New Flavor Opportunaties at a Future ee Collider

1000,000,000,000+

As a Tera - Z+

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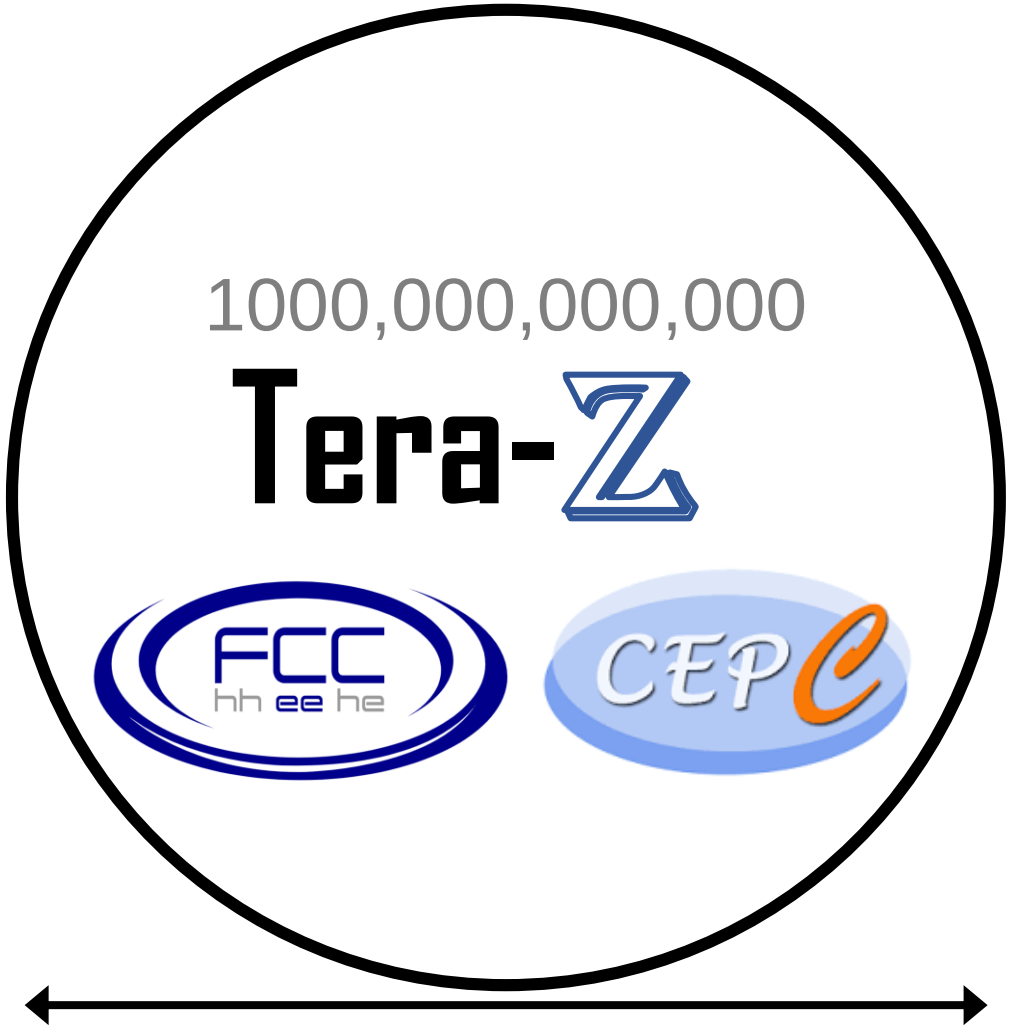
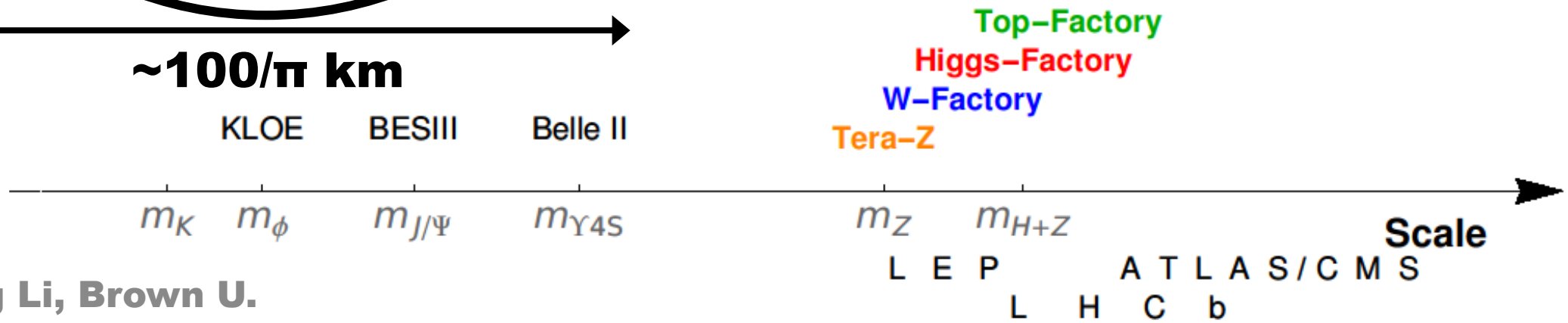
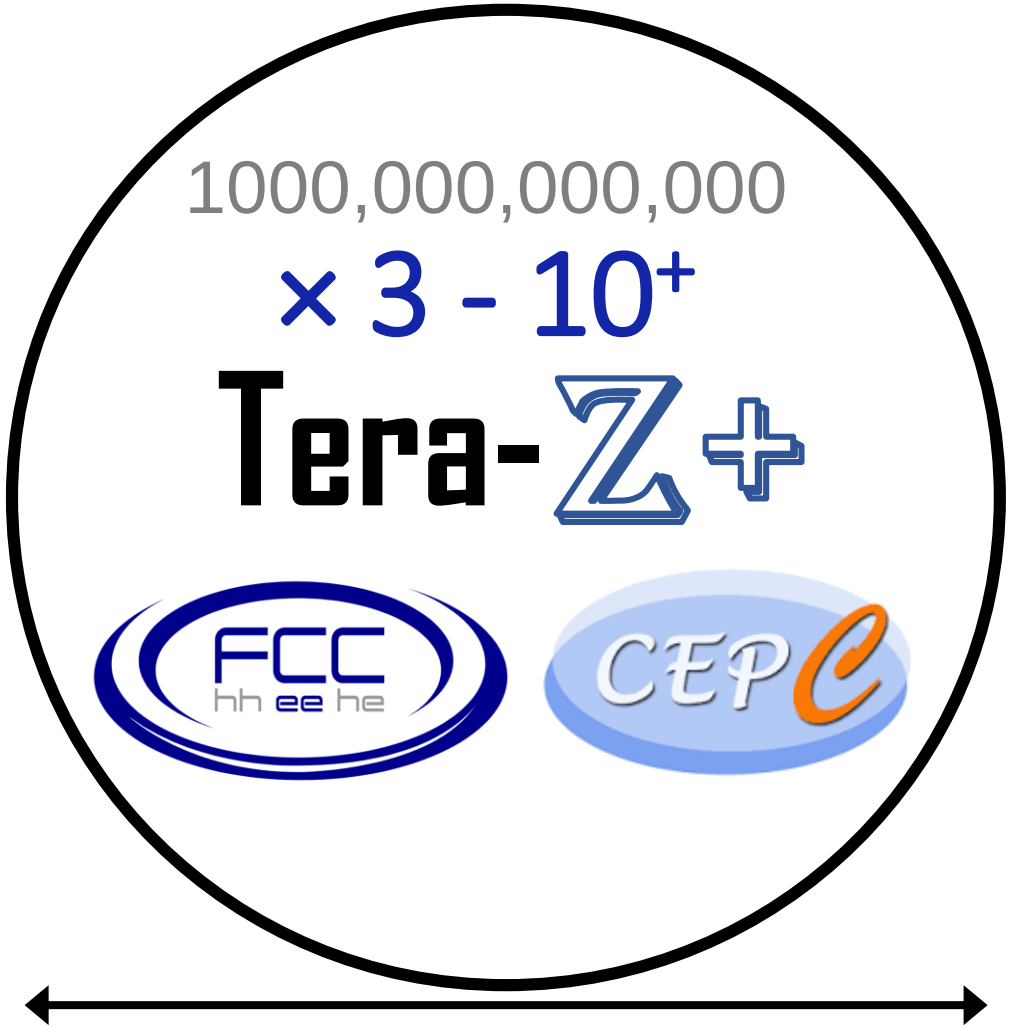
Dec. 11, 2022 HFCPV 2022



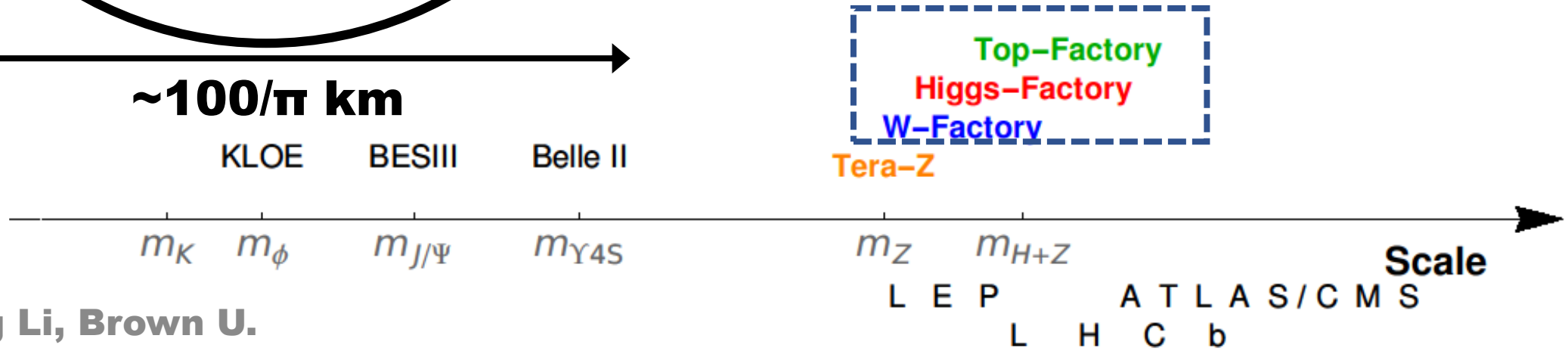
- Clean lepton collider (good for ν, γ, τ, e … Big advantages vs. hadronic ones)
- $O(10^{11+})$ b/c/τ (> B-factory of 50 ab^{-1})
- Generates all kinds of hadrons (B_c, Λ_b, T_{bb}…)
- Large energy (20-45 GeV) and boost for precision measurements
- Most advanced tech. infused detectors





- 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)



Great ways to probe new physics
Great prize awaits?

Still a lot to understand
even we can write down $\mathcal{L}_{\rm SM}$

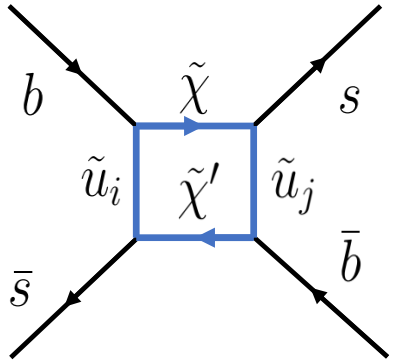
Flavor and New Physics

Heavy flavors (b, c, and τ) are long-lived particle, width < 10^{-11} GeV ≪ mass:

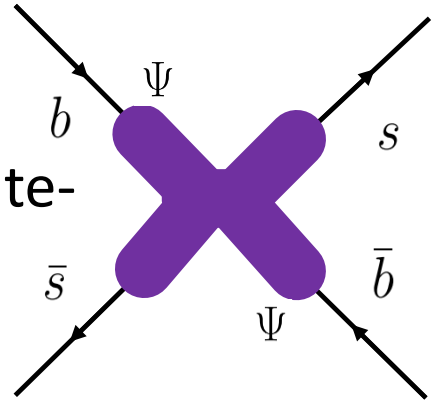
$$\Gamma_{\rm SM} \sim \frac{G_F^2 m_f^5}{192\pi^3} \times \text{const} \propto \frac{m_f^5}{m_W^4} \ .$$

$$\Gamma_{\rm BSM} \propto \frac{m_f^5}{\Lambda_{\rm NP}^2 m_W^2} \text{ (w/ interference), or } \frac{m_f^5}{\Lambda_{\rm NP}^4} \text{ (w/o interference)}$$

SUSY-like

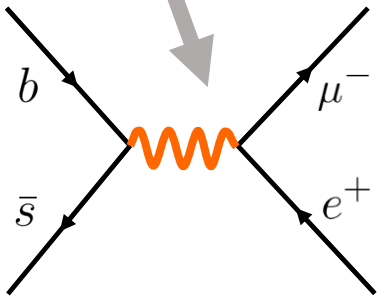


Composite-like



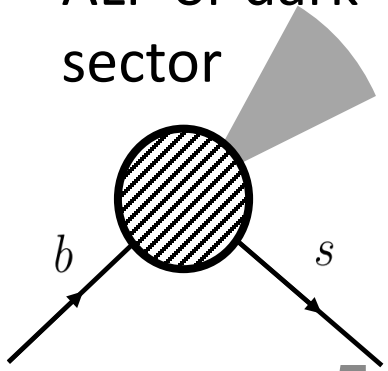
$$\left(\frac{m_W^2}{\Lambda_{\rm NP}^2} \text{ or } \frac{m_W^4}{\Lambda_{\rm NP}^4} \gg \frac{m_f^4}{\Lambda_{\rm NP}^4}\right)$$

Large rates with moderate suppression



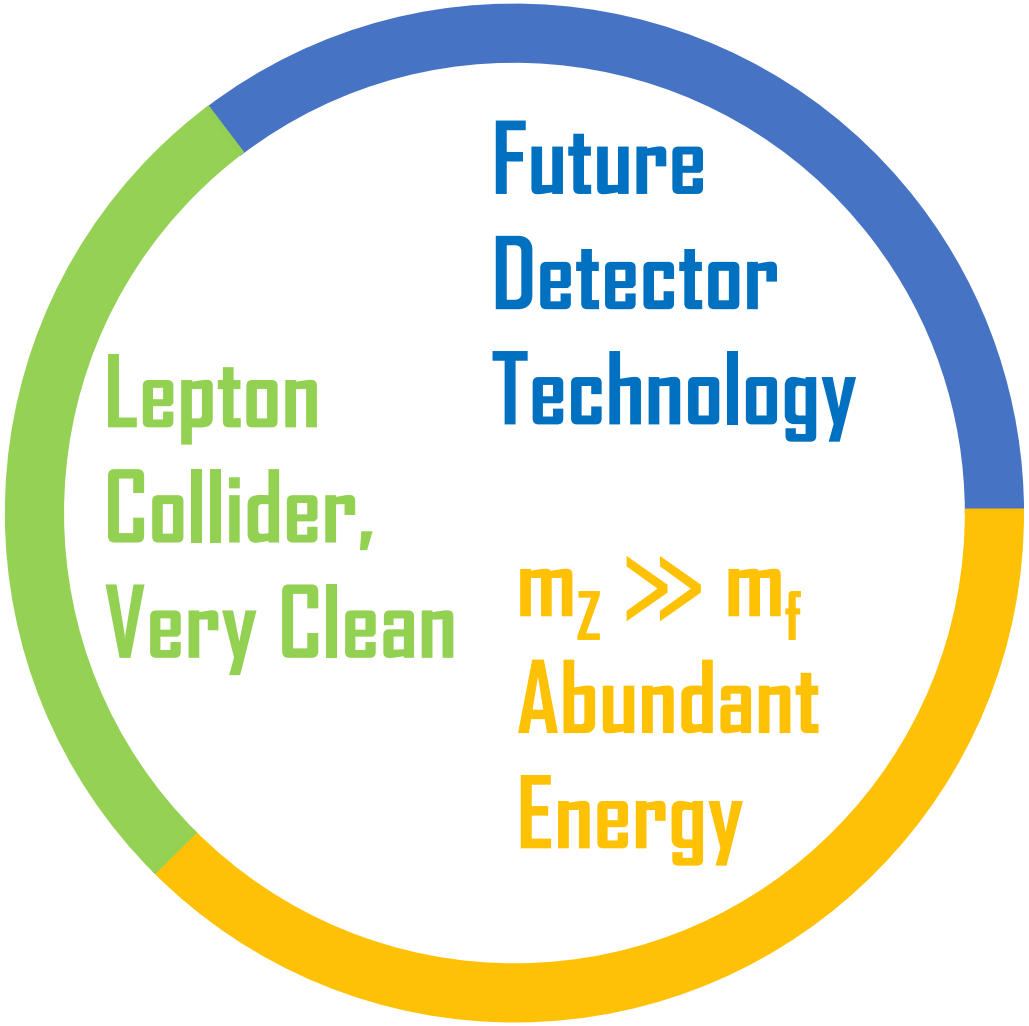
Lepton Flavor Violation

ALP or dark sector



Recognizing "Golden" Modes

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



- Baryonic tracks
- Electron and Muon
- $b \to c \to \tau$ cascade
- Long-lived particles

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

Recent Progress

Disclaimer: *Priorities are given to numerical results with (fast or full) simulations in stead of theoretical works.*

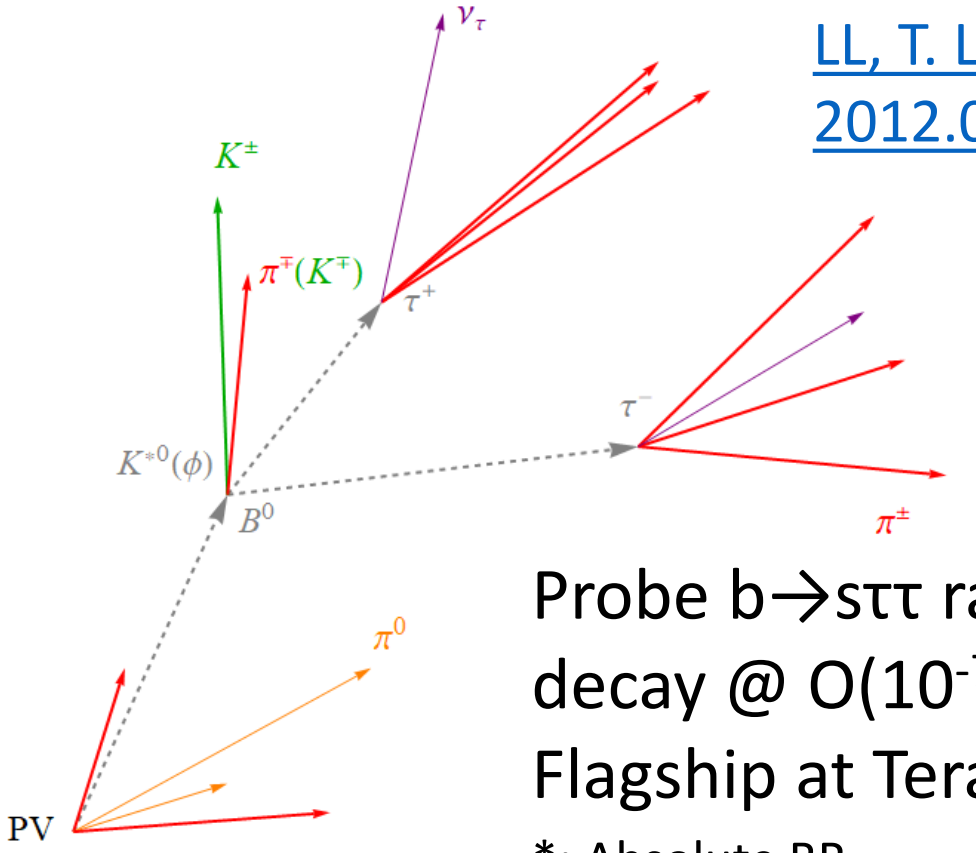
Apologize for any missing contributions due to personal ignorance and prejudice.

CEPC Flavor White Paper (Ongoing)

Taken from the flavor physics white paper (in preparation)

Heavy Quark Weak Decays (FCNC)

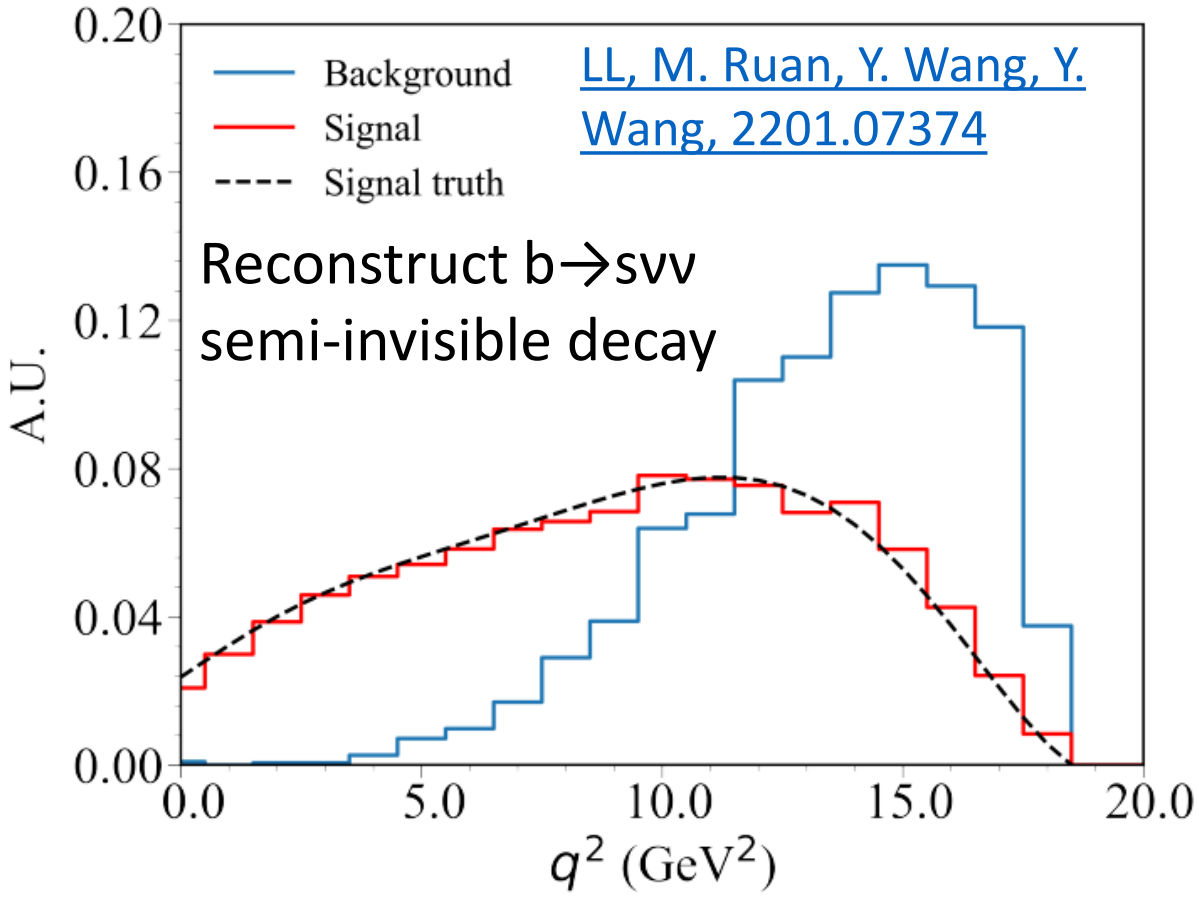
- Rare decays, sensitive to BSM
- Partially motivated by R_K and R_{K^*} anomalies



LL, T. Liu, 2012.00665

Probe b→sττ rare decay @ $O(10^{-7})$*
Flagship at Tera-Z

*: Absolute BR



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

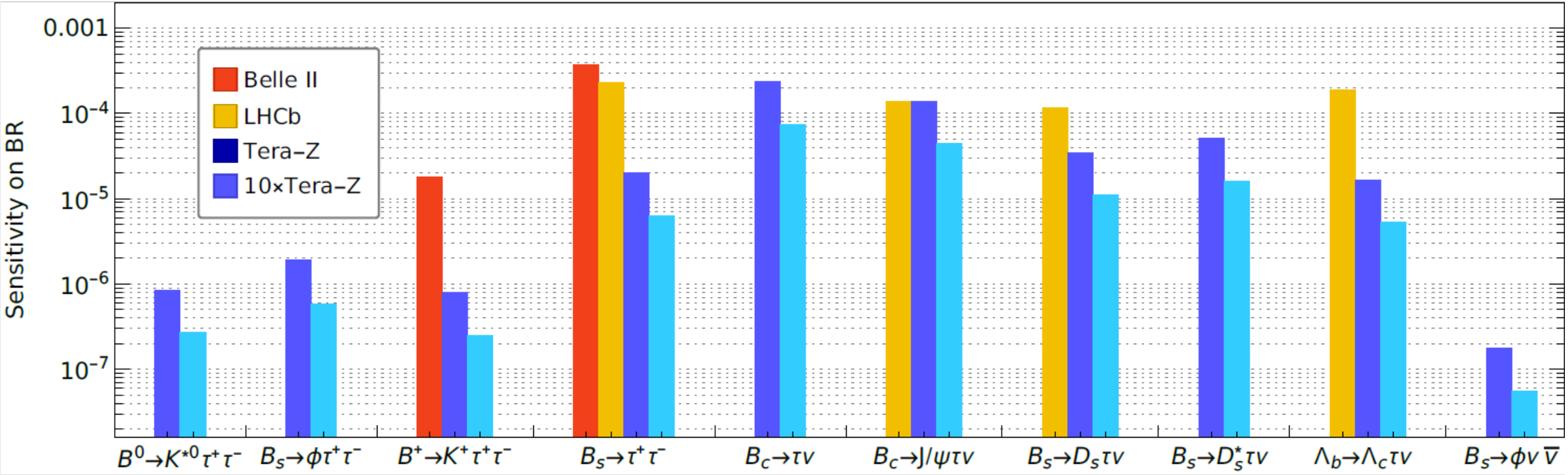
See also:
S. Descotes-Genon, S. Fajfer, J. Kamenik, M. Novoa-Brunet 2208.10880

Heavy Quark Weak Decays (FCCC)

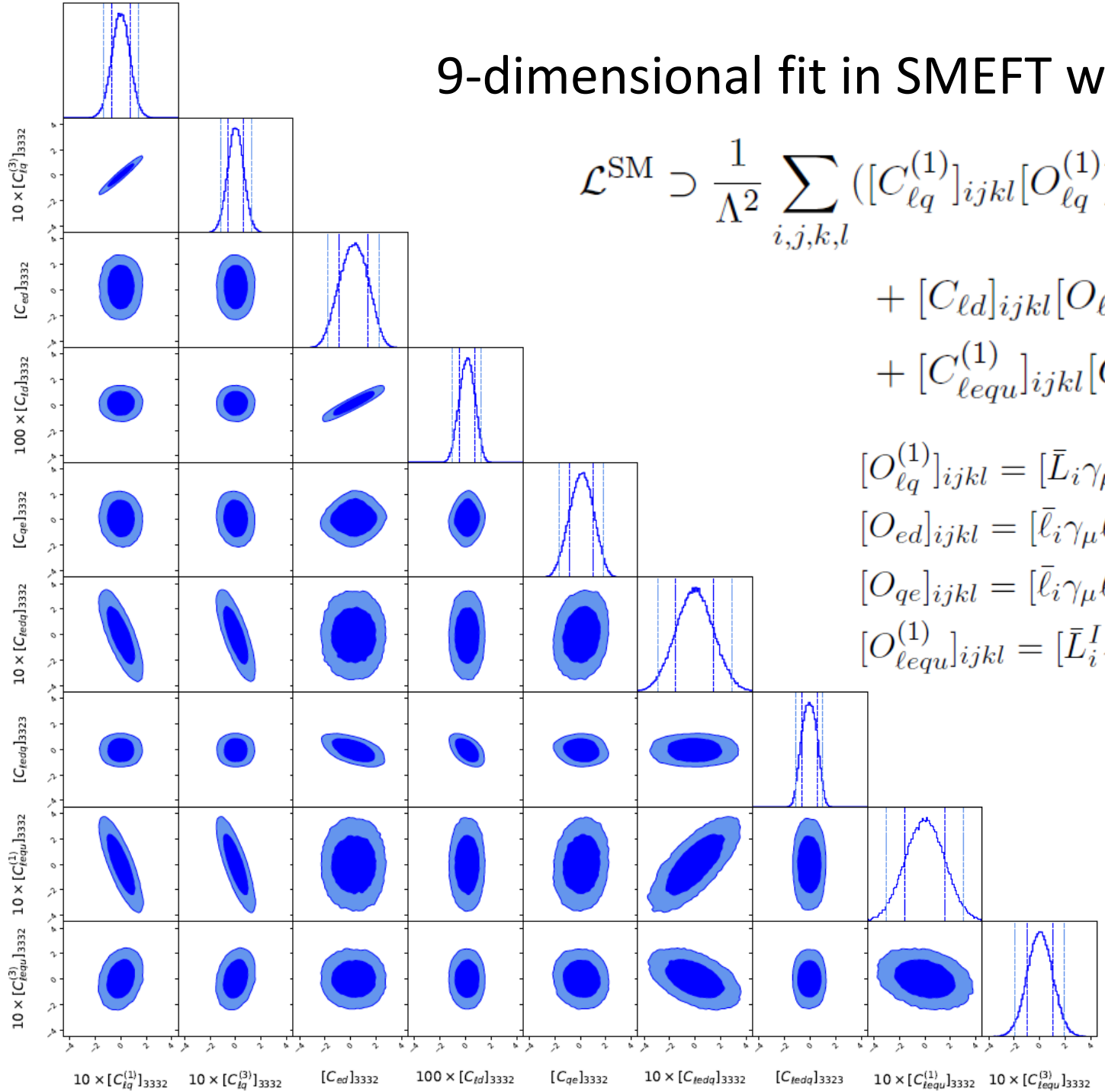
See also
Y. Amhis, M. Hartmann, C. Helsens D. Hill, O. Sumensari 2105.13330
T. Zheng, J. Xu, L. Cao, D. Yu, W. Wang et al., 2007.08234

M. Ho, T.H. Kwok, X. Jiang, LL, Tao Liu, 2212.02433

- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- Current focus: (Semi)leptonic modes



9-dimensional fit in SMEFT with effectively 9 LFUV observables



$$\mathcal{L}^{\rm SM} \supset \frac{1}{\Lambda^2} \sum_{i,j,k,l} \Big([C_{\ell q}^{(1)}]_{ijkl} [O_{\ell q}^{(1)}]_{ijkl} + [C_{\ell q}^{(3)}]_{ijkl} [O_{\ell q}^{(3)}]_{ijkl} + [C_{ed}]_{ijkl} [O_{ed}]_{ijkl}$$

$$+ [C_{\ell d}]_{ijkl} [O_{\ell d}]_{ijkl} + [C_{qe}]_{ijkl} [O_{qe}]_{ijkl} + [C_{\ell edq}]_{ijkl} [O_{\ell edq}]_{ijkl}$$

$$+ [C_{\ell equ}^{(1)}]_{ijkl} [O_{\ell equ}^{(1)}]_{ijkl} + [C_{\ell equ}^{(3)}]_{ijkl} [O_{\ell equ}^{(3)}]_{ijkl} \Big) + \text{h.c.} \ ,$$

$$[O_{\ell q}^{(1)}]_{ijkl} = [\bar{L}_i \gamma_\mu L_j][\bar{Q}_k \gamma^\mu Q_l] \ , \qquad [O_{\ell q}^{(3)}]_{ijkl} = [\bar{L}_i \gamma_\mu \sigma^a L_j][\bar{Q}_k \gamma^\mu \sigma^a Q_l] \ ,$$

$$[O_{ed}]_{ijkl} = [\bar{\ell}_i \gamma_\mu \ell_j][\bar{d}_k \gamma^\mu d_l] \ , \qquad [O_{\ell d}]_{ijkl} = [\bar{L}_i \gamma_\mu L_j][\bar{d}_k \gamma^\mu d_l] \ ,$$

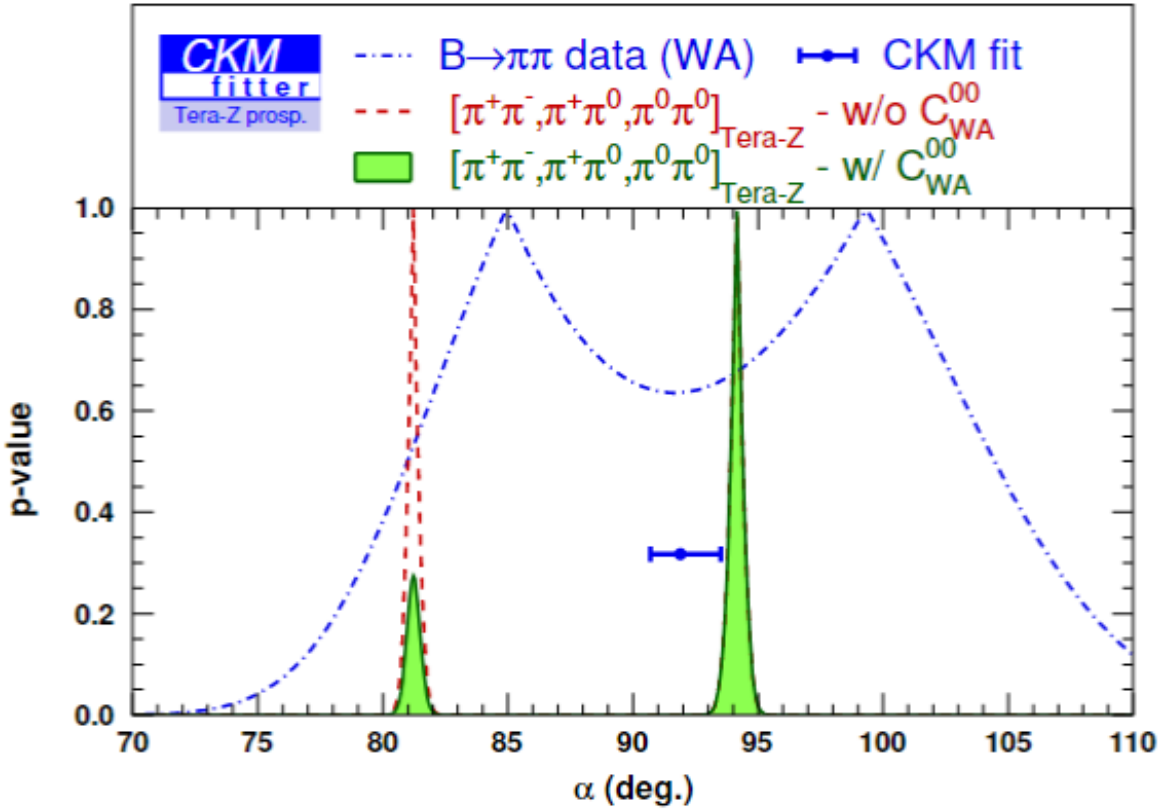
$$[O_{qe}]_{ijkl} = [\bar{\ell}_i \gamma_\mu \ell_j][\bar{Q}_k \gamma^\mu Q_l] \ , \qquad [O_{\ell edq}]_{ijkl} = [\bar{L}_i^I \ell_j][\bar{d}_k Q_l^I] \ ,$$

$$[O_{\ell equ}^{(1)}]_{ijkl} = [\bar{L}_i^I \ell_j] \epsilon_{IJ} [\bar{Q}_k^J u_l] \ , \qquad [O_{\ell equ}^{(3)}]_{ijkl} = [\bar{L}_i^I \sigma_{\mu\nu} \ell_j] \epsilon_{IJ} [\bar{Q}_k^J \sigma^{\mu\nu} u_l] \ ,$$

Probing O(10) TeV BSM or higher

CPV

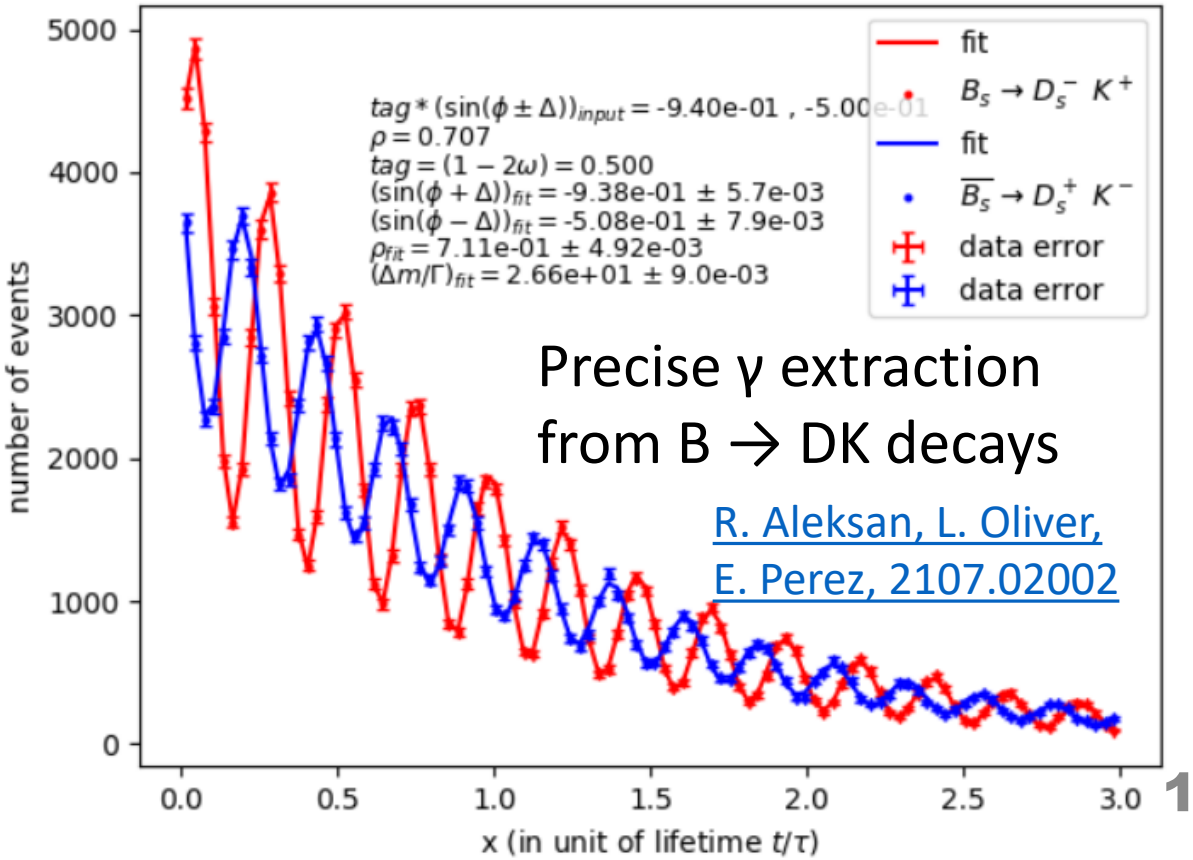
- Multiple new ways of measurement
- Current focus: B decays



Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan, In prep

Measure CKM α down to O(0.4) degree, Removing mirror solutions

See also: J. Charles, S. Descotes-Genon, Zoltan Ligeti, S. Monteil, M. Papucci, K. Trabelsi, L. Silva, 2006.04824
R. Aleksan, L. Oliver, E. Perez, 2107.05311
X. Li, M Ruan, M. Zhao, 2205.10565

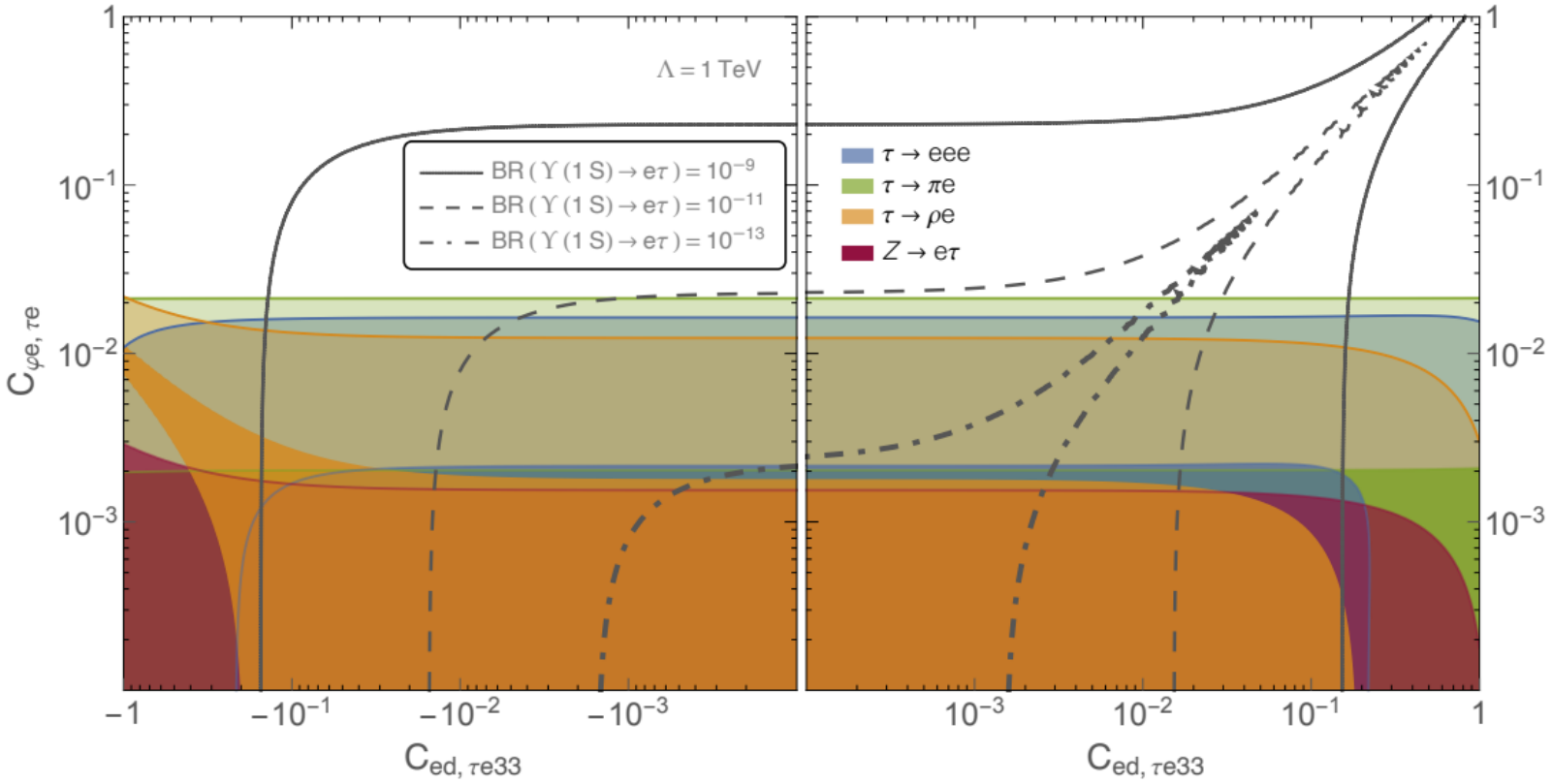


Precise γ extraction from B → DK decays

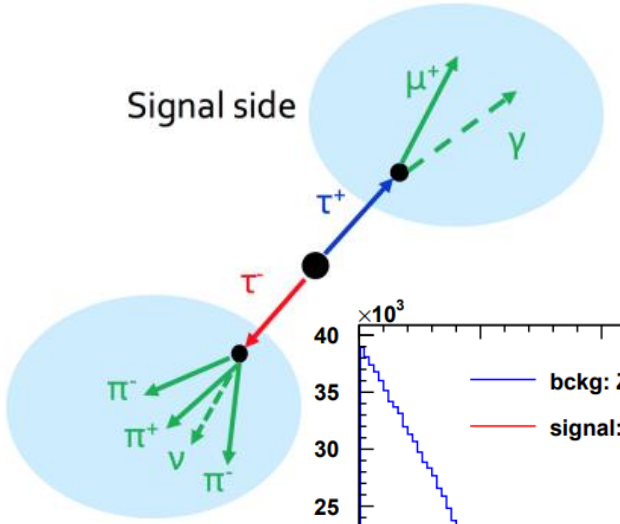
R. Aleksan, L. Oliver, E. Perez, 2107.02002

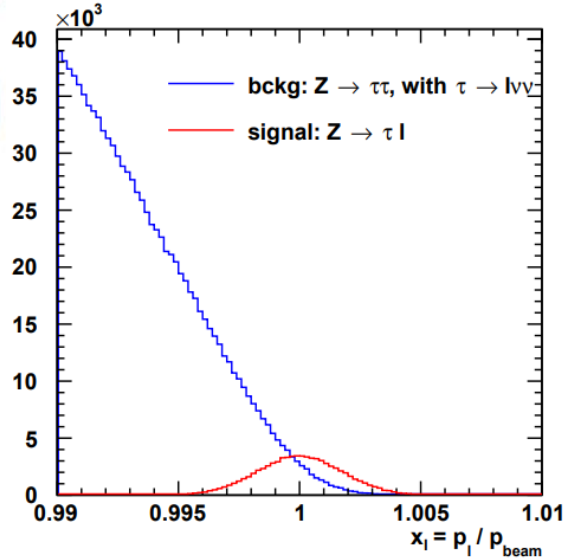
Tau and Lepton Sector

- A most powerful tau machine
- Current focus: charged lepton flavor violation (cLFV)



L. Calibbi, T. Li, X. Marcano, M.A. Schmidt, 2207.10913





M. Dam, 1811.09408

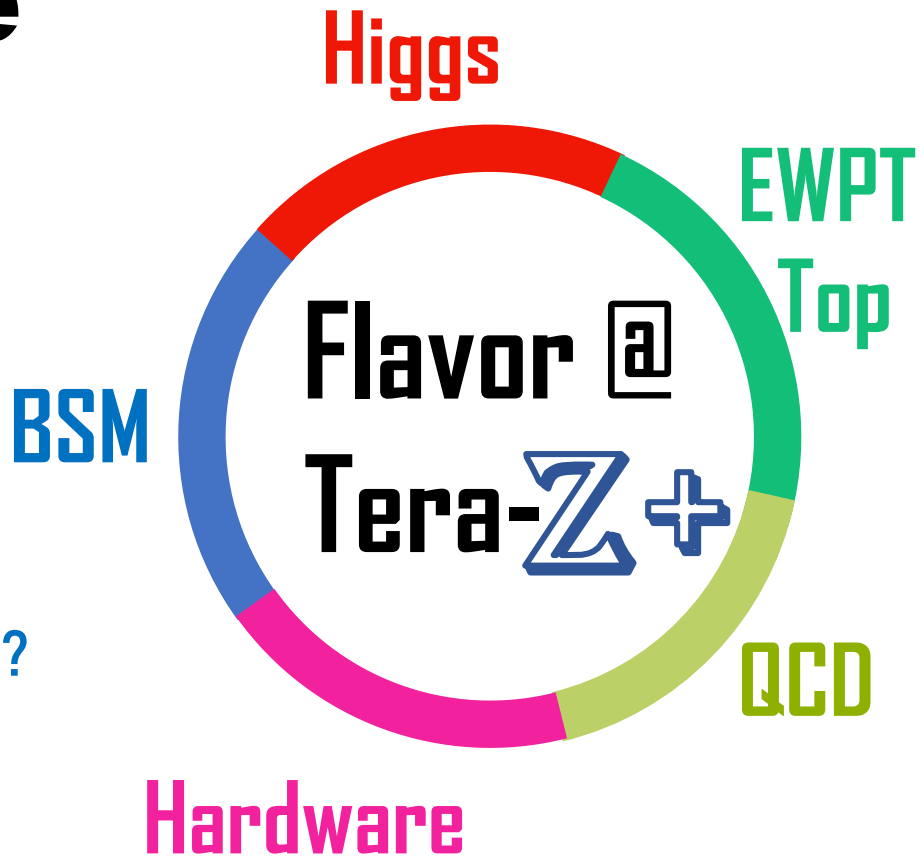
Complementarity between Z pole, quarkonia, and lepton cLFV decays

See also: L. Calibbi, X. Marcano, J. Roy, 2107.10273
M. Dam, 2107.12832

Summary: A flavor-centric perspective

- ❑ 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!