Testing Lepton Flavor Universality at the Z Pole

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Based on arXiv:2012.00665 with Tao Liu and ongoing projects

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LFUV B Anomalies in FCCC/FCNC

	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 et al., 2018][Altmannshofer et al., 2018]

[Aaij et al., 2021][Aaij et al., 2020].

Also evidence for a BR($B_s \to \phi\mu\mu$), $m^2_{\mu\mu} \in [1, 6]$ GeV^2 below SM by $\sim 3\sigma$ [Aaij et al., 2015]

The physics should be well covered in previous talks...

Unique Opportunities at the Z pole

Z-factories ($10^9 - 10^{13}$ Zs) are also flavor factories:

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^{8}	$\sim 2 \times 10^{13}$	3.2×10^{7}	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^{5}	2.2×10^{8}	2.2×10^{9}
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^{7}	1.0×10^{10}	1.0×10^{11}

VS. B Factories

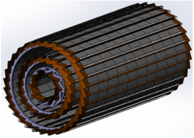
- Much higher b quark boost (by $\mathcal{O}(10)$)
- Better track momentum measurements
- Larger displacements with smaller uncertainty
- Abundant heavy b hadron

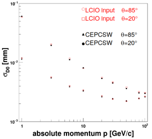
VS. Hadron Colliders

- Fixed E_{cm}
- Clean environment
- Direct missing momenta measurement
- Larger detector acceptance
- Better flavor tagging efficiency

Key Detector Features for Flavor Physics

Materials from talks in the April CEPC meeting



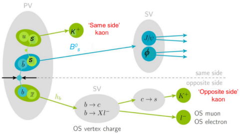


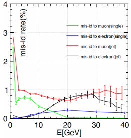
Tracking sys, grants $\mathcal{O}(10)$ fs sensitivity.

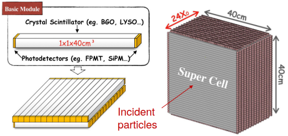
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater acceptance for displaced signals.

Advanced PID coming from the combination of $dE(N)/dx$ method, time resolution and calorimetry:

- Flavor tagging for everything.
- Suppressing backgrounds in general.
- Clean leptonic/baryonic modes.
- ...







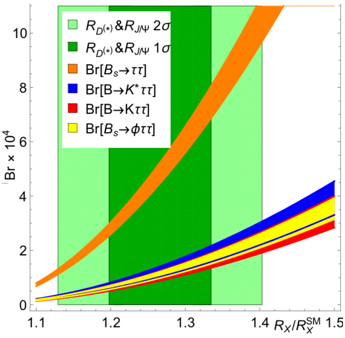
Calorimetry gives neutral energy and angular resolution.

- Better $\not{p}$ measurement for neutrinos.
- Excited states such as D_s^* and radiative decays.
- Distinguishing π^0/η..., allowing h^0X modes.
- ...

LFU Test with $b \to s\tau\tau$ Measurements

Current $b \to c\tau\nu$ anomalies indicate large enhancement of $b \to s\tau\tau$ rates. [Capdevila et al., 2018]

Current experiment constraint on BR $\sim 10^{-2.5}$



$$\delta C_9^\tau = -\delta C_{10}^\tau$$

$$= \frac{-2\pi V_{cb}}{\alpha V_{tb} V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{\rm SM}}} - 1\right)$$

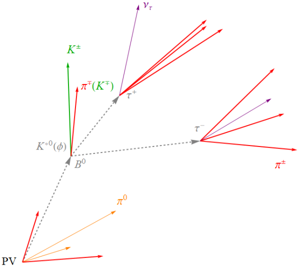
$$\sim \mathcal{O}(10) \times C_{9/10}^{\rm SM}$$

$$O_{9(10)}^\tau = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_L b][\bar{\tau}\gamma_\mu(\gamma^5)\tau]\,,$$

$$O_{9(10)}^{\prime\tau} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_R b][\bar{\tau}\gamma_\mu(\gamma^5)\tau]\,.$$

From SM ($\mathcal{O}(10^{-7})$) to $\mathcal{O}(10^{-4})$

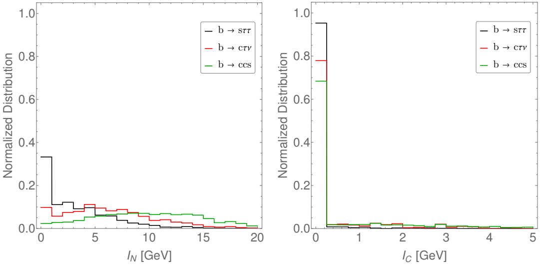
LFU Test with $b \to s\tau\tau$ Measurements



Use $\tau \to \pi^\pm\pi^\pm\pi^\mp\nu$ decay to locate each vertex

Full reconstruction possible (hard for B-factories)

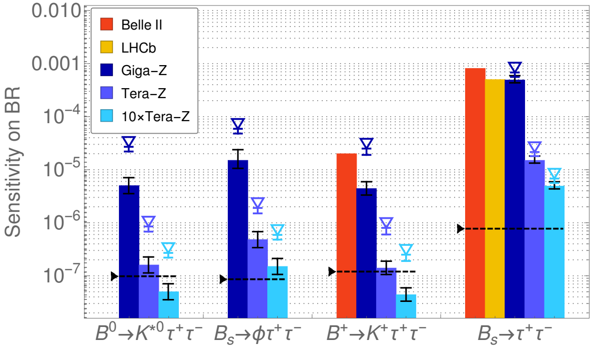
Dominant background from inclusive $D^\pm_{(s)} \to \pi^\pm\pi^\pm\pi^\mp + X$ decays ($\mathcal{O}(10^5)$ larger as $b \to c\bar{c}s$ is common)



Clean environment ⇒ good bkg rejection (hard for hadron colliders)

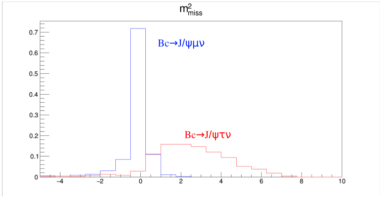
Projected Limits

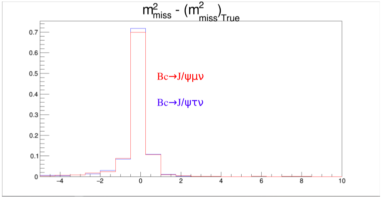
More details in the published work (arXiv:2012.00665) [Li and Liu, 2020]



Constraints on EFT couplings from $\mathcal{O}(10^3)$ (current) $\to$ $\mathcal{O}(10)$

LFU Test with FCCC (Prelim.)

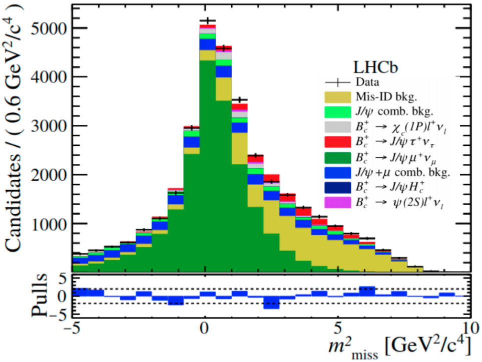




E.g. $R_{J/\psi}$ measurement with

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

Improved reconstruction quality, also expecting lower combinatoric bkg and mis-ID.



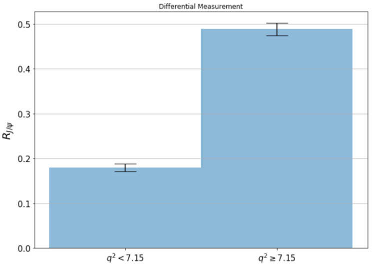
$R_{J/\psi}$ Measurement at Tera-Z (II) (Prelim.)

Cut flow and expected yields targeting $B_c^+ \to J/\psi\,\tau\,\nu_\tau$ mode at Tera-Z:

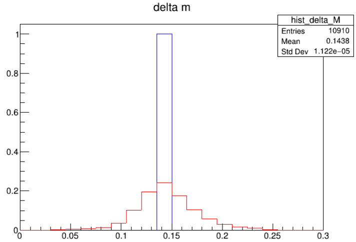
Preliminary!	# of B_c^+ at Tera-Z	$\epsilon_{3\mu}$	ϵ_{pre}	ϵ_{BDT}	Tera-Z yield
$B_c^+ \to J/\psi\,\tau\,\nu_\tau$	$\sim 2.2 \times 10^8$	5.5×10^{-5}	0.34	6.6×10^{-1}	$\sim 2.7 \times 10^3$
$B_c^+ \to J/\psi\,\mu\,\nu_\mu$	$\sim 2.2 \times 10^8$	1.3×10^{-3}	0.35	2.7×10^{-3}	$\sim 2.7 \times 10^2$
$B_c^+ \to \chi_c(1P)\,l^+\,\nu_l$	$\sim 2.2 \times 10^8$	–	–	2.1×10^{-2}	$\sim 8.1 \times 10^1$
$J/\psi + \mu$ comb. bkg.	–	–	0.069	1.6×10^{-2}	$\sim 1.4 \times 10^3$
Mis-ID bkg.	–	–	–	6.3×10^{-3}	$\sim \epsilon_{\mu\pi} \times 6.0 \times 10^3$
Fake-J/ψ bkg.	–	–	–	–	$< r_h \times 9.6 \times 10^0$

The expected precision is $\mathcal{O}(30)$ better, limited by the signal size.

Better result with luminosity$^+$ and using e instead of μ!



Further LFU Tests with FCCC (Prelim).



R_{D_s} and $R_{D_s^*}$:

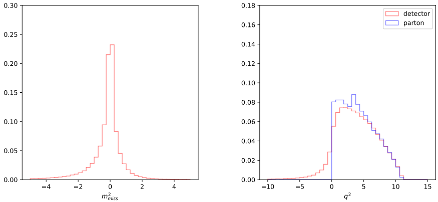
$$R_{D_s^{(*)}} \equiv \frac{\text{BR}(B_s \to D_s^{(*)-}\tau\nu)}{\text{BR}(B_s \to D_s^{(*)-}\ell\nu)}\,. \qquad (1)$$

The key is to separate D_s and D_s^*.
Challenging as BR($D_s^{*-} \to D_s^- +$ soft γ)$\simeq 94\%$.

R_{Λ_c}:

$$R_{\Lambda_c} \equiv \frac{\text{BR}(\Lambda_b \to \Lambda_c\tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c\ell\nu)}\,. \qquad (2)$$

using the $\Lambda_c \to pK\pi$ decay, clean vertex w/ low bkg.



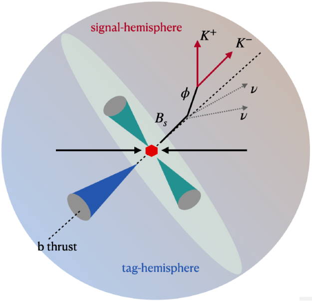
Uncertainty $\lesssim \mathcal{O}(10^{-2})$ for all channels with S/B $\gtrsim \mathcal{O}(1)$.

Rare FCNC Decays: $B_s \to \phi\nu\nu$ (Prelim.)

$b \to s\nu\nu$ transitions also important for LFU tests. Related with $b \to c\tau(\ell)\nu$ and $b \to s\tau\tau(\ell\ell)$ via gauge invariance.

	Experimental	SM Prediction
BR($B^0 \to K^0\nu\bar{\nu}$)	$< 2.6 \times 10^{-5}$	$(2.17 \pm 0.30) \times 10^{-6}$
BR($B^0 \to K^{*0}\nu\bar{\nu}$)	$< 1.8 \times 10^{-5}$	$(9.48 \pm 1.10) \times 10^{-6}$
BR($B^\pm \to K^\pm\nu\bar{\nu}$)	$< 1.6 \times 10^{-5}$	$(4.68 \pm 0.64) \times 10^{-6}$
BR($B^\pm \to K^{*\pm}\nu\bar{\nu}$)	$< 4.0 \times 10^{-5}$	$(10.22 \pm 1.19) \times 10^{-6}$
BR($B_s \to \phi\nu\bar{\nu}$)	$< 5.4 \times 10^{-3}$	$(9.93 \pm 0.72) \times 10^{-6}$

[Tanabashi et al., 2018, Straub, 2015, Geng and Liu, 2003]



Current limit of this channel still led by LEP: (limited production at B factories, $\vec{\not{p}}$ not achievable at hadron colliders).

Full detector simulation predicts an $\mathcal{O}(10^{-2})$ precision.

Summary

- Flavor physics is related to BSM, SM precision tests, pQCD, lattice, ... everything! Tera-Z is the bridge.
- Flavor studies at the Z pole benefit from:
  1. Large luminosity (from accelerator physics)
  2. Clean environment and moderate energy (from m_Z)
  3. Good or even revolutionary detectors (from detector R&D)
- The potential discovery of $b \to s\tau\tau$ is unique at Z-factories.
- Other related FCCC/FCNC tests are promising.
- New collider/detector at the precision era: new challenges!
  1. LFUV, LFV, LNV, BNV...
  2. CKM and CPV measurements...
  3. Precision (τ) physics...
  4. Exotics, spectroscopy, double heavy flavor...

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Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$.
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Capdevila, B., Crivellin, A., Descotes-Genon, S., Hofer, L., and Matias, J. (2018).
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