Title: Flavorful Probes of New Physics

Speakers: Katherine Fraser

Collection/Series: Particle Physics

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Abstract:

Measurements of the flavor structure of the Standard Model can be precise probes of physics beyond it. In this talk, we describe two implications of various flavor physics measurements. First, we discuss the use of Froggatt-Nielsen (FN) models for explaining the Standard Model flavor hierarchy. We define wrinkles, extra suppression or enhancement factors which modify the expected scaling of coupling sizes from FN models. We show how wrinkles can change the expected size of couplings to new physics in FN models, and how they naturally appear in various models, as well as discuss the example of the recent B->K\nu\nu measurement. In the second half of this talk, we use a SMEFT approach to illustrate the complementarity between future muon colliders and precision experiments for probing lepton flavor violation.

Flavorful Probes of New Physics

Katherine Fraser
Department of Physics & Miller Institute
University of California, Berkeley
and Lawrence Berkeley National Lab
kfraser@berkeley.edu

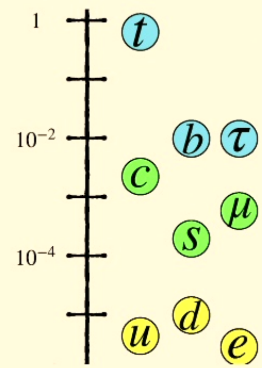
Perimeter Seminar 2025

Based on:
[arXiv: 2308.01340, w/ P. Asadi, A. Bhattacharya, S. Homiller, A. Parikh]
[Work in Progress w/ P. Asadi, H. Bagherian, S. Homiller, and Q. Lu]

Outline

1. Wrinkles in the Froggatt-Nielsen Mechanism

2. LFV at Future Muon Colliders



[Image: University of Basel]

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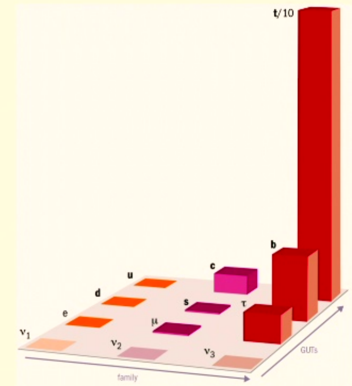
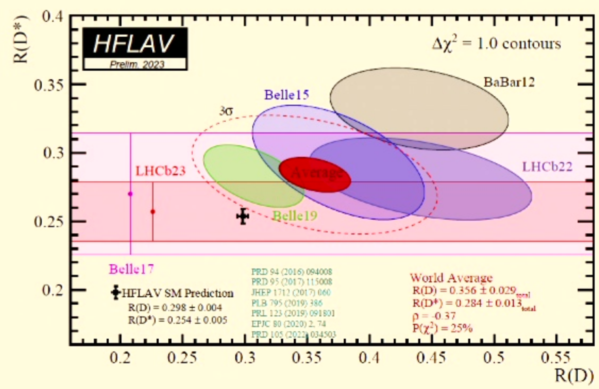
Why flavor physics?

- Understanding the SM flavor hierarchy
- Small or nonexistant SM backgrounds
- Experimental anomalies
- Many precise experiments





[Image: Cern Courier]

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Preview: Wrinkles in FN

Froggatt-Nielsen is a mechanism for explaining the flavor hierarchy using powers v/M. Explaining the SM fixes the charges of all the particles.

Typically, if we add (low energy) BSM particles, their couplings to SM particles are also fixed by FN.

We propose wrinkles as a way of quantifying how far you can parametrically change the vanilla FN ansatz and still have a FN-type UV completition, without introducing additional scales.

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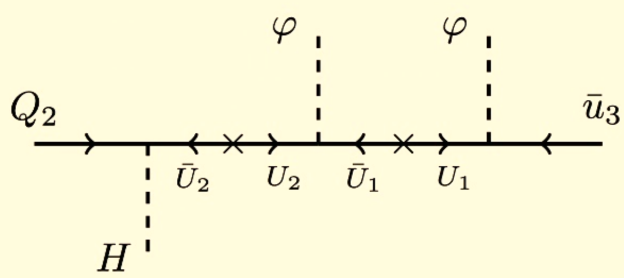
Froggatt-Nielsen (FN) Models

The simplest FN model [Froggatt & Nielsen, '79] contains:

- A horizontal symmetry $U(1)_H$, spontaneously broken by a heavy complex scalar φ called the flavon
- Multiple heavy fermions U_i with charge $[i]_H$ and mass $\sim M$
- All fermions U_i necessary for SM Yukawas exist



$$Y^{23} \sim \lambda^{|[Q_2]_H + [\bar{u}_3]_H|}$$

$$\lambda = \frac{\langle \varphi \rangle}{M}$$

More complicated variations have also been developed, including: inverted models, ones with additional symmetries, or multiple expansion parameters.

Katherine Fraser, kfraser@berkeley.edu

Explaining the Standard Model

Horizontal charges of SM particles are fixed by masses and mixing parameters.

Mixing Matrices

$$V_{ij}^{CKM} \sim \lambda^{|[Q_i]_H-[Q_j]_H|} \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad U_{ij}^{PMNS} \sim \lambda^{|[L_i]_H-[L_j]_H|} \begin{pmatrix} 1 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

SM hierarchies follow the Wolfenstein parameterization; λ is the Cabibo angle

SM Masses

$$y_i^u \sim (\lambda^7, \lambda^3, 1) \quad \lambda^{|[Q_i]_H+[\bar{u}_i]_H|} \qquad y_i^d \sim (\lambda^6, \lambda^5, \lambda^2) \quad \lambda^{|[Q_i]_H+[\bar{d}_i]_H|} \qquad y_i^l \sim (\lambda^8, \lambda^5, \lambda^3) \quad \lambda^{|[L_i]_H+[\bar{e}_i]_H|}$$

Off diagonal elements also important for the correct mass eigenstate diagonalization.

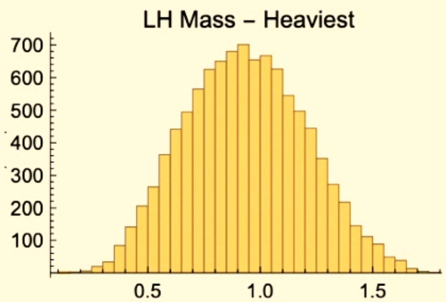
Katherine Fraser, kfraser@berkeley.edu

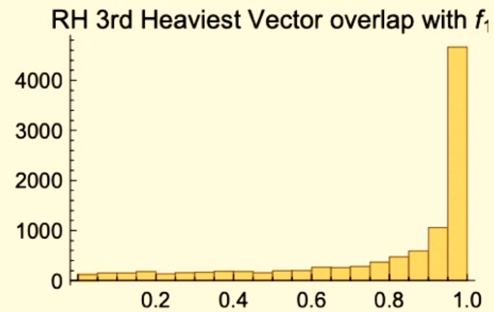
Result 1: Allowed FN Charges

- Mixing matrices and masses only fix absolute values.
- Some freedom in allowed: monotonicity is not required for first generation fermions.
- For SUSY theories, holomorphy sets X = -Y = -1, chooses postivie sign for RH fermions

*Up to \pm 1 shifts

	Gen. 1	Gen. 2	Gen. 3
Q	$-q_0 - 3X$	$-q_0 - 2X$	$-q_0$
$\bar{u}$	$q_0 + 3X \pm 7$	$q_0 - X$	q_0
$\bar{d}$	$q_0 + 3X \pm 6$	$q_0 - 3X$	$q_0 - 2X$
L	$l_0 + Y$	l_0	l_0
$\bar{e}$	$-l_0 - Y \pm 8$	$-l_0 + 5Y$	$-l_0 + 3Y$





Also need to check eigenstates are correct by testing $\mathcal{O}(1)$ coefficients

Katherine Fraser, kfraser@berkeley.edu

Adding Particles to FN Models

Suppose we want to add new (low energy) BSM particles. These particles can be treated as spurions of

$$G_{flavor} = SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e \times U(1)^5$$

In vanilla FN models, the size of new physics spurions are also fixed by the FN charges.

Ex: S_1 Leptoquark. Has charge: $(\overline{3},1,1/3)$

Lagrangian:

$$\mathscr{L} \supset -\Delta^{ij}_{QL}\epsilon^{ab}S_1 Q_{bi}L_{aj} - \Delta^{ij}_{\bar{u}\bar{e}}S_1^{\dagger}\bar{u}_i\bar{e}_j + \text{h.c.}$$

Yukawa Coupling Sizes:

$$\Delta^{ij}_{QL} \sim \lambda^{|[Q_i]_H + [L_j]_H|} \text{ and } \Delta^{ij}_{\bar{u}\bar{e}} \sim \lambda^{|[\bar{e}_j]_H + [\bar{u}_i]_H|}$$

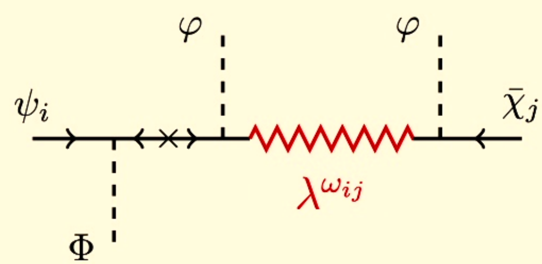
Katherine Fraser, kfraser@berkeley.edu

Result 2: Wrinkles

But this recipe is deceptive! Simple UV modifications to FN can break this scaling.

Wrinkles are a naturally arising way of parameterizing deviations from the vanilla FN ansatz. They quantify how far we can deviate and have a FN-type UV completition.

$$Y^{ij}_{\psi\bar{\chi}} \sim W^{ij}_{\psi\bar{\chi}}\lambda^{|[\psi_i]+[\bar{\chi}_j]|} \equiv \lambda^{\omega_{ij}+|[\psi_i]+[\bar{\chi}_j]|}$$



Wrinkles can modify either the new or the SM yukawas. SM coupling changes must be compensated for by modified charges.

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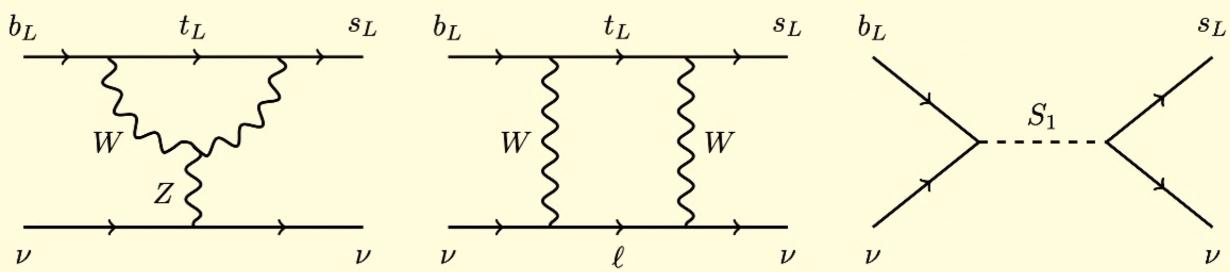
Example: $B^+ \to K^+\overline{\nu}\nu$ with the S_1 Leptoquark

$B^+ \to K^+\overline{\nu}\nu$ is theoretically clean & Belle II has a (not yet significant) hint of a deviation from the SM.

$$\text{Belle II} = (1.1 \pm 0.4) \times 10^{-5}$$

$$\text{SM} = (0.46 \pm 0.05) \times 10^{-5}$$

$B^+ \to K^+\overline{\nu}\nu$ gets contributions from the SM at one loop and the S_1 leptoquark at tree level.



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Strongest Constraints on FN

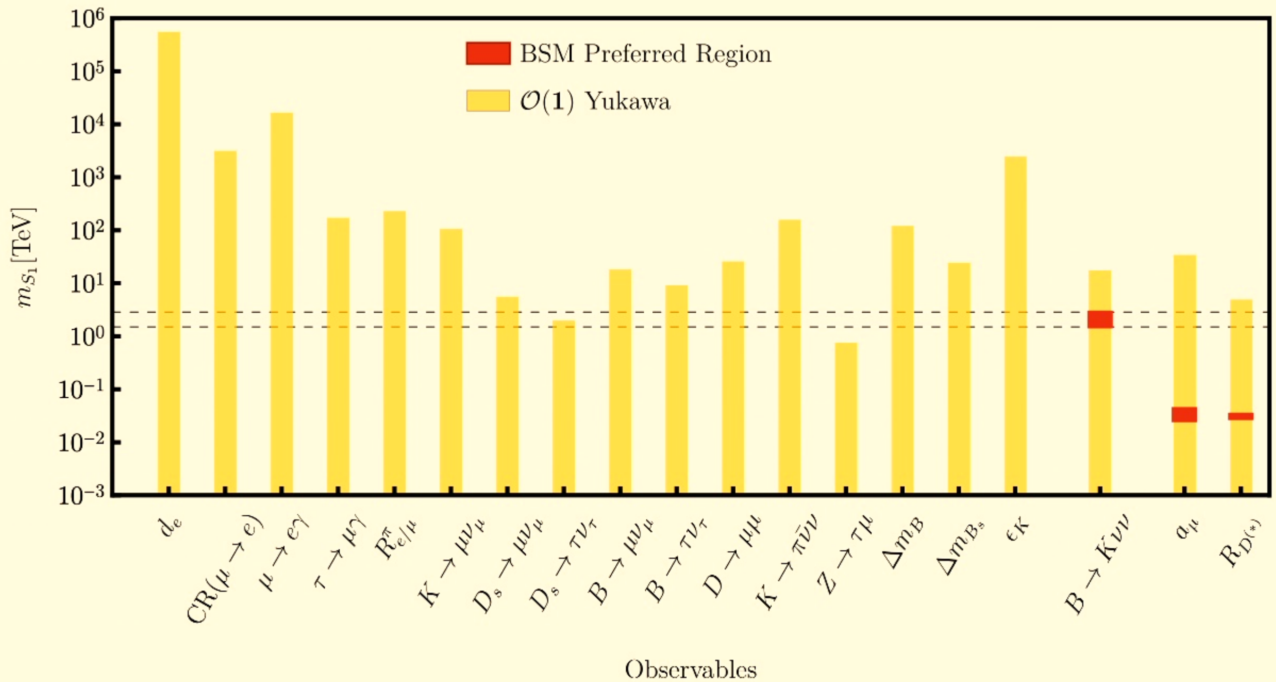
Observable	S_1 Yukawa Couplings	Experimental Result	Future Bounds
$\mathrm{BR}(B^+ \to K^+ \bar{\nu}\nu)$	$\Delta_{QL}^{3i} \times (\Delta_{QL}^{2j})^*$	$(1.1 \pm 0.4) \times 10^{-5}$ [Belle II]	-
electron EDM	$(V^* \Delta_{QL})^{31} \times (\Delta_{\bar{u}\bar{e}}^{31})^*$	$< 4.1 \times 10^{-30}\ e\,\mathrm{cm}$ [JILA]	$< 10^{-31}\ e$ cm [2002.02332] [2009.00346]
$\mathrm{BR}(\mu \to e\gamma)$	$(V^* \Delta_{QL})^{32} \times \Delta_{\bar{u}\bar{e}}^{31}$ $\Delta_{\bar{u}\bar{e}}^{32\,*} \times (V^* \Delta_{QL})^{31\,*}$	$< 4.2 \times 10^{-13}$ [MEG]	$< 6 \times 10^{-14}$ [MEG II]
$\mathrm{CR}(\mu \to e)_N$	$(V^* \Delta_{QL})^{11\,*} \times (V^* \Delta_{QL})^{12}$	$< 7.0 \times 10^{-13}$ [SINDRUM II]	$< 2.5 \times 10^{-18}$ [Mu2e]
$\mathrm{BR}(\tau \to \mu\gamma)$	$(V^* \Delta_{QL})^{33} \times \Delta_{\bar{u}\bar{e}}^{32}$ $\Delta_{\bar{u}\bar{e}}^{33\,*} \times (V^* \Delta_{QL})^{32\,*}$	$< 4.2 \times 10^{-8}$ [Belle]	$< 6.9 \times 10^{-9}$ [Belle II]
$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu)$	$\Delta_{QL}^{2k} \times (\Delta_{QL}^{1k})^*$	$< 1.88 \times 10^{-10}$ [NA62]	$(8.4 \pm 0.4) \times 10^{-11}$ [NA62]
Δm_{B_s}	$(\Delta_{QL}\,\Delta_{QL}^{\dagger})^{32}$	$\Delta C_{B_s} \leq 0.09$ [1812.07638] from UTfit	$\Delta C_{B_s} \leq 0.026$ [1812.07638] using HL-LHC, Belle II

[See 2308.01340 for refs]

Katherine Fraser, kfraser@berkeley.edu

Constraints

With $\mathcal{O}(1)$ couplings, other correlated constraints rule out the $B^+ \to K^+\bar{\nu}\nu$ preferred region:



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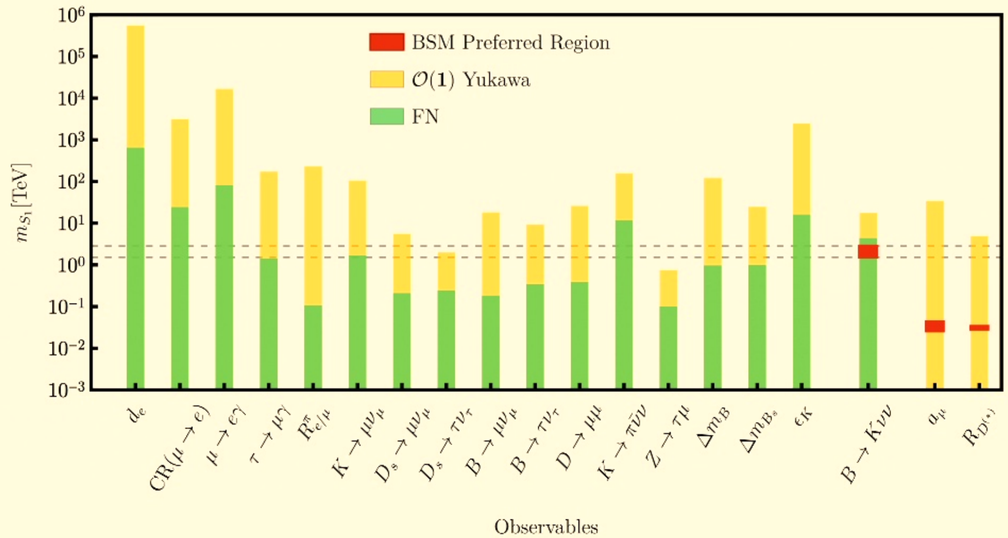
Constraints

With vanilla FN couplings, the $B^+ \to K^+\overline{\nu}\nu$ preferred region is still ruled out:

$$[Q_i] = (3,2,0), \quad [\bar{u}_i] = (4,1,0), \quad [\bar{d}_i] = (3,3,2), \quad [L_i] = (0,-1,-1), \quad [\bar{e}_i] = (8,6,4)$$

$$\Delta_{QL} \sim \begin{pmatrix} \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^2 & \lambda & \lambda \\ 1 & \lambda & \lambda \end{pmatrix}, \qquad \Delta_{\bar{u}\bar{e}} \sim \begin{pmatrix} \lambda^{12} & \lambda^{10} & \lambda^8 \\ \lambda^9 & \lambda^7 & \lambda^5 \\ \lambda^8 & \lambda^6 & \lambda^4 \end{pmatrix}$$



Katherine Fraser, kfraser@berkeley.edu

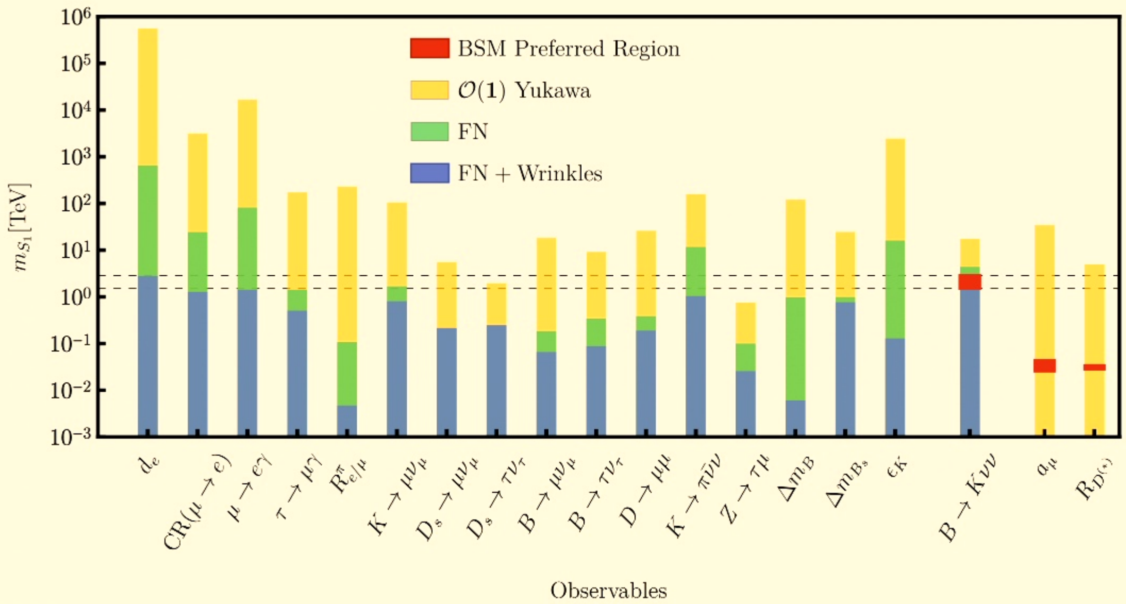
Constraints

With wrinkles, we can obtain a viable solution:

$$[Q_i] = (3,2,0), \quad [\bar{u}_i] = (4,1,0), \quad [\bar{d}_i] = (3,3,2), \quad [L_i] = (0,-1,-1), \quad [\bar{e}_i] = (8,6,4)$$

$$W^{ij}_{\bar{u}\bar{e}} = \lambda^3, \qquad W_{QL} = \begin{pmatrix} \lambda^3 & \lambda^3 & \lambda^3 \\ \lambda^3 & 1 & 1 \\ \lambda^3 & 1 & 1 \end{pmatrix}$$

Respects $\omega \gtrsim 1/16\pi^2$



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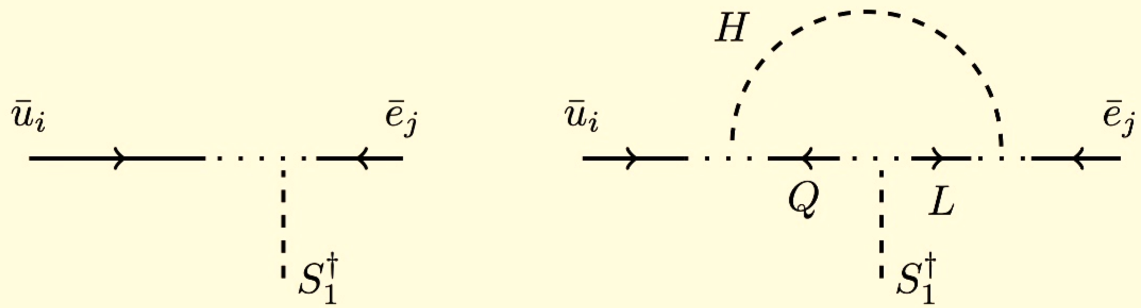
Radiative Corrections and Predictivity

- Wrinkled FN models are still predictive: flexibility is not unlimited.
- Requiring tree-level contributions dominate over loops gives a set of consistency conditions:

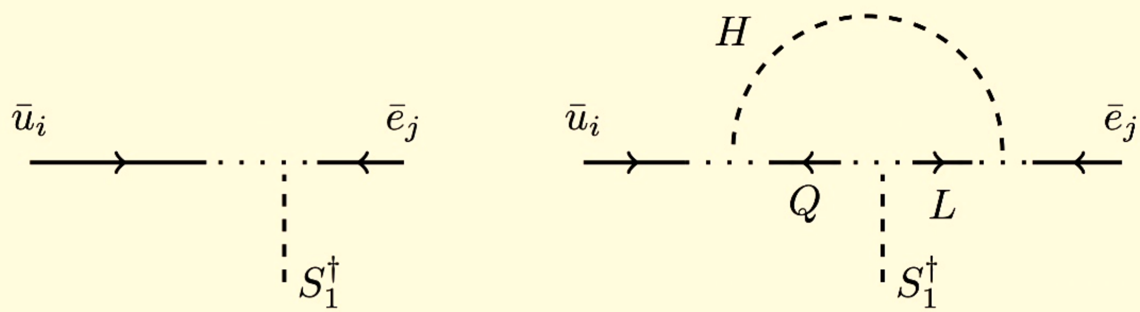


$$|\,\Delta^{ij}_{\bar{u}\bar{e}}\,| \gtrsim \frac{1}{16\pi^2}\,|\,(Y^T_{Q\bar{u}}\cdot\Delta^*_{QL}\cdot Y_{L\bar{e}})^{ij}\,|$$

- In order to satisfy these inequalities, it is *sufficient* (but *not necessary*), to take $W^{ij}_{\psi\bar{\chi}} \gtrsim \frac{1}{16\pi^2}$ (assuming $\omega^{ij}_{\psi\chi} \geq 0$)

Katherine Fraser, kfraser@berkeley.edu

Example: Consistency Conditions



$$|\Delta^{ij}_{\bar{u}\bar{e}}| \gtrsim \frac{1}{16\pi^2} |(Y^T_{Q\bar{u}} \cdot \Delta^*_{QL} \cdot Y_{L\bar{e}})^{ij}|$$

$\underbrace{|\Delta^{ij}_{\bar{u}\bar{e}}|}_{\lambda^{\omega^{ij}_{\bar{u}\bar{e}} + |[\bar{u}_i]_H + [\bar{e}_j]_H|}}$ $\qquad$ $\underbrace{\Delta^*_{QL}}_{\lambda^{\omega^{kl}_{QL} + |[Q_k]_H + [L_l]_H|}}$

$$\Rightarrow \omega^{33}_{\bar{u}\bar{e}} \lesssim 2 + \omega^{33}_{QL} + \log_\lambda \frac{1}{16\pi^2}$$

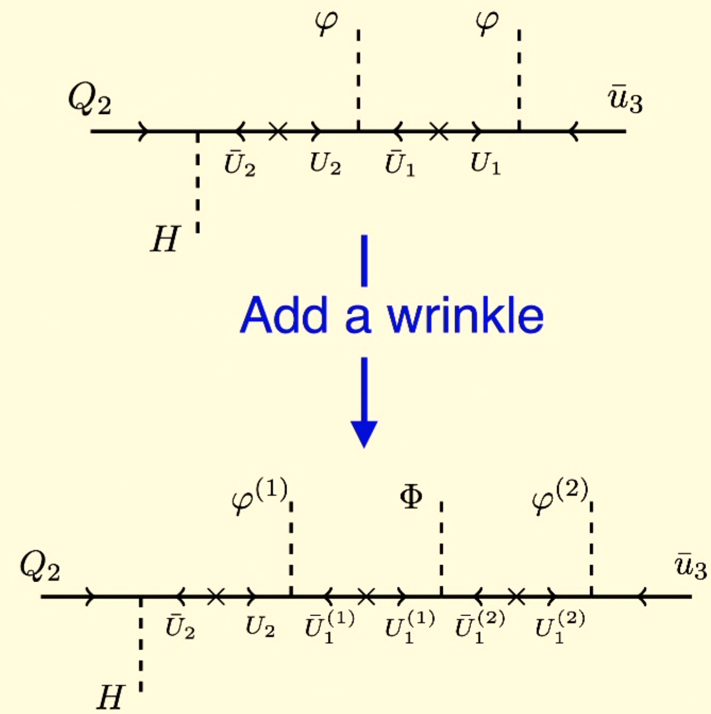
So up to 5 wrinkles in $\Delta^{33}_{\bar{u}\bar{e}}$ are allowed without wrinkles in Δ^{33}_{QL}

Katherine Fraser, kfraser@berkeley.edu

Example UV Completition: Modified Heavy Fermions

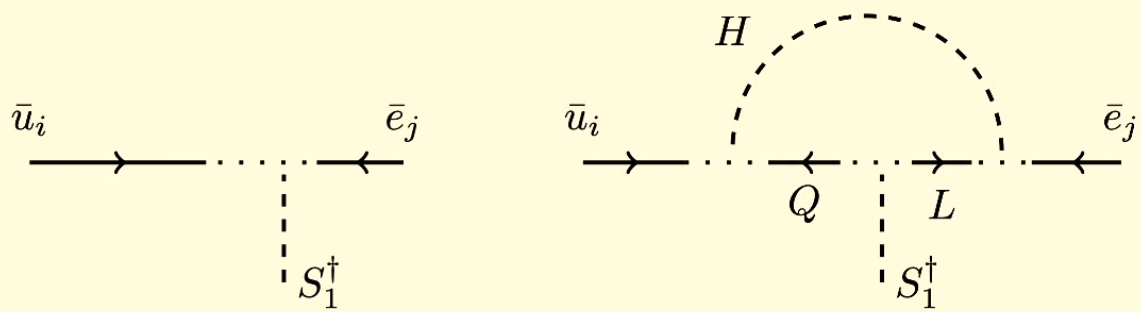
Wrinkles arise naturally from UV dynamics. An example is charging heavy fermions under additional symmetries:

Particle	$U(1)_H$	$SU(N_1)$	$SU(N_2)$
U_i $i \neq 1$	i	1	1
$U_1^{(1)}$	1	N_1	1
$U_1^{(2)}$	1	1	N_2
$\varphi^{(1)}$	-1	N_1	1
$\varphi^{(2)}$	-1	1	$\overline{N}_2$
$\Phi^{(1,2)}$	0	$\overline{N}_1$	N_2



Katherine Fraser, kfraser@berkeley.edu

Example: Consistency Conditions



$$|\Delta^{ij}_{\bar{u}\bar{e}}| \gtrsim \frac{1}{16\pi^2} |(Y^T_{Q\bar{u}} \cdot \Delta^*_{QL} \cdot Y_{L\bar{e}})^{ij}|$$

$\underbrace{|\Delta^{ij}_{\bar{u}\bar{e}}|}_{\lambda^{\omega^{ij}_{\bar{u}\bar{e}} + |[\bar{u}_i]_H + [\bar{e}_j]_H|}}$, $\underbrace{\Delta^*_{QL}}_{\lambda^{\omega^{kl}_{QL} + |[Q_k]_H + [L_l]_H|}}$

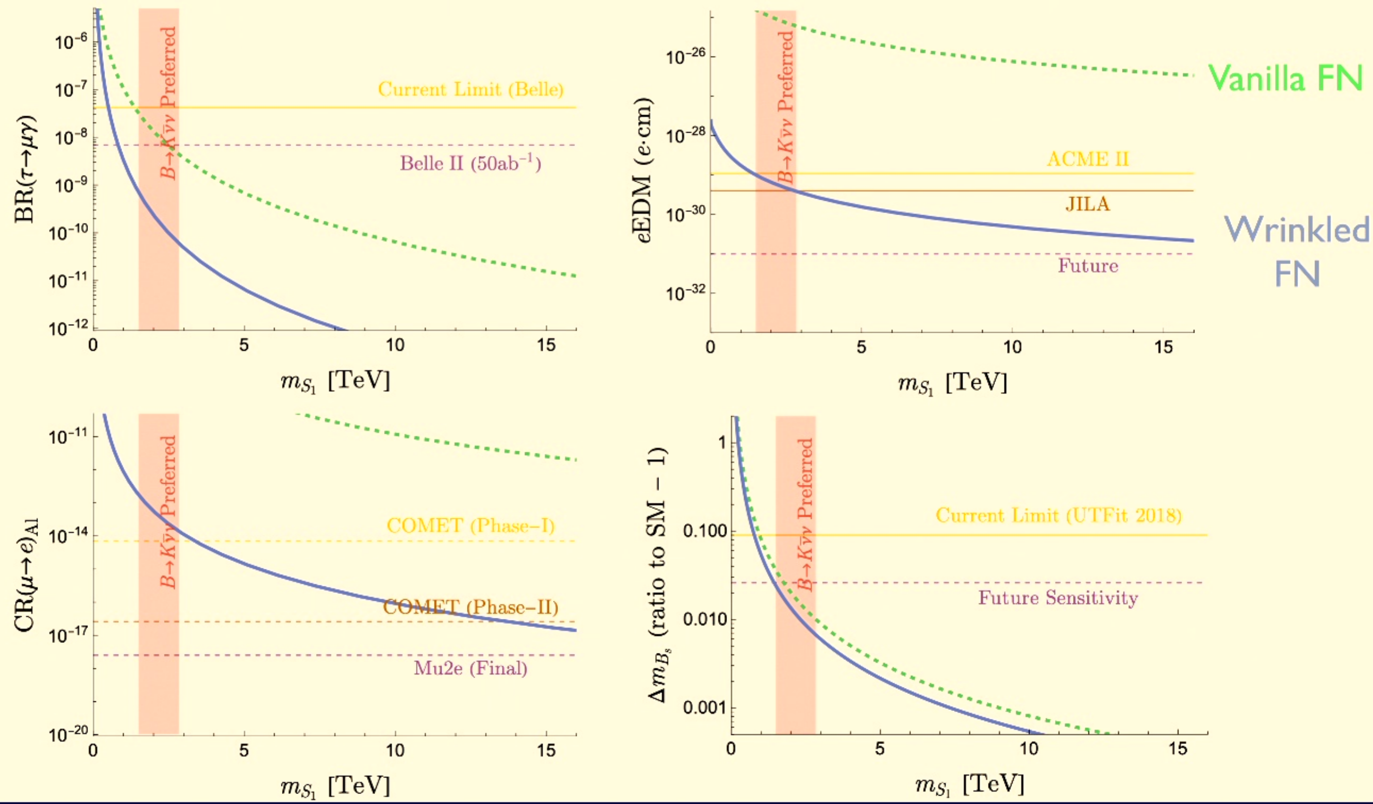
$$\Rightarrow \omega^{33}_{\bar{u}\bar{e}} \lesssim 2 + \omega^{33}_{QL} + \log_\lambda \frac{1}{16\pi^2}$$

So up to 5 wrinkles in $\Delta^{33}_{\bar{u}\bar{e}}$ are allowed without wrinkles in Δ^{33}_{QL}

Katherine Fraser, kfraser@berkeley.edu

S_1 Example: Future Measurements

Although our wrinkled ansatz is viable now, upcoming experiments will test it:



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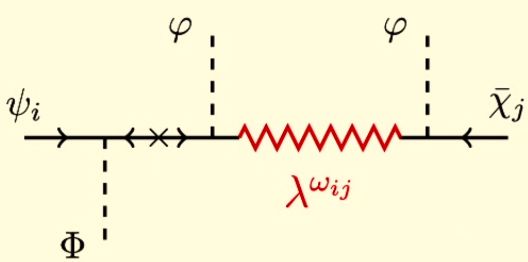
Summary and Next Steps

Wrinkles are a way of parametrically changing new physics couplings in FN without introducing additional scales.



They arise naturally in the UV and can improve the consistency between measurements.

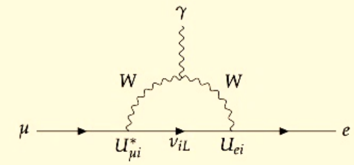
Next steps:

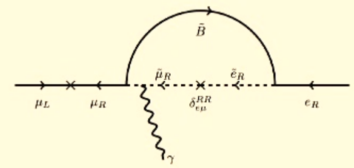
- Systematics studies of modifying $U(1)_H$ charges, $\mathcal{O}(1)$ numbers, other spurions
- Understand realistic UV patterns of wrinkles
- Implement an analog of wrinkles in other mechanisms for generating flavor hiearchies

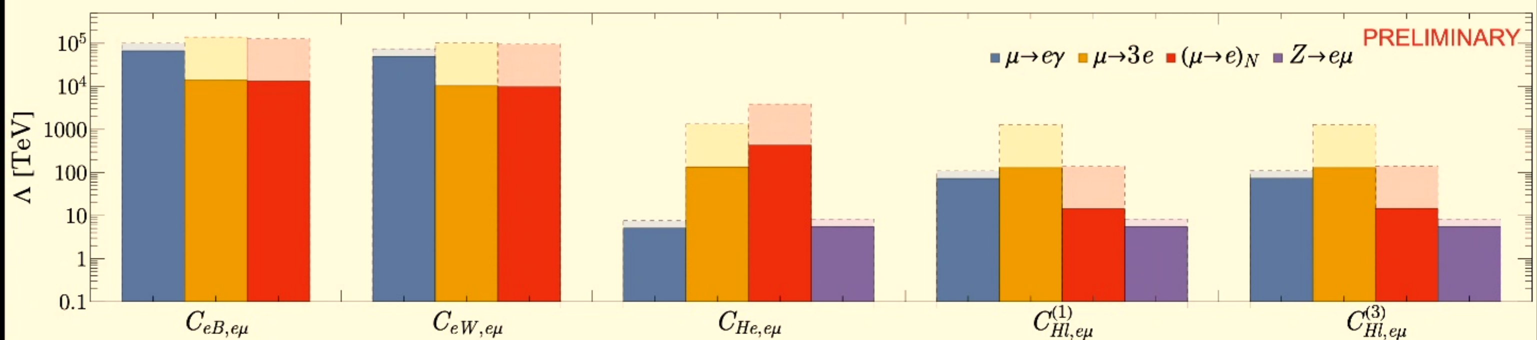
Katherine Fraser, kfraser@berkeley.edu

Lepton Flavor Violation

- Charged LFV is a smoking gun for BSM because all SM contributions are neutrino mass suppressed
- LFV arises in simple models, including SUSY (SUSY breaking causes nondiagonal sleptons interactions) and leptoquarks.







However, current probes of LFV are sensitive to scales that are much higher than typical searches. Can a muon collider do better?

Katherine Fraser, kfraser@berkeley.edu

Probing LFV with a Muon Collider

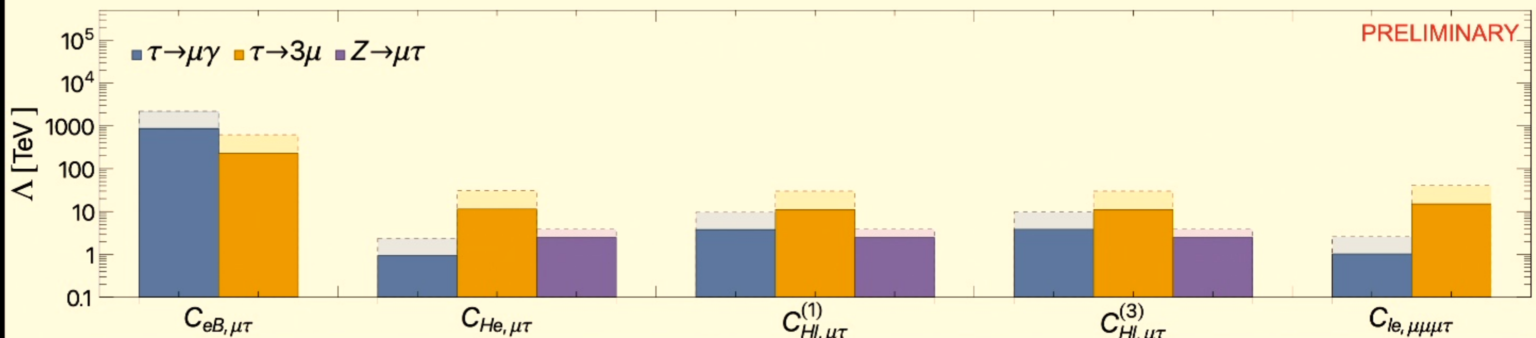
- Probing LFV is interesting at any potential future collider; it has already been studied for FCC-ee/CEPC. [Altmannshofer et al: 2305.03869]
- Muon colliders have some qualitative differences which might allow probing different parameter space:
  - Higher energy
  - Sensitive to different coefficient combinations $(\mu \to \tau)$
- Previous studies at muon colliders have focused on specific models, for example SUSY. [Homiller et al: 2203.08825, 2103.14043]

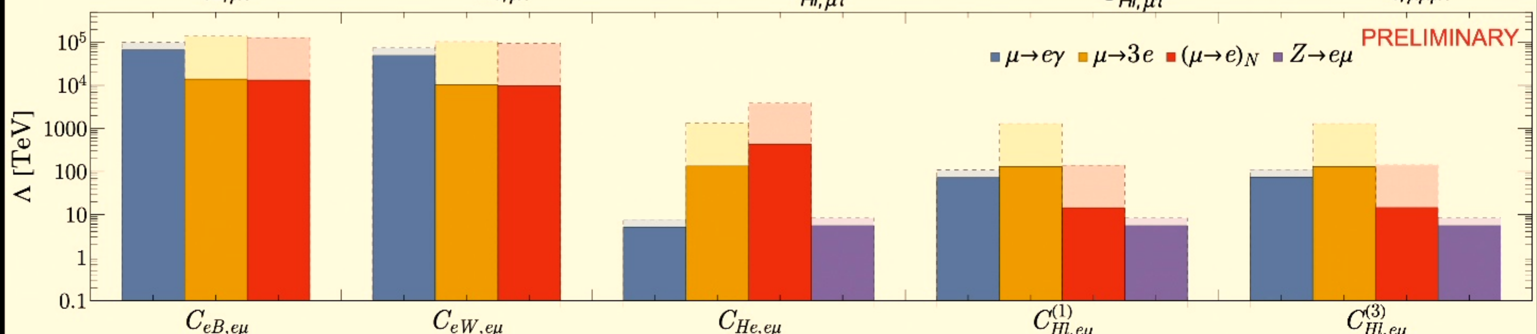
Katherine Fraser, kfraser@berkeley.edu

H and 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]





Katherine Fraser, kfraser@berkeley.edu

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

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

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

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

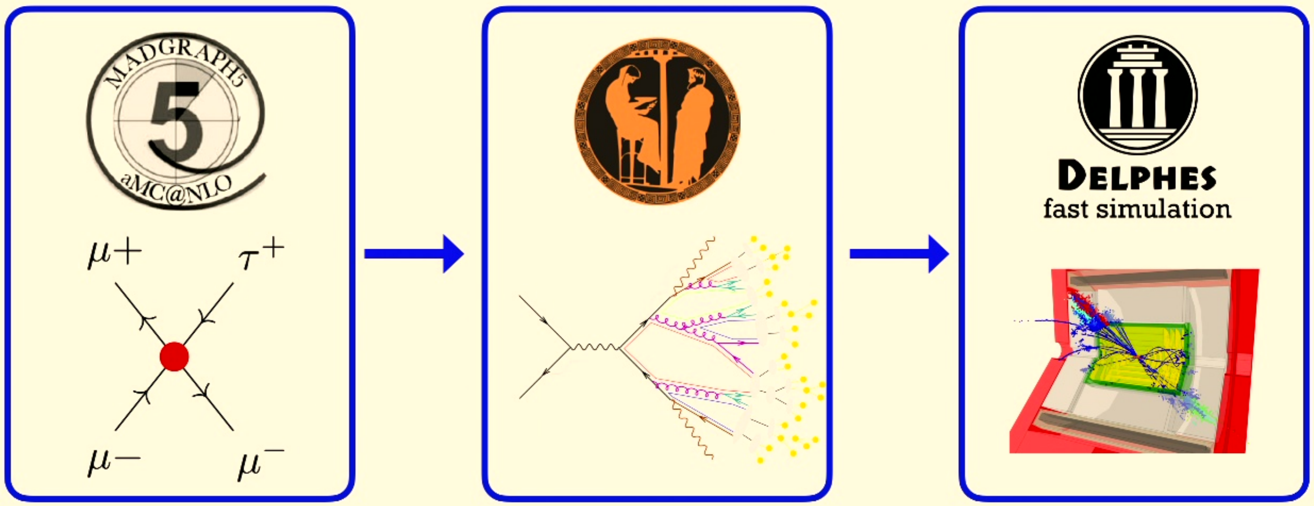
[Manohar et al: http://einstein.ucsd.edu/]

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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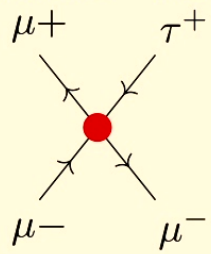
Example: $\mu\mu \rightarrow \mu\tau$

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

2.1×10^6 Events



The Largest Backgrounds:

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

4.0×10^4 Events

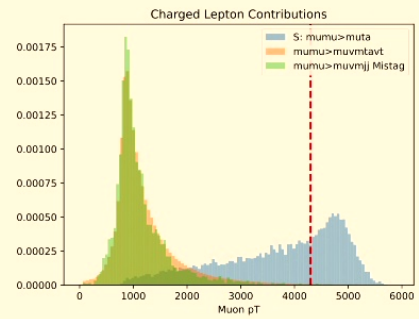
Including: $\mu\mu \rightarrow \tau\tau$, $\mu\mu \rightarrow ww$

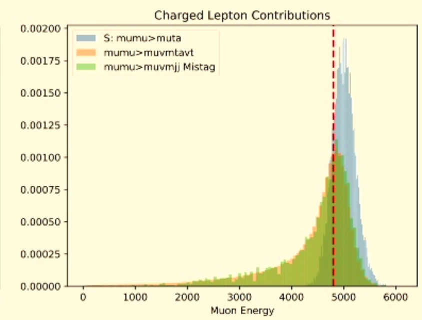
2) $\mu\mu \rightarrow \mu\bar{\nu}_\mu j$, jet mistag:

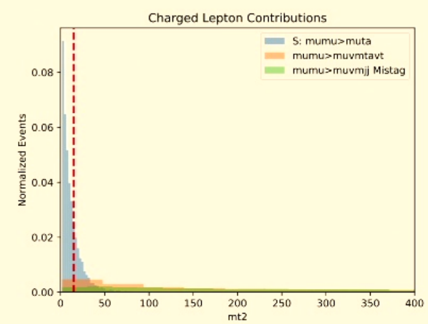
2.1×10^3 Events

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

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







Remaining events:

Signal:

4.3×10^5

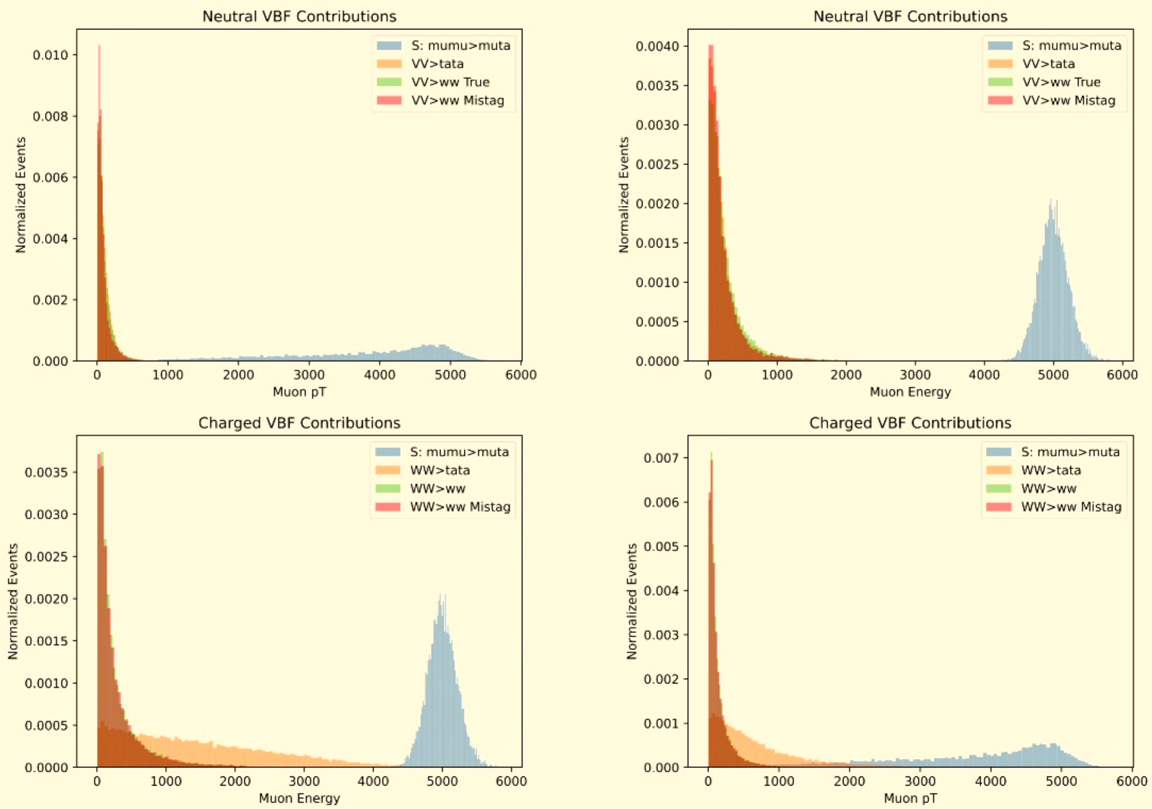
Background Events:

3

Katherine Fraser, kfraser@berkeley.edu

Example: $\mu\mu \rightarrow \mu\tau$

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



Note: Each histogram is independently normalized to one

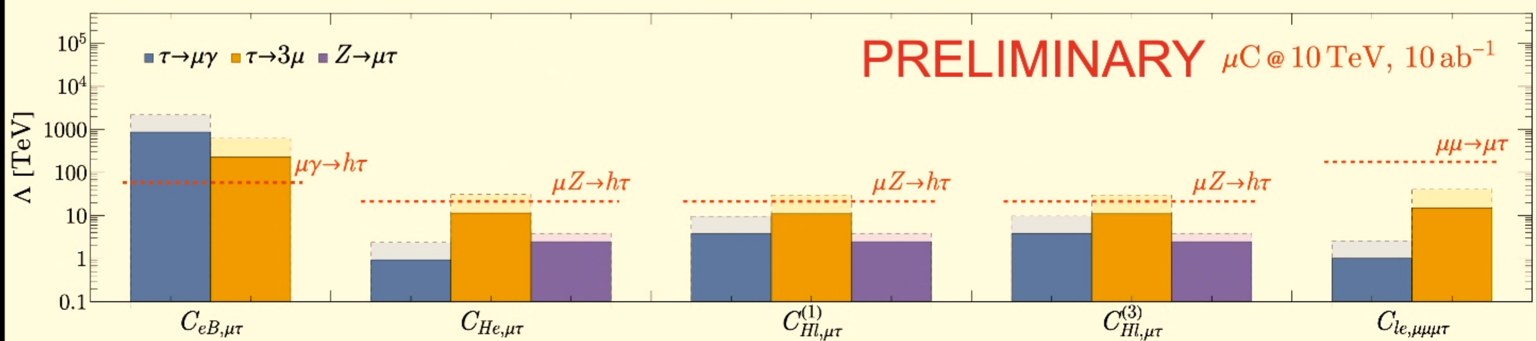
Katherine Fraser, kfraser@berkeley.edu

Scattering Results

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

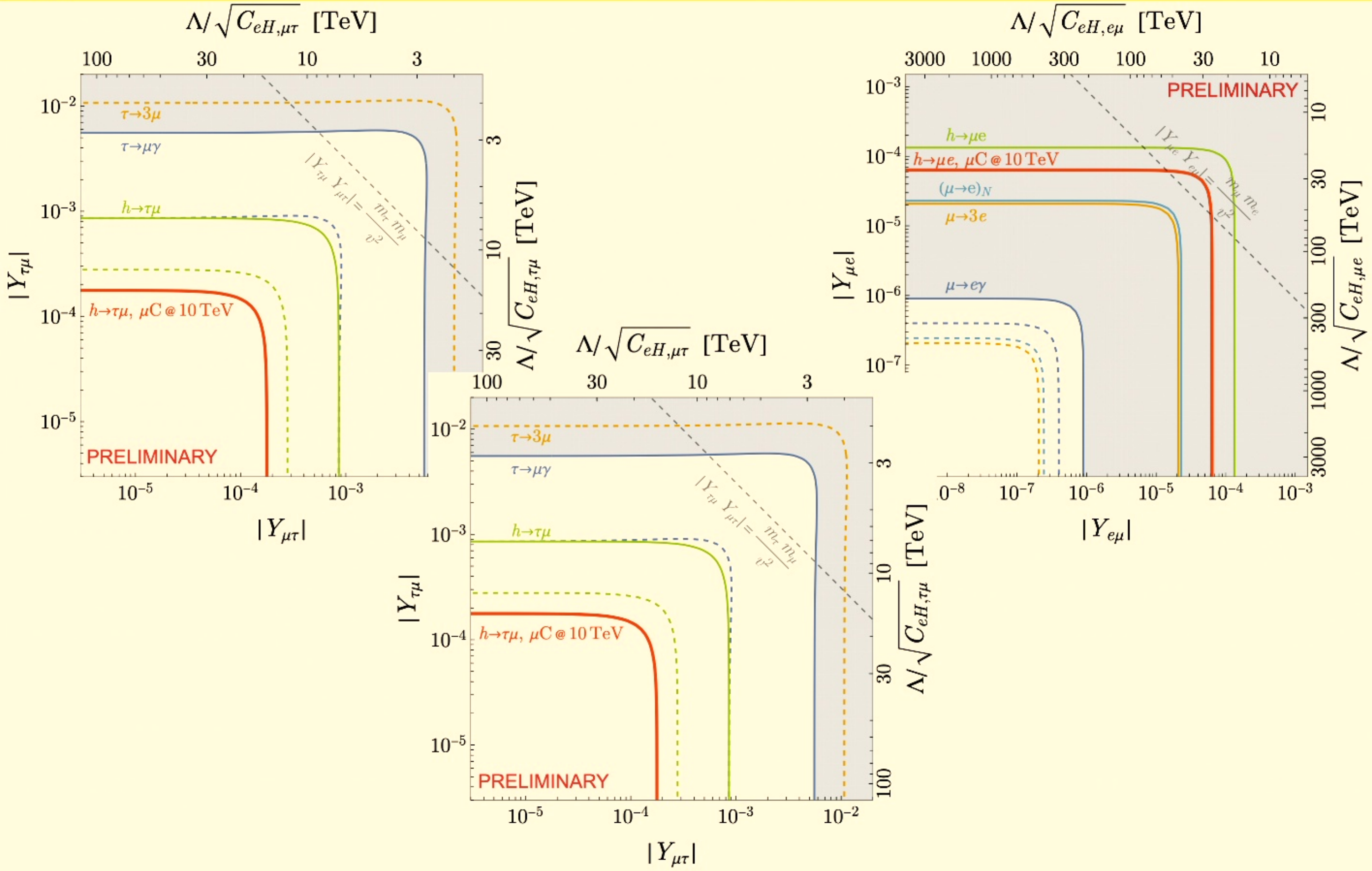
For higgs operators, muon colliders slightly beat current low energy experiments, but next generation low energy experiments will beat their reach.

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



Katherine Fraser, kfraser@berkeley.edu

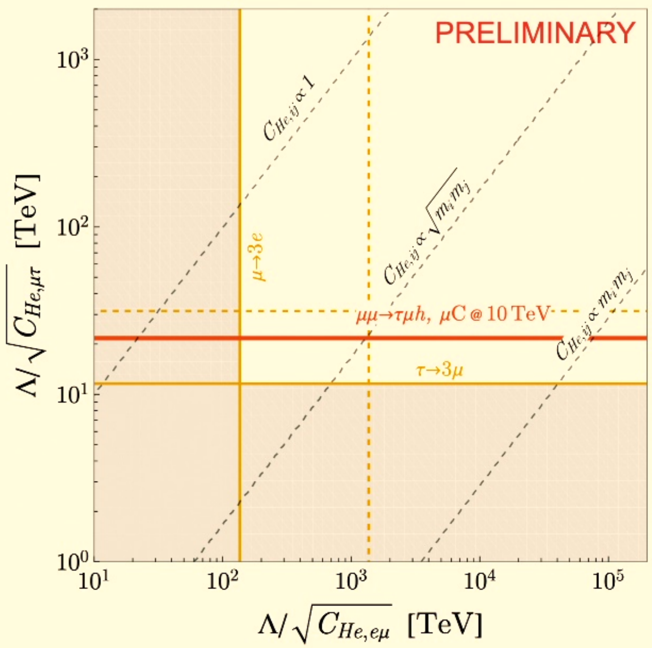
High Energy Constraints: Higgs Decays



Katherine Fraser, kfraser@berkeley.edu

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.

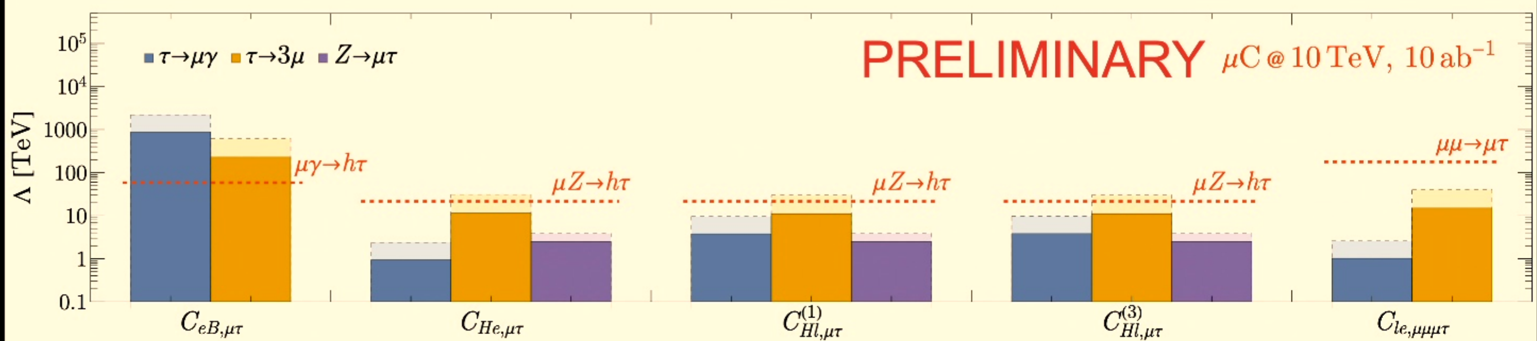


Katherine Fraser, kfraser@berkeley.edu

Summary and Next Steps

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

It would be an especially sensitive probe of four fermion operators, and could be used to probe flavor ansatz because of sensitivity to different combinations of coefficients.



Katherine Fraser, kfraser@berkeley.edu