LFU Tests and Rare B Decays at the Z Pole

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CEPC Snomass Progress

FCCC and FCNC B Anomalies

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

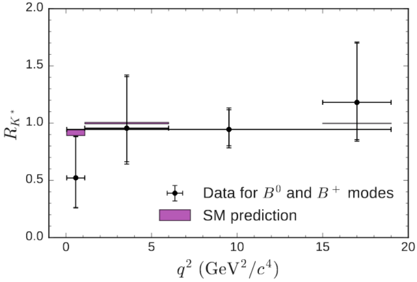
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \,, \tag{1}$$

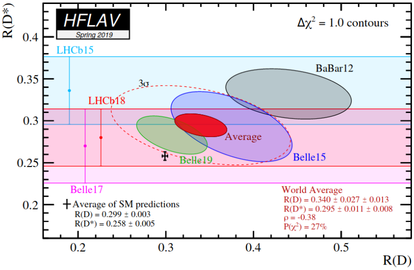
$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \,, \tag{2}$$

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

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)].

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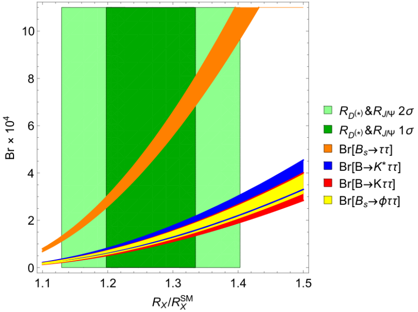
LFU Test with $b \to s\tau\tau$ Measurements

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

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



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

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

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

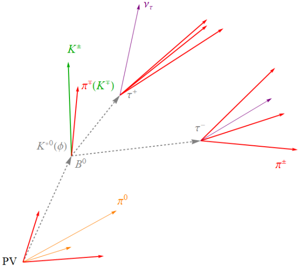
From SM ($\mathcal{O}(10^{-7})$) to $\mathcal{O}(10^{-4})$

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

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

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

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%
$D^\pm_s$	$m = 1.968$ 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%
		$\pi^\pm\pi^\pm\pi^\mp K^0_S$	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%
		$\pi^\pm\pi^\pm\pi^\mp K^0_S$	3.0%

Kinematic Constraints

Flying direction is also the momentum direction:

$$\vec{p}_{B^0} \times \vec{V}_{B^0} = 0 \ \Rightarrow (\vec{p}_{K^{*0}} + \sum_{i=1,2} \vec{p}_{\tau,i}) \times \vec{V}_{B^0} = 0 \ , \qquad (4)$$

$$\vec{p}_{\tau,i} \times \vec{V}_{\tau,i} = 0. \qquad (5)$$

The solution of neutrino momenta thus take the form

$$\vec{p}_{\nu,i} = \frac{-\vec{p}_{K^{*0}} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}}{\vec{V}_{\tau,i} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}} \vec{V}_{\tau,i} - \vec{p}_{3\pi,i} \ , \qquad (6)$$

which is invariant under a rescaling of displacements ($\vec{V}$).

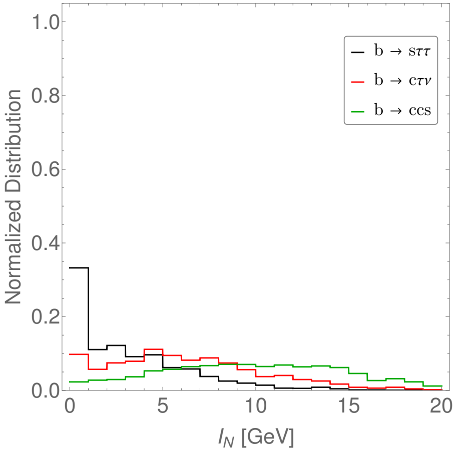
Overwhelmingly Large SM Backgrounds

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



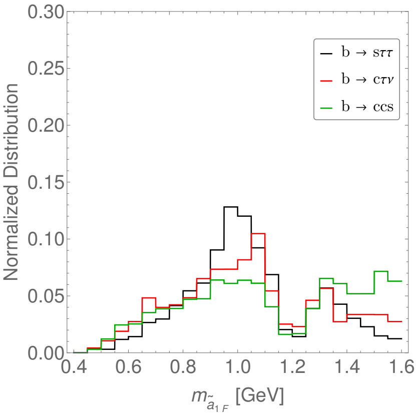
Good calorimetry saves the day!

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.

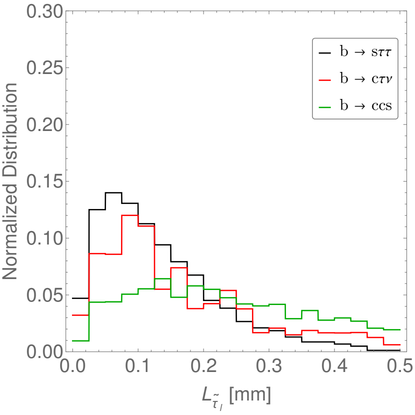
More advanced calorimetry: even better (e.g. π^0 reconstruction)?

Efforts to Remove Backgrounds (II)

We also impose other cuts. Soft enough without exploiting simplified simulations.



$3\pi^{\pm}$ vertex structures



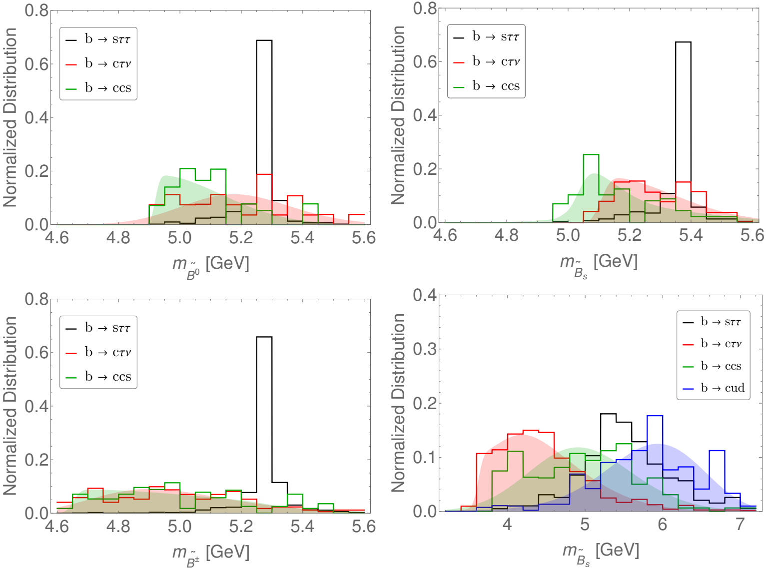
Decay time measurements

Result of $b \to s\tau\tau$ at Z Pole

We study 4 benchmark channels ($B \to K^{*0}\tau^+\tau^-$, $B_s \to \phi\tau^+\tau^-$, $B^+ \to K^+\tau^+\tau^-$ and $B_s \to \tau^+\tau^-$). Having S/B ratio $\sim$ a few % for the first three channels.

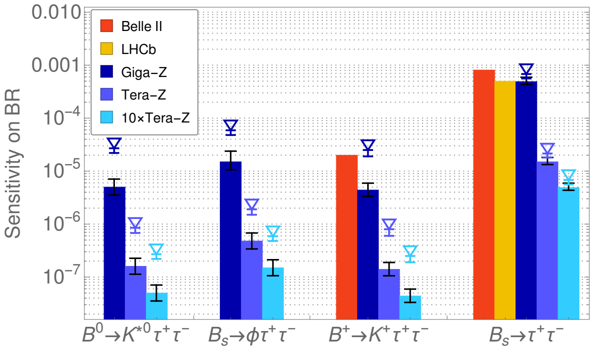
Process	N_{evt}	ϵ_{pre}	ϵ_1	ϵ_2	ϵ_3	$\epsilon_{m_{\tilde{B}}}$	Tera-Z Yield
$B \to K^{*0}\tau^+\tau^-$	1.2×10^4	3.3×10^{-3}	6.3×10^{-1}	7.3×10^{-1}	8.8×10^{-1}	6.4×10^{-1}	1.0×10^1
$b \to c\tau\nu$	1.8×10^7	2.5×10^{-4}	1.8×10^{-1}	4.9×10^{-1}	7.0×10^{-1}	7.4×10^{-2}	2.1×10^1
$b \to c\bar{c}s$	2.4×10^9	2.9×10^{-4}	4.2×10^{-2}	4.0×10^{-1}	4.7×10^{-1}	4.5×10^{-2}	2.4×10^2
$B_s \to \phi\tau^+\tau^-$	2.8×10^3	2.0×10^{-3}	6.3×10^{-1}	7.3×10^{-1}	8.8×10^{-1}	6.3×10^{-1}	1.4
$b \to c\tau\nu$	8.8×10^5	4.2×10^{-4}	2.4×10^{-1}	5.4×10^{-1}	8.1×10^{-1}	1.2×10^{-1}	4.7
$b \to c\bar{c}s$	3.5×10^8	3.0×10^{-4}	6.3×10^{-2}	3.5×10^{-1}	5.1×10^{-1}	5.2×10^{-2}	6.0×10^1
$B^+ \to K^+\tau^+\tau^-$	1.4×10^4	5.9×10^{-3}	6.3×10^{-1}	6.9×10^{-1}	9.0×10^{-1}	6.0×10^{-1}	2.0×10^1
$b \to c\tau\nu$	1.1×10^7	3.3×10^{-3}	2.1×10^{-1}	4.7×10^{-1}	7.9×10^{-1}	2.6×10^{-2}	7.5×10^1
$b \to c\bar{c}s$	5.3×10^8	2.3×10^{-3}	6.2×10^{-2}	3.2×10^{-1}	6.9×10^{-1}	2.8×10^{-2}	4.5×10^2
$B_s \to \tau^+\tau^-$	2.5×10^4	9.2×10^{-3}	5.4×10^{-1}	6.4×10^{-1}	6.7×10^{-1}	6.6×10^{-1}	3.4×10^1
$b \to c\tau\nu$	4.1×10^9	5.4×10^{-3}	2.1×10^{-1}	5.0×10^{-1}	5.0×10^{-1}	1.6×10^{-1}	1.9×10^5
$b \to c\bar{c}s$	5.8×10^9	6.2×10^{-3}	5.3×10^{-2}	3.8×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	1.2×10^5
$b \to c\bar{u}d$	3.5×10^9	9.9×10^{-3}	1.9×10^{-1}	4.7×10^{-1}	1.1×10^{-1}	4.8×10^{-1}	1.6×10^5

Reconstructed Signals and Backgrounds



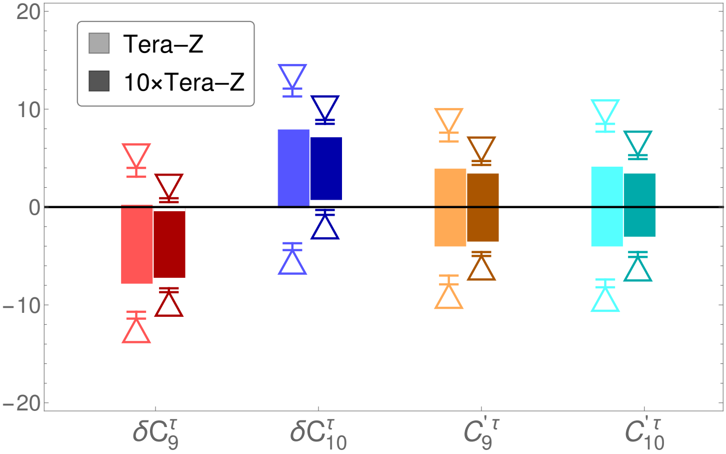
Projected Limits

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



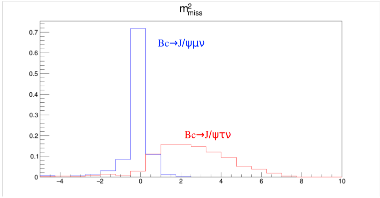
Traditional cut-based analysis: $\mathcal{O}(10^{-5} - 10^{-7})$ precision. Still affected by limited detector spacial resolution ("∇" symbols): Motivation for detector R&D!

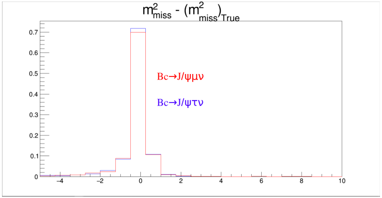
Constraints on EFT



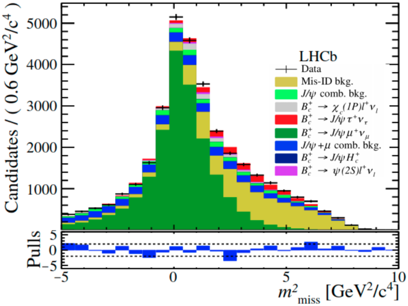
Marginalized 1σ constraints on EFT operators. Current experimental constraint $\sim 10^3$.

LFU Test with $R_{J/\psi}$ Measurement (Prelim.)



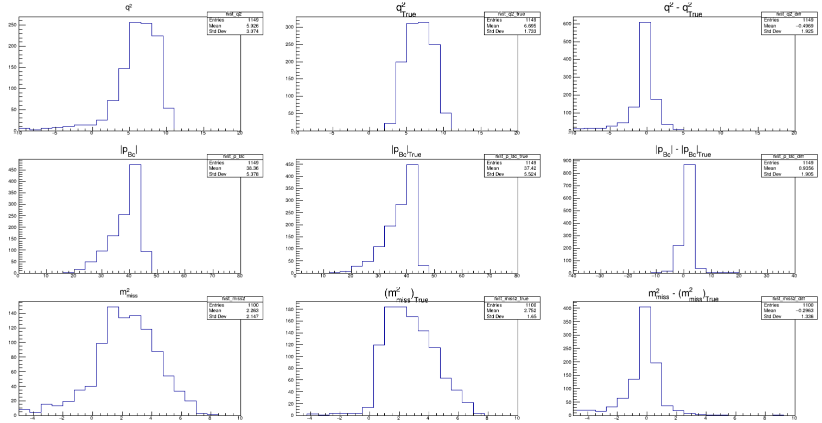


Improved reconstruction quality, also expecting lower combinatoric bkg and mis-ID.



LFU Test with $R_{J/\psi}$ Measurement (Prelim.)

More details on signal reconstruction (including 10 μm vertex uncertainties):



LFU Test with $R_{J/\psi}$ Measurement (Prelim.)

Preliminary!	N_{B_c} at Tera-Z	BR	ϵ_1	ϵ_2	Tera-Z yield
$B_c^+ \to J/\psi\,\tau^+\,\nu_\tau$	$\sim 2.2\times10^8$	0.53%	1.03%	17.59%	$\sim 2.11\times10^3$
$B_c^+ \to J/\psi\,\mu^+\,\nu_\mu$	$\sim 2.2\times10^8$	2.24%	5.93%	22.48%	$\sim 6.57\times10^4$
$J/\psi+\mu$ comb. bkg.	–	–	5.93%	3.16%	$\sim 4.10\times10^4$
$B_c^+ \to \chi_c(1P)\,l^+\,\nu_l$	$\sim 2.2\times10^8$	–	–	–	$\sim 2.31\times10^3$
Mis-ID bkg.	–	–	5.93%	–	$\epsilon_{\mu\pi}\times7.18\times10^5$
J/ψ comb. bkg.	–	–	–	–	$< r_h\times4.60\times10^3$

BR: Theoretical BR (from [Leljak et al.(2019)Leljak, Melic, and Patra], and [Wang et al.(2009)Wang, Wang, and Lu])
ϵ_1: Theoretical BR of 3 muons final states ($\tau^+\to\mu^+\,\bar\nu_\mu\,\nu_\tau$, $J/\psi\to\mu^+\mu^-$)
ϵ_2: Overall efficiency with the LHCb cuts ($\frac{\#\text{ of reconstruction}}{\#\text{ of truth level }3\mu}$)
$\epsilon_{\mu\pi}$: Rate of misidentifying π^+ as μ^+, $\epsilon_{\mu\pi}\ll1$.
$r_h = h/h_{LHCb}\lesssim 1$: the ratio w/ LHCb.

Without detailed analysis and optimal cuts, a Tera-Z can improve the $R_{J/\psi}$ precision by $\mathcal{O}(10)$.

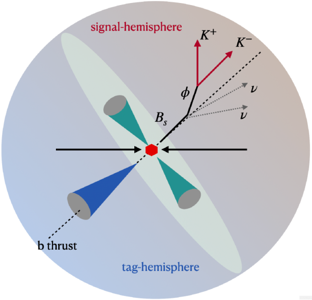
A Todo list

- Better understanding of mis-ID & combinatoric backgrounds.
- Global flavor sensitivity of Z factories.
- Coarse grained differentiate measurement
- More FCCC channels to test LFU ($R_{D_s^{(*)}}$, $R_{\Lambda_b^{(*)}}$, etc)
- Implication of new physics (SMEFT style)

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
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$(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$	$(11.84 \pm 0.19) \times 10^{-6}$



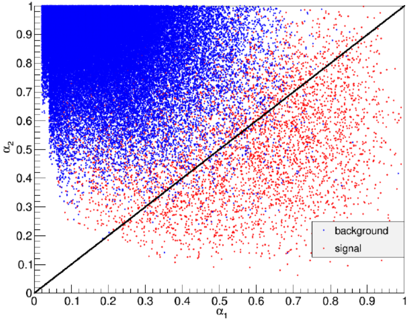
[Tanabashi et al.(2018)] [Straub(2015)] [Geng and Liu(2003)]

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

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

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

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

	N_S	N_B	S/sqrt(B)	sqrt(S+B)/S
Total	180000	1.5e+11	0.46	2.15
$N_\phi > 0$	6.78e4	4.82e+09	0.98	1.02
$E_l < 1$ GeV	5.55e4	2.05e9	1.22	0.82
$E_{Neutral}^{ISO} < 2.7$ GeV	4.59e4	6.91e8	1.75	0.57
$E_{track}^{ISO} < 4$ GeV	4.25e4	4.17e8	2.08	0.48
$\alpha < 0.8$	1.71e4	5.77e+5	22.52	0.045
Efficiency	0.095	3.85e-06		

Based on CEPC full simulation.
Current stage: considering better event reconstruction. Also need to accumulate more data.

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