Scrutinizing B Anomalies with the Future Lepton Machine

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

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Prologue

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

[Someone Awesome (2019?)]

Lepton Flavor Universality (Violation)

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

However, in both flavor changing neutral current (FCNC) and flavor changing neutral current (FCCC) processes

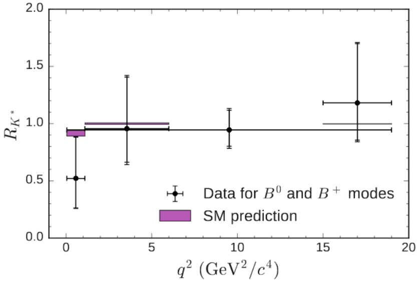
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \ , \tag{1}$$

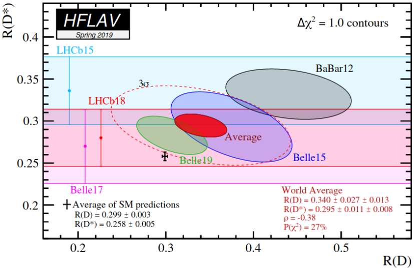
$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \ , \tag{2}$$

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

LFU is challenged.

B Anomalies Indicating LFUV



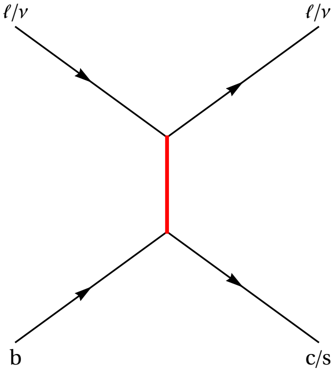


	Experimental	SM Prediction	Comments
R_K	$0.846^{+0.044}_{-0.041}$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^{\pm}$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_{pK}	$0.86^{+0.14}_{-0.11} \pm 0.05$	~ 1	$m_{\ell\ell} \in [0.1, 6.0]$ GeV^2,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

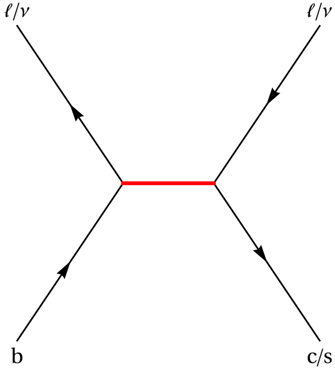
[Tanabashi et al., 2018][Altmannshofer et al., 2018][Aaij et al., 2021][Aaij et al., 2020].

LFUV in BSM: Simplified Models (LO)

Induced by two types of heavy mediators:



Colorless Mediators



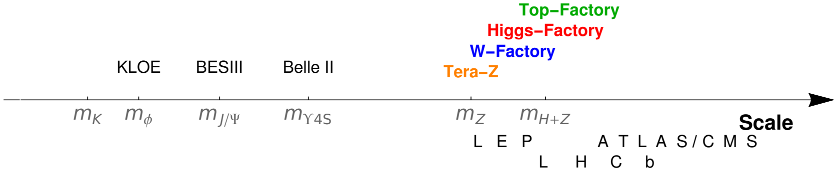
Colored Mediators (Leptoquarks)

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}



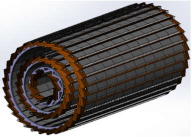
VS. B Factories

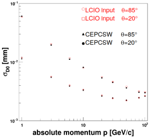
- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement

Key Detector Features for Flavor Physics



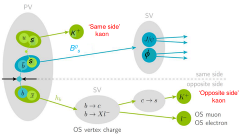


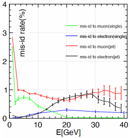
Tracking sys, grants $\mathcal{O}(10)$ fs sensitivity.

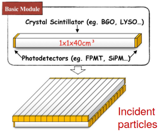
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater acceptance for displaced signals.

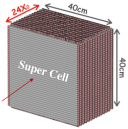
Advanced PID coming from the combination of $dE(N)/dx$ method, time resolution and calorimetry:

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





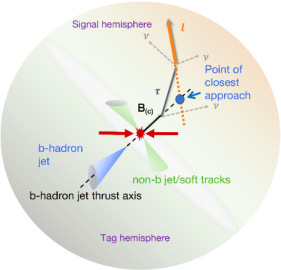




Calorimetry gives neutral energy and angular resolution.

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

Pinning Down B Anomalies



Charged current $b \to c\tau\nu$ decays [Zheng et al., 2020, Amhis et al., 2021].

Absolute precision $\sim 10^{-4}$
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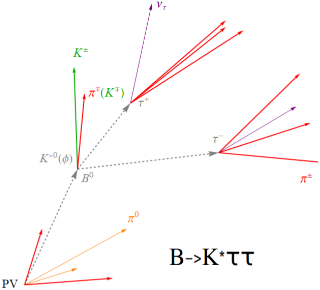
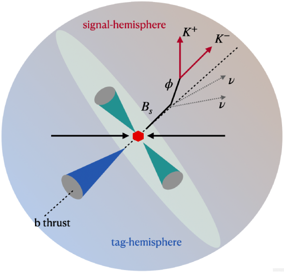


Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

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]

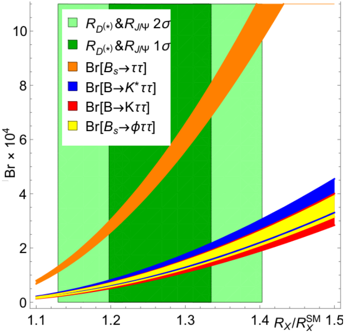
Absolute precision $\sim 10^{-7}$.

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



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

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

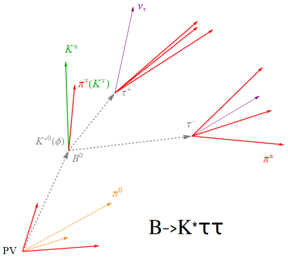
$$\sim \mathcal{O}(10) \times C_{9/10}^{\mathrm{SM}}$$

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

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

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

Overwhelmingly Large SM Backgrounds



Use τ 3-prong decay to locate each vertex

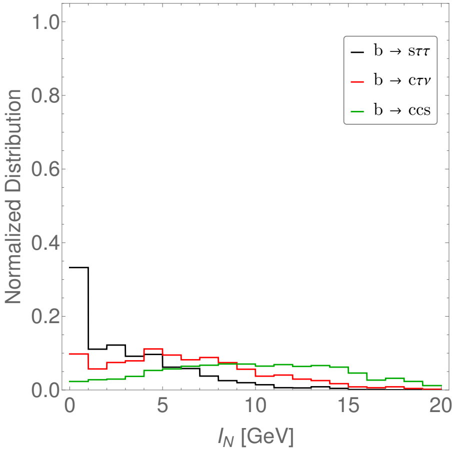
Dominant background from inclusive $D^\pm_{(s)}$ hadronic decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	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%

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



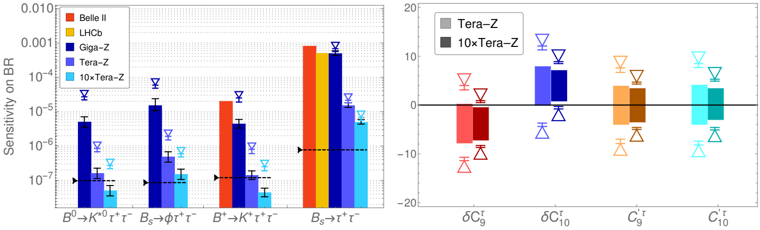
Good calorimetry saves the day!

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)?

Projected Limits

More details in the published work [Li and Liu, 2020]:



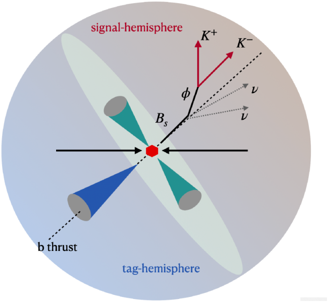
- Traditional cut-based analysis: $\mathcal{O}(10^{-5} - 10^{-7})$ precision.
- Still affected by limited detector spacial resolution ("∇" symbols): Motivation for detector R&D!
- EFT-wise way beyond current experimental constraints ($\mathcal{O}(10^3)$).

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

$b \to s\nu\nu$ 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]

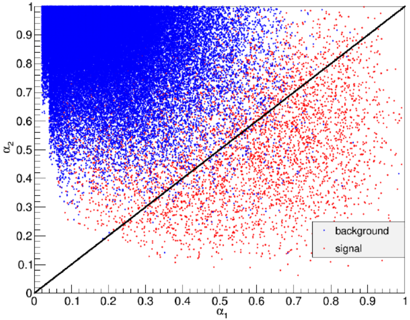


Current limit of this channel still led by LEP: (limited production at B factories, $\vec{p}_\nu$ not achievable at hadron colliders).

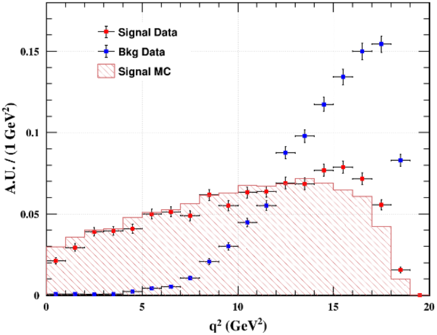
Most likely to have breakthrough at Z factories. Based on full simulation.

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.



Kinematic differences inspired by LEP measurements.

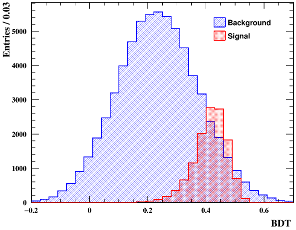


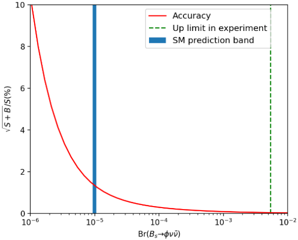
Error of $q^2 \equiv m_{\nu\nu}^2 \sim 2.5$ GeV^2 only.

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

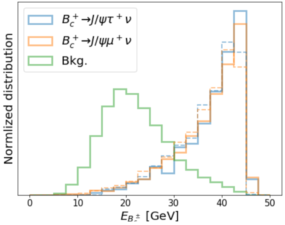
Cuts	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events ($10^{12}Z$)	3.03×10^{5}	4.28×10^{11}	1.20×10^{11}	1.51×10^{11}	6.99×10^{11}	276
$N_{\phi(\to K^+K^-)}>0$	1.24×10^{5}	1.27×10^{10}	7.23×10^{9}	8.56×10^{9}	2.85×10^{10}	136
[a]Signal 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
$(1-\alpha_1)/\theta^{\rm miss}_\phi<2.0$	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}	

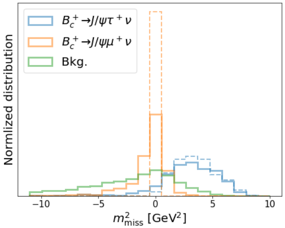
$\sim 1\%$ relative ($\sim 10^{-7}$ absolute) precision





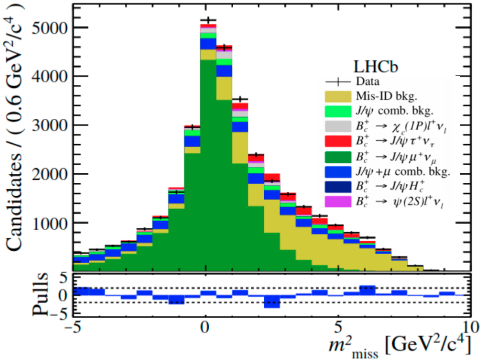
Further LFU Tests with FCCC (Prelim).





$R_{J/\psi}$ measurement with
$\tau \to \mu\nu\nu,\ J/\psi \to \mu\mu$

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



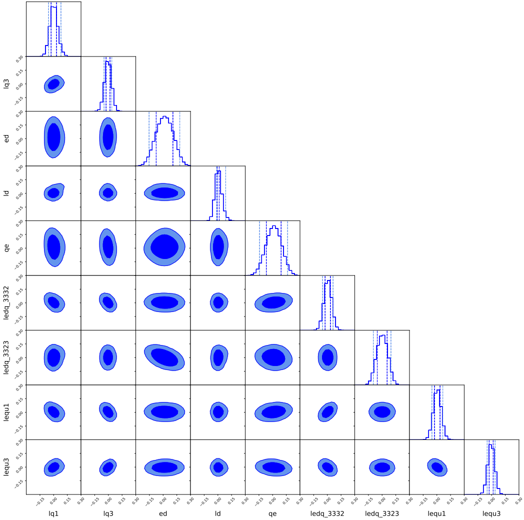
Further LFU Tests with FCCC (II) (Prelim).

Angles between theoretical sensitivity $\partial_{C_i}\Gamma(b \to c\tau\nu)$ in the 5-D theory space:

θ	$J(\psi)$	D	D^*	D_s	D_s^*	Λ_b	B_c
$J(\psi)$	-	$103°$	$3.01°$	$109°$	$1.96°$	$22.9°$	$81.8°$
D	$103°$	-	$102°$	$6.55°$	$102°$	$82.8°$	$90°$
D^*	$3.01°$	$102°$	-	$107°$	$4.45°$	$20.6°$	$81.2°$
D_s	$109°$	$6.55°$	$107°$	-	$108°$	$88°$	$90°$
D_s^*	$1.96°$	$102°$	$4.45°$	$108°$	-	$23.3°$	$82.8°$
Λ_b	$22.9°$	$82.8°$	$20.6°$	$88°$	$23.3°$	-	$79.6°$
B_c	$81.8°$	$90°$	$81.2°$	$90°$	$82.8°$	$79.6°$	-

Vector (from $R_{J/\psi}$ and $R_{D^*_{(s)}}$), pseudoscalar (from $R_{D_{(s)}}$), baryonic (from R_{Λ_c}) and annihilation (from $B_c \to \tau\nu$, see also [Zheng et al., 2020]) decays are all necessary.

SMEFT Projections (Prelim).



Preliminary: 9 effective channels:($R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, R_{Λ_c}, $B_c \to \tau\nu$, $B \to K\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $B^0 \to K\tau\tau$, $B^+ \to K^+\tau\tau$, $B_s \to \tau\tau$...)

$\Leftarrow$ Dim-6 SMEFT basis at NP scale Λ=3 TeV. Probimg ~ 10 TeV scale for unitary 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!
  1. LFUV, LFV, LNV, BNV...
  2. CKM and CPV measurements...
  3. Precision (τ) physics...
  4. Exotics, spectroscopy, double heavy flavor...

Aaij, R. et al. (2020).
Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays.
JHEP, 05:040.

Aaij, R. et al. (2021).
Test of lepton universality in beauty-quark decays.

Altmannshofer, W. et al. (2018).
The Belle II Physics Book.

Amhis, Y., Hartmann, M., Helsens, C., Hill, D., and Sumensari, O. (2021).
Prospects for $B_c^+ \to \tau^+\nu_\tau$ at FCC-ee.

Capdevila, B., Crivellin, A., Descotes-Genon, S., Hofer, L., and Matias, J. (2018).
Searching for New Physics with $b \to s\tau^+\tau^-$ processes.
Phys. Rev. Lett., 120(18):181802.

Geng, C. and Liu, C. (2003).

Study of $B_s \to (\eta, \eta', \phi)\ell\bar{\ell}$ decays.
J. Phys. G, 29:1103–1118.

Li, L. and Liu, T. (2020).
$b \to s\tau^+\tau^-$ Physics at Future Z Factories.

Straub, D. M. (2015).
$b \to k^{(*)}\nu\bar{\nu}$ sm predictions.

Tanabashi, M. et al. (2018).
Review of Particle Physics.
Phys. Rev., D98(3):030001.

Zheng, T., Xu, J., Cao, L., Yu, D., Wang, W., Prell, S., Cheung, Y.-K. E., and Ruan, M. (2020).
Analysis of $B_c \to \tau\nu_\tau$ at CEPC.