EDM Experiments vs TeV-Scale New Physics

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Based on: arXiv:2104.02679 with Daniel Aloni, Pouya Asadi, Yuichiro Nakai, Motoo Suzuki

Question

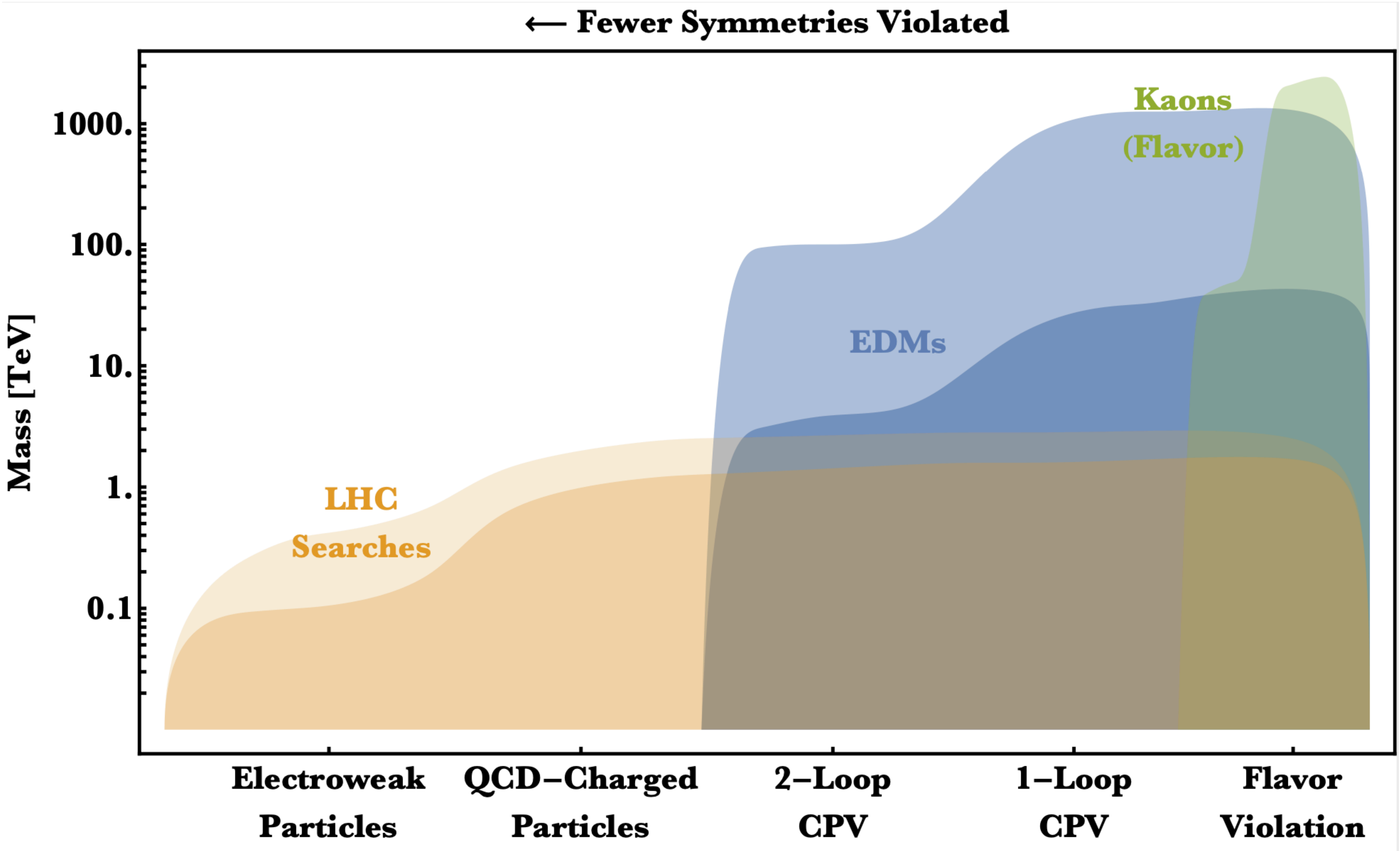
Electron EDM experiments are now probing mass scales well above 1 TeV.

Colliders and muon $g-2$ experiments are looking for particles around 1 TeV.

Are EDM experiments bad news for such searches?

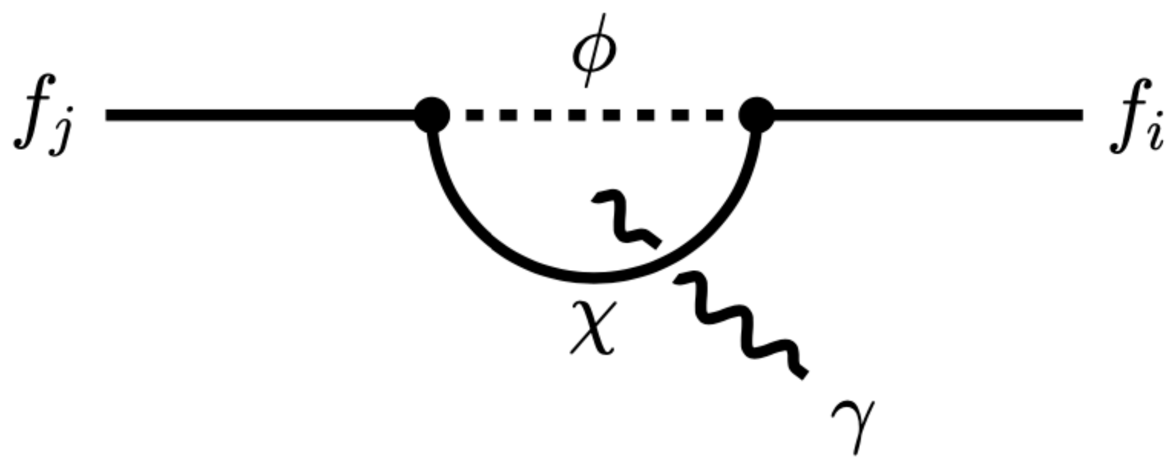
To answer this, we should think more about the fundamental physics of **CP** and **flavor**.

Mass Reach Comparison: A Cartoon



from discussions with John Doyle, 2017

Lepton Dipole Operators

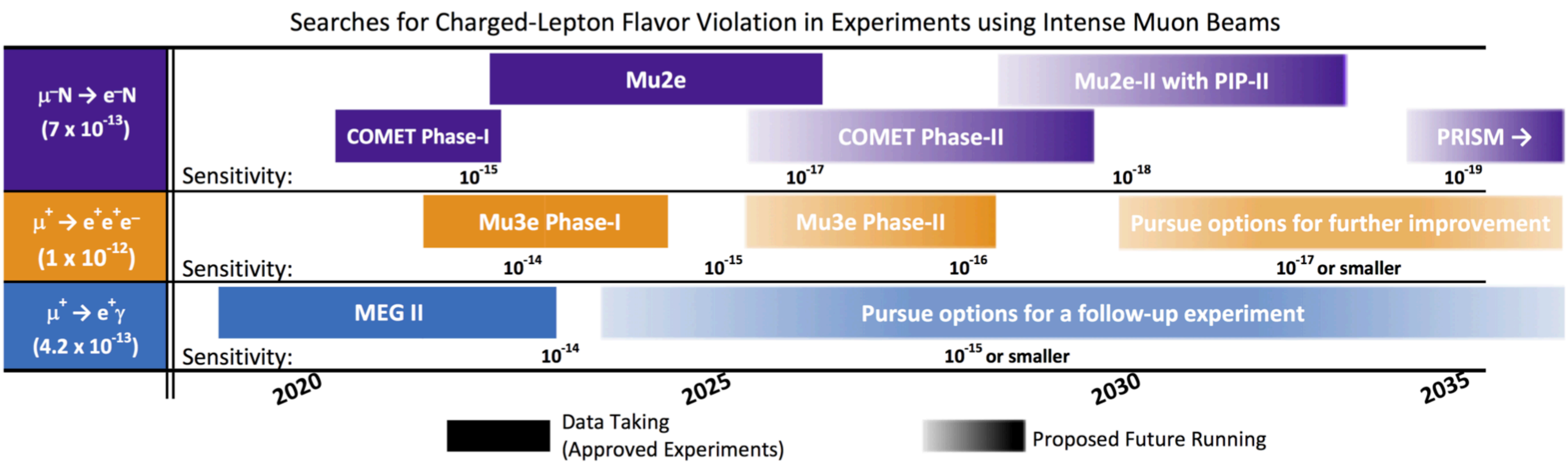


- Electron EDM
- Muon $g-2$
- $\mu \to e\gamma$
- $\tau \to \mu\gamma, \tau \to e\gamma$

If we see new physics in one of these, do we expect to see new physics in all of these?

Is new physics in muon $g-2$ already excluded? E.g., by lack of new physics in the electron EDM?

Charged Lepton Flavor Violation



Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations

Comparisons: Flavor & CP Observables

Observable	Current bound	Current Λ (TeV)	Future reach	Future Λ (TeV)
eEDM	$1.1 \times 10^{-29}\ e\,\text{cm}$	1.0×10^{3}	$\sim 10^{-32}\ e\,\text{cm}$	3.3×10^{4}
$\text{BR}\,(\mu \to e\gamma)$	4.2×10^{-13}	57.	$\sim 10^{-14}$	1.5×10^{2}
$\text{R}\,(\mu N \to eN)$	7×10^{-13} (Au)	12.	$\sim 10^{-17}$ (Al)	1.8×10^{2}
$\text{BR}\,(\mu \to 3e)$	10^{-12}	13.	$\sim 10^{-16}$	1.3×10^{2}

Bound based on $$c_{ij} = \frac{eg^2}{16\pi^2}\frac{m_\mu}{\Lambda^2}$$

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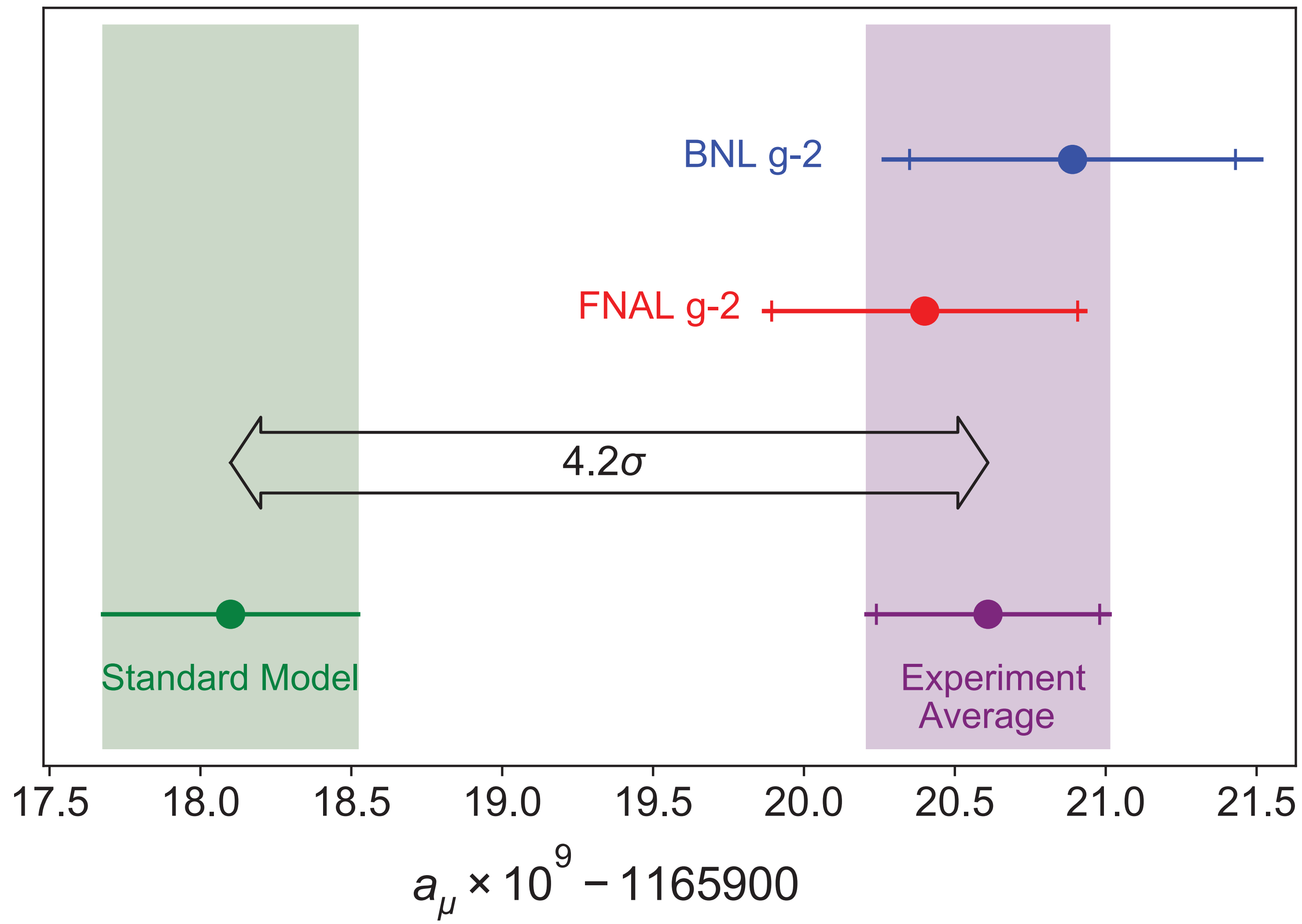
Somewhat arbitrary choice! ***Not*** MFV.

Rough attempt at apples-to-apples comparison.

Models of flavor/CP change which are best.

Fermilab's Update on Muon $g-2$



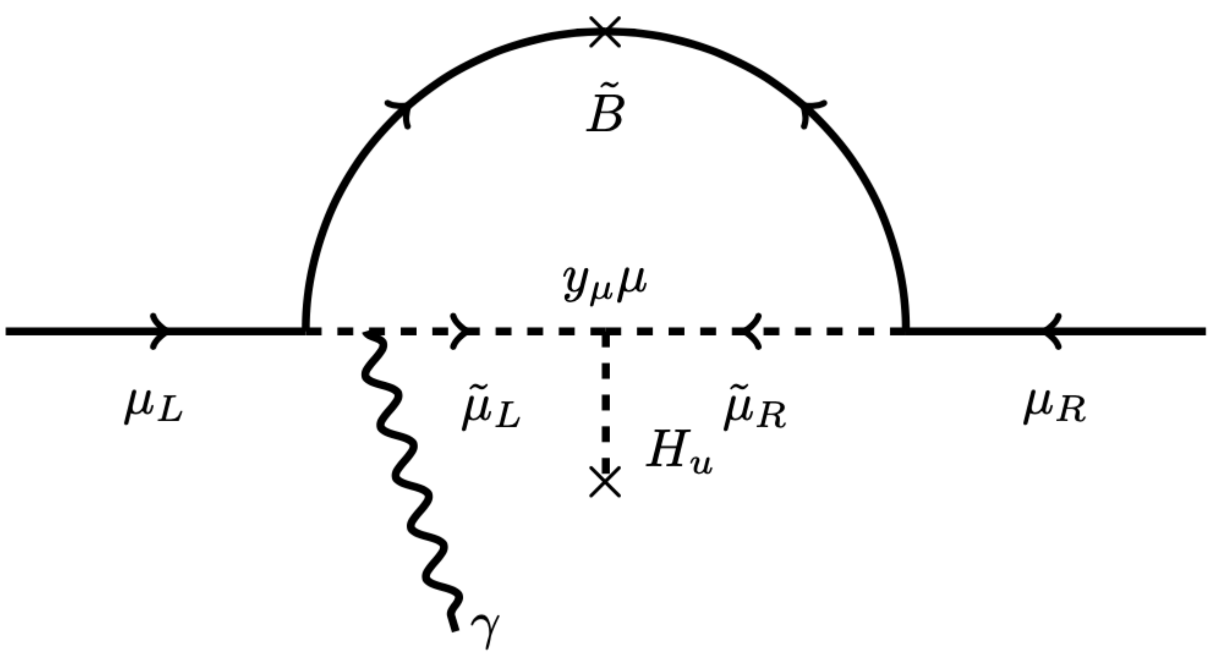
LHC Run 3 should be targeting electroweak physics (e.g. sleptons/charginos/neutralinos in SUSY, but more generally). But ***not ruled out yet***.

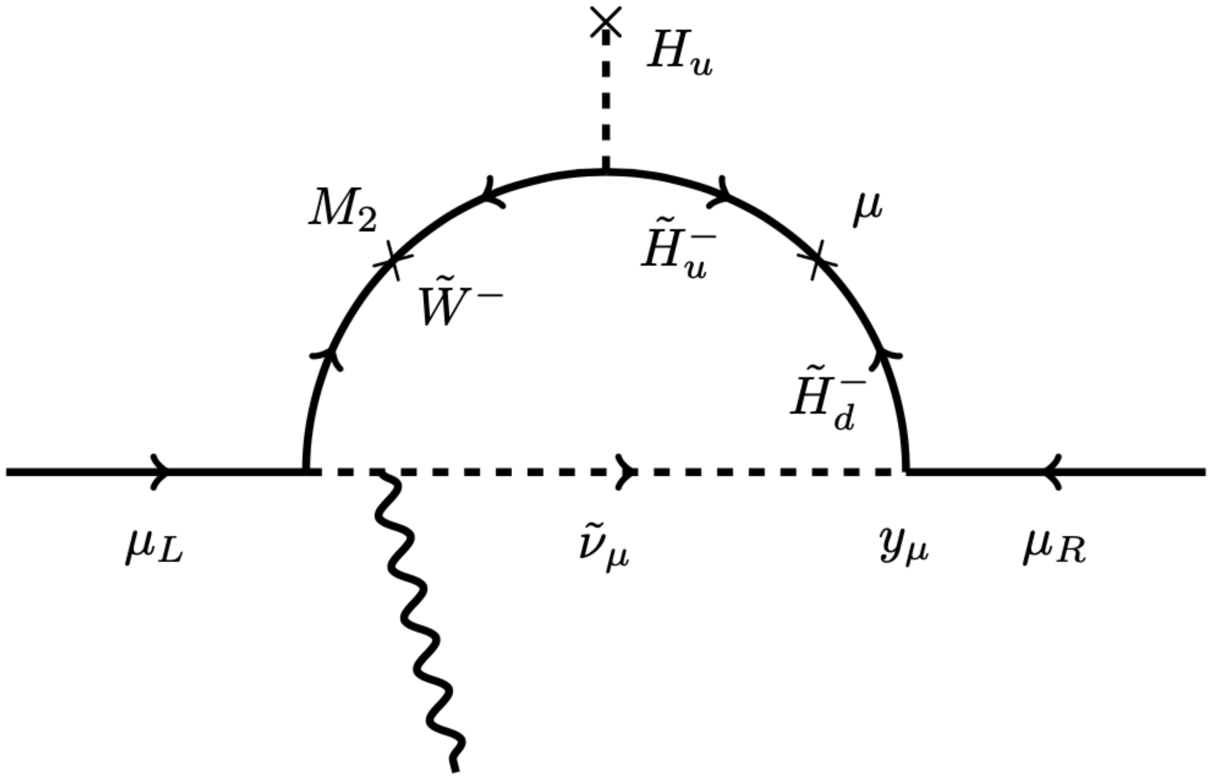
Muon $g-2$ and SUSY

Basic dimensional analysis: new physics around weak scale!

$$\Delta a_\mu \sim \left(\frac{g^2}{8\pi^2}\right)\left(\frac{m_\mu}{M_{\mathrm{BSM}}}\right)^2 \sim 2.5\times 10^{-9} \Rightarrow M_{\mathrm{BSM}} \sim 150\ \mathrm{GeV}$$

e.g., from smuon/bino or sneutrino/chargino loops:





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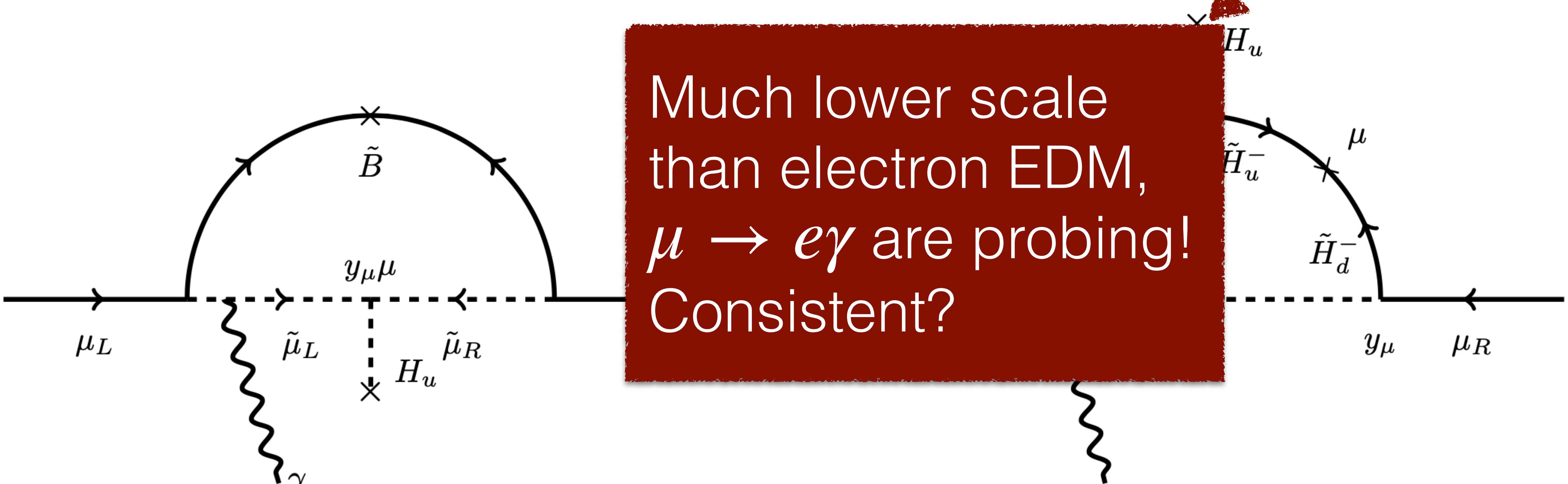
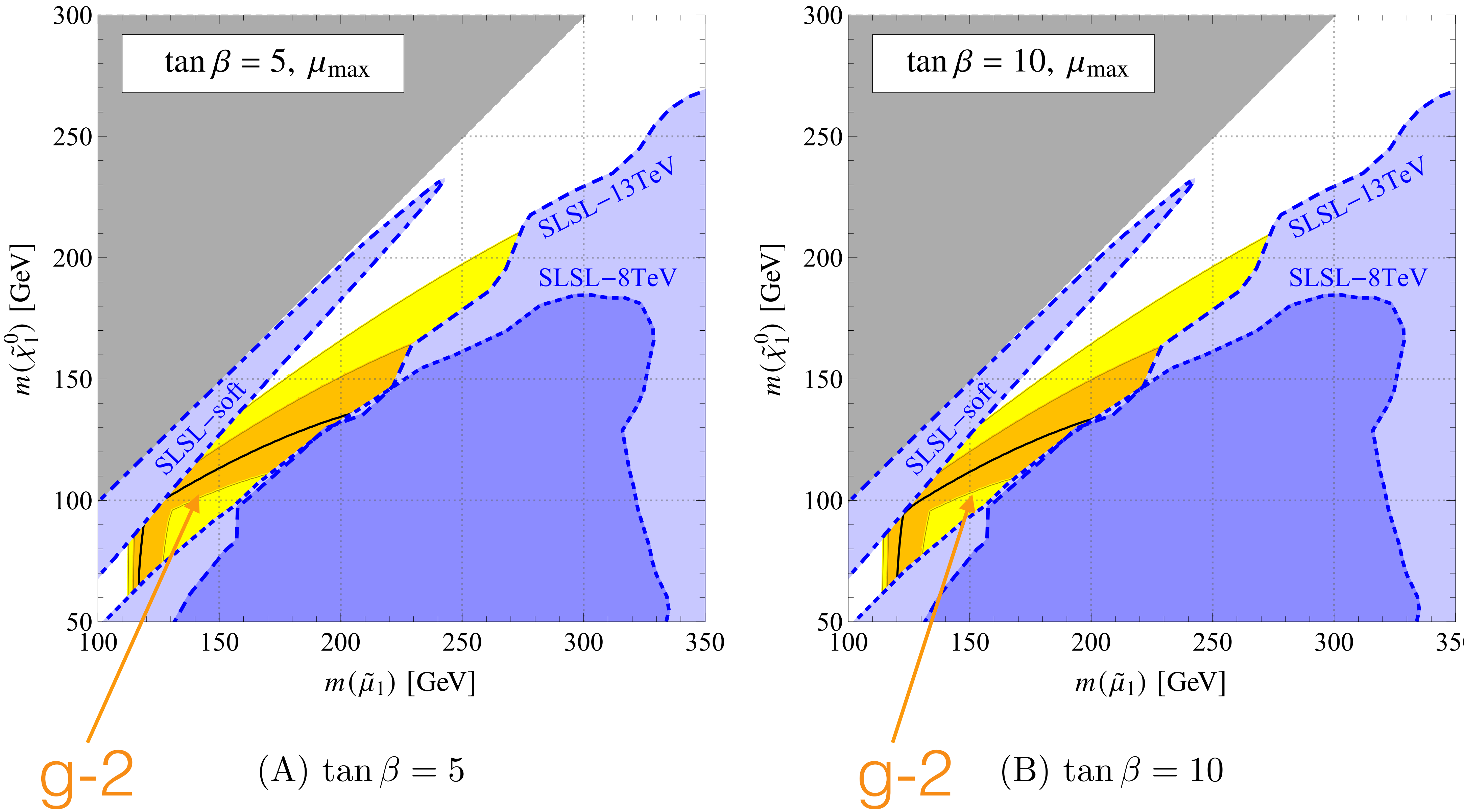


Much lower scale than electron EDM, $\mu \to e\gamma$ are probing! Consistent?

Example: bino dominated loop $\propto \frac{\alpha_Y}{4\pi} \frac{m_\mu^2 M_1 \mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} \tan\beta$

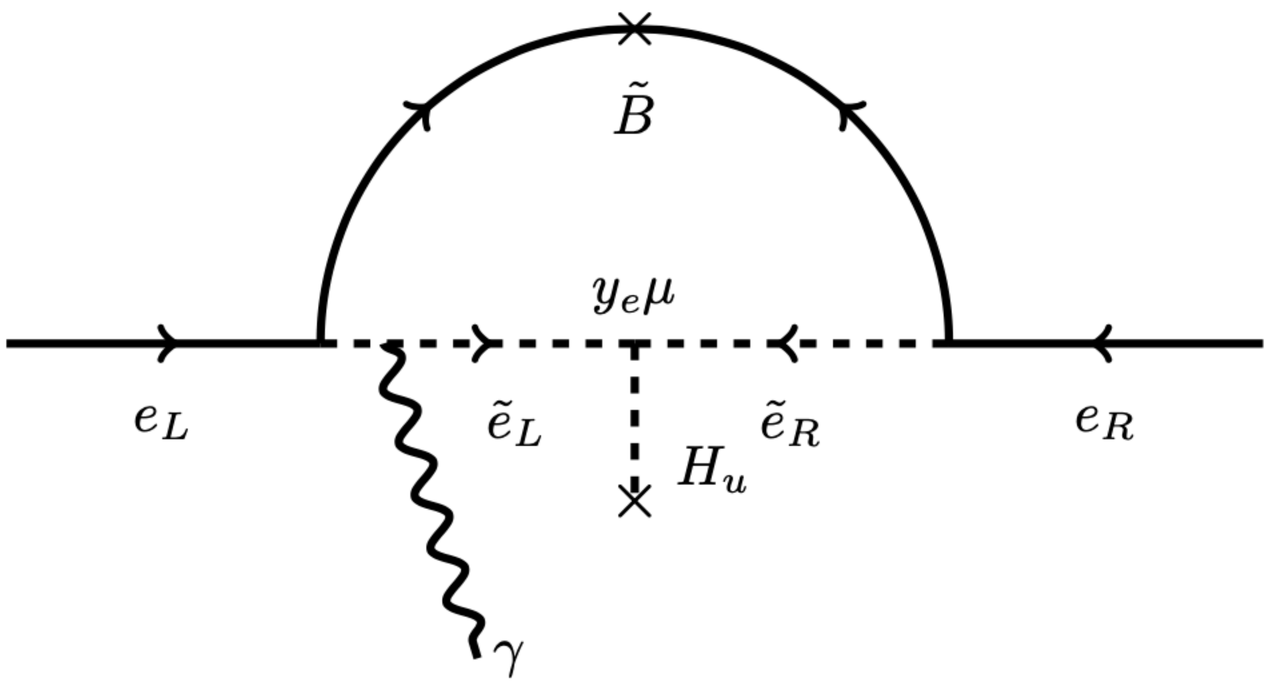
smuons, bino ***Escapes LHC discovery so far.***

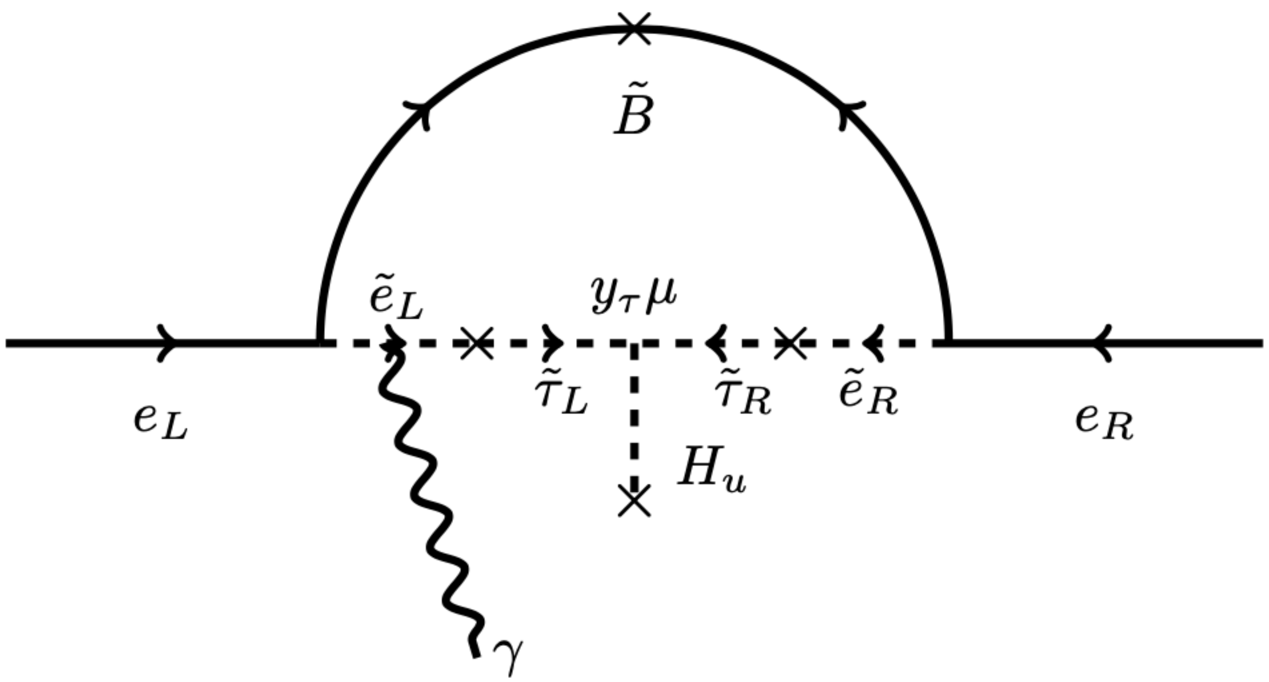


(A) $\tan\beta = 5$ (B) $\tan\beta = 10$

Endo, Hamaguchi, Iwamoto, Kitahara 2104.03217

CP Violation with and without Flavor Violation





$$\propto m_e(\mu M_1)$$

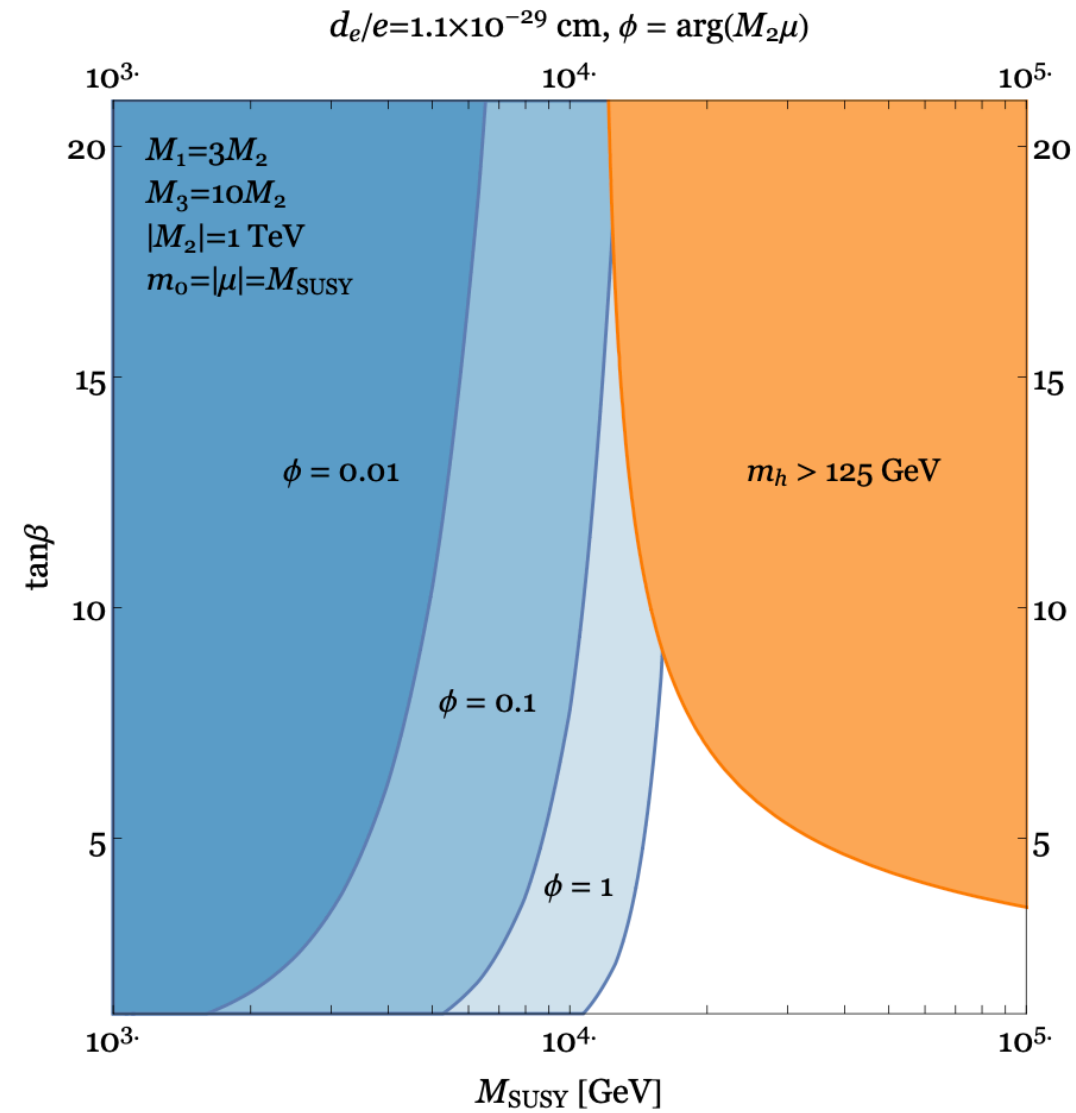
higgsino mass

bino mass

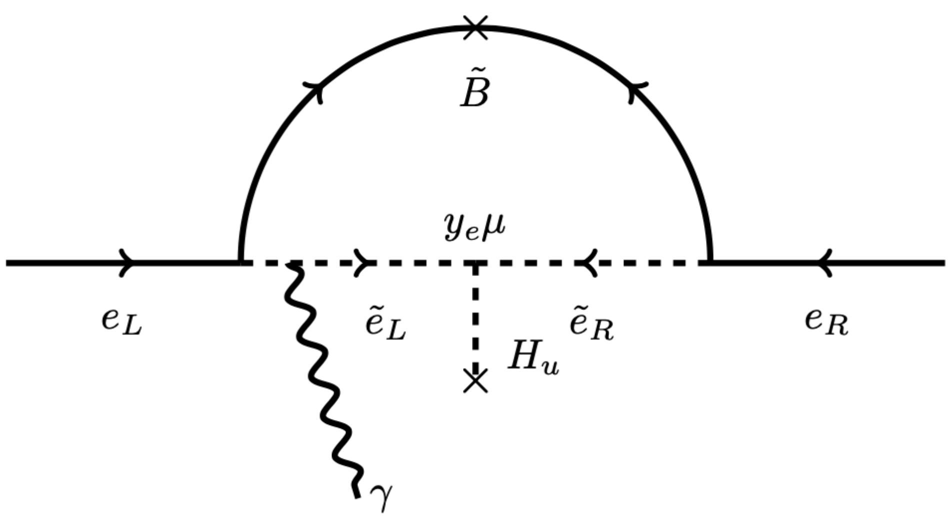
$$\propto m_\tau(\mu M_1(\delta^{LL}_{e\tau})(\delta^{RR}_{\tau e}))$$

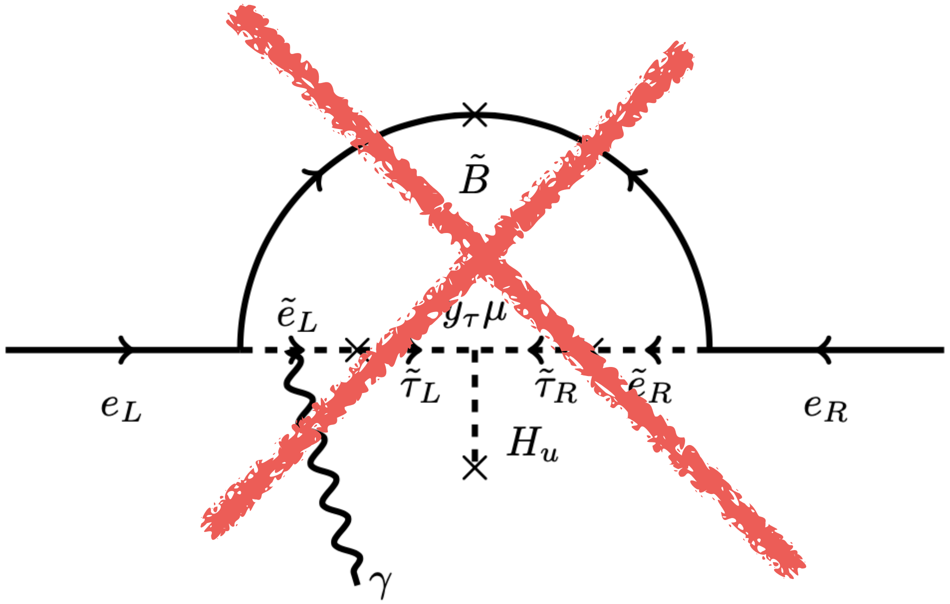
slepton flavor mixing

EDM Bounds with CP but no Flavor Violation



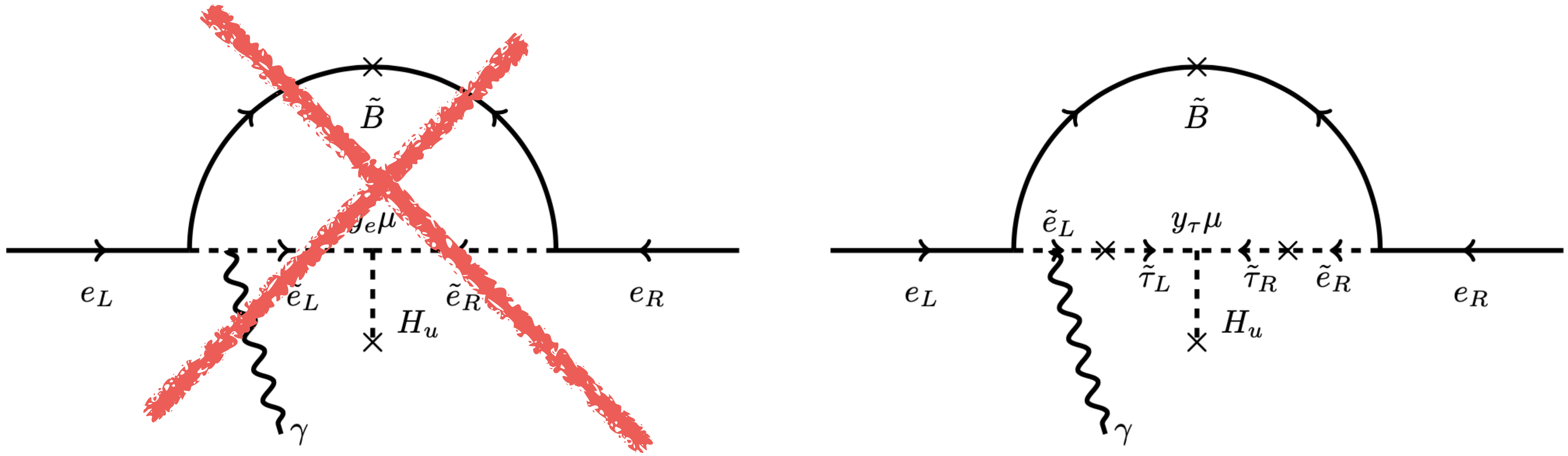
In the past, when estimating the mass scale probes by EDMs, I have generally assumed **Minimal Flavor Violation**, expecting flavor violation to usually make bounds ***stronger.***





EDM Bounds with Correlated Flavor and CP Violation

However, in some models it may be the other way around: flavor-violating interactions can be the ***dominant source of CP violation***.



To explain such a model, I should first review the notion of **"horizontal symmetries."**

Flavor puzzle

Patterns of masses and mixings

$$(Y_u)_{ij}(h \cdot q_i)\bar{u}_j + (Y_d)_{ij} h^\dagger q_i \bar{d}_j + (Y_e)_{ij} h^\dagger \ell_i \bar{e}_j$$

$(1,2)_{1/2}(3,2)_{1/6}(\bar{3},1)_{-2/3}$ $(1,2)_{-1/2}(3,2)_{1/6}(\bar{3},1)_{1/3}$ $(1,2)_{-1/2}(1,2)_{-1/2}(1,1)_1$

Mass eigenvalues in GeV:

173, 1.3, 0.002 4.2, 0.093, 0.005 1.8, 0.106, 0.0005

Three to five orders of magnitude spread. Mixings also very structured (in quark sector):

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

Froggatt-Nielsen models

One or more additional U(1) charges, *different in different generations*. ("**Horizontal symmetry**.")

Example: $H(h) = 0$
$H(q_1) = 3,\ H(q_2) = 2,\ H(q_3) = 0$
$H(\bar{u}_1) = 4,\ H(\bar{u}_2) = 1,\ H(\bar{u}_3) = 0$

This allows ***only*** the top-quark Yukawa coupling,

$$(Y_u)_{33}(h \cdot q_3)\bar{u}_3$$

because it is H-neutral, explaining why the top is so heavy.

Froggatt, Nielsen,
Nucl.Phys.B 147 (1979), 277

Froggatt-Nielsen models

Don't want to ***completely*** forbid other masses. Suppose the H-symmetry is ***spontaneously broken*** by the vacuum expectation value of a gauge-singlet scalar S:

$$H(S) = -1, \quad \frac{\langle S \rangle}{\Lambda} \sim \lambda \approx 0.2$$

In this way we can reproduce small masses/mixings, e.g., with our charge assignments:

$$c_{22}\left(\frac{S}{\Lambda}\right)^3 (h \cdot q_2)\bar{u}_2 \sim c_{22}\lambda^3 (h \cdot q_2)\bar{u}_2 \sim \mathcal{O}(1) \times (1.4\,\mathrm{GeV}) c\bar{c}$$

$$c_{11}\left(\frac{S}{\Lambda}\right)^7 (h \cdot q_1)\bar{u}_1 \sim c_{11}\lambda^7 (h \cdot q_1)\bar{u}_1 \sim \mathcal{O}(1) \times (2.2\,\mathrm{MeV}) u\bar{u}$$

CP as a spontaneously broken symmetry

CP as a fundamental symmetry, **spontaneously broken.**

Not hard to arrange, e.g., supersymmetric example:

$$W = X(S_1\bar{S}_1 - \lambda^4) + Y(c_1 S_2^4 + c_2 S_2^3 S_1^3 + c_3 S_1^6)$$

$$\langle S_1 \rangle = \lambda^2, \quad \langle S_2 \rangle^2 = \frac{-c_2 \pm \sqrt{c_2^2 - 4c_1c_3}}{2c_1} \langle S_1 \rangle^3 \sim \mathrm{e}^{i \times \mathcal{O}(1)} \lambda^6$$

Plays a role in some proposed solutions to the Strong CP problem (Nelson / Barr)

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Invariant, O(1) CPV phase when solving for minimum of potential.

$$W = X(S_1\bar{S}_1 - \lambda^4 \ldots {}_1^6)$$

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The Nir-Rattazzi Idea

CP as a fundamental symmetry, **spontaneously broken,** ***by VEVs of fields carrying flavor (horizontal) charge.***

$$H(S_1) = -2, \quad H(S_2) = -3$$

Yukawa terms can acquire CPV phases, e.g.,
$\left(\frac{S_2}{\Lambda}\right)(h \cdot q_i)\bar{u}_j$ allowed if $H(q_i) + H(\bar{u}_j) = 3$.

Not hard to build a model that gets the CKM phase right.

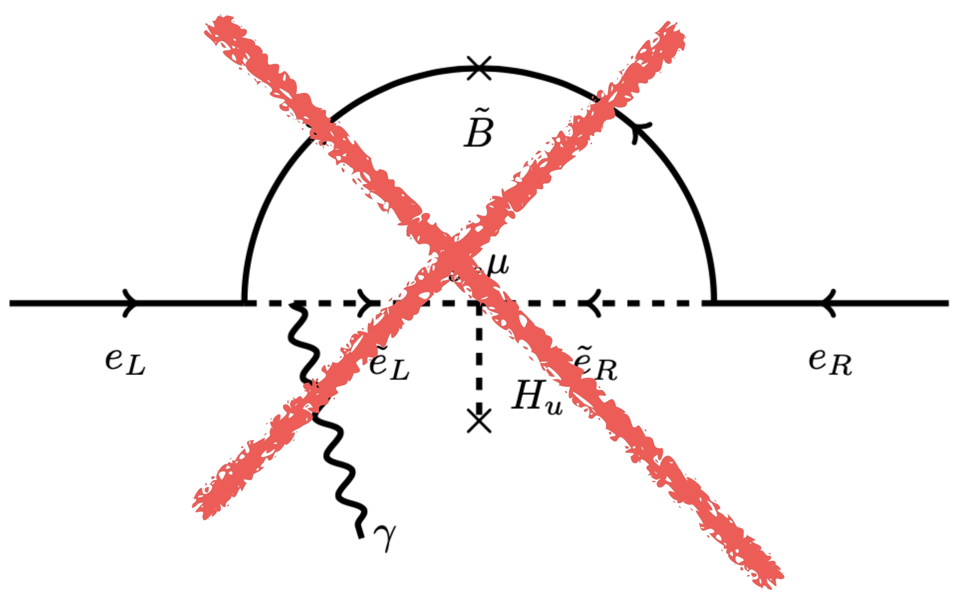
Yosef Nir and Riccardo Rattazzi, arXiv:hep-ph/9603233

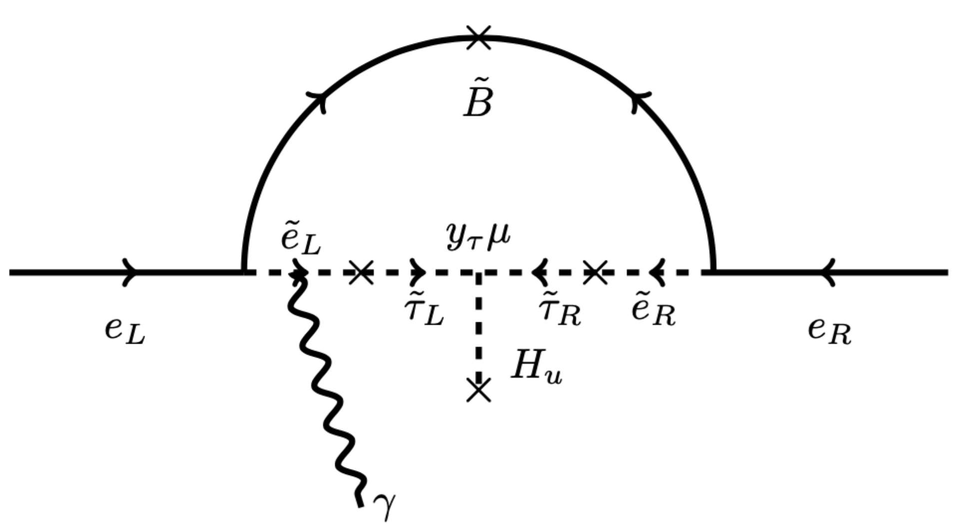
Suppressed CPV *without* Flavor Violation

If CP violation comes only from flavor-violating VEVs, then **flavor-conserving CPV is very suppressed**.

$$\mu \sim \mu_0 \left[1 + \left(\frac{S_1^\dagger}{\Lambda} \right)^3 \left(\frac{S_2}{\Lambda} \right)^2 \right] \sim \mu_0 (1 + \mathcal{O}(10^{-9}) i)$$

Can completely change expectations about relative size of EDM contributions, EDMs versus $\mu \to e\gamma$





Our Recent Work

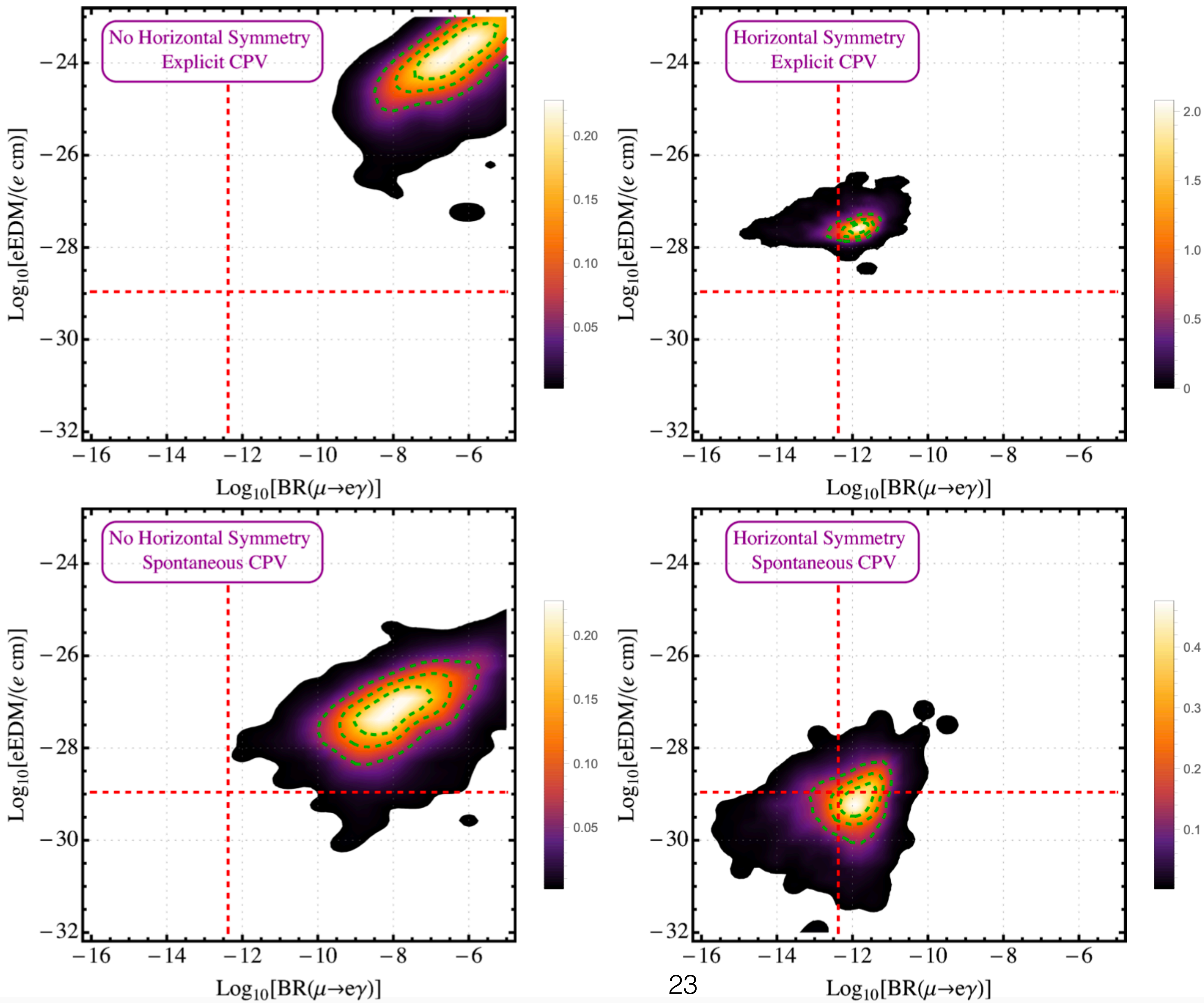
We have extended the Nir-Rattazzi idea to the **lepton sector,** including **Majorana neutrino masses.**

For horizontal charges that achieve the right pattern of masses and mixings, we can compute the electron EDM, charged lepton flavor violation, and muon $g-2$, and understand the relative reach.

(Simplest models can't fit muon $g-2$ without substantial fine-tuning; work in progress achieves this.)

arXiv:2104.02679 with Daniel Aloni, Pouya Asadi, Yuichiro Nakai, Motoo Suzuki

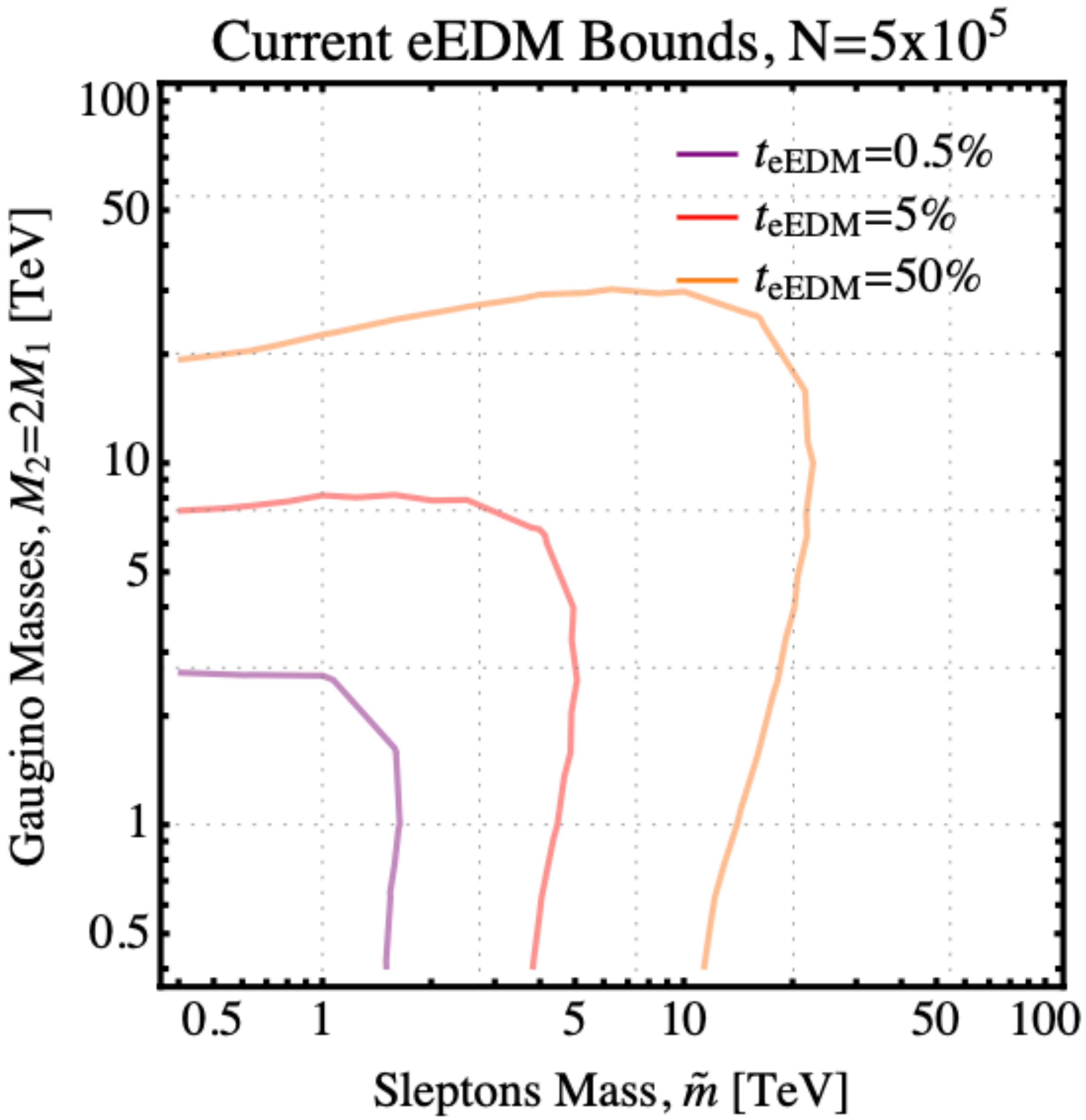
Flavor and CP symmetries



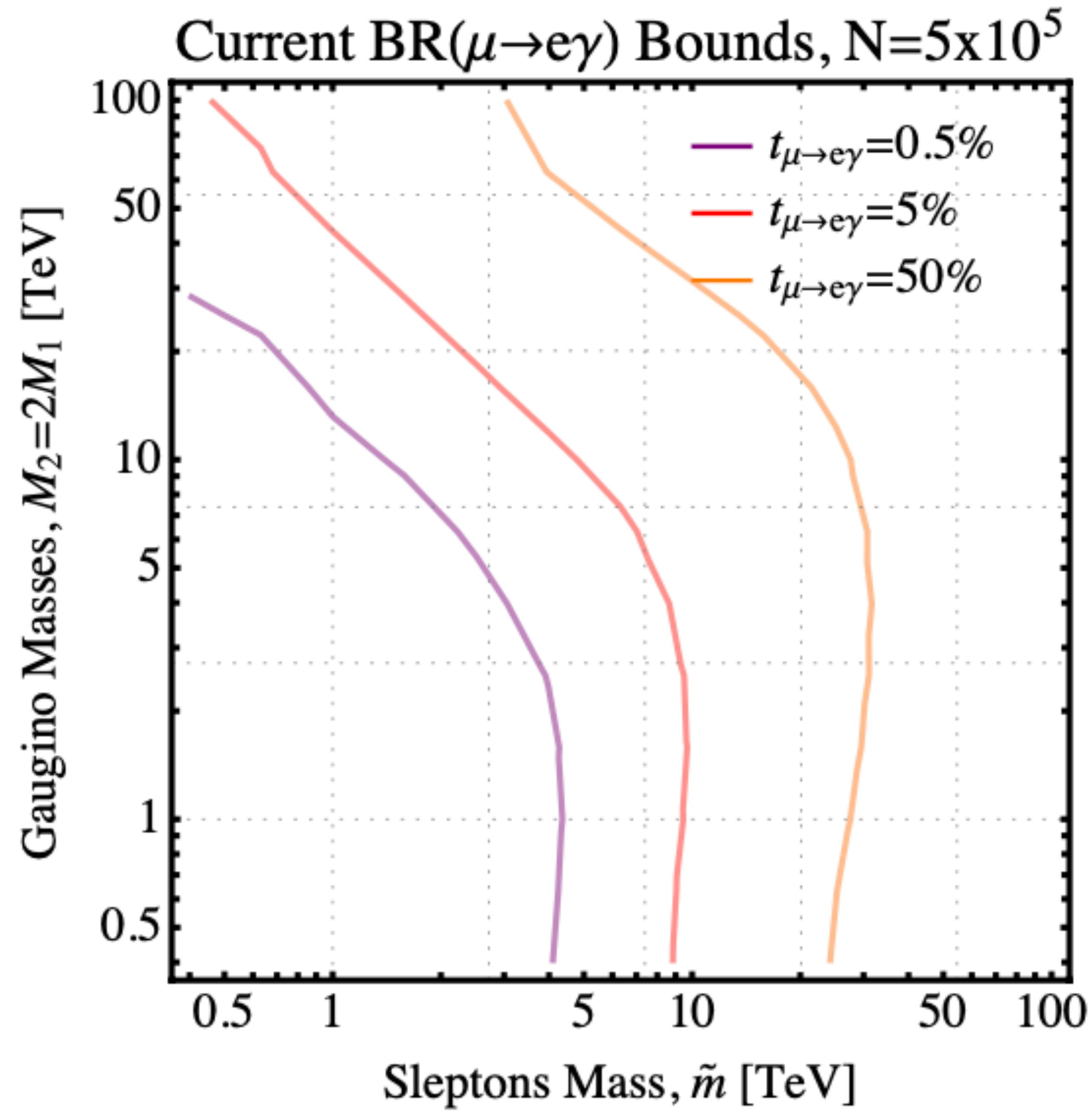
~10 TeV scalars, 1 TeV gauginos

Aloni, Asadi, Nakai, MR, Suzuki '21

Current Bounds on a Flavor Model

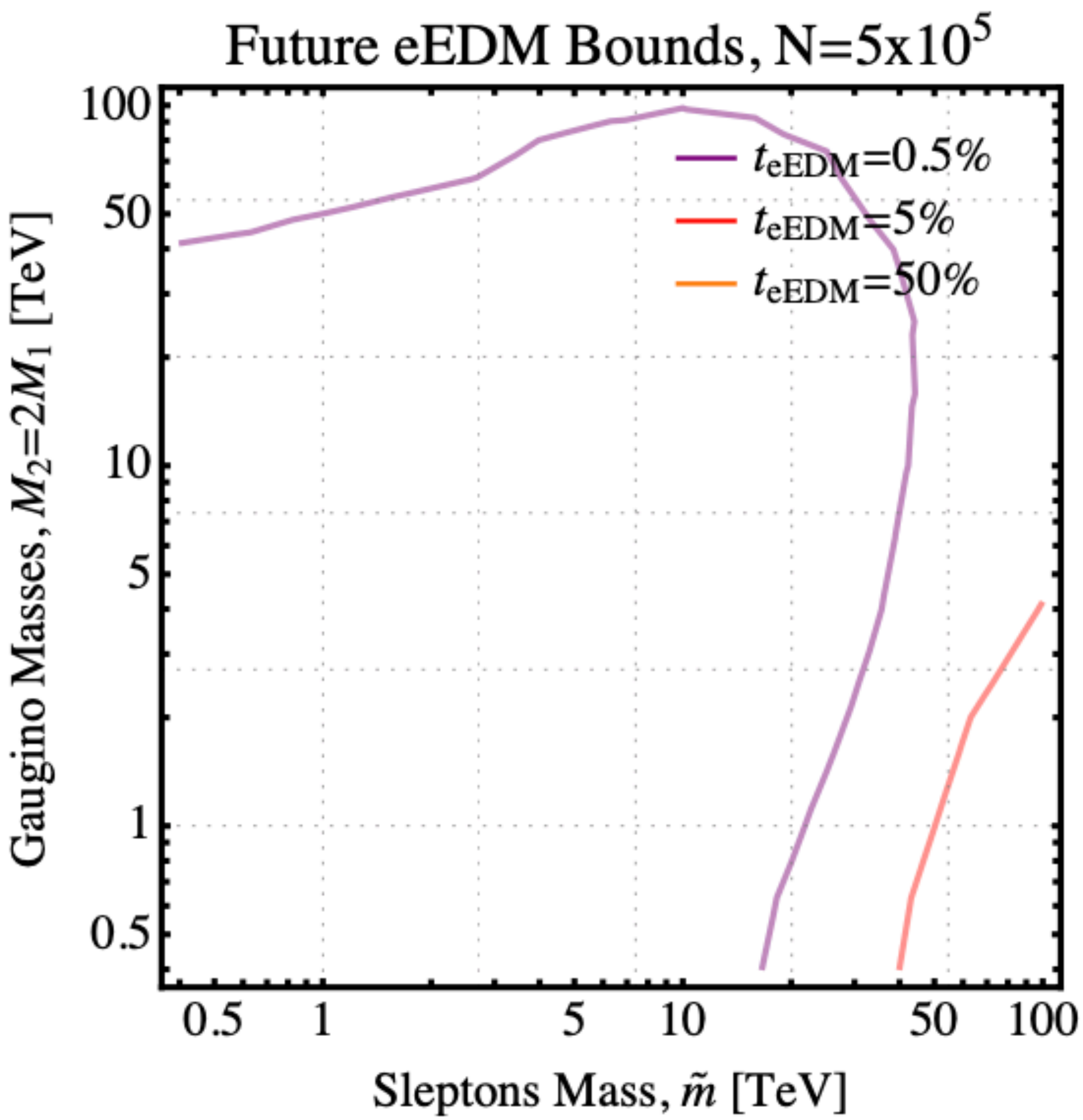


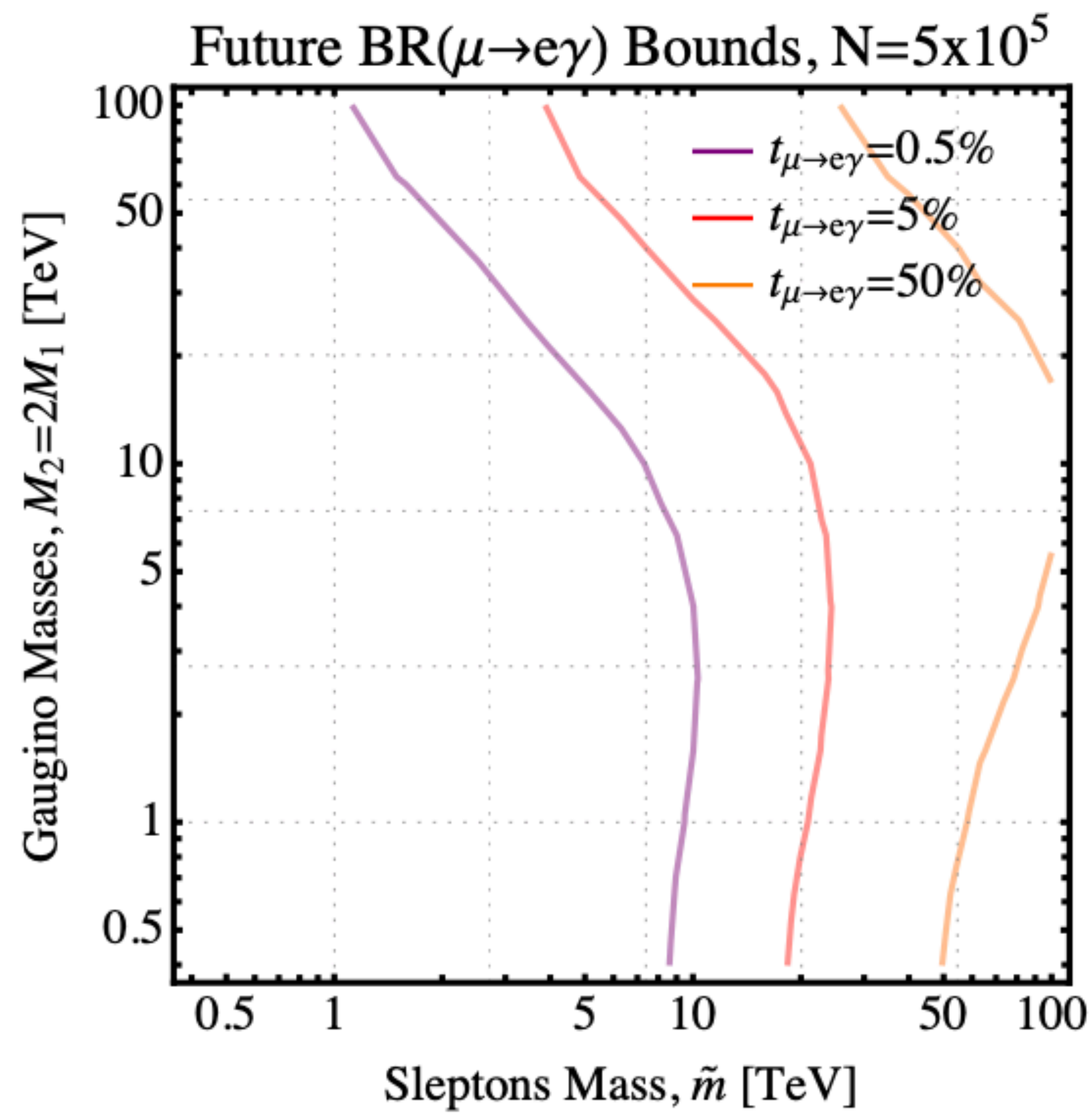
$1.1 \times 10^{-29}\, e\,\mathrm{cm}$



4.2×10^{-13}

Future Bounds on a Flavor Model





$10^{-32}\, e\,\text{cm}$ $\qquad$ 10^{-14}

Note square-root vs. 1/4-power scaling

Conclusions

EDMs can arise from TeV-scale particles if both flavor and CP are spontaneously broken symmetries.

Conceptual questions: what does it mean for CP to be a gauge symmetry? Cosmological defects?

The coming ~decade of experiments could give rise to **correlated signals** in EDMs, $g-2$, $\mu \to e\gamma$, neutrino CP phase. Pattern as "**fingerprint**" of underlying fundamental physics.