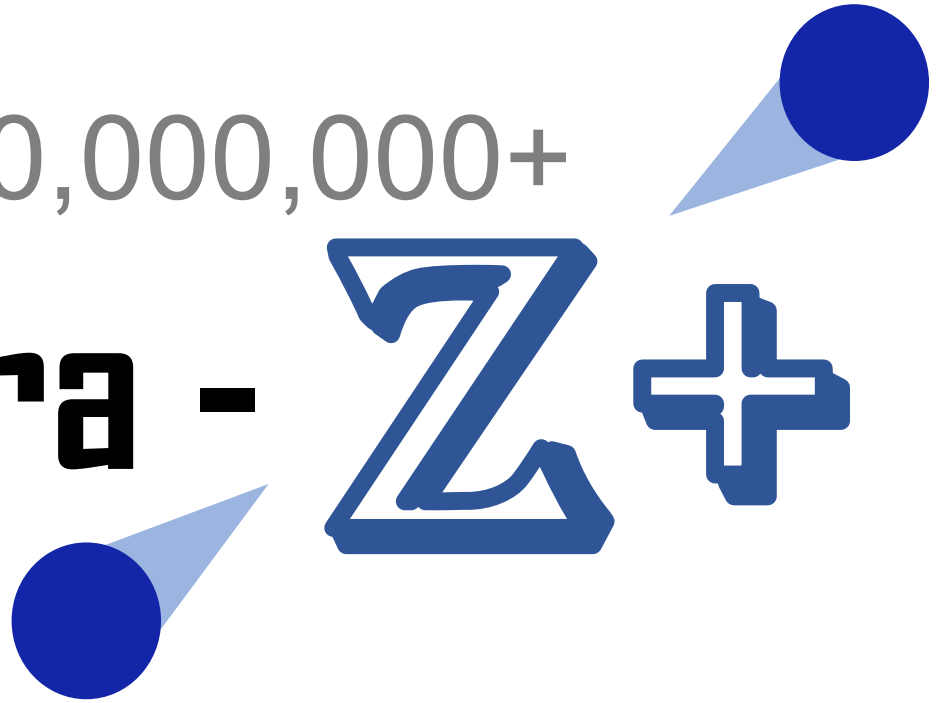
Flavor physics at Future Circular Lepton Collider

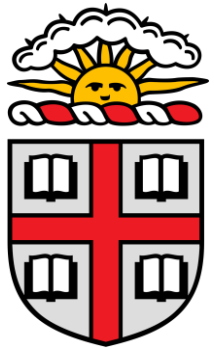
1000,000,000,000+

As a Tera - Z+



Lingfeng Li, Brown U. Sep. 12, 2022

ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders



Prologue

"Don't just leave flavor physics to flavor physicists."

[Someone Awesome, 2019?]

"Non-flavor physicists must be amused first."

[me, 2022]

Tera-Z as a Z and Flavor Factory

b-hadrons	Belle II ($50+5$ ab^{-1})	LHCb (300 fb^{-1})	Tera-Z
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B^{\pm}$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	3.1×10^{10}
$B_c^{\pm}$	-	1×10^{11}	1.8×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}
$c(\bar{c})$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^{11}
$\tau^{\pm}$	9×10^{10}	-	7.4×10^{10}

1000,000,000,000

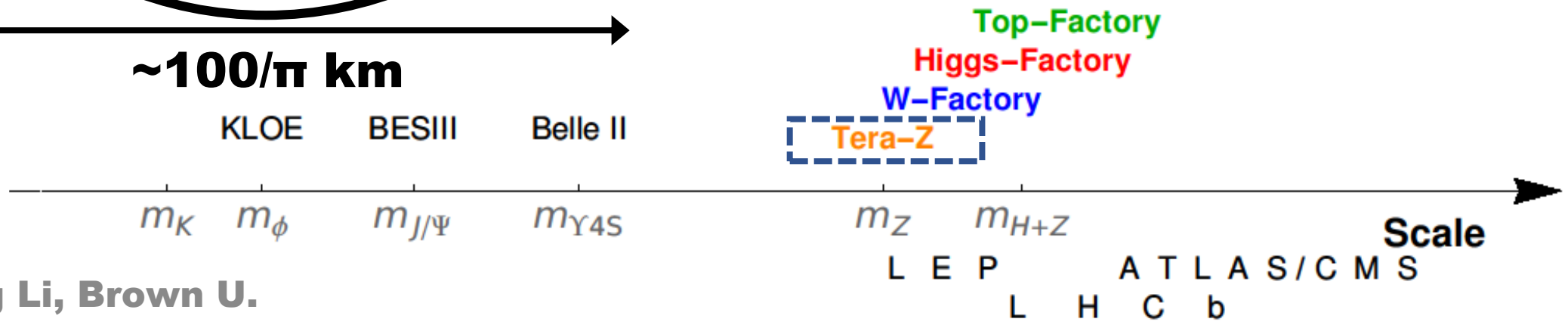
Tera-Z

FCC hh ee he

CEPC

~100/π km

- 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



1000,000,000,000

× 3 - 10+

Tera-Z+

FCC hh ee he

CEPC

~100/π km

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

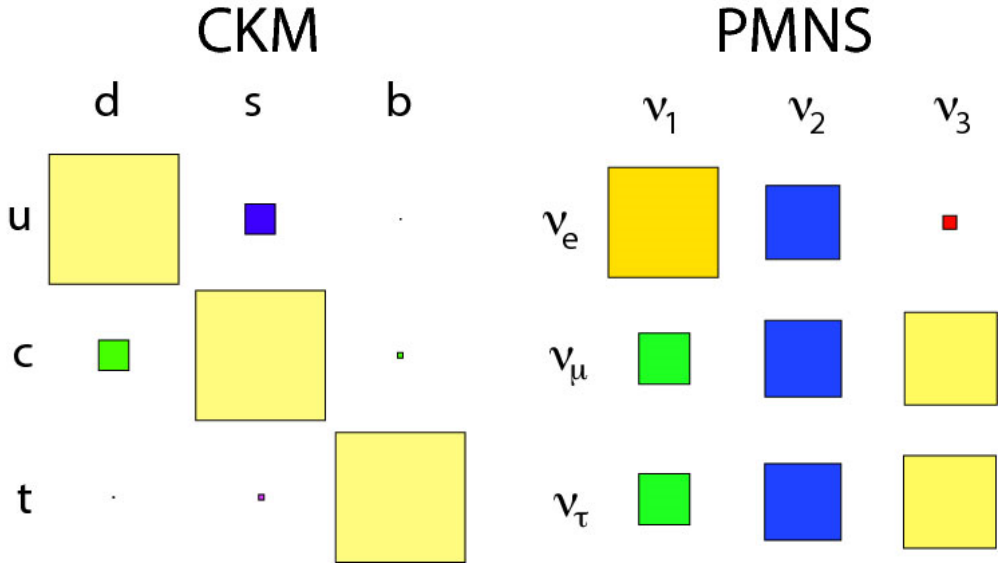
Flavor physics also need energy larger than 91 GeV
(e.g., $|V_{cb}|$ from W decays)

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

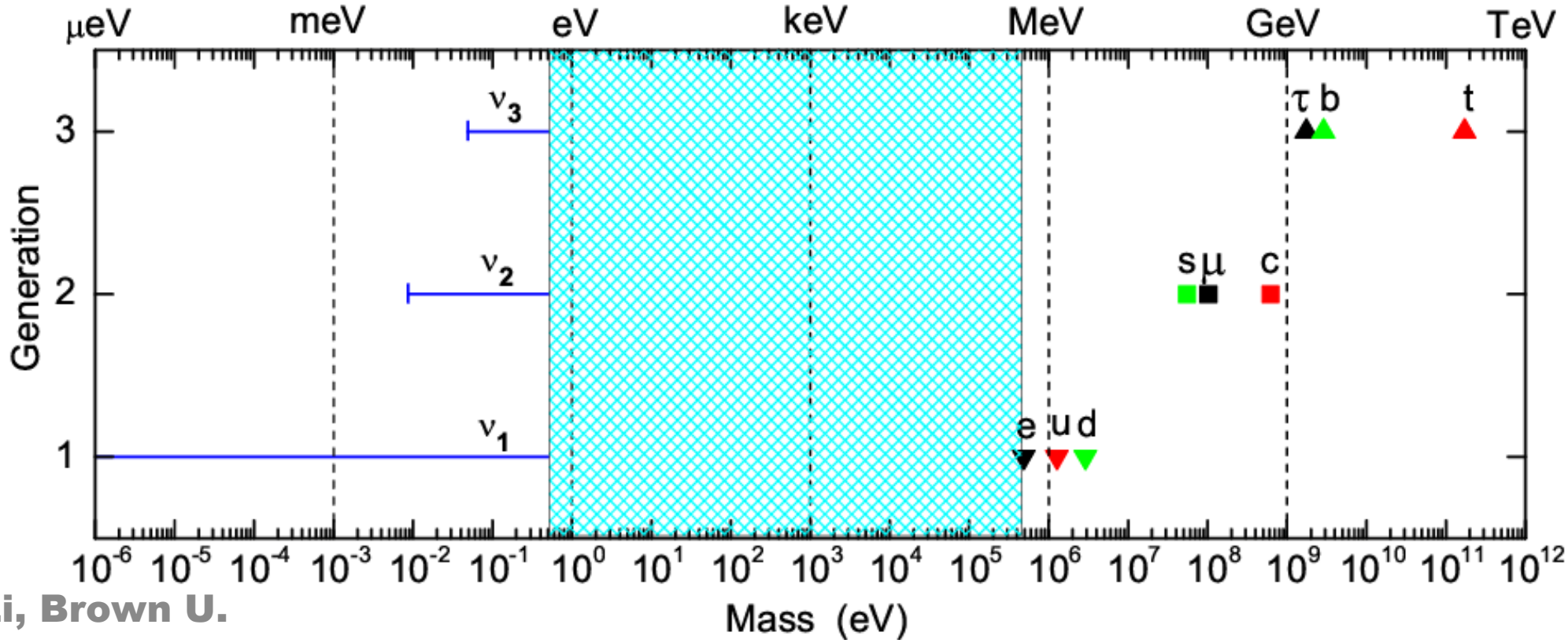
Great ways to probe new physics
Great prize awaits?

Who Ordered These?

Flavor mixing and CP violation patterns



Large flavor hierarchy



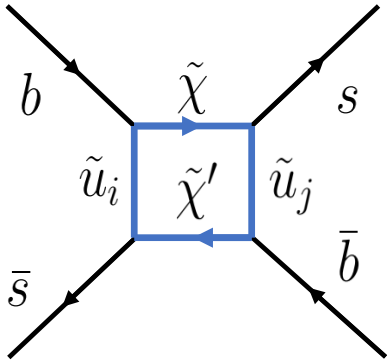
Flavor and New Physics

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

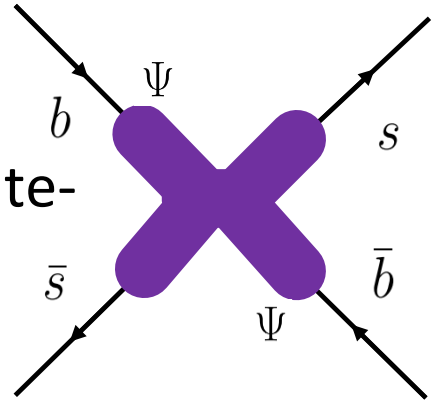
$$\Gamma_{\rm SM} \sim \frac{G_F^2 m_f^5}{192\pi^3} \times \text{const} \propto \frac{m_f^5}{m_W^4} \ .$$

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

SUSY-like

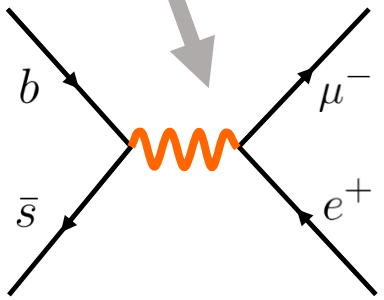


Composite-like



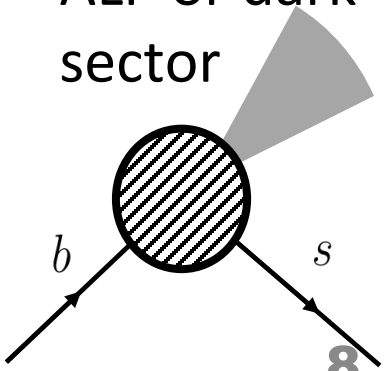
$$\left(\frac{m_W^2}{\Lambda_{\rm NP}^2} \text{ or } \frac{m_W^4}{\Lambda_{\rm NP}^4} \gg \frac{m_f^4}{\Lambda_{\rm NP}^4}\right)$$

Large rates with moderate suppression



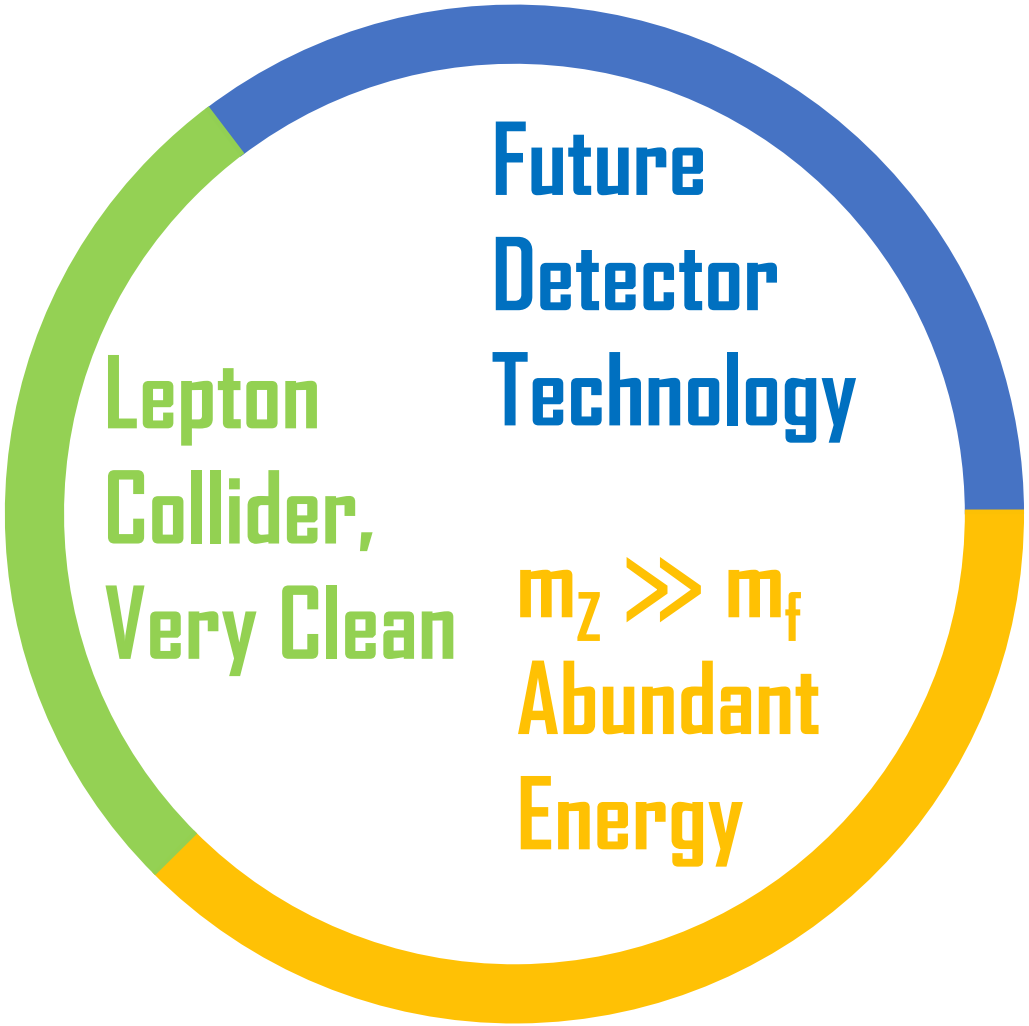
Lepton Flavor Violation

ALP or dark sector



Recognizing "Golden" Modes

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



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

- Boost: O(fs) time scales
- Heavy species: Bc, Λ_b, tetraquarks...
- 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.

Precision Flavor Measurements

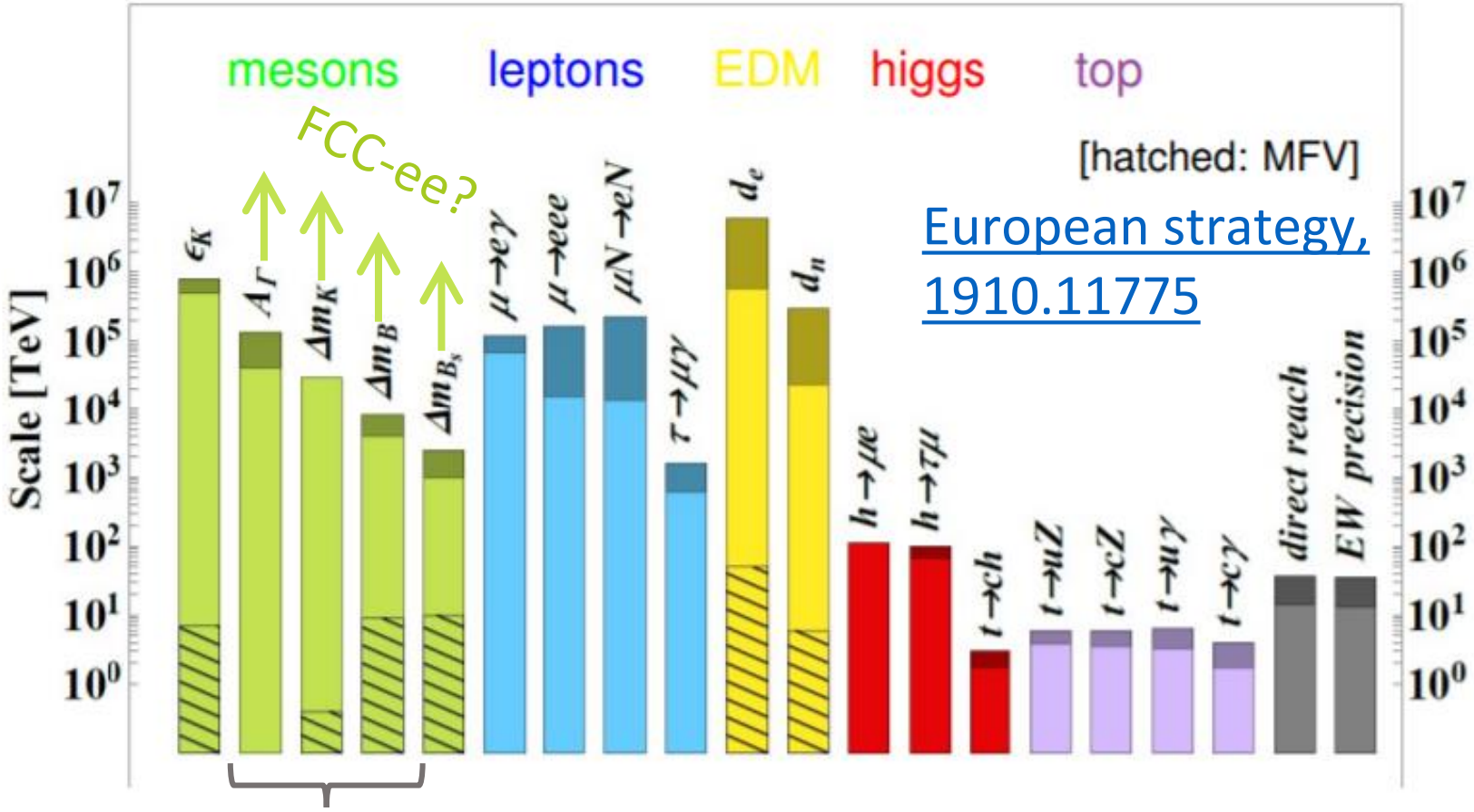
	Central values	Uncertainties: Current [18]	Phase I	Phase II	+FCC-ee Phase III
$\lvert V_{ud}\rvert$	0.97437	±0.00021	id	id	id
$\lvert V_{us}\rvert\, f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id
$\lvert V_{cd}\rvert$	0.2248	±0.0043	±0.003	id	id
$\lvert V_{cs}\rvert$	0.9735	±0.0094	id	id	id
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id
$\lvert V_{cb}\rvert_{\rm SL} \times 10^3$	42.26	±0.58	±0.60	±0.44	id
$\lvert V_{cb}\rvert_{W\to cb} \times 10^3$		—	—	—	±0.17
$\lvert V_{ub}\rvert_{\rm SL} \times 10^3$	3.56	±0.22	±0.042	±0.032	id
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.04	±0.02	±0.009
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	—	±0.03	±0.02	id
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008
α [°] (mod 180°)	91.9	±4.4	±0.6	id	id
γ [°] (mod 180°)	66.7	±5.6	±1	±0.25	±0.20
β_s [rad]	−0.035	±0.021	±0.014	±0.004	±0.002
$A_{\rm SL}^d \times 10^4$	−6	±19	±5	±2	±0.25
$A_{\rm SL}^s \times 10^5$	3	±300	±70	±30	±2.5

J. Charles, Z. Ligeti, S. Monteil, M. Papucci et al., 2006.04824

Lot's of unknown values (identical to previous phases) in the Tera-Z era
Expect improvements?

Also many values to be verified (may need more simulations)
Both stat. and syst.

Precision Flavor Measurements (II)

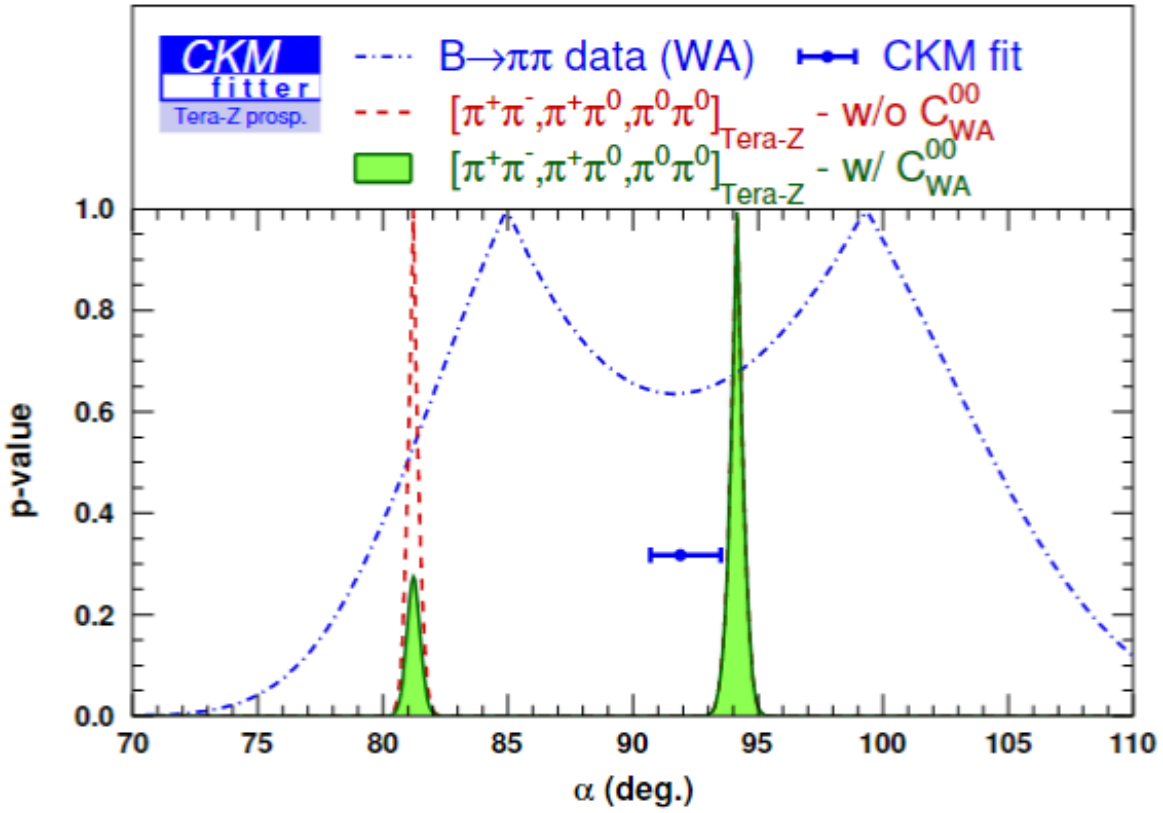


Probing high BSM scales with ΔF=2 measurements (future Belle II + LHCb)

See Luca Selvistrini's talk & J. Charles, Z. Ligeti, S. Monteil, M. Papucci et al., 2006.04824 for more details

CPV Angles

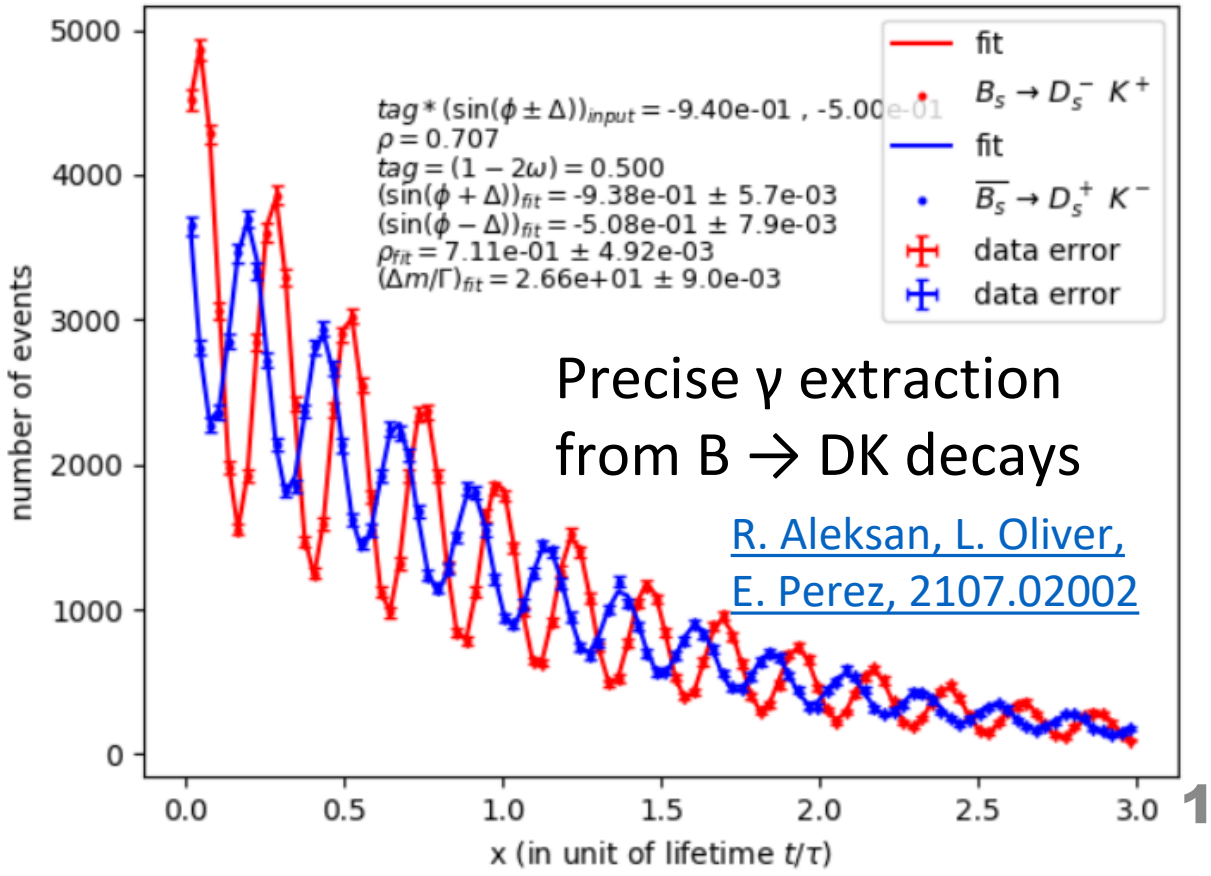
- Multiple new ways of measurement
- Current focus: B decays



↑: Measurement of α using $B\to\pi^0\pi^0\to4\gamma$ (!)
Removing mirror solutions

Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan, 2208.08237

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

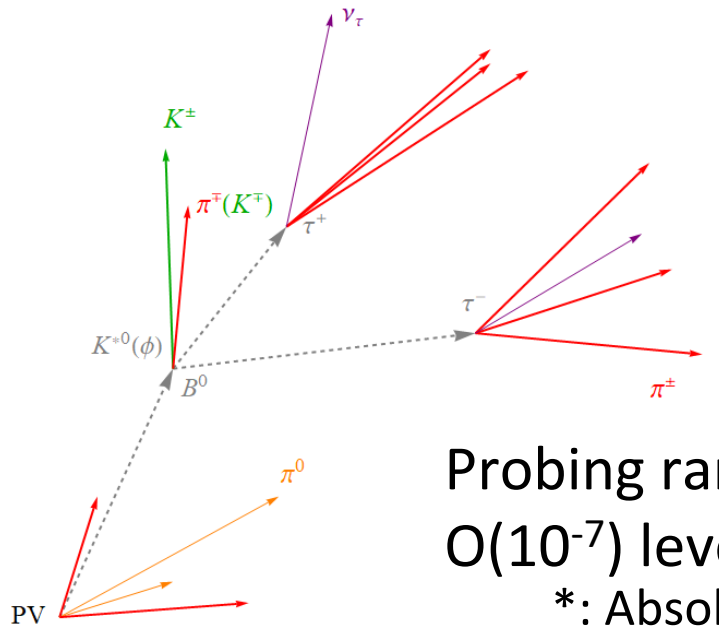


Precise γ extraction from B → DK decays

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

FCNC: Dileptonic Modes

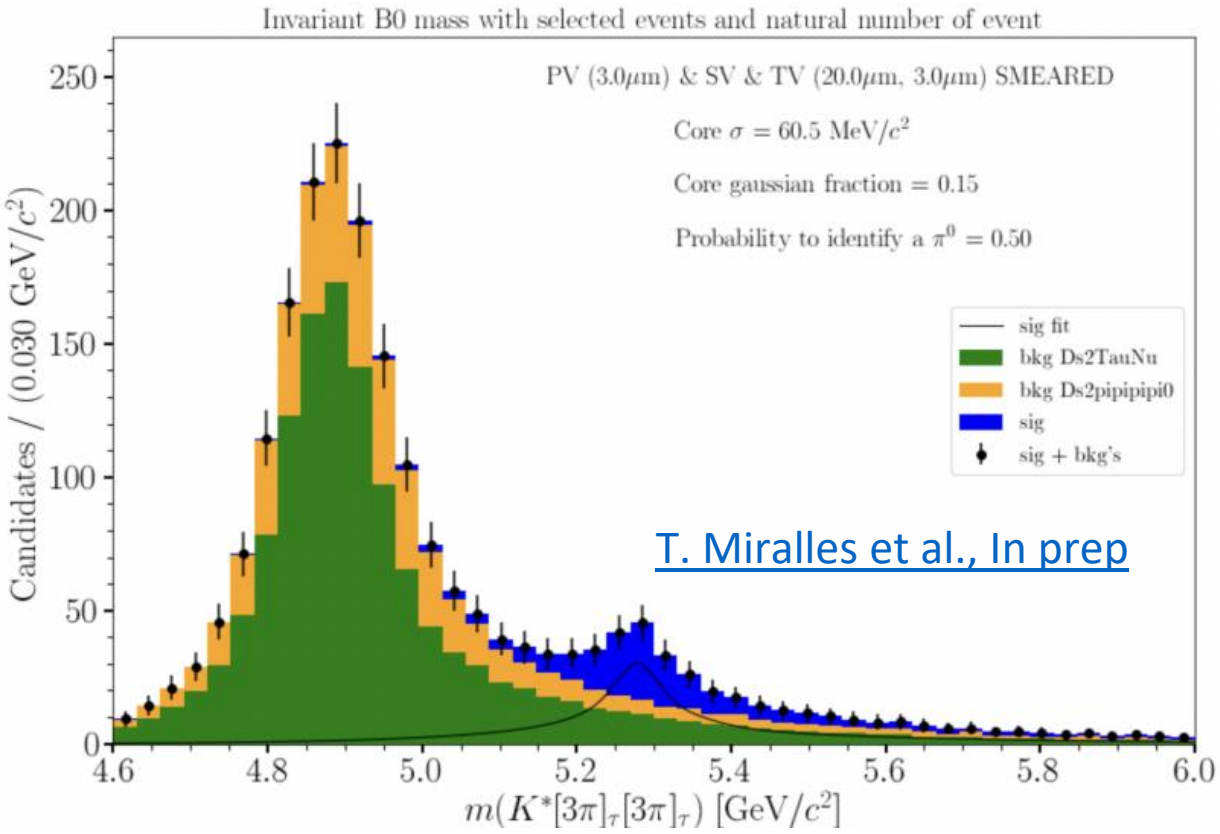
- Rare decays, sensitive to BSM
- Partially motivated by R_K and R_{K^*} anomalies
- Flagship mode: b→sττ, highly sensitive to LFUv in 3rd generation



[LL, T. Liu, 2012.00665]

Probing rare decay BR @ $O(10^{-7})$ level*

*: Absolute BR

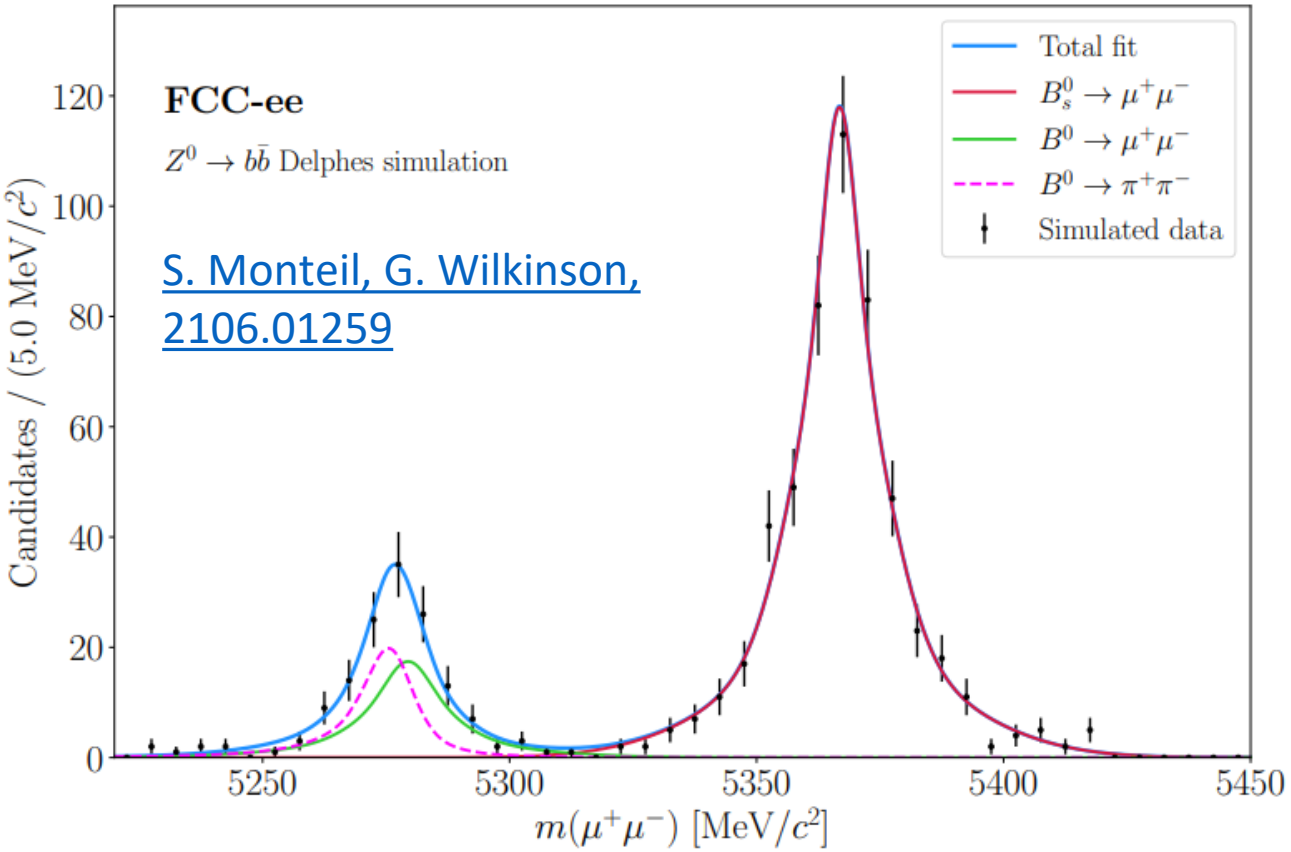


[T. Miralles et al., In prep]

↑: Even better background mitigation by π^0 reconstruction from background D_s decays

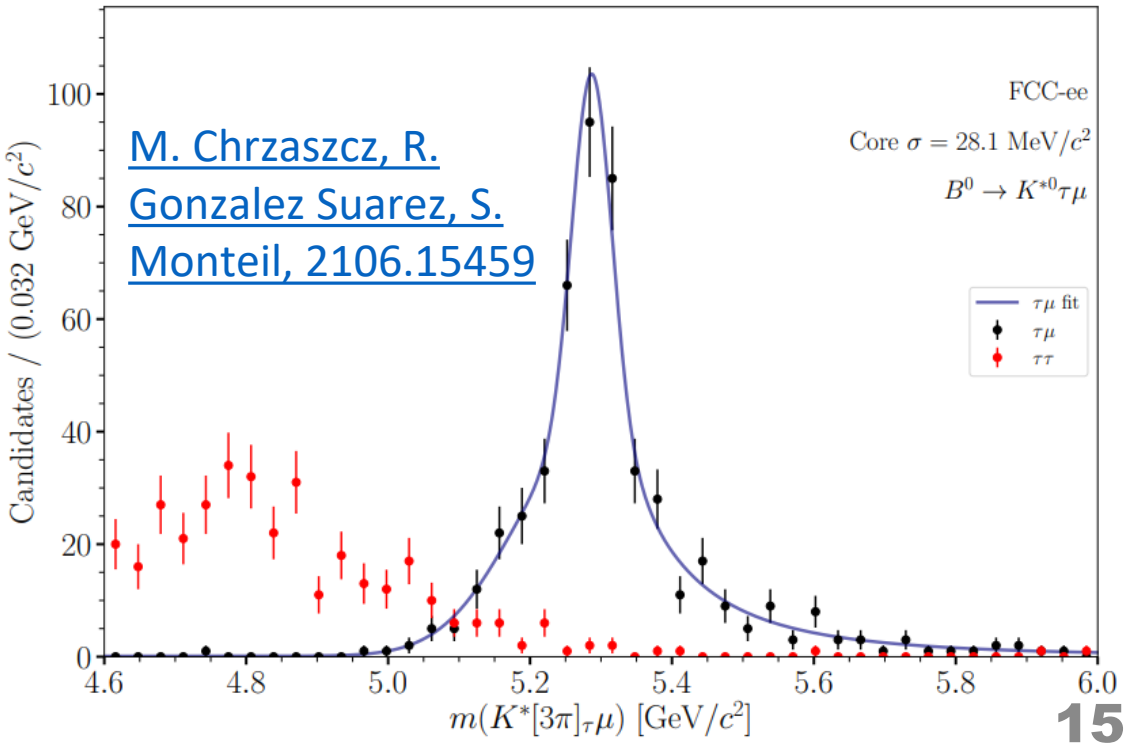
See also:
[J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva, 1705. 11106]

FCNC: Dileptonic Modes (II)



S. Monteil, G. Wilkinson, 2106.01259

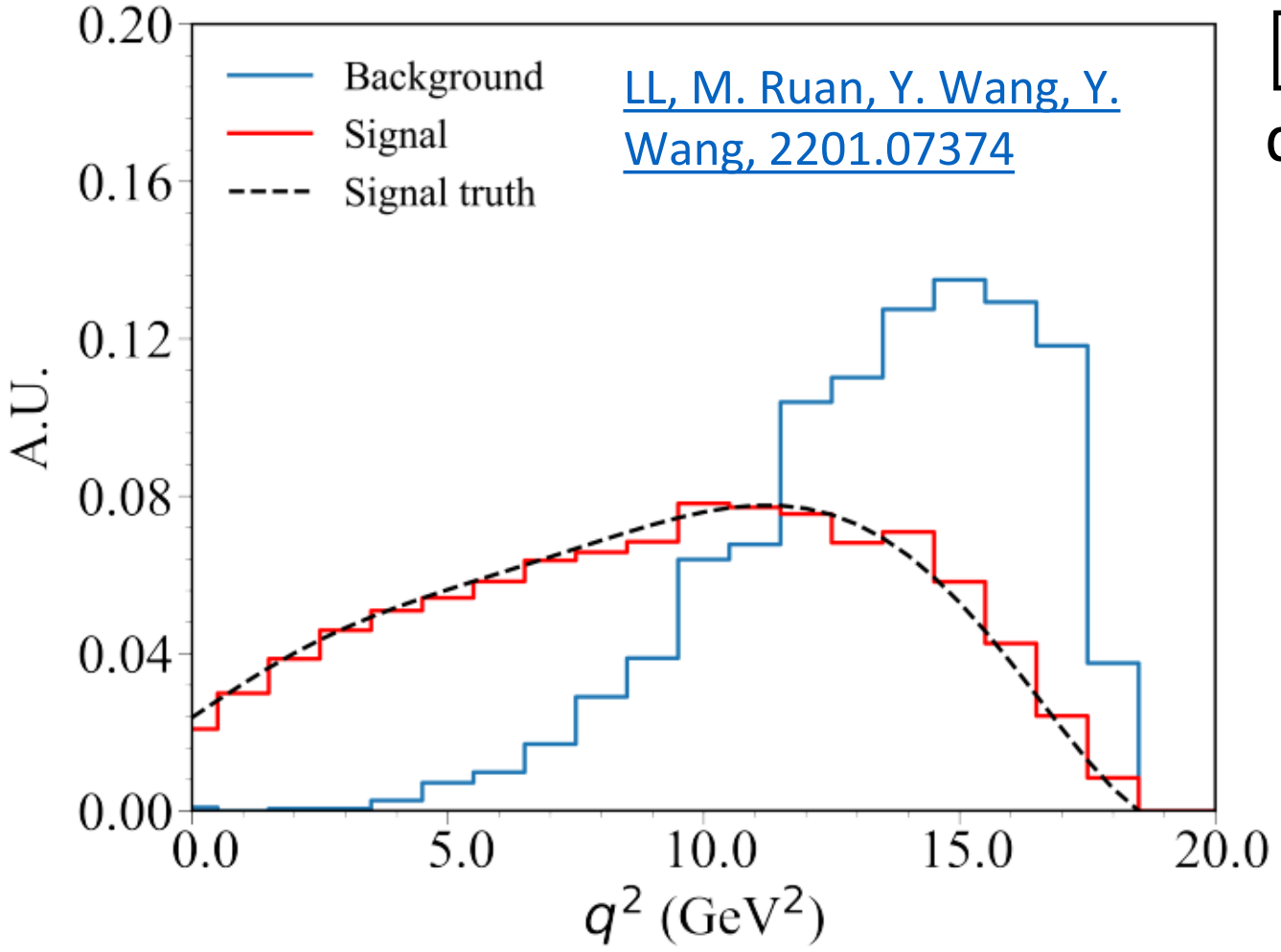
←: Measurements for both $B_d \to \mu\mu$ & $B_s \to \mu\mu$. $B_d \to \pi\pi$ background under control due to advanced PID tech.



M. Chrzaszcz, R. Gonzalez Suarez, S. Monteil, 2106.15459

→ : Extended to flavor violating modes, e.g., $B_d \to K^*\tau\mu$.

FCNC: Di-neutrino Modes & More

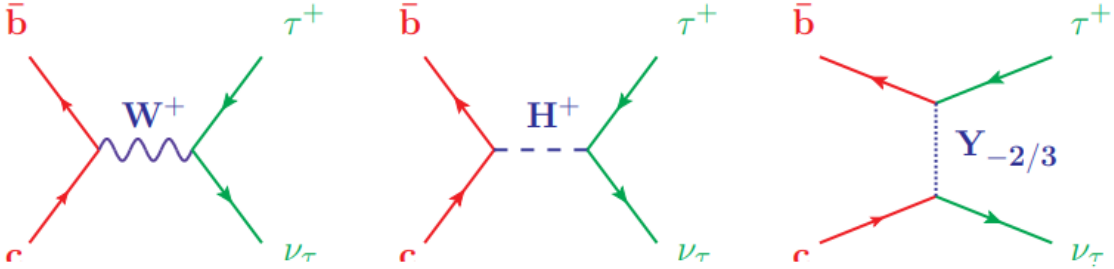


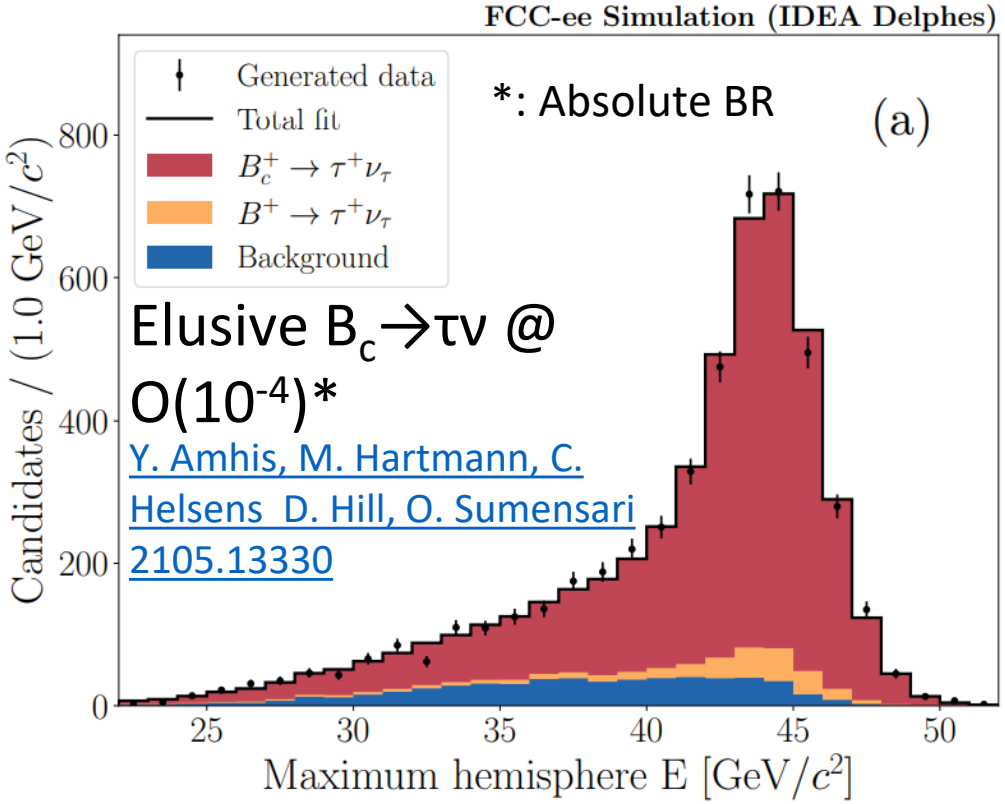
←: Reconstruct b→svv semi-invisible decay, error on $q^2 < 3$ GeV^2

- Can also constraint BSM physics, e.g., axion(-(like-particle) from flavor decays J. Camalich, M. Pospelov,P. Vuong, R. Ziegler, J. Zupan, 2002.04623
- Great potential for radiative decays

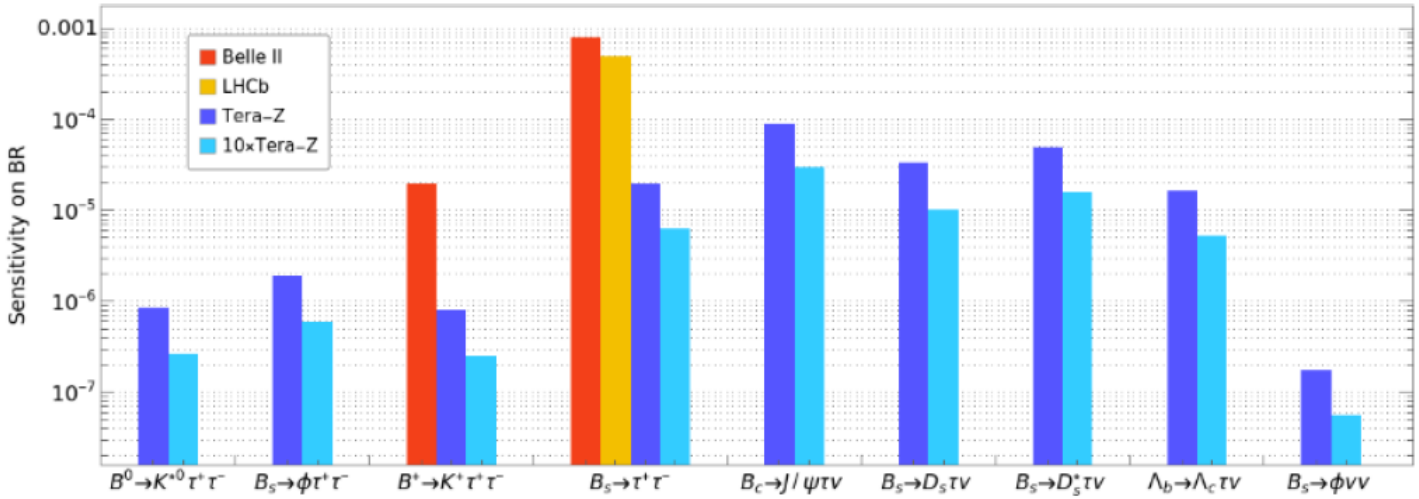
Heavy Quark Weak Decays (FCCC)

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





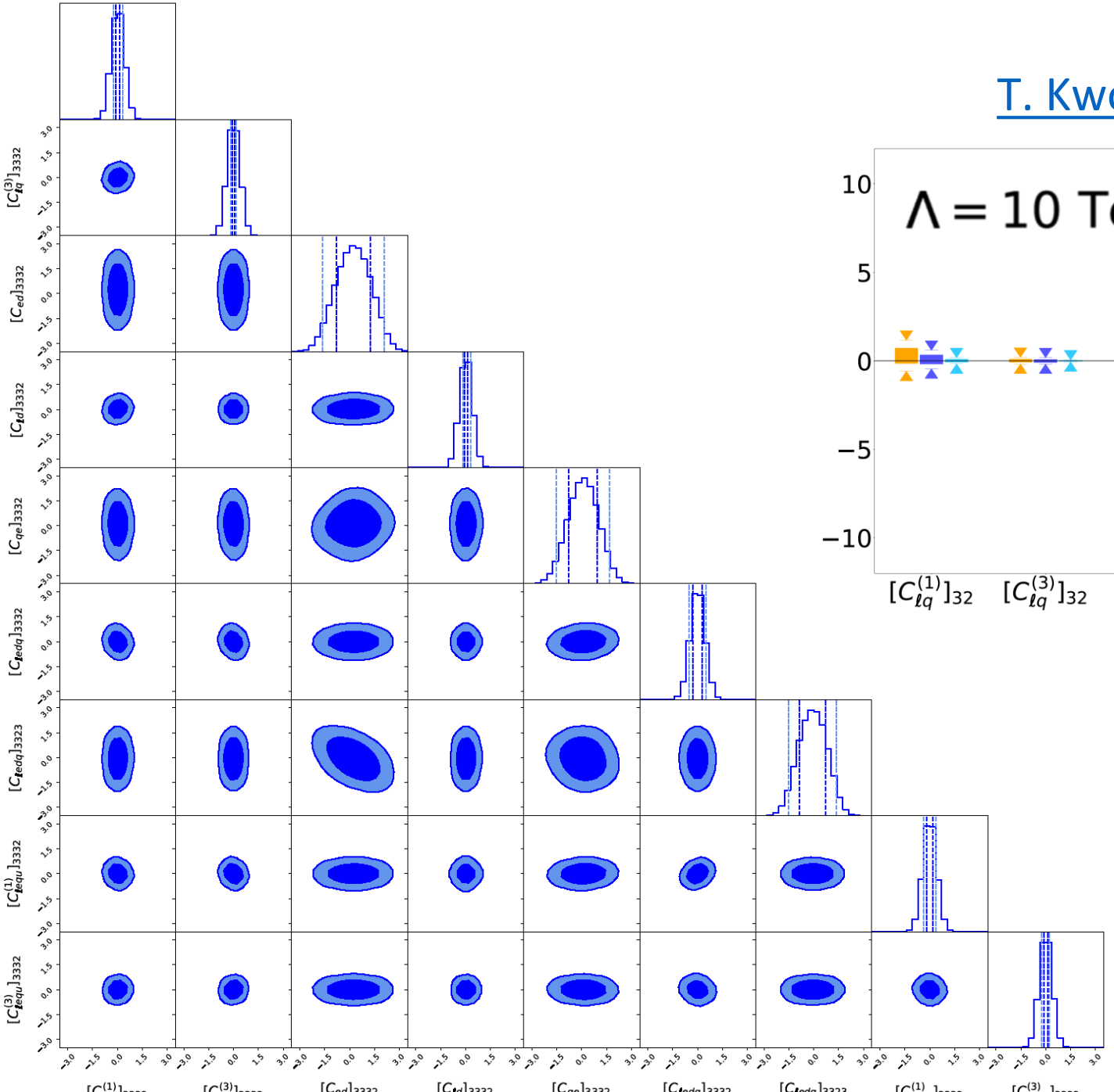
- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- Current focus: (Semi)leptonic modes

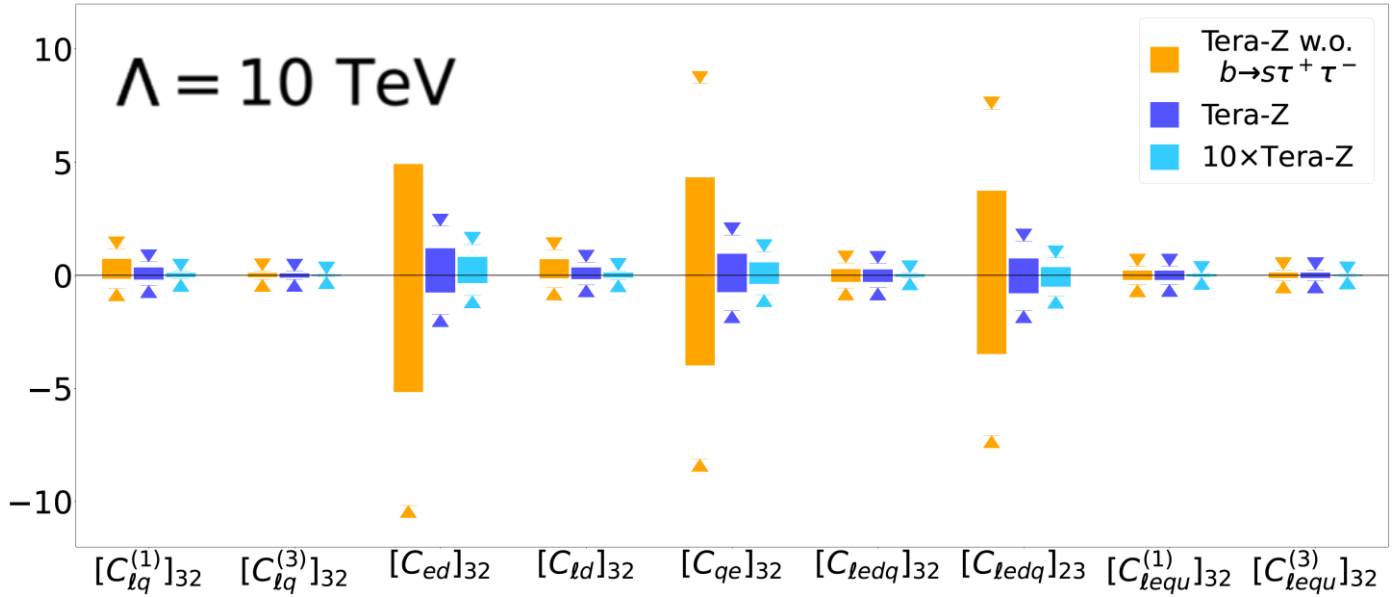


↑: $R_{J/\psi}$, $R_{Ds(*)}$, $R_{\Lambda b}$ projections on the way

T. Kwok, X. Jiang, LL, Tao Liu, In prep

T. Kwok, X. Jiang, LL, Tao Liu, In prep



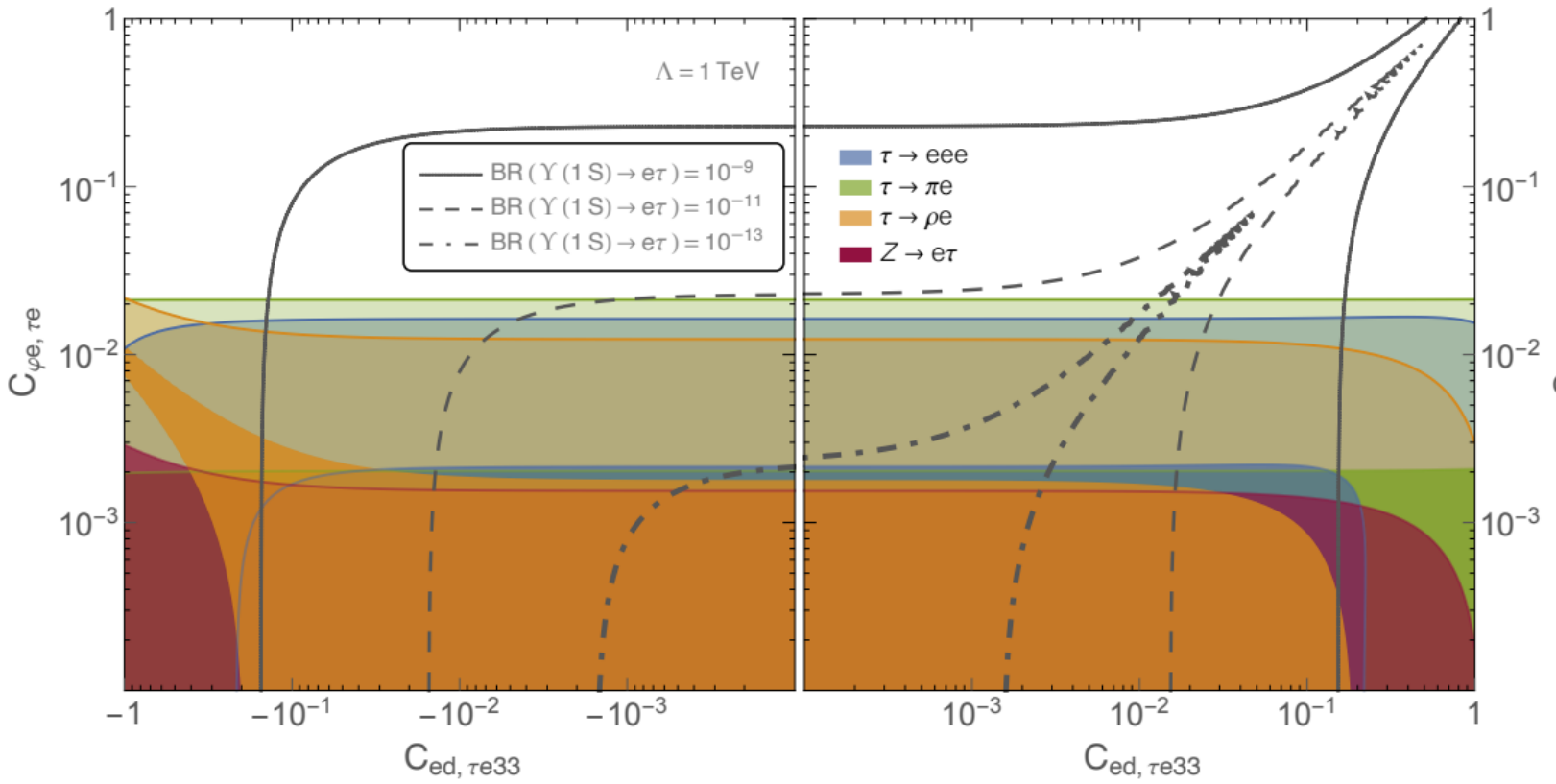


Probe O(10) TeV BSM in 9 dimensions by combining multiple semileptonic & rare modes

Tau and Lepton Sector

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

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



↗: Complementarity on cLFV new physics between exotic Z, quarkonia, and lepton decays

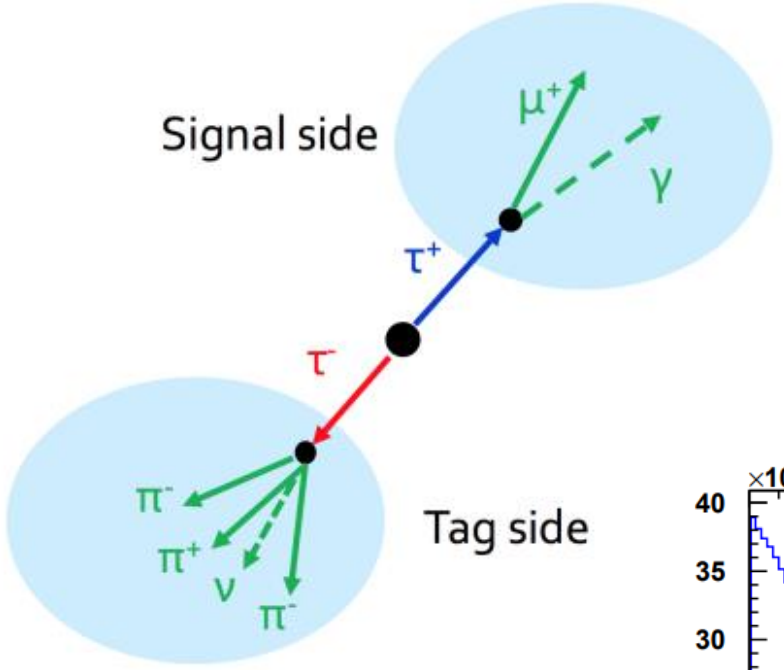
See also: L. Calibbi, X. Marcano, J. Roy, 2107.10273

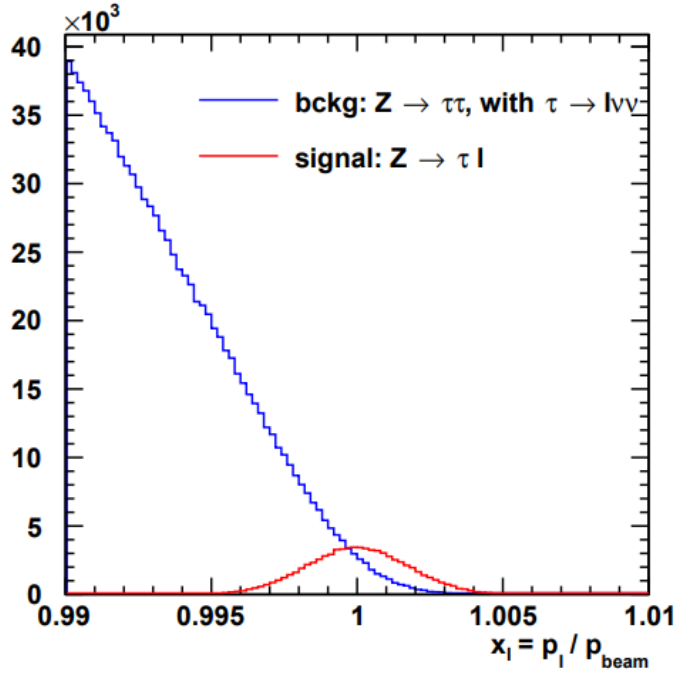
Tau and Lepton Sector (II)

Interesting studies include:

- Lifetime (better vertex resolution)
- Lepton universality via tau decays (good lepton PID)
- Hadronic decays and QCD coupling (ECAL resolution)
- Polarimetry (also for EW)

More discussions to be found in Alberto Lusiani's talk



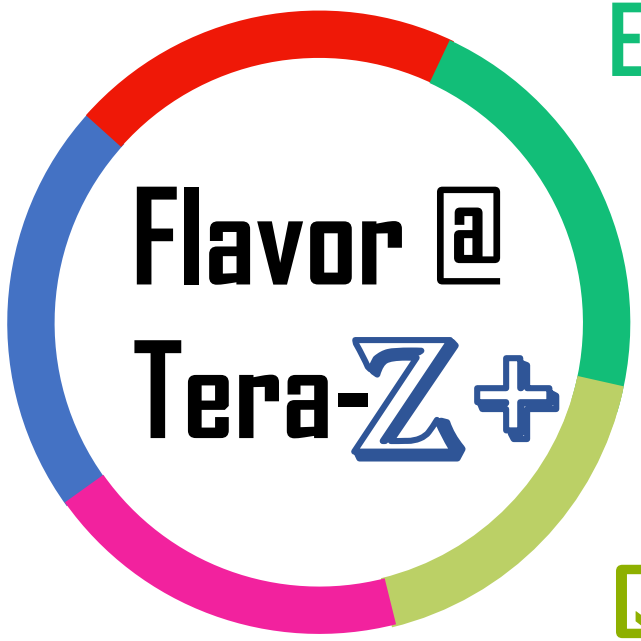


M. Dam, 1811.09408

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!