Testing Lepton Flavour Universality at Future Z Factories

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CEPC Day; 21 Sep 2022
Disclaimer: Preliminary Results

BROWN

What is Lepton Flavour Universality (LFU)? and why?

Standard Model **HYPOTHESIZES**:
"Three generations of leptons are the same: having same couplings to the SM gauge bosons, except having different masses."

Why should this hold? Any secret behind generations?
Need to be tested with **high precision**!!!

- Testing and Understanding SM
- Many SM extensions consist of extra interactions that could lead to LFU violation (e.g. leptoquark, Z', ...)
- Flavour physics is good for indirect BSM searches.
  - Sensitive to SM suppressed decays
  - Some BSM models have stronger couplings to 3-rd generation (e.g. b, τ)

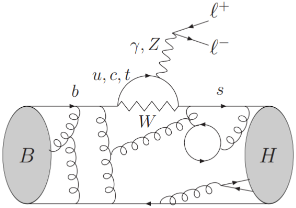
How to test LFU?

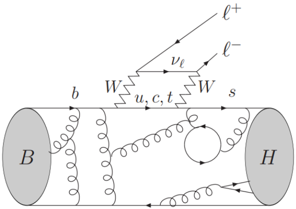
- Electroweak: e.g. $Z \to \ell^- \ell^+$, $W^- \to \ell^- \bar{\nu}_\ell$, ...
  Measuring: $\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}}$, $\frac{\Gamma_{W^-\to\tau^-\bar{\nu}_\tau}}{\Gamma_{W^-\to\mu^-\bar{\nu}_\mu}}$, ...
- Pseudoscalar meson decays: e.g. $K^- \to \ell^- \bar{\nu}_\ell$, $\pi^- \to \ell^- \bar{\nu}_\ell$, ...
  Measuring: $\frac{\Gamma_{K^-\to e^-\bar{\nu}_e}}{\Gamma_{K^-\to\mu^-\bar{\nu}_\mu}}$, $\frac{\Gamma_{\pi^-\to e^-\bar{\nu}_e}}{\Gamma_{\pi^-\to\mu^-\bar{\nu}_\mu}}$, ...
- Leptonic decays: e.g. $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$, ...
  Measuring: $\frac{g_\mu}{g_e}$, $\frac{g_\tau}{g_\mu}$, $\frac{g_\tau}{g_e}$
- Quarkonia decays: e.g. $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, ...
  Measuring: $\frac{\Gamma_{J/\psi\to e^+e^-}}{\Gamma_{J/\psi\to\mu^+\mu^-}}$

NO indications for violation in these sectors

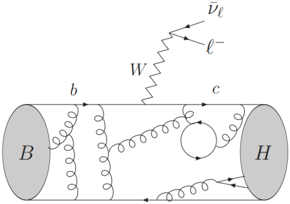
How to test LFU?

- b-hadron decays: [Bifani et al. (2019)]
  - FCNC: e.g. $B^0 \to K^* \ell^+ \ell^-$ [Li and Liu (2021)]





  - FCCC: e.g. $B_c^+ \to J/\psi \ell^+ \nu_\ell$



Experimental deviations from SM predictions (up to $\sim 2-3\sigma$)!!!

Goal: Setting baseline for $b \to c\tau\nu$ studies at Tera-Z

Advantages of Z-pole (focusing more on our study):

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)]

Signals (FCCC: $b \to c\tau\nu$)

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

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

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

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

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

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

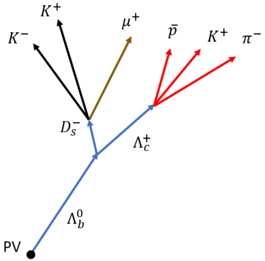
Tera-Z can produce many such H_b, while B-factories can't do!
(or just few)

H_c decays to charged final states: H_c can be fully reconstructed!

Backgrounds

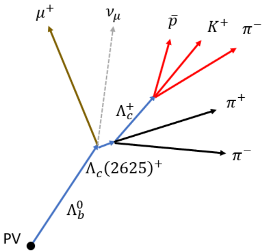
- **Wrong μ production**

  e.g.
  $\Lambda_b \to \Lambda_c D_s (\to (\phi \to KK)\mu)$



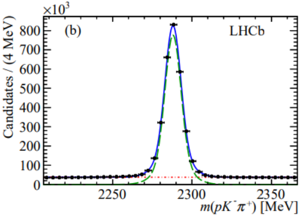
- **Wrong H_c production**

  e.g.
  $\Lambda_b \to \Lambda_c(2625)(\to \Lambda_c \pi\pi)\mu\nu$



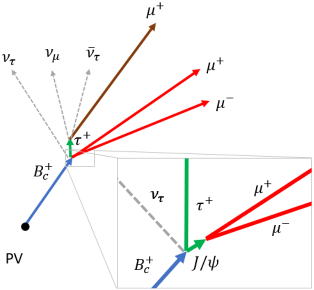
$+$ other types. (See Backups)

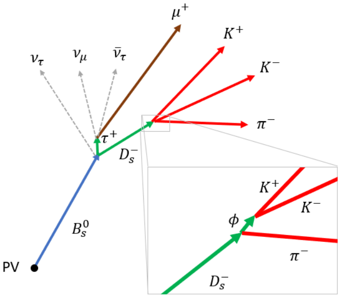
Reconstruction Scheme



1. Reconstruct H_c, and identify muon
2. Deduce b-hadron decay vertex

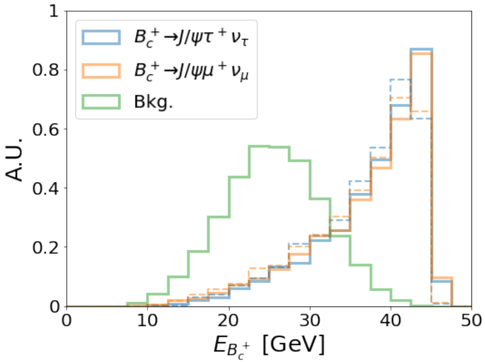
- If H_c is prompt:
  H_b decay vertex $= H_c$ decay vertex
- If H_c is not prompt:
  H_b decay vertex $=$ point at H_c trajectory closest to μ track





Reconstruction Scheme (Cont'd)

3. Deduce *b*-hadron energy (Detail see [Li et al. (2022)]):
   - Imbalance between 2 'objects' decayed from Z

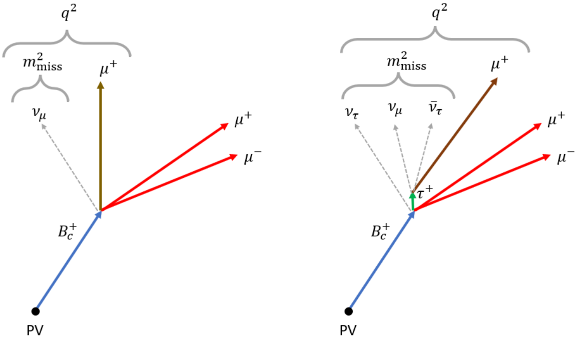


Solid: reconstruction
Dashed: truth

Reconstruction agrees with truth! (error $\sim \mathcal{O}(1\text{GeV})$)

Discriminators for τ, μ Channel Separation

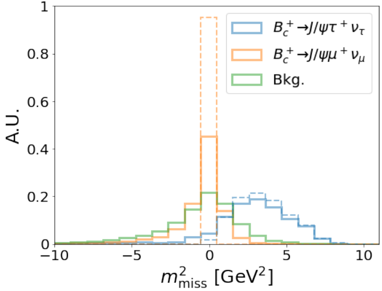
- Momentum transferred to lepton system: $q^2 \equiv (p_{B_c} - p_{J/\psi})^2$
- Missing mass: $m^2_{\text{miss}} \equiv (p_{B_c} - p_{J/\psi} - p_{\mu})^2$
- The closest distance between secondary vertex (SV) and muon track

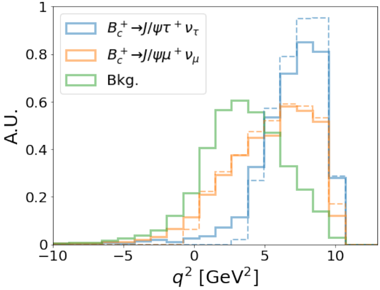


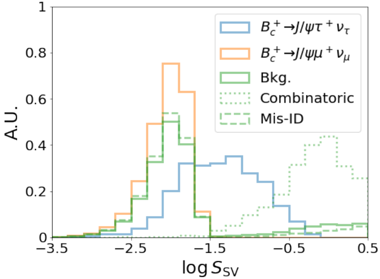
Not only τ/μ, but also Background separation!

Discriminators for τ, μ Channel Separation

Different distribution in μ & τ! Can also cut backgrounds!!!

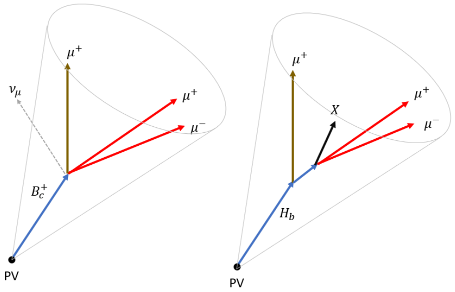


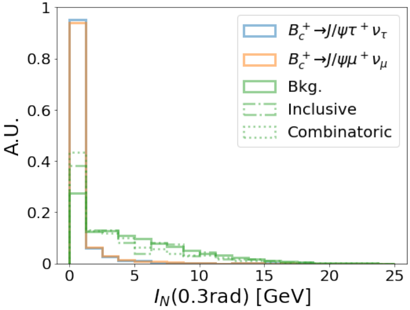




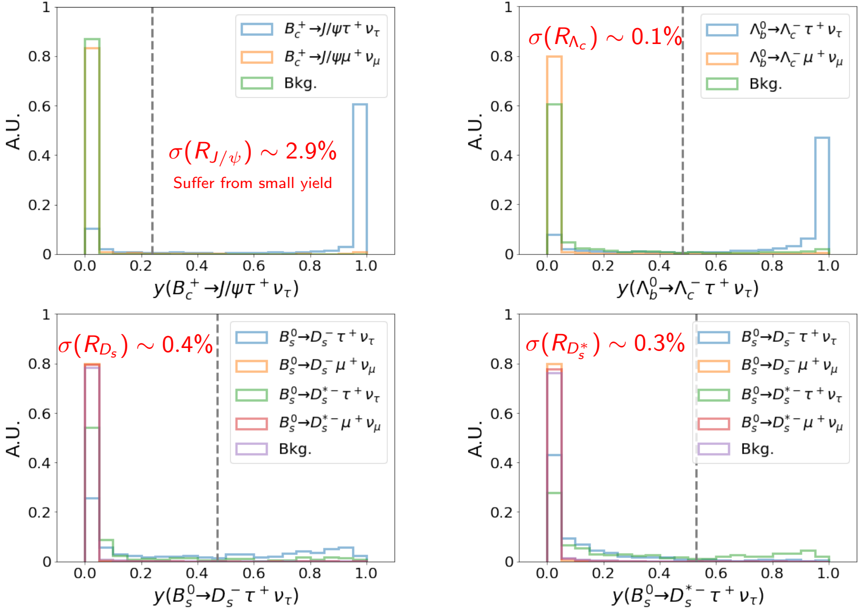
Discriminators for Background Separation

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

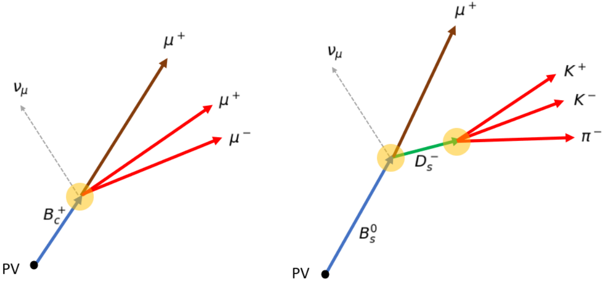




Stat. only BDT results (Preliminary)



Detector Tracking Resolutions

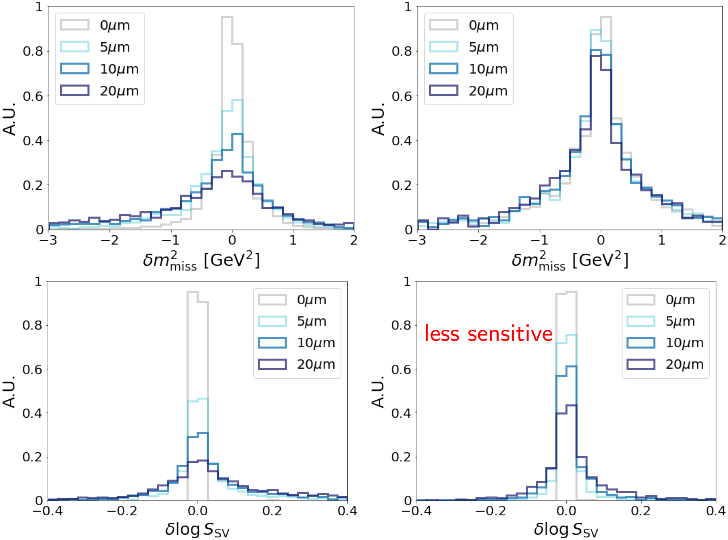


Robustness: Vary vertex noise level $(0, 5, \mathbf{10}, 20\ \mu\text{m})$

Detector Tracking Resolutions

Error: $\delta =$(reco. - truth)

$B_c^+ \to J/\psi\tau^+\nu_\tau$ $B_s^0 \to D_s^{*-}\tau^+\nu_\tau$



σ degradation $\lesssim 16\%$ (all measurements)

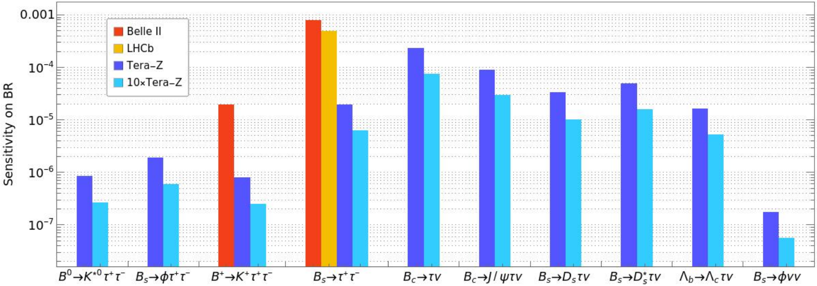
Other Variations on the Study

- Effects of Δm in $R(D_s^{(*)})$
  - $\Delta m \equiv m(KK\pi\gamma) - m(KK\pi)$
  - Main discriminator for D_s, D_s^* signals separation
  - Studied the ECAL effects: threshold and resolution

- Event shape in $R(J/\psi)$
  - Studied FW Moments: $H_{EE;l} = \sum_{i,j} \frac{E_i E_j}{s} P_l(\cos\Omega_{ij})$
  - Global effect of event shape in multi heavy flavours event
  - Extra event shape info. improved S/B by $\sim \mathcal{O}(10\%)$

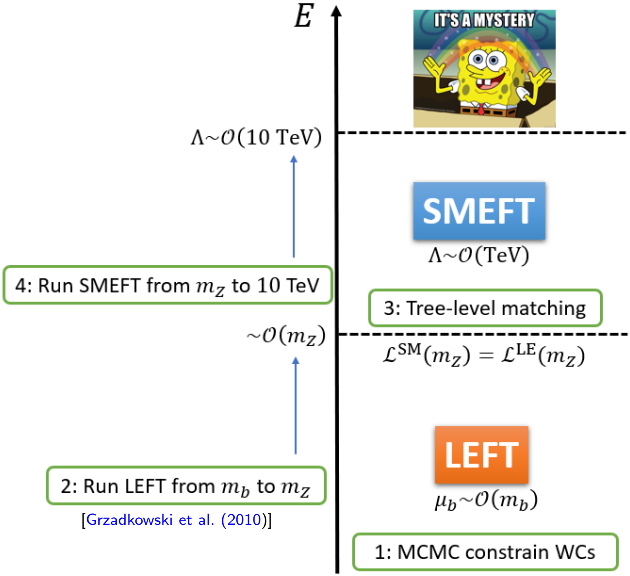
More details: see backup slides

Short Summary on Channel Based B decays BR sensitivity at Tera-Z



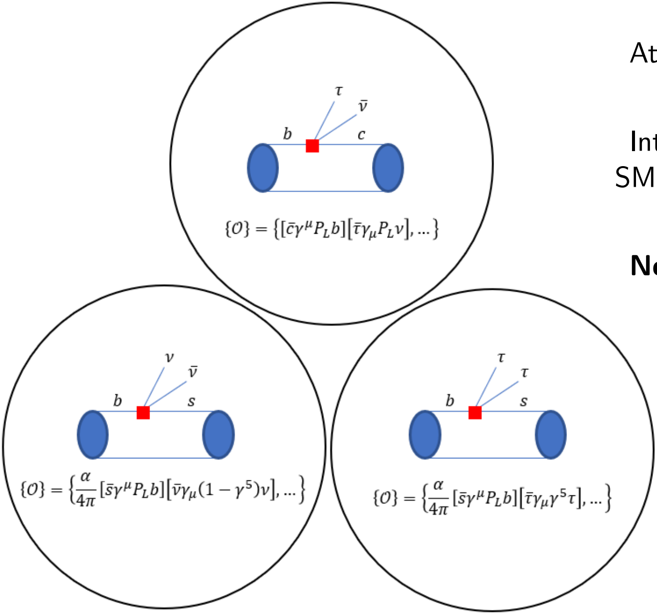
$|\leftarrow$ *This Study* $\rightarrow|$

Theoretical Workflow



[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

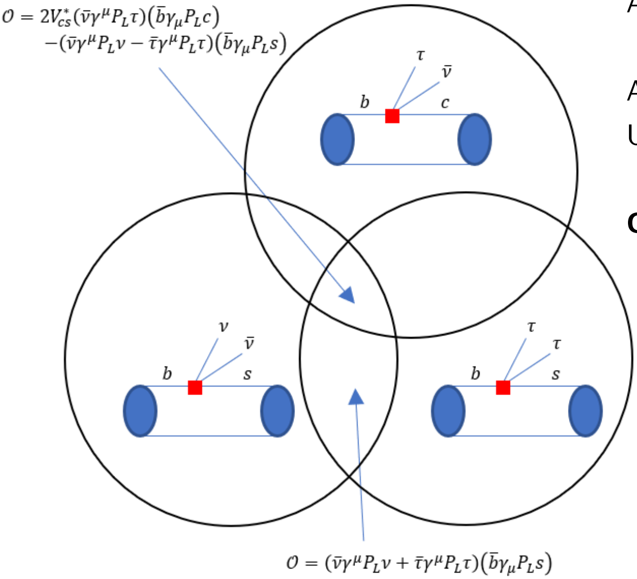


At $\mu \sim m_b$

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

No correlation

SMEFT



At $\Lambda \sim 1$ TeV

All SM fields

Under SM sym

Correlated!!!

LEFT

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

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

- 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: $\mathrm{Br}(B_c \to \tau\nu)$ [Zheng et al. (2020)]

[1] τ means those violate LFU explicitly

LEFT

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

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

- 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 $b \to s\nu\nu$:

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

- 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)]

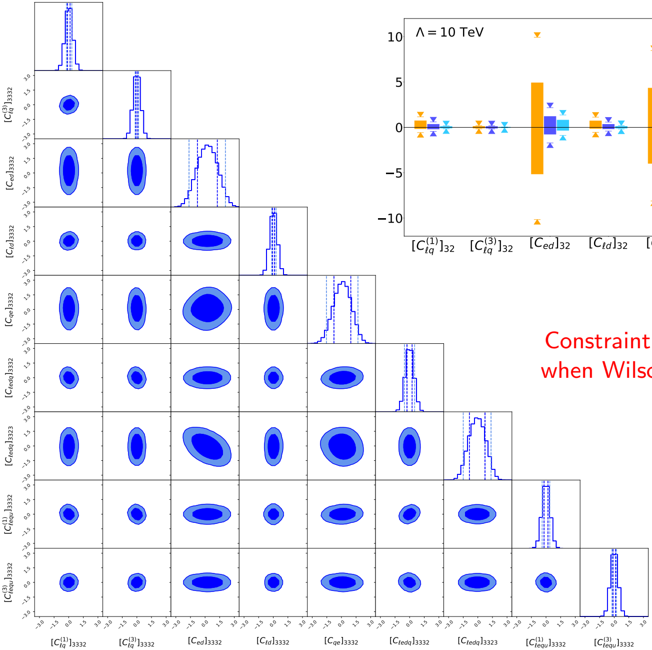
SMEFT

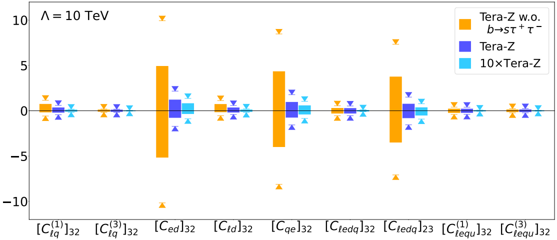
$$\mathcal{L}^{\rm dim6} \supset \frac{1}{\Lambda^2}\sum_{i,j,k,l}\Big([C^{(1)}_{\ell q}]_{ijkl}[O^{(1)}_{\ell q}]_{ijkl} + [C^{(3)}_{\ell q}]_{ijkl}[O^{(3)}_{\ell q}]_{ijkl} + [C_{ed}]_{ijkl}[O_{ed}]_{ijkl}$$
$$+ [C_{\ell d}]_{ijkl}[O_{\ell d}]_{ijkl} + [C_{qe}]_{ijkl}[O_{qe}]_{ijkl} + [C_{\ell edq}]_{ijkl}[O_{\ell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

- After matching: 9 LFUV operators in dim6 SMEFT

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

Wilson Coefficients Constraints (Preliminary)





Constraint of NP up to $\mathcal{O}(10 \text{ TeV})$ when Wilson Coeff. are about $\mathcal{O}(1)$

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 Tera-Z
- High precision in $R_{J/\psi}$, $R_{D_s^{(*)}}$, R_{Λ_c}: $\mathcal{O}(0.1\%) - \mathcal{O}(1\%)$
  - Abundant and energetic b-hadrons
  - Clean environment
  - Known initial energy
- EFT can prob NP up to 10TeV
  - Constraint of NP up to $\mathcal{O}$(10 TeV) when Wilson Coeff. are about $\mathcal{O}(1)$

Thank you!

Backup: General Background types

Inclusive Bkg.:

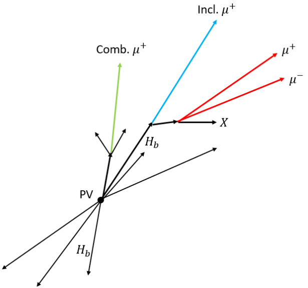
- Feed-down processes, e.g. $B_c \to \chi_c(\to J/\psi X)\ell\nu$
- Different kinematics to signals

Combinatoric Bkg.:

- Wrongly reconstructing unrelated $H_c + \mu$ ($H_c = J/\psi,\ D_s,\ \Lambda_c$)
- Larger isolation variables than signals

Fake narrow resonance Bkg.:

- Wrongly reconstructing the remnants $H_c = J/\psi,\ D_s,\ \Lambda_c$



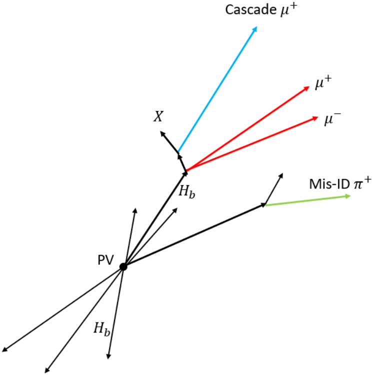
- Inclusive: $J/\psi(\mu\mu) + \mu$
- Comb.: $J/\psi\ (\mu\mu) + \mu$
- Fake resonance: Wrong, e.g. $J/\psi\ (\mu^-\mu^+)$

Cascade Bkg.:

- ℓ is NOT from semileptonic decay, e.g. $B^0 = D^0(\to \ell)J/\psi X$
- Larger isolation variables than signals

Muon mis-ID Bkg.:

- Misidentifying $\pi^{\pm}$ as μ, with $\mathcal{O}(1\%)$ [Lippmann (2012); Yu et al. (2021)]



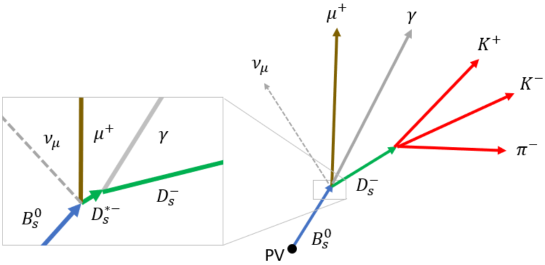
- Cascade: $J/\psi(\mu\mu) + \mu$
- Mis-ID: $J/\psi\ (\mu\mu) + \pi$

Backup: Vertex noise level effects

Measurement	0 μm	5 μm	10 μm	20 μm
$R_{J/\psi}$	2.17×10^{-2}	2.69×10^{-2}	2.89×10^{-2}	3.18×10^{-2}
R_{D_s}	3.16×10^{-3}	3.61×10^{-3}	4.10×10^{-3}	4.76×10^{-3}
$R_{D_s^*}$	2.47×10^{-3}	2.77×10^{-3}	3.27×10^{-3}	3.31×10^{-3}
$\rho(R_{D_s}, R_{D_s^*})$	-0.48	-0.45	-0.49	-0.50
R_{Λ_c}	8.32×10^{-4}	9.27×10^{-4}	9.74×10^{-4}	1.07×10^{-3}

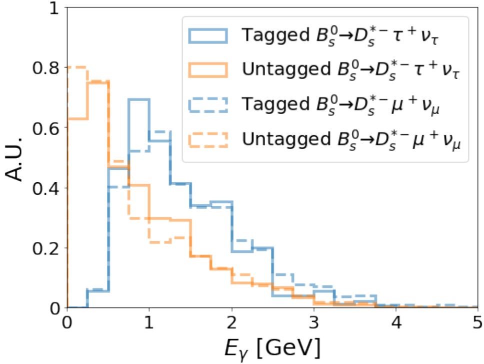
Table: Comparison on measurement uncertainties under different vertex noise levels.

Effects of Δm in $R(D_s^{(*)})$



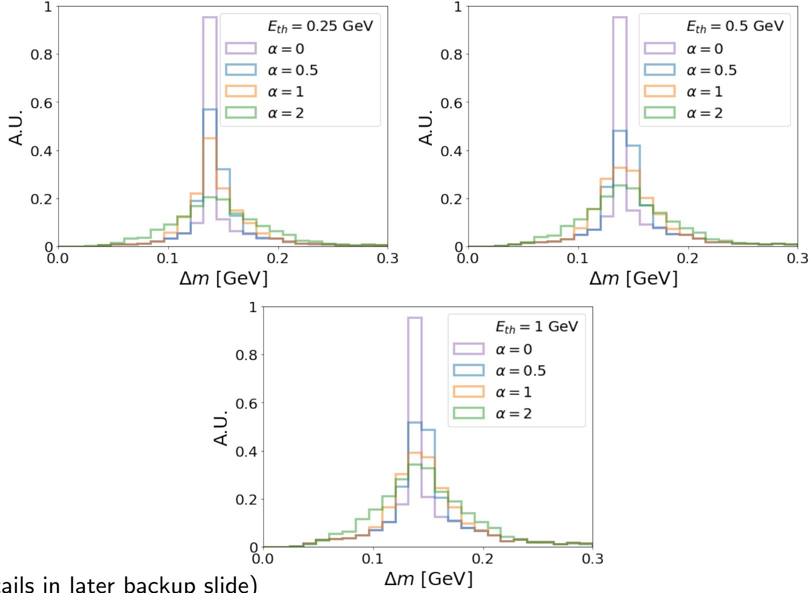
- $\Delta m \equiv m(KK\pi\gamma) - m(KK\pi)$
  - Use the γ in signal-hemisphere and gives Δm closest to Δm^{phys}
- Two main sources of error affecting Δm resolution:
  - ECAL energy threshold (E_{th})
  - ECAL resolution
    (modeled by scaling parameter α: width of Δm distribution)
    ($\alpha = 0$: Perfect; $0 < \alpha < 1$: Optimistic;
    $\alpha = 1$: Default; $\alpha > 1$: Conservative.)

Effects of Δm in $R(D_s^{(*)})$



- Most of the untagged photons are soft (below energy threshold $E_{\text{th}} = 0.5$ GeV)

Backup: Effects of Δm in $R(D_s^{(*)})$

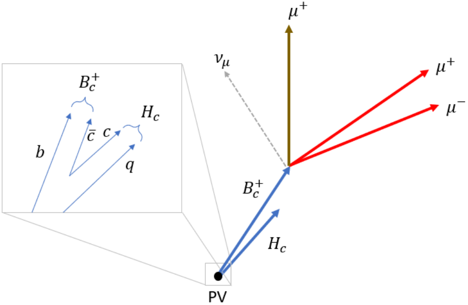


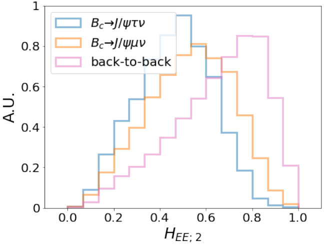
(Details in later backup slide)

Backup: Event shape in $R_{J/\psi}$

Define the FW Moment [Fox and Wolfram (1978)]:

$$H_{EE;l} = \sum_{i,j} \frac{E_i E_j}{s} P_l(\cos \Omega_{ij})$$

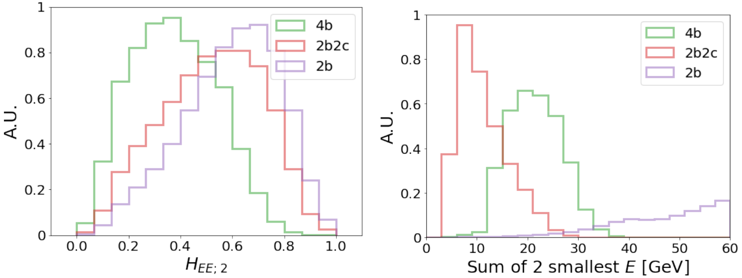




Backup: Event shape in $R_{J/\psi}$

Different types of Comb. backgrounds:

- $4b$: Events of $4b$ quarks created by QCD
- $2b2c$: Events of $b\bar{b}$ and $c\bar{c}$ pairs created by QCD
- $2b$: Events of $2b$ quarks created by QCD



Adding FWM to BDT improves S/B by $\sim \mathcal{O}(10\%)$ while keeping uncertainty about unchanged.

Backup: Δm effects

$\alpha \setminus E_{\mathrm{th}}$	0.25 GeV	0.5 GeV	1 GeV
0	53.38% 54.23%	39.80% 40.77%	25.82% 27.83%
0.5	51.49% 52.63%	38.85% 39.95%	25.12% 27.27%
1	50.71% 51.73%	38.07% 39.20%	24.80% 26.89%
2	48.90% 50.02%	36.34% 37.64%	23.86% 25.81%

Table: Tagging efficiency of the D_s^{*-} photons, for the detector profiles characterized by E_{th} and α. The two numbers in each entry are defined for $B_s^0 \to D_s^{*-} \tau^+ \nu_\tau$ and $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$, respectively.

$\alpha \setminus E_{\mathrm{th}}$	0.25 GeV		0.5 GeV		1 GeV	
0	3.48×10^{-3} 2.78×10^{-3}	(-0.31)	4.02×10^{-3} 3.24×10^{-3}	(-0.46)	4.53×10^{-3} 3.40×10^{-3}	(-0.50)
0.5	3.55×10^{-3} 2.74×10^{-3}	(-0.31)	3.90×10^{-3} 2.90×10^{-3}	(-0.45)	4.56×10^{-3} 3.27×10^{-3}	(-0.51)
1	3.52×10^{-3} 2.65×10^{-3}	(-0.32)	4.10×10^{-3} 3.27×10^{-3}	(-0.49)	4.54×10^{-3} 3.38×10^{-3}	(-0.50)
2	3.40×10^{-3} 2.83×10^{-3}	(-0.33)	4.52×10^{-3} 3.40×10^{-3}	(-0.50)	4.16×10^{-3} 3.40×10^{-3}	(-0.52)

Table: Expected BDT (relative) precisions of measuring R_{D_s} and $R_{D_s^*}$, for the detector profiles characterized by E_{th} and α. The number in the bracket denotes the correlation between the D_s and D_s^* measurements.

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