LFV Jets Precision Semileptonic Muon CKM

Tau W–Factory Bottom

FCNC

Flavor

Mixing

CPV Exotic

BSM

Phase One Study

BNV

QCD

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

1000,000,000,000

× 3 - 10+

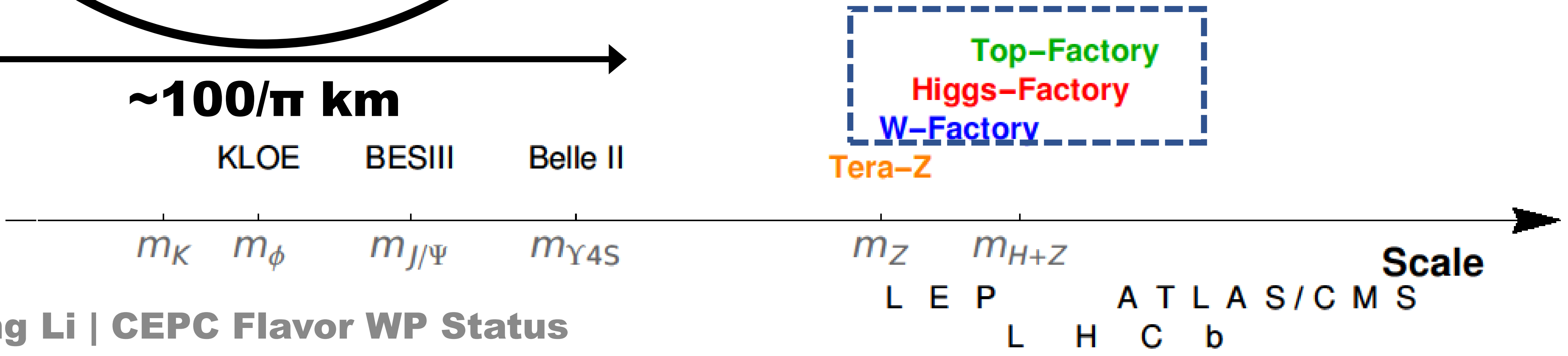
Tera-Z+

CEPC FCC hh ee he

~100/π km

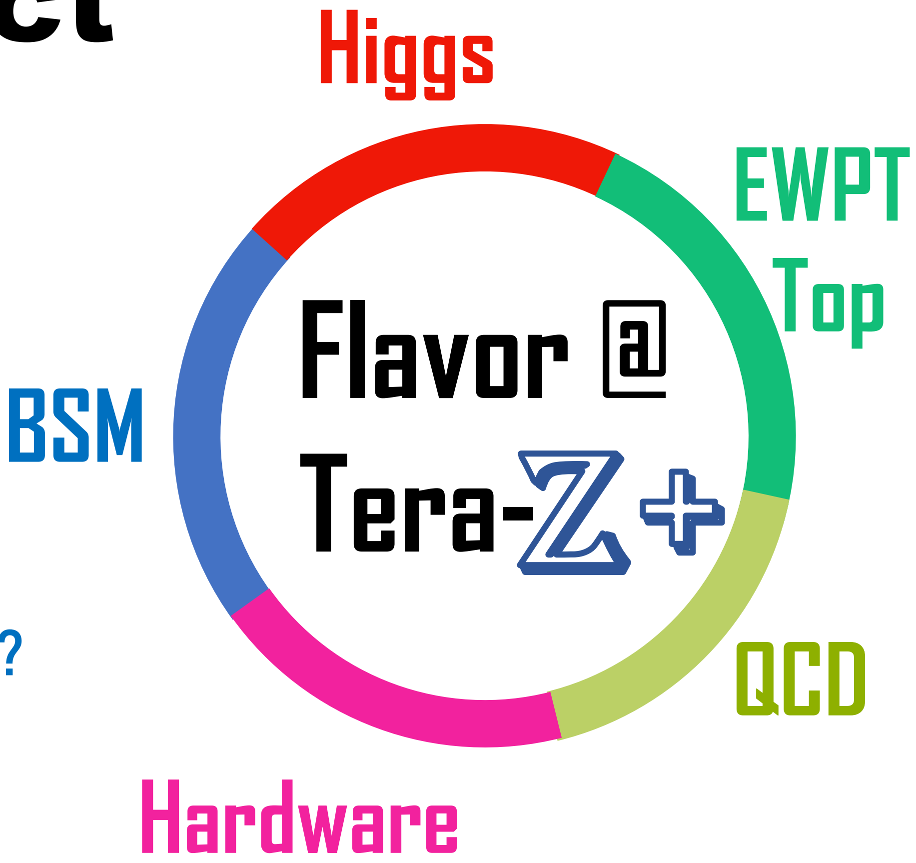
- Higher luminosity as the accelerator design keeps upgrading
- ≥ 2 interaction points and various detectors

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



Support the CEPC Project

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



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

- ❑ 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!

Contents

ECFA, 2401.07564

Status and Timeline

Jul.21 – Apr.23
- ❑ Initiation of white paper, material collection

Apr.23 – Jun.23
- ❑ Drafting

Jun.23 – Jul.23
- ❑ First draft finished,

Jul.23- Dec.23
- ❑ Internal review by experts

Dec.23- Soon
- ❑ External review (>20 international reviewers)
- ❑ Filling in Phase II studies

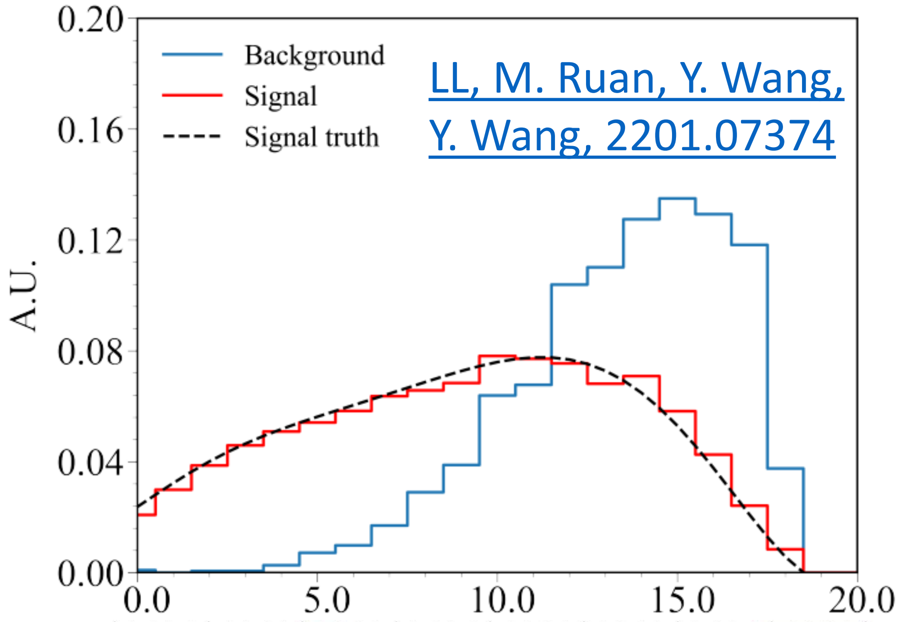
Table of Contents

Public access and progress here

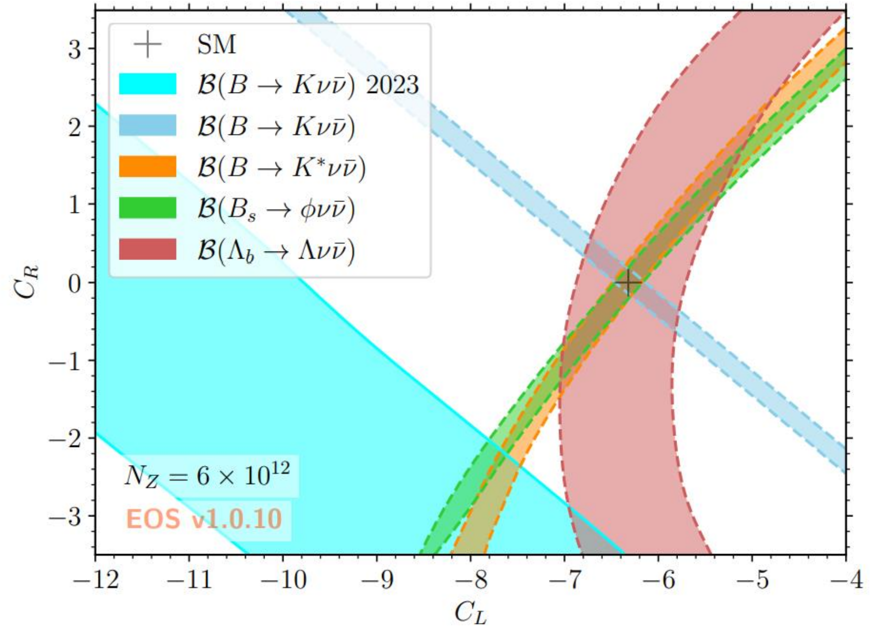
https://indico.ihep.ac.cn/event/20312/

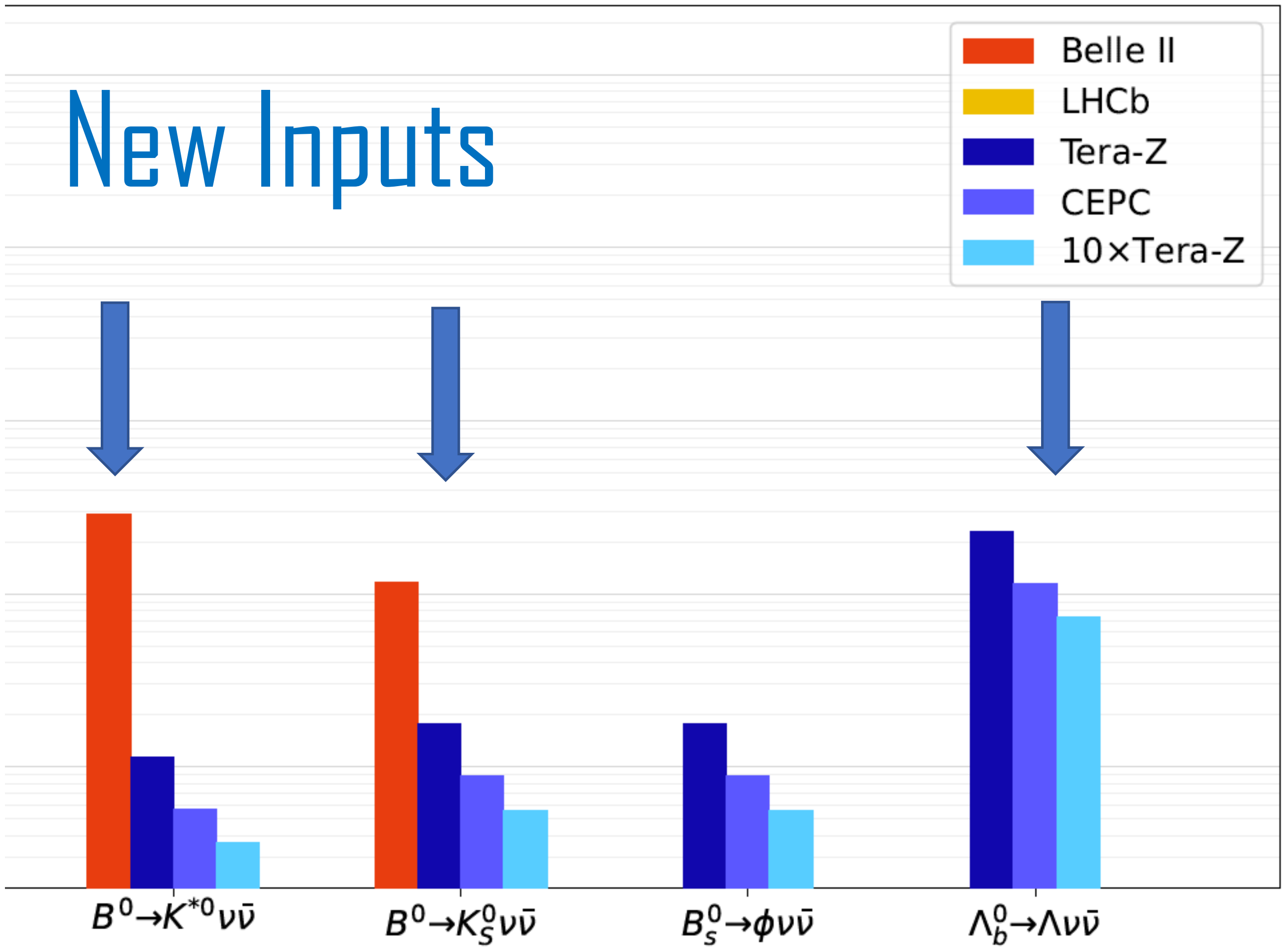
4.3 Neutrino Modes

Reconstruct b→sνν semi-invisible decay



LL, M. Ruan, Y. Wang, Y. Wang, 2201.07374





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

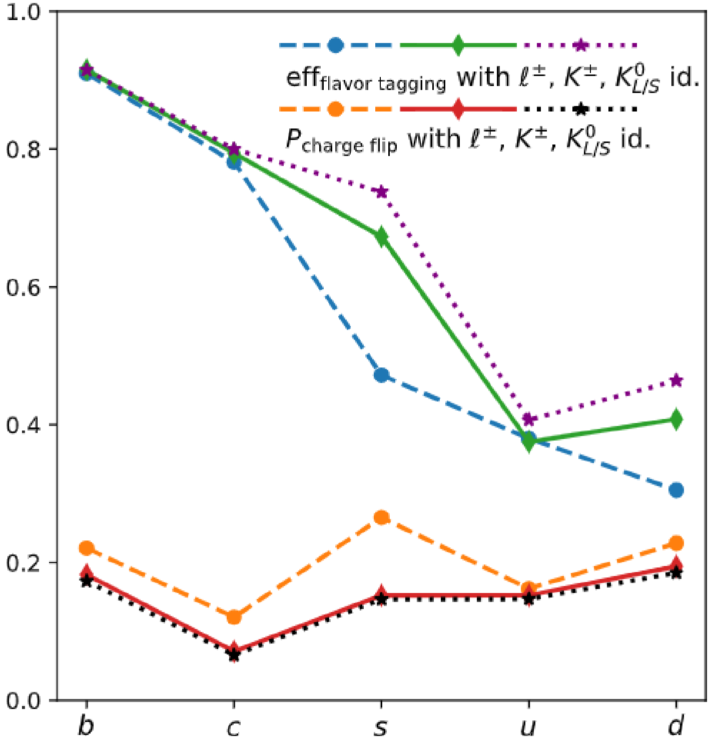
5 Measuring CP Asymmetries

Taken from HFLAV2019

Flavor Tagging

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

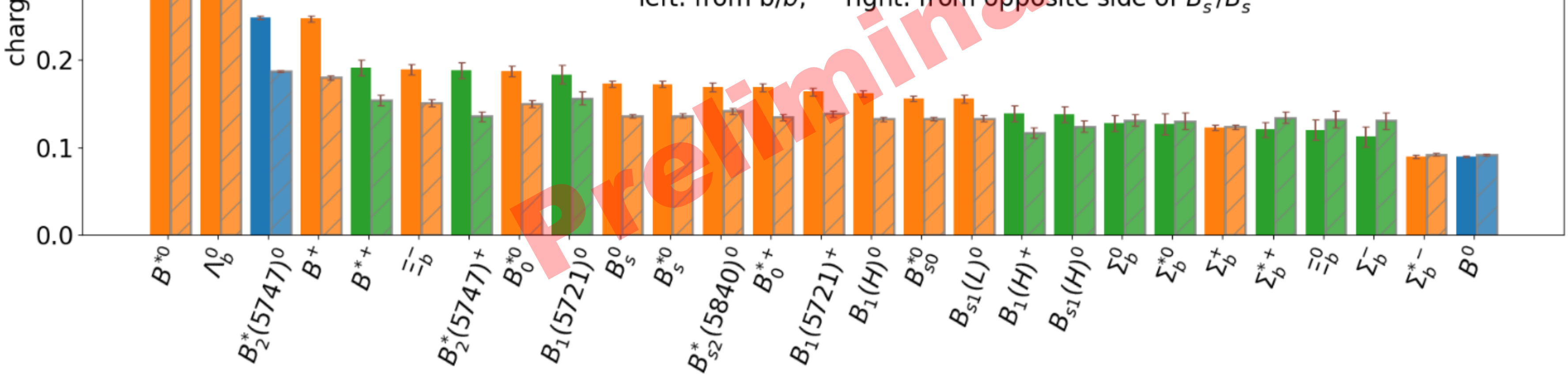
Effective tagging power @ LEP ~ 20%, expected to improve further @ CEPC (vs. ~5% @LHCb & ~35% @ Belle II)

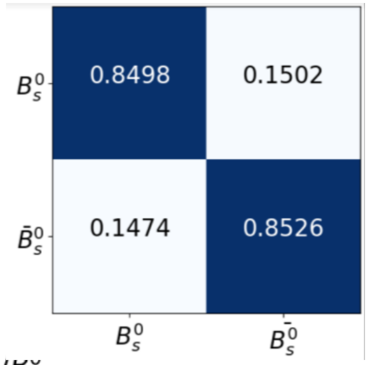


[H. Liang, Y. Zhu, Y. Wang, Y. Che, C. Zhou, H. Qu et al, 2310.03440]

Yes, but…

Y. Zhu et al., in prep





In the next talk

10 Flavor Physics beyond the Z Pole

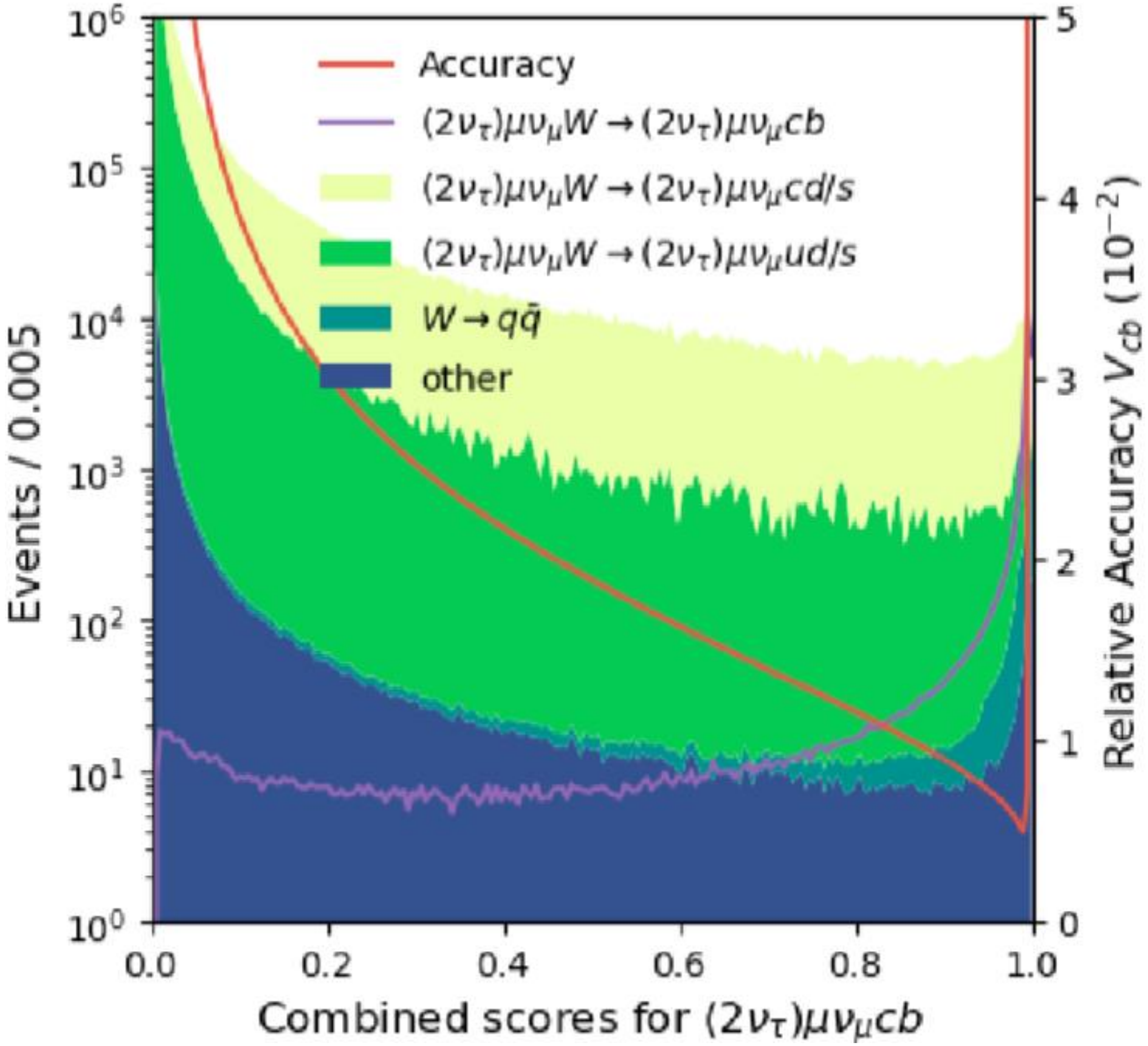
10.1 $|V_{cb}|$ and W Decays

10.2 Exotic and FCNC Higgs Decays

10.3 Top FCNC

H. Liang et al., in prep

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



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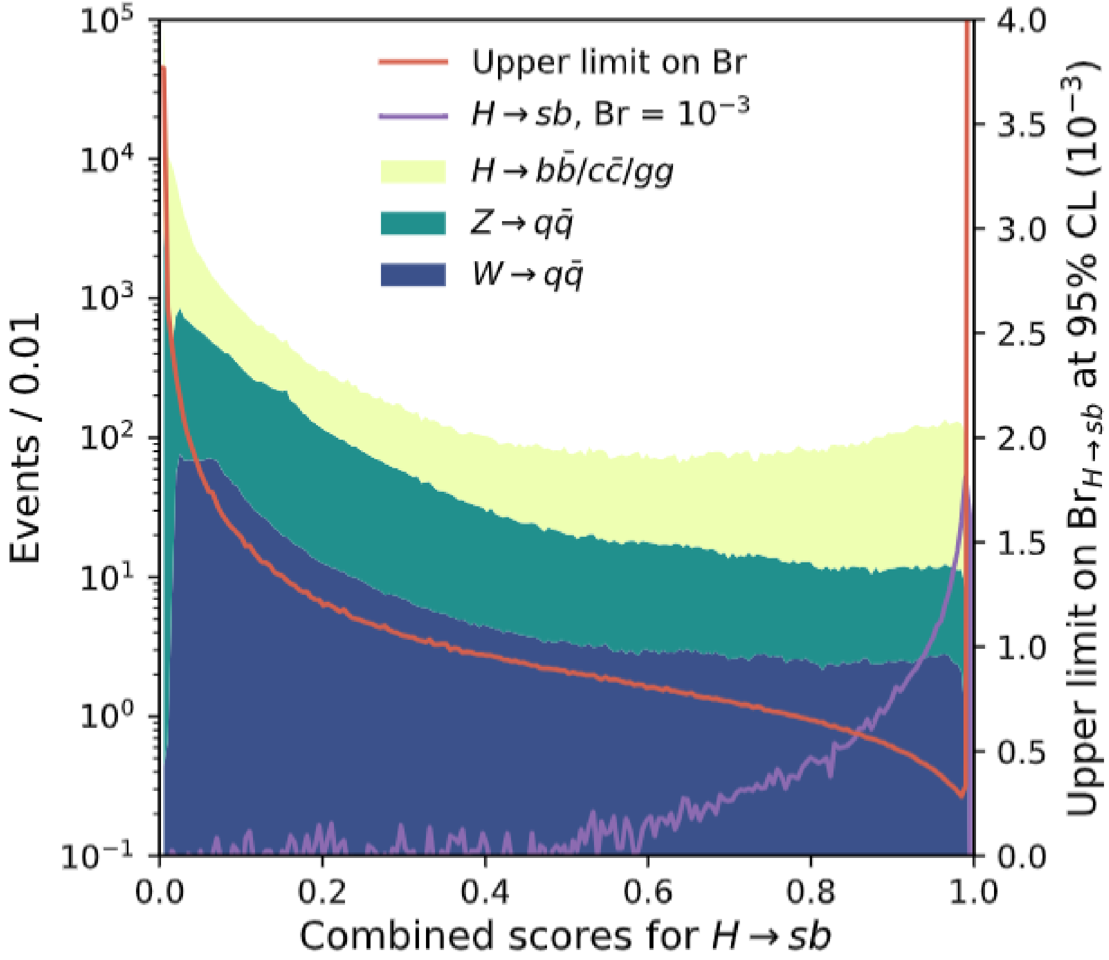

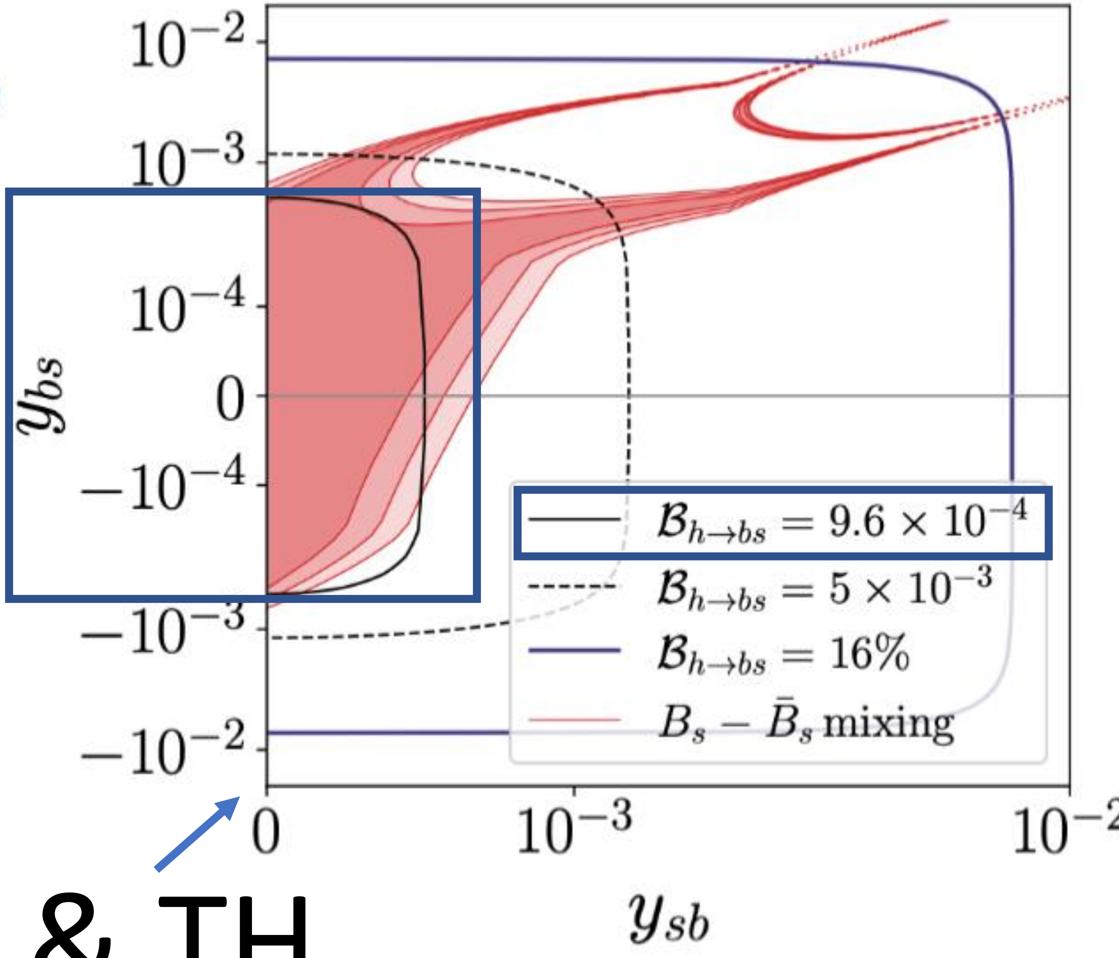

Exp & TH

J. F. Kamenik, A. Korajac, M. Szewc, M. Tammaro 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

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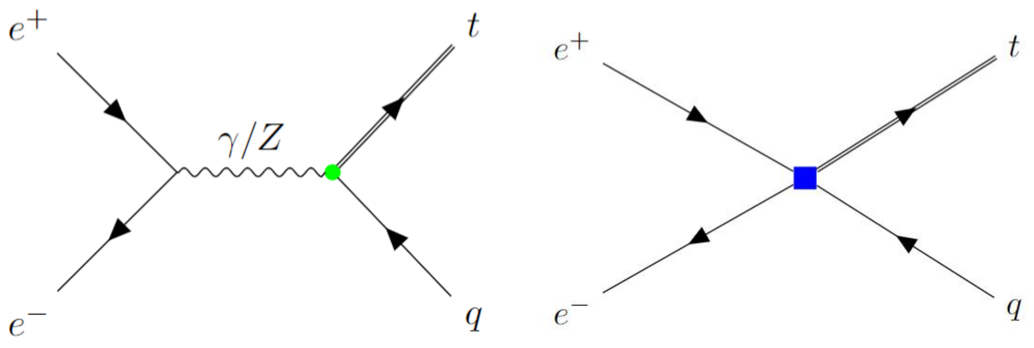
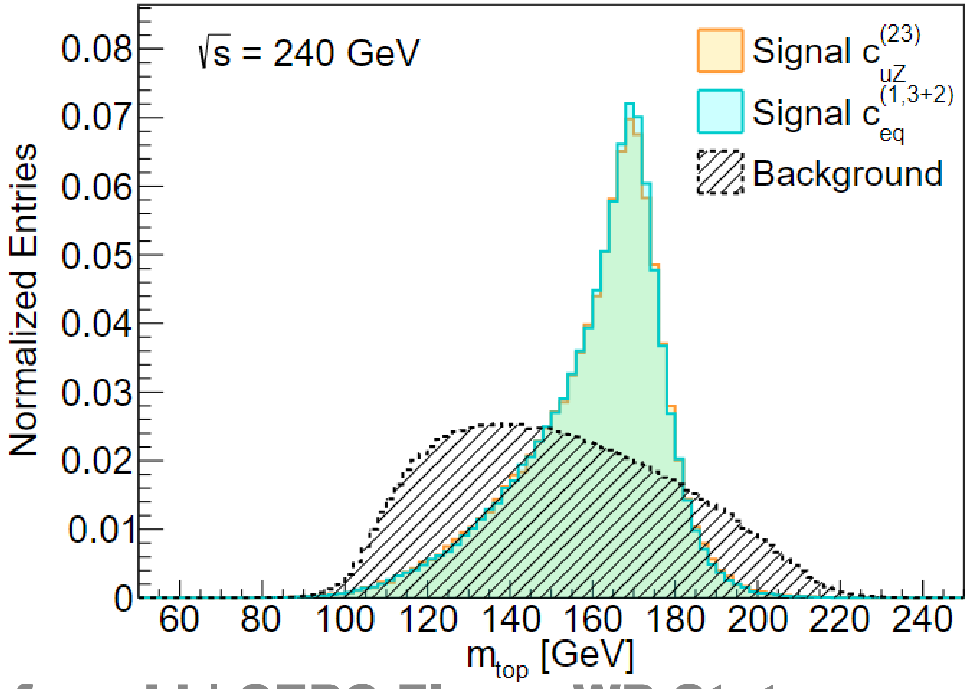
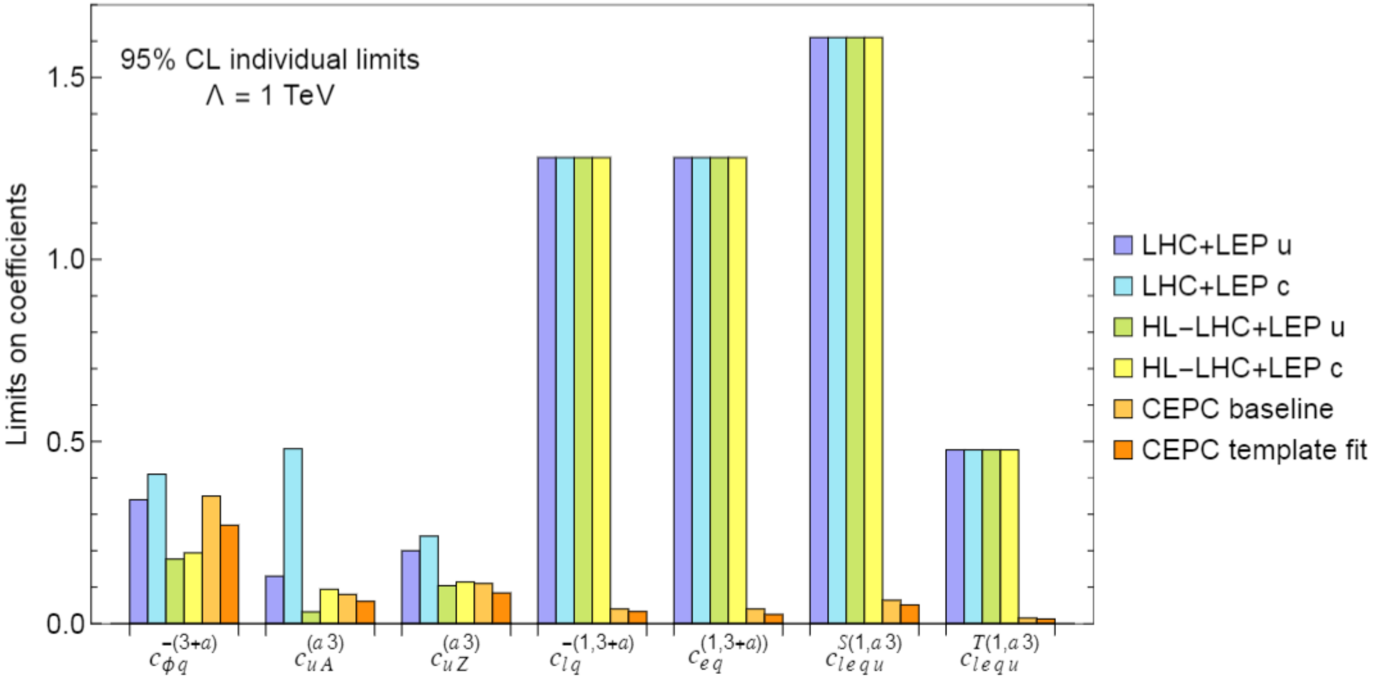
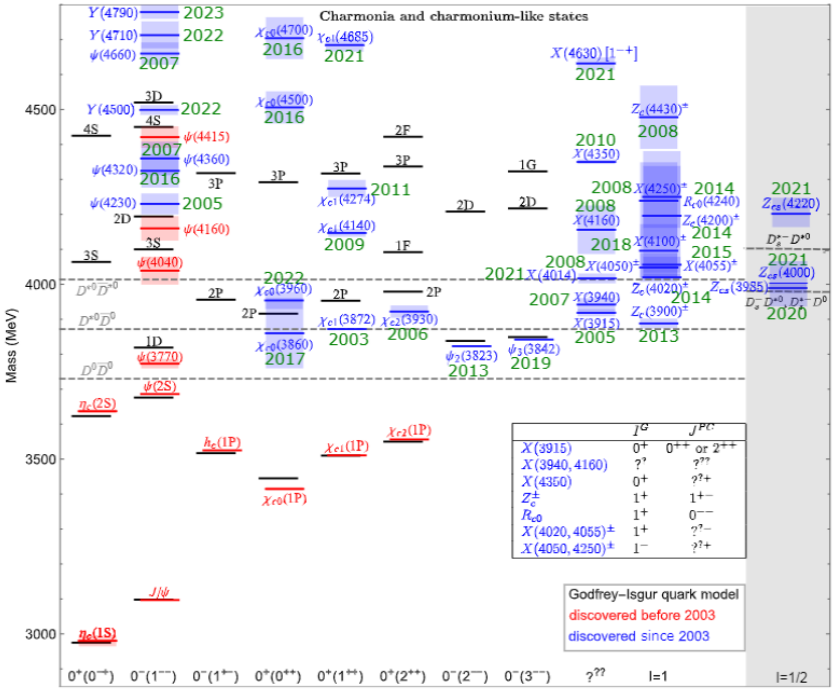


L. Shi and C. Zhang, 1906.04573

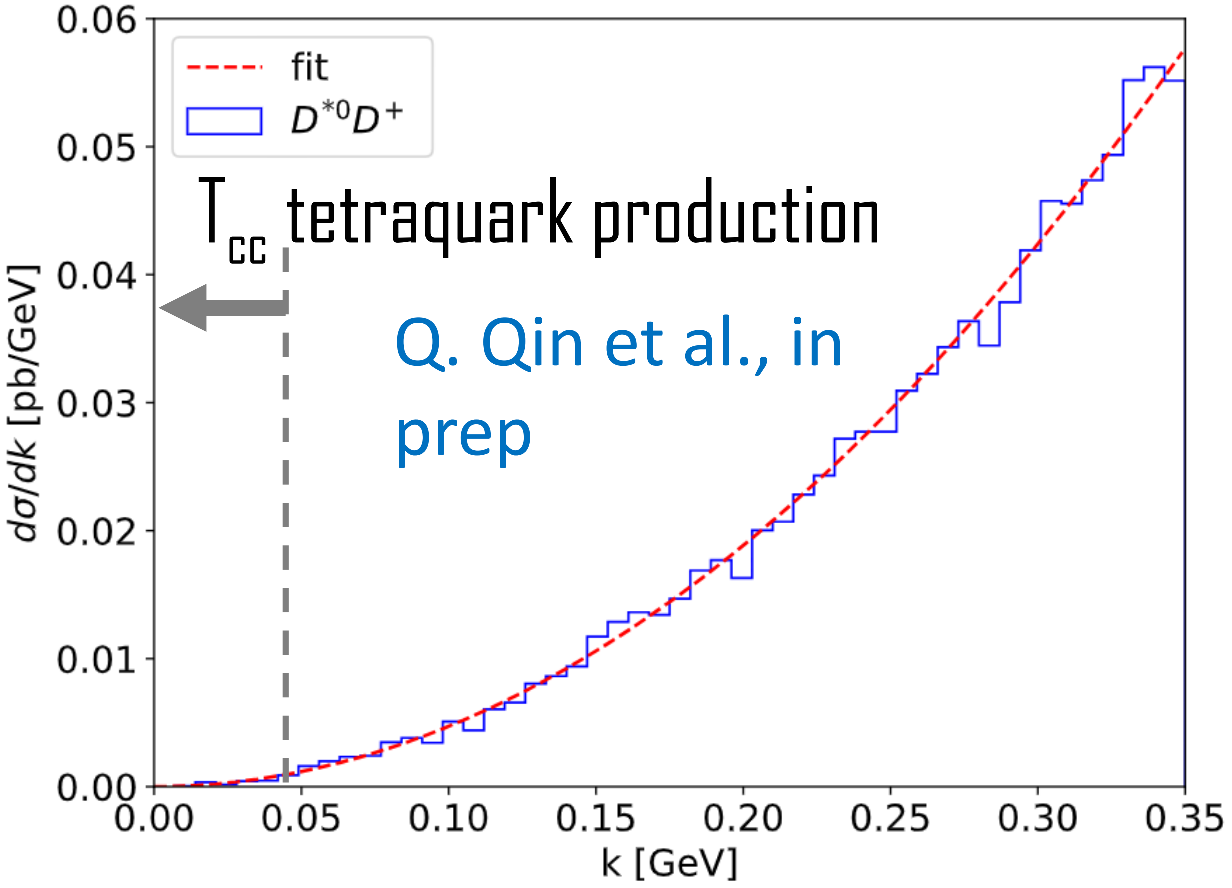




11 Spectroscopy and Exotics

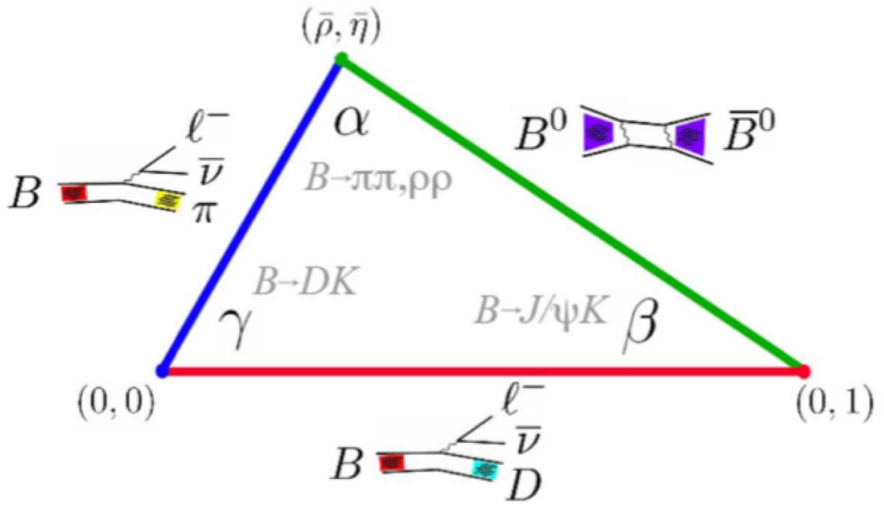


- A lot of states, guaranteed DISCOVERY at CEPC?
- Z→bbbb, bbcc, cccc processes may give rise to highly exotic species
- Production & decay largely unknown



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

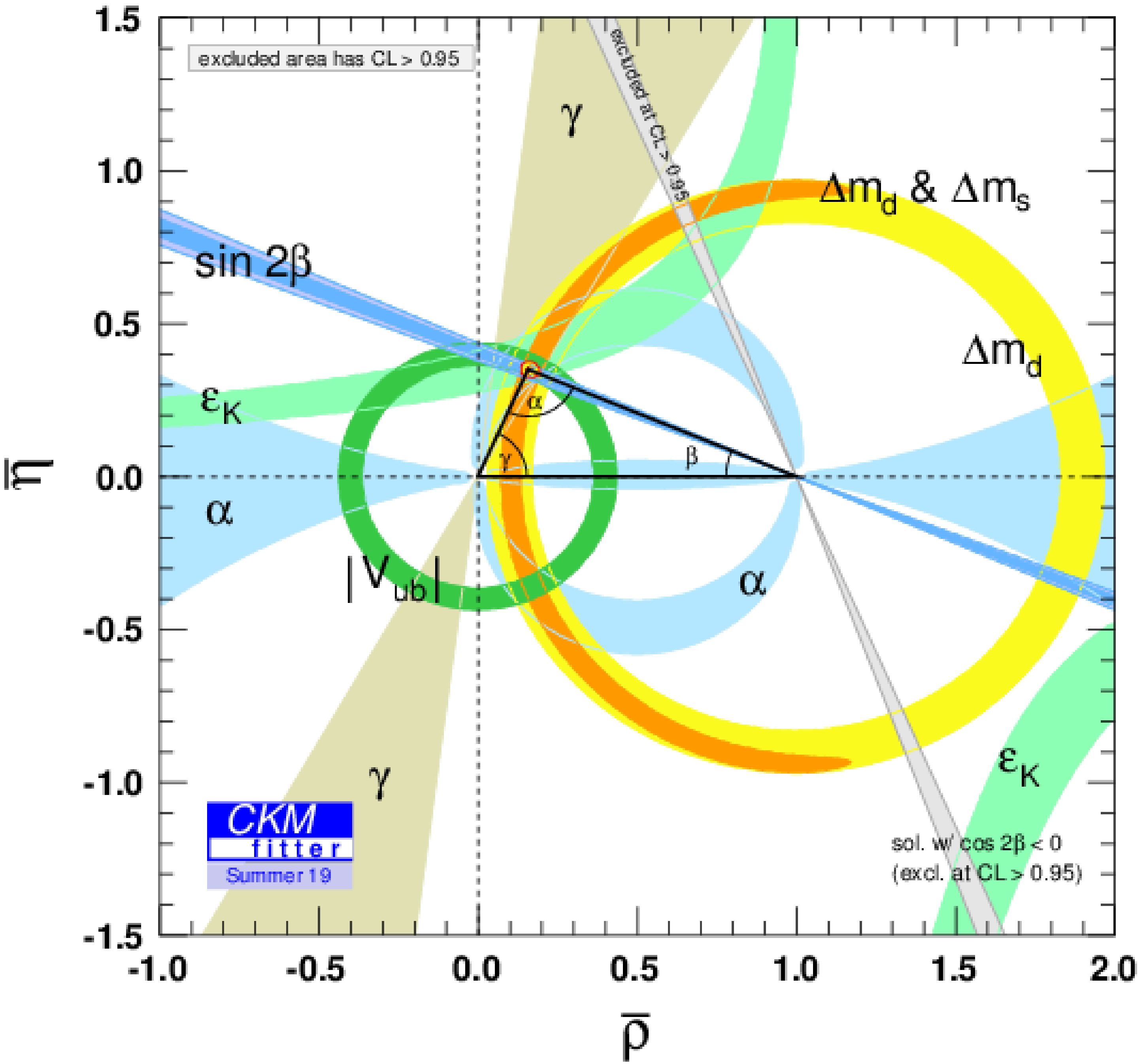


Table of Collected Performance

No.	Process	$\sqrt{s}$ (GeV)	Parameter of interest	Observable	Current precision	CEPC Precision	Estimation method	Key detector performance	Relevant Section
1	$Z \to \mu\mu a$	91.2	-	BR upper limit	-	$\lesssim 3 \times 10^{-11}$ [251]	Fast simulation	Tracker Missing energy	12
2	$B \to K\hat{\pi}(\to \mu\mu)$	91.2	-	BR upper limit	-	$\lesssim 10^{-10}$ [261]	Fast simulation	Tracker Vertex	12
3	$Z \to \pi^+\pi^-$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-10})$ [109]	Guesstimate	Tracker PID	9
4	$Z \to \pi^+\pi^-\pi^0$	91.2	-	BR upper limit	-	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
5	$b \to s\tau^+\tau^-$	91.2	-	BR upper limit	-	$B^0 \to K^{*0}\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \to \phi\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B^+ \to K^+\tau^+\tau^- \sim \mathcal{O}(10^{-6})$ $B_s \to \tau^+\tau^-$ $\mathcal{O}(10^{-5})$ [71]	Fast simulation	Tracker Vertex Jet origin ID	4
6	$Z \to \rho\gamma$	91.2	-	BR upper limit	$< 2.5 \times 10^{-5}$ [150]	$\mathcal{O}(10^{-9})$ [109]	Guesstimate	Tracker PID ECAL	9
7	$Z \to J/\psi\gamma$	91.2	-	BR upper limit	$< 1.4 \times 10^{-6}$ [150]	$10^{-9} - 10^{-10}$ [109]	Guesstimate	Tracker PID ECAL	9
8	$Z \to \tau\mu$	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	$Z \to \tau e$	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	$Z \to \mu e$	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	$\tau \to \mu a$	91.2	-	BR upper limit	$\lesssim 7 \times 10^{-4}$ [259]		$\lesssim$ 3–5 $\times 10^{-6}$	Fast simulation	Tracker Missing energy	12
12	$\tau \to \mu\mu\mu$	91.2	-	BR upper limit	$< 2.1 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
13	$\tau \to eee$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
14	$\tau \to e\mu\mu$	91.2	-	BR upper limit	$< 2.7 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
15	$\tau \to \mu ee$	91.2	-	BR upper limit	$< 1.8 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID	8
16	$\tau \to \mu\gamma$	91.2	-	BR upper limit	$< 4.4 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID ECAL	8
17	$\tau \to e\gamma$	91.2	-	BR upper limit	$< 3.3 \times 10^{-8}$	[150]	$\mathcal{O}(10^{-10})$ [108, 109]	Guesstimate	Tracker Lepton ID ECAL	8
18	$B_c \to \tau\nu$	91.2	$\|V_{cb}\|$	$\sigma(\mu)/\mu$	BR$\lesssim$ 30% [267]		$\mathcal{O}(1\%)$ [63]	Full simulation	Tracker Lepton ID Missing energy Jet origin ID	3
19	$B_s \to \phi\nu\bar{\nu}$	91.2	-	$\sigma(\mu)/\mu$	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	$\tau \to \ell\nu\bar{\nu}$	91.2	-	BR	$\pm 4 \times 10^{-4}$ [150]		$\pm 3 \times 10^{-5}$ [108]	Guesstimate	Tracker Lepton ID Missing energy	8

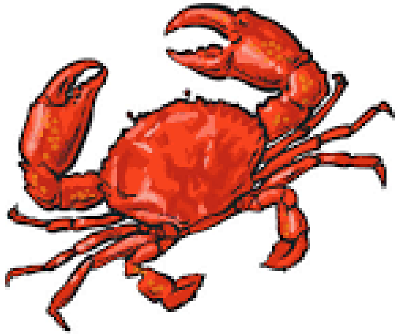
23	$Z \to \pi^+\pi^-$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-10})$ [118]	Conjecture	Tracker PID	9
24	$Z \to \pi^+\pi^-\pi^0$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-9})$ [118]	Conjecture	Tracker PID ECAL	9
25	$Z \to \rho\gamma$	91.2	BR	$< 2.5 \times 10^{-5}$ [156]	$\lesssim \mathcal{O}(10^{-9})$ [118]	Conjecture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

32	$H \to sb$	240	BR	$\lesssim 10^{-2}$ [302]	$\lesssim 0.02\%$—0.1% [33]	Full simulation	Jet origin ID	10
33	$H \to sd$	240	BR	-	$\lesssim 0.02\%$—0.1% [33]	Full simulation	Jet origin ID	10
34	$H \to db$	240	BR	$\lesssim 10^{-2}$ [302]	$\lesssim 0.02\%$—0.1% [33]	Full simulation	Jet origin ID	10
35	$H \to uc$	240	BR	-	$\lesssim 0.02\%$—0.1% [33]	Full simulation	Jet origin ID	10
36	$H \to ss$	240	BR	$\lesssim 0.3\%$ [303, 304]	$\lesssim 0.1\%$ [33]	Full simulation	Jet origin ID	10
37	$H \to uu$	240	BR	$\lesssim 3.5\%$ $\kappa_u < 560$ [305]	$\lesssim 0.1\%$ [33] $\kappa_u < 101$	Full simulation	Jet origin ID	10
38	$H \to dd$	240	BR	$\lesssim 3.5\%$ $\kappa_d < 260$ [305]	$\lesssim 0.1\%$ [33] $\kappa_d < 37$	Full simulation	Jet origin ID	10
39	$e^+e^- \to tq$	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	$WW \to \mu\nu qq$ $WW \to \tau(\to \mu\nu\nu)\nu qq$	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

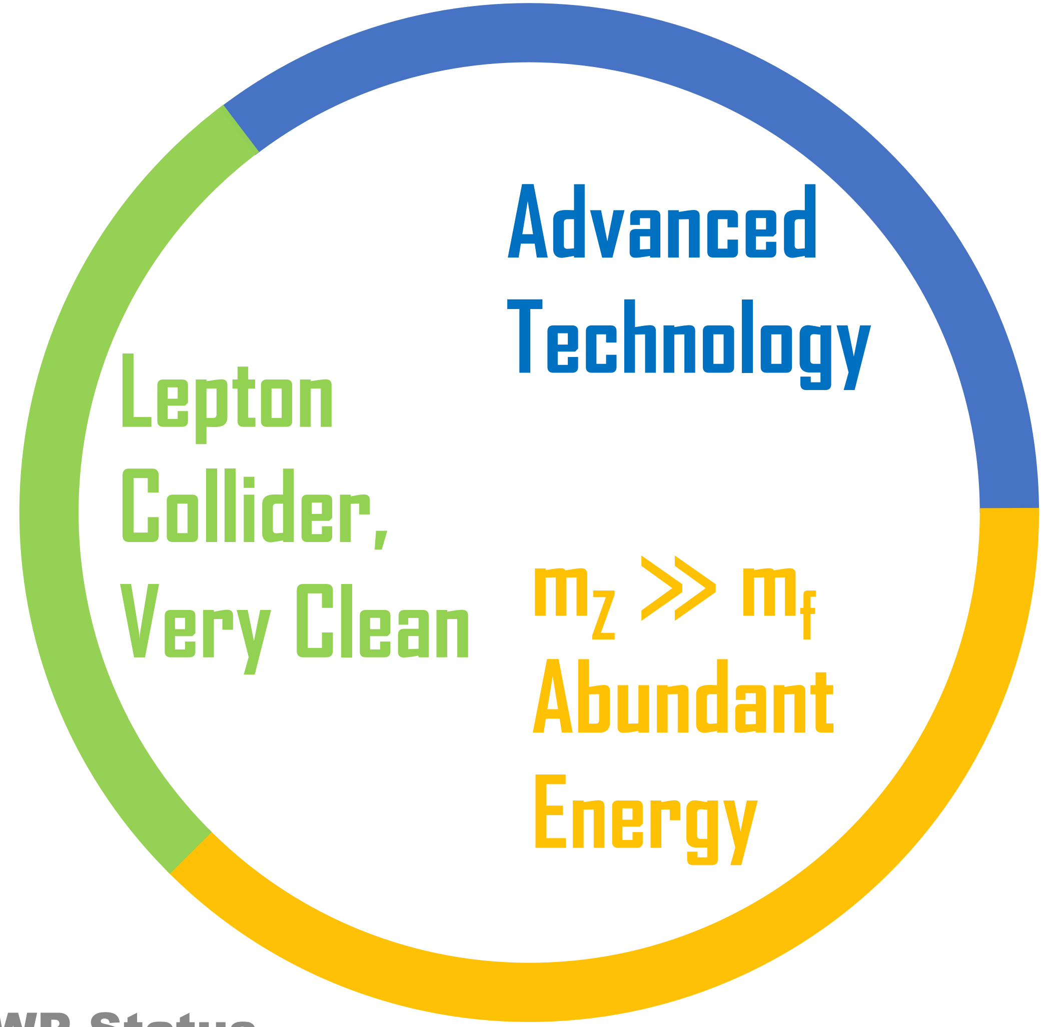
W decay for the $|V_{cb}|$

+ Previous efforts

BACKUP SLIDES

Three Cornerstones of CEPC

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



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

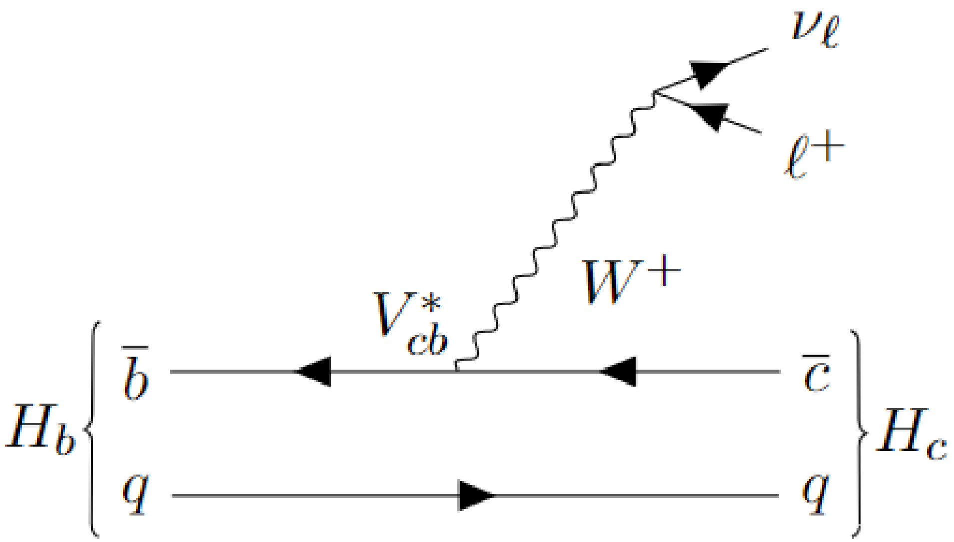
- ❑ Boost: O(fs) time scales
- ❑ Heavy Species: Bs, Bc, Λb, exotics…
- ❑ Multiple soft tracks

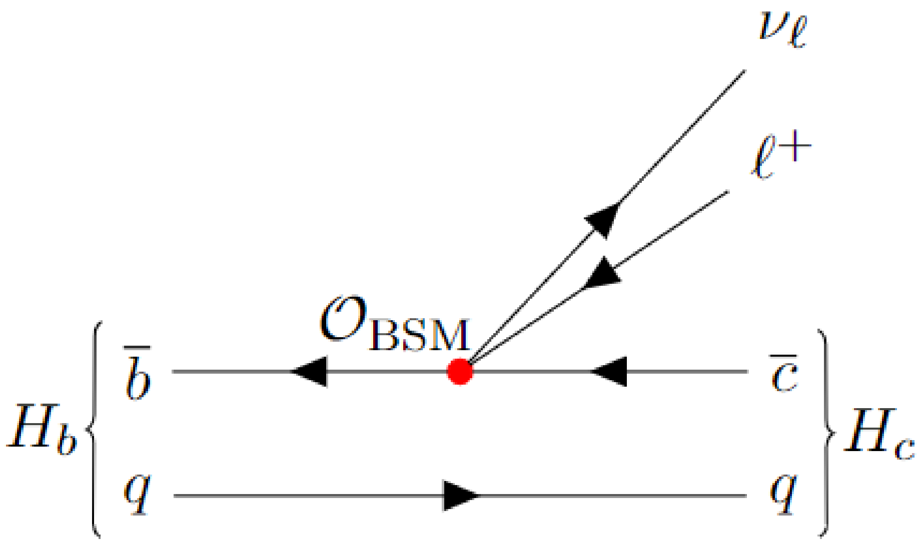
3 Charged Current Semileptonic and Leptonic b Decays

3.1 Theoretical Interpretation

3.2 Recent Progress and Directions to be Explored

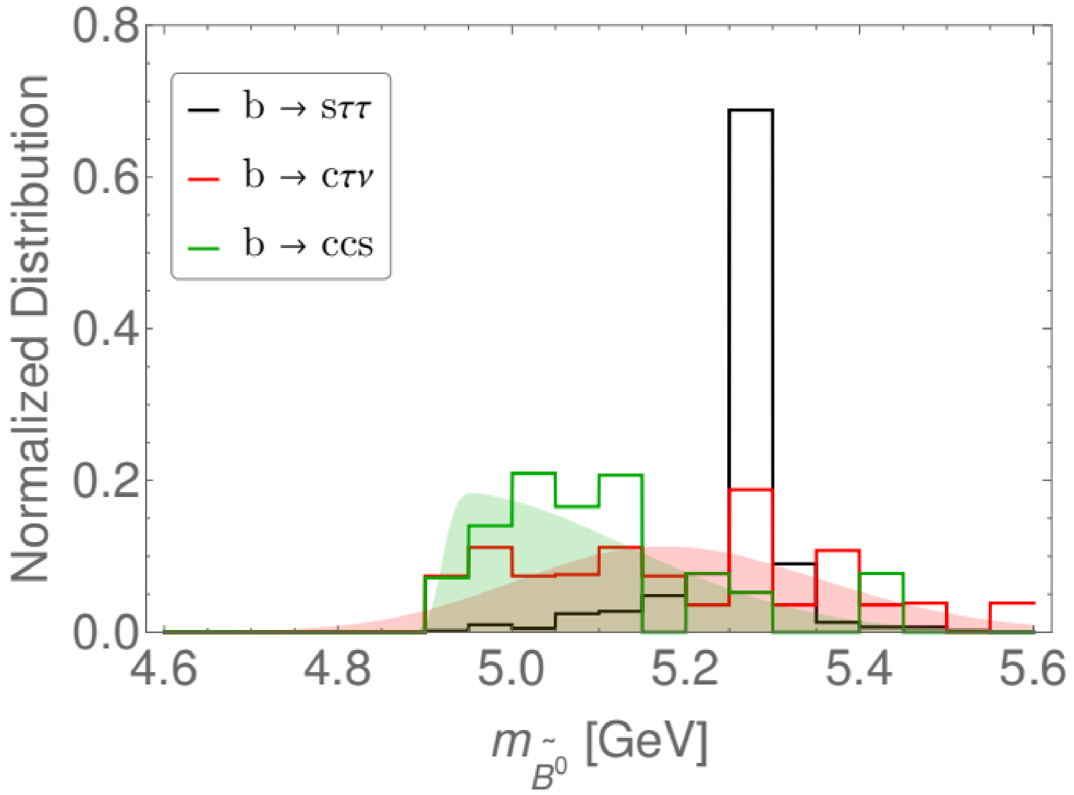
- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- CP asymmetries are clean
- Probe new physics, e.g. $\Lambda_{\rm NP}^{\rm SL} \sim (G_F|V_{cb}|\delta_{\rm SL})^{-\frac{1}{2}} \sim (1.5 \text{ TeV}) \times \delta_{\rm SL}^{-\frac{1}{2}}$





4 Rare/Penguin and Forbidden b Decays

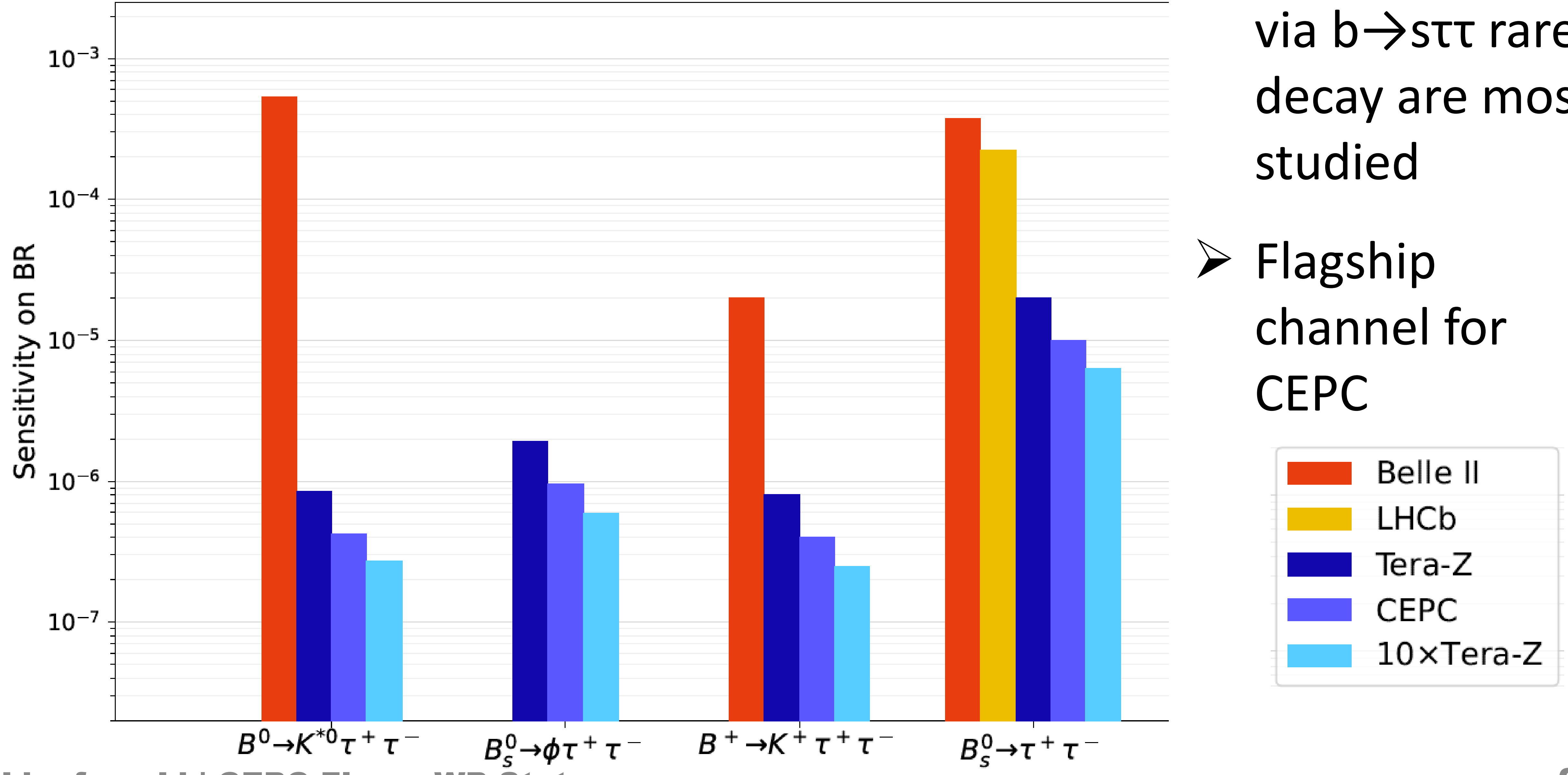
J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva 1705. 11106
LL, T. Liu, 2012.00665



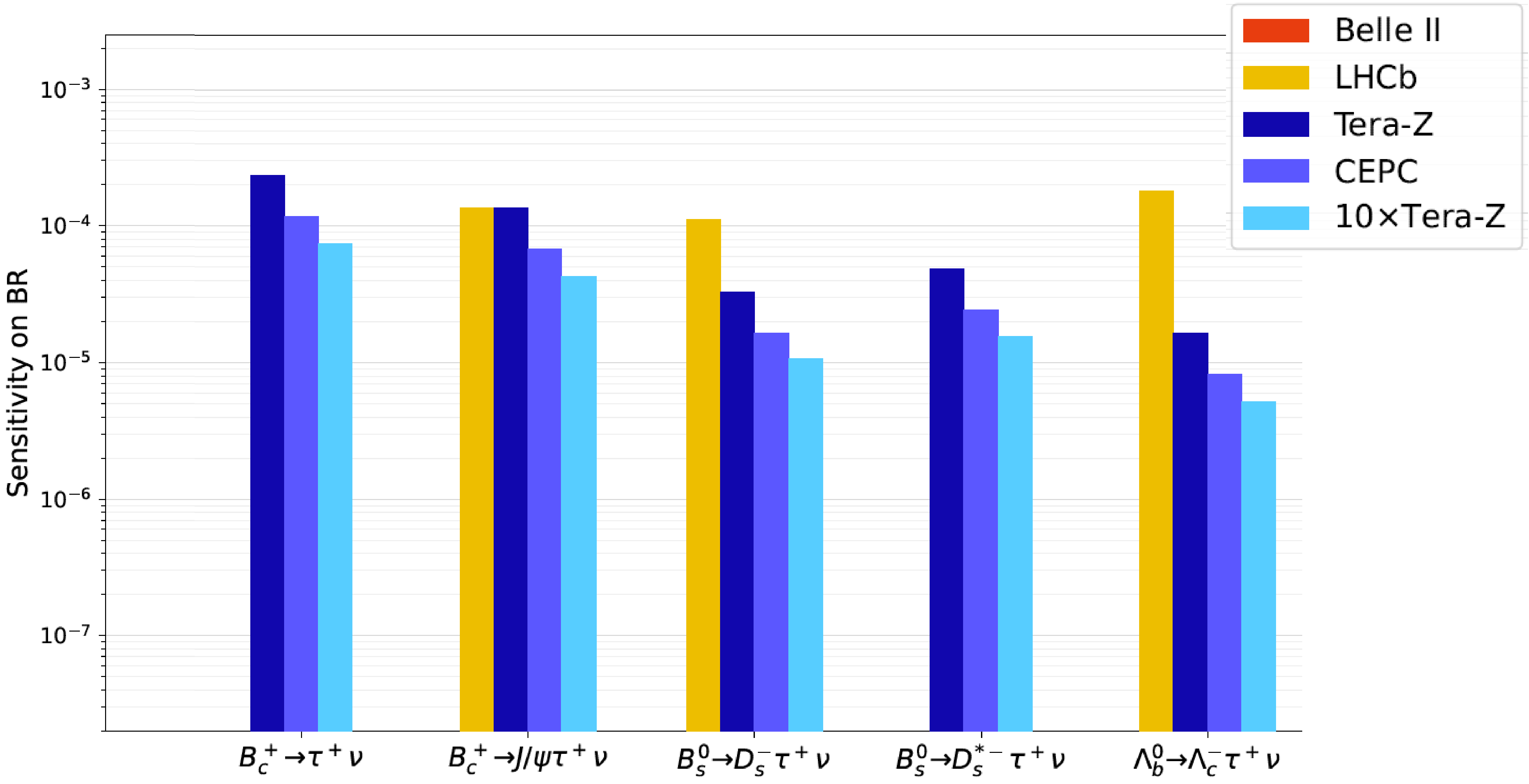
- Partially motivated by B anomalies
- Rare decays, sensitive to BSM and probe multi-TeV

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

See also:
S. Descotes-Genon, S. Fajfer, J. Kamenik, M. Novoa-Brunet 2208.10880

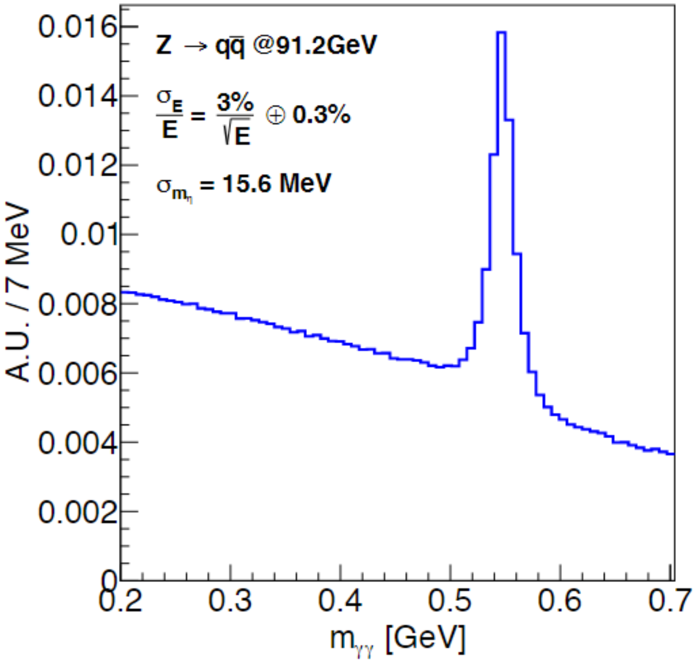


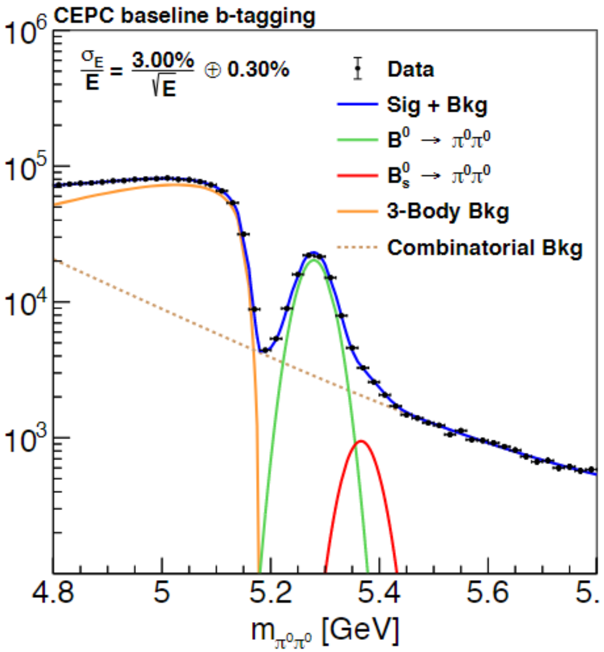
- The LFU test via b→sττ rare decay are most studied
- Flagship channel for CEPC

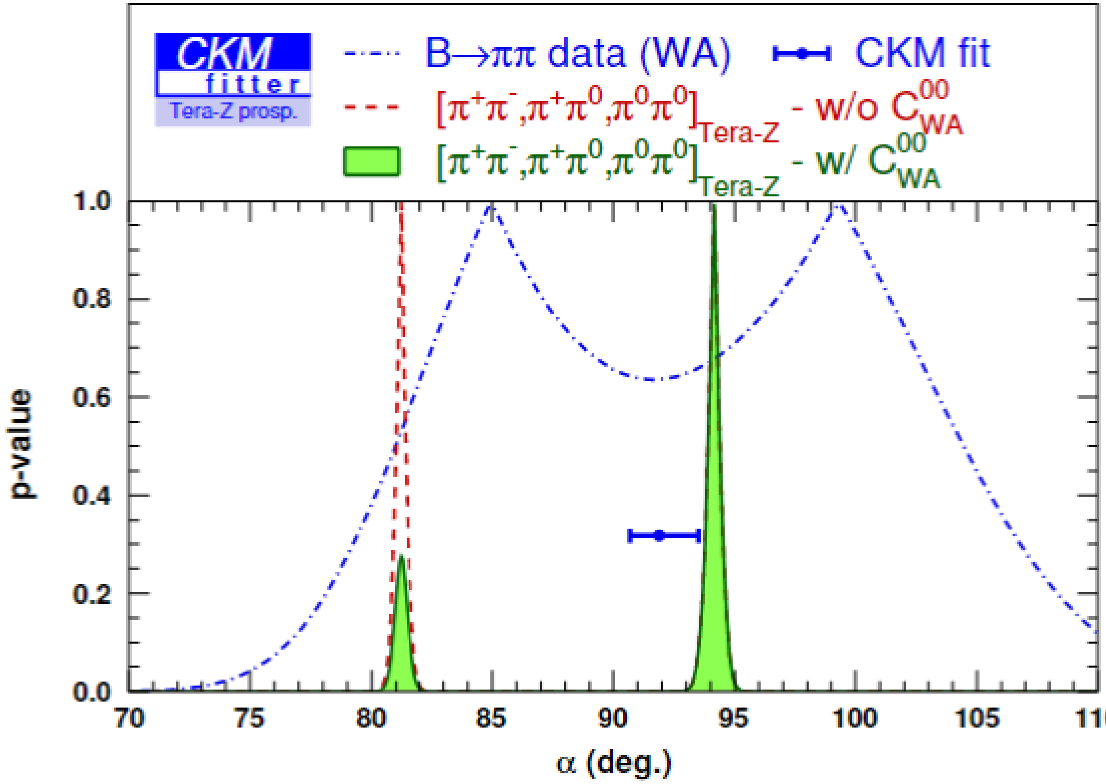


Belle II
LHCb
Tera-Z
CEPC
10×Tera-Z
Sensitivity on BR
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$B_c^+ \to \tau^+ \nu$
$B_c^+ \to J/\psi \tau^+ \nu$
$B_s^0 \to D_s^- \tau^+ \nu$
$B_s^0 \to D_s^{*-} \tau^+ \nu$
$\Lambda_b^0 \to \Lambda_c^- \tau^+ \nu$

Time-Integrated CP Asymmetry







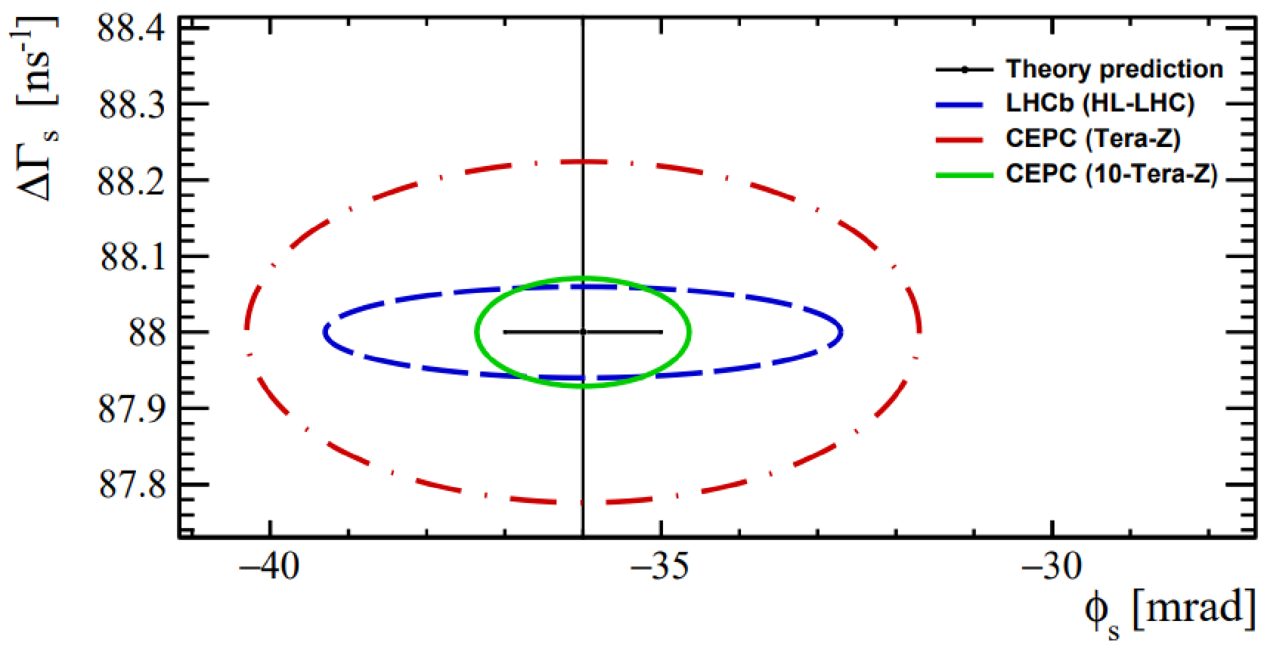
[Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan]

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 $B \to \pi^0\pi^0 \to 4\gamma$

But only if ECAL is crystal

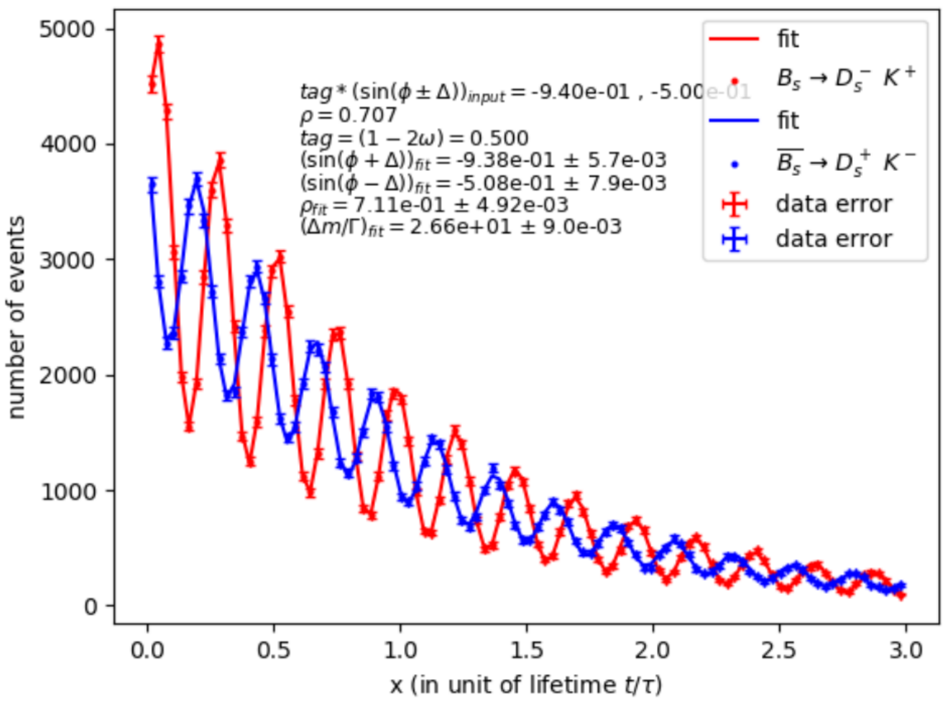
Time-Dependent CP Asymmetry



[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]

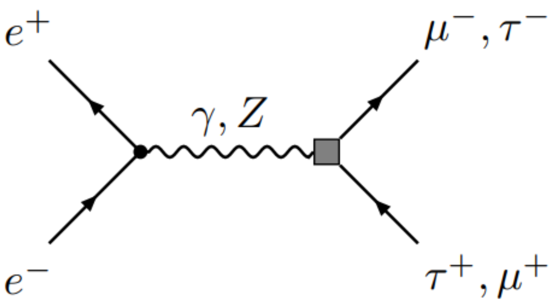


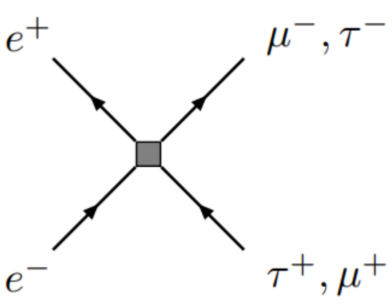
Time-dependent measurement of B→DK to give α_s and β_s, helpful to fix the value of angle γ

[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





$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{x_c}_{\rm bkg}$ [10^{-6}]	$N_{\rm bkg}$	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

W. Altmannshofer, P. Munbodh, T. Oh, 2305.03869

BR(Z →τμ) limit down to 10^{-9}

Also from runs of higher E_{cm}

Recommendations:

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

8 Charm and Strange Physics

Γ_9	$(u\,\overline{u} + c\,\overline{c})/2$	$(11.6 \pm 0.6)\%$
Γ_{10}	$(d\,\overline{d} + s\,\overline{s} + b\,\overline{b})/3$	$(15.6 \pm 0.4)\%$

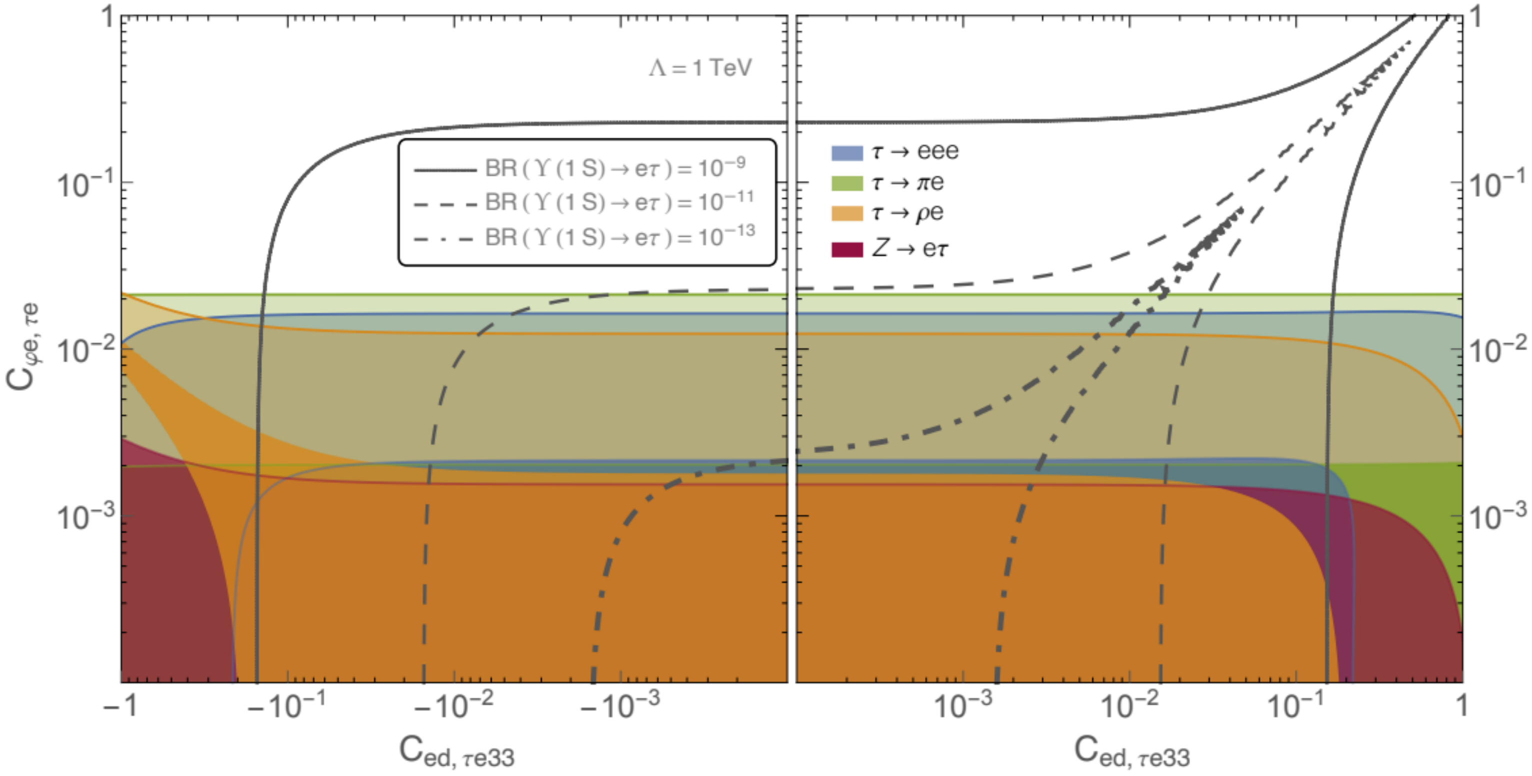
- Z decay also produces a lot of c and s quarks
- More s quarks ($K^{(*)}$,Λ…) produced by QCD
- Also building blocks of b physics

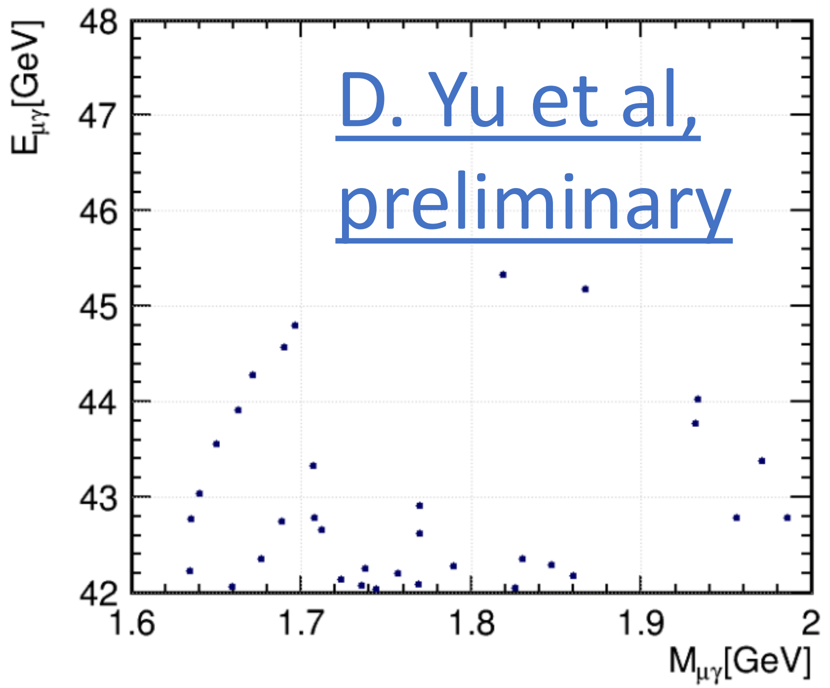
Recommendations:

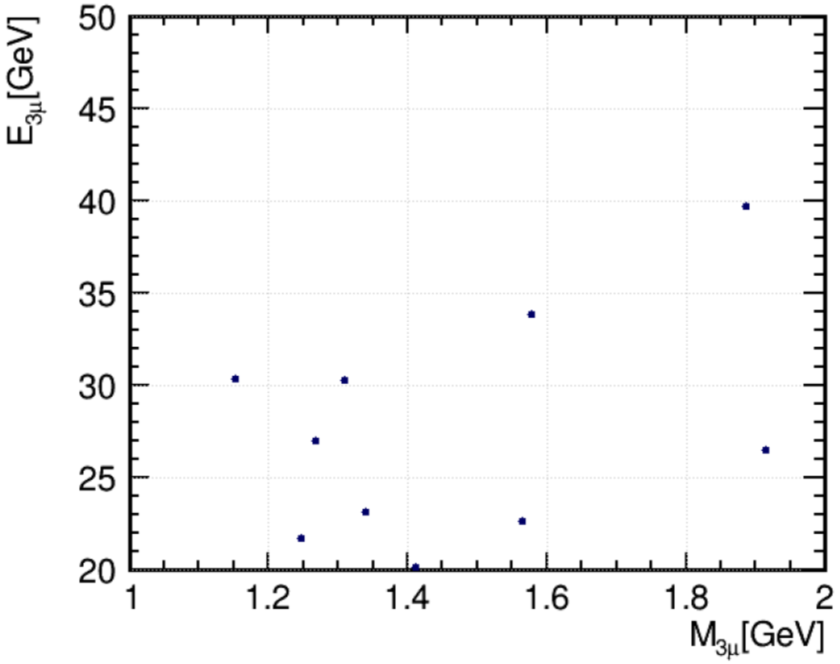
- Have a charm physics program in parallel to bottom ones in the next phase
- Focus on K_S and Λ rare decays, e.g. $K_S \rightarrow \mu\mu(+\gamma)$, complementary to future kaon factories

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
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited

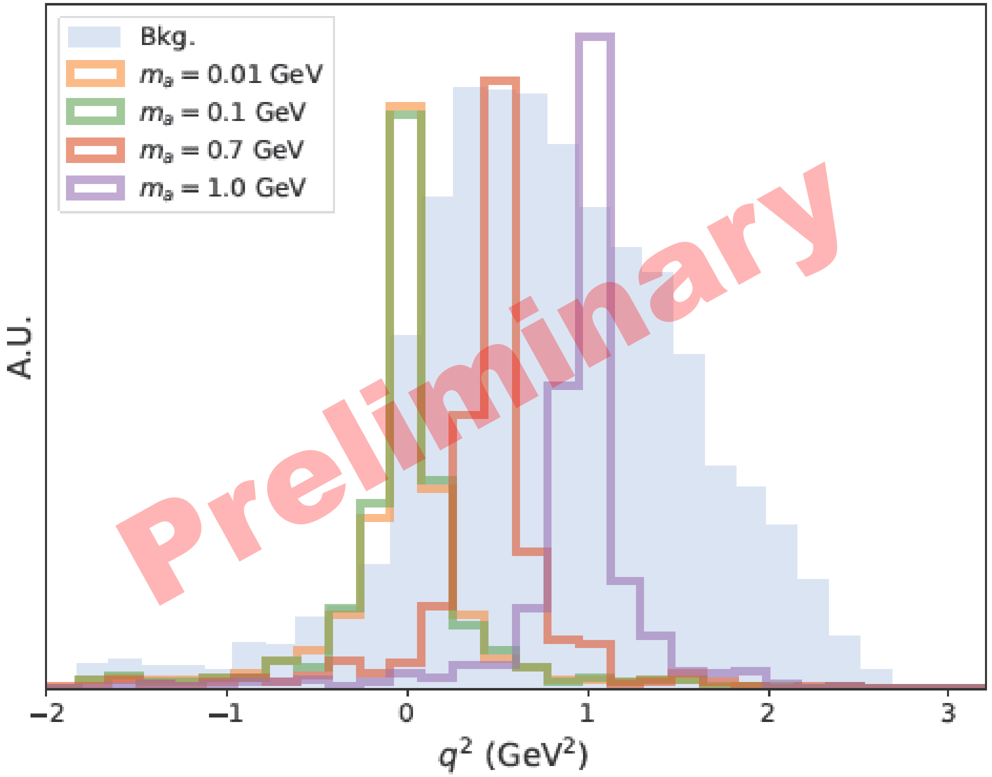
M. Dam, 1811.09408

- More exotic τ decay modes
- Hadronic τ decay for f_K, V_{us}, and α_s (m_τ)
- 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.