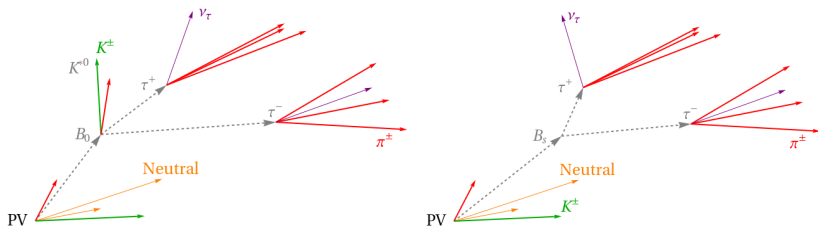


# The Future of $b \rightarrow s\tau\tau$ Phenomenology at Z-Pole

Lingfeng Li and Tao Liu

Januray 2020, HKUST



*“Don't leave flavor physics to flavor physicists.”*

[Someone Awesome (2019?)]

*“Then dont’ leave it to me, please!”*

[me (2019)]

## The future of $b \rightarrow s\tau\tau$ phenomenology at Z-Pole

$b \rightarrow s\tau\tau$ : Relation with flavor anomalies? A plausible story.

Z-Pole: Unique features compared to other experiments.

Phenomenology: How does signal looks like? Background estimation.

Future: Precision estimation for each channel. A to-do list.

# $b \rightarrow sll$ and $b \rightarrow cTV$ Anomalies

In FCNC process:

$$R_{K^{(*)}} \equiv \frac{\text{BR}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\text{BR}(B \rightarrow K^{(*)} e^+ e^-)}, \quad (1)$$

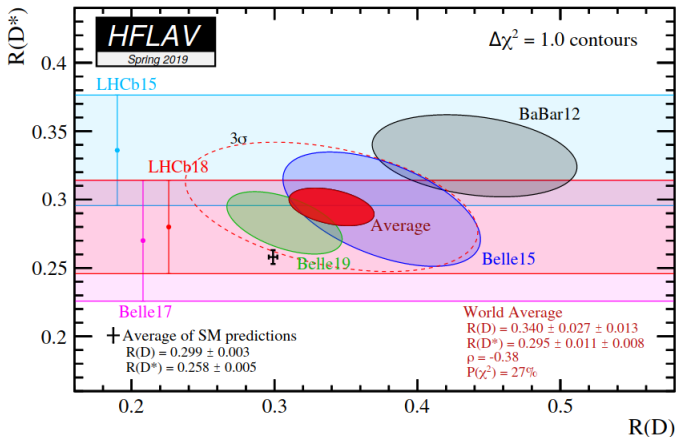
In CC process:

$$R_{D^{(*)}} \equiv \frac{\text{BR}(B \rightarrow D^{(*)} \tau \nu)}{\text{BR}(B \rightarrow D^{(*)} \ell \nu)}, \quad (2)$$

$$R_{J/\psi} \equiv \frac{\text{BR}(B_c \rightarrow J/\psi \tau \nu)}{\text{BR}(B_c \rightarrow J/\psi \ell \nu)}, \quad (3)$$

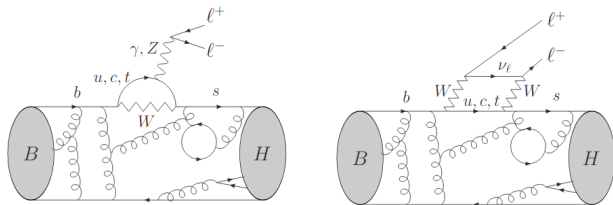
challenges lepton flavor universality(LFU).

# $b \rightarrow sll$ and $b \rightarrow cTV$ Anomalies



[Amhis et al.(2019)]

## Section II: Anomalies and $b \rightarrow s\tau\tau$



[Bifani et al.(2019)Bifani, Descotes-Genon, Romero Vidal, and Schune]

Channel	$\text{BR}_{\text{SM}}$	$q^2 \equiv m_{\tau\tau} \text{ (GeV}^2\text{)}$
$B^0 \rightarrow K^{*0}\tau\tau$	$(0.98 \pm 0.10) \times 10^{-7}$	[15,19]
$B_s \rightarrow \phi\tau\tau$	$(0.86 \pm 0.06) \times 10^{-7}$	[15,18.8]
$B^\pm \rightarrow K^\pm\tau\tau,$	$(1.20 \pm 0.12) \times 10^{-7}$	[15,22]
$B_s \rightarrow \tau\tau,$	$(7.73 \pm 0.49) \times 10^{-7}$	-

[Capdevila et al.(2018)Capdevila, Crivellin, Descotes-Genon, Hofer, and Matias]

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

# $b \rightarrow c\ell\nu$ (CC) operators

$$H_{b \rightarrow c\ell\nu}^{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \sum_i C_i O_i, \quad (4)$$

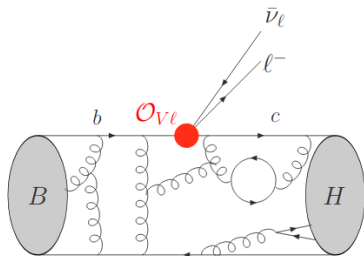
$$O_{VL(R)}^{cbl\nu} = [\bar{c}\gamma^\mu b][\bar{\ell}\gamma_\mu P_{L(R)}\nu], \quad (5)$$

$$O_{AL(R)}^{cbl\nu} = [\bar{c}\gamma^\mu \gamma^5 b][\bar{\ell}\gamma_\mu P_{L(R)}\nu], \quad (6)$$

$$O_{SL(R)}^{cbl\nu} = [\bar{c}b][\bar{\ell}P_{L(R)}\nu], \quad (7)$$

$$O_{PL(R)}^{cbl\nu} = [\bar{c}\gamma^5 b][\bar{\ell}P_{L(R)}\nu], \quad (8)$$

$$O_{TL(R)}^{cbl\nu} = [\bar{c}\sigma^{\mu\nu} b][\bar{\ell}\sigma_{\mu\nu} P_{L(R)}\nu], \quad (9)$$



Only  $L$  operators survive w/o right-handed neutrinos.

Assuming a sizable  $(O_V - O_A)^{\text{NP}} \sim 1$  is the case (allowed by data).

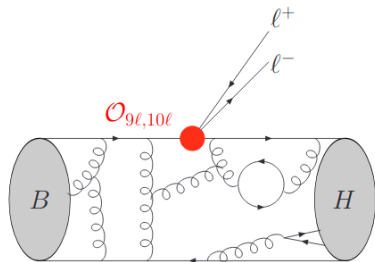
## $b \rightarrow sll$ and $b \rightarrow s\nu\nu$ (NC) operators

$b \rightarrow s\tau\tau$ :

$$H_{b \rightarrow s\tau\tau}^{\text{eff}} = H_{b \rightarrow s\tau\tau}^{\text{SM}} + \frac{-4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \times \quad (10)$$
$$[C_9^{\text{NP}} O_9^\tau + C_{10}^{\text{NP}} O_{10}^\tau + C_{9'} O_{9'}^\tau + C_{10'} O_{10'}^\tau].$$

$$O_{9(10)}^\tau = \frac{\alpha}{4\pi} [\bar{s}\gamma^\mu P_L b][\bar{\tau}\gamma_\mu(\gamma^5)\tau] \quad (11)$$

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



$b \rightarrow s\nu\nu$ :

$$H_{b \rightarrow s\nu_i\nu_j}^{\text{eff}} = \frac{-\alpha G_F V_{tb} V_{ts}^*}{\sqrt{2}\pi} (C_L^{(ij)} [\bar{s}\gamma^\mu P_L b][\bar{\nu}_i\gamma_\mu P_L \nu_j]). \quad (12)$$

Strongly constrained by  $\text{BR}(B \rightarrow K^{(*)}\nu\nu)$

Assuming NP respects  $SU(2)_{EW}$

$$[O_{q\ell}^{(1)}]_{ijkl} = (\bar{Q}_i \gamma^\mu Q_j)(\bar{L}_k \gamma_\mu L_l), \quad (13)$$

$$[O_{q\ell}^{(3)}]_{ijkl} = (\bar{Q}_i \gamma^\mu \sigma^a Q_j)(\bar{L}_k \gamma_\mu \sigma^a L_l), \quad (14)$$

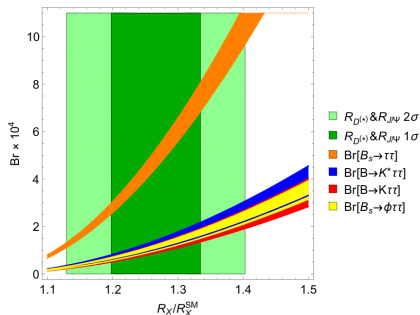
$b \rightarrow s\nu\nu$  sensitive to  $O^{(1)} - O^{(3)}$ , if imposing they are the same:

$$\begin{aligned} [O_{q\ell}^{(1)}]_{2333} + [O_{q\ell}^{(3)}]_{2333} &\sim [\bar{c} \gamma^\mu P_L b][\bar{\nu} \gamma^\mu P_L \nu_\tau] + [\bar{s} \gamma^\mu P_L b][\bar{\nu} \gamma^\mu P_L \nu] \\ &\Rightarrow (O_{VL}^T - O_{AL}^T)/2 + \frac{4\pi}{\alpha}(O_9^T - O_{10}^T)/2. \end{aligned} \quad (15)$$

CC amplitudes are tied with NC amplitudes

# Enhanced BR( $b \rightarrow s\tau\tau$ )

$\Rightarrow$  A moderate deviation in CC may change NC processes largely.



$$\begin{aligned}
 -C_9^{\text{NP}} &= C_{10}^{\text{NP}} \\
 &= \frac{2\pi V_{cb}}{\alpha V_{tb} V_{ts}^*} \left( \sqrt{\frac{R_X}{R_X^{\text{SM}}}} - 1 \right) \\
 &\sim \mathcal{O}(10) \times C_{9/10}^{\text{SM}}
 \end{aligned}$$

[Capdevila et al.(2018)Capdevila, Crivellin, Descotes-Genon, Hofer, and Matias]

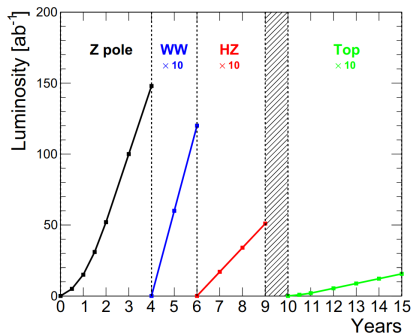
Can be generated by NP like vector Leptoquark  $U_1$ .

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

# Section III: Unique Opportunities at Z-Pole

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

[Dong et al.(2018)]



[Abada et al.(2019)]

# Unique Opportunities at Z-Pole (2)

Particle	Tera-Z	Belle II	LHCb
<b><i>b</i> hadrons</b>			
$B^+$	$6 \times 10^{10}$	$3 \times 10^{10}$ (50 ab <sup>-1</sup> on $\Upsilon(4S)$ )	$3 \times 10^{13}$
$B^0$	$6 \times 10^{10}$	$3 \times 10^{10}$ (50 ab <sup>-1</sup> on $\Upsilon(4S)$ )	$3 \times 10^{13}$
$B_s$	$2 \times 10^{10}$	$3 \times 10^8$ (5 ab <sup>-1</sup> on $\Upsilon(5S)$ )	$8 \times 10^{12}$
<i>b</i> baryons	$1 \times 10^{10}$		$1 \times 10^{13}$
$\Lambda_b$	$1 \times 10^{10}$		$1 \times 10^{13}$
<b><i>c</i> hadrons</b>			
$D^0$	$2 \times 10^{11}$		
$D^+$	$6 \times 10^{10}$		
$D_s^+$	$3 \times 10^{10}$		
$\Lambda_c^+$	$2 \times 10^{10}$		
$\tau^+$	$3 \times 10^{10}$	$5 \times 10^{10}$ (50 ab <sup>-1</sup> on $\Upsilon(4S)$ )	

[Dong et al.(2018)]

## $\tau$ Final States

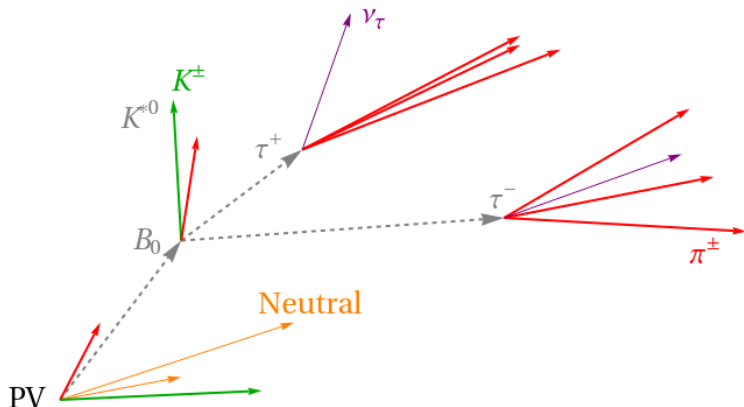
Short lifetime:  $c\tau(\tau) \approx 20\%$  of  $c\tau(B)$

Decay to 2+ body: decay products have low energy in the rest frame

B-Factory	Z-Factory
$\vec{V}(B) \sim 120 \mu\text{m}$	$\sim 3\text{mm}$
$\vec{V}(\tau) - \vec{V}(B) \sim 25 \mu\text{m}$	$\sim 0.6\text{mm}$
$E(\pi^\pm) \text{ from } \tau \lesssim 1 \text{ GeV}$	$\sim 5 \text{ GeV}$

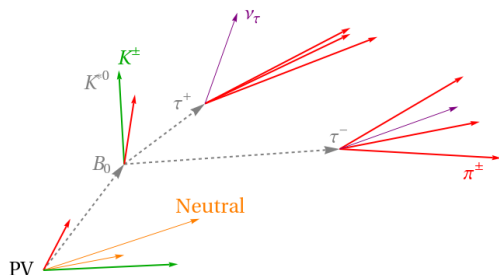
Mostly due to the boosted  $b$  from  $Z$  decay.

## Section III: $b \rightarrow s\tau\tau$ Event Reconstruction Z Pole



A target  $B^0 \rightarrow K^{*0}\tau\tau$  event to be reconstructed. Both  $\nu$  are missing, and all **Neutral** particles with larger error in direction and  $E$ .

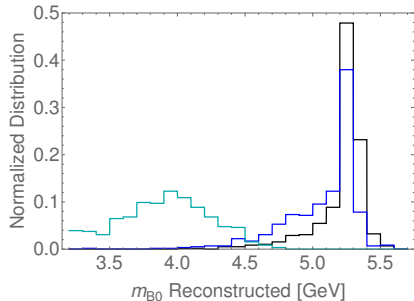
# Complete Reconstruction



- ▶ 6 d.o.f. ( $\nu$  momenta)
- ▶ 3 displacement vectors
- ▶  $\Rightarrow$  6 independent constraints
- ▶ Full reconstruction
- ▶ No on-shell condition needed

# Reconstruction of $B^0 \rightarrow K^{*0} \tau \tau$

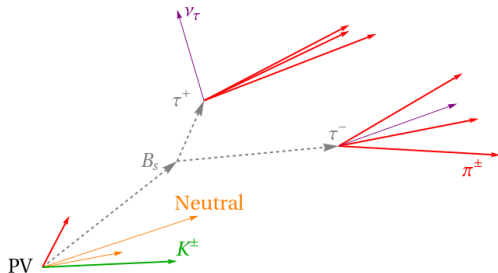
The reconstructed  $m_{B^0}$ , which centered around its physical value 5.28 GeV.



- Cyan: Visible Only
- Blue: From displacements
- Black: Optimized w/  $m_\tau$

Very similar performance when reconstructing  $B_s \rightarrow \phi \tau \tau$ .

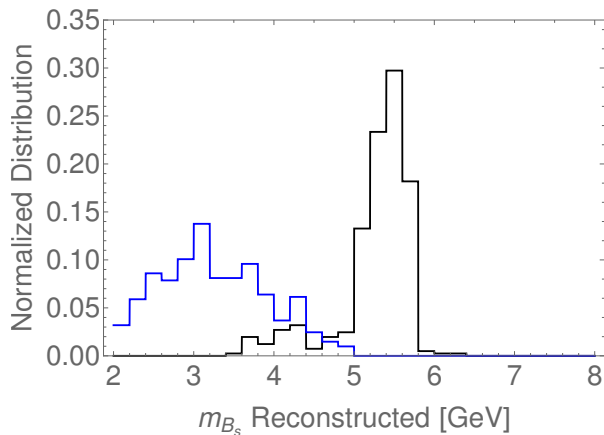
# Incomplete Reconstruction



- ▶ Still 6 d.o.f.
- ▶ Only 2 detectable displacement vectors
- ▶ Need  $\tau$  mass-shell condition
- ▶ Method similar to the LHCb study [Mord(2015)]

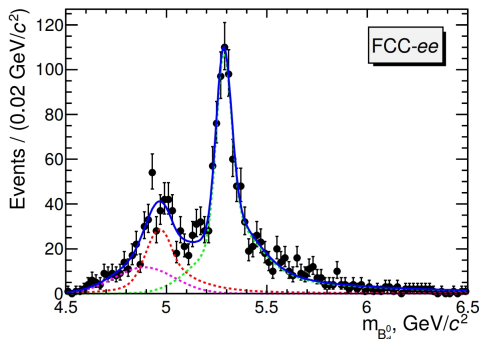
A target  $B_s \rightarrow \tau\tau$  event to be reconstructed.

# Reconstruction of $B_s \rightarrow \tau\tau$



## Section IV: Phenomenology

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



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

Does it mean we can measure down to  $\mathcal{O}(10^{-7})$  BR with  $\mathcal{O}(10\%)$  precision?

# A Hint



## Possible Backgrounds (2)

	Properties	Decay Mode	BR
$\tau$	$m = 1.777 \text{ GeV}$	$\pi^\pm \pi^\pm \pi^\mp \nu$	9.31%
	$c\tau = 87.0 \text{ } \mu\text{m}$	$\pi^\pm \pi^\pm \pi^\mp \pi^0 \nu$	4.62%
$D_s$	$m = 1.968 \text{ GeV}$	$\tau \nu$	5.48%
	$c\tau = 151 \text{ } \mu\text{m}$	$\pi^\pm \pi^\pm \pi^\mp$	1.09%
		$\pi^\pm \pi^\pm \pi^\mp \pi^0$	1.7%
		$\pi^\pm \pi^\pm \pi^\mp 2\pi^0$	$\sim 20\%$
		$\pi^\pm \pi^\pm \pi^\mp \phi$	1.26%
$D^\pm$	$m = 1.870 \text{ GeV}$	$\tau \nu$	$< 0.12\%$
	$c\tau = 311 \text{ } \mu\text{m}$	$\pi^\pm \pi^\pm \pi^\mp$	0.117%
		$\pi^\pm \pi^\pm \pi^\mp \pi^0$	1.1%
		$\pi^\pm \pi^\pm \pi^\mp K_s^0$	2.97%

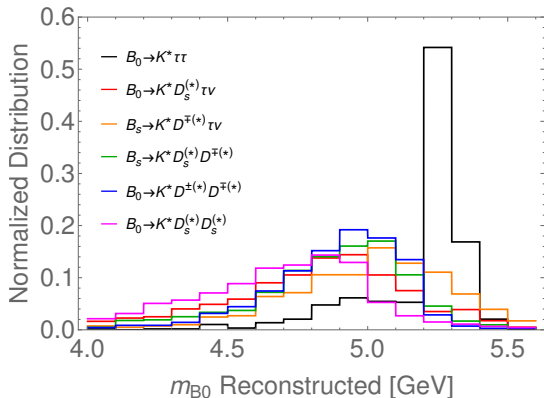
Neutral components also from PV

## Possible Backgrounds (3)

Example	Typical BR	Comments
$b \rightarrow ccs$ Type		
e.g. $B_s \rightarrow D_s^{\pm(*)} D_s^{\mp(*)} K^{*0}$	$\mathcal{O}(10^{-2})$	
$b \rightarrow c\tau\nu$ Type		
e.g. $B^0 \rightarrow K^{*0} D_s^{(*)} \tau\nu$	$\mathcal{O}(10^{-3})$	Harder discrimination
$b \rightarrow cud$ Type		
e.g. $B^0 \rightarrow D^{(*)\mp} \pi^{\pm} \pi^{\pm} \pi^{\mp} (\text{NR})$	$\mathcal{O}(10^{-2})$	Affects $B_s \rightarrow \tau\tau$

# Reconstructed Mass Difference of Various Bkgs

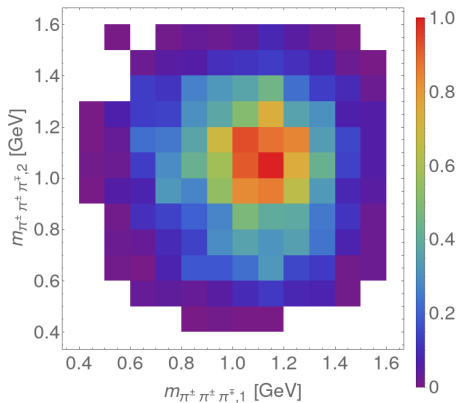
Normalized signal and background  $m_{B_0}$  distributions.



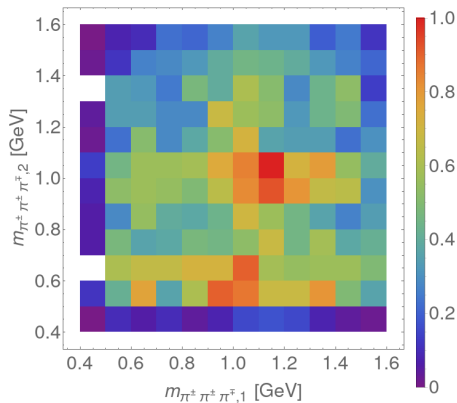
Have to use other features...

# As $\tau \rightarrow \pi^\pm \pi^\pm \pi^\mp \nu$ mostly through $a_1^\pm(1260) \rightarrow \rho\pi \dots$

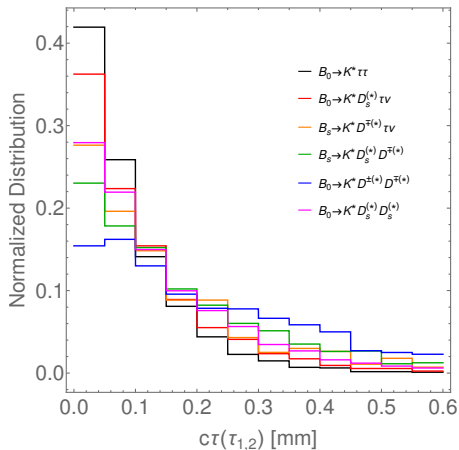
Invariant mass of each  $\pi^\pm \pi^\pm \pi^\mp$ :



Signals



$D_s D_s$  background



$c\tau(\tau)$ : 0.087 mm,  $c\tau(D_S)$ : 0.151 mm,  $c\tau(D^\pm)$ : 0.311 mm

## Section X: Results and Discussion

Estimated yield for  $B^0 \rightarrow K^{*0} \tau \tau$  signal and backgrounds:

Channel	BR	Preselection $\times 10^3$	Features $\times 10^2$	Mass $\times 10^2$	Tera-Z Yield
$B^0 \rightarrow K^{*0} \tau \tau$	$0.98 \times 10^{-7}$	4.14	37.6	35.7	6.54
$B^0 \rightarrow K^{*0} D_s^{(*)} \tau \nu$	$x \times 10^{-4}$	0.623	5.08	1.36	9.3x
$B_s \rightarrow K^{*0} D_{\mp}^{(*)} \tau^{\pm} \nu$	$x \times 10^{-4}$	0.267	8.85	2.87	3.3x
$B_s \rightarrow D_s^{\pm(*)} D_{\mp}^{(*)} K^{*0}$	$1.1 \times 10^{-2}$	0.589	2.27	1.07	98.9
$B^0 \rightarrow D_s^{\pm(*)} D_{\mp}^{(*)} K^{*0}$	$1.1 \times 10^{-2}$	0.261	3.14	0.43	98.3
$B^0 \rightarrow D_s^{(*)} D_s^{(*)} K^{*0}$	$0.7x \times 10^{-2}$	0.739	1.27	0.37	38.4x

- ▶ Based on traditional analysis
- ▶  $\gtrsim \mathcal{O}(10^3)$  separation
- ▶  $b \rightarrow ccs \gtrsim b \rightarrow c\tau\nu$

# Expectation and Comparison

	Belle-II	LHCb (HL-LHC)	Tera-Z	10×Tera-Z
$B^0 \rightarrow K^{*0} \tau \tau$	-	-	$5 \times 10^{-7}$	$1 \times 10^{-7}$
$B_s \rightarrow \phi \tau \tau$	-	-	$2 \times 10^{-6}$	$7 \times 10^{-7}$
$B^\pm \rightarrow K^\pm \tau \tau$	$2.0 \times 10^{-5}$	-	$4 \times 10^{-7}$	$1 \times 10^{-7}$
$B_s \rightarrow \tau \tau$	$8.1 \times 10^{-4}$	$5 \times 10^{-4}$	$6 \times 10^{-5}$	$2 \times 10^{-5}$

Belle-II projection from [Altmannshofer et al.(2018)], LHCb  
projection from [Aaij et al.(2018b)]

## Concluding Remarks

“Due to the presence of **s**trange flavor anomalies, it is necessary to get **d**own to the **b**ottom of various  $b \rightarrow s\tau\tau$  channels and do precise measurements. Making the full use of Z factories, which can provide us **u**p to  $10^{11}$  clean  $B$  meson decays, is then one of our **t**op priorities. However, we must beware of large **c**harm backgrounds.”

[Tao and me (2020)]

More flavor physics at Z pole:

- ▶ Differential distribution/  $\tau$  polarization measurements.
- ▶  $B_c$  physics (See the next talk).
- ▶ Other  $b \rightarrow X\tau\tau$  decay modes (e.g.  $B^\pm \rightarrow \pi^\pm\tau\tau \dots$ )
- ▶  $B$  baryon physics (e.g.  $\Lambda_b$  polarization measurement. [Kats(2017)])
- ▶ Time dependent CPV of various modes.

# Backup and Preliminary

# $b \rightarrow sll$ and $b \rightarrow cTV$ Anomalies

	Experimental	SM Prediction	Comments
$R_K$	$0.745^{+0.090}_{-0.074} \pm 0.036$	$1.00 \pm 0.01$	$m_{\ell\ell} \in [1.0, 6.0] \text{ GeV}^2$ , via $B^\pm$ .
$R_{K^*}$	$0.69^{+0.12}_{-0.09}$	$0.996 \pm 0.002$	$m_{\ell\ell} \in [1.1, 6.0] \text{ GeV}^2$ , via $B^0$ .
$R_D$	$0.340 \pm 0.030$	$0.299 \pm 0.003$	$B^0$ and $B^\pm$ combined.
$R_{D^*}$	$0.295 \pm 0.014$	$0.258 \pm 0.005$	$B^0$ and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	$0.25-0.28$	
$\text{BR}(B^0 \rightarrow K^{*0} \nu\nu)$	$< 2.7 \times 10^{-5}$	$(9.6 \pm 0.9) \times 10^{-6}$	
$\text{BR}(B^\pm \rightarrow K^\pm \nu\nu)$	$< 1.6 \times 10^{-5}$	$(4.6 \pm 0.5) \times 10^{-6}$	

[Bordone et al.(2016)Bordone, Isidori, and Pattori][Jger and Martin Camalich(2016)][Aaij et al.(2018a)]

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

# Simplified Theories

Model	Spin	SM charge	$b \rightarrow c\tau\nu$ operators at $\Lambda$
Scalars	0	$(1, 2)_0$	$O_S^\tau, O_P^\tau$
$W'$	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	$(3, 2)_{\frac{5}{6}}$	$O_S^\tau + O_P^\tau$

## 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
- ▶ Provide  $W'$  vector
- ▶ Also provide 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 CC anomalies

# Comparison with Belle II

## Belle II → Z factory

**D\* Slow pion Tracking efficiency**

30-50% → > 90%

**Boost**

120  $\mu\text{m}$  → 3mm

**B isolation**

Overlapping → Highly displaced

**Low B-frame momentum Lepton ID**

Poor/moderate → Very good

**Neutrino reconstruction**

B tag → Vertex + energy flow (Z mass constrains)

Taken from Elisabetta Barberio's talk

# Comparison with LHCb

**Flavour tagging efficiency**

**LHCb → Z factory**

5% → ~ 40% -80% (lepton tag)

**EM showers**

Pile up → Not an issue

**K<sub>s</sub> acceptance (decay inside the tracking)**

Poor/moderate → Very good

**Hermetic**

Forward → Barrel/symmetric

**Trigger**

Finite efficiency for hadronic → ~100%

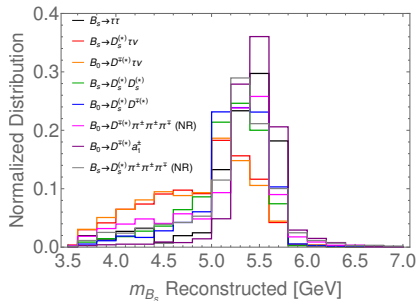
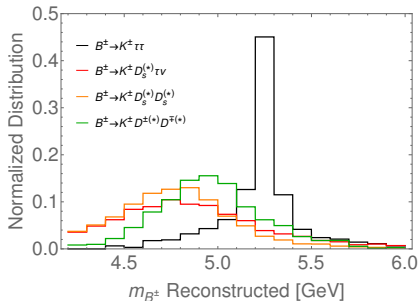
Taken from Elisabetta Barberio's talk

# Linear Constraints

$$\vec{p}_{B(s)} \propto \vec{V}_{K^*,\phi} \Rightarrow \sum_{i=1,2} (\vec{p}_{K^*,\phi} + \vec{p}_{\tau,i} + \vec{p}_{\nu,i}) \times \vec{V}_{K^*,\phi} = 0, \quad (16)$$

$$\vec{p}_{\tau,i} \propto (\vec{V}_{\tau,i} - \vec{V}_{K^*,\phi}) \Rightarrow (\vec{p}_{\tau,i} + \vec{p}_{\nu,i}) \times (\vec{V}_{\tau,i} - \vec{V}_{K^*,\phi}) = 0. \quad (17)$$

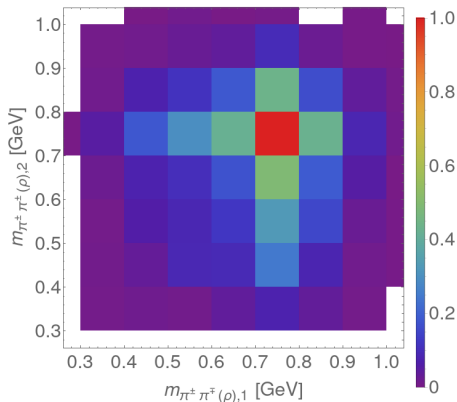
# Reconstructed Mass Difference of Various Bkgs (2)



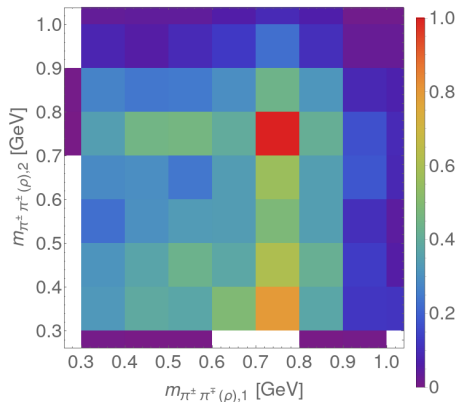
For incomplete reconstruction cases, the mass reconstructed is not as useful.

# As $\tau \rightarrow \pi^\pm \pi^\pm \pi^\mp \nu$ mostly through $a_1^\pm(1260) \rightarrow \rho\pi$ (2)

Invariant mass of the  $\pi^+\pi^-$  pairs closer to  $m_\rho$ :

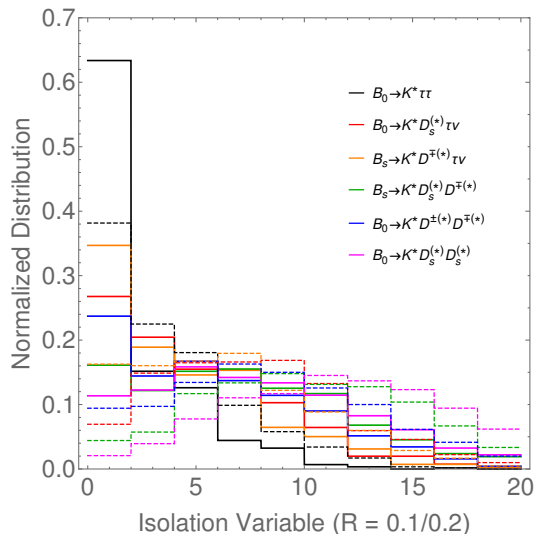


Signals



$D_s D_s$  background

# Isolation Variables



Neutral energy within a certain cone.

e.g. from

$$D_s \rightarrow \pi^\pm \pi^\pm \pi^\mp + n\pi^0$$

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

# Yield of $B_s \rightarrow \phi\tau\tau$

Channel	Assumed BR	$\epsilon_{\text{pre}} \times 10^3$	$\epsilon_{\text{Score}} \times 10^2$	$\epsilon_{\text{Rec}} \times 10^2$	Tera-Z Yield
$B_s \rightarrow \phi\tau\tau$	$1.2 \times 10^{-7}$	3.68	40.8	38.4	1.59
$B_s \rightarrow \phi D_s^{(*)}\tau\nu$	$x \times 10^{-4}$	0.96	5.91	3.65	42.2 x
$B^0 \rightarrow \phi D^{(*)}\tau^+\nu$	$x \times 10^{-4}$	0.51	10.4	2.79	10.0 x
$B_s \rightarrow D_s^{(*)}D_s^{(*)}\phi$	$x \times 10^{-2}$	1.63	1.20	0.41	18.5 x
$B^0 \rightarrow D_s^{\pm(*)}D^{\mp(*)}\phi$	$x \times 10^{-2}$	0.90	2.58	0.40	88.5 x
$B_s \rightarrow D^{\pm(*)}D^{\mp(*)}\phi$	$x \times 10^{-2}$	0.55	3.81	3.07	24.1 x

# Yield of $B^\pm \rightarrow K^\pm \tau \tau$

Channel	Assumed BR	$\epsilon_{\text{pre}} \times 10^3$	$\epsilon_{\text{Score}} \times 10^2$	$\epsilon_{\text{Rec}} \times 10^2$	Tera-Z Yield
$B^\pm \rightarrow K^\pm \tau \tau$	$1.2 \times 10^{-7}$	6.85	39.0	39.7	20.0
$B^\pm \rightarrow D_s^{\mp(*)} K^\pm \tau^\pm \nu$	$1.3 \times 10^{-4}$	3.80	6.76	2.43	$1.95 \times 10^2$
$B^\pm \rightarrow D_s^{(*)} D_s^{(*)} K^\pm$	$1.9 \times 10^{-3}$	5.99	1.18	1.34	$4.73 \times 10^2$
$B^\pm \rightarrow D^{\pm(*)} D^{\mp(*)} K^\pm$	$2.8 \times 10^{-3}$	0.57	2.75	3.99	$3.97 \times 10^2$

# Yield of $B_s \rightarrow \tau\tau$

Channel	Assumed BR	$\epsilon_{\text{pre}} \times 10^3$	$\epsilon_{\text{Score}} \times 10^2$	$\epsilon_{\text{Rec}} \times 10^2$	Tera-Z Yield
$B_s \rightarrow \tau\tau$	$7.73 \times 10^{-7}$	4.35	18.9	75.3	15.3
$B_s \rightarrow D_s^{(*)}\tau\nu$	$2.4 \times 10^{-2}$	6.07	2.89	20.8	$2.81 \times 10^4$
$B^0 \rightarrow D^{\mp(*)}\tau^{\pm}\nu$	$2.7 \times 10^{-2}$	3.61	3.09	17.3	$6.26 \times 10^4$
$B_s \rightarrow D_s^{(*)}D_s^{(*)}$	$4.5 \times 10^{-2}$	7.40	0.59	41.6	$8.76 \times 10^4$
$B^0 \rightarrow D^{(*)\pm}D_s^{(*)}$	$4.03 \times 10^{-2}$	4.45	0.73	45.4	$2.13 \times 10^4$
$B^0 \rightarrow D^{(*)\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ (NR)	$7.7 \times 10^{-3}$	1.35	0.55	40.0	$2.74 \times 10^3$
$B^0 \rightarrow D^{(*)\mp}a_1$	$1.9 \times 10^{-2}$	8.73	0.59	88.5	$1.05 \times 10^5$
$B_s \rightarrow D_s^{(*)}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ (NR)	$1.38 \times 10^{-2}$	2.91	0.63	60.0	$4.86 \times 10^3$

# $B_s \rightarrow \tau\tau$ Reconstruction

$$\vec{V}_{\tau,1} = \hat{\tau}_{B_s}(\vec{p}_{\tau,1} + \vec{p}_{\tau,2}) + \hat{\tau}_{\tau,1}\vec{p}_{\tau,1}, \quad (18)$$

$$\vec{V}_{\tau,2} = \hat{\tau}_{B_s}(\vec{p}_{\tau,1} + \vec{p}_{\tau,2}) + \hat{\tau}_{\tau,2}\vec{p}_{\tau,2}, \quad (19)$$

$$\mathbf{V} = \mathbf{H}\mathbf{P}, \quad \mathbf{H} \equiv \begin{pmatrix} \hat{\tau}_{\tau,1} + \hat{\tau}_{B_s} & \hat{\tau}_{B_s} \\ \hat{\tau}_{B_s} & \hat{\tau}_{\tau,2} + \hat{\tau}_{B_s} \end{pmatrix}, \quad \mathbf{V} \equiv \begin{pmatrix} \vec{V}_{\tau,1} \\ \vec{V}_{\tau,2} \end{pmatrix}, \quad \mathbf{P} \equiv \begin{pmatrix} \vec{p}_{\tau,1} \\ \vec{p}_{\tau,2} \end{pmatrix}, \quad (20)$$

$$\chi^2 = \sum \frac{|m_{\tau,\text{rec}}^2 - m_{\tau}^2|}{m_{\tau}^2} + \left( \frac{m_{B_s,\text{rec}} - m_{B_s}}{m_{B_s}} \right)^2 \quad (21)$$
$$+ \frac{\sum_{i \neq j} |\mathbf{V}\mathbf{V}^T - \mathbf{H}\mathbf{P}\mathbf{P}^T\mathbf{H}|_{ij}}{\sum_{i \neq j} |\mathbf{V}\mathbf{V}^T|_{ij}}.$$



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Measurement of the ratio of branching fractions

$$\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau) / \mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu).$$

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