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Semileptonic b Decays at Future Z Factories

For:
The 2022 international workshop
on the high energy
Circular Electron-Positron Collider

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On-going work in collaboration with
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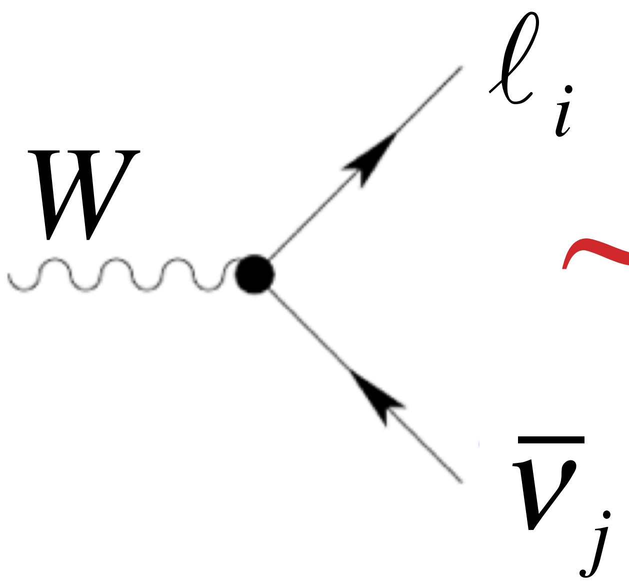
2022.10.25

Lepton Flavor Universality (LFU)

Standard Model: 3 generations of leptons

- Same Coupling to Gauge
- Different Masses



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

$$e: 0.511\ \mathrm{MeV}$$
$$\mu: 105.66\ \mathrm{MeV}$$
$$\tau: 1777\ \mathrm{MeV}$$

Precise Measurement

- A Test of SM
- Hints for BSM

B Anomalies And LFUV

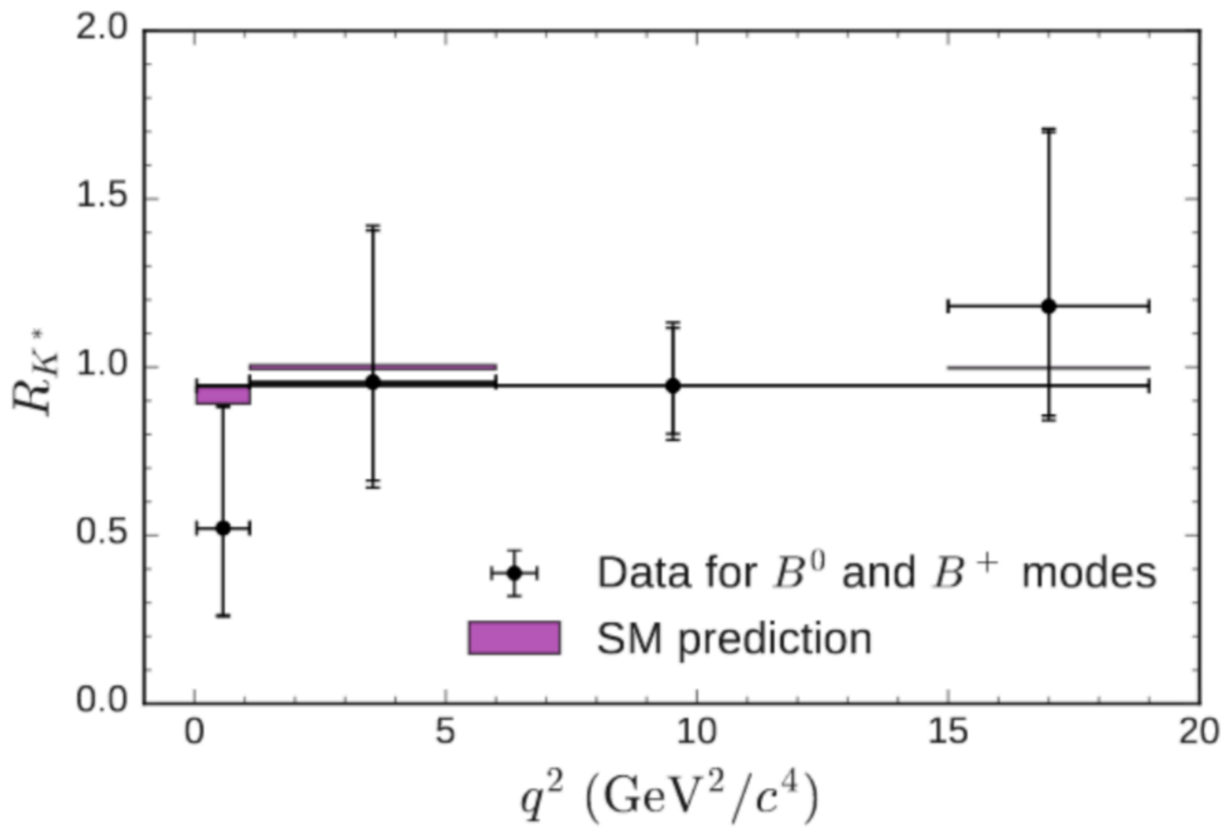
$$R_{H_c} = \frac{\mathrm{Br}\,(H_b \to H_c \tau \nu)}{\mathrm{Br}\,(H_b \to H_c \mu \nu)}$$

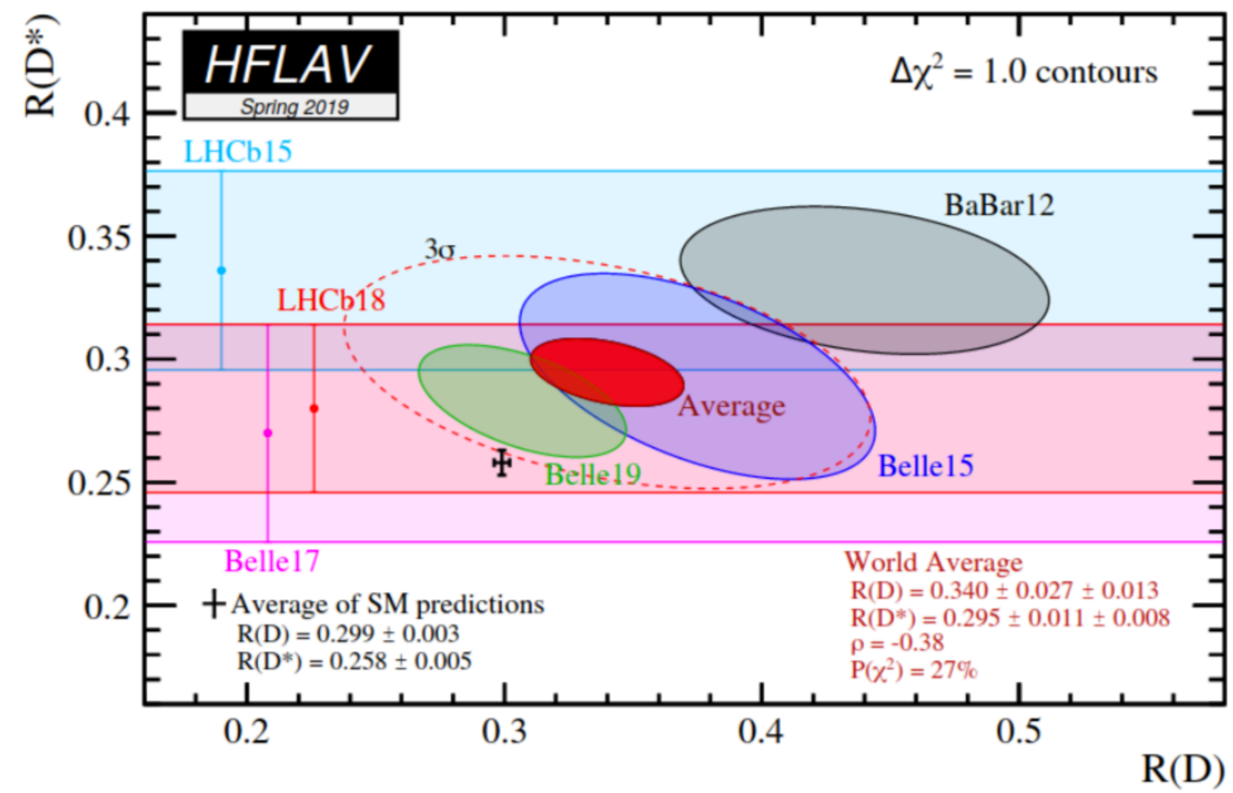
Experimental Results

VS.

SM Predictions

B Anomalies And LFUV



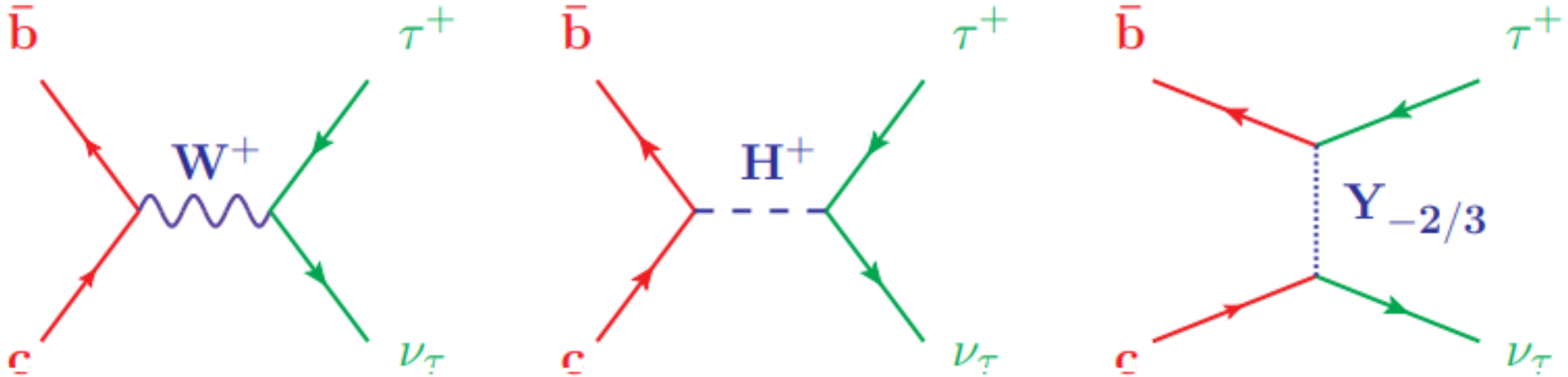


	Experimental	SM Prediction	Comments
R_K	$0.846^{+0.044}_{-0.041}$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_{pK}	$0.86^{+0.14}_{-0.11} \pm 0.05$	~ 1	$m_{\ell\ell} \in [0.1, 6.0]$ GeV^2, via Λ_b.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28	

[Tanabashi, M. et al. (2018)] [Altmannshofer, W. et al. (2018)]
[Aaij, R. et al. (2020)] [Aaij, R. et al. (2021)]

B anomalies indicate LFUV.

Tree-level BSM realizations:



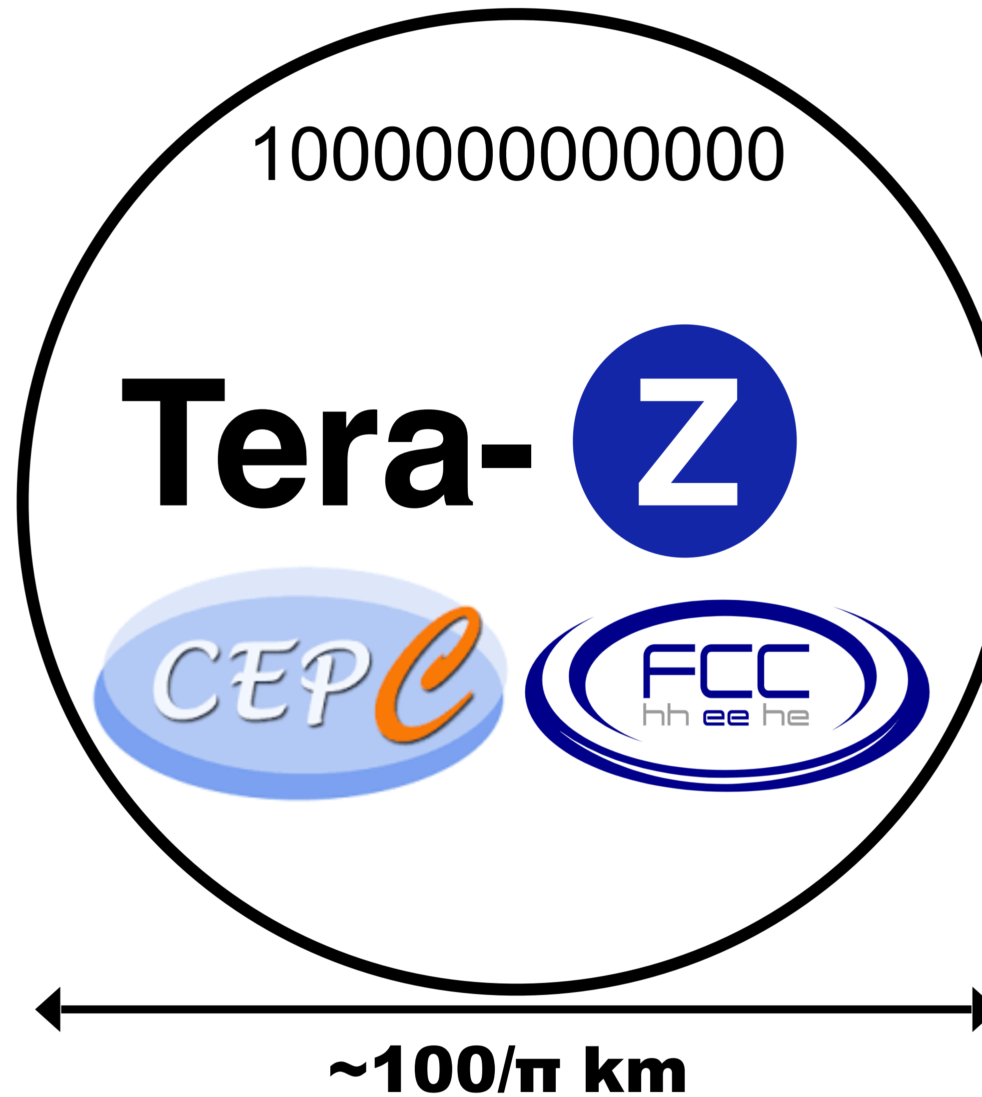
SM uncoloured coloured

[Zheng. et al.]

Future Z Factories

Circular Lepton Collider

- Clean environment
- b hadron abundance: $O(10^{11+})$
- Directly measure missing momentum
- Large energy (20-45 GeV) and boost for precision measurements
- More advanced Detector Technology



Semileptonic Decay $b \to c\tau\nu$

- 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.]

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

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SU(2)

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

Signals

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

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

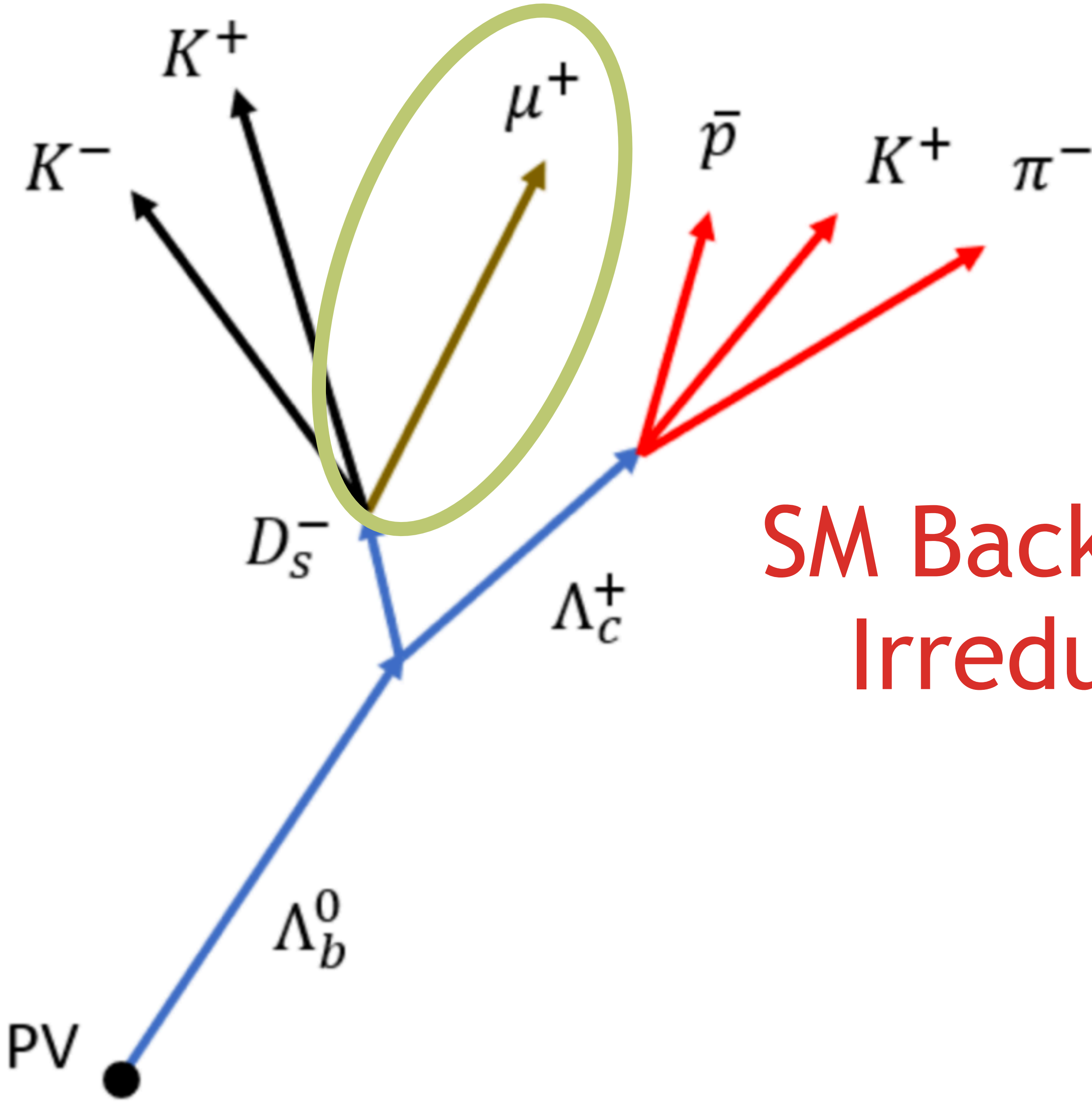
- $$R_{D_s^{(*)}} = \frac{\mathrm{Br}\,(\mathrm{B}_s \to D_s^{(*)}\tau\nu)}{\mathrm{Br}\,(B_s \to D_s^{(*)}\mu\nu)}$$

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

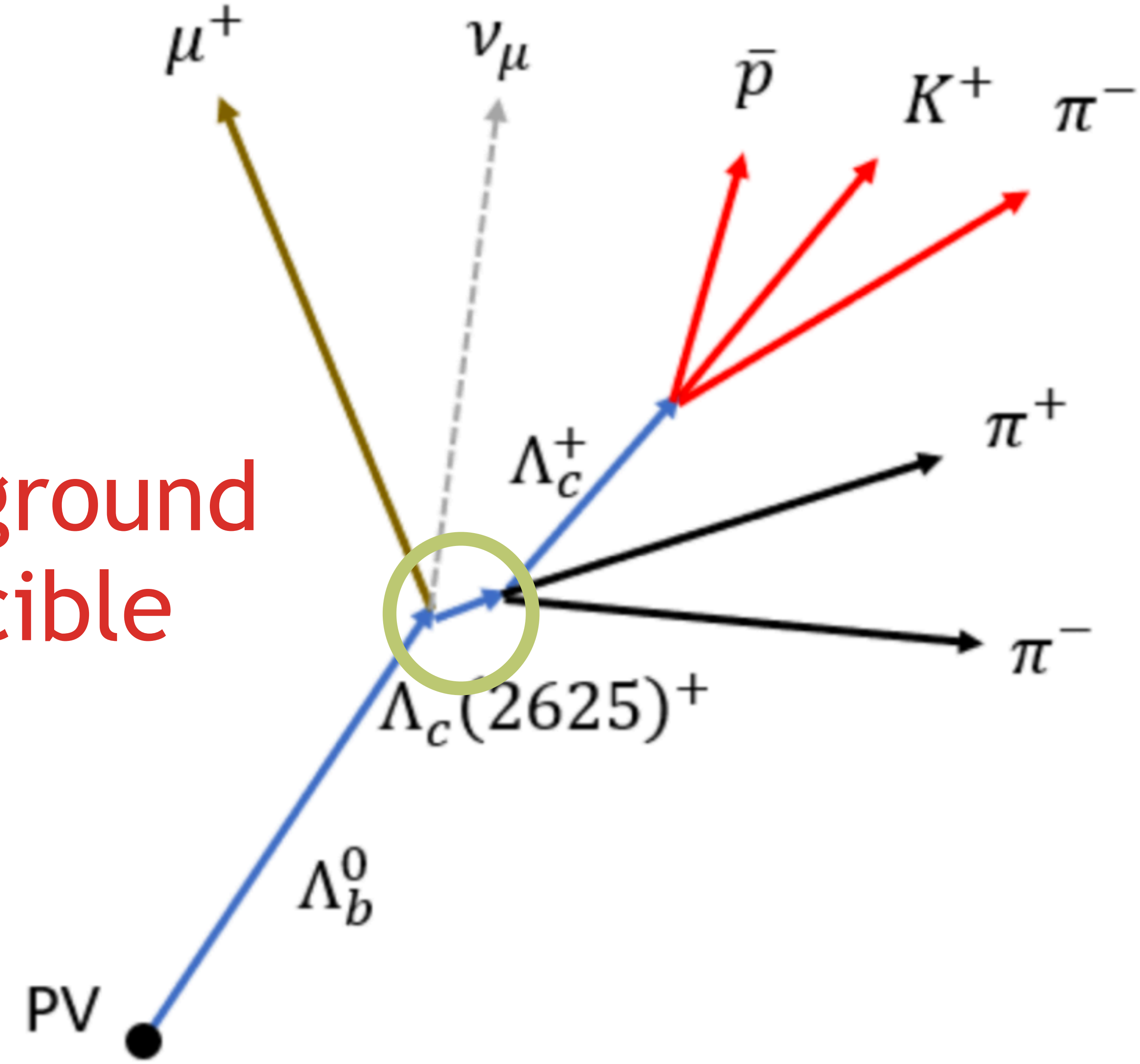
- $$R_{\Lambda_c} = \frac{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\tau\nu)}{\mathrm{Br}\,(\Lambda_b \to \Lambda_c\mu\nu)}$$

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

Possible Backgrounds



SM Background Irreducible

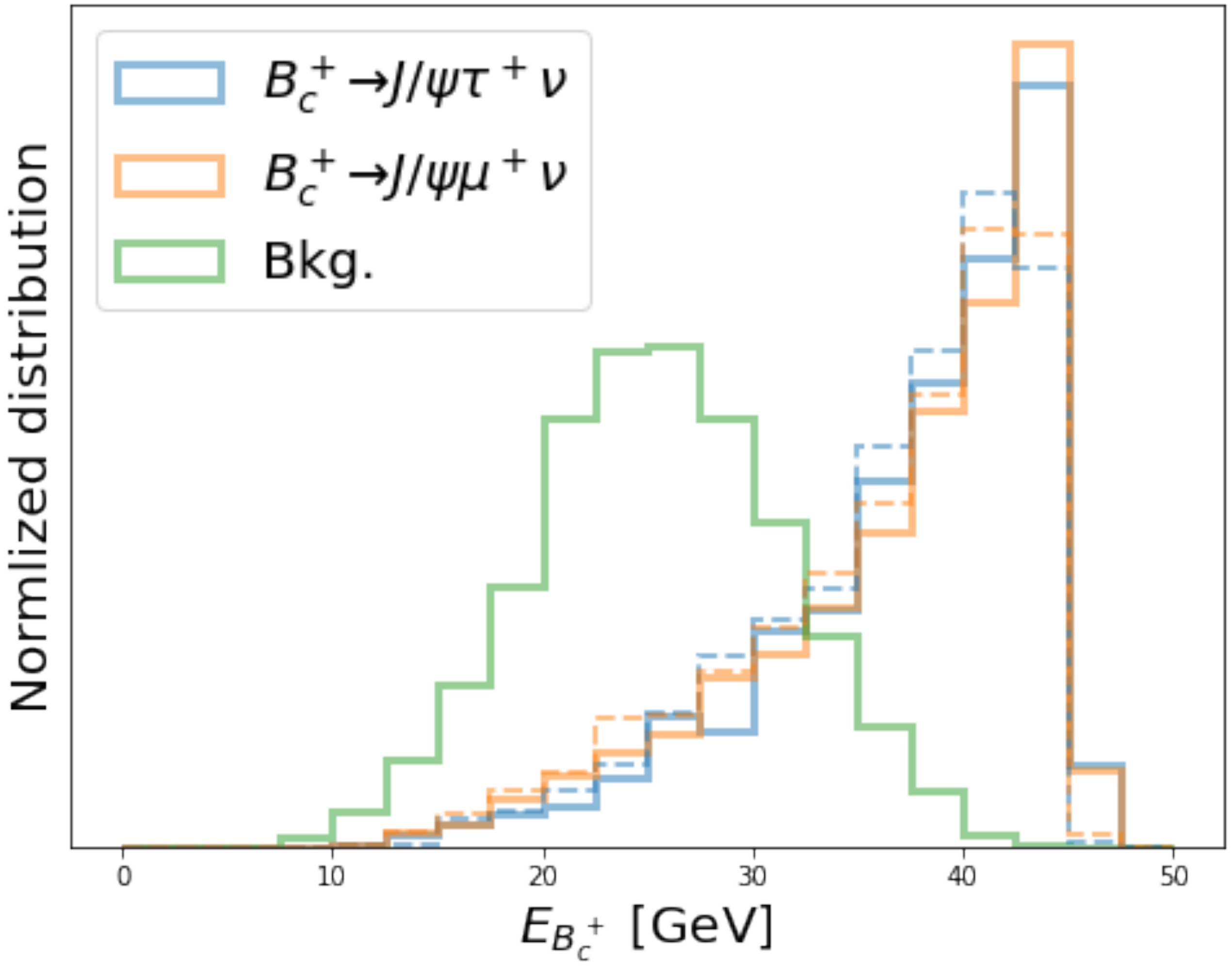


"Wrongly" produced Muon

"Wrongly" produced H_c

+ Others

Reconstruction



Solid: reconstruction;
Dashed: truth level.

ERROR $\sim \mathcal{O}(1\,\mathrm{GeV})$

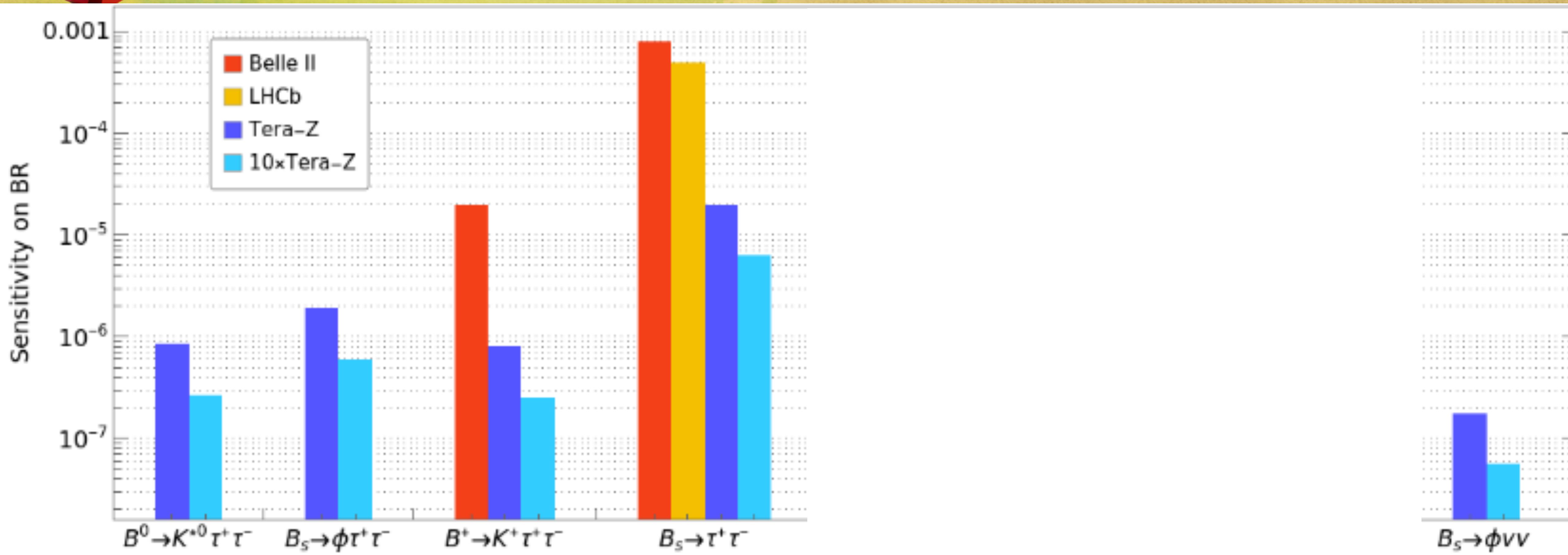
Results

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



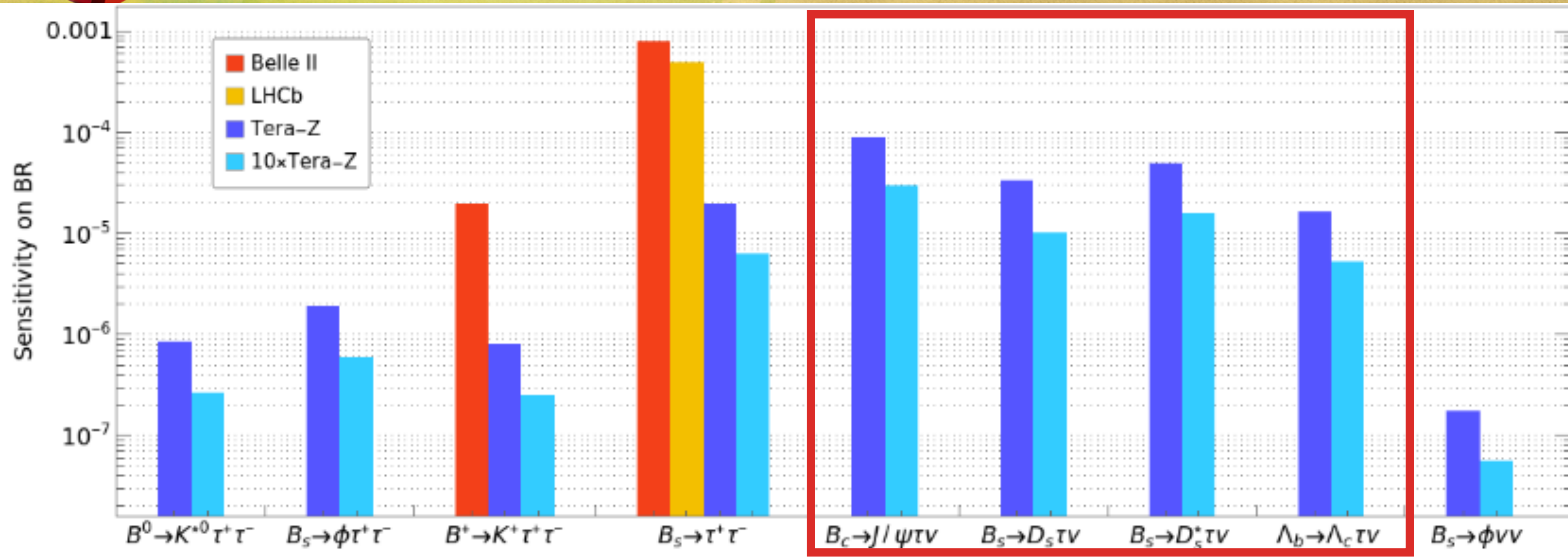
[Li and Liu (2021)]

$$b \to s\tau\tau$$

[Li et al. (2022)]

$$b \to s\nu\nu$$

Results



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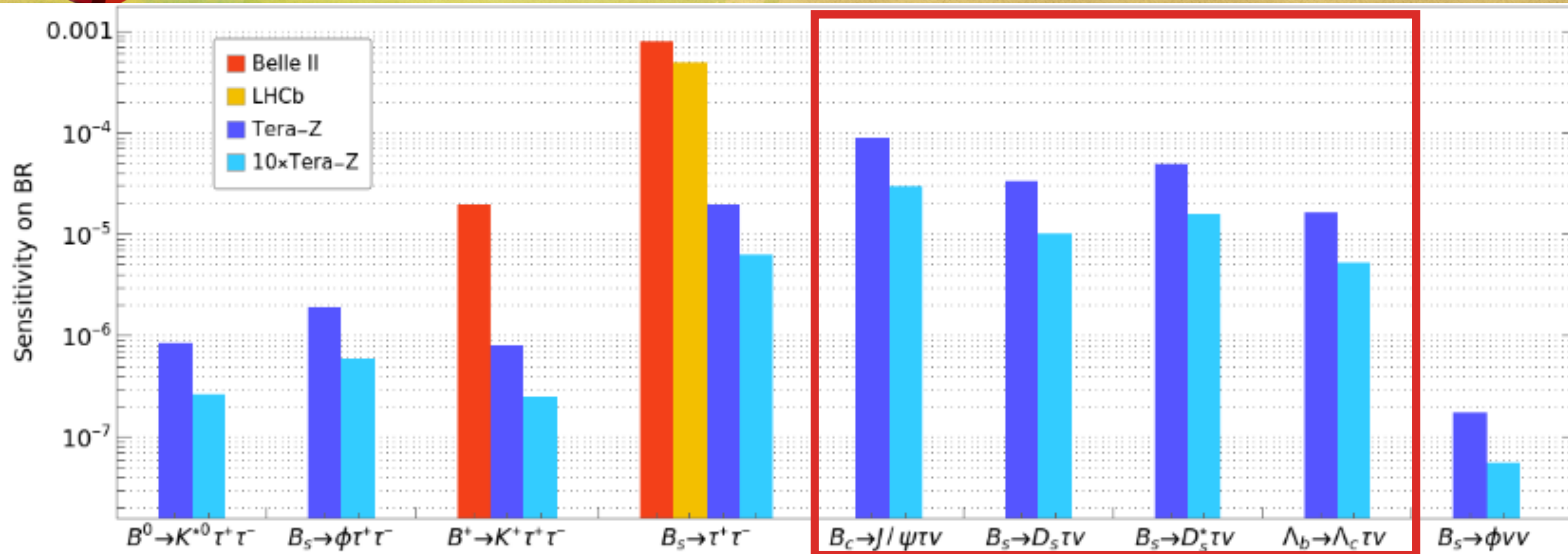

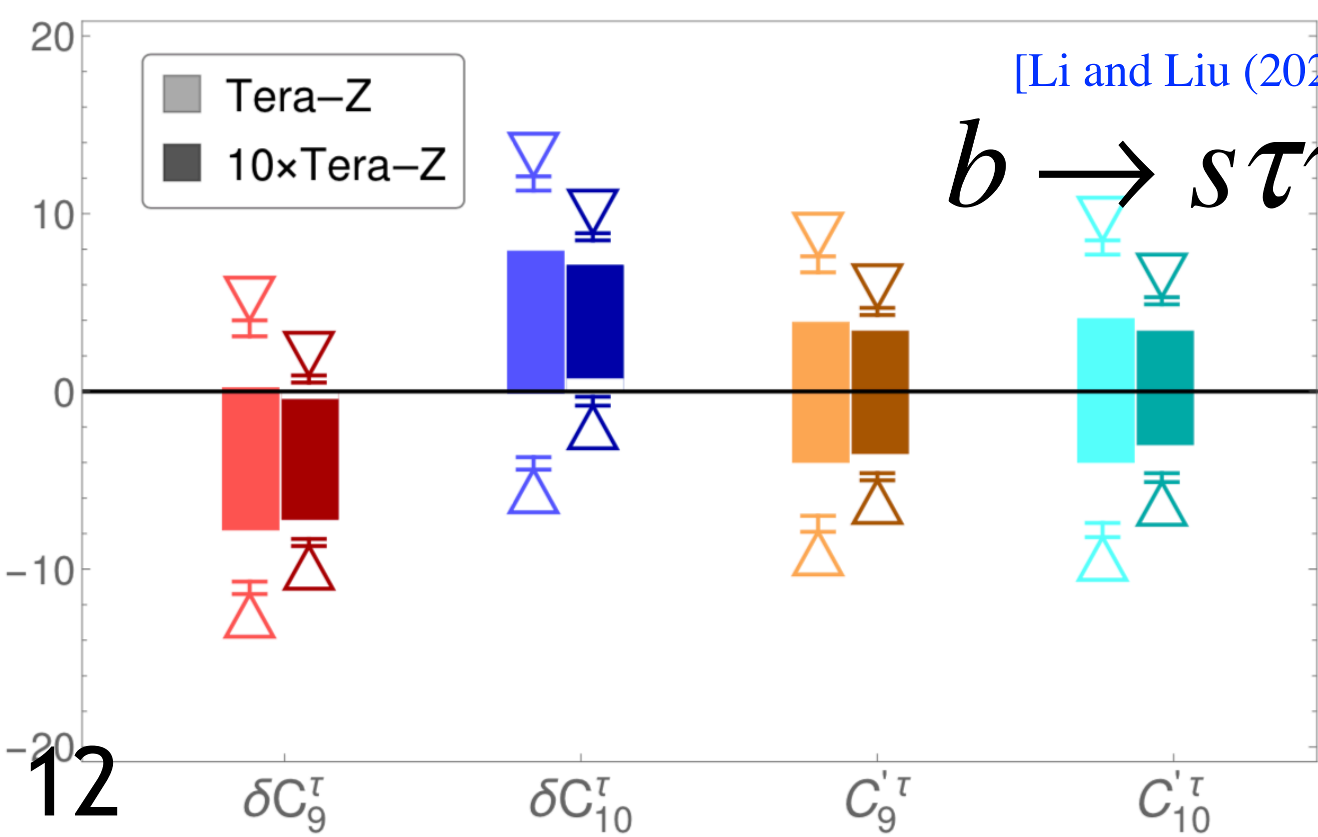

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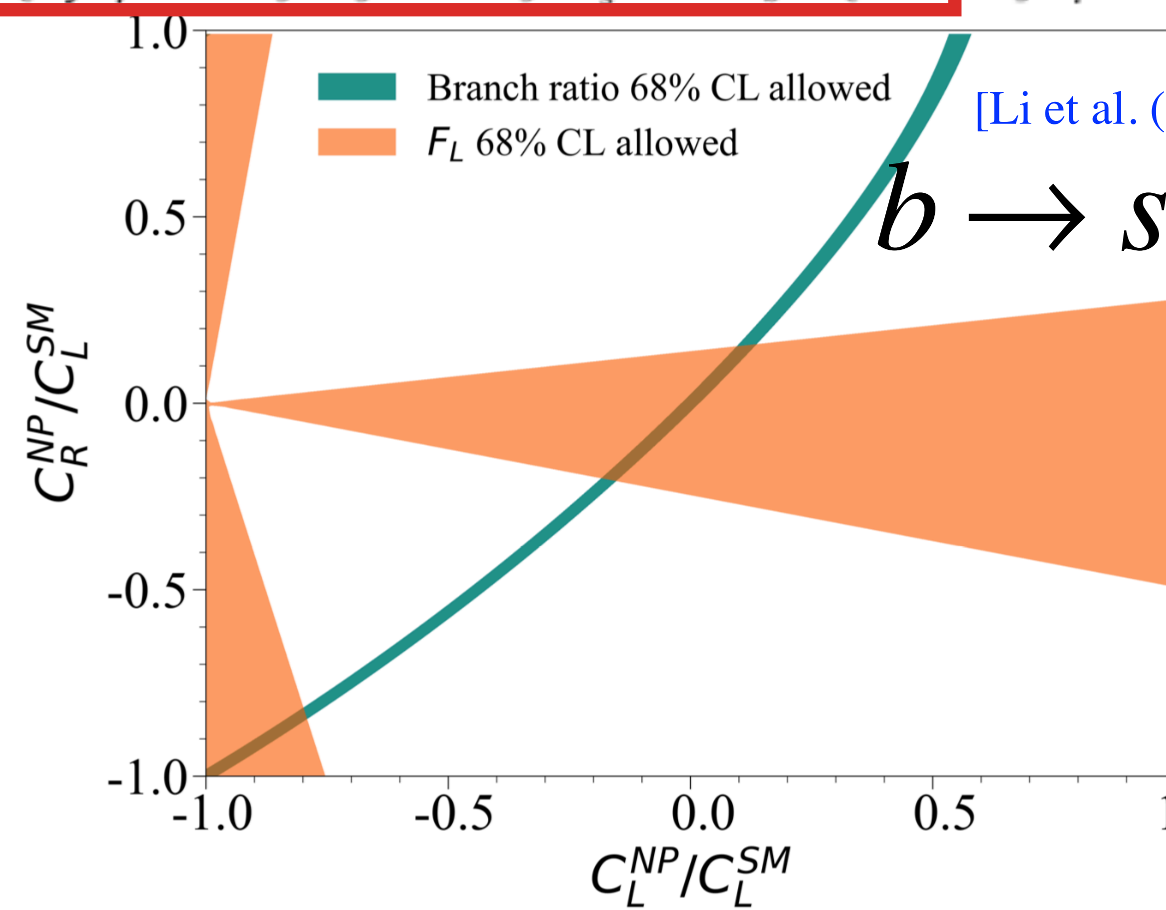


[Li et al. (2022)]

$b \to s\nu\nu$

Theoretical Aspects

- EFT method: Low-Energy EFT and SMEFT

  SM deviations: τ sector only!

- Wilson coefficients

- FCCC and FCNC both matter!

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

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

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

Down Basis Expansion

SU(2)

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

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

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

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

[Grzadkowski et al. (2010)]

Methodology

STEP 1: Use MCMC to constrain LEFT WCs.

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

[Aebischer et al. (2018)]

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

$$\Lambda = 10\,\mathrm{TeV}.$$

[Aebischer et al. (2018)]

Parameters Used for MCMC Fitting

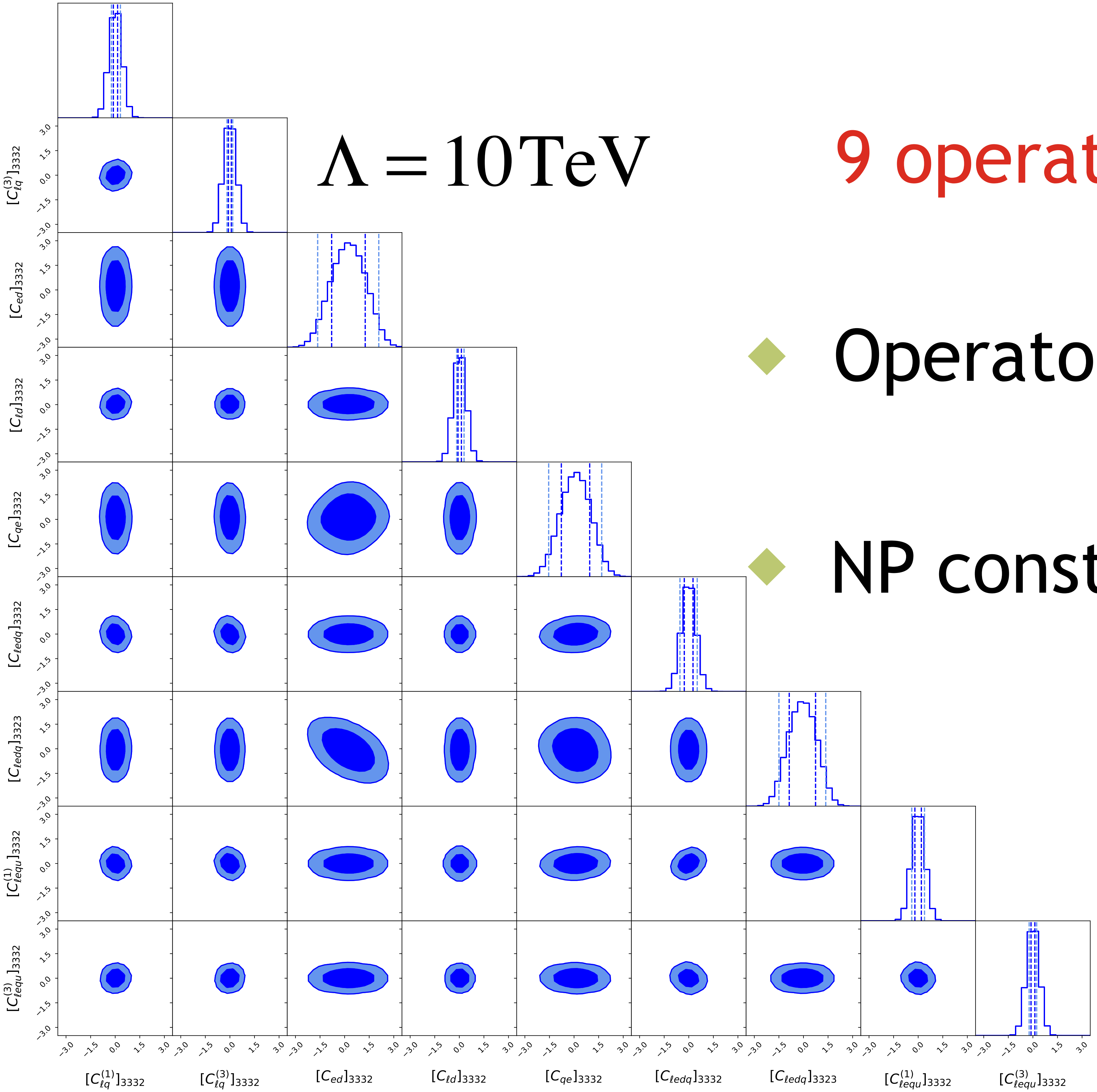
[Zheng. et al.] [Li and Liu (2021)] [Li et al. (2022)] [Altmannshofer, W. et al. (2018)] [Aaij et al. (2018)]

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}	-	-
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}	-	-
$\text{BR}(B_c \to \tau\nu)$	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

SMEFT Constraints

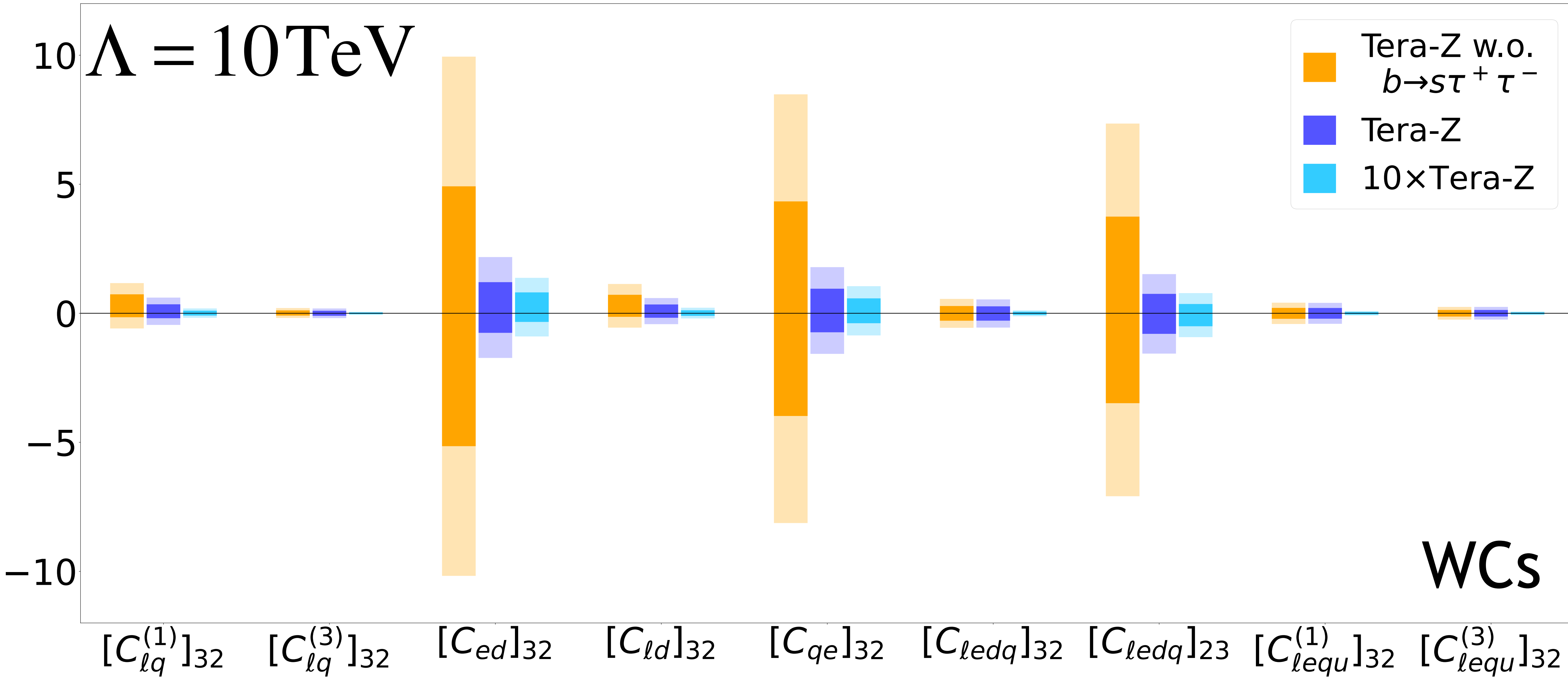


$\Lambda = 10\text{TeV}$

9 operators in total

- Operator correlations
- NP constrained at Tera-Z

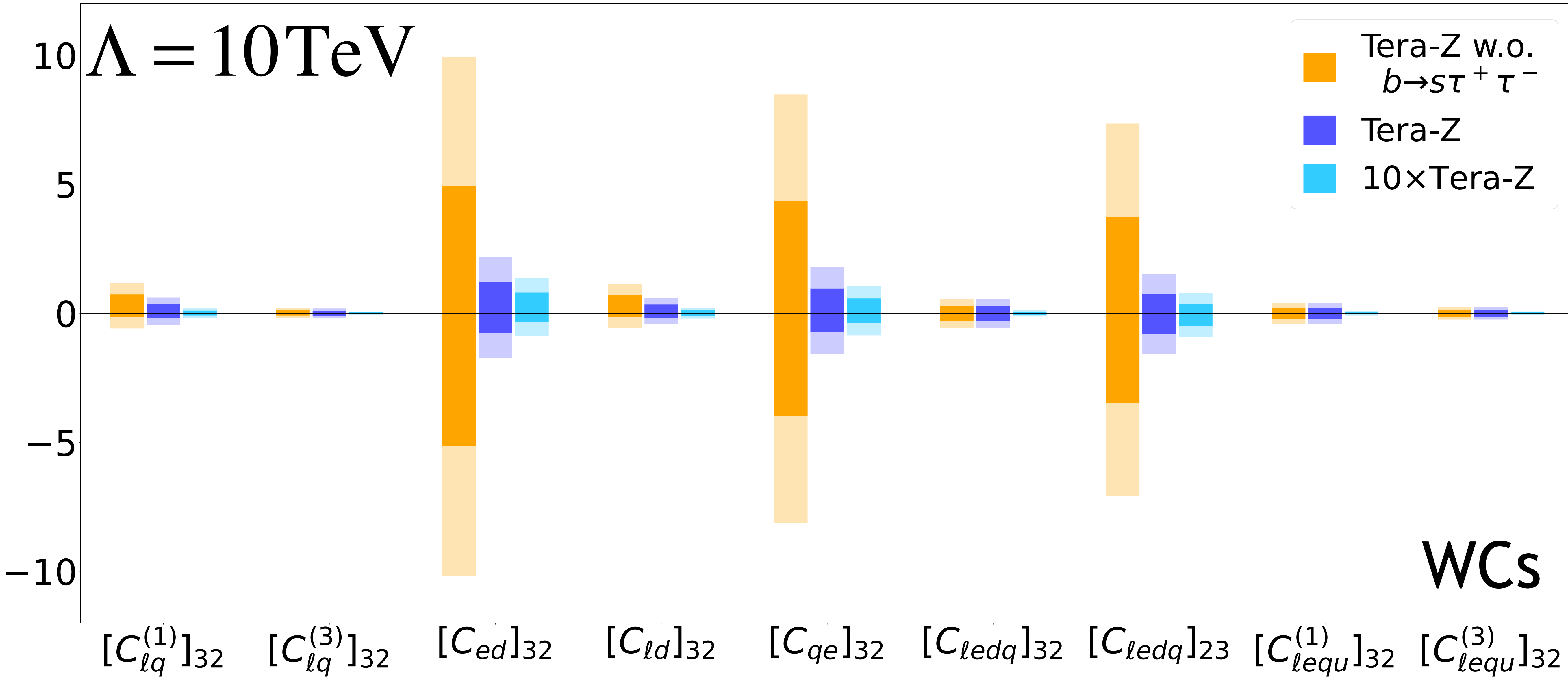
SMEFT Constraints



1D Marginalized Constraints:

Tera-Z, 10×Tera-Z, Tera-Z but w.o. $b \to s\tau\tau$

SMEFT Constraints



Constrain NP Sensitively:
Very Promising!

1D Marginalized Constraints:

Tera-Z, 10×Tera-Z, Tera-Z but w.o. $b \to s\tau\tau$

Conclusion

- Great advantages of Z factories: large luminosity, clean environment and etc.

- LFU being tested via precise measurements of B anomalies at Tera-Z.

$$R_{J/\psi}, R_{D_s^{(*)}}, R_{\Lambda_c} \sim \mathcal{O}(0.1\%) - \mathcal{O}(1\%)$$

- Multi-TeV NP being well constrained at Tera-Z.