Complementary Probes of Lepton Flavor at a Muon Collider

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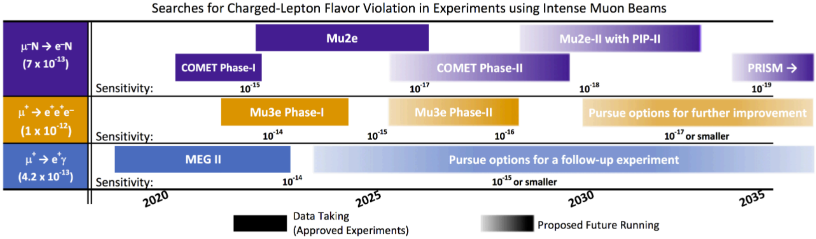
- Fermion masses and mixing structure is one of the outstanding problems of the Standard Model
- Near the scale where the flavor pattern is established, charged lepton flavor violating (CLFV) processes may happen with much larger rate
- Low-energy probes of flavor-violating processes are powerful, but cannot elucidate the underlying mechanism of flavor violation

Precision Measurements are Advancing Steadily


Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams

[1812.06540 for 2020 Update of the European Strategy for Particle Physics]

1 order of magnitude in sensitivity
= 1/4 order of magnitude in mass scale of new physics

Why Muon Colliders Specifically?

A muon collider combines the advantage of an e^+e^- and a pp collider:

- e^+e^-: all of the beam energy $\sqrt{s}$ is available for collision. Clean environment without debris from dissociated protons.
- pp: loss of energy by synchrotron radiation is small

Even a 10 TeV muon collider will be a significant upgrade in energy reach from the LHC, with a clean environment enabling precision measurements

Outline

Combination of high energy reach and clean environment means a muon collider can

- Probe flavor-violating four-fermion interactions at a high scale (this talk: $\tau 3\mu$ and $\mu 3e$ operators)
- Elucidate the mechanism of CLFV through direct production (this talk: in the context of MSSM)

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Four-fermion operator: Standard Model background and cuts

LFV signal process: $\mu^+\mu^- \to \mu\tau$

SM backgrounds:

- $\mu^+\mu^- \to \mu\upsilon_\mu\tau\upsilon_\tau$
- $\mu^+\mu^- \to \tau^+\tau^-$ with one $\tau \to \mu\upsilon_\mu\upsilon_\tau$

Simple cuts on energy and missing momentum:

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

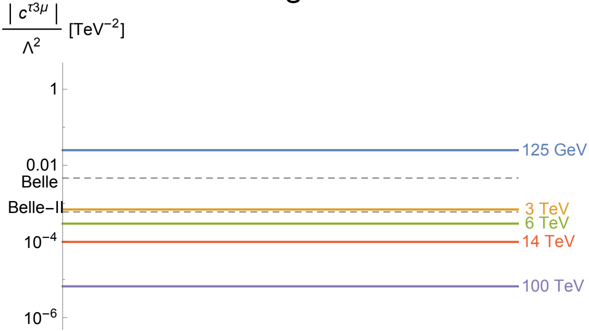
Accounting for ISR, keeps $\sim 90\%$ of signal while rejecting $\sim 99\%$ of background

Competitive Bounds on Effective Operators

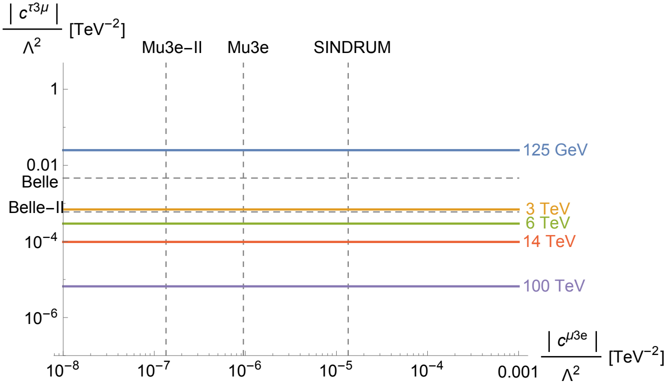
Collider constraint on $\frac{c^{\tau 3\mu}}{\Lambda^2}\tau\mu\mu\mu$ from search for $\mu^+\mu^- \to \mu\tau$

Competitive Bounds on Effective Operators

Collider constraint on $\frac{c^{\tau 3\mu}}{\Lambda^2}\tau\mu\mu\mu$ from search for $\mu^+\mu^- \to \mu\tau$ assuming 1 ab^{-1} of data

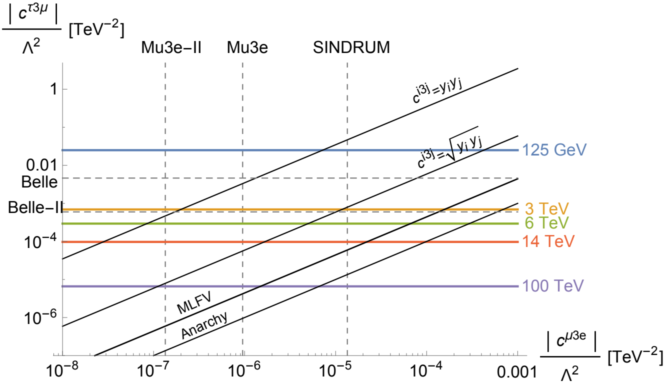


Competitive Bounds on Effective Operators



Precision constraint on $\frac{c^{\mu 3e}}{\Lambda^2}\mu eee$ from search for $\mu \to 3e$

Competitive Bounds on Effective Operators



Given a flavor ansatz, can relate the two constraints.

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Simplified MSSM: selectron and smuon and bino

Assume all scalar superpartners are decoupled except right-handed selectron and smuon. Mixing matrix is 2×2

$$\mathcal{M}^2_{\tilde{l},RR} = \begin{pmatrix} \Delta_{RR,11} & \tilde{m}^2_{E,12} \\ \tilde{m}^2_{E,12} & \Delta_{RR,22} \end{pmatrix} \tag{1}$$

with a single mixing angle:

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

Also assume a pure Bino LSP.

Collider searches for $\mu^+\mu^- \to \tilde{e}^+_{1,2}\tilde{e}^-_{1,2} \to \mu e \tilde{B}\tilde{B}$

MSSM: Standard Model background and cuts

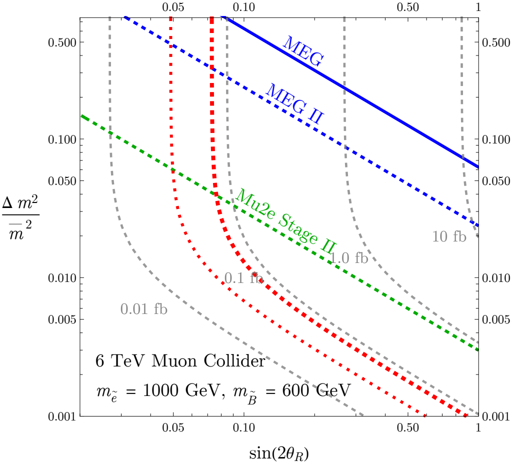
- Signal process: $\mu^+\mu^- \rightarrow \tilde{e}^+_{1,2}\tilde{e}^-_{1,2} \rightarrow \mu e \tilde{B}\tilde{B}$
- Irreducible background: WW production
- Assume that all the relevant particle masses are known from flavor-conserving channels. Background can be efficiently rejected by checking if they correctly reconstruct the kinematics.
- $\sim 98\%$ of signal events and $\sim 1/500$ of background events reconstruct

Scenario 1: nearly degenerate sleptons

$$\Delta m^2 = m^2_{\tilde{e}_1} - m^2_{\tilde{e}_2}$$

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

red curves:
reach at 1 and 5 ab^{-1}



Assumes particle masses already measured using flavor-conserving channels

Scenario 2: a single light slepton

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

red curves:
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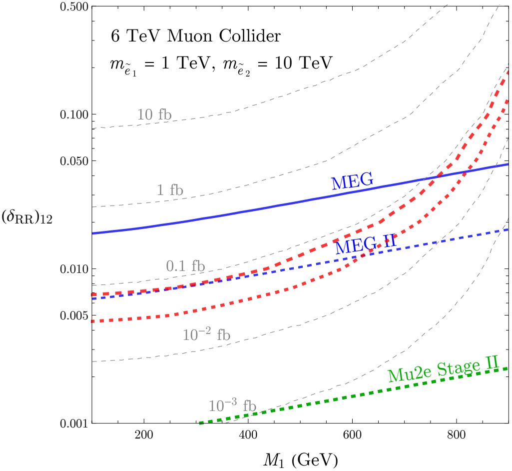

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Conclusions and Outlook

- A high-energy muon collider is a unique probe of lepton flavor violation (LFV) that is complementary to current and future low-energy searches

- It can directly measure the same LFV processes that are searched for in muon and tau decays
  - sensitivities to other LFV channels should be studied
  - what models motivate the flavor ansatz?

- It can also elucidate the underlying mechanism of LFV through direct production
  - need more systematic handling of backgrounds and production modes
  - need to go beyond the very simplified SUSY scenarios

Backup slides

Current bounds from low energy probes

$l_i \to l_j + \gamma$	$l_i \to l_j l_k l_l$	$l_i \xrightarrow{\text{Nucleus}} l_j$
$h^\dagger \ell_i \bar{\sigma}^{\mu\nu} \bar{e}_j B_{\mu\nu}$	$\left(\bar{l}_i \Gamma_1 l_j\right)\left(\bar{l}_k \Gamma_2 l_l\right)$	$\left(\bar{l}_i \Gamma_1 l_j\right)\left(\bar{q}\, \Gamma_2 q\right)$
$h^\dagger \ell_i \sigma^i \bar{\sigma}^{\mu\nu} \bar{e}_j W^i_{\mu\nu}$		

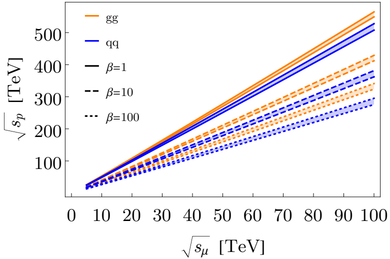
The operators scale as $\sim \frac{1}{\Lambda^2}$ ($\sim \frac{v}{\Lambda^2}$) when generated by new physics as mass scale Λ.

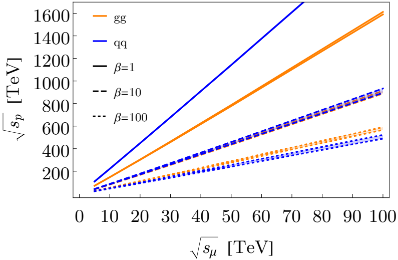
Current bounds from low energy probes

MEG	SINDRUM
BR$(\mu \to e\gamma) < 4.2 \times 10^{-13}$	BR$(\mu \to 3e) < 1.0 \times 10^{-12}$
$\mathcal{O}_{\mu e\gamma} \sim \left(\frac{\lambda}{16\pi^2}\right)^k \frac{ev}{\Lambda^2}$	$\mathcal{O}_{\mu 3e} \sim \left(\frac{\lambda}{16\pi^2}\right)^k \frac{1}{\Lambda^2}$

$$\Lambda > \begin{cases} 3.8 \times 10^4 \text{ TeV} & \text{(0 loop)} \\ 2000 \text{ TeV} & \text{(1 loop)} \\ 100 \text{ TeV} & \text{(2 loop)} \end{cases} \qquad \begin{cases} 273 \text{ TeV} & \text{(0 loop)} \\ 14.1 \text{ TeV} & \text{(1 loop)} \\ 0.73 \text{ TeV} & \text{(2 loop)} \end{cases}$$

Energy reach of muon vs proton colliders





$2 \rightarrow 1$ scattering

$2 \rightarrow 2$ scattering

Conservative projected luminosities

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\text{int}}^{\text{con}}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

Table: Energy and luminosity benchmarks considered in this work.

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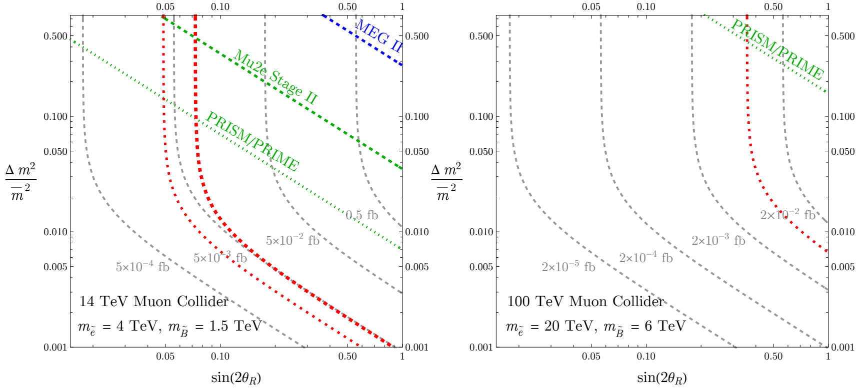
Nearly degenerate sleptons, higher energy



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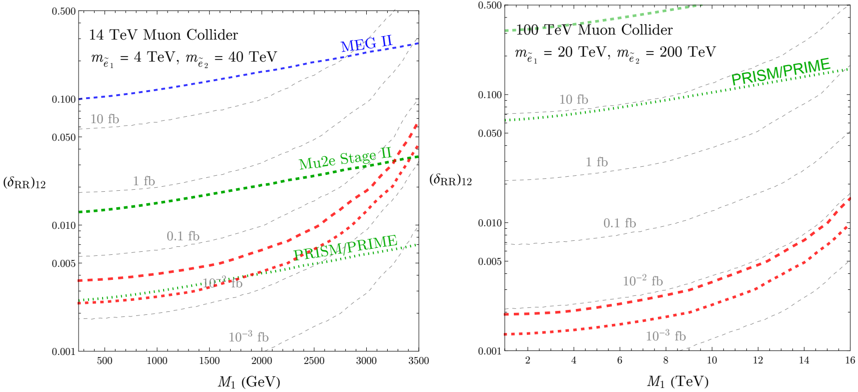
Single slepton, higher energy



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