Testing Lepton Flavor Universality at Future Z Factories

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Based on arXiv:2212.02433 with Tin Seng Manfred Ho, Xu-Hui Jiang, Lingfeng Li, Tao Liu

What is LFU? And Why?

SM assumes:

Three generations of leptons are the same (having same couplings to the SM gauge bosons) except having different masses.

[See also Laing Sun's Talk]

SM assumes LFU

Why is it true? Is it even true?
Secret behind the 3 generations?

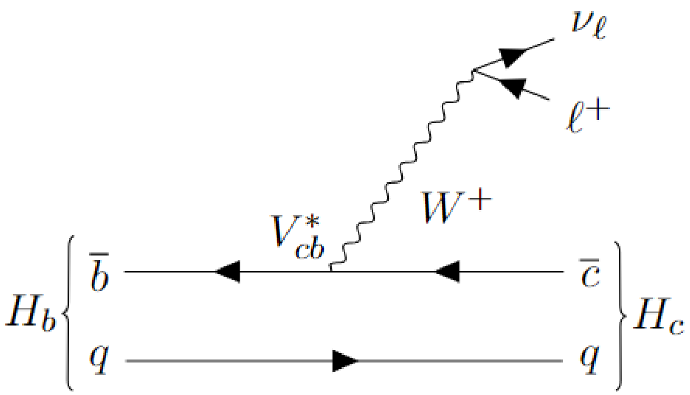
Need to be tested with high precision!!!

SM extensions > extra LFU violating interactions
Flavor physics > indirect BSM searches.

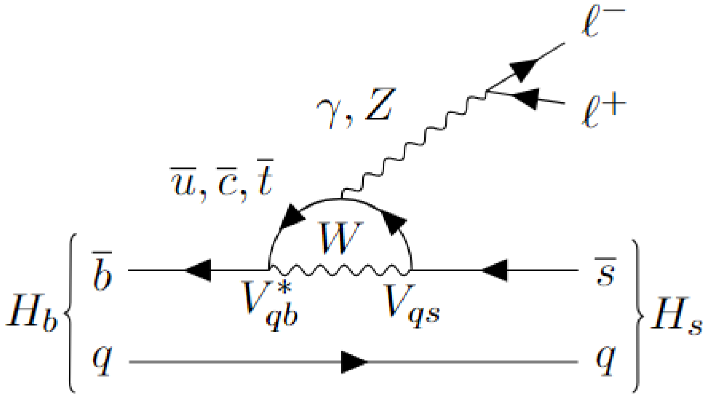
How to Test LFU?

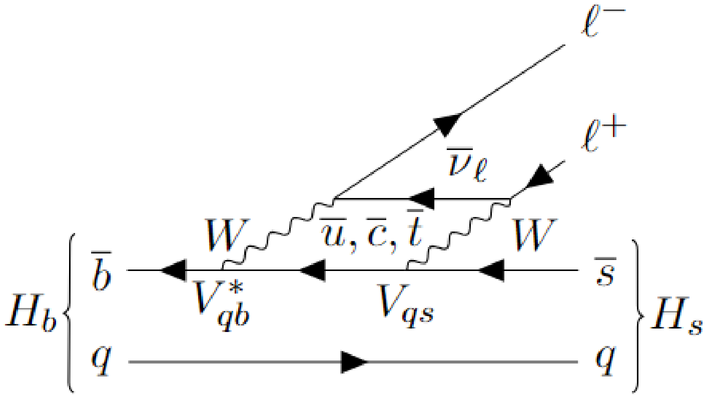
b-hadron decays:

FCCC:



FCNC:

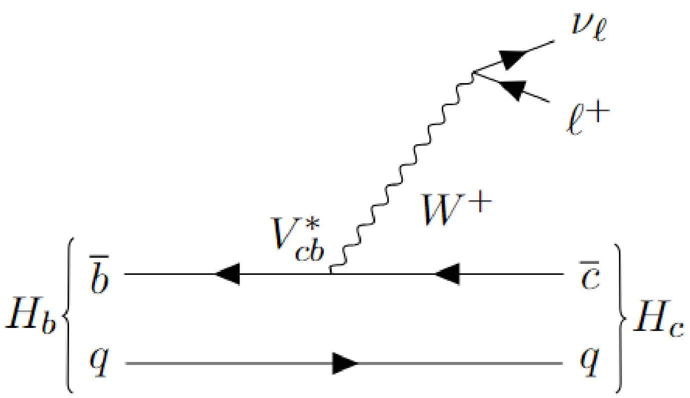




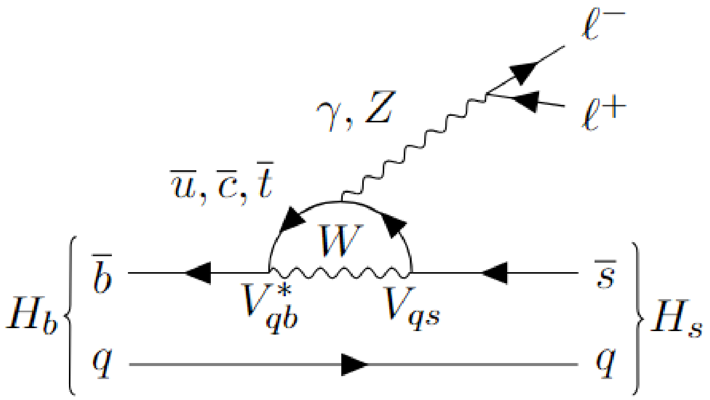
How to Test LFU?

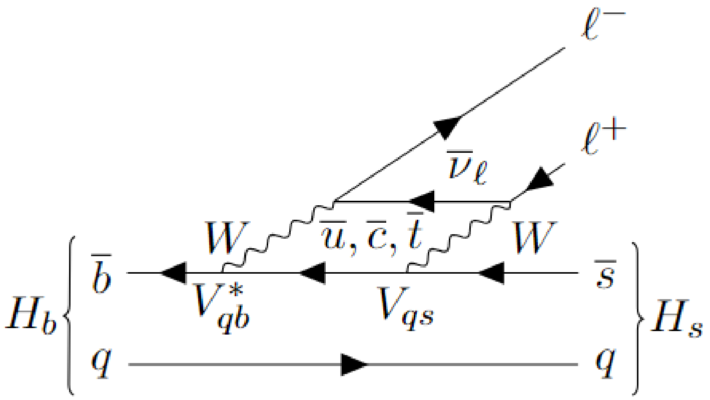
b-hadron decays:

FCCC:



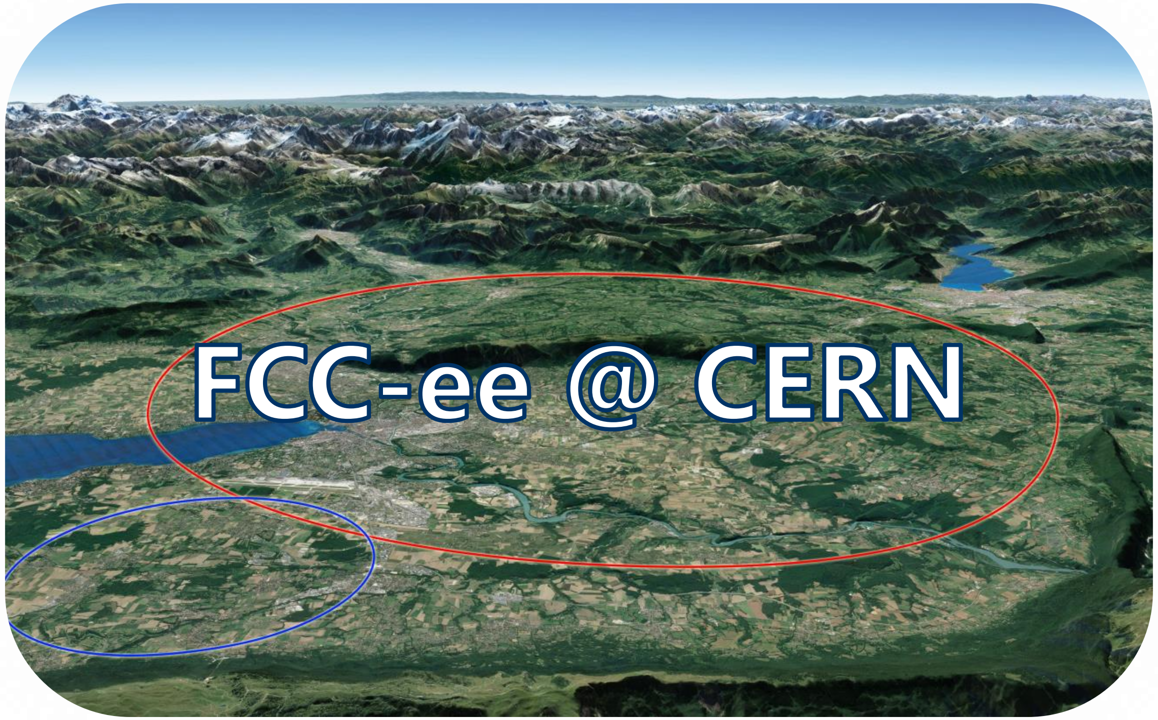
FCNC:





Future Z Factories

ee circular collider at COM energy ~ 91GeV
Produces O(10^{12}-10^{13}) Z bosons [Tera / 10×Tera-Z]



Why Z Factories?

Z Factories v.s. b Factories

- Abundant H_b
- High boost
- Better tracking
- Low vertex uncertainty
- …

Z Factories v.s. Hadronic Machine

- Clean environment
- High acceptance
- Fixed E_{cm}
- Direct E_{miss} measurement
- Better flavor tagging
- …

Goal: Set b>cτν baseline for Z Factories

Advantages of Z Factories for us?

Variety b-hadrons accessible:

▶ **b factories (e.g. Belle II) can't produce B_c^+, Λ_b^0, (only few B_s^0)**

Having ν(s) Produced: (crucial to getting H_b info.)

▶ **Better handle than LHCb**

Studying τ Mode:

▶ **More precise info. about τ decay**

[Dong et al. (2018); Abada et al. (2019); Fujii et al. (2019); Berger et al. (2017); Aaij et al. (2018); Altmannshofer et al. (2018)]

Signal (FCCC: b>cτν)

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

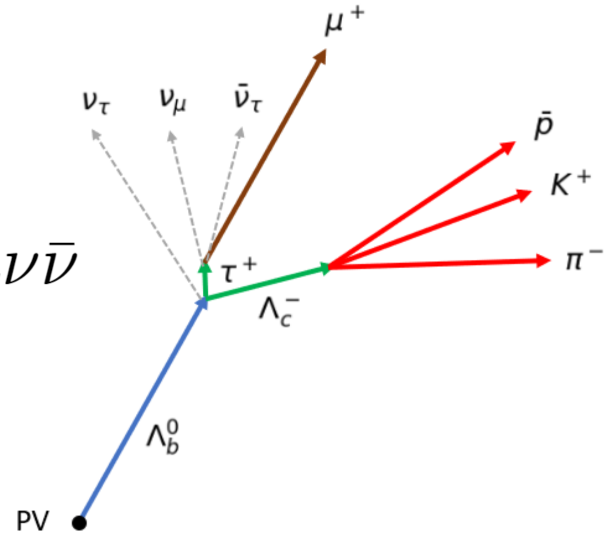
$$J/\psi \to \mu\mu,\ \tau \to \mu\nu\bar{\nu}$$

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

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

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

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

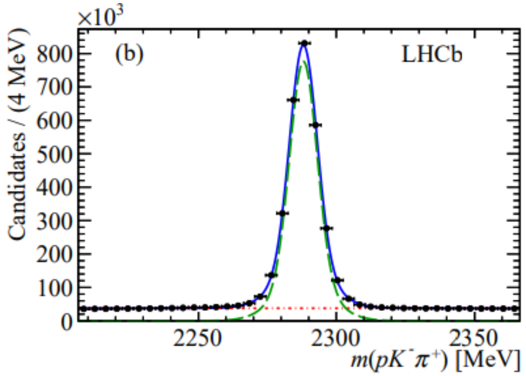


H_c decays to charged final states: H_c can be fully reconstructed!
Tera-Z can produce many of such H_b, while B-factories can't do! (or just few)

Reconstruction Scheme

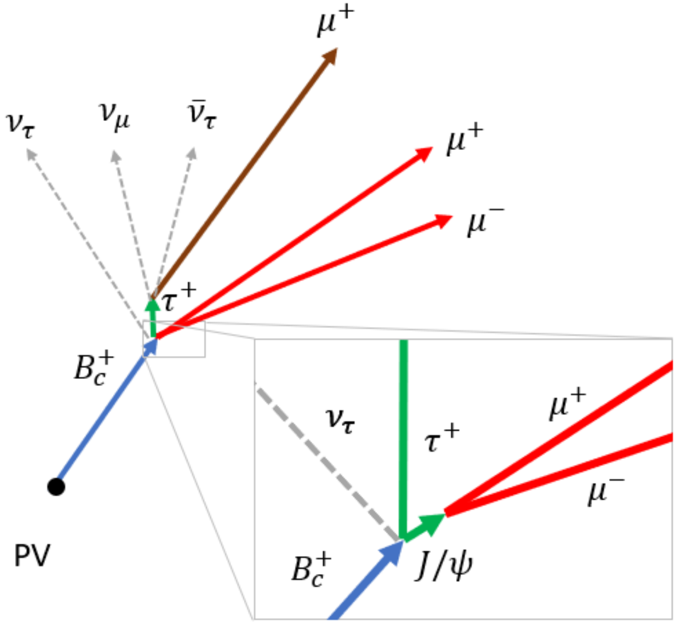
1. **Reconstruct H_c and identify μ**

2. **Deduce H_b decay vertex**



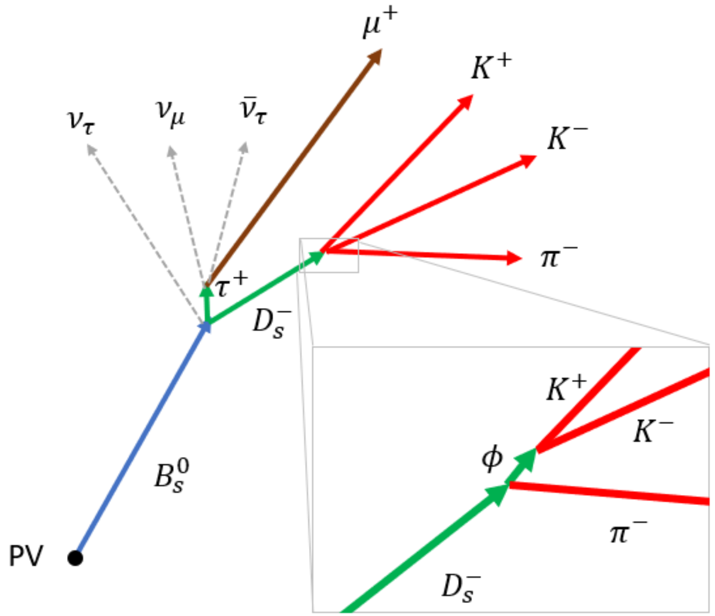
If H_c is prompt:

H_b decay vertex = H_c decay vertex



If H_c is not prompt:

H_b decay vertex =
point at H_c trajectory closest to μ track

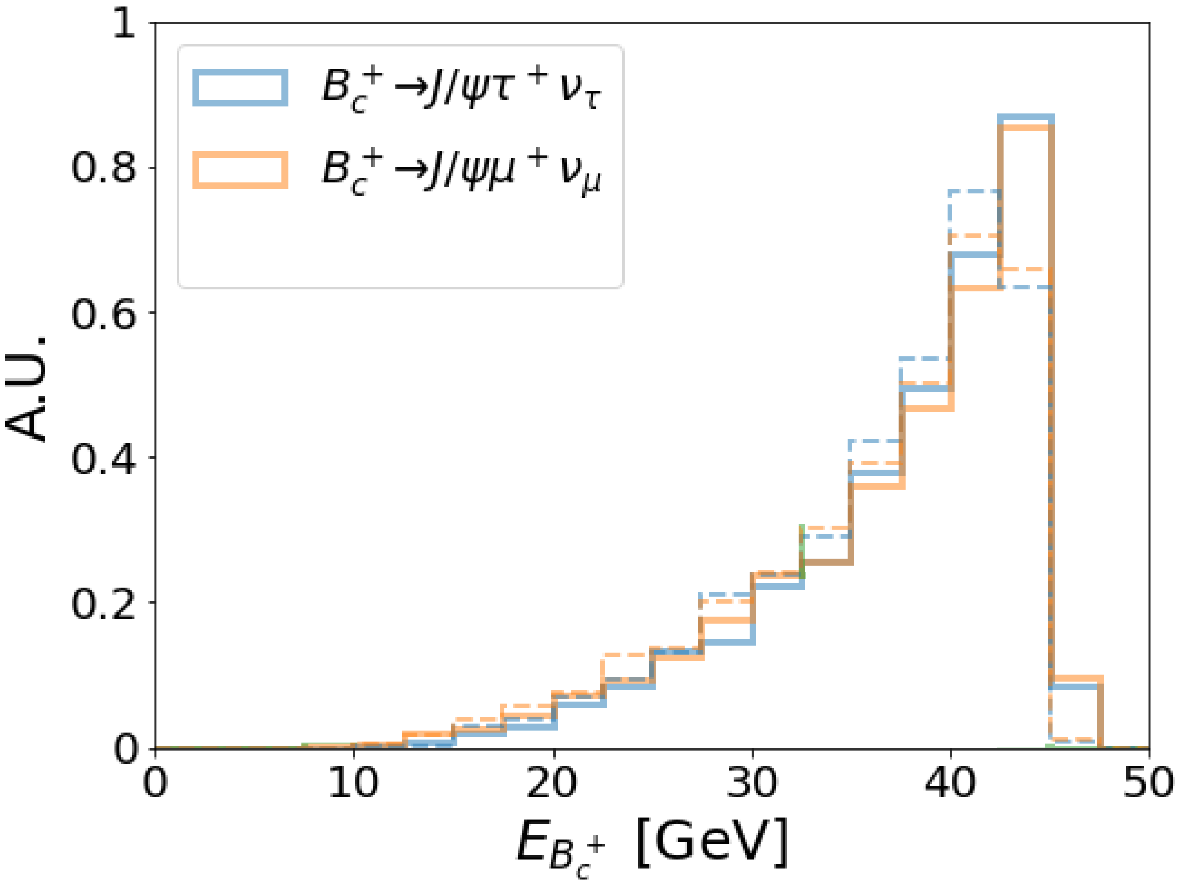


Reconstruction Scheme

3. Deduce b-hadron energy:

(Energy-momentum conversation)

In good agreement!
(error ~ O(1GeV))



- - Truth

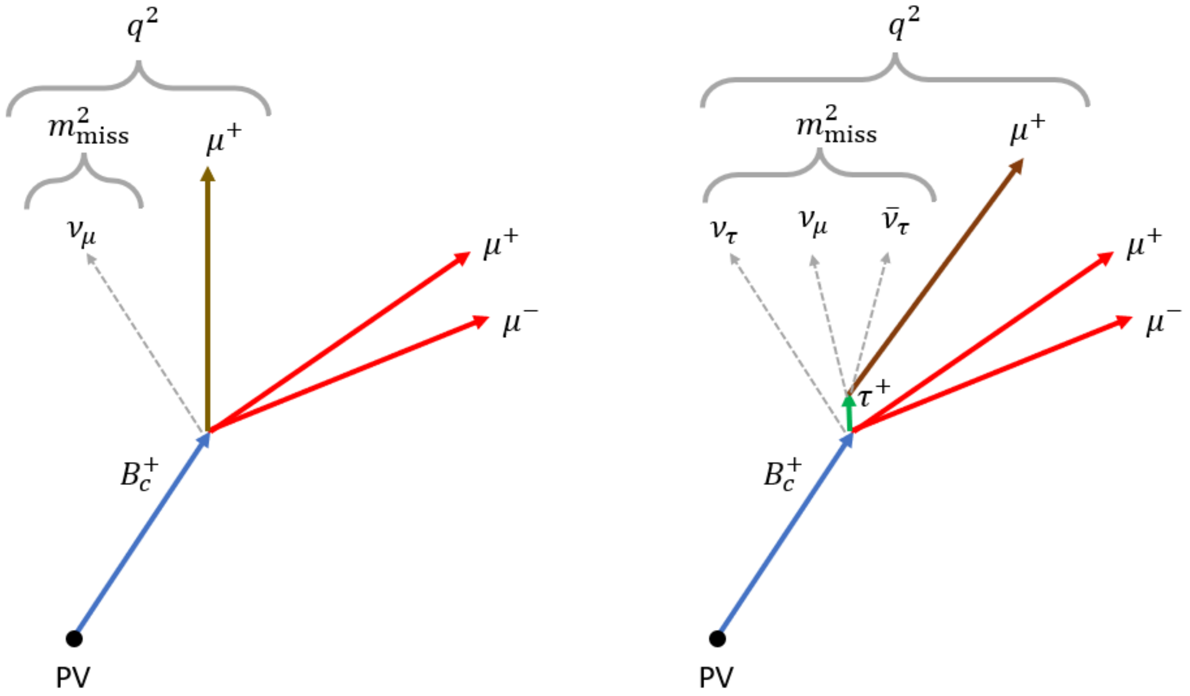
— Reconstruction

Discriminators for τ , μ Channel Separation

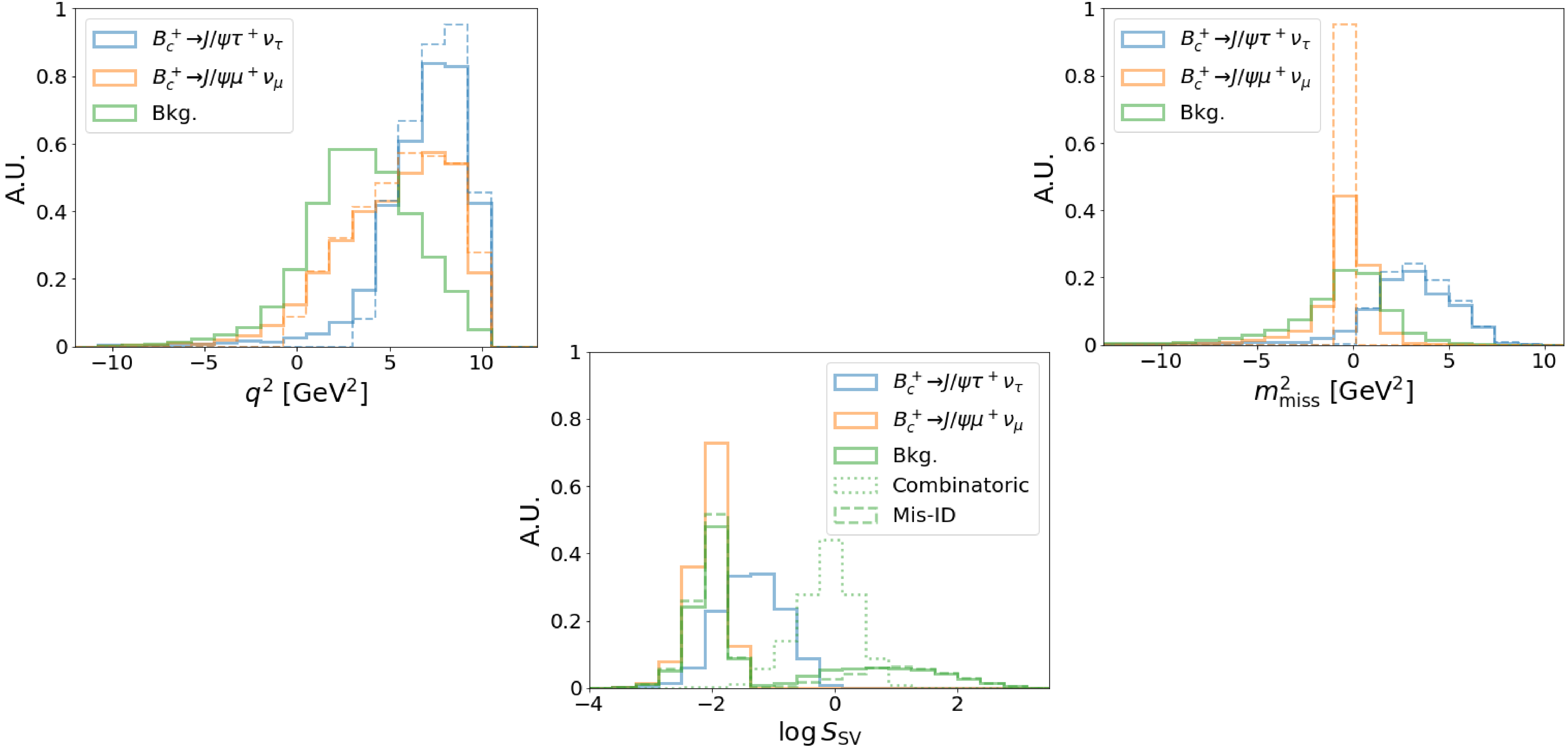
Momentum transferred to lepton system: $q^2 \equiv (p_{Bc} - p_{J/\psi})^2$

Missing mass: $m^2_{miss} \equiv (p_{Bc} - p_{J/\psi} - p_{\mu})^2$

The closest distance between secondary vertex (SV) and muon track



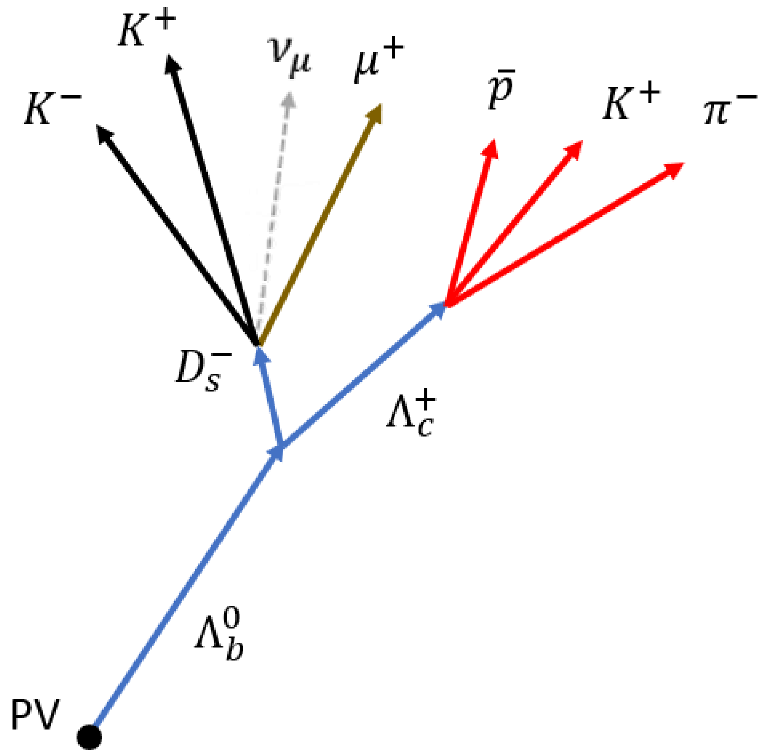
Discriminators for τ , μ Channel Separation



Backgrounds

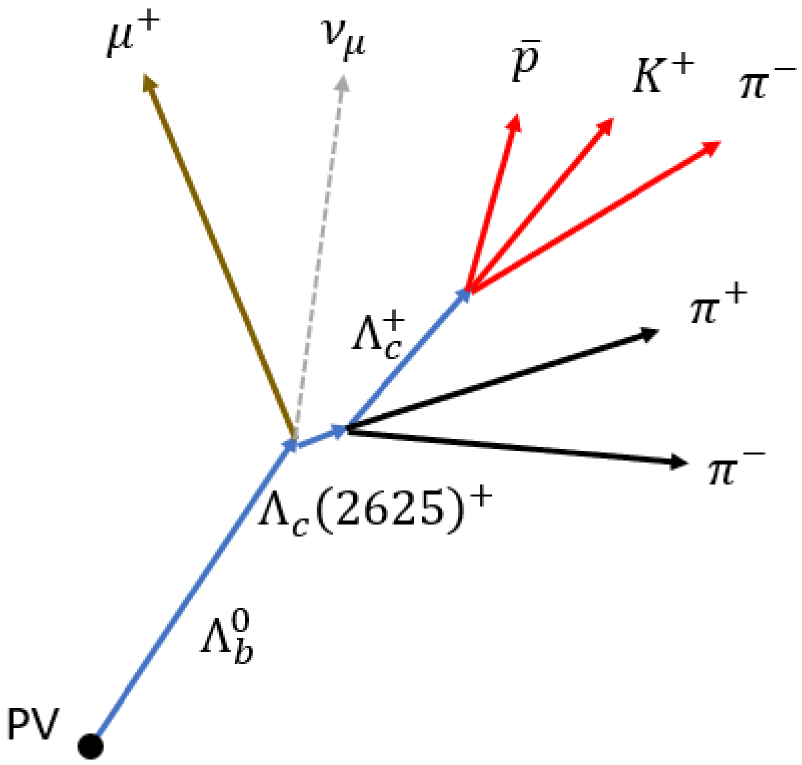
Wrong lepton Production

For example:



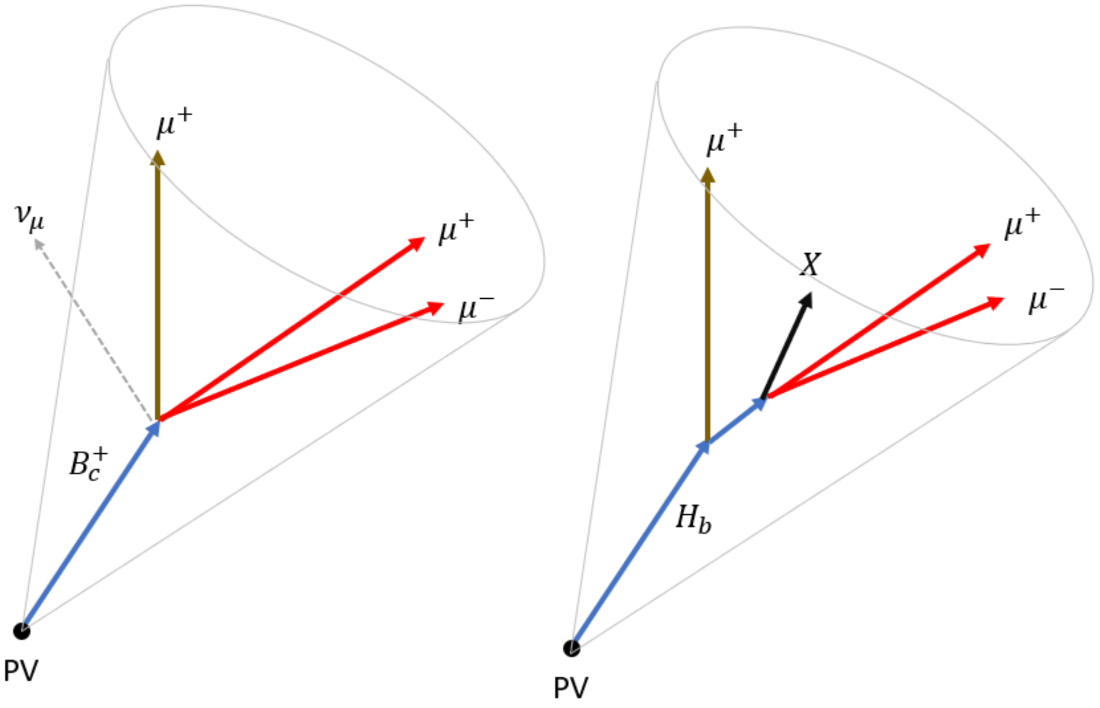
Wrong H_c Production

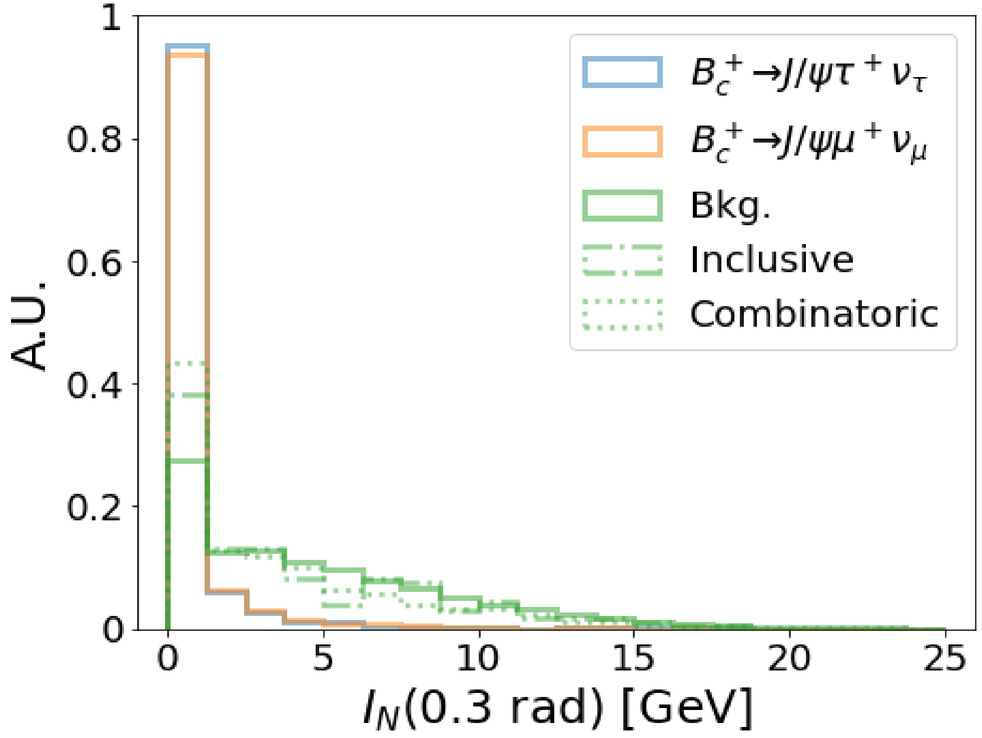
For example:



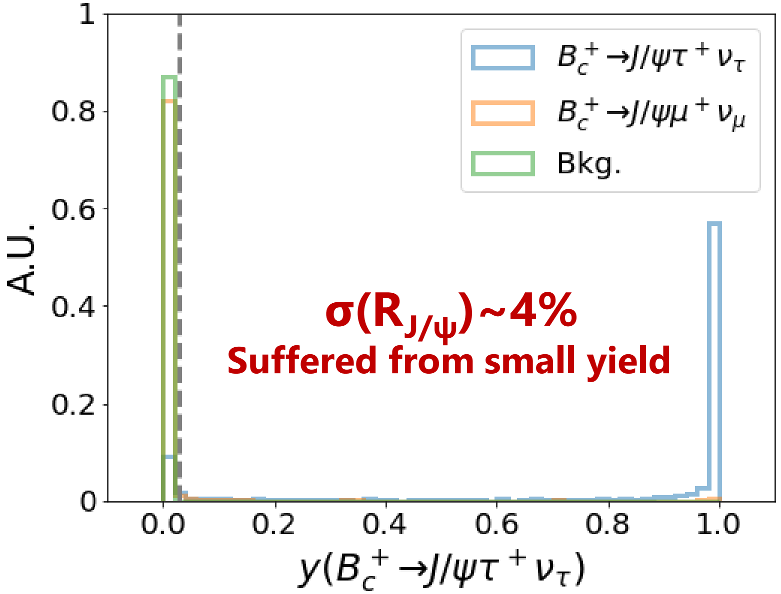
Discriminators for Background Separation

Isolation variable:
total energy, except the tagged final states, inside 0.3(0.6) rad of B cone



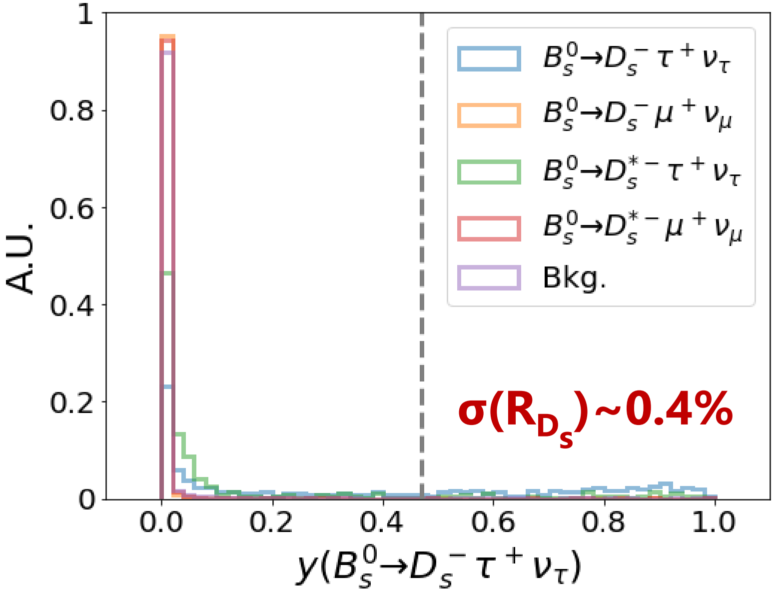


Stat. only BDT results

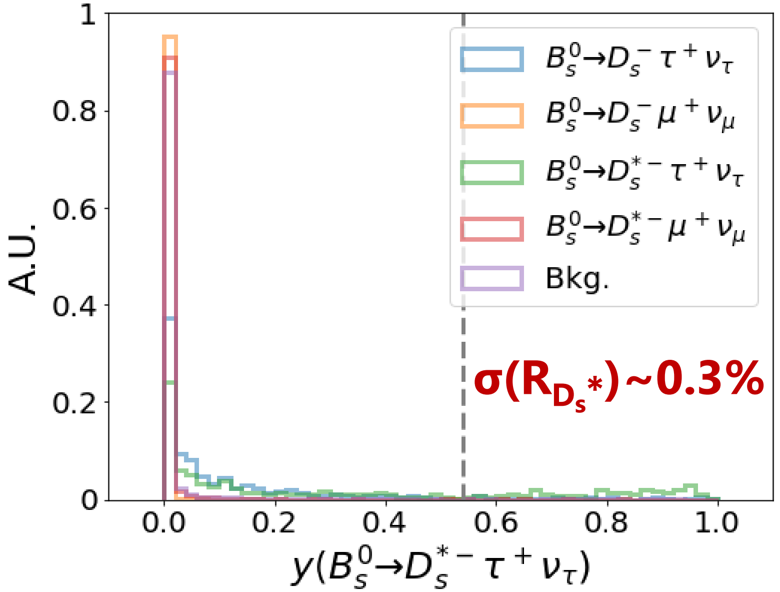


$\sigma(R_{J/\psi})$~4%

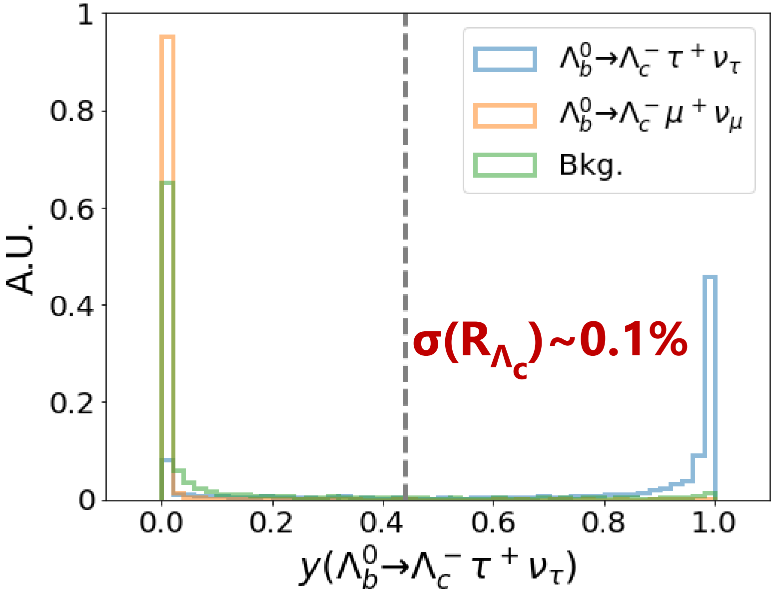
Suffered from small yield



$\sigma(R_{D_s})$~0.4%



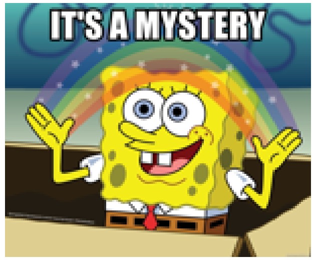
$\sigma(R_{D_s^*})$~0.3%



$\sigma(R_{\Lambda_c})$~0.1%

Theoretical Workflow

E



$\Lambda \sim \mathcal{O}(10\ \mathrm{TeV})$

SMEFT

$\Lambda \sim \mathcal{O}(\mathrm{TeV})$

4: Run SMEFT from m_Z to 10 TeV

3: Tree-level matching

$\sim \mathcal{O}(m_Z)$

$\mathcal{L}^{\mathrm{SM}}(m_Z) = \mathcal{L}^{\mathrm{LE}}(m_Z)$

LEFT

$\mu_b \sim \mathcal{O}(m_b)$

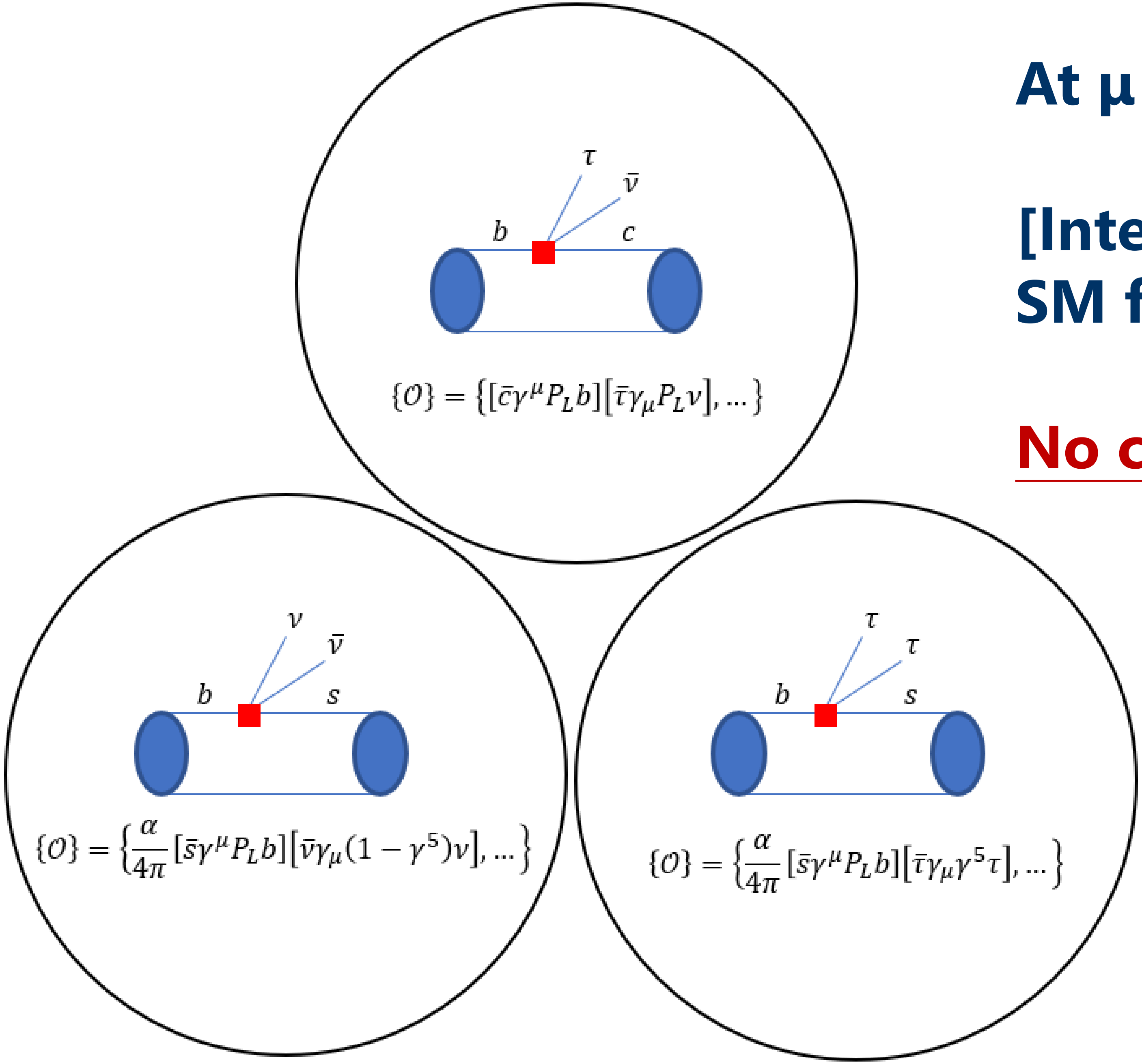
2: Run LEFT from m_b to m_Z

[Grzadkowski et al. (2010)]

1: MCMC constrain WCs

[Buras et al. (2015); Angelescu et al. (2018); Feruglio et al. (2018), Hu et al. (2019); Alasfar et al. (2020); Fajfer et al. (2021); Cornella et al. (2021)]

LEFT



$$\{\mathcal{O}\} = \left\{[\bar{c}\gamma^{\mu}P_L b][\bar{\tau}\gamma_{\mu}P_L \nu], \dots\right\}$$

$$\{\mathcal{O}\} = \left\{\frac{\alpha}{4\pi}[\bar{s}\gamma^{\mu}P_L b][\bar{\nu}\gamma_{\mu}(1-\gamma^5)\nu], \dots\right\}$$

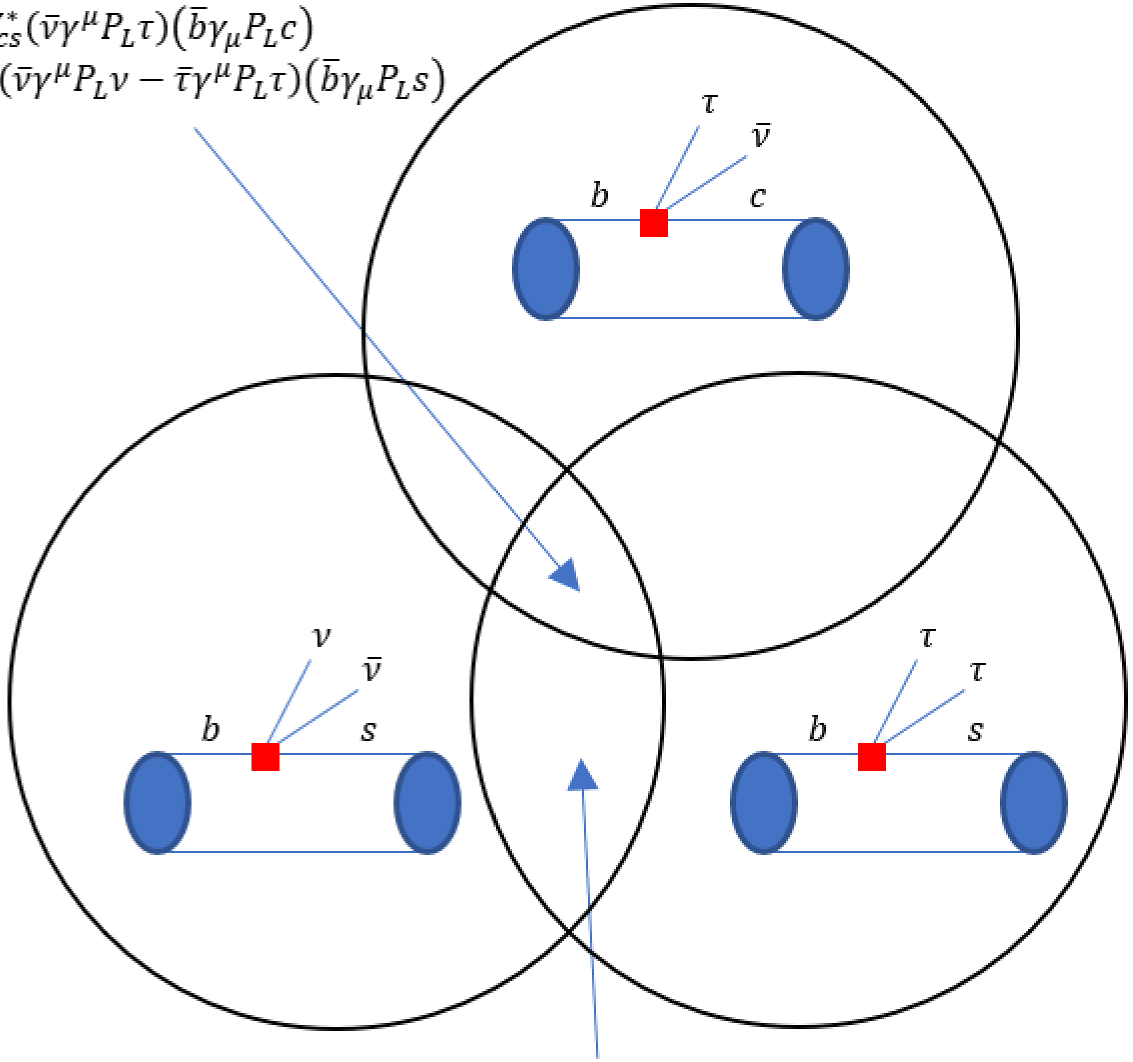
$$\{\mathcal{O}\} = \left\{\frac{\alpha}{4\pi}[\bar{s}\gamma^{\mu}P_L b][\bar{\tau}\gamma_{\mu}\gamma^5\tau], \dots\right\}$$

At $\mu \sim m_b$

[Integrate out heavy SM fields (W , Z , h, t)]

No correlation

SMEFT



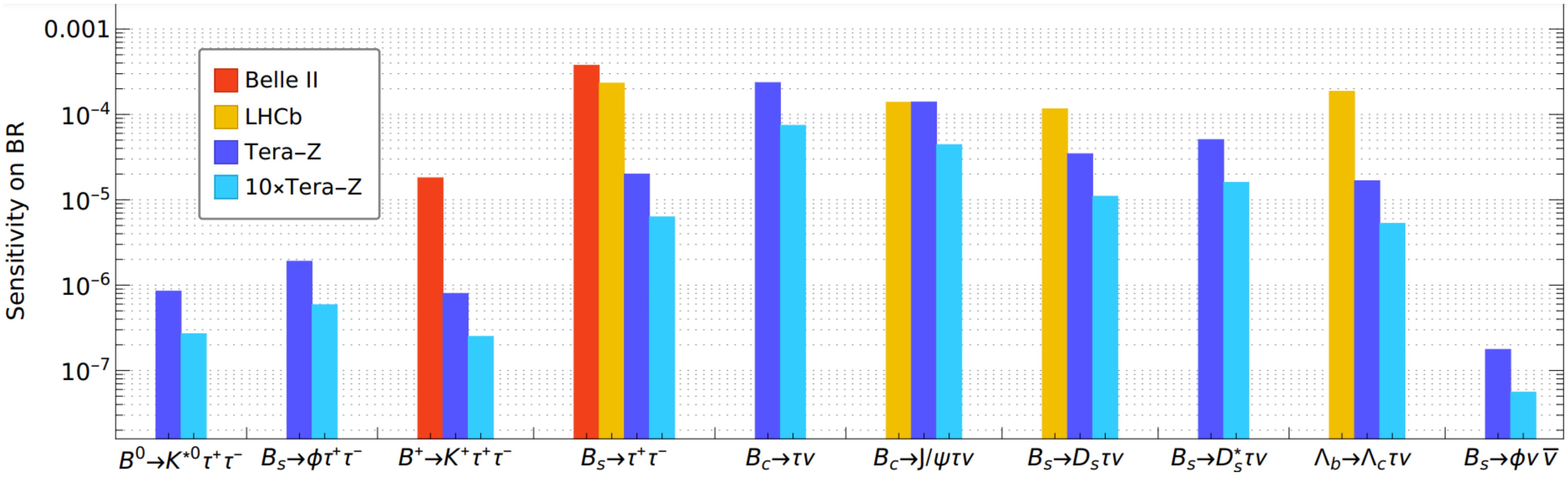
$$\mathcal{O} = 2V_{cs}^{*}(\bar{\nu}\gamma^{\mu}P_L\tau)(\bar{b}\gamma_{\mu}P_L c)$$
$$-(\bar{\nu}\gamma^{\mu}P_L\nu - \bar{\tau}\gamma^{\mu}P_L\tau)(\bar{b}\gamma_{\mu}P_L s)$$

$$\mathcal{O} = (\bar{\nu}\gamma^{\mu}P_L\nu + \bar{\tau}\gamma^{\mu}P_L\tau)(\bar{b}\gamma_{\mu}P_L s)$$

At Λ ~ multi-TeV

[All SM fields Under SM sym]

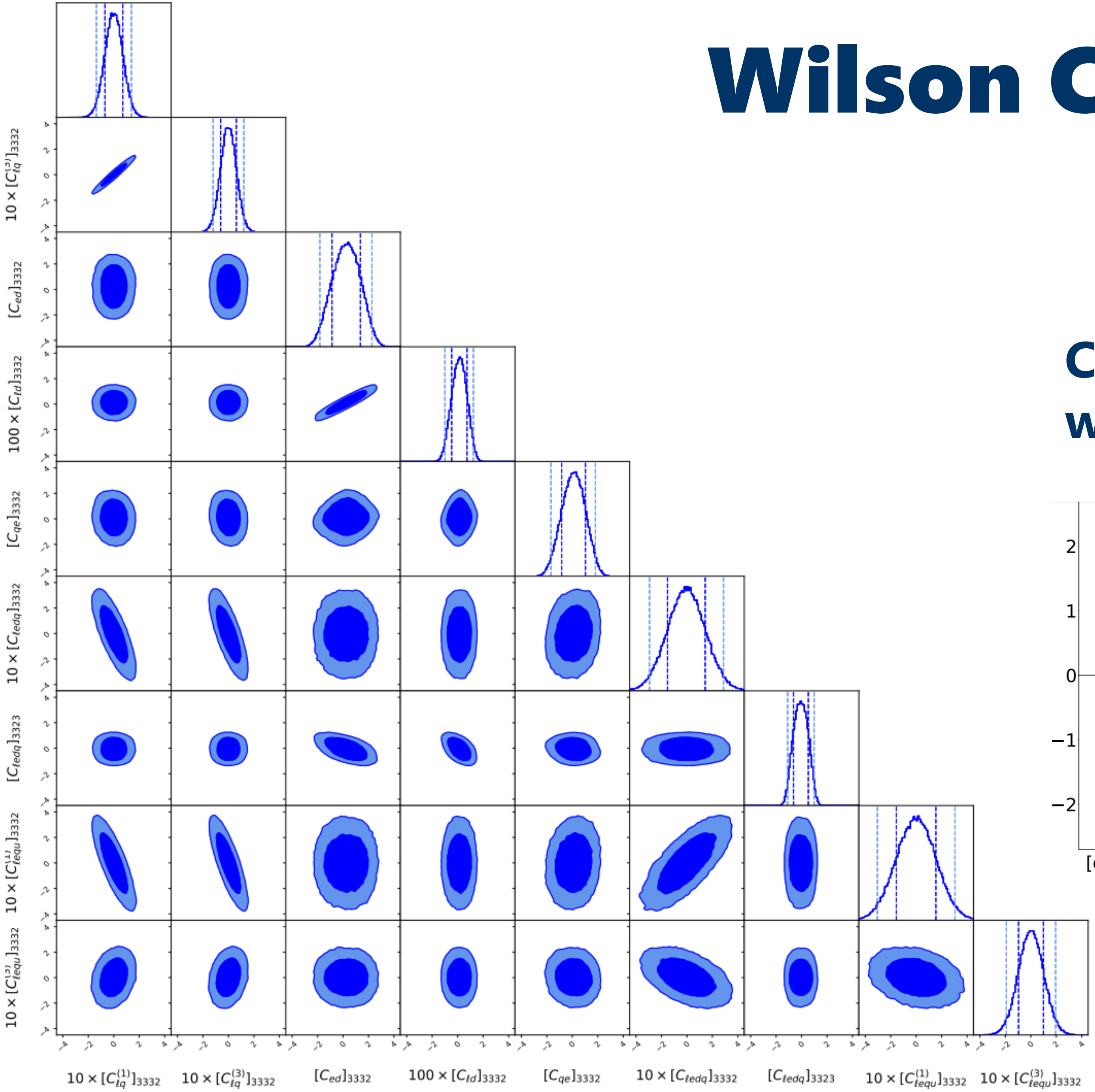
Correlated!!!



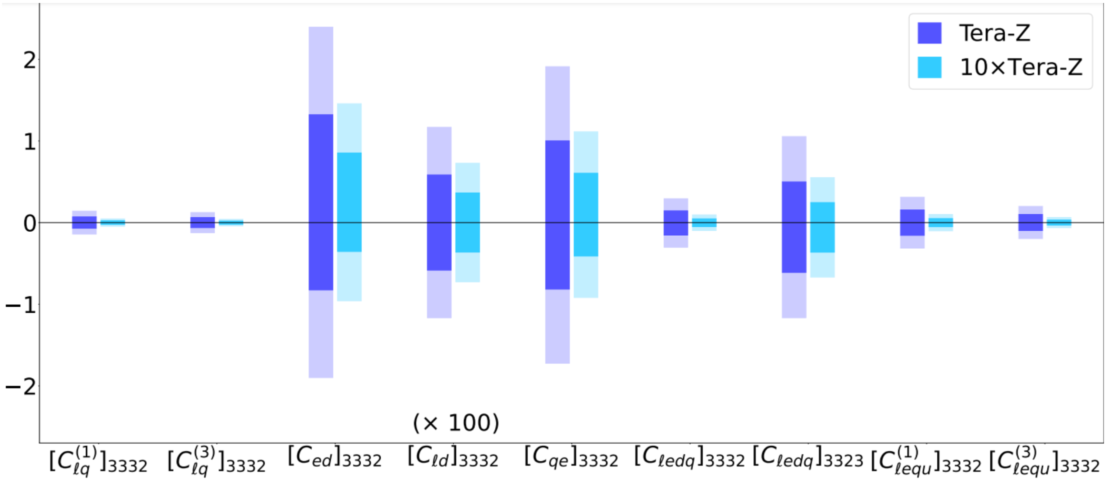
This Study

[Zheng et al. (2020); Kamenik et al. (2017); Capdevila et al. (2018); Li and Liu (2021); Buras et al. (2015); Li et al. (2022)]

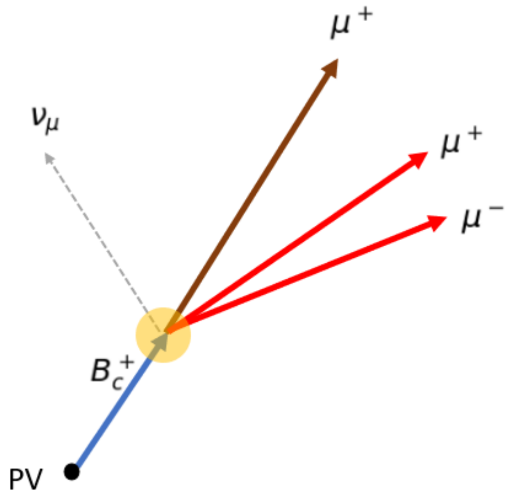
Wilson Coeff. Constraints

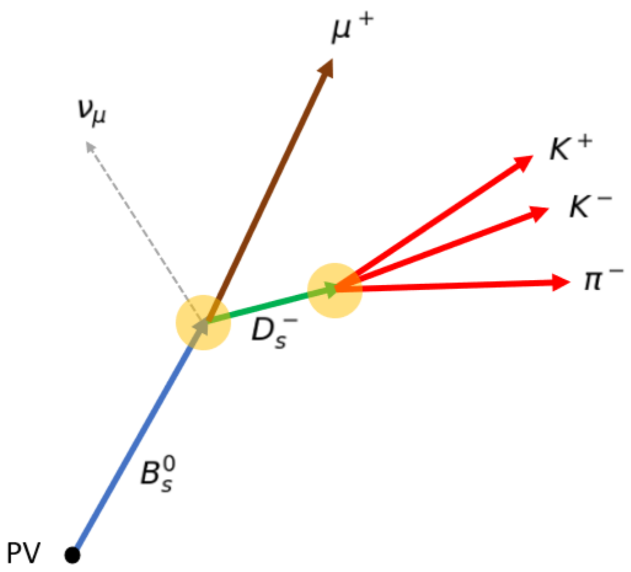


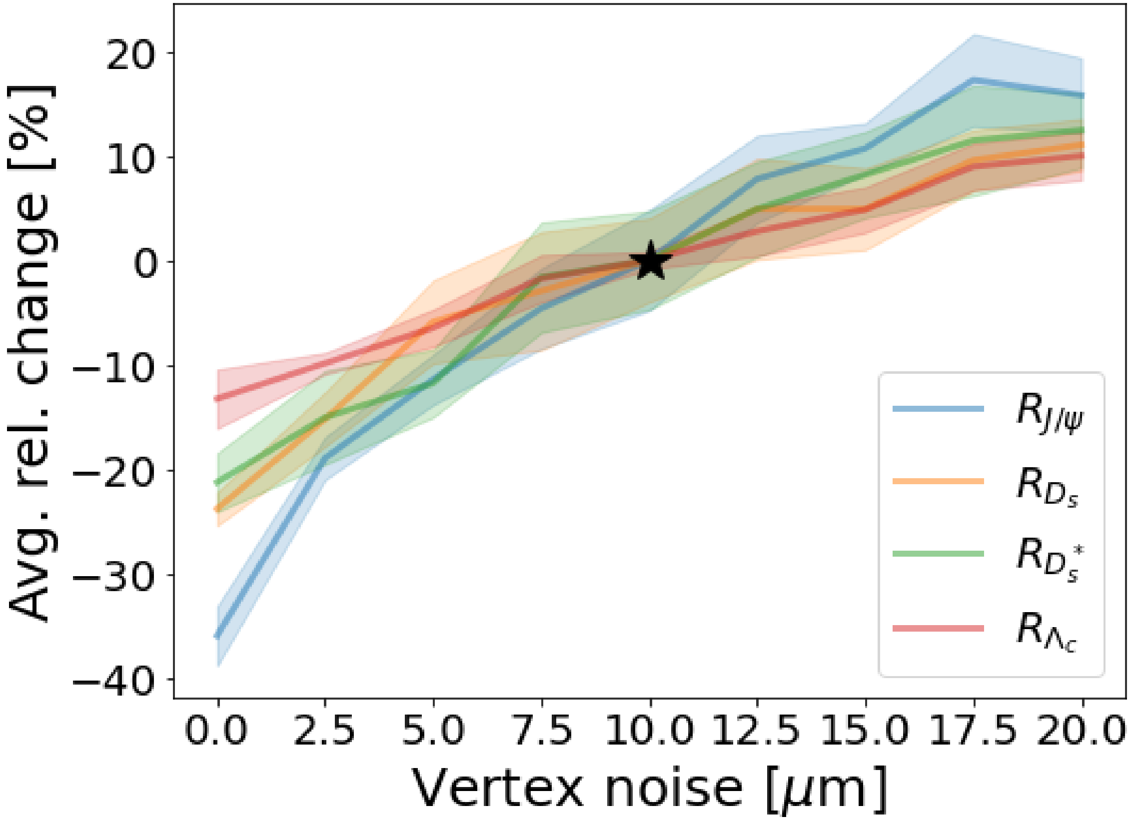
Constraint of NP up to multi-TeV when Wilson Coeff. are about O(1)



Detector Tracking Resolutions







Robustness: Vary vertex noise level (0, .., **10**,…, 20 µm)

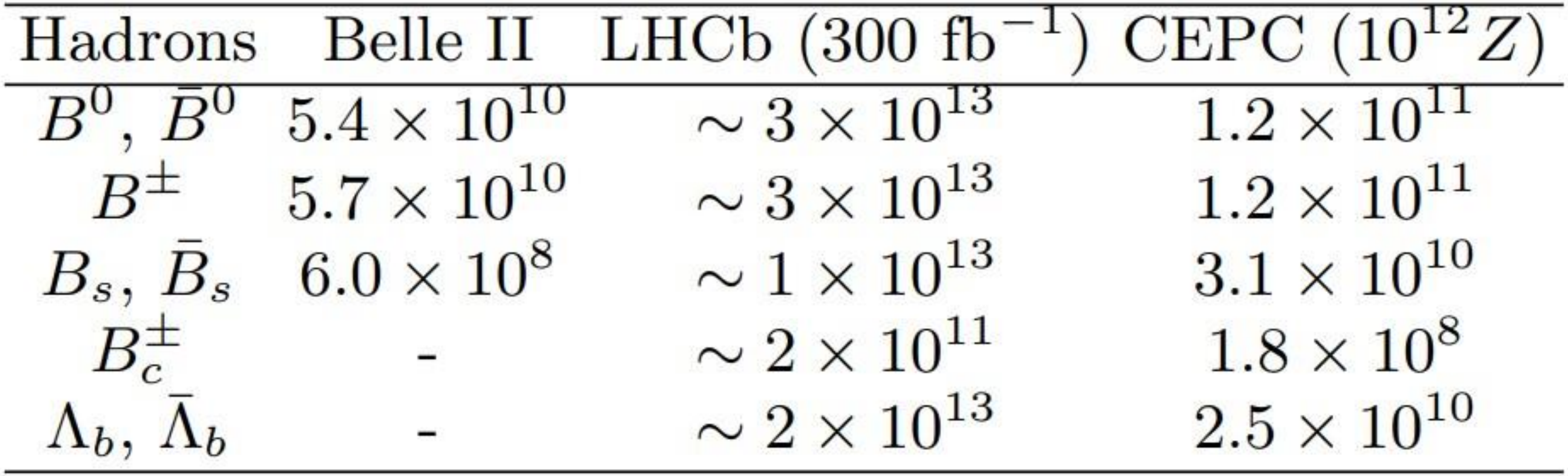
Conclusion

Z-pole can test Lepton Flavor Universality,
the secret behind generations, in a clean way!!!

- Setting up a baseline of $b \rightarrow c\tau\nu$ for Z Factories
- High precision in $R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, $R_{\Lambda c}$: O(0.1%) − O(1%)
  - Abundant and energetic H_b
  - Clean environment
  - Known initial energy
- EFT can prob NP up to 10TeV
  - Constraint of NP up to multi-TeV when Wilson Coeff. Are about O(1)

BACKUP

BACKUP



Hadrons	Belle II	LHCb (300 fb^{-1})	CEPC ($10^{12} Z$)
B^0, $\bar{B}^0$	5.4×10^{10}	$\sim 3 \times 10^{13}$	1.2×10^{11}
$B^\pm$	5.7×10^{10}	$\sim 3 \times 10^{13}$	1.2×10^{11}
B_s, $\bar{B}_s$	6.0×10^8	$\sim 1 \times 10^{13}$	3.1×10^{10}
$B_c^\pm$	-	$\sim 2 \times 10^{11}$	1.8×10^8
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	2.5×10^{10}

BACKUP

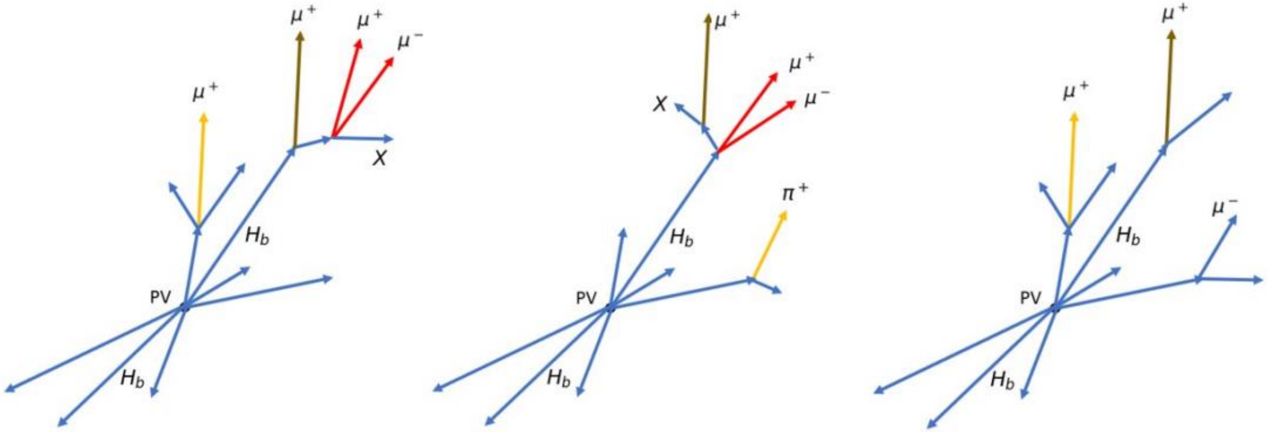
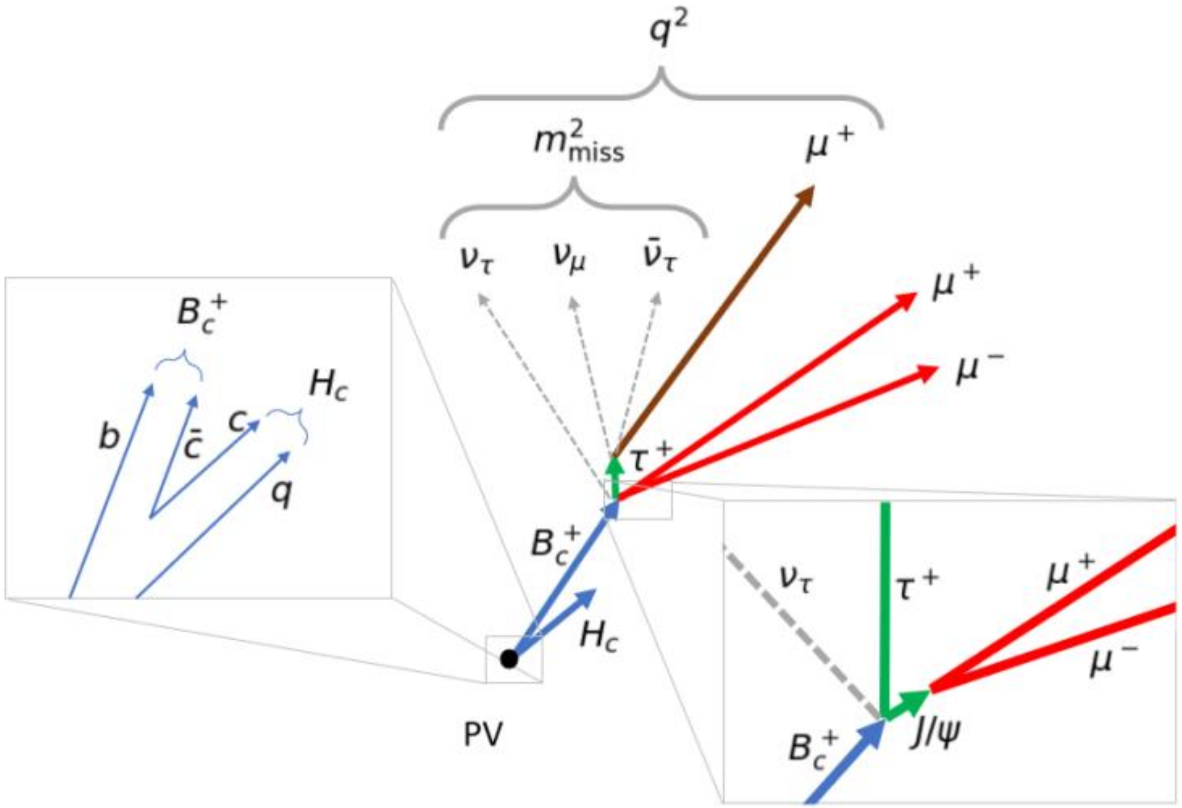
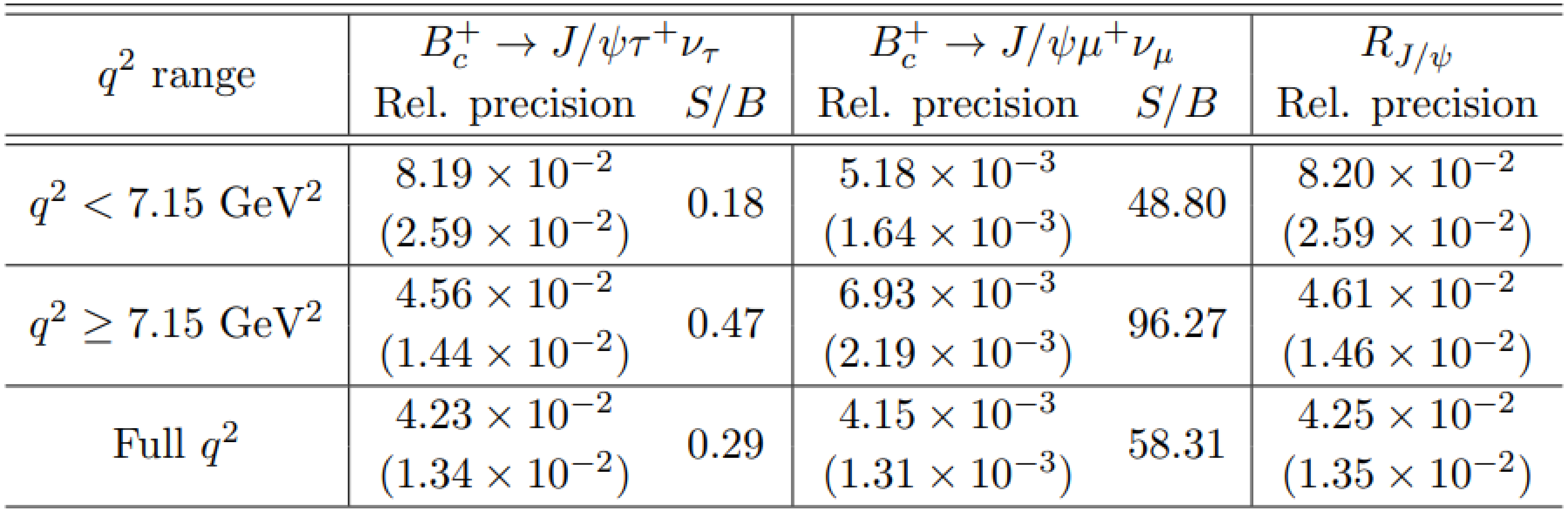


Figure 2: Schematics of the universal backgrounds in the $R_{J/\psi}$ measurement. **Left:** The typical topology for the inclusive backgrounds and the combinatoric backgrounds, where B_c^+ is reconstructed combining muons produced by the J/ψ (red), and the unpaired muon from semi-leptonic H_b decay (brown) or irrelevant particle decay (orange), respectively. **Middle:** The typical topology for the cascade backgrounds and the Mis-ID backgrounds, where B_c^+ is reconstructed combining the muons decayed from J/ψ (red), and the unpaired muon from intermediate hadron decay (brown) and pion misidentification (orange), respectively. **Right:** The typical topology for the fake H_c backgrounds, where the muons which do not share a parent particle (brown and orange) are used to reconstruct J/ψ.

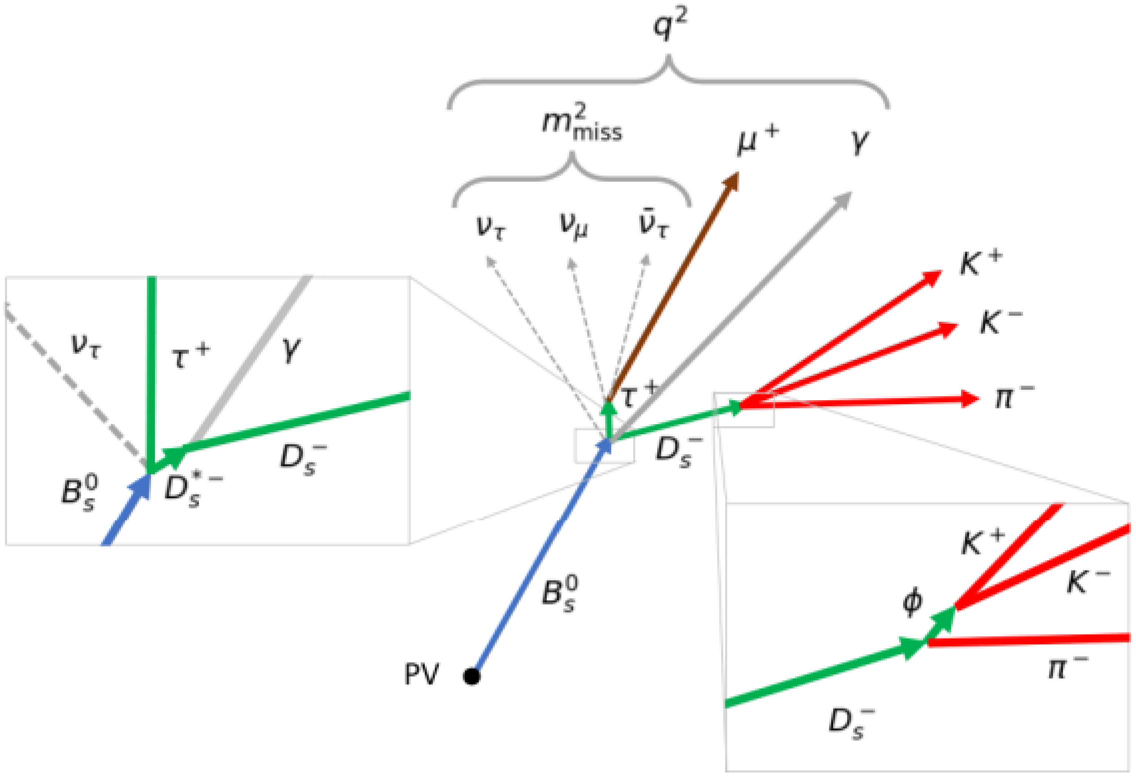


Channel	Events at Tera-Z	$N(3\mu)$	$N(J/\psi)$	$N(B_c^+)$	Total eff.
$B_c^+ \to J/\psi\tau^+\nu_\tau$	9.83×10^3	6.53×10^3	3.83×10^3	3.08×10^3	31.34%
$B_c^+ \to J/\psi\mu^+\nu_\mu$	2.39×10^5	1.63×10^5	9.66×10^4	8.40×10^4	35.13%
Inclusive bkg.	1.27×10^4	8.20×10^3	5.29×10^3	3.90×10^3	30.63%
Cascade bkg.	1.81×10^4	4.89×10^3	3.32×10^3	1.84×10^3	10.15%
Combinatoric bkg.	4.64×10^7	3.93×10^7	2.66×10^7	7.78×10^4	0.17%
Mis-ID bkg.	$\epsilon_{\mu\pi} \times 1.45 \times 10^9$	$\epsilon_{\mu\pi} \times 1.03 \times 10^9$	$\epsilon_{\mu\pi} \times 6.96 \times 10^8$	$\epsilon_{\mu\pi} \times 1.10 \times 10^8$	7.61%

BACKUP

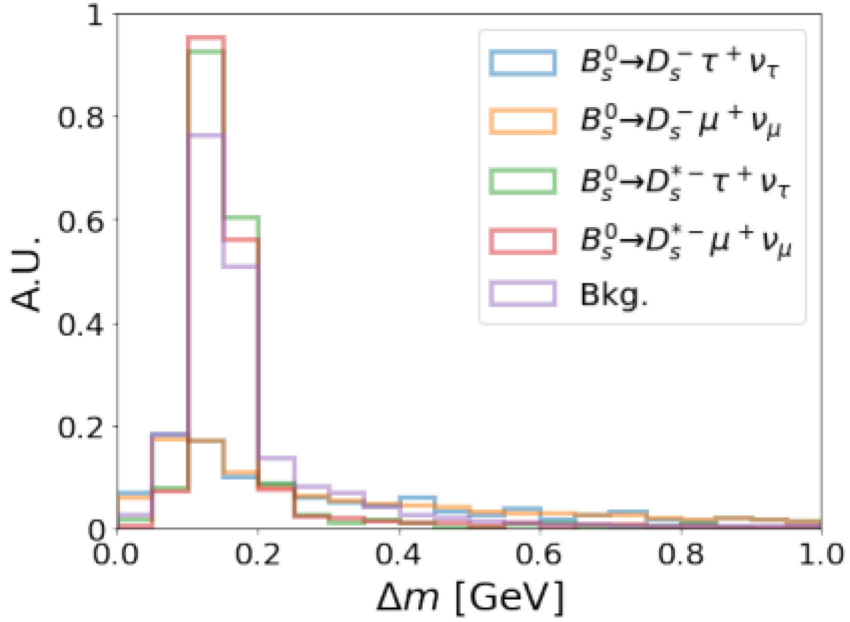


q^2 range	$B_c^+ \to J/\psi\tau^+\nu_\tau$		$B_c^+ \to J/\psi\mu^+\nu_\mu$		$R_{J/\psi}$
	Rel. precision	S/B	Rel. precision	S/B	Rel. precision
$q^2 < 7.15$ GeV^2	8.19×10^{-2} (2.59×10^{-2})	0.18	5.18×10^{-3} (1.64×10^{-3})	48.80	8.20×10^{-2} (2.59×10^{-2})
$q^2 \geq 7.15$ GeV^2	4.56×10^{-2} (1.44×10^{-2})	0.47	6.93×10^{-3} (2.19×10^{-3})	96.27	4.61×10^{-2} (1.46×10^{-2})
Full q^2	4.23×10^{-2} (1.34×10^{-2})	0.29	4.15×10^{-3} (1.31×10^{-3})	58.31	4.25×10^{-2} (1.35×10^{-2})



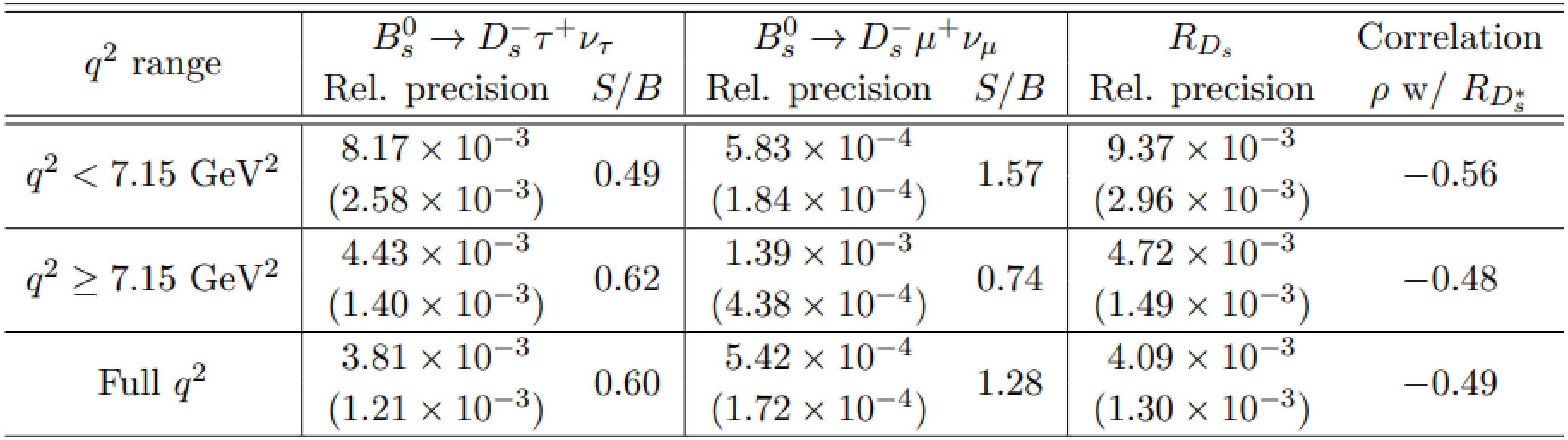
Channel	Events at Tera-Z	$N(KK\pi\mu)$	$N(D_s^-)$	$N(B_s^0)$	Total eff.
$B_s^0 \to D_s^- \tau^+ \nu_\tau$	1.03×10^6	7.92×10^5	6.45×10^5	4.81×10^5	46.77%
$B_s^0 \to D_s^- \mu^+ \nu_\mu$	1.50×10^7	1.18×10^7	9.93×10^6	8.41×10^6	56.08%
$B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$	1.72×10^6	1.30×10^6	1.05×10^6	7.65×10^5	44.61%
$B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$	3.35×10^7	2.56×10^7	2.11×10^7	1.78×10^7	53.11%
Inclusive bkg.	5.78×10^6	4.28×10^6	3.28×10^6	2.72×10^6	47.03%
Cascade bkg.	8.44×10^7	6.20×10^7	2.33×10^7	8.71×10^6	10.33%
Combinatoric bkg.	1.36×10^8	1.16×10^8	2.24×10^7	2.17×10^4	0.02%
Mis-ID bkg.	$\epsilon_{\mu\pi} \times 1.05 \times 10^{10}$	$\epsilon_{\mu\pi} \times 4.33 \times 10^9$	$\epsilon_{\mu\pi} \times 8.41 \times 10^8$	$\epsilon_{\mu\pi} \times 8.50 \times 10^7$	0.81%

BACKUP

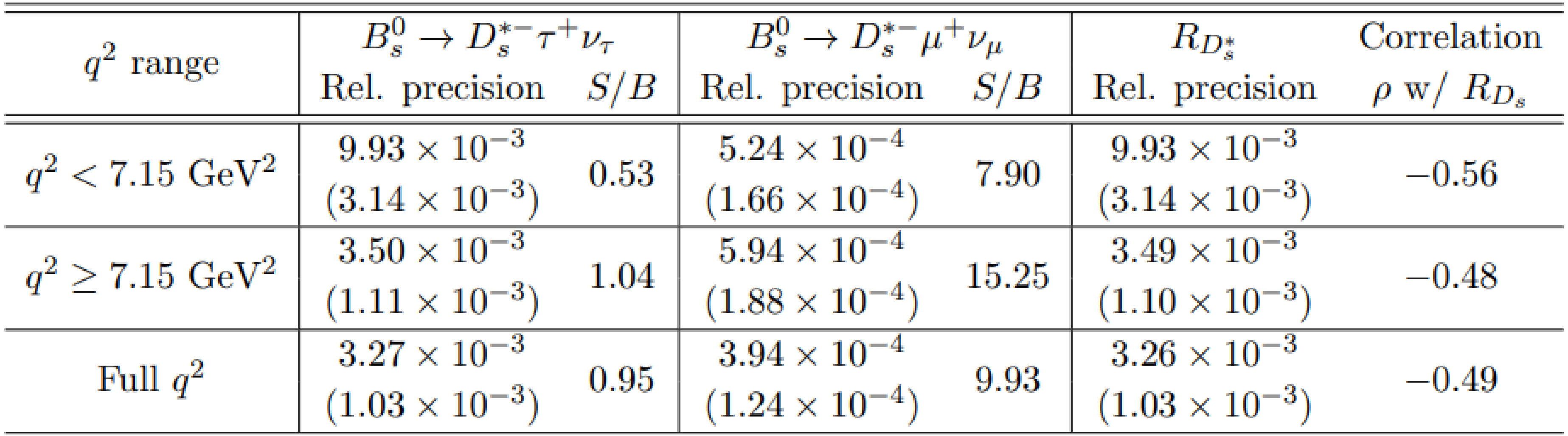


A.U.
1
0.8
0.6
0.4
0.2
0
0.0
0.2
0.4
0.6
0.8
1.0
Δm [GeV]
$B_s^0 \to D_s^- \tau^+ \nu_\tau$
$B_s^0 \to D_s^- \mu^+ \nu_\mu$
$B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$
$B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$
Bkg.

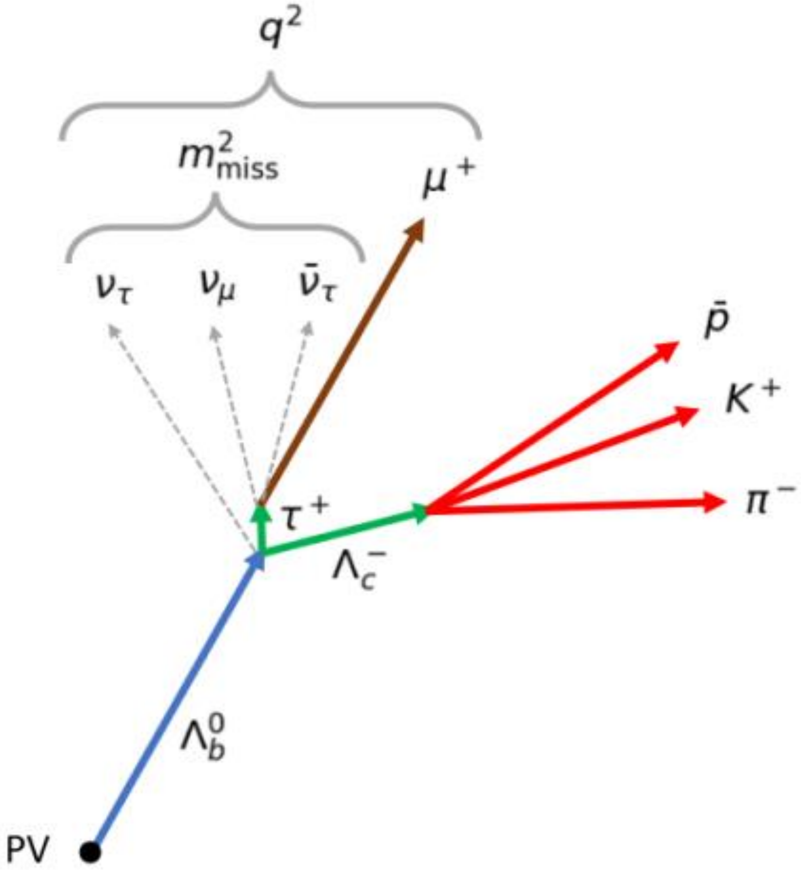
BACKUP



q^2 range	$B_s^0 \to D_s^- \tau^+ \nu_\tau$		$B_s^0 \to D_s^- \mu^+ \nu_\mu$		R_{D_s}	Correlation
	Rel. precision	S/B	Rel. precision	S/B	Rel. precision	ρ w/ $R_{D_s^*}$
$q^2 < 7.15$ GeV^2	8.17×10^{-3} (2.58×10^{-3})	0.49	5.83×10^{-4} (1.84×10^{-4})	1.57	9.37×10^{-3} (2.96×10^{-3})	-0.56
$q^2 \geq 7.15$ GeV^2	4.43×10^{-3} (1.40×10^{-3})	0.62	1.39×10^{-3} (4.38×10^{-4})	0.74	4.72×10^{-3} (1.49×10^{-3})	-0.48
Full q^2	3.81×10^{-3} (1.21×10^{-3})	0.60	5.42×10^{-4} (1.72×10^{-4})	1.28	4.09×10^{-3} (1.30×10^{-3})	-0.49

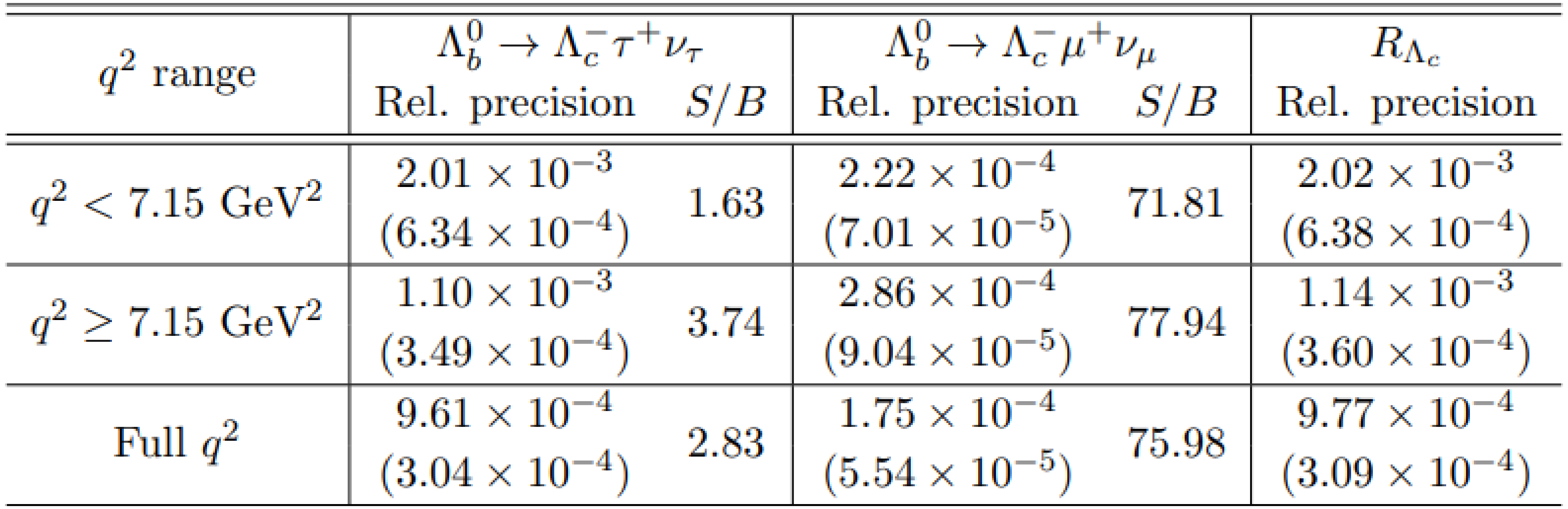


q^2 range	$B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$		$B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$		$R_{D_s^*}$	Correlation
	Rel. precision	S/B	Rel. precision	S/B	Rel. precision	ρ w/ R_{D_s}
$q^2 < 7.15$ GeV^2	9.93×10^{-3} (3.14×10^{-3})	0.53	5.24×10^{-4} (1.66×10^{-4})	7.90	9.93×10^{-3} (3.14×10^{-3})	-0.56
$q^2 \geq 7.15$ GeV^2	3.50×10^{-3} (1.11×10^{-3})	1.04	5.94×10^{-4} (1.88×10^{-4})	15.25	3.49×10^{-3} (1.10×10^{-3})	-0.48
Full q^2	3.27×10^{-3} (1.03×10^{-3})	0.95	3.94×10^{-4} (1.24×10^{-4})	9.93	3.26×10^{-3} (1.03×10^{-3})	-0.49



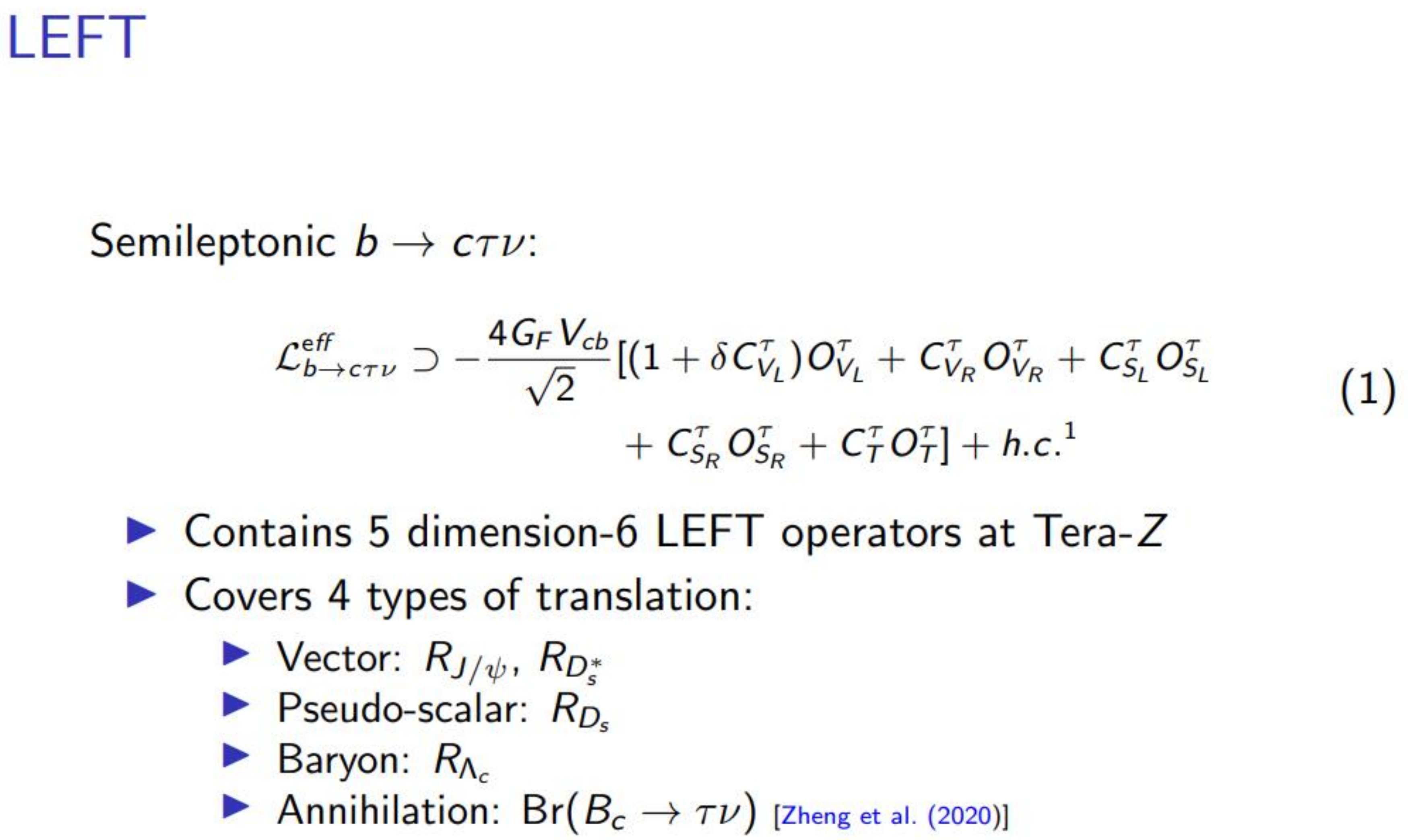
Channel	Events at Tera-Z	$N(pK\pi\mu)$	$N(\Lambda_c^+)$	$N(\Lambda_b^0)$	Total eff.
$\Lambda_b^0 \to \Lambda_c^- \tau^+ \nu_\tau$	4.46×10^6	3.52×10^6	2.96×10^6	2.22×10^6	49.89%
$\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\mu$	7.58×10^7	6.23×10^7	5.26×10^7	4.48×10^7	59.11%
Inclusive bkg.	2.75×10^6	2.17×10^6	6.75×10^5	5.79×10^5	21.05%
Cascade bkg.	1.03×10^6	8.05×10^5	4.05×10^5	2.18×10^5	21.19%
Combinatoric bkg.	1.57×10^7	1.33×10^7	4.93×10^5	7.91×10^2	0.01%
Mis-ID bkg.	$\epsilon_{\mu\pi} \times 1.36 \times 10^9$	$\epsilon_{\mu\pi} \times 5.43 \times 10^8$	$\epsilon_{\mu\pi} \times 4.05 \times 10^7$	$\epsilon_{\mu\pi} \times 1.52 \times 10^7$	1.12%

BACKUP



q^2 range	$\Lambda_b^0 \to \Lambda_c^- \tau^+ \nu_\tau$		$\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\mu$		R_{Λ_c}
	Rel. precision	S/B	Rel. precision	S/B	Rel. precision
$q^2 < 7.15$ GeV^2	2.01×10^{-3} (6.34×10^{-4})	1.63	2.22×10^{-4} (7.01×10^{-5})	71.81	2.02×10^{-3} (6.38×10^{-4})
$q^2 \geq 7.15$ GeV^2	1.10×10^{-3} (3.49×10^{-4})	3.74	2.86×10^{-4} (9.04×10^{-5})	77.94	1.14×10^{-3} (3.60×10^{-4})
Full q^2	9.61×10^{-4} (3.04×10^{-4})	2.83	1.75×10^{-4} (5.54×10^{-5})	75.98	9.77×10^{-4} (3.09×10^{-4})

BACKUP



LEFT

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

$$\mathcal{L}^{\text{eff}}_{b\to c\tau\nu} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\delta C^{\tau}_{V_L})O^{\tau}_{V_L} + C^{\tau}_{V_R}O^{\tau}_{V_R} + C^{\tau}_{S_L}O^{\tau}_{S_L} + C^{\tau}_{S_R}O^{\tau}_{S_R} + C^{\tau}_{T}O^{\tau}_{T}] + h.c.^{1} \tag{1}$$

- Contains 5 dimension-6 LEFT operators at Tera-Z
- Covers 4 types of translation:
  - Vector: $R_{J/\psi}$, $R_{D_s^*}$
  - Pseudo-scalar: R_{D_s}
  - Baryon: R_{Λ_c}
  - Annihilation: $\text{Br}(B_c \to \tau\nu)$ [Zheng et al. (2020)]

BACKUP

LEFT

FCNC $b \to s\tau\tau$:

$$\begin{aligned}\mathcal{L}^{\text{eff}}_{b\to s\tau^+\tau^-} = +\frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}}[(C_9^\tau|_{\text{SM}} + \delta C_9^\tau)O_9^\tau + (C_{10}^\tau|_{\text{SM}} + \delta C_{10}^\tau)O_{10}^\tau \\ + C_9'^\tau O_9'^\tau + C_{10}'^\tau O_{10}'^\tau + C_S^\tau O_S^\tau \\ + C_S'^\tau O_S'^\tau + C_P^\tau O_P^\tau + C_P'^\tau O_P'^\tau \\ + C_T^\tau O_T^\tau + C_{T5}^\tau O_{T5}^\tau] + h.c.\end{aligned} \quad (2)$$

- Contains 10 dimension-6 LEFT operators at Tera-Z
- Related to: $\text{Br}(B \to K\tau\tau)$, $\text{Br}(B \to K^*\tau\tau)$, $\text{Br}(B_s \to \phi\tau\tau)$, $\text{Br}(B_s \to \tau\tau)$[Kamenik et al. (2017); Capdevila et al. (2018); Li and Liu (2021)]

FCNC $b \to s\nu\nu$:

$$\mathcal{L}^{\text{eff}}_{b\to s\bar{\nu}\nu} = +\frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}}[C_L^\nu O_L^\nu + C_R^\nu O_R^\nu] + h.c. \quad (3)$$

- Contains 2 dimension-6 LEFT operators at Tera-Z
- Related to: $\text{Br}(B \to K\nu\nu)$, $\text{Br}(B \to K^*\nu\nu)$, $\text{Br}(B_s \to \phi\nu\nu)$[Buras et al. (2015); Li et al. (2022)]

BACKUP

SMEFT

$$\mathcal{L}^{\text{dim6}} \supset \frac{1}{\Lambda^2} \sum_{i,j,k,l} \Big([C_{\ell q}^{(1)}]_{ijkl}[O_{\ell q}^{(1)}]_{ijkl} + [C_{\ell q}^{(3)}]_{ijkl}[O_{\ell q}^{(3)}]_{ijkl} + [C_{ed}]_{ijkl}[O_{ed}]_{ijkl}$$
$$+ [C_{\ell d}]_{ijkl}[O_{\ell d}]_{ijkl} + [C_{qe}]_{ijkl}[O_{qe}]_{ijkl} + [C_{\ell edq}]_{ijkl}[O_{\ell edq}]_{ijkl}$$
$$+ [C_{\ell equ}^{(1)}]_{ijkl}[O_{\ell equ}^{(1)}]_{ijkl} + [C_{\ell equ}^{(3)}]_{ijkl}[O_{\ell equ}^{(3)}]_{ijkl} \Big) + h.c.$$

- After matching: 9 LFUV operators in dim6 SMEFT

SMEFT Operator	Expansion in Down Basis
$[O_{lq}^{(1)}]_{3332}$	$(\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{lq}^{(3)}]_{3332}$	$2V_{cs}^*(\bar{\nu}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L c) - (\bar{\nu}\gamma^\mu P_L \nu - \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{ed}]_{3332}$	$(\bar{\tau}\gamma^\mu P_R \tau)(\bar{b}\gamma_\mu P_R s)$
$[O_{ld}]_{3332}$	$(\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_R s)$
$[O_{qe}]_{3332}$	$(\bar{\tau}\gamma^\mu P_R \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{ledq}]_{3332}$	$V_{cs}^*(\bar{\nu} P_R \tau)(\bar{b} P_L c) + (\bar{\tau} P_R \tau)(\bar{b} P_L s)$
$[O_{ledq}]_{3323}$	$(\bar{\tau} P_R \tau)(\bar{s} P_L b)$
$[O_{lequ}^{(1)}]_{3332}$	$V_{cs}^*(\bar{\nu} P_R \tau)(\bar{b} P_R c)$
$[O_{lequ}^{(3)}]_{3332}$	$V_{cs}^*(\bar{\nu}\sigma^{\mu\nu} P_R \tau)(\bar{b}\sigma_{\mu\nu} P_R c)$

BACKUP

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