

# Probing Lepton Flavor at a Muon Collider

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# Why Lepton Flavor?

Understanding the pattern of fermion masses & mixing angles in the SM is a key outstanding problem

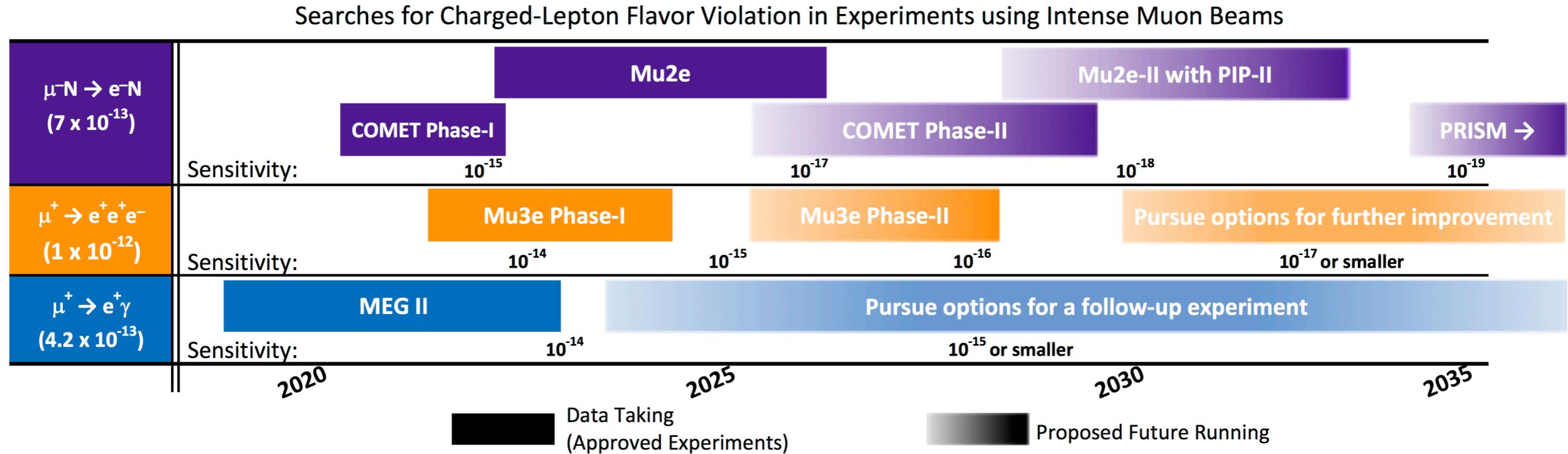
At the scale where this pattern is established we expect much larger rates of flavor-violating processes

- In reverse, low-energy measurements of LFV are powerful indirect probes of high-scale physics

Important to test these processes at *higher energies* – a high-energy muon collider is perfectly suited for this task

# Forthcoming CLFV Experiments

Sensitivity set to improve by orders of magnitude in coming decade



Indirectly probing physics responsible for the flavor pattern of the SM at the 10s of TeV scale or beyond

But *cannot* elucidate the source of new physics in the case of a deviation

# Outline

Demonstrate complementary capabilities of a high-energy muon collider in two different contexts:

- Flavor-Violating four-fermion interactions
  - Probe the *same processes* as low-energy experiments but at a higher scale
- Direct production of superpartners with flavor-violating interactions in the MSSM
  - Muon collider can *produce new particles* responsible for flavor-violation

# LFV Point Interactions

See similar analysis  
for  $e^+e^-$  case in  
[1410.1485]

Current limits on  $\ell_i \rightarrow 3\ell_j$  decays:

$$\text{BR}(\mu \rightarrow 3e) < 1.0 \times 10^{-12} \text{ (SINDRUM)}$$

$$\text{BR}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8} \text{ (Belle)} \quad \leftarrow \text{Focus on this case}$$

$$\mathcal{L} \supset \frac{c^{\tau 3\mu}}{\Lambda^2} (\bar{\mu} \gamma^\mu \mu) (\bar{\tau} \gamma_\mu \mu) + \text{h.c.}$$

(Assuming all L/R-handed interactions are the same)

At a muon collider we can probe these interactions directly via:

$$\mu^+ \mu^- \rightarrow \mu^\pm \tau^\mp$$

No irreducible backgrounds in the SM, and rate  $\propto s$

# SM Backgrounds are Easy to Remove

Two primary backgrounds:

- $\mu^+ \mu^- \rightarrow \mu \nu_\mu \tau \nu_\tau$  via intermediate  $W$  bosons
- $\mu^+ \mu^- \rightarrow \tau^+ \tau^-$  with one  $\tau \rightarrow \mu \nu_\mu \nu_\tau$  decay

→ Both involve missing energy, straightforward to remove with cuts on Energy & missing momentum.

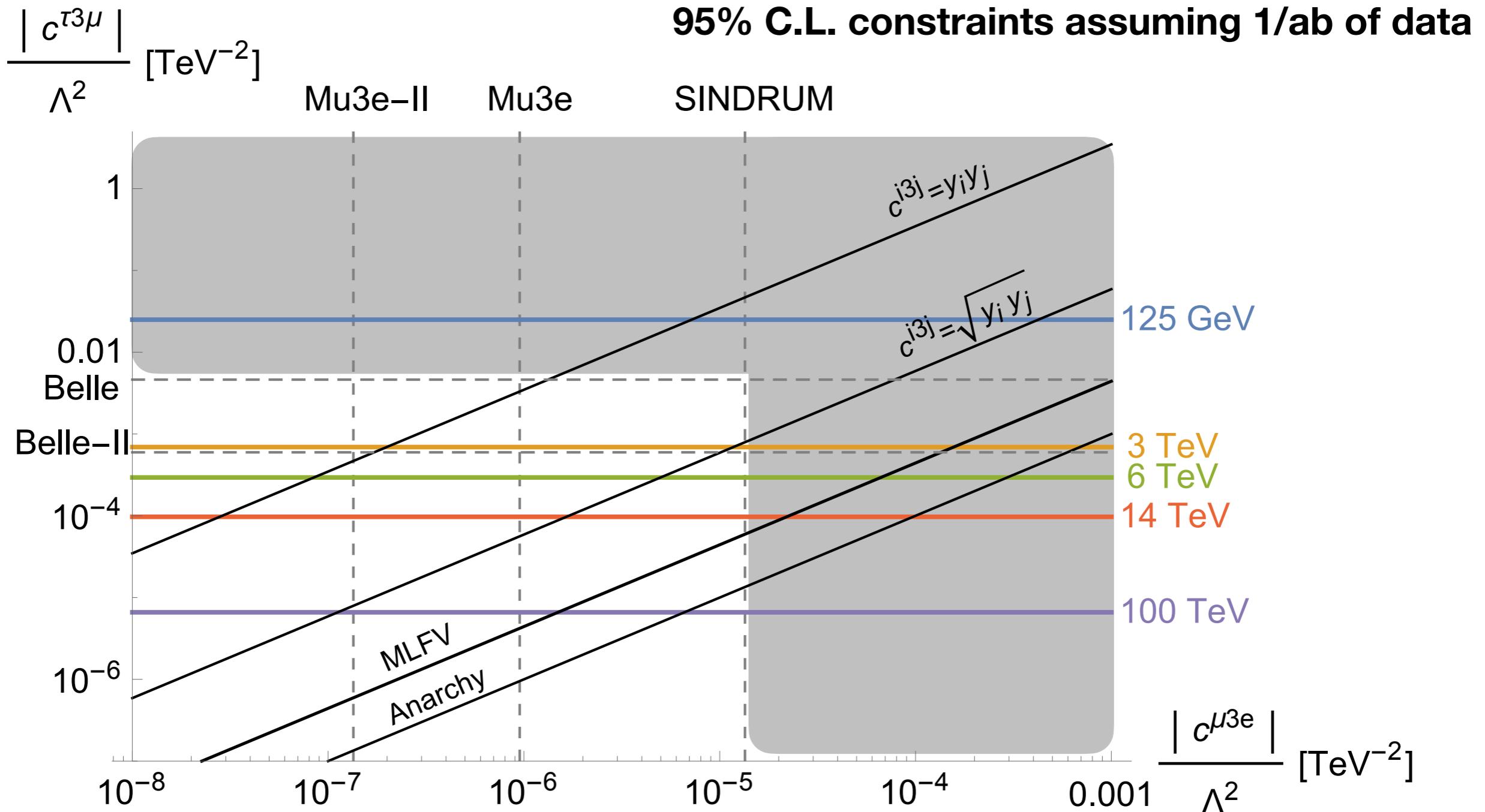
Specifically, we require:

- $E_\mu > 0.9 \frac{\sqrt{s}}{2}$
- muon momentum separated from the sum of the remaining visible particles by  $> 170^\circ$

Accounting for ISR, keeps ~90% of the signal while removing ~90% of the  $WW$  and >99% of the  $\tau\tau$  backgrounds.

# Projected Bounds

Comparing to Low-energy  $\mu \rightarrow 3e$  bounds requires some Ansatz



# Validity and Outlook

Unpacking these bounds a bit:

$$3 \text{ TeV } (1 \text{ ab}^{-1}) : \frac{\Lambda}{\sqrt{c^{\tau 3\mu}}} > 40 \text{ TeV}$$

Interpretation relies heavily  
on flavor model:

$$14 \text{ TeV } (20 \text{ ab}^{-1}) : \frac{\Lambda}{\sqrt{c^{\tau 3\mu}}} > 450 \text{ TeV}$$

$$100 \text{ TeV } (20 \text{ ab}^{-1}) : \frac{\Lambda}{\sqrt{c^{\tau 3\mu}}} > 1750 \text{ TeV}$$

$$\begin{array}{ccc} c^{\tau 3\mu} = \sqrt{y_\mu y_\tau} & \nearrow & \Lambda > 87 \text{ TeV} \\ \searrow & c^{\tau 3\mu} = y_\mu y_\tau & \Lambda > 4 \text{ TeV} \end{array}$$

Naively expect similar sensitivity to  
other processes, e.g.:

$$\mu^+ \mu^- \rightarrow \mu^\pm e^\mp$$

Caution: EFT description invalid here!  
(but the relevant physics would clearly  
be within reach!)

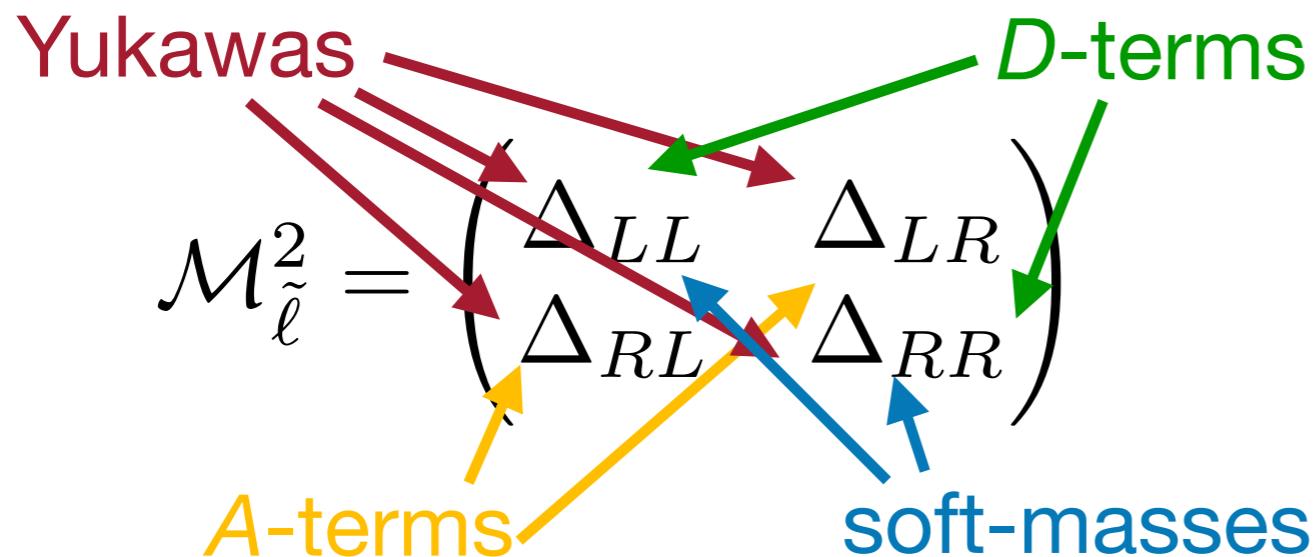
$$\mu^+ \mu^- \rightarrow \tau^\pm e^\mp$$

$(\Delta L = 2)$

Are there models where these  
constraints are relevant as well?

# LFV in the MSSM

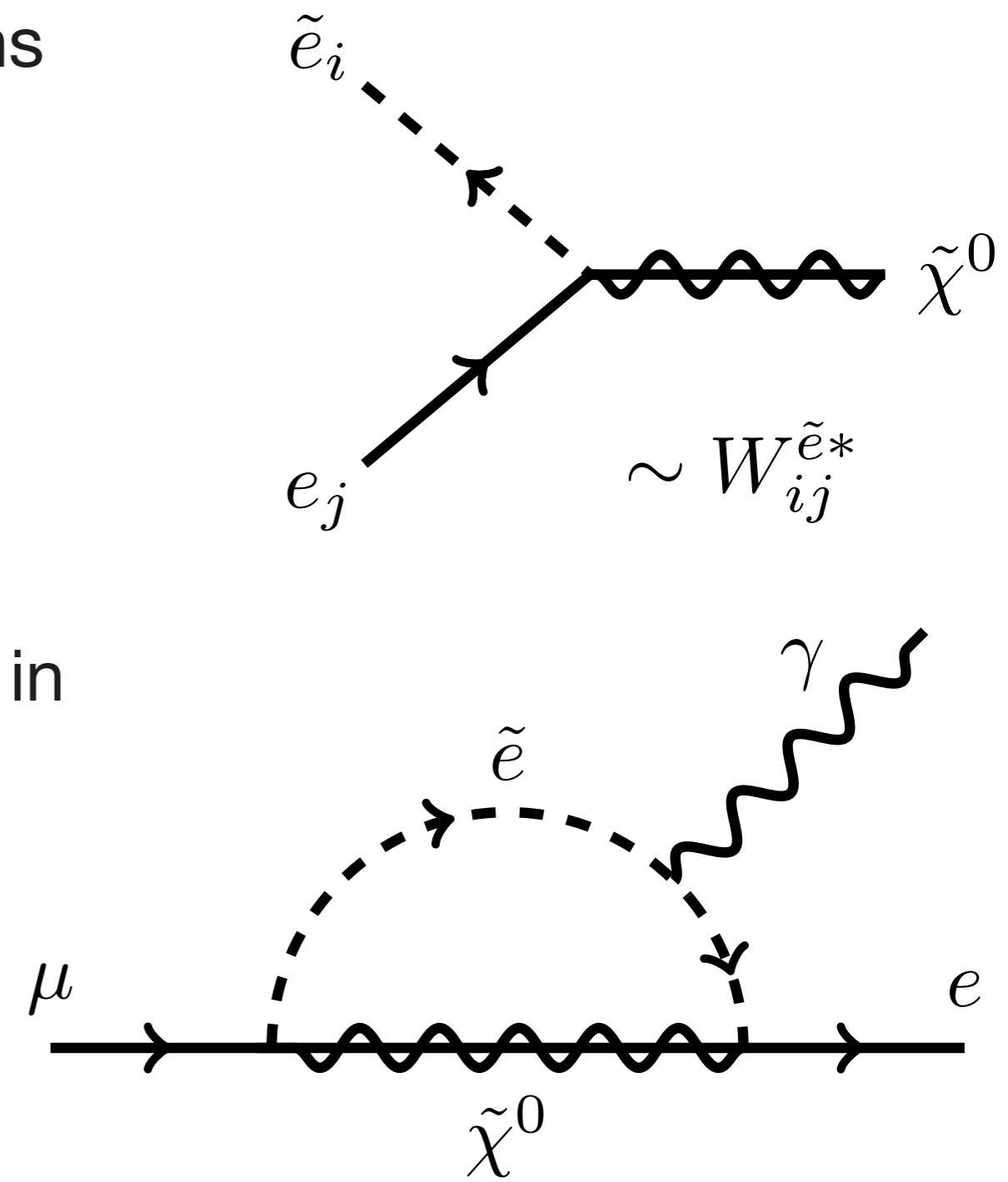
The  $6 \times 6$  mass matrix for the sleptons



a *priori* has no reason to be diagonal in the same basis as the SM Yukawas

→ vertices violate lepton flavor

Can be avoided with assumptions on mechanism for SUSY-breaking, but important to understand the structure of the MSSM



# Simplified SUSY Scenario

Assume all scalar superpartners other than right-handed selectron and smuon decouple

$$\mathcal{M}_{\tilde{\ell},RR}^2 = \begin{pmatrix} \Delta_{RR,11} & \tilde{m}_{E,12}^2 \\ \tilde{m}_{E,12}^2 & \Delta_{RR,22} \end{pmatrix}$$

Reduces to a  $2 \times 2$  mixing problem with mixing angle:

$$\frac{1}{2} \sin(2\theta_R) = \frac{\tilde{m}_{E,12}^2}{m_{\tilde{e}_1}^2 - m_{\tilde{e}_2}^2}$$

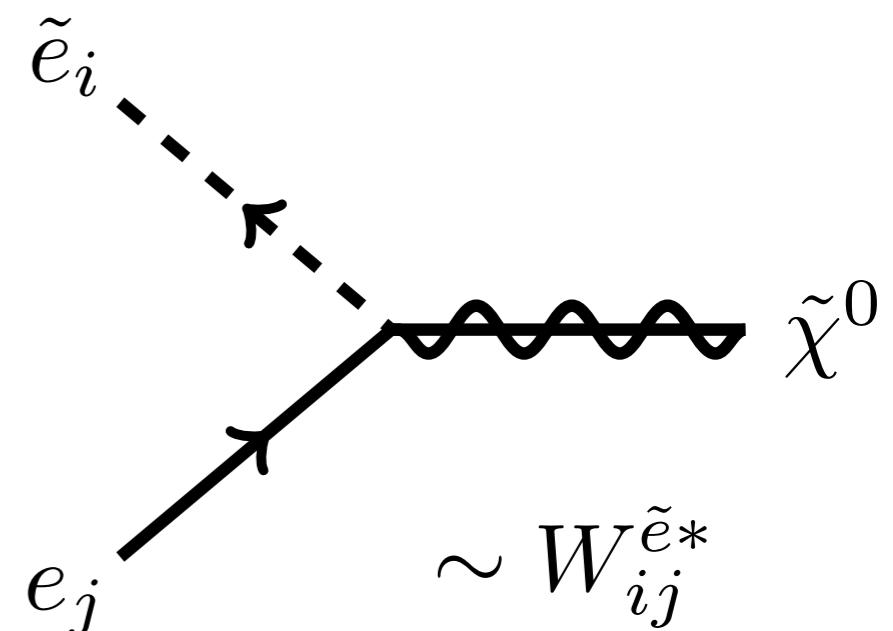
Finally, assume a pure Bino LSP and that the effects of the other neutralinos decouple, and work in the mass-insertion approximation.

# LFV in Slepton Pair Production

A high-energy lepton collider allows us to probe the LFV vertex in the MSSM *directly* via slepton pair production:

$$\mu^+ \mu^- \rightarrow \tilde{e}_{1,2}^+ \tilde{e}_{1,2}^- \rightarrow \mu^\pm e^\mp \tilde{\chi}^0 \tilde{\chi}^0$$

Observed as MET



Focus on s-channel production

(VBF contributions may also be interesting at highest energies)

Consider two scenarios:

- Two “light” sleptons, nearly degenerate in mass
- One light RH selectron with a small mixing with  $\tilde{\mu}_R$

# Removing Backgrounds

Neutralinos appear as missing momentum, so there is an *irreducible* background from  $WW$  production

**But:** Assume we already know the slepton & neutralino masses

Energy/momentum conservation + slepton mass-shell constraints let us fully reconstruct neutralino momenta!

→ Generally impossible for background events

In simulation:

~98% of signal events reconstruct

~ 1 / 500 background events

We assume these efficiencies are flat to estimate the reach of muon collider options

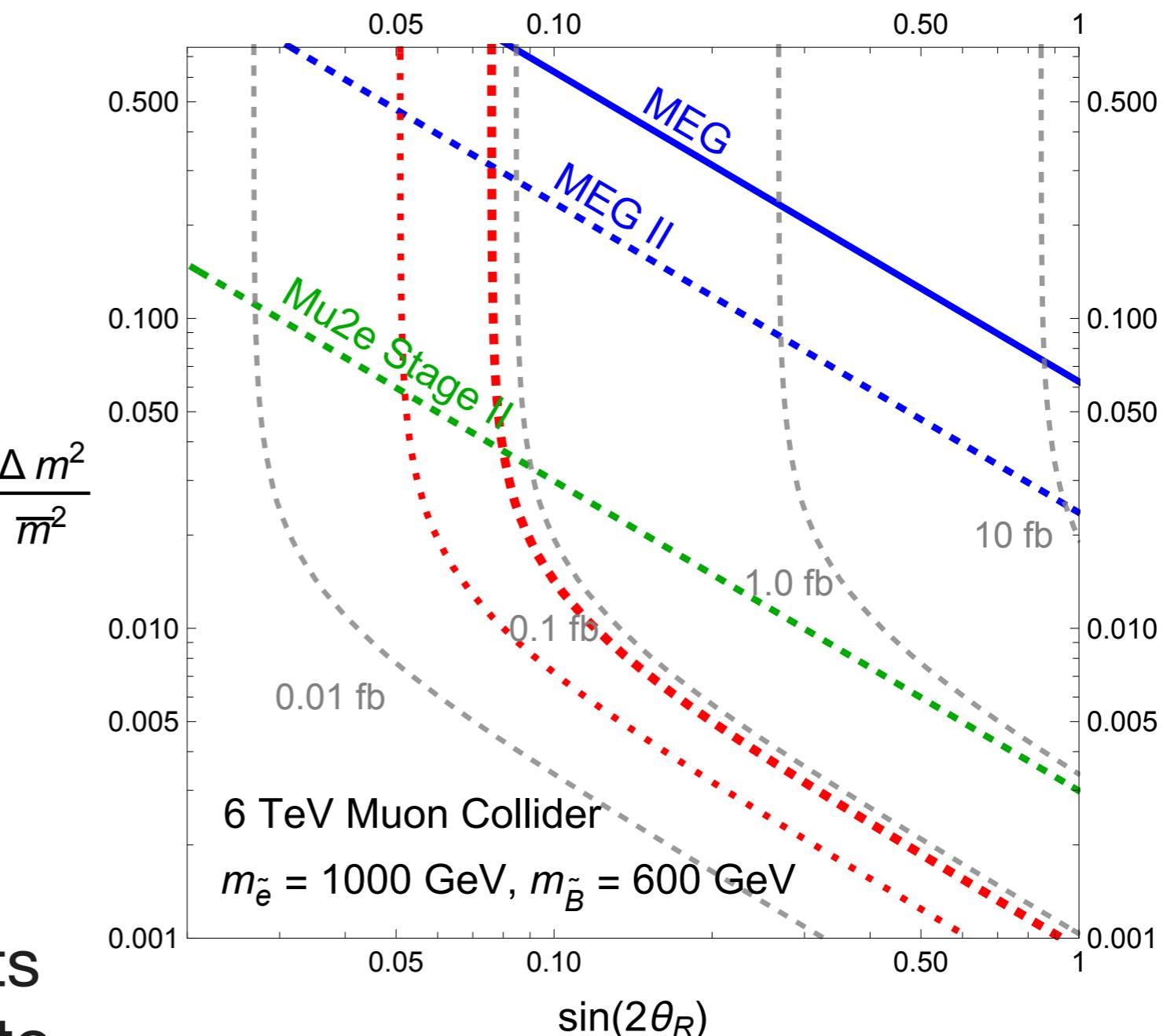
# Nearly-Degenerate Sleptons

If mass splitting is small, flavor-violating signals are suppressed:

$$(\delta_{RR})_{12} \simeq \frac{1}{2} \frac{\Delta m^2}{\bar{m}^2} \sin(2\theta_R)$$

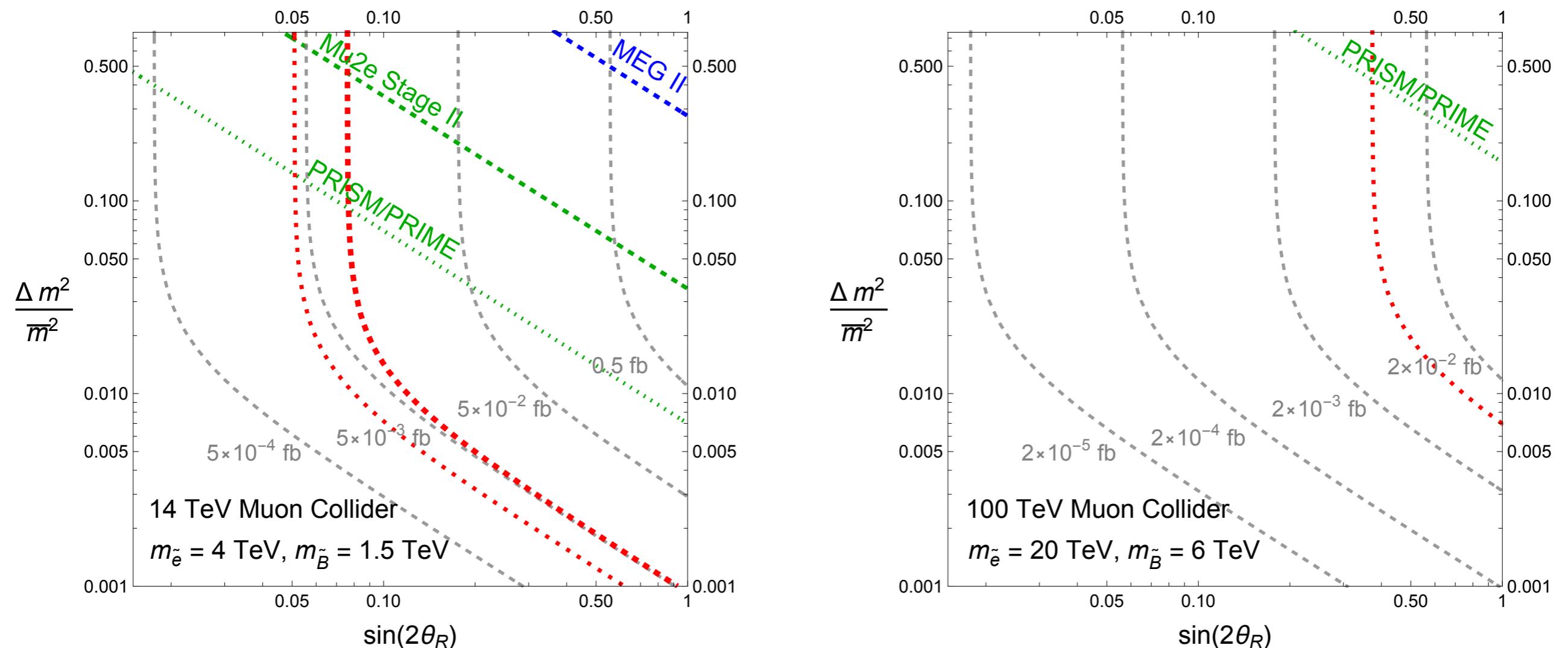
the “super-GIM mechanism”

A 6 TeV muon collider can directly observe these effects with sensitivity comparable to Mu2e final sensitivity



Time integrated “slepton oscillation” signals  
(Arkani-Hamed et al, hep-ph/9603431)

# Nearly-Degenerate Sleptons



...or completely outpace the most optimistic future low-energy experiments with higher energy collisions

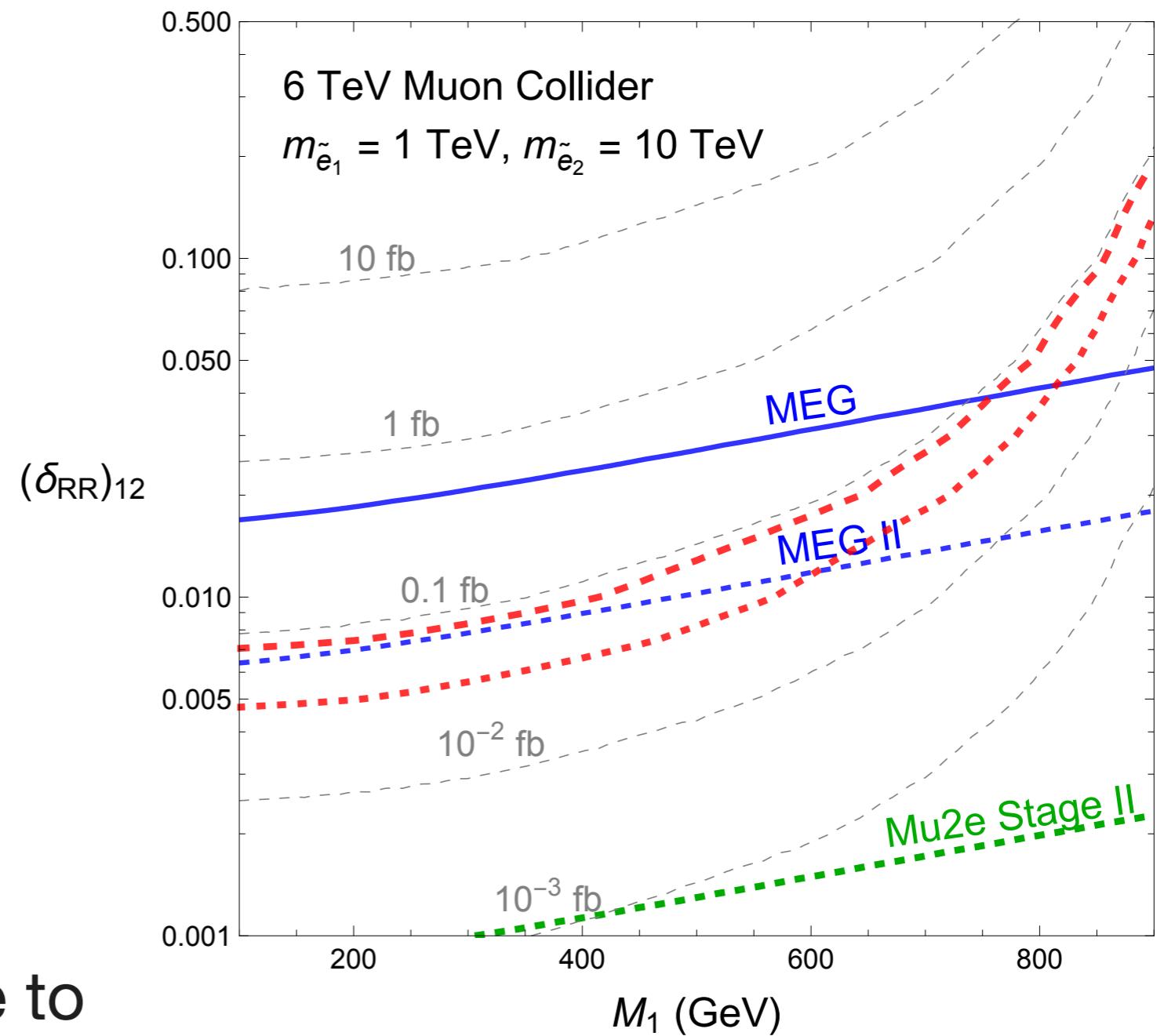
# A Single Light Slepton

Alternatively, we can take only one slepton to be within reach of collider

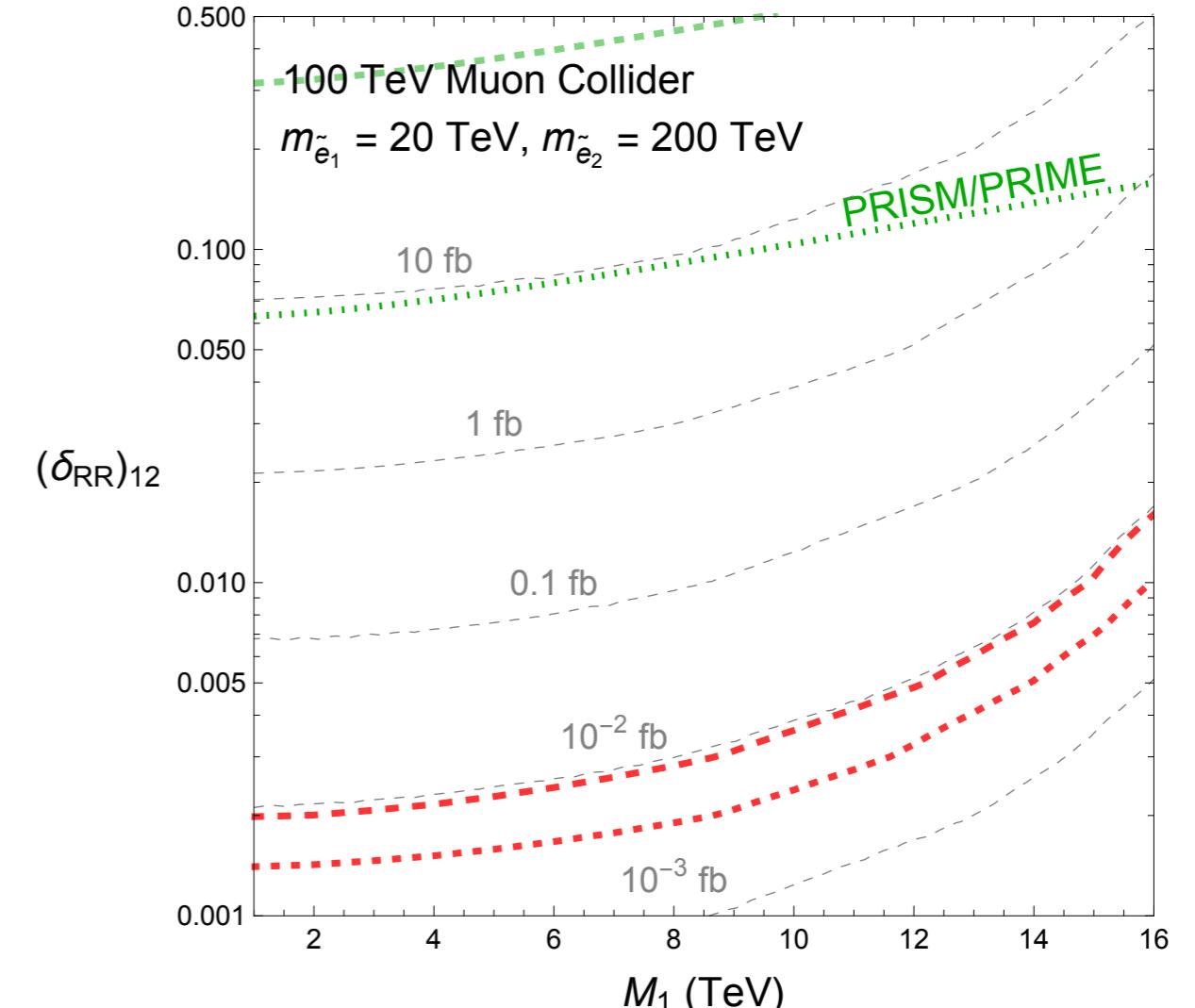
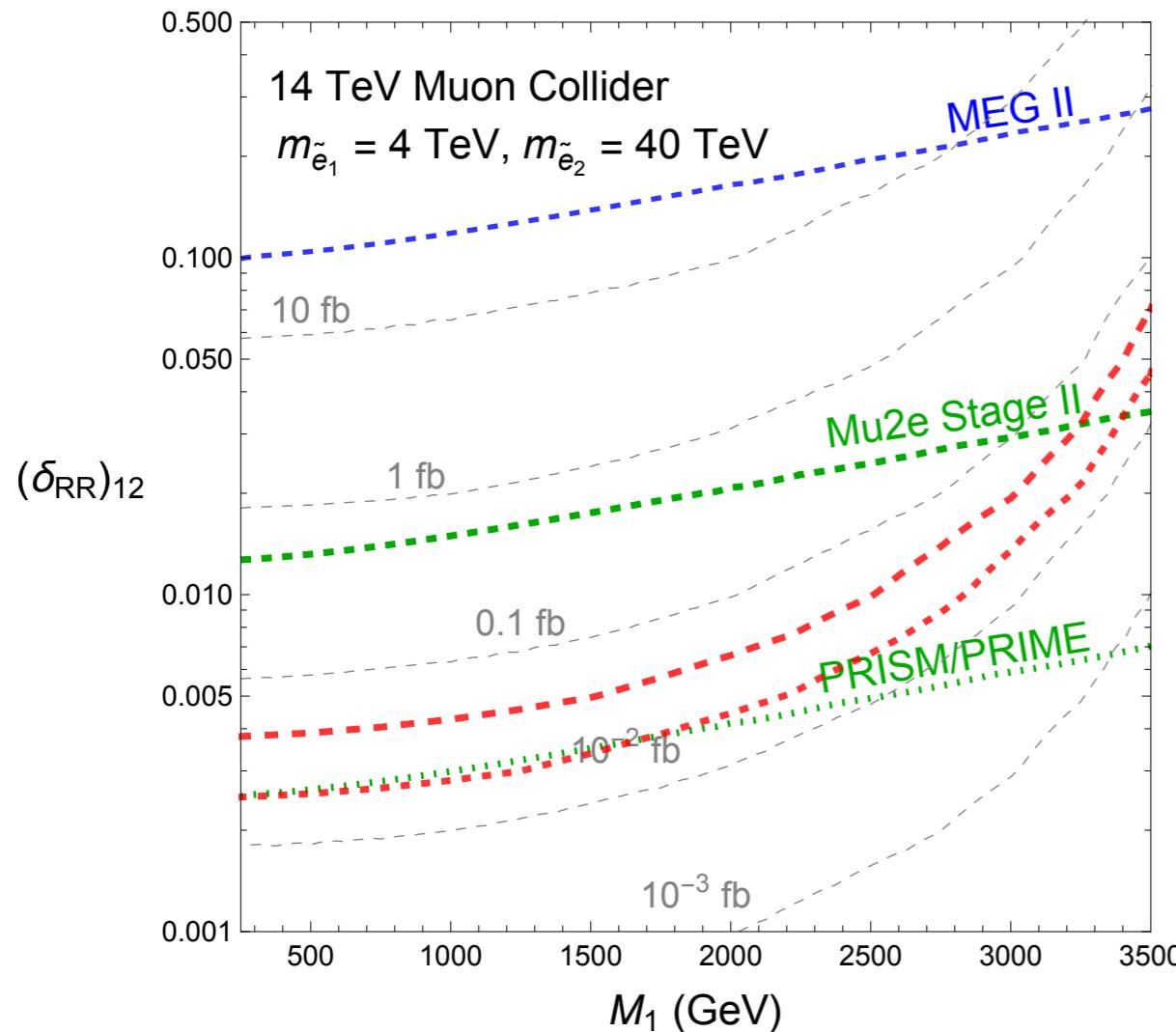
Plot constraints as a function of the Bino mass and

$$(\delta_{RR})_{12} \equiv \frac{\tilde{m}_{E,12}^2}{\sqrt{\Delta_{RR,11}\Delta_{RR,22}}}$$

Without additional suppression, very sensitive to LFV at the  $\sim$  TeV scale



# A Single Light Slepton



A 14 TeV lepton collider would directly probe the most sensitive future low-energy experiments

# Conclusions & Outlook

- A high-energy muon collider gives us a unique probe to lepton flavor that is complementary to planned low-energy searches
- Can directly measure *the same* LFV processes that are searched for in muon and tau decays
  - Sensitivity to other LFV channels should also be explored
  - Are there other / more favorable choices of flavor Ansatz?
- Can also *directly* probe flavorful new physics at the multi-TeV scale, and provide good measurements of their structure
  - Better handling of backgrounds & other production modes is needed
  - What does this look like outside our (very) simplified scenarios?
  - What can we say about concrete flavor-structures?