香港科技大學
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Testing Lepton Flavor Universality at Future Lepton Colliders

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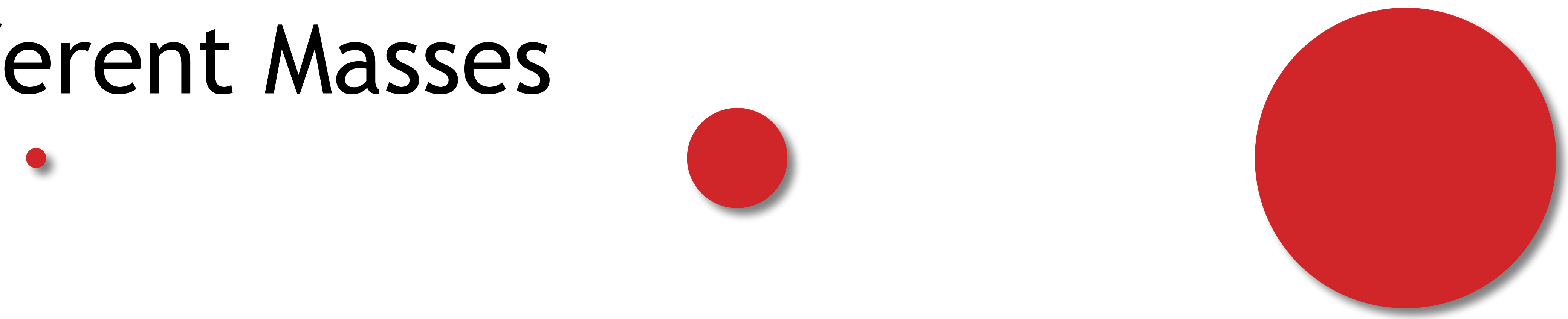
Lepton Flavor Universality (LFU)

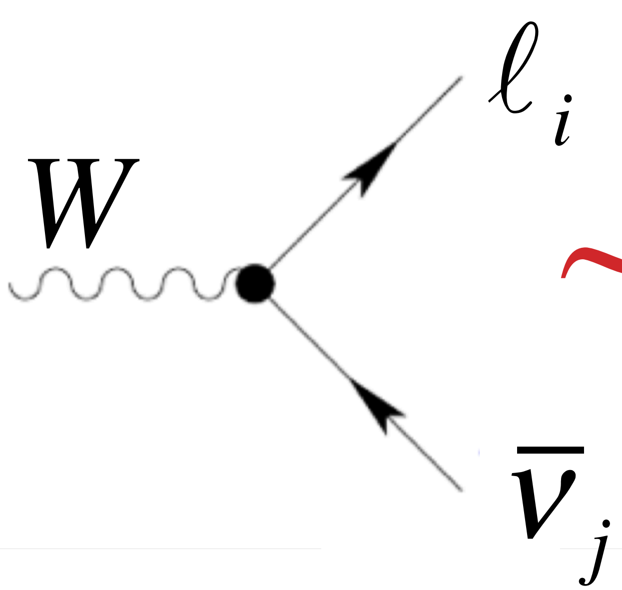
Standard Model: 3 generations of leptons

- Different Masses



e : 0.511 MeV μ : 105.66 MeV τ : 1.777 GeV

- A Universal Coupling to Gauge



$$\sim g\,\delta_{ij}$$

One of the hypothesis in the SM

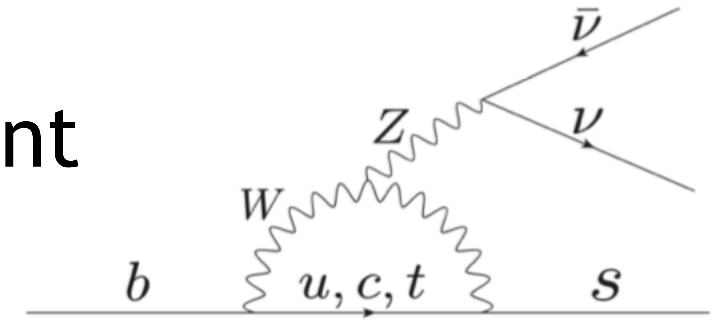
Lepton Flavor Universality (LFU)

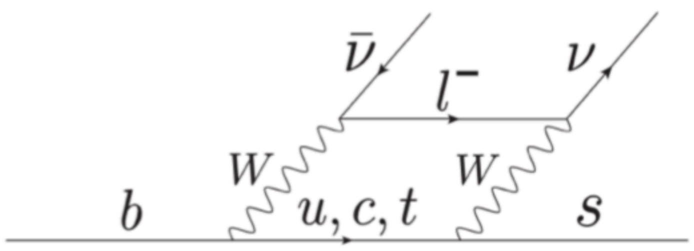
Precise Measurement

- A Test of SM
- Hints for BSM

Very Sensitive in Flavor Physics

Flavor Changing Neutral Current
(FCNC)





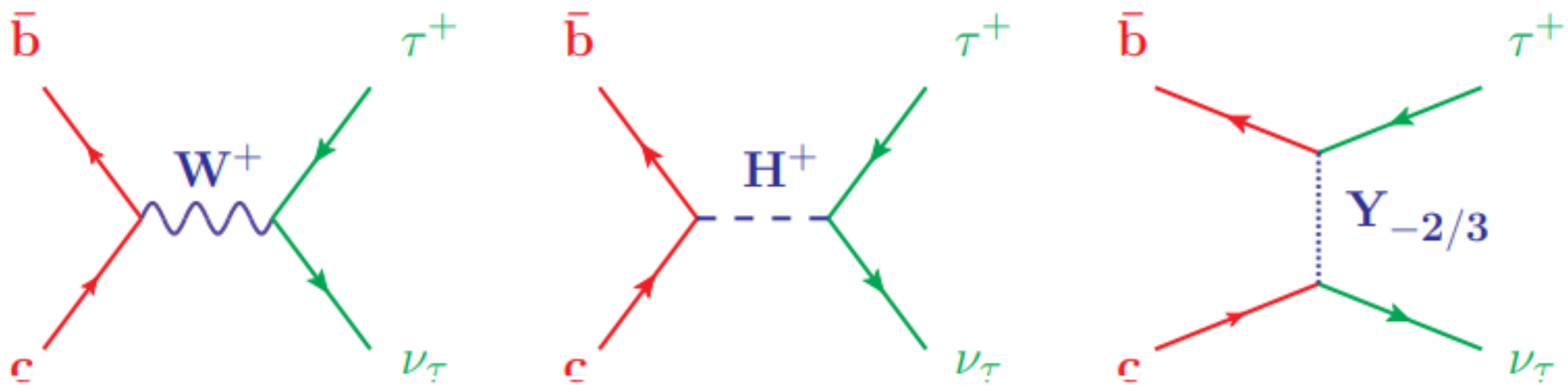
SM: Loop-level suppression. $\Gamma \sim \frac{m_f^5}{m_W^4}$

BSM with LFUV: $m_W \to \Lambda_{NP}$

Flavor Changing Charged Current (FCCC)

LFU Violation

Tree-level BSM realizations:



SM uncoloured coloured

[Zheng. et al.]

Hadron Decay

$$R_{H_c} = \frac{\mathrm{Br}\,(H_b \to H_c \tau \nu)}{\mathrm{Br}\,(H_b \to H_c \mu \nu)}$$

H_b

meson or baryon containing b quark

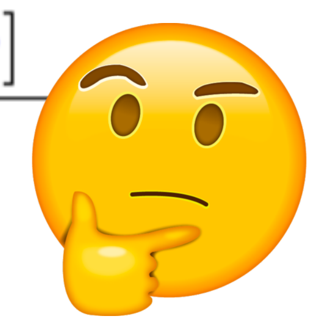
H_c

meson or baryon containing c quark

SM Predictions VS. Experimental Results

	H_b	H_c	SM Prediction [2]	Experimental Average
R_D	B^0, $B^\pm$	D^0, $D^\pm$	0.307 [1, 2]	0.340 ± 0.030 [3]
R_{D^*}	B^0, $B^\pm$	D^{*0}, $D^{*\pm}$	0.253 [1, 2]	0.295 ± 0.014 [3]
$R_{J/\psi}$	B_c	J/ψ	0.289 [4–6]	$0.71 \pm 0.17 \pm 0.18$ [7]
R_{D_s}	B_s	D_s	0.393 [2, 8–13]	N/A
$R_{D_s^*}$	B_s	D_s^*	0.303 [2, 8, 10, 13]	N/A
R_{Λ_c}	Λ_b	Λ_c	0.334 [14–18]	0.242 ± 0.076 [19]

Simply Fluctuations? Or BSM with LFUV?

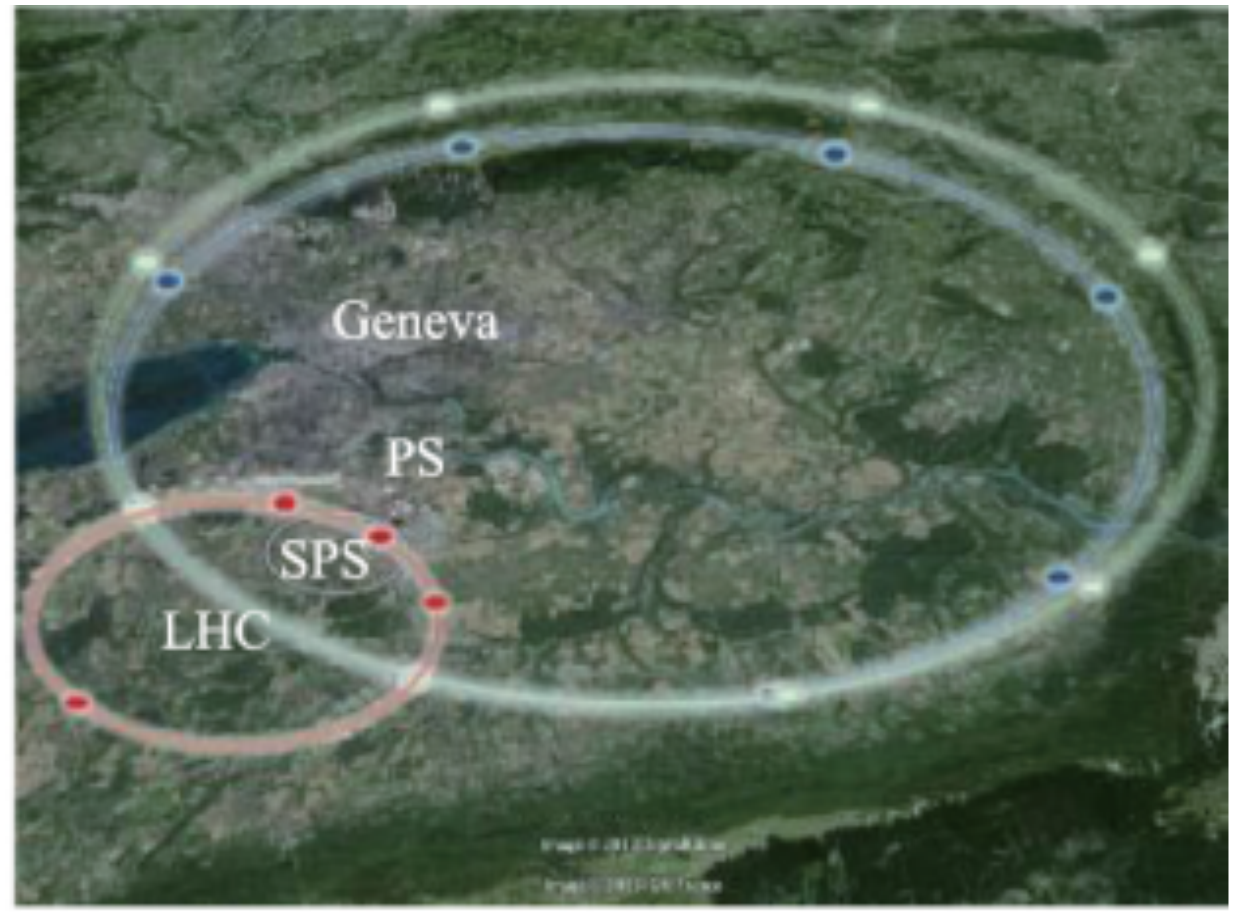


Where to Test Such?

CEPC

FCC-ee

(a)

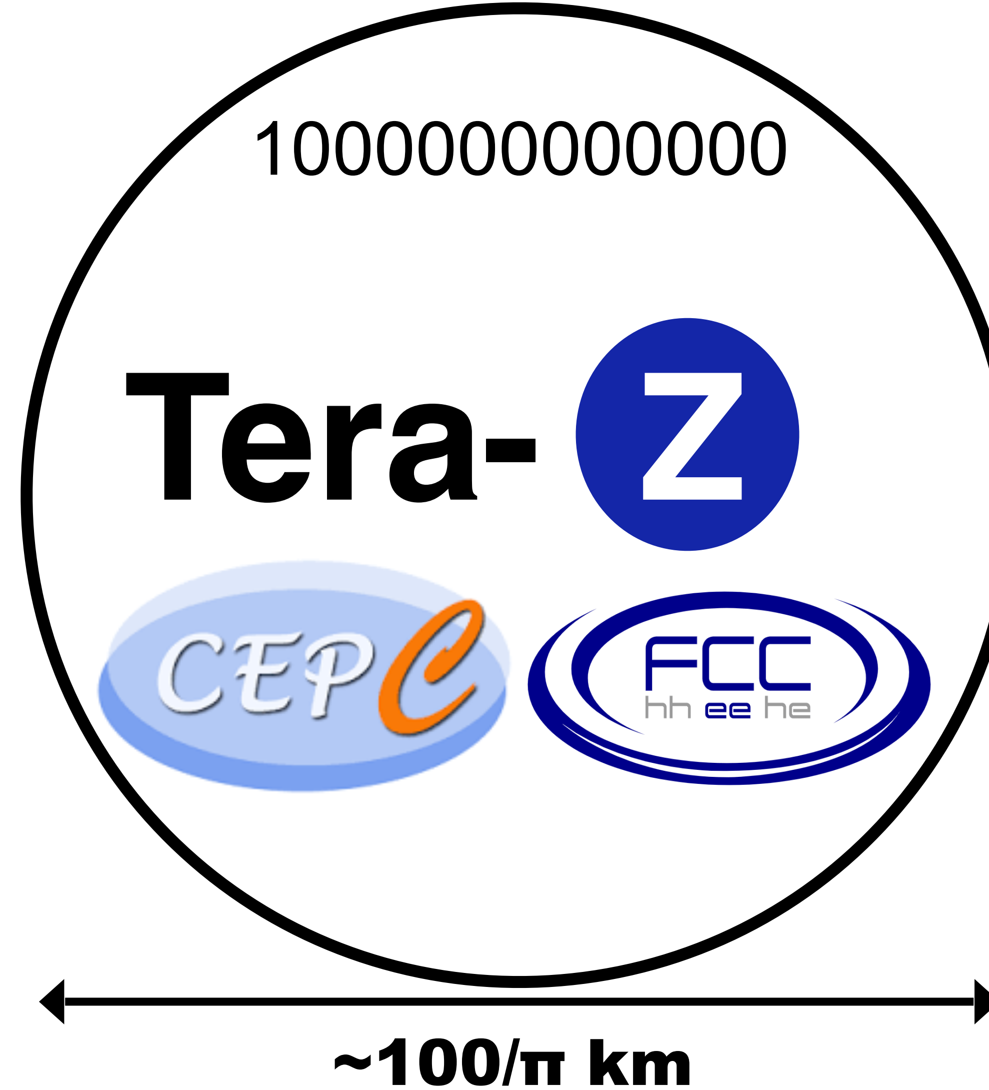


(b)

China

Europe

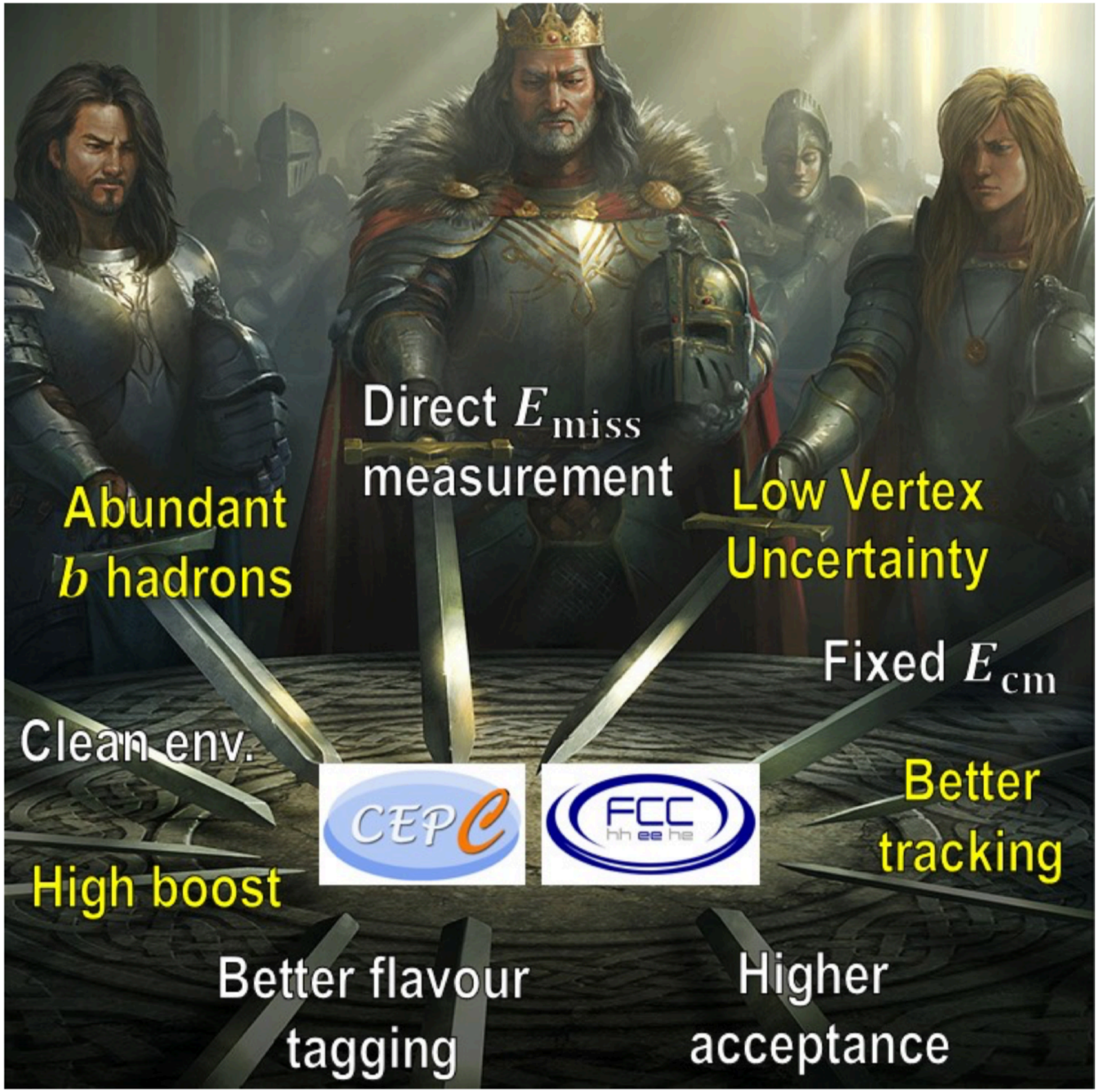
Study at Z-Pole: Z Factory



Not only electroweak,
but also flavor!

	Belle II	LHCb	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	6×10^{13}	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	6×10^{13}	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^{8}	2×10^{13}	3.1×10^{10}	3.1×10^{11}
$B_c^\pm$	-	4×10^{11}	1.8×10^{8}	1.8×10^{9}
Λ_b, $\bar{\Lambda}_b$	-	2×10^{13}	2.5×10^{10}	2.5×10^{11}

Comparison With Other Facilities



White: compared to LHCb; Yellow: compared to B-factories

Motivation

Set a baseline for the studies at Tera-Z.

$$R_{H_c} = \frac{\mathrm{Br}\,(H_b \to H_c \tau \nu)}{\mathrm{Br}\,(H_b \to H_c \mu \nu)}$$

Vector	$R_{J/\psi}$	and	$R_{D_s^*}$
Pseudoscalar	R_{D_s}		
Baryonic	R_{Λ_c}		
Annihilation	$\mathrm{Br}(B_c \to \tau \nu)$ [Zheng. et al.]		

SU(2)

Other studies: $b \to s\tau\tau$ [Li and Liu (2021)] $b \to s\nu\nu$ [Li et al. (2022)]

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Signals

- $$R_{J/\psi} = \frac{\mathrm{Br}\,(\mathrm{B}_c \to J/\psi\tau\nu)}{\mathrm{Br}\,(B_c \to J/\psi\mu\nu)}$$

$$J/\psi \to \mu\mu, \tau \to \mu\nu\bar{\nu}$$

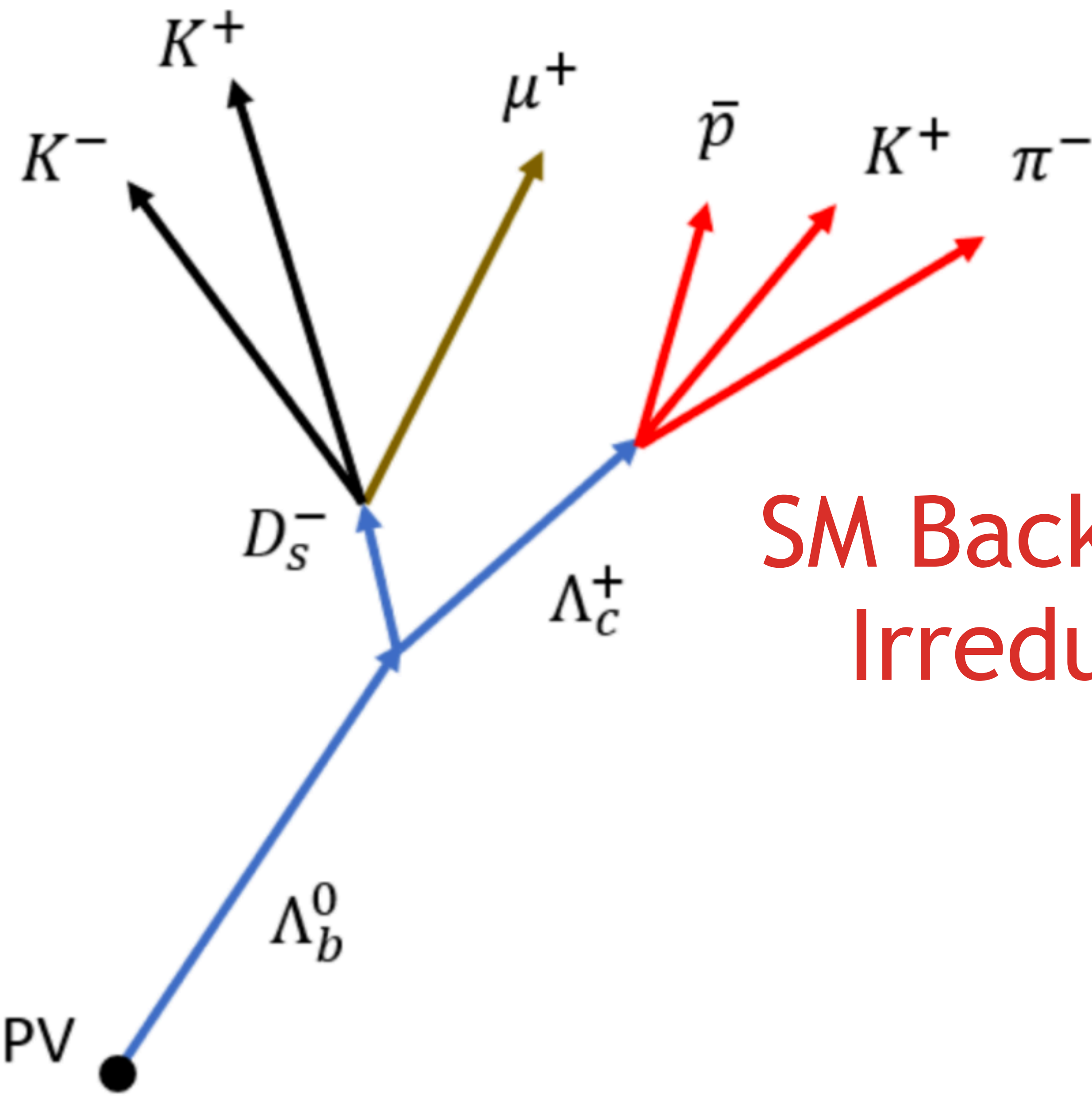
- $$R_{D_s^{(*)}} = \frac{\mathrm{Br}\,(\mathrm{B}_s \to D_s^{(*)}\tau\nu)}{\mathrm{Br}\,(B_s \to D_s^{(*)}\mu\nu)}$$

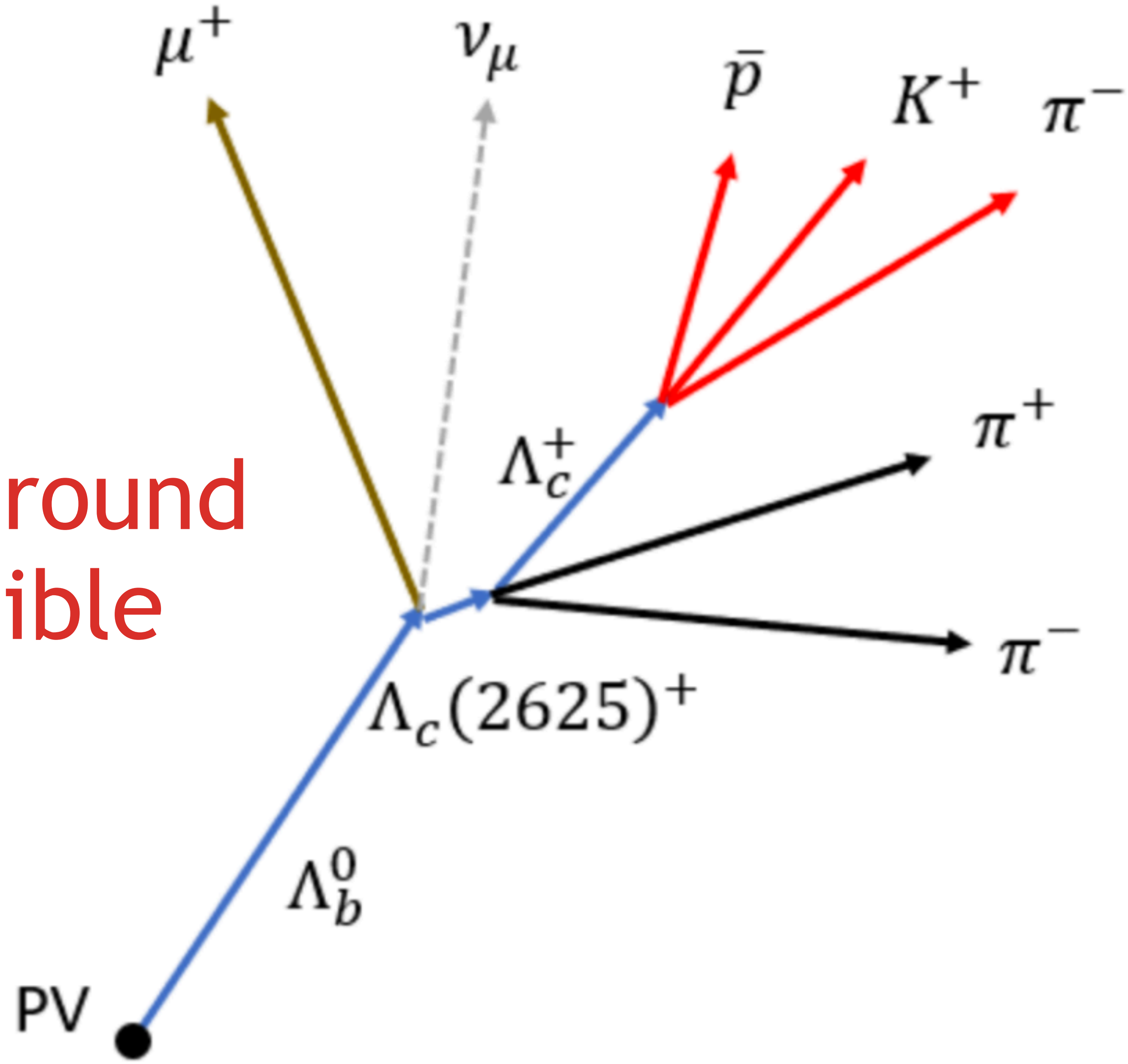
$$D_s^* \to D_s\gamma, D_s \to \phi(\to KK)\pi, \tau \to \mu\nu\bar{\nu}$$

- $$R_{\Lambda_c} = \frac{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\tau\nu)}{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\mu\nu)}$$

$$\Lambda_c \to pK\pi, \tau \to \mu\nu\bar{\nu}$$

Possible Backgrounds





SM Background
Irreducible

"Wrongly" produced Muon

"Wrongly" produced H_c

+ Others

Results

Conservative: no event-level involved.

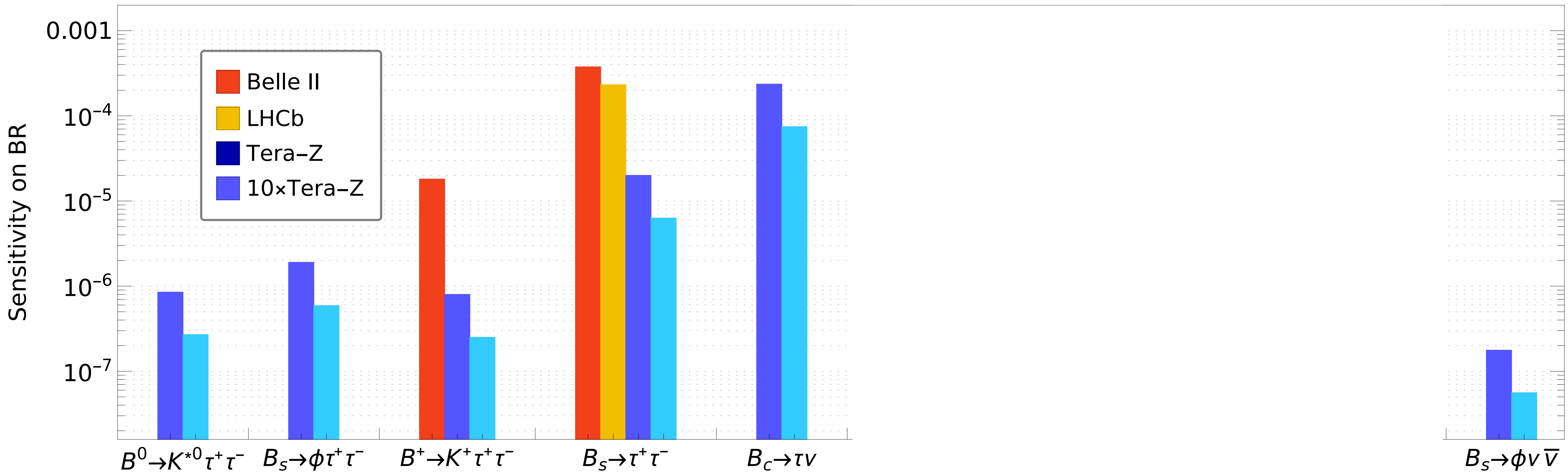
Physical Quantity	SM Value	Tera-Z	10×Tera-Z
$R_{J/\psi}$	0.289	2.89×10^{-2}	9.15×10^{-3}
R_{D_s}	0.393	4.15×10^{-3}	1.31×10^{-3}
$R_{D_s^*}$	0.303	3.25×10^{-3}	1.03×10^{-3}
R_{Λ_c}	0.334	9.74×10^{-4}	3.08×10^{-4}
$\mathrm{BR}(B_c \to \tau\nu)$ [Zheng. et al.]	2.36×10^{-2} [6]	0.01 [6]	3.16×10^{-3}

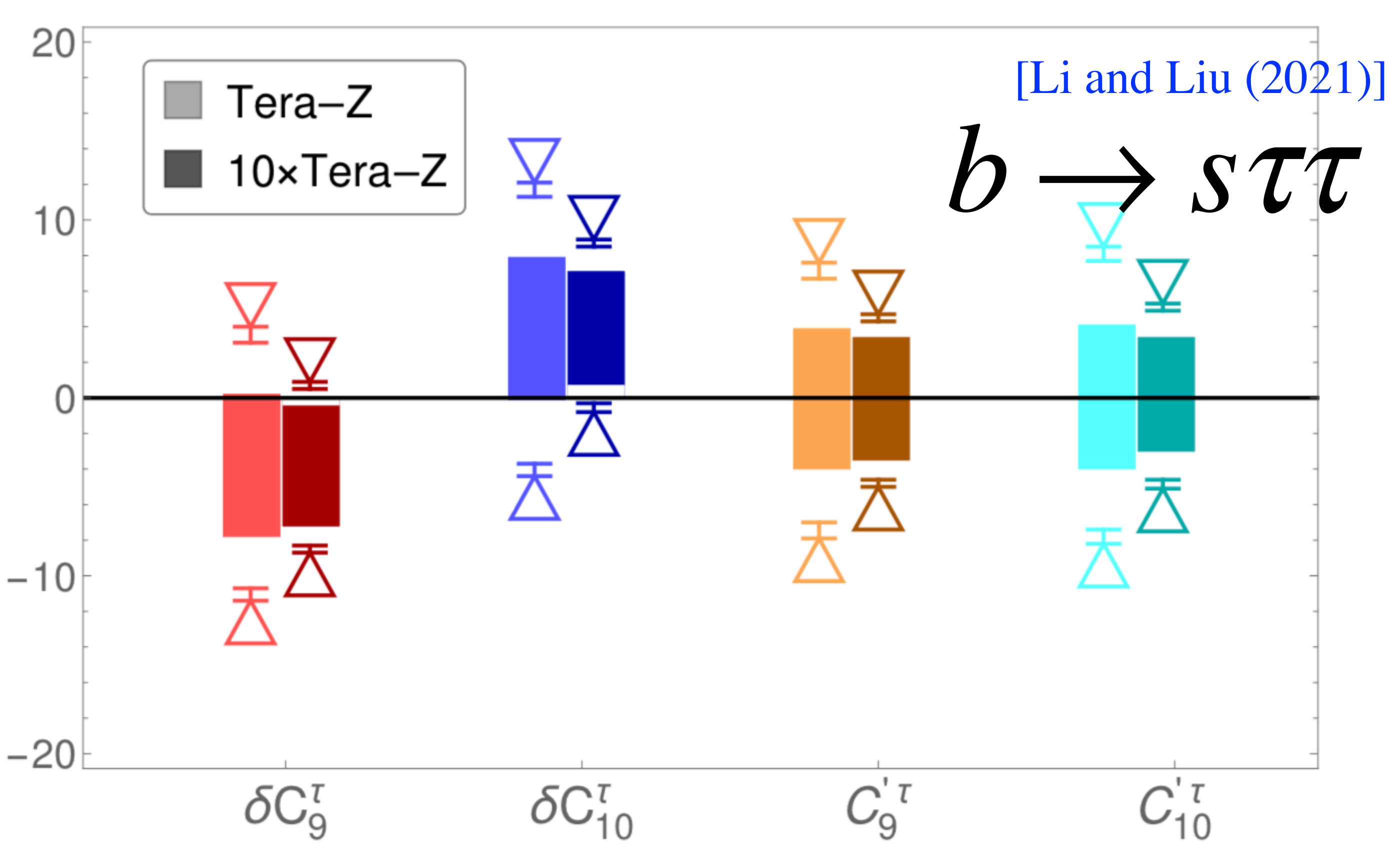
Relative Uncertainties at Tera-Z:

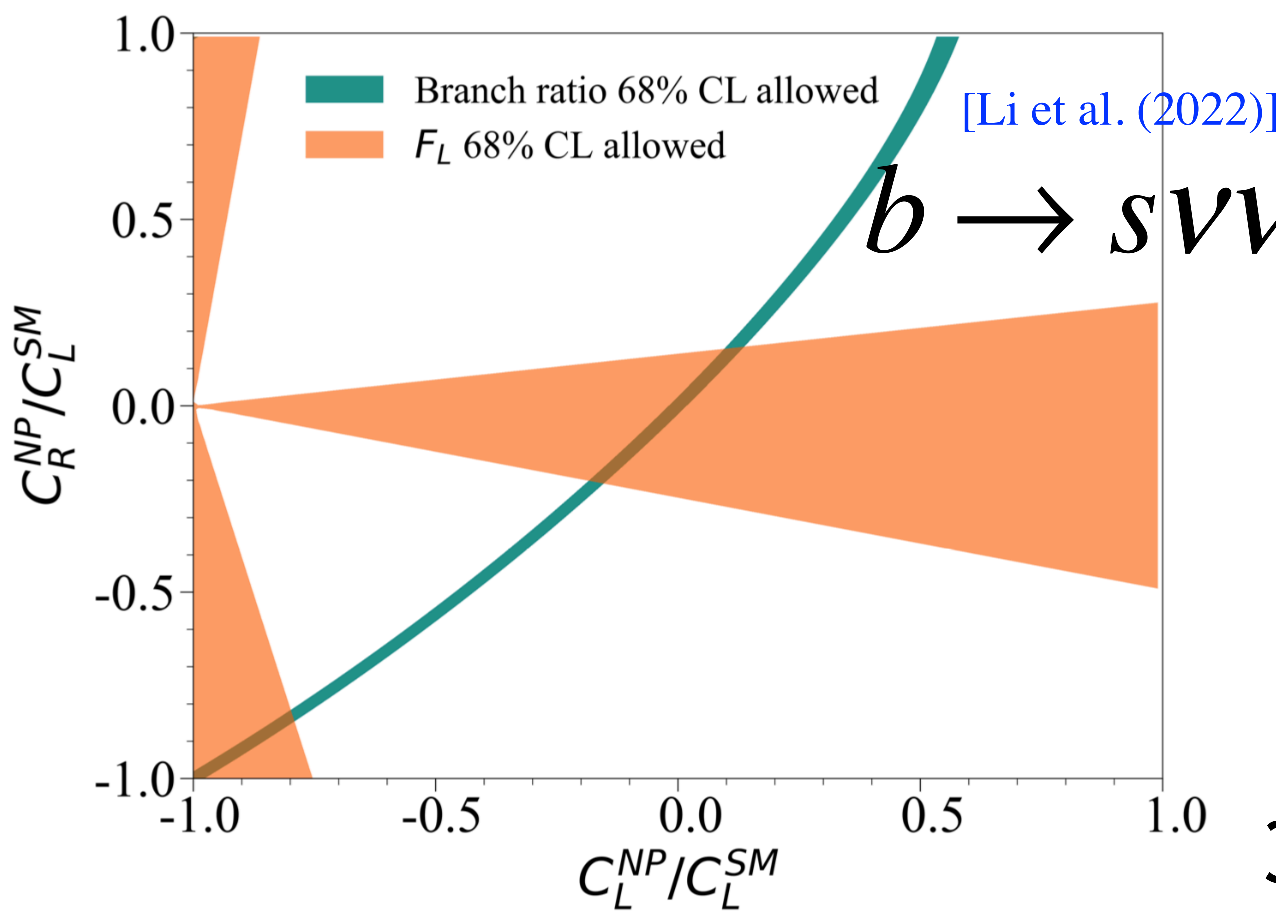
$$\mathcal{O}(0.1\%) - \mathcal{O}(1\%)$$

Results

Systematic ~ a factor of statistical rel. uncert.







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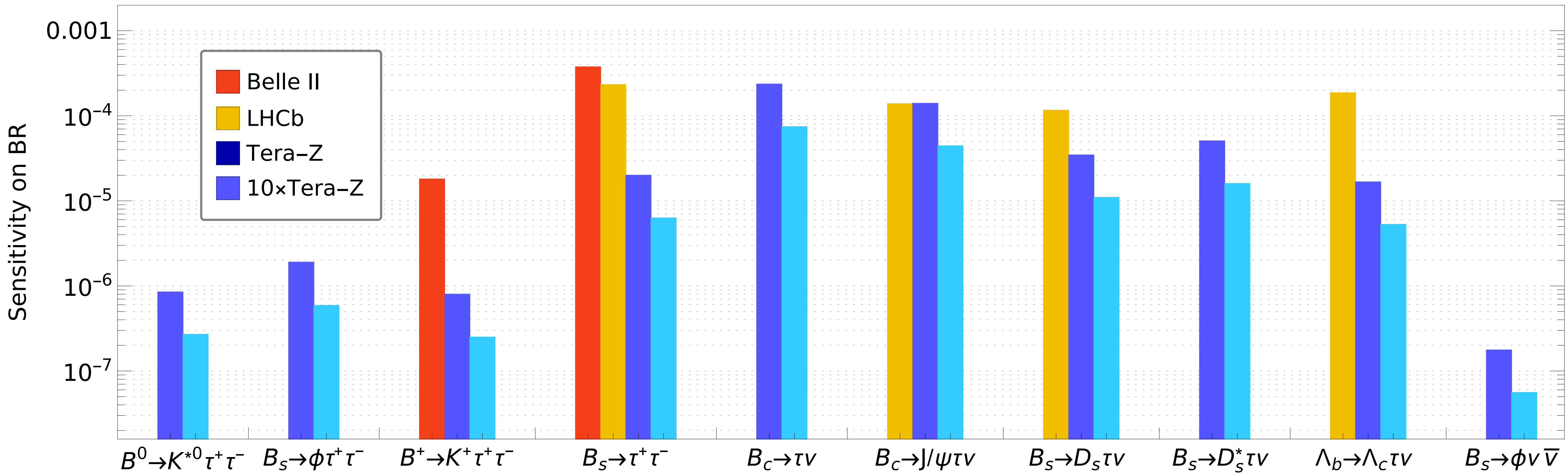
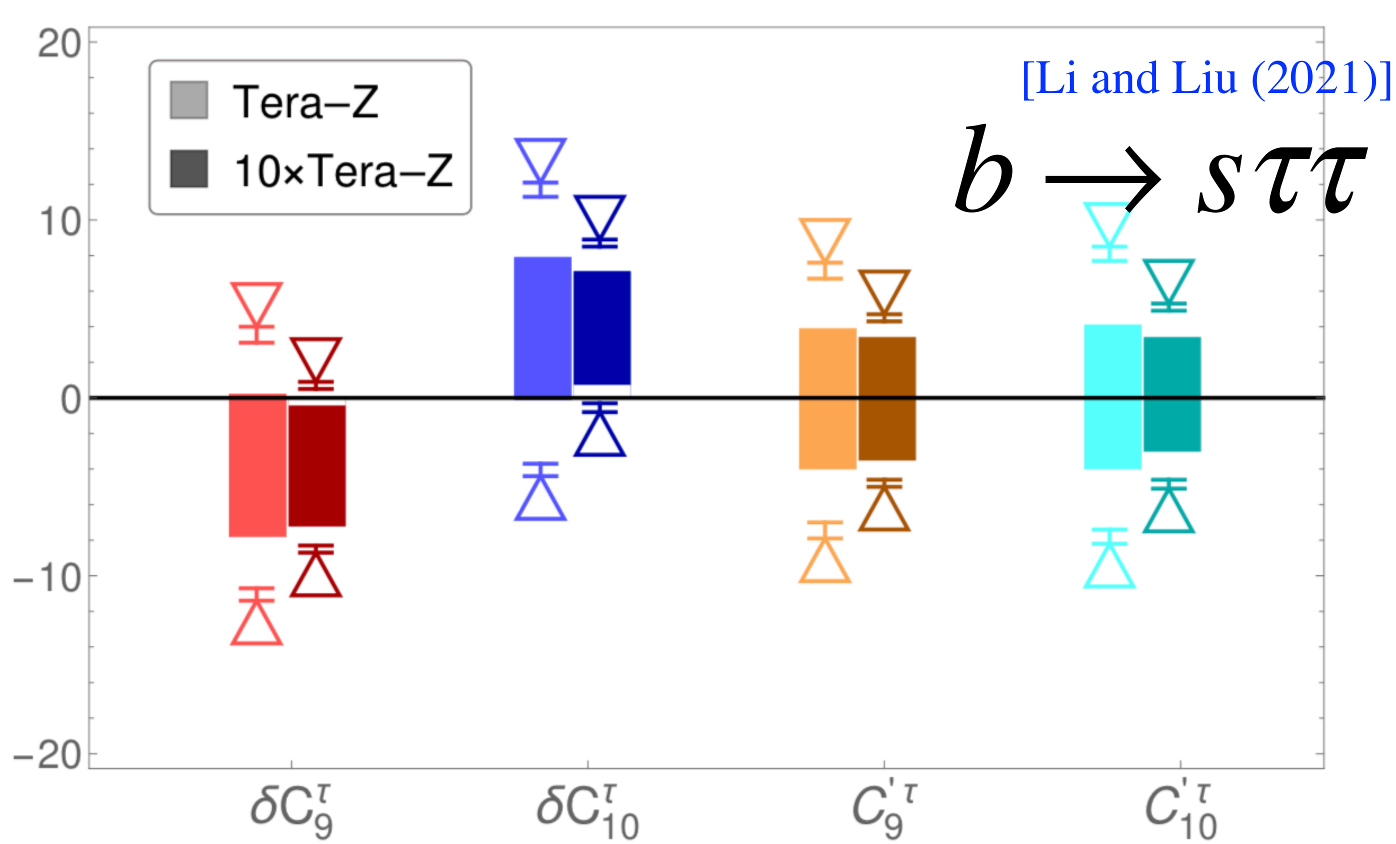
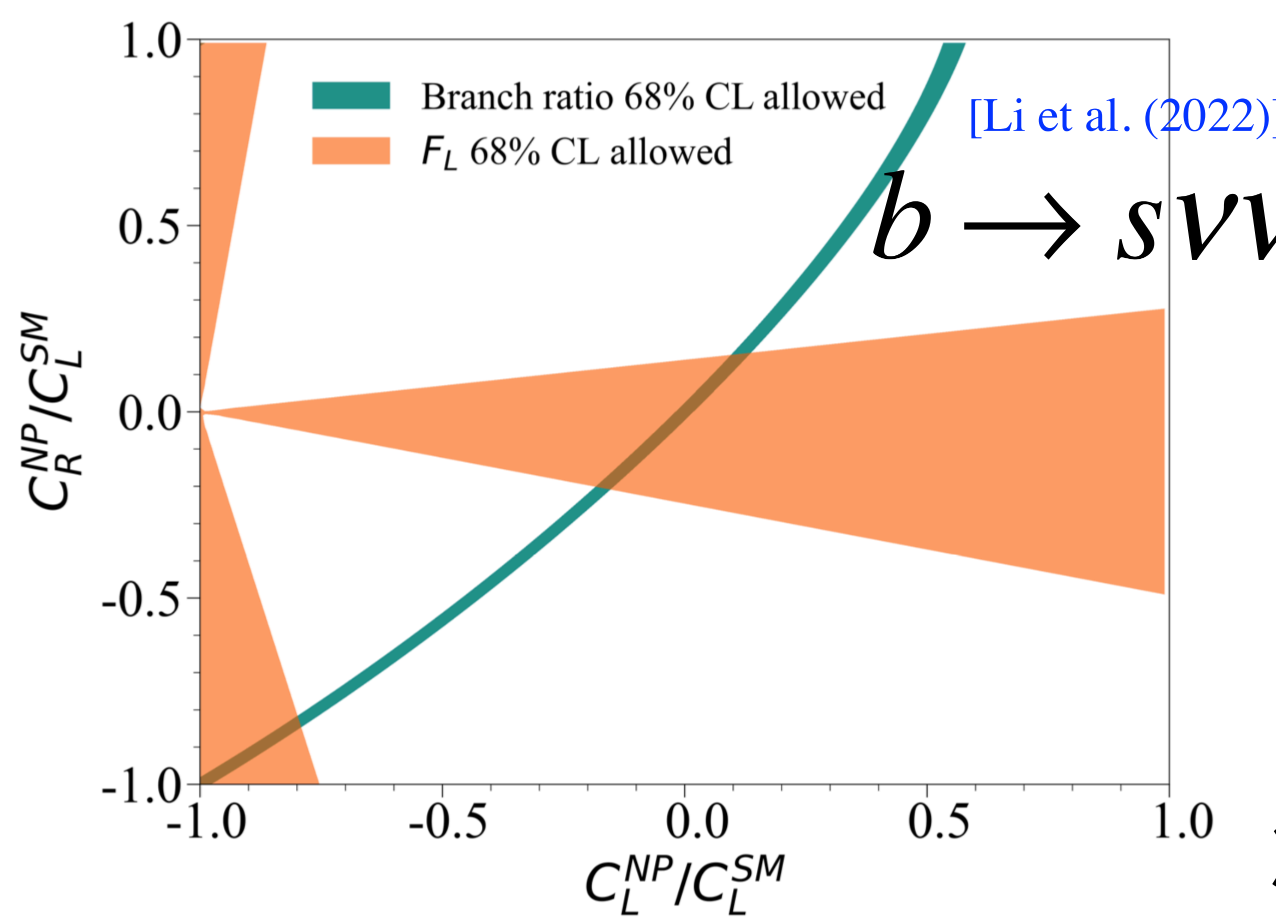






Theoretical Aspects

- EFT method: Low-Energy EFT and SMEFT

SM deviations: τ sector only!

- RG Running and Matching

Low-Energy EFT (LEFT)

EFT Scale $\sim m_b \quad << m_Z$

4-5 GeV

Examples:

$$O^{\tau}_{S_R} = [\bar{c} P_R b][\bar{\tau} P_L \nu]$$

$$O^{\tau}_{V_L} = [\bar{c} \gamma^{\mu} P_L b][\bar{\tau} \gamma_{\mu} P_L \nu]$$

- Different Lorentz structures

  Scalar/Vector Mediator?

- Independent, no correlation

[Jenkins et al. (2018)]

SMEFT (Up to Dim-6 Operators)

[Grzadkowski et al. (2010)]

$$\frac{1}{\Lambda^2} C_i O_i$$

NP Scale! $\sim \mathcal{O}(\text{TeV})$

Down Basis Expansion

SU(2)

$$[O_{lq}^{(1)}]_{3332} \qquad (\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$$

$$[O_{lq}^{(3)}]_{3332} \qquad 2V_{cs}^*(\bar{\nu}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L c)$$

$$-(\bar{\nu}\gamma^\mu P_L \nu - \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$$

- Correlation exists!
- FCCC and FCNC constrained by same operators

FCCC and FCNC both matter!

[Aebischer et al. (2018)]

Methodology

STEP 1: Use MCMC to constrain LEFT WCs.

12 Observables: $b \to c\tau\nu \quad b \to s\tau\tau \quad b \to s\nu\nu$

STEP 2: Run LEFT from b mass to Z mass.

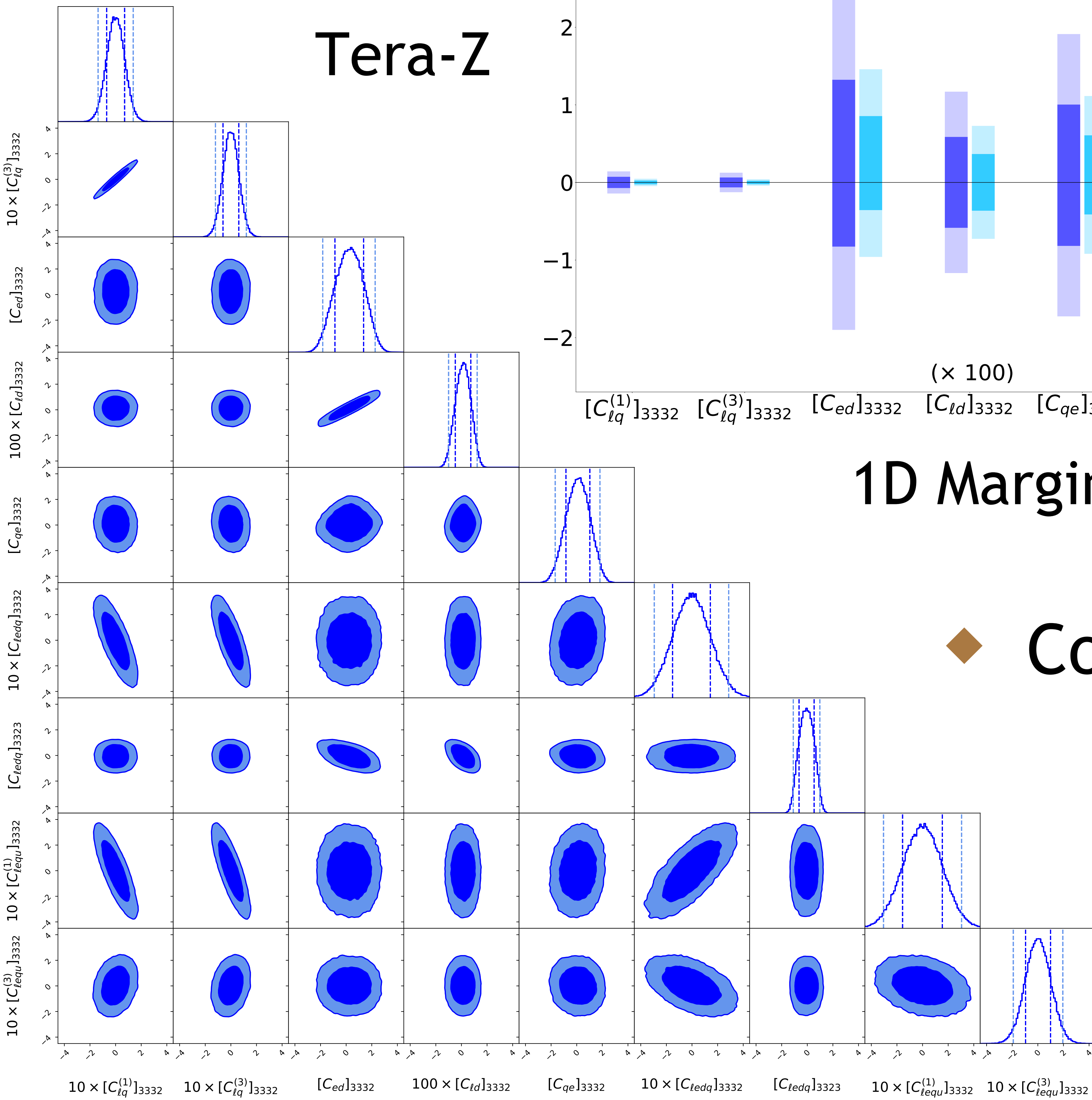
STEP 3: Tree-level matching at Z pole.

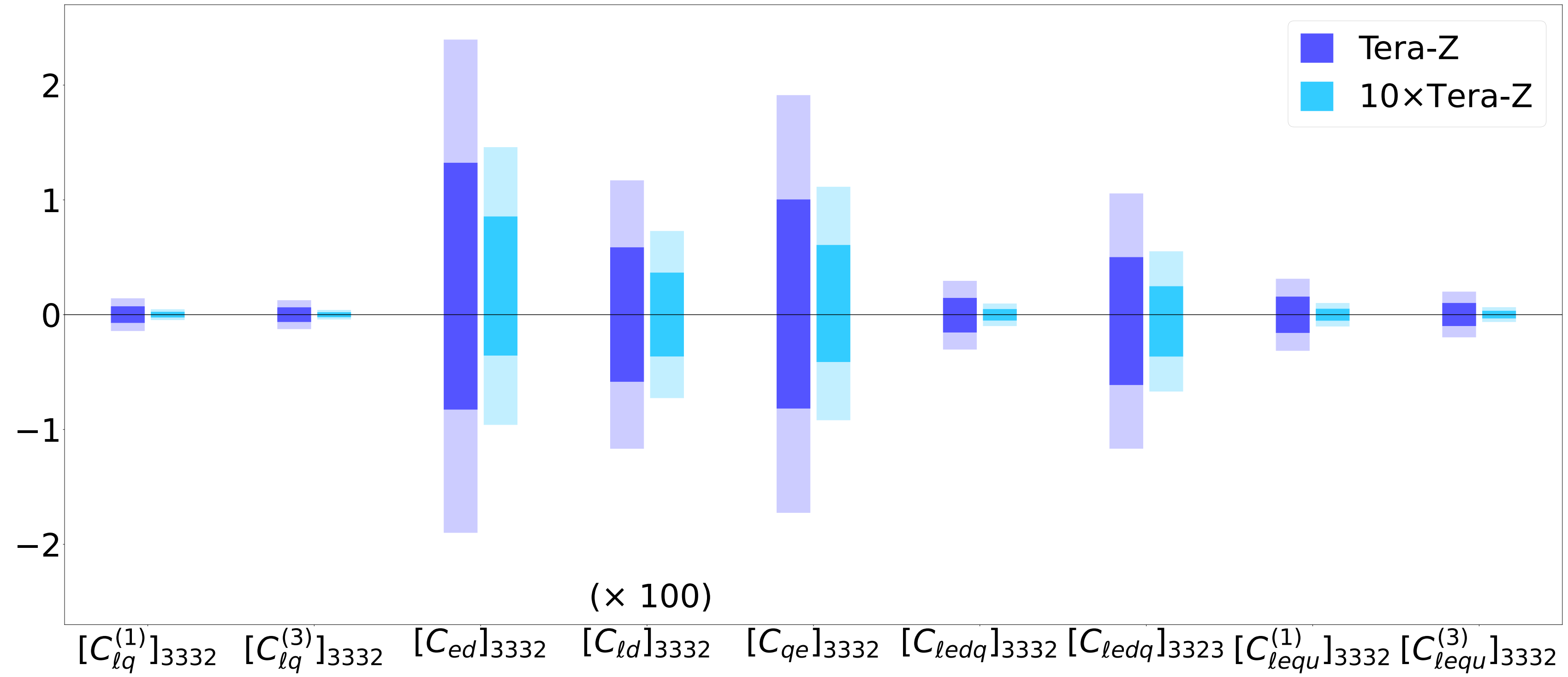
$$\mathcal{L}_{\mathrm{SMEFT}}(m_Z) = \mathcal{L}_{\mathrm{LEFT}}(m_Z)$$

STEP 4: Run SMEFT from Z mass to SMEFT scale $\Lambda = 10\,\mathrm{TeV}$.

SMEFT Constraints

9 operators in total





1D Marginalized Constraints.

- Constrain Muti-TeV NP Sensitively.
- Correlations!

$\Lambda = 10\text{TeV}$

Conclusions and Many Thanks

- Great advantages of Z factories: large luminosity, clean environment and etc.
- LFU being tested via precise measurements at Tera-Z.
- Multi-TeV NP being well constrained at Tera-Z.

Back-Up

Back-Up

Preselection

- **The 3μ selection.** The events with exactly three muon tracks ($p_T > 0.1$ GeV), and at least two of them sharing the same vertex, are selected.

- **The J/ψ selection.** Two of the three muons need to be oppositely charged. Their momentum satisfies $|\vec{p}| > 2.5$ GeV. The leading transverse momentum must be > 0.75 GeV, while their total p_T must be > 1 GeV. These two muons form a common vertex, with its distance to the primary vertex (PV) > 0.1 mm. Besides, these two muons must have an invariant mass with $|m_{\mu^+\mu^-} - m_{J/\psi}| < 27.5$ MeV for them to be considered as the J/ψ decay products.

- **The B_c^+ selection.** We divide the space into signal and tag hemispheres with a plane perpendicular to the displacement of the reconstructed J/ψ. The J/ψ vertex appears in the signal hemisphere. The unpaired third muon (μ_3) appears in the signal hemisphere also and has $p_T > 0.375$ GeV and $|\vec{p}| > 1.5$ GeV. The 3μ system needs to have an invariant mass smaller than $m_{B_c^+}$.

Back-Up

BKG

Cascade backgrounds We refer to $H_b \to H_c\tau(\mu)\nu + X$ as "cascade backgrounds". Here H_b decays hadronically. In the simulation, any non-signal b-hadron events, if containing the $H_c + \mu$ produced not via semileptonic b-hadron decay at truth level, will be recognized as the cascade backgrounds.

Combinatoric backgrounds We refer to $H_c\tau(\mu)\nu + X$ as "combinatoric backgrounds". Here H_c and $\tau(\mu)$ do not share a parent particle at the truth level. In the simulation, any reconstructed b-hadron events, if containing the $H_c + \mu$ but not identified as the inclusive and cascade backgrounds, will be recognized as the combinatoric backgrounds.

Muon mis-ID backgrounds We refer to $H_c\mu_\pi + X$ as "muon mis-ID backgrounds". Here μ_π denotes the muon misidentified from pion. In the simulation, any $H_c\pi + X$ events will be recognized as the mis-ID background, weighted by the mis-ID probability $\epsilon_{\mu\pi} = 1\%$ as mentioned above.

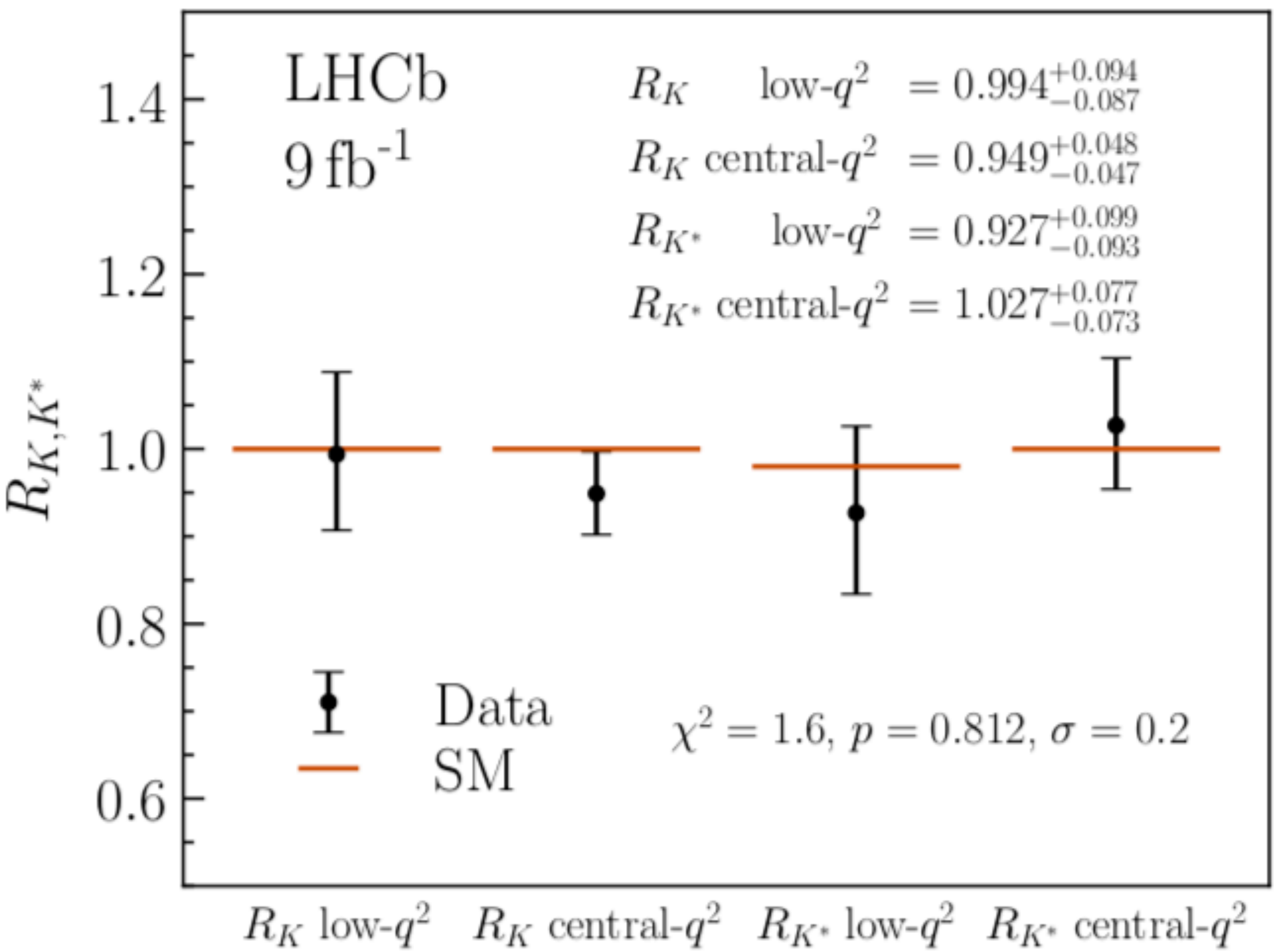
Fake H_c backgrounds We refer to $H_{c,F}\mu + X$ as "fake H_c backgrounds". Here $H_{c,F}$ denotes the fake H_c resonance, with the latter decaying as: $J/\psi \to \mu^+\mu^-$, $D_s^- \to K^+K^-\pi^-$, or $\Lambda_c^- \to \bar{p}K^+\pi^-$ in this study. These backgrounds represent the chance that the remnants for reconstructing H_c are not from H_c decays at the truth level. In the analysis, they appear as a continuous distribution of the reconstructed m_{H_c}. A good width resolution of resonance is thus essential for suppressing these backgrounds. In practice, the resonance width is determined by the resolution of the tracking system, given $\Gamma_{H_c} \lesssim \mathcal{O}(\text{keV}) \ll \Delta_{\text{track}}$, where Δ_{track} denotes the tracker smearing effect. We can estimate the level of these backgrounds from the relevant LHCb studies [7, 54, 55]. As summarized in Tab. 3, the rations of the H_c events and the continuous backgrounds in the resonant bin for the reconstructed m_{H_c} are at most a few percent. The reconstructed resonance widths are expected to be further improved at the future Z factories [7, 54, 55]. Furthermore, the fake H_c background sizes can easily be extrapolated by sideband m_{H_c} distributions. So the effect of this type of background can be safely neglected in R_{H_c} precision projections.

Recent LHCb Measurements

Improved lepton universality measurements show agreement with the Standard Model

By **admin**

DEC 20, 2022 lepton universality, RK, RK*



$$R_{K,K^*} = \frac{\mathrm{Br}\,(\mathrm{B}^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{Br}\,(\mathrm{B}^{(+,0)} \to K^{(+,*0)}e^+e^-)}$$

Compatible with SM.

[LHCb collaboration, 2022]

Observables Used for MCMC Fitting

[Zheng. et al.] [Li and Liu (2021)] [Li et al. (2022)] [Altmannshofer, W. et al. (2018)] [Aaij et al. (2018)]

Physical Quantity	SM Value	Tera-Z	10×Tera-Z	Belle II	LHCb
$R_{J/\psi}$	0.289	2.89×10^{-2}	9.15×10^{-3}	-	-
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$R_{D_s^*}$	0.303	3.25×10^{-3}	1.03×10^{-3}	-	-
R_{Λ_c}	0.334	9.74×10^{-4}	3.08×10^{-4}	-	-
$\text{BR}(B_c \to \tau\nu)$	2.36×10^{-2} [6]	0.01 [6]	3.16×10^{-3}	-	-
$\text{BR}(B^+ \to K^+\tau^+\tau^-)$	1.01×10^{-7}	7.92 [7]	2.48 [7]	198 [11]	-
$\text{BR}(B^0 \to K^{*0}\tau^+\tau^-)$	0.825×10^{-7}	10.3 [7]	3.27 [7]	-	-
$\text{BR}(B_s \to \phi\tau^+\tau^-)$	0.777×10^{-7}	24.5 [7]	7.59 [7]	-	-
$\text{BR}(B_s \to \tau^+\tau^-)$	7.12×10^{-7}	28.1 [7]	8.85 [7]	-	702 [12]
$\text{BR}(B^+ \to K^+\bar{\nu}\nu)$	4.6×10^{-6} [11]	-	-	0.11 [11]	-
$\text{BR}(B^0 \to K^{*0}\bar{\nu}\nu)$	9.6×10^{-6} [11]	-	-	0.096 [11]	-
$\text{BR}(B_s \to \phi\bar{\nu}\nu)$	9.93×10^{-6} [77]	1.78×10^{-2} [77]	5.63×10^{-3}	-	-

12 observables:

9 effective, some others similar