Lepton Flavor Universality at Z pole

Lingfeng Li (Hong Kong University of Science and Technology)

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Prologue

"Don't leave flavor physics to flavor physicists."

[Someone Awesome (2019?)]

Flavor Physics and BSM

Searching for BSM signals(light/long lived)

$\Rightarrow$ Large SM flavored background

Measuring some SM flavor couplings

$\Rightarrow$ Accidentally find a strong BSM evidence

Lepton Flavor Universality (Violation)

Lepton flavor universality (LFU) demands that charged leptons have (almost) identical interactions, only differ by their Yukawa couplings and hence their masses.

However, in both flavor changing neutral current (FCNC) and flavor changing neutral current (FCCC) processes

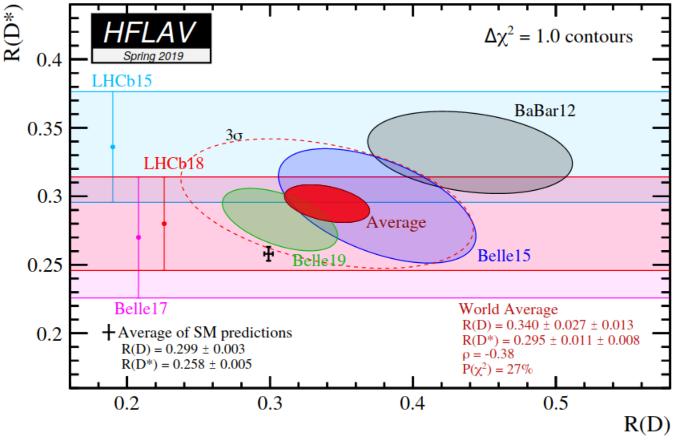
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} , \tag{1}$$

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} , \tag{2}$$

$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c \to J/\psi\tau\nu)}{\mathrm{BR}(B_c \to J/\psi\ell\nu)} , \tag{3}$$

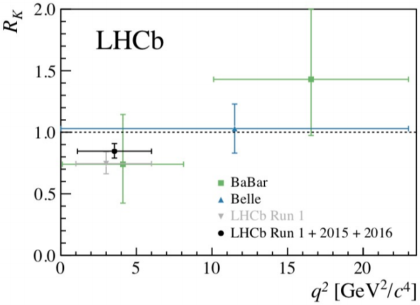
LFU is challenged.

FCCC B Anomalies

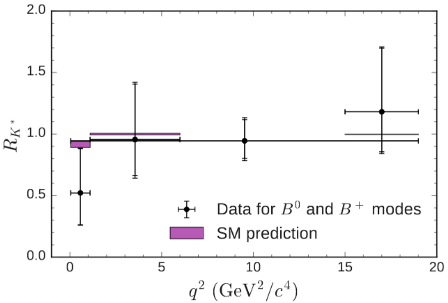


[Amhis et al.(2019)]

FCNC Anomalies



R_K [Aaij et al.(2019)].



R_{K^*} [Abdesselam et al.(2019)].

Deviations in low-q^2 bins: robust against $c\bar{c}$ resonant/loop contributions (SM prediction ~ 1).

FCCC and FCNC B Anomalies

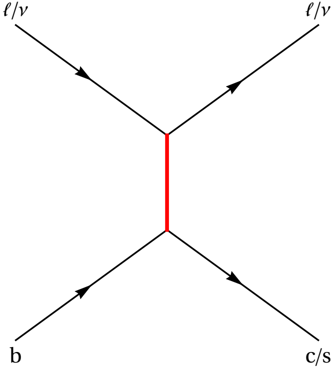
	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^{\pm}$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^{\pm}$ combined.
R_{D^*}	0.295 ± 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)].

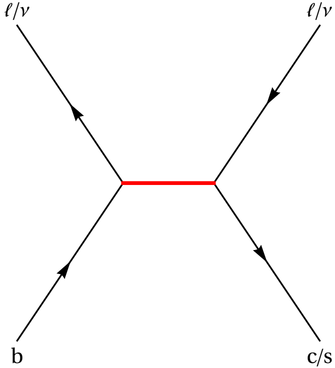
Also evidence for a BR($B_s \to \phi\mu\mu$), $m^2_{\mu\mu} \in [1, 6]$ GeV^2 below SM by $\sim 3\sigma$ [Aaij et al.(2015)]

LFUV in BSM: Simplified Models at Tree Level

Induced by two types of heavy mediators:



Colorless Mediators



Colored Mediators (Leptoquarks)

LFUV in BSM: Simplified Models at Tree Level (II)

Model	Spin	SM charge	$b \to c\tau\nu$ operators
Scalars	0	$(1,2)_0$	O_S^τ, O_P^τ
W'/Z'	1	$(1,3)_0$	$O_V^\tau - O_A^\tau$
LQ S_1	0	$(\bar{3},1)_{\frac{1}{3}}$	$O_V^\tau - O_A^\tau$, $O_S^\tau - O_P^\tau - 4O_T^\tau$
LQ S_3	0	$(\bar{3},3)_{\frac{1}{3}}$	$O_V^\tau - O_A^\tau$
LQ R_2	0	$(3,2)_{\frac{7}{6}}$	$O_S^\tau - O_P^\tau + 4O_T^\tau$
LQ U_1	1	$(3,1)_{\frac{2}{3}}$	$O_V^\tau - O_A^\tau$, $O_S^\tau + O_P^\tau$
LQ U_3	1	$(3,3)_{\frac{2}{3}}$	$O_V^\tau - O_A^\tau$
LQ V_3	1	$(3,2)_{\frac{5}{6}}$	$O_S^\tau + O_P^\tau$

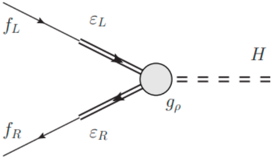
Simplified models favored by data

Other constraints from $\bar{K} - K$ mixing, $b \to s\nu\nu$ ...

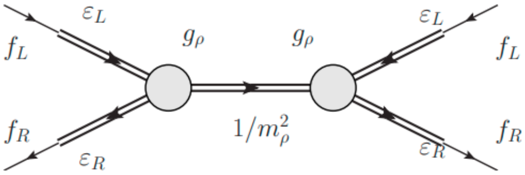
Motivated BSM Scenarios: Composite

Higgs is the pNGB of a larger global symmetry, fermion masses from partial compositeness.

[Barbieri et al.(2017)Barbieri, Murphy, and Senia, Barbieri(2019)]...



- Hierarchy of anomalies (Gen. $3 \gg 2 \gg 1$)
- Provide W'/Z' ("ρ")
- Also LQ in Pari-Salam extension



Plots from Marco Nardecchia's talk

Motivated BSM Scenarios: Dark Sector

Dark-sector-like models (light and small coupling): Well explained in the previous talk!

[Altmannshofer et al.(2016)Altmannshofer, Gori, Profumo, and Queiroz, Bonilla et al.(2018)Bonilla, Modak, Srivastava, and Valle, Bauer et al.(2018)Bauer, Foldenauer, and Jaeckel, Liu et al.(2018)Liu, Liu, Wagner, and Wang]...

Motivated by various arguments:

- Dark matter candidate
- $(g-2)_\mu$ anomaly (e.g. $U(1)_{\mu-\tau}$ model)
- Relation with the neutrino sector

Unlikely to resolve FCCC B anomalies without extra charged mediators.

Unique Opportunities at Z pole

Giga-Z, Tera-Z and 10$\times$Tera-Z: a phase of future linear/circular lepton colliders. [Fujii et al.(2019), Dong et al.(2018), Abada et al.(2019)]

Z factories are also $b(c/\tau)$ factories:

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10$\times$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}

Comparison between B Factories and Hadron Colliders

Combines the characteristics of both B factories ($\Upsilon(4S, 5S)$ pole) and hadron colliders.

VS. B Factories

- Much higher b quark boost
- Better track momentum measurements
- Larger displacements with smaller uncertainty
- Abundant heavy b hadron production

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VS. Hadron Colliders

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

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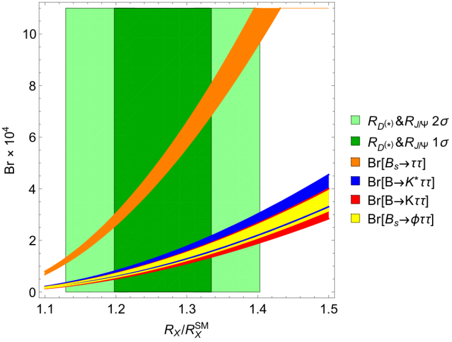
Example 1: $b \to s\tau\tau$ measurements

Current $b \to c\tau\nu$ anomalies indicate large enhancement of $b \to s\tau\tau$ rates. [Capdevila et al.(2018)Capdevila, Crivellin, Descotes-Genon, Hofer, and Matias]



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

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

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

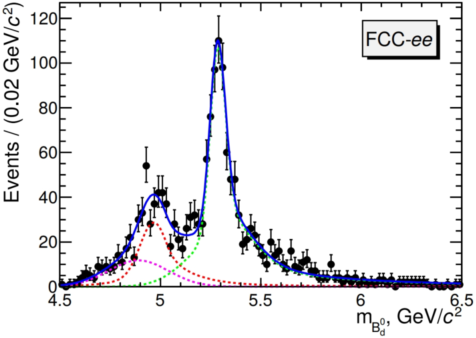
From SM ($\mathcal{O}(10^{-7})$) to $\mathcal{O}(10^{-4})$

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

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

Example 1: $b \to s\tau\tau$ measurements

At Tera-Z, $\mathcal{O}(50)$ $B^0 \to K^{*0}\tau^+\tau^-$ events can be reconstructed, $\mathcal{O}(500)$ at FCC-ee.

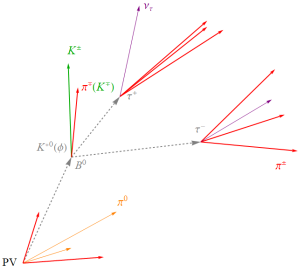


[Kamenik et al.(2017)Kamenik, Monteil, Semkiv, and Silva]

Measure $\mathcal{O}(10^{-7})$ BR with $\mathcal{O}(10\%)$ precision?

A Hint

Example 1: $b \to s\tau\tau$ measurements



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

Fake 3π vertex from $D^\pm_{(s)} \to \pi^\pm\pi^\pm\pi^\mp + X$ decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.3%
	$c\tau = 87.0$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.6%
$D_s^\pm$	$m = 1.968$ GeV	$\tau^\pm\nu$	5.5%
	$c\tau = 151$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	0.6%
		$\pi^\pm\pi^\pm\pi^\mp 2\pi^0$	4.6%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	0.3%
		$\pi^\pm\pi^\pm\pi^\mp\phi$	1.2%
$D^\pm$	$m = 1.870$ GeV	$\tau^\pm\nu$	$< 0.12\%$
	$c\tau = 311$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	1.1%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	3.0%

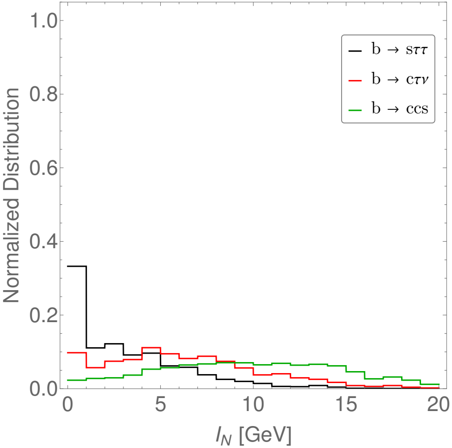
Overwhelmingly Large SM Backgrounds

Background overwhelming ($\mathcal{O}(10^5)$ larger before cuts) rather than background free!

Example	Typical BR
$b \to c\bar{c}s$ Type	
e.g. $B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$	$\mathcal{O}(10^{-2} - 10^{-3})$
$b \to c\tau\nu$ Type	
e.g. $B^0 \to K^{*0} D_s^{(*)-} \tau^+ \nu$	$\mathcal{O}(10^{-3} - 10^{-5})$
$b \to c\bar{u}d$ Type	
e.g. $B^0 \to D^{(*)-} \pi^+ \pi^+ \pi^-$	$\mathcal{O}(10^{-2} - 10^{-3})$

No relevant background studies before!

Efforts to Remove Backgrounds



Energy of neutral components and very displaced tracks (from K_S^0) within a certain cone.

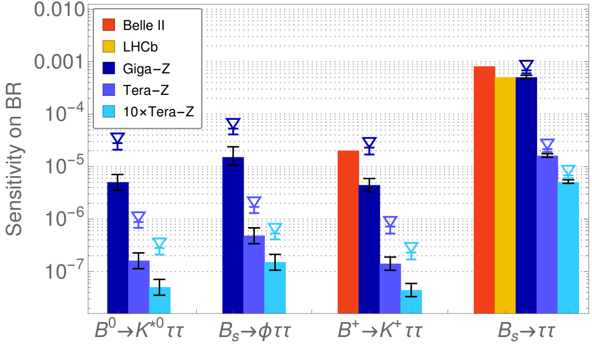
e.g. from $D_s \to \pi^\pm\pi^\pm\pi^\mp + n\pi^0$

$IV(\tau) \lesssim IV(D^\pm) \lesssim IV(D_s)$

Other discriminators include $\pi^\pm\pi^\pm\pi^\mp$ invariant mass structures and decay lifetimes.

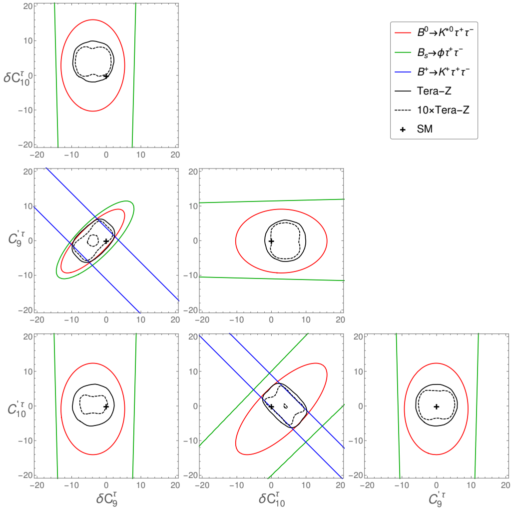
Result of $b \to s\tau\tau$ at Z Pole (Preliminary)

Work w/ Tao Liu, in preparation:



$\mathcal{O}(10^{-5} - 10^{-7})$ precision at Tera-Z, still affected by limited detector spacial resolution (5-10 μm)

Constraints on EFT (Preliminary)



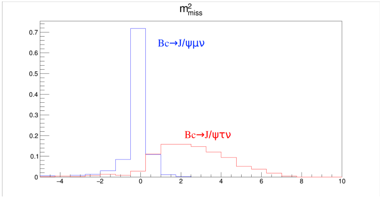
Example 2: $R_{J/\psi}$ measurement at Z Pole (Preliminary)

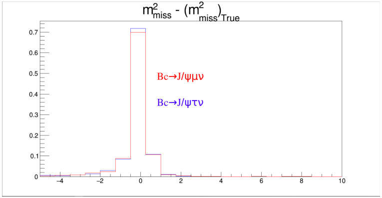
Current status of B_c measurements mostly come from LHCb:

$J/\psi(1S)\,\ell^+\,\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1}) \times 10^{-5}$
$J/\psi(1S)\,\pi^+$	seen
$J/\psi(1S)\,K^+$	seen
$J/\psi(1S)\,\pi^+\,\pi^+\,\pi^-$	seen
$J/\psi(1S)\,a_1(1260)$	$< 1.2 \times 10^{-3}$
$J/\psi(1S)\,K^+\,K^-\,\pi^+$	seen
$\psi(2S)\,\pi^+$	seen
$J/\psi(1S)\,D_s^+$	seen
$J/\psi(1S)\,D_s^{*+}$	seen
$D^*(2010)^+\,\overline{D}^0$	$< 6.2 \times 10^{-3}$
$D^+\,K^{*0}$	$< 0.20 \times 10^{-6}$
$D^+\,\overline{K}^{*0}$	$< 0.16 \times 10^{-6}$
$D_s^+\,K^{*0}$	$< 0.28 \times 10^{-6}$
$D_s^+\,\overline{K}^{*0}$	$< 0.4 \times 10^{-6}$
$D_s^+\,\phi$	$< 0.32 \times 10^{-6}$
$K^+\,K^0$	$< 4.6 \times 10^{-7}$
$B_s^0\,\pi^+$ / B($\overline{b} \to B_s$)	$(2.37\,^{+0.37}_{-0.35}) \times 10^{-3}$

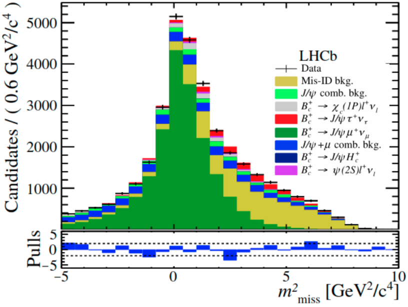
Z pole will be an important complementary to hadron colliders

Example 2: $R_{J/\psi}$ measurement at Z Pole (Preliminary)





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



Work w/ Tin Seng Manfred Ho, Tsz Hong Kwok and Tao Liu, early stage.

Example 3: $B_s \to \phi\nu\nu$ (Preliminary)

Work w/ Yanyun Duan, Shu Li, Manqi Ruan, Yudong Wang ......

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

$$\mathcal{L}^{\rm dim6} \supset \frac{1}{\Lambda^2} \sum_{i,j,k,l} \Big([C_{q\ell}^{(1)}]_{ijkl}[O_{q\ell}^{(1)}]_{ijkl} + [C_{q\ell}^{(3)}]_{ijkl}[O_{q\ell}^{(3)}]_{ijkl} + [C_{de}]_{ijkl}[O_{de}]_{ijkl} \tag{4}$$
$$+ [C_{qe}]_{ijkl}[O_{qe}]_{ijkl}[C_{d\ell}]_{ijkl} + [O_{d\ell}]_{ijkl} + [C_{dq\ell e}]_{ijkl}[O_{dq\ell e}]_{ijkl} \Big) + \text{h.c.}\ .$$

$$[O_{q\ell}^{(1)}]_{ijkl} = [\bar{Q}_i\gamma^\mu Q_j][\bar{L}_k\gamma_\mu L_l],\ [O_{q\ell}^{(3)}]_{ijkl} = [\bar{Q}_i\gamma^\mu\sigma^a Q_j][\bar{L}_k\gamma_\mu\sigma^a L_l]\ , \tag{5}$$

$$[O_{de}]_{ijkl} = [\bar{d}_i\gamma^\mu d_j][\bar{\ell}_k\gamma_\mu\ell_l]\ ,\ [O_{qe}]_{ijkl} = [\bar{Q}_i\gamma^\mu Q_j][\bar{\ell}_k\gamma_\mu\ell_l]\ , \tag{6}$$

$$[O_{d\ell}]_{ijkl} = [\bar{d}_i\gamma^\mu d_j][\bar{L}_k\gamma_\mu L_l]\ ,\ [O_{dq\ell e}]_{ijkl} = [\bar{d}_i Q_j^I][\bar{L}_k^I\ell_l]\ , \tag{7}$$

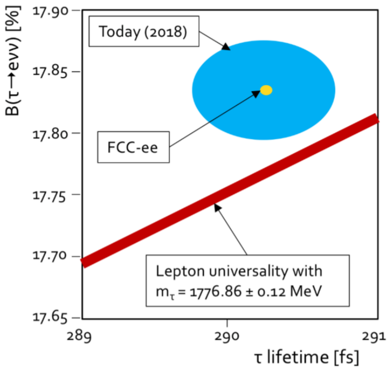
Flavor anomalies mostly in $\{ijkl\}$=$\{3233\}$ and $\{3222\}$.

Example 3: $B_s \to \phi\nu\nu$ (Preliminary)

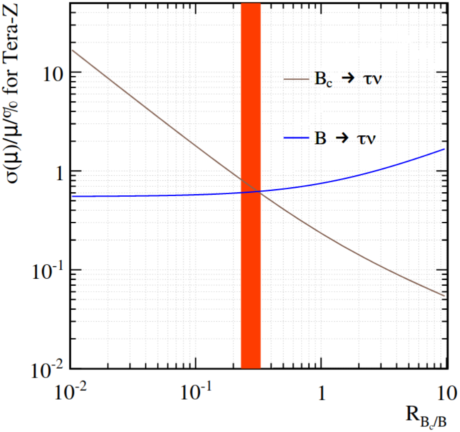
Current limit of this channel still led by LEP: BR$< 5.4 \times 10^{-3}$ (limited production at B factories, not achievable at hadron colliders).

Conditions	**Signal**	$b\bar{b}$	S/B	$S/\sqrt{S+B}$
Total	1.8e5	1.5e11	1.2e-6	0.46
$N_{\phi\to K^+K^-} > 0$	8.3e4	4.1e9	2.0e-5	1.29
$E_{lepton} < 0.2$ GeV	7.9e4	1.8e9	4.46e-5	1.88
$\alpha < 0.8$	2.9e4	2.0e5	0.148	61.29
Efficiency	0.162	1.32e-6		

Further Examples: τ decay and $B_c \to \tau\nu$



$\tau \to e\nu\nu$/lifetime measurements [Dam(2019)].



$B_c \to \tau\nu$ measurement

[Zheng et al.(2020)Zheng, Xu, Cao, Yu, Wang, Prell, Cheung, and Ruan]

(See Taifan's talk tomorrow)

Summary

- BSM and flavor physics are closely related at CEPC.
- LFU Tests at the Z pole provide a solid and effective way to resolve the flavor puzzle and constrain BSM.
- New collider/detector at the precision era: new challenges to theory and phenomenology!
- Multiple studies on the way!

Thank You!

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