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Probing Lepton Number Violation with Same-Sign Muon Colliders

Abhik Sarkar
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[2505.20936]

Subhaditya Bhattacharya, Soumyajit Datta, **Abhik Sarkar**

Why Search for Lepton Number Violation (LNV)?

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Lepton Number

$$\Delta L = N_\ell - N_{\overline{\ell}}$$

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- Conserved within individual generations

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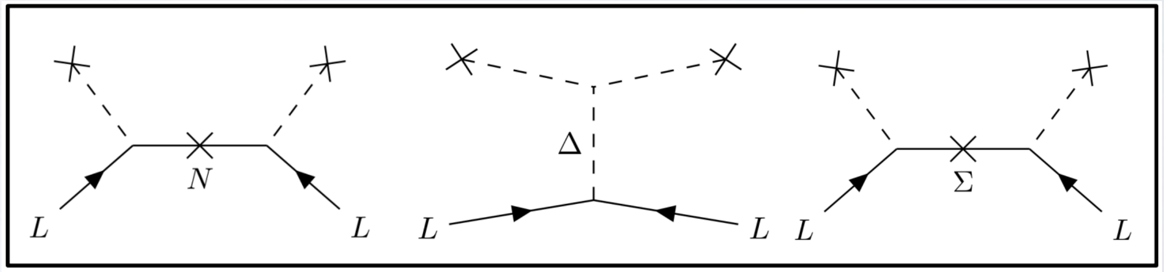
Neutrino Mass

- No neutrino mass in the Standard Model

$$\overline{\nu_L}\,\nu_R\,(\times) \quad \overline{\nu_L^c}\,\nu_L\,(\times)$$

- Neutrino oscillation measurements indicate neutrinos have non-zero mass
- Simplest way to generate neutrino mass is through the dim-5 Weinberg operator

$$(\overline{\ell^c_{L_\alpha}}\,\tilde{H}^*)(\tilde{H}^\dagger\,\ell_{L_\beta}) \longrightarrow (\overline{\nu^c_{L_\alpha}}\,\nu_{L_\beta})$$



- Seesaw models: LNV via following terms

$$\overline{\nu_R^c}\,\nu_R\ \text{(I)} \quad \tilde{H}^\dagger \Delta H\ \text{(II)} \quad \mathrm{Tr}(\overline{\Sigma^c}\,\Sigma)\ \text{(III)}$$

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Leptogenesis

$$\text{BAU} : \eta_B = (n_B - n_{\overline{B}})/n_\gamma \sim 6 \times 10^{-10}$$

- Necessary (Sakharov's) conditions for BAU:
  - Baryon/Lepton number violation
  - C and CP violation
  - Departure from thermal equilibrium
- In leptogenesis, asymmetry in lepton number converted to baryon number via sphalerons

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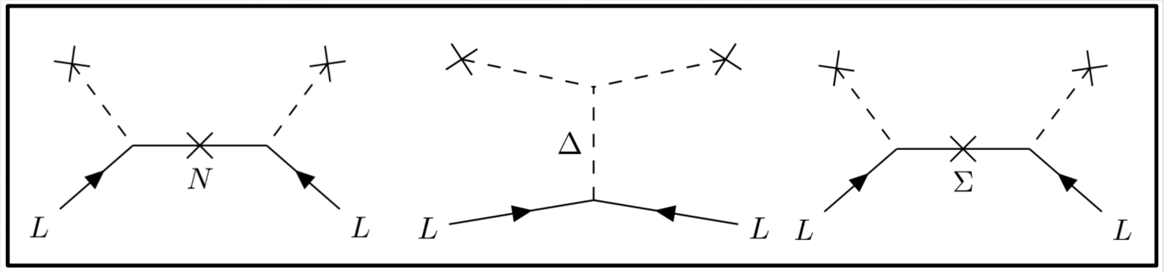

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Standard Model Effective Field Theory (SMEFT): Extension of the Standard Model (SM) with higher dimensional operators constructed out of SM fields.

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{C_{\mathscr{W}}\mathscr{O}^{(5)}_{\mathscr{W}}}{\Lambda} + \sum_i \frac{C_i\mathscr{O}^{(6)}_i}{\Lambda^2} + \sum_j \frac{C_j\mathscr{O}^{(7)}_j}{\Lambda^3} + \cdots \mathscr{O}(1/\Lambda^{n>3})$$

Weinberg Operator
1 ($\Delta L = 2$)

59 Operators
4 ($\Delta B = \Delta L = 1$)

18 Operators
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Dimension 5 Operator

- We focus our study on pure LNV operators, starting with Weinberg operator
- Absolute neutrino mass measurement constrain the electron flavor significantly

$$m_{ee} < 0.8\text{ eV} \implies \Lambda_{ee} = (v^2/m_{ee}) \gtrsim 10^{12}\text{ TeV}$$

[KATRIN, Nature Phys. 18 (2022) 2, 160-166]

- Other flavors relatively less constrained and can be probed at future colliders

Dimension 7 Operators

- 12 operators violating lepton number by 2 units, divided into 6 classes based on fields

Type	$\mathcal{O}$	Operator
$\Psi^2 H^4$	$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}L_r^m\right)H^jH^n\left(H^\dagger H\right)$
$\Psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}\gamma_\mu e_r\right)H^j\left(H^m iD^\mu H^n\right)$
$\Psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
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$\Psi^2 H^2 X$	$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}\sigma_{\mu\nu}L_r^m\right)H^jH^nB^{\mu\nu}$
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$\Psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p}L_r^i\right)\left(\overline{L_s^{cj}}L_t^m\right)H^n$
	$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}L_r^i\right)\left(\overline{u_s^c}e_t\right)H^j$
	$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$
	$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$
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The Lorentz structure is equivalent to that of Weinberg Operator for vertices with < 3 Higgs

Higgs-current operators

Associated with SM neutrino dipole moments

Four-fermion operators

Purely leptonic operator

[Fridell et. al. JHEP 05 (2024) 154]

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Our study focuses on **8** operators: **3** Higgs-current type and **5** four-fermion type.

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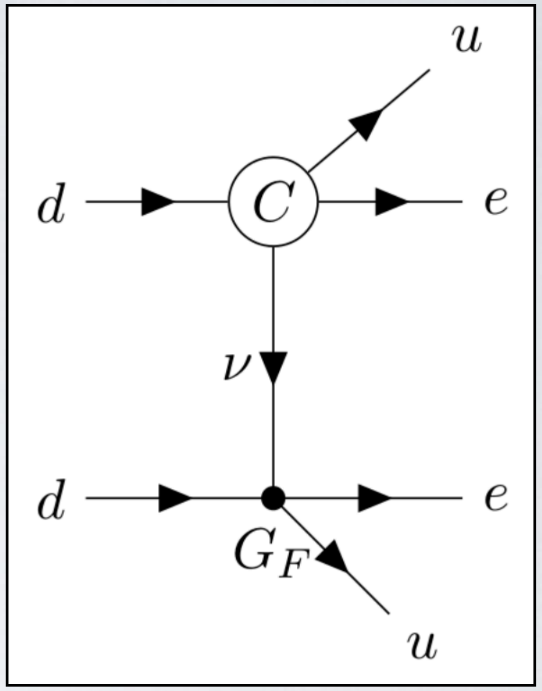
- Absent in SM, LNV by 2 units
- Lowest energy manifestation of LNV, no observation yet
- Existing bound on half life:

$$T_{1/2} > 10^{26} \text{ years}$$

[KamLAND-Zen PRL 130 (2023) 5, 051801]



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SMEFT Wilson Coefficient	Value $[\text{TeV}^{-3}]$	Λ_{NP} [TeV]
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C_{LeHD}	$1.55 \cdot 10^{-7}$	186
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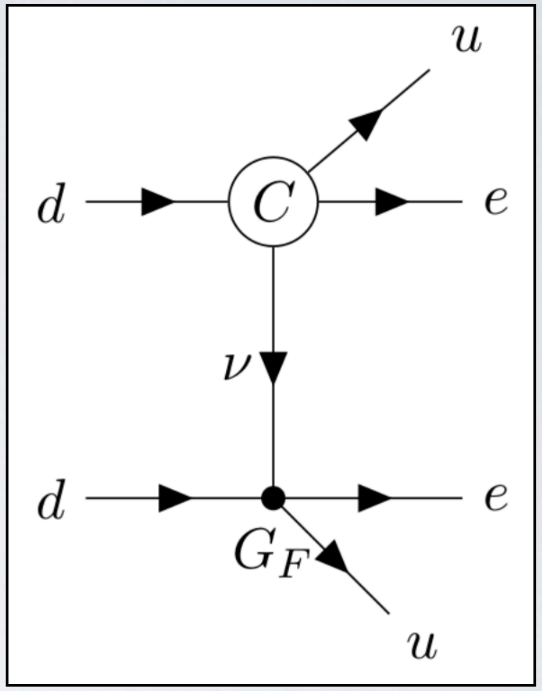

Strongest constraints on LNV operators

$$T_{1/2}^{-1} = g_A^4 \sum_k G_{0k} \, |\mathscr{A}_k(C_i)|^2$$

Atomic phase space factors

Subamplitudes

vDoBe calculates the limits on SMEFT/LEFT operators

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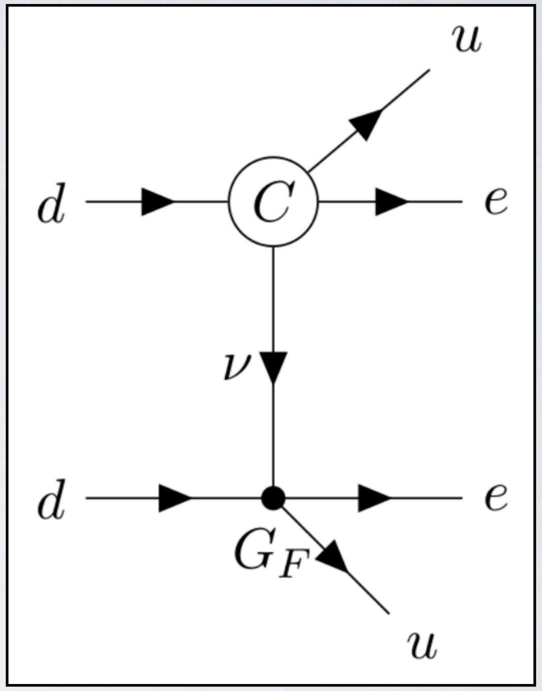

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These limits apply to electron sector, **muon** and tau flavors are still unconstrained.

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- Bounds from LHC → Recast of same-sign muons + jets search (ATLAS, 2019)

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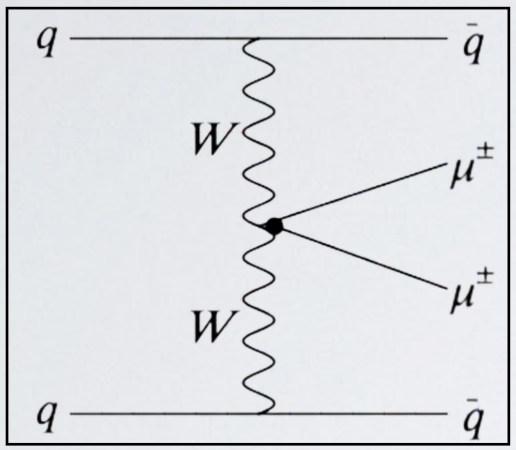

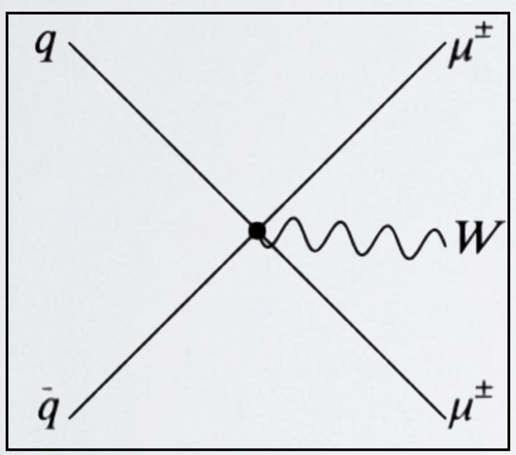

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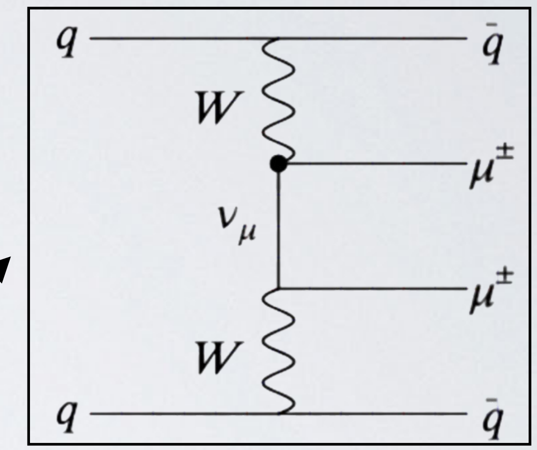

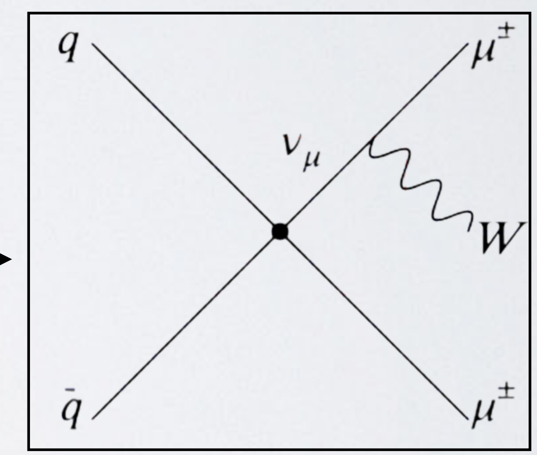

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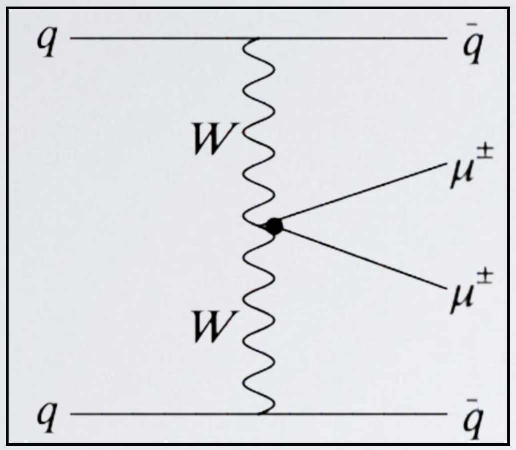

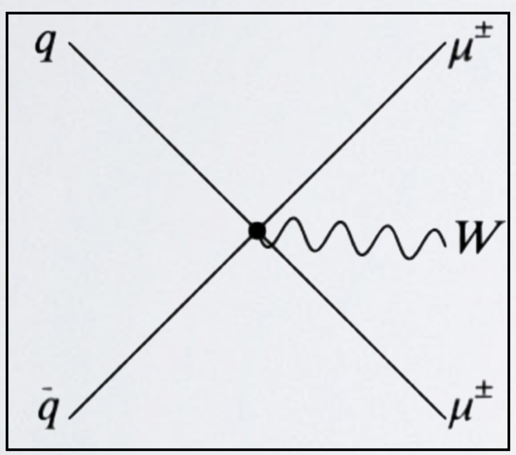

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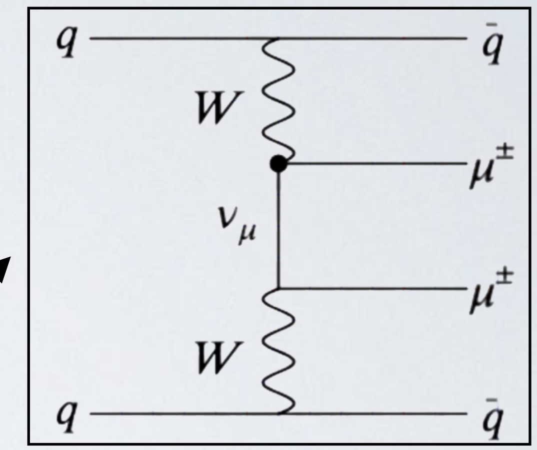

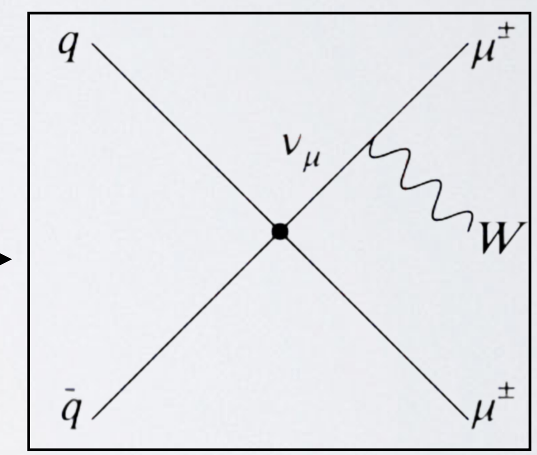

- Signature: Initial state (ΔL = 0, hadronic); Final state (ΔL = 2; SS muons + no MET)
- Four-fermion operators strongly constrained at the LHC due to contact vertices

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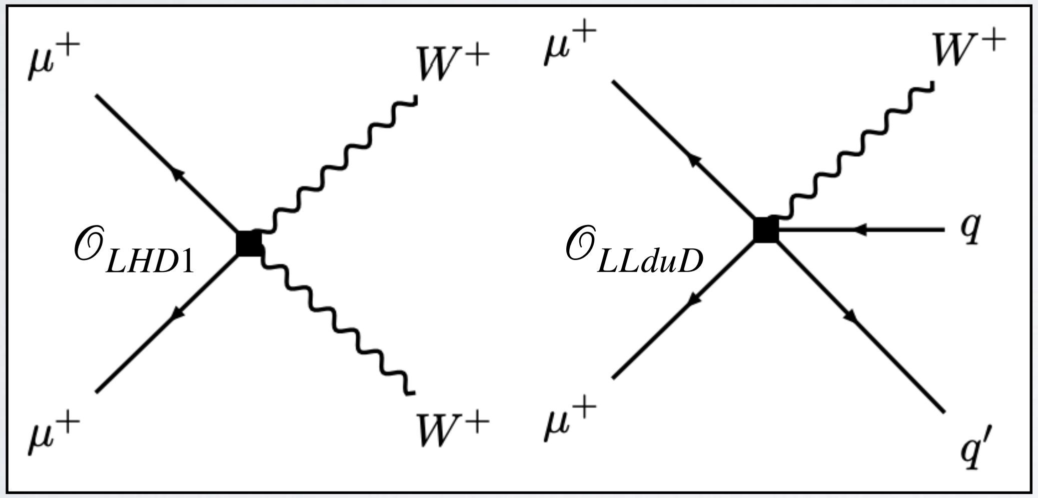

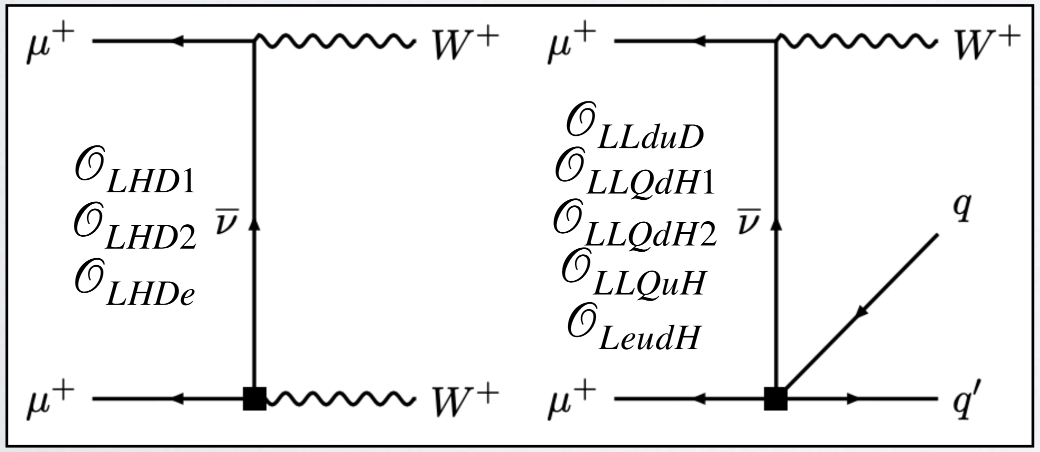

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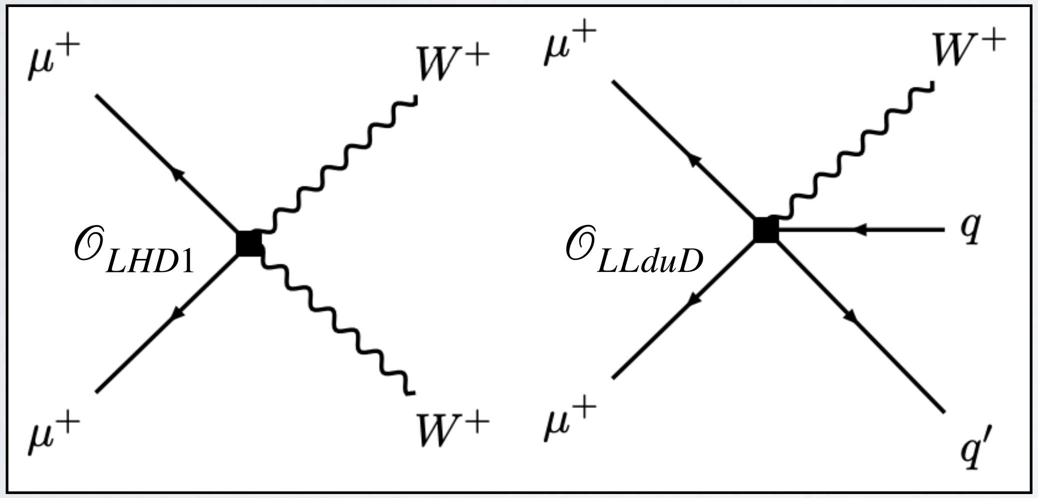

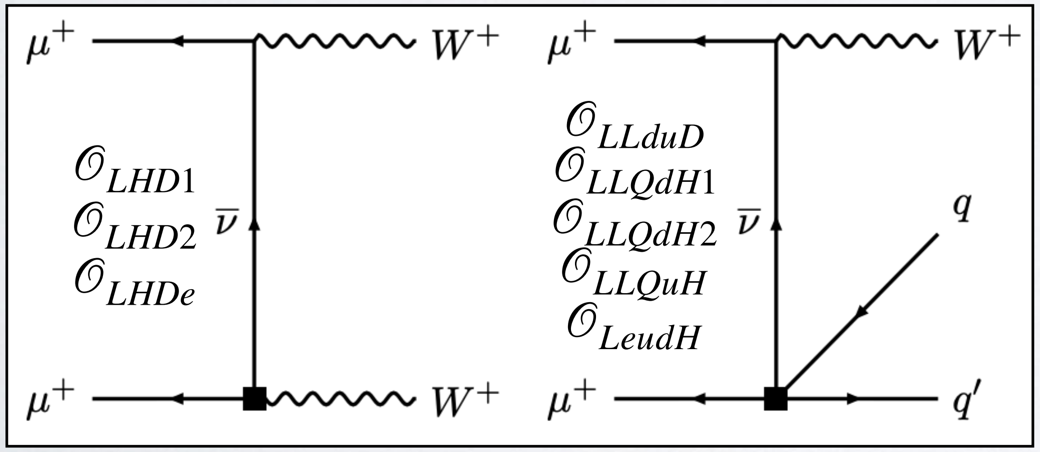

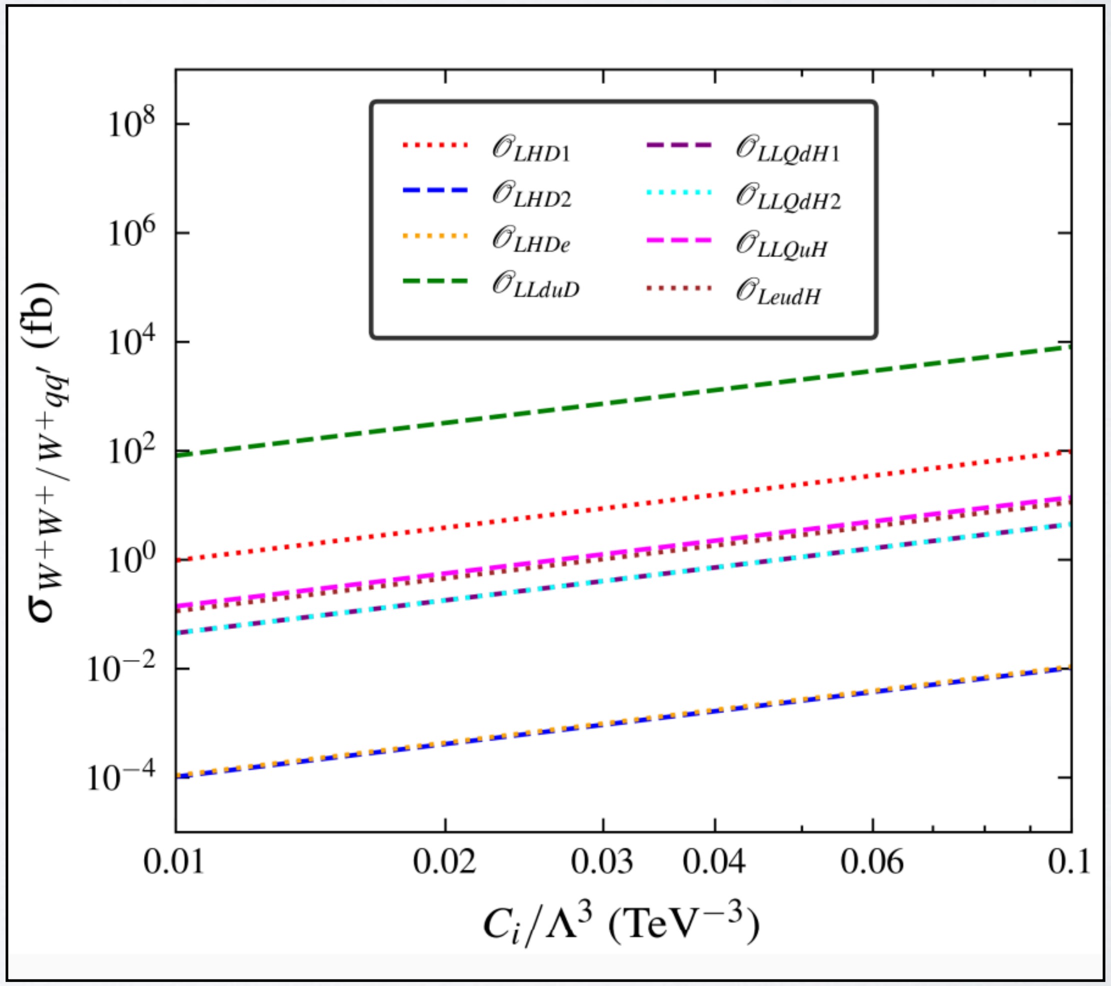

Collider Analysis

- Signal Selection: 2 fat jets with masses > 10 GeV
- 2 fat jets favorable for Higgs-current operators
- 3 fat jets may improve four-fermion operators
- We veto leptons in final state, signature of LNV
- SM backgrounds:

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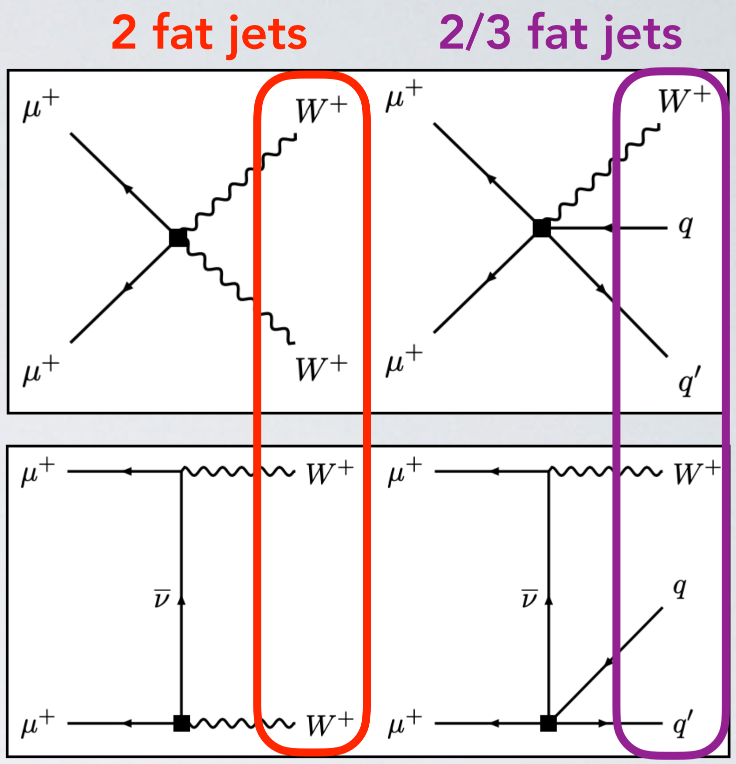

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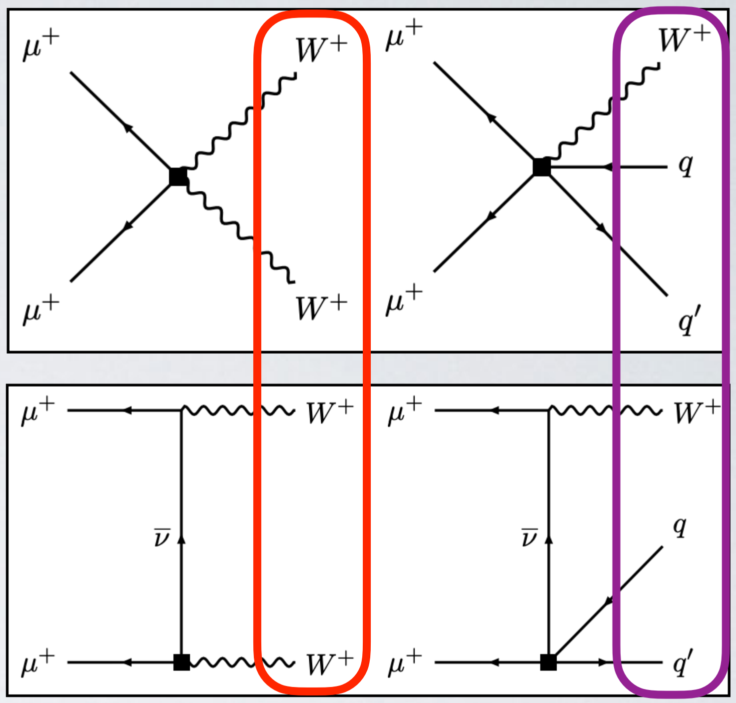
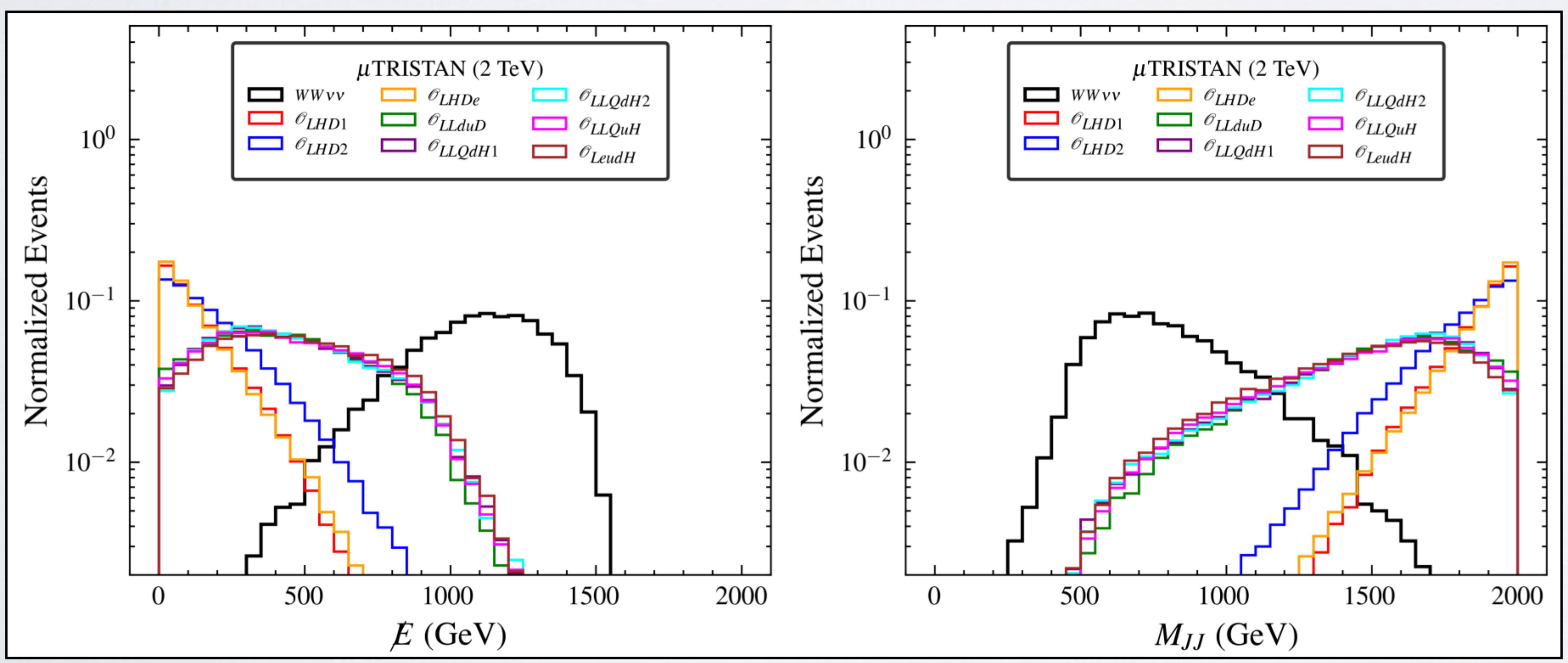
2/3 fat jets



$$\mathrm{ME} = \sqrt{s} - \sum E$$

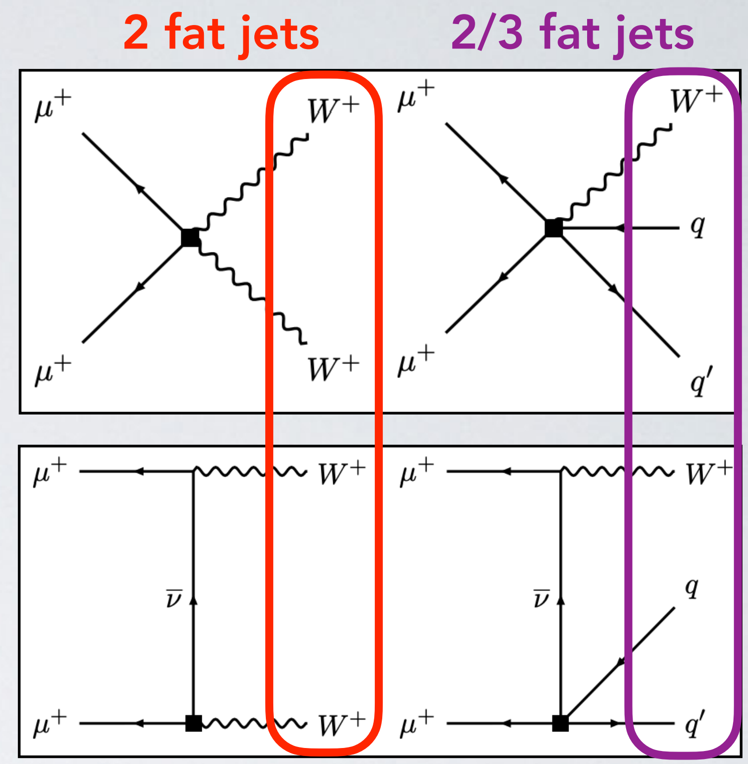
$$M_{JJ} = \sqrt{\left(p_{J_1} + p_{J_2}\right)^2}$$



Collider Analysis

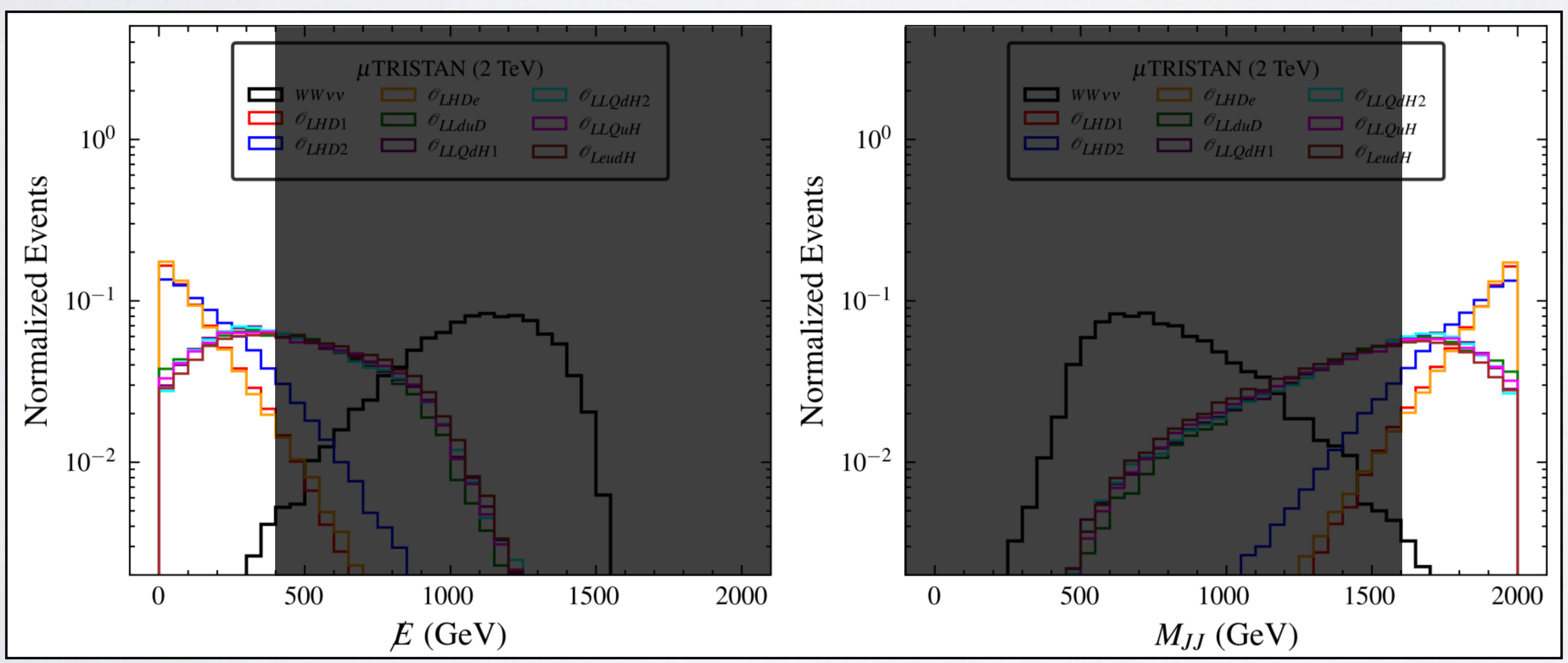
- Signal Selection: 2 fat jets with masses > 10 GeV
- 2 fat jets favorable for Higgs-current operators
- 3 fat jets may improve four-fermion operators
- We veto leptons in final state, signature of LNV
- SM backgrounds:

$$\overline{\nu}\overline{\nu}W^+W^+,\ \ \mu^+\overline{\nu}W^+,\ \ \mu^+\mu^+Z,\ \ \mu^+\overline{\nu}W^+Z$$



$$\mathrm{ME} = \sqrt{s} - \sum E$$

$$M_{JJ} = \sqrt{\left(p_{J_1} + p_{J_2}\right)^2}$$



Cuts

ME < 400 GeV

M_{JJ} > 1600 GeV

Efficiency

Higgs-current

78% - 58%

Four-fermion

19% - 16%

Backgrounds

~ 0.06%

Projected Sensitivity of LNV Effective Operators

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We perform a binned Chi-Squared analysis to obtain the 95% exclusion limits.

$$\chi^2 = \sum_r^{\text{bins}} \left(\frac{\mathcal{Q}_r(C_i) - \mathcal{Q}_r(0)}{\sqrt{\mathcal{Q}_r(0)}} \right)^2$$

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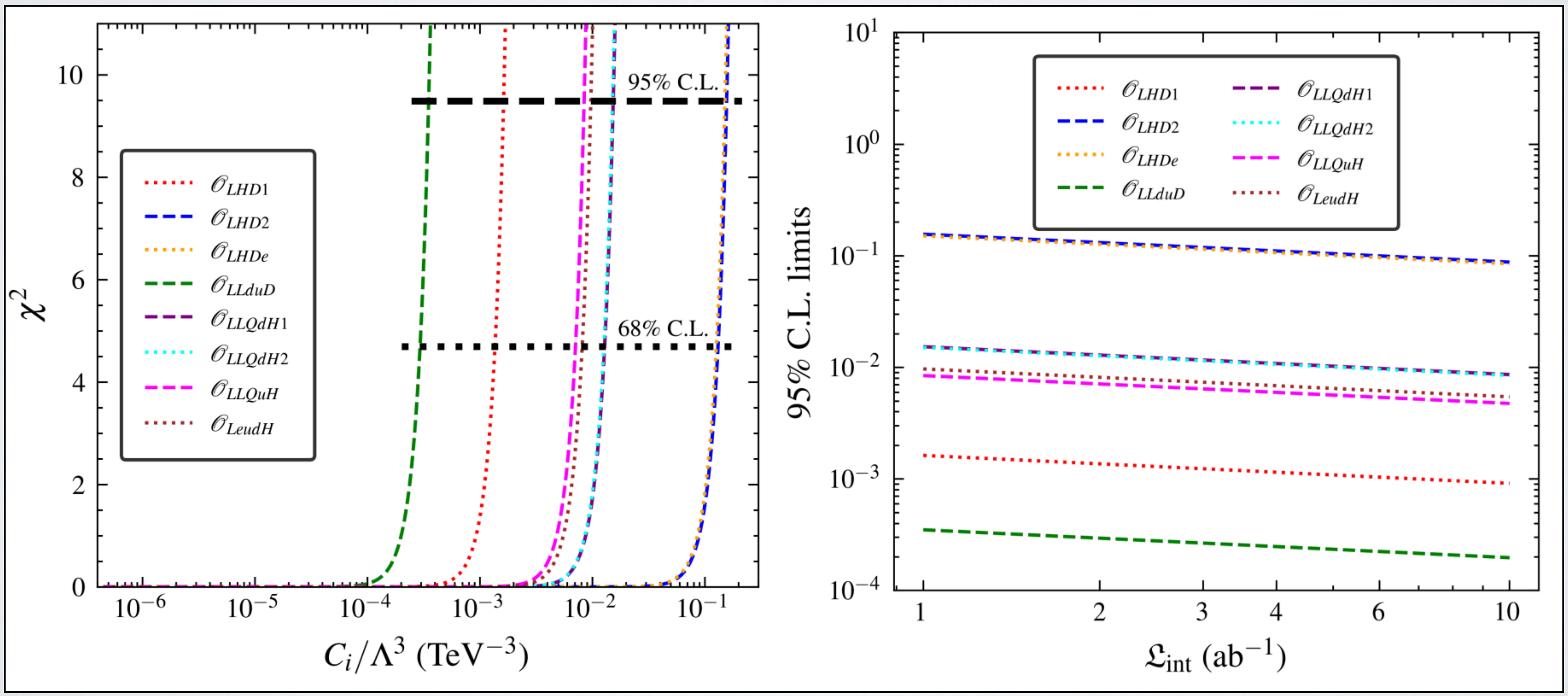

Higgs-current operators more sensitivite than at the FCC-hh

Four-fermion operators have sensitivities comparable to the FCC-hh

Operators	FCC-hh 100 TeV 30 ab^{-1}		μTRISTAN 2 TeV 1 ab^{-1}	
	Λ (TeV)	C_i/Λ^3 (TeV^{-3})	Λ (TeV)	C_i/Λ^3 (TeV^{-3})
$\mathcal{O}_{LHD1}$	4.90	8.500×10^{-3}	8.50	1.627×10^{-3}
$\mathcal{O}_{LHD2}$	0.18	1.715×10^{2}	1.86	1.563×10^{-1}
$\mathcal{O}_{LHDe}$	0.44	1.174×10^{1}	1.88	1.511×10^{-1}
$\mathcal{O}_{LLduD}$	19.0	1.458×10^{-4}	14.2	3.507×10^{-4}
$\mathcal{O}_{LLQdH1}$	4.30	1.258×10^{-2}	4.02	1.534×10^{-2}
$\mathcal{O}_{LLQdH2}$	3.10	3.357×10^{-2}	4.04	1.510×10^{-2}
$\mathcal{O}_{LLQuH}$	5.40	6.351×10^{-3}	4.92	8.451×10^{-3}
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[Fridell et. al. JHEP 05 (2024) 154]

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Weinberg Operator at μTRISTAN

- The sensitivity of muon-flavored Weinberg operator can be studied at μTRISTAN
- Absolute muon neutrino mass measurement constrain the muon flavor EFT scale

$$m_{\mu\mu} < 0.17 \text{ MeV} \implies \Lambda_{\mu\mu} = (v^2/m_{\mu\mu}) \gtrsim 10^5 \text{ TeV}$$

[Assamagan et. al. PRD 53 (1996) 6065-6077]

- Bounds from existing and future colliders:
  - $\Lambda > 1.42$ TeV (LHC); $\Lambda > 21.8$ TeV (FCC-hh); $\Lambda > 399$ TeV (μTRISTAN)
- μTRISTAN most sensitive among future colliders, still around O(100) below $\Lambda_{\mu\mu}$

Implications for New Physics (NP) Models

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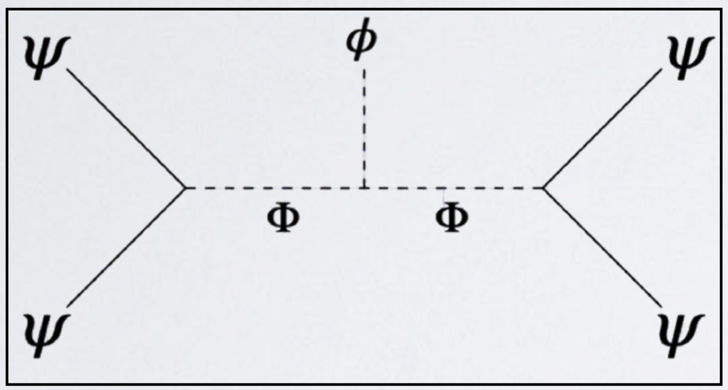
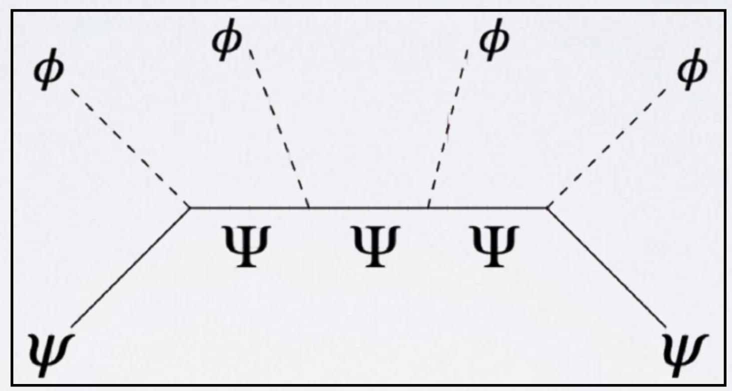
These effective operators can be systematically mapped onto a large set of UV completions. We present simplified field embeddings for these classes.

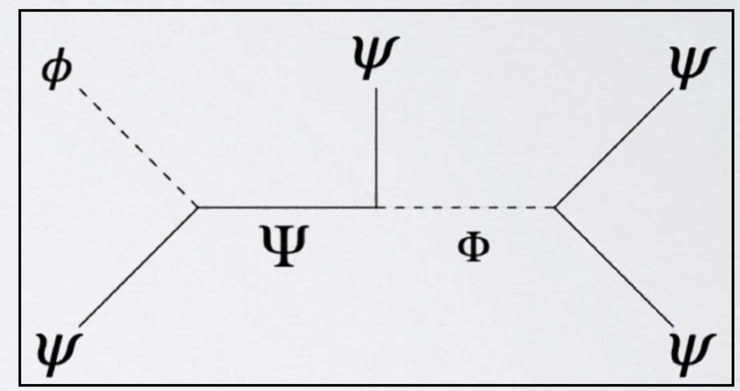
$$\text{Heavy Fields} : \Psi\,(\text{Fermion})\,,\ \Phi\,(\text{Boson})\,.$$
$$\text{Light Fields} : \psi\,(\text{Fermion})\,,\ \phi\,(\text{Boson})\,.$$



$\psi^4\phi \quad \psi^4 D$



$\psi^2\phi^2 D^2 \quad \psi^2\phi^3 D$



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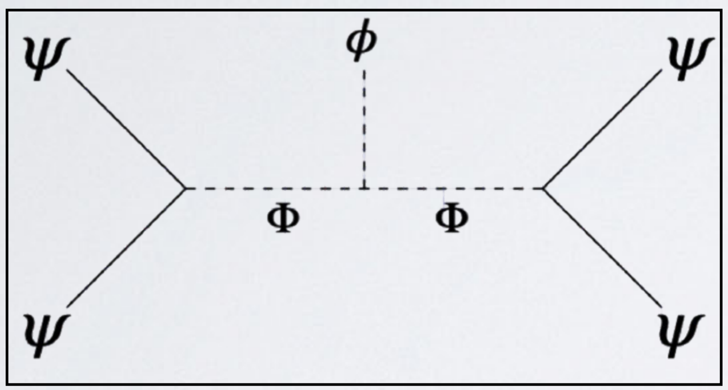

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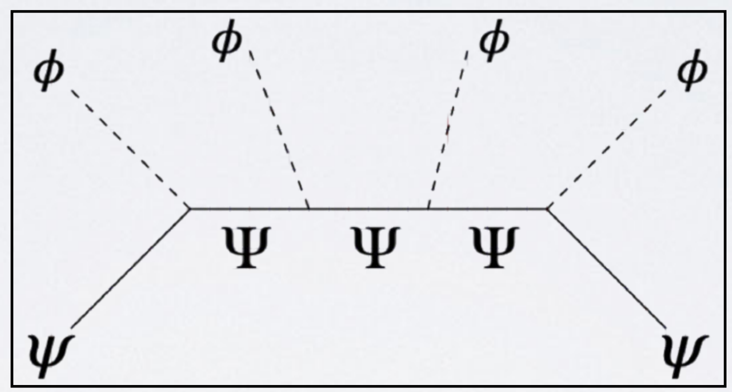

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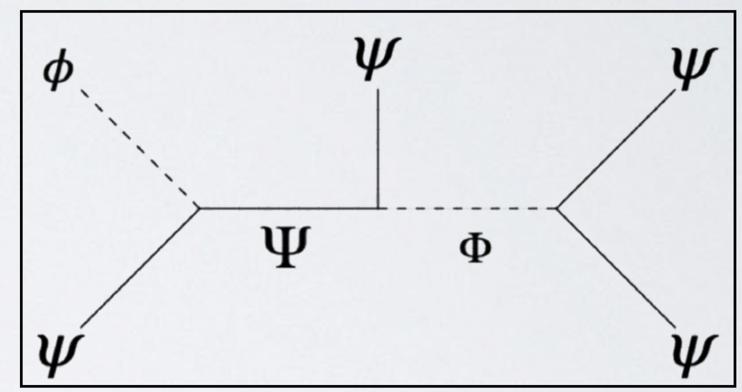

$\psi^4\phi \quad \psi^4 D$

- LNV operators beyond electron flavor still accessible, can be probed at colliders
- Same-sign muon collider provides a unique, clean environment to probe LNV
- UV completions beyond RHNs can induce LNV effective operators, emphasizing that the observable LNV need not be tied solely to neutrino mass generation

THANK YOU

[ImageCredit: The University of Tokyo]