# Status of the CEPC Flavor Physics White Paper (Phase I)

1000,000,000,000+

# Or Flavor Physics at Tera - Z+

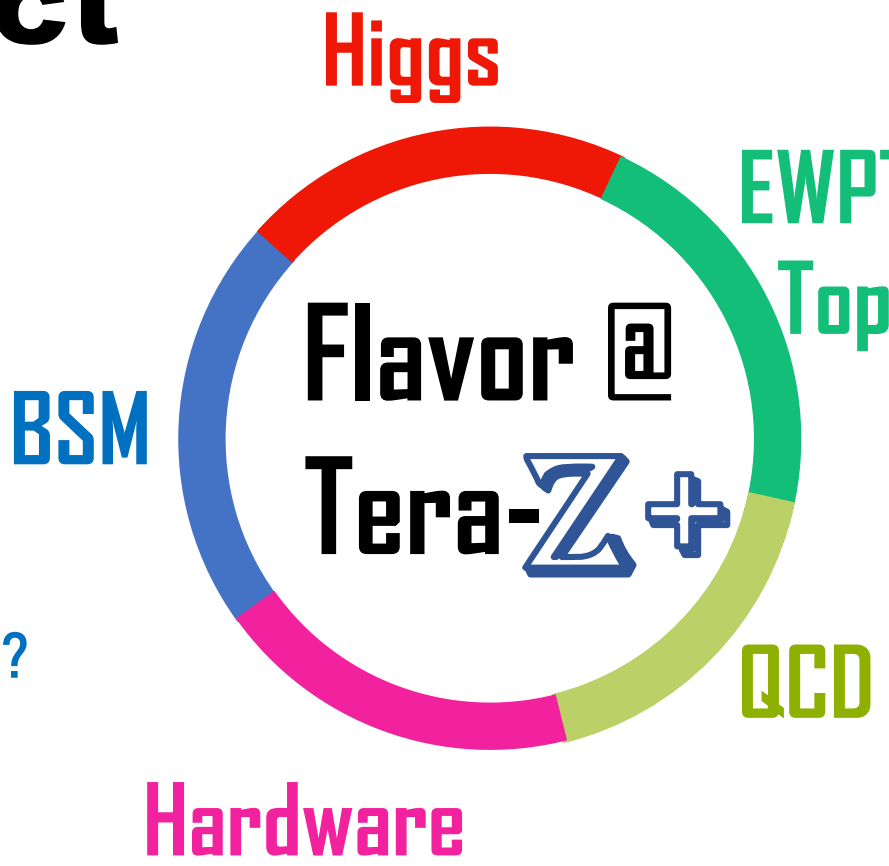
Lingfeng Li  Brown University

Jul. 4, 2023

The 2023 international workshop on the CEPC

# 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!

# Status and Timeline


- ❑ Initiation of white paper, material collection
- ❑ Drafting
- ❑ First draft finished, under internal review
- ❑ External review by experts
- ❑ Preprint Publish

# Table of Contents



➢ Includes >20 individual studies and ~10 preliminary studies

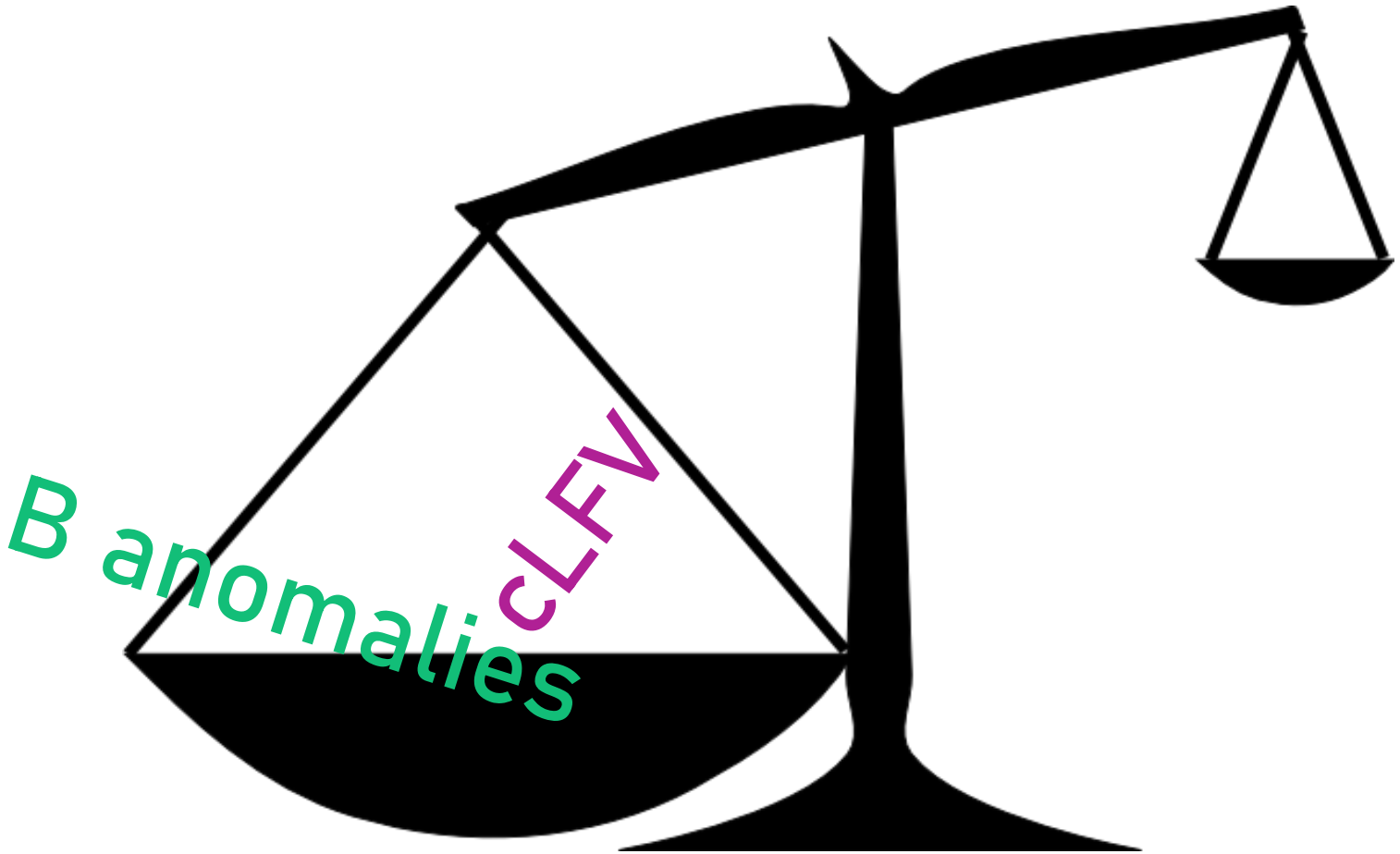
# The Purpose of the Flavor Physics White Paper (Phase I)

- To summarize the known results in an organized way
- To provide guidance and recommendation for studies in the next phase
- To resonate on relevant programs (e.g. flavor phys. @ FCC-ee)

# Major Challenges

- Excessive statistics, data flow, and precision goals require **understanding and control** of experimental systematics (otherwise the projections will be very wrong)
- Recognize the **most valuable** analyses for CEPC, even overlooked ones
- Encorporate the appropriate **theory** (not always available)

# The Primary Concern (Biased View)



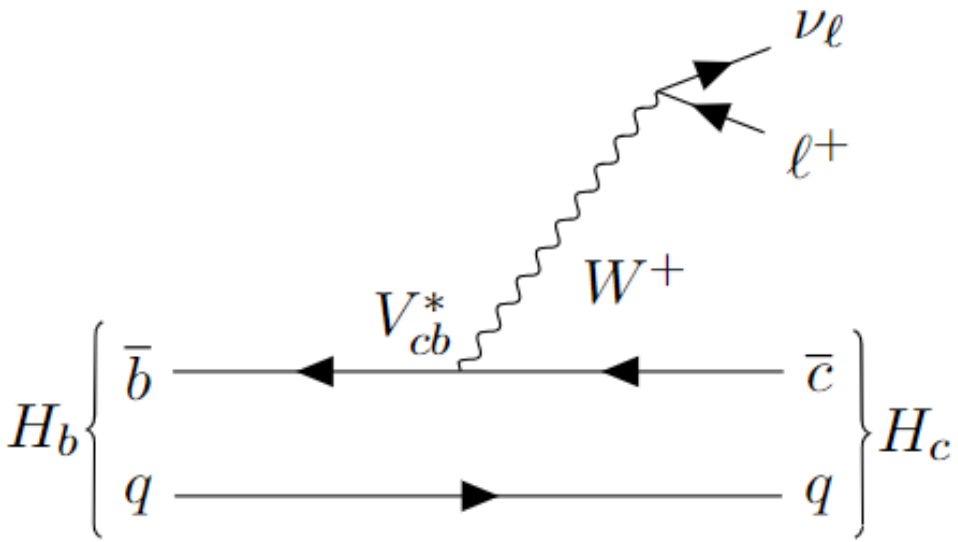

CKM
CP Asy.
Spectroscopy
Hadronization
BNV
Charm……

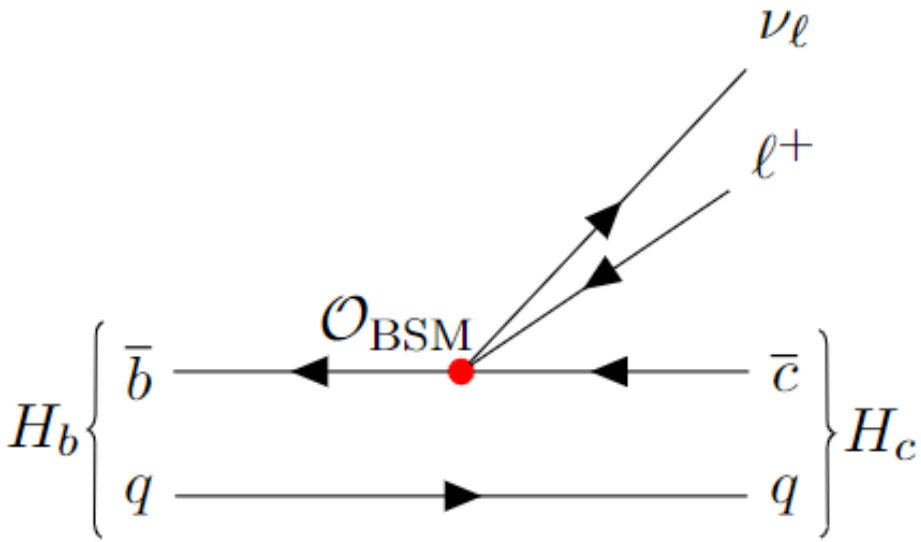
## 3 Charged Current Semileptonic and Leptonic $b$ Decays

### 3.1 Theoretical Interpretation

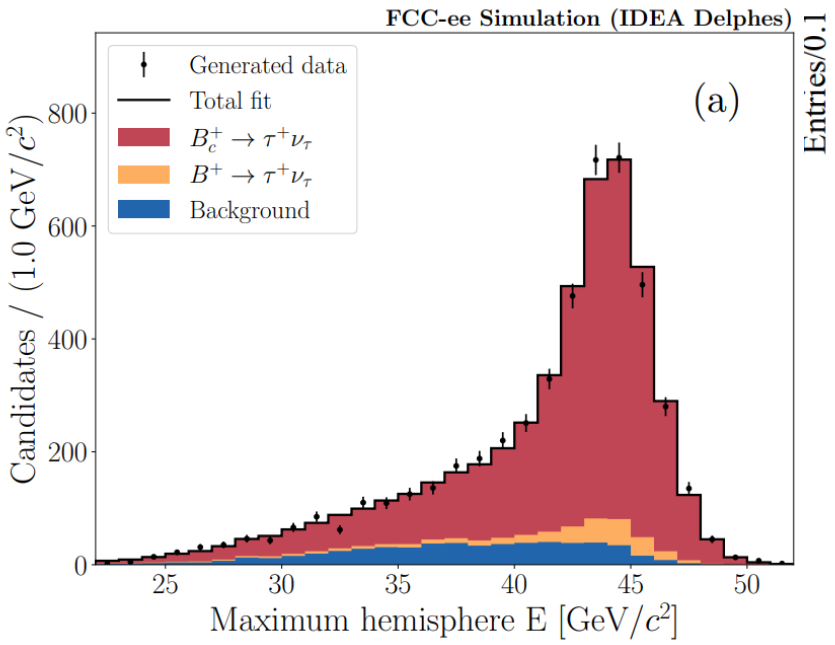
### 3.2 Recent Progress and Directions to be Explored

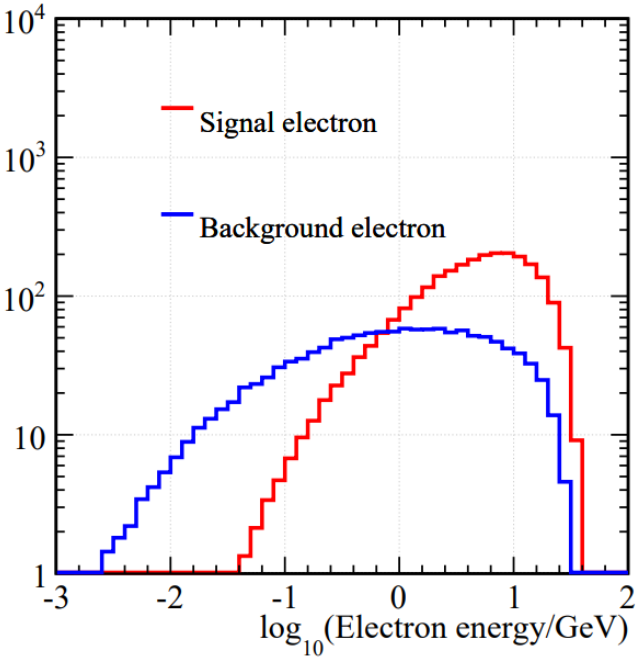
- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- CP asymmetries are clean
- Potentially probe higher scales of new physics

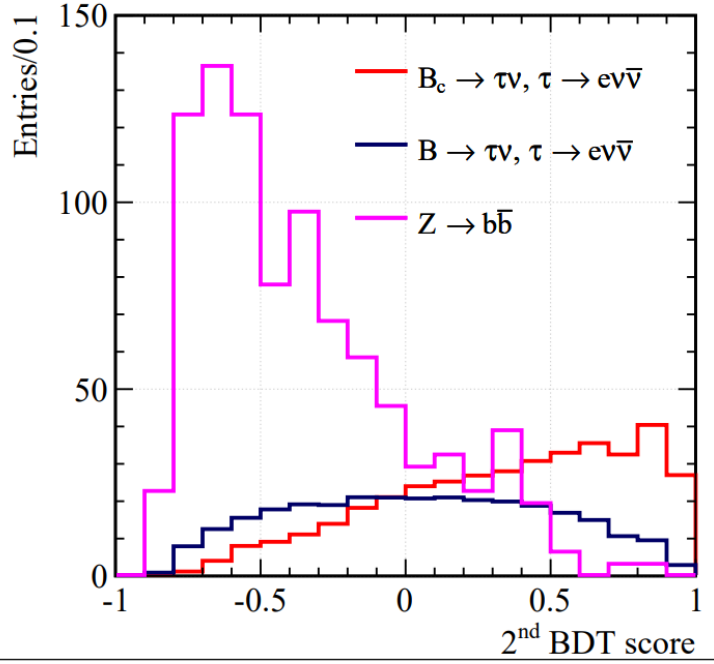


# $B_c \to \tau\nu$ measurement, unique at CEPC



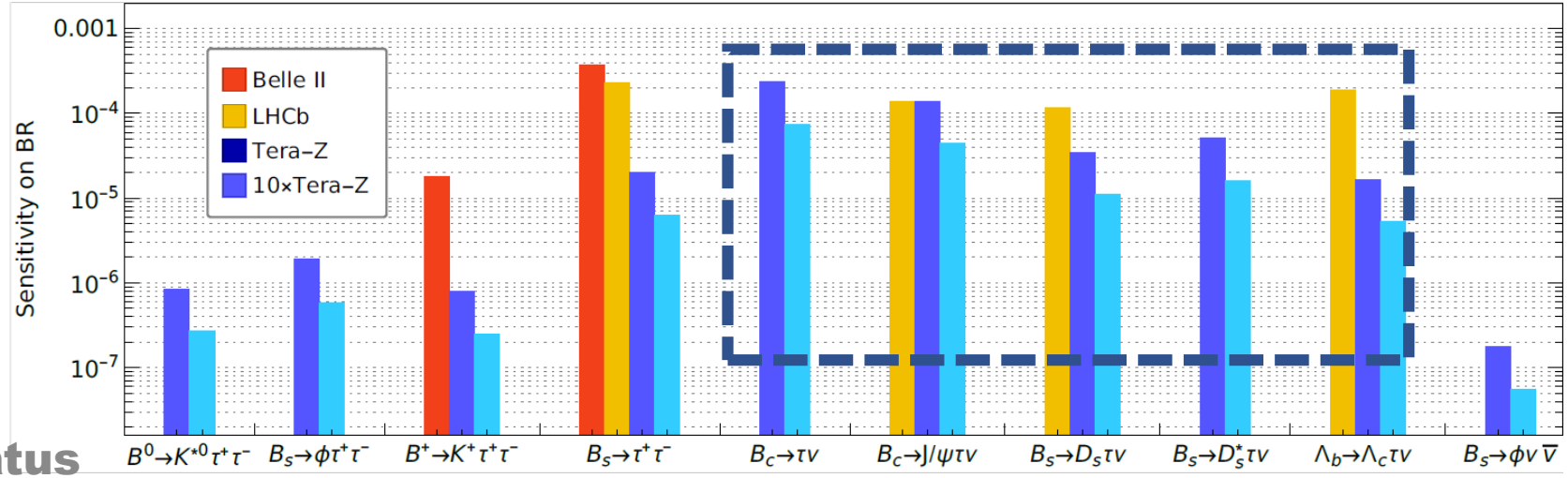




Y. Amhis, M. Hartmann, C. Helsens D. Hill, O. Sumensari 2105.13330

T. Zheng, J. Xu, L. Cao, D. Yu, W. Wang et al., 2007.08234

# LFU tests with various transition types

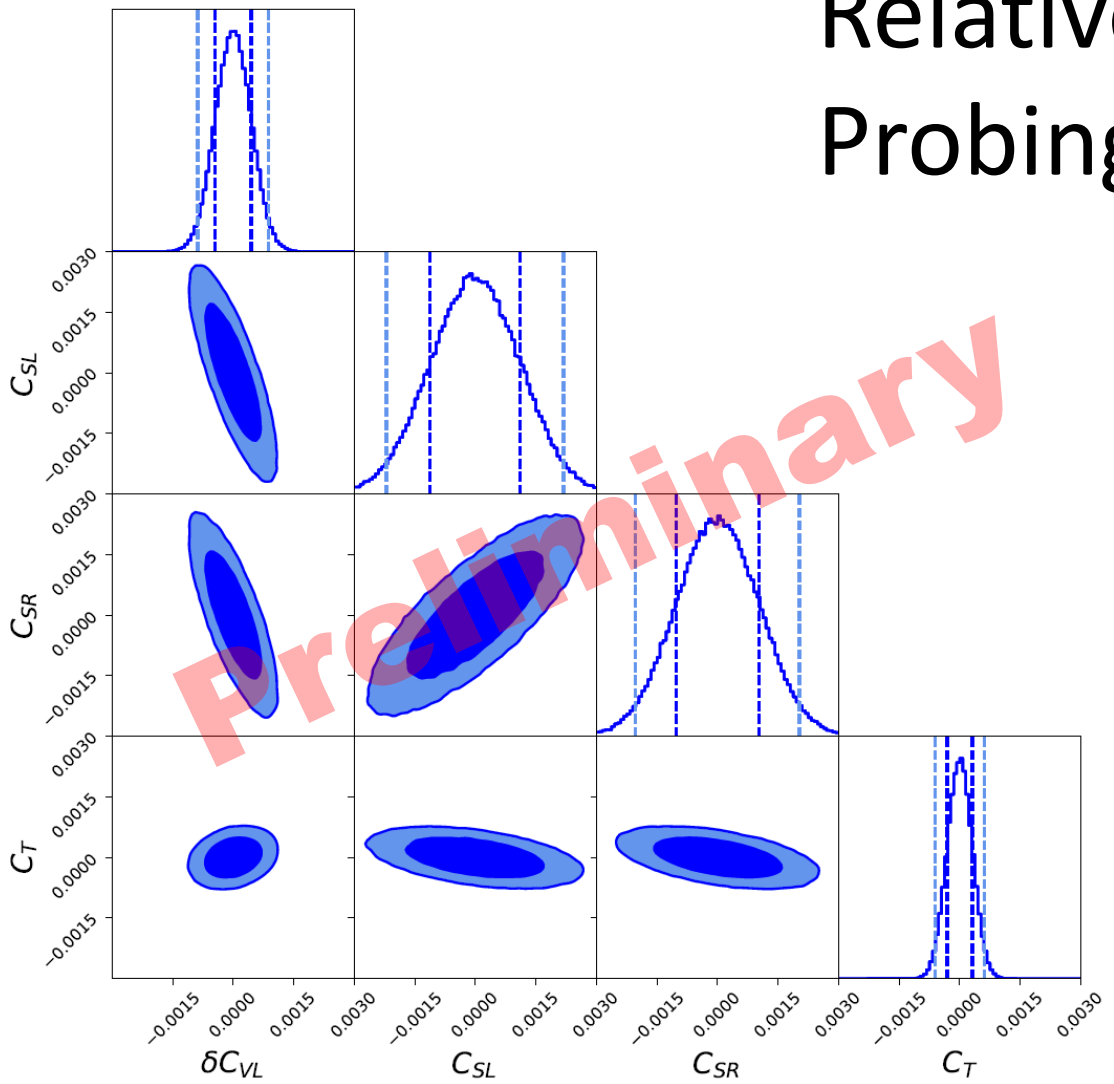
See Anson Kwok's talk



# Section Summary and Suggestions

Relative precisions ≲ O(1%) achieved

Probing multi-TeV scales already




Recommended future steps:

- ❖ Differential measurements (polarimetry, asymmetry …)
- ❖ Extend the search on more final states
- ❖ Evaluate electron modes with electron PID

# 4 Rare/Penguin and Forbidden $b$ Decays

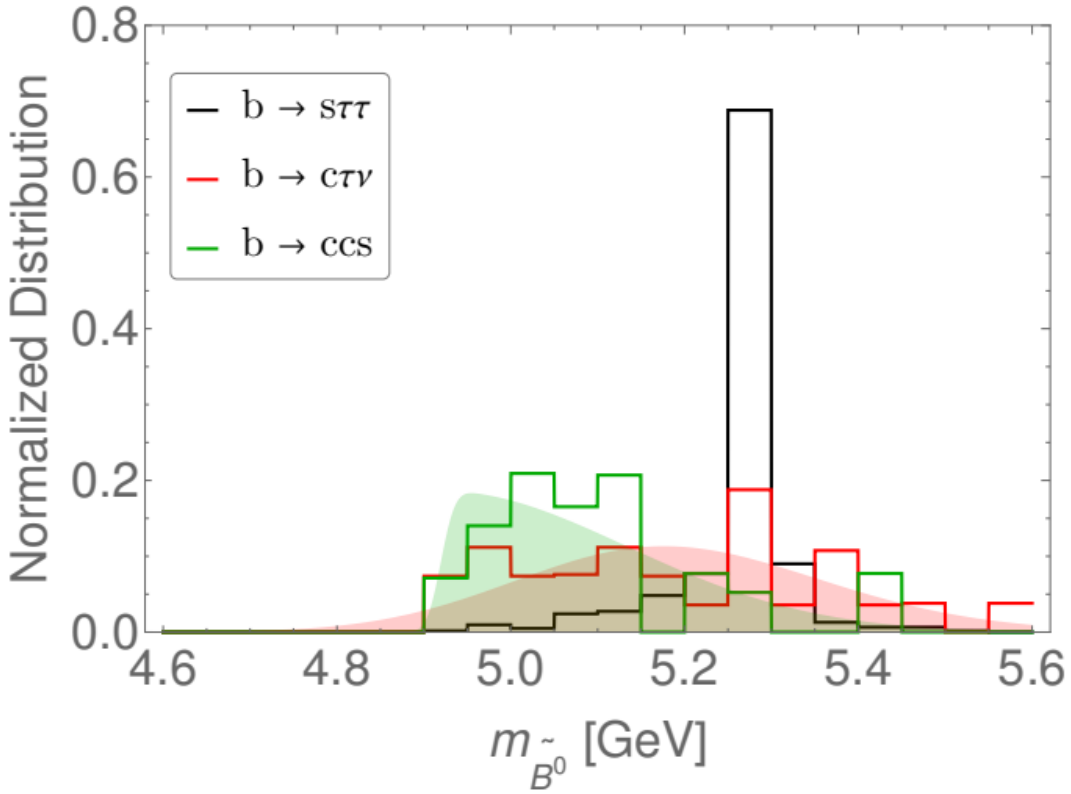
## 4.1 Theoretical Interpretation (preliminary)

## 4.2 Dileptonic Modes

## 4.3 Neutrino Modes

## 4.4 Radiative Modes

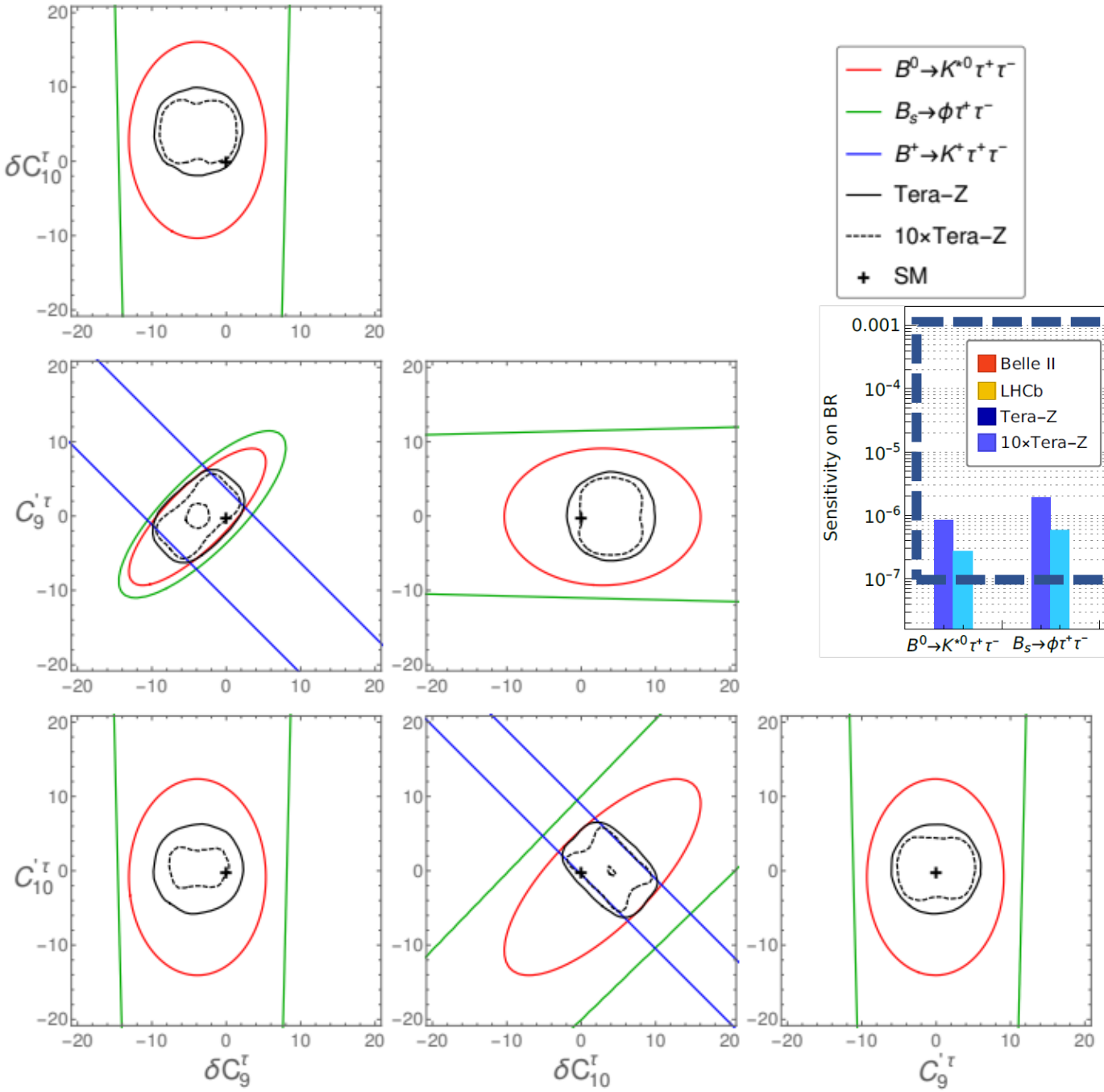
J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva 1705. 11106
LL, T. Liu, 2012.00665



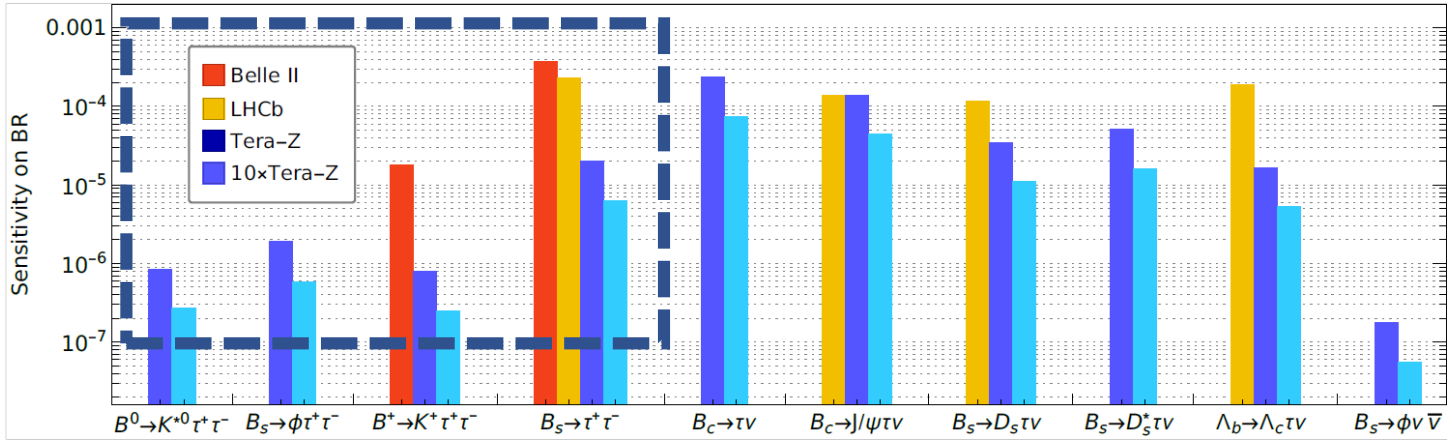

- Partially motivated by B anomalies
- Rare decays, sensitive to BSM and probe multi-TeV

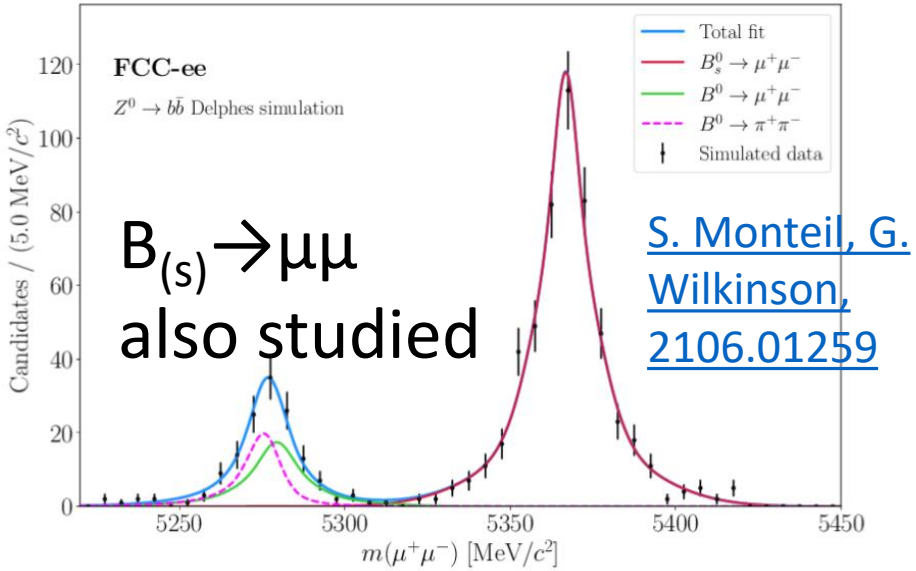
$$\Lambda_{\rm NP} \simeq \left(\frac{\alpha}{4\pi}\frac{m_t^2}{m_W^2}G_F|V_{tb}V_{ts}^*|\delta_{\rm rare}\right)^{-\frac{1}{2}} \simeq (30\ {\rm TeV}) \times \delta_{\rm rare}^{-\frac{1}{2}}$$

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

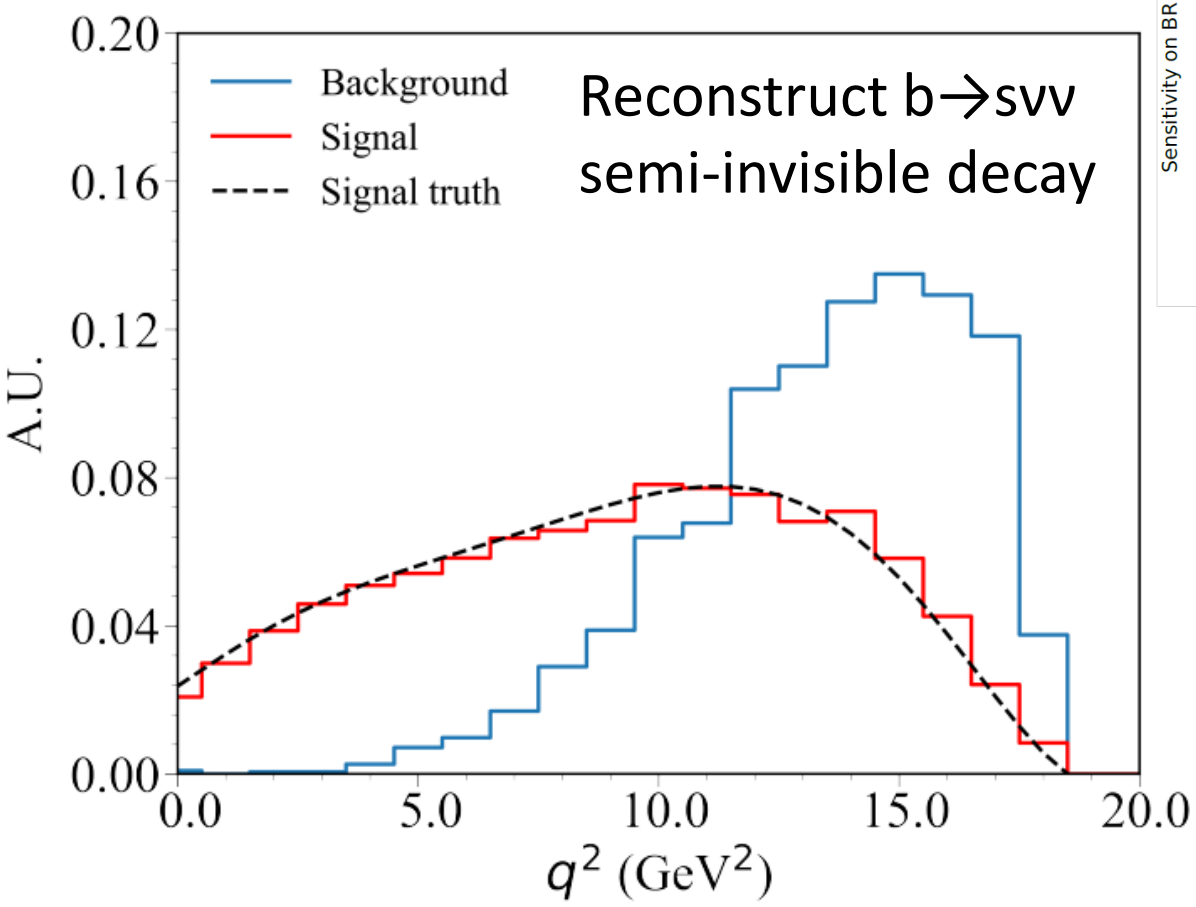


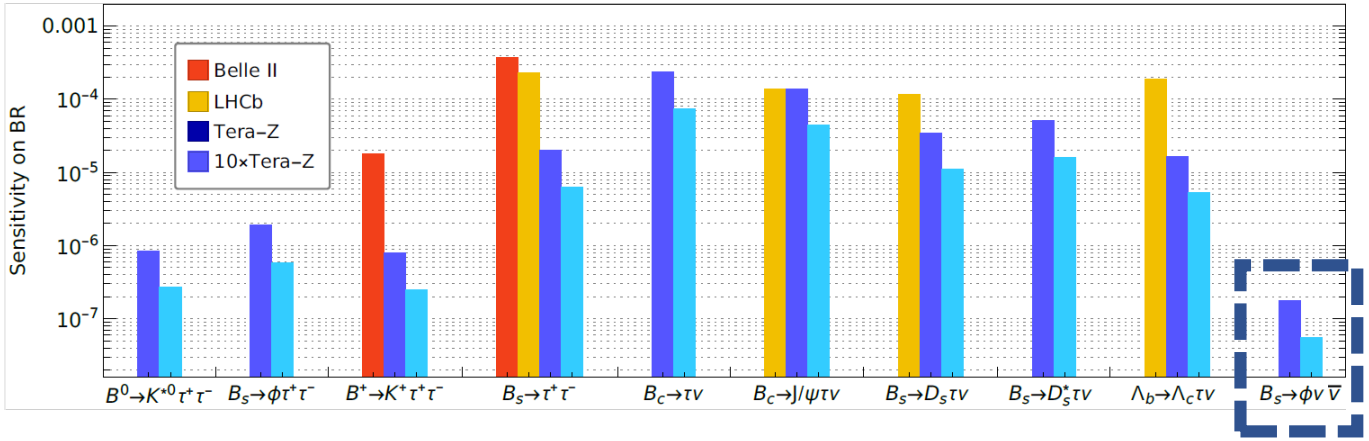

$B_{(s)} \to \mu\mu$ also studied

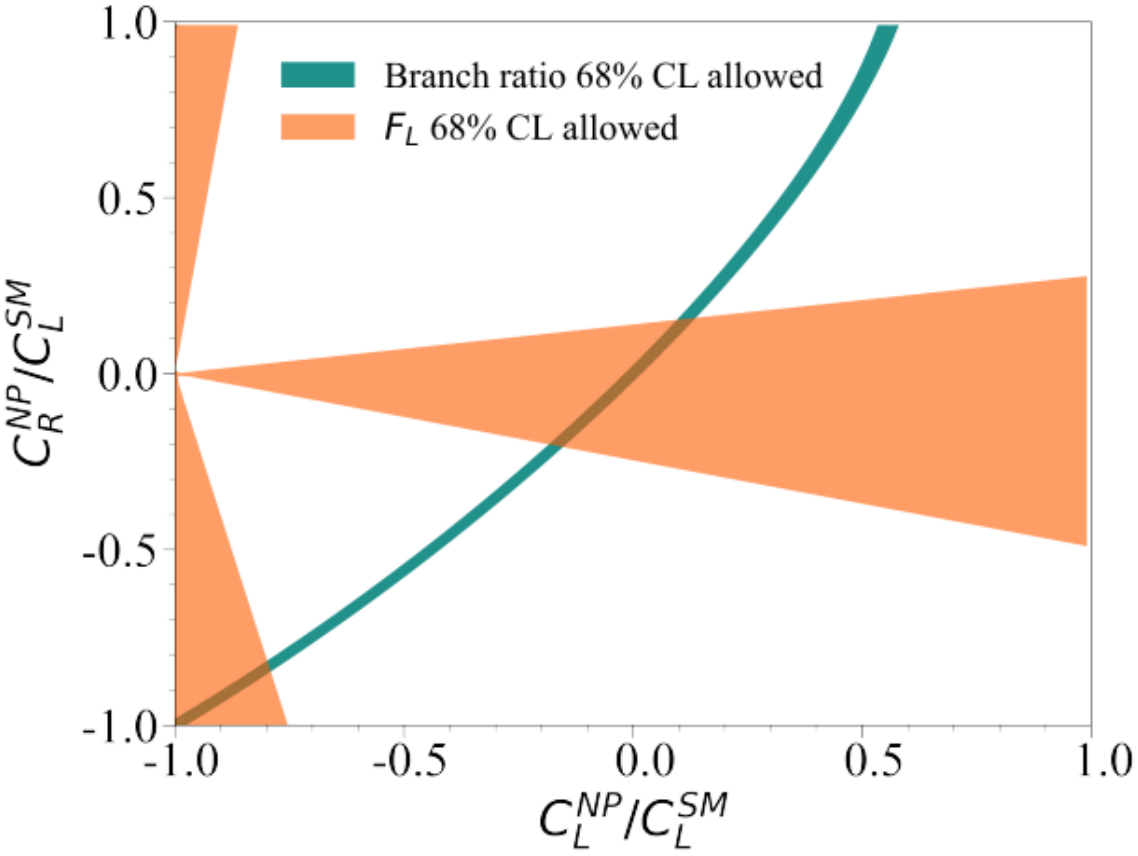
S. Monteil, G. Wilkinson, 2106.01259

# 4.3 Neutrino Modes




Reconstruct b→svv semi-invisible decay




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

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

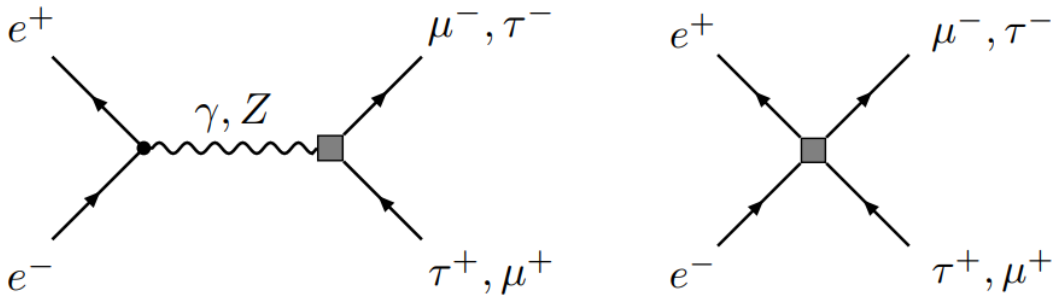
- Most decays are rare (BR < $10^{-5}$).
- Relative precisions vary from O($10^{-2}$ -1) determined by final states, probing multi-TeV already
- Unique advantages at CEPC

# Section Summary and Suggestions

- Benchmark studies for (double) radiative decays with proper ECAL simulations
- Modes of heavy hadrons like $\Lambda_b$
- Systematically dominated e vs. μ LFU tests

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

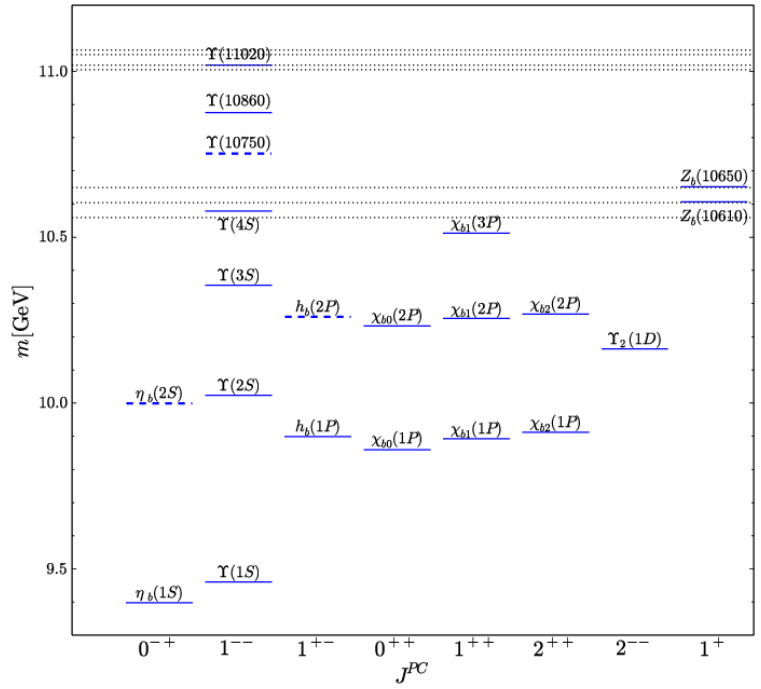
W. Altmannshofer, P. Munbodh, T. Oh, 2305.03869

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

**Recommendations:**

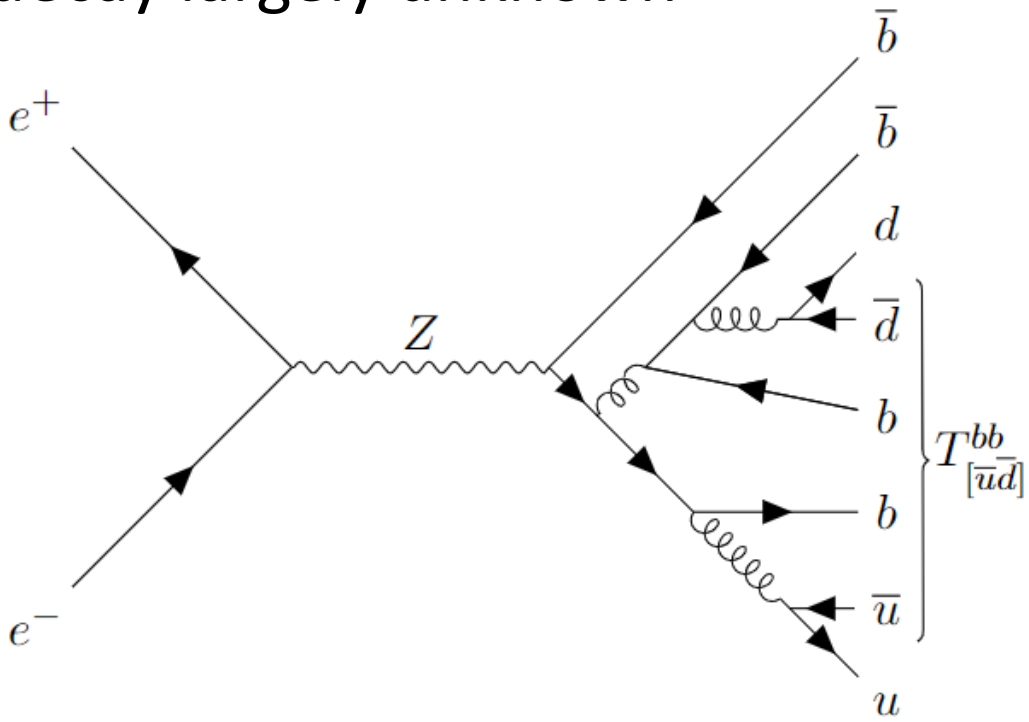
- Need studies on lepton and baryon number violation in the next phases

# 7 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

Recent studies on production of tetraquarks & doubly-flavored baryons J. Niu, J. Li, H. Bi, H. Ma, 2305.15362 A. Ali, A.Y. Parkhomenko, Q. Qin, W. Wang, 1805.02535




**Recommendations:**

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

# 8 Charm and Strange Physics

| | | |
|---|---|---|
| $\Gamma_9$ | $(u\,\bar{u} + c\,\bar{c})/2$ | $(11.6 \pm 0.6)\%$ |
| $\Gamma_{10}$ | $(d\,\bar{d} + s\,\bar{s} + b\,\bar{b})/3$ | $(15.6 \pm 0.4)\%$ |

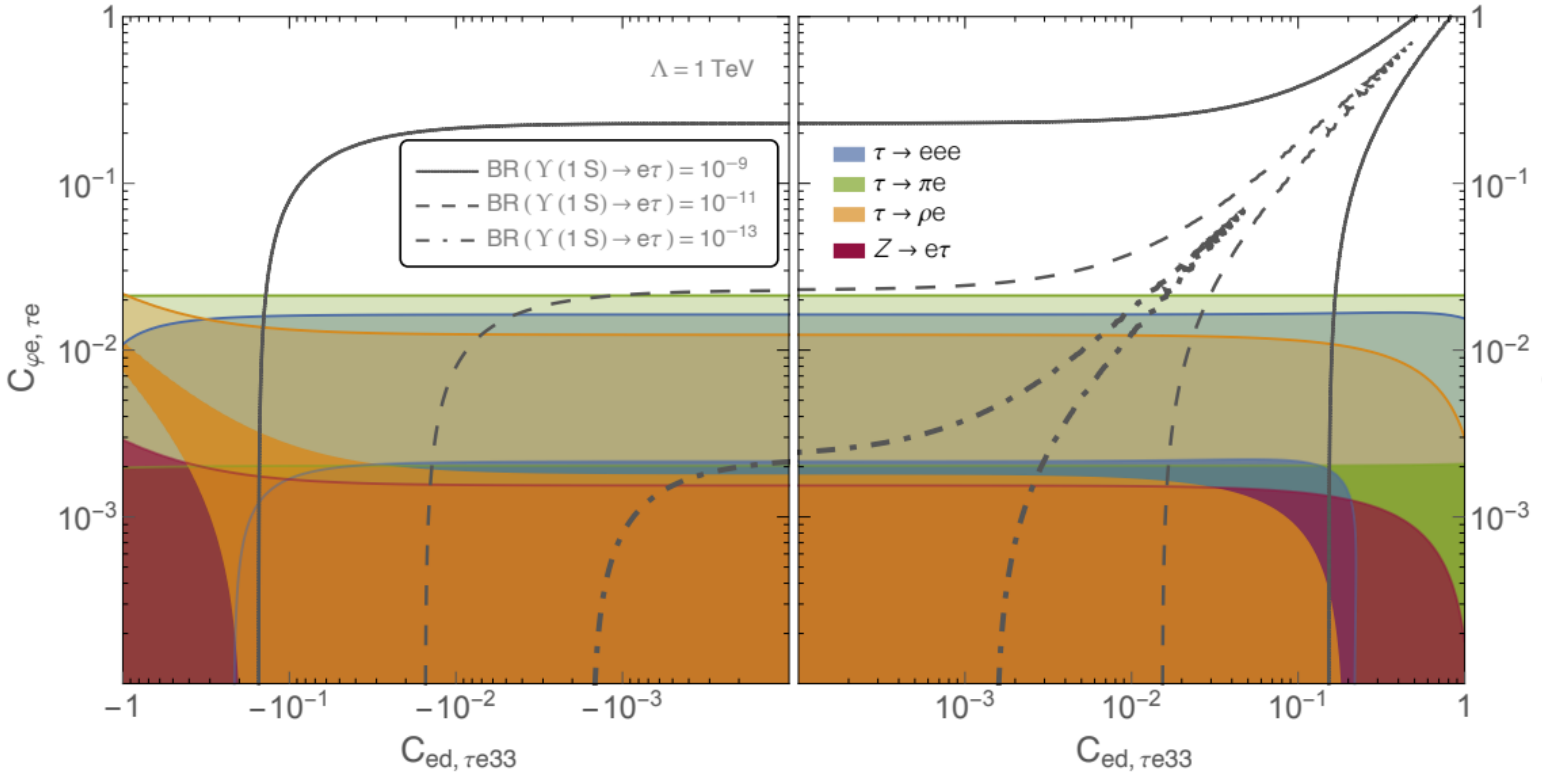
- Z decay also produces a lot of c and s quarks
- More s quarks ($K^{(*)}$,Λ…) produced by QCD
- Also building blocks of b physics

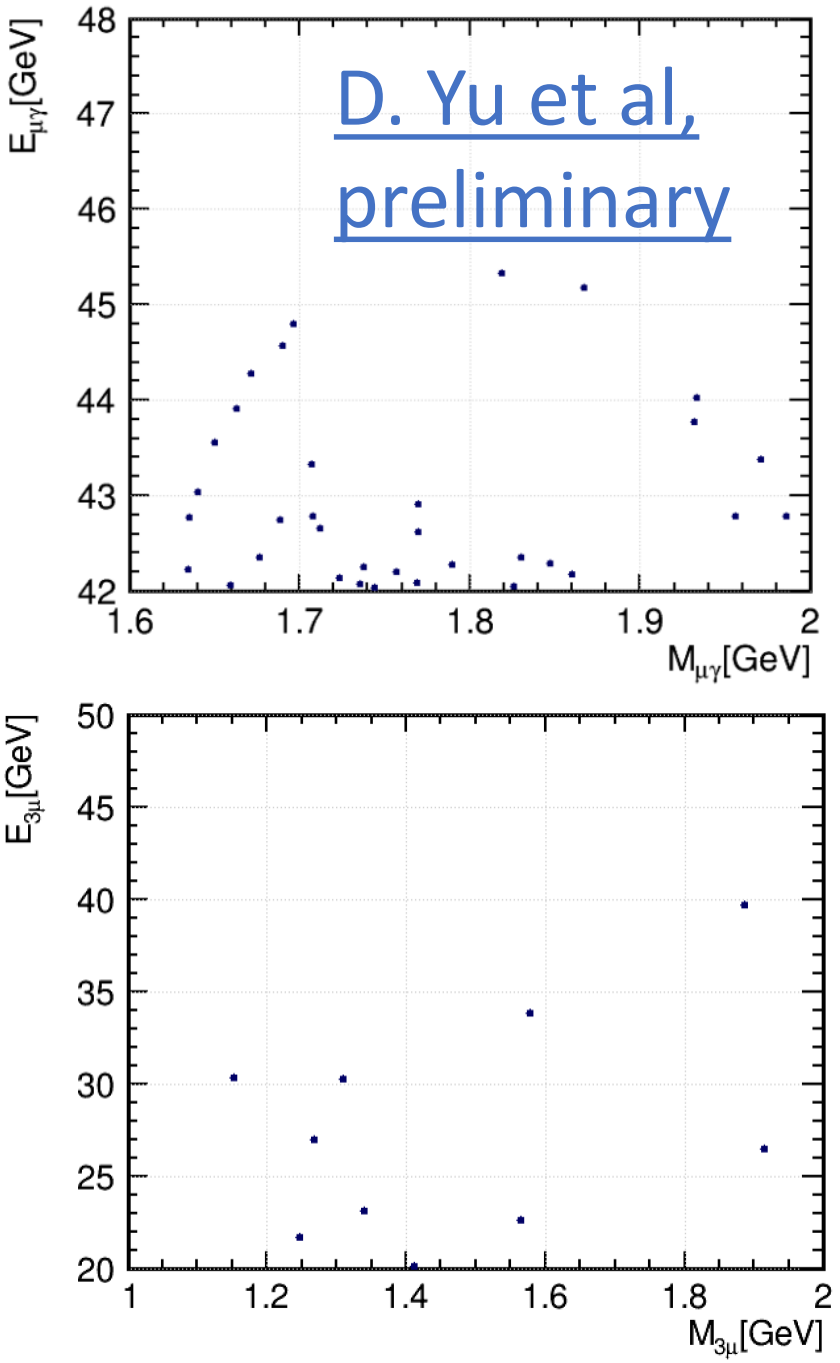
**Recommendations:**

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

# 9 $\tau$ 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($\tau \to \ell\nu\bar{\nu}$) | $\pm 4 \times 10^{-4}$ | $\pm 3 \times 10^{-5}$ | | 0.1× the ALEPH systematics |
| m($\tau$) [MeV] | $\pm 0.12$ | $\pm 0.004 \pm 0.1$ | | $\sigma(p_{\text{track}})$ limited |
| BR($\tau \to 3\mu$) | $< 2.1 \times 10^{-8}$ | $\mathcal{O}(10^{-10})$ | same | bkg free |
| BR($\tau \to 3e$) | $< 2.7 \times 10^{-8}$ | $\mathcal{O}(10^{-10})$ | | bkg free |
| BR($\tau \to e\mu\mu$) | $< 2.7 \times 10^{-8}$ | $\mathcal{O}(10^{-10})$ | | bkg free |
| BR($\tau \to \mu ee$) | $< 1.8 \times 10^{-8}$ | $\mathcal{O}(10^{-10})$ | | bkg free |
| 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 |
| 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 $\alpha_s$ ($m_\tau$)
- τ polarimetry/asymmetry at the Z pole for extracting EWPO

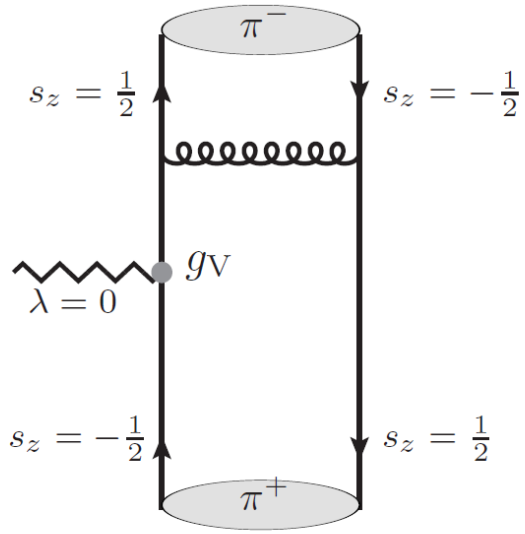
# 10 Flavor Physics at Higher Energies

## 10.1 Exclusive Hadronic Decays of Heavy SM Bosons

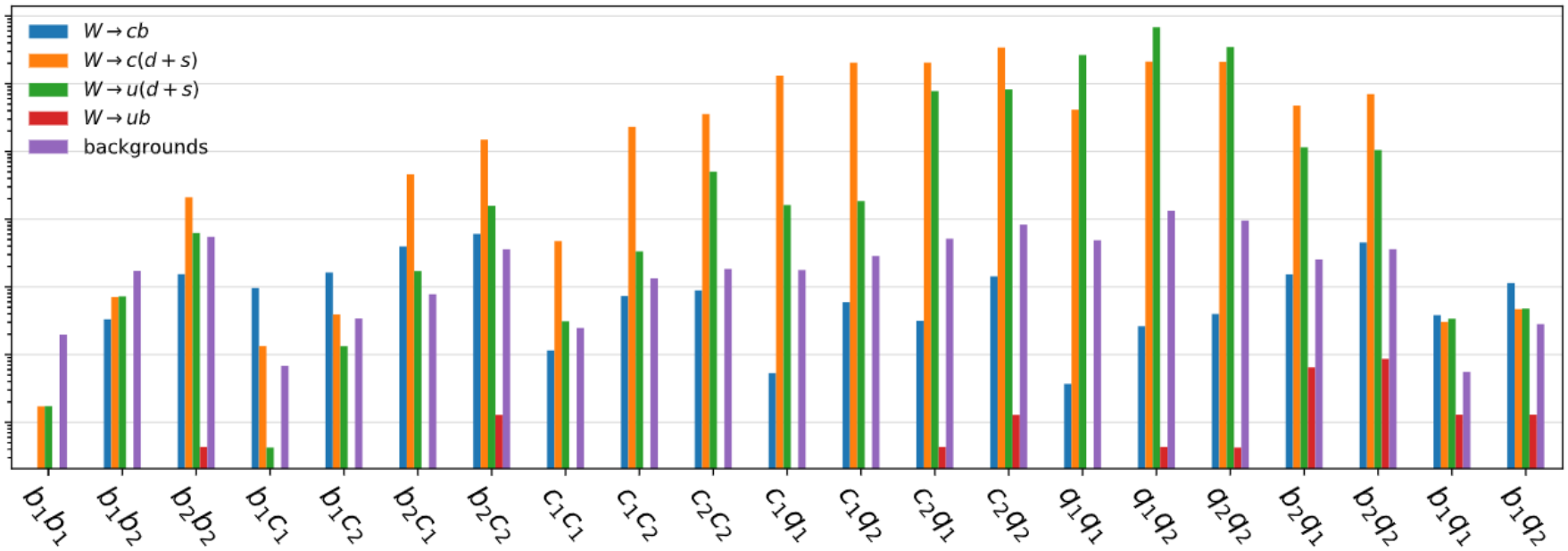
## 10.2 $|V_{cb}|$ measurement from on-shell $W$ Decays

## 10.3 Other Possibilities

See Hao Liang's talk




$(a)\ Z \to \pi^+\pi^-$



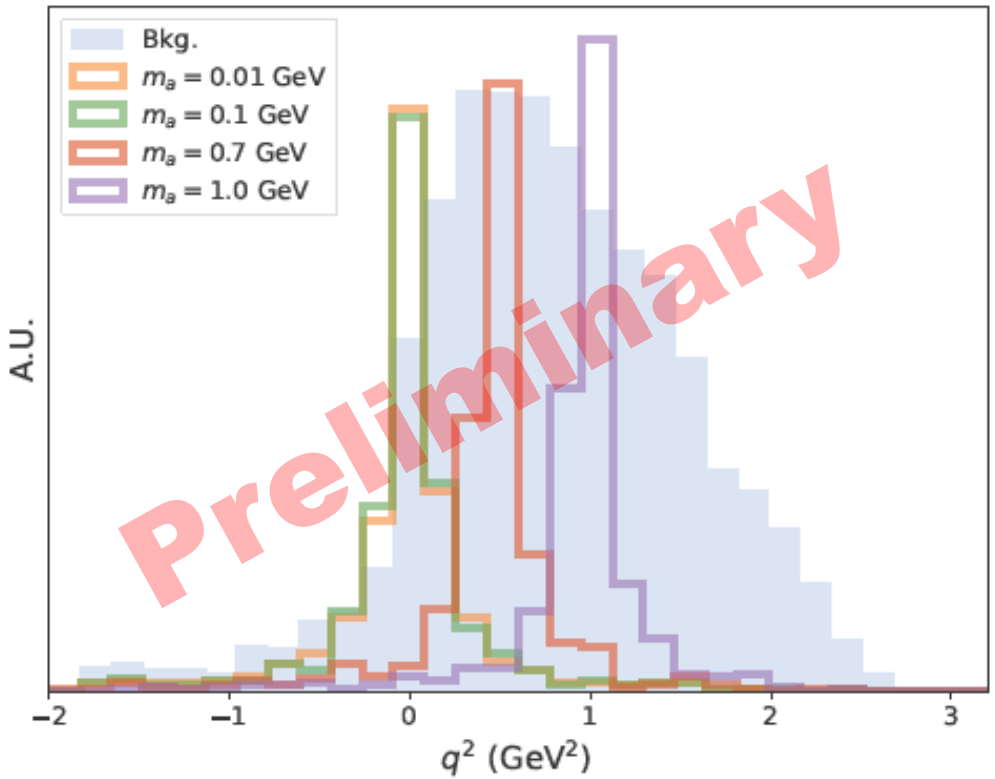

Current Recommendation:

❖Flavored hadronization, also crucial for EW & Higgs

# 11 Production of BSM States from Heavy Flavor Decays

## 11.1 Light BSM states produced via their coupling with leptons

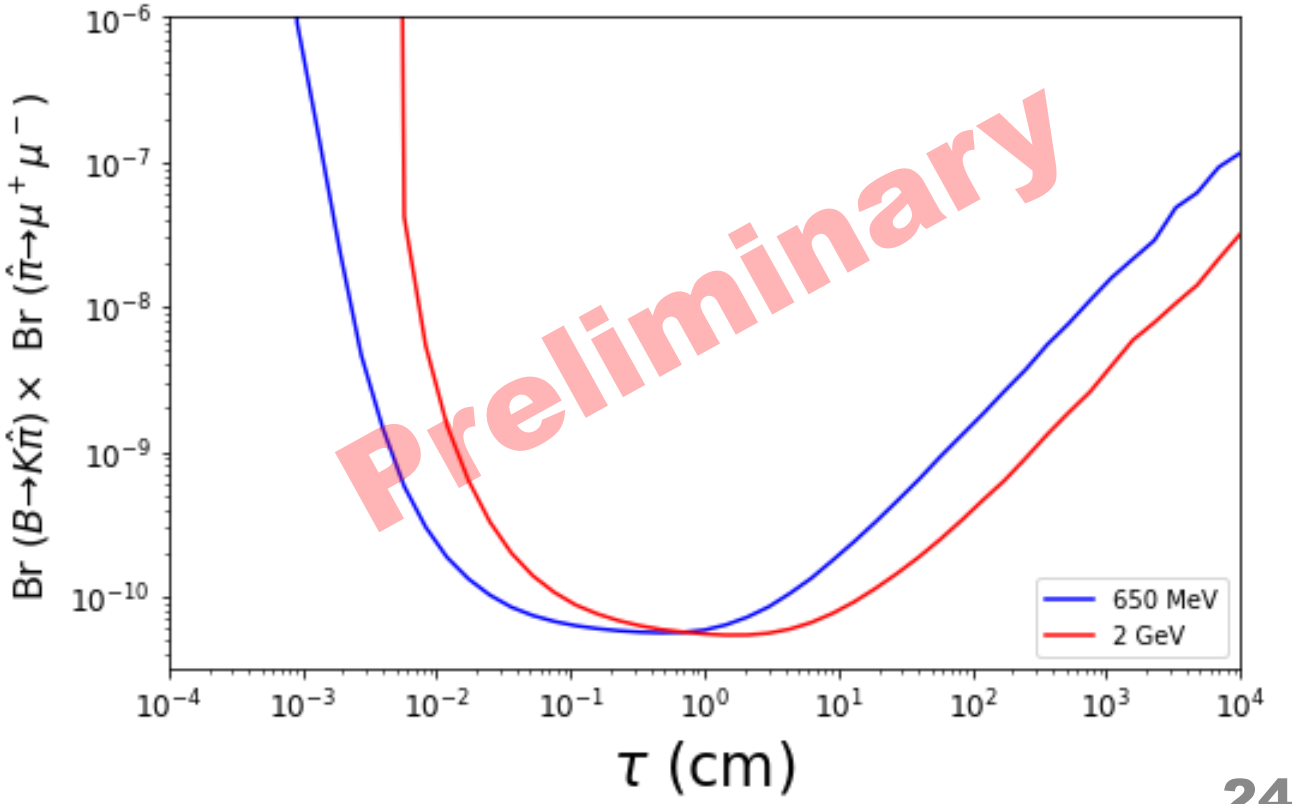
## 11.2 Light BSM states produced from FCNC quark decays




Dark sector from τ decays

Anson Kwok et al., in prep

Long lived particle from B FCNC rare decays Xuhui Jiang et al., in prep.



# 5 Hadronic $b$ Decays and $CP$ Violation Measurements

## 5.1 Theoretical Interpretation (preliminary)

## 5 Measuring $CP$ Asymmetries

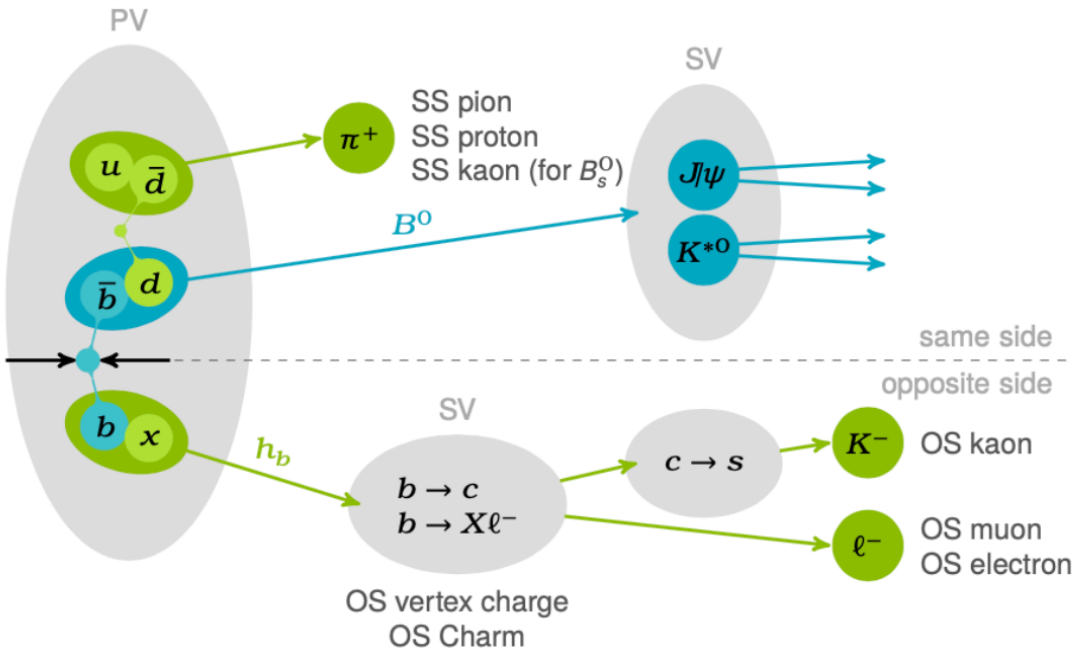


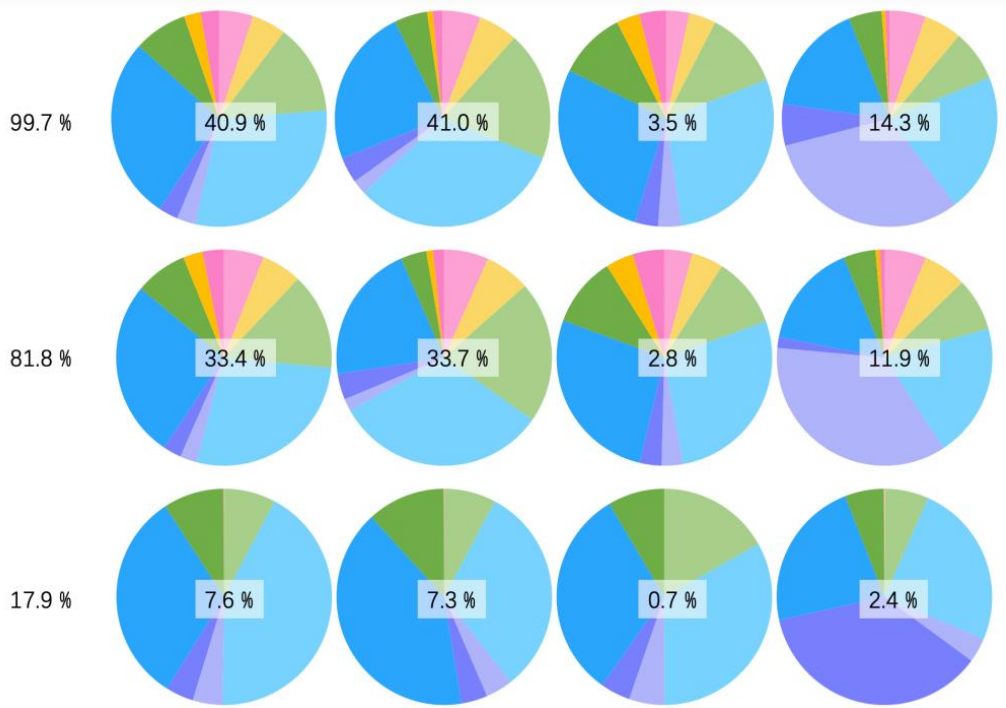
Taken from HFLAV2019

# 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)

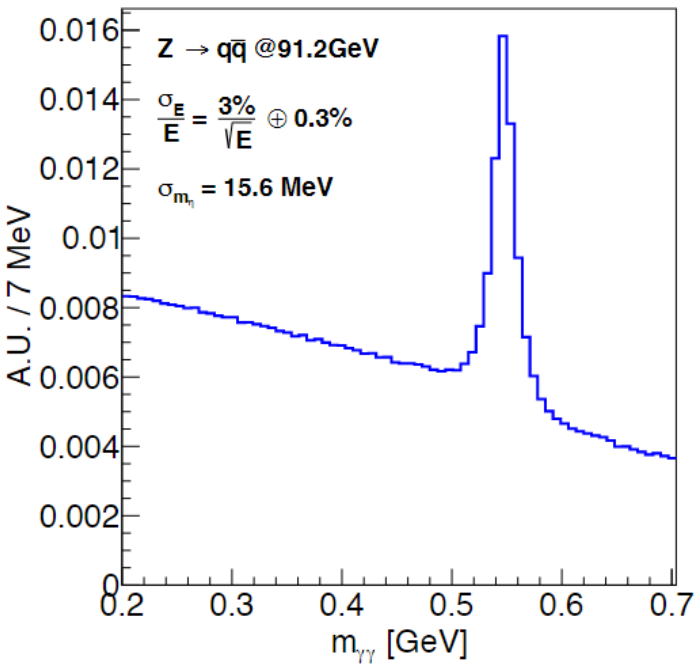


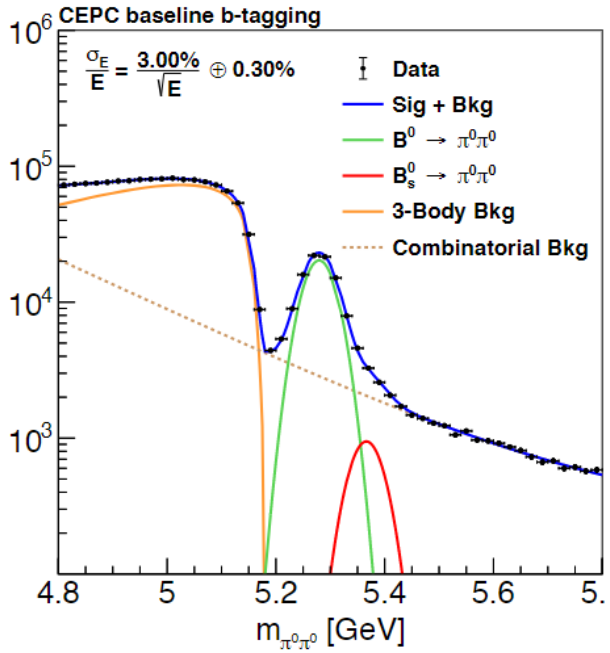



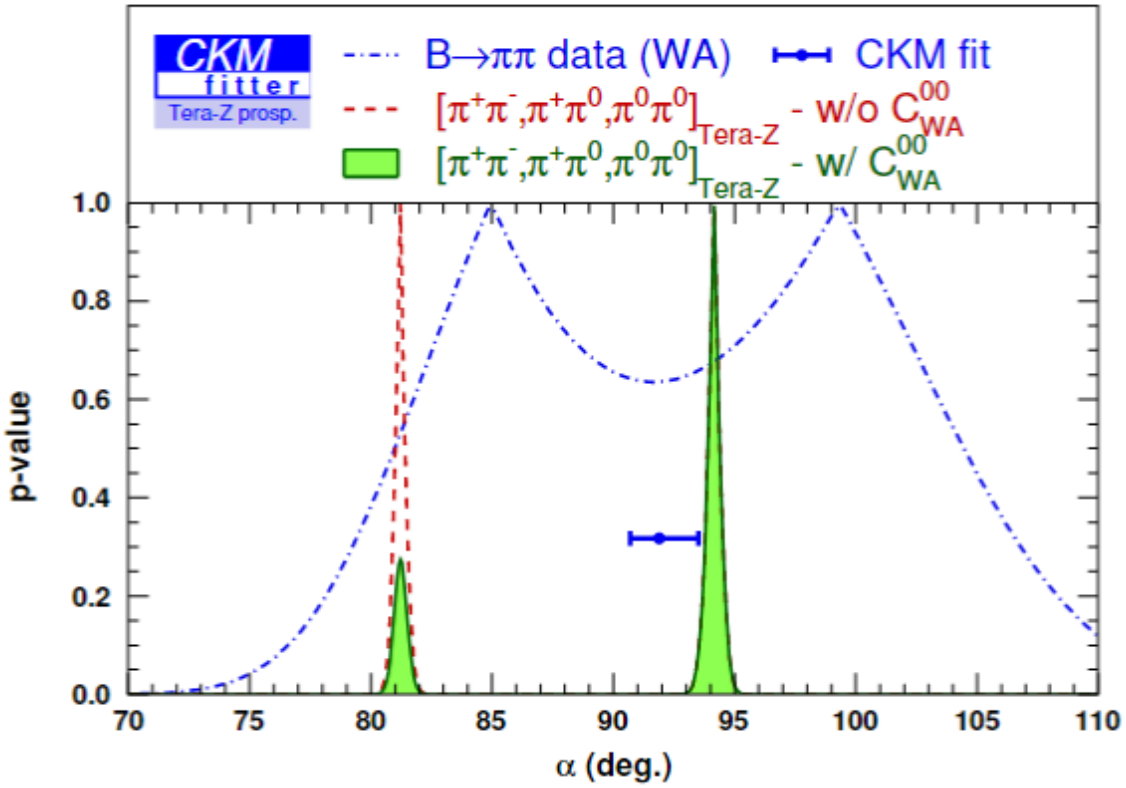

Tagging strategys are similar to LEP and LHCb

Preliminary study on going

# Time-Integrated CP Asymmetry



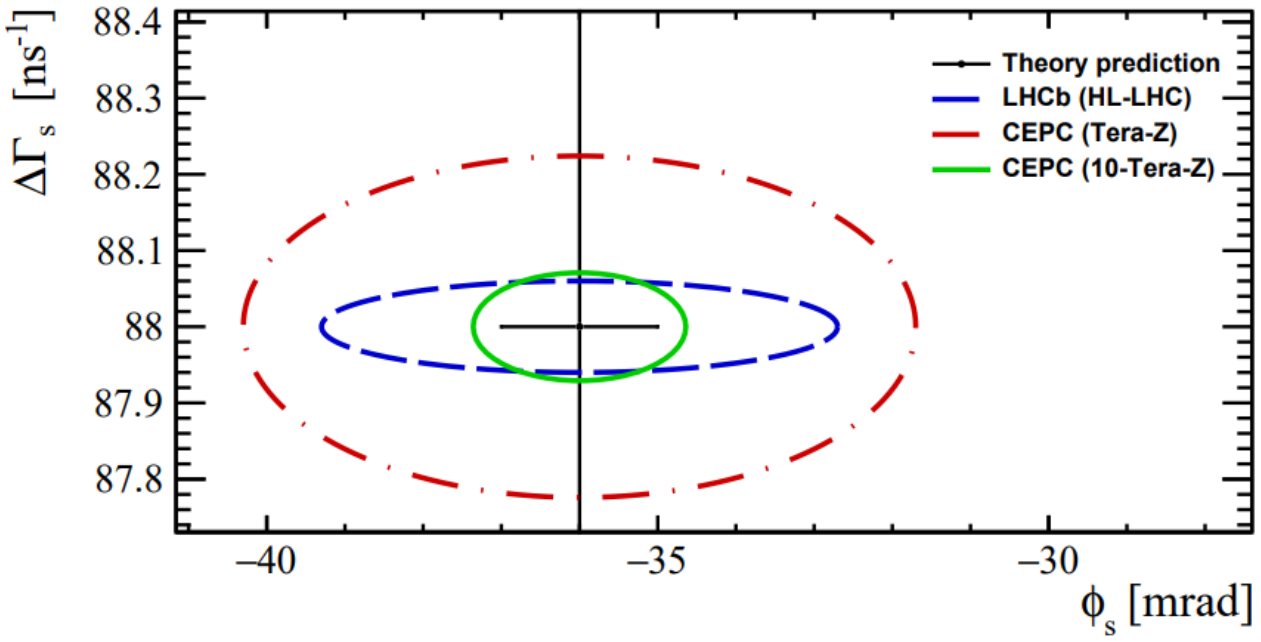

[Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan]

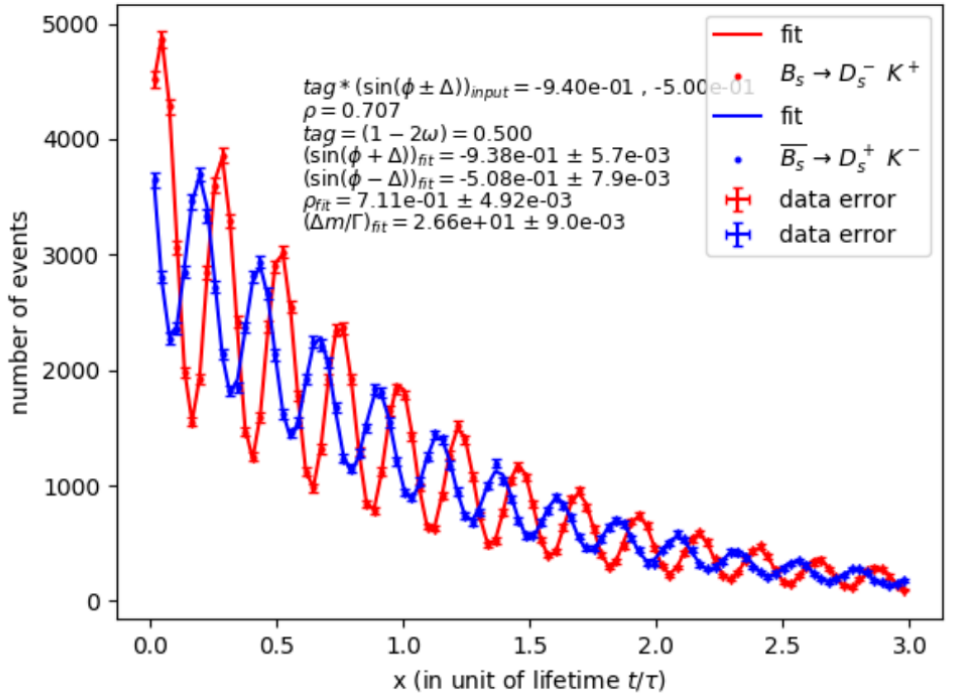
See also: [J. Charles, S. Descotes-Genon, Zoltan Ligeti, S. Monteil, M. Papucci, K. Trabelsi, L. Silva, 2006.04824]

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 $\beta_s$ measurement by time-dependent $B_s \to J/\psi\phi \to \mu\mu KK$

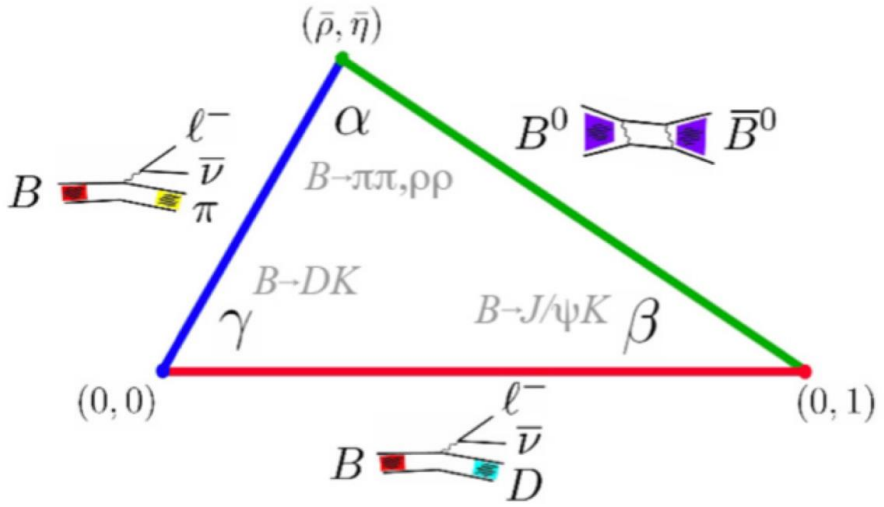
See also [R. Aleksan, L. Oliver, 2205.07823](#)

Time-dependent measurement of $B \to DK$ to give $\alpha_s$ and $\beta_s$, helpful to fix the value of angle $\gamma$

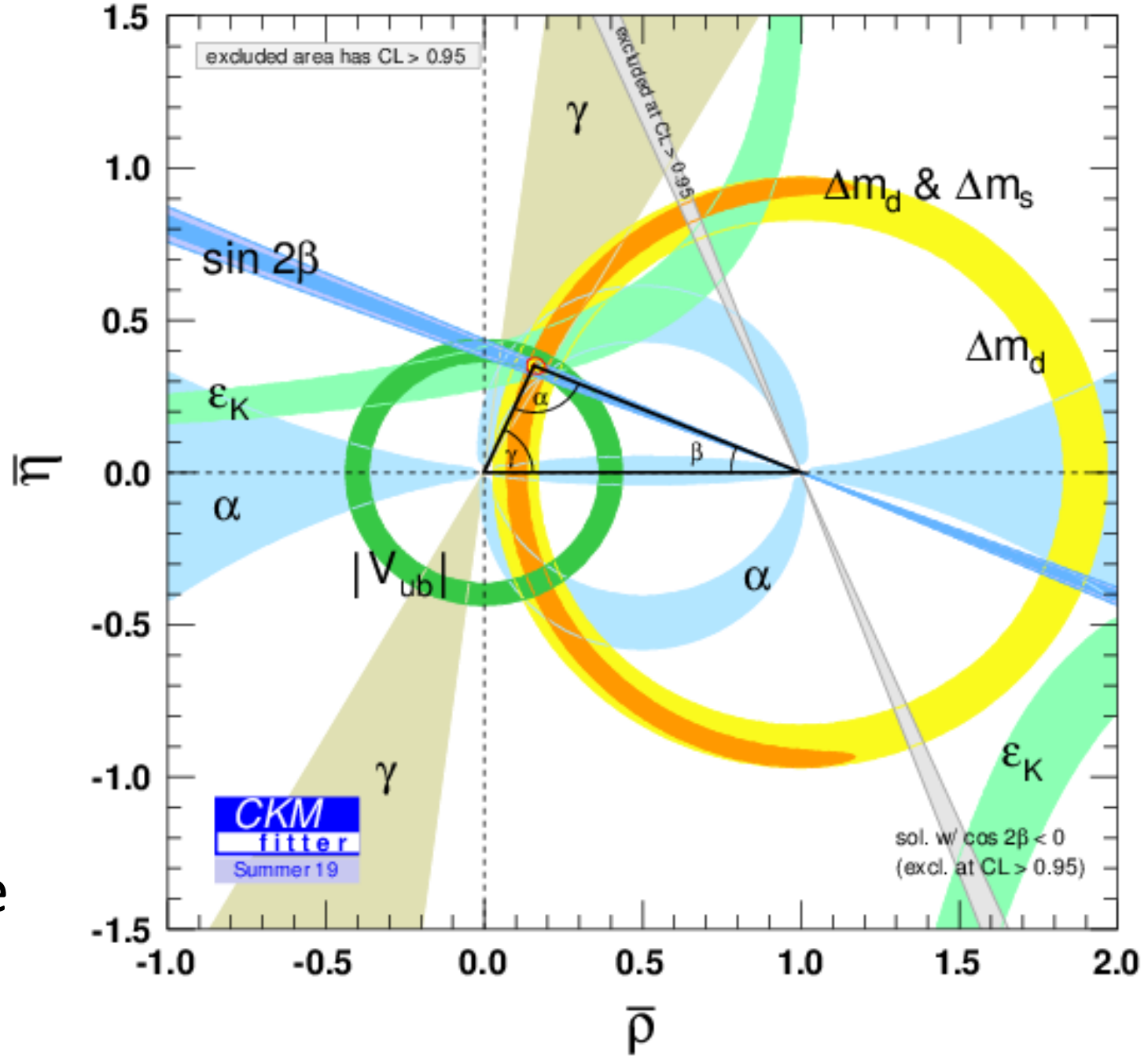
[R. Aleksan, L. Oliver, E. Perez, 2107.02002](#)
[R. Aleksan, L. Oliver, E. Perez, 2107.05311](#)

# Potential Advantages?

- Asymmetry closer to LHCb instead of B factories
- Time resolution and PID
- Access to heavier b-hadrons




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



# Summary

- Flavor program at CEPC is a healthy/urgent need
- Atypical layout for a flavor document due to inputs
- https://www.overleaf.com/project/628f0728edf9ab937611359c

*"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."*