Tau Flavor Universality at CEPC

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Based on arXiv:2212.02433
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SM assumes:

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

SM assumes LFU

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

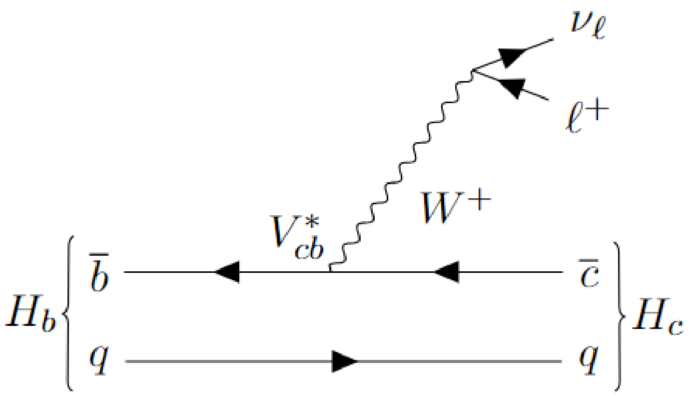
Need to be tested with high precision!!!

SM extensions > extra LFU violating interactions
Flavor physics > indirect BSM searches.
[Many BSM models have stronger couplings to 3rd generation (e.g. b, τ)]

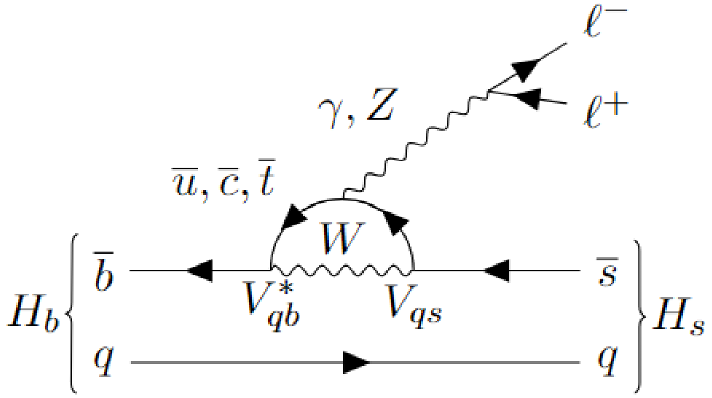
How to Test LFU?

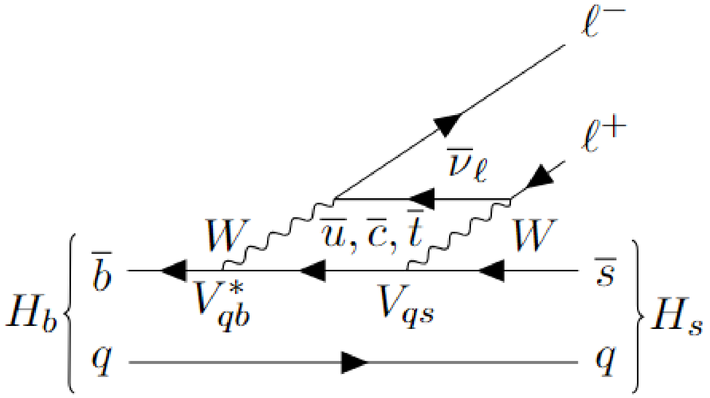
b-hadron decays:

FCCC:



FCNC:

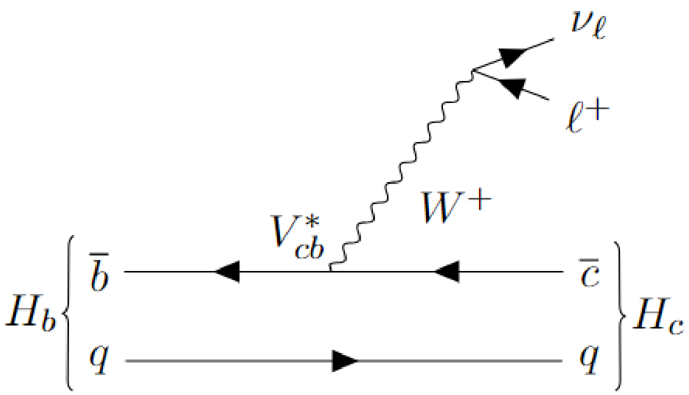




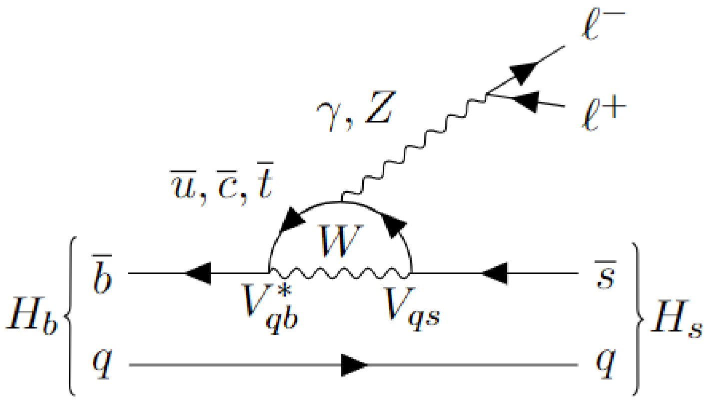
How to Test LFU?

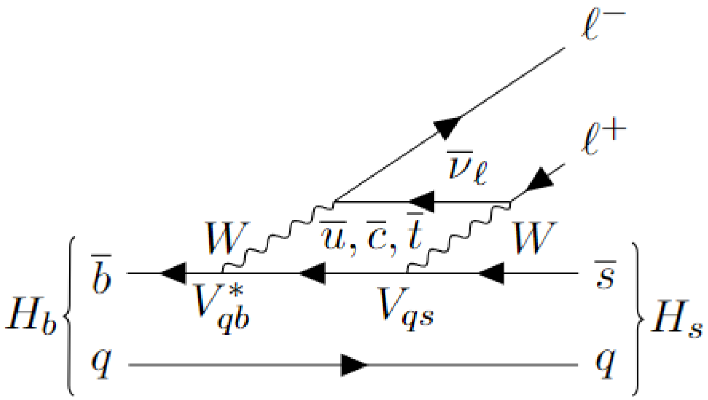
b-hadron decays:

FCCC:



FCNC:





Future Z Factories

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\text{cm}^{-2}\text{s}^{-1}$, per IP)	191.7	26.7	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6.9	21.6	1
Event yields	4.1×10^{12}	2×10^{7}	4.3×10^{6}	6×10^{5}

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
- …

Why Z Factories?

Discussed by many talks!

Z Factories v.s. b Factories

- Abundant H_b
- High boost
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- …

Z Factories v.s. Hadronic Machine

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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)

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

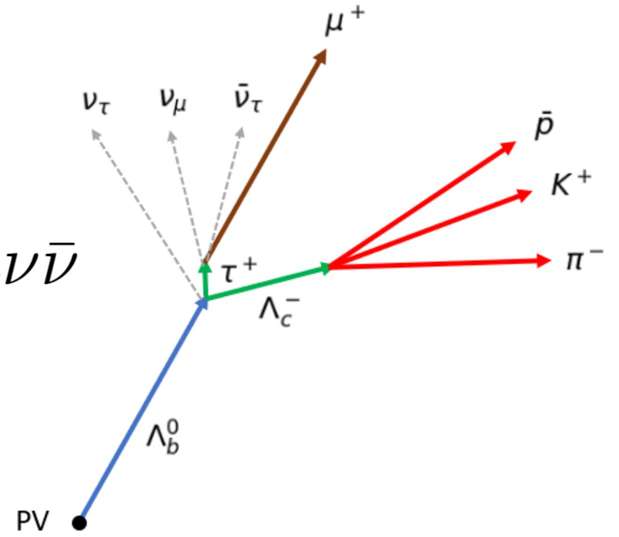
$$J/\psi \to \mu\mu,\ \tau \to \mu\nu\bar{\nu}$$

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

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

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

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

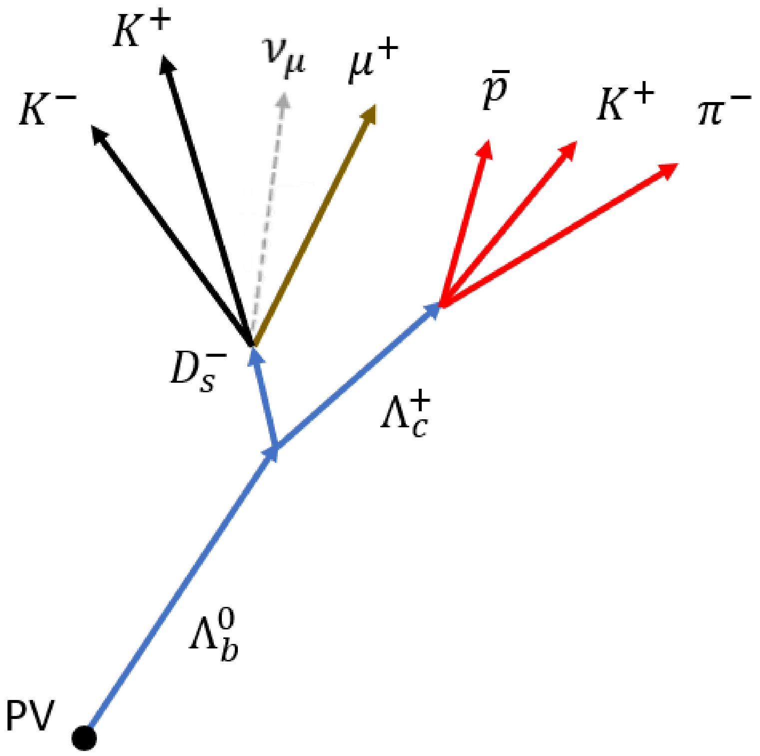


Tera-Z can produce many of such H_b, while B-factories can't do! (or just few)
H_c decays to charged final states: H_c can be fully reconstructed!

Backgrounds

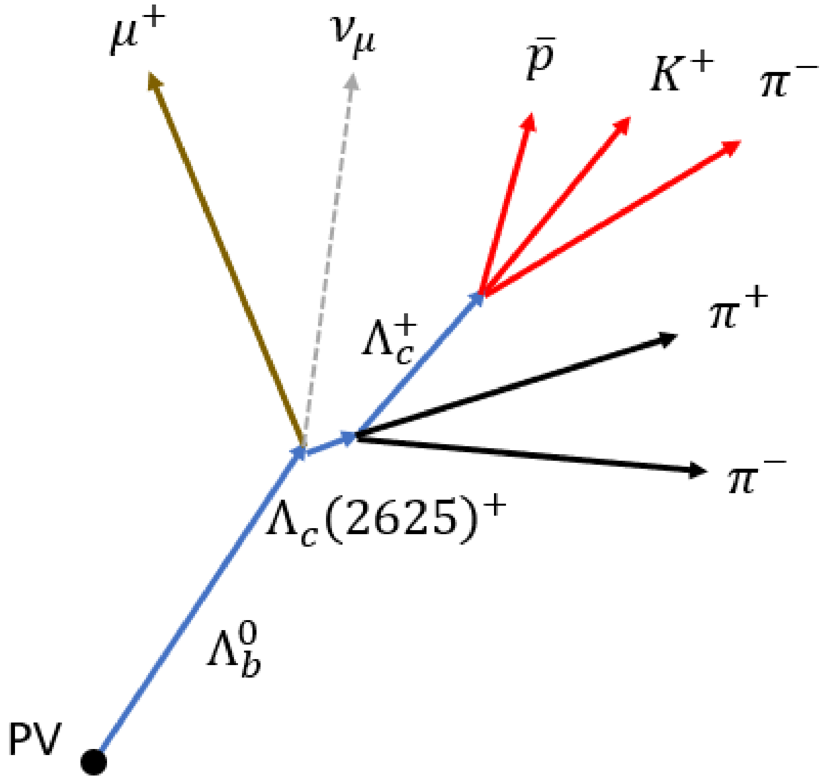
Wrong μ Production

For example:



Wrong H_c Production

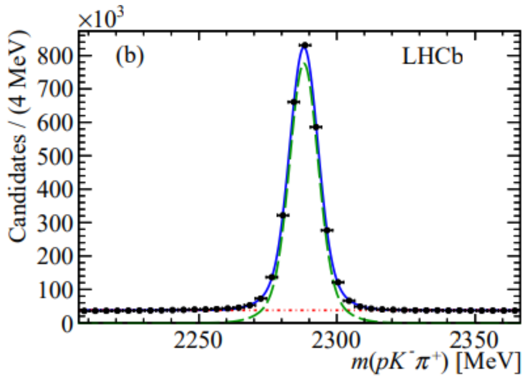
For example:



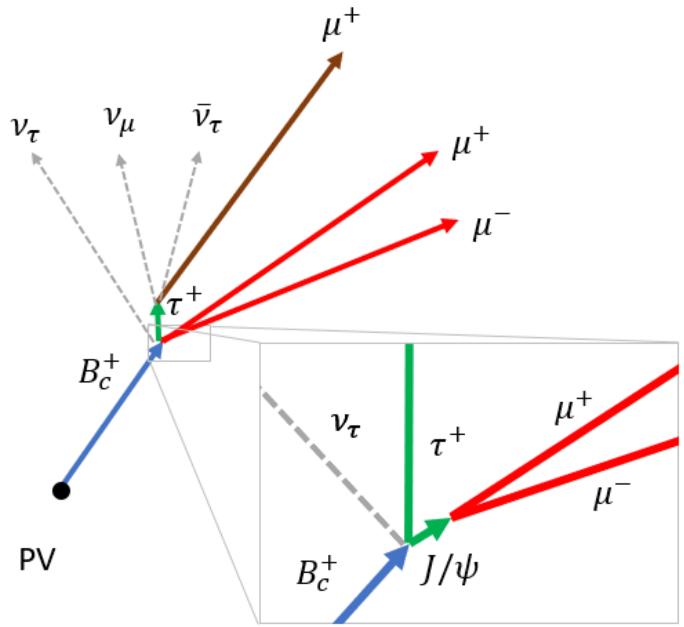
Reconstruction Scheme

1. Reconstruct H_c and identify μ

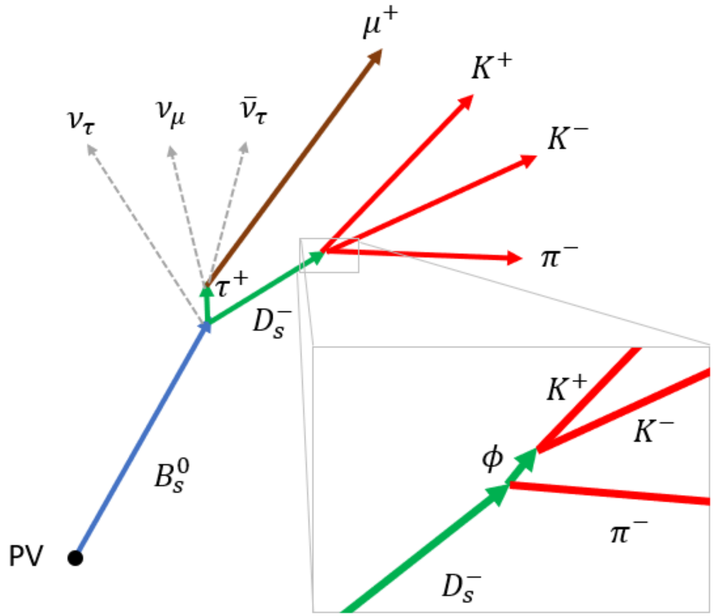
2. Deduce H_b decay vertex



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

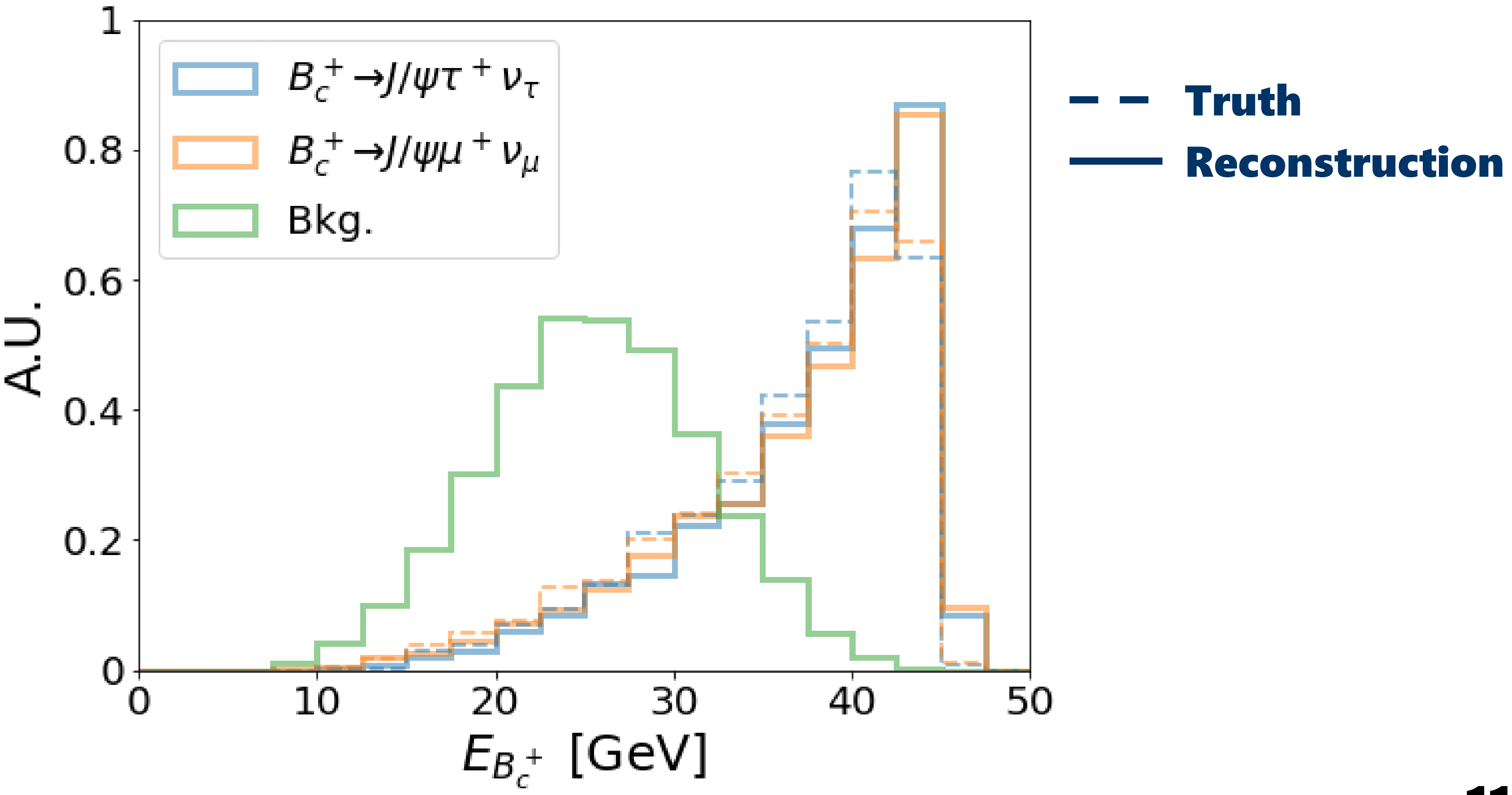


Reconstruction Scheme

3. Deduce b-hadron energy:

(Energy-momentum conversation)

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

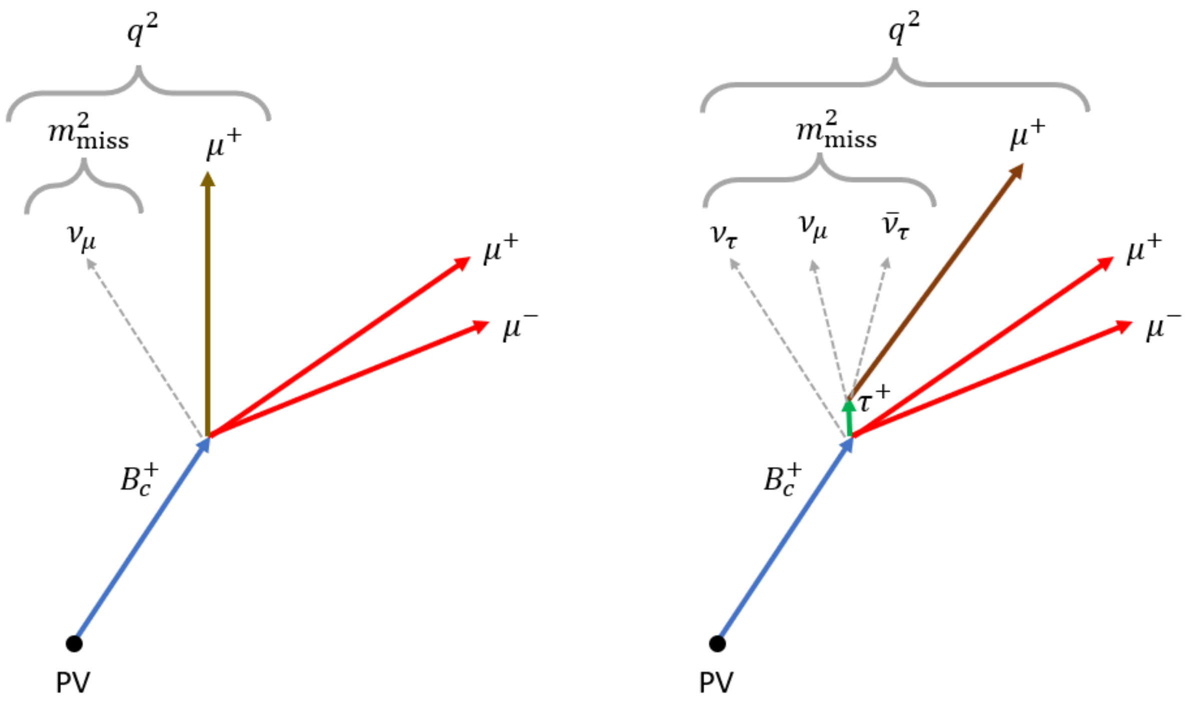


Discriminators for τ , μ Channel Separation

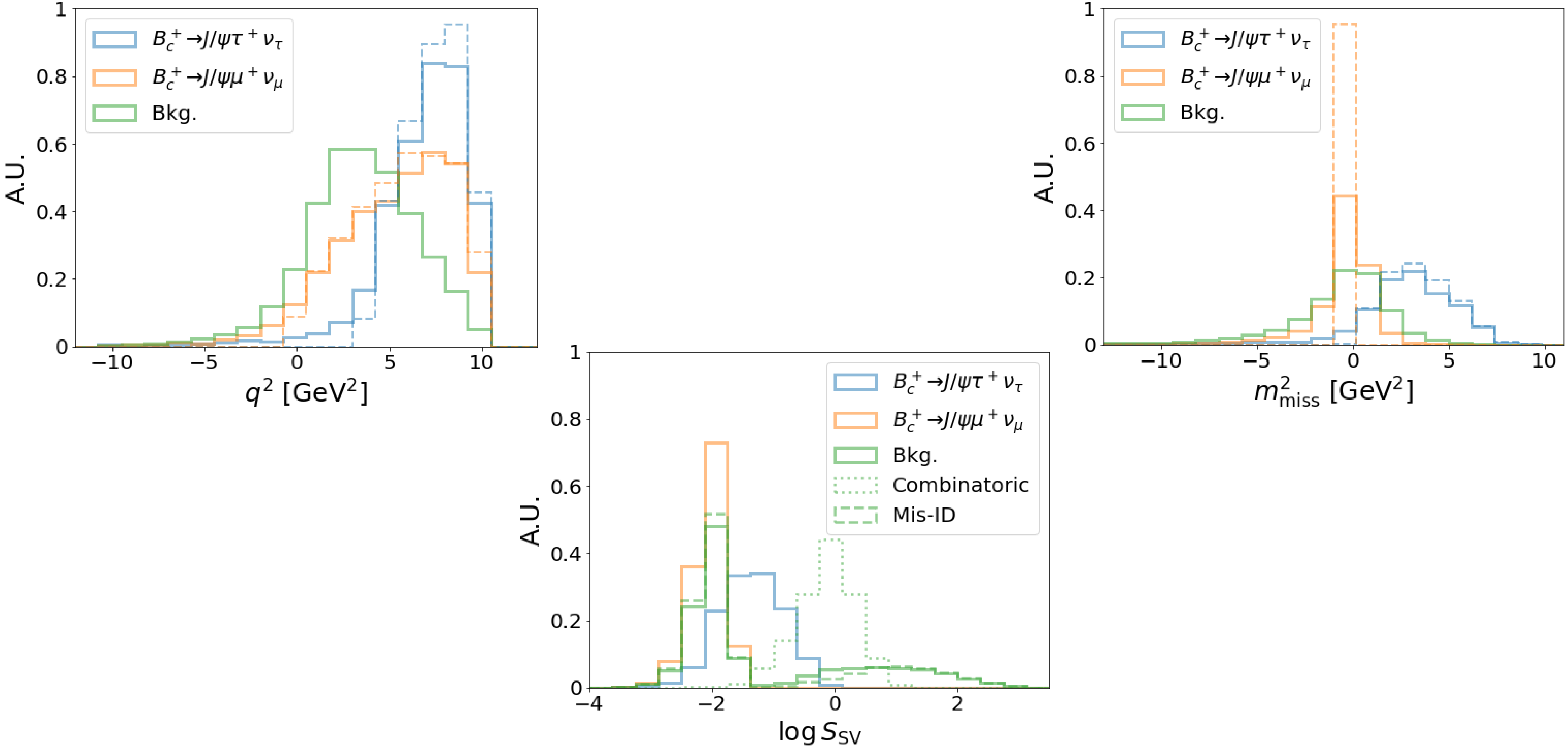
Momentum transferred to lepton system: $q^2 \equiv (p_{Bc} - p_{J/\psi})^2$

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

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

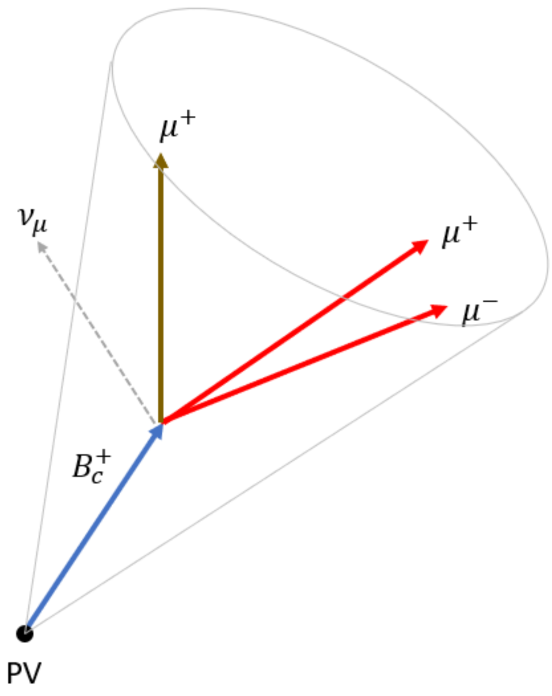


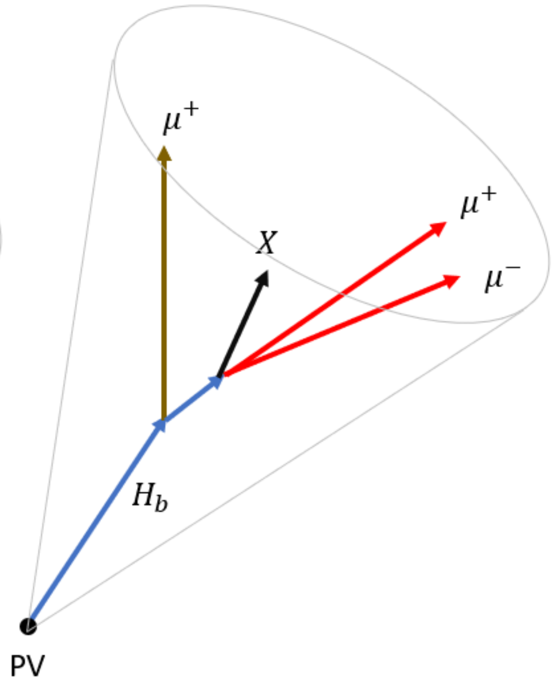
Discriminators for τ , μ Channel Separation

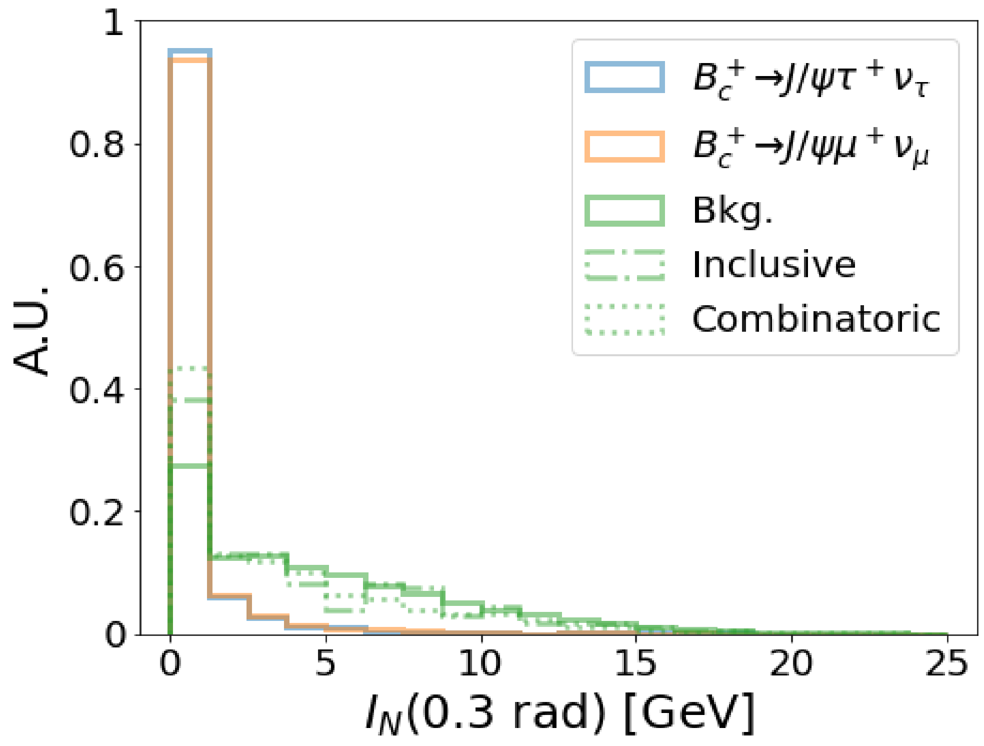


Discriminators for Background Separation

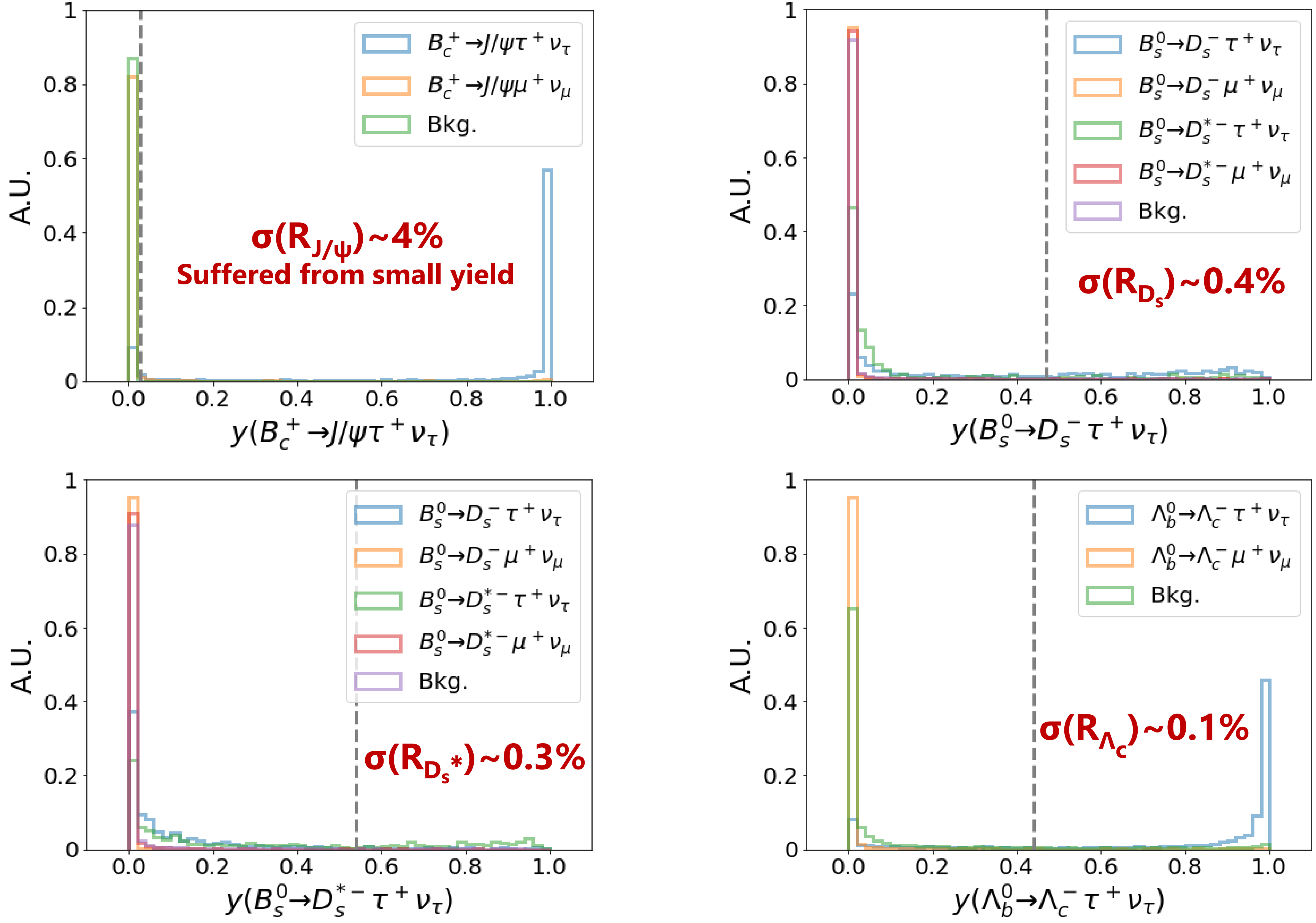
Isolation variable:
total energy, except the tagged final states, inside 0.3(0.6) rad of B cone



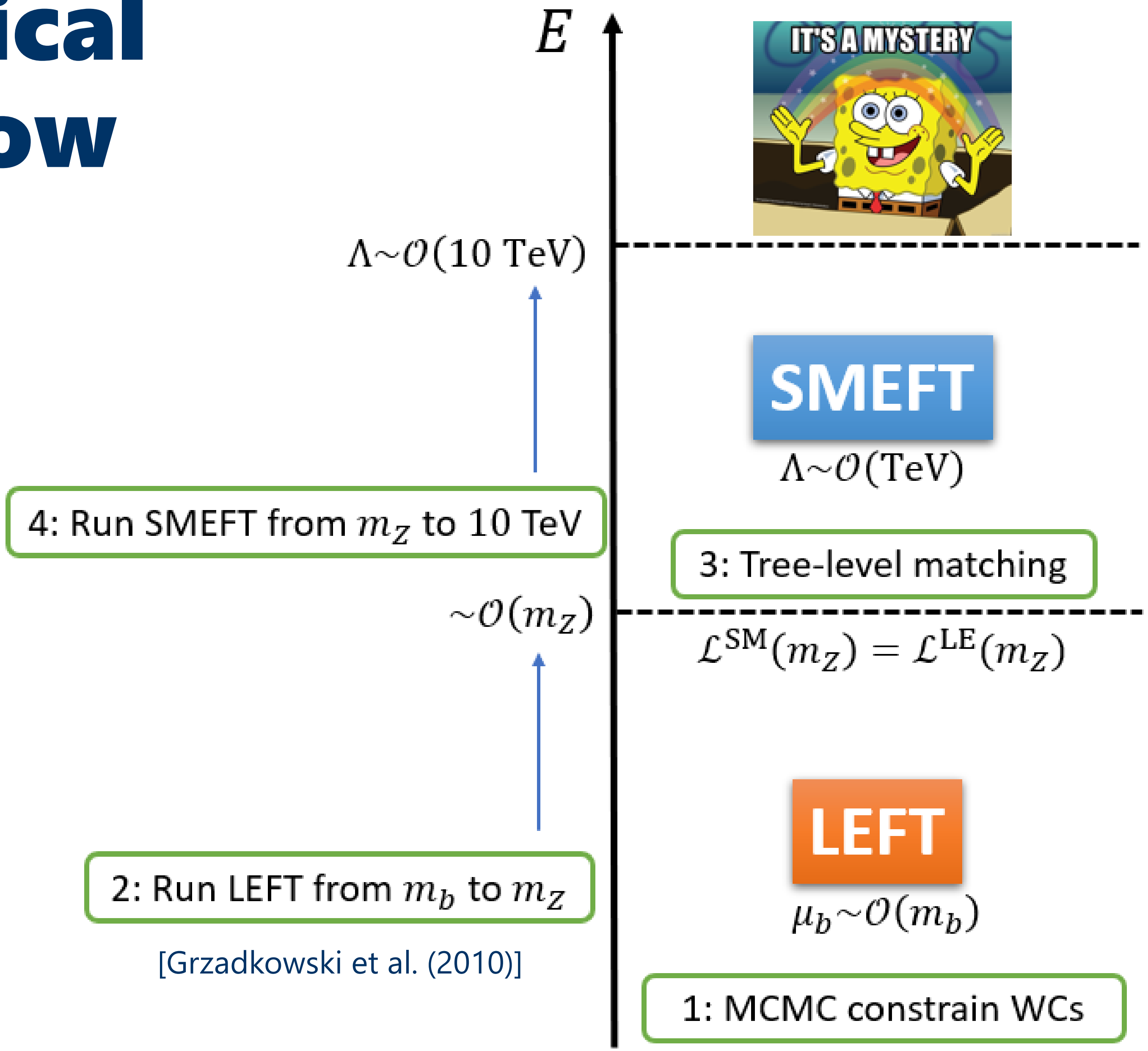




Stat. only BDT results



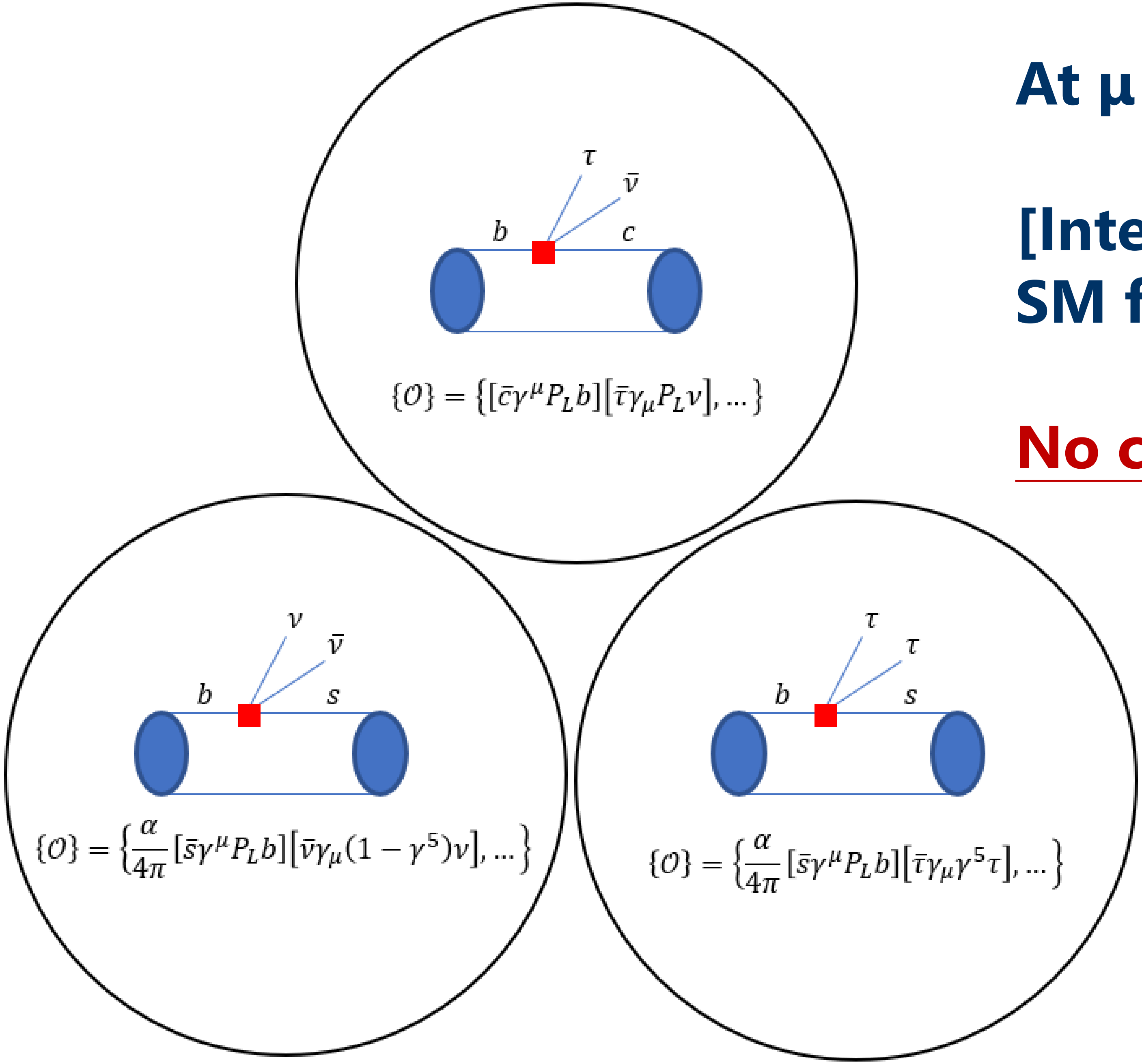
Theoretical Workflow



[Grzadkowski et al. (2010)]

[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

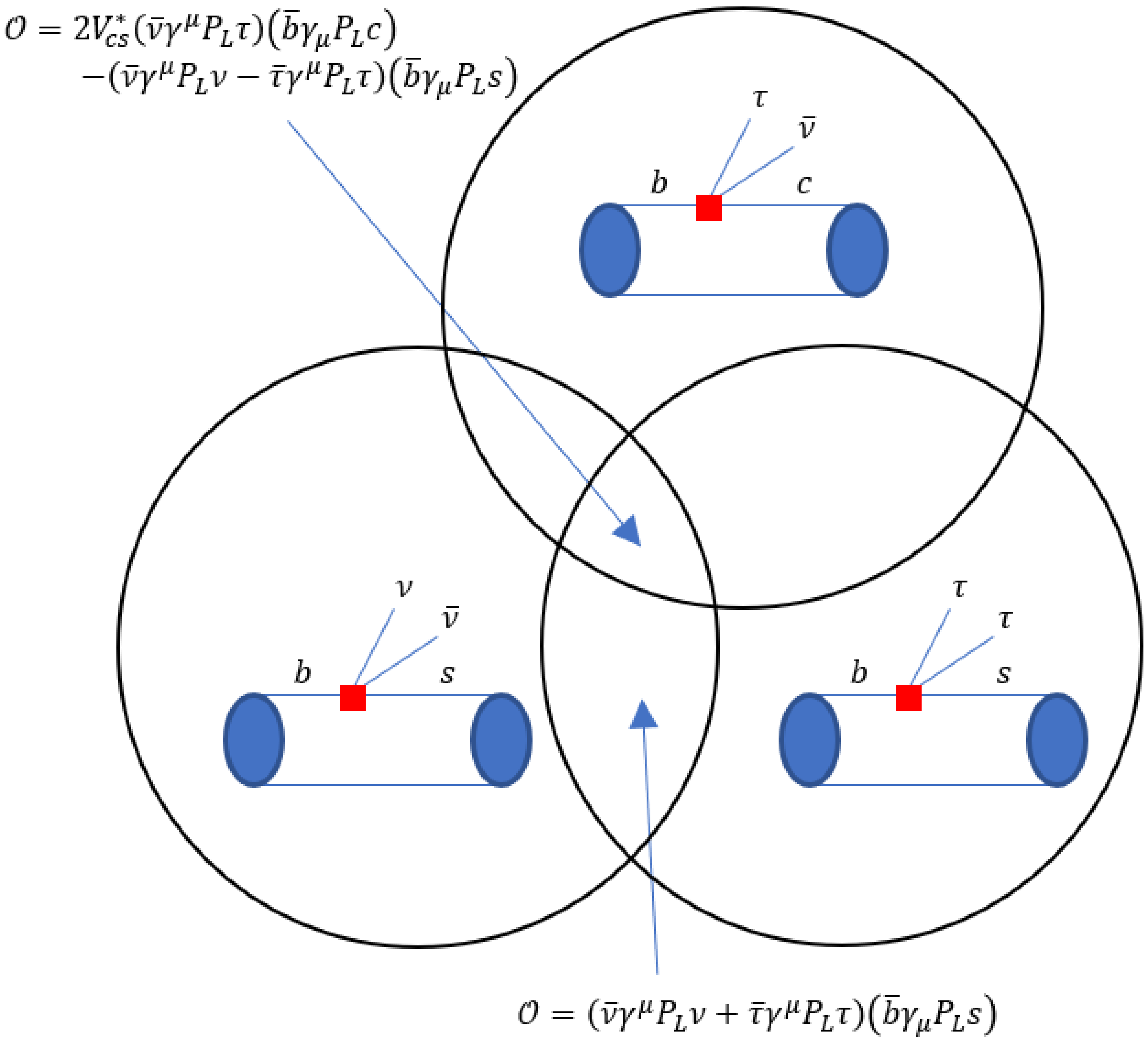


At $\mu \sim m_b$

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

No correlation

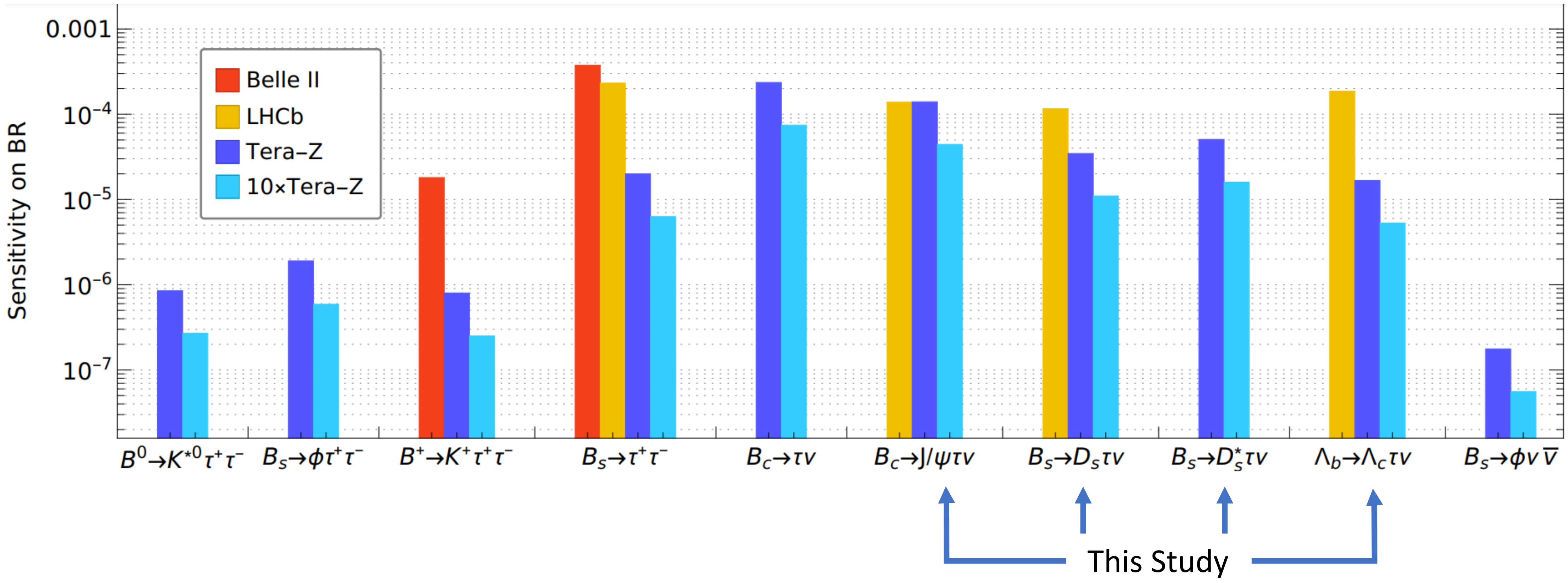
SMEFT



At Λ ~ multi-TeV

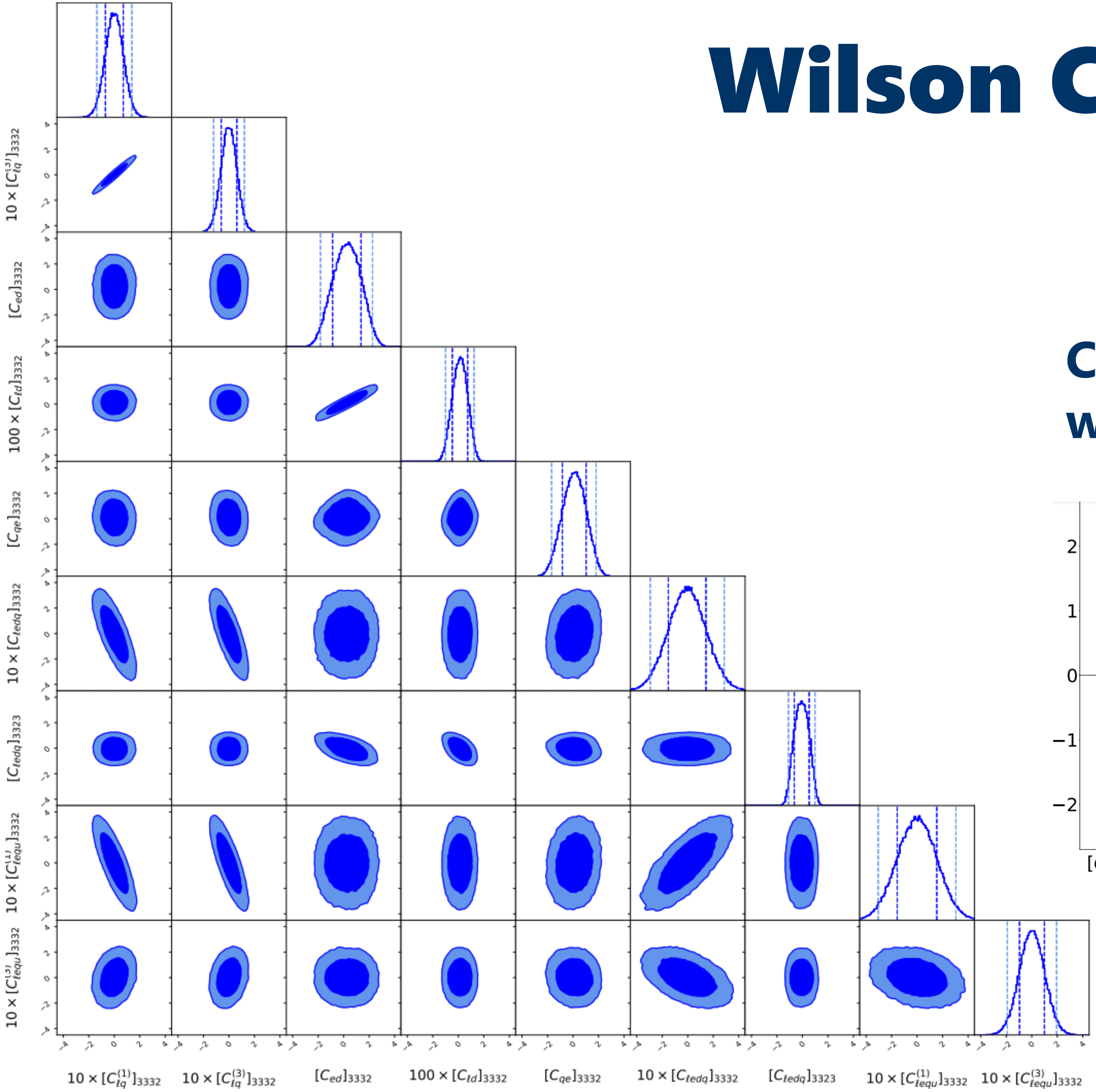
[All SM fields Under SM sym]

Correlated!!!

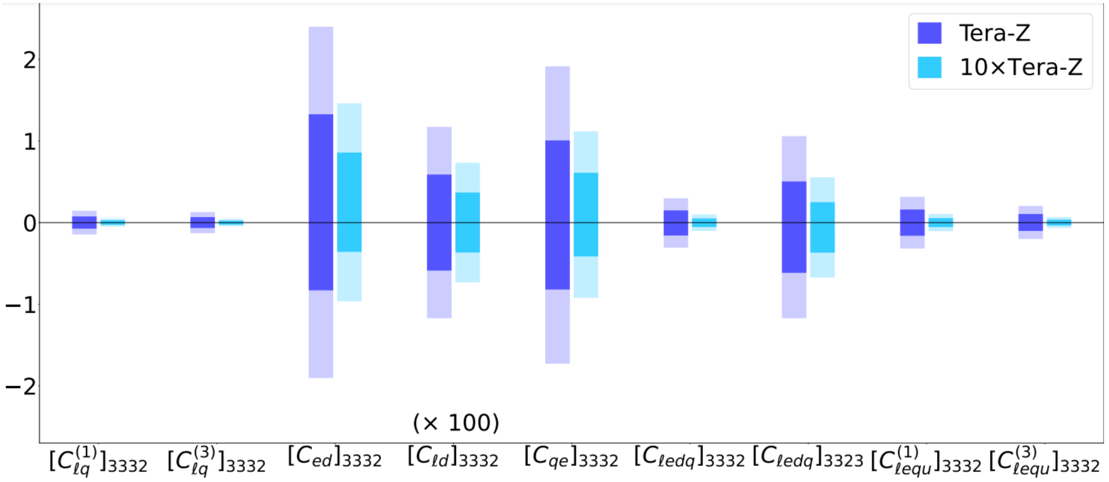


[Zheng et al. (2020); Kamenik et al. (2017); Capdevila et al. (2018); Li and Liu (2021); Buras et al. (2015); Li et al. (2022)]

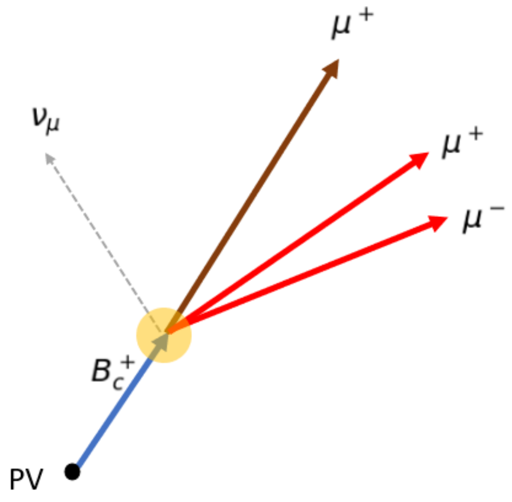
Wilson Coeff. Constraints

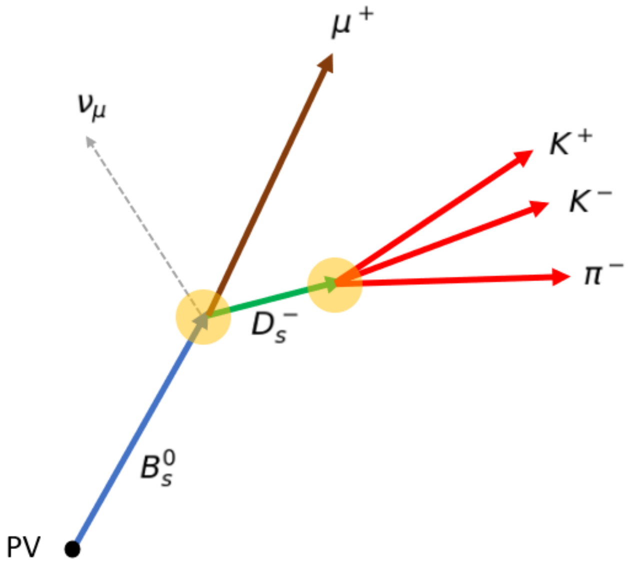


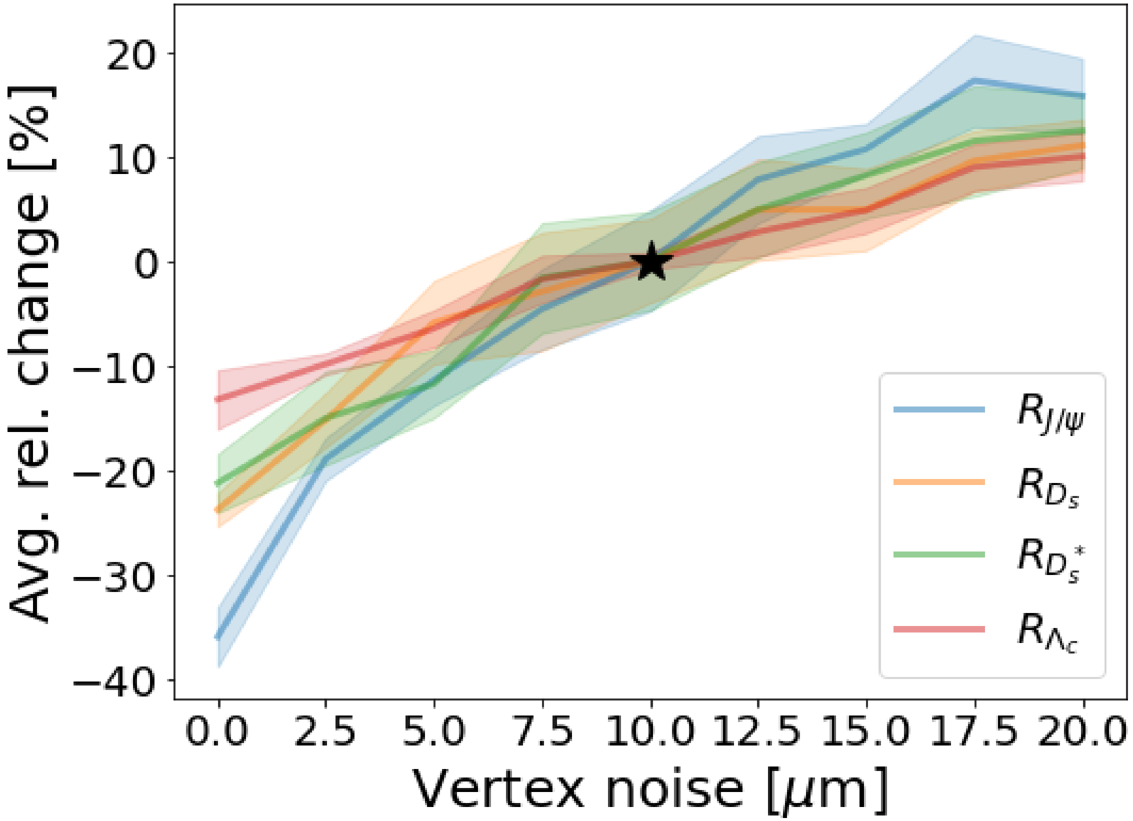
Constraint of NP up to multi-TeV when Wilson Coeff. are about O(1)



Detector Tracking Resolutions







Robustness: Vary vertex noise level (0, 5, **10**, 20 μm)

Conclusion

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

- Setting up a baseline of $b \to c\tau\nu$ 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

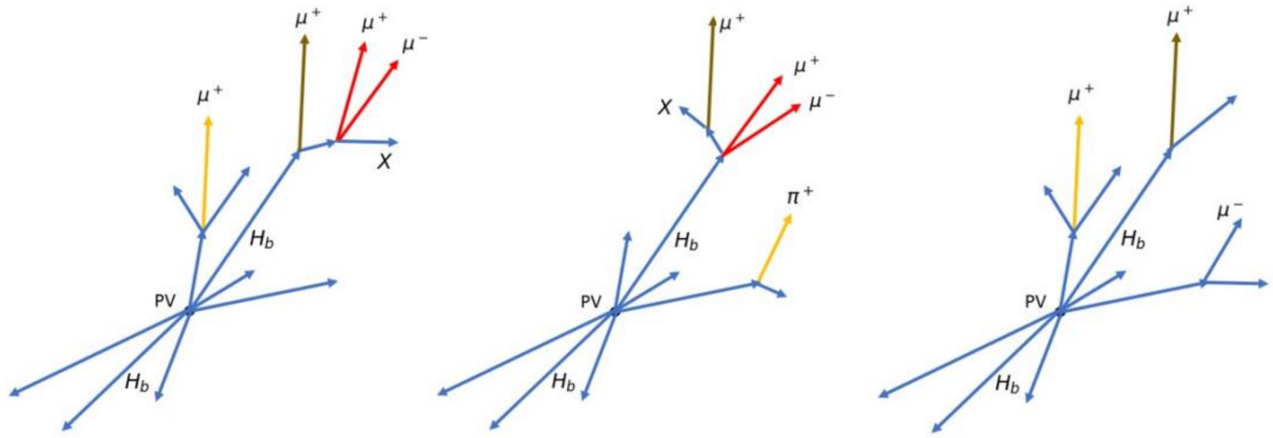
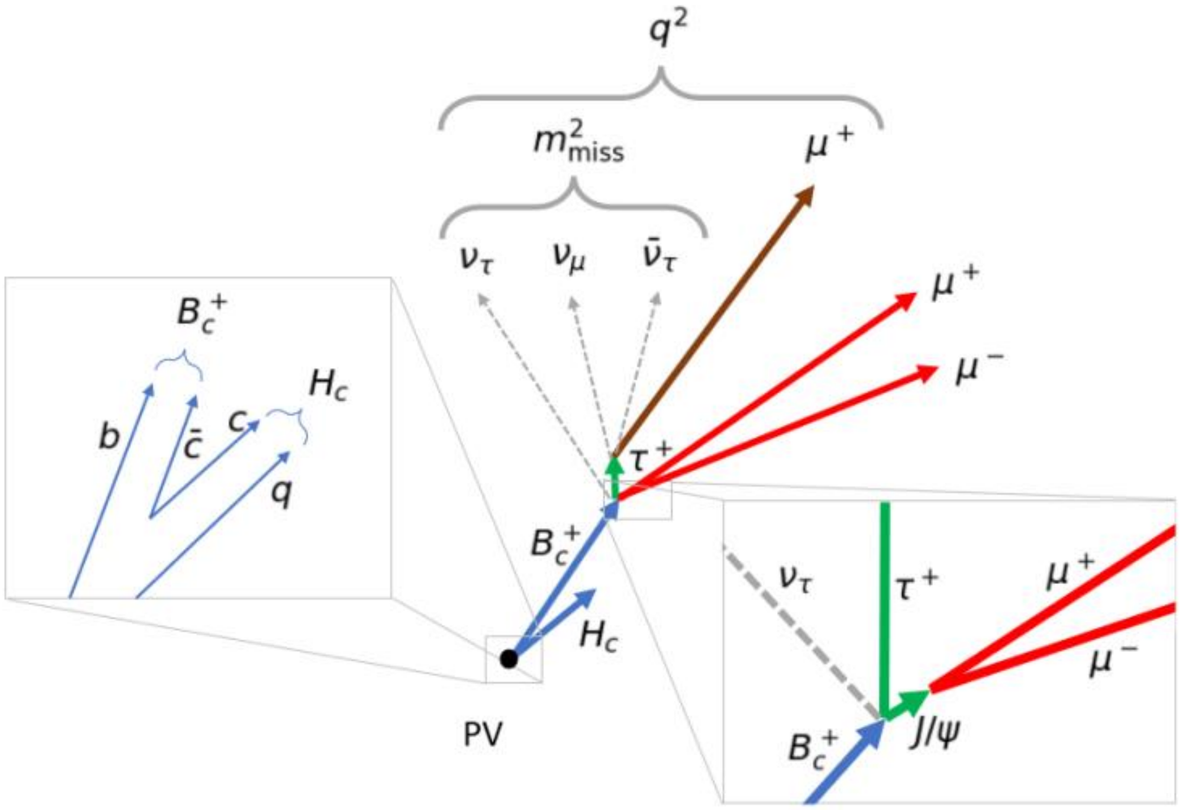


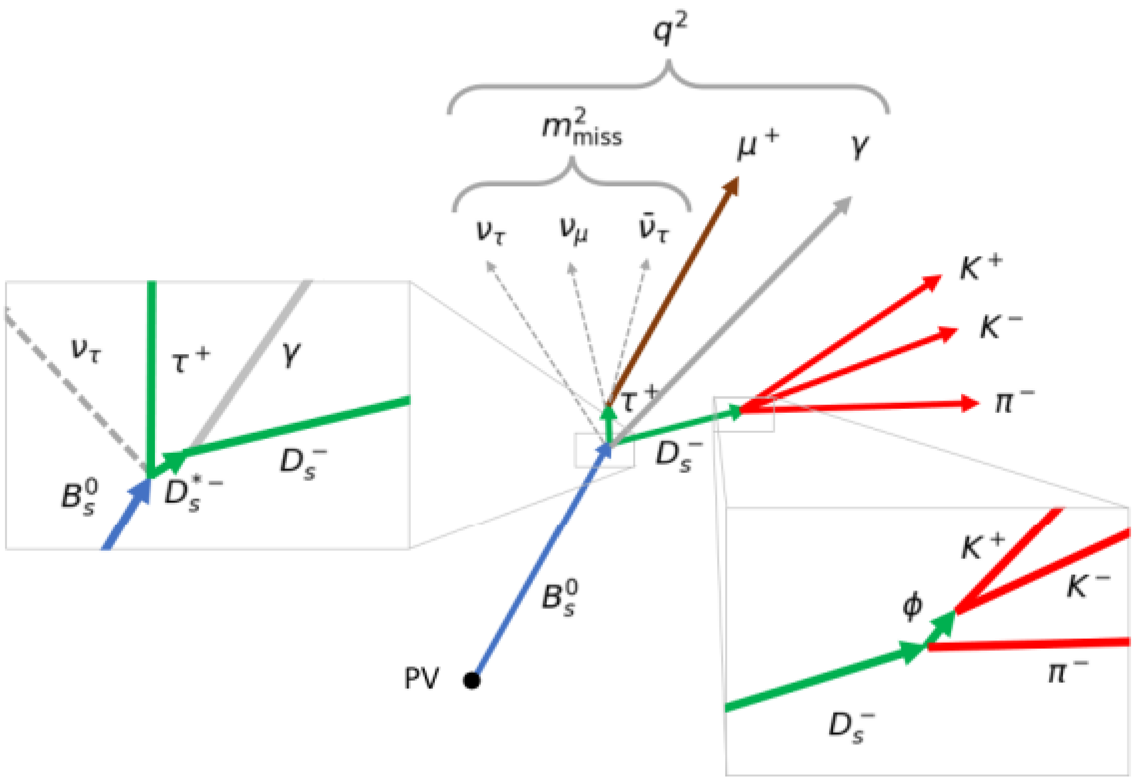
Figure 2: Schematics of the universal backgrounds in the $R_{J/\psi}$ measurement. **Left:** The typical topology for the inclusive backgrounds and the combinatoric backgrounds, where B_c^+ is reconstructed combining muons produced by the J/ψ (red), and the unpaired muon from semi-leptonic H_b decay (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%

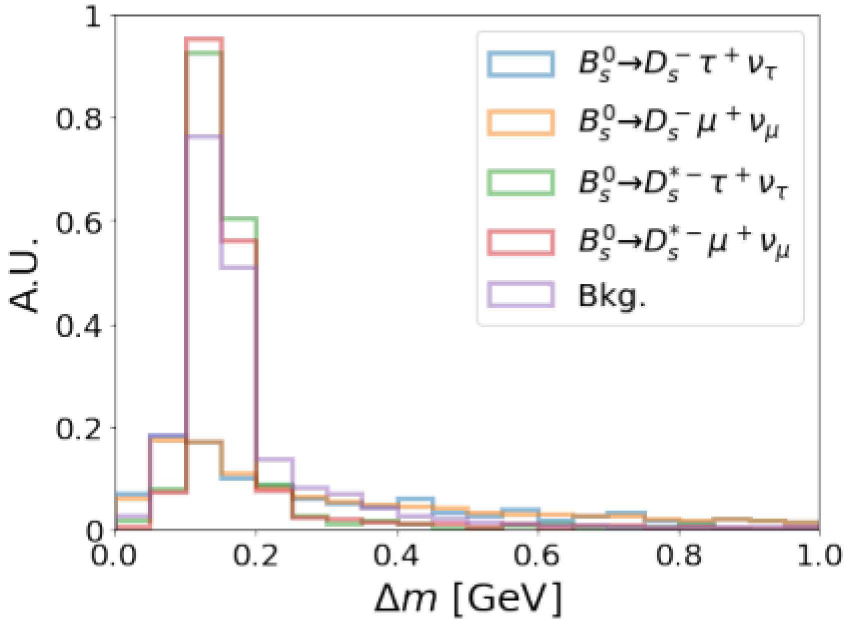
BACKUP

q^2 range	$B_c^+ \to J/\psi\tau^+\nu_\tau$ Rel. precision	$B_c^+ \to J/\psi\tau^+\nu_\tau$ S/B	$B_c^+ \to J/\psi\mu^+\nu_\mu$ Rel. precision	$B_c^+ \to J/\psi\mu^+\nu_\mu$ S/B	$R_{J/\psi}$ 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%

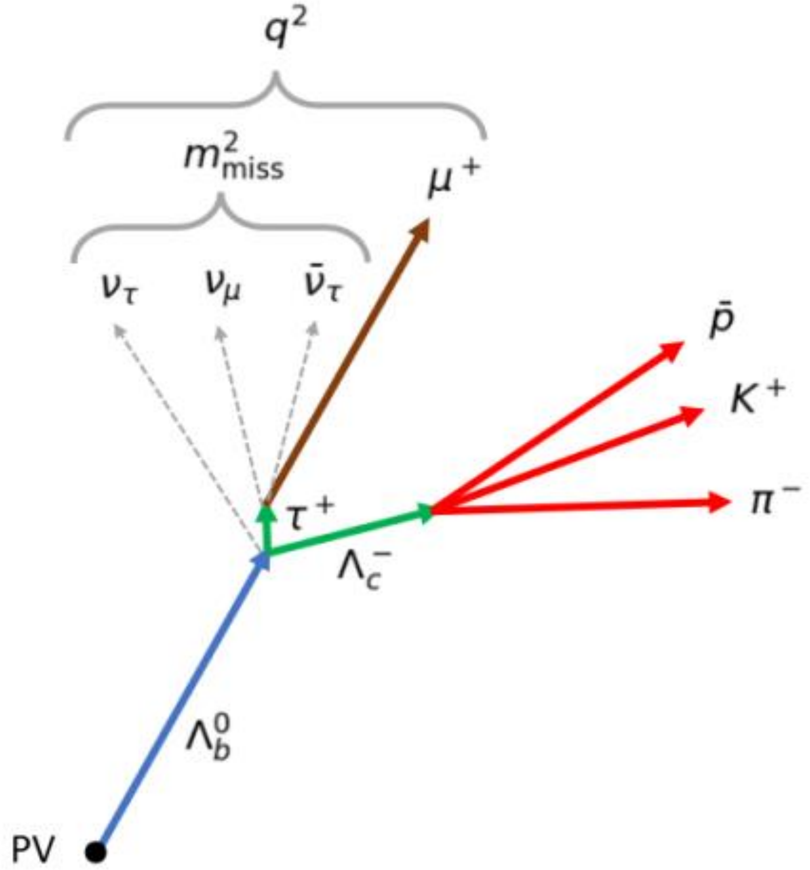
BACKUP


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	$B_s^0 \to D_s^- \tau^+ \nu_\tau$ Rel. precision	$B_s^0 \to D_s^- \tau^+ \nu_\tau$ S/B	$B_s^0 \to D_s^- \mu^+ \nu_\mu$ Rel. precision	$B_s^0 \to D_s^- \mu^+ \nu_\mu$ S/B	R_{D_s} Rel. precision	Correlation 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	$B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$ Rel. precision	$B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$ S/B	$B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ Rel. precision	$B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$ S/B	$R_{D_s^*}$ Rel. precision	Correlation 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	$\Lambda_b^0 \to \Lambda_c^- \tau^+ \nu_\tau$ Rel. precision	$\Lambda_b^0 \to \Lambda_c^- \tau^+ \nu_\tau$ S/B	$\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\mu$ Rel. precision	$\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\mu$ S/B	R_{Λ_c} 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})

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