Resolving Flavor Anomalies at CEPC

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Prologue

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

[Someone Awesome (2019?)]

FCCC and FCNC B Anomalies

If lepton flavor universality are not violated, good theoretical predictions for the following ratios:

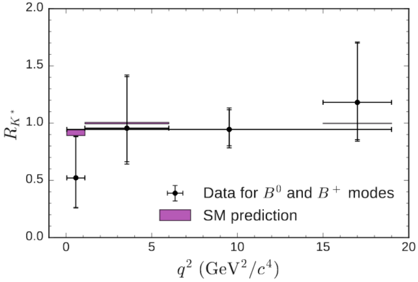
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \ , \tag{1}$$

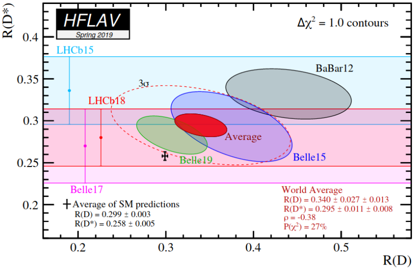
$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \ , \tag{2}$$

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

Systematic uncertainty largely cancel.

FCCC and FCNC B Anomalies



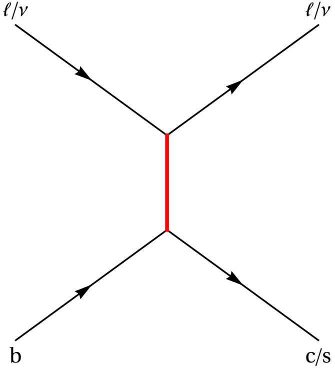


	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295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

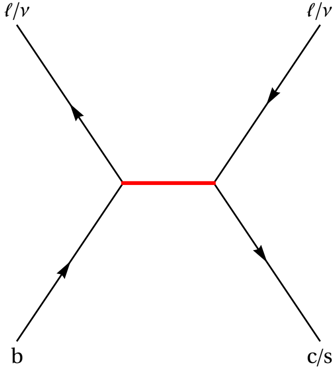
[Tanabashi et al.(2018)][Altmannshofer et al.(2018)].

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
V'	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	$(3,2)_{\frac{5}{6}}$	$O_S^\tau + O_P^\tau$

Most favored simplified model

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

LFUV in BSM: Theories

Higgs/Gauge extension:

[Crivellin et al.(2012)Crivellin, Greub, and Kokulu, Fajfer et al.(2012)Fajfer, Kamenik, Nisandzic, and Zupan, Boucenna et al.(2016)Boucenna, Celis, Fuentes-Martin, Vicente, and Virto]...

- Provide colorless mediators

Composite models:

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

- LFUV from partial compositeness
- Provide V' vector
- Also provide leptoquark (LQ) U_1

Dark-sector-like models:

[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]...

- Can solve a lot of problems
- Unlikely to explain FCCC anomalies

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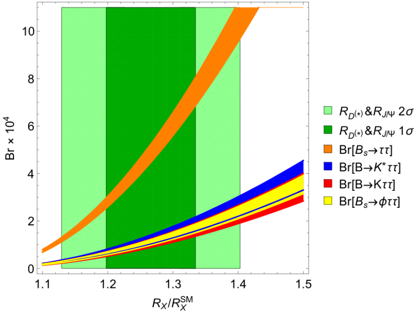
Example 1: $b \to s\tau\tau$ measurements

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]

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



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

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

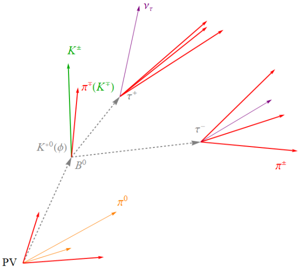
$$\sim \mathcal{O}(10) \times C_{9/10}^{\rm SM}$$

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

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

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

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

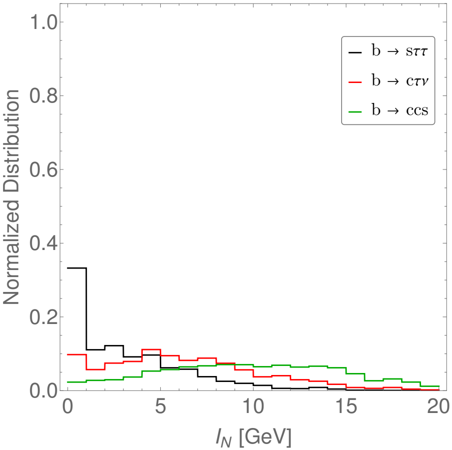
Overwhelmingly Large SM Backgrounds

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.

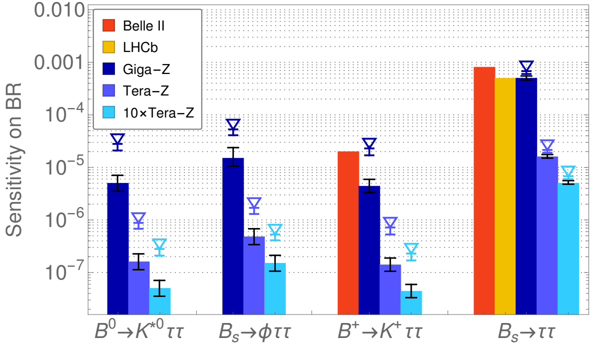
e.g. from $D_s \to \pi^\pm\pi^\pm\pi^\mp + n\pi^0$

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

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

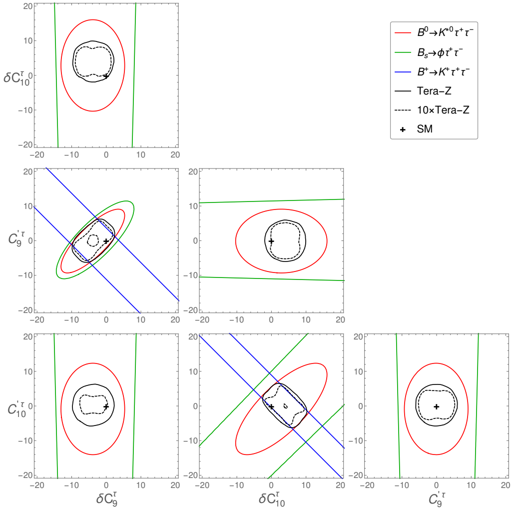
Result of $b \to s\tau\tau$ at Z Pole (Preliminary)

Work w/ Tao Liu, in preparation:

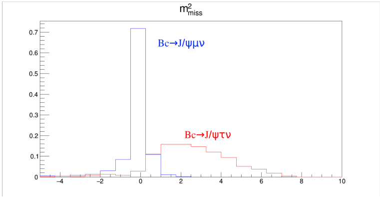


Traditional cut-based analysis: $\mathcal{O}(10^{-5} - 10^{-7})$ precision.
Still affected by limited detector spacial resolution ("∇" symbols): Motivation for detector R&D!

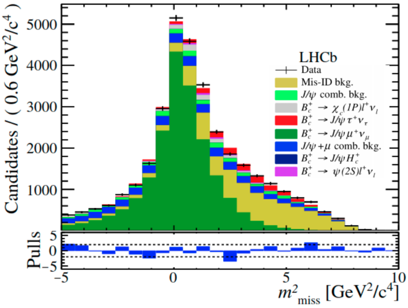
Constraints on EFT (Preliminary)

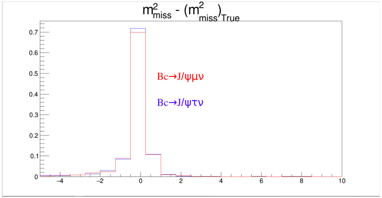


Example 2: $R_{J/\psi}$ measurement at Z Pole (Preliminary)



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)

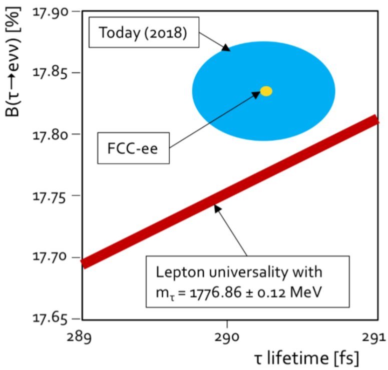
Work w/ Yanyun Duan, Shu Li, Manqi Ruan, Yudong Wang ......

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

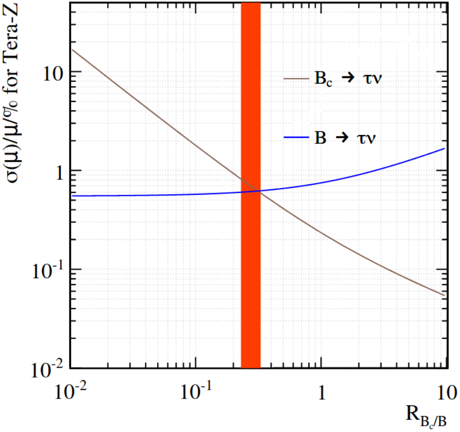
Conditions	Signal	$b\bar{b}$	S/B	$S/\sqrt{S+B}$
Total	1.8e5	1.5e11	1.2e-6	0.46
$N_{\phi\to K^+K^-} > 0$	8.3e4	4.1e9	2.0e-5	1.29
$E_{lepton} < 0.2$ GeV	7.9e4	1.8e9	4.46e-5	1.88
$\alpha < 0.8$	2.9e4	2.0e5	0.148	61.29
Efficiency	0.162	1.32e-6		

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).

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]

Summary

- Flavor physics is related to BSM, SM precision tests, Detector R&D, ... everything!
- 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 ($b \to s\tau\tau$, $R_{J/\psi}$, $b \to s\nu\nu$) and published works!

Thank You!

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