Flavor Physics at Future Z-Factories: $b \to s\tau\tau$ Measurements and Beyond

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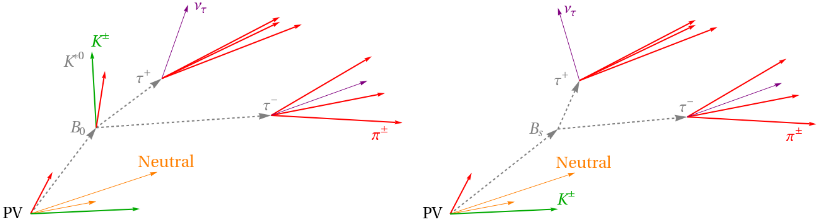


Section I: Introduction

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

[Someone Awesome (2019?)]

You Know...

"I am in!"

[me (2019)]

Outline

Flavor and $b \to s\tau\tau$: What motivates our search and why $b \to s\tau\tau$ matters.

Z-factories: Unique advance at Z pole.

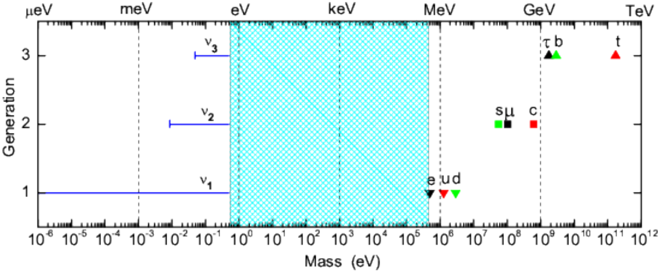
Measurements: How does signal looks like? Underdiscussed SM backgrounds.

In the future: Precision estimation for each channel. Constraints on NP operators.

Beyond $b \to s\tau\tau$: A wide open field of flavor, move on from the current status.

Prologue: Lepton Flavor Universality (Violation)

We are familiar with flavor, but do we really understand flavor?



[Xing(2014)]

Lepton flavor universality (LFU) demands that charged leptons have (almost) identical interactions, only differ by their Yukawa couplings and hence their masses.

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

In FCNC processes:

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

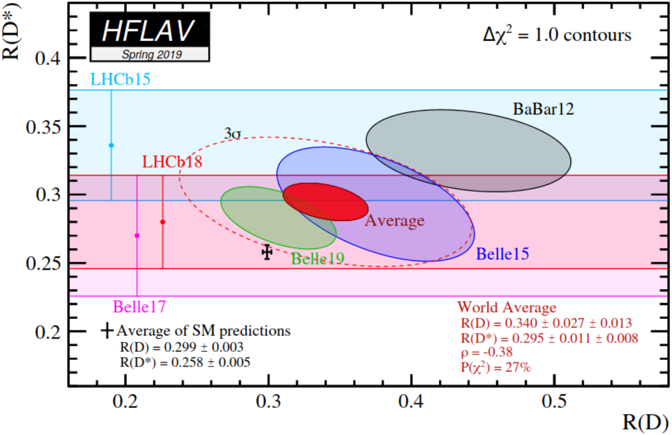
and FCCC processes:

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

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

challenges LFU.

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



[Amhis et al.(2019)]

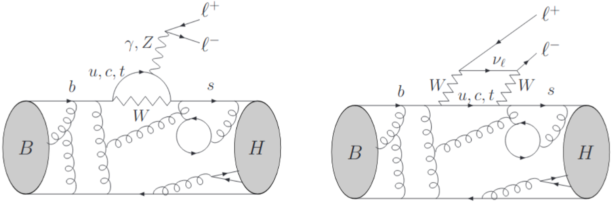
$b \to s\ell\ell$ and $b \to c\tau\nu$ Anomalies

	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	
BR$(B^0 \to K^{*0}\nu\nu)$	$< 2.7 \times 10^{-5}$	$(9.6 \pm 0.9) \times 10^{-6}$	
BR$(B^{\pm} \to K^{\pm}\nu\nu)$	$< 1.6 \times 10^{-5}$	$(4.6 \pm 0.5) \times 10^{-6}$	

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

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

Section II: Anomalies and $b \to s\tau\tau$



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

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

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

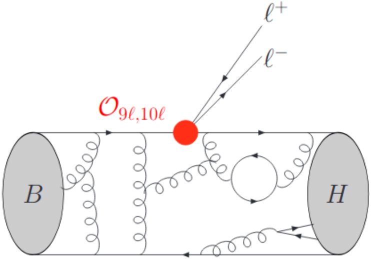
[Kamenik et al.(2017)Kamenik, Monteil, Semkiv, and Silva]

$b \to s\ell\ell$ and $b \to s\nu\nu$ (FCNC) Operators

$b \to s\tau\tau$:

$$H^{\rm eff}_{b\to s\tau\tau} = H^{\rm SM}_{b\to s\tau\tau} + \frac{-4G_F V_{tb}V^*_{ts}}{\sqrt{2}} \times \qquad (4)$$
$$[C^{\rm NP}_9 O^\tau_9 + C^{\rm NP}_{10} O^\tau_{10} + C_{9'} O^\tau_{9'} + C_{10'} O^\tau_{10'}] \, .$$

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



$b \to s\nu\nu$:

$$H^{\rm eff}_{b\to s\nu_i\nu_j} = \frac{-\alpha G_F V_{tb}V^*_{ts}}{\sqrt{2}\pi}(C^{(ij)}_L[\bar{s}\gamma^\mu P_L b][\bar{\nu}_i\gamma_\mu P_L \nu_j]) \, . \qquad (6)$$

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

$b \to c\ell\nu$ (FCCC) Operators

$$H^{\text{eff}}_{b\to c\ell\nu} = \frac{4G_F V_{cb}}{\sqrt{2}} \sum_i C_i O_i \ , \tag{7}$$

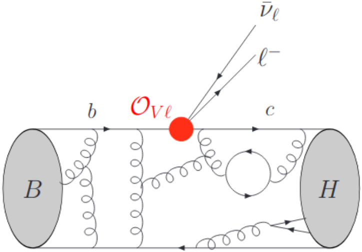
$$O^{cb\ell\nu}_{VL(R)} = [\bar{c}\gamma^\mu b][\bar{\ell}\gamma_\mu P_{L(R)}\nu] \ , \tag{8}$$

$$O^{cb\ell\nu}_{AL(R)} = [\bar{c}\gamma^\mu\gamma^5 b][\bar{\ell}\gamma_\mu P_{L(R)}\nu] \ , \tag{9}$$

$$O^{cb\ell\nu}_{SL(R)} = [\bar{c}b][\bar{\ell}P_{L(R)}\nu] \ , \tag{10}$$

$$O^{cb\ell\nu}_{PL(R)} = [\bar{c}\gamma^5 b][\bar{\ell}P_{L(R)}\nu] \ , \tag{11}$$

$$O^{cb\ell\nu}_{TL(R)} = [\bar{c}\sigma^{\mu\nu} b][\bar{\ell}\sigma_{\mu\nu}P_{L(R)}\nu] \ , \tag{12}$$



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

Assuming a sizable $(O^\tau_{VL} - O^\tau_{AL})^{\text{NP}} \sim 1$ is the case (allowed by data).

In SMEFT Base

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

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

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

$b \to s\nu\nu$ constrains $O^{(1)} - O^{(3)} \sim 0$, the remaining combination:

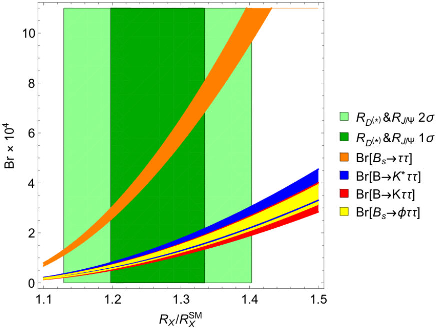
$$[O_{q\ell}^{(1)}]_{2333} + [O_{q\ell}^{(3)}]_{2333} \sim [\bar{c}\gamma^\mu P_L b][\bar{\tau}\gamma^\mu P_L \nu_\tau] + [\bar{s}\gamma^\mu P_L b][\bar{\tau}\gamma^\mu P_L \tau]$$

$$\Rightarrow (O_{VL}^\tau - O_{AL}^\tau)/2 + \frac{4\pi}{\alpha}(O_9^\tau - O_{10}^\tau)/2 \ . \tag{15}$$

FCCC amplitudes are tied with FCNC amplitudes

Enhanced BR$(b \to s\tau\tau)$

A moderate deviation in CC may change NC processes largely.



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

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

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

- LFUV by partial compositeness (especially 3rd generation!)
- Provide W' 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

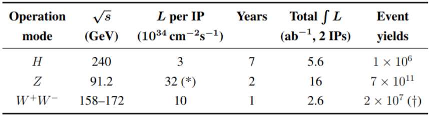
NP: Simplified Theories

Model	Spin	SM charge	$b \to c\tau\nu$ operators at Λ
Scalars	0	$(1,2)_0$	O^τ_S, O^τ_P
W'	1	$(1,3)_0$	$O^\tau_V - O^\tau_A$
LQ S_1	0	$(\bar{3},1)_{\frac{1}{3}}$	$O^\tau_V - O^\tau_A$, $O^\tau_S - O^\tau_P - 4O^\tau_T$
LQ S_3	0	$(\bar{3},3)_{\frac{1}{3}}$	$O^\tau_V - O^\tau_A$
LQ R_2	0	$(3,2)_{\frac{7}{6}}$	$O^\tau_S - O^\tau_P + 4O^\tau_T$
LQ U_1	1	$(3,1)_{\frac{2}{3}}$	$O^\tau_V - O^\tau_A$, $O^\tau_S + O^\tau_P$
LQ U_3	1	$(3,3)_{\frac{2}{3}}$	$O^\tau_V - O^\tau_A$
LQ V_3	1	$(3,2)_{\frac{5}{6}}$	$O^\tau_S + O^\tau_P$

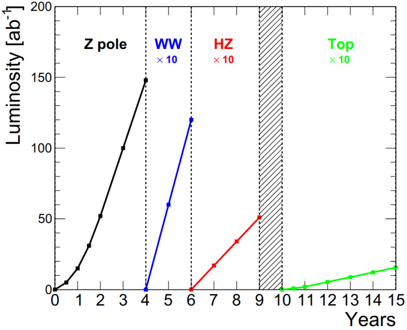
Favored simplifed models.

Section III: Unique Opportunities at Z pole

Z-factory will be a phase of future circular lepton collider.

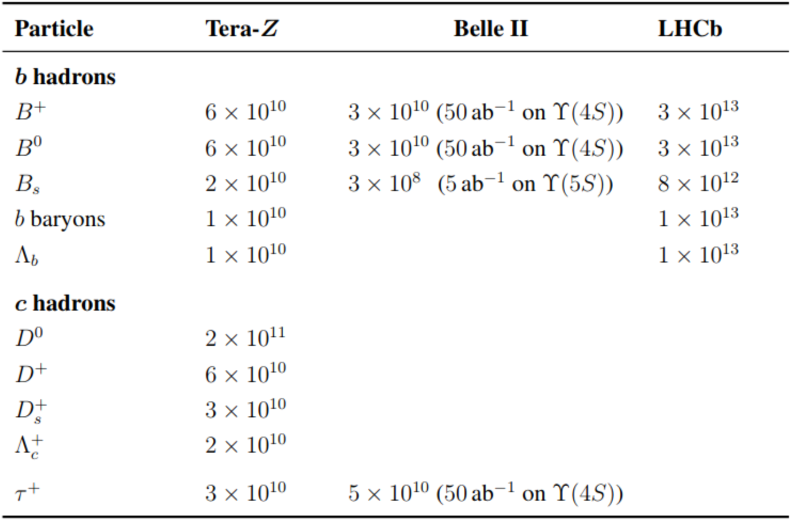


Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)



[Dong et al.(2018)][Abada et al.(2019)]

Unique Opportunities at Z pole (2)



Particle	**Tera-Z**	**Belle II**	**LHCb**
***b* hadrons**			
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
***c* hadrons**			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

[Dong et al.(2018)]

τ Final States

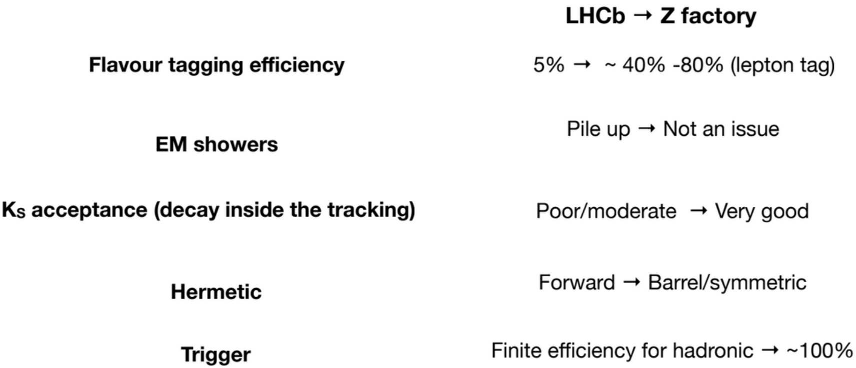
Short lifetime: $c\tau(\tau) \approx 20\%$ of $c\tau(B)$

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

B-Factory	Z-Factory
$\vec{V}(B) \sim 120\ \mu$m	$\sim$3mm
$\vec{V}(\tau) \sim 25\ \mu$m	$\sim$ 0.6mm
E($\pi^{\pm}$) from $\tau \lesssim 1$ GeV	$\gtrsim 2$ GeV

Mostly due to the boosted b from Z decay.

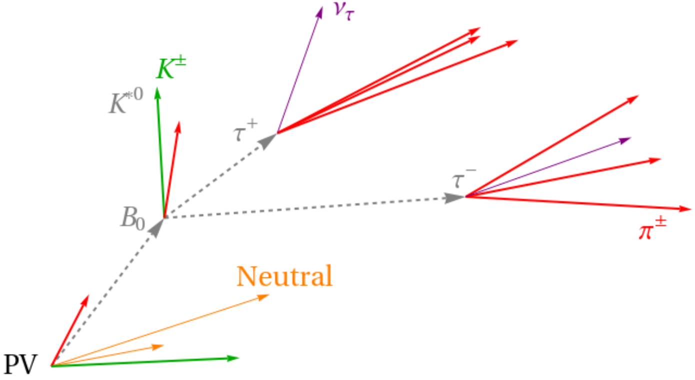
Comparison with LHCb



	LHCb → Z factory
Flavour tagging efficiency	5% → ~ 40% -80% (lepton tag)
EM showers	Pile up → Not an issue
K_S acceptance (decay inside the tracking)	Poor/moderate → Very good
Hermetic	Forward → Barrel/symmetric
Trigger	Finite efficiency for hadronic → ~100%

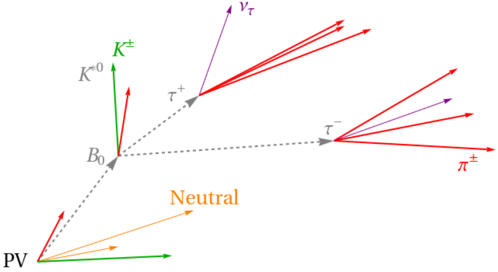
Taken from Elisabetta Barberio's talk during GRC 2019

Section IV: $b \to s\tau\tau$ Event Reconstruction Z Pole



A target $B^0 \to K^{*0}\tau^+\tau^-$ event to be reconstructed. Both ν are missing w/ neutral particles with larger error.

Complete Reconstruction



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

Linear Constraints

Flying direction is also the momentum direction:

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

$$\vec{p}_{\tau,i} \times \vec{V}_{\tau,i} = 0. \tag{17}$$

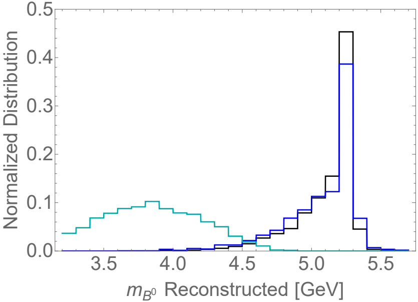
The solution of neutrino momenta thus take the form

$$\vec{p}_{\nu,i} = \frac{-\vec{p}_{K^{*0}} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}}{\vec{V}_{\tau,i} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}} \vec{V}_{\tau,i} - \vec{p}_{3\pi,i} \ , \tag{18}$$

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

Reconstruction of $B^0 \to K^{*0}\tau^+\tau^-$

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



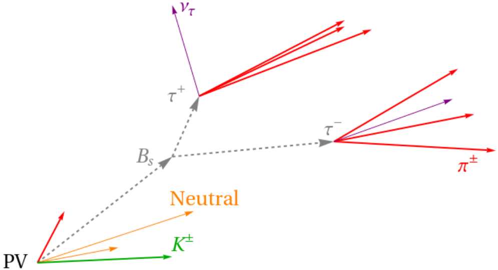
Cyan: Visible Only

Blue: From displacements

Black: Optimized w/ m_τ

Very similar performance when reconstructing $B_s \to \phi\tau^+\tau^-$.

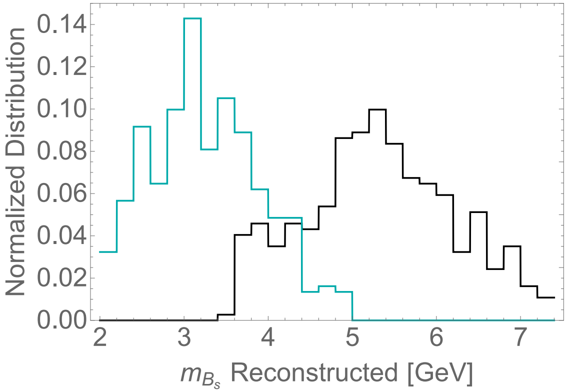
Partial Reconstruction



- Still 6 d.o.f.
- Only 2 detectable displacement vectors
- Need τ mass-shell condition
- Method similar to the LHCb study [Mordà(2015)]

A target $B_s \to \tau^+\tau^-$ event to be reconstructed.

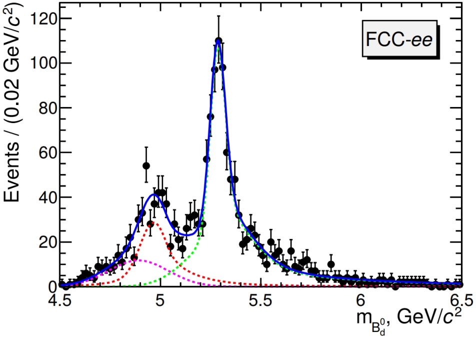
Reconstruction of $B_s \to \tau^+\tau^-$



Introducing preference on solutions with mass closer to m_{B_s} reproduces a narrow distribution, but also enforces backgrounds toward signal region.

Section V: Phenomenology

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



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

Measure $\mathcal{O}(10^{-7})$ BR with $\mathcal{O}(10\%)$ precision?

A Hint

Possible Backgrounds (2)

	Properties	Decay Mode	BR
τ	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.31%
	$c\tau = 87.0\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.62%
D_s	$m = 1.968$ GeV	$\tau\nu$	5.48%
	$c\tau = 151\ \mu$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%
$D^\pm$	$m = 1.870$ GeV	$\tau\nu$	$< 0.12\%$
	$c\tau = 311\ \mu$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%

π^0, K_S^0... from PV are not discernible with D decay products

Possible Backgrounds (3)

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

Example: Estimated $B^0 \to K^{*0}\tau^+\tau^-$ Backgrounds

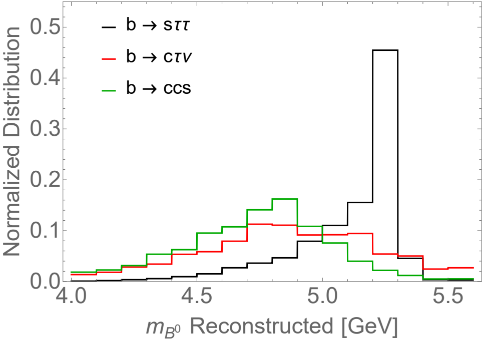
We list major backgrounds with leading CKM contribution.

Channel	Estimated BR
$b \to c\bar{c}s$ Type	
$B^0 \to K^{*0} D^{(*)+} D^{(*)-}$	1.1×10^{-2}
$B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$	1.1×10^{-2}
$B^0 \to K^{*0} D_s^{(*)+} D_s^{(*)-}$	7×10^{-3}
$b \to c\tau\nu$ Type	
$B_s \to K^{*0} D^{(*)-} \tau^+ \nu$	7×10^{-5}
$B^0 \to K^{*0} D_s^{(*)-} \tau^+ \nu$	7×10^{-5}

Typical background rates are $\mathcal{O}(10^5)$ larger than signal rate.

Reconstructed Mass of Various Bkgs

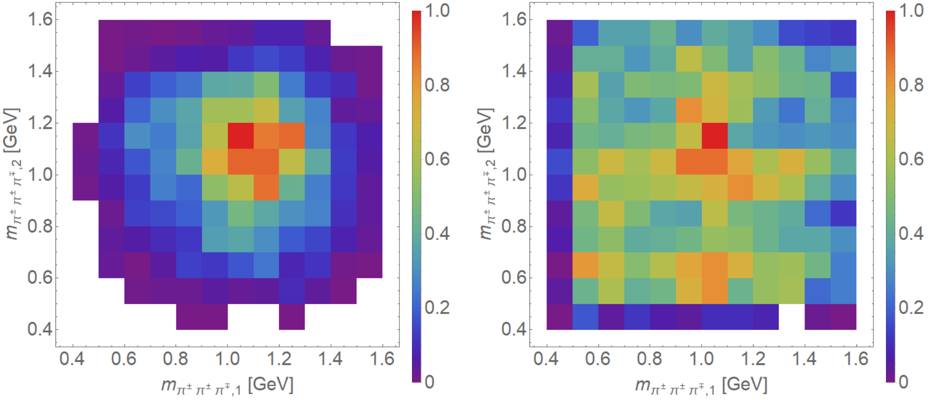
Normalized signal and background m_{B_0} distributions.



Not enough for detection, need to use other features largely independent of reconstruction.

As $\tau \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ mostly through $a_1^{\pm}(1260) \to \rho\pi$ ...

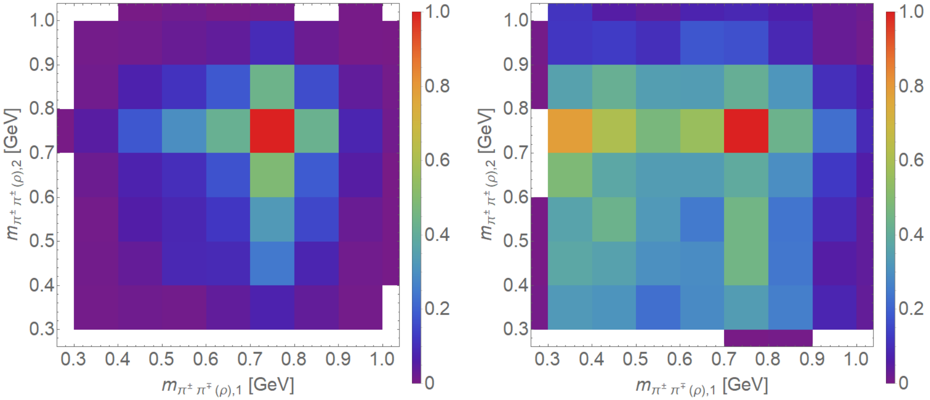
Invariant mass of each $\pi^{\pm}\pi^{\pm}\pi^{\mp}$:



Signals D_sD_s background

As $\tau \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ mostly through $a_1^{\pm}(1260) \to \rho\pi$ (2)

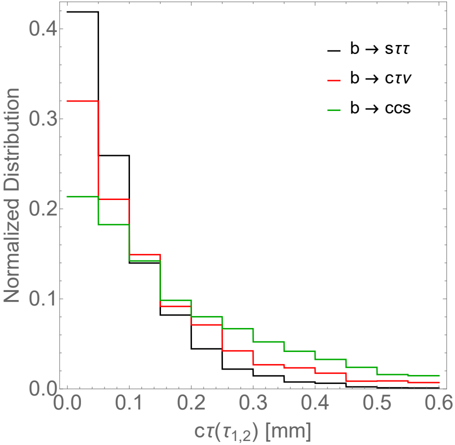
Invariant mass of the $\pi^+\pi^-$ pairs closer to m_ρ:



Signals

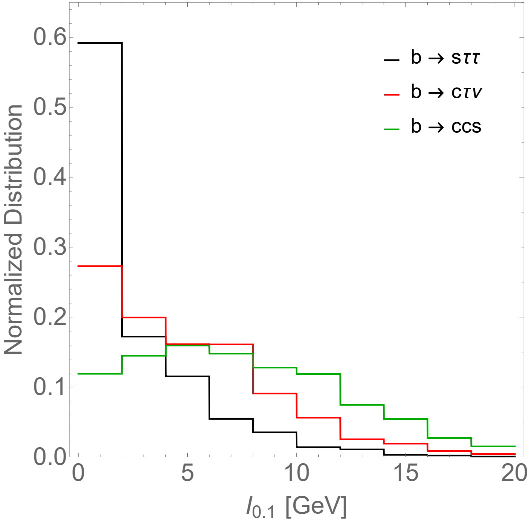
D_sD_s background

τ Lifetimes Reconstructed



$c\tau(\tau)$: 0.087 mm, $c\tau(D_s)$: 0.151 mm, $c\tau(D^{\pm})$: 0.311 mm

Vertex Isolation



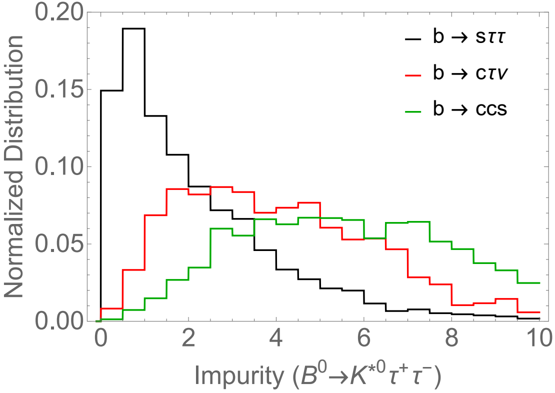
Energy of neutral components and very displaced tracks (from K_S^0) within a certain cone.

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

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

Separating Signal and Backgrounds

A simple linear combination of observable:



Reconstruction insensitive. Impurity < 1 events are chosen.

Section VI: Results and Discussion

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

Channel	BR	$\epsilon_{\text{pre}} \times 10^3$	$\epsilon_{\text{Impurity}} \times 10^2$	$\epsilon_{\text{Rec}} \times 10^2$	Tera-Z Yield
$B^0 \to K^{*0}\tau\tau$	0.98×10^{-7}	3.86	33.9	52.4	8.0
$B^0 \to K^{*0} D_s^{(*)-}\tau^+\nu$	7×10^{-5}	0.60	4.85	2.15	5.2
$B_s \to K^{*0} D^{(*)-}\tau^+\nu$	7×10^{-5}	0.26	3.43	3.66	0.7
$B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$	1.1×10^{-2}	0.46	0.83	2.04	2.7×10^1
$B^0 \to K^{*0} D^{(*)+} D^{(*)-}$	1.1×10^{-2}	0.16	0.57	1.03	1.3×10^1
$B^0 \to K^{*0} D_s^{(*)+} D_s^{(*)-}$	7×10^{-3}	0.89	1.36	1.60	1.7×10^2

- Traditional analysis.
- $\gtrsim \mathcal{O}(10^3)$ separation, healthy S/B ratio.
- Background type: $b \to ccs \ \gtrsim \ b \to c\tau\nu$.

Expectation and Comparison

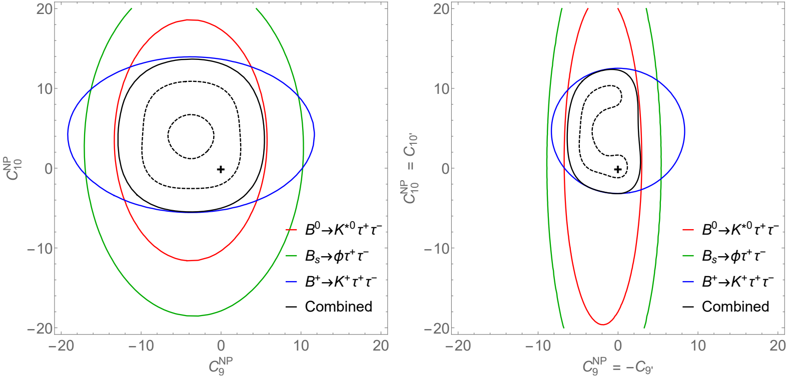
	Belle-II	LHCb (HL-LHC)	Tera-Z	10×Tera-Z
$B^0 \to K^{*0}\tau^+\tau^-$	-	-	1.8×10^{-7}	5.6×10^{-8}
$B_s \to \phi\tau^+\tau^-$	-	-	4.4×10^{-7}	1.4×10^{-7}
$B^+ \to K^+\tau^+\tau^-$	$< 2.0 \times 10^{-5}$	-	1.8×10^{-7}	5.6×10^{-8}
$B_s \to \tau^+\tau^-$	8.1×10^{-4}	5×10^{-4}	4.8×10^{-5}	1.5×10^{-5}

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

For the Giga-Z factories from linear machines, the precisions are of $\mathcal{O}(10^{-3} - 10^{-5})$ due to the small luminosity.

Constraint on LFUV Operators

Four coefficients ($C_9^{\rm NP}$, $C_{10}^{\rm NP}$, $C_{9'}$ and $C_{10'}$), here we show two scenarios:



Constraining NP operators within $\mathcal{O}(10)$.

Brief Summary

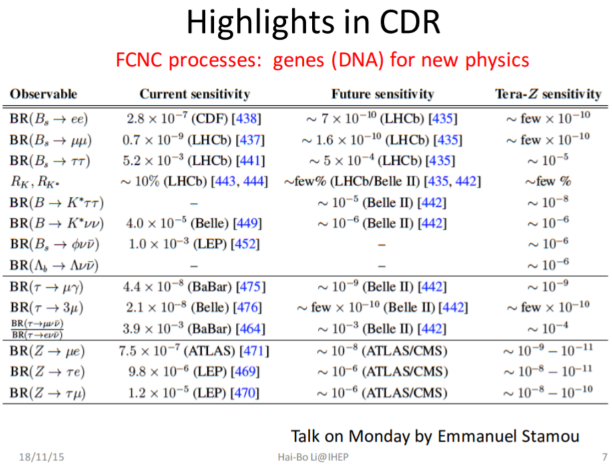
What we have done:

- Build reconstruction/analysis frameworks for each channel.
- Suppress large SM backgrounds coming from D meson, which are insufficiently discussed .
- Show that $b \to s\tau^+\tau^-$ rates can be measured down to unique and unprecedented $\mathcal{O}(10^{-5} - 10^{-7})$ level.

To be done:

- More detailed studies (e.g. differential and τ polarization measurements).
- New techniques: machine learning, advanced calorimetry (e.g. π^0 reconstruction [Shen et al.(2019)Shen, Xiao, Li, Qin, Wang, Wang, Zhang, and Ruan], reconstruction w/ missing energy).

Section VII: Outlook of Flavor @ Z pole



Highlights in CDR

FCNC processes: genes (DNA) for new physics

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Talk on Monday by Emmanuel Stamou

18/11/15 Hai-Bo Li@IHEP 7

Need to move on from the 2015 picture (inputs to the CEPC CDR and FCC studies)

Horizon of Open Directions

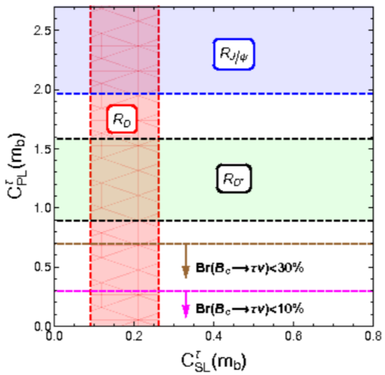
More flavor physics at Z pole:

- "Conventional" but unknown (e.g. $R_{D^{(*)}}$, $R_{K^{(*)}}$).
- "Known" but not exact yet (e.g. $b \to s\nu\nu$).
- B_c physics (or other double heavy-flavor ones).
- Other heavy b hadron (e.g. Λ_b) physics.
- Time dependent CPV measurements.
- Tau physics.
- Charm physics.
- Exotic hadron (e.g. pentaquark, XYZ) physics.
- Synergize with BSM searches.

……

B_c Physics(1)

Produced by double heavy flavor process at Z pole Current knowledge from Z pole and hadron colliders

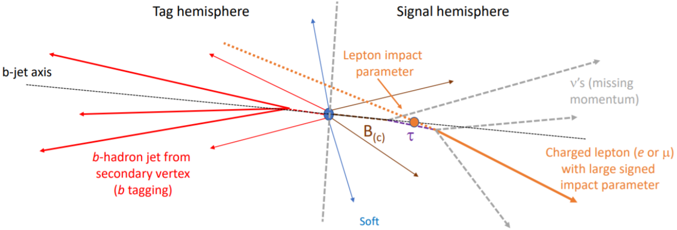


[Aaij et al.(2018b)]

$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1})$	$\times 10^{-5}$
$J/\psi(1S)\pi^+$	seen	
$J/\psi(1S)K^+$	seen	
$J/\psi(1S)\pi^+\pi^+\pi^-$	seen	
$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$
$J/\psi(1S)K^+K^-\pi^+$	seen	
$\psi(2S)\pi^+$	seen	
$J/\psi(1S)D_s^+$	seen	
$J/\psi(1S)D_s^{*+}$	seen	
$D^*(2010)^+\overline{D}^0$	< 6.2	$\times 10^{-3}$
D^+K^{*0}	< 0.20	$\times 10^{-6}$
$D^+\overline{K}^{*0}$	< 0.16	$\times 10^{-6}$
$D_s^+K^{*0}$	< 0.28	$\times 10^{-6}$
$D_s^+\overline{K}^{*0}$	< 0.4	$\times 10^{-6}$
$D_s^+\phi$	< 0.32	$\times 10^{-6}$
K^+K^0	< 4.6	$\times 10^{-7}$
$B_s^0\pi^+$ / B($\overline{b} \to B_s$)	$(2.37\ ^{+0.37}_{-0.35})$	$\times 10^{-3}$

BR$\times f(\bar{b} \to B_c)$ taken from PDG report.

B_c Physics(2)



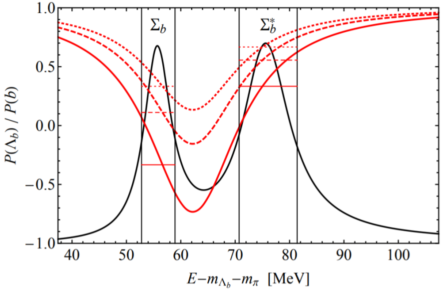
Taken from Taifan's talk during the January meeting, $\mathcal{O}(1)\%$ precision on BR$(B_c \to \tau\nu)$

- Any way to measure BR$(Z \to B_c + X)$, hence $f(\bar{b} \to B_c)$?
- $B_c \to J/\psi D^{(*)}$, $B_c \to D^{(*)}\ell\nu$, R_{η_c}?
- The extra charm produced may help?

Heavy b hadron, e.g. Λ_b physics

Λ_b is common (comparable with B_s) at Z pole.

- $\Lambda_b \to \Lambda\ell\ell(\tau\tau)$.
- $\Lambda_b \to \Lambda_c\ell(\tau)\nu$.
- Polarization related: Keeps $\mathcal{O}(1)$ of b polarization before washed out by $\Sigma_b^{(*)}$ decay [Kats(2017)].



[Galanti et al.(2015)Galanti, Giammanco, Grossman, Kats, Stamou, and Zupan]

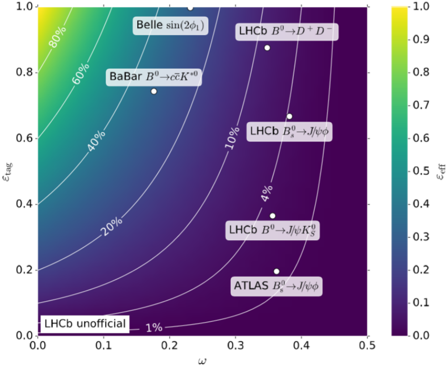
Asymmetries cancelling large uncertainties:

$$A_{\mathrm{pol,FB}} = \frac{(\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{L}} - (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{R}}}{(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{L}} + (\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{R}}}\ ,$$

$$A_{\theta_S} - \bar{A}_{\theta_S} \sim \frac{(\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}})_{\Lambda_b} - (\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}})_{\bar{\Lambda}_b}}{(\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}})_{\Lambda_b} + (\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}})_{\bar{\Lambda}_b}}$$

[Hiller and Kagan(2002)]

Time Dependent CPV Measurements



Flavor tagging $b = +1, 0$ or -1 is a key issue $(B^0 \leftrightarrow \bar{B}^0)$

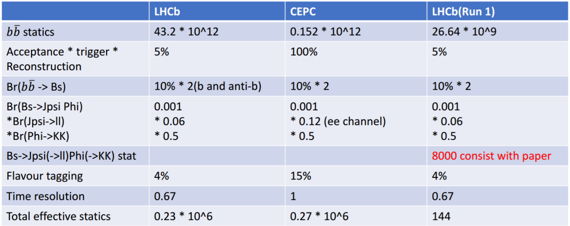
- $\epsilon_{\rm eff} = \epsilon_{\rm tag}(1 - 2\omega)^2$
- Cleaner environment may allow stronger tagging power than LHCb ($\gtrsim 15\%$).

[Aaij et al.(2018b)]

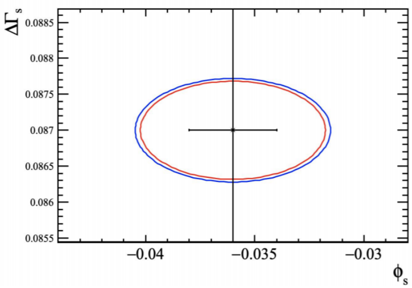
Other prospects: PV reconstruction (and thus no tag side interference effect [Long et al.(2003)Long, Baak, Cahn, and Kirkby]), better spacial/energy resolutions, etc.

Time Dependent CPV Measurements(2)

Example: CPV in $B_s \to J/\psi\phi$ (from Mingrui Zhao's talk).



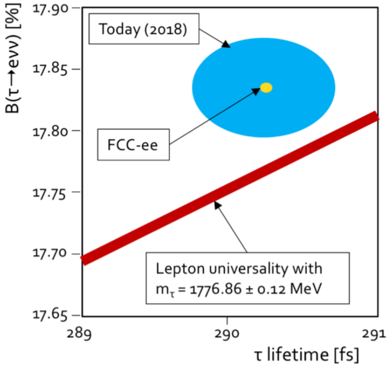
	LHCb	CEPC	LHCb(Run 1)
$b\bar{b}$ statics	43.2 * 10^12	0.152 * 10^12	26.64 * 10^9
Acceptance * trigger * Reconstruction	5%	100%	5%
Br($b\bar{b}$ -> Bs)	10% * 2(b and anti-b)	10% * 2	10% * 2
Br(Bs->Jpsi Phi) *Br(Jpsi->ll) *Br(Phi->KK)	0.001 * 0.06 * 0.5	0.001 * 0.12 (ee channel) * 0.5	0.001 * 0.06 * 0.5
Bs->Jpsi(->ll)Phi(->KK) stat			8000 consist with paper
Flavour tagging	4%	15%	4%
Time resolution	0.67	1	0.67
Total effective statics	0.23 * 10^6	0.27 * 10^6	144



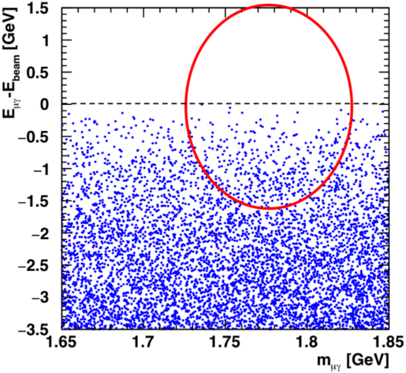
Better efficiency/acceptance and tagging power ensure a performance of CEPC comparable to LHCb(HL-LHC).

Tau Physics

Z-factory also a τ factory [Dam(2019)].



τ properties measurements

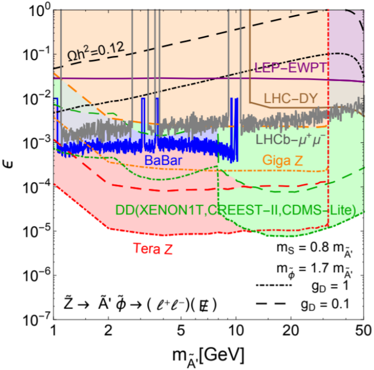


BR$(\tau \to \mu\gamma)$ measurement

- CPV τ decays, e.g. in $\tau \to K_S^0 \nu + n\pi$ (tension w/ SM).
- $Z \to \tau\tau$ polarization ($\sin\theta_W$ down to $\mathcal{O}(10^{-6})$).
- Hadronic and inclusive modes (e.g. $\alpha_s(m_\tau^2)$).

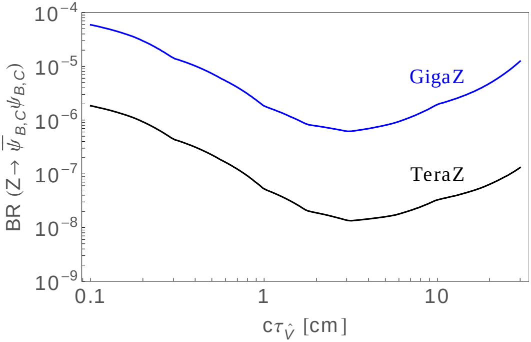
Synergy with BSM Searches

Light dark sector particles produced by Z exotic decays and go back to SM, giving narrow resonances.



Weakly interacting, dark photon like signal

[Liu et al.(2018)Liu, Liu, Wagner, and Wang]



Strongly interacting, emerging jet like signal

[Cheng et al.(2019)Cheng, Li, Salvioni, and Verhaaren]

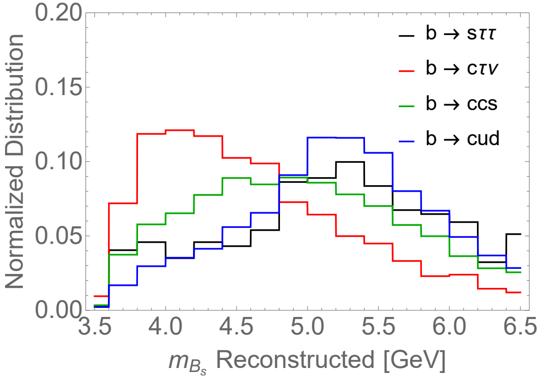
Conclusion

- Z-factories are the perfect bridge between flavor and high energy precision physics.
- It is possible to see $b \to s\tau^+\tau^-$ transitions with Tera-Z.
- A lot of work remains to be done for a solid "taste" of physics at Z pole.

Backup Slides

Backup and Preliminary

Reconstructed Mass Difference of Various Bkgs (2)



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

Background Estimation

Preliminary estimation of BR$(B^0 \to K^{*0} D^{(*)+} D^{(*)-})$ by [Renato(2017-09-27)]:

$$\frac{\mathrm{BR}(B^0 \to D^{(*)0} \bar{D}^{(*)0} K^{*0})}{\mathrm{BR}(B^0 \to D^{(*)+} D^{(*)-} K^{*0})} \simeq \frac{\mathrm{BR}(B^0 \to D^{(*)0} \bar{D}^{(*)0} K^{0})}{\mathrm{BR}(B^0 \to D^{(*)+} D^{(*)-} K^{0})} , \tag{19}$$

and

$$\frac{\mathrm{BR}(B^0 \to D^{(*)0} \bar{D}^{(*)0} K^{*0})}{\mathrm{BR}(B^0 \to D^{(*)0} \bar{D}^{(*)0} K^{0})} \simeq \frac{\mathrm{BR}(B^0 \to D^{0} K^{*0})}{\mathrm{BR}(B^0 \to D^{0} K^{0})} . \tag{20}$$

Background Estimation(2)

To estimate BR$(B_s \to \phi D^{(*)+} D^{(*)-})$, use previous results and:

$$\frac{\mathrm{BR}(B_s \to \phi D^{(*)+} D^{(*)-})}{\mathrm{BR}(B^0 \to K^{*0} D^{(*)+} D^{(*)-})} \simeq \frac{\mathrm{BR}(B_s \to \phi X_{c\bar{c}})}{\mathrm{BR}(B^0 \to K^{*0} X_{c\bar{c}})} \,. \tag{21}$$

~ 0.4 after averaging several charmonium modes.

Impurity Definition

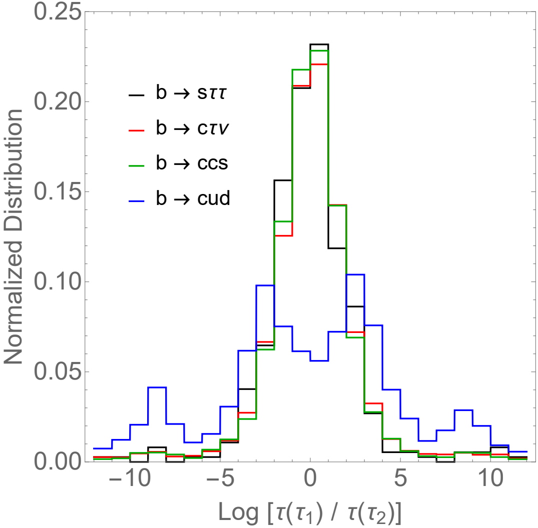
Takes the same form for all channels:

$$0.4\frac{I_{0.1}}{\mathsf{GeV}}+0.2\frac{I_{0.2}}{\mathsf{GeV}}+0.3\frac{|(m_{\pi^\pm\pi^\mp(\rho),1}-m_{\rho^0})(m_{\pi^\pm\pi^\mp(\rho),2}-m_{\rho^0})|}{m_\tau^2} \tag{22}$$

$$+0.1\sum_{i=1,2}\frac{(m_{\pi^\pm\pi^\pm\pi^\mp,i}-m_{a_1})^2}{m_\tau^2}+0.3\sum_{i=1,2}\frac{\tau_{\tau(\mathrm{rec}),\mathrm{i}}}{\tau_\tau}+0.3\ \mathsf{Log}^2\left[\frac{\tau_{\tau(\mathrm{rec},1)}}{\tau_{\tau(\mathrm{rec},2)}}\right].$$

The orange term is to remove $b \to c\bar{u}d$ and only applies to $B_s \to \tau^+\tau^-$ channel.

Reconstructed τ Lifetime Ratio



Obvious difference for $b \to c\bar{u}d$ type backgrounds.

Yield of $B_s \to \phi\tau^+\tau^-$

Channel	Assumed BR	$\epsilon_{\rm pre} \times 10^3$	$\epsilon_{\rm Score} \times 10^2$	$\epsilon_{\rm Rec} \times 10^2$	Tera-Z Yield
$B_s \to \phi\tau^+\tau^-$	0.86×10^{-7}	2.48	34.1	54.7	1.3
$B_s \to \phi D_s^{(*)-}\tau^+\nu$	5×10^{-5}	0.56	6.03	2.47	5.0
$B^0 \to \phi D^{(*)-}\tau^+\nu$	5×10^{-5}	0.26	6.80	2.16	0.6
$B_s \to \phi D_s^{(*)+} D_s^{(*)-}$	3×10^{-3}	0.97	1.37	1.39	1.8×10^1
$B^0 \to \phi D_s^{(*)+} D^{(*)-}$	5×10^{-3}	0.25	1.64	0.70	1.7×10^1
$B_s \to \phi D^{(*)+} D^{(*)-}$	5×10^{-3}	0.16	1.61	0.60	2.5

Yield of $B^+ \to K^+\tau^+\tau^-$

Channel	Assumed BR	$\epsilon_{\rm pre} \times 10^3$	$\epsilon_{\rm Score} \times 10^2$	$\epsilon_{\rm Rec} \times 10^2$	Tera-Z Yield
$B^+ \to K^+\tau^+\tau^-$	1.2×10^{-7}	5.95	36.2	52.3	20.0
$B^+ \to K^+D_s^{(*)-}\tau^+\nu$	1.3×10^{-4}	3.61	6.59	2.50	1.5×10^2
$B^+ \to K^+D_s^{(*)+}D_s^{(*)-}$	1.9×10^{-3}	6.03	1.03	2.35	5.7×10^2
$B^+ \to K^+D^{(*)+}D^{(*)-}$	2.8×10^{-3}	0.48	1.08	4.69	1.4×10^2

Yield of $B_s \to \tau^+\tau^-$

Channel	Assumed BR	$\epsilon_{\rm pre} \times 10^3$	$\epsilon_{\rm Score} \times 10^2$	$\epsilon_{\rm Rec} \times 10^2$	Tera-Z Yield
$B_s \to \tau^+\tau^-$	7.73×10^{-7}	3.97	14.0	60.8	8.4
$B_s \to D_s^{(*)-}\tau^+\nu$	2.4×10^{-2}	5.59	3.43	27.7	4.1×10^4
$B^0 \to D^{(*)-}\tau^+\nu$	2.7×10^{-2}	3.24	3.49	25.5	9.3×10^4
$B_s \to D_s^{(*)+}D_s^{(*)-}$	4.5×10^{-2}	6.82	0.51	47.8	8.0×10^4
$B^0 \to D_s^{(*)+}D^{(*)-}$	4.03×10^{-2}	4.11	0.43	54.5	1.4×10^4
$B^0 \to D^{(*)-}\pi^+\pi^+\pi^-$	7.7×10^{-3}	1.13	1.05	44.3	4.9×10^3
$B^0 \to D^{(*)-}a_1^+$	1.9×10^{-2}	7.43	0.24	58.0	2.4×10^4
$B_s \to D_s^{(*)-}\pi^+\pi^+\pi^-$	1.38×10^{-2}	2.38	0.23	52.4	1.3×10^3
$B_s \to D_s^{(*)-}a_1^+$	2.1×10^{-2}	9.4	0.47	56.7	1.7×10^4

BR and NP Operators

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

$$\mathrm{BR}(B^0 \to K^{*0}\tau^+\tau^-) \times 10^7 = 0.98 + 0.38C_9^{\mathrm{NP}} - 0.14C_{10}^{\mathrm{NP}} - 0.30C_{9'} + 0.12C_{10'} - 0.08C_9^{\mathrm{NP}}C_{9'} - 0.03C_{10}^{\mathrm{NP}}C_{10'} + 0.05(C_9^{\mathrm{NP}})^2 + 0.02(C_{10}^{\mathrm{NP}})^2 + 0.05(C_{9'})^2 + 0.02(C_{10'})^2 \,, \tag{23}$$

$$\mathrm{BR}(B_s \to \phi\tau^+\tau^-) \times 10^7 = 0.86 + 0.34C_9^{\mathrm{NP}} - 0.11C_{10}^{\mathrm{NP}} - 0.28C_{9'} + 0.10C_{10'} - 0.08C_9^{\mathrm{NP}}C_{9'} - 0.02C_{10}^{\mathrm{NP}}C_{10'} + 0.05(C_9^{\mathrm{NP}})^2 + 0.01(C_{10}^{\mathrm{NP}})^2 + 0.05(C_{9'})^2 + 0.01(C_{10'})^2 \,, \tag{24}$$

$$\mathrm{BR}(B^+ \to K^+\tau^+\tau^-) \times 10^7 = 1.20 + 0.15C_9^{\mathrm{NP}} - 0.42C_{10}^{\mathrm{NP}} + 0.15C_{9'} - 0.42C_{10'} + 0.04C_9^{\mathrm{NP}}C_{9'} + 0.10C_{10}^{\mathrm{NP}}C_{10'} + 0.02(C_9^{\mathrm{NP}})^2 + 0.05(C_{10}^{\mathrm{NP}})^2 + 0.02(C_{9'})^2 + 0.05(C_{10'})^2 \,. \tag{25}$$

Finite Spacial Resolution

9 extra d.o.f. from $\vec{V}$ uncertainties $\rightarrow$ rescaling invariance of 3 $\vec{V}_i \rightarrow \rightarrow$ 6 d.o.f remains.

When applied to $B^0 \rightarrow K^{*0}\tau^+\tau^-$ with all $\vec{V}$ smeared by 10 μm: An naive attempt try to cancel the impact: ~ 200 MeV larger STD in $m_{B^0,(\mathrm{rec})}$ (or increase by 90%).

Reconstruction success rate only drops by $\sim 7\%$.

$B_s \to \tau^+\tau^-$ Reconstruction

$$\vec{V}_{\tau,1} = \hat{\tau}_{B_s}(\vec{p}_{\tau,1} + \vec{p}_{\tau,2}) + \hat{\tau}_{\tau,1}\vec{p}_{\tau,1} \ , \tag{26}$$

$$\vec{V}_{\tau,2} = \hat{\tau}_{B_s}(\vec{p}_{\tau,1} + \vec{p}_{\tau,2}) + \hat{\tau}_{\tau,2}\vec{p}_{\tau,2} \ , \tag{27}$$

$$\mathbf{V} = \mathbf{HP} \ , \ \mathbf{H} \equiv \begin{pmatrix} \hat{\tau}_{\tau,1} + \hat{\tau}_{B_s} & \hat{\tau}_{B_s} \\ \hat{\tau}_{B_s} & \hat{\tau}_{\tau,2} + \hat{\tau}_{B_s} \end{pmatrix} \ , \tag{28}$$

$$\mathbf{V} \equiv \begin{pmatrix} \vec{V}_{\tau,1} \\ \vec{V}_{\tau,2} \end{pmatrix} \ , \ \mathbf{P} \equiv \begin{pmatrix} \vec{p}_{\tau,1} \\ \vec{p}_{\tau,2} \end{pmatrix} .$$

Reconstruct by minizing

$$\epsilon^2 = \sum_{i=1,2} \frac{[m_{\tau(\mathrm{rec}),i} - m_\tau]^2}{m_\tau^2} + \sum_{i,j} \frac{|(\mathbf{V} - \mathbf{HP})|_{ij}^2}{|\mathbf{V}|_{ij}^2} \ . \tag{29}$$

R. Aaij et al.
Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$.
Phys. Rev. Lett., 120(12):121801, 2018a.
doi: 10.1103/PhysRevLett.120.121801.

Roel Aaij et al.
Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era.
2018b.

A. Abada et al.
Future Circular Collider.
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