Searches for Lepton Flavor Violation at the EIC

Kaori Fuyuto

LANL → KEK

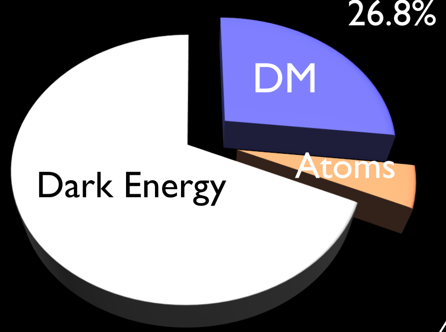
KEK
High Energy Accelerator Research Organization

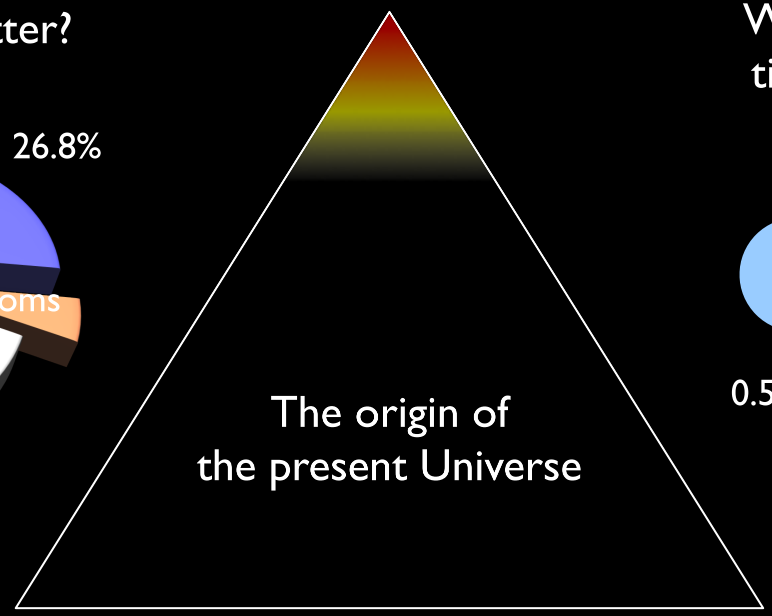
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
S. Banerjee, V. Cirigliano, et al, Snowmass White Papaer, 2203.14919
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497 (Accepted by JHEP)

July 22nd, 2025
At Stony Brook U

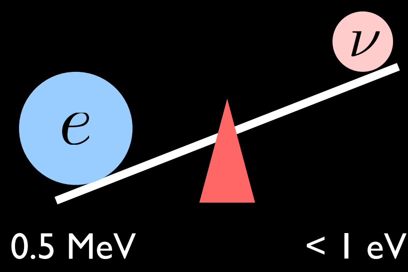
We still don't know much about our Universe.

What is Dark Matter?





What is the origin of tiny neutrino mass ?



Why is there more matter than antimatter? $$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Need Physics Beyond the Standard Model

Charged Lepton Flavor Violation

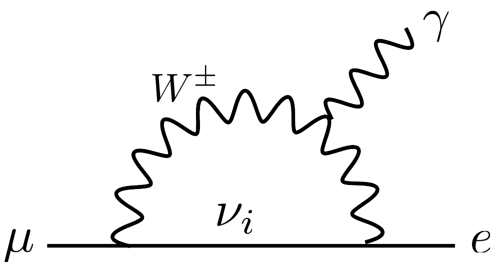
Searches for CLFV are strong tools to probe BSM physics.

*Beyond the minimal extension of the SM

Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

Ex) SM + neutrino mass (νSM)



Petcov '77, Marciano-Sanda '77 ....

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\nu-{\rm mass}}$$

Dirac or Majorana

$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_{\rm em}}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W} \right|^2 < 10^{-54}$$

Extremely small!

Charged Lepton Flavor Violation

Searches for CLFV are strong tools to probe BSM physics.

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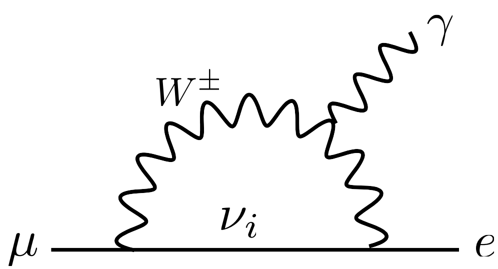
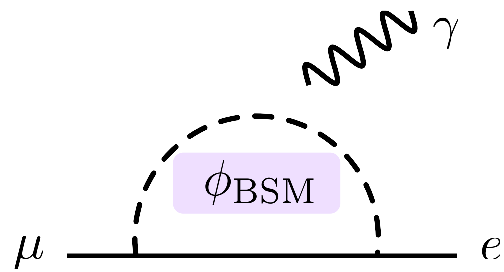


Petcov '77, Marciano-Sanda '77 ....



$\mathrm{Br}(\mu \to e\gamma) < 10^{-54}$ $\ll$ $\mathrm{Br}(\mu \to e\gamma)_{\rm BSM}$

✔ The Observations of CLFV would point to new physics beyond νSM.

*Underlying mechanism of the neutrino mass.

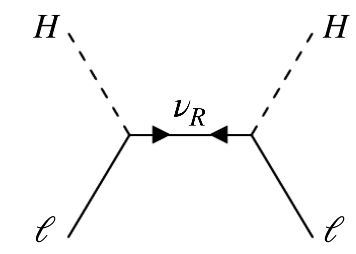
Charged Lepton Flavor Violation

Models that explain neutrino mass usually introduce CLFV at tree or loop level.

e.g., A. Abada, et al, JHEP 12 (2007) 061

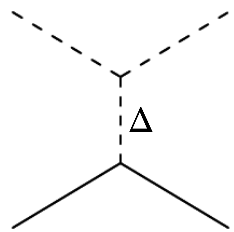
ν mass

Type I



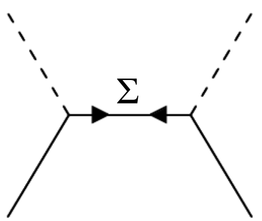
$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

Type II



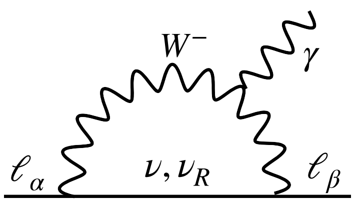
$$m_\nu \sim Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

Type III

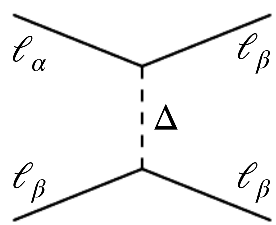


$$m_\nu \sim \frac{Y_\Sigma^2 v^2}{M_\Sigma}$$

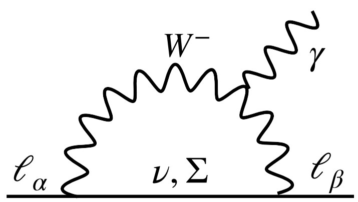
LFV



$$\ell_\alpha \to \ell_\beta \gamma$$

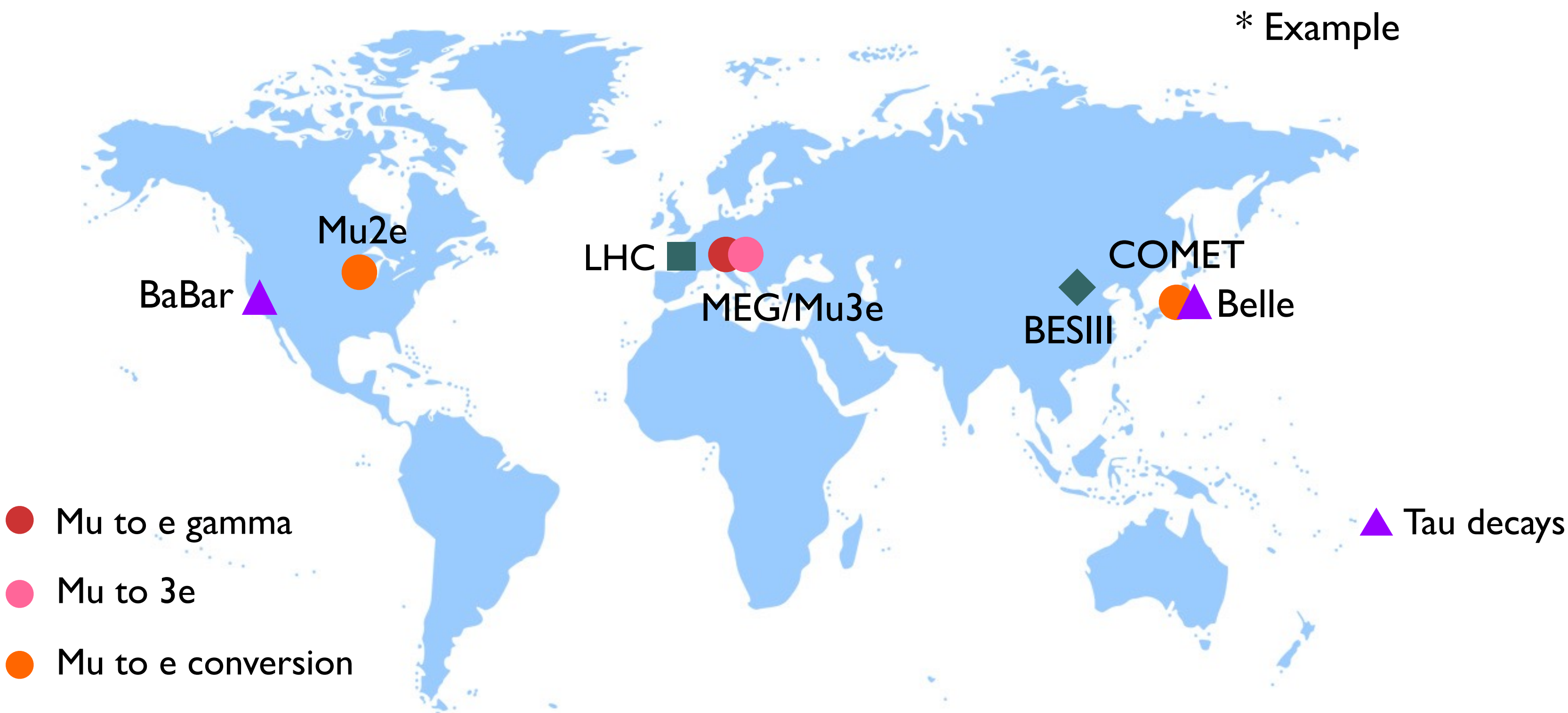


$$\ell_\alpha^- \to \ell_\beta^- \ell_\beta^+ \ell_\beta^-$$



$$\ell_\alpha \to \ell_\beta \gamma$$

CLFV searches



$$\mathrm{BR}(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

MEG II Collaboration, 2310.12614

$$\mathrm{BR}(\mu^- \, \mathrm{Ti} \to e^- \, \mathrm{Ti}) < 6.1 \times 10^{-13}$$

P. Wintz, Conf. Proc. C 980420, 534 (1998).

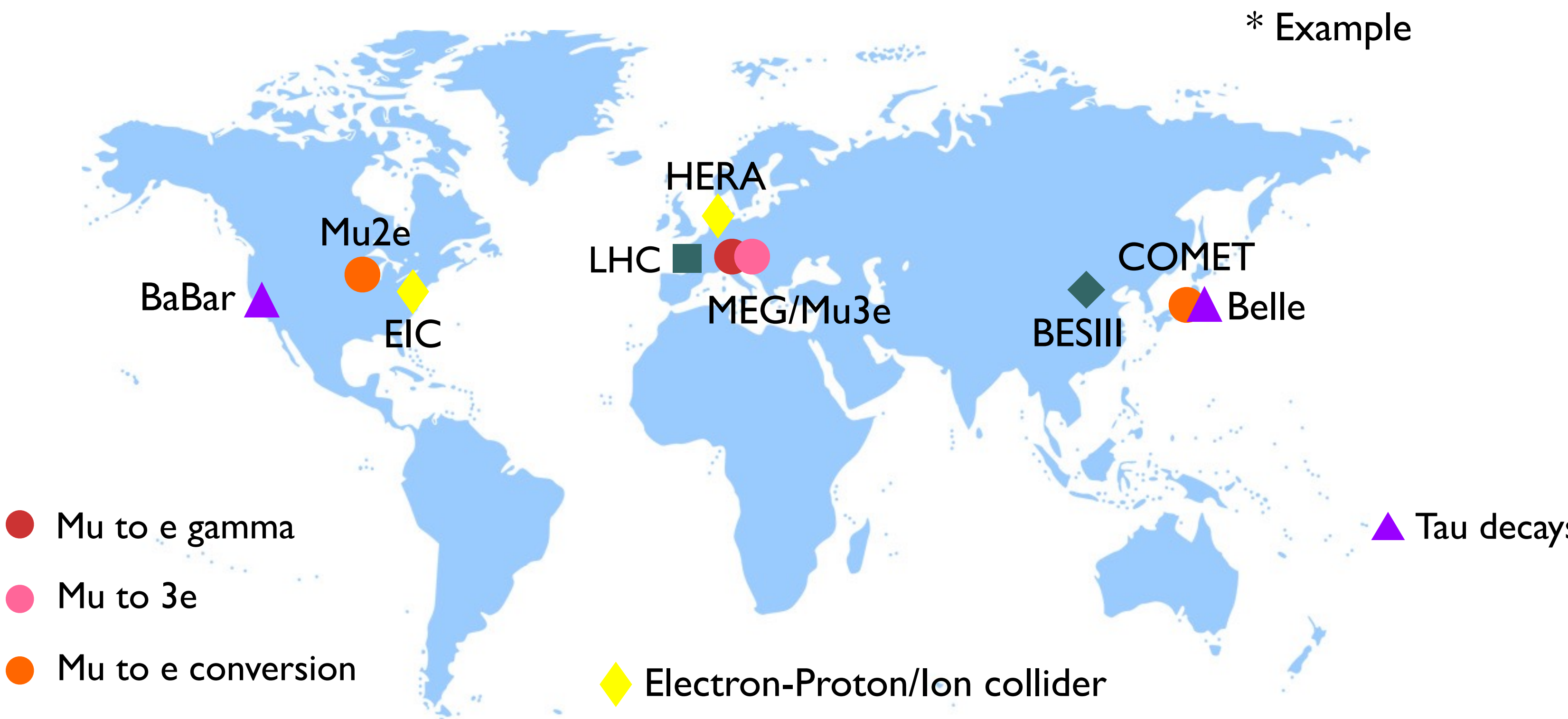
$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

BaBar, PRL104 (2010) 021802

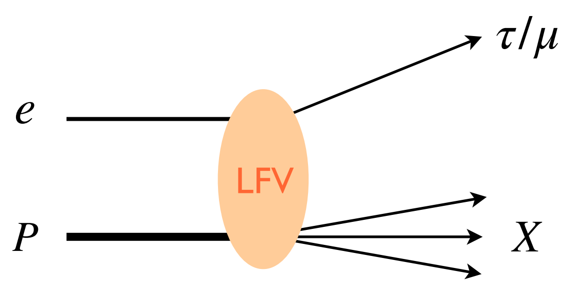
$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

Belle, PLB719 (2013) 346-353

CLFV searches



$ep \to \tau/\mu \;\; X \;\; @ \;\; \mathrm{EIC}$



$\sqrt{S} = 20 \sim 140\ \mathrm{GeV}$

$\mathscr{L} = 10^{33-34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

*Higher than HERA

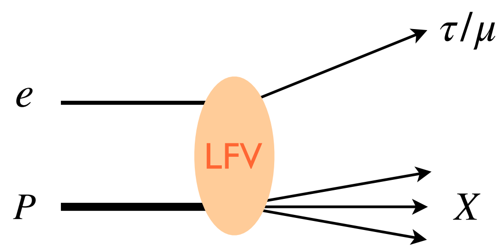
CLFV searches

V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan, JHEP03(2021)256
F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti, arXiv 2411.13497

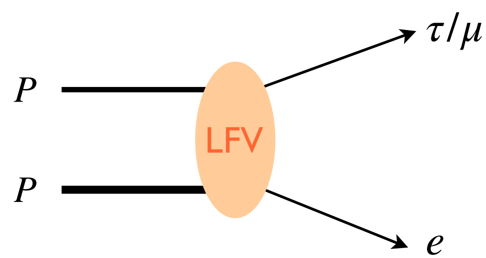
✔ Model-Independent Analysis of CLFV process at low- and high-energy

EIC vs LHC vs Low-Energy CLFV searches

$ep \to \tau/\mu \; X$ @ EIC

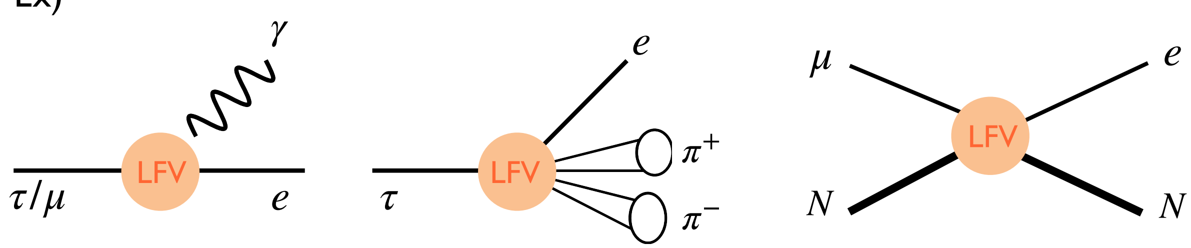


$pp \to e \; \tau/\mu$ @LHC



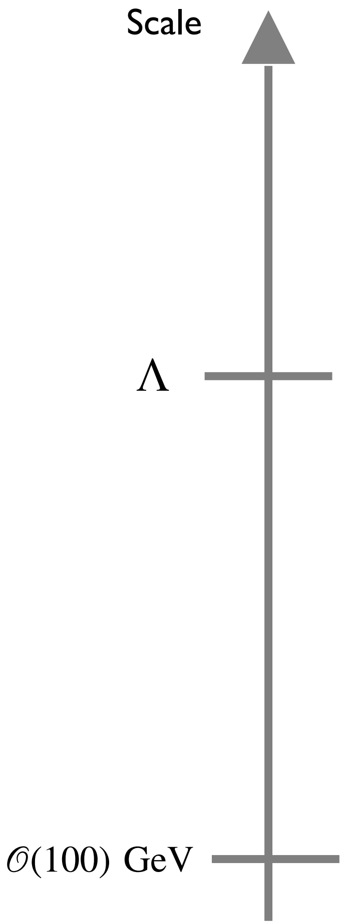
τ, μ, and meson decays

Ex)



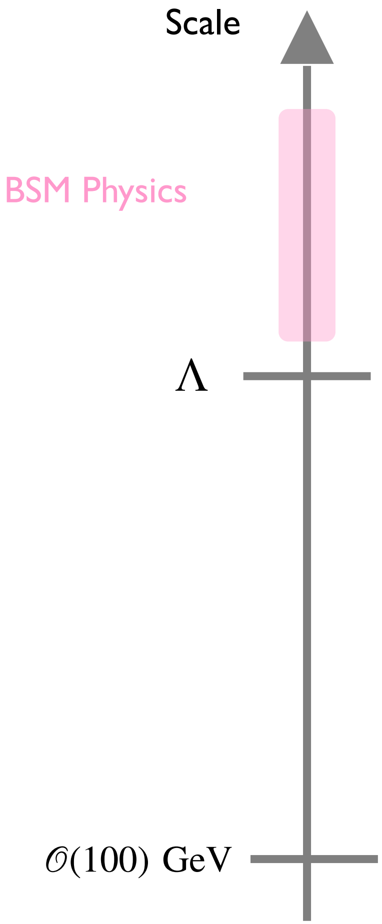
Model-Independent Analysis

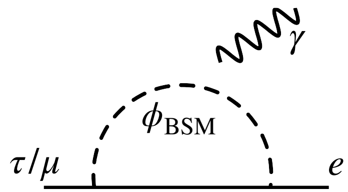
SMEFT : Standard Model Effective Field Theory

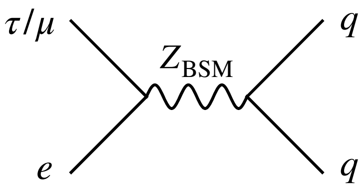


Model-Independent Analysis

SMEFT : Standard Model Effective Field Theory







Model-Independent Analysis

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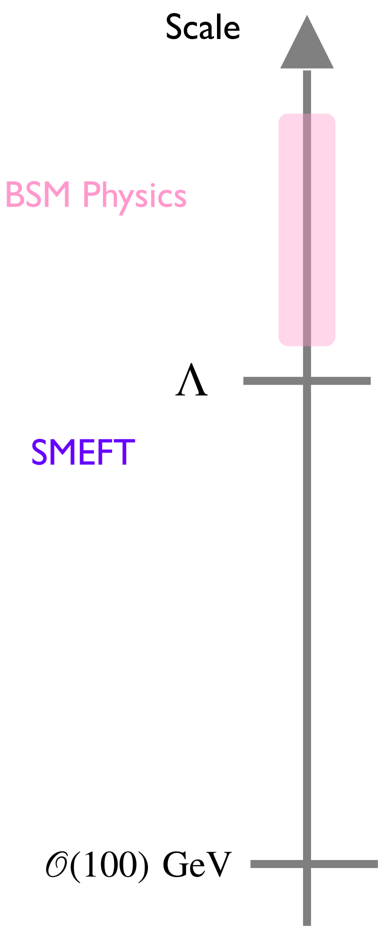
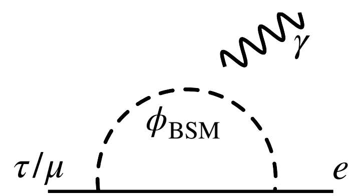
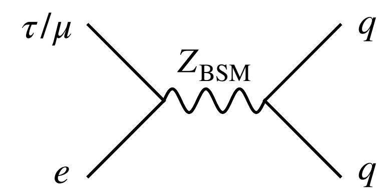


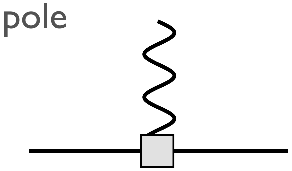




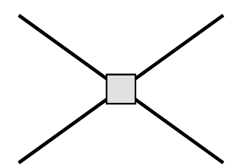
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C^{(d)} O^{(d)}$$

Higher Dimensional Operators

Dipole



4 Fermion



All possible interactions based on gauge and Lorentz invariance

✔ EFT can apply to concrete models

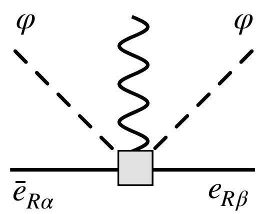
CLFV operators

4 different types of LFV operators (dim 6)

$$\mathscr{L}_{\mathrm{LFV}} = \mathscr{L}_{\psi^2\varphi^2 D} + \mathscr{L}_{\psi^2 X\varphi} + \mathscr{L}_{\psi^2\varphi^3} + \mathscr{L}_{\psi^4}$$

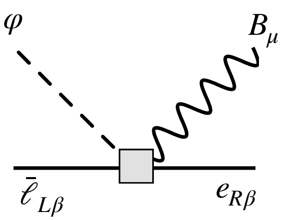
X : Gauge boson ψ : Fermion φ : Higgs

$^*\mathscr{O}(100)$ independent operators



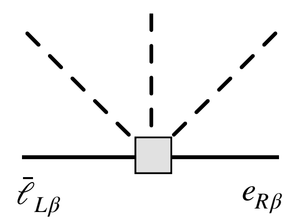
Ex) $\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\ \bar{e}_{R\alpha}\gamma_\mu e_{R\beta}$

3



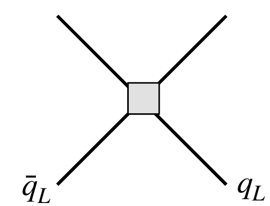
$\bar{\ell}_{L\alpha}\sigma^{\mu\nu}B_{\mu\nu}\varphi e_{R\beta}$

2



$\varphi^\dagger\varphi\ \bar{\ell}_{L\alpha}\varphi e_{R\beta}$

1



$\bar{\ell}_L\gamma^\mu\ell_L\ \bar{q}_L\gamma_\mu q_L$

10

x 9 for generic quark flavor

CLFV operators

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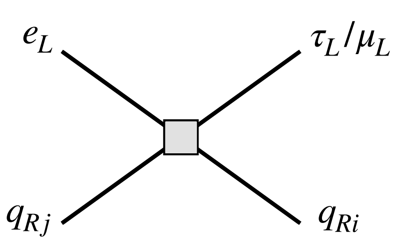
X : Gauge boson ψ : Fermion φ : Higgs

$$\supset -\frac{4G_F}{\sqrt{2}} \sum_{\substack{\ell = \tau,\mu \\ q = u,d}} [C_{Lq}]_{\ell e i j}\, \bar{\ell}_L \gamma^\mu e_L\, \bar{q}_{Ri}\gamma_\mu q_{Rj}$$



*Assume a generic quark flavor structure

Ex) $$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

**Focus on tau-electron case.*

Low-Energy Tau and Meson Decay

Decay mode		Upper limit (90 % C.L.)	
$\tau \to e\pi^+\pi^-$	uu/dd/ss	2.3×10^{-8}	Belle PLB719(2013)346
$\tau \to e\pi^0$		8×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta$		9.2×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta'$		1.6×10^{-7}	Belle PLB648(2007)341
$\tau \to eK_S$	ds/sd	2.6×10^{-8}	Belle PLB692(2010)4
$\tau \to e\pi^+K^-$		3.7×10^{-8}	Belle PLB719(2013)346
$\tau \to e\pi^-K^+$		3.1×10^{-8}	Belle PLB719(2013)346
$B^0 \to e^\pm\tau^\mp$	db/bd	1.6×10^{-5}	Belle PRD104(2021)9
$B^+ \to \pi^+e^+\tau^-$		7.4×10^{-5}	BaBar PRD86(2012)012004
$B^+ \to \pi^+e^-\tau^+$		2.0×10^{-5}	BaBar PRD86(2012)012004
$B^+ \to K^+e^+\tau^-$	sb/bs	1.53×10^{-5}	Belle PRL130(2023)26 261802
$B^+ \to K^+e^-\tau^+$		1.5×10^{-5}	Belle PRL130(2023)26 261802

Low-Energy Tau and Meson Decay

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$\tau \to e\eta$		9.2×10^{-8}	Belle PLB648(2007)341
$\tau \to e\eta'$		1.6×10^{-7}	Belle PLB648(2007)341

- Certain combinations of CLFV operators can be bounded.

Ex) $$\mathrm{BR}(\tau \to e\pi^+\pi^-) \simeq 0.5 \times \left| [C_{Lu}]_{uu} - [C_{Ld}]_{dd} \right|^2$$

A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

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A. Celis, V. Cirigliano, E. Passemar, PRD89(2014)095014

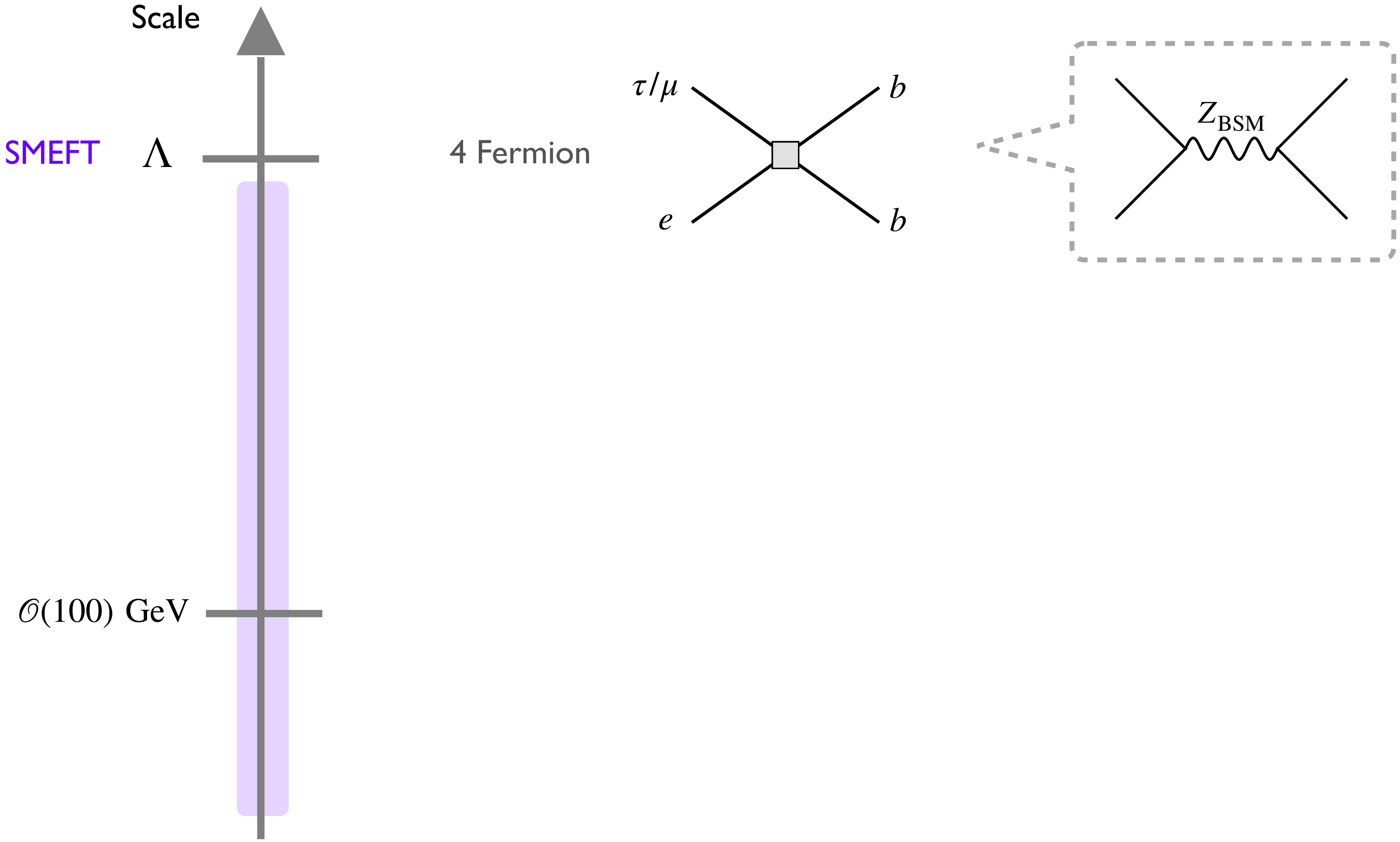
- Quark-flavor conserving processes are generated by light quarks operators

$$[C_{Lu}]_{\tau e} = \begin{pmatrix} [C_{Lu}]_{uu} & [C_{Lu}]_{uc} & [C_{Lu}]_{ut} \\ [C_{Lu}]_{cu} & [C_{Lu}]_{cc} & [C_{Lu}]_{ct} \\ [C_{Lu}]_{tu} & [C_{Lu}]_{tc} & [C_{Lu}]_{tt} \end{pmatrix} \qquad [C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

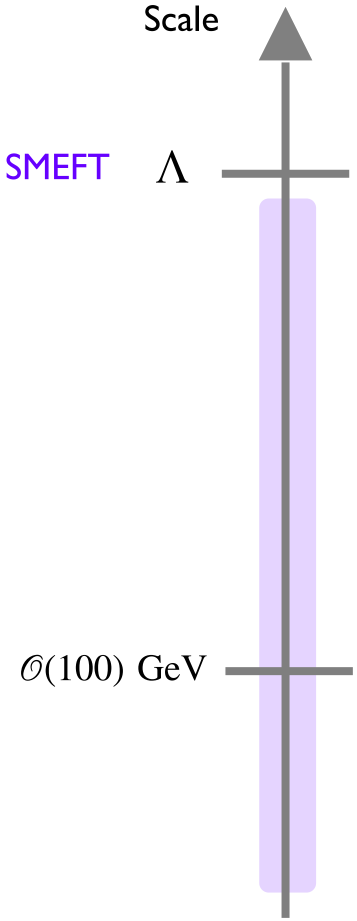
How?

Model-Independent Analysis

Scale Running Effects based on the Renormalization Group Equations

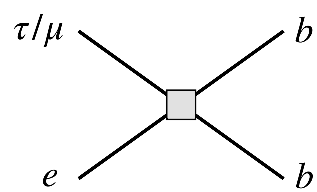


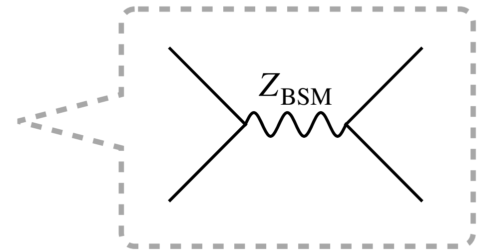
Model-Independent Analysis

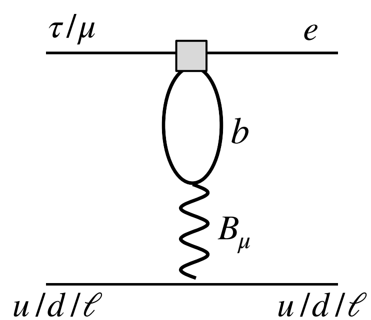


Scale Running Effects based on the Renormalization Group Equations

4 Fermion

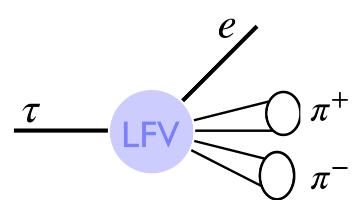






Ex) $$\mu \frac{d}{d\mu}[C_{Lu}]_{dd} = \frac{4}{3} N_c \frac{g_1^2}{(4\pi)^2} \mathrm{y}_{\mathrm{d}}^2 \, [C_{Ld}]_{bb}$$

For example,

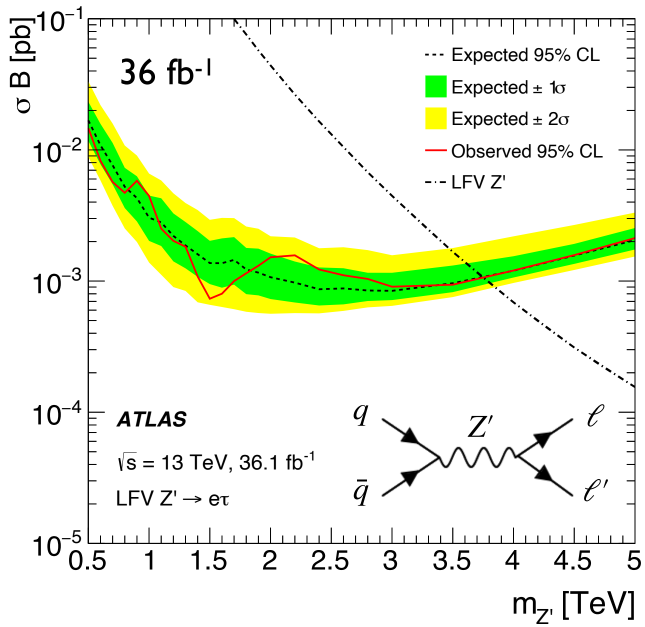


$$[C_{Lu}]_{uu}, [C_{Ld}]_{dd} \sim \frac{g^2}{(4\pi)^2}[C_{Ld}]_{bb}$$

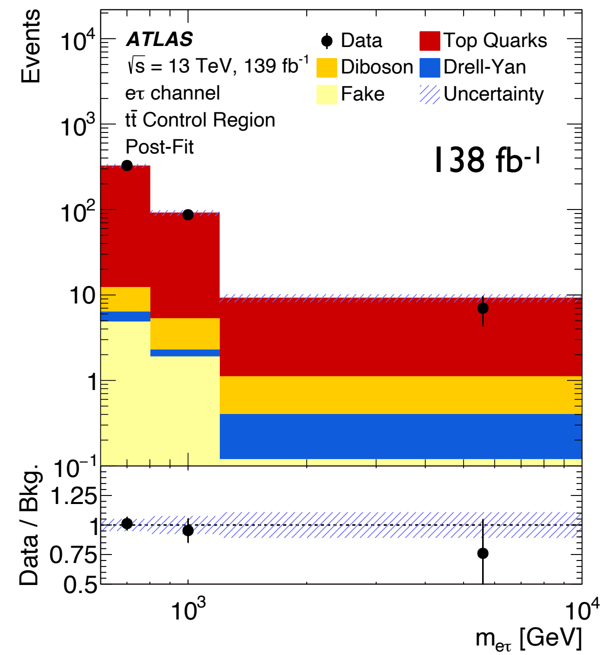
Loop effect $\sim \mathcal{O}(10^{-3})$

LHC search

ATLAS Collaboration, PRD98(2018)092008



ATLAS Collaboration, JHEP 10 (2023) 082



- Bound on CLFV top decay by ATLAS with 79.8 fb^{-1}: $\mathrm{BR}(t \to q\ell\ell') < 1.86 \times 10^{-5}$ (95 % CL.)

ATLAS collaboration, ATLAS-CONF-2018-044

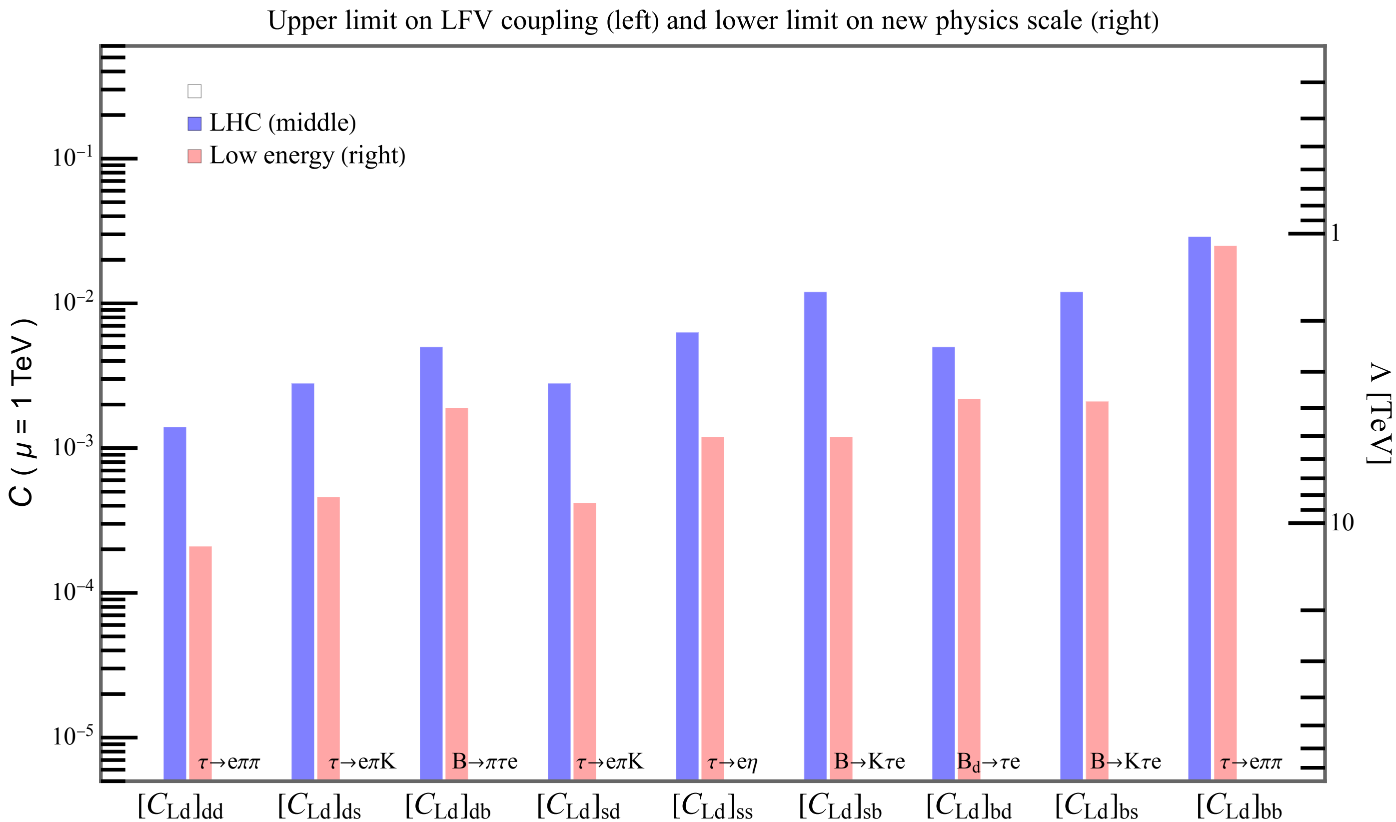
- ATLAS published pp → l l' bounds in high-mass final states using 36 fb^{-1}

  '22 ATLAS and '23 CMS results with 138 and 139 fb^{-1}

ATLAS JHEP 10 (2023) 082
CMS JHEP 05 (2023) 227

Existing bounds

* Single Operator Analysis

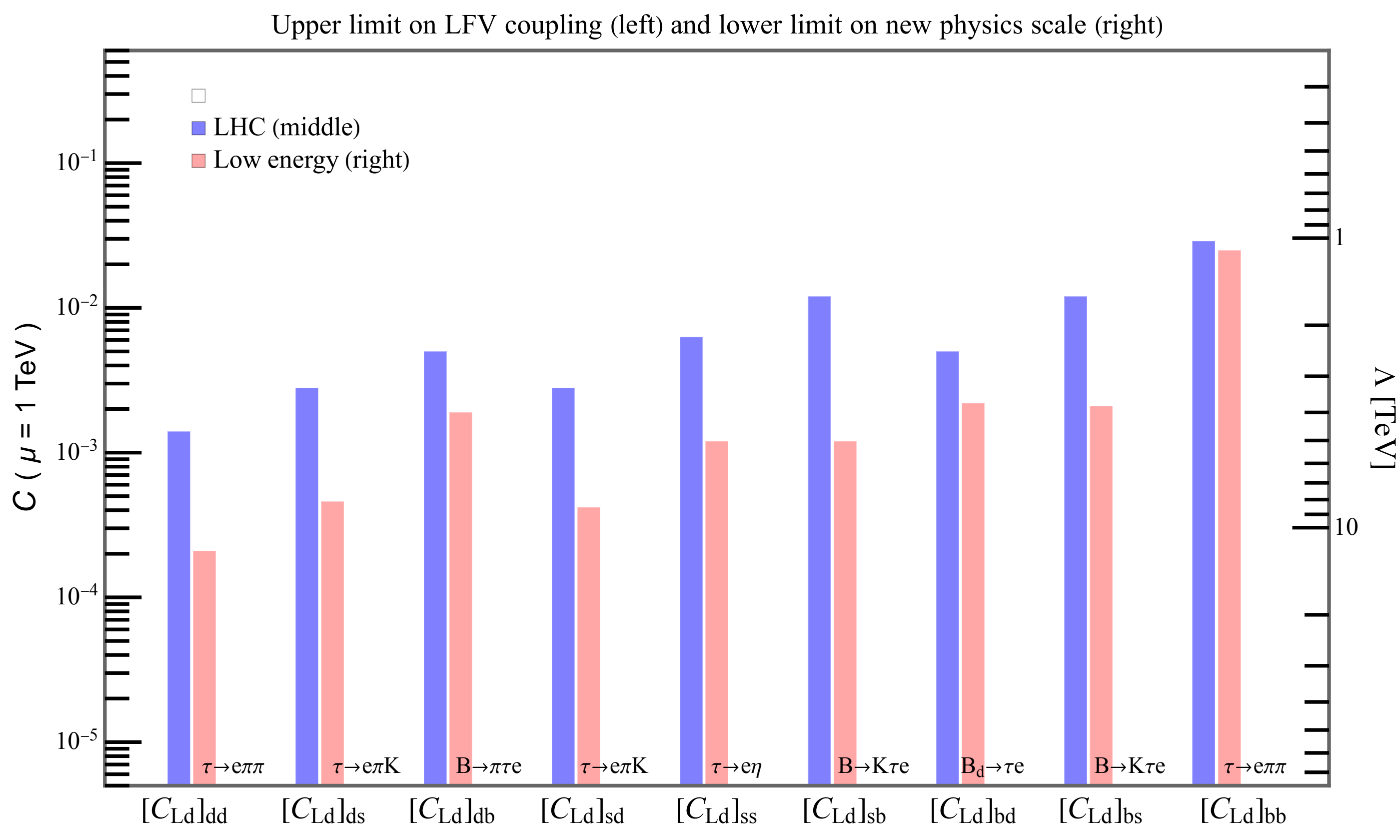


$[C_{Ld}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{d}_{Ri}\gamma_\mu d_{Rj}$

- Operators with d-type quarks sector well constrained by low-energy
- PDF and loop suppression in $[C_{Ld}]_{bb}$

Existing bounds

* Single Operator Analysis

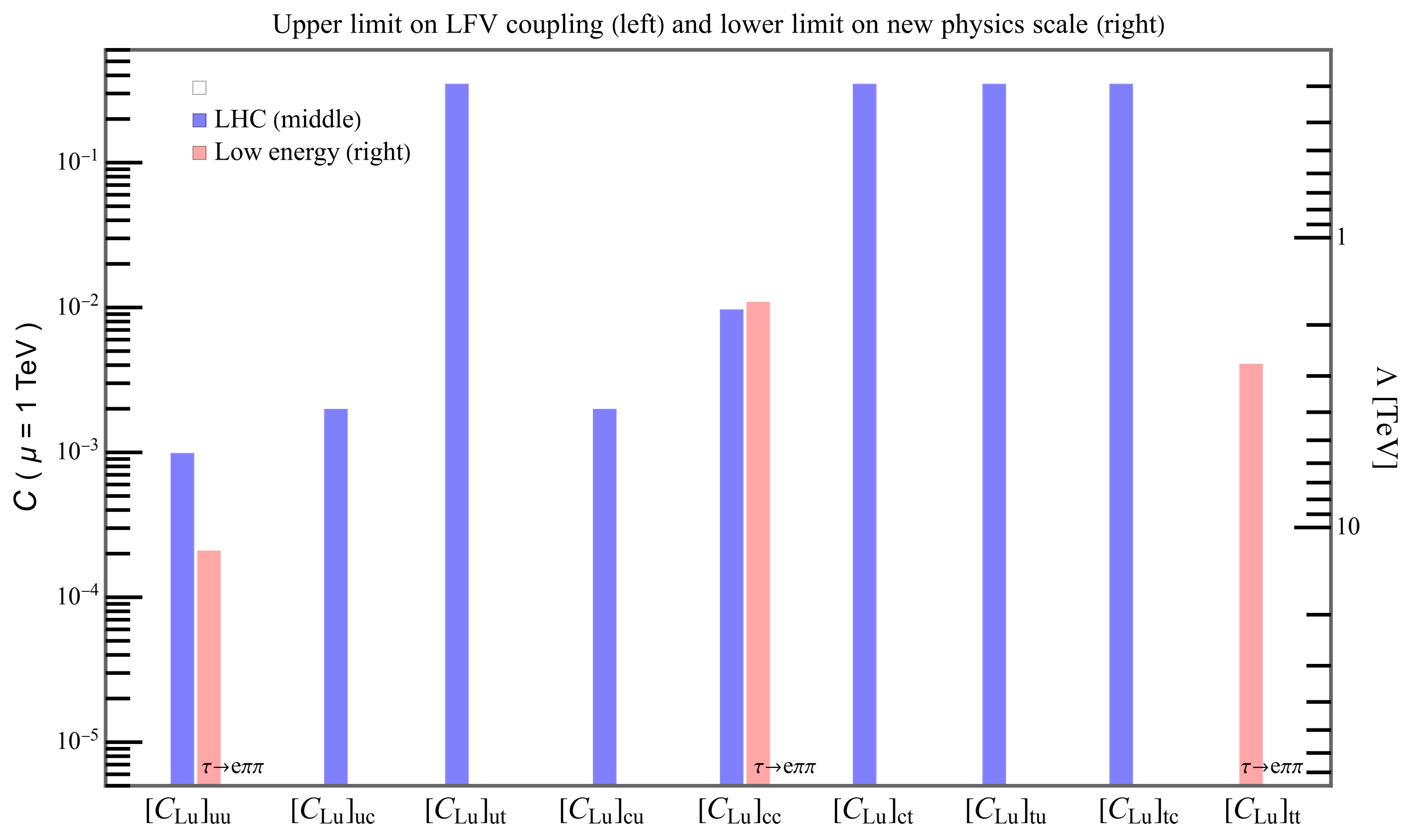


$$\frac{4G_F}{\sqrt{2}}C = \frac{1}{\Lambda^2}$$

Lower bound on the scale : $\Lambda \gtrsim 10$ TeV from $[C_{Ld}]_{dd}$

Existing bounds

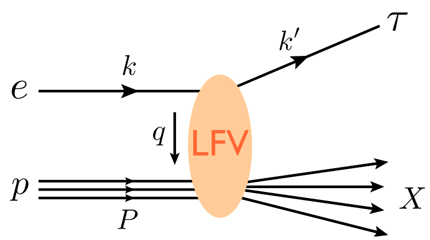
* Single Operator Analysis



$$[C_{Lu}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{u}_{Ri} \gamma_\mu u_{Rj}$$

- Less constrained by low energy than d-type operators
- Strong bound on $[C_{Lu}]_{tt}$ from $\tau \to e\pi^+\pi^-$

EIC Analysis



- Cross sections : $\mathcal{O}(1-10)$ pb at $\sqrt{S} = 141$ GeV

  e.g., 19 pb for $[C_{Lu}]_{uu}$ and 0.8 pb for $[C_{Ld}]_{bb}$

- Major backgrounds 1) Neutral Current $ep \to ej$

  2) Charged Current $ep \to \nu_e j$

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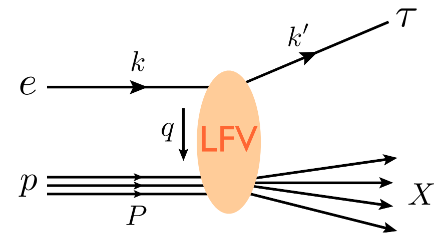

- Major backgrounds
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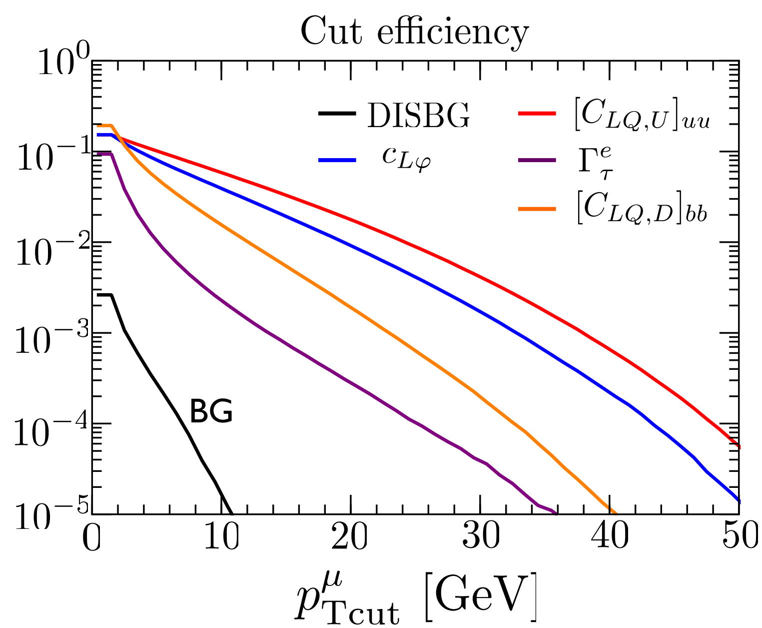
- Promising ID channel

$$\mathrm{BR}(\tau \to e\bar{\nu}_e\nu_\tau) = 17.82\,\%$$

✔ $$\mathrm{BR}(\tau \to \mu\bar{\nu}_\mu\nu_\tau) = 17.39\,\%$$

$$\mathrm{BR}(\tau \to X_h\nu_\tau) = 64.8\,\%$$

$p_T^\mu > 10$ GeV, $E_T > 15$ GeV, $p_T^{j_1} > 20$ GeV



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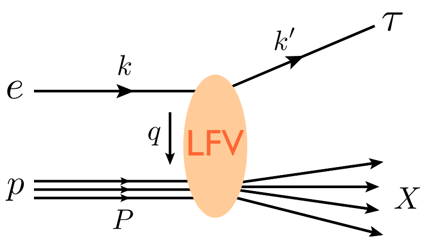

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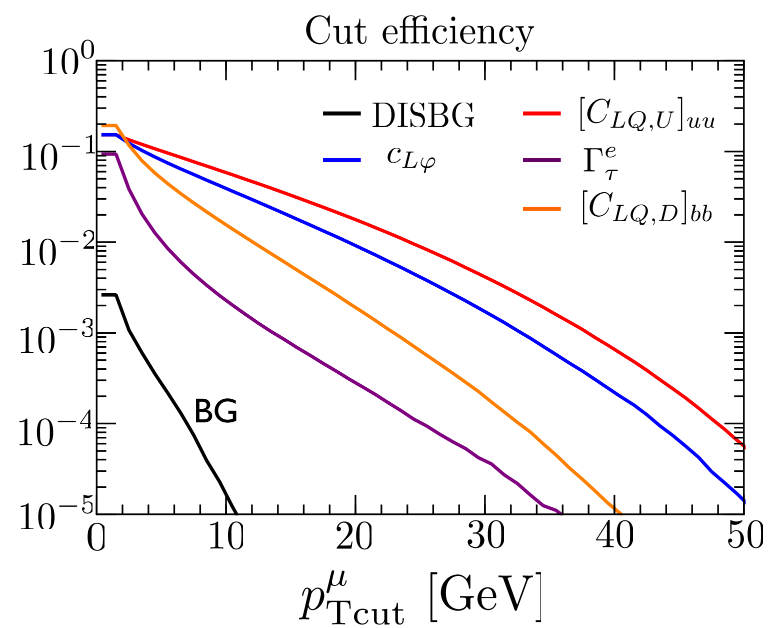
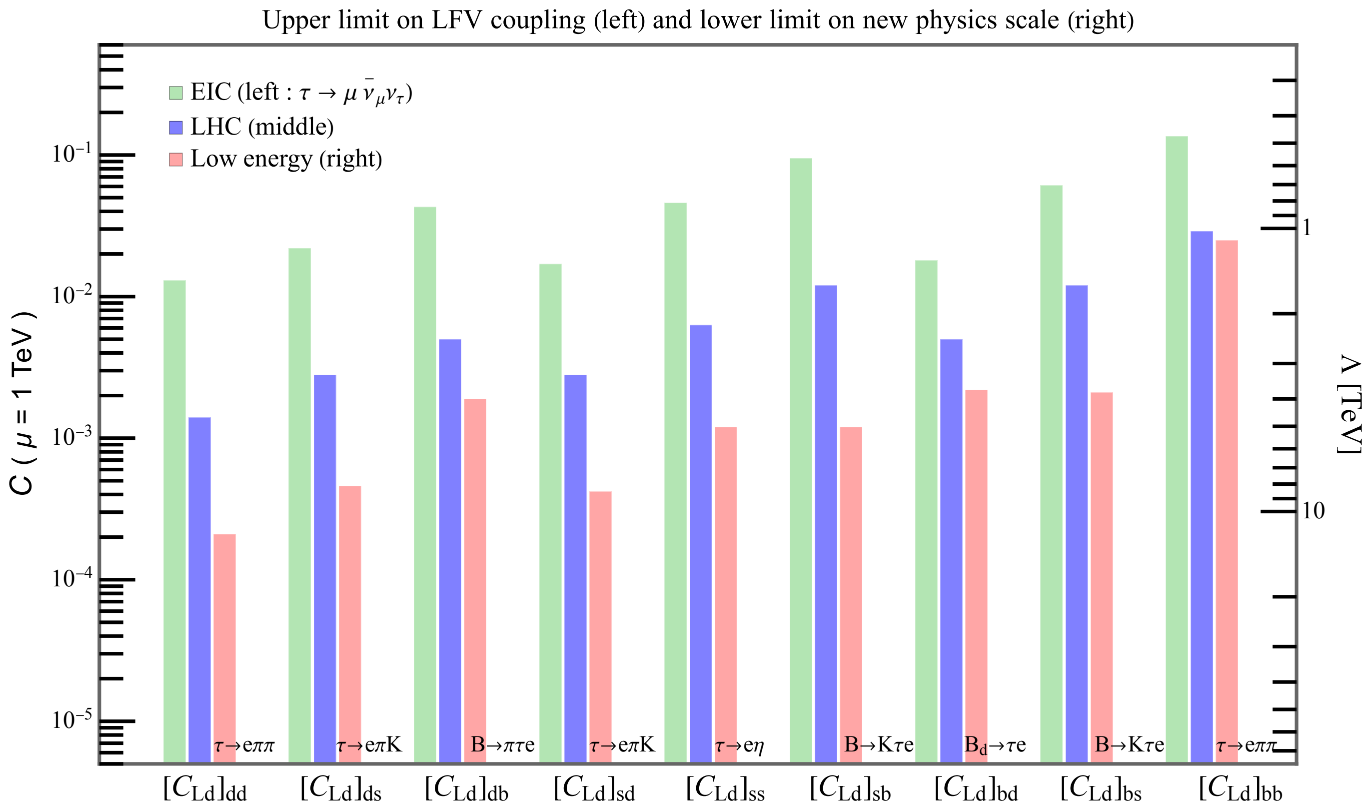
E.g., Cut Efficiencies
- 6 - 10% for valence quarks
- A few % for heavy quarks



EIC vs Current limits

*Single Operator Analysis

$\sqrt{S} = 141$ GeV, $\mathscr{L} = 100$ fb^{-1} @EIC



$[C_{Ld}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{d}_{Ri}\gamma_\mu d_{Rj}$

- Overall, stronger limits from low-energy and LHC
- Possibility that the EIC can compete is in $[C_{Ld}]_{bb}$

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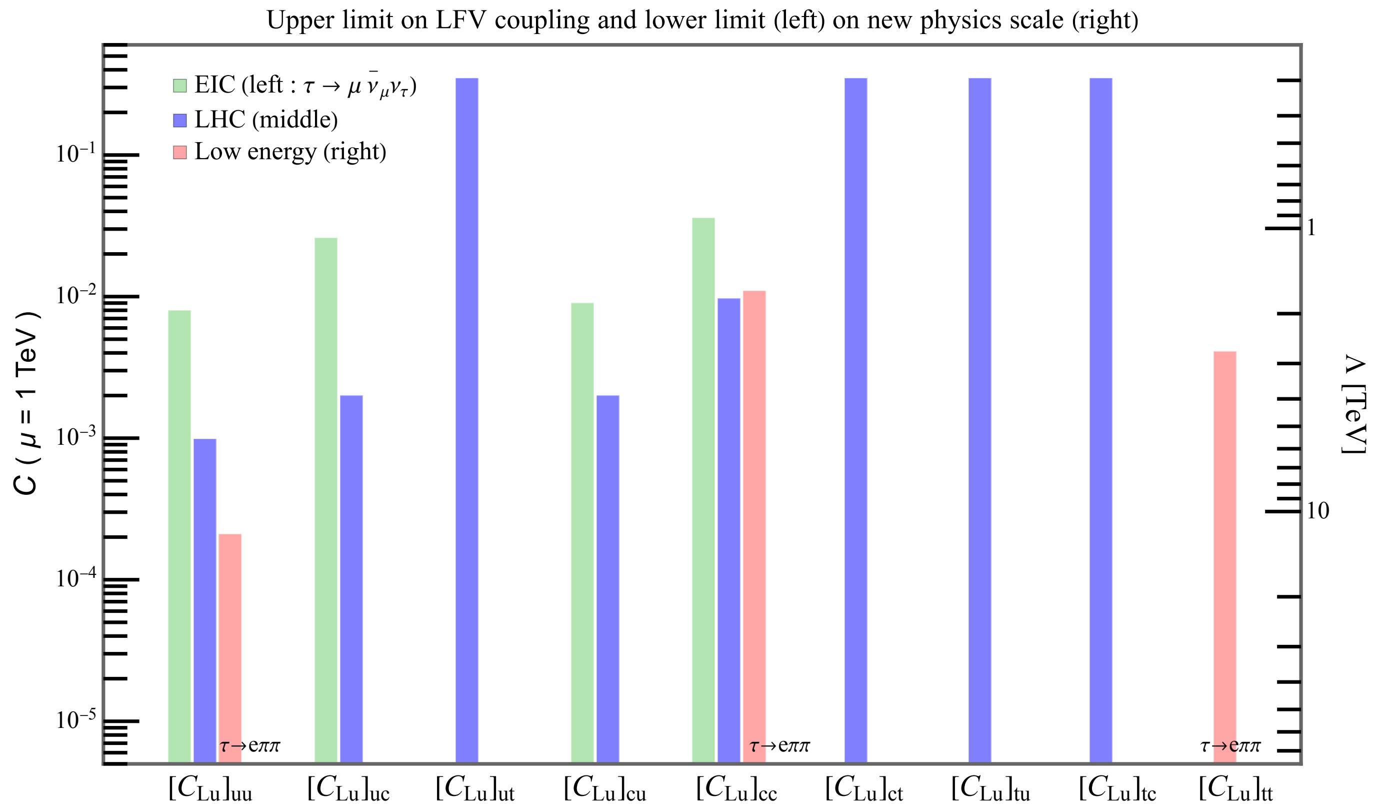

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- Overall, stronger limits from low-energy and LHC
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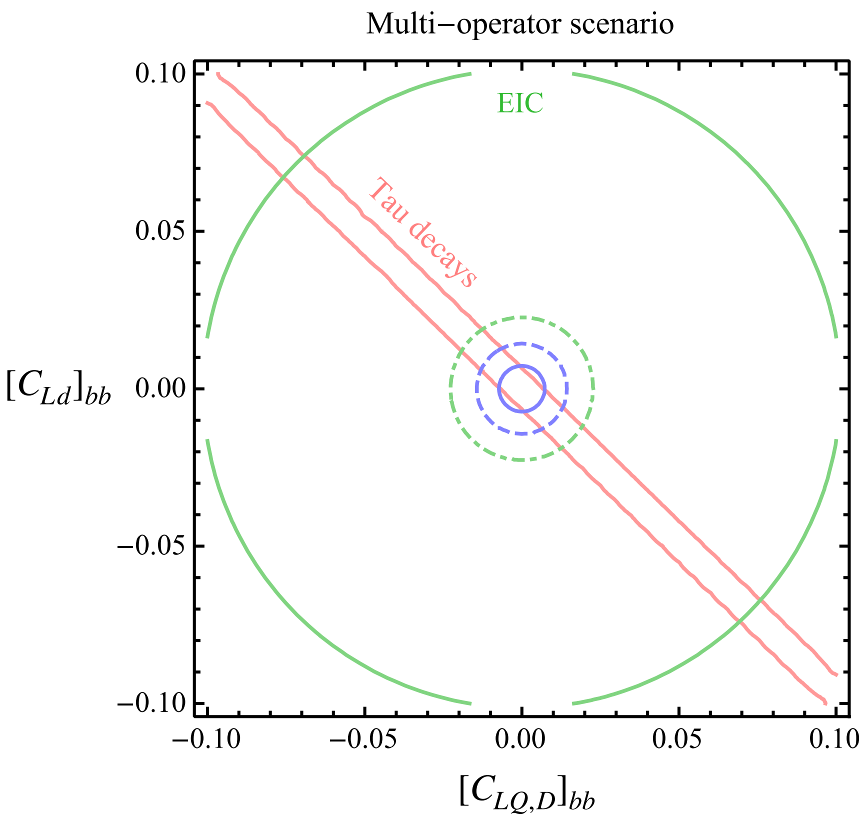
Multi-operator scenario

S. Banerjee, V. Cirigliano, et al,
Snowmass White Papaer, 2203.14919



*Case with 8 nonzero CLFV operators

Z couplings + down-type 4F operators

$$\mathscr{L}_{\rm LFV} \supset -\frac{g_2}{c_W}\left(c^{(1)}_{L\varphi}+c^{(3)}_{L\varphi}\right)\bar{\tau}_L\gamma^\mu Z_\mu e_L$$

$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}\left[C_{Ld}\right]_{aa}\bar{\tau}_L\gamma^\mu e_L \bar{d}_{Ra}\gamma_\mu d_{Ra}$$

$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}\left[C_{LQ,D}\right]_{aa}\bar{\tau}_L\gamma^\mu e_L \bar{d}_{La}\gamma_\mu d_{La}$$

- Collider probes are necessary to close the free direction.

*Need a numerical approach to deal with multi-coupling scenario

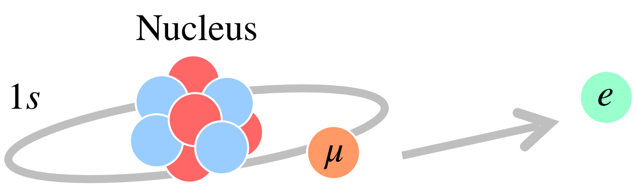
What about $e \rightarrow \mu$ case?

What about $e \to \mu$ case?

Muon to Electron conversion in Muonic Atom

$$\mu^- + (A, Z) \to e^- + (A, Z)$$

*Mono-energetic electron



$$E_e = m_\mu - B_\mu - E_{\rm rec}$$

$$B_\mu \simeq \frac{(Z\alpha_{\rm em})^2}{2} m_\mu$$

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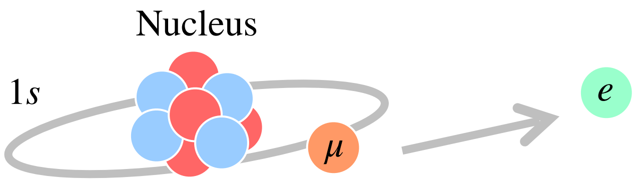

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Y. Kuno (for the COMET Collaboration), Prog. Theor. Phys. 2013, 022C01 (2013).

Process	$\Gamma_{\rm capt} \times 10^{-15}$ [MeV]	Upper Bound
$\mu^- + {\rm Ti} \to e^- + {\rm Ti}$	1.705	6.1×10^{-13}
$\mu^- + {\rm Au} \to e^- + {\rm Au}$	8.603	7×10^{-13}

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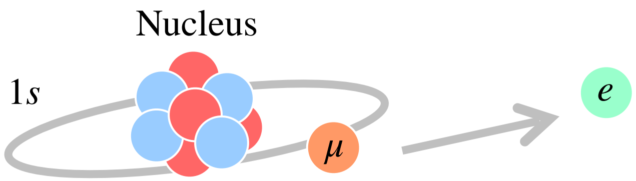

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$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$	0.463	Expected $\mathcal{O}(10^{-17})$

Aluminum Target
@ Mu2E and COMET

* Improvement by 4 orders of magnitude

Low-Energy Muon and Meson Decay

Decay mode		Upper limit (90 % C . L.)		
$\mu + \mathrm{Ti} \to e + \mathrm{Ti}$		6.1×10^{-13}	SINDRUM – II	CPC 980420 (1998) 534
$\mu \to 3e$		1.0×10^{-12}	SINDRUM	NPB 299 (1988)1
$K_L^0 \to e^\pm \mu^\mp$	ds/ds	4.7×10^{-12}	E871	PRL81(1998)5734
$K_L^0 \to \pi^0 e^\pm \mu^\mp$		7.6×10^{-11}	KTeV	PRL100(2008)131803
$K^+ \to \pi^+ e^+ \mu^-$		6.6×10^{-11}	NA62	PRL127(2021)131802
$K^+ \to \pi^+ e^- \mu^+$		1.3×10^{-11}	E865	PRD72(2005)012005
$D^0 \to e^\pm \mu^\mp$	uc/cu	1.3×10^{-8}	LHCb	PLB754(2016)167
$D^0 \to \pi^0 e^\pm \mu^\mp$		8.0×10^{-7}	BaBar	PRD101(2020)112003
$D^+ \to \pi^+ e^+ \mu^-$		2.1×10^{-7}	LHCb	JHEP06(2021)044
$D^+ \to \pi^+ e^- \mu^+$		2.2×10^{-7}	LHCb	JHEP06(2021)044
$D_s^+ \to K^+ e^+ \mu^-$		7.9×10^{-7}	LHCb	JHEP06(2021)044
$D_s^+ \to K^+ e^- \mu^+$		5.6×10^{-7}	LHCb	JHEP06(2021)044
$B^0 \to e^\pm \mu^\mp$	db/bd	1.0×10^{-9}	LHCb	JHEP03(2018)078
$B^+ \to \pi^+ e^\pm \mu^\mp$		1.7×10^{-7}	BaBar	PRL99(2007)051801
$B^+ \to K^+ e^- \mu^+$	sb/bs	6.4×10^{-9}	LHCb	PRL123(2019)241802
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$B_s \to e^\pm \mu^\mp$		5.4×10^{-9}	LHCb	JHEP03(2018)078

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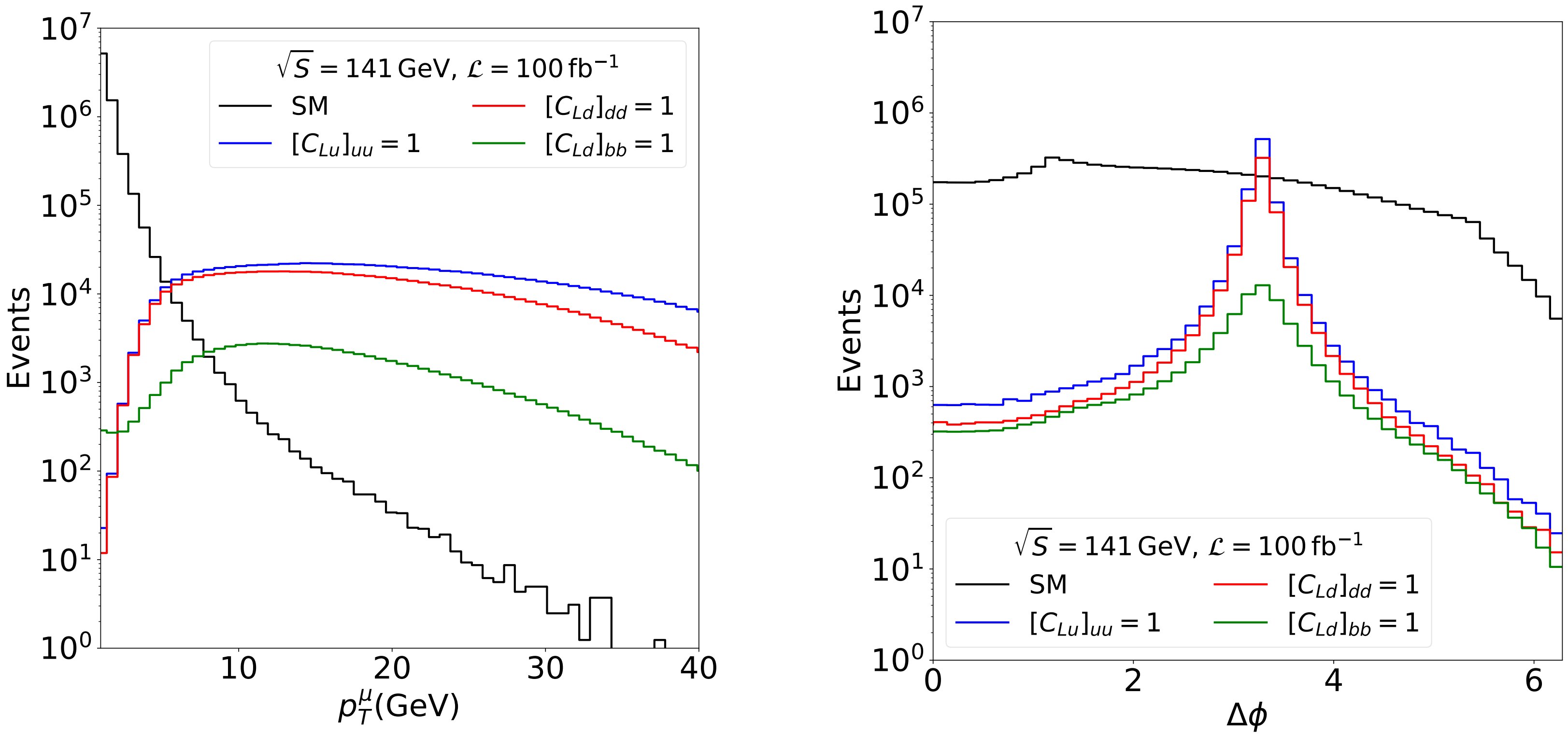
EIC Analysis

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti
arXiv 2411.13497 (Accepted by JHEP)

Require one muon with high p_T^μ and one jet, not to have electrons with high p_T^e



SM BGs (black line) : Small p_T^μ and little azimuthal correlation between muon and jet

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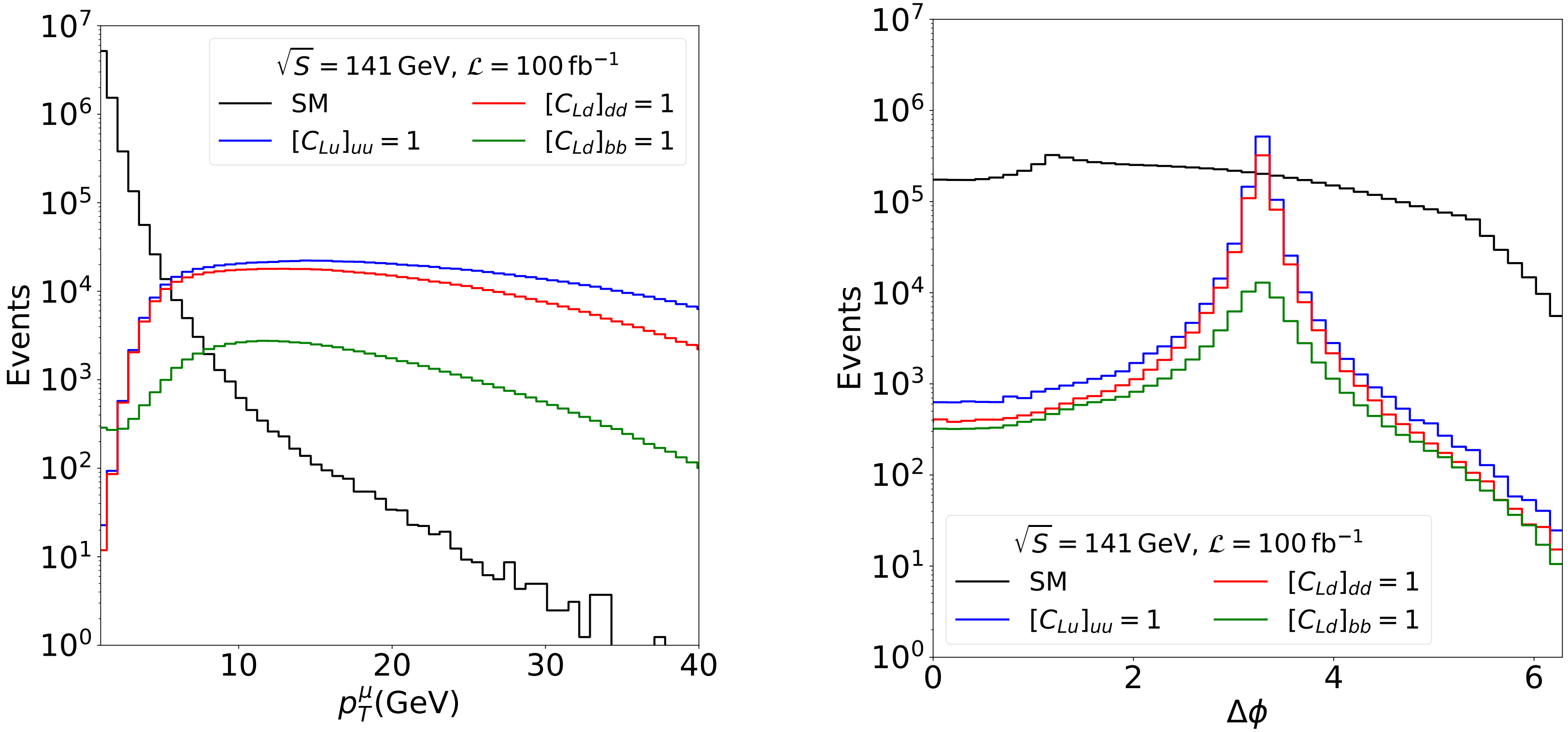

$$p_T^\mu > 20 \text{ GeV}, \;\; p_T^e < 5 \text{ GeV}, \;\; p_T^j > 20 \text{ GeV}, \;\; 2 < \Delta\phi < 4$$

EIC vs Current limits

F. Delzanno, KF, S. Gonzalez-Solis, E. Mereghetti
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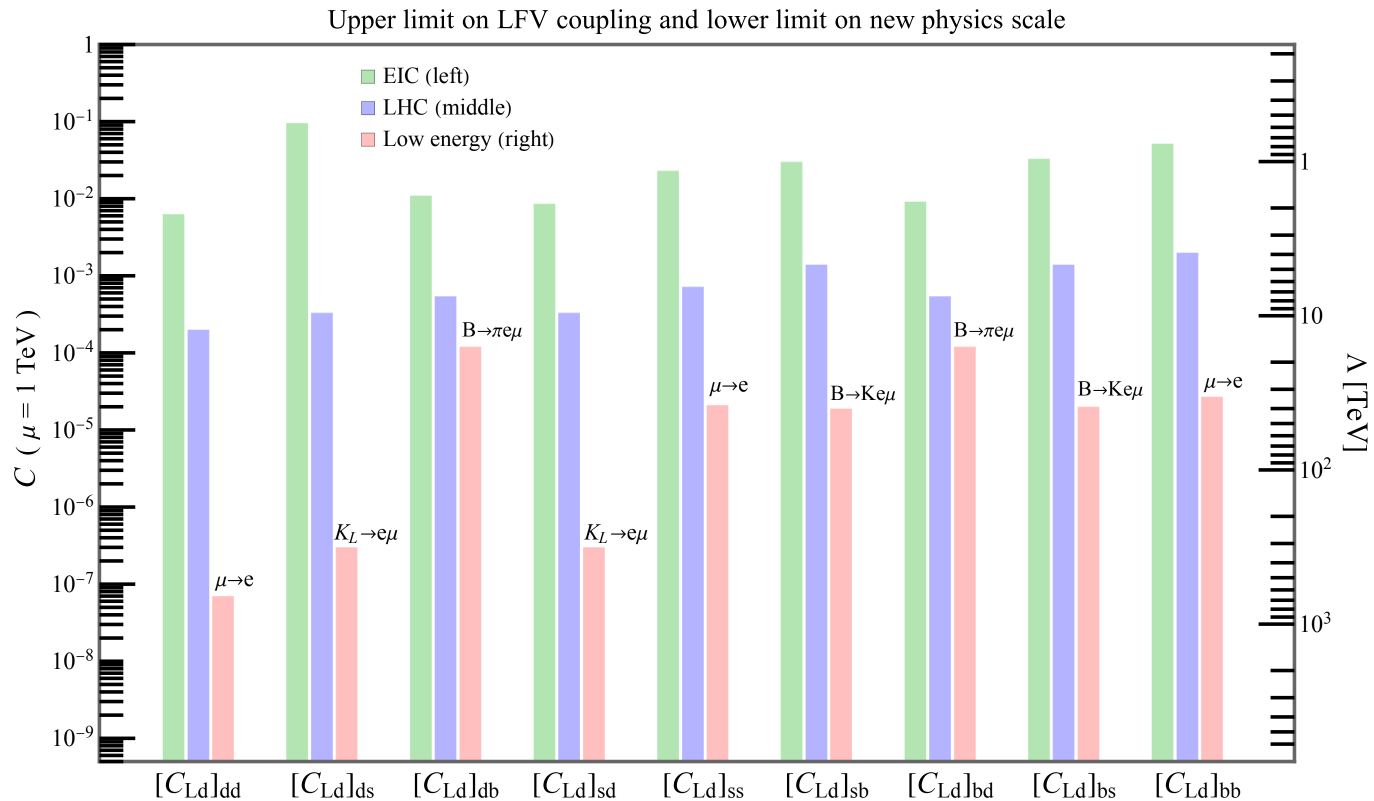
* Single Operator Analysis



$[C_{Ld}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{d}_{Ri}\gamma_\mu d_{Rj}$

- $\mu \to e$ conversion currently gives strong bound

EIC vs Current limits

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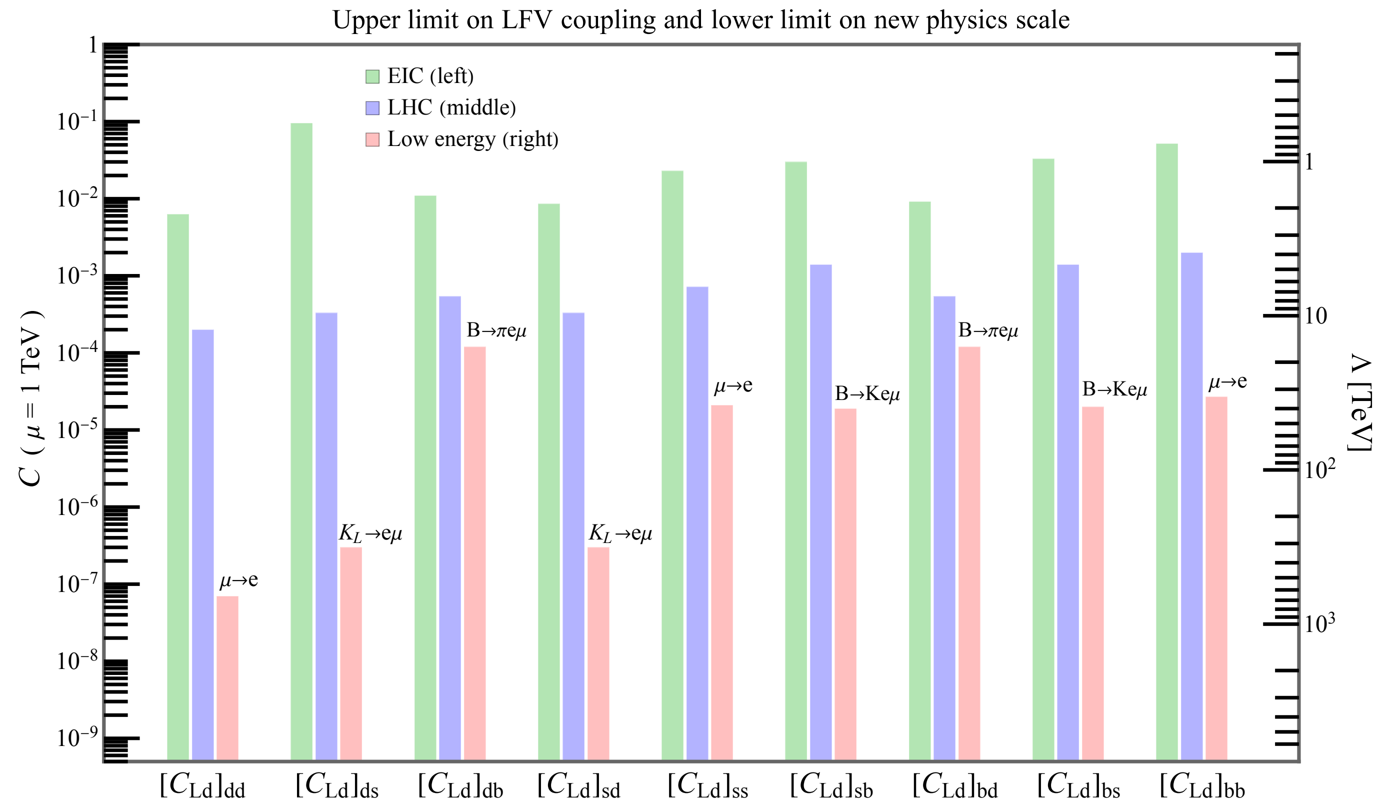

$$\frac{4G_F}{\sqrt{2}}C = \frac{1}{\Lambda^2}$$

Lower bound on the scale : $\Lambda \gtrsim \mathcal{O}(100)$ TeV from $[C_{Ld}]_{dd}$

EIC vs Current limits

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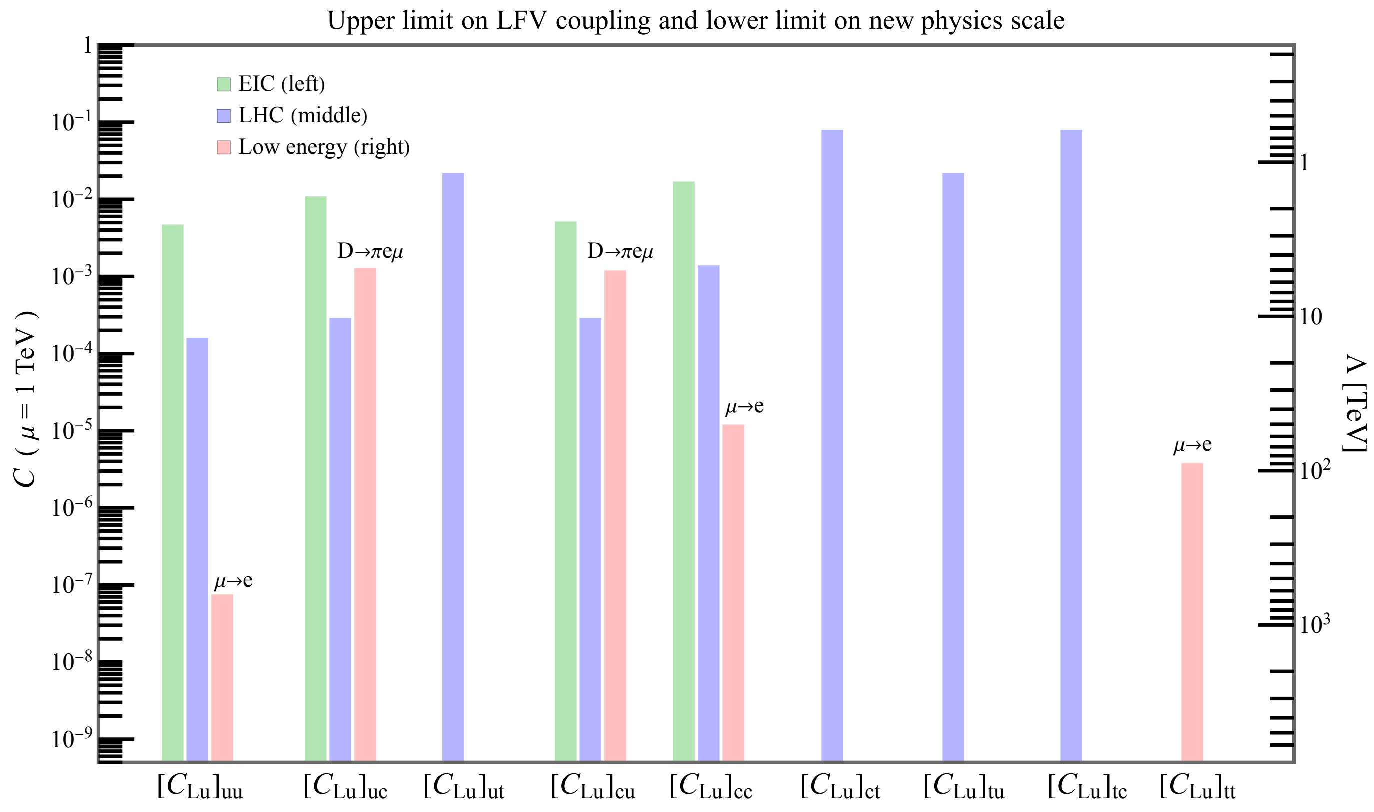


$[C_{Lu}]_{ij}\ \bar{\tau}_L \gamma^\mu e_L\ \bar{u}_{Ri} \gamma_\mu u_{Rj}$

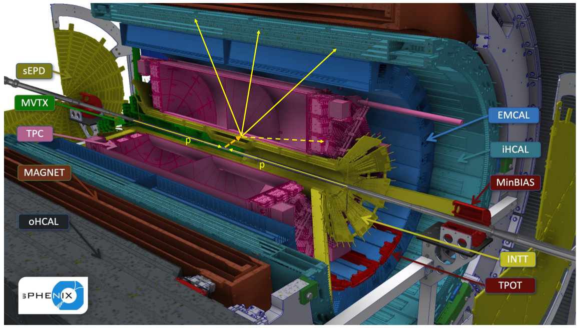
- A factor of 10 weaker bound on $[C_{Lu}]_{cu}$ at the EIC

Study on Experimental Side

Thanks to Ming Liu!

Study tau tagging using sPHENIX p+p data and utilizing AI/ML algorithms that can optimize the tagging efficiency.

- Displaced tau-decay vertex
- Narrow jet from tau hadronic decay
- Single muon/hadron from tau decays



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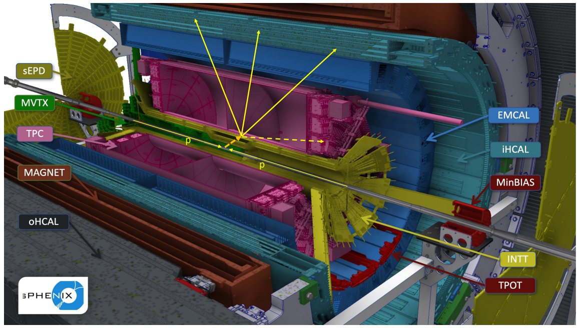
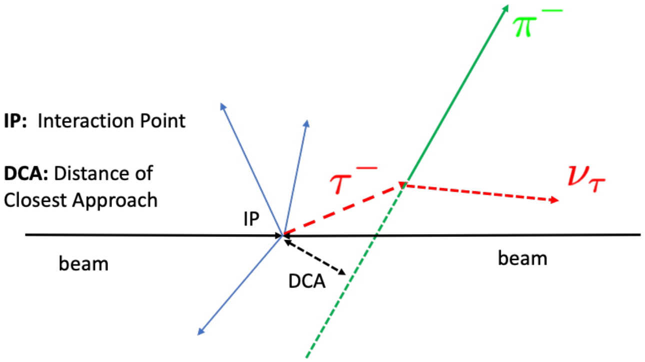


sPHENIX : proton+proton collisions data from Run2024

- Identify the displaced τ decay vertex from the collision point (called primary vertex)
- Simulation of p+p → Upsilon → Tau+ Tau-



EIC: e+proton collisions

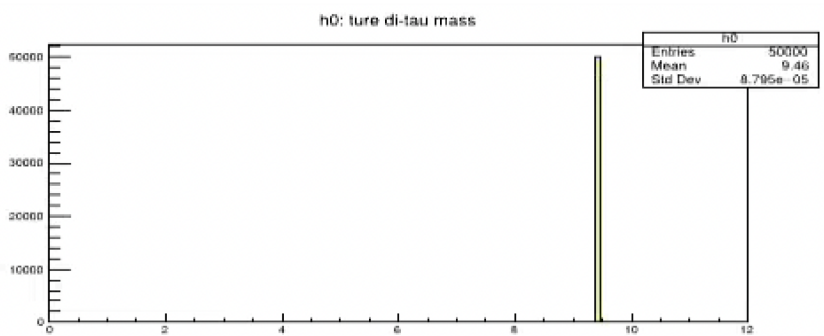
Simulations of ep collisions from the ePIC detector setup

Study on Experimental Side

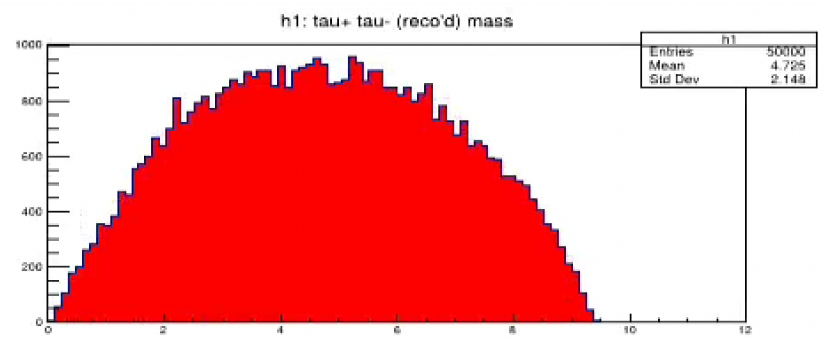
Thanks to Ming Liu!

Tau Tagging @ sPHENIX: $pp \to \Upsilon \to \tau^- \tau^+$

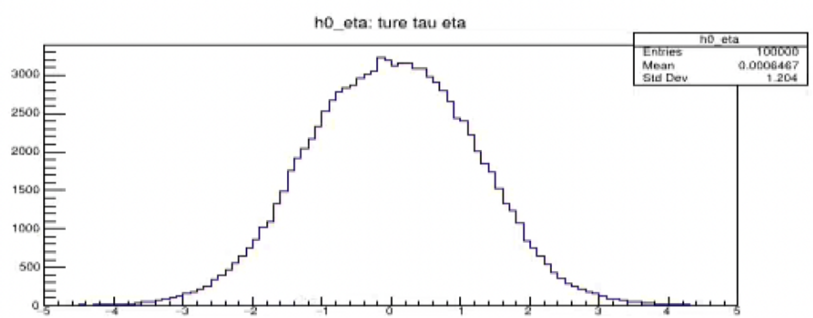
Invariant mass of Tau+ and Tau-:



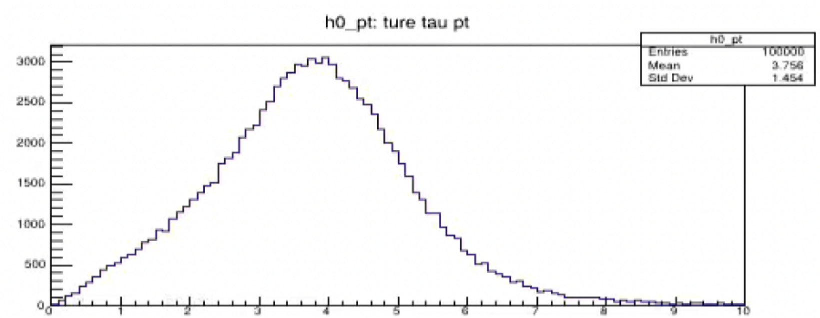
True Tau kinematics (p,e):
Mass = 9.46GeV



Reconstructed Tau kinematics (p,e),
missing neutrinos: <mass> ~5 GeV



η



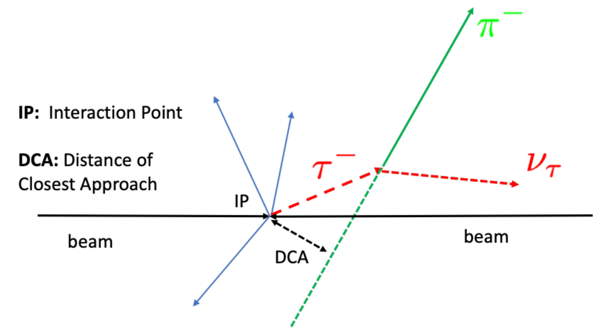
p_T

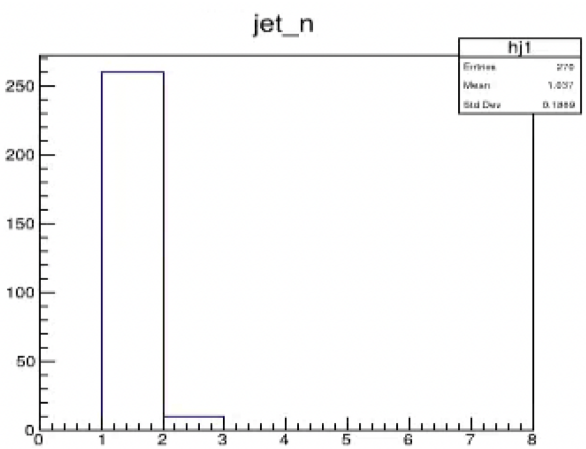
Study on Experimental Side

Thanks to Ming Liu!

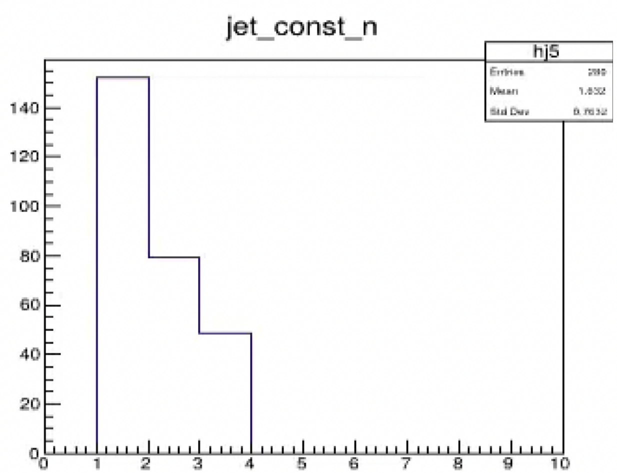
Tau sample selection: pT(ture) > 5GeV

Tau-jet reconstruction:
1) reconstructed from "visible tracks" with DCA > 0
2) anti-kT, R = 1.0

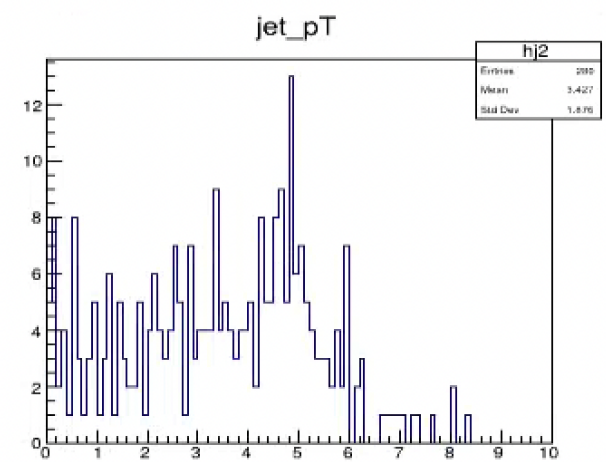




Mostly single jet:
Tracks with DCA>0



# of particles in jets



"Reconstructed" jet pT,
w/o neutrinos

Summary

Searches for Lepton Flavor Violations are Powerful Probes of BSM Physics.

- Systematic Analysis based on SMEFT

  - The RGEs allow to constrain CLFV heavy quark operators

- Operators involving b and c in $e - \tau$ case are promising at the EIC

- Collider searches are essential in multi-operator scenarios

- Strong bound in $e - \mu$ case especially from $\mu \to e$ conversion

Outlook/Discussion

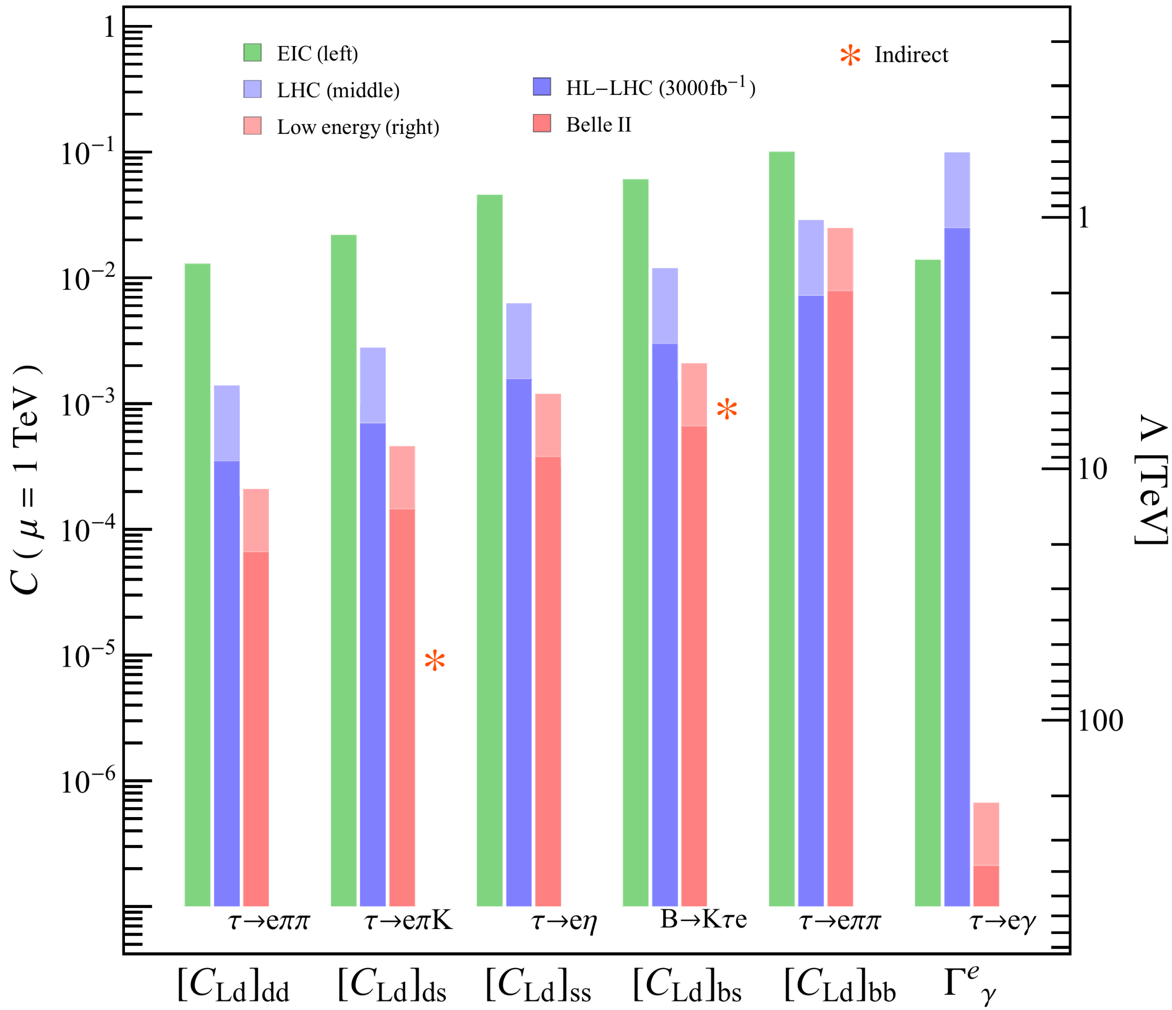
- Multi-Operator Analysis using Machine Learning
- Experimental study of tau lepton tagging
- LNV / Sterile Neutrino Searches at the EIC

Thank you for your attention!

Backup slides

Apple to Apple

S. Banerjee, V. Cirigliano, et al,
Snowmass White Papaer, 2203.14919

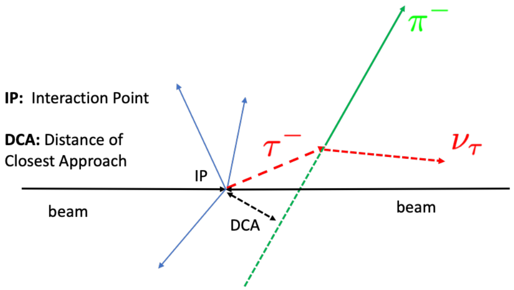


Study on Experimental Side

Thanks to Ming Liu!

How to tag Tau leptons experimentally?

- Exploit tau-lepton decay topology
  - Displaced track(s) from tau decay
  - Pencil-like isolated track(s)
- Study tau-lepton tagging algorithms using sPHENIX p+p data,
  - Identify displaced tracks with silicon pixel detectors (MVTX)
  - Tag pencil-like "jets" with EMCal and HCal
- EIC/ePIC detector simulations
  - Tau-lepton tagging with algorithms developed from sPHENIX data



Search for:

- "Tau-> nv_tau + pi+", BR = 11.5%,
  displaced isolated single track
- "Tau -> pi+ 2pi0 + nv_tau" , BR = 9.5%,
  pencil-like jets
- "Tau-> muon/e + nv_mu/e + nv_tau", BR = 17.8%,
  displaced isolated single track

Benchmark performance:

$$\Upsilon \rightarrow \tau^+ + \tau^-$$

broad mass of di-hadron and di-lepton of "tau candidates"

Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau$		17.8
$\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \rightarrow h^-\nu_\tau$		11.5
$\tau^- \rightarrow h^-\pi^0\nu_\tau$	$\rho(770)$	25.9
$\tau^- \rightarrow h^-\pi^0\pi^0\nu_\tau$	$a_1(1260)$	9.5
$\tau^- \rightarrow h^-h^+h^-\nu_\tau$	$a_1(1260)$	9.8
$\tau^- \rightarrow h^-h^+h^-\pi^0\nu_\tau$		4.8
Other		3.3

*Study tau tagging algorithms using sPHENIX p+p data and utilize ML to optimize the tagging efficiency.