Testing Lepton Flavor Universality at Z pole

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Oct. 2, 2020, Snowmass RF1

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

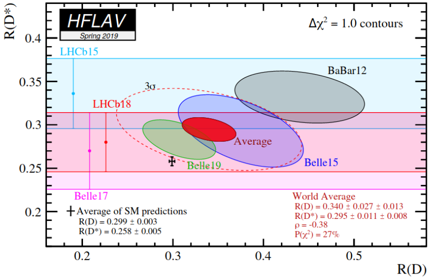
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \,, \tag{1}$$

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

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

LFU is challenged.

$b \to s\ell\ell$ and $b \to c\tau\nu$ 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	

$2 - 3\sigma$ deviation from SM!

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

LFUV Motivated by BSM Physics

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(2019), Azatov et al.(2018)Azatov, Bardhan, Ghosh, Sgarlata, and Venturini]...

- LFUV by partial compositeness (especially 3rd generation!)
- Provide $SU(3)$ triplet vector mediator
- Also provide leptoquark (LQ) U_1

Dark-sector-like models (light and small coupling):

[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×Tera-Z: a phase of future linear/circular lepton colliders. [Fujii et al.(2019), Dong et al.(2018), Abada et al.(2019)]

Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

	sign($P(e^-), P(e^+)$) =				
	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	60.4	46.1	35.9	29.4	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

Expected b hadron yields:

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}

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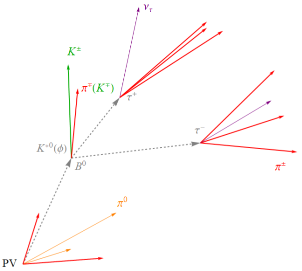
Example 1: $b \to s\tau\tau$ measurements

Use $\tau \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ decay, locate each vertex and reconstruct



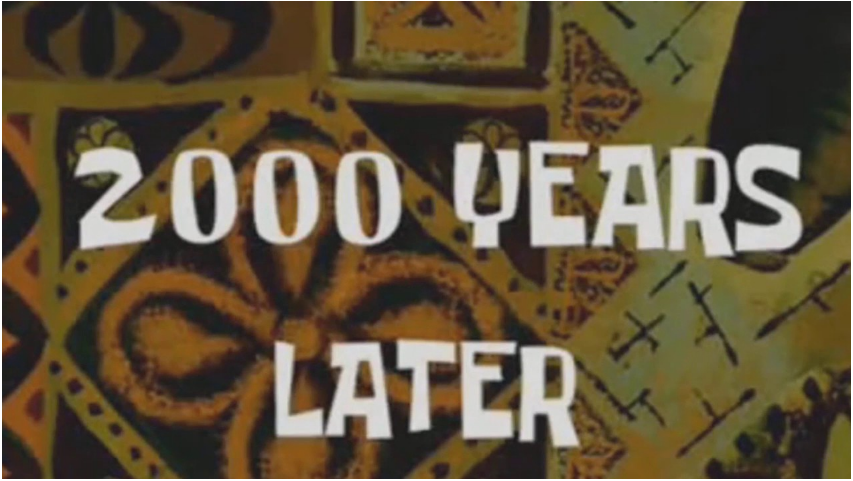
BR$(B^0 \to K^{*0}\tau^+\tau^-) \sim 10^{-7}$ in the SM

Overwhelmingly large background from $D^{\pm}_{(s)} \to \pi^{\pm}\pi^{\pm}\pi^{\mp} + X$ decays:

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. $B^0 \to D^{(*)-}\pi^+\pi^+\pi^-$	$\mathcal{O}(10^{-2} - 10^{-3})$

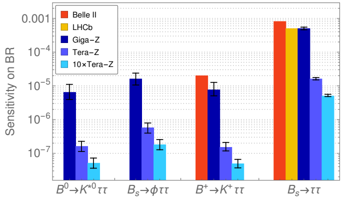
No relevant background studies before!

Spend Some Time on Serious Phenomenology!



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

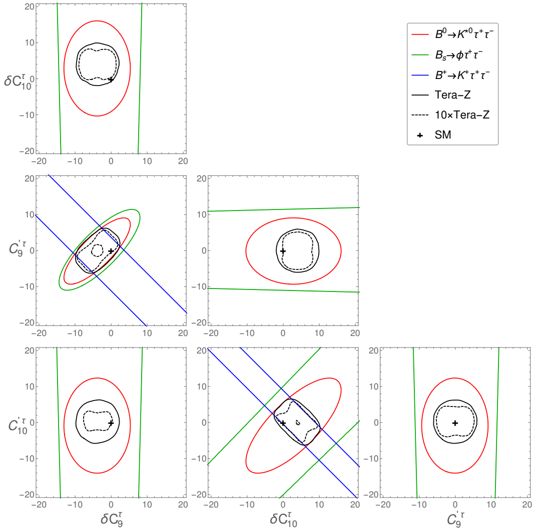
$\mathcal{O}(10^{-5} - 10^{-7})$ precision at Tera-Z:



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

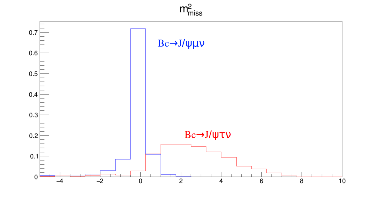
$$O'^{\tau}_{9(10)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^{\mu}P_R b][\bar{\tau}\gamma_{\mu}(\gamma^5)\tau] \ .$$

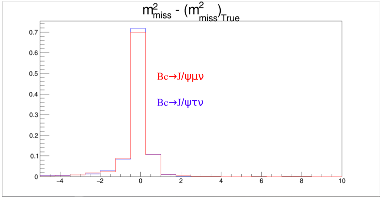
Constraining LFUV new physics:



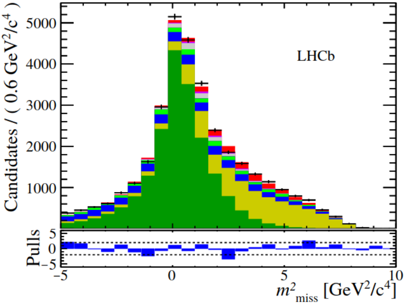
Example 2: $R_{J/\psi}$ measurement at Z Pole (Preliminary)

Improved reconstruction w/ momentum/energy conservation





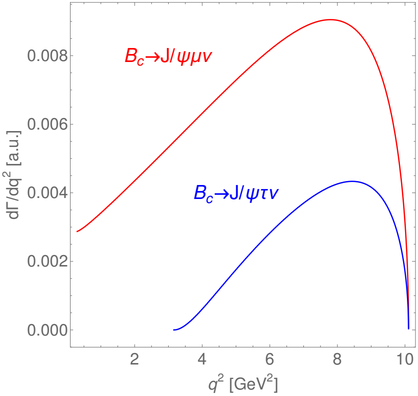
Compared to LHCb measurements:



Unique chance to do many interesting B_c physics!

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

Differential measurements possible! $\Rightarrow$ better BSM sensitivity at higher q^2.



Form factors from perturbative QCD [Watanabe(2018)].

Future Plan

- Study different FCCC $b \to c\tau\nu$ measurements at Z pole.
- The possibilities of differential measurements.
- Consider the overall picture in terms of SMEFT, and combining other Z pole results (e.g. $B_s \to \phi\nu\nu / B_c \to \tau\nu$, see Yudong & Taifan's talk.).

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