The 2023 International Workshop on the High Energy Circular Electron Positron Collider
Nanjing, 2023 Oct.

Flavor Physics at CEPC

- A General Perspective

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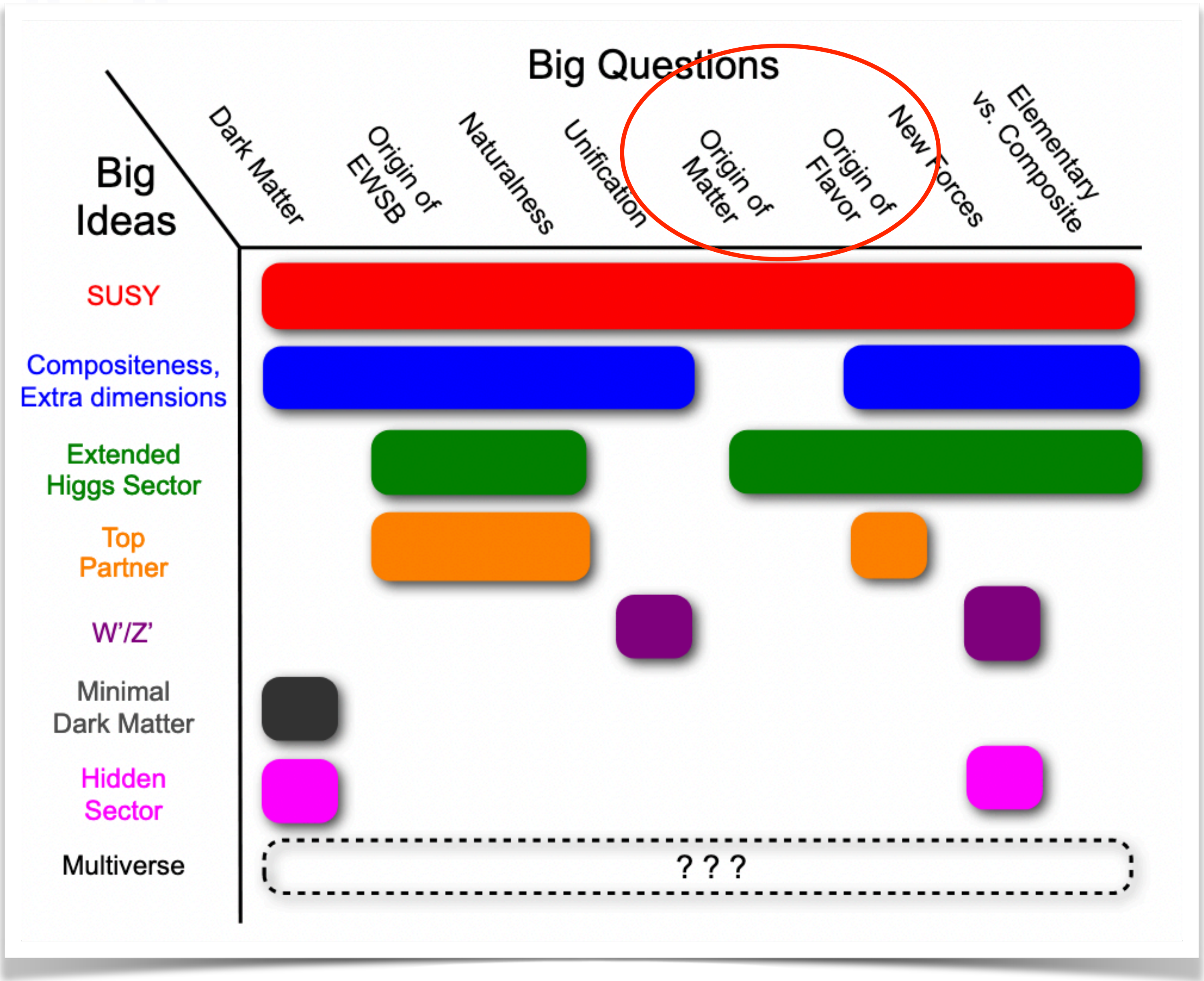
Flavor Physics



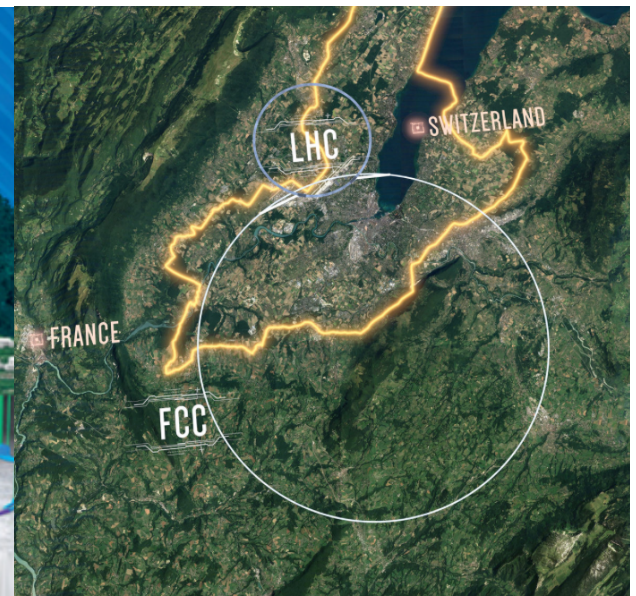
[Working group report for Snowmass 2013]

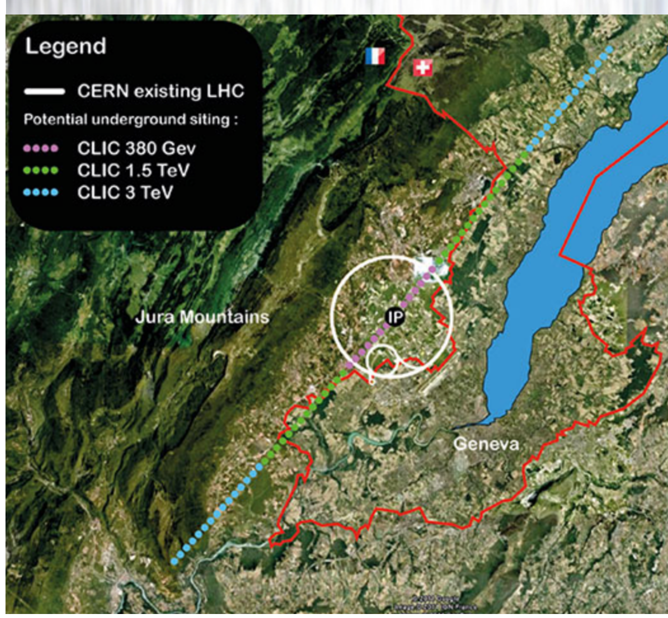
$$\mathcal{L}_{SM} \supset i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij} \psi_j \phi$$

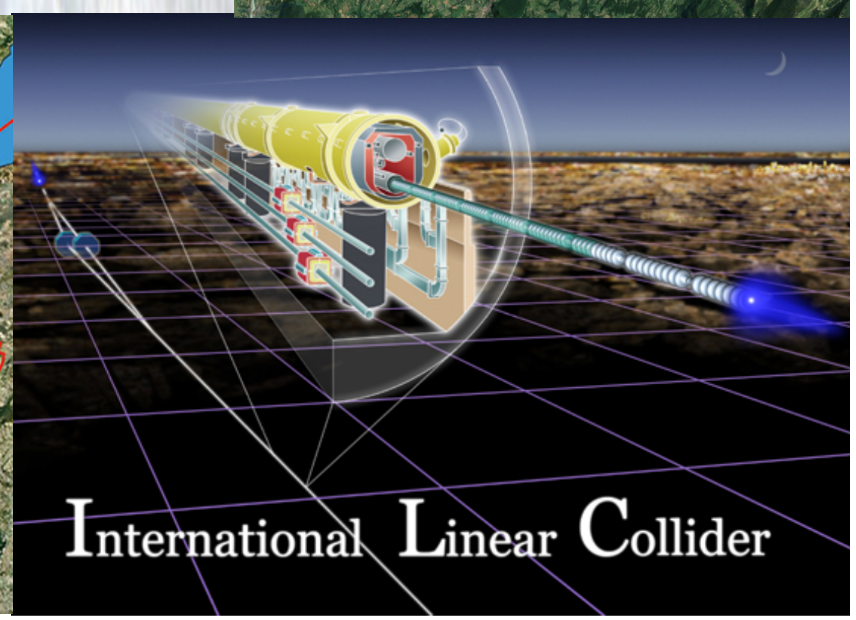
- Coupling pattern
- Mass texture
- Underlying symmetry
- CP phase
- … …

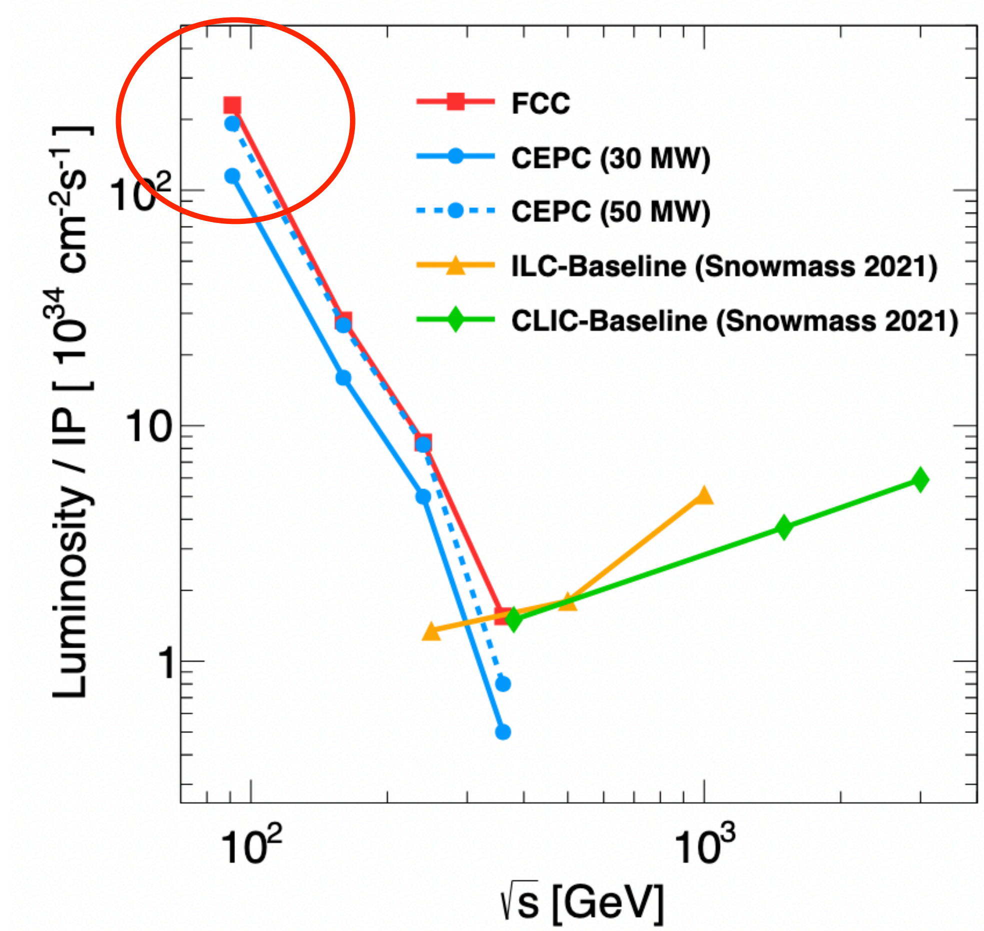
Precision Frontier of Next Decades

The precision frontier of next decades in Higgs and electroweak physics is expected to be defined by a new e⁻e⁺ collider.









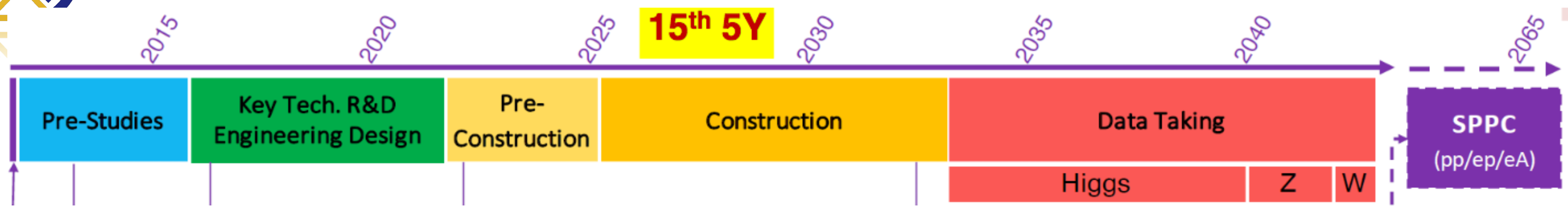
Circular version is especially suited for the study on flavor physics, for its high luminosity at Z pole

Key Collider Features for Flavor Physics

- Clean collider environment
  - Low QCD backgrounds
  - Negligible pile-ups
  - Approximately fixed E_{cm}
- Beam energy much larger than the quark and lepton masses
  - Boosted dynamics
  - Higher precision of measuring momentum and efficiency for reconstructing vertex
  - Belle II: asymmetric beam energy has been taken to improve event reconstruction
- High production rate of relevant mesons, baryons, leptons, etc. at Z pole
  - Belle II has no statistics for heavy hadrons due to the limitation of energy threshold.

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×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}

Roadmap of CEPC-SppC (Upon Approval)



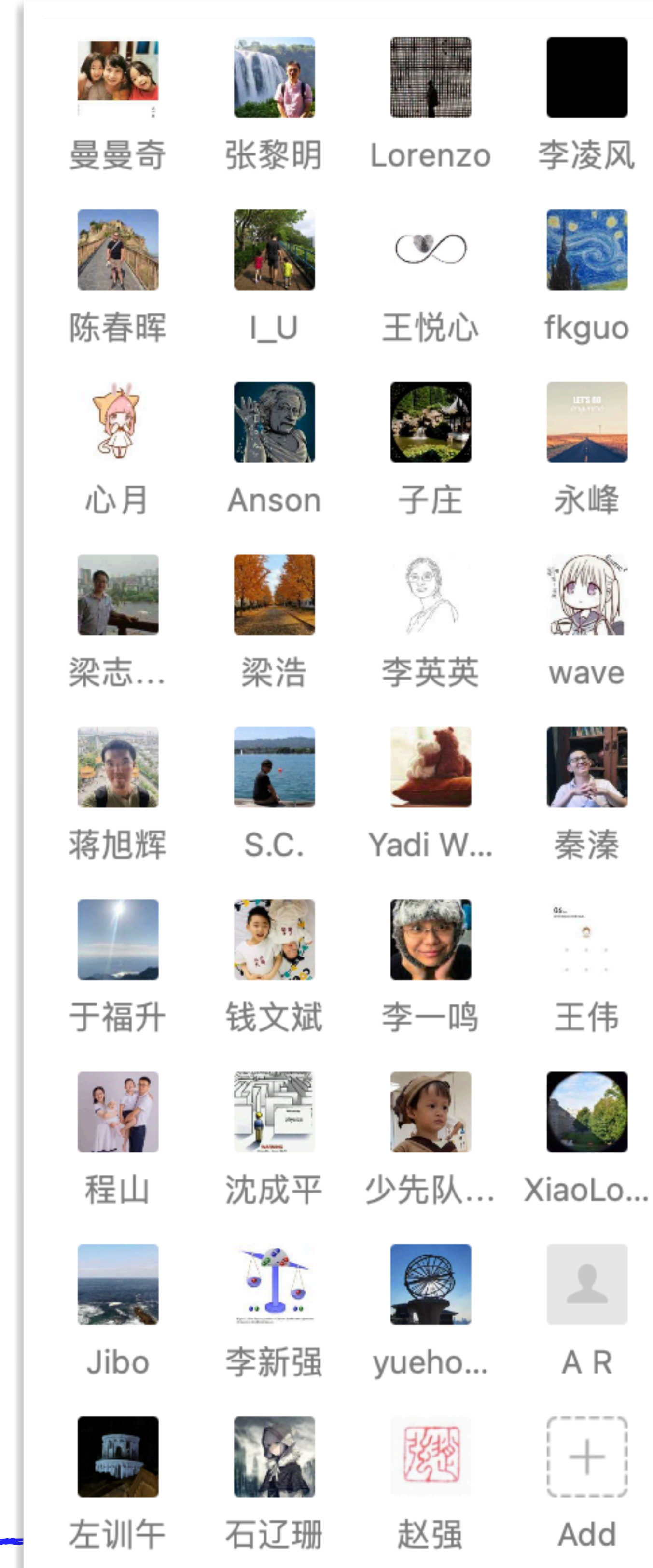
[Xinchou Lou, 2022 HEP program at JCIAS, HKUST]

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

[see Yuhui Li's talk]

White Paper on Flavor Physics at CEPC

Contents



The Goals

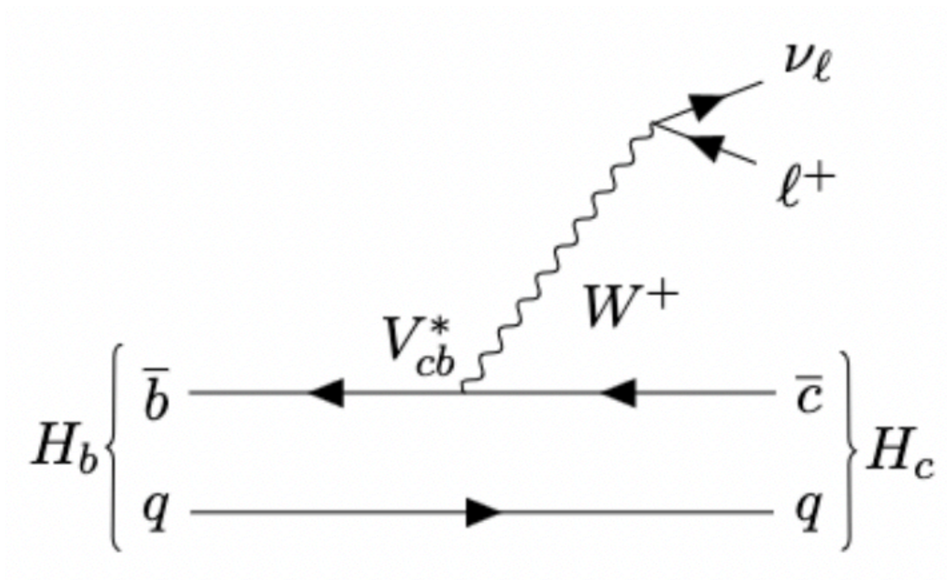
- Present a phase-I picture on the CEPC potential, mainly at Z pole, in exploring flavor physics
- Identify ``golden'' channels for critical physics
  - High scientific value
  - Challenging or even inaccessible for existing experiments
    - complex event topology
    - suppressed productions at other machines
- Develop new observables or methodologies, e.g., ML-based ones, for flavor physics
- As the technology roadmap is close for CEPC and FCC-ee, many of the CEPC studies can be applied to FCC-ee and vice versa

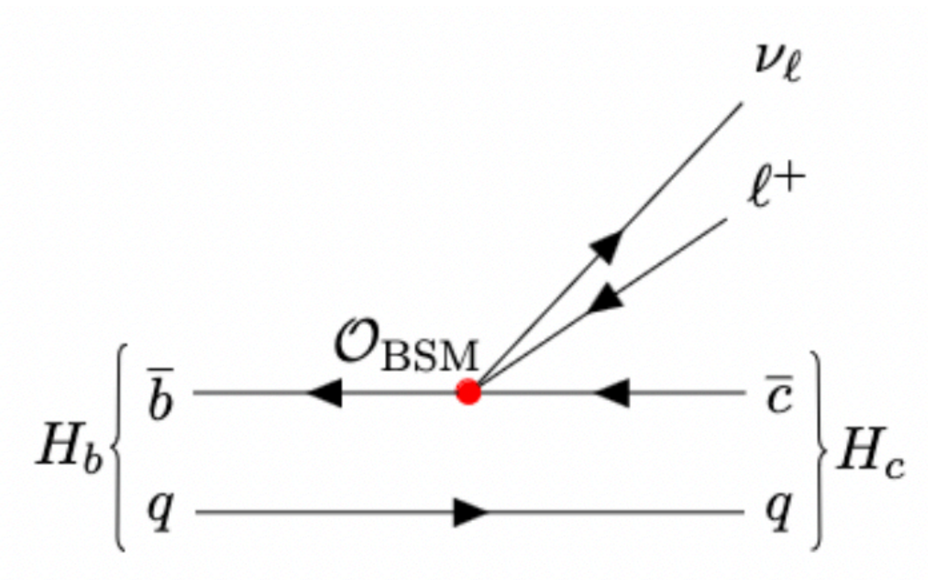
Most highlights below involve tau lepton decays:

- Scientifically, crucial for achieving a picture of all flavors.
- Technically, multi-body decays for tau leptons complicate the event topology and kinematics.
  - The decay products tend to be soft in B-factories, while the signature of neutrinos as missing momentum is inaccessible at hadron colliders.
  - The reconstruction of tau leptons and other intermediate particles can benefit from the excellent collider environment of the CEPC and the high-performance of its detector.
- => define a series of the most representative cases for flavor physics at the CEPC.

Highlight I - $b \to c\tau\nu$

Historically, FCCC-mediated beta decays have resulted in the discovery of weak interactions. They can be used to test lepton flavor universality.





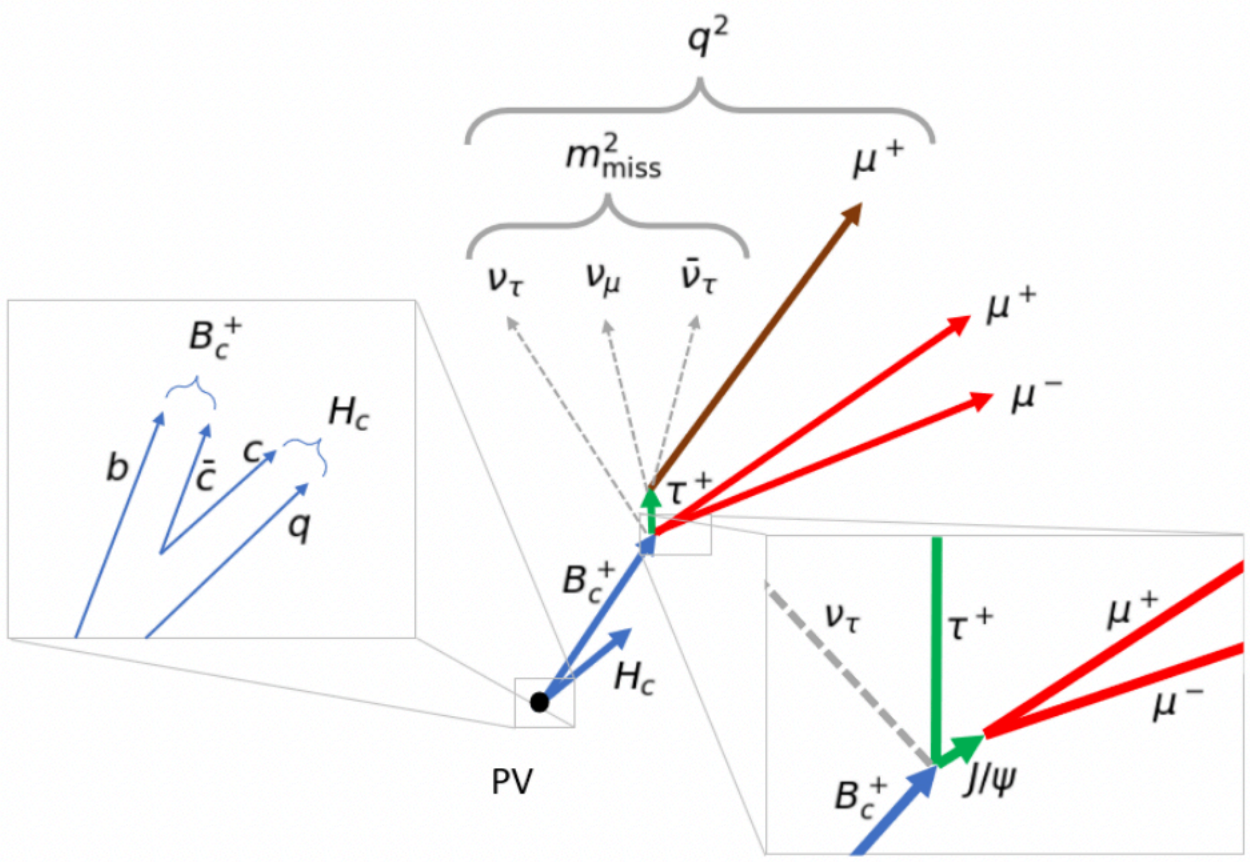
	H_b	H_c	SM Prediction [2]	Experimental Average
~~R_D~~	~~B^0, B^+~~	~~D^0, D^+~~	~~0.307 [1, 2]~~	~~0.340 ± 0.030 [3]~~
~~R_{D^*}~~	~~$B^0, B^\pm$~~	~~$D^{*0}, D^{*\pm}$~~	~~0.253 [1, 2]~~	~~0.295 ± 0.014 [3]~~
$R_{J/\psi}$	B_c	J/ψ	0.289 [4–6]	$0.71 \pm 0.17 \pm 0.18$ [7]
R_{D_s}	B_s	D_s	0.393 [2, 8–13]	N/A
$R_{D_s^*}$	B_s	D_s^*	0.303 [2, 8, 10, 13]	N/A
R_{Λ_c}	Λ_b	Λ_c	0.334 [14–18]	0.242 ± 0.076 [19]

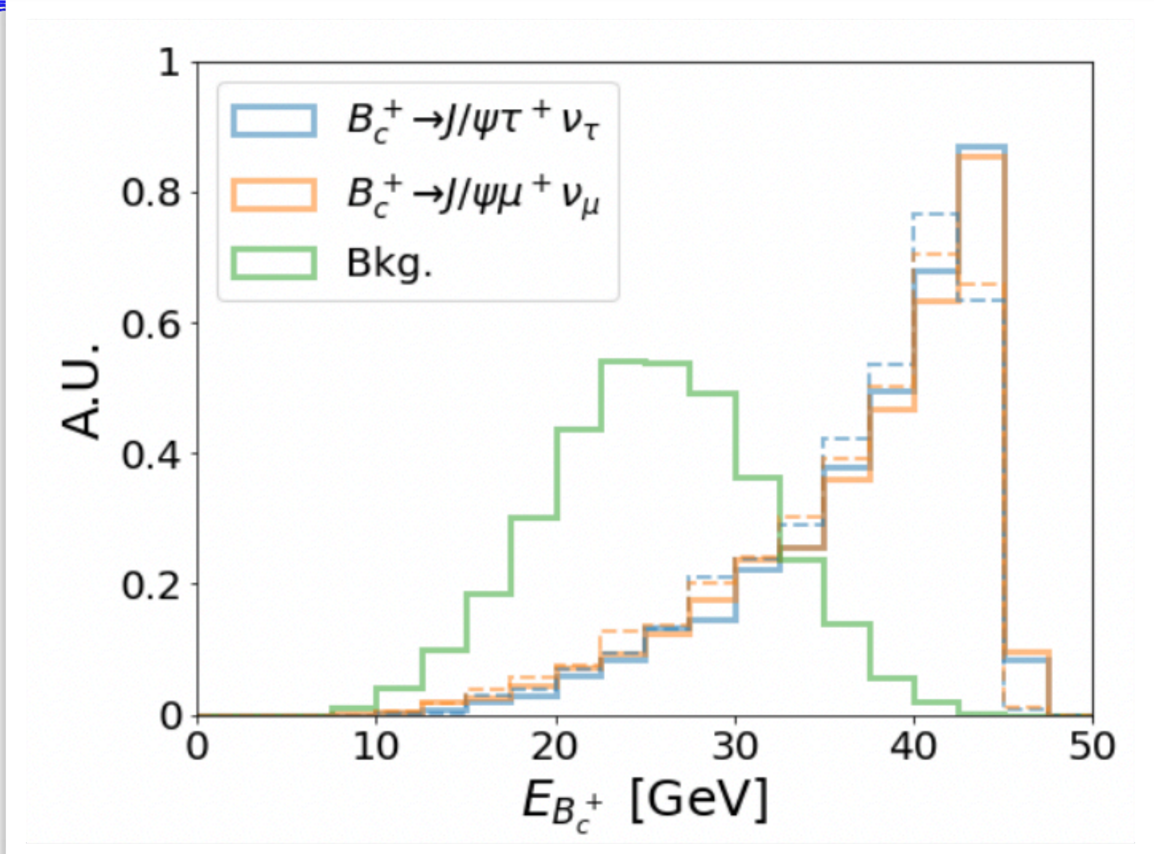
$$R_{H_c} \equiv \frac{\mathrm{Br}(H_b \to H_c\tau\nu)}{\mathrm{Br}(H_b \to H_c\ell\nu)}$$

Current measurements: either no sensitivity or have a precision ~30%.

Highlight I - $b \to c\tau\nu$

Track-based strategy
(approximate reconstructed J/psi vertex as the Bc+ vertex)



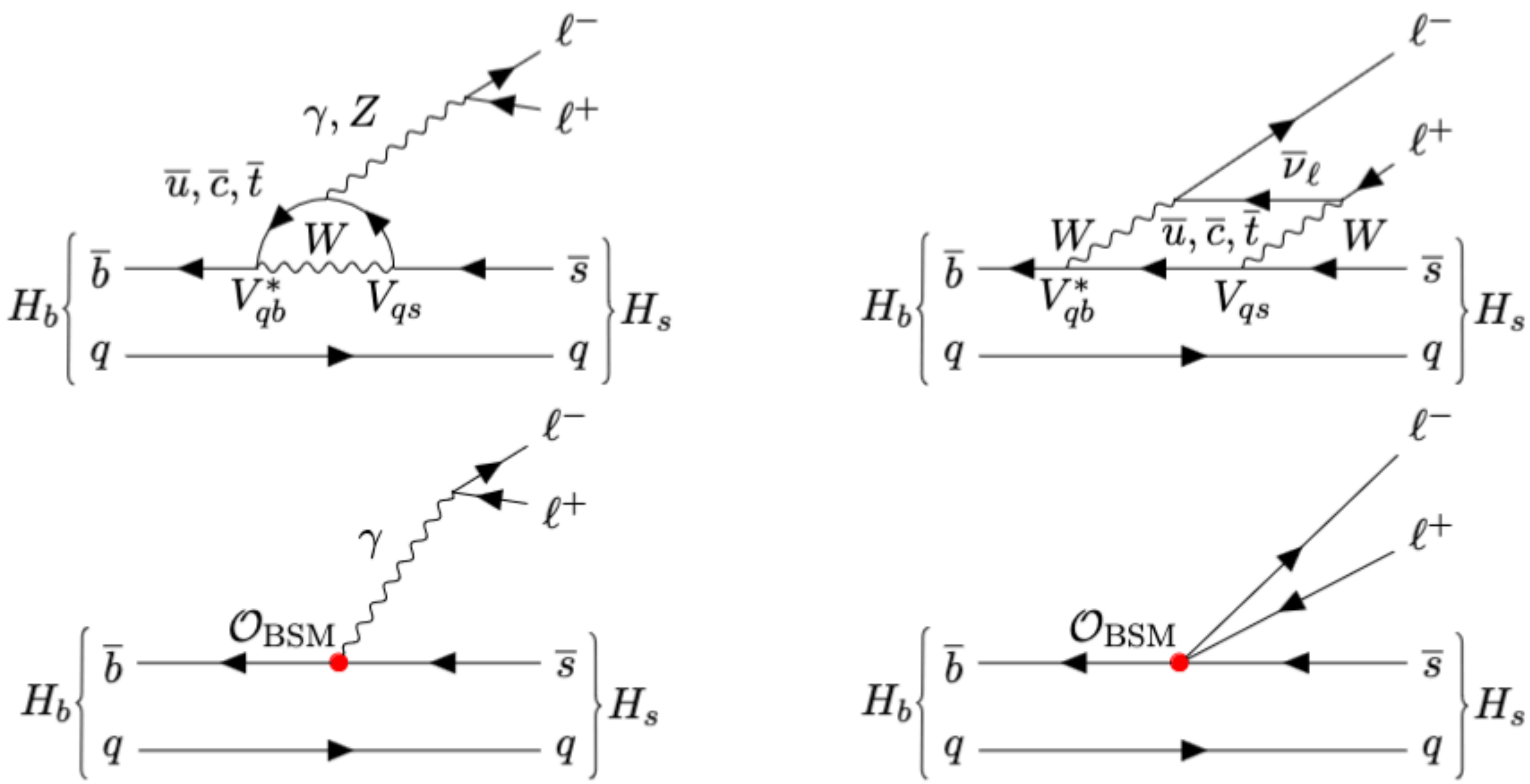


$R_{J/\psi}$ Rel. precision	4.25×10^{-2} (1.35×10^{-2})
R_{D_s} Rel. precision	4.09×10^{-3} (1.30×10^{-3})
$R_{D_s^*}$ Rel. precision	3.26×10^{-3} (1.03×10^{-3})
R_{Λ_c} Rel. precision	9.77×10^{-4} (3.09×10^{-4})

[T. Ho, X. Jiang, T. Kwok, L. Li and TL, arXiv: 2212.02433]

See also [Amhis et al. (2021), Zheng et al. (2020)]

Highlight II - $b \to s\tau\tau$



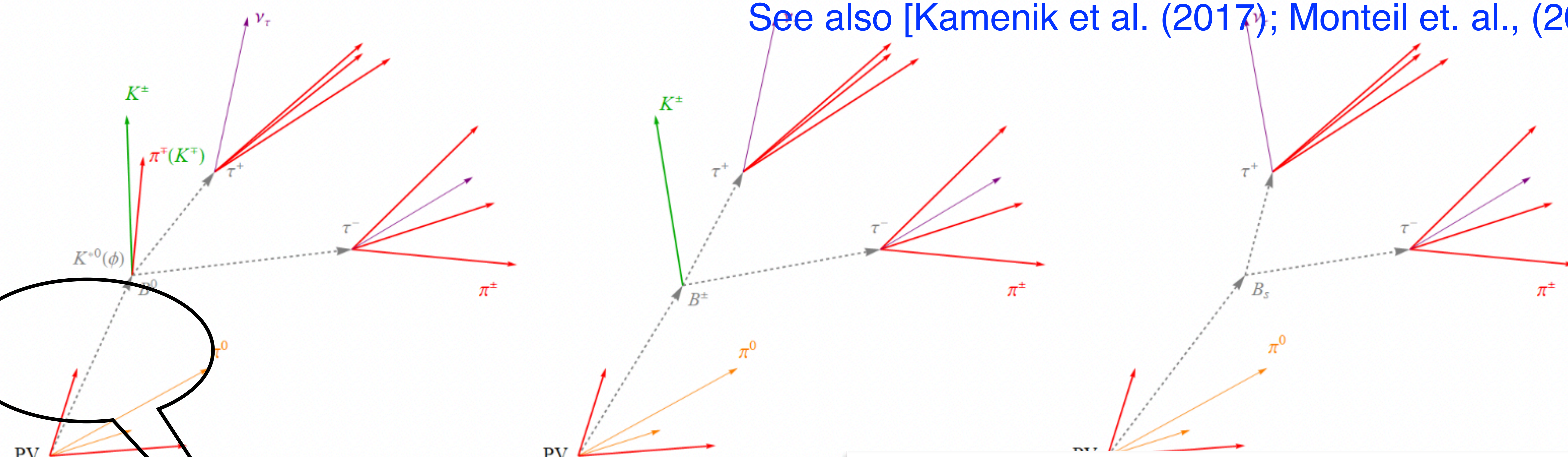
Channel	SM prediction for BR	$q^2 \equiv m^2_{\tau\tau}$ (GeV^2)
$B^0 \to K^{*0}\tau^+\tau^-$	$(0.98 \pm 0.10) \times 10^{-7}$ [11]	[15,19]
$B_s \to \phi\tau^+\tau^-$	$(0.86 \pm 0.06) \times 10^{-7}$ [11]	[15,18.8]
$B^+ \to K^+\tau^+\tau^-$	$(1.20 \pm 0.12) \times 10^{-7}$ [11]	[15,22]
$B_s \to \tau^+\tau^-$	$(7.73 \pm 0.49) \times 10^{-7}$ [12]	-

Current sensitivity is still far from the SM prediction.

Highlight II - $b \to s\tau\tau$

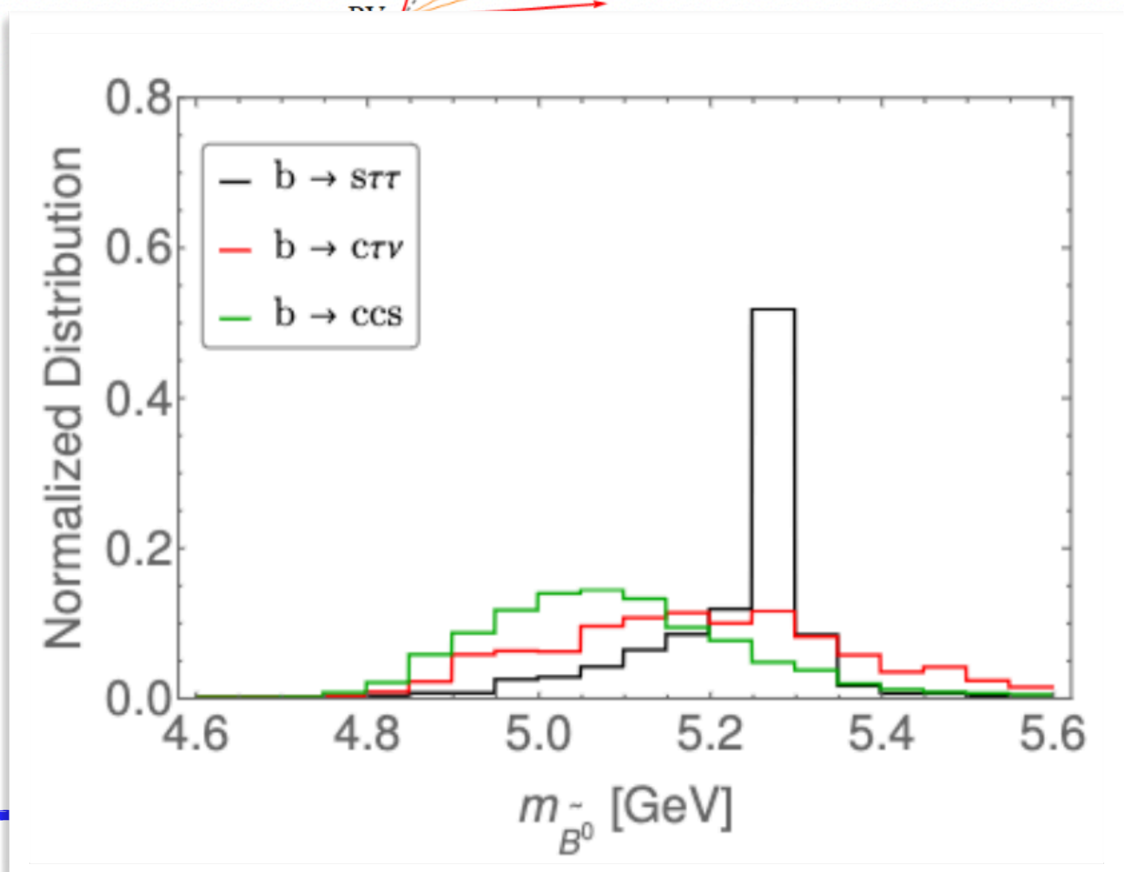
[TL and L. F. Li, JHEP (2021)]

See also [Kamenik et al. (2017); Monteil et. al., (2021)]

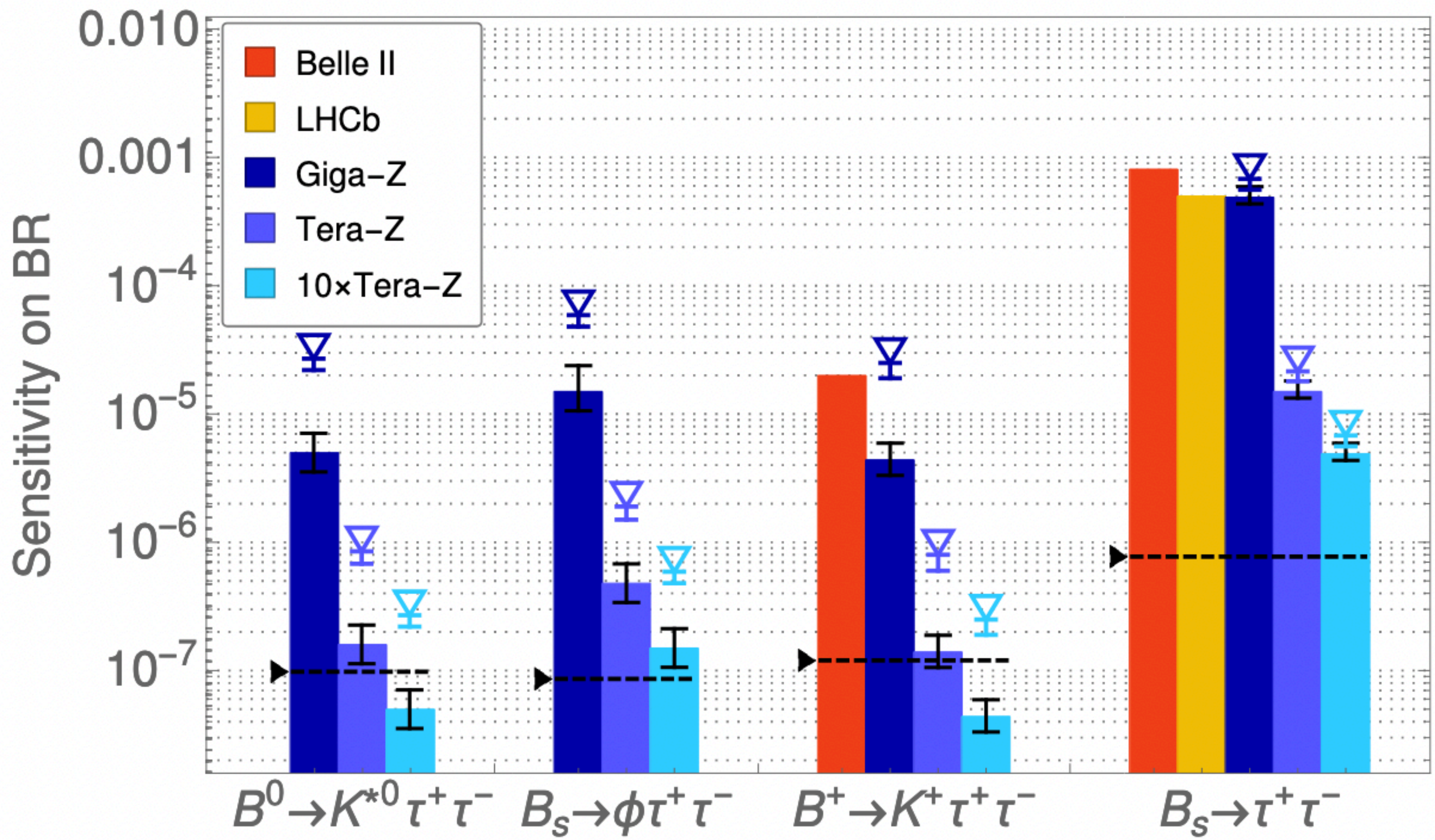


Track-based reconstruction strategy

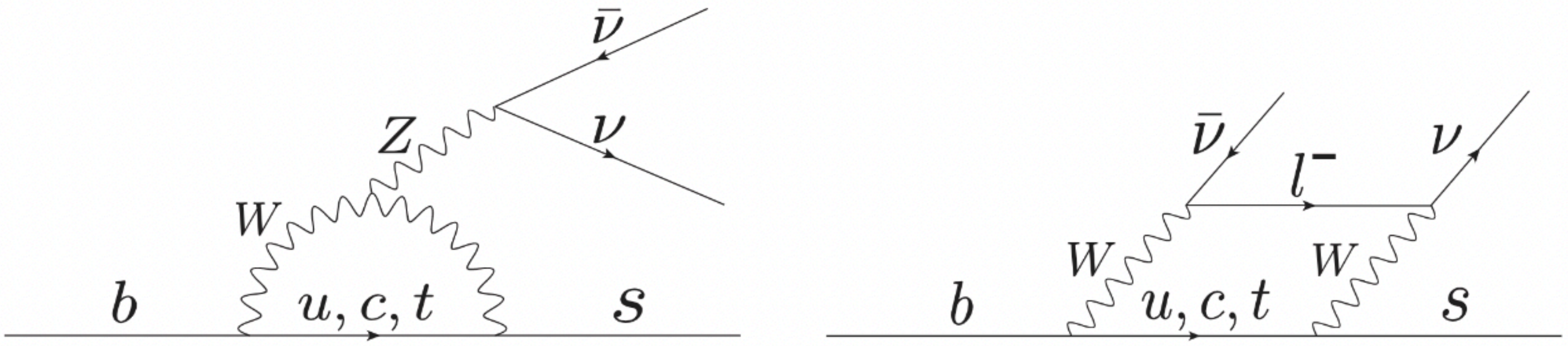
$$\vec{p}_{\nu,i} = \frac{-\vec{p}_{K^{*0}} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}}{\vec{V}_{\tau,i} \times \vec{V}_{B^0} \cdot \vec{V}_{\tau,j}} \vec{V}_{\tau,i} - \vec{p}_{3\pi,i}$$



Highlight II - $b \to s\tau\tau$

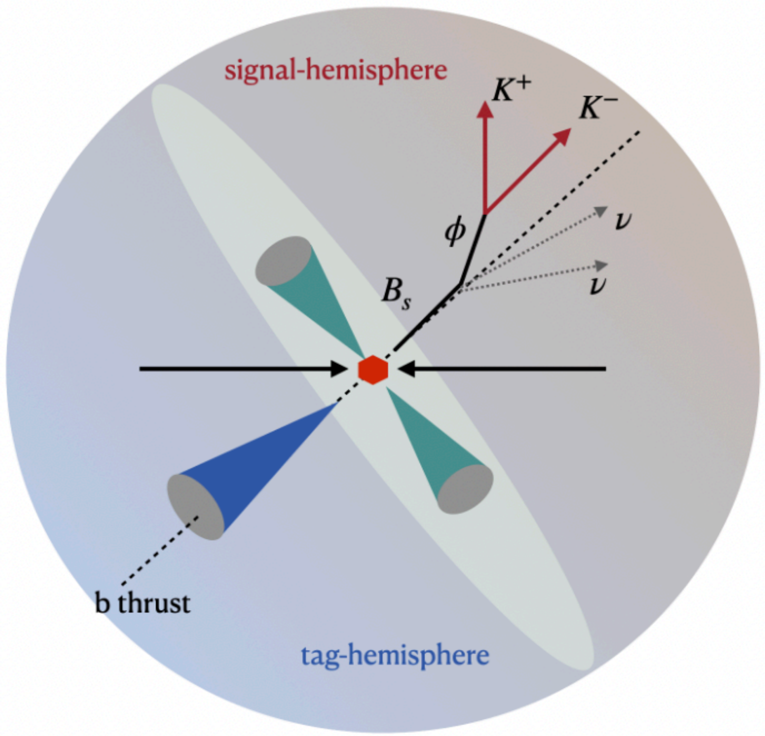


Highlight III - $b \to s\nu\nu$



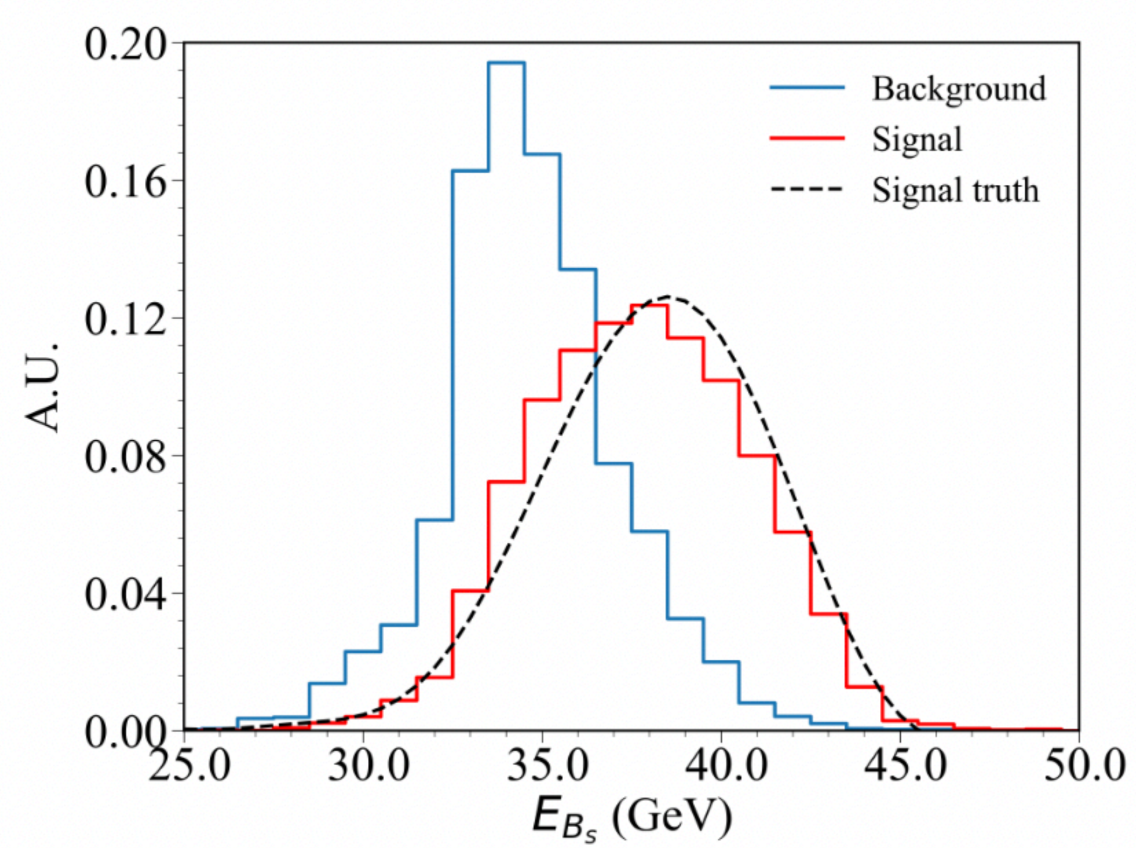
	Current Limit	Detector	SM Prediction
$BR(B^0 \to K^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$BR(B^0 \to K^{*0} \nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$BR(B^\pm \to K^\pm \nu\bar{\nu})$	$< 1.6 \times 10^{-5}$ [4]	BABAR	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$BR(B^\pm \to K^{*\pm} \nu\bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$BR(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$ [6]	DELPHI	$(9.93 \pm 0.72) \times 10^{-6}$

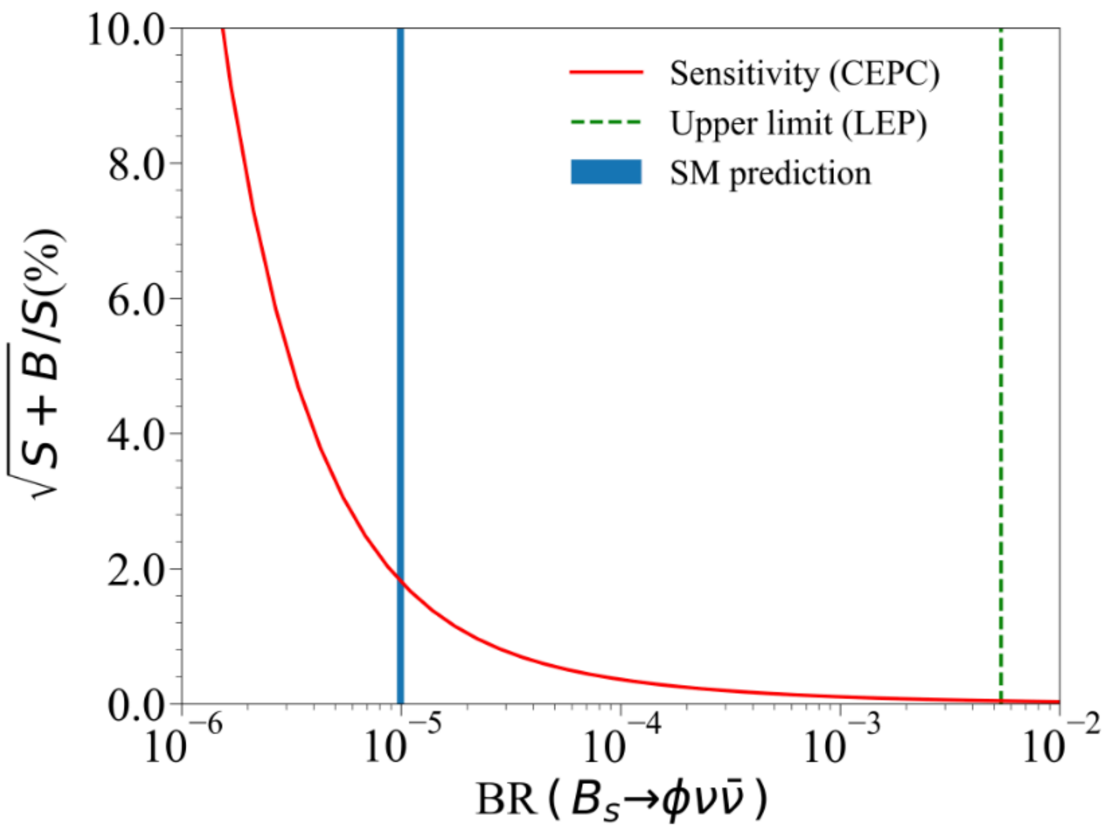
Highlight III - $b \to s\nu\nu$



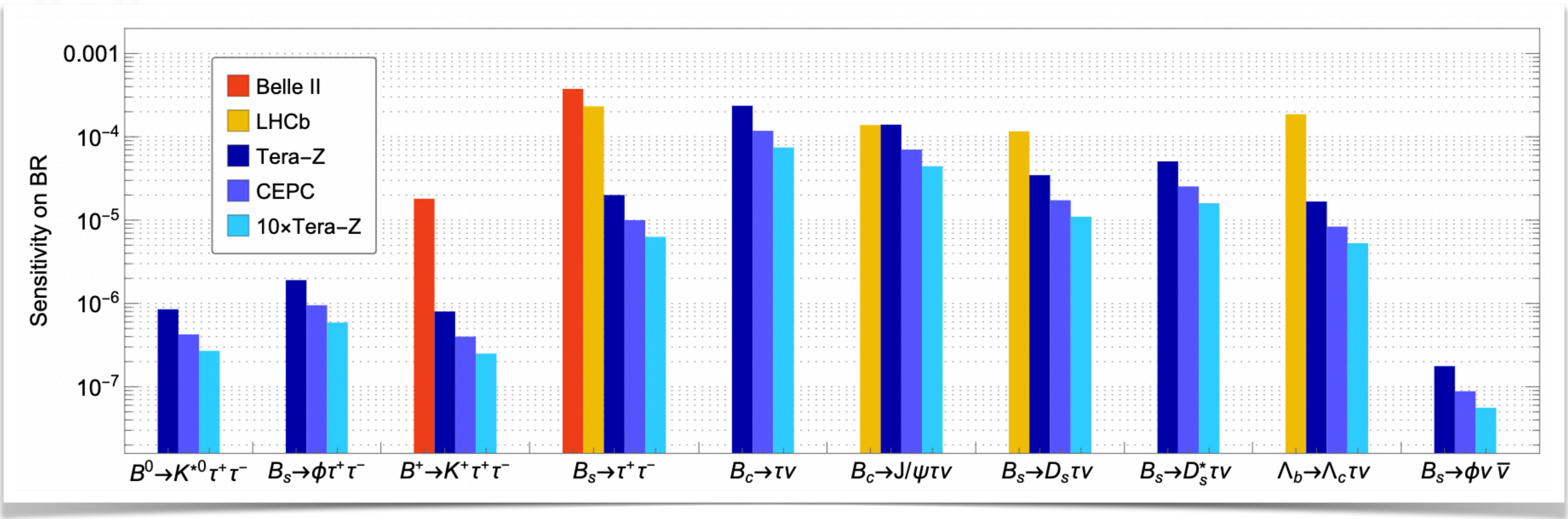
[L. Li, M. Ruan, et. al., Phys.Rev.D 105 (2022)]

See also [Batell et al. (2011), Dror et al. (2017)]





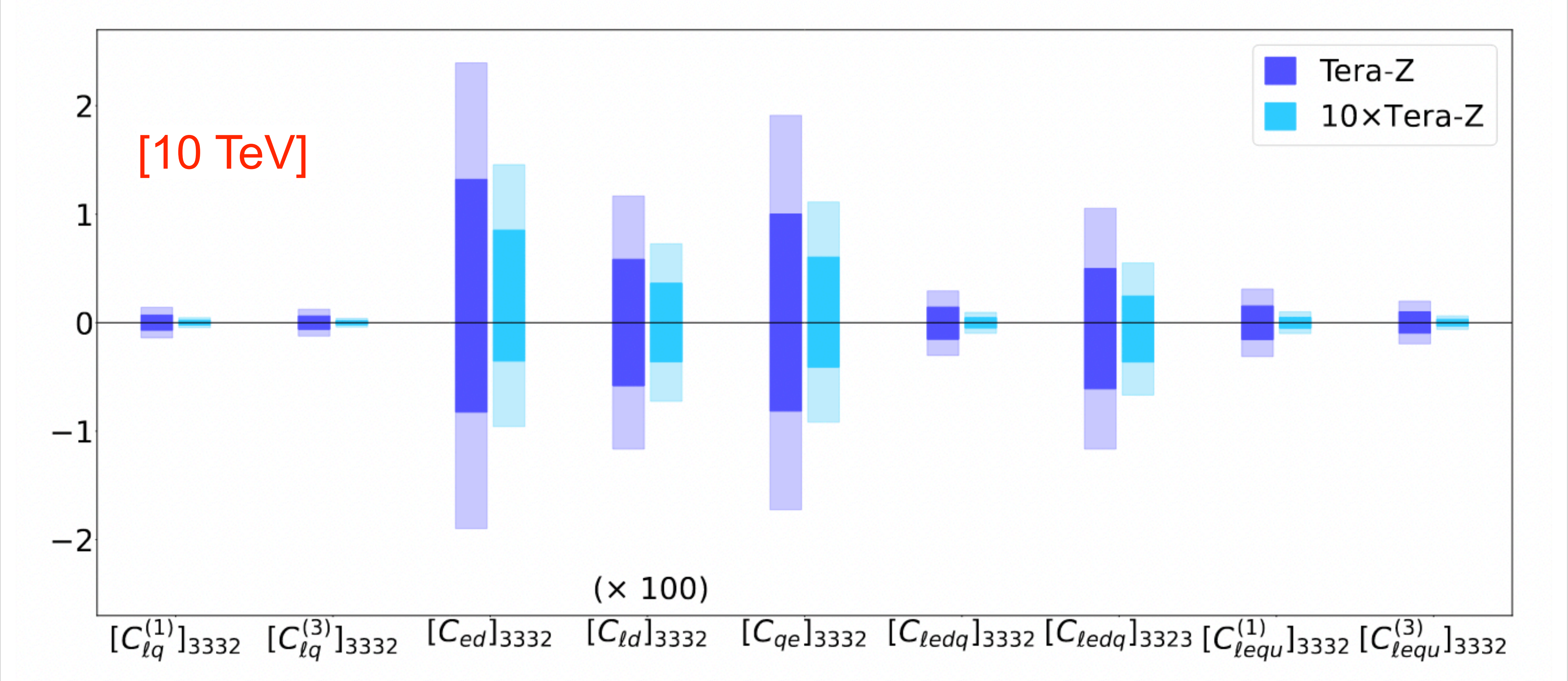
An Overall Picture



Important for achieving a full test of lepton flavor universality, one of the main hypothetical principles in the SM.

Interpretation in SMEFT

SMEFT operators	SMEFT operators (down basis)
$[O_{lq}^{(1)}]_{3332}$	$[\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau][\bar{b}\gamma_\mu P_L s]$
$[O_{lq}^{(3)}]_{3332}$	$2V_{cs}^*[\bar{\nu}\gamma^\mu P_L \tau][\bar{b}\gamma_\mu P_L c] - [\bar{\nu}\gamma^\mu P_L \nu - \bar{\tau}\gamma^\mu P_L \tau][\bar{b}\gamma_\mu P_L s]$
$[O_{ed}]_{3332}$	$[\bar{\tau}\gamma^\mu P_R \tau][\bar{b}\gamma_\mu P_R s]$
$[O_{ld}]_{3332}$	$[\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau][\bar{b}\gamma_\mu P_R s]$
$[O_{qe}]_{3332}$	$[\bar{\tau}\gamma^\mu P_R \tau][\bar{b}\gamma_\mu P_L s]$
$[O_{ledq}]_{3332}$	$V_{cs}^*[\bar{\nu} P_R \tau][\bar{b} P_L c] + [\bar{\tau} P_R \tau][\bar{b} P_L s]$
$[O_{ledq}]_{3323}$	$[\bar{\tau} P_R \tau][\bar{s} P_L b]$
$[O_{lequ}^{(1)}]_{3332}$	$V_{cs}^*[\bar{\nu} P_R \tau][\bar{b} P_R c]$
$[O_{lequ}^{(3)}]_{3332}$	$V_{cs}^*[\bar{\nu}\sigma^{\mu\nu} P_R \tau][\bar{b}\sigma_{\mu\nu} P_R c]$



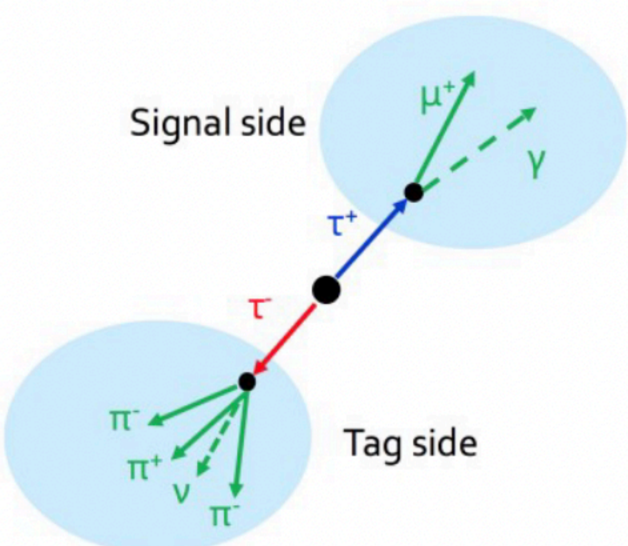
Highlight IV - Tau Physics

[Pich (2014); Celis et al. (2014); Calibbi and Signorelli (2018); Calibbi et. al. (2021, 2022) Dam (2019, 2021)]

Z pole is also good for the test of lepton flavor violation

Measurement	Current [104–106]	FCC [107]	CEPC prelim.	Comments
$\mathrm{BR}(Z \to \tau\mu)$	$< 6.5 \times 10^{-6}$	$\mathcal{O}(10^{-9})$	same [108]	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 5.0 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	1×10^{-9} [109]	PID limited

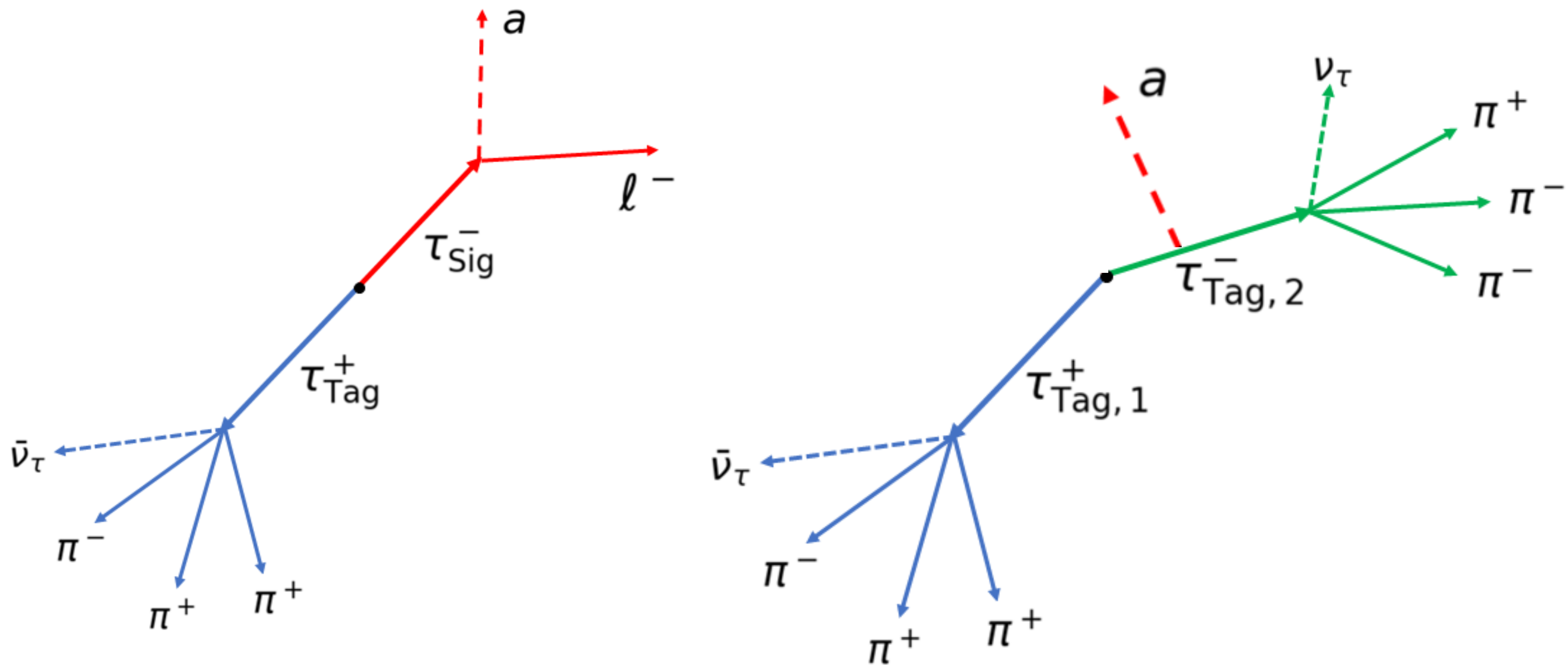
$\sim \mathcal{O}(10^{10} - 10^{11})\, \tau^+\tau^-$ pair events are expected to produce at Z pole



Measurement	Current [149]	FCC [107]	CEPC prelim. [108]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to \mu\mu\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to eee)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		

Highlight V - Light Hidden Bosons

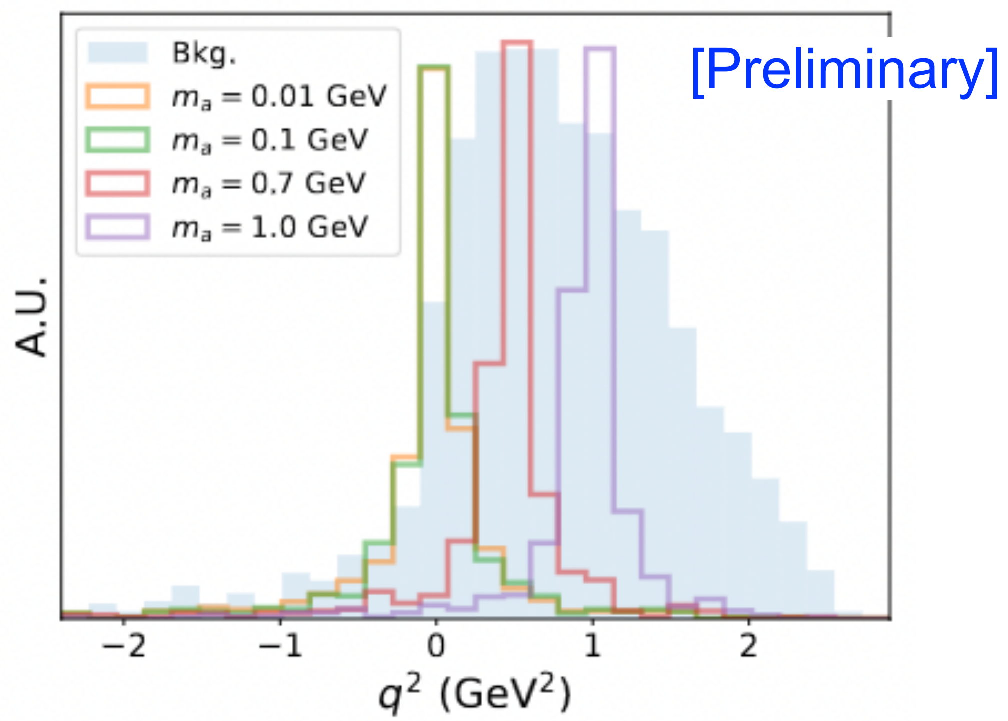
[A. Kwok, TL and L. F. Li, in preparation]

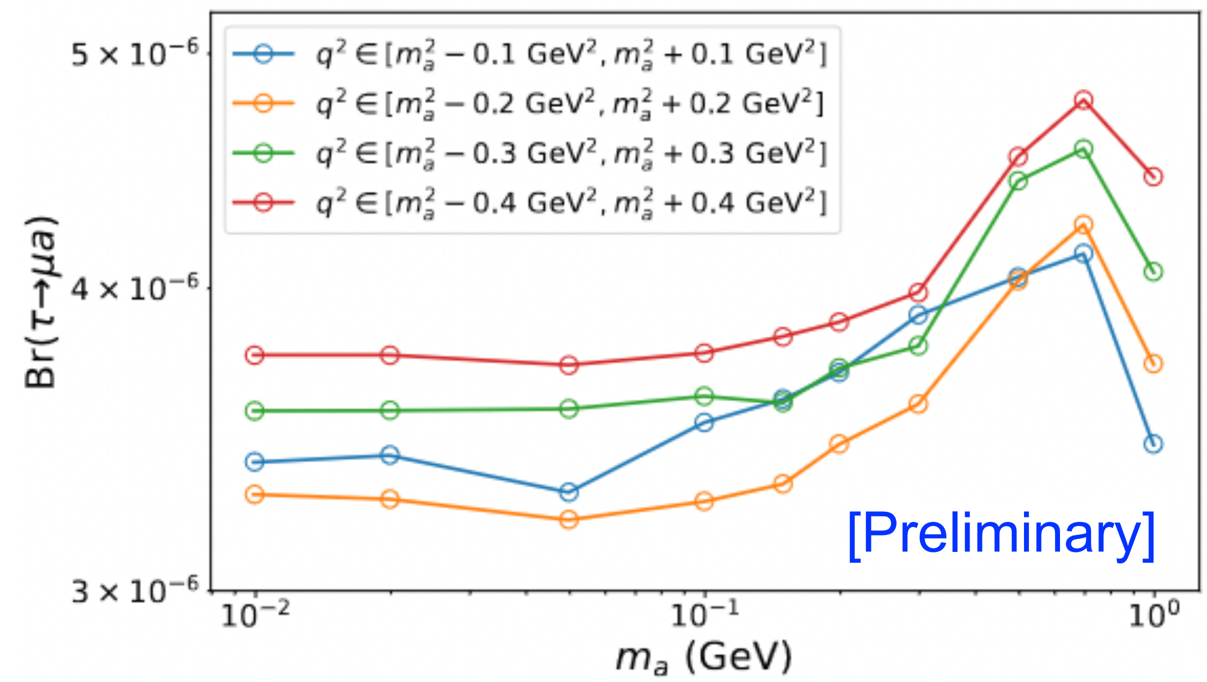


- The light boson can be invisible (missing energy) or visible
- The coupling can be flavor-conserving or violating
- The discussions are applied for both lepton and quark sector

Highlight V - Light Hidden Bosons

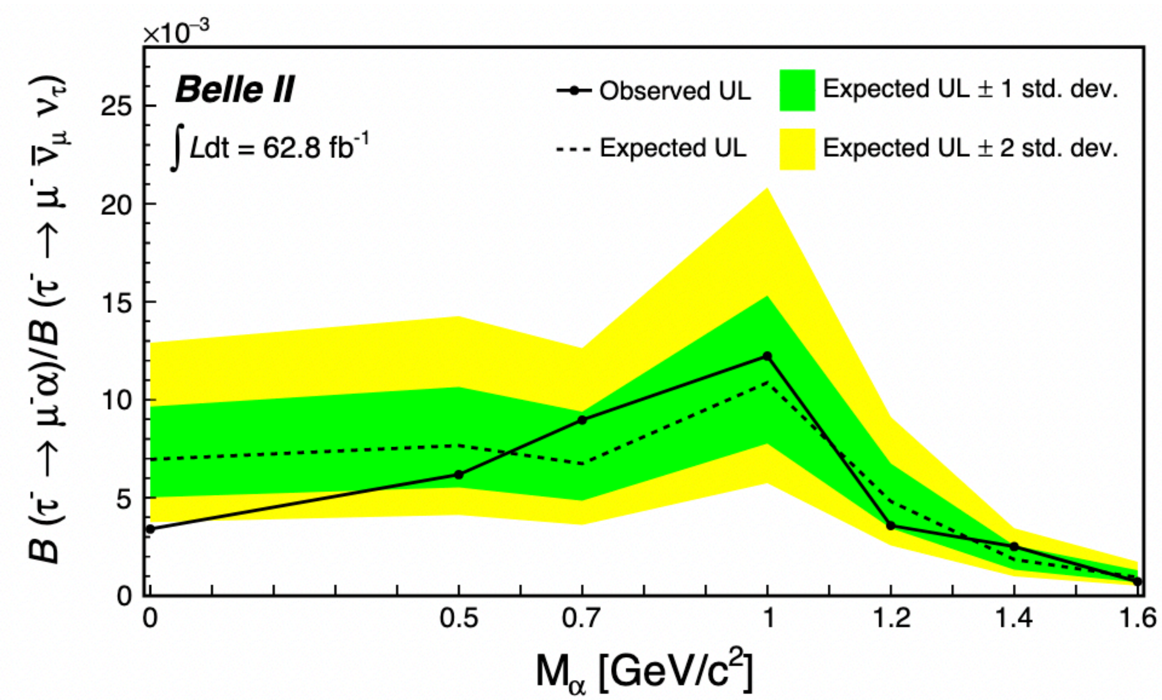
$$Z \to \tau(\to \ell + \text{Missing})\tau(\to 3\pi\nu)$$



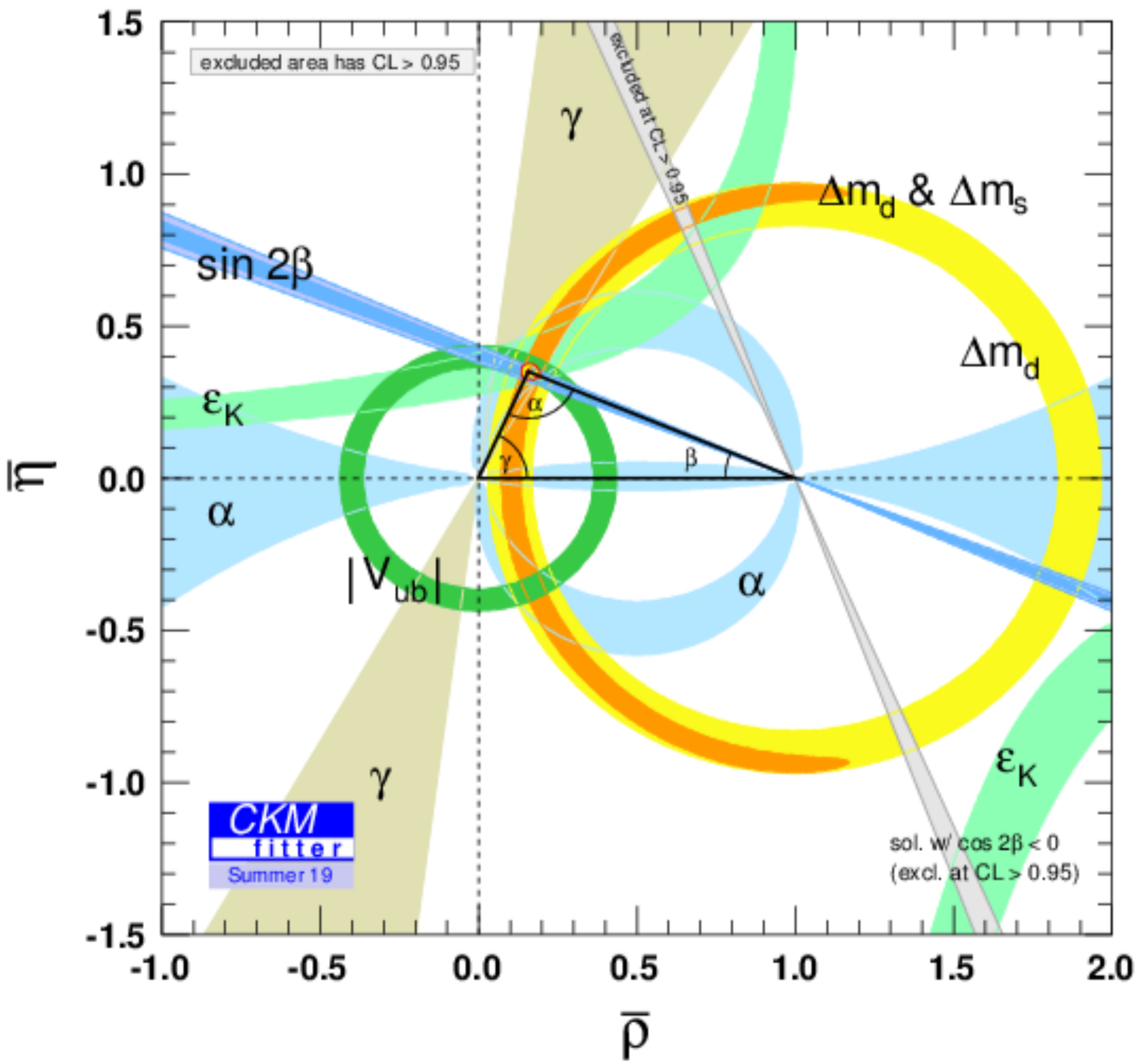


Translate to Br($\tau \to \mu a$) ~ O (10^{-5}) for Belle II (50/ab)

[Belle II collaboration, Phys.Rev.Lett (2023)]



Highlight VI - CKM Measurement

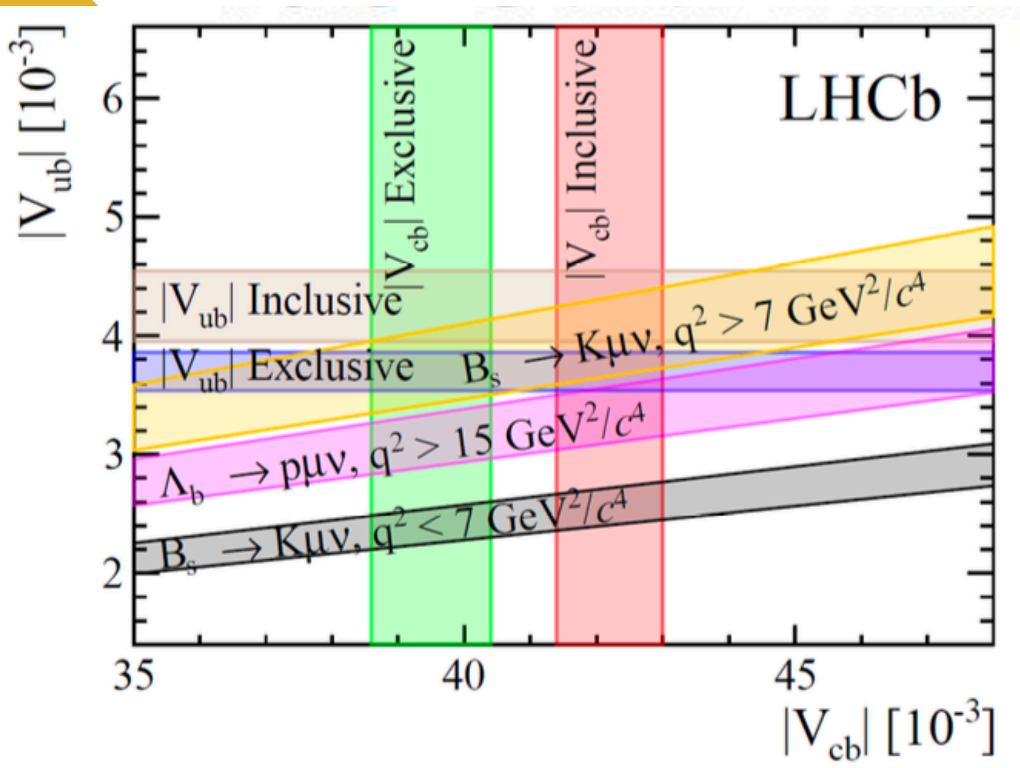


$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

- A CEPC version will be very informative
- Relevant inputs are still missing
- A task for next stage work

Highlight VI - CKM Measurement

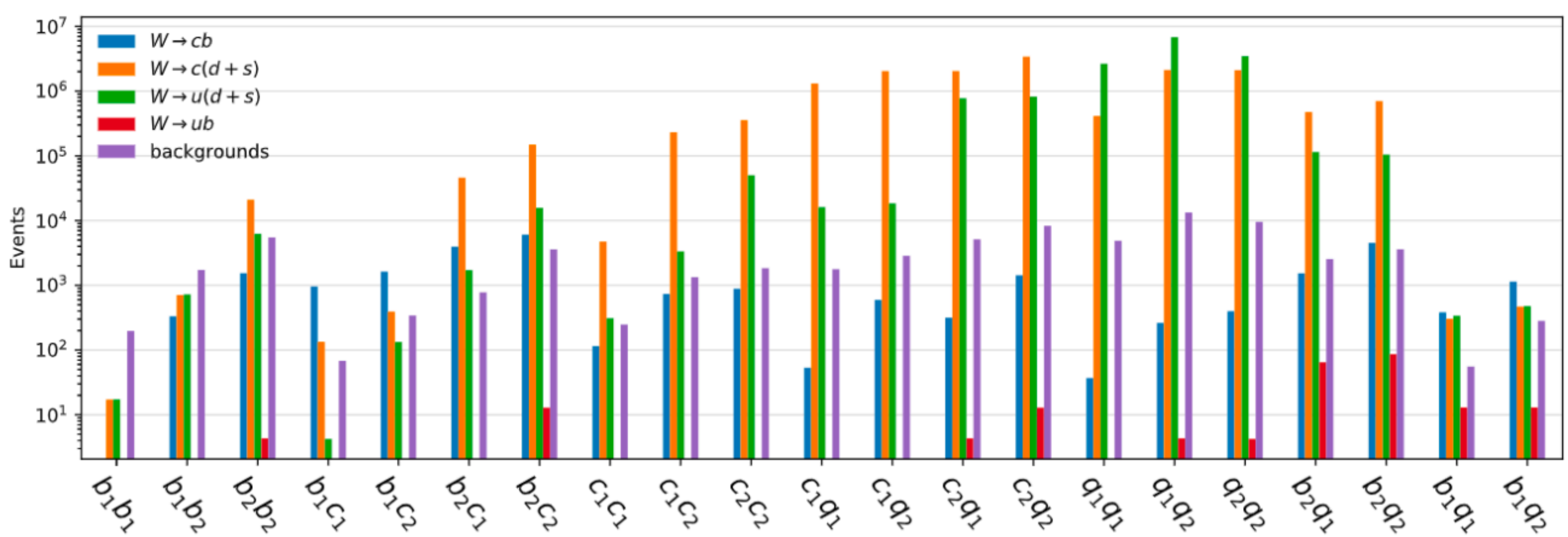


One relevant case is to determine V_{cb}

- Measure b -> c transition at Z pole
- Measure W -> bc at WW threshold

Current precision is of percent level. Could be improved by one more order of magnitude

[Liang et. al., in preparation]



Other Opportunities

Contents

[For more details, see Lingfeng Li's talk]

[See Qin Qin's talk]

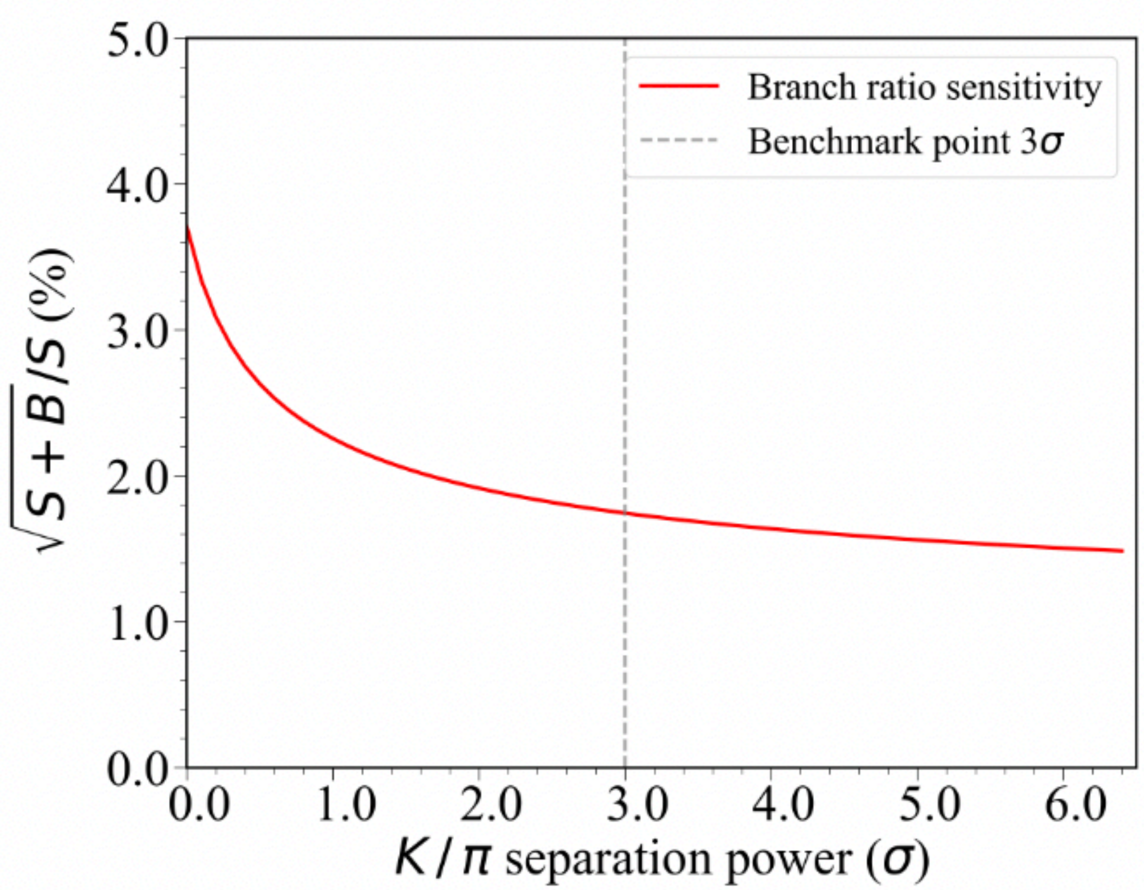
[See Fusheng Yu's talk]

[For more details, see Tsz Hong Kwok's talk]

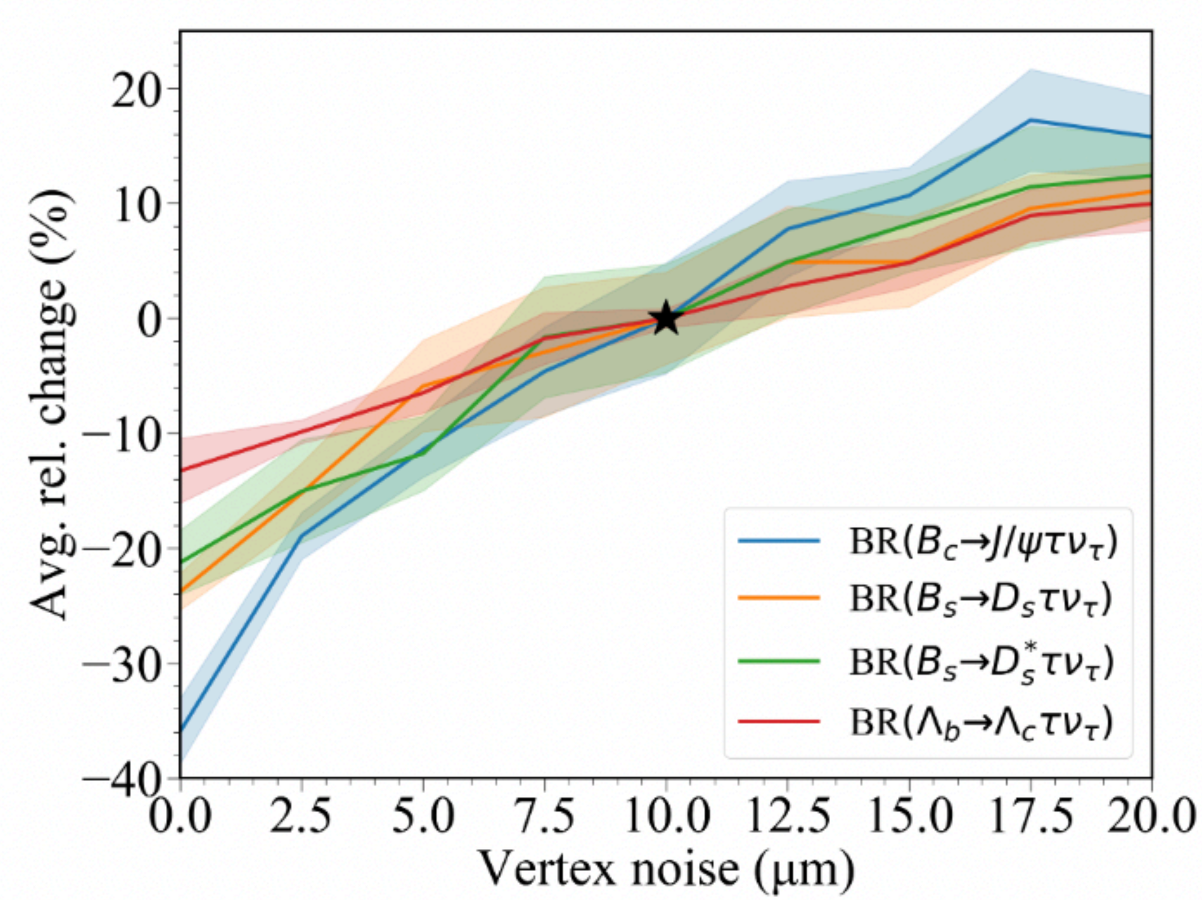
[See Guo Fengkun's talk]

More Comments

- Detector performance
  - Baseline detector profile has been applied for most of these studies
  - Study on the relation between the sensitivities and detector performance can help to optimize both detector design and physics target precision



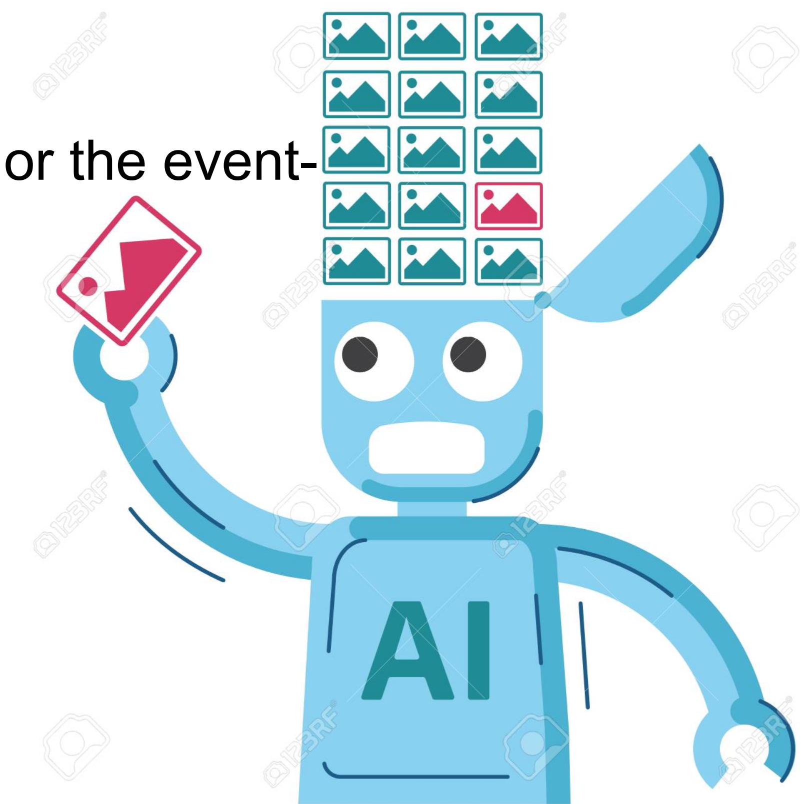
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$ vs. PID performance



$\mathrm{BR}(H_b \to H_c\tau\nu_\tau)$ vs. detector vertex noise

More Comments

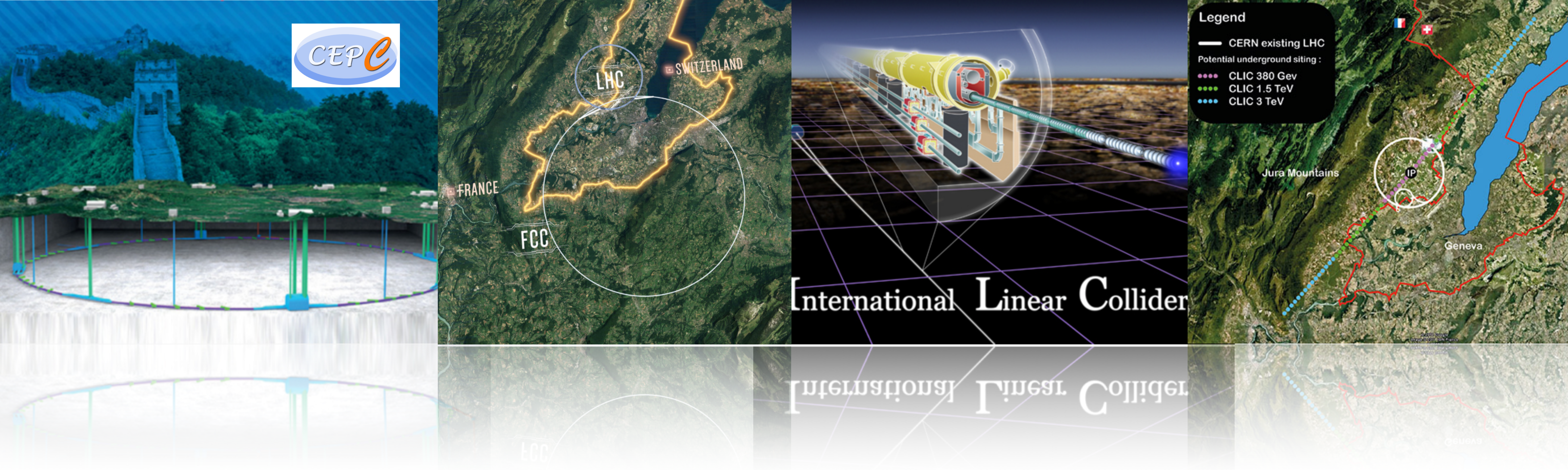
- Systematics understanding
  - Current discussions of sensitivities are essentially statistical
  - Can the experimental systematics be controlled to be below or comparable to the statistical ones?
  - Can theoretical accuracy for the background calculations and the signal predictions catch up with experiment progress by the time of CEPC data taking?
- Advanced analysis tools such as deep neural network
  - Many of these studies so far are cut-based
  - To what extent the ML tool can help if the event topology is complex or the event-level message is relevant



More Comments

- Theoretical understanding
  - Full understanding on the relationship between various flavor phenomena and fundamental physics is demanded
  - Explore the potential impacts of flavor physics for the matter evolution of the universe, such as the origin of baryon asymmetry (for an early effort, see, [TL, M. Ramsey-Musolf, J. Shu, Phys.Rev.Lett. 108 (2012)])

The Large Hadron Collider beauty (LHCb) experiment specializes in investigating the slight differences between matter and antimatter by studying a type of particle called the "beauty quark", or "b quark".



Take-home Message

We live at a unique juncture in history!

As a multi-functional machine, we would like to know the capability of the next-generation e-e+ colliders like CEPC, to push forward the relevant physics frontiers.

As part of its physics potential, Higgs physics, electroweak precision measurements and top physics at such an e-e+ collider have been extensively studied

Flavor physics is of high scientific value. The opportunities brought up by such a machine should be fully explored also. Efforts have been initiated in recent years. But, more comprehensive study is still needed. Stay tuned!

大學教育資助委員會
University Grants Committee

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