

Email: xjiangaj at connect dot ust dot hk



Semileptonic b Decays at Future Z Factories

Xuhui Jiang

蒋旭辉

The Hong Kong University
of Science and Technology

For:

The 16th TeV Workshop
at
Tsinghua University

On-going work in collaboration
with

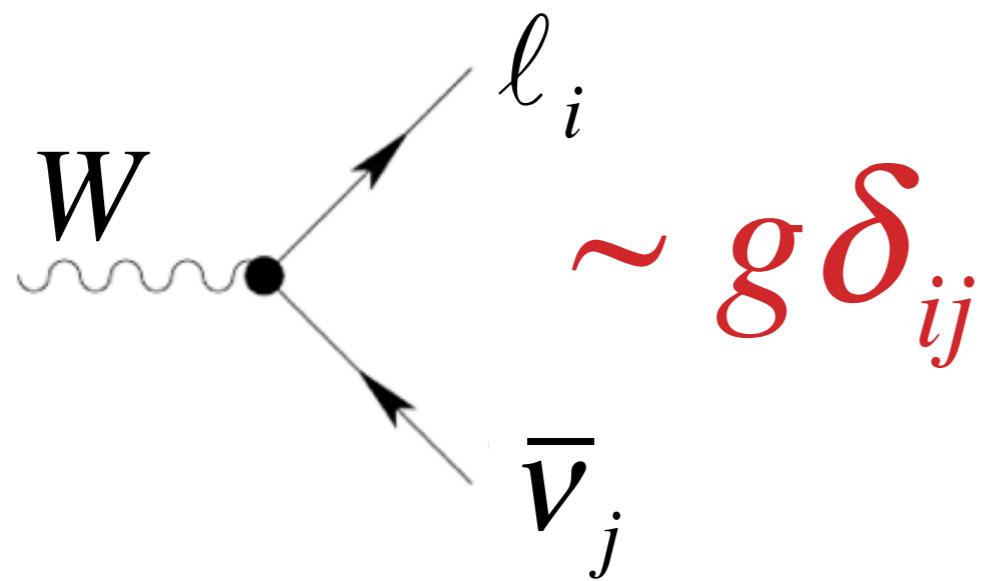
Tin Seng (Manfred) Ho,
Tsz Hong (Anson) Kwok
Lingfeng Li and Tao Liu



Lepton Flavor Universality (LFU)

Standard Model: 3 generations of leptons

- ◆ Same Coupling to Gauge
- ◆ Different Masses



$$\begin{aligned} e &: 0.511 \text{ MeV} \\ \mu &: 105.66 \text{ MeV} \\ \tau &: 1777 \text{ MeV} \end{aligned}$$

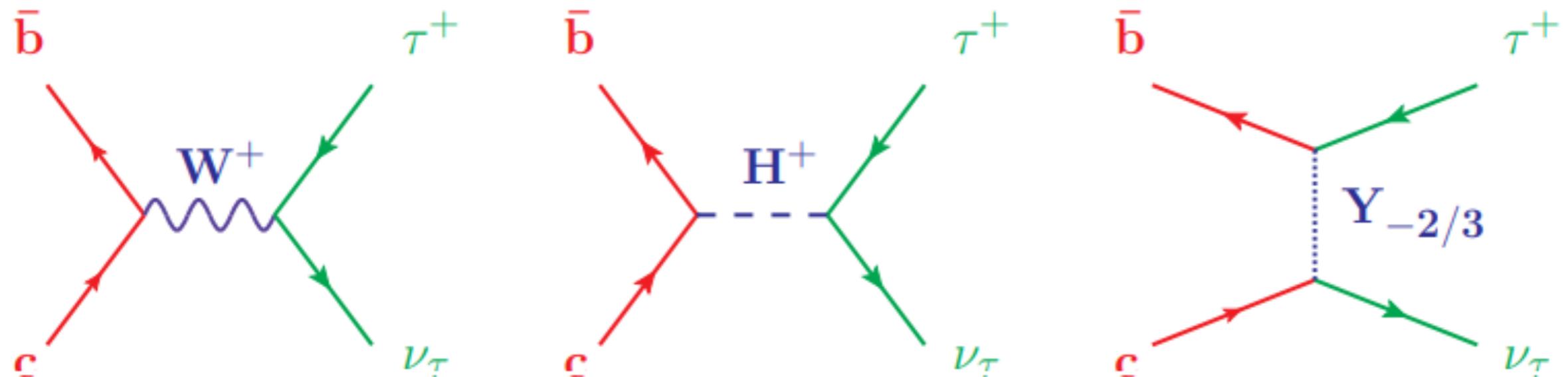
Precise Measurement

- ◆ A Test of SM
- ◆ Hints for BSM



LFU Violation

Tree-level BSM realizations:



SM

uncoloured

coloured

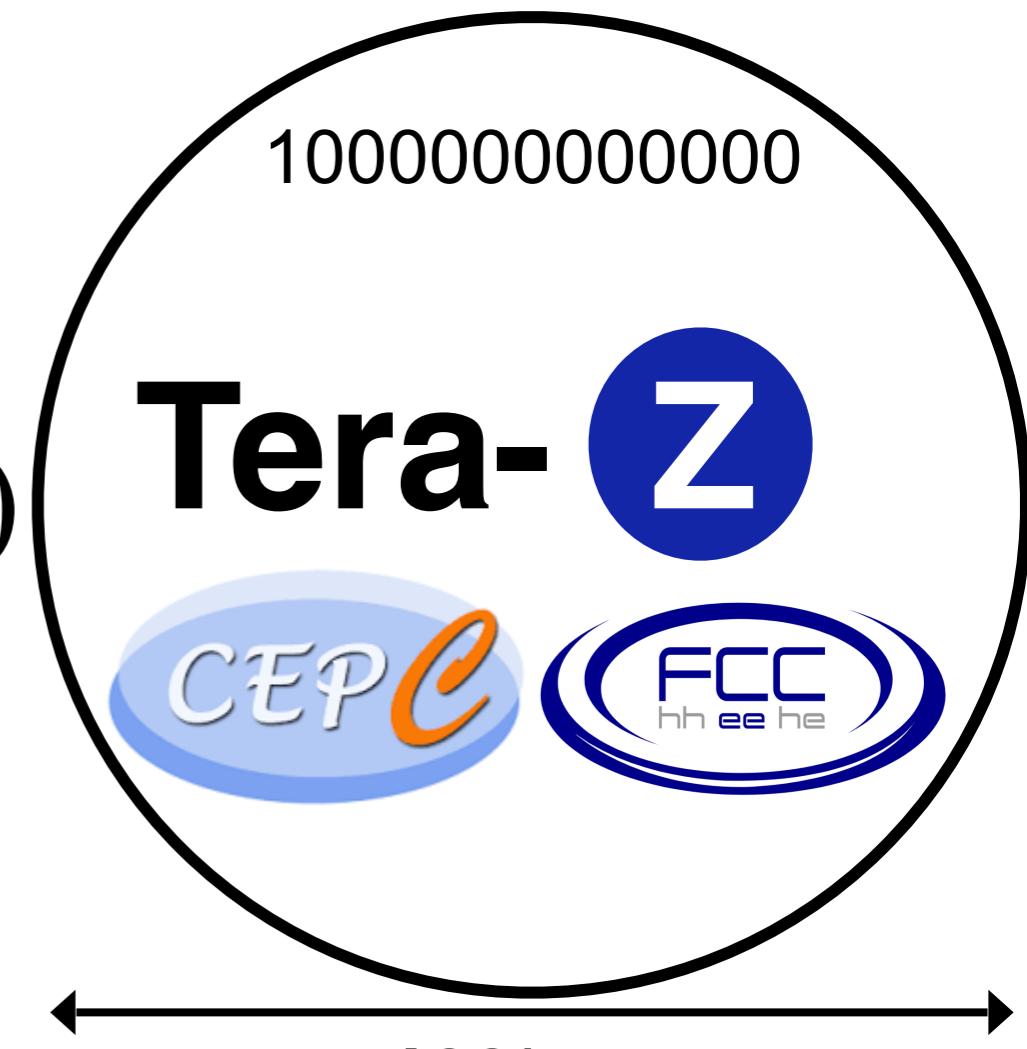
[Zheng, et al.]



Future Z Factories

Circular Lepton Collider

- ◆ Clean environment
- ◆ b hadron abundance: $0(10^{11+})$
- ◆ Directly measure missing momentum
- ◆ Large energy (20-45 GeV) and boost for precision measurements
- ◆ More advanced Detector Technology





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

- ◆ Set a baseline for the studies at Tera-Z.

$$R_{H_c} = \frac{\text{Br}(H_b \rightarrow H_c \tau\nu)}{\text{Br}(H_b \rightarrow H_c \mu\nu)}$$

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

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



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

- ◆ Set a baseline for the studies at Tera-Z.

$$R_{H_c} = \frac{\text{Br}(H_b \rightarrow H_c \tau\nu)}{\text{Br}(H_b \rightarrow H_c \mu\nu)}$$

- ◆ Vector $R_{J/\psi}$ and $R_{D_s^*}$
- ◆ Pseudoscalar R_{D_s}
- ◆ Baryonic R_{Λ_c}

- ◆ Annihilation $\text{Br}(B_c \rightarrow \tau\nu)$ [Zheng. et al.]

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



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

- ◆ Set a baseline for the studies at Tera-Z.

$$R_{H_c} = \frac{\text{Br}(H_b \rightarrow H_c \tau\nu)}{\text{Br}(H_b \rightarrow H_c \mu\nu)}$$

- ◆ Vector $R_{J/\psi}$ and $R_{D_s^*}$
- ◆ Pseudoscalar R_{D_s}
- ◆ Baryonic R_{Λ_c}

- ◆ Annihilation $\text{Br}(B_c \rightarrow \tau\nu)$ [Zheng. et al.]

SU(2)

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



Signals

◆ $R_{J/\psi} = \frac{\text{Br}(\text{B}_c \rightarrow J/\psi \tau \nu)}{\text{Br}(B_c \rightarrow J/\psi \mu \nu)}$

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

◆ $R_{D_s^{(*)}} = \frac{\text{Br}(\text{B}_s \rightarrow D_s^{(*)} \tau \nu)}{\text{Br}(B_s \rightarrow D_s^{(*)} \mu \nu)}$

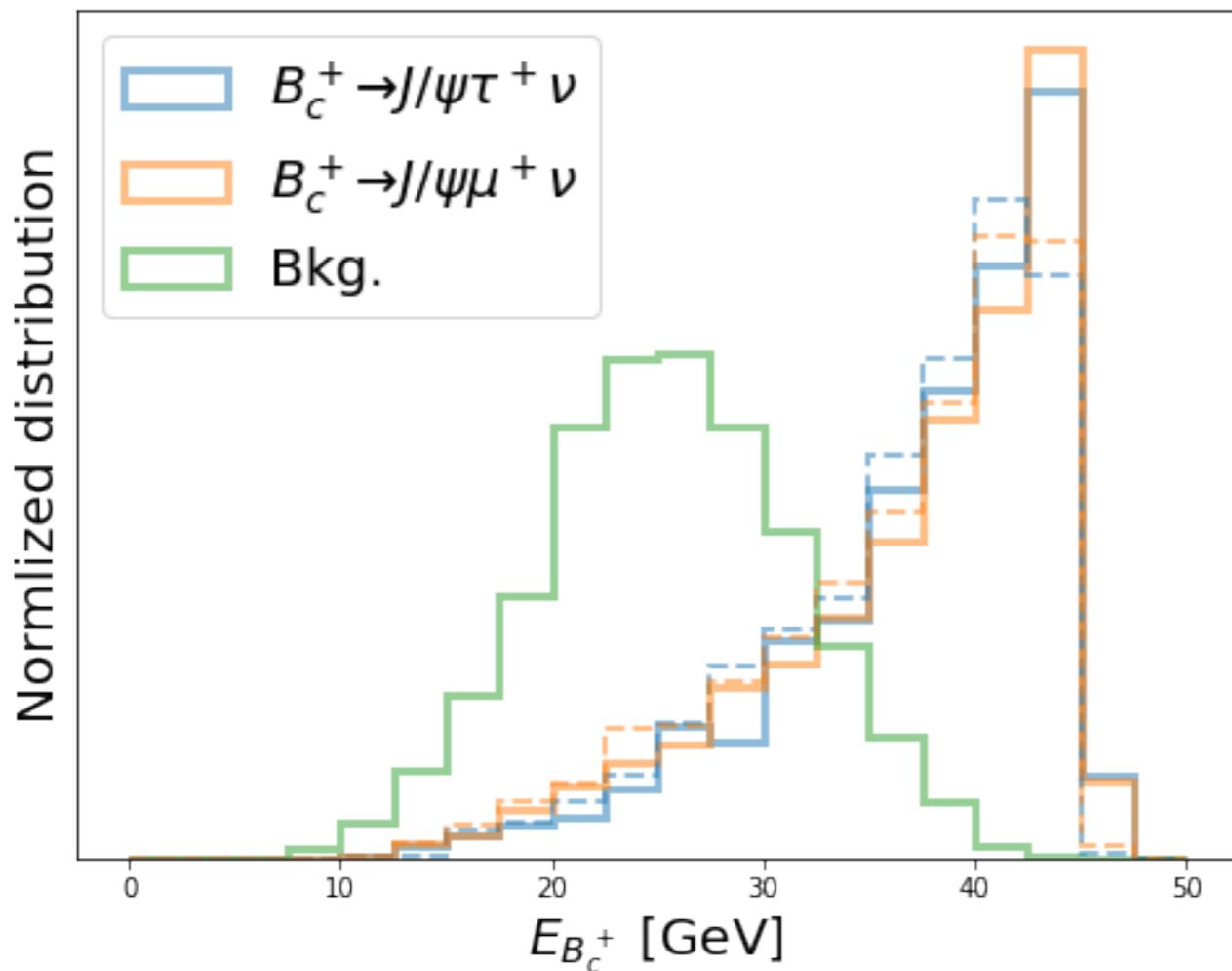
$$D_s^* \rightarrow D_s \gamma, D_s \rightarrow \phi(\rightarrow KK) \pi, \tau \rightarrow \mu\nu\bar{\nu}$$

◆ $R_{\Lambda_c} = \frac{\text{Br}(\Lambda_b \rightarrow \Lambda_c \tau \nu)}{\text{Br}(\Lambda_b \rightarrow \Lambda_c \mu \nu)}$

$$\Lambda_c \rightarrow p K \pi, \tau \rightarrow \mu\nu\bar{\nu}$$



Reconstruction



Solid: reconstruction;
Dashed: truth level.

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



Results

Physical Quantity	SM Value	Tera-Z	$10 \times$ 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}
$\text{BR}(B_c \rightarrow \tau\nu)$	2.36×10^{-2} [6]	0.01 [6]	3.16×10^{-3}

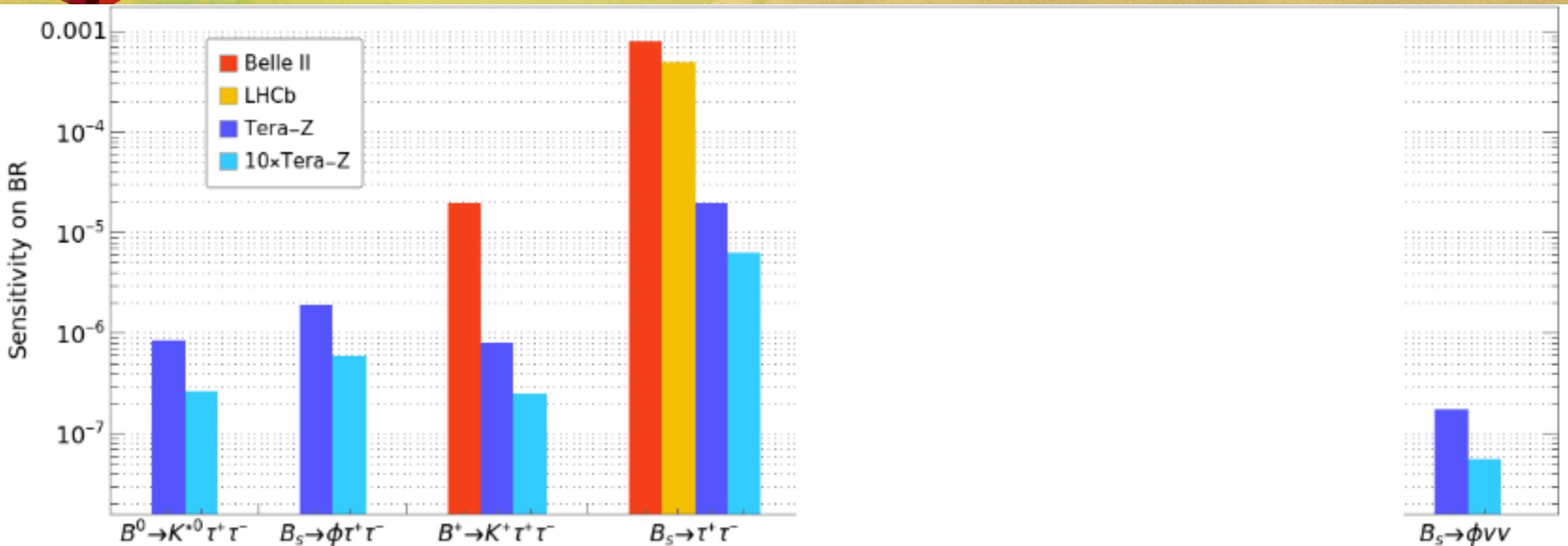
[Zheng. et al.]

Relative Uncertainties at Tera-Z:

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



Results



[Li and Liu (2021)]

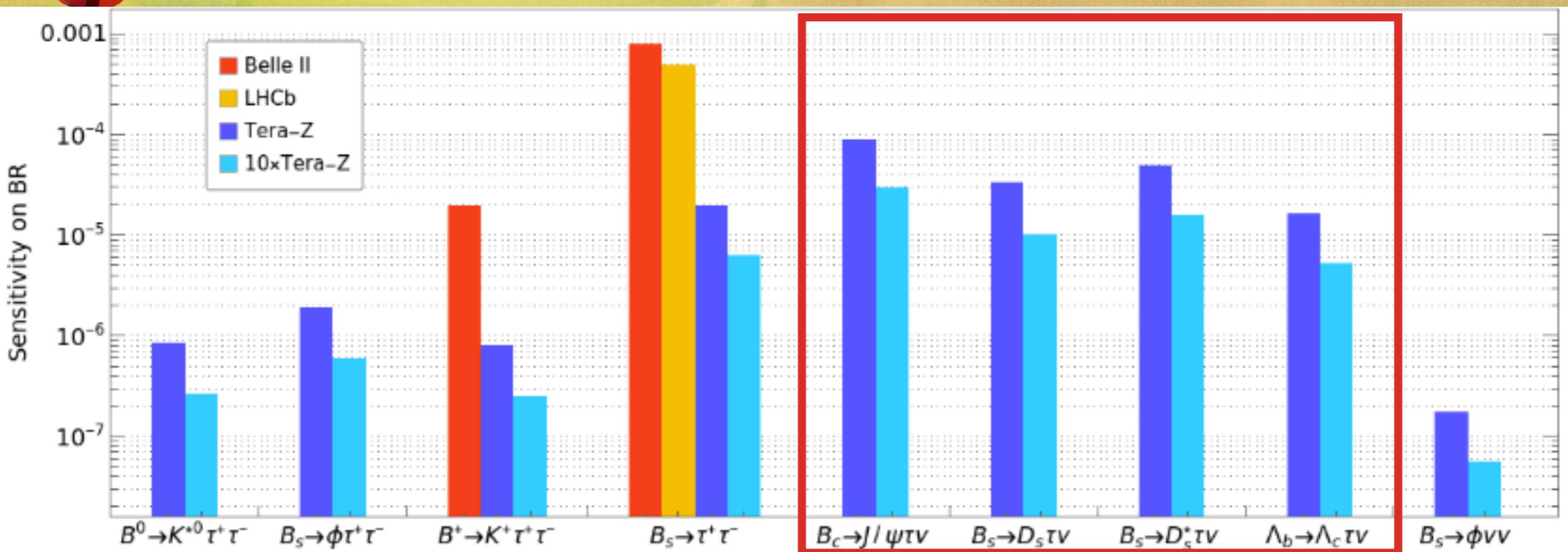
$$b \rightarrow s \tau \tau$$

[Li et al. (2022)]

$$b \rightarrow s VV$$



Results



[Li and Liu (2021)]

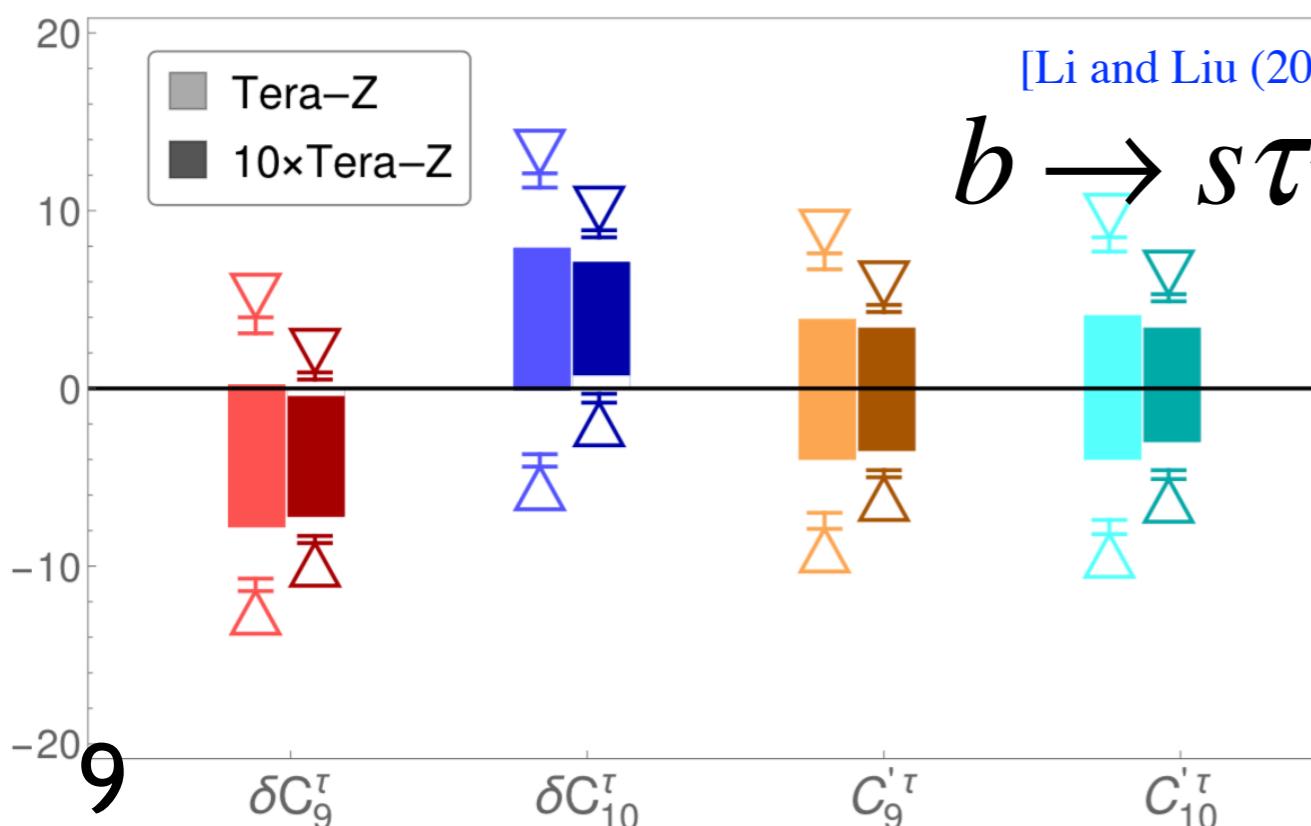
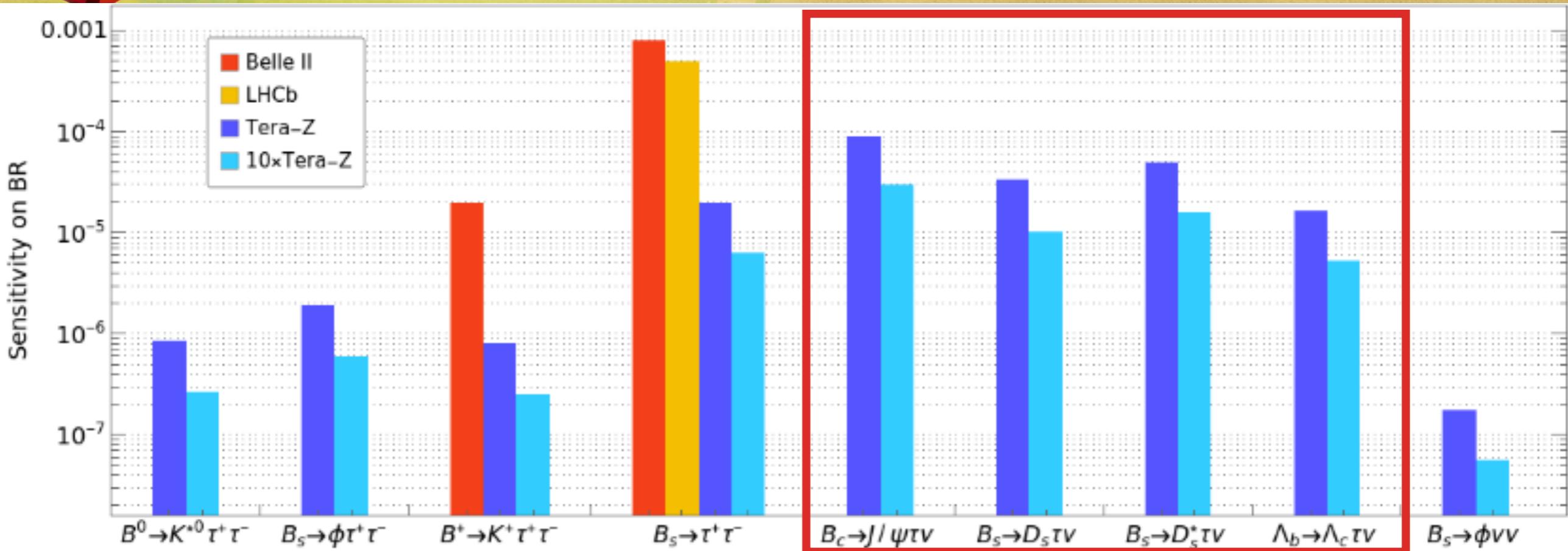
$$b \rightarrow s \tau \tau$$

[Li et al. (2022)]

$$b \rightarrow s VV$$

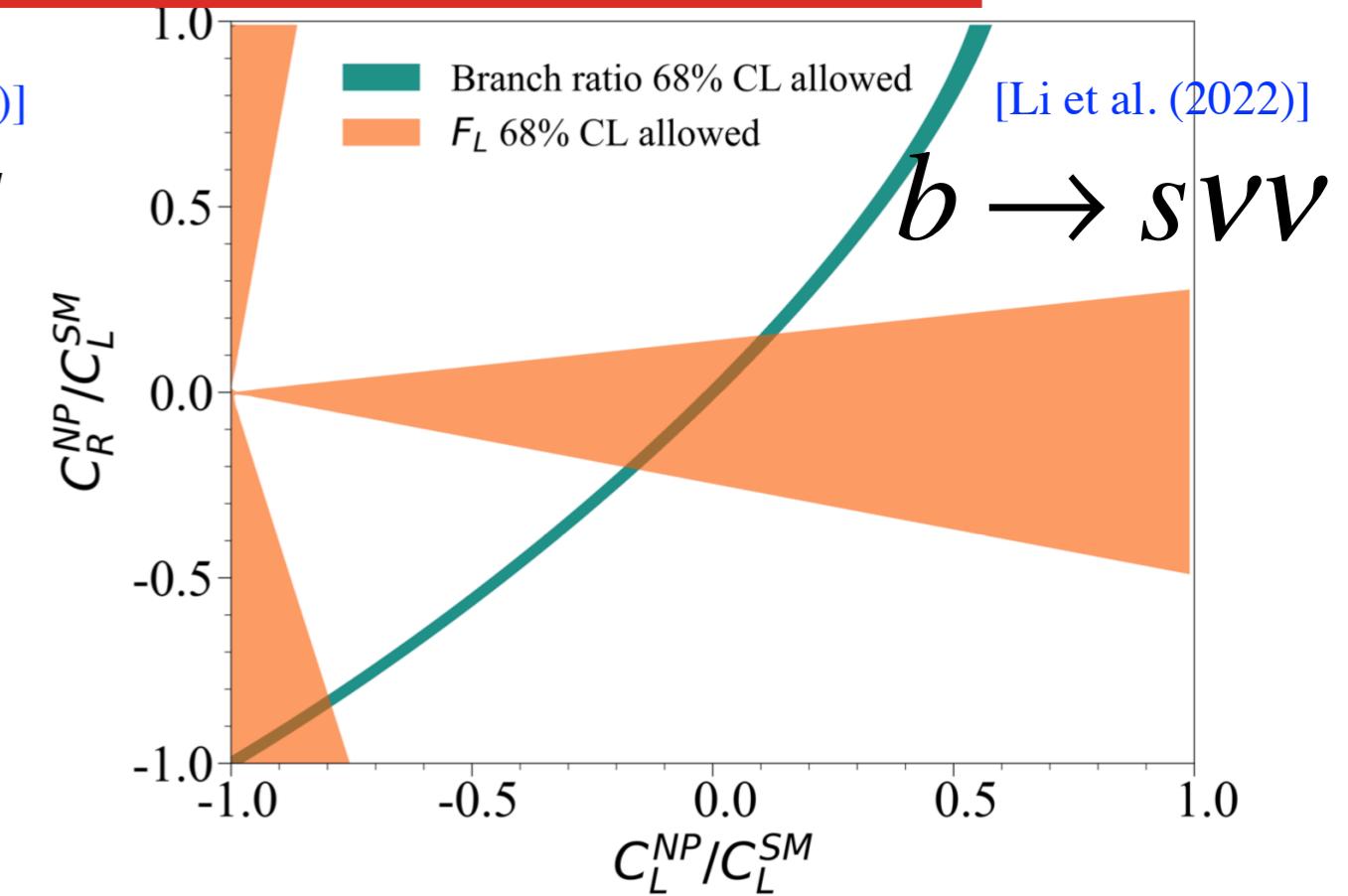


Results



[Li and Liu (2021)]

$$b \rightarrow s \tau \tau$$



[Li et al. (2022)]

$$b \rightarrow s VV$$



Theoretical Aspects

- ◆ EFT method: Low-Energy EFT and SMEFT
 - ◆ SM deviations: τ sector only!
 - ◆ RG Running and Matching



Low-Energy EFT (LEFT)

EFT Scale $\sim m_b \ll m_Z$

4-5 GeV

Examples:

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

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

- ◆ Different Lorentz structures
Scalar/Vector Mediator?
- ◆ Independent, no correlation

[Jenkins et al. (2018)]



SMEFT (Up to Dim-6 Operators)

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

[Grzadkowski et al. (2010)]

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

Down Basis Expansion

$$[O_{lq}^{(1)}]_{3332}$$

$$(\bar{v}\gamma^\mu P_L v + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$$

$$[O_{lq}^{(3)}]_{3332}$$

$$2V_{cs}^*(\bar{v}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L c)$$

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

SU(2)

◆ Correlation exists!

◆ FCCC and FCNC constrained by same operators



SMEFT (Up to Dim-6 Operators)

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

[Grzadkowski et al. (2010)]

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

Down Basis Expansion

$$[O_{lq}^{(1)}]_{3332}$$

$$(\bar{v}\gamma^\mu P_L v + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$$

$$[O_{lq}^{(3)}]_{3332}$$

$$2V_{cs}^*(\bar{v}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L c)$$

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

SU(2)

◆ Correlation exists!

◆ FCCC and FCNC constrained by same operators

FCCC and FCNC both matter!



Methodology

STEP 1: Use MCMC to constrain LEFT WCs.

12 Observables: $b \rightarrow c\tau\nu$ $b \rightarrow s\tau\tau$ $b \rightarrow sv\nu$

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

STEP 3: Tree-level matching at Z pole.

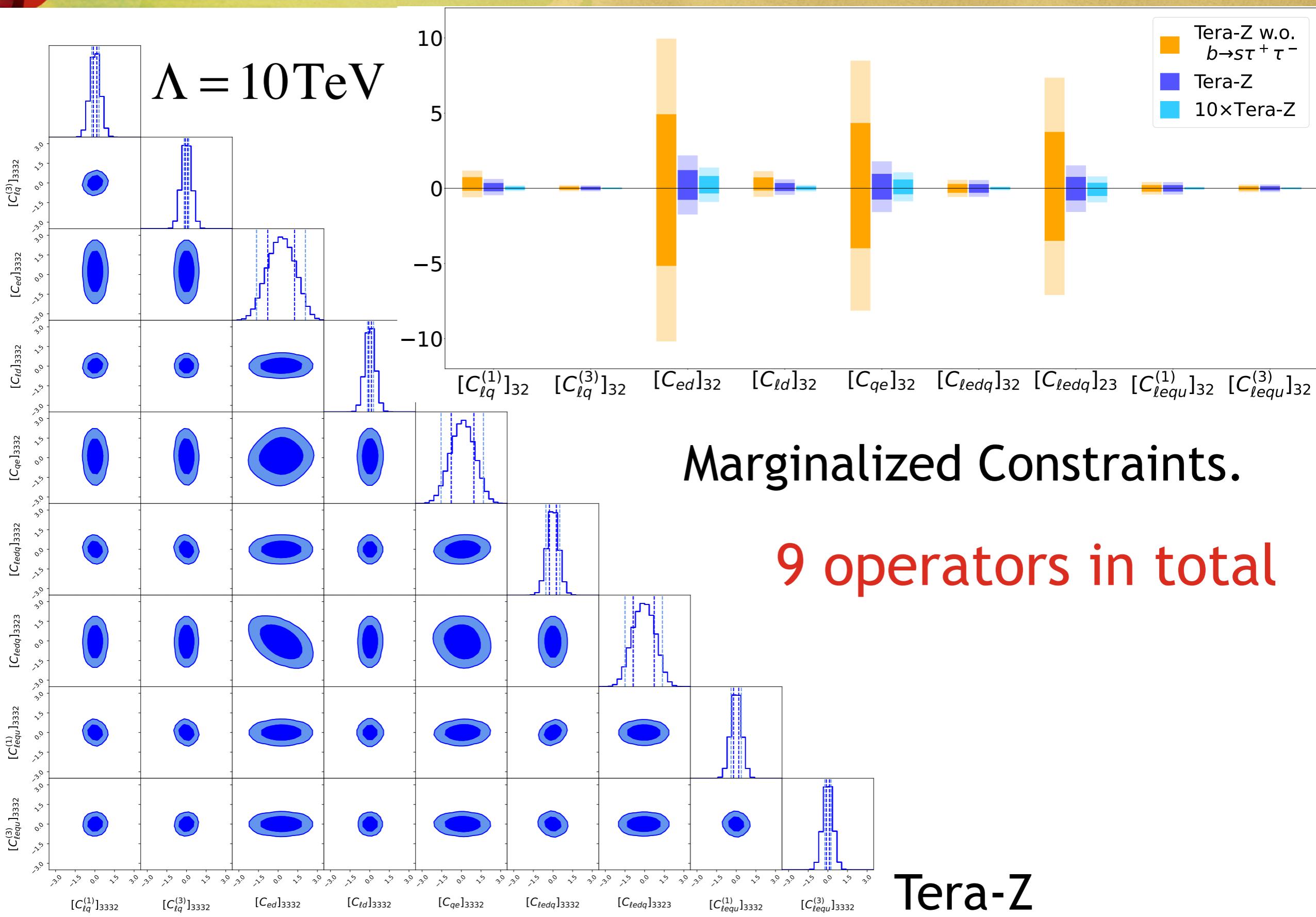
$$\mathcal{L}_{\text{SMEFT}}(m_Z) = \mathcal{L}_{\text{LEFT}}(m_Z)$$

STEP 4: Run SMEFT from Z mass to SMEFT scale

$$\Lambda = 10 \text{ TeV}.$$

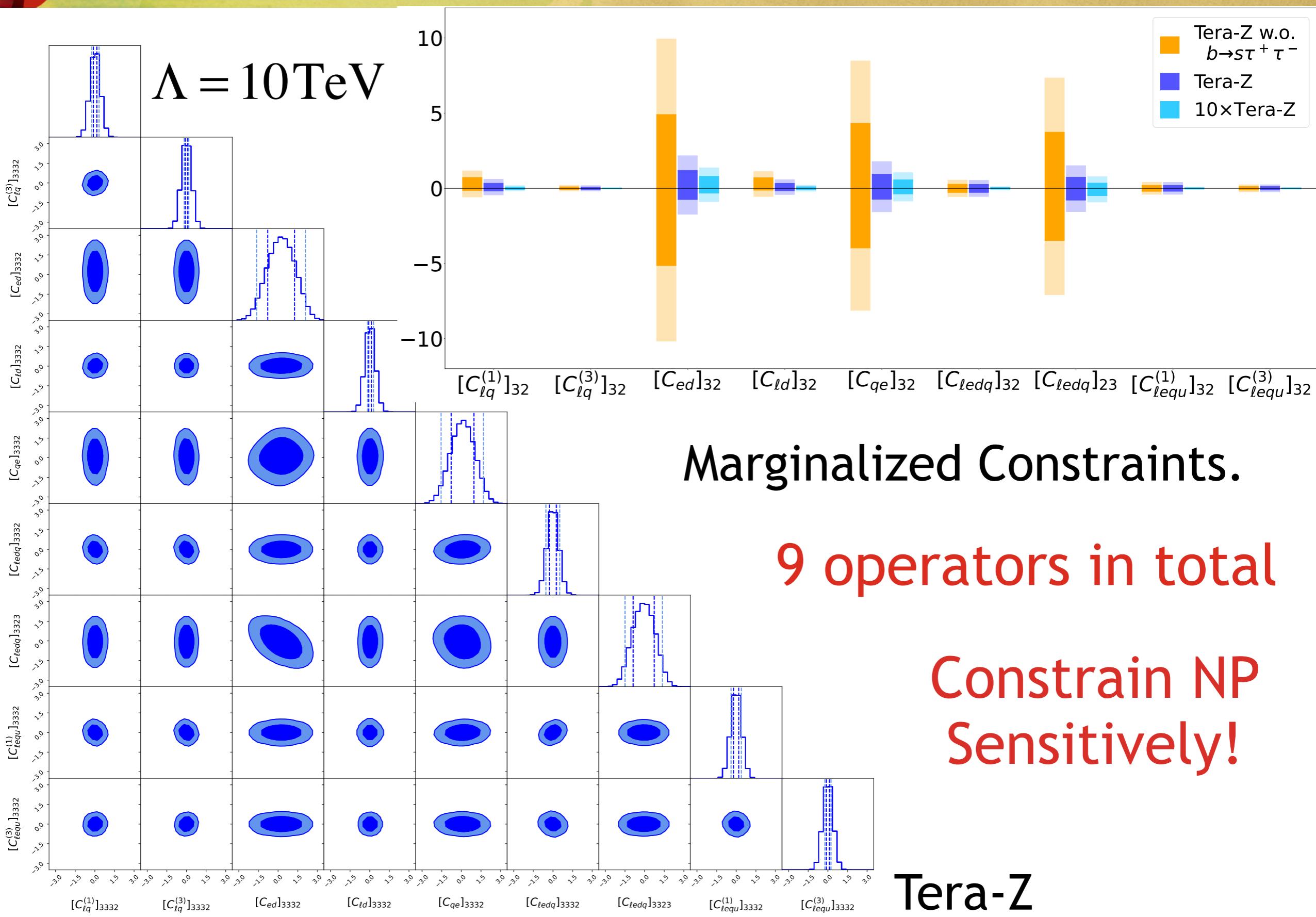


SMEFT Constraints





SMEFT Constraints





Conclusion

- ◆ Great advantages of Z factories: large luminosity, clean environment and etc.
- ◆ LFU being tested via precise measurements 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.