Theoretical Perspectives on Lepton Flavor Violation

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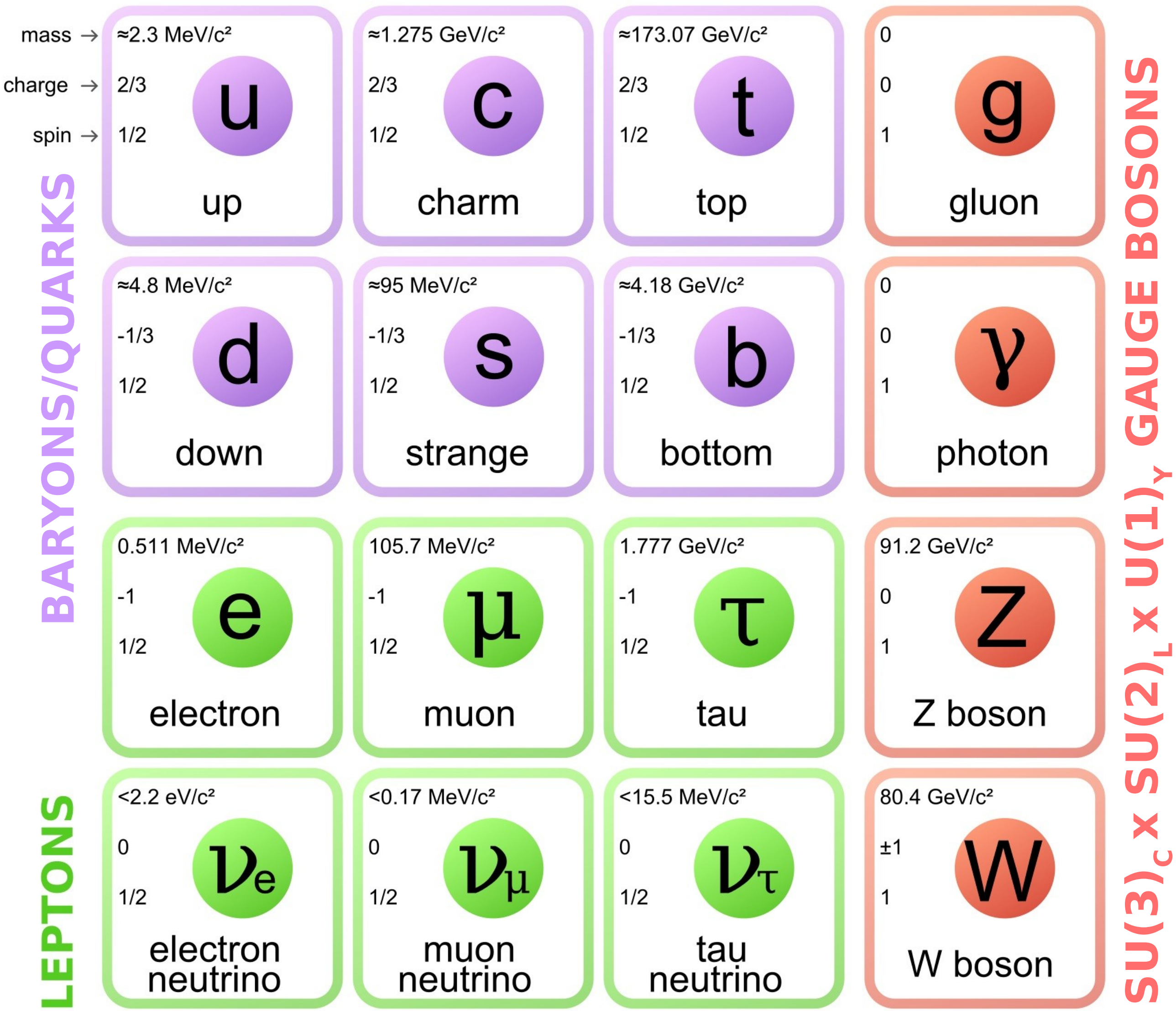
06/03/2024

4-VA Advancing The Commonwealth

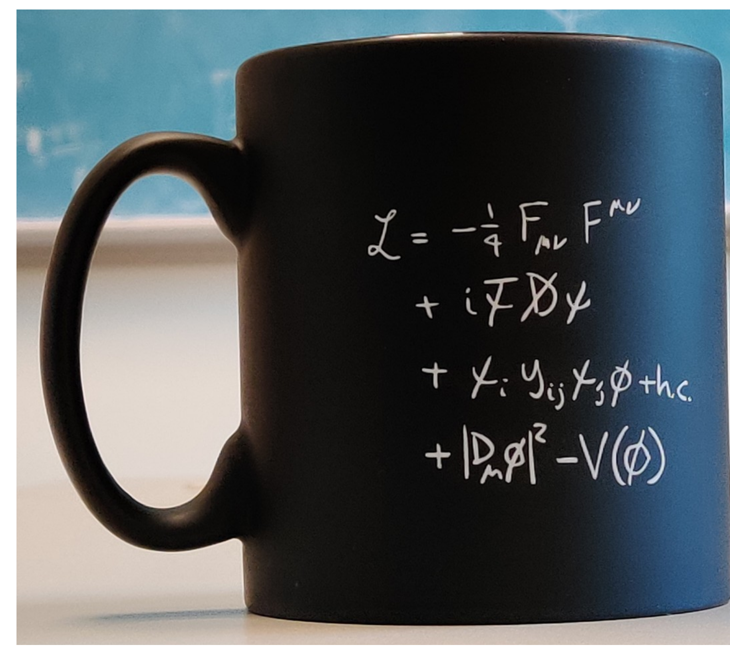
University of Virginia

NSF

Standard Model of Particle Physics



Englert & Higgs '13



[wikipedia]

Symmetries of the Standard Model

- Rephasing quark and lepton fields:

$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_{\mathrm{L}_e} \times \mathrm{U}(1)_{\mathrm{L}_\mu} \times \mathrm{U}(1)_{\mathrm{L}_\tau}$$
$$=$$
$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_\mathrm{L} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$

See talk by Yury Kolomensky.

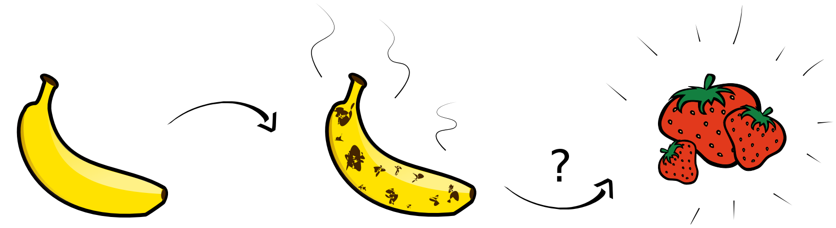
⇒ Lepton flavor conservation

- ($\mathrm{U}(1)_{\mathrm{B+L}}$ broken to Z_3 non-perturbatively, but unobservable.)

['t Hooft, PRL '76]

Four conservation laws predicted by SM

Flavor violating decays

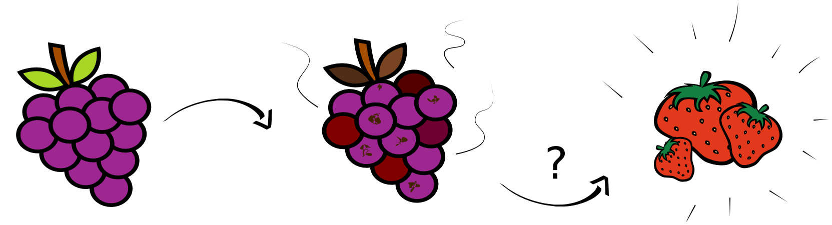


- Background-free search: high sensitivity.
- Prime example: $\mu \to e\gamma$ @ MEG.
- Observation = new particles.
- $\mu \to e$ conversion @ Mu2e can probe scales up to 10^7 GeV.

See talk by Yongyi Wu.

LFV	process	current	future	exp
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	3.1×10^{-13}	6×10^{-14}	MEG-II
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}	Mu3e
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-16}	Mu2e, COMET
	$h \to e\bar{\mu}$	6×10^{-5}	6×10^{-6}	LHC
	$Z \to e\bar{\mu}$	3×10^{-7}	5×10^{-8}	LHC
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	–	–

Flavor violating decays



- Produce tauons at B factories (Belle II, LHCb).

See talk by Seema Choudhury.

- Observation = new particles.
- $\tau^- \to e^- e^+ e^-$ @ Belle II will probe scales up to 2×10^4 GeV.

LFV	process	current	future	exp
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8}	9×10^{-9}	Belle II
	$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	5×10^{-10}	Belle II
	$\tau \to e\,\text{had}$	$\mathcal{O}(10^{-8})$	$\mathcal{O}(10^{-10})$	Belle II
	$h \to e\bar{\tau}$	2×10^{-3}	2×10^{-4}	LHC
	$Z \to e\bar{\tau}$	5×10^{-6}	10^{-6}	LHC
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-6})$	Belle II

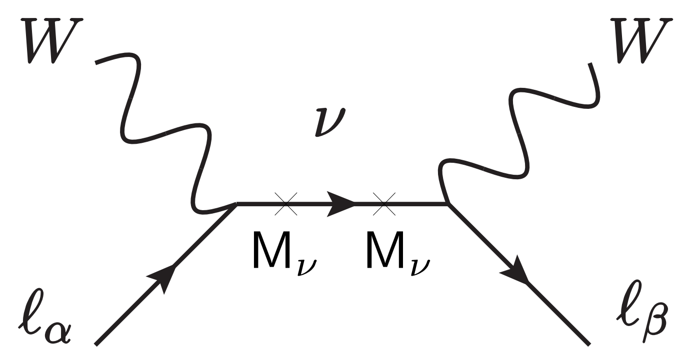
- Should/can *not be compared* to μ decays!

Neutrino oscillations = flavor violation

- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

  $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$

  is broken! See talk by Patrick Huber.



- Amplitudes for *charged* lepton flavor violation are untestably suppressed:

$$\mathcal{A}(\ell_\alpha^- \to \ell_\beta^-) \propto \frac{(M_\nu M_\nu^\dagger)_{\alpha\beta}}{M_W^2} < 10^{-24}\,.$$

$\leftarrow$ $\mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-52}$

- Most (neutrino mass) models also generate CLFV rates unsuppressed by M_ν that could be observable.

Why look for CLFV?

- SM prediction: $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$, i.e. no LFV!
  - Background-free searches, high sensitivity.
- Neutrino oscillations = LFV!
  - M_ν-induced CLFV tiny: CLFV is *complementary*.
- New physics generically and easily gives testable CLFV.
  - Predictions require fixed flavor structure (PMNS, CKM) and new scale (g-2, LFUV in B, W-mass, DM,…).

Let's study CLFV model-agnostically*

* assuming *heavy* new physics

Standard Model Effective Field Theory

- 888 CLFV operators at d=6:

$$\frac{C_{ij}}{\Lambda^2}\ell_i^c\sigma_{\alpha\beta}\ell_j H F^{\alpha\beta}\,,\ \frac{C_{ij}}{\Lambda^2}\ell_i^c\gamma^\alpha\ell_j\, H^\dagger D_\alpha H\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j\ell_n^c\ell_m\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j q_n^c q_m$$

[Weinberg ‘79; Buchmüller & Wyler, ‘86; Grzadkowski++, ‘10; Fonseca, ‘17]

- Model-dependent coefficients; can get testable rates.

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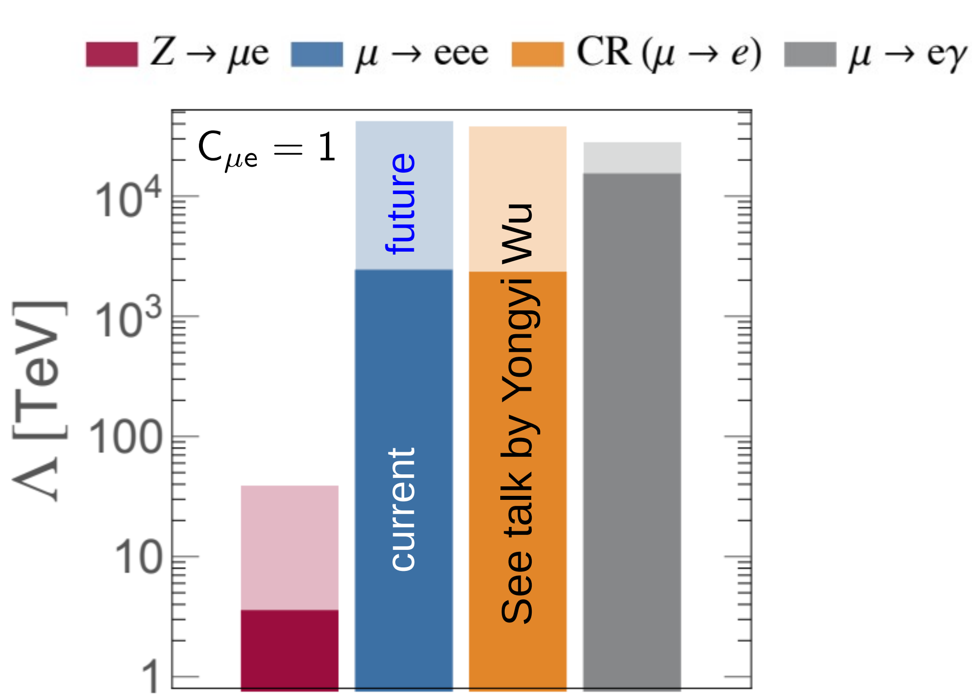

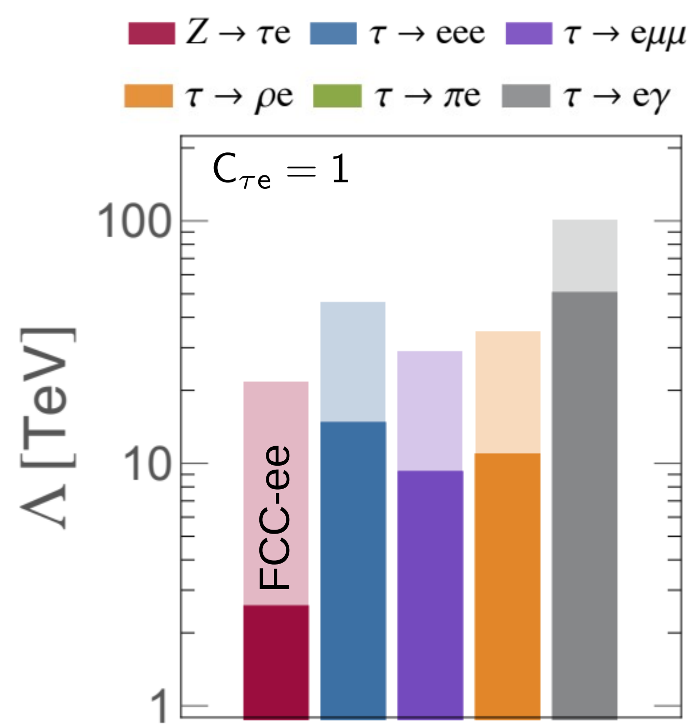

[Calibbi, Marcano, Roy, 2107.10273]

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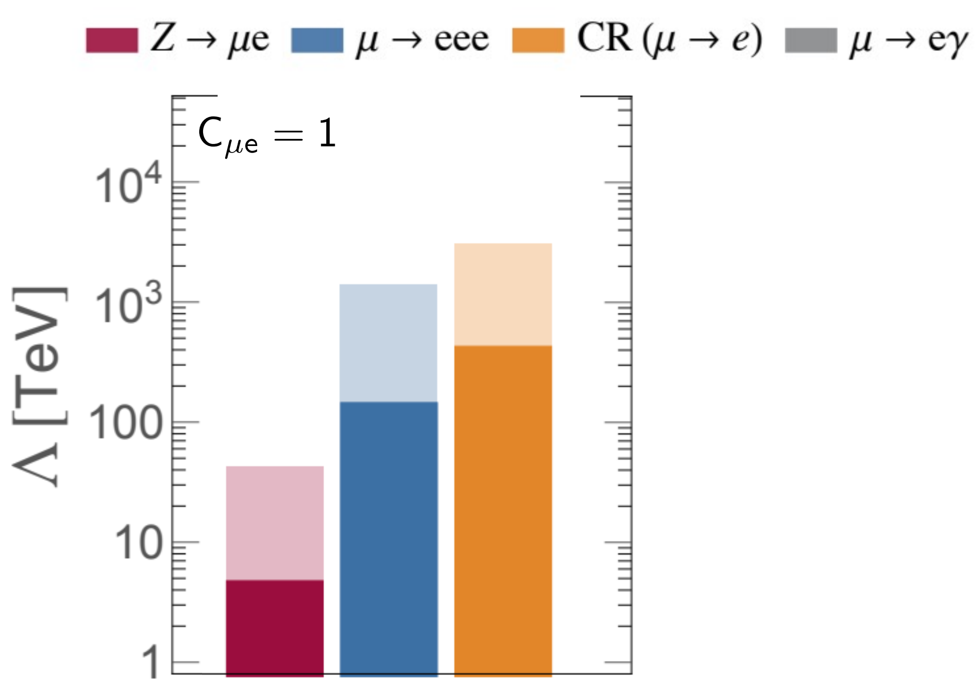

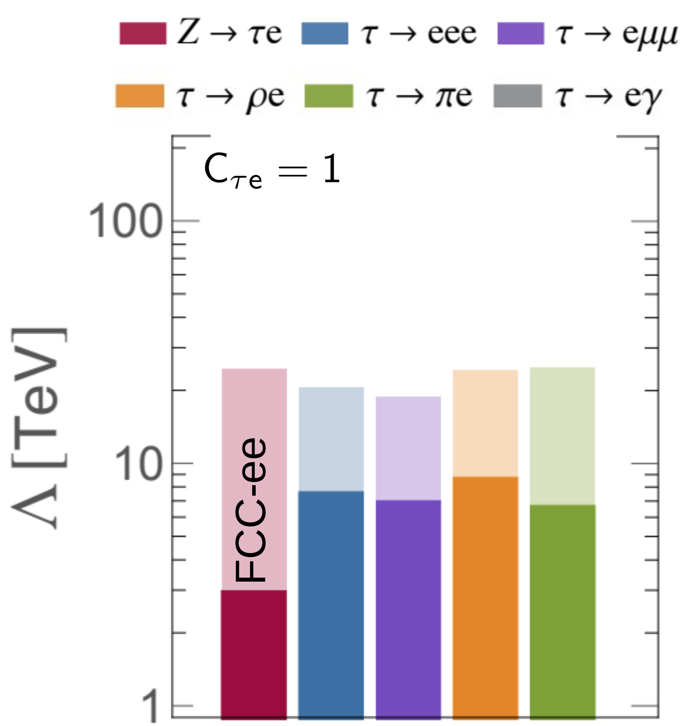

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[Weinberg ‘79; Buchmüller & Wyler, ‘86; Grzadkowski++, ‘10; Fonseca, ‘17]

- Model-dependent coefficients; can get testable rates.
  - $\ell_i \to \ell_j\ell_m\bar{\ell}_n\ :\ \mu\to ee\bar{e}\,,\ \ \tau\to ee\bar{e}, e\mu\bar{e}, \mu\mu\bar{e}, \ldots$
  - $\mu\mu\bar{e}\bar{e}$: $\Delta L_\mu = 2 \Rightarrow$ Muonium-antimuonium conversion

    [Conlin & Petrov, 2005.10276; Fukuyama, Mimura, Uesaka, 2108.10736; ...]

  - $\tau\tau\bar{\mu}\bar{\mu}, \ldots$: $\Delta L_\tau = 2$, partly constrained by LFUV $\frac{\Gamma(\tau\to\mu\nu\nu)}{\Gamma(\tau\to e\nu\nu)}$

    but right-handed ones are tough:

    $$\text{BR}(Z\to\tau_R\tau_R\overline{\mu}_R\overline{\mu}_R)\simeq 4\times 10^{-11}\,(100\,\text{GeV}/\Lambda)^4$$

    [**JH** & Sokhashvili, 2401.09580]

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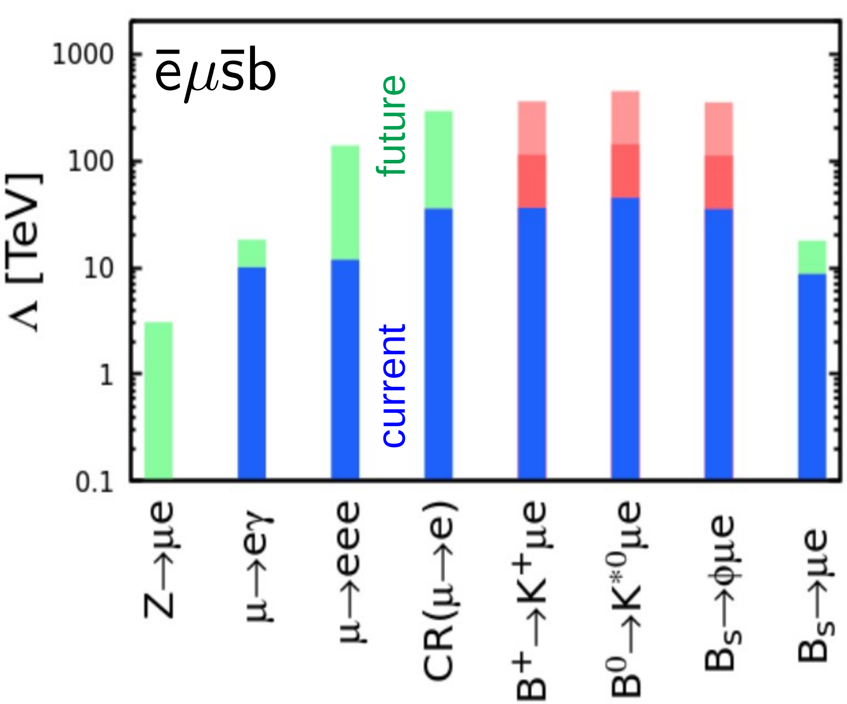
$\overline{L}_e\gamma_\alpha L_\mu\, \overline{Q}_2\gamma^\alpha Q_3/\Lambda^2$



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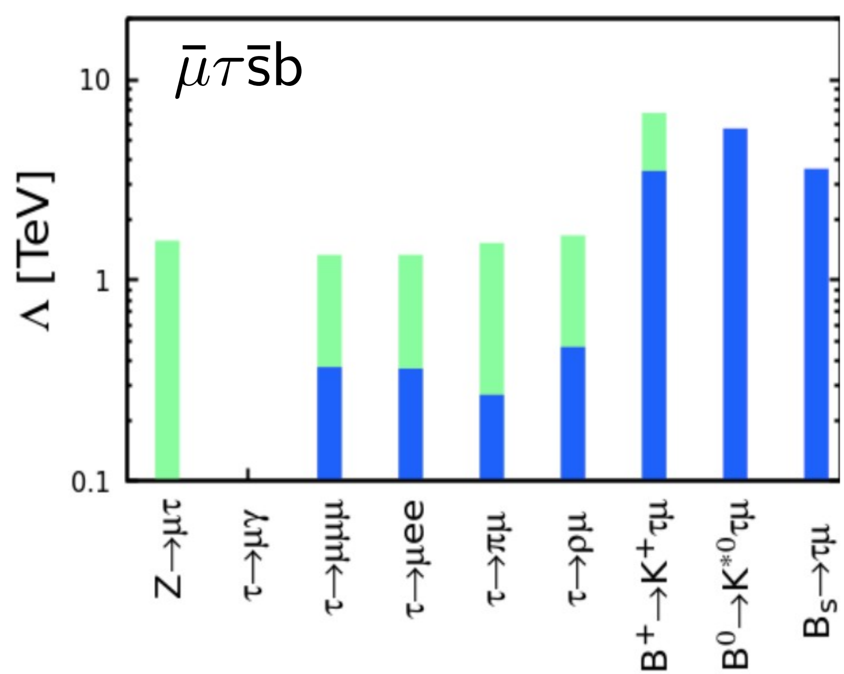

[Ali++, 2312.05071]

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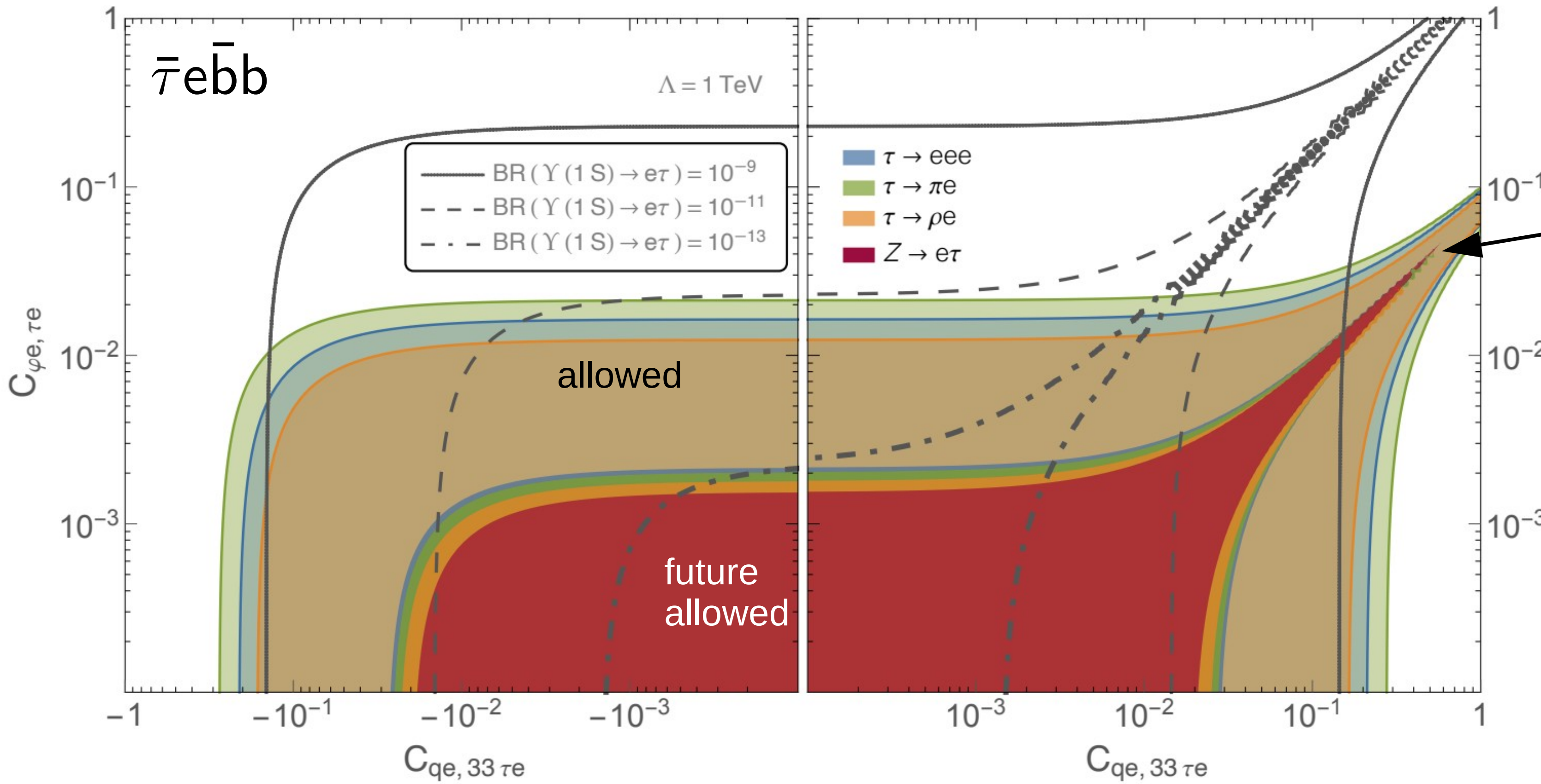
- Model-dependent coefficients; can get testable rates.

[Calibbi++, 2207.10913]



Flat direction allows for large $\Upsilon \to e\tau$

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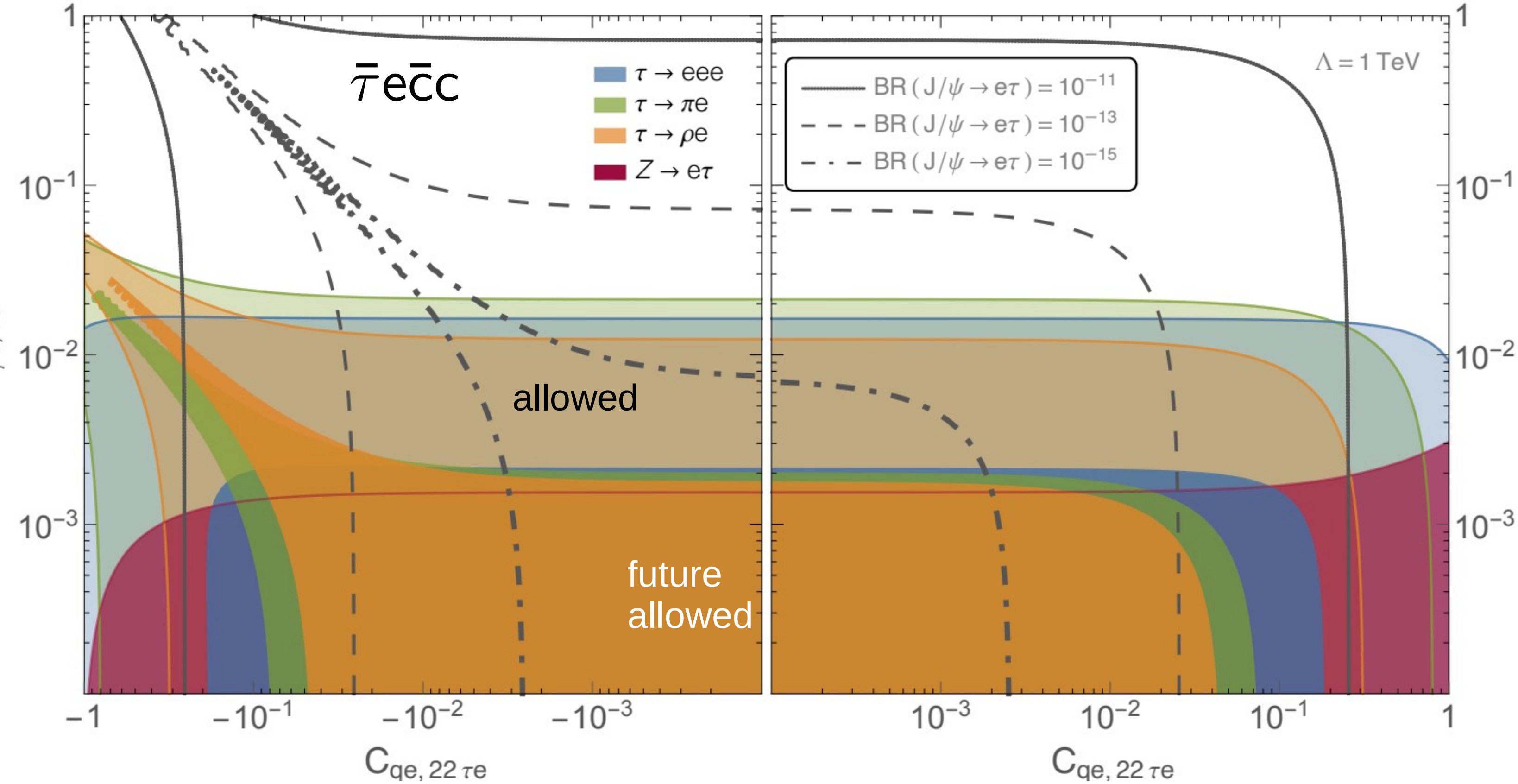

Difficult to get $J/\Psi \to e\tau$ above 10^{-9} with these two operators.

See talk by Xudong Yu.

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[Weinberg ‘79; Buchmüller & Wyler, ‘86; Grzadkowski++, ‘10; Fonseca, ‘17]

- Model-dependent coefficients; can get testable rates:

$$\ell\to\ell'\gamma,\ \ell\to\ell'\ell''\ell''',\ \mu\to \mathrm{e}\ \text{conv.},\ \mathrm{Z}\to\ell\ell',\ \text{had}\to\ell\ell',\ \dots$$

- Not all constrained, e.g. $\Delta L_\tau = 2$. [**JH** & Sokhashvili, 2401.09580]

- CLFV even sensitive to some d=8 operators, e.g. $\frac{\bar{L}_\mu H e_R\, GG}{\Lambda^4}$.
  [Petrov & Zhuridov, ‘14; Davidson++ 2007.09612; Ardu & Davidson ‘21]

- Not clear if / how $U(1)_{L_\mu - L_\tau}\times U(1)_{L_\mu+L_\tau-2L_e}$ is broken, need as many observations as possible.
  [Lew & Volkas, 9410277; **JH**, 1610.07623]

Standard **M**odel **E**ffective **F**ield **T**heory

- 546 more CLFV operators at d=6:

$$\frac{y^1}{\Lambda^2} duQL_\alpha + \frac{y^2}{\Lambda^2} QQQL_\alpha + \frac{y^3}{\Lambda^2} QQu\ell_\alpha + \frac{y^4}{\Lambda^2} duu\ell_\alpha$$

- Violates lepton flavor but also baryon and lepton number!
- $\Rightarrow$ proton decay! $p \to e^+\pi^0,\ \mu^+\pi^0,\ \bar{\nu}\pi^+, \ldots$

  with Super-K limits of $t_{1/2} \sim 10^{34}$ years or $\Lambda \sim 10^{15}$ GeV!

Standard Model Effective Field Theory

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$$\frac{y^1}{\Lambda^2}\mathrm{duQL}_\alpha + \frac{y^2}{\Lambda^2}\mathrm{QQQL}_\alpha + \frac{y^3}{\Lambda^2}\mathrm{QQu}\ell_\alpha + \frac{y^4}{\Lambda^2}\mathrm{duu}\ell_\alpha$$

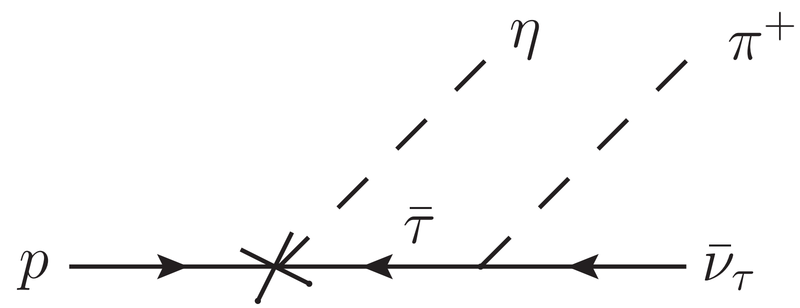
- Violates lepton flavor but also baryon and lepton number!
- $\Rightarrow$ proton decay! $\quad \mathrm{p} \to \mathrm{e}^+\pi^0,\ \mu^+\pi^0,\ \bar{\nu}\pi^+, \ldots$

  with Super-K limits of $t_{1/2}$~10^{34} years or $\Lambda \sim 10^{15}$ GeV!
- What about $\tau^- \to \bar{\mathrm{p}}\pi^0, \bar{\mathrm{p}}\eta$?
  - Best-case scenario: $y^1 = y^2 = 0$ and $y^3 = y^4$:

$$\underbrace{\tau(\mathrm{p}\to\eta\pi^+\bar{\nu}_\tau)}_{\text{Only old inclusive limits}} \simeq 100\,\mathrm{yr}\ \underbrace{\left(\frac{10^{-5}}{\mathrm{BR}(\tau\to\bar{\mathrm{p}}\eta)}\right)}_{\text{[CLEO '99]}}$$

Only old inclusive limits
[**JH** & Takhistov, PRD '20],
could easily be improved by Super-K!

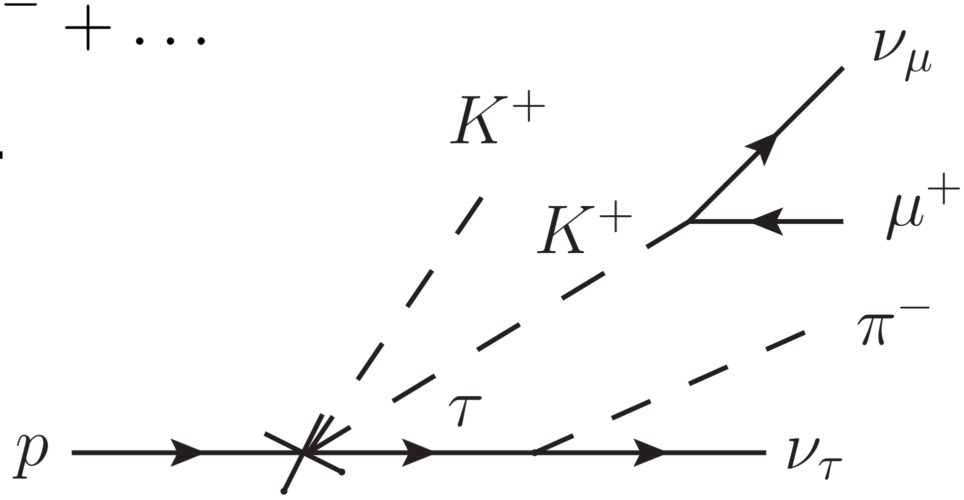
[CLEO '99]



[**JH** & Watkins, 2405.18478]

$\Delta B = -\Delta L_\tau = 1$ operators

- d=7 operator: $\text{dssH}\bar{\text{L}}_\tau \propto \bar{\tau}\Xi^- + \dots$
- No neutrinos, two s quarks.
- Two-body tau decays but five-body nucleon decays!
- Off-shell τ and K, double suppression by G_F:



$$\tau(\text{p} \to \text{K}^+\mu^+\nu_\mu\pi^-\nu_\tau) \simeq \mathcal{O}(10^{28})\,\text{yr}\left(\frac{10^{-8}}{\text{BR}(\tau\to\Xi\pi)}\right)$$

$\Xi \to \Lambda\pi$, $\Lambda \to \text{N}\pi$

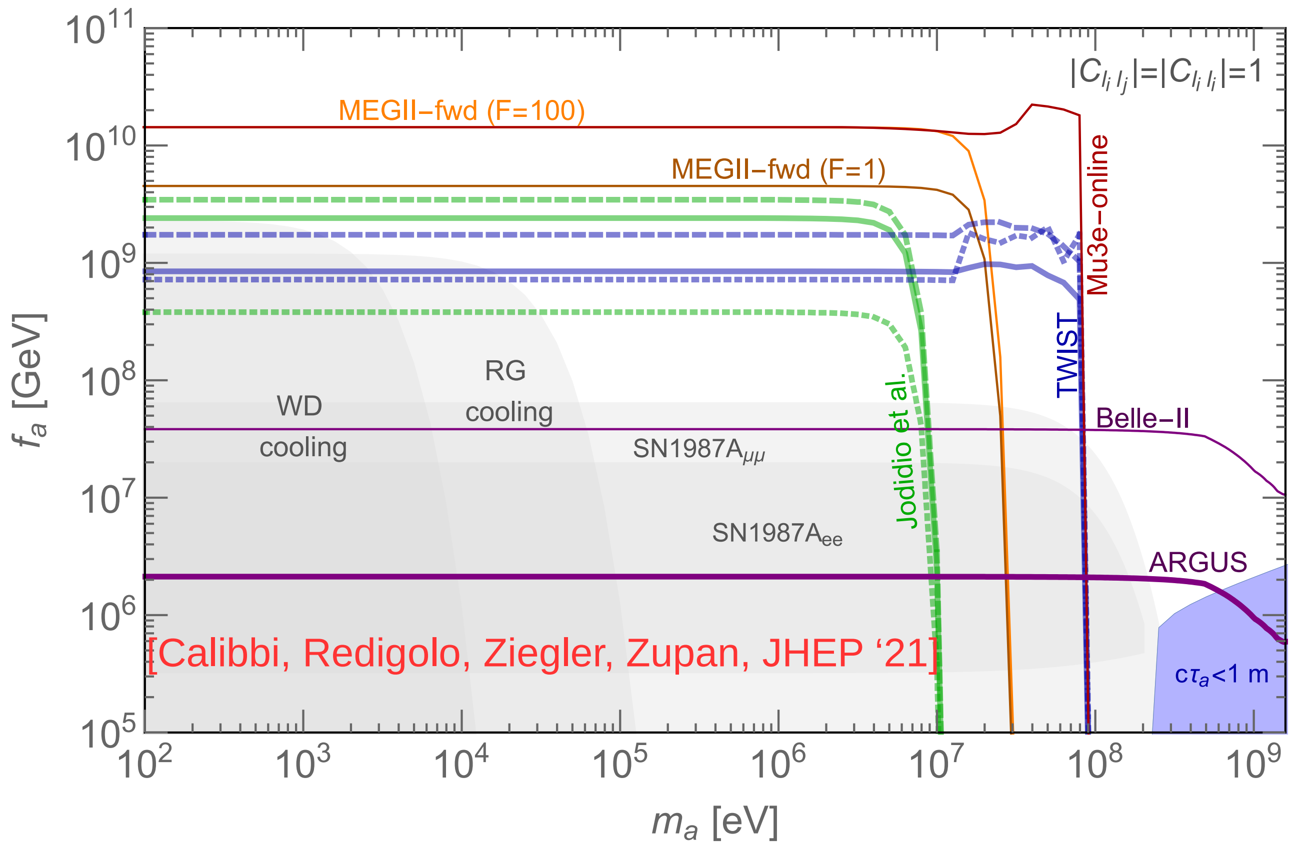
[JH & Watkins, 2405.18478]

- ΔB tau decays most competitive in hyperon channels.

New channels for Super-K & Belle II

How about *light* new particles?

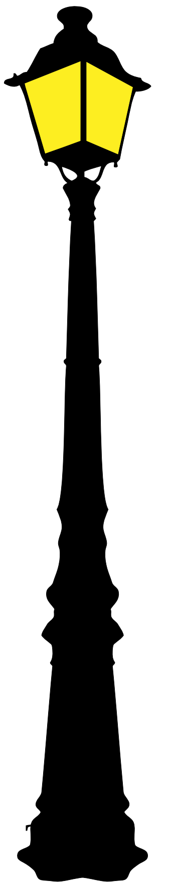
- SMEFT only works for *heavy* new particles!
- *Light* new particles X give new signatures:
- $\mu \to e X$ or $\tau \to \ell X$, maybe followed by (displaced) $X \to \ell^+\ell^-, \gamma\gamma$?
  [**JH** & Rodejohann, PLB ‘18; Cheung++, JHEP ‘21]
- Mu3e and Belle II can improve limits, maybe others too?
  [i Tormo++, PRD ‘11; Uesaka, PRD ‘20; Knapen++, 2311.17915]



Active research area with new ideas

Summary

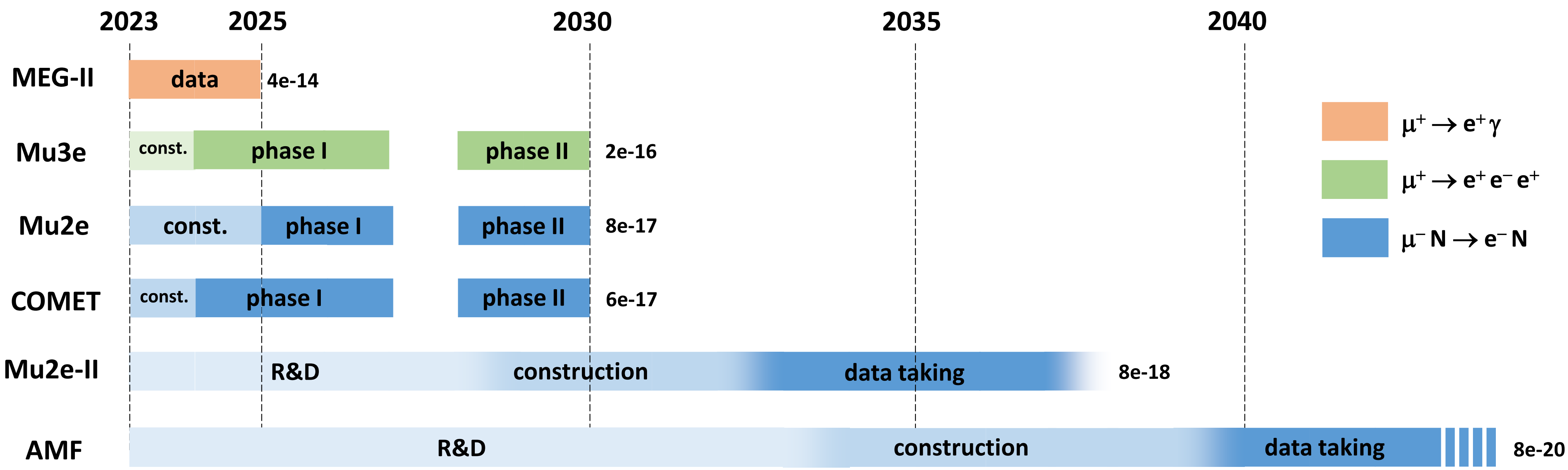
- Charged LFV gives info *complementary* to ν oscillations.
- Generically predicted by BSM, could be around the corner.
- Huge complementarity landscape, can't just rely on $\mu \to e\gamma$.
- Good limits on *most* d=6 LFV SMEFT coefficients.
- Many channels still unexplored!
- Light new physics opens new avenues.
- Hope for sign in Mu3e, MEG II, Belle II, Mu2e, LHC(b),...



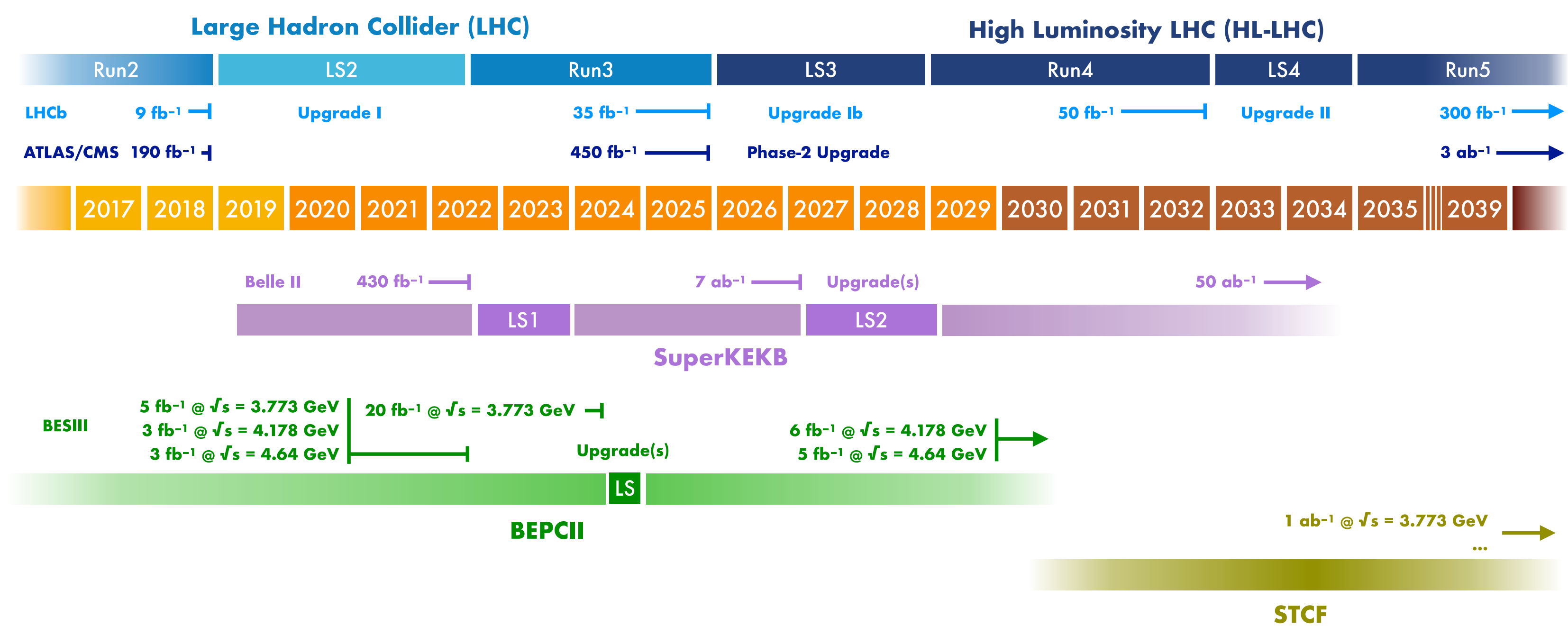
Explore every corner of our lamppost!

Backup

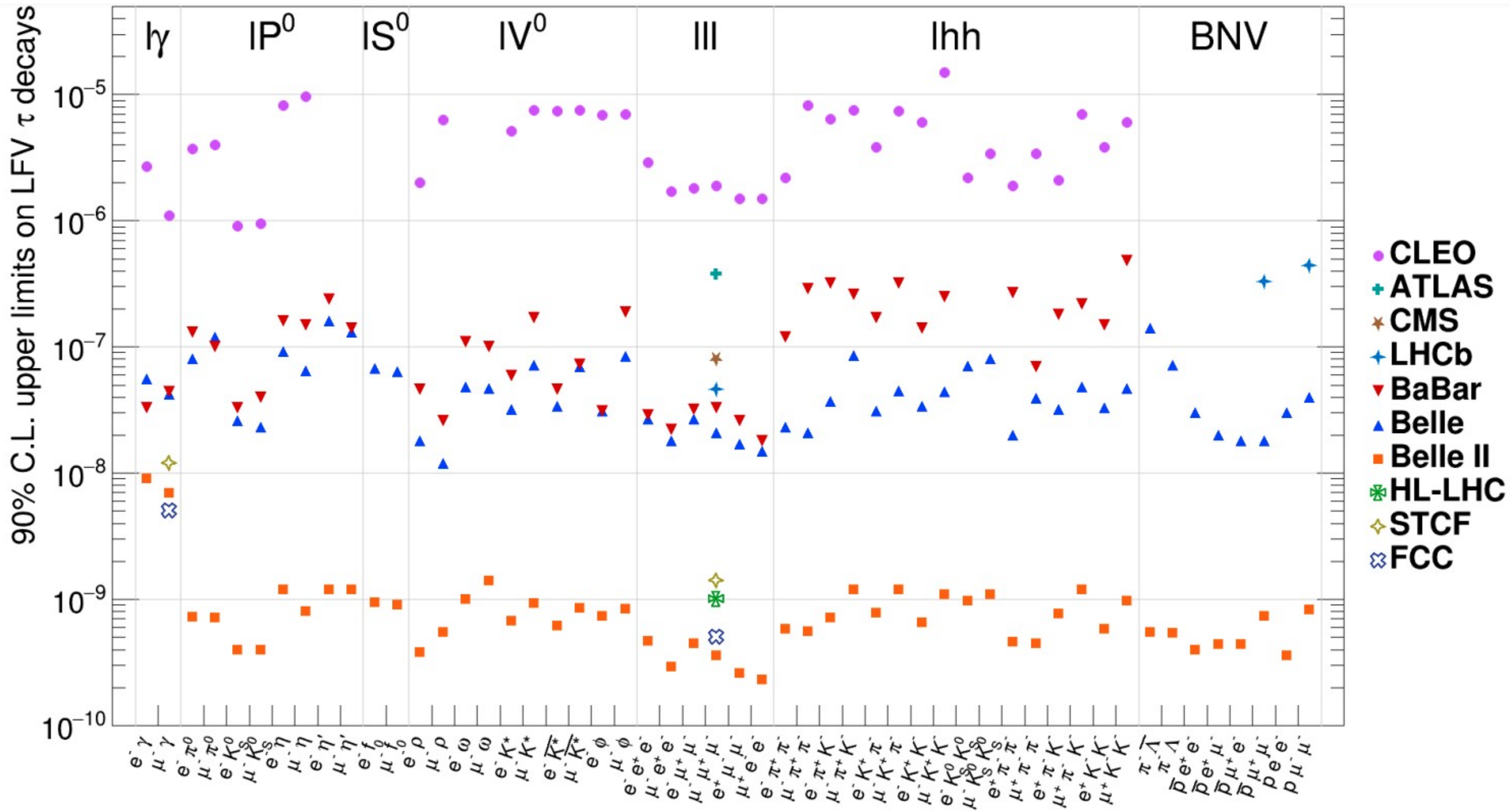
LFV Timelines



[Artuso, Bernstein, Petrov, *Snowmass 2021 Rare and Precision Frontier Report*, 2210.04765]



LFV in tau sector



[Banerjee++, 2203.14919]