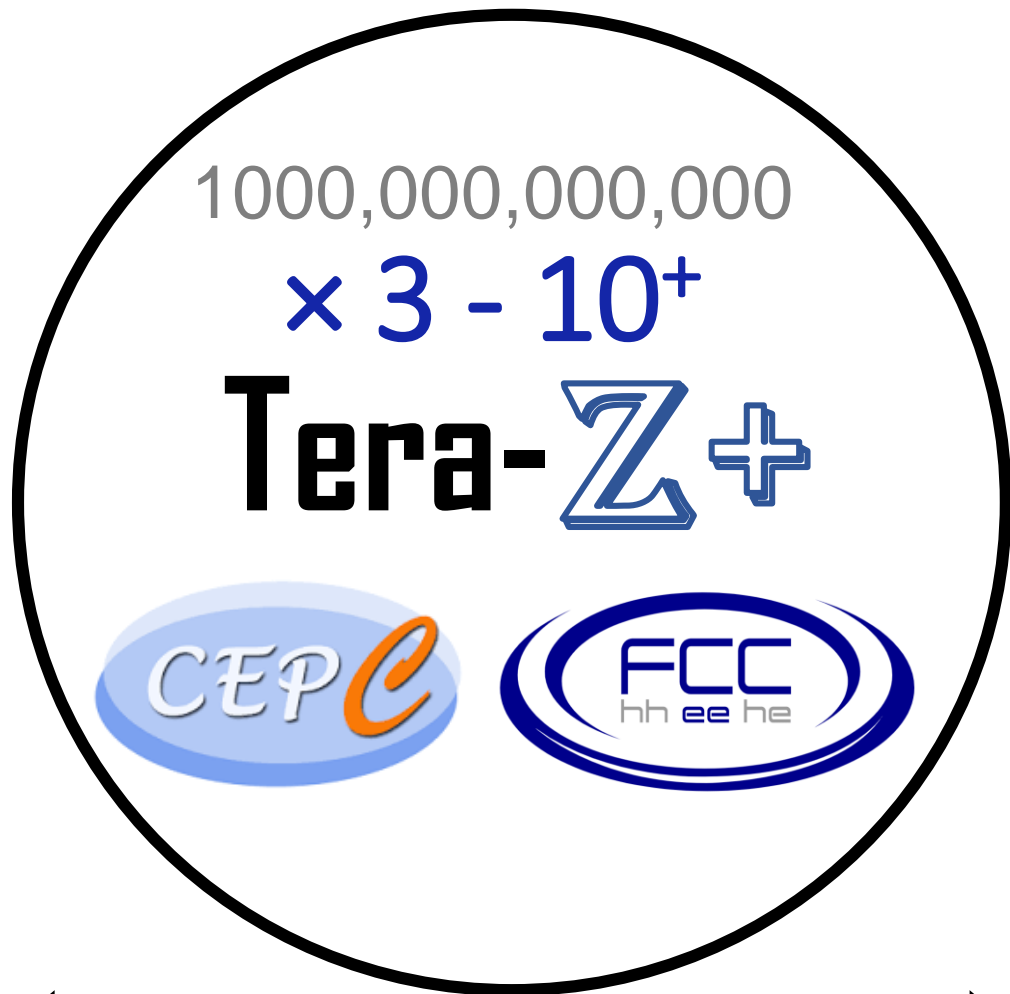


LFV Jets Precision Semileptonic Muon CKM
Tau W-Factory Bottom
FCNC Mixing
CPV Exotic
BSM Phase One Study BNV
CEPC Tera-Z+ PID
Higgs LFUV 1,000,000,000,000
Strange Anomaly Detector Time
LNV Vertex Charm

Lingfeng Li

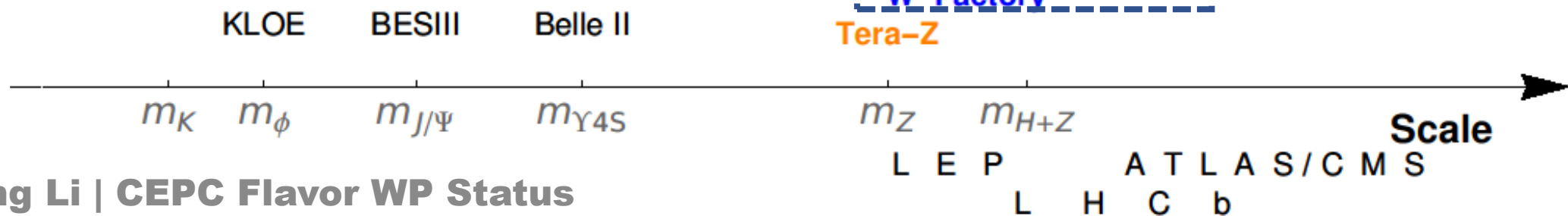
Brown University

4/8/2024 Marseille, France



- Higher luminosity as the accelerator design keeps upgrading
- ≥ 2 interaction points and various detectors

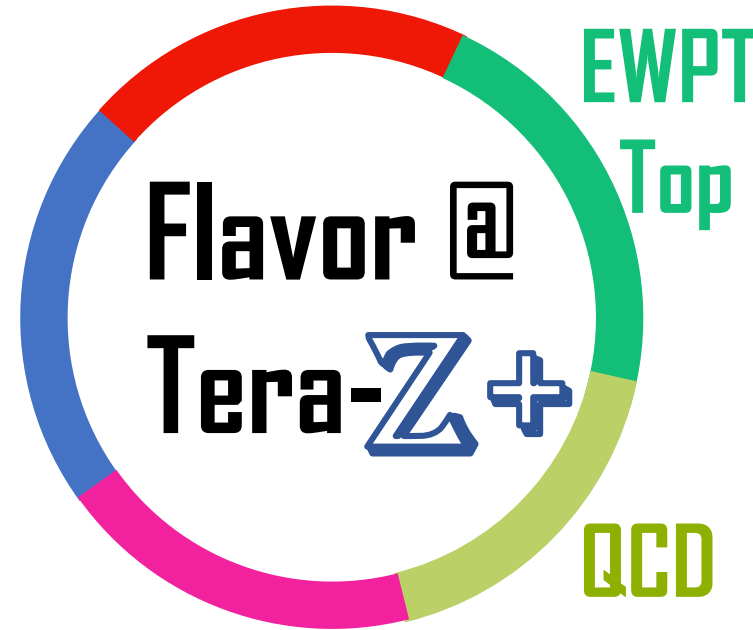
Flavor physics also need energy larger than 91 GeV (e.g., $|V_{cb}|$ from W decays)



Support the CEPC Project

- Origin of matter?
understand lepton and baryon numbers
- Light dark matter?
- Lepton Flavor Universality anomalies?

BSM



Hardware





- Origin of flavor hierarchy?
- CP violation phases from Yukawa?

- Flavor physics beyond the Tera-Z phase?
- Common need in τ phys.

- How does asymptotic freedom work with flavor?
- New formalism beyond the conventional meson-baryon picture?

- Use a plethora of data to improve hadronization

Most demanding field:
We need better tracker, E(H)CAL, electronics... everything!

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Status and Timeline

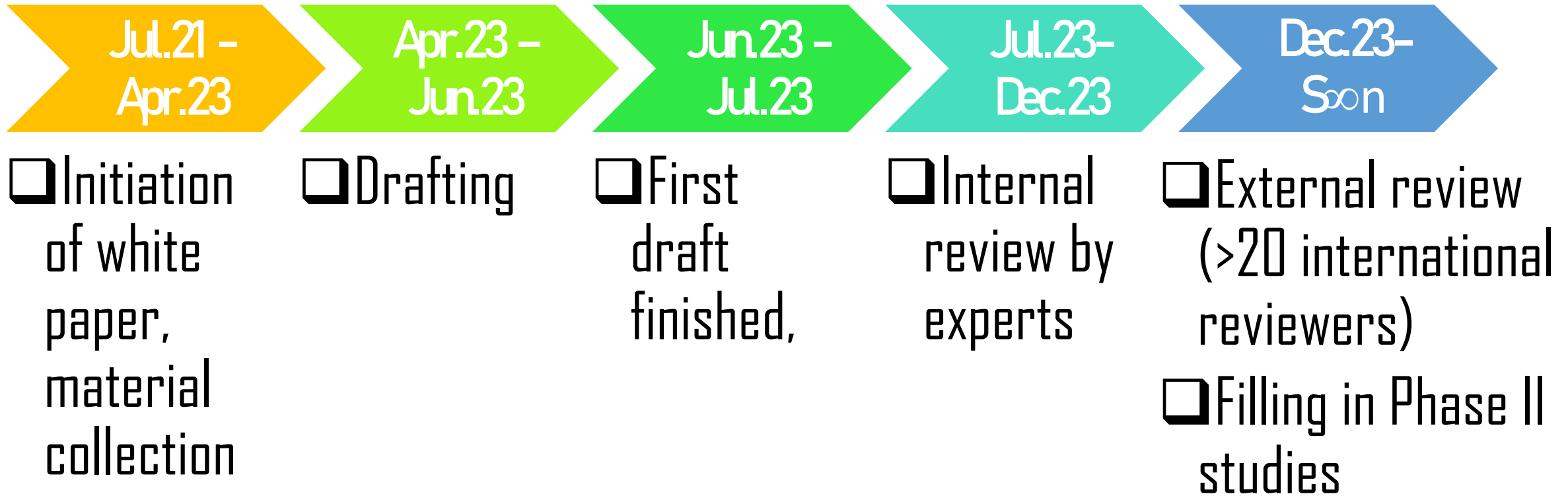
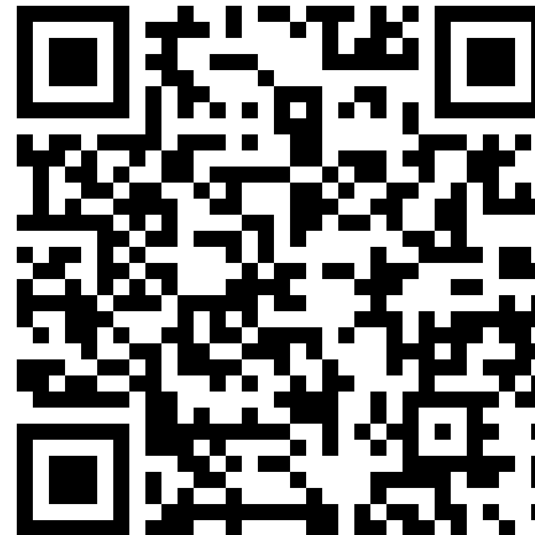


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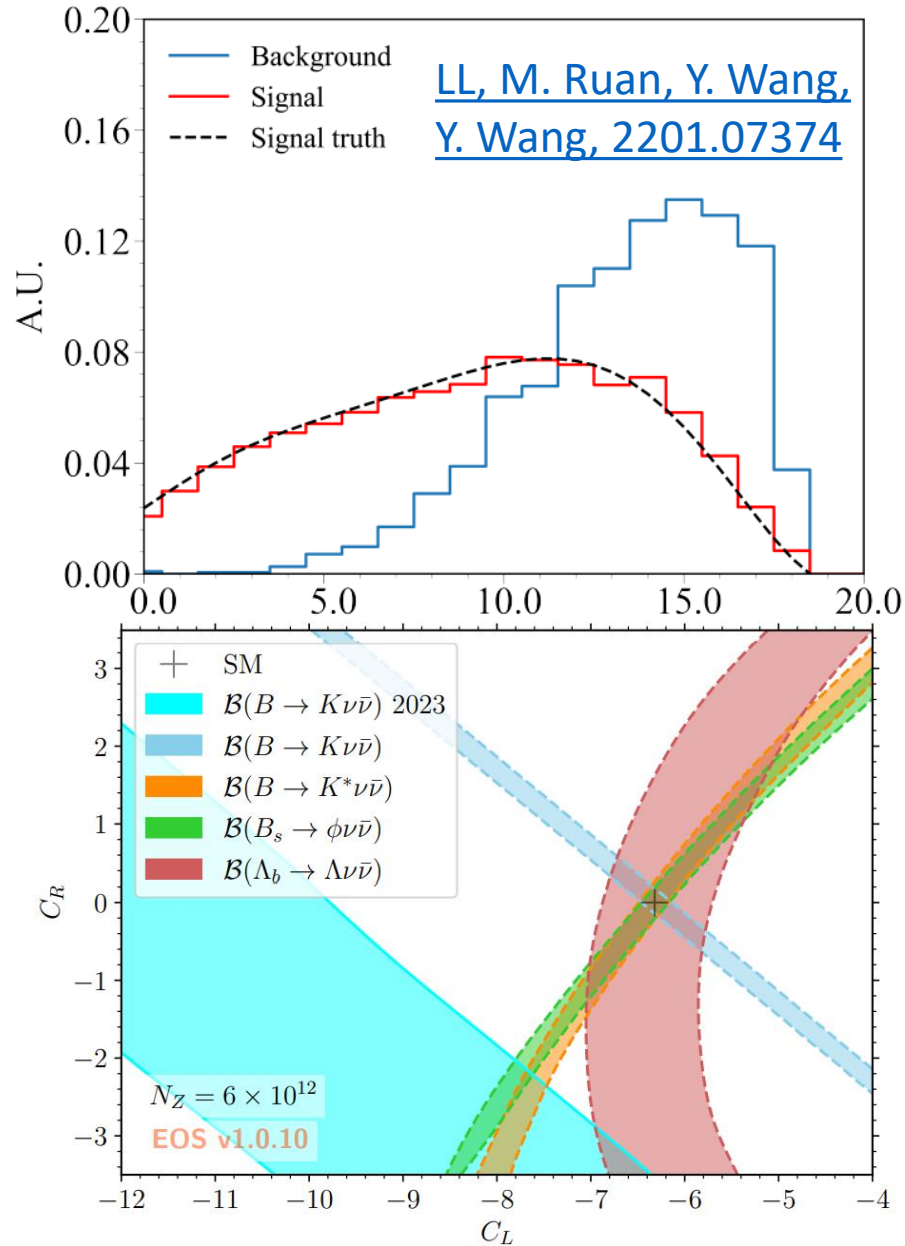
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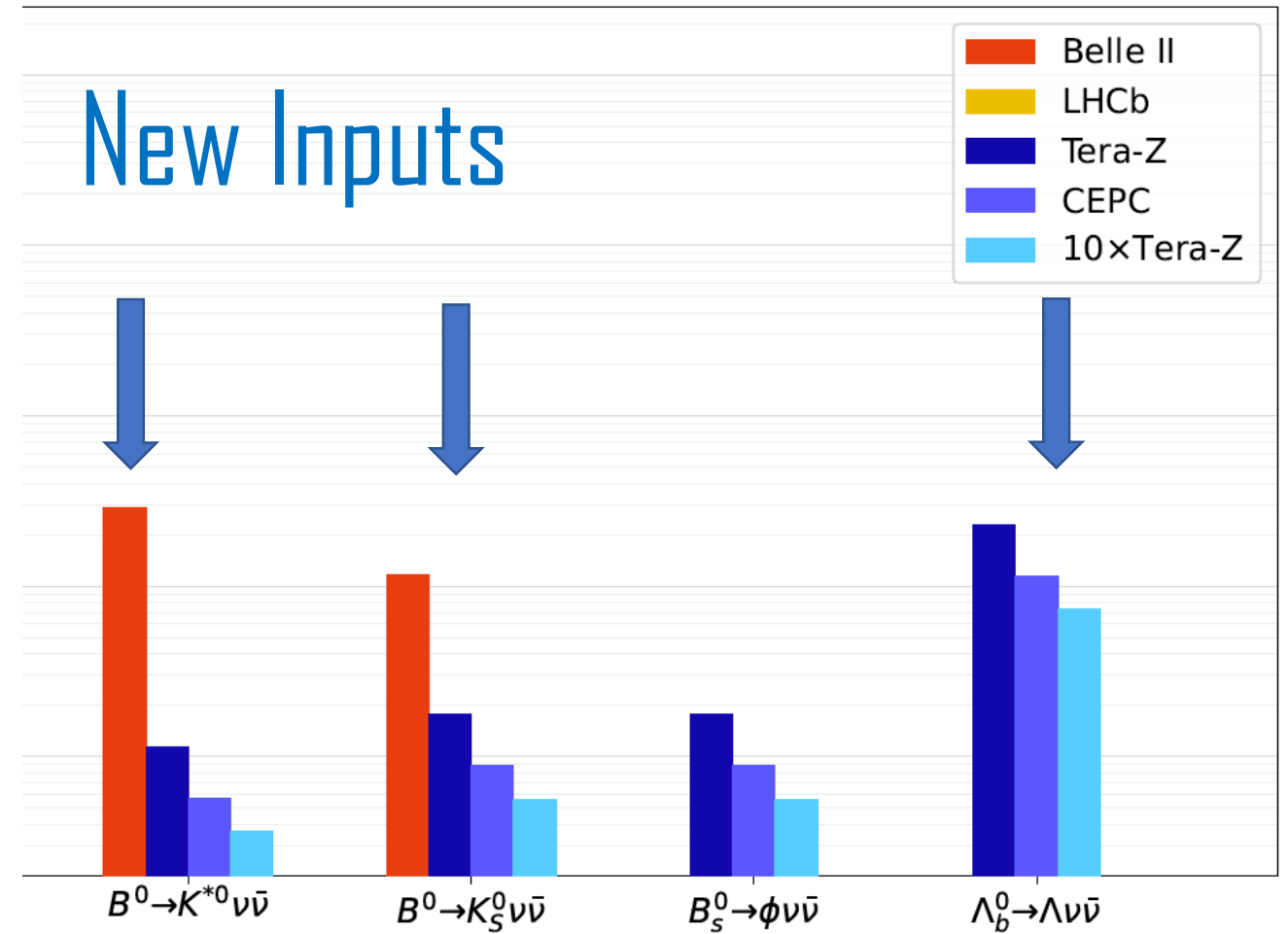
Public access and
progress here

[https://indico.ihep.
ac.cn/event/20312/](https://indico.ihep.ac.cn/event/20312/)

4.3 Neutrino Modes



Reconstruct $b \rightarrow s\nu\bar{\nu}$ semi-invisible decay



Y. Ahmis, M. Kenzie, M. Reboud and A. Wiederhold, 2309.11353

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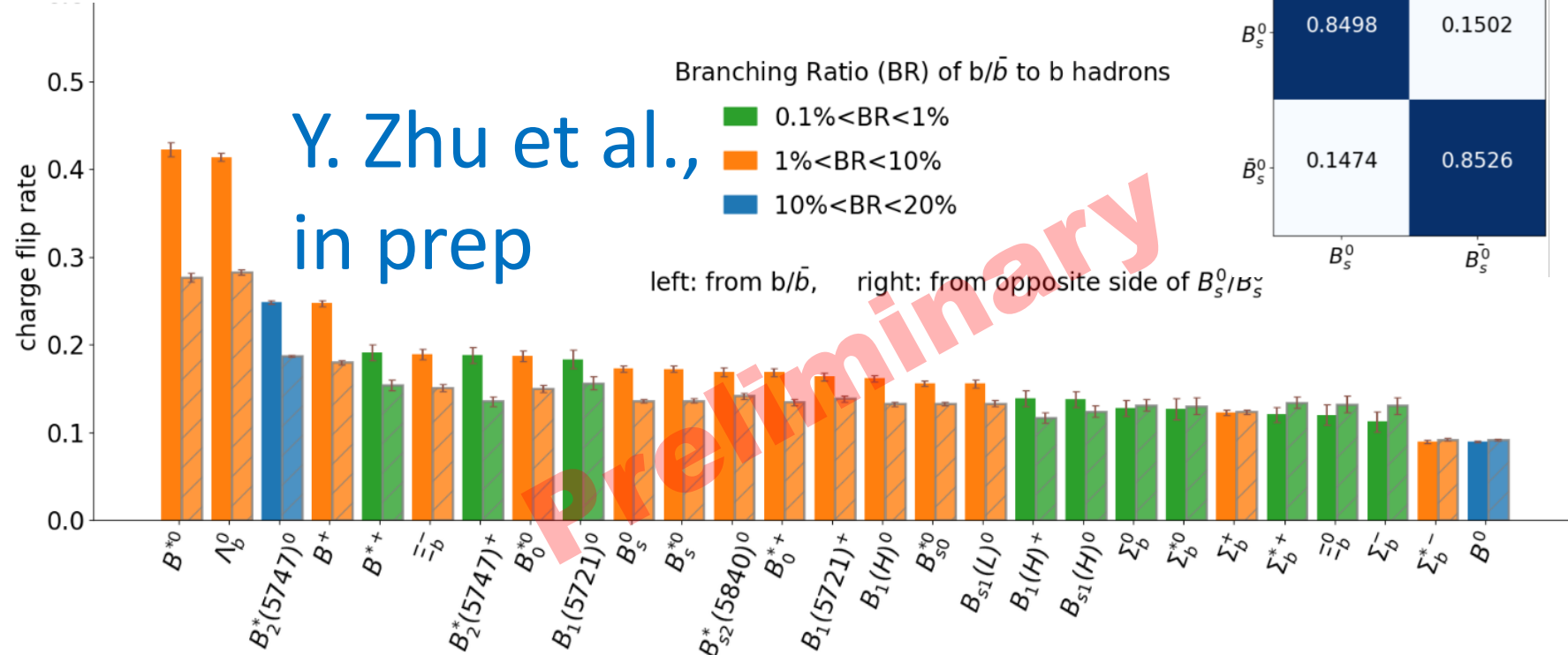
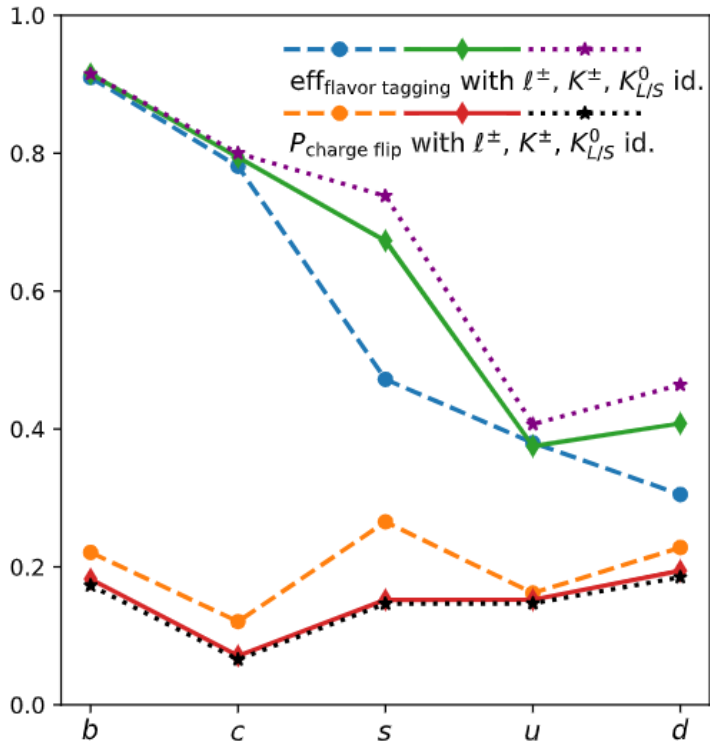
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Flavor Tagging

$$\epsilon_{\text{eff}} = \epsilon(1 - 2\omega_{\text{mistag}})^2$$

Effective tagging power @ LEP ~ 20%,
 expected to improve further @ CEPC
 (vs. ~5% @ LHCb & ~35% @ Belle II)

Yes, but...



[H. Liang, Y. Zhu, Y. Wang, Y. Che, C. Zhou, H. Qu et al, 2310.03440](#)

In the next talk 9

10 Flavor Physics beyond the Z Pole

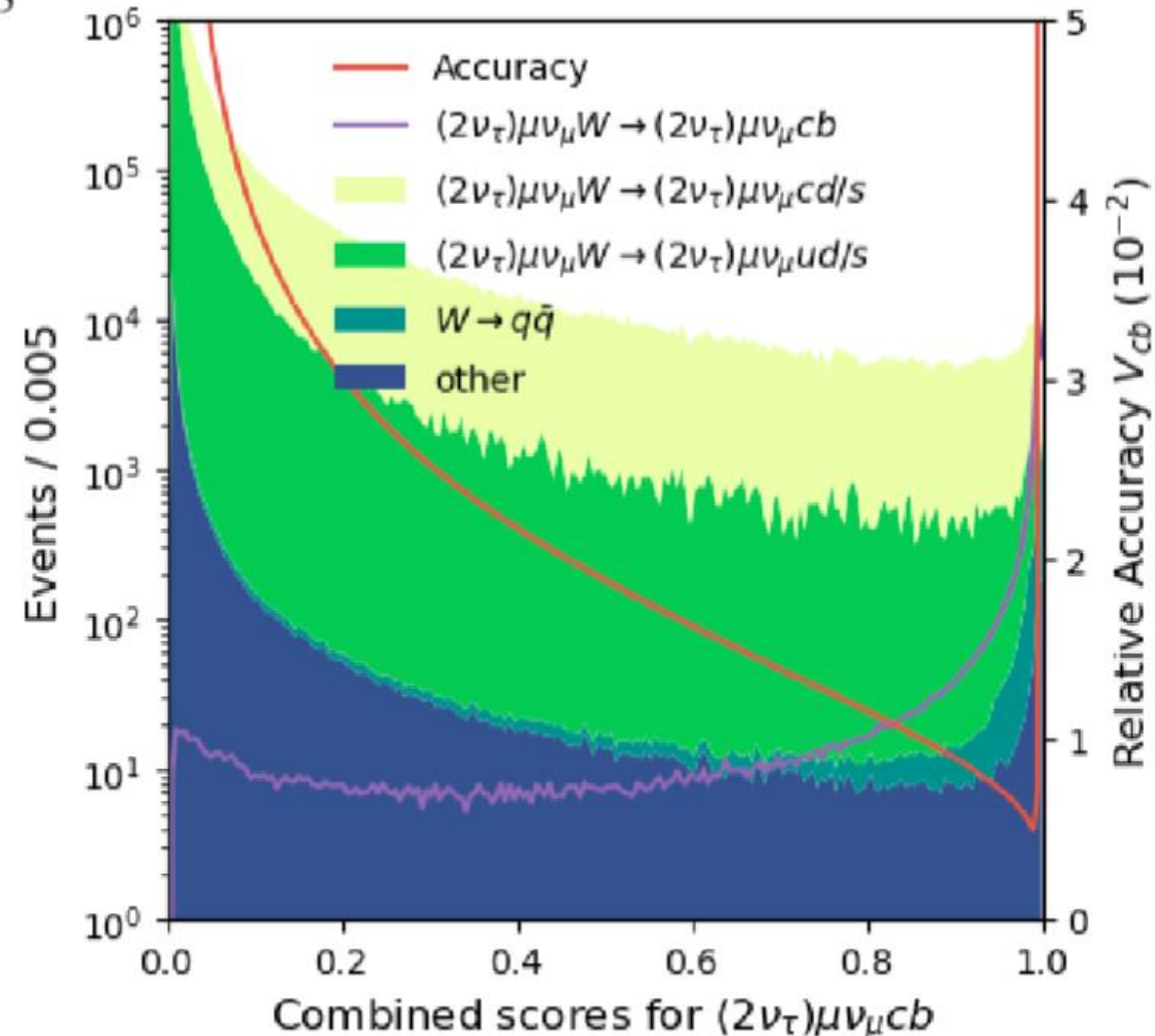
10.1 $|V_{cb}|$ and W Decays

10.2 Exotic and FCNC Higgs Decays

10.3 Top FCNC

- Higgs factory mode leading instead of WW threshold
- ML (e.g. particle net) helps greatly
- Low theoretical uncertainties
- $O(0.5\%)$ stat.+ theo. uncertainty

H. Liang et al., in prep

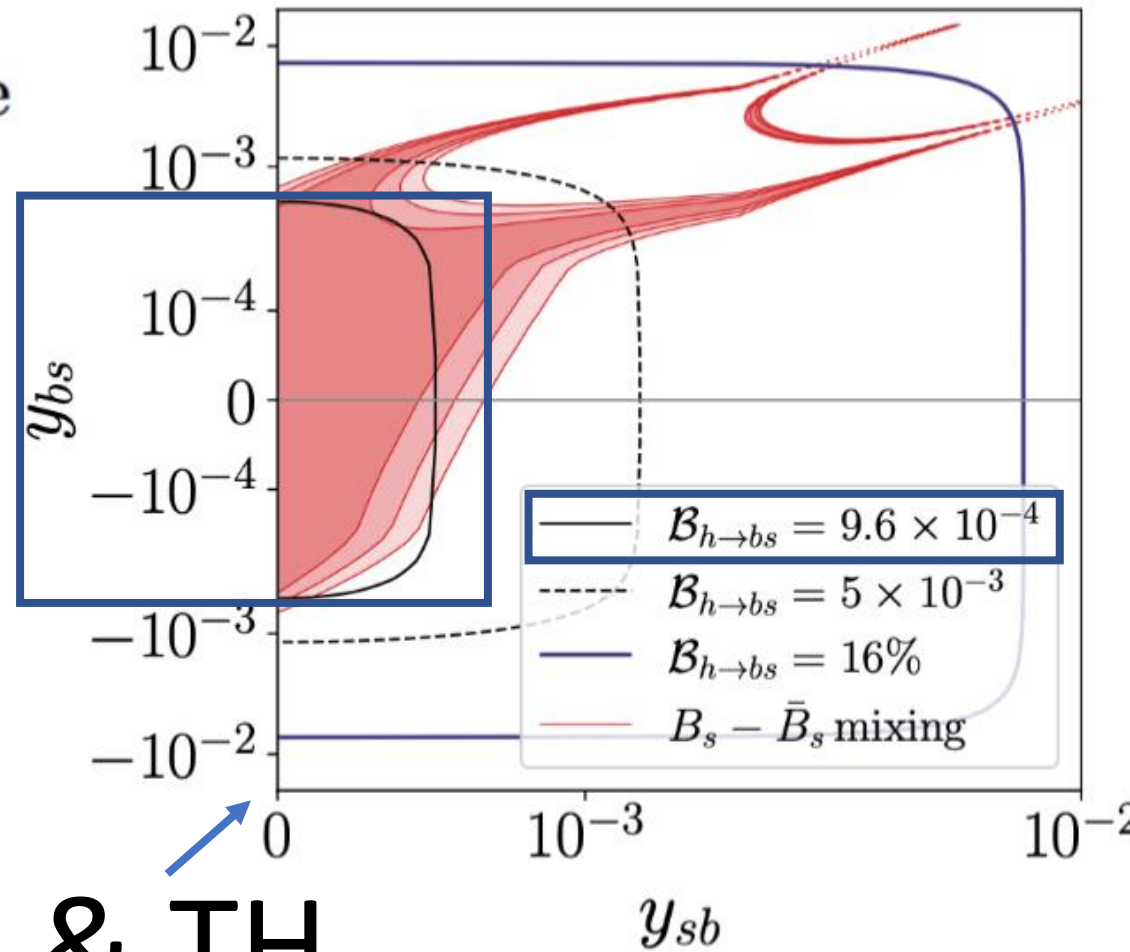
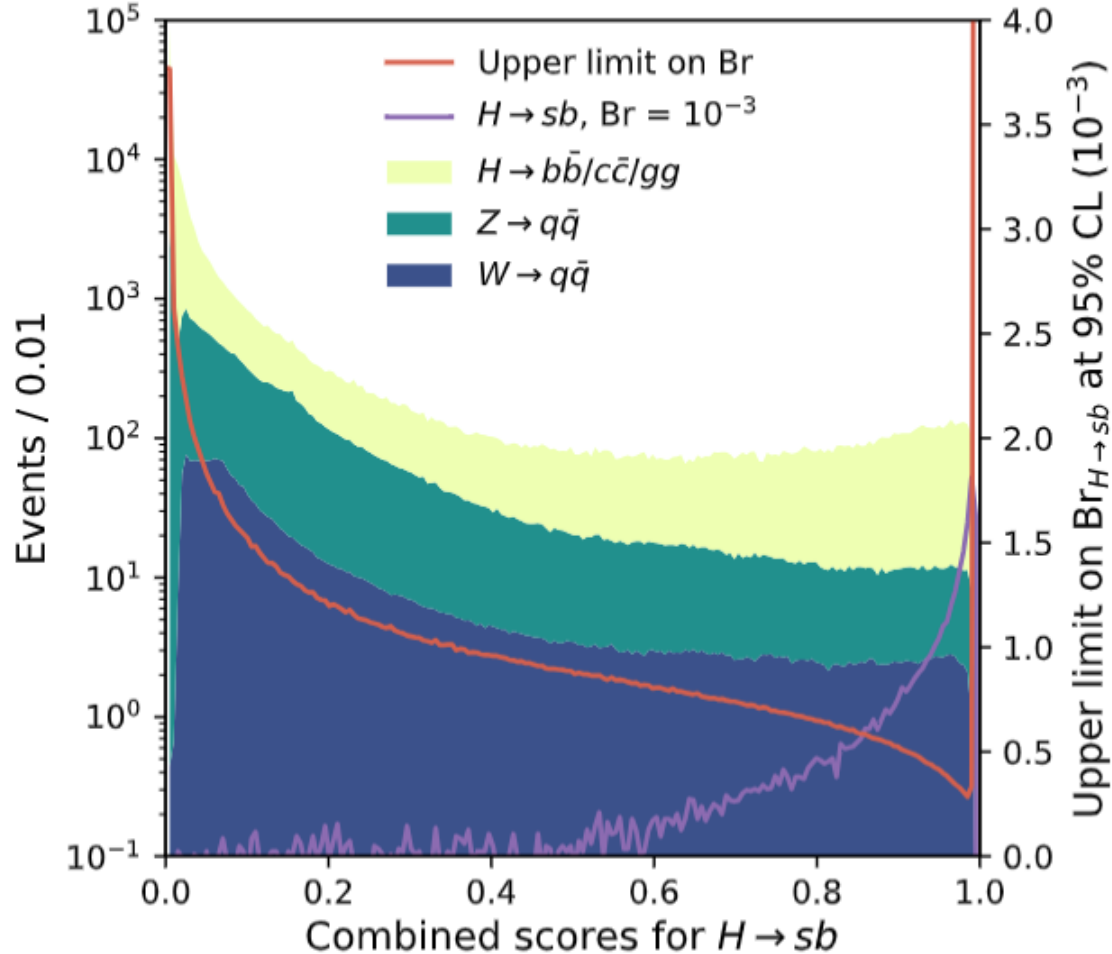


10 Flavor Physics beyond the Z Pole

10.1 $|V_{cb}|$ and W Decays

10.2 Exotic and FCNC Higgs Decays

10.3 Top FCNC



Exp & TH

[J. F. Kamenik, A. Korajac, M. Szewc, M. Tamaro and J. Zupan, 2306.17520](#)

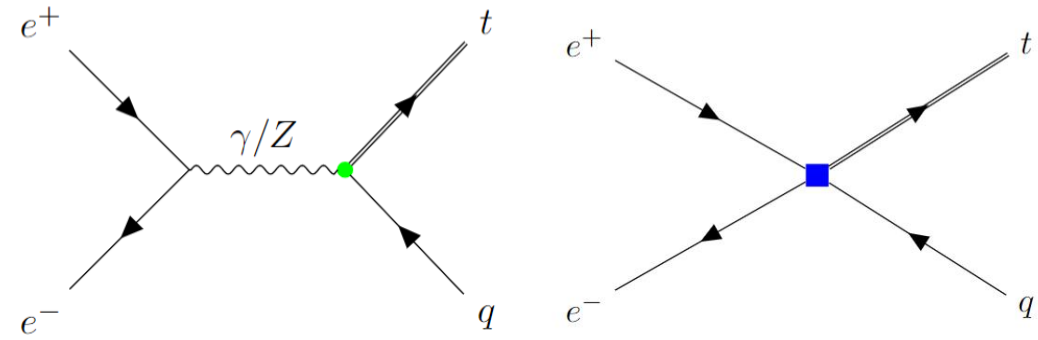
[H. Liang, Y. Zhu, Y. Wang, Y. Che, C. Zhou, H. Qu et al, 2310.03440](#)

10 Flavor Physics beyond the Z Pole

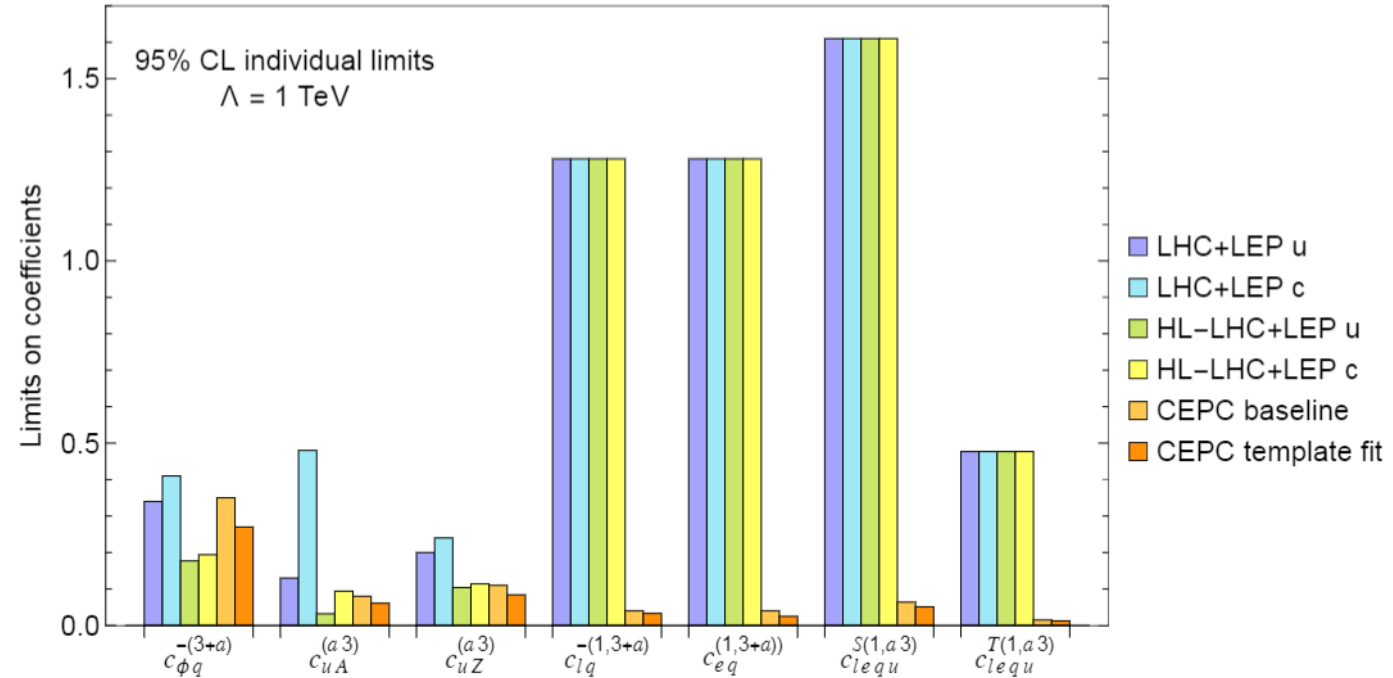
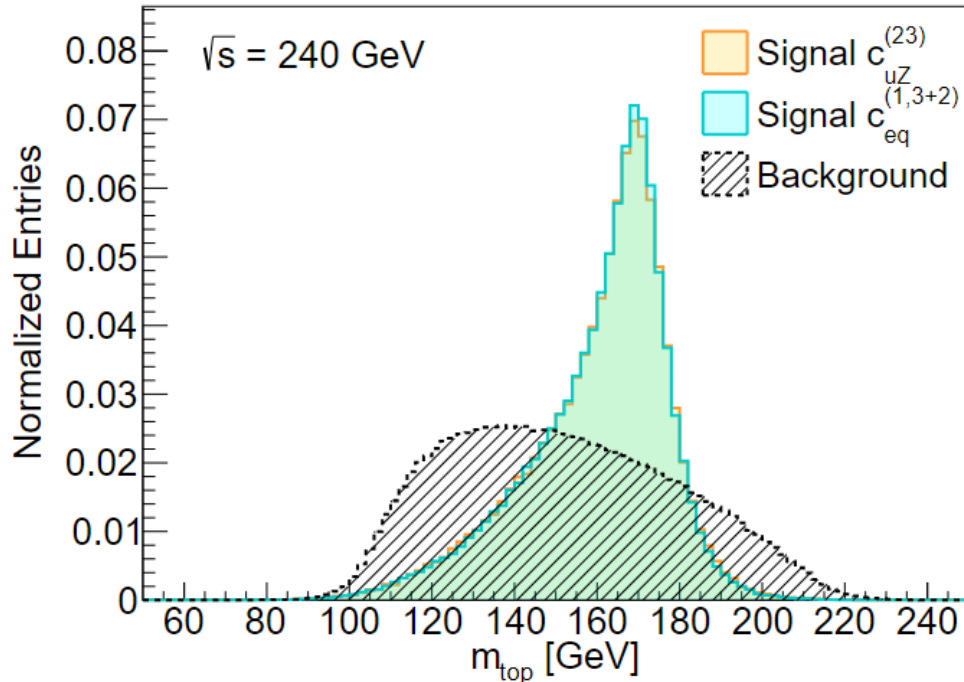
10.1 $|V_{cb}|$ and W Decays

10.2 Exotic and FCNC Higgs Decays

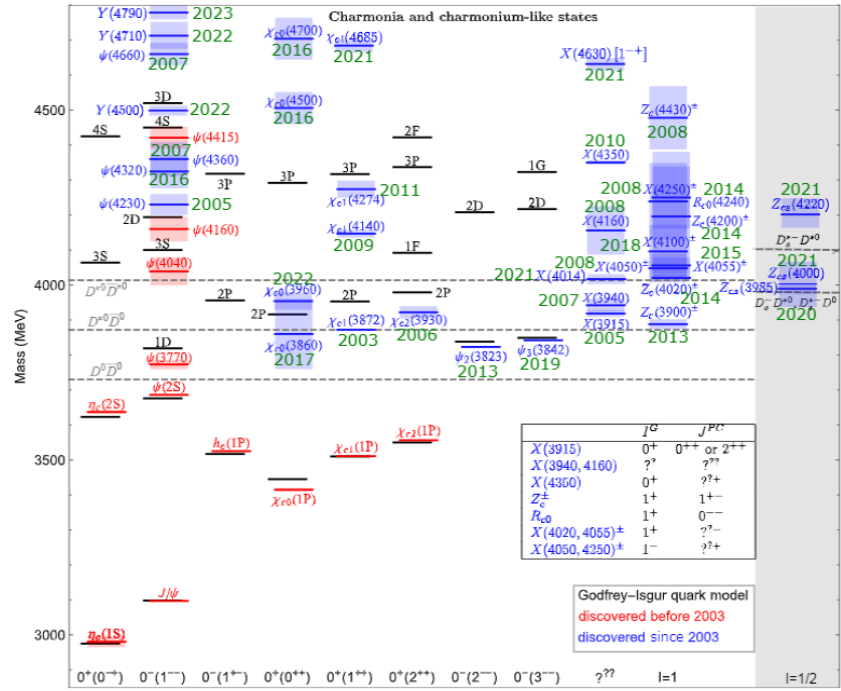
10.3 Top FCNC



[L. Shi and C. Zhang, 1906.04573](#)



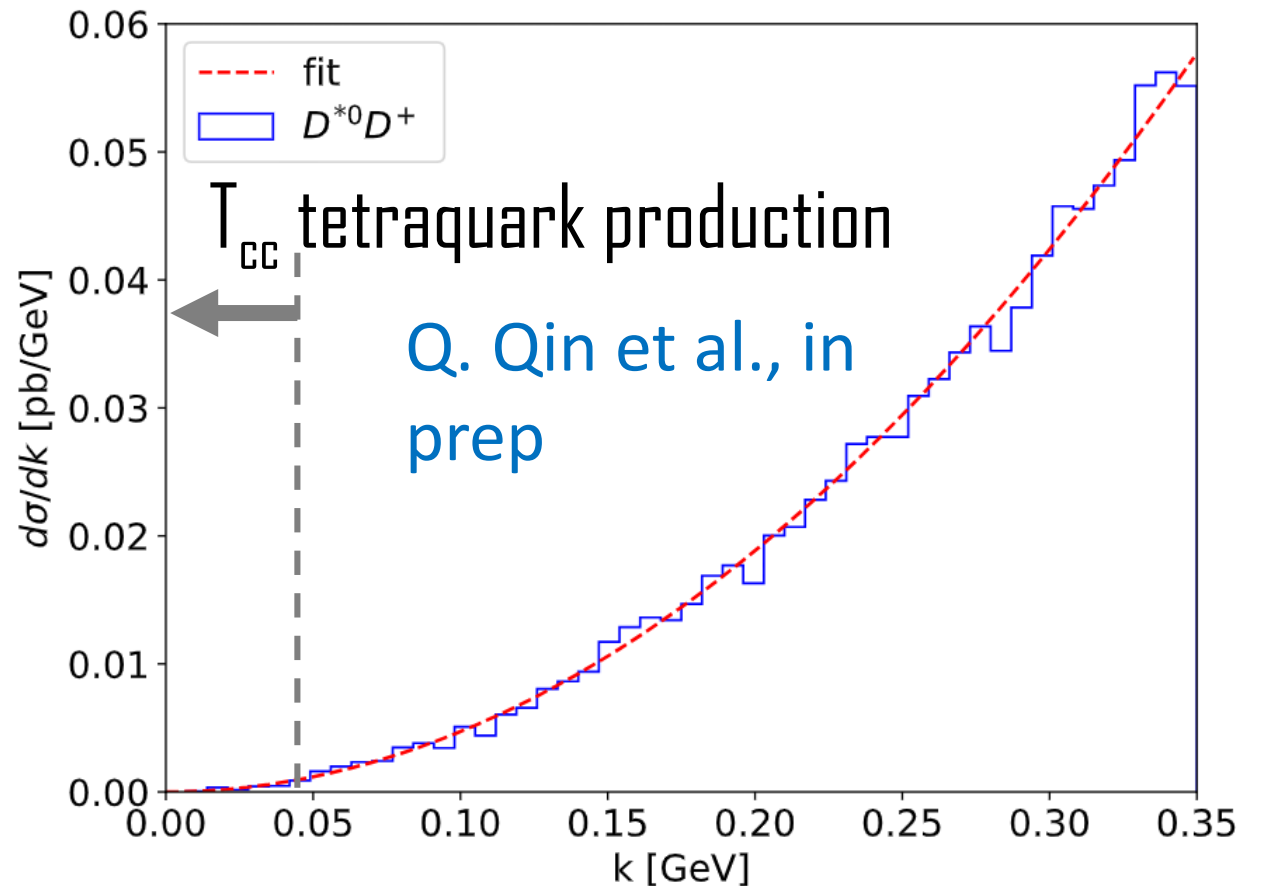
11 Spectroscopy and Exotics

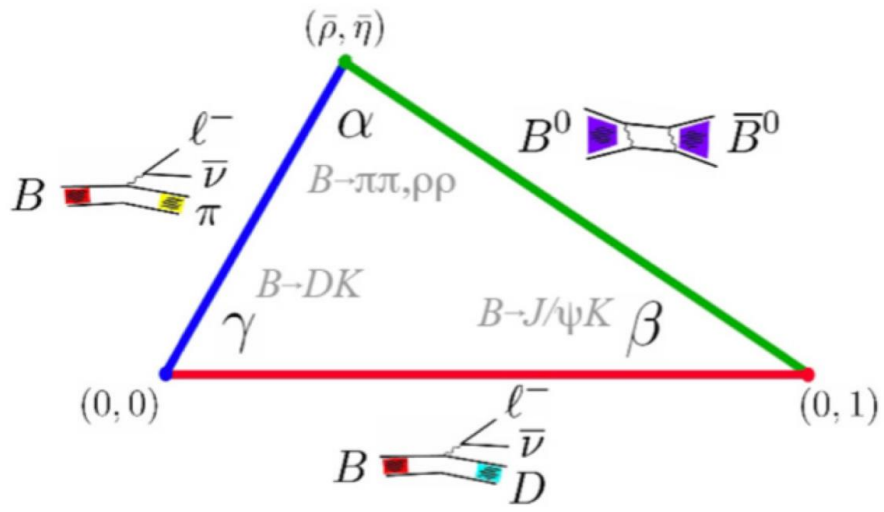


- A lot of states, guaranteed DISCOVERY at CEPC?
- $Z \rightarrow bbbb, bbcc, cccc$ processes may give rise to highly exotic species
- Production & decay largely unknown

Recommendations:

- ❖ More theory inputs for simulation
- ❖ Analysis framework to be developed





- ❖ We certainly want a CEPC version
- ❖ Need many more experiment and theory inputs
- ❖ Move on to the next phase

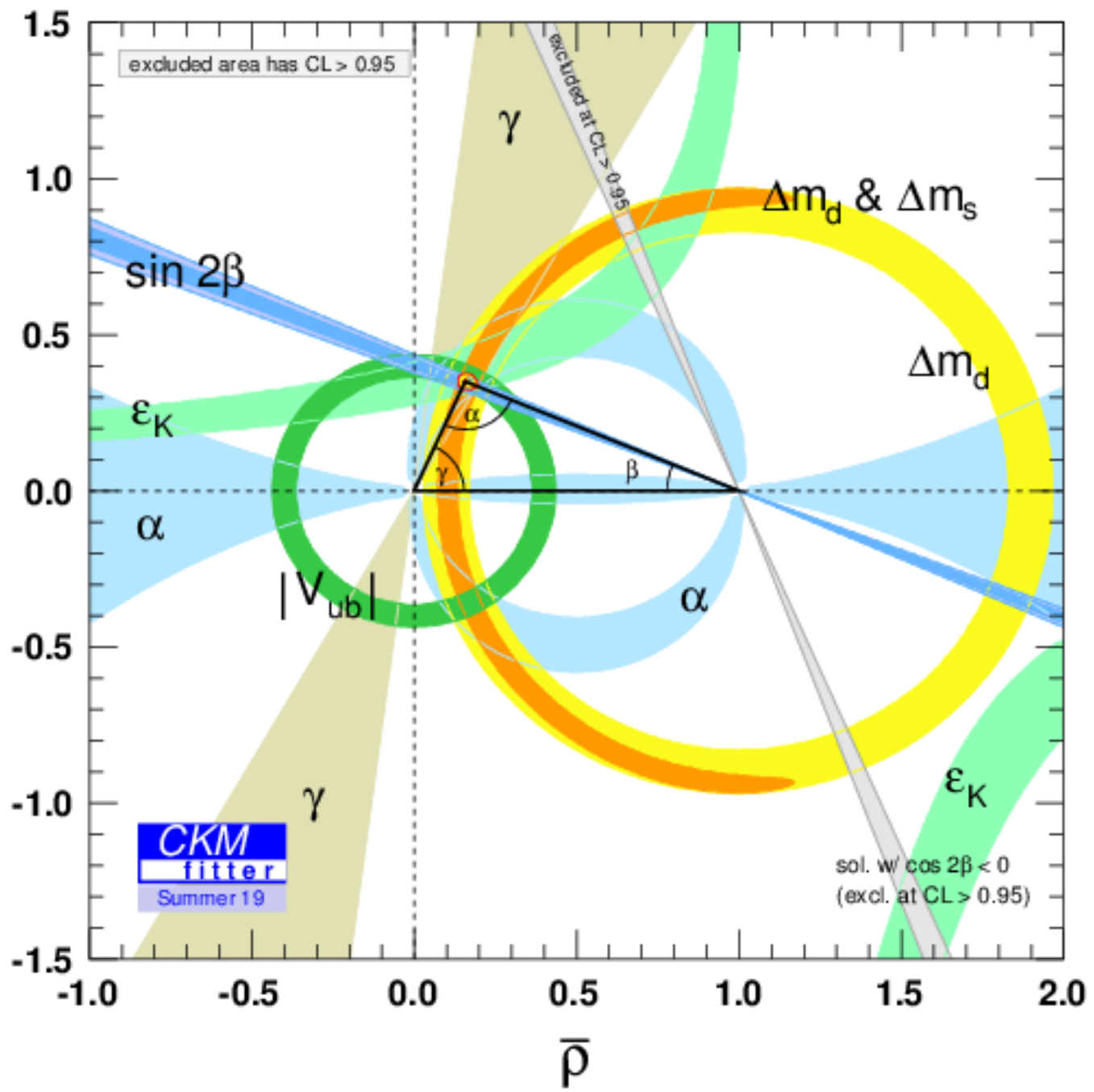


Table of Collected Performance

No.	Process	\sqrt{s} (GeV)	Parameter of interest	Observable	Current precision	CEPC Precision	Estimation method	Key detector performance	Relevant Section
1	$Z \rightarrow \mu\mu a$	91.2	-	BR upper limit	-	$\lesssim 3 \times 10^{-11}$ [251]	Fast simulation	Tracker Missing energy	12
2	$B \rightarrow K\hat{\pi}(\rightarrow \mu\mu)$	91.2	-	BR upper limit	-	$\lesssim 10^{-10}$ [261]	Fast simulation	Tracker Vertex	12
3	$Z \rightarrow \pi^+\pi^-$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-10})$ [109]	Guesstimate	Tracker PID	9
4	$Z \rightarrow \pi^+\pi^-\pi^0$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
5	$b \rightarrow s\tau^+\tau^-$	91.2	-	BR upper limit	-	$B^0 \rightarrow K^{*0}\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \rightarrow \phi\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B^+ \rightarrow K^+\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \rightarrow \tau^+\tau^- \mathcal{O}(10^{-5})$	[71] Fast simulation	Tracker Vertex Jet origin ID	4
6	$Z \rightarrow \rho\gamma$	91.2	-	BR upper limit	$< 2.5 \times 10^{-5}$ [150]	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
7	$Z \rightarrow J/\psi\gamma$	91.2	-	BR upper limit	$< 1.4 \times 10^{-6}$ [150]	$10^{-9} - 10^{-10}$ [109]	Guesstimate	Tracker PID ECAL	9
8	$Z \rightarrow \tau\mu$	91.2	-	BR upper limit	$< 6.5 \times 10^{-6}$ [105–107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-9} [110]	Guesstimate	E_{beam} Tracker PID	6

9	$Z \rightarrow \tau e$	91.2	-	BR upper limit	$< 5.0 \times 10^{-6}$	[105–107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-9} [110]	Guesstimate	E_{beam} Tracker PID	6
10	$Z \rightarrow \mu e$	91.2	-	BR upper limit	$< 7.5 \times 10^{-7}$	[105–107]	$\mathcal{O}(10^{-9})$ [108, 109] $\mathcal{O}(10^{-9})$ [108, 109] 1×10^{-9} [110]	Guesstimate	E_{beam} Tracker PID	6
11	$\tau \rightarrow \mu a$	91.2	-	BR upper limit	$\lesssim 7 \times 10^{-4}$	[259]	$\lesssim 3\text{--}5 \times 10^{-6}$	Fast simulation	Tracker Missing energy	12
12	$\tau \rightarrow \mu\mu\mu$	91.2	-	BR upper limit	$< 2.1 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
13	$\tau \rightarrow eee$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
14	$\tau \rightarrow e\mu\mu$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
15	$\tau \rightarrow \mu ee$	91.2	-	BR upper limit	$< 1.8 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
16	$\tau \rightarrow \mu\gamma$	91.2	-	BR upper limit	$< 4.4 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID ECAL	8
17	$\tau \rightarrow e\gamma$	91.2	-	BR upper limit	$< 3.3 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID ECAL	8
18	$B_c \rightarrow \tau\nu$	91.2	$ V_{cb} $	$\sigma(\mu)/\mu$	$\text{BR} \lesssim 30\%$	[267]	$\mathcal{O}(1\%)$ [63]	Full simulation	Tracker Lepton ID Missing energy Jet origin ID	3
19	$B_s \rightarrow \phi\nu\bar{\nu}$	91.2	-	$\sigma(\mu)/\mu$	$\text{BR} < 5.4 \times 10^{-3}$	[150]	$\lesssim 2\%$ [35]	Full simulation	Tracker Vertex Missing energy PID	4
20		91.2		τ_τ (s) lifetime	$\pm 5 \times 10^{-16}$	[150]	$\pm 1 \times 10^{-18}$ [108]	Guesstimate	-	8
21		91.2		m_τ (MeV)	± 0.12	[150]	$\pm 0.004 \pm 0.1$ [108]	Guesstimate	-	8
22	$\tau \rightarrow \ell\nu\bar{\nu}$	91.2	-	BR	$\pm 4 \times 10^{-4}$	[150]	$\pm 3 \times 10^{-5}$ [108]	Guesstimate	Tracker Lepton ID Missing energy	8

23	$Z \rightarrow \pi^+\pi^-$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-10})$ [118]	Conjecture	Tracker PID	9
24	$Z \rightarrow \pi^+\pi^-\pi^0$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-9})$ [118]	Conjecture	Tracker PID ECAL	9
25	$Z \rightarrow \rho\gamma$	91.2	BR	$< 2.5 \times 10^{-5}$ [156]	$\lesssim \mathcal{O}(10^{-9})$ [118]	Conjecture	Tracker PID ECAL	9
26	$Z \rightarrow J/\psi\gamma$	91.2	BR	$< 1.4 \times 10^{-6}$ [156]	$\lesssim 10^{-9}$ – 10^{-10} [118]	Conjecture	Tracker PID ECAL	9
27	$Z \rightarrow \tau\mu$	91.2	BR	$< 6.5 \times 10^{-6}$ [114–116]	$\lesssim \mathcal{O}(10^{-9})$ [117, 118]	Conjecture	E_{beam} Tracker PID	6
28	$Z \rightarrow \tau e$	91.2	BR	$< 5.0 \times 10^{-6}$ [114–116]	$\lesssim \mathcal{O}(10^{-9})$ [117, 118]	Conjecture	E_{beam} Tracker PID	6
29	$Z \rightarrow \mu e$	91.2	BR	$< 7.5 \times 10^{-7}$ [114–116]	$\lesssim 1 \times 10^{-9}$ [111]	Conjecture	E_{beam} Tracker PID	6
30	$Z \rightarrow \mu\mu X_{\text{inv}}$	91.2	BR	-	$\lesssim 3 \times 10^{-11}$ [282]	Fast simulation	Tracker Missing energy	12
31	$\tau \rightarrow \mu X_{\text{inv}}$	91.2	BR	$\lesssim 7 \times 10^{-4}$ [290]	$\lesssim 3$ – 5×10^{-6}	Fast simulation	Tracker Missing energy	12
32	$H \rightarrow sb$	240	BR	$\lesssim 10^{-2}$ [302]	$\lesssim 0.02\%$ – 0.1% [33]	Full simulation	Jet origin ID	10

32	$H \rightarrow sb$	240	BR	$\lesssim 10^{-2}$ [302]	$\lesssim 0.02\%—0.1\%$ [33]	Full simulation	Jet origin ID	10
33	$H \rightarrow sd$	240	BR	-	$\lesssim 0.02\%—0.1\%$ [33]	Full simulation	Jet origin ID	10
34	$H \rightarrow db$	240	BR	$\lesssim 10^{-2}$ [302]	$\lesssim 0.02\%—0.1\%$ [33]	Full simulation	Jet origin ID	10
35	$H \rightarrow uc$	240	BR	-	$\lesssim 0.02\%—0.1\%$ [33]	Full simulation	Jet origin ID	10
36	$H \rightarrow ss$	240	BR	$\lesssim 0.3\%$ [303, 304]	$\lesssim 0.1\%$ [33]	Full simulation	Jet origin ID	10
37	$H \rightarrow uu$	240	BR	$\lesssim 3.5\%$ $\kappa_u < 560$ [305]	$\lesssim 0.1\%$ [33] $\kappa_u < 101$	Full simulation	Jet origin ID	10
38	$H \rightarrow dd$	240	BR	$\lesssim 3.5\%$ $\kappa_d < 260$ [305]	$\lesssim 0.1\%$ [33] $\kappa_d < 37$	Full simulation	Jet origin ID	10
39	$e^+e^- \rightarrow tq$	240	cross section	two-fermion, LHC [212–216] four-fermion, LEP2 [217, 218]	1–2 orders of magnitude improvement compared to LEP2 [211]	Fast simulation	Tracker Missing energy Jet origin ID	10
40	$WW \rightarrow \mu\nu qq$ $WW \rightarrow \tau(\rightarrow \mu\nu\nu)\nu qq$	240	$ V_{cb} $	$\pm 0.5 \times 10^{-3}$ (inclusive) $\pm 0.6 \times 10^{-3}$ (exclusive) [156] $\pm 1.2 \times 10^{-3}$ (average)	$\lesssim \pm 0.2 \times 10^{-3}$ [205]	Full simulation	Jet origin ID	10

Summary: New Ingredients



Bsvv updates



Top FCNC



Charge tagging of B_s



Higgs FCNC



Spectroscopy



W decay for the $|V_{cb}|$



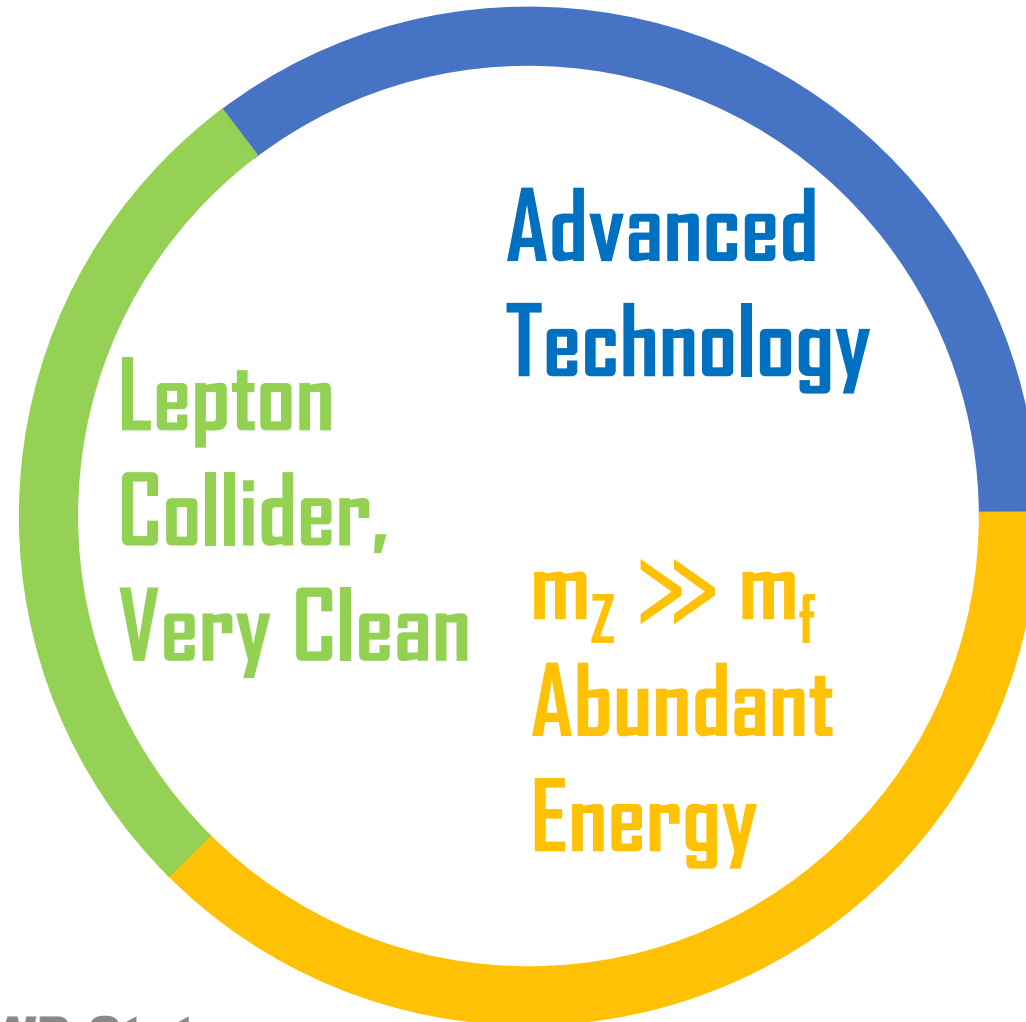
+ Previous efforts



BACKUP SLIDES

Three Cornerstones of CEPC

- Neutrinos
- Neutrals
(photon/ π^0 / η ...)
- Rare modes
- BSM states



- PID
- Flavor Tagging
- $b \rightarrow c \rightarrow \tau$ cascade
- Long-lived particles

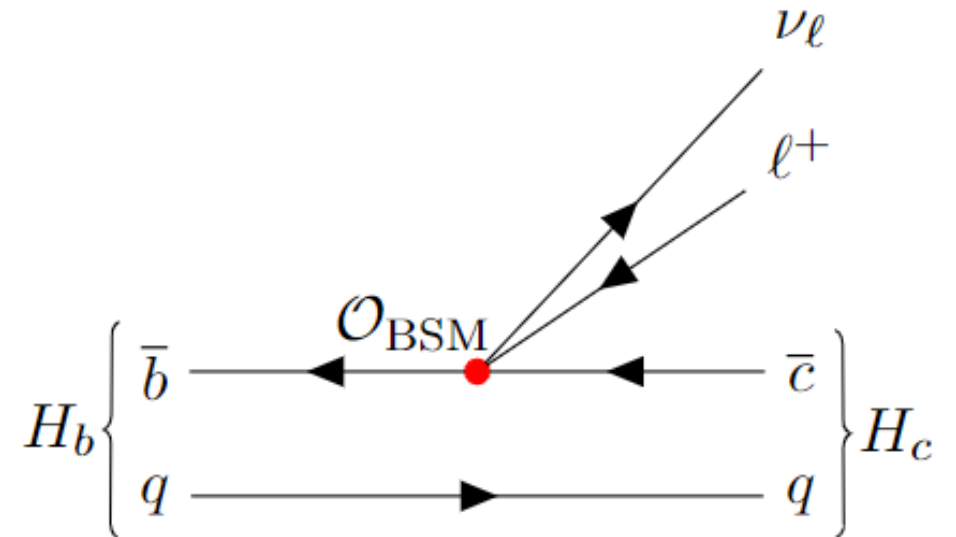
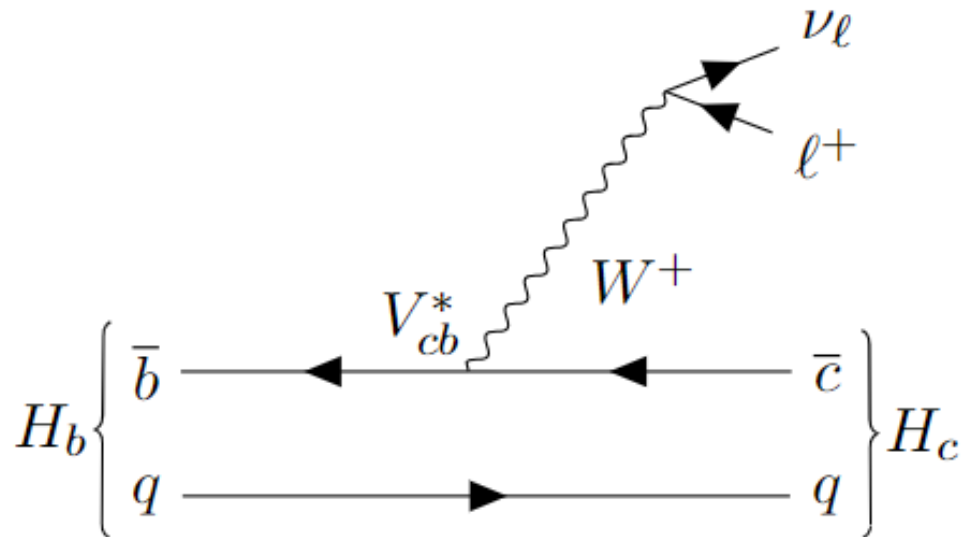
- Boost: 0(fs) time scales
- Heavy Species: Bs, Bc, Λ_b , exotics...
- Multiple soft tracks

3 Charged Current Semileptonic and Leptonic b Decays

3.1 Theoretical Interpretation

3.2 Recent Progress and Directions to be Explored

- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- CP asymmetries are clean
- Probe new physics, e.g. $\Lambda_{\text{NP}}^{\text{SL}} \sim (G_F |V_{cb}| \delta_{\text{SL}})^{-\frac{1}{2}} \sim (1.5 \text{ TeV}) \times \delta_{\text{SL}}^{-\frac{1}{2}}$



4 Rare/Penguin and Forbidden b Decays

4.1 Theoretical Interpretation (preliminary)

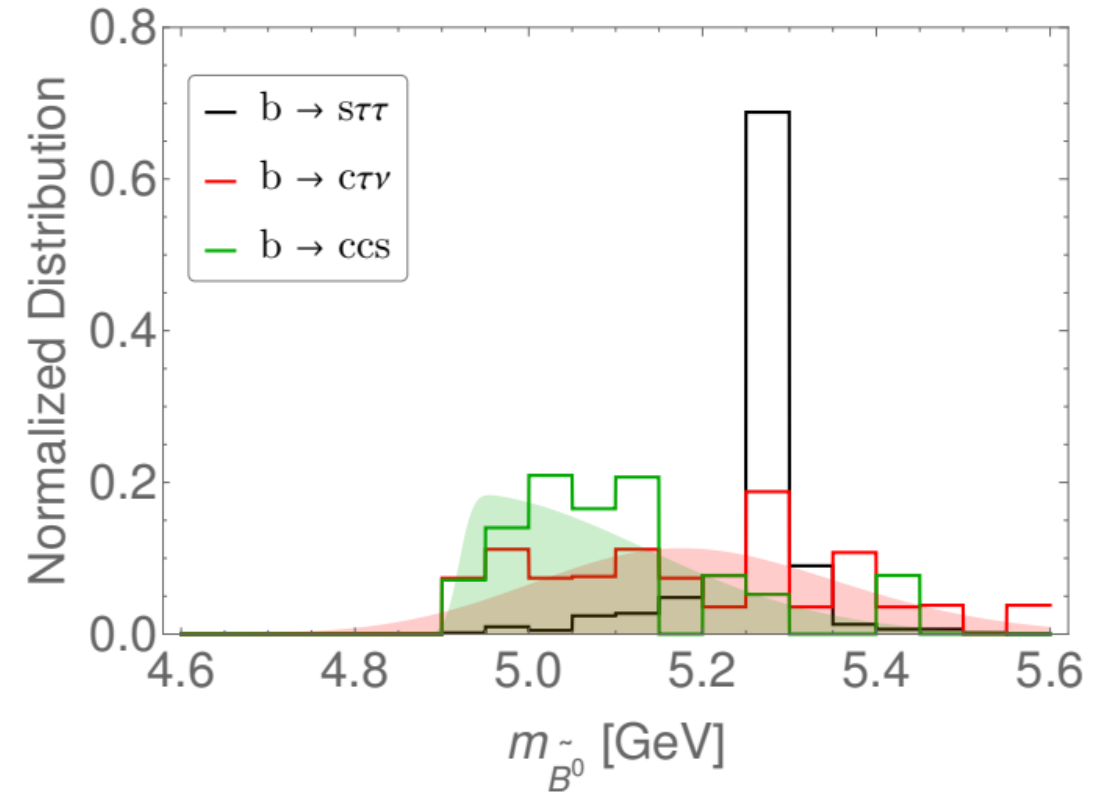
4.2 Dileptonic Modes

4.3 Neutrino Modes

4.4 Radiative Modes

[J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva 1705. 11106](#)
[LL, T. Liu, 2012.00665](#)

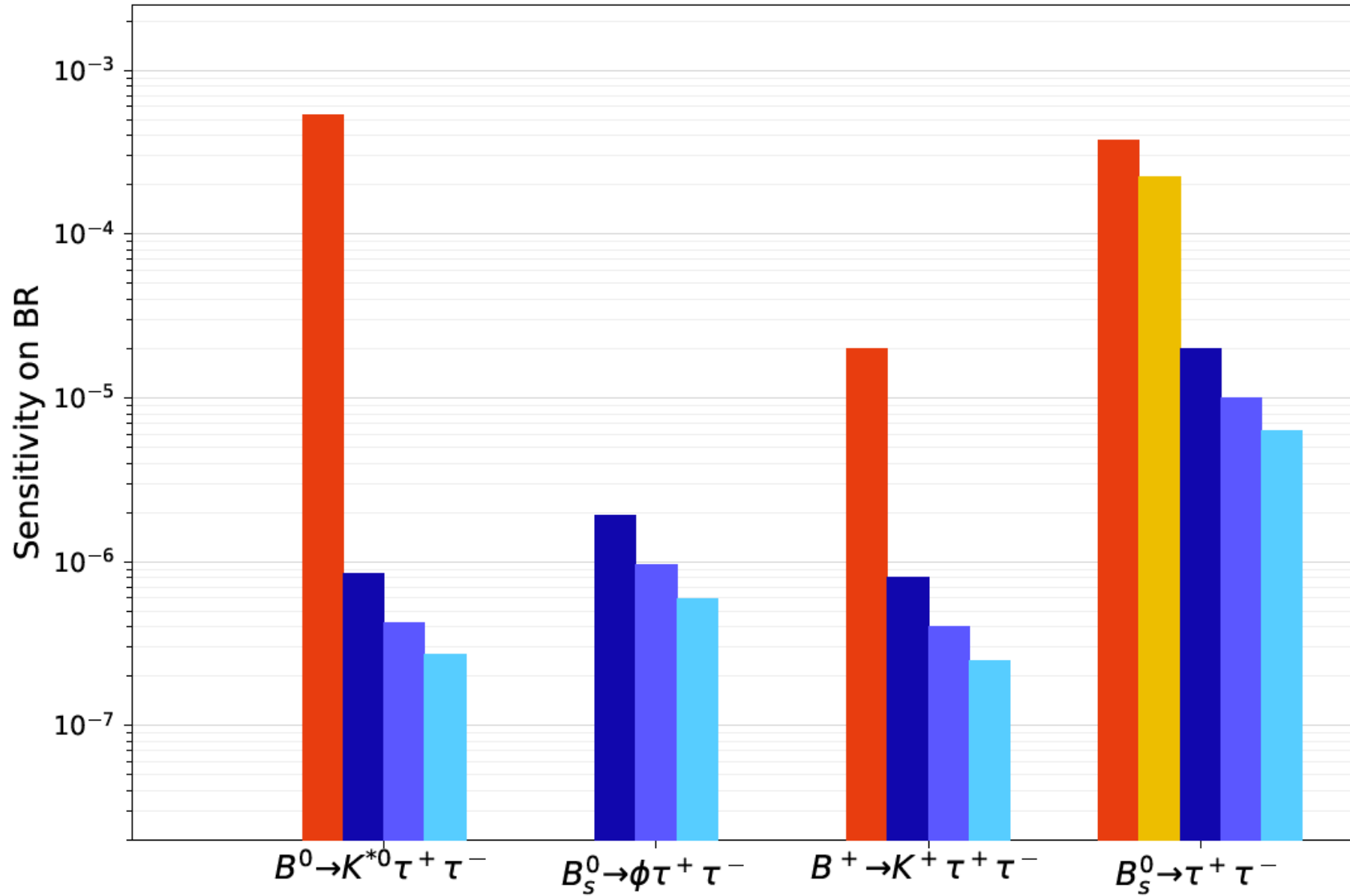
- Partially motivated by B anomalies
- Rare decays, sensitive to BSM and probe multi-TeV



$$\Lambda_{\text{NP}} \simeq \left(\frac{\alpha}{4\pi} \frac{m_t^2}{m_W^2} G_F |V_{tb} V_{ts}^*| \delta_{\text{rare}} \right)^{-\frac{1}{2}} \simeq (30 \text{ TeV}) \times \delta_{\text{rare}}^{-\frac{1}{2}}$$

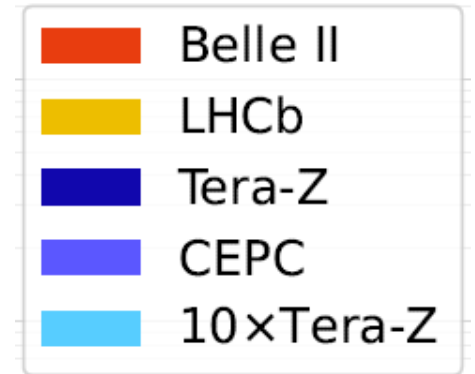
See also:

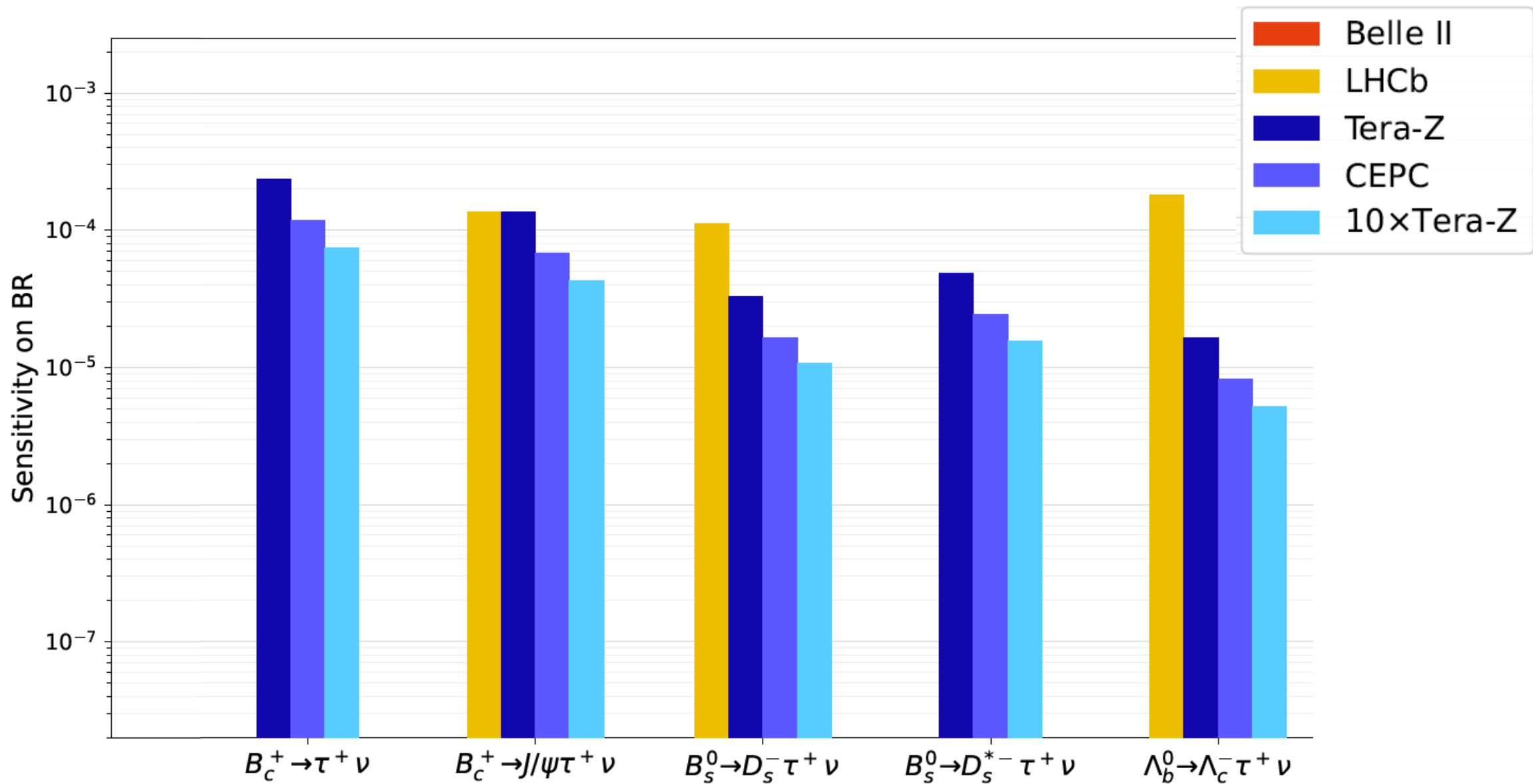
[S. Descotes-Genon, S. Fajfer, J. Kamenik, M. Novoa-Brunet 2208.10880](#)



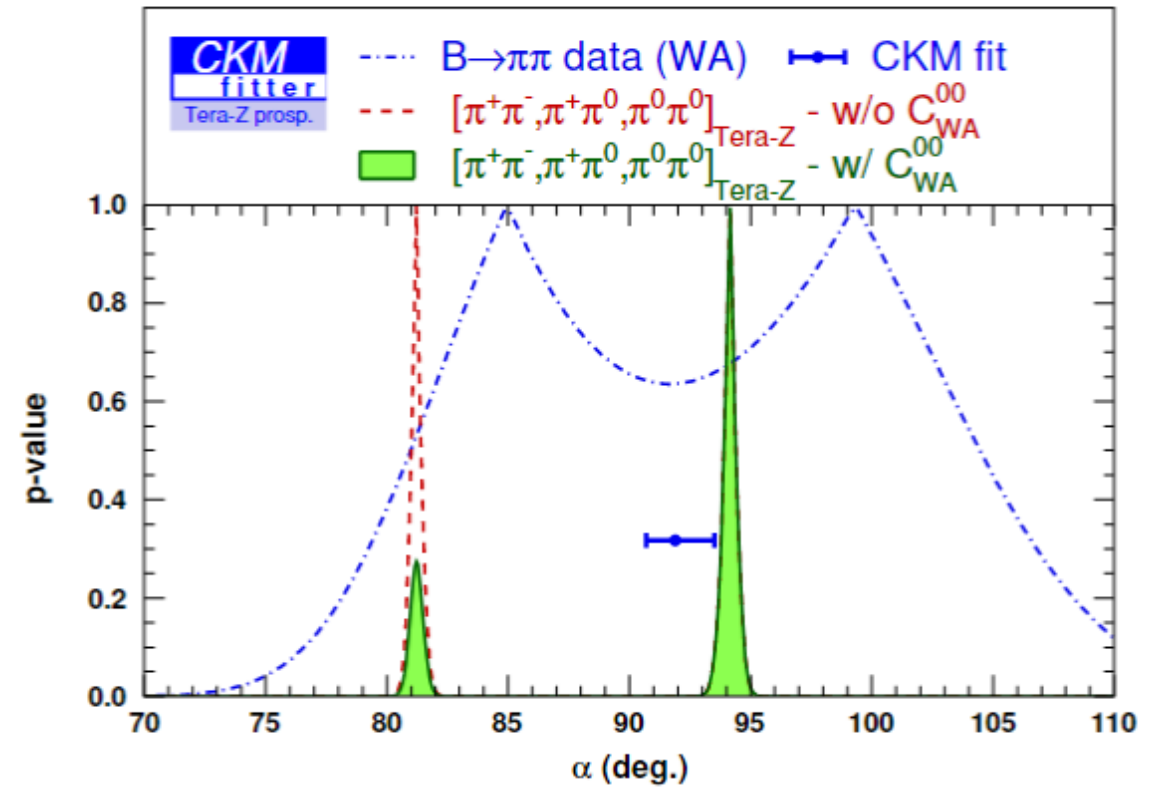
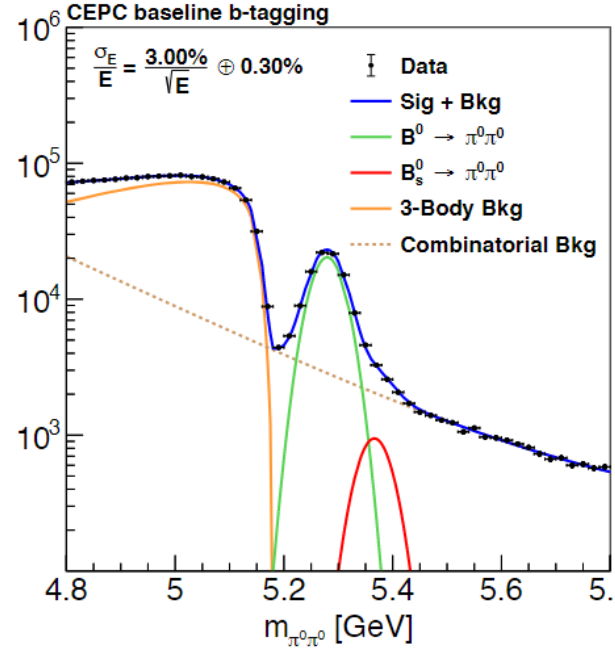
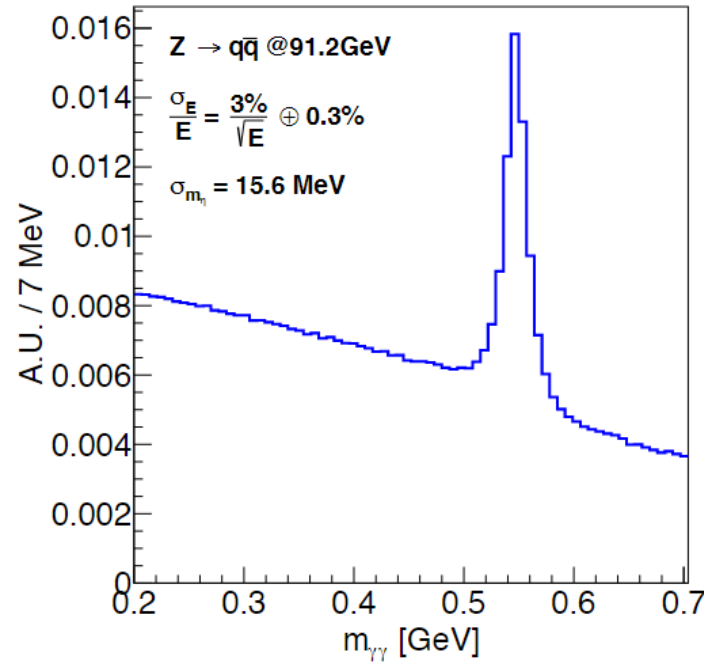
➤ The LFU test via $b \rightarrow s \tau \tau$ rare decay are most studied

➤ Flagship channel for CEPC





Time-Integrated CP Asymmetry

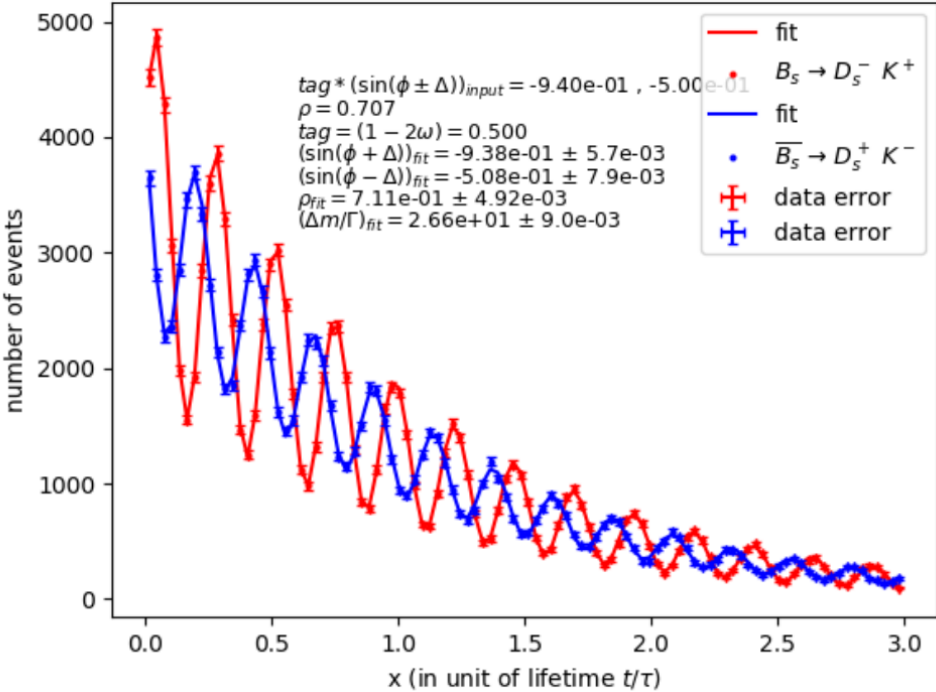
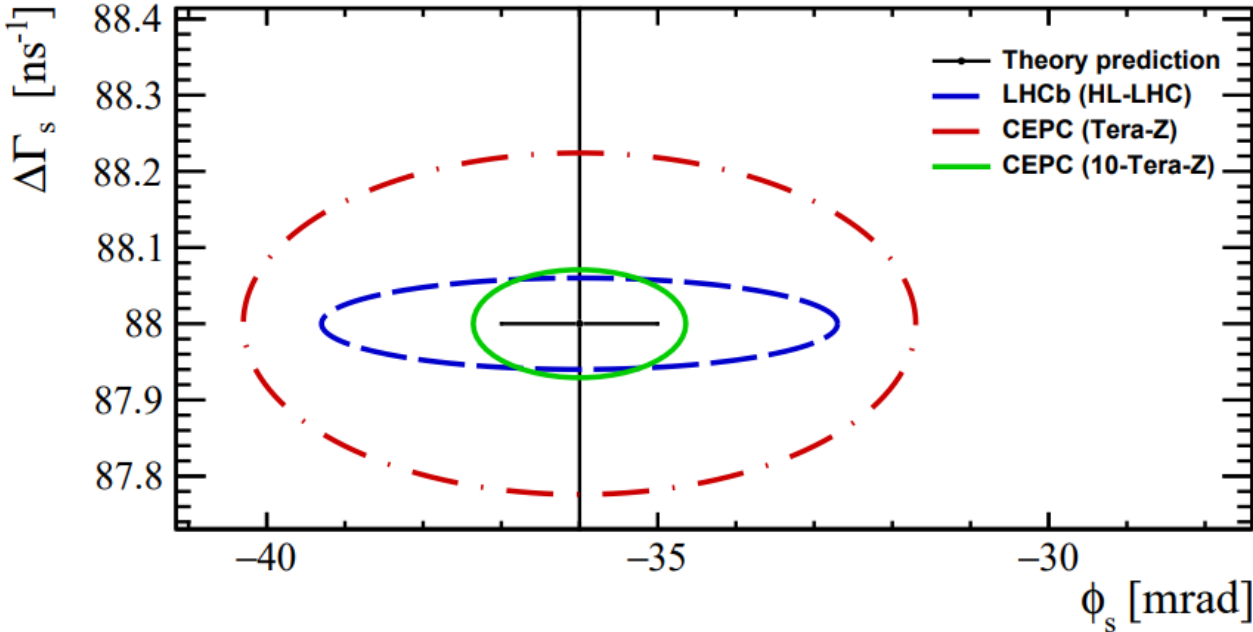


[Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan](#)

See also: [J. Charles, S. Descotes-Genon, Zoltan Ligeti, S. Monteil, M. Papucci, K. Trabelsi, L. Silva, 2006.04824](#)

Measure CKM α down to 0.4 deg by $B \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
 But only if ECAL is crystal

Time-Dependent CP Asymmetry



[X. Li, M Ruan, M. Zhao, 2205.10565](#)

Angle β_s measurement by time-dependent $B_s \rightarrow J/\psi \phi \rightarrow \mu\mu KK$

See also [R. Aleksan, L. Oliver, 2205.07823](#)

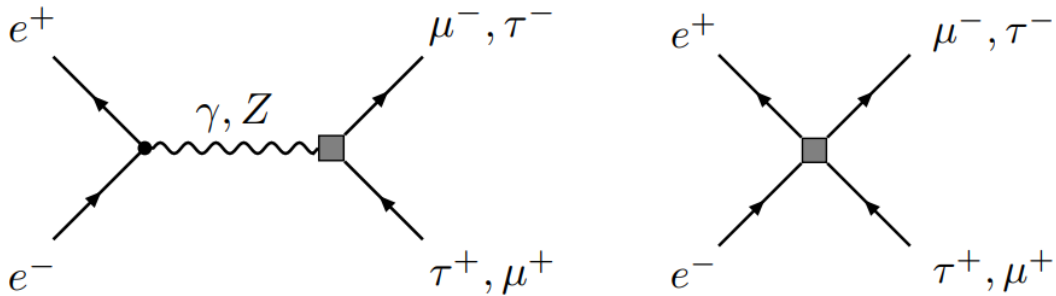
Time-dependent measurement of $B \rightarrow DK$ to give α_s and β_s , helpful to fix the value of angle γ

[R. Aleksan, L. Oliver, E. Perez, 2107.02002](#)

[R. Aleksan, L. Oliver, E. Perez, 2107.05311](#)

6 Testing SM Global Symmetry with Flavor

- lepton flavor, lepton number and baryon number are conserved in flavor physics
- Clear sign of new physics if violation observed



[W. Altmannshofer, P. Munbodh, T. Oh, 2305.03869](#)

BR(\$Z \to \tau\mu\$) limit down to 10^{-9}
 Also from runs of higher E_{cm}

\sqrt{s} [GeV]	\mathcal{L}_{int} [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\text{bkg}}^{x_c}$ [10^{-6}]	N_{bkg}	σ [ab]
91.2 (Z-pole)	50	0.92	1.35	1.53	6400 ± 80	55
87.7 (off-peak)	25	0.92	1.33	1.46	350 ± 20	27
93.9 (off-peak)	25	0.92	1.37	1.59	620 ± 25	35
160 (WW)	6	0.99	1.89	2.49	3 ± 2	17
240 (ZH)	20	1.20	2.60	4.42	7 ± 3	6.6
360 ($t\bar{t}$)	1	1.41	3.74	8.61	0.3 ± 0.5	72

Recommendations:

- ❖ Need studies on lepton and baryon number violation in the next phases

8 Charm and Strange Physics

$$\Gamma_9 \quad (u \bar{u} + c \bar{c})/2 \quad (11.6 \pm 0.6)\%$$

$$\Gamma_{10} \quad (d \bar{d} + s \bar{s} + b \bar{b})/3 \quad (15.6 \pm 0.4)\%$$

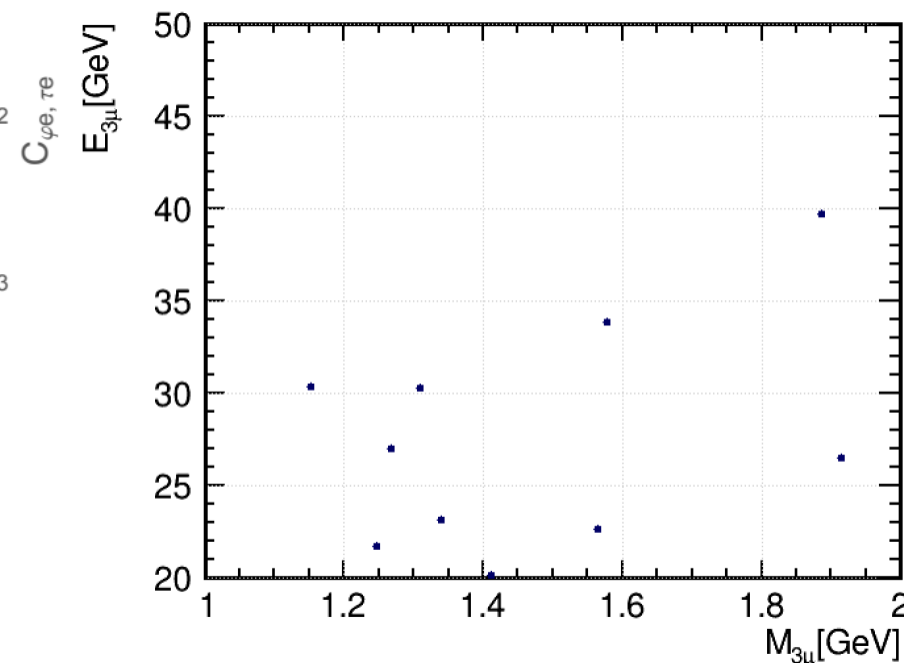
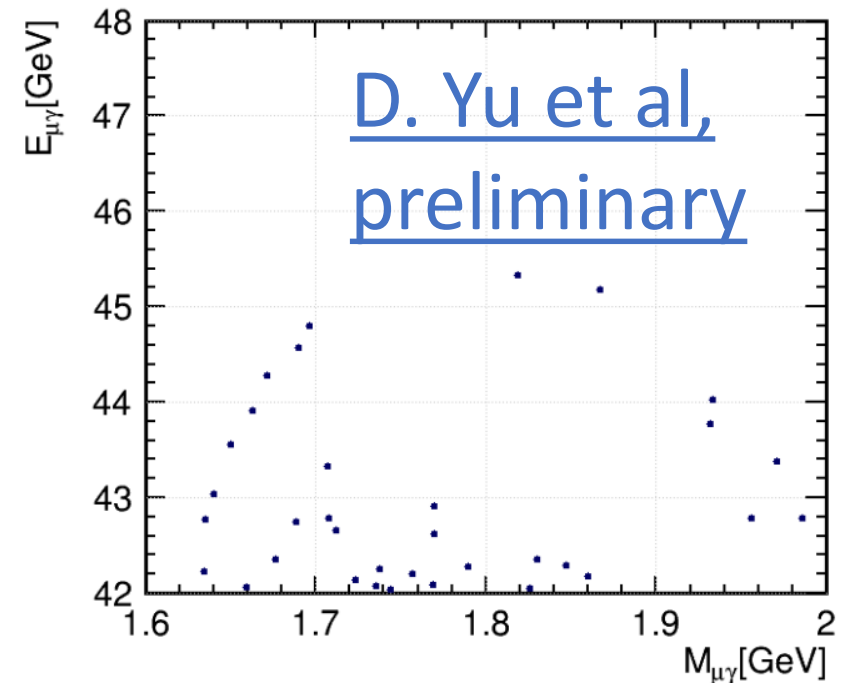
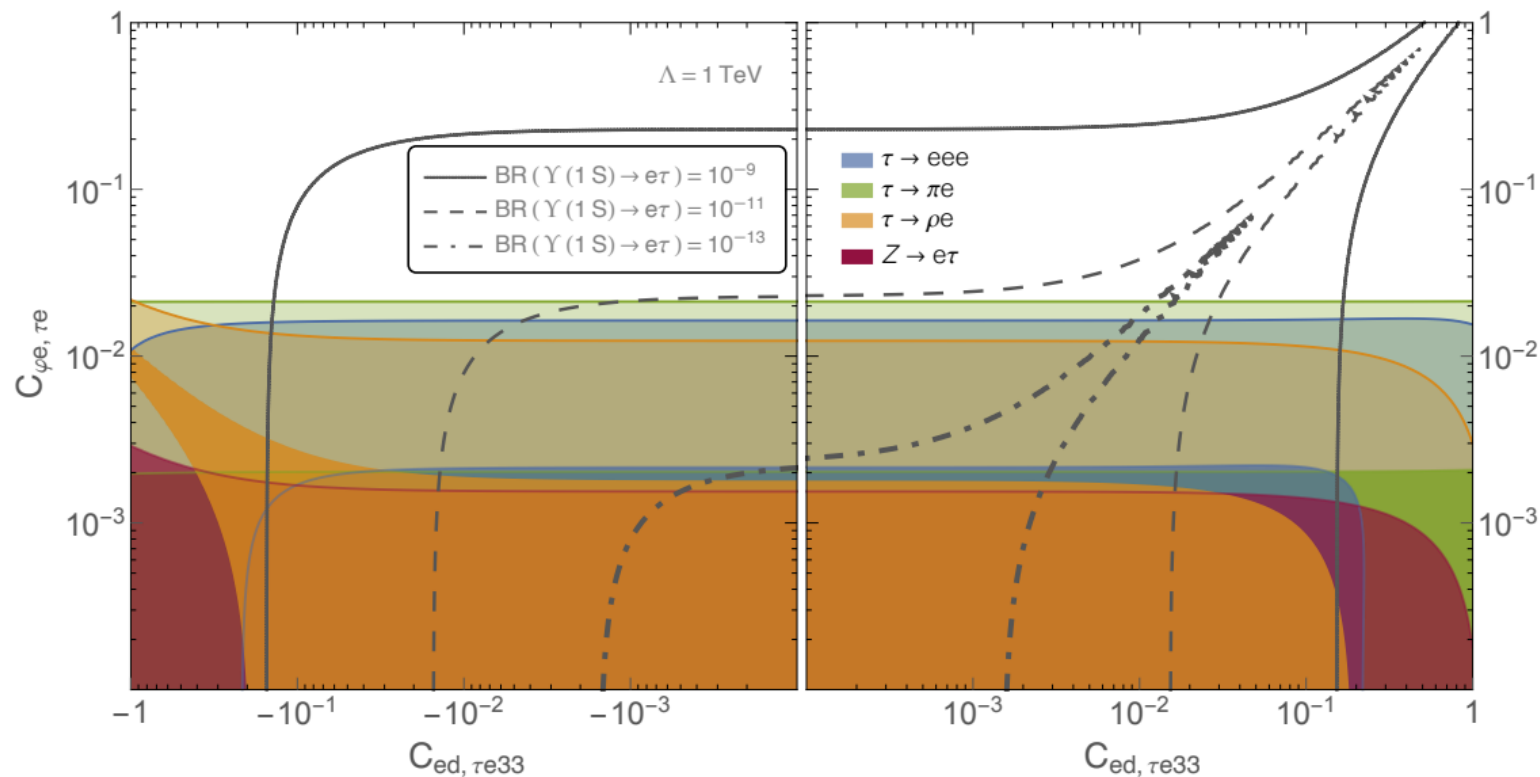
- Z decay also produces a lot of c and s quarks
- More s quarks ($K^{(*)}, \Lambda \dots$) produced by QCD
- Also building blocks of b physics

Recommendations:

- ❖ Have a charm physics program in parallel to bottom ones in the next phase
- ❖ Focus on K_S and Λ rare decays, e.g. $K_S \rightarrow \mu\mu(+\gamma)$, complementary to future kaon factories

9 τ Physics

- A most powerful tau machine
- Essential for EW and QCD in precision
- Most studies focus on exotic decays



[L. Calibbi, T. Li, X. Marcano, M.A. Schmidt, 2207.10913](#)

[L. Calibbi, X. Marcano, J. Roy, 2107.10273](#) [M. Dam, 2107.12832](#)

Section Summary and Suggestions

Measurement	Current [104]	FCC [102]	Tera-Z Prelim. [105]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
BR($\tau \rightarrow \ell \nu \bar{\nu}$)	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		0.1× the ALEPH systematics
m(τ) [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\text{track}})$ limited
BR($\tau \rightarrow 3\mu$)	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
BR($\tau \rightarrow 3e$)	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau \rightarrow e\mu\mu$)	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau \rightarrow \mu ee$)	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
BR($\tau \rightarrow \mu\gamma$)	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	Z $\rightarrow \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited
BR($\tau \rightarrow e\gamma$)	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		Z $\rightarrow \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited

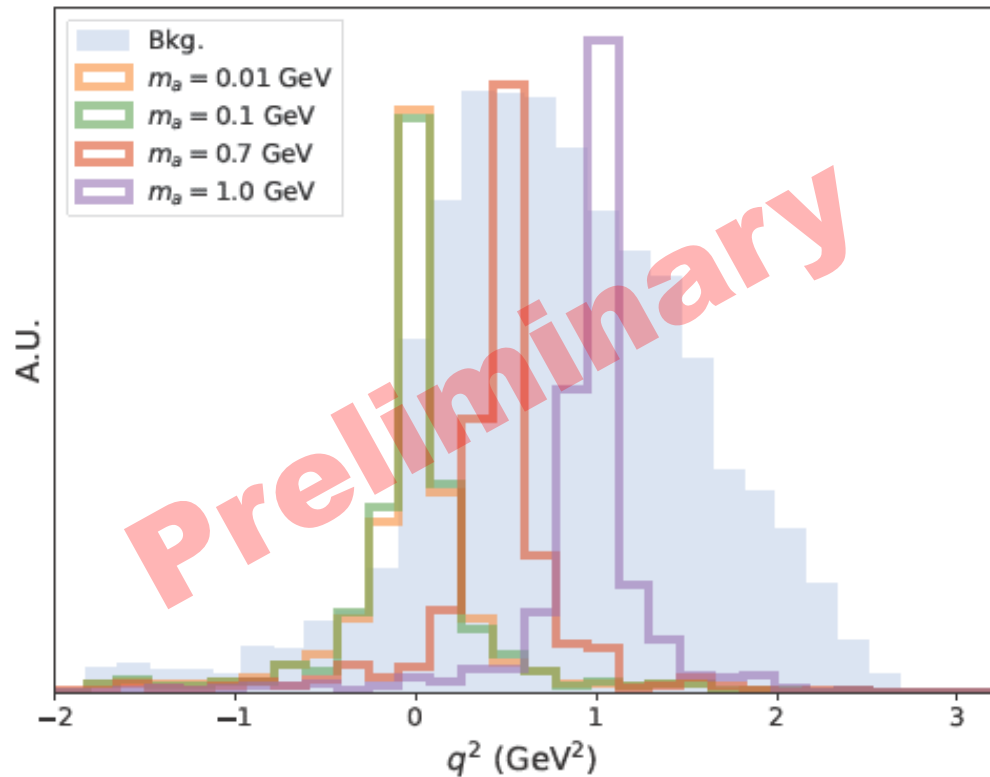
[M. Dam, 1811.09408](#)

- ❖ More exotic τ decay modes
- ❖ Hadronic τ decay for f_K , V_{us} , and $\alpha_s(m_\tau)$
- ❖ τ polarimetry/asymmetry at the Z pole for extracting EWPO

11 Production of BSM States from Heavy Flavor Decays

11.1 Light BSM states produced via their coupling with leptons

11.2 Light BSM states produced from FCNC quark decays



Dark sector from τ decays (LFV)

Anson Kwok et al., in prep

Long lived particle from B FCNC rare decays (starting at MFV)

Xuhui Jiang et al., in prep.

