Discovering LFV at a Future Muon Collider:

A SMEFT Approach

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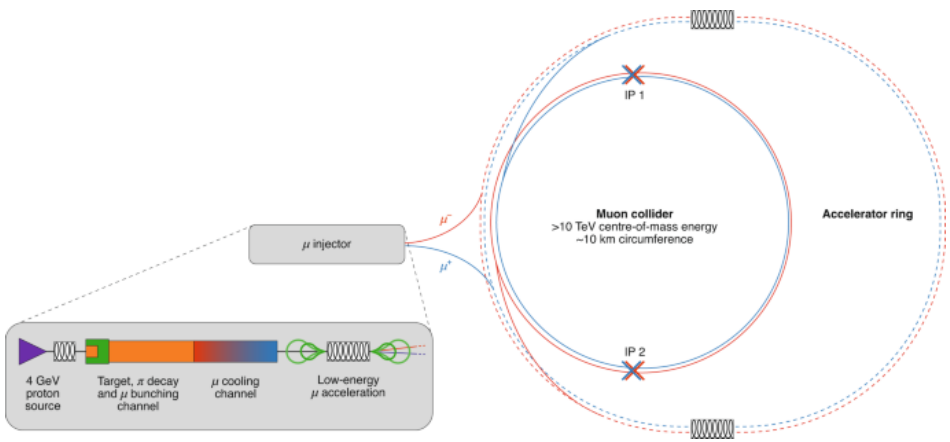
Based on:

[2506.XXXXX w/ P. Asadi, H. Bagherian, S. Homiller, and Q. Lu]

Future Colliders

Many potential options for new colliders have been proposed, including: Circular Electron Colliders [FCC-ee, CEPC], Hadron Colliders [FCC-hh], Linear Electron Colliders [Wake Field Machines], and Muon Colliders. Theoretical motivation plays a critical part in this choice.

- A Muon Collider is both a high energy and a precision machine, so it would be able to see lots of exciting new physics!
  [Muon Smasher's Guide: 2103.14043; Muon Collider Forum: 2209.01318; IMCC: 2203.07256, 2203.07224, 2203.07964, 2203.07261, 2407.12450, …]
- The accelerator community is optimistic that challenges are solvable.



<u>Machine Overview</u>:

* Proton source hits target and produces pions
* Pions decay to muons
* Muons are collected into beam and cooled
* Muons are accelerated and injected into the collider

[Image: International Muon Collider Collaboration]

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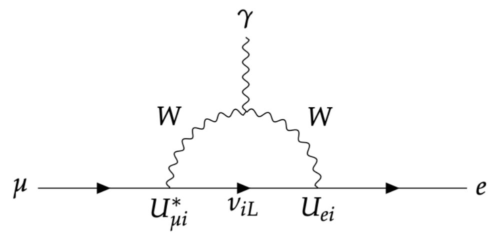
Models of Lepton Flavor Violation

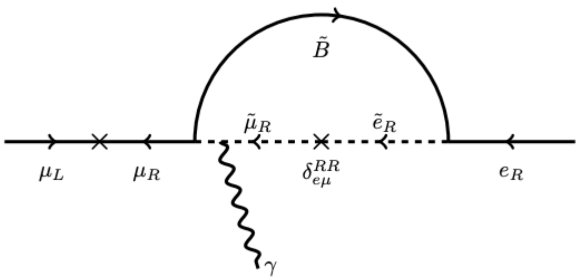
- Charged LFV is a smoking gun for BSM because all SM contributions are neutrino mass suppressed

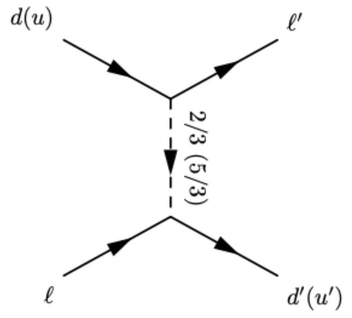


- LFV arises in simple models:
  - In SUSY, SUSY breaking causes nondiagonal sleptons interactions)

    [Homiller et al, 2203.08825]
  - Leptoquarks can mediate cLFV through for example rare meson decays.

    [Fajfer et al, 1603.04993]





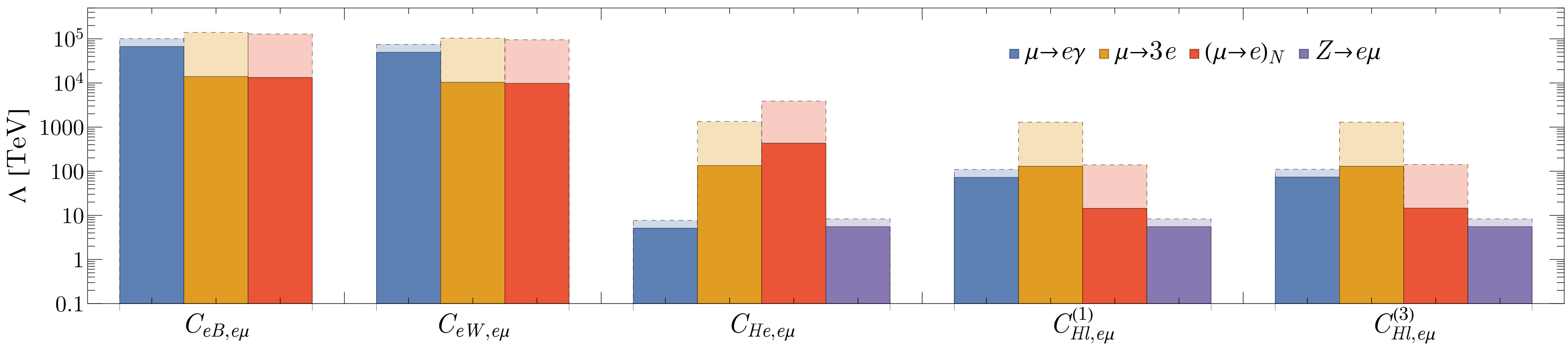
A SMEFT Approach

- We use a Standard Model Effective Field Theory (SMEFT) approach to be model agnostic.
- In SMEFT, we add all higher dimensional operators which respect the SM gauge symmetries.
- For simplicity, we only work to dimension six and turn on operators with no quarks (at high energy) - this is 9 total operators

4-Lepton Operators	Dipole Operators	Lepton - Higgs Operators
$\mathcal{O}_{ll} = (\bar{L}_i \gamma_\mu L_j)(\bar{L}_k \gamma^\mu L_m)$	$\mathcal{O}_{eW} = (\bar{L}_i \sigma^{\mu\nu} e_j)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_i \gamma^\mu e_j)$
$\mathcal{O}_{ee} = (\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_m)$	$\mathcal{O}_{eB} = (\bar{L}_i \sigma^{\mu\nu} e_j) H B_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}_i \gamma^\mu L_j)$
$\mathcal{O}_{le} = (\bar{L}_i \gamma_\mu L_j)(\bar{e}_k \gamma^\mu e_m)$		$\mathcal{O}^{(3)}_{Hl} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}_i \tau^I \gamma^\mu L_j)$
		$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}_i e_j H)$

LFV Experiments

There are many current precision probes of LFV. They are sensitive to scales that are much higher than typical searches. Can a muon collider do better?



Probing LFV with a Muon Collider

- Probing LFV is interesting at any potential future collider; it has already been studied for FCC-ee/CEPC.
  [Altmannshofer et al: 2305.03869]

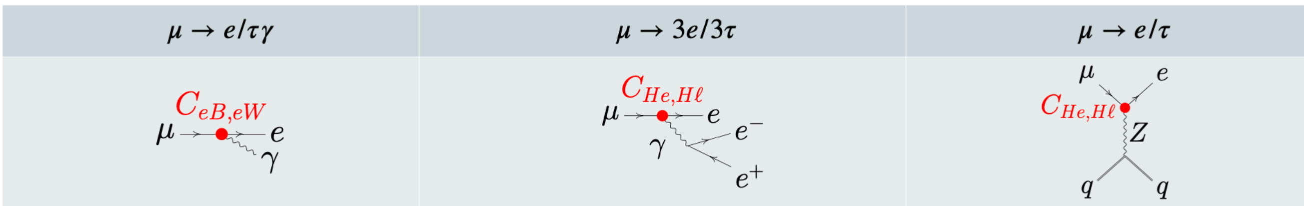
- Muon colliders have some qualitative differences which might allow probing different parameter space:
  - Higher energy
  - Sensitive to different coefficient combinations $(\mu \to \tau)$

- Previous studies at muon colliders have focused on specific models, for example SUSY.
  [Homiller et al: 2203.08825, 2103.14043]

Low Energy Lepton Decays

Our current strongest limits on $\mu \leftrightarrow e$ LFV come from muon decays ($\mu \to e\gamma$, $\mu \to 3e$) and $\mu N \to eN$ conversion in nuclei.

LFV involving τs are most strongly constrained by B factories.



	Current Limit		Projected Limit	
$\mathrm{BR}(\mu \to e\gamma)$	3.1×10^{-13}	[MEG + MEG -II]	6.0×10^{-14}	[MEG-II]
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	[BaBar]	3.0×10^{-9}	[Belle-II]
$\mathrm{BR}(\tau \to \mu\gamma)$	4.2×10^{-8}	[Belle]	1.0×10^{-9}	[Belle-II]
$\mathrm{BR}(\mu \to 3e)$	1.0×10^{-12}	[SINDRUM]	$\sim 1 \times 10^{-16}$	[Mu3e]
$\mathrm{BR}(\tau \to 3e)$	2.7×10^{-8}	[Belle]	4.6×10^{-10}	[Belle II]
$\mathrm{BR}(\tau \to 3\mu)$	1.9×10^{-8}	[Belle II]	3.5×10^{-10}	[Belle II]
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	1.8×10^{-8}	[Belle]	3×10^{-10}	[Belle II]
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	2.7×10^{-8}	[Belle]	5×10^{-10}	[Belle II]
$\mathrm{CR}(\mu \to e)_{\mathrm{Ti}}$	4.3×10^{-12}	[SINDRUM-II]	—	
$\mathrm{CR}(\mu \to e)_{\mathrm{Au}}$	7.0×10^{-13}	[SINDRUM-II]	—	
$\mathrm{CR}(\mu \to e)_{\mathrm{Al}}$	—		$\sim 6 \times 10^{-17}$	[Mu2e Run 2]

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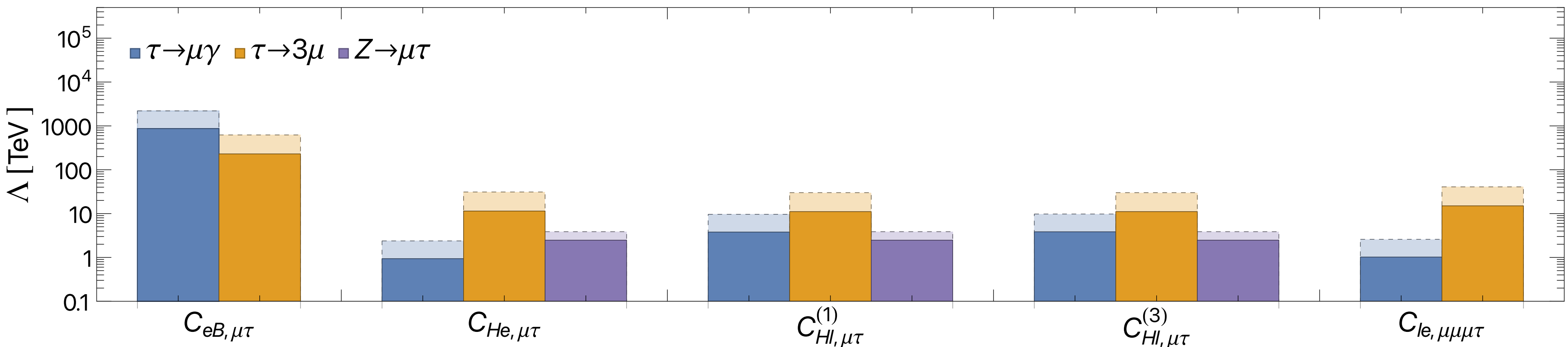
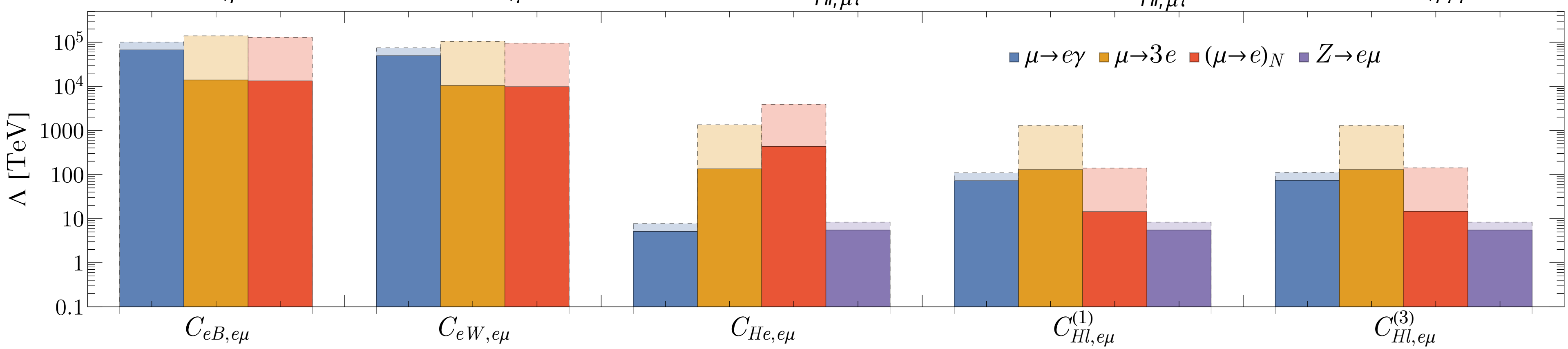
Z decays

There are also limits on LFV Z decays:

	Current Limit		Projected Limit	
$\mathrm{BR}(Z \to \mu e)$	2.6×10^{-7}	[ATLAS]	$\sim 5 \times 10^{-8}$	[HL-LHC]
$\mathrm{BR}(Z \to \tau e)$	5.0×10^{-6}	[ATLAS]	$\sim 1 \times 10^{-6}$	[HL-LHC]
$\mathrm{BR}(Z \to \tau \mu)$	6.5×10^{-6}	[ATLAS]	$\sim 1 \times 10^{-6}$	[HL-LHC]





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Matching onto IR Observables

For Z decays, we can work directly in terms of SMEFT operators, using the 1-loop RGE to run down to the applicable scale.

For μ and τ decays, run down to the weak scale, then match onto low energy effective field theory (LEFT) operators:

$$\mathcal{O}_{e\gamma,ij} = \bar{e}_{L,i}\sigma^{\mu\nu}e_{R,j}F_{\mu\nu}\,, \quad \mathcal{O}^{V,LL}_{ee,prst} = (\bar{e}_{L,p}\gamma^{\mu}e_{L,r})(\bar{e}_{L,s}\gamma_{\mu}e_{L,t})\,, \quad \mathcal{O}^{V,RR}_{ee,prst} = (\bar{e}_{R,p}\gamma^{\mu}e_{R,r})(\bar{e}_{R,s}\gamma_{\mu}e_{R,t})\,,$$
$$\mathcal{O}^{V,LR}_{ee,prst} = (\bar{e}_{L,p}\gamma^{\mu}e_{L,r})(\bar{e}_{R,s}\gamma_{\mu}e_{R,t})\,, \quad \mathcal{O}^{S,RR}_{ee,prst} = (\bar{e}_{L,p}e_{R,r})(\bar{e}_{L,s}e_{R,t})\,.$$

Running below the weak scale in the LEFT will also generate the quark operators

$$\mathcal{O}^{V,LL}_{eq,prst} = (\bar{e}_{L,p}\gamma^{\mu}e_{L,r})(\bar{q}_{L,s}\gamma_{\mu}q_{L,t})\,, \quad \mathcal{O}^{V,RR}_{eq,prst} = (\bar{e}_{R,p}\gamma^{\mu}e_{R,r})(\bar{q}_{R,s}\gamma_{\mu}q_{R,t})\,,$$
$$\mathcal{O}^{V,LR}_{eq,prst} = (\bar{e}_{L,p}\gamma^{\mu}e_{L,r})(\bar{q}_{R,s}\gamma_{\mu}q_{R,t})\,,$$
$$\mathcal{O}^{S,RR}_{eq,prst} = (\bar{e}_{L,p}e_{R,r})(\bar{q}_{L,s}q_{R,t})\,, \quad \mathcal{O}^{S,RL}_{eq,prst} = (\bar{e}_{L,p}e_{R,r})(\bar{q}_{R,s}q_{L,t})\,,$$

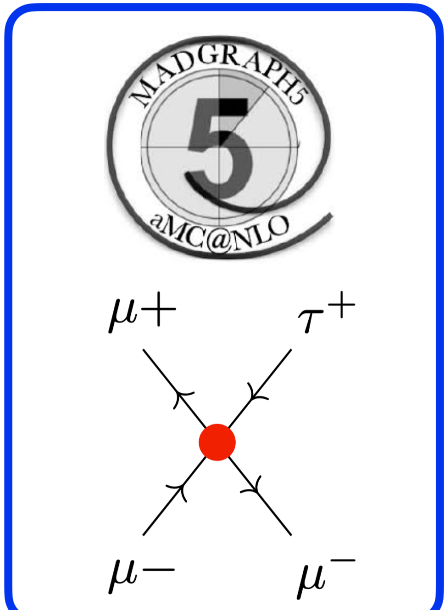
[Manohar et al: http://einstein.ucsd.edu/]

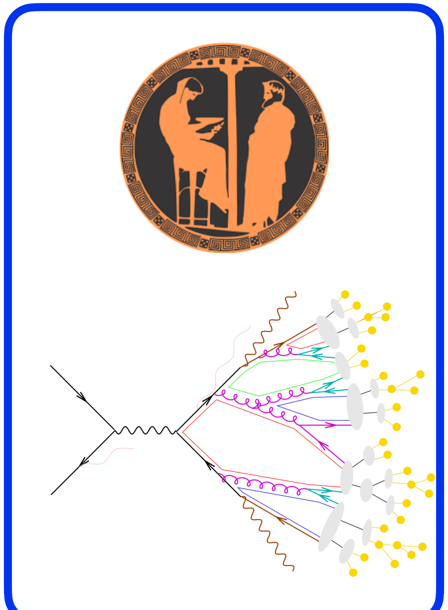
High Energy Constraints: The Pipeline

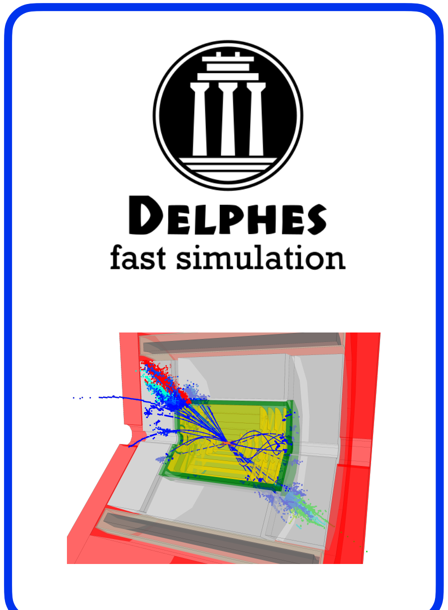
To understand the reach for each operator, we perform studies with MadGraph/Pythia/DELPHES.

We consider the full set of possible processes pick ones with the largest cross section in more detail.

Simulate backgrounds to get a rough estimate of reach using a simple cut and count analysis.







[Images: D. Deppenfeld 2015 PITP lecture, CERN]

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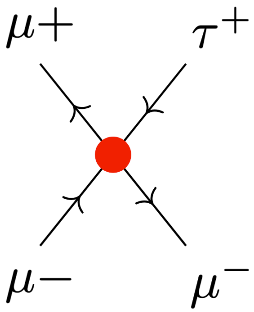
Example: $\mu\mu \to \mu\tau$

Turn on C_{ee}^{2223} operator to get a signal:

2.1×10^6 Events



The Largest Backgrounds:

1) $\mu\mu \to \tau\mu\bar{\nu}_\mu\nu_\tau$

4.0×10^4 Events

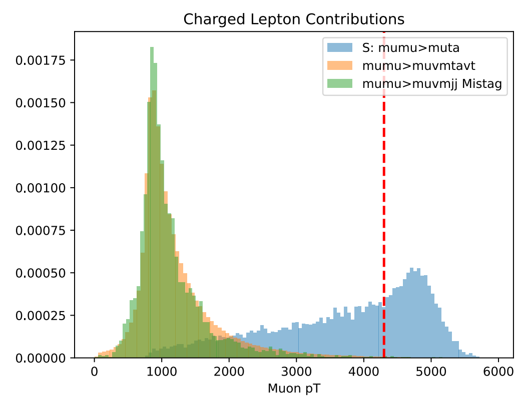
Including: $\mu\mu \to \tau\tau$, $\mu\mu \to ww$

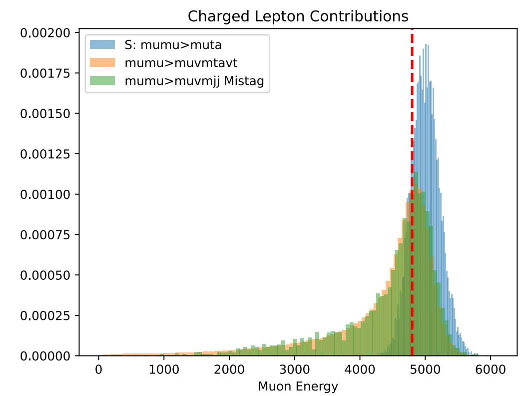
2) $\mu\mu \to \mu\bar{\nu}_\mu j$, jet mistag:

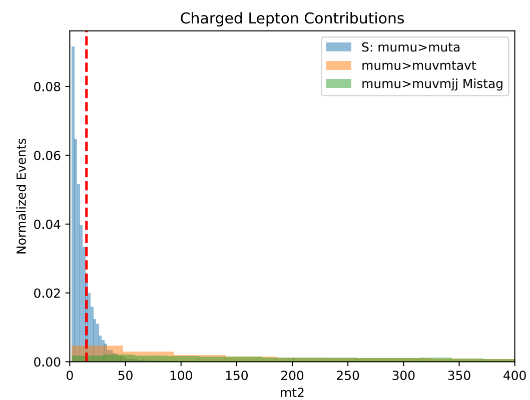
2.1×10^3 Events

Including: $\mu\mu \to ww$ (jet mistag)

Add cuts to separate signal from background: Muon pT > 4200, Muon E > 4900, mt2 < 15







Remaining events:

Signal:

4.3×10^5

Background Events:

3

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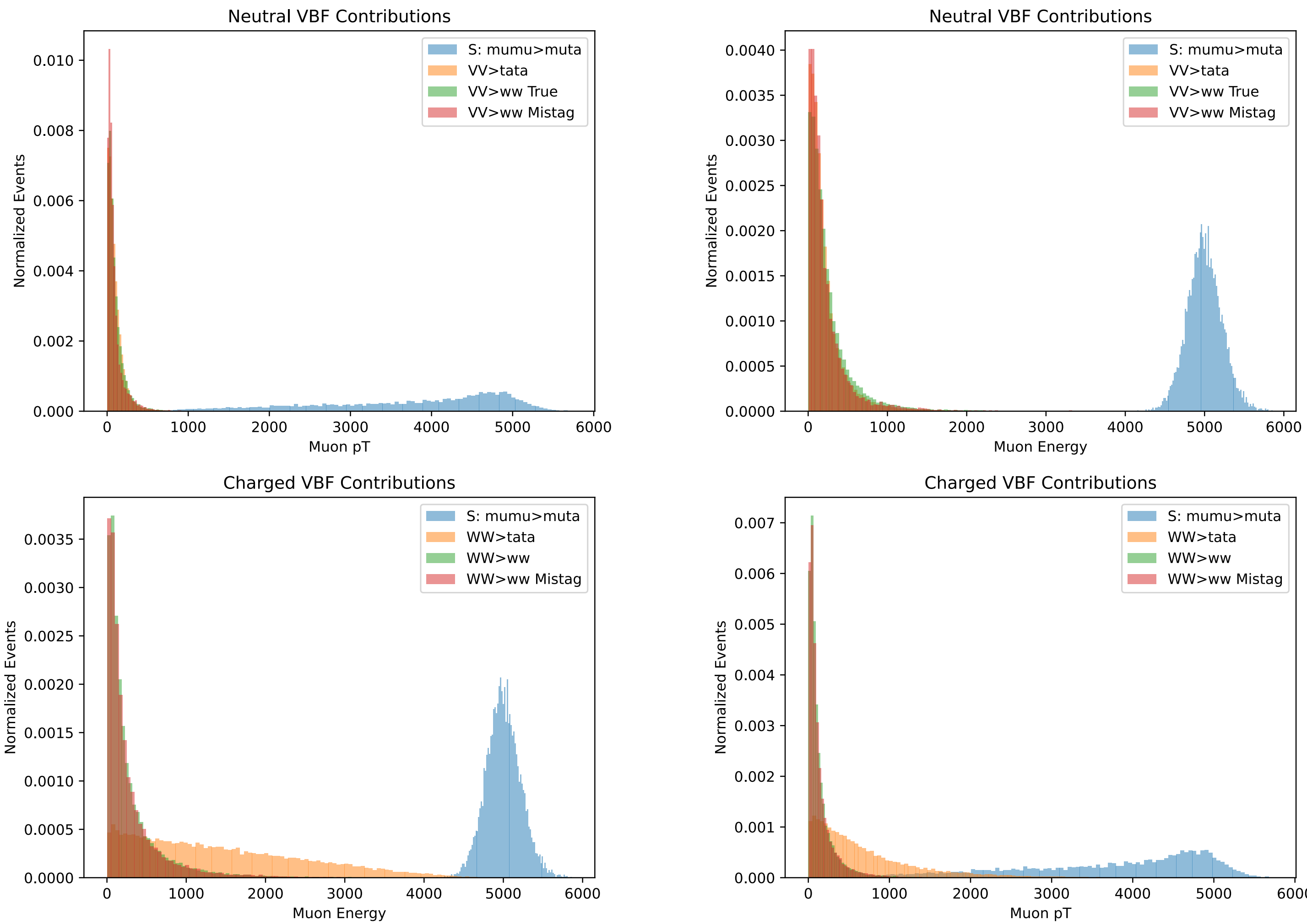
Example: $\mu\mu \to \mu\tau$

VBF backgrounds are negligible, since they are well separated in muon pT and Energy



Note: Each histogram is independently normalized to one

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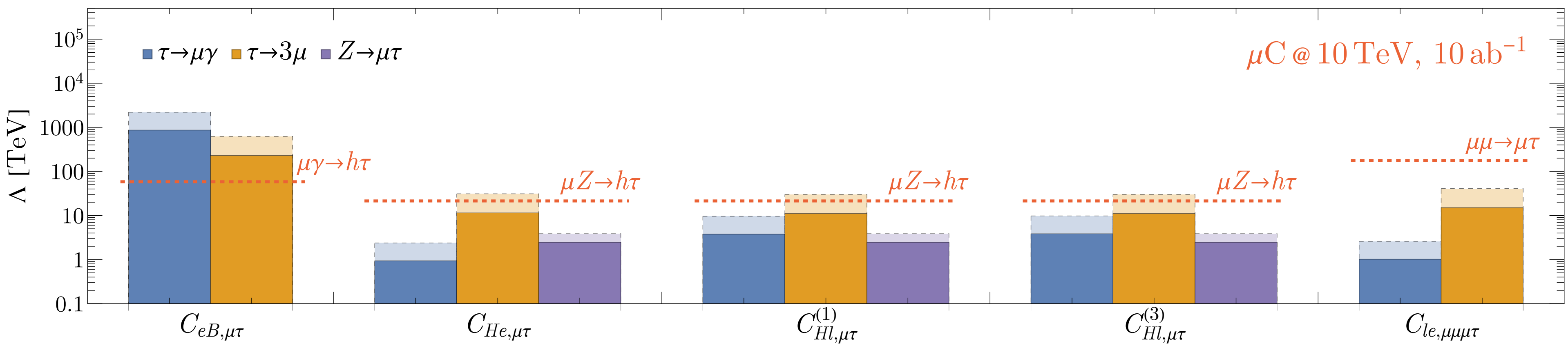
Scattering Results

The performance of a muon collider compared to existing and planned experiments depends on the operator.

For higgs operators, muon colliders slightly beat current low energy experiments, but next generation low energy experiments will beat their reach.

For four fermion operators, muon colliders improve new physics reach by many orders of magnitude.



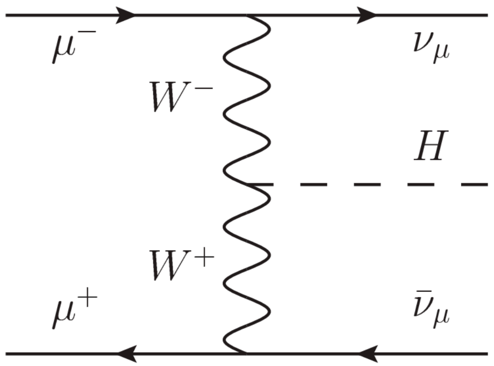
Higgs Decays at a Muon Collider

Flavor conserving higgs decays have already been studied at muon colliders.

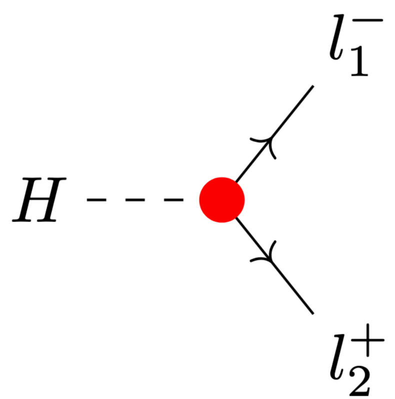
[Forslund & Meade (et al): 2203.09425, 2405.19314]
[Wulzer et al: 2012.11555, Han et al: 2008.12204, Chiesa et al: 2003.13628]

Here, we want to know how well we can probe flavor violating yukawa couplings.

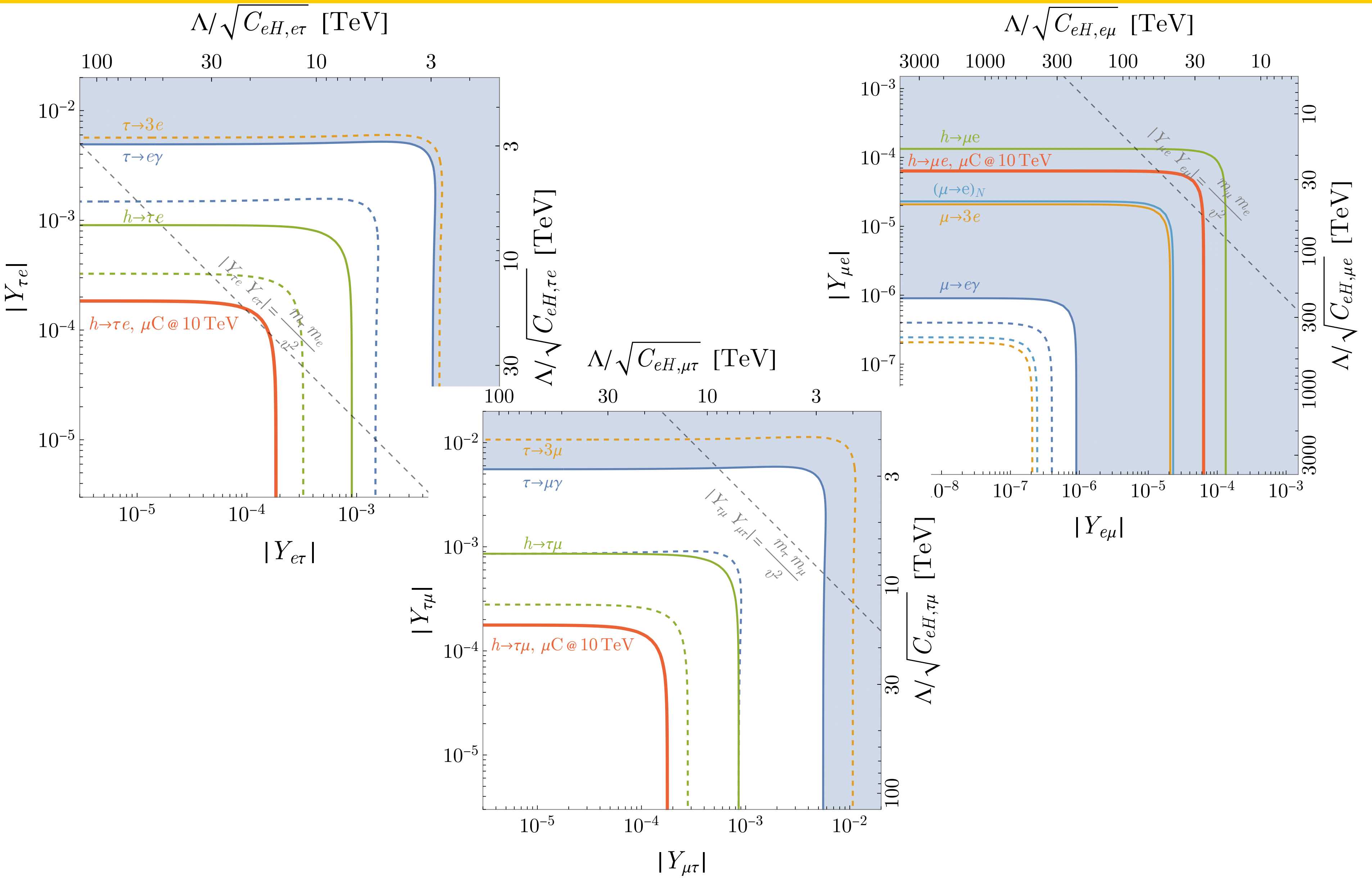
Higgs produced through VBF, primarily WBF, and decays through $h \to l_1^+ l_2^-$.



Primary backgrounds are is $h \to w^+ w^-$, $h \to \tau^+ \tau^-$



High Energy Constraints: Higgs Decays



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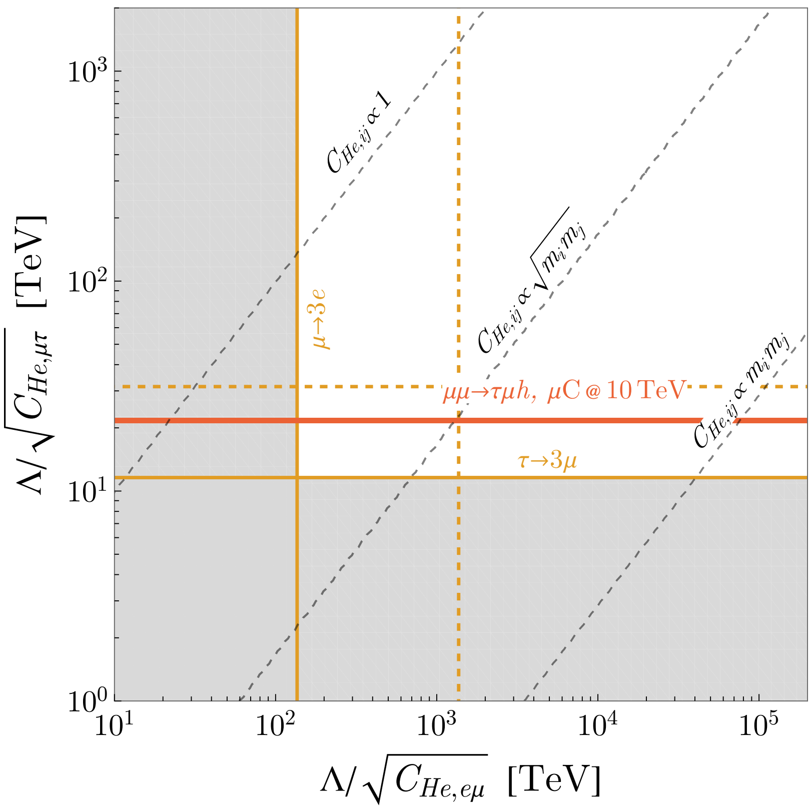
Testing Flavor Ansatz

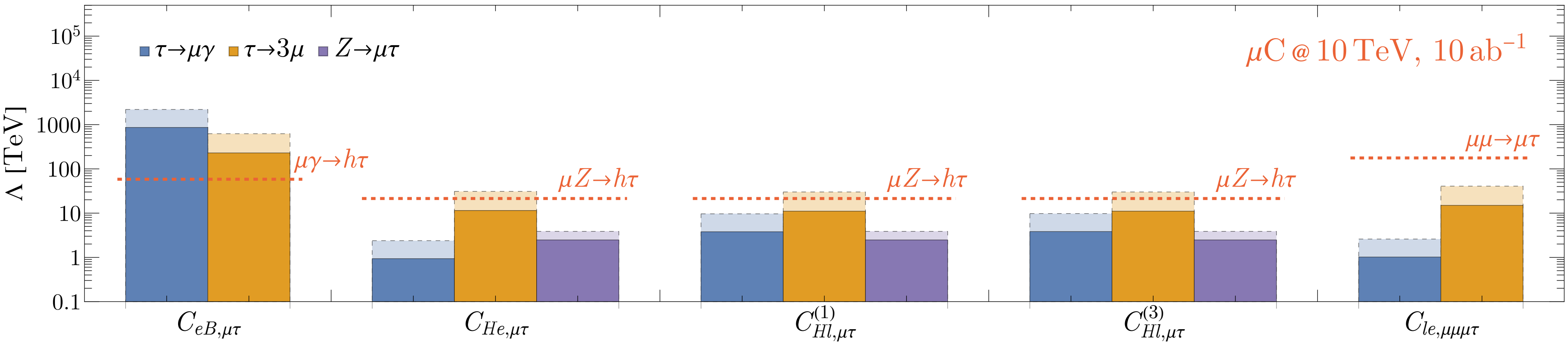
- Specific flavor ansatz can be tested because muon colliders probe multiple combinations of operators.
- Muon colliders can break degeneracies which are "flat directions" for low energy observables.



Summary

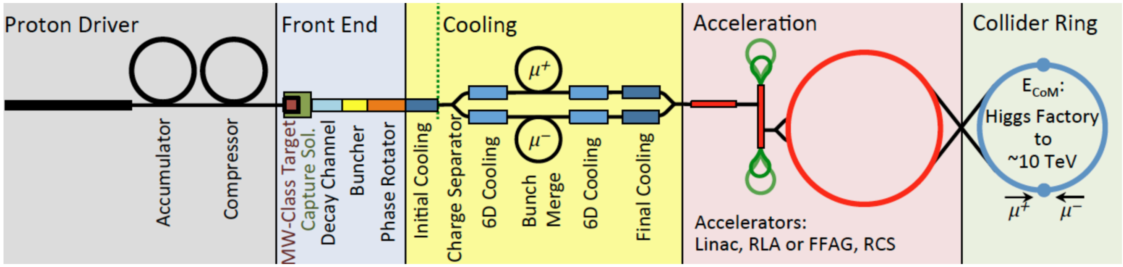
A muon collider could explore new LFV physics beyond the current reach of low energy experiments.

In the case of four fermion operators, muon colliders can improve upon all currently planned future experiments by orders of magnitude. They can also probe different flavor combinations.



Back Up Slides

Muon Collider Technology



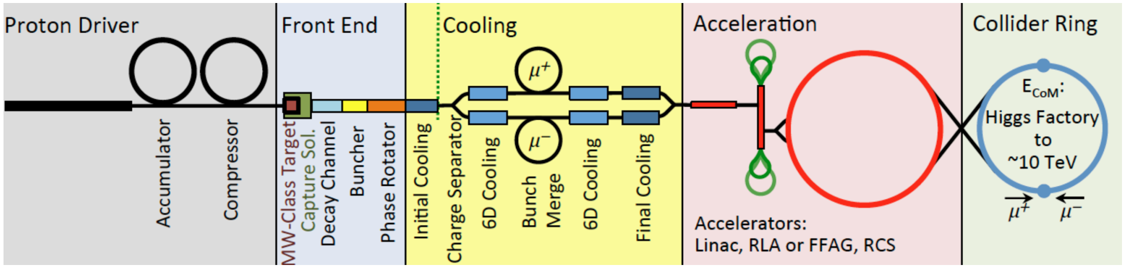
[Muon Collider Forum: 2209.01318]

Challenge: Robust targets For porton beams.
Potential Solutions: Many possible target materials are being studied by the RaDIATE collaboration, with R&D since 2012. Some neutrino beams progress can be repurposed, but need to survive higher thermal stress (due to single bunches and faster repititon rate).

Challenge: Muon Cooling
Potential Solutions: Happens in two stages.

a. First stage: Ionization cooling, because its the only fast enough method. Beam loses momentum through ionization in an absorber, then RF cavities restore momentum only along beam. Has been demonstrated by MICE experiment [MICE: 1907.08562]. RF cavities in magnetic field are challenging.
b. Second stage: Solenoid reduces transverse emittance while increasing longitudinal emittance, but is beyond existing solenoid technology. Other technologies also being considered

Muon Collider Technology



[Muon Collider Forum: 2209.01318]

Challenge: Accleration to the 10TeV scale with short cycles, low repitition rate, and high average field bend.
Potential Solutions: Pulsed dipole magnets are a viable solution but require R&D on viable power supplies.

Challenge: Beam Induced Background and Magnet Deterioration
Potential Solutions: Implement precision timing and particle flow, potentially with the aid of ML. Add shielding nozzles made of tungsten and borated polyethylene in the outer portion of the cone in the inner detector and cylinders of iron, concrete and borated polyethylene surround the beam pipe.

Challenge: Neutrino beam exiting far from collisions can cause dangerous radiation.
Potential Solution: Placing the beam line underground and components on movers which can be tilted periodically brings radiation down to safe levels

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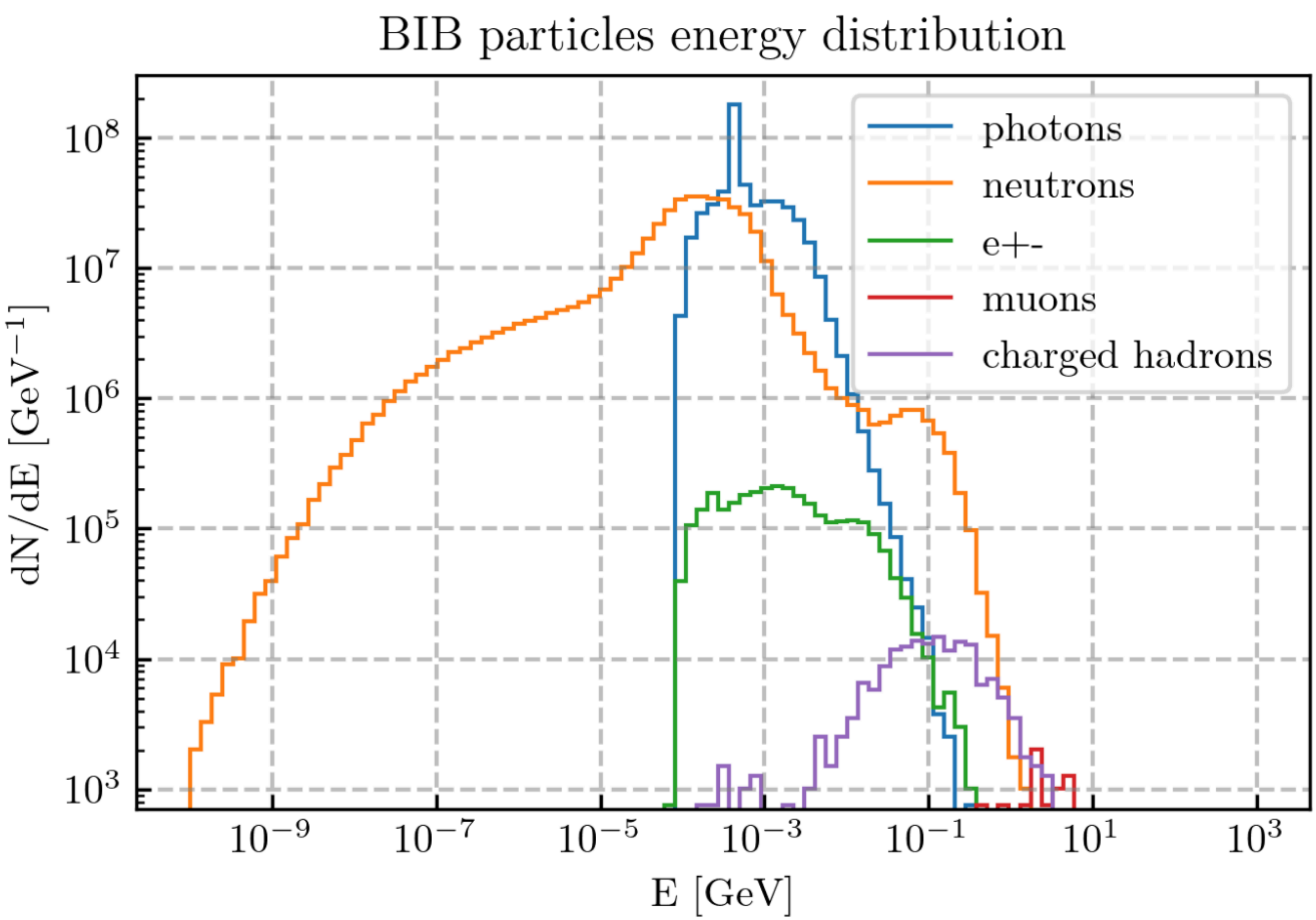
Beam Induced Background



[Image: Calzolari et al, PoS (ICHEP2024) 819]

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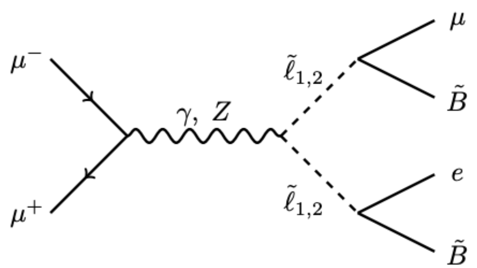
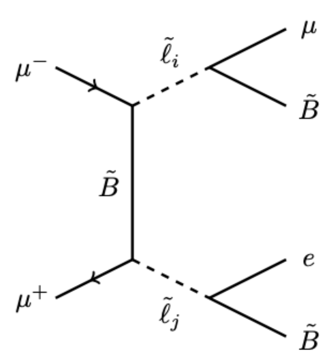
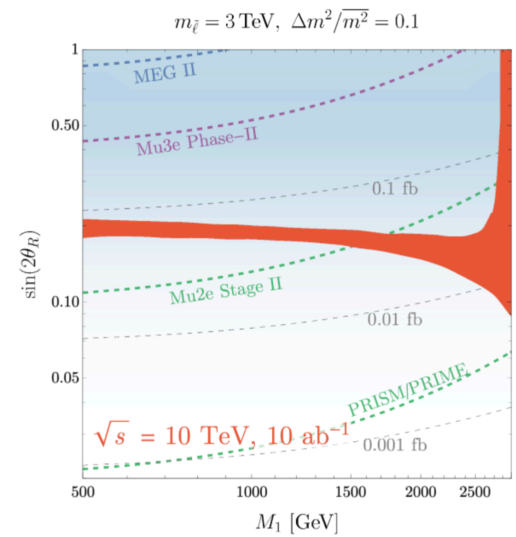
LFV Study in SUSY Models

- With SUSY, LFV occurs when sleptons are not diagonal in same basis as leptons. This comes from SUSY breaking.

- Study assumes only RH sleptons and lightest neutralino (bino-like) are light. Then the signal is $\mu^+\mu^- \to \mu e \tilde{B}\tilde{B}$. SUSY background of $\tau\tau\tilde{B}\tilde{B}$ decaying into μe is small but SM W^+W^- decays need to be rejected by reconstructing neutrino kinematics.







[Homiller et al: 2203.08825, 2103.14043]

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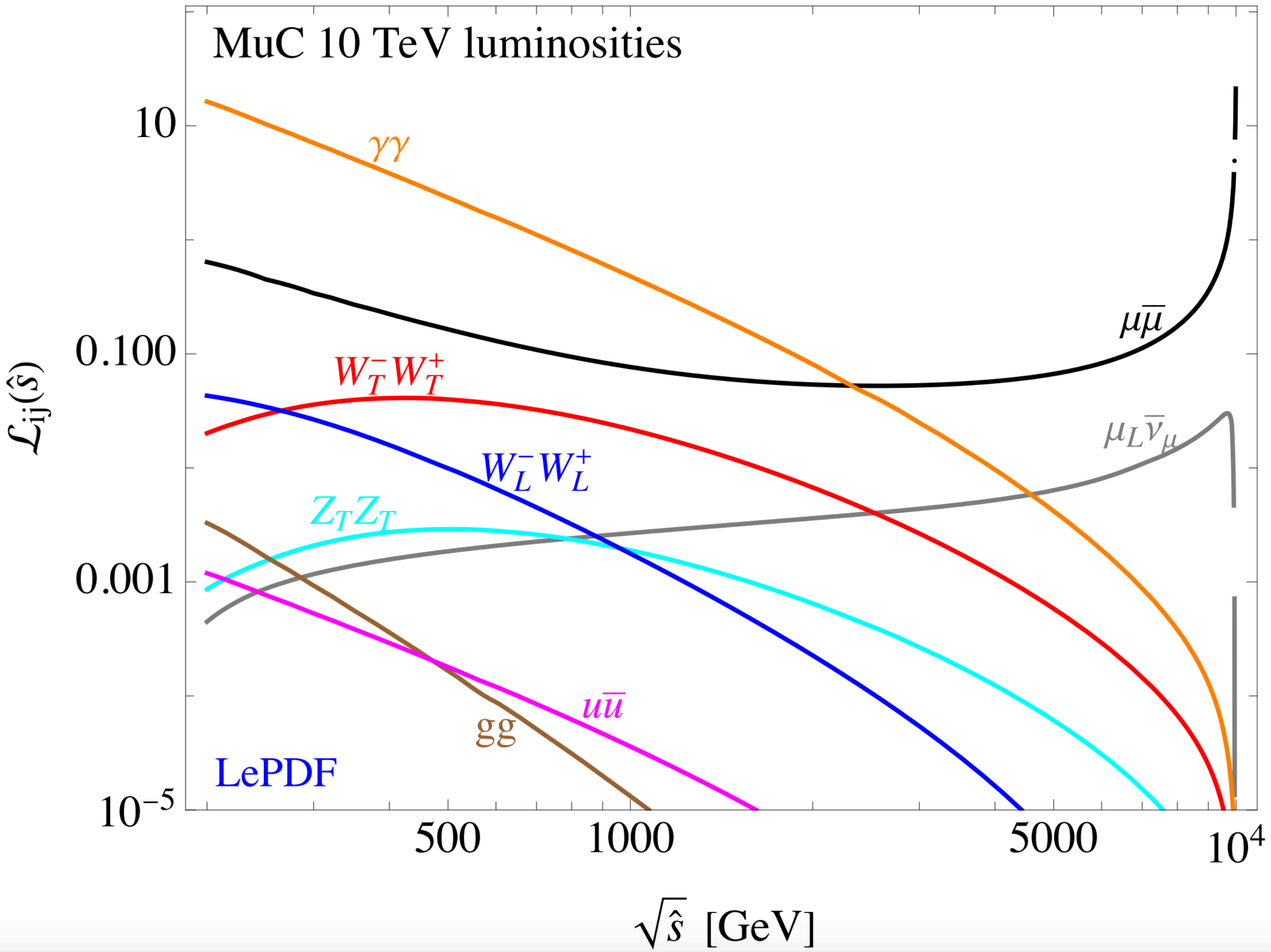
Muon Colliders Produce Vector Bosons



[Image: Garosi et al 2303.16964]

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MT2

$$(M_{\mathrm{T}}^{(i)})^2 = (m^{\mathrm{vis}(i)})^2 + m_{\mathrm{X}}^2 + 2\left(E_{\mathrm{T}}^{\mathrm{vis}(i)} E_{\mathrm{T}}^{\mathrm{X}(i)} - \vec{p}_{\mathrm{T}}^{\,\mathrm{miss\ vis}(i)} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{miss\ X}(i)}\right)$$

$$M_{\mathrm{T2}}(m_{\mathrm{X}}) = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss\,X}(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss\,X}(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)}\right)\right]$$