Probing LFUV Effects at the Z pole

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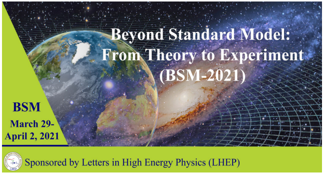
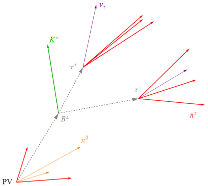
Based on 2012.00665 and ongoing projects

Apr. 1, BSM 2021





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

FCCC and FCNC B Anomalies

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

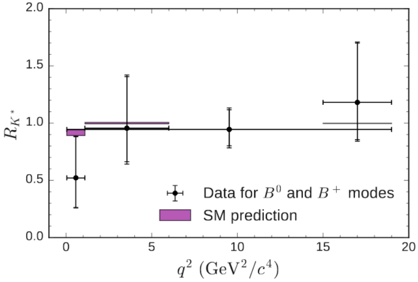
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \,, \tag{1}$$

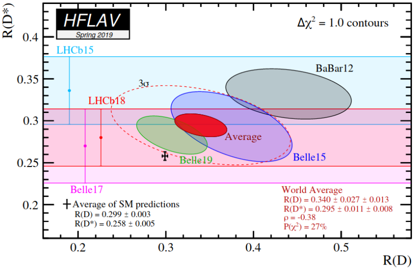
$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \,, \tag{2}$$

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

Systematic uncertainty largely cancel.

FCCC and FCNC B Anomalies



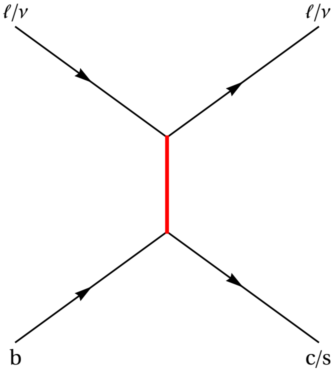


	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295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

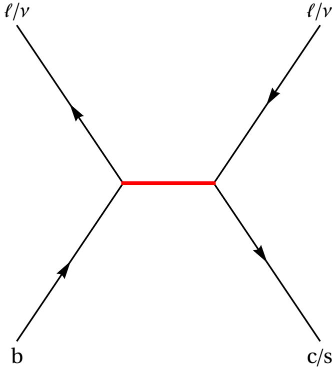
[Tanabashi et al., 2018][Altmannshofer et al., 2018].

LFUV in BSM: Simplified Models (LO)

Induced by two types of heavy mediators:



Colorless Mediators



Colored Mediators (Leptoquarks)

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]

Z factories are also $b(c/\tau)$ 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. Proposed Experiments: How do Golden Modes Look Like?

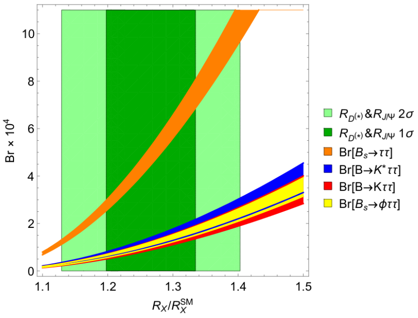
Multiple charged tracks	Vs. Belle II, low track energy
Multiple time scale $\mathcal{O}(10)$ fs	Vs. Belle II, low track displacement
h^0 or γ (but no more than 1-2)	Vs. LHCb, large QCD noise
e instead of μ ?	Vs. LHCb, relying on MS
ν or other invisible fellas	Vs. LHCb, no sensitivity in principle
Λ or $K_S \to h^+h^-$	Vs. LHCb, low acceptance
Baryonic modes (p or $\Sigma^{\pm}$?)	Vs. both, advanced PID
Heavy hadrons ($B_s,\ B_c,\ \Lambda_b$, Ξ_b, ...)	Vs. Belle II, imited $\sqrt{s}$
Double heavy flavor (B_c, exotics...)	Vs. both, unique @ the Z pole
...	...

Sounds like ideal for LFU tests.

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 $\sim 10^{-2.5}$



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

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

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

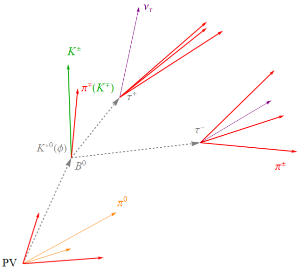
$$O_{9(10)}^\tau = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_L b][\bar{\tau}\gamma_\mu(\gamma^5)\tau] \, ,$$

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

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

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

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



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

Dominant background from inclusive $D^\pm_{(s)}$ hadronic decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.3%
	$c\tau = 87.0\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.6%
$D_s^\pm$	$m = 1.968$ GeV	$\tau^\pm\nu$	5.5%
	$c\tau = 151\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	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	$\tau^\pm\nu$	$< 0.12\%$
	$c\tau = 311\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	1.1%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	3.0%

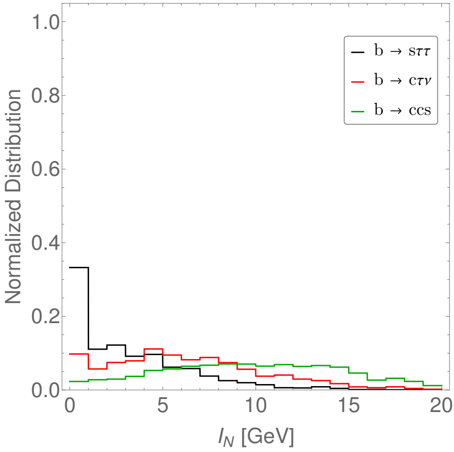
Overwhelmingly Large SM Backgrounds

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

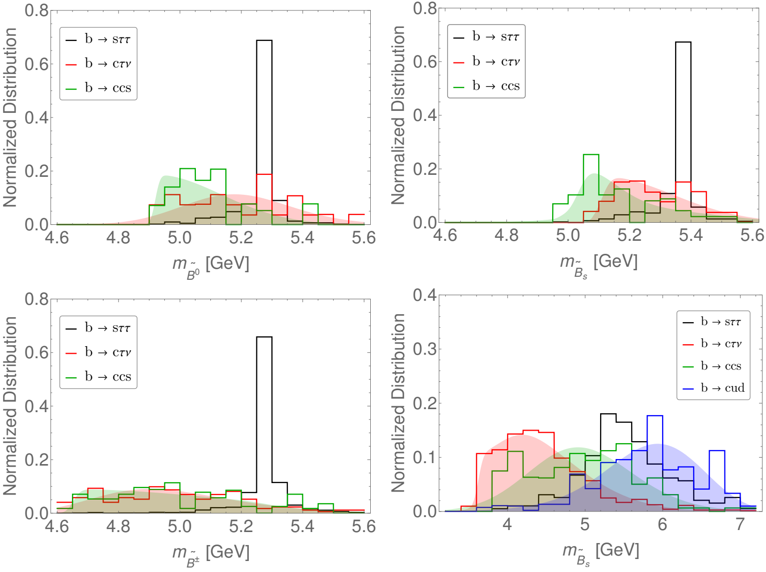


Good calorimetry saves the day!

Quite environment at the Z pole, using isolation variables to veto extra neutral particles (e.g. from $D_s \to \pi^\pm\pi^\pm\pi^\mp + n\pi^0$) and displaced K_S^0.

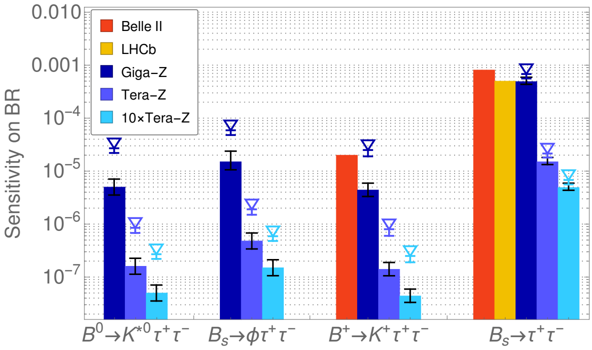
More advanced calorimetry: even better (e.g. π^0 reconstruction)?

Reconstructed Signals and Backgrounds



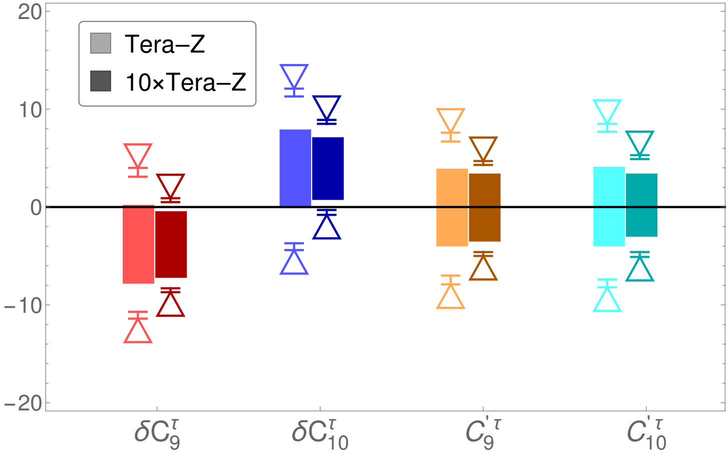
Projected Limits

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



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

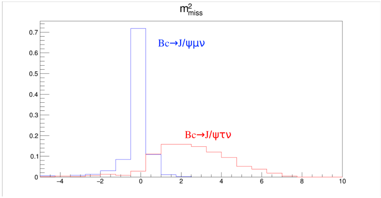
Constraints on EFT

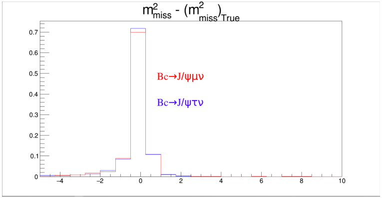


Marginalized 1σ constraints on EFT operators. Current experimental constraint $\sim 10^3$.

LFU Test with FCCC (Prelim.)

Work w/ Tin Seng Manfred Ho, Xuhui Jiang, Tsz Hong Kwok and Tao Liu

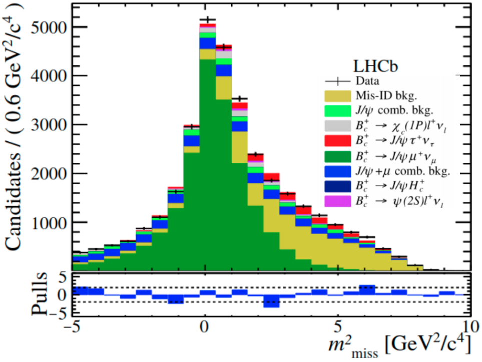




E.g. $R_{J\psi}$ measurement with

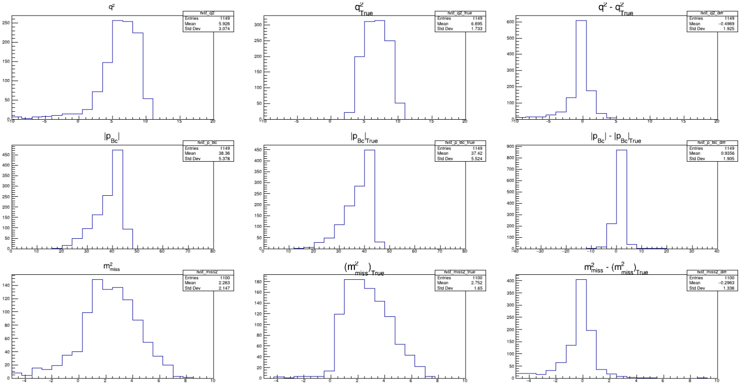
$\tau \to \mu\nu\nu,\ J/\psi \to \mu\mu$

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



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

More details on signal reconstruction (including vertex uncertainties):



Reconstruction quality is satisfying.

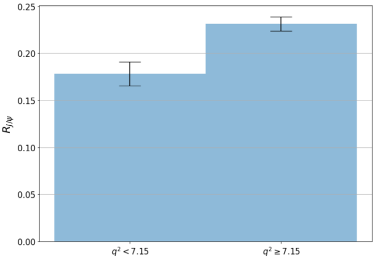
$R_{J/\psi}$ Measurement at Tera-Z (II) (Prelim.)

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

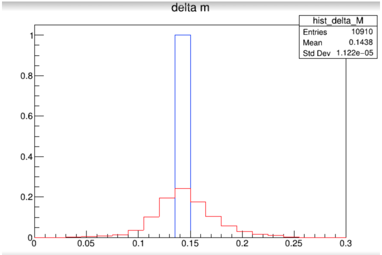
Preliminary!	# of B_c^+ at Tera-Z	$\epsilon_{3\mu}$	ϵ_{pre}	ϵ_{BDT}	Tera-Z yield
$B_c^+ \to J/\psi\,\tau\,\nu_\tau$	$\sim 2.2 \times 10^8$	5.5×10^{-5}	0.34	6.6×10^{-1}	$\sim 2.7 \times 10^3$
$B_c^+ \to J/\psi\,\mu\,\nu_\mu$	$\sim 2.2 \times 10^8$	1.3×10^{-3}	0.35	2.7×10^{-3}	$\sim 2.7 \times 10^2$
$B_c^+ \to \chi_c(1P)\,l^+\,\nu_l$	$\sim 2.2 \times 10^8$	–	–	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 $R_{D_s^*}$:

$$R_{D_s^{(*)}} \equiv \frac{\text{BR}(B_s \to D_s^{(*)-}\tau\nu)}{\text{BR}(B_s \to D_s^{(*)-}\ell\nu)} \,. \quad (4)$$

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

R_{Λ_c}:

$$R_{\Lambda_c} \equiv \frac{\text{BR}(\Lambda_b \to \Lambda_c\tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c\ell\nu)} \,. \quad (5)$$

The baryon number (carried by p) becomes

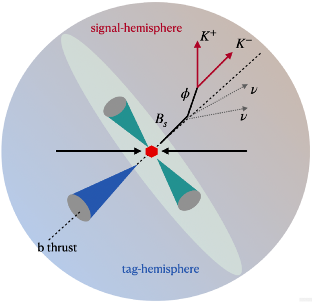
important.

Vector (from $R_{J/\psi}$ and $R_{D^*_{(s)}}$), pseudoscalar (from $R_{D_{(s)}}$). baryonic (from R_{Λ_c}) and singular (from $B_c \to \tau\nu$ [Zheng et al., 2020]) decay form factors are all necessary to better constrain LFUV.

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

$b \to s\nu\nu$ 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.

	Experimental	SM Prediction
$\text{BR}(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$	$(2.17 \pm 0.30) \times 10^{-6}$
$\text{BR}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$	$(9.48 \pm 1.10) \times 10^{-6}$
$\text{BR}(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$	$(4.68 \pm 0.64) \times 10^{-6}$
$\text{BR}(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$	$(10.22 \pm 1.19) \times 10^{-6}$
$\text{BR}(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$	$(11.84 \pm 0.19) \times 10^{-6}$



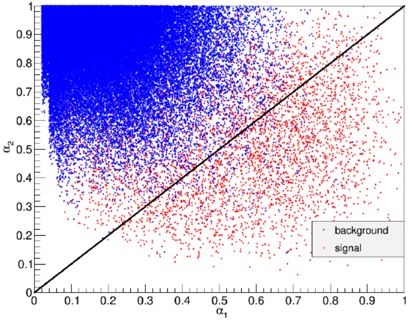
[Tanabashi et al., 2018] [Straub, 2015] [Geng and Liu, 2003]

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

Most likely to have breakthrough at Z factories.

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

The dominant background comes from $B \to D^{(*)}\ell(\tau)\nu$, $D^{(*)} \to \phi X$ with no lepton tagged.



Inspired by LEP measurements

$$\alpha_1 = \frac{E_\phi}{E_{\text{vis}}^{\text{sig}}}, \ \alpha_2 = \frac{E_{\text{vis}}^{\text{sig}}}{m_Z/2}$$

Separate sig vs. bkg by

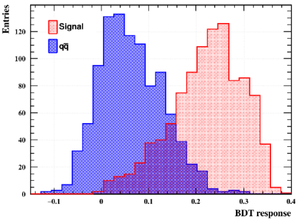
$$\alpha \equiv \alpha_2/\alpha_1 = \frac{E_{\text{vis}}^{\text{sig2}}}{E_\phi(m_Z/2)}$$

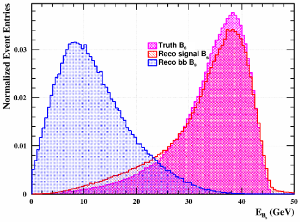
- Calorimetry greatly benefits the measurement.
- Challenges tracker performance (soft ℓ, IP, etc.)

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

conditions	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
total generated	1.8e5	1.12e11	1.585e11	1.58511	1.20e11	1.51e11	7e11	464.81
b-tag > 0.6	1.359e5	8.0931e8	1.18558e9	1.1685e9	8.2392e9	1.1852e11	1.2992e+11	265.22
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	51171	1.06277e7	1.30285e7	3.29526e7	2.15203e8	3.84348e9	4.11529e9	125.36
$E_\phi < 45$ GeV Kaon IP > 0.008 mm Energy asymmetry > 8 GeV	42054	3.3382e6	3.07042e6	6.26759e6	4.86347e7	1.04533e9	1.10665e9	79.10
Energy total < 85	40579	408759	746859	856441	1.28413e7	5.30604e8	5.45457e8	57.56
$E_{B_s} > 30$	32033	68126	0	38929	1.18081e6	4.93844e7	5.06723e7	22.23
$\alpha < 1.0$	22699	0	0	0	516605	7.70471e6	8.22132e6	12.65
$E_\mu < 1.1$ GeV and $E_e < 1.0$ GeV	20091	0	0	0	110922	2.18398e6	2.2949e6	7.57
$(1-\alpha_1)/\theta_{<miss,\phi>} < 2.0$	13543	0	0	0	29060	426879	455940	5.06
BDT score > 0.22	7285	0	0	0	0	5240	5240	1.53
Efficiency(%)	4.448	0	0	0	0	3.47e-6	7.49e-7	-

Based on CEPC full simulation.





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!

Thank You!

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