Heavy Flavor Physics at Future Z Factories

(Using LFU Tests as an Example)

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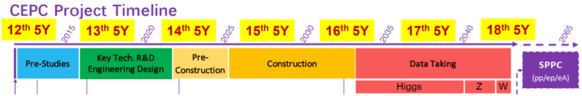
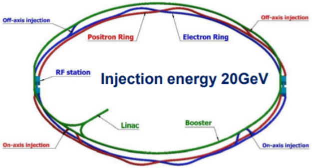
Based on arXiv:2012.00665 with Tao Liu
and several ongoing projects

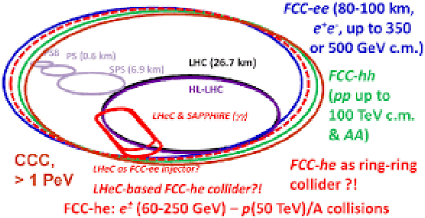
Dec. 2, Light Cone 2021, Jeju Island

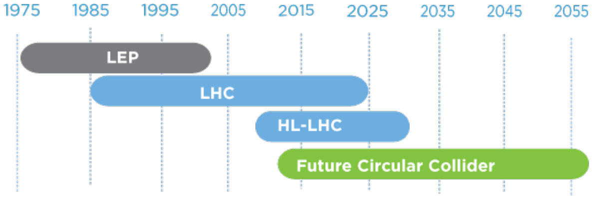
Intro: What are future Z Factories?



- 100 km collider and booster ring







Plan Ahead for the Future Z Factories

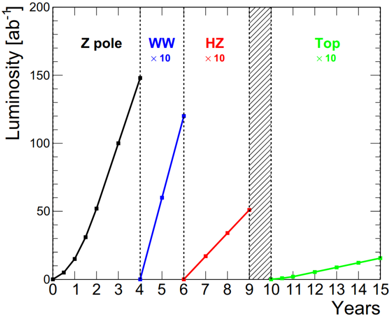
Make the best use of data: flavor physics "for free".

	ttbar	Higgs	W	Z
Number of IPs	2			

Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	7.7
CDR	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	5.0	115	15.4	0.5
	$\int L\,dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	1.7×10^6	2.5×10^{12}	3×10^7	3×10^5

	ttbar	Higgs	W	Z
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

CEPC $\sim 2.5\times$Tera-Z



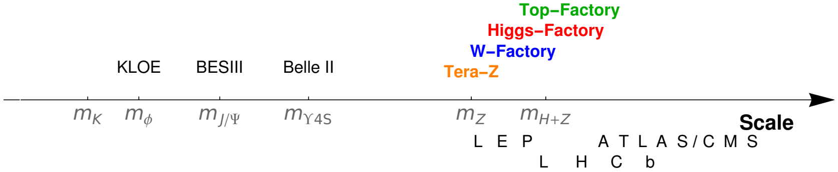
FCC-ee $\sim 7\times$ Tera-Z

Flavor Physics at the Z Pole

Z Factory $\supseteq$ Flavor Factory

Particle-ID $\supseteq$ Flavor-ID!

Channel	Belle II	LHCb	Giga-Z (10^9 Z)	Tera-Z (10^{12} Z)
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}
c, $\bar{c}$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^8	2.4×10^{11}
τ^+, τ^-	9×10^{10}	-	7.4×10^7	7.4×10^{10}



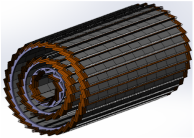
VS. B Factories

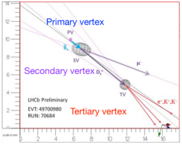
- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement

Key Detector Features for Flavor Physics



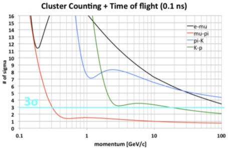


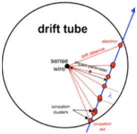
Tracking sys, grants $\mathcal{O}(10)$ fs sensitivity.

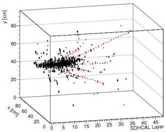
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater acceptance for displaced signals.

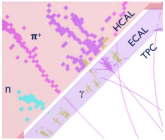
Advanced PID coming from the combination of different methods.

- Flavor tagging for everything.
- Suppressing backgrounds in general.
- Clean leptonic/baryonic modes.





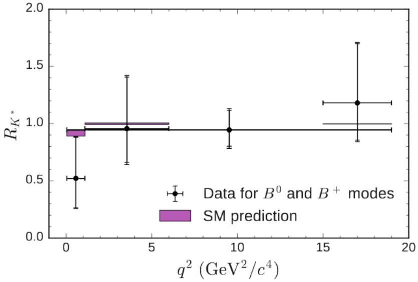


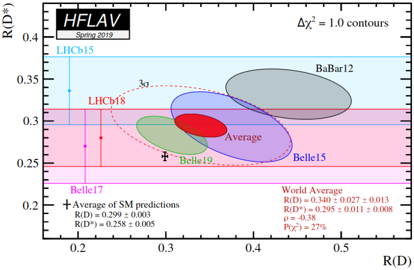


Calorimetry gives neutral energy and angular resolution.

- Better $\not{p}$ measurement for neutrinos.
- Excited states such as D_s^* and radiative decays.
- Distinguishing π^0/η..., allowing h^0X modes.

B Anomalies Indicating LFUV

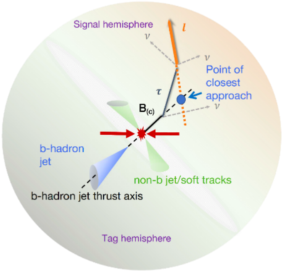




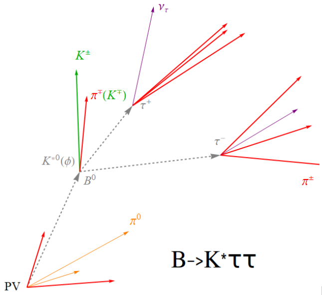
	Experimental	SM Prediction	Comments
R_K	$0.846^{+0.044}_{-0.041}$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^{\pm}$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_{pK}	$0.86^{+0.14}_{-0.11} \pm 0.05$	~ 1	$m_{\ell\ell} \in [0.1, 6.0]$ GeV^2, via Λ_b.
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][Aaij et al., 2021][Aaij et al., 2020].

Pinning Down B Anomalies

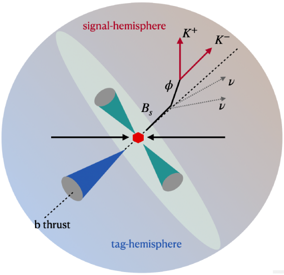


Charged current $b \to c\tau\nu$ decays [Zheng et al., 2020, Amhis et al., 2021]. Absolute precision $\sim 10^{-4}$.



Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

Absolute precision $\lesssim 10^{-6}$: $\sim 10^3 - 10^4$ improvement from current limits.



Neutral current $B_s \to \phi\nu\bar{\nu}$ decay [In preparation]

Not an anomaly yet but closely related

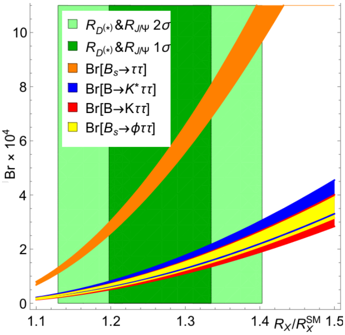
Absolute precision $\sim 10^{-7}$.

Unique opportunities at the Z-pole

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 $\mathcal{O}(10^{-2.5})$



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

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

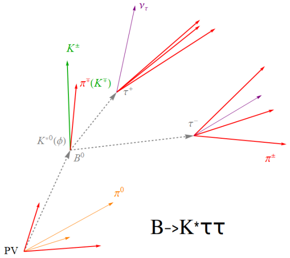
$$\sim \mathcal{O}(10) \times C_{9/10}^{\rm SM}$$

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

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

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

Overwhelmingly Large SM Backgrounds



Use τ 3-prong decay to locate each vertex

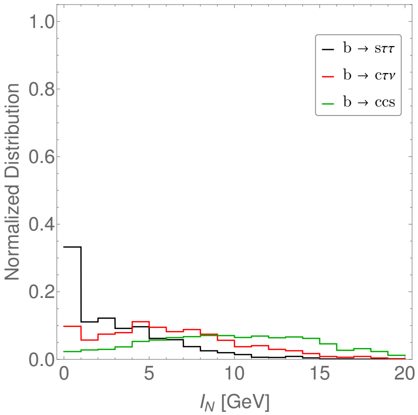
Dominant background from inclusive $D^\pm_{(s)}$ hadronic decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV $c\tau = 87.0$ μm	$\pi^\pm\pi^\pm\pi^\mp\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	9.3% 4.6%
$D_s^\pm$	$m = 1.968$ GeV $c\tau = 151$ μm	$\tau^\pm\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0$ $\pi^\pm\pi^\pm\pi^\mp 2\pi^0$ $\pi^\pm\pi^\pm\pi^\mp K_S^0$ $\pi^\pm\pi^\pm\pi^\mp\phi$	5.5% 0.6% 4.6% 0.3% 1.2%
$D^\pm$	$m = 1.870$ GeV $c\tau = 311$ μm	$\tau^\pm\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0$ $\pi^\pm\pi^\pm\pi^\mp K_S^0$	$< 0.12\%$ 1.1% 3.0%

Background types		Typical BR
$b \to c\bar{c}s$	(e.g. $B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$)	$\mathcal{O}(10^{-2} - 10^{-3})$
$b \to c\tau\nu$	(e.g. $B^0 \to K^{*0} D_s^{(*)-} \tau^+\nu$)	$\mathcal{O}(10^{-3} - 10^{-5})$
$b \to c\bar{u}d$	(e.g. $B^0 \to D^{(*)-}\pi^+\pi^+\pi^-$)	$\mathcal{O}(10^{-2} - 10^{-3})$

Background overwhelming ($\mathcal{O}(10^5)$ larger before cuts) rather than background free!

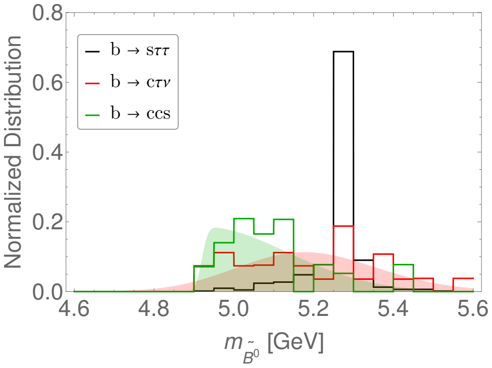
Efforts to Remove Backgrounds



$\Leftarrow$ Good calorimetry saves the day by vetoing extra neutral particles from $D_{(s)}$ decays.

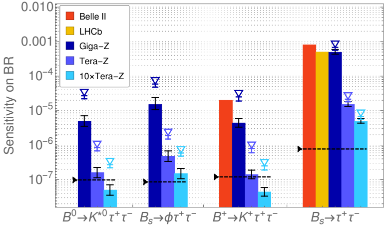
(Potential improvements with "smart" algorithms.)

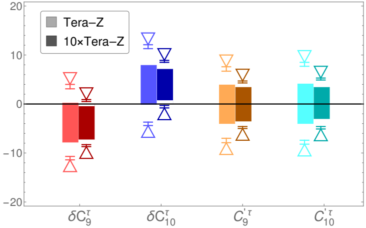
$\Rightarrow$ Kinmematics of each vertex/track provide B mass peak reconstruction.



Projected Limits

More details in the published work [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!
- EFT-wise way beyond current experimental constraints ($\mathcal{O}(10^3)$).

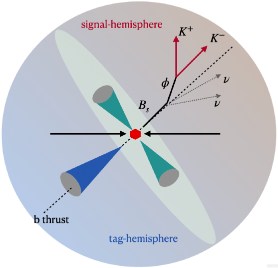
Rare FCNC Decays: $B_s \to \phi\nu\nu$ (Prelim.)

w/ Manqi Ruan, Yudong Wang et al.

$b \to s\nu\nu$ 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($B_s \to \phi\nu\bar{\nu}$)	$< 5.4 \times 10^{-3}$	$(9.93 \pm 0.72) \times 10^{-6}$

[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).

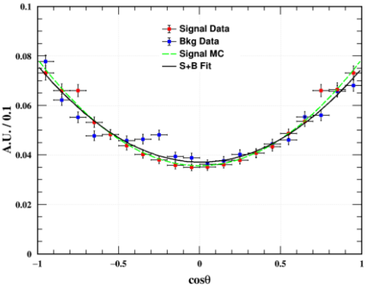
Most likely to have a breakthrough at Z factories.

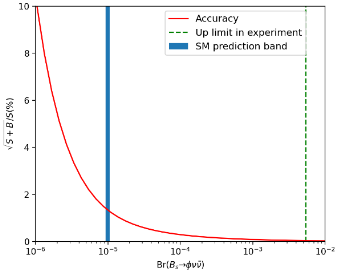
Based on the full simulation of the CEPC.

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

Cuts	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events ($10^{12} Z$)	3.03×10^{5}	4.28×10^{11}	1.20×10^{11}	1.51×10^{11}	6.99×10^{11}	276
$N_{\phi(\to K^+K^-)} > 0$	1.24×10^{5}	1.27×10^{10}	7.23×10^{9}	8.56×10^{9}	2.85×10^{10}	136
[a]Signal ϕ	9.00×10^{4}	1.39×10^{9}	1.55×10^{9}	3.14×10^{9}	6.08×10^{9}	86.7
Energy asymmetry > 8 GeV	7.61×10^{4}	2.97×10^{8}	3.61×10^{8}	9.05×10^{8}	1.56×10^{9}	51.9
Energy total < 85 GeV	7.36×10^{4}	6.28×10^{7}	1.16×10^{8}	4.65×10^{8}	6.44×10^{8}	34.5
$E^N_{B_s} > 28$ GeV	6.40×10^{4}	1.77×10^{7}	3.03×10^{7}	8.83×10^{7}	1.36×10^{8}	18.2
$\alpha < 1.0$	4.34×10^{4}	6.22×10^{6}	6.42×10^{6}	1.00×10^{7}	2.26×10^{7}	11.0
b-tag > 0.6	3.34×10^{4}	$< 2.0\times10^{4}$	2.54×10^{5}	6.44×10^{6}	6.69×10^{6}	7.76
$E_\mu < 1.2$ GeV and $E_e < 1.2$ GeV	3.02×10^{4}	-	1.08×10^{5}	2.33×10^{6}	2.44×10^{6}	5.20
$(1-\alpha_1)/\theta^{\text{miss}}_\phi < 2.0$	2.04×10^{4}	-	2.82×10^{4}	4.53×10^{5}	4.81×10^{5}	3.47
$q^2 < 9.0$ GeV	1.27×10^{4}	-	1.11×10^{4}	5.48×10^{4}	6.59×10^{4}	2.20
BDT response> 0.29	1.23×10^{4}	-	$< 2\times10^{3}$	1.65×10^{4}	$< 1.85\times10^{4}$	1.43
Efficiency	4.06%	-	$< 1.67\times10^{-8}$	1.09×10^{-7}	2.65×10^{-8}	

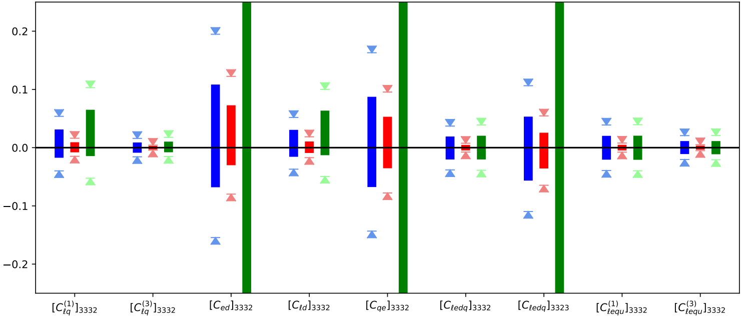
$\sim 1\%$ relative ($\sim 10^{-7}$ absolute) precision





Also able to provide the polarization info of the vector ϕ.

SMEFT Projections (Prelim).



$\Uparrow$ Tera-Z, $10\times$Tera-Z, Tera-Z but forgot $b \to s\tau\tau$

(The worst three $\sim \mathcal{O}(0.5)$.)

Probing ~ 10 TeV scale for $\mathcal{O}(1)$ couplings.

Summary

- Flavor physics is related to BSM, SM precision tests, pQCD, lattice, ... everything! Tera-Z is the bridge.
- Flavor studies at the Z-pole benefit from:
  1. Large luminosity (from accelerator physics)
  2. Clean environment and moderate energy (from m_Z)
  3. Good or even revolutionary detectors (from detector R&D)
- New collider/detector at the precision era: new challenges!

- A flavor physics white paper is ongoing. Contributions from all over the community are necessary.

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