Muon Colliders and Complementary Probes

Based mostly on 2103.14043, 2203.08825

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In collaboration with Qianshu Lu & Matthew Reece
(and many others)

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Why is Complementarity Important?

~~"There is no guarantee of new physics at the TeV scale, so we need low-energy experiments to give us an indirect signal of new physics and build the case for future colliders."~~

A strong case for exploring the TeV scale already exists; low energy experiments are important for telling us about the *structure* of SM *and* BSM physics we might find there!

Goal: understand what these indirect tell us about new physics, and how we can test this directly at colliders!

Let's see how this works in a few examples…

Example: Lepton Flavor Violation

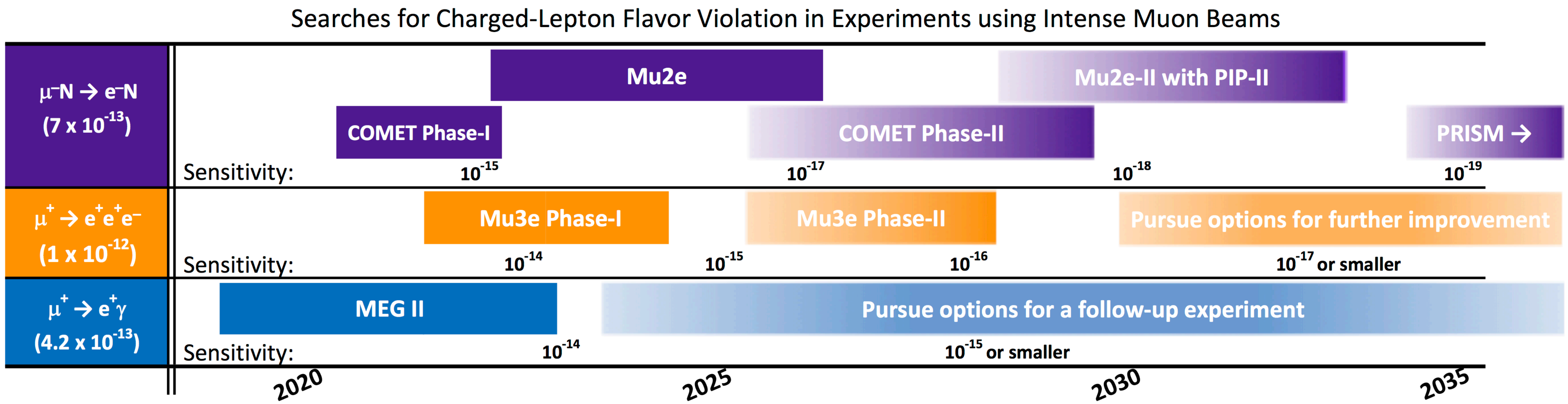
Lepton number is an accidental symmetry of the SM — generically violated by new physics.

However, current bounds suggest it must be very small:

$$\mathrm{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

(MEG + MEG II, 2310.12614)

Lesson: BSM couplings to leptons must be *flavor universal* or *aligned*



From [1812.06540]; see [2209.00142] and references within for more recent projections

cLFV in the MSSM

Focus on the right-handed selectron/smuon system:

$$\begin{pmatrix} \tilde{e}_R^\dagger & \tilde{\mu}_R^\dagger \end{pmatrix} \begin{pmatrix} m_R^2 + \Delta_{ee}^{RR} & \Delta_{e\mu}^{RR} \\ \left(\Delta_{e\mu}^{RR}\right)^* & m_R^2 + \Delta_{\mu\mu}^{RR} \end{pmatrix} \begin{pmatrix} \tilde{e}_R \\ \tilde{\mu}_R \end{pmatrix}$$

Universal terms dictated by SUSY, gauge invariance

When dominant, LFV suppressed by “super-GIM” mechanism

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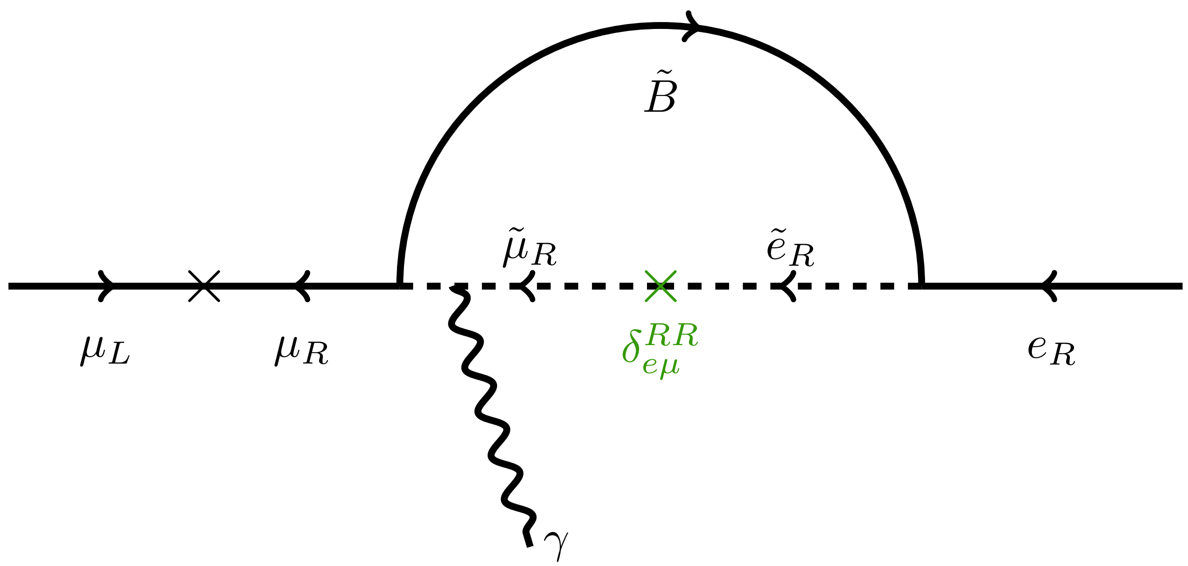
Flavor-violating, soft supersymmetry breaking terms

$\Longrightarrow$ flavor-violation a window into theory of SUSY-breaking

Low-Energy Constraints on the MSSM

For simplicity, assume lightest neutralino is pure Bino and that the other superpartners decouple.

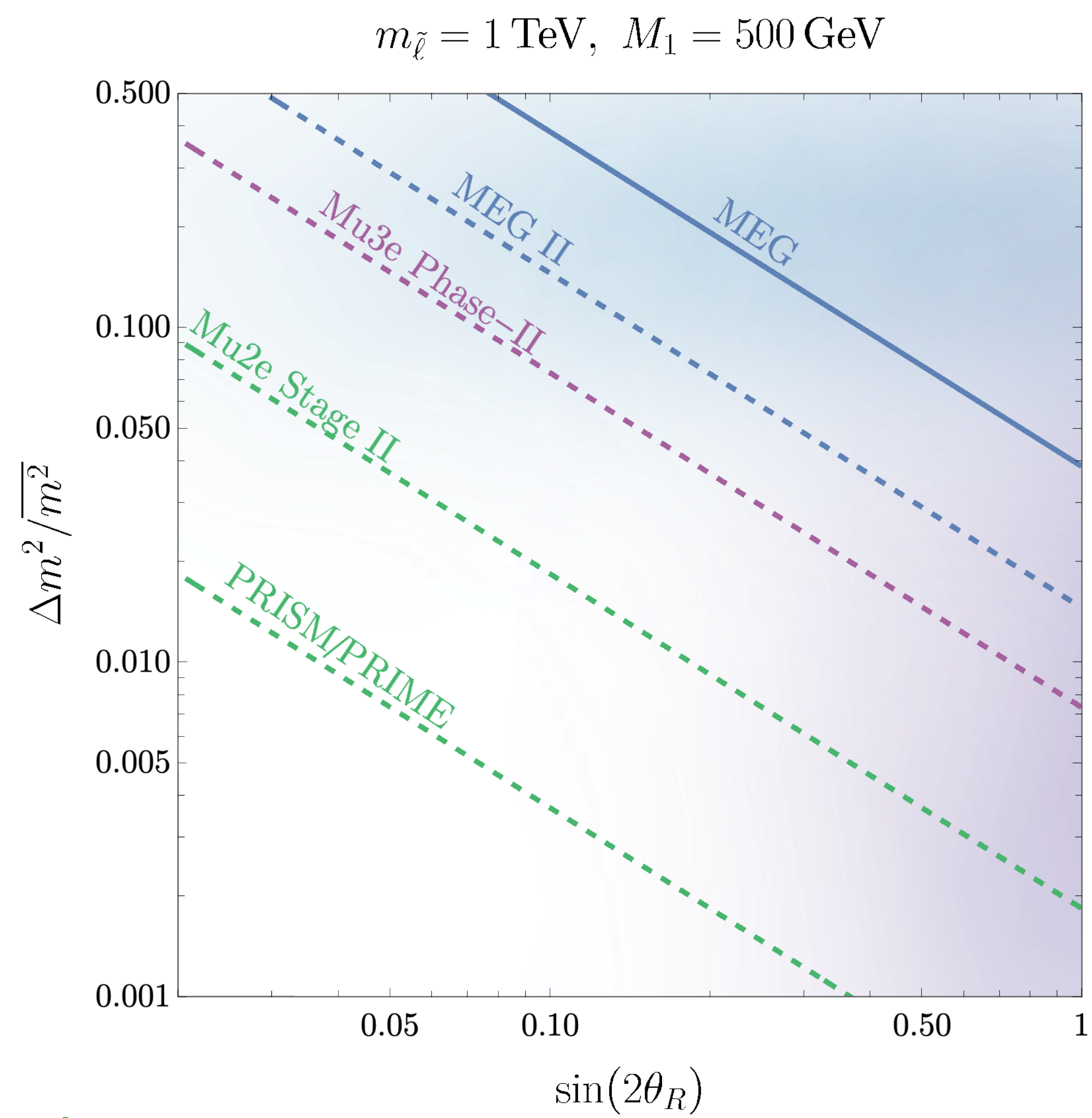
LFV dictated by dipole operator:



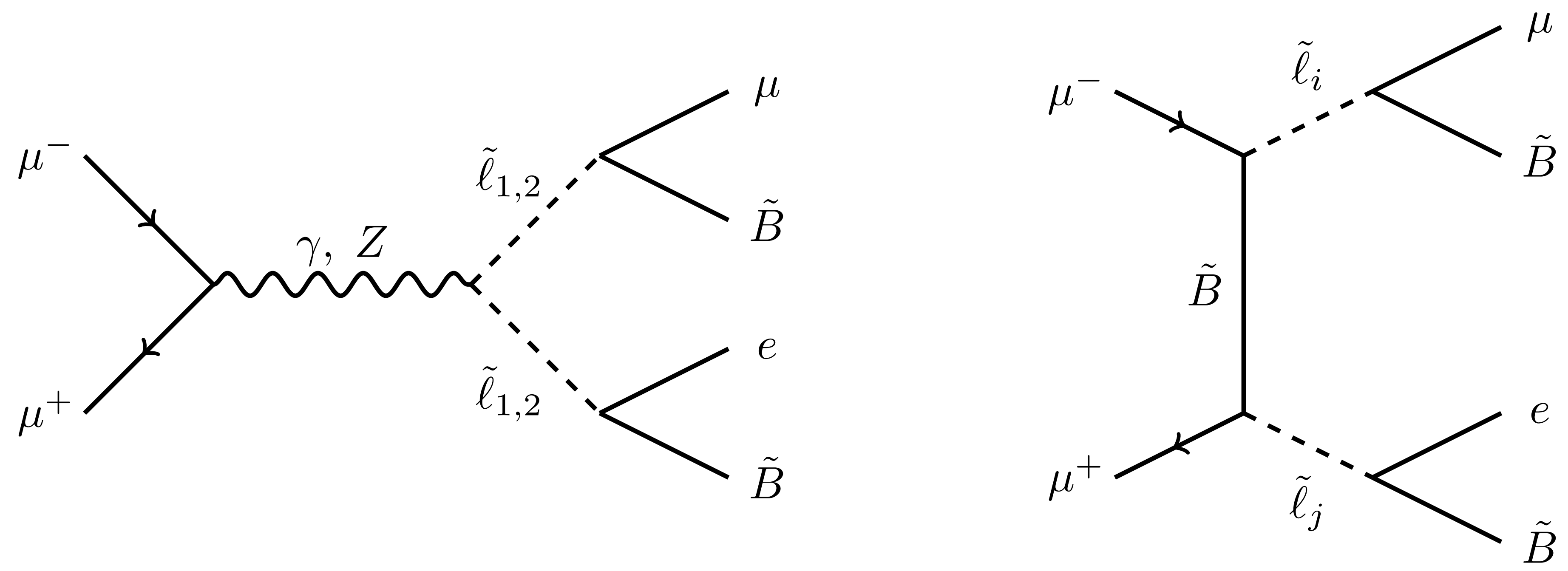
$$\mathcal{A}^R_{\mu e} = m_\mu \frac{\alpha_Y}{\pi} \delta^{RR}_{\mu e} \frac{1}{\overline{m^2}} f_{1n}\left(\frac{|M_1|^2}{\overline{m^2}}\right)$$

$$\delta^{RR}_{\mu e} = \frac{1}{2}\frac{\Delta m^2}{\overline{m^2}} \sin(2\theta_R)$$

Mass-insertion parameter governing flavor violation



LFV Signals at a Muon Collider:



The same physics can be *directly* tested at a muon collider via slepton pair-production with LFV decays!

$\Longrightarrow$ Rates at MuC depend on the same parameters as the low-energy LFV signals $(\sin 2\theta_R,\ \Delta m^2,\ \overline{m^2},\ M_1)$

This story was studied extensively in the context of e^+e^- machines

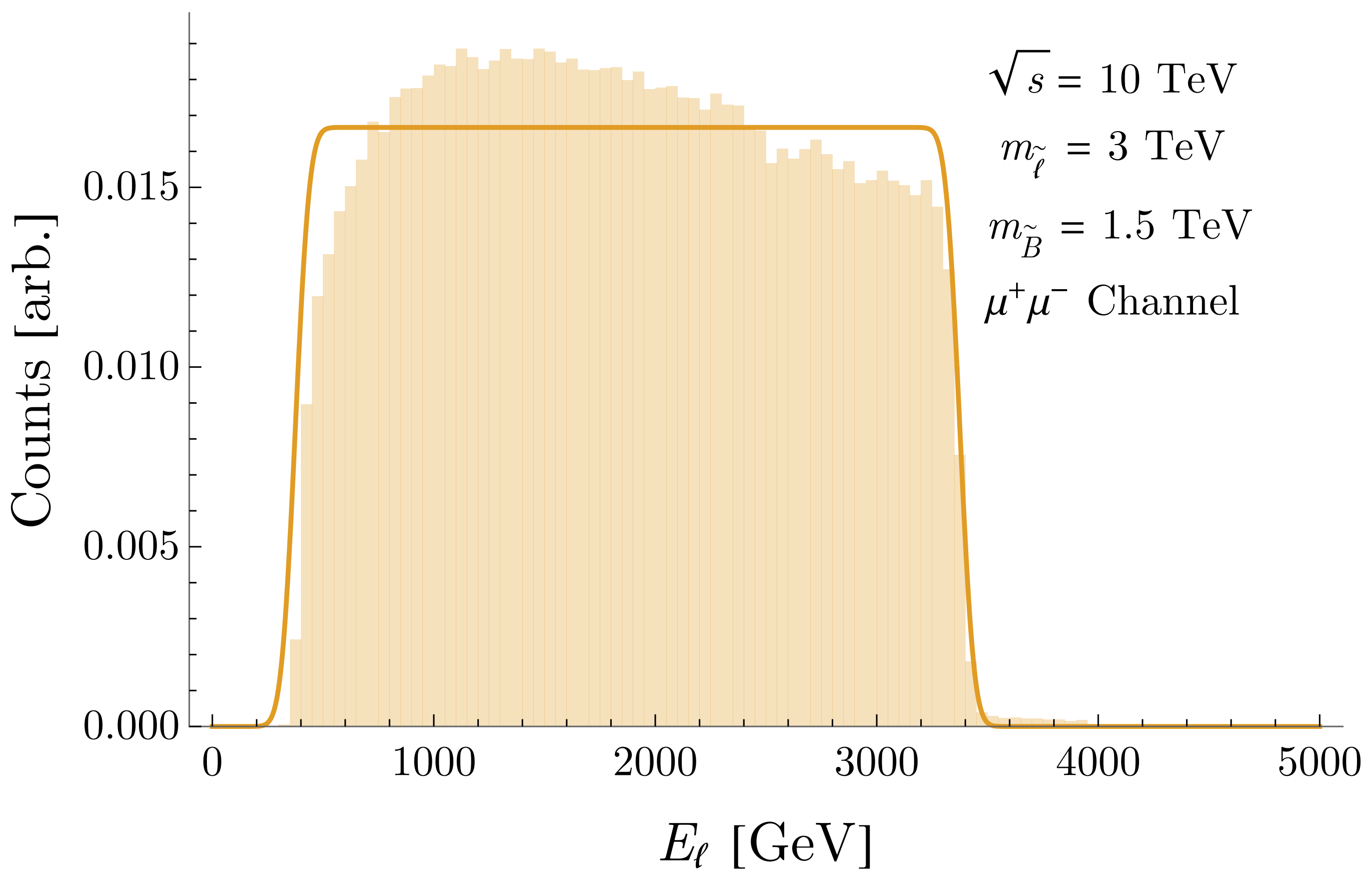
Arkani-Hamed, Cheng, Feng, Hall [hep-ph/9603431]

(see their discussion of the interference/oscillation effects in particular!)

New Challenges at a Muon Collider

Uncovering LFV signal requires eliminating W^+W^- backgrounds.

$\Longrightarrow$ Utilize measurement of the masses in flavor-symmetric final states:



Lepton energy spectrum has endpoints given by the slepton, Bino masses:

$$E_\ell = \frac{\sqrt{s}}{4}\left(1 - \frac{M_1^2}{m_{\tilde{\ell}}^2}\right)(1 + \beta\cos\theta_0)$$

(In context of e^+e^- machines, see e.g., Conley, Dreiner, Weinemann [1012.1035])

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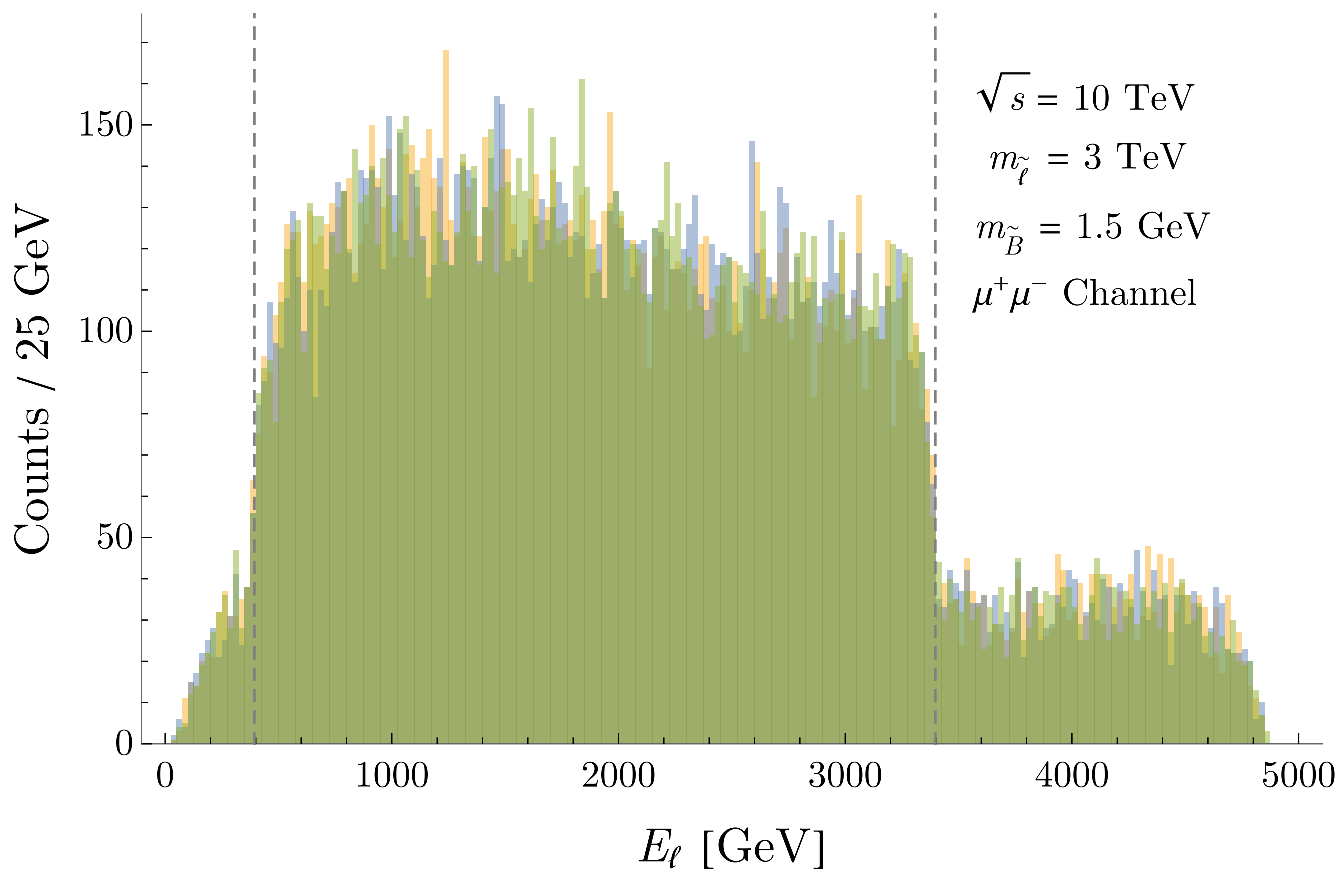

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Backgrounds parameterized with simple templates, performed likelihood fit for the endpoints

(see Freitas, [1107.3853] for an earlier study)

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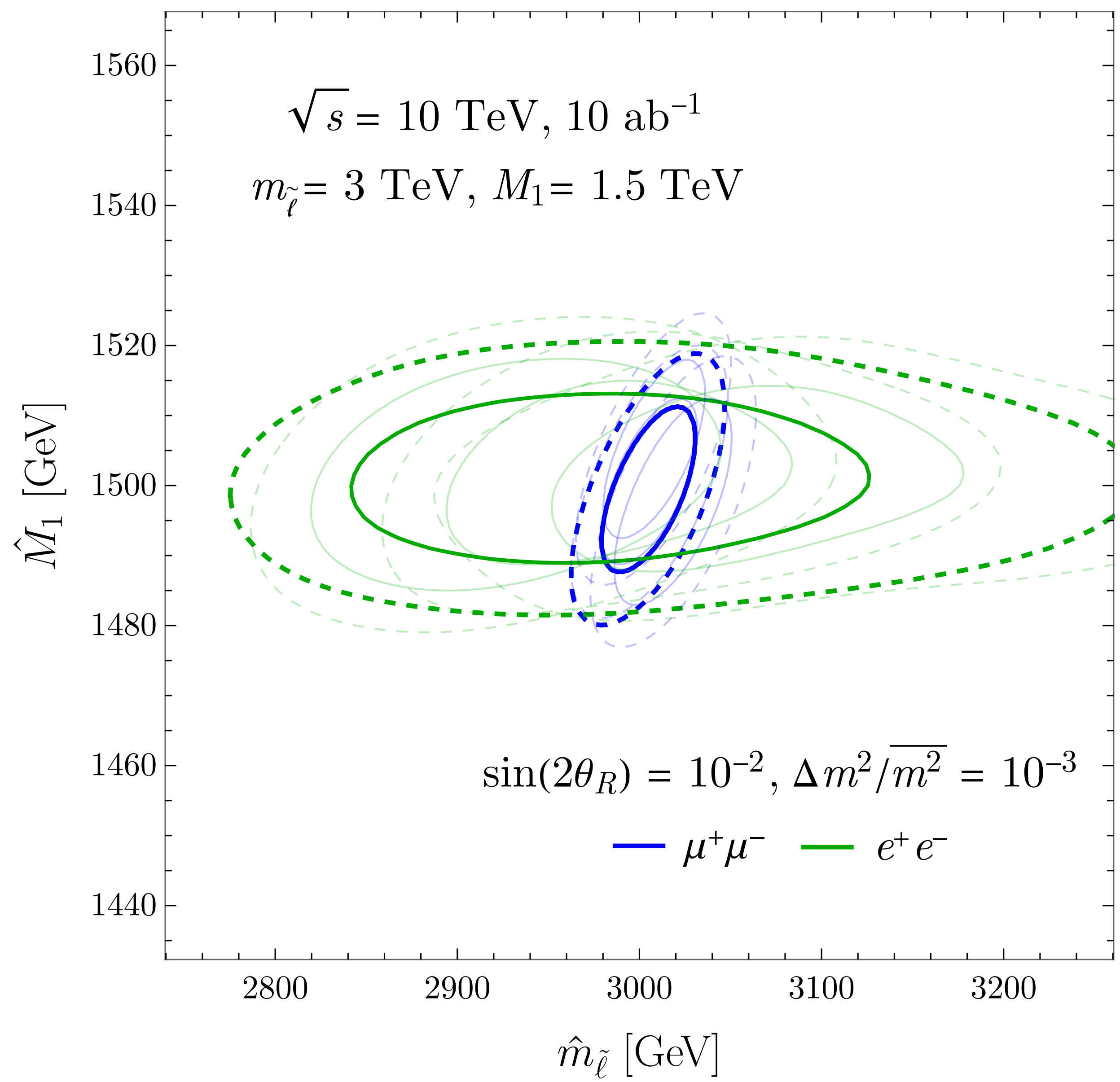

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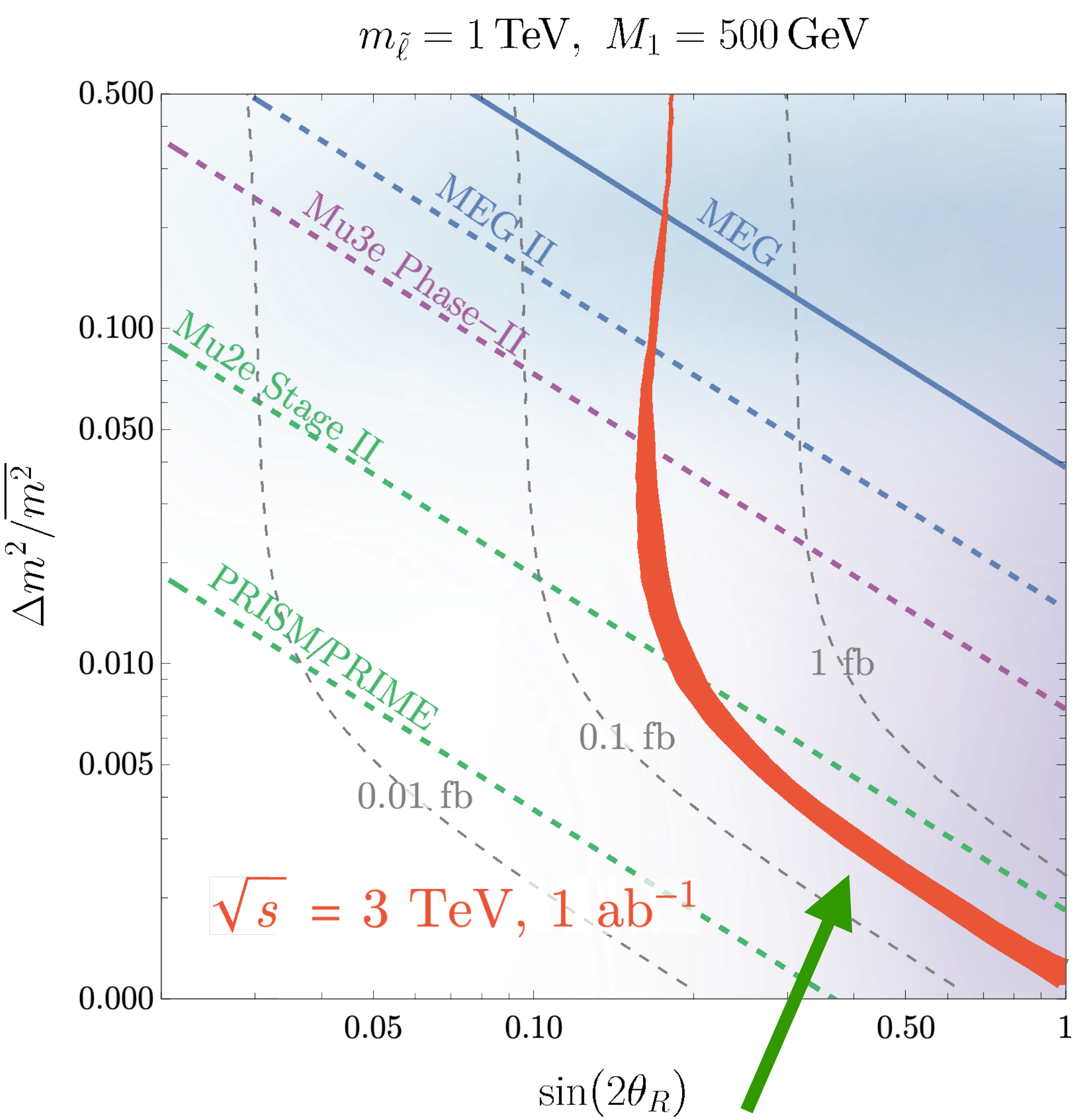
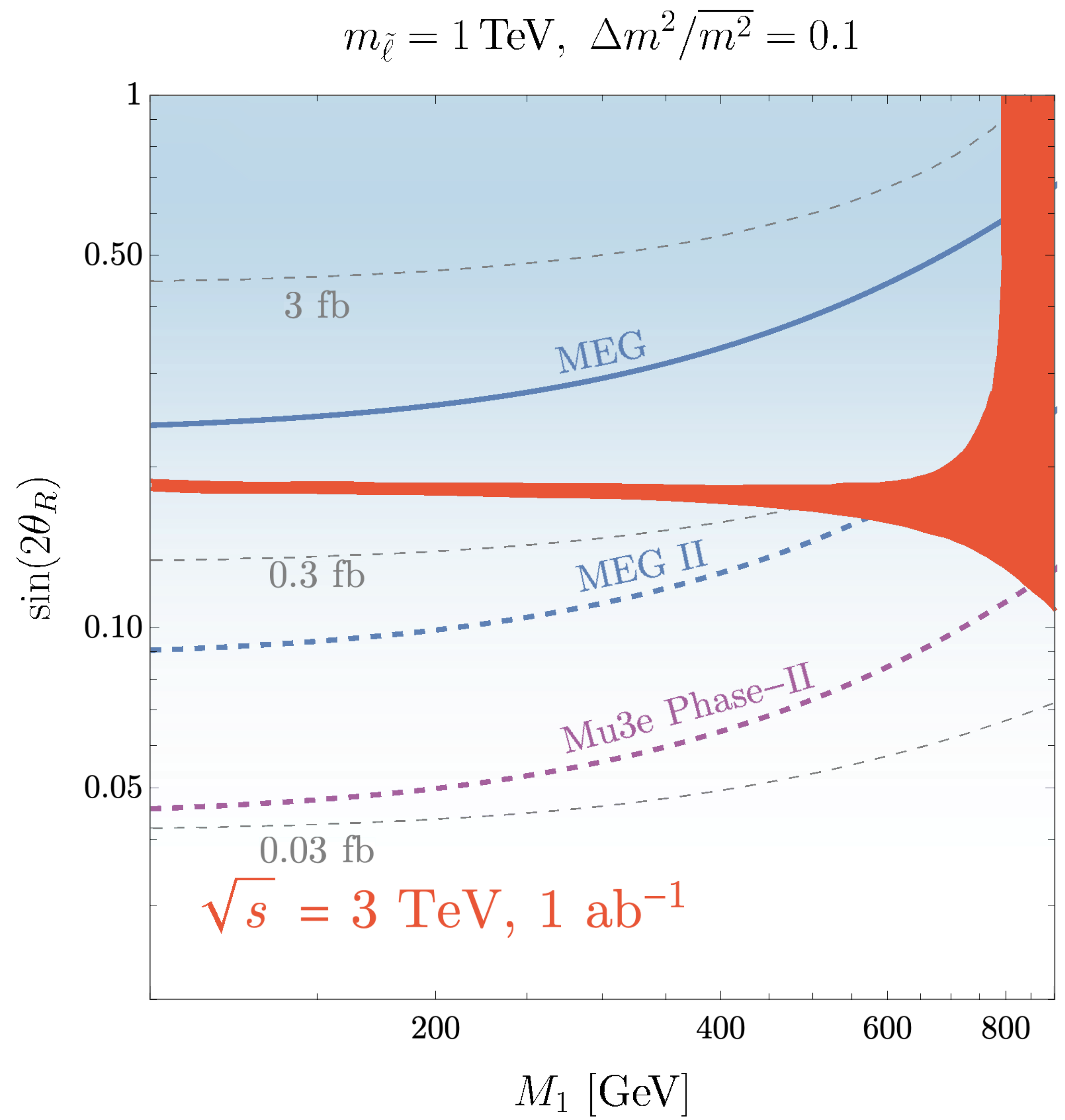
Muon Collider Discovery Reach





Suppression at small mass splitting due to interference

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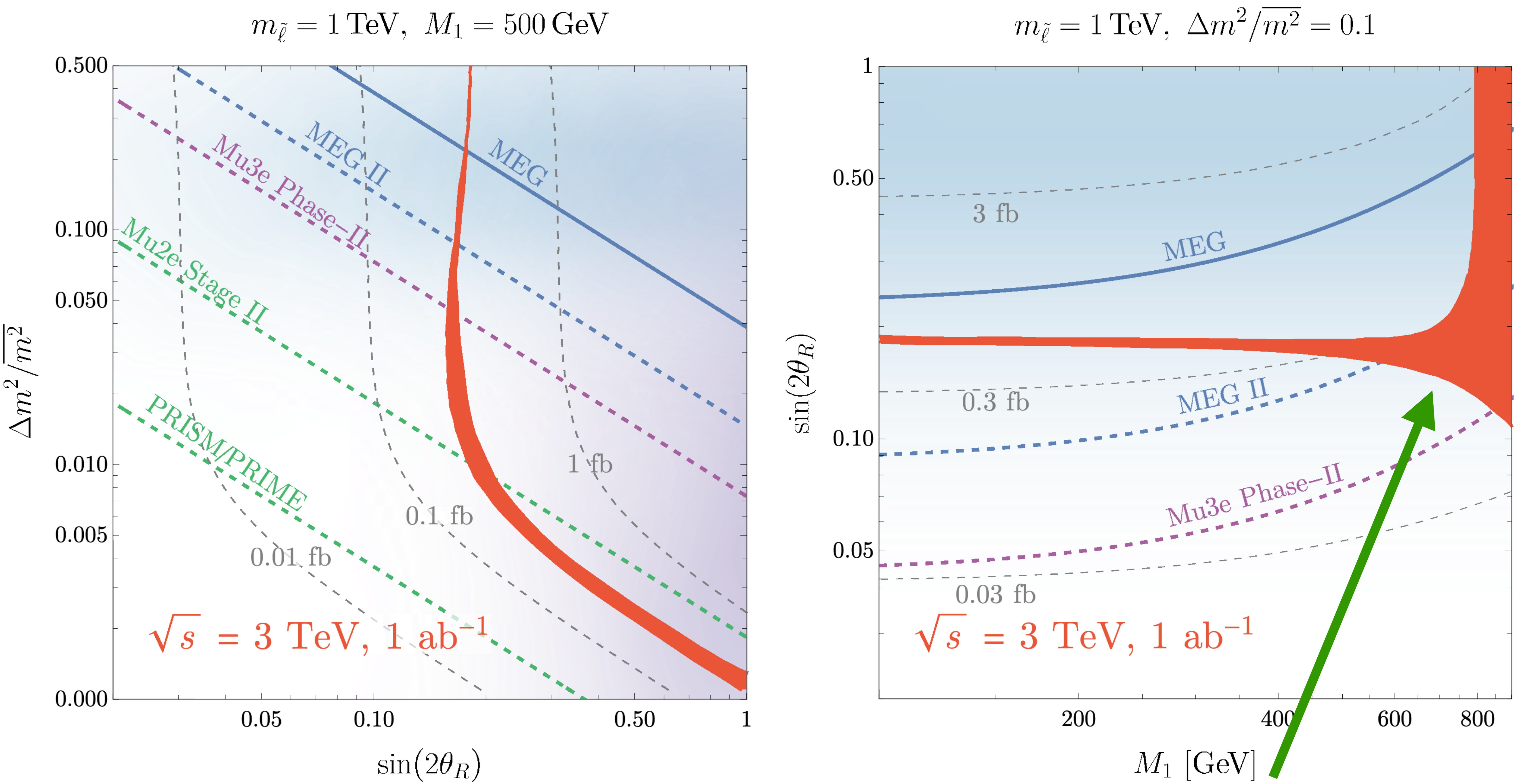

Difficult to measure the masses in the compressed region

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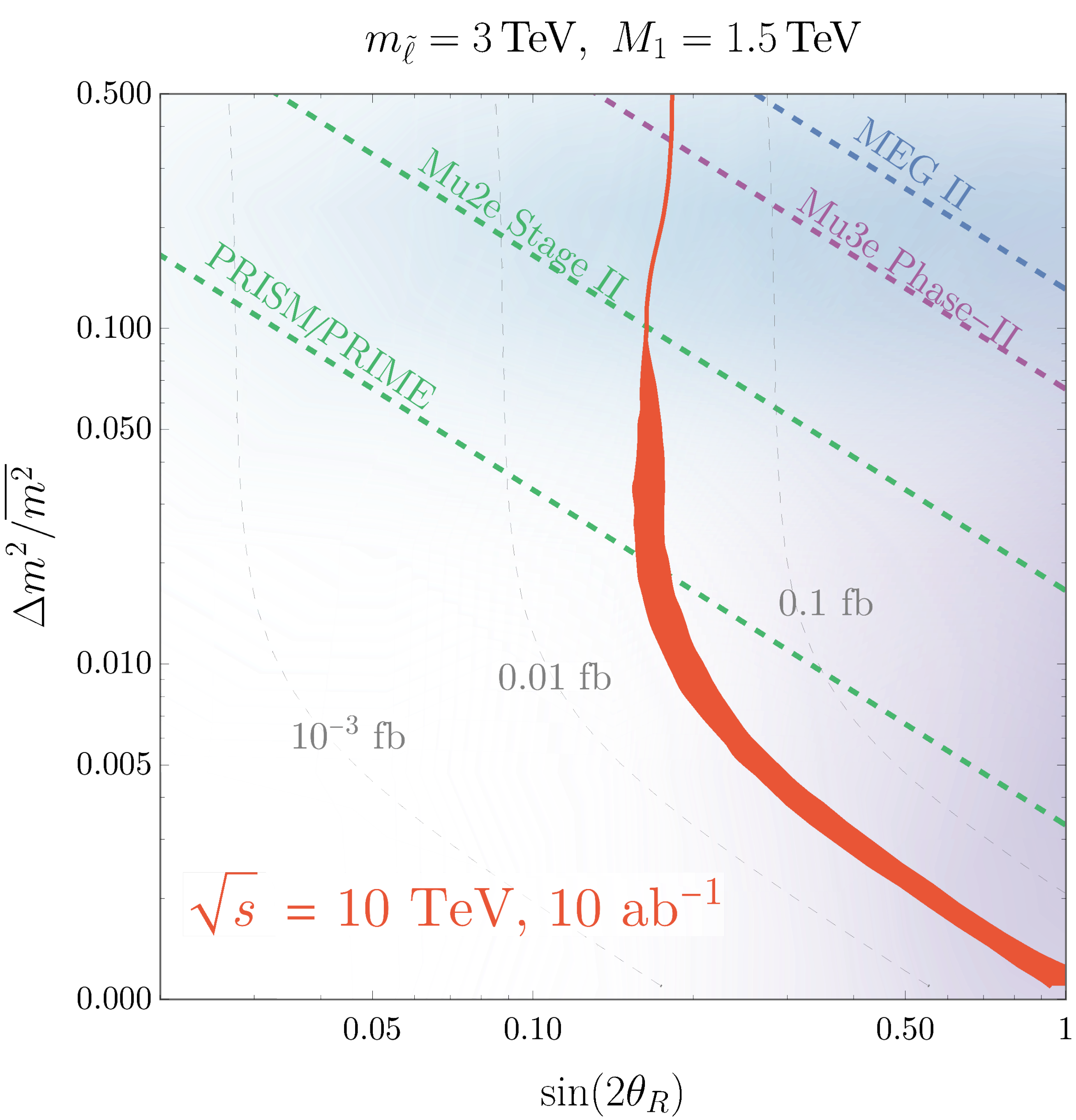
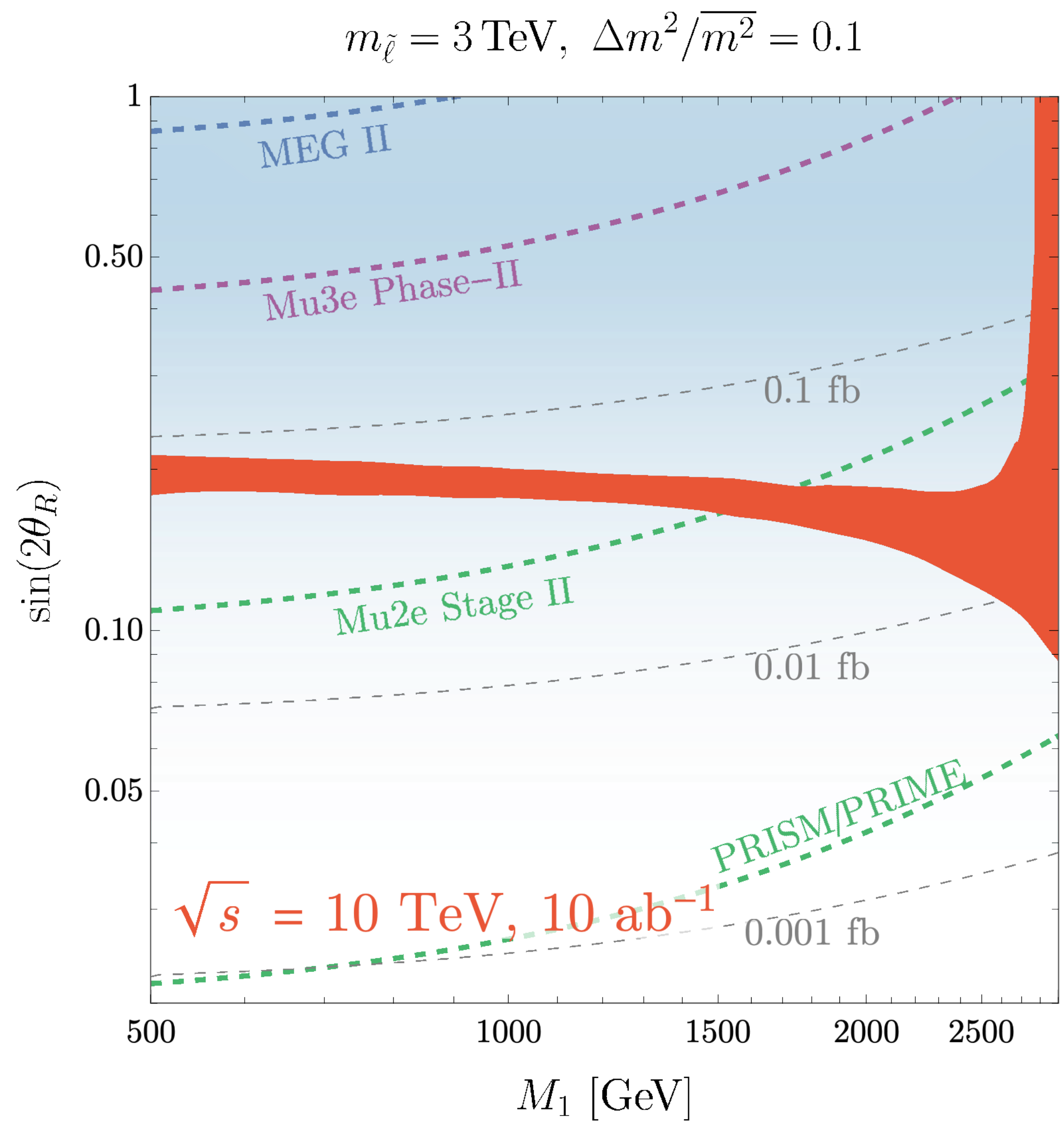




Second Example: Electron EDM

In the SM, the electron electric dipole moment is vanishingly small, due to the flavor structure of the SM.

New sources of CP violation can lead to large corrections, even at 2 loops:

$$d_e \sim \sin(\delta_{\rm CP}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^2 \simeq 10^{-32}\, e\,{\rm cm}\, \sin(\delta_{\rm CP}) \times \left(\frac{20\,{\rm TeV}}{M}\right)^2$$

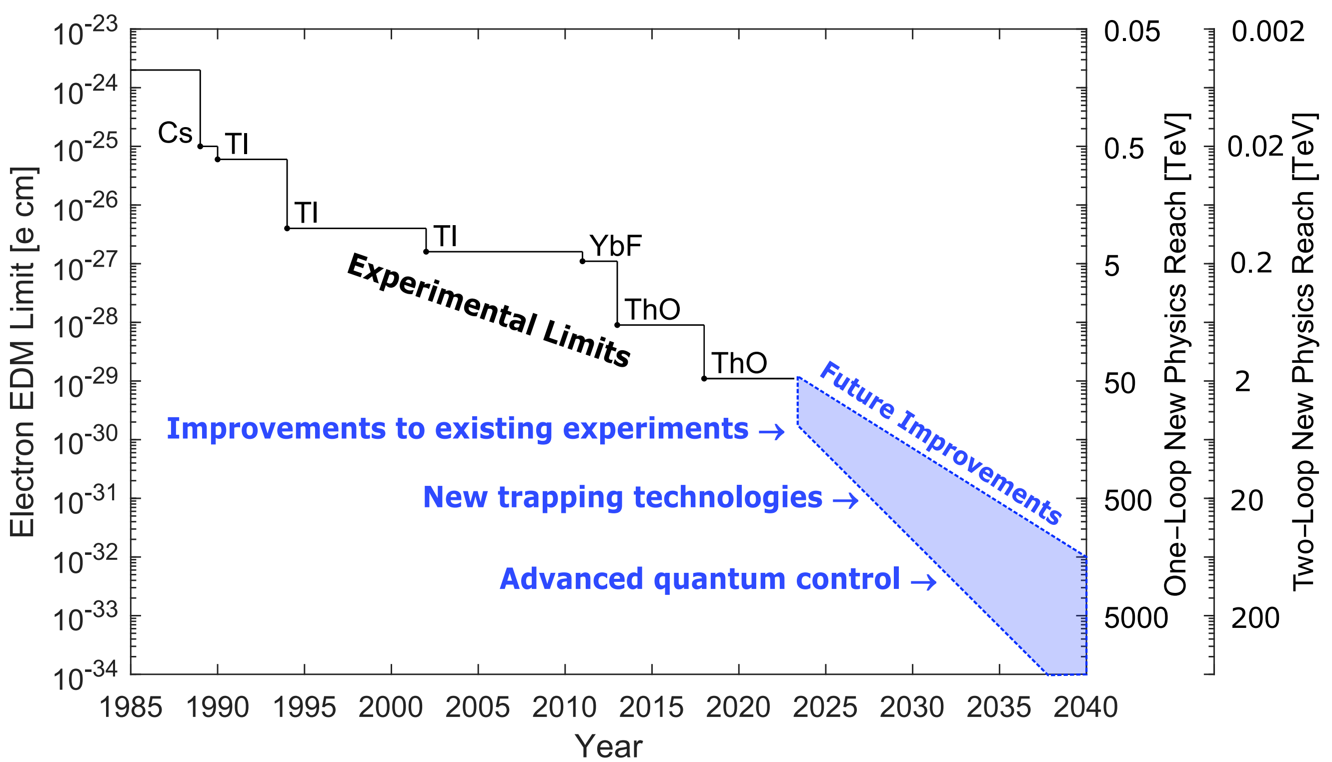
Current bound:

$$|d_e| < 4.1 \times 10^{-30}\, e\,{\rm cm}$$

Roussy, Caldwell et al (JILA) [2212.11841]

New technologies are set to improve this by orders of magnitude in the next decade!

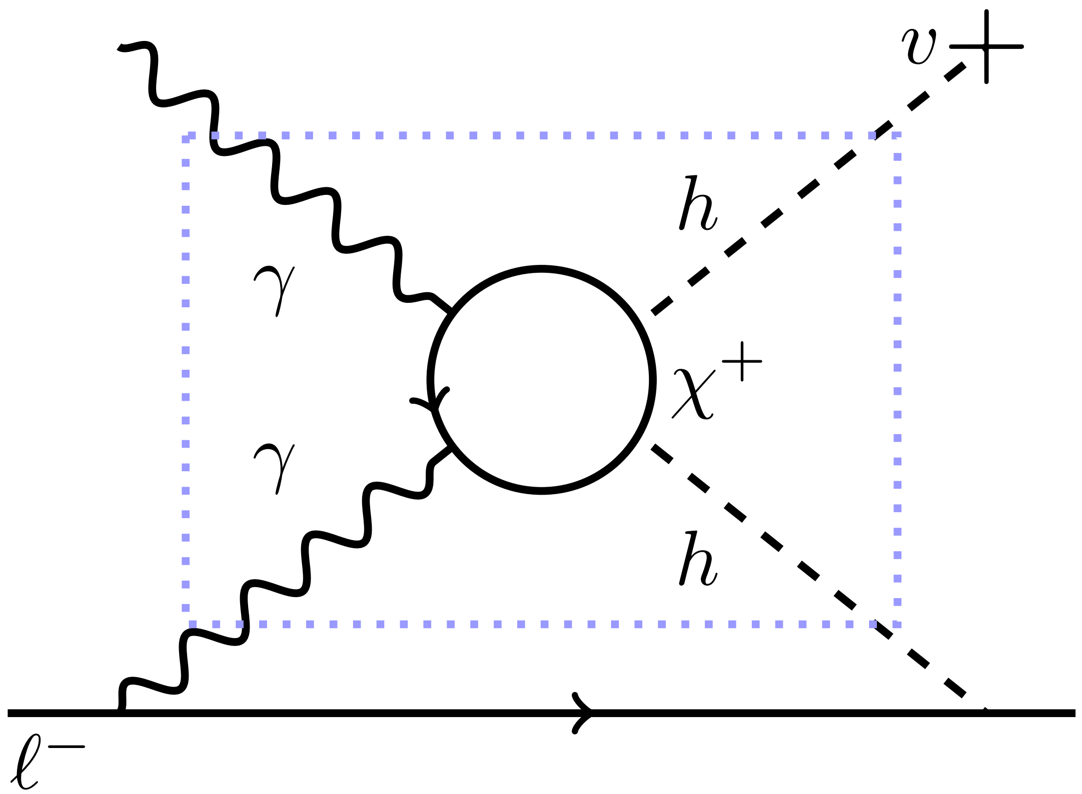
See, e.g., Alarcon et al [2203.08103] from Snowmass



Testing EDM Physics at TeV Energies?

Work in progress with J. Lodman, A. Parikh & M. Reece

This two-loop sensitivity is intriguing because *any* electroweak particle interacting with the Higgs contributes to an EDM via “Barr-Zee diagrams”:



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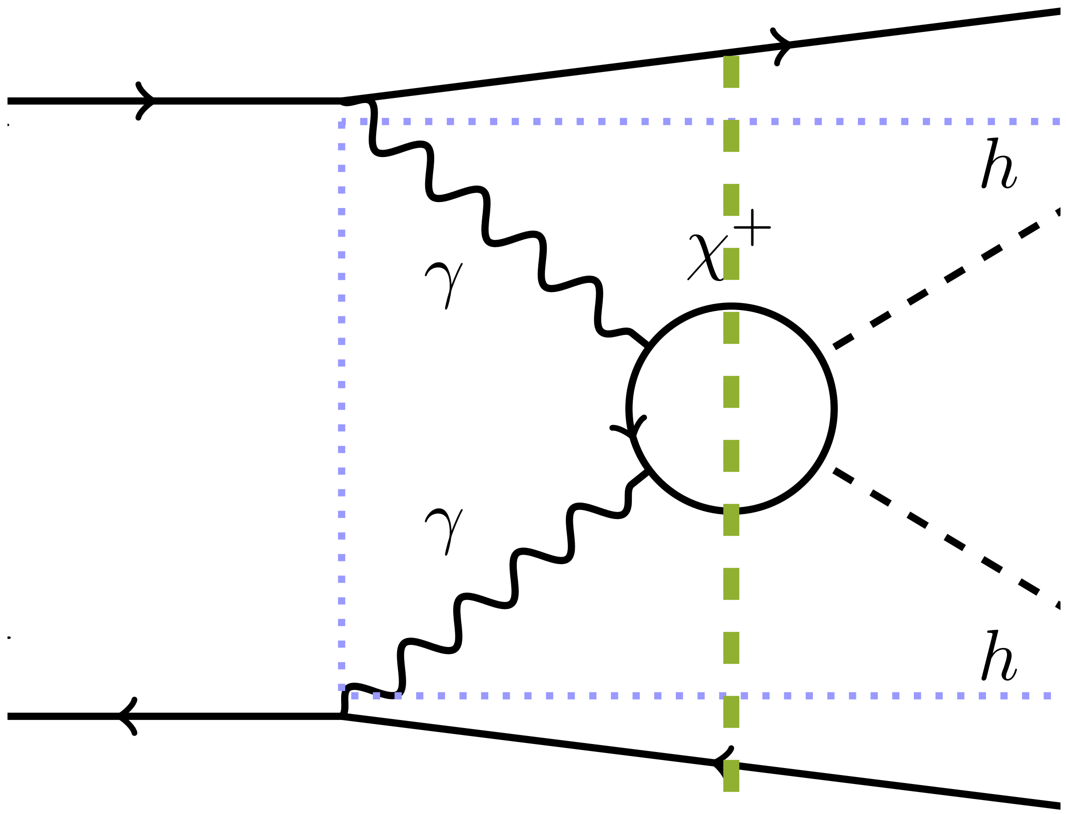

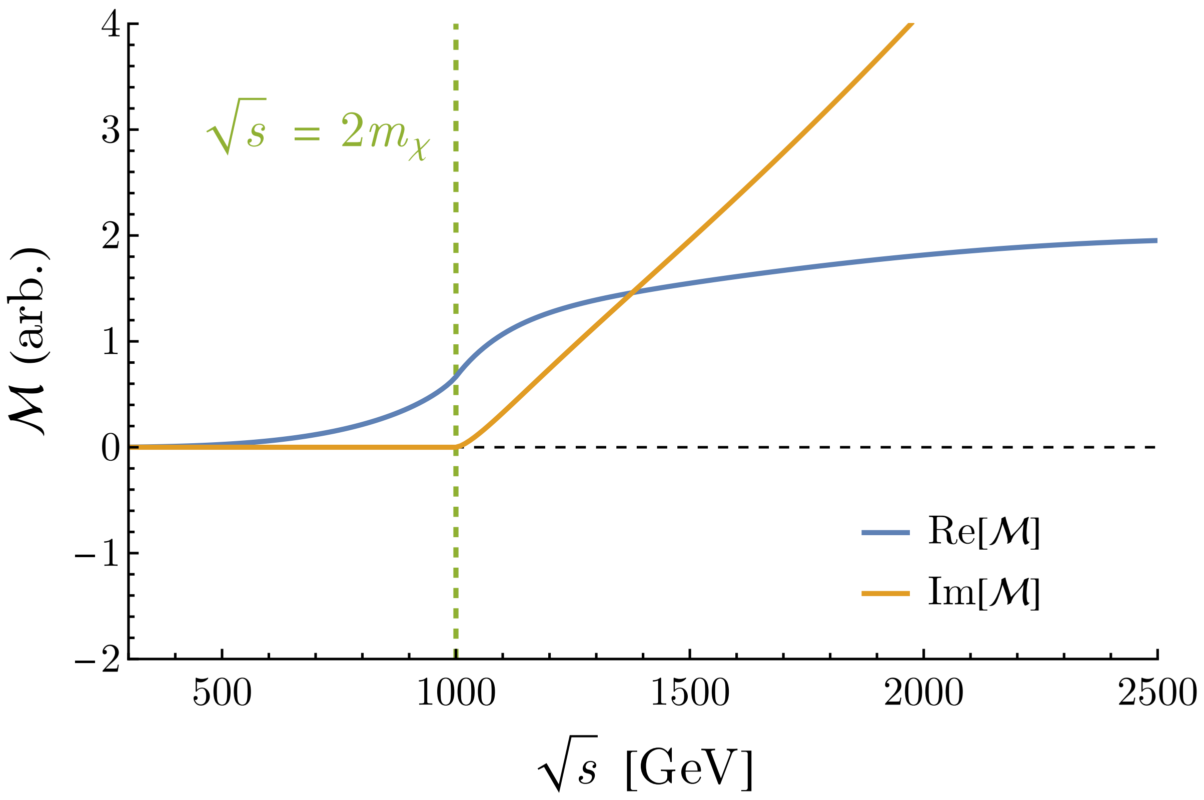

Analogous topologies lead to processes such as $\gamma\gamma \to hh,\ W^+W^- \to hh$…

…with distinct kinematic features that can be looked for!

Conclusions

- Lots of forthcoming experiments in the next ~10 years which could give indirect signal of new physics at the ~few TeV scale (cLFV, eEDMs, …)
- Important to chart the space of models probed here, and demonstrate their signals at a high-energy muon collider
- A muon collider isn't just for *discovering* new physics, but for *studying* it!
- Lots of other examples left to explore…

Thanks for your attention!