle II anticipation, have a strong impact on the CKM angle (alpha measurements), discover the other three modes for the 1st time.
- Strongly Depends on the b-tagging performance (ILD is good enough) and the ECAL intrinsic resolution (provide 30 MeV mass resolution for B-meson... 5 times better than ILD ECAL)

Current Progress in LFU Tests (II)



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$b \to s\tau^+\tau^-$ physics at future Z factories

Lingfeng Li & Tao Liu

Journal of High Energy Physics **2021**, Article number: 64 (2021) | Cite this article

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

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

Updated result on $\sin^2\theta_{eff}^{l}$ measurement

Table 2. Sensitivity S of different final state particles.

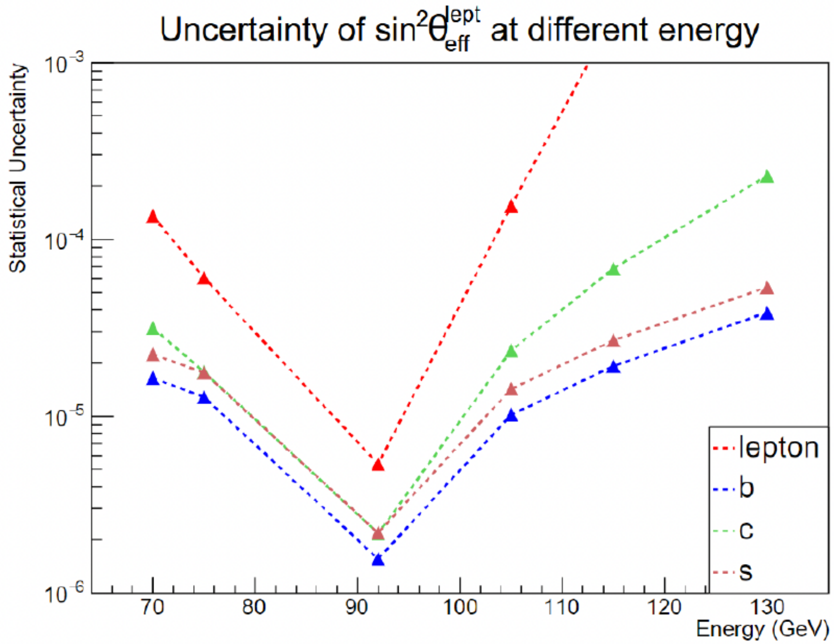
$\sqrt{s}$/GeV	S of $A_{FB}^{e/\mu}$	S of A_{FB}^{d}	S of A_{FB}^{u}	S of A_{FB}^{s}	S of A_{FB}^{c}	S of A_{FB}^{b}
70	0.224	4.396	1.435	4.403	1.445	4.352
75	0.530	5.264	2.598	5.269	2.616	5.237
92	1.644	5.553	4.200	5.553	4.201	5.549
105	0.269	4.597	1.993	4.598	1.994	4.586
115	0.035	3.956	1.091	3.958	1.087	3.942
130	0.027	3.279	0.531	3.280	0.520	3.261

Table 3. Cross section of process $e^+e^- \to f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/GeV	σ_μ/mb	σ_d/mb	σ_u/mb	σ_s/mb	σ_c/mb	σ_b/mb
70	0.039	0.032	0.066	0.031	0.058	0.028
75	0.039	0.047	0.073	0.046	0.065	0.043
92	1.196	5.366	4.228	5.366	4.222	5.268
105	0.075	0.271	0.231	0.271	0.227	0.265
115	0.042	0.135	0.122	0.135	0.118	0.132
130	0.026	0.071	0.068	0.071	0.066	0.069

Verify the RG behavior… using ~1 month of data taking

Expected statistical uncertainties on $\sin^2\theta_{eff}^{l}$ measurement.
(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)



$\sqrt{s}$	b	c	s
70	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}
75	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
92	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}
105	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}
115	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}
130	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}

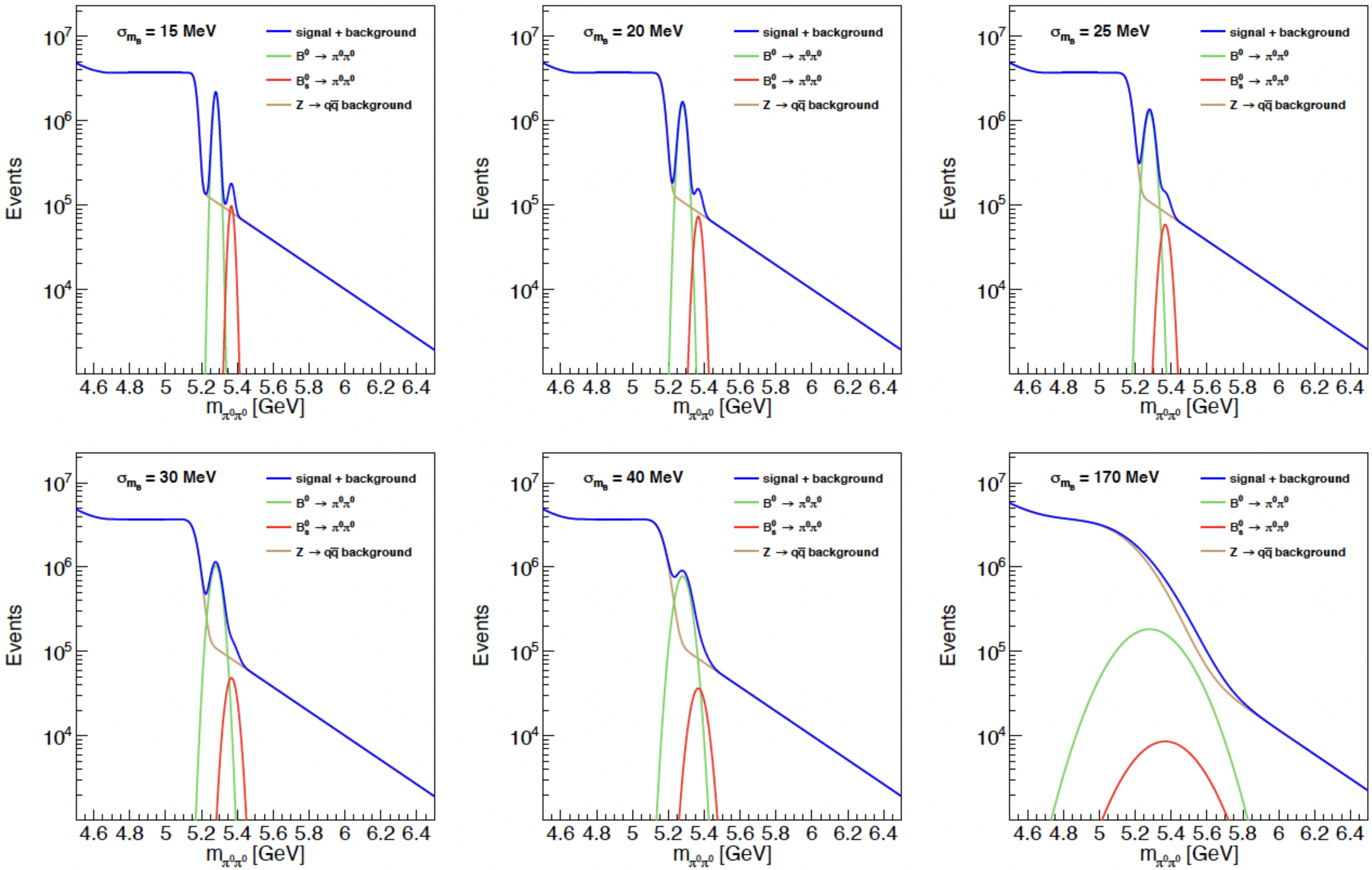


Figure 11: $m_{\pi^0\pi^0}$ distributions of $B^0 \to \pi^0\pi^0$, $B_s^0 \to \pi^0\pi^0$, and $Z \to q\bar{q}$ background at different B mass resolutions when applying CEPC baseline b-tagging.