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Title: Fundamental symmetry tests in the lepton sector

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Fundamental symmetry tests in the lepton sector

Kaori Fuyuto

Los Alamos National Laboratory

W. Dekens, J. de Vries, KF, E. Mereghetti, G. Zhou
JHEP06(2020)097

V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan
JHEP03(2021)256

December 1, 2021
University of Arizona

Outline :

1. Introduction

2. Neutrinoless double beta decay

   - EFT approach with light sterile neutrino

   - Application to leptoquark model

3. LFV Tau to e transition

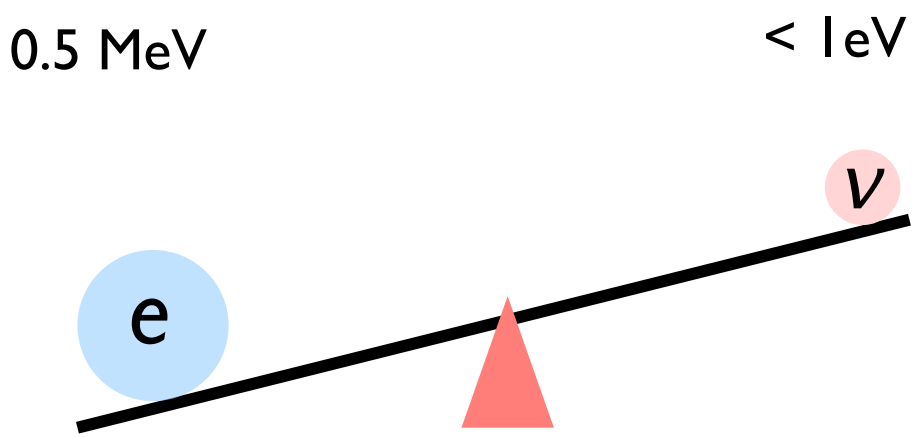
   - EIC vs other experiments

4. Summary

Introduction

Neutrino mass

The observation of neutrino oscillation confirms neutrinos have mass.



Open question :

What is the origin of the tiny but non-vanishing masses of the neutrinos?

Neutrino mass

Key approach : Fundamental symmetry tests

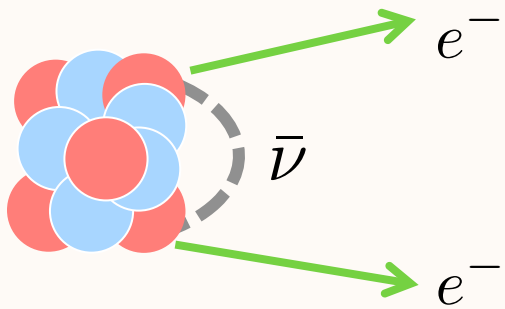
* Search for violation of symmetry which is preserved in the Standard Model

Neutrino mass

Key approach : Fundamental symmetry tests

1) Lepton number violation

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



* This process violates lepton number by two units.

Neutrino mass

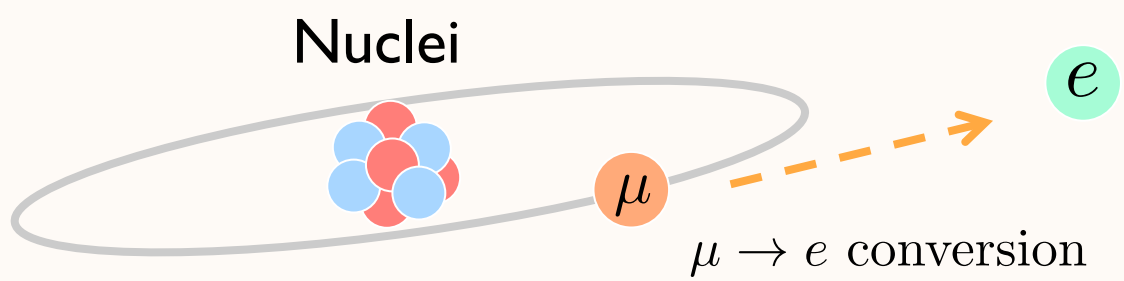
Key approach : Fundamental symmetry tests

1) Lepton number violation

2) Charged-lepton flavor violation

Ex) $\mu \to e\gamma,\ \mu \to e$ conversion, $\tau \to e\gamma \cdots$

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



Neutrino mass

Key approach : Fundamental symmetry tests

1) Lepton number violation

2) Charged-lepton flavor violation

$$\text{Ex)}\ \mu \to e\gamma,\ \ \mu \to e \text{ conversion},\ \ \tau \to e\gamma \cdots$$

Why important?

Various hypotheses, i.e., New Physics, to explain nonzero neutrino mass predict the violation.

* Neutrinoless double beta decay and Tau to e LFV

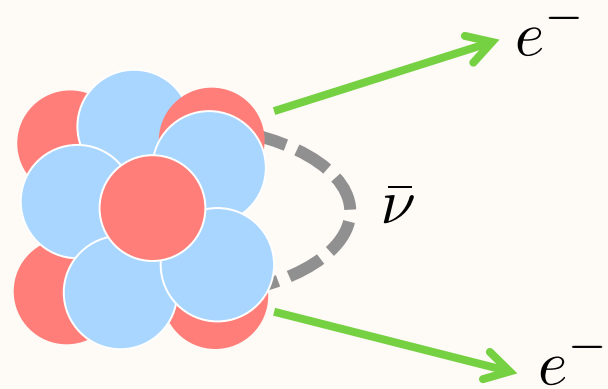
Today

Neutrinoless double beta decay

Neutrinoless double beta decay

Double β decay without neutrino emission

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



The process can occur if neutrino is a *Majorana* particle.

Majorana mass

Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa Majorana Mass

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \mathrm{H.C}$$

Majorana mass

Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa Majorana Mass

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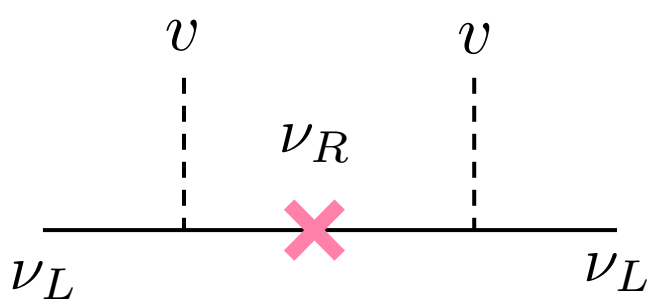


: Mass insertion

v : Higgs VEV

Majorana mass

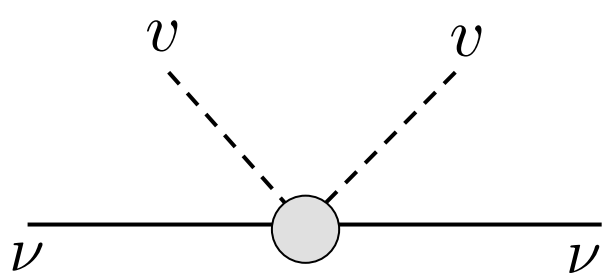
Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa Majorana Mass

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \mathrm{H.C}$$

Majorana mass term is induced.



$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\bar{\nu} m_\nu \nu$$

$$(\nu = \nu^c)$$

Majorana mass

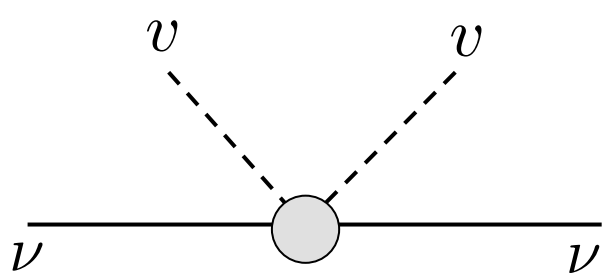
Right-handed neutrino : ν_R

~ Gauge singlet (Sterile neutrino)

Yukawa Majorana Mass

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \mathrm{H.C}$$

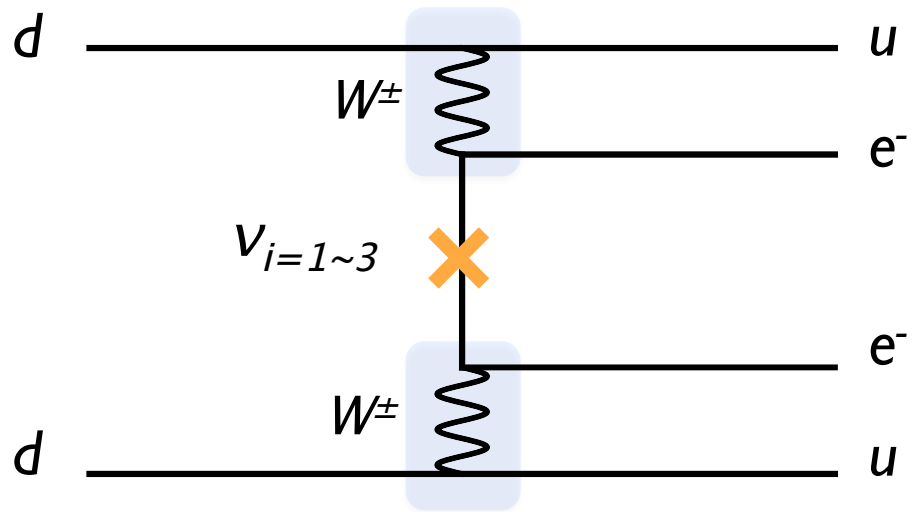
If M_R is much heavier than EW scale,



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

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$



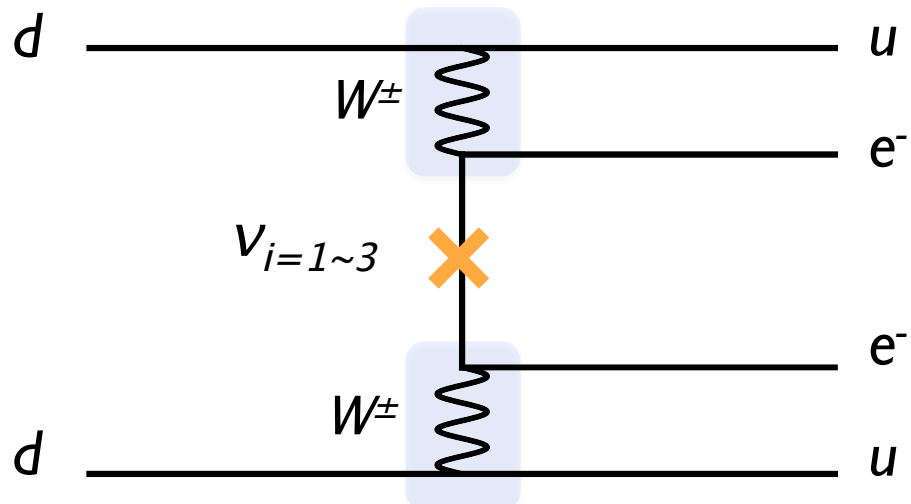
: Mass insertion

Left-handed vector operator :

$$\mathcal{L}^{(6)} = \frac{G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\rm VLL} \nu \quad \Big| \quad C^{(6)}_{\rm VLL} = -2 V_{ud} U_{ei}$$

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$



$$\mathcal{A}_{0\nu2\beta} \sim \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{\mathrm{q}^2 + m_i^2} \sim \frac{1}{\mathrm{q}^2}\left(\sum_{i=1}^{3} U_{ei}^2 m_i\right)$$

O(100) MeV

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

$$\Delta m^2_{21} = m_2^2 - m_1^2 = 7.39 \times 10^{-5}\ [\mathrm{eV}^2]$$

$$\Delta m^2_{31} = m_3^2 - m_1^2 = \pm 2.5 \times 10^{-3}\ [\mathrm{eV}^2]$$

From PDG

$$\mathcal{A}_{0\nu2\beta} \sim \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{\mathrm{q}^2 + m_i^2} \sim \frac{1}{\mathrm{q}^2} \left(\sum_{i=1}^{3} U_{ei}^2 m_i \right)$$

O(100) MeV

Oscillation data

Standard case

Three light Majorana neutrinos : $\nu_{i=1\sim3}$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.39 \times 10^{-5}\ [\mathrm{eV}^2]$$

$$\Delta m_{31}^2 = m_3^2 - m_1^2 = \pm 2.5 \times 10^{-3}\ [\mathrm{eV}^2]$$

From PDG

Inverse half-life : $\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 G_{0\nu} \left|\mathcal{A}_{0\nu2\beta}\right|^2$

$g_A = 1.27,\ G_{0\nu}$: Phase space factor

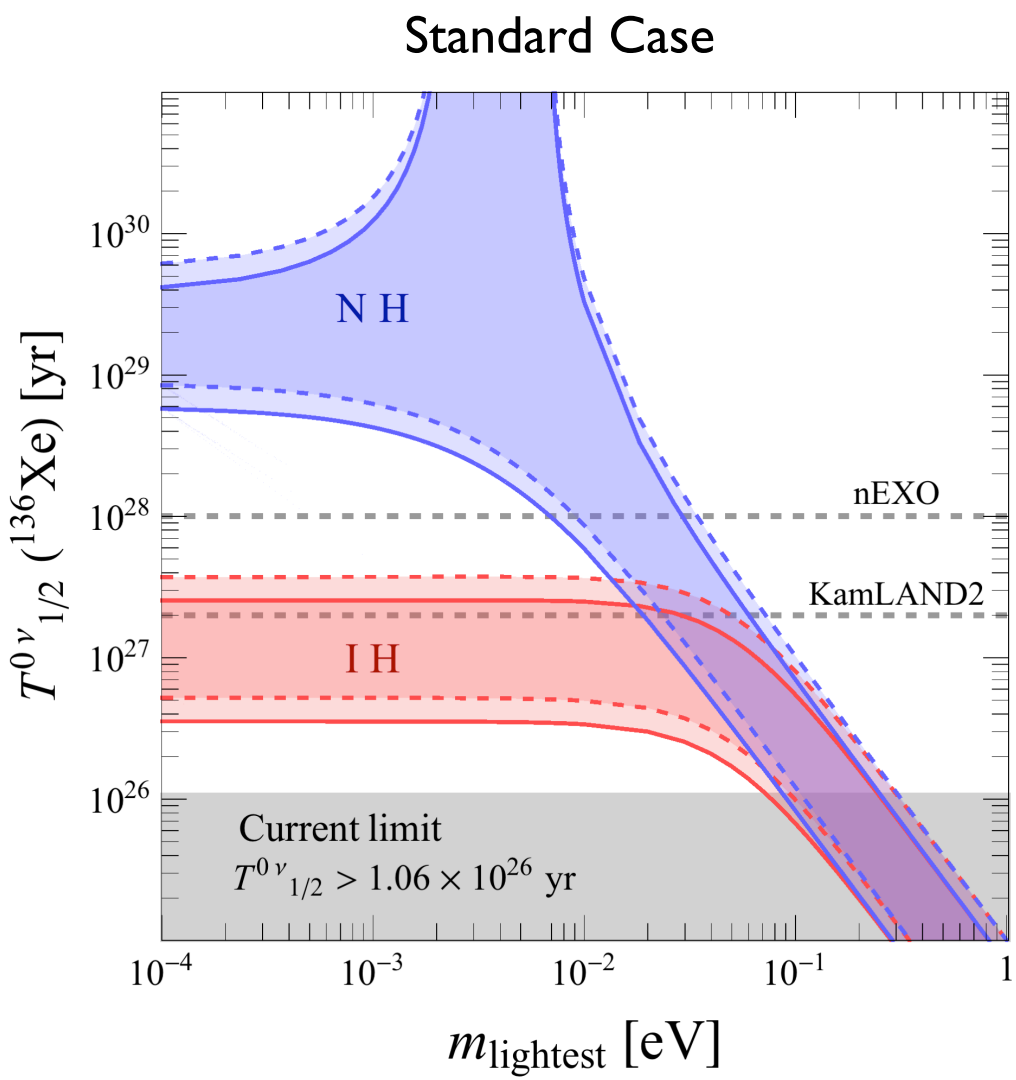
Search for $0\nu2\beta$

Isotope	Experiment	Current limit ($\times 10^{25}$yr)		Future sensitivity ($\times 10^{25}$yr)	
^{48}Ca	ELEGANT−IV	5.8×10^{-3}	[2]	–	
	CANDLES	6.2×10^{-3}	[23]	10^{-2}	[28]
	NEMO−3	2.0×10^{-3}	[9]		
^{76}Ge	MAJORANA DEMONSTRATOR	2.7	[22]	–	
	GERDA	9.0	[24]	–	
	LEGEND	–		10^3	[29]
^{82}Se	CUPID	3.5×10^{-1}	[25]		
	NEMO−3	2.5×10^{-2}	[20]		
	SuperNEMO	–		10	[30]
^{96}Zr	NEMO−3	9.2×10^{-4}	[3]		
^{100}Mo	NEMO−3	1.1×10^{-1}	[8]		
	CUPID−1T	–		9.2×10^2	[37]
	AMoRE	9.5×10^{-3}	[26]	5.0×10	[31]
^{116}Cd	NEMO−3	1.0×10^{-2}	[13]		
^{128}Te	–	1.1×10^{-2}	[1]	–	
^{130}Te	CUORE	3.2	[21]	9.0	[32]
	SNO+	–		1.0×10^2	[33]
^{136}Xe	KamLAND-Zen	10.7	[10]	2.0×10^2	
	EXO−200	3.5	[27]	10^3	[34]
	NEXT	–		2.0×10^2	[35]
	PandaX	–		1.0×10^2	[36]
^{150}Nd	NEMO−3	2.0×10^{-3}	[12]		

$$T^{0\nu}_{1/2}\left(^{136}\mathrm{Xe}\right) > 1.06 \times 10^{26}\ \mathrm{yr}$$

KamLAND-Zen
PRL117(2016) 082503

Current limit on half-life



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

* Bands

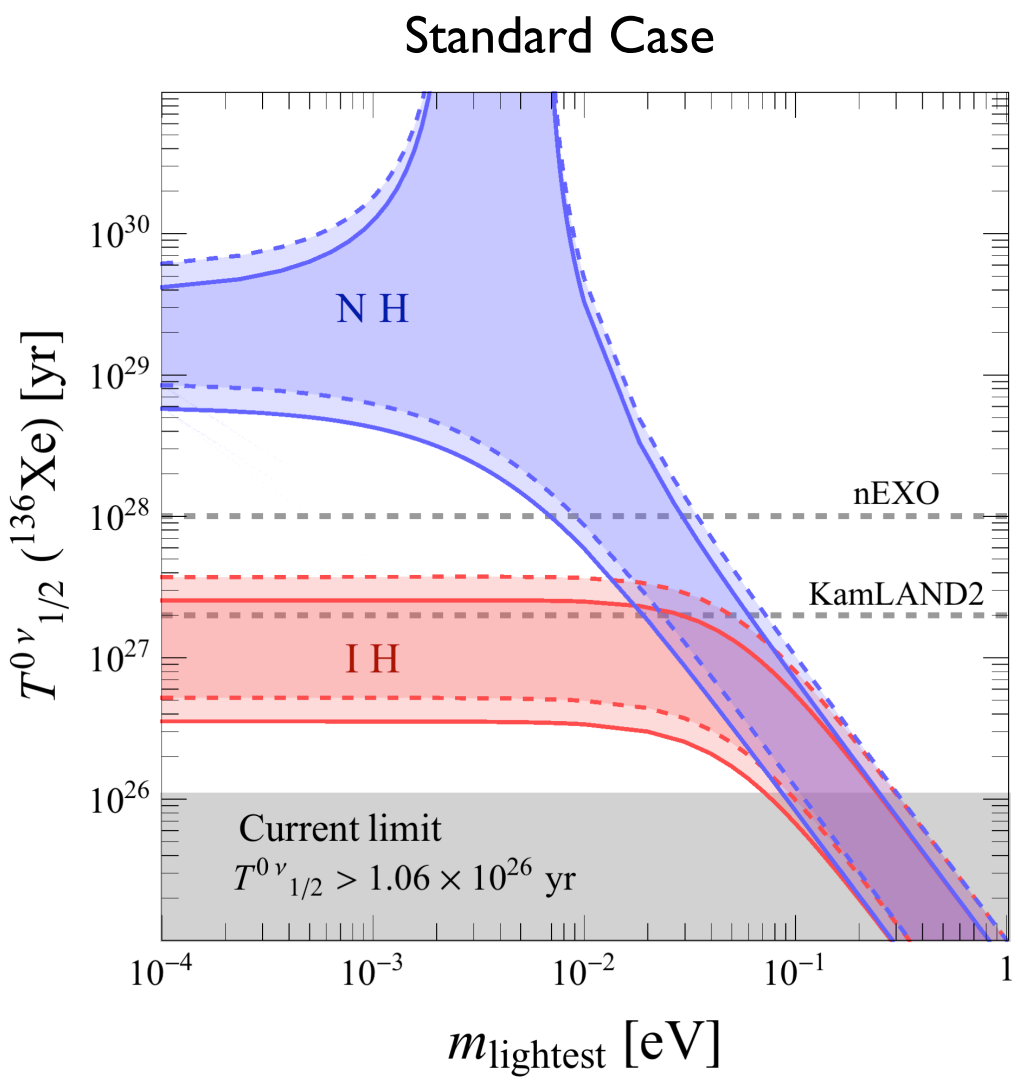
1) Majorana phase

2) Matrix elements

QRPA

Shell

Current limit on half-life



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

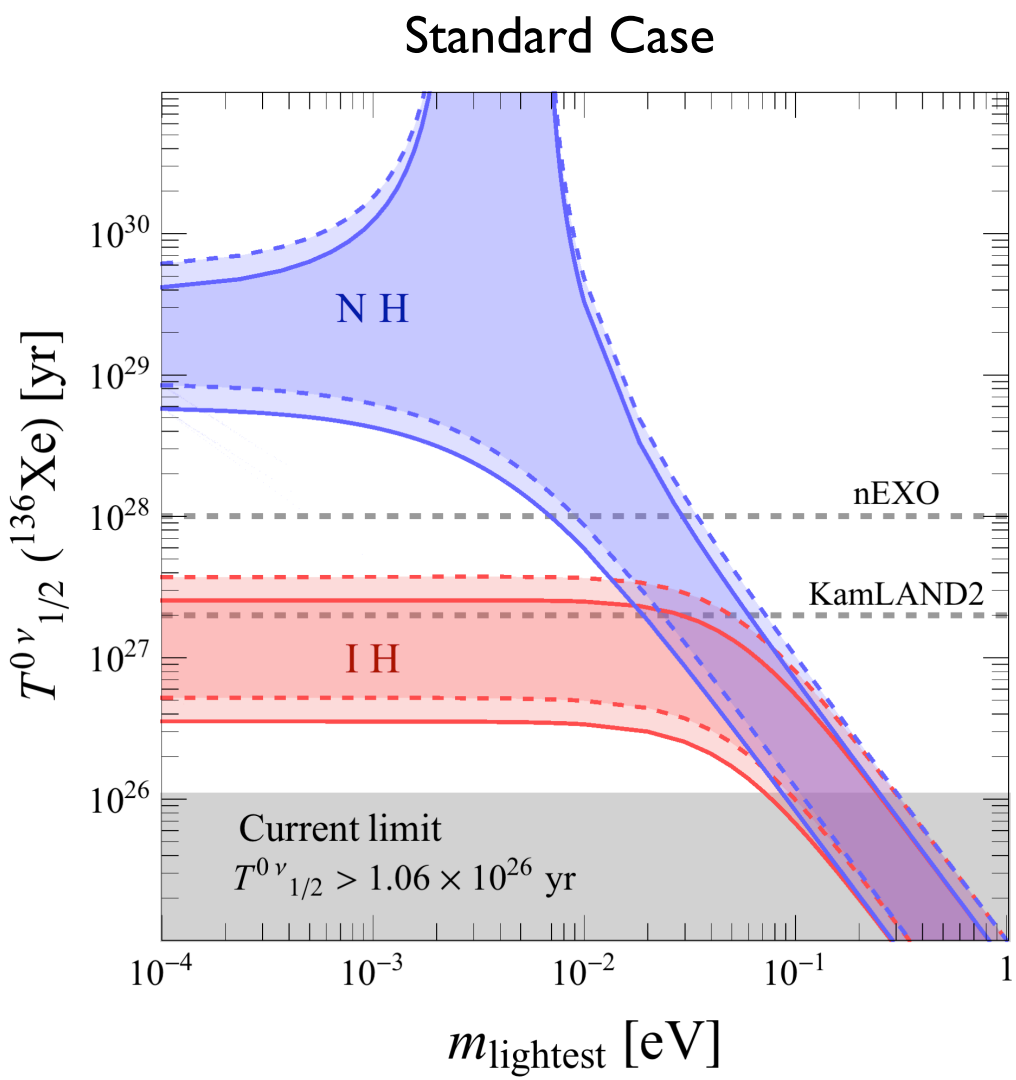
Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

Ruled out :

$$0.1 \text{ eV} \lesssim m_{\rm lightest}$$

Current limit on half-life



Normal Hierarchy (NH)

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Inverted Hierarchy (IH)

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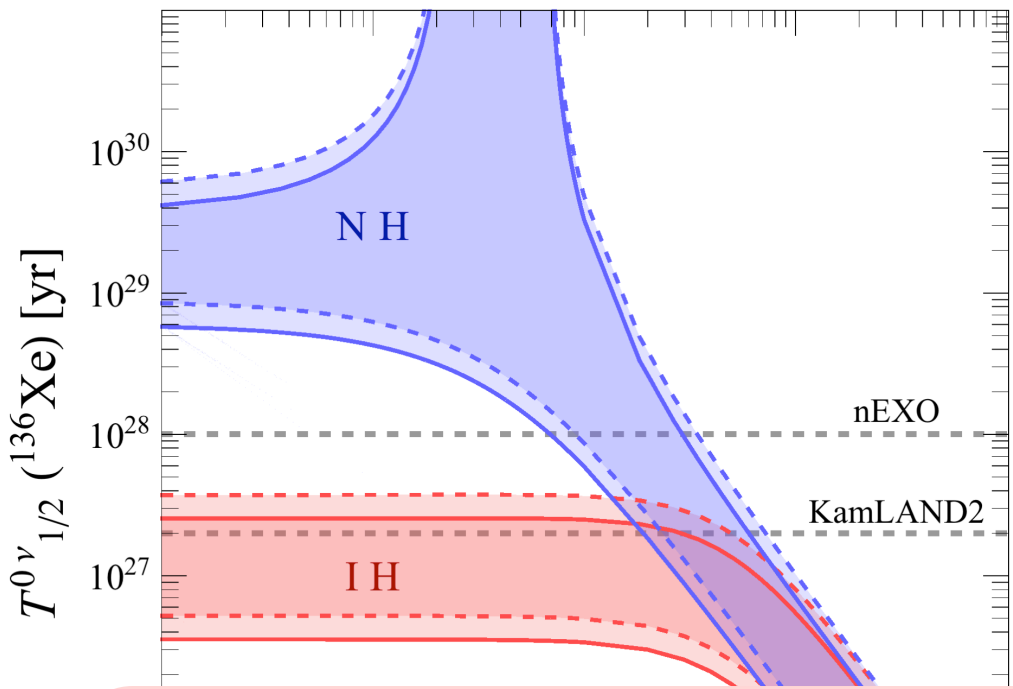
Future sensitivity

$\sim 10^{27}$ yr : KamLAND2-Zen

$\sim 10^{28}$ yr : nEXO

Current limit on half-life

Standard Case



Normal Hierarchy (NH)

$$m_1 < m_2 < m_3$$

Inverted Hierarchy (IH)

$$m_3 < m_1 < m_2$$

Future sensitivity

2-Zen

Standard case : Three light Majorana neutrinos $(M_R \gg v)$

What about light M_R case?

Beyond the standard case

For more details, see
M. Drewes, 1303.6912

Other phenomenological aspects:

M_R

$\gtrsim 10^9$ GeV

$\sim$ TeV

$\sim$ keV

$\sim$ eV

Wide mass range!

BAU

Thermal Leptogenesis

W. Buchmuller, et al ,Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

Resonant Leptogenesis

E. K. Akhmedov, et al, PRL81(1998)1359

DM

DM candidate

S. Dodelson, L. M. Widrow, PRL72(1994)17

Anomalies

Short-baseline neutrino oscillation

LSND : PRD64(2001)112007
MiniBooNE : PRL110(2013)161801 $\bar{\nu}_\mu \to \bar{\nu}_e$
Reactor anomaly : PRD83(2011)073006
MiniBooNE : PRL121(2018)221801 $\nu_\mu \to \nu_e$
PRL102(2009)101802

Beyond the standard case

For more details, see
M. Drewes, 1303.6912

* Need theoretical analysis in light of light sterile neutrinos

M_R

$\gtrsim 10^9$ GeV

$\sim$ TeV

$\sim$ keV

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BAU

Thermal Leptogenesis

W. Buchmuller, et al ,Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

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PRL102(2009)101802

Wide mass range!

Our study

- Model-independent analysis in the light ν_R scenario

  ~ Effective Field Theory

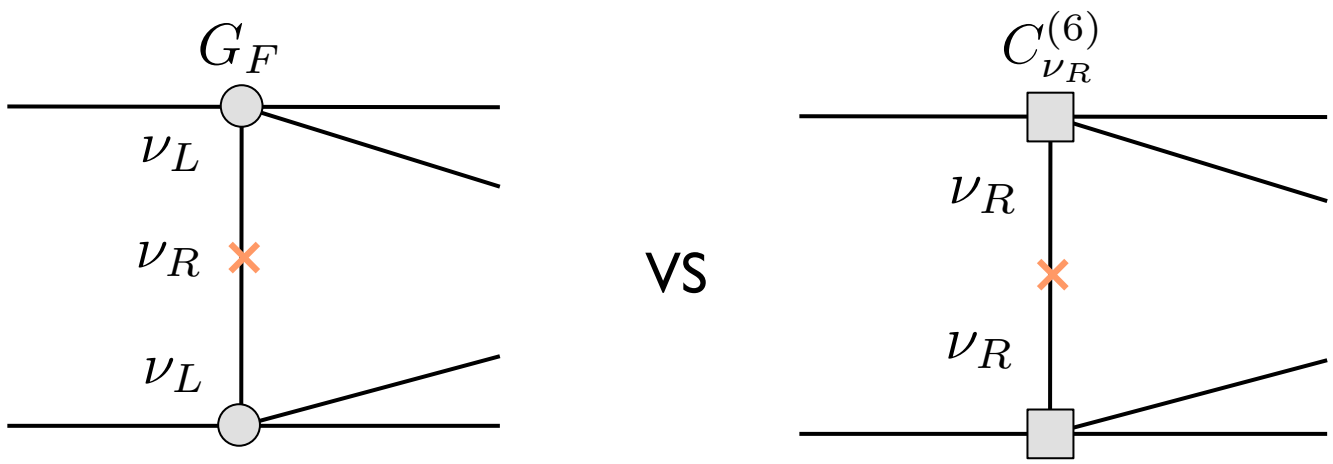
Our study

Model-independent analysis in the light ν_R scenario

~ Effective Field Theory

* Non-standard interactions (d = 6)

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \frac{1}{\Lambda^2} C_{\nu_R}^{(6)} \mathcal{O}^{(6)}$$



Our study

Model-independent analysis in the light ν_R scenario

~ Effective Field Theory

* Non-standard interactions (d = 6)

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \frac{1}{\Lambda^2} C_{\nu_R}^{(6)} \mathcal{O}^{(6)}$$

* Derive the master formula depending on M_R

Mass range : M_R

$\mathrm{eV} \longleftrightarrow 10^{15}\mathrm{GeV}$

Capture the behavior of light- and high-mass neutrino

SM + Light sterile neutrinos EFT

EFT approach

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 082(2017)
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 097(2018)

$\Lambda_{\rm new}$

~ 100 GeV

~ 1 GeV

~ 1 MeV

SM + sterile neutrino EFT

$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$

Neutrino mass

Integrate out heavy SM particles + ν_R (≥1GeV)

EFT approach

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)
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$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$

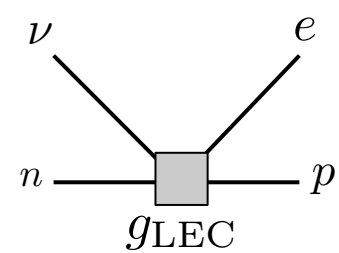
~ 100 GeV

Neutrino mass

Integrate out heavy SM particles + ν_R ($\geq$1 GeV)

~ 1 GeV

Chiral Perturbation Theory



~ 1 MeV

" Inverse half-life "

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left| \mathcal{A}_{0\nu 2\beta} \left(g_{\rm LEC}, C^{(6)}_{\nu_R}, M_{\rm NME} \right) \right|^2$$

$g_A = 1.27,\ G_{0\nu}$: Phase space factor

EFT approach

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)
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$\Lambda_{\rm new}$

SM + sterile neutrino EFT

$$\mathcal{L} = \mathcal{L}_{\rm SM+\nu_R} + \frac{1}{\Lambda^2} C^{(6)}_{\nu_R} \mathcal{O}^{(6)} + \cdots$$

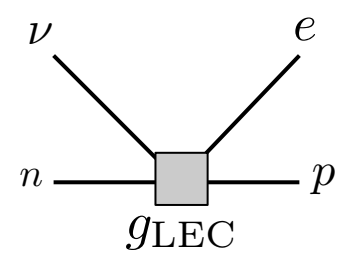
~ 100 GeV

Neutrino mass

Integrate out heavy SM particles + ν_R ($\geq$1 GeV)

~ 1 GeV

Chiral Perturbation Theory



~ 1 MeV

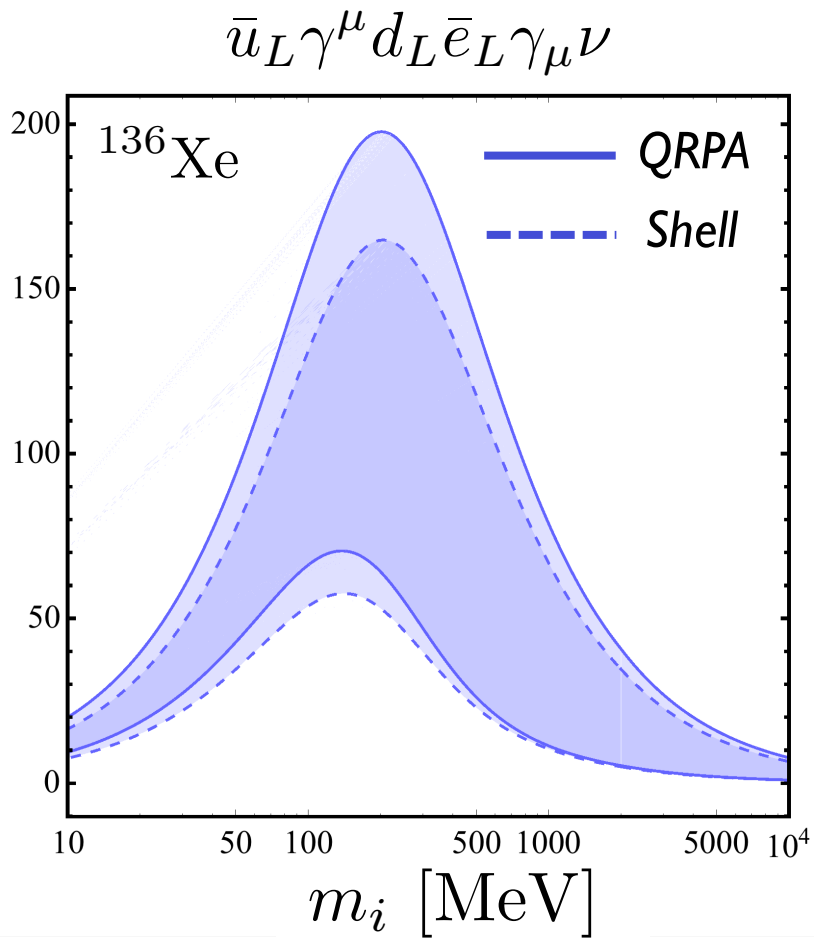
" Inverse half-life "

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 G_{0\nu} \left| \mathcal{A}_{0\nu 2\beta} \left(g_{\rm LEC}, C^{(6)}_{\nu_R}, M_{\rm NME} \right) \right|^2$$

"Interpolation formulae"

EFT approach

Mass dependence of the amplitude : $|\mathcal{A}_{0\nu 2\beta}(m_i)|_{^{136}\mathrm{Xe}}$



- Two different NMEs
- Peak around O(100) MeV

$$\frac{m_i}{q^2 + m_i^2}$$

O(100) MeV

- Similar behavior in literature

J.Barea, et al PRD92(2015)093001

- Large uncertainty in LECs

1. Standard interaction

2. Non-standard interaction

(Leptoquark)

3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \mathrm{H.C}$$

* Standard interactions

Mass matrix : $(M_\nu)_{i4,4i} \neq 0$

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ 0 & 0 & 0 & M_D^* \\ M_D^* & M_D^* & M_D^* & M_R \end{pmatrix}$$

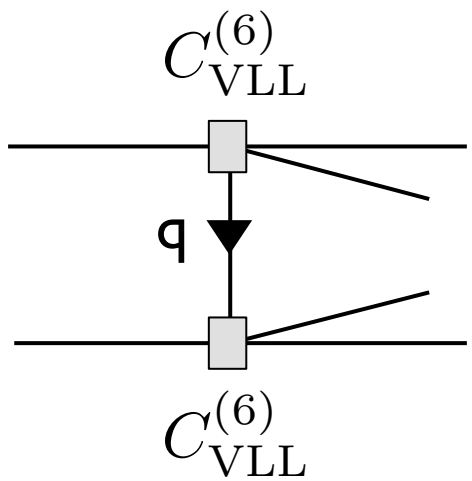
Yukawa

Majorana

3+1 scenario

One sterile neutrino : m_4

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\rm VLL} \nu \qquad C^{(6)}_{\rm VLL} = -2V_{ud}U_{ij}$$



$\mathrm{q} \sim O(100)\mathrm{MeV}$

For $\mathrm{q}^2 \gg m_i^2$

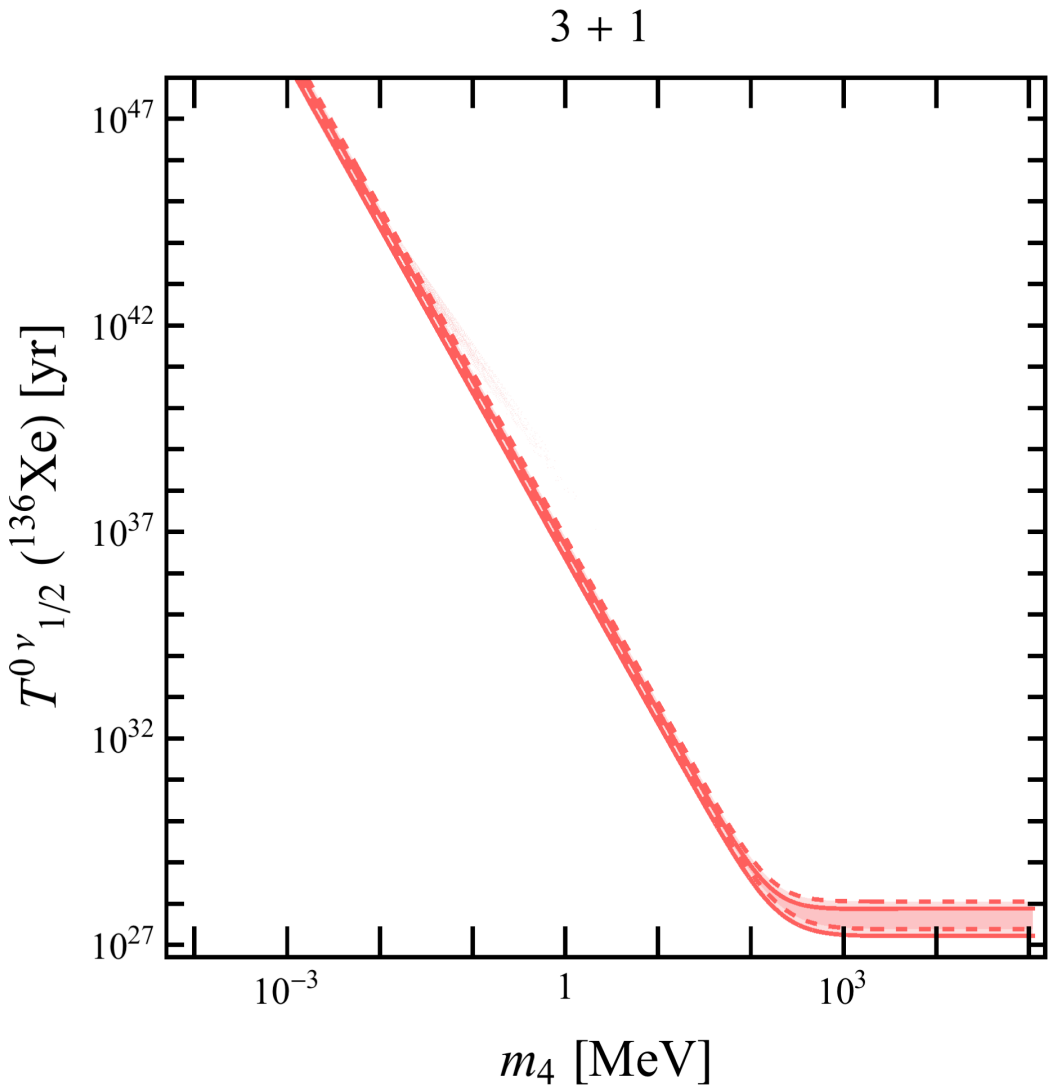
$$\sim \frac{m_i}{\mathrm{q}^2} U_{ei}^2 \left(1 + \frac{m_i^2}{\mathrm{q}^2} + \cdots\right)$$

LO vanishes

$$m_i U_{ei}^2 = (M_\nu)_{11} = 0$$

* Cancellation of LO contribution in light-mass region

m_4 vs Half-life (^{136}Xe)



The half-life is well above experimental reach.

1. Standard interaction

2. Non-standard interaction

(Leptoquark)

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos

Leptoquark

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Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos

Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\mathrm{LQ}} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$

Leptoquark

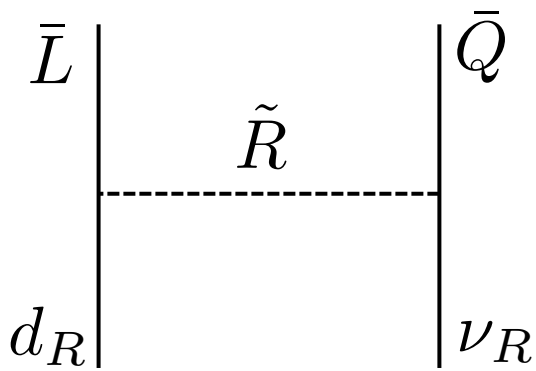
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos

Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\rm LQ} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$



Gauge-invariant dim6 operator:

$$\mathcal{L}^{(6)}_{\nu_R} = C^{(6)}_{LdQ\nu}\left(\bar{L}d_R\right)\epsilon\left(\bar{Q}\nu_R\right)$$

$$C^{(6)}_{LdQ\nu} = \frac{1}{m^2_{LQ}}y^{\overline{LR}}y^{RL*}$$

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
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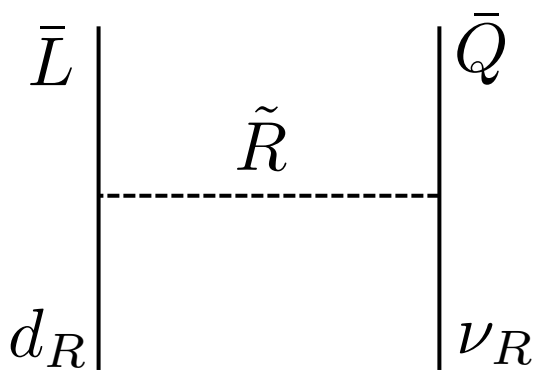


LQ parameters :

$$m_{\rm LQ} = 10\ {\rm TeV} \qquad y^{\overline{LR}}y^{RL*} = 1.0$$

Leptoquark

Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\mathrm{SRR}} \nu_i + \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\mathrm{TRR}} \nu_i\right]$$

$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu}\, U^*_{Ni} \qquad \begin{array}{l} N = 4 \\ i = 1 \sim 4 \end{array}$$

Leptoquark

Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\mathrm{SRR}} \nu_i + \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\mathrm{TRR}} \nu_i\right]$$

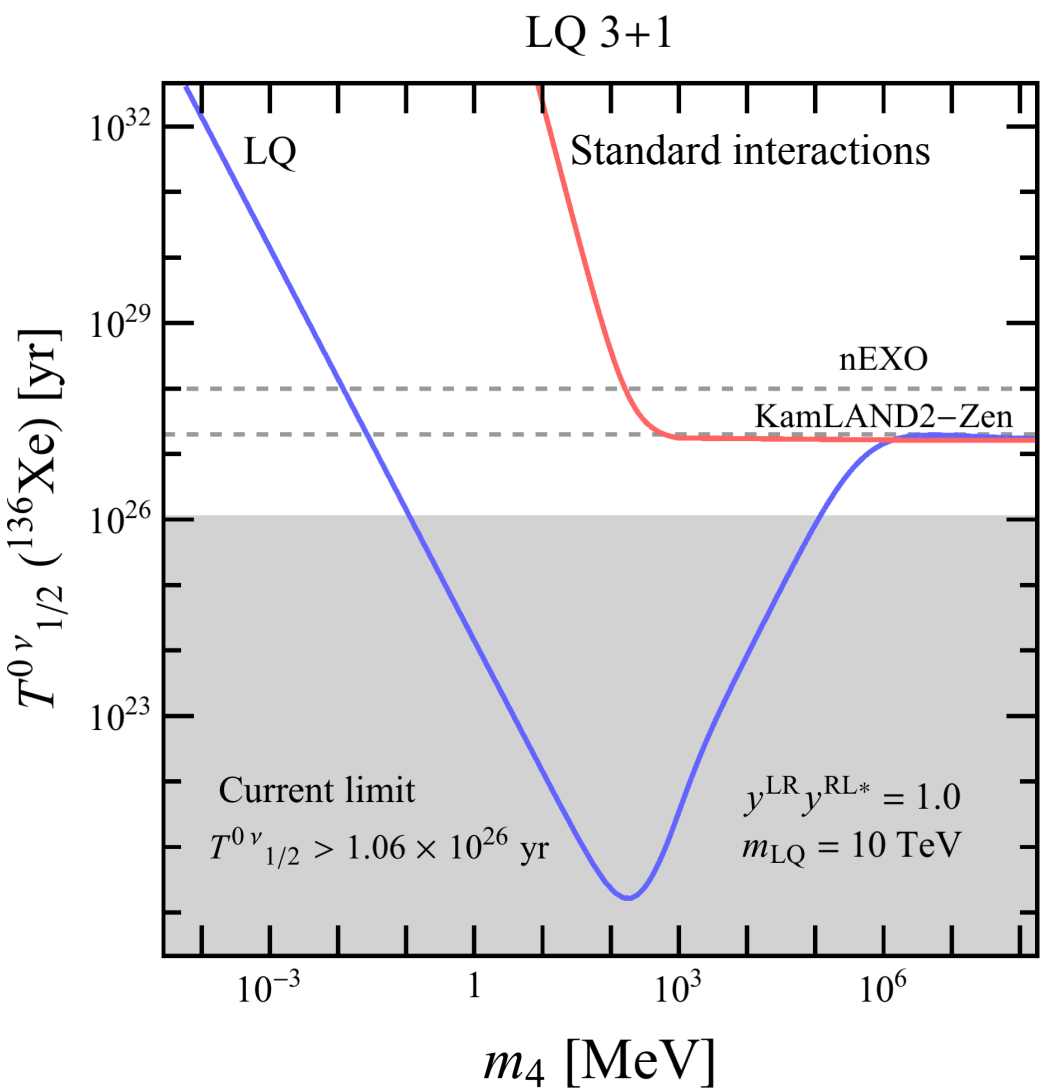
$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu}\, U^*_{Ni} \qquad \begin{array}{l} N = 4 \\ i = 1 \sim 4 \end{array}$$

$$+\frac{2G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu C^{(6)}_{\mathrm{VLL}} \nu$$

Induced by mixing
(No LQ interaction)

$$C^{(6)}_{\mathrm{VLL}} = -2V_{ud} U_{ij} \qquad i = 1 \sim 3,\ j = 1 \sim 4$$

3+1 : m_4 vs Half-life

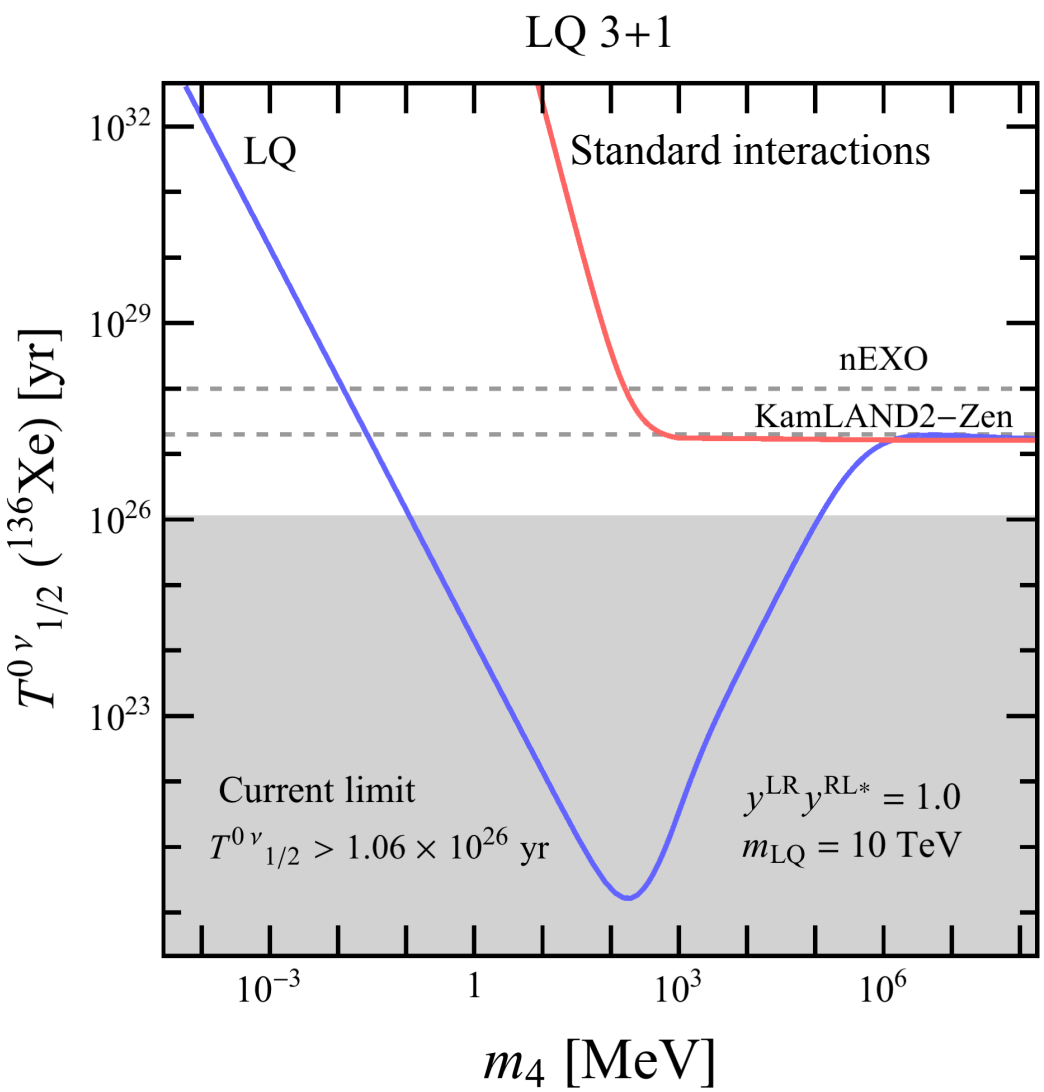


Blue : LQ interaction

Pink : No LQ interaction (vector contribution)

* LQ interactions dominate over standard contributions.

3+1 : m_4 vs Half-life



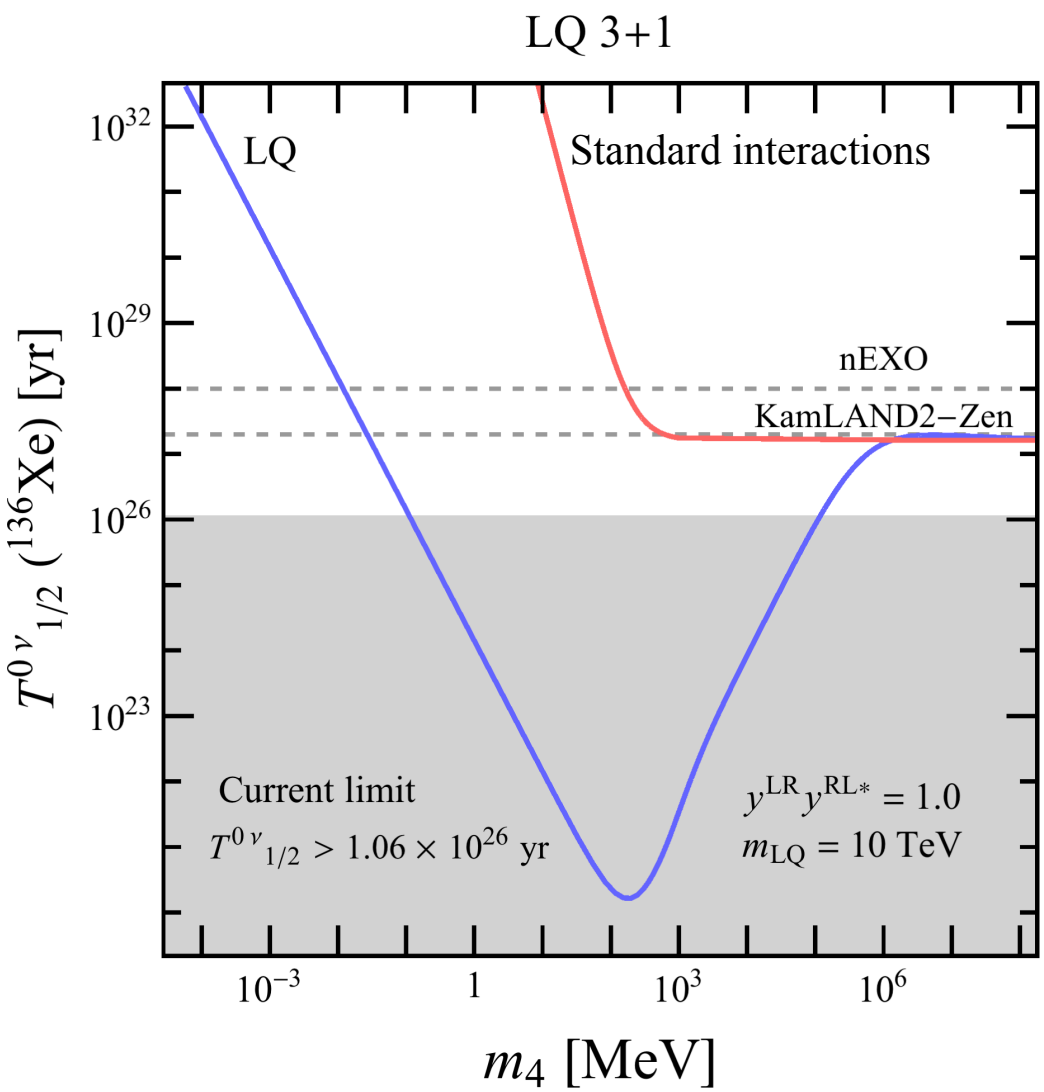
Blue : LQ interaction

Pink : No LQ interaction (vector contribution)

Ruled out

$$0.1 \text{ MeV} \lesssim m_4 \lesssim 100 \text{ GeV}$$

3+1 : m_4 vs Half-life



Future sensitivity

$\sim 10^{27}$ yr : KamLAND2-Zen

$\sim 10^{28}$ yr : nEXO

$$m_4 \gtrsim 10 \text{ keV}$$

Tau to e transition

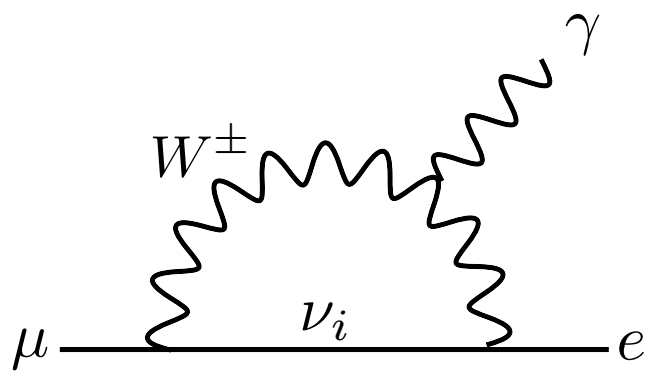
CLFV

Nonzero neutrino mass induces CLFV.

Ex) Minimal extension of the SM

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

Dirac or Majorana



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

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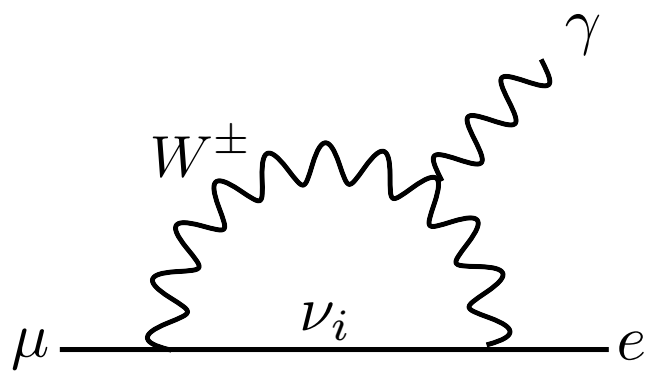


Petcov '77, Marciano-Sanda '77 ....

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

Extremely small!

The predicted BR is too small to be observed.

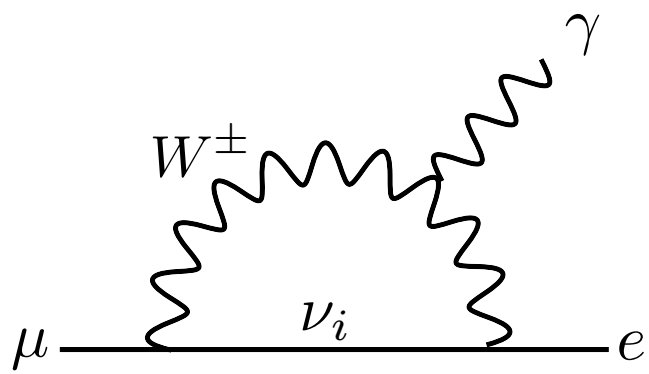
CLFV

Nonzero neutrino mass induces CLFV.

Ex) Minimal extension of the SM

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

Dirac or Majorana



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

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

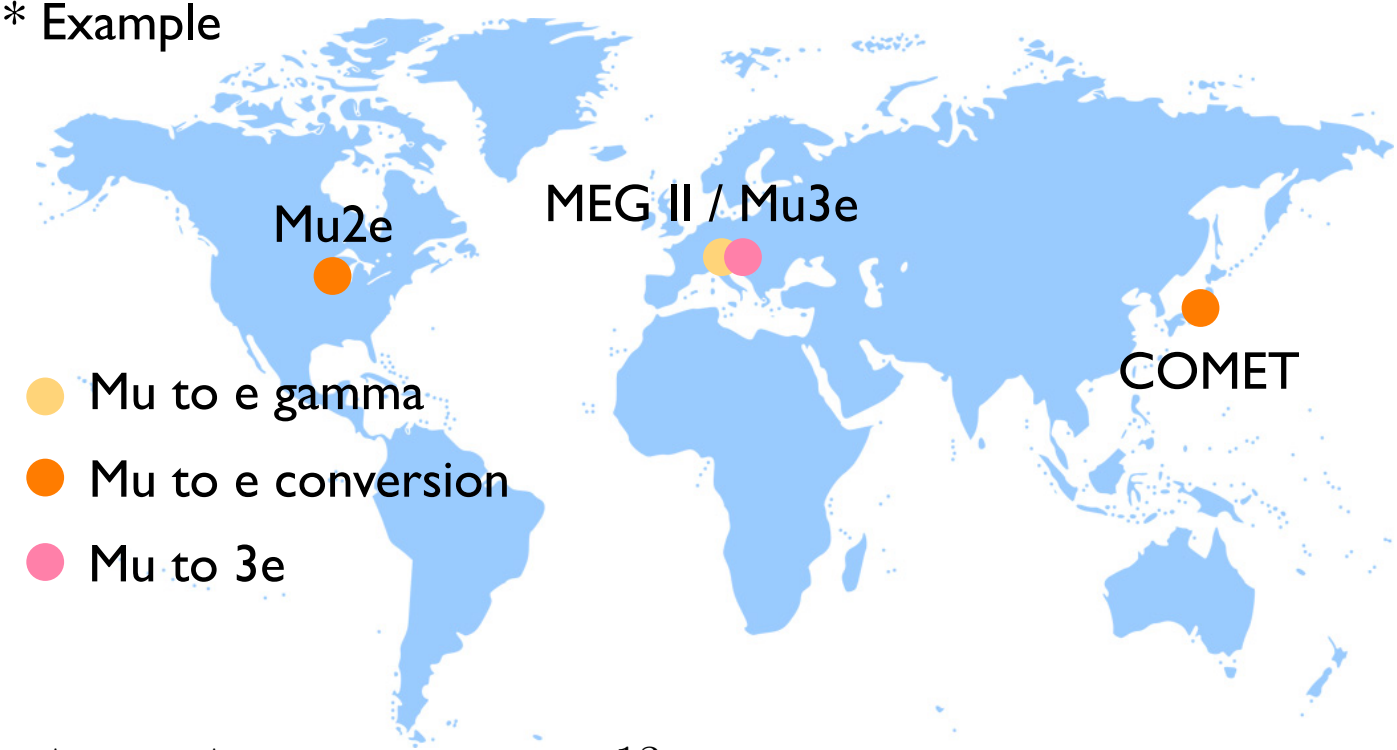
Extremely small!

The observation of CLFV would imply another contribution.

Present searches

CLFV searches have been ongoing.

* Example



$$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$ MEG Collaboration, Eur. Phys. J. C 76(8), 434 (2016).

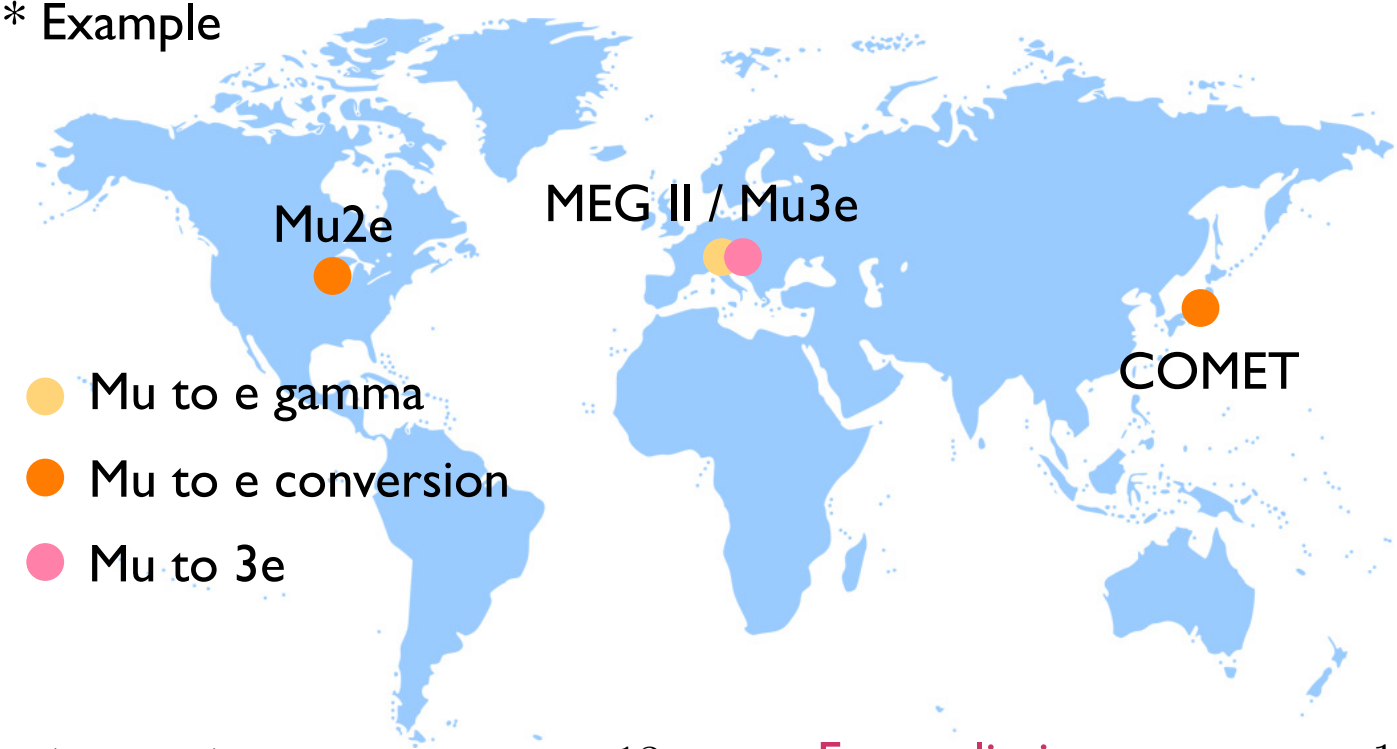
$$\mathrm{BR}(\mu^- \ \mathrm{Au} \to e^- \ \mathrm{Au}) < 7 \times 10^{-13}$$ SINDRUM II, Eur. Phys. J. C 47(2), 337–346 (2006).

$$\mathrm{BR}(\mu^+ \to e^+e^-e^+) < 1 \times 10^{-12}$$ SINDRUM, Nucl.Phys.B 299 (1988) 1-6

Present searches

CLFV searches have been ongoing.

* Example

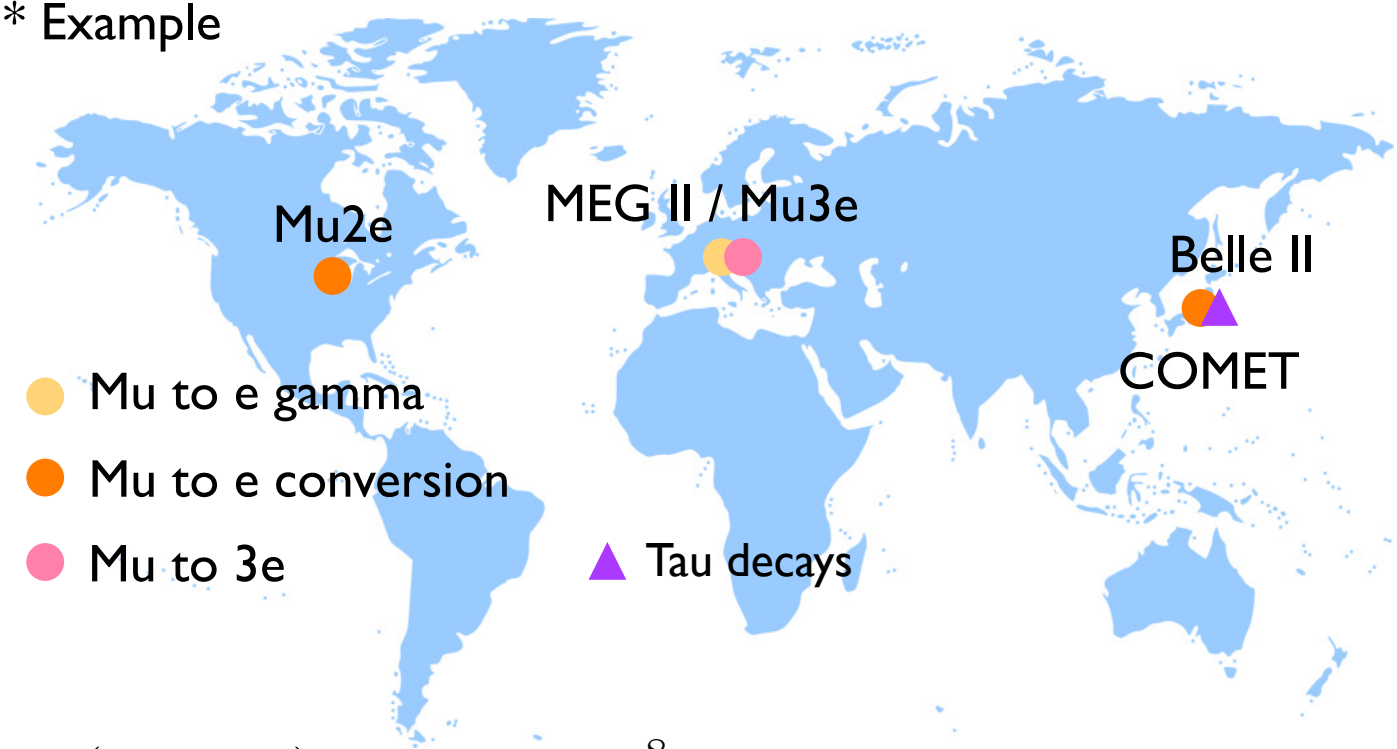


		Future limit
$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$	→	$< 6 \times 10^{-14}$
$\mathrm{BR}(\mu^- \ \mathrm{Au} \to e^- \ \mathrm{Au}) < 7 \times 10^{-13}$	→	$< 3 \times 10^{-17}$
$\mathrm{BR}(\mu^+ \to e^+e^-e^+) < 1 \times 10^{-12}$	→	$< 2 \times 10^{-15}$

Present searches

CLFV searches have been ongoing.

* Example



$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$ BaBar, Phys.Rev.Lett. 104 (2010) 021802

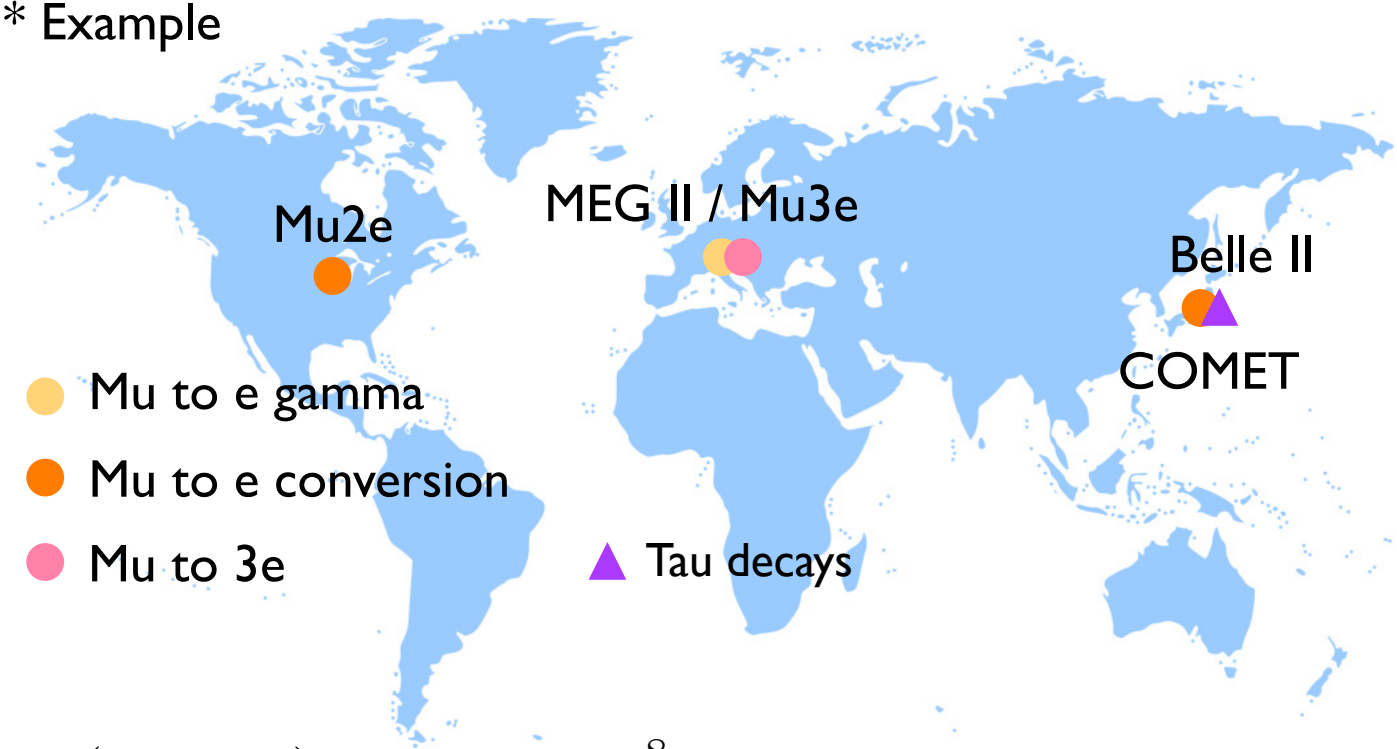
$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$ Belle, Phys.Lett.B 719 (2013) 346-353

$$\mathrm{BR}(\tau \to e\pi^0) < 8 \times 10^{-8}$$ Belle, Phys.Lett.B 648 (2007) 341-350

Present searches

CLFV searches have been ongoing.

* Example



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

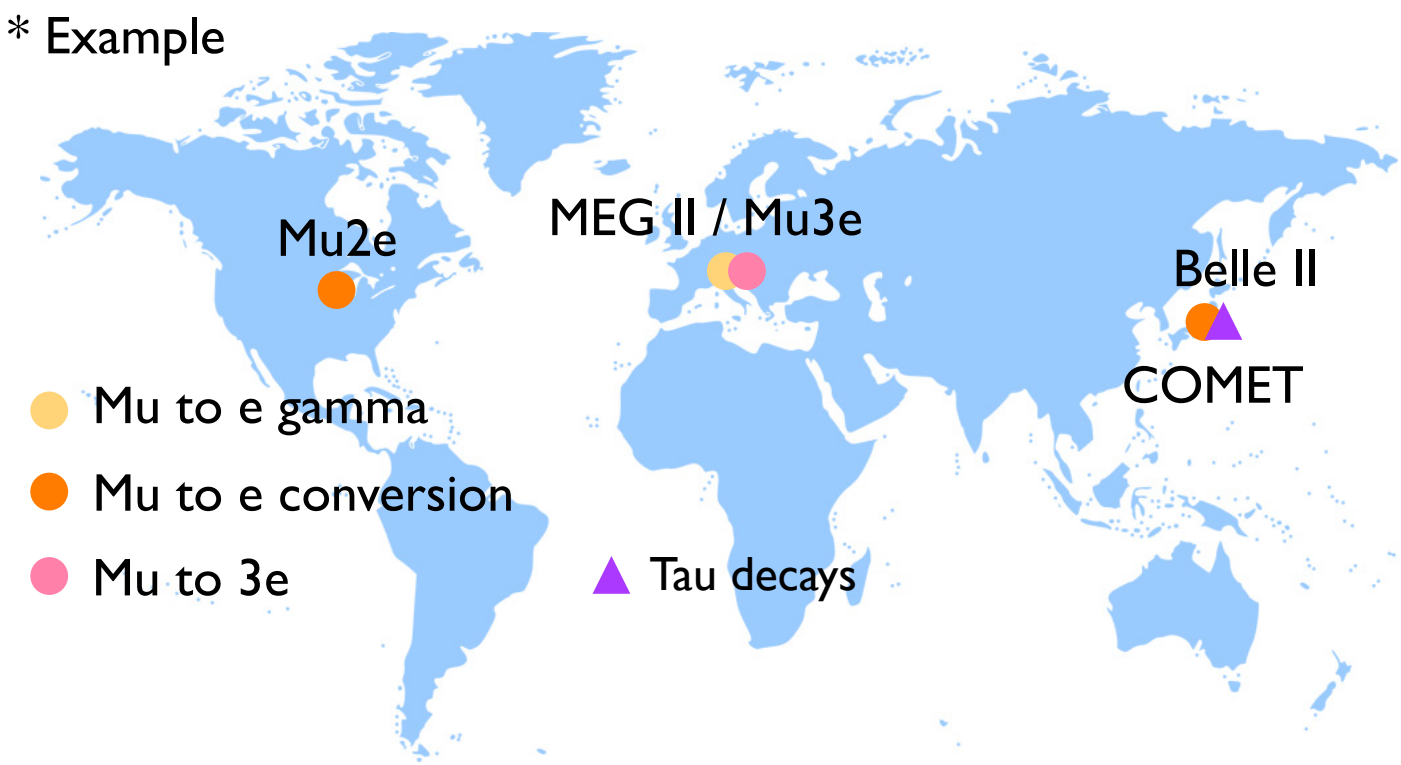
$$\mathrm{BR}(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8}$$

$$\mathrm{BR}(\tau \to e\pi^0) < 8 \times 10^{-8}$$

Semileptonic tau decays

Present searches

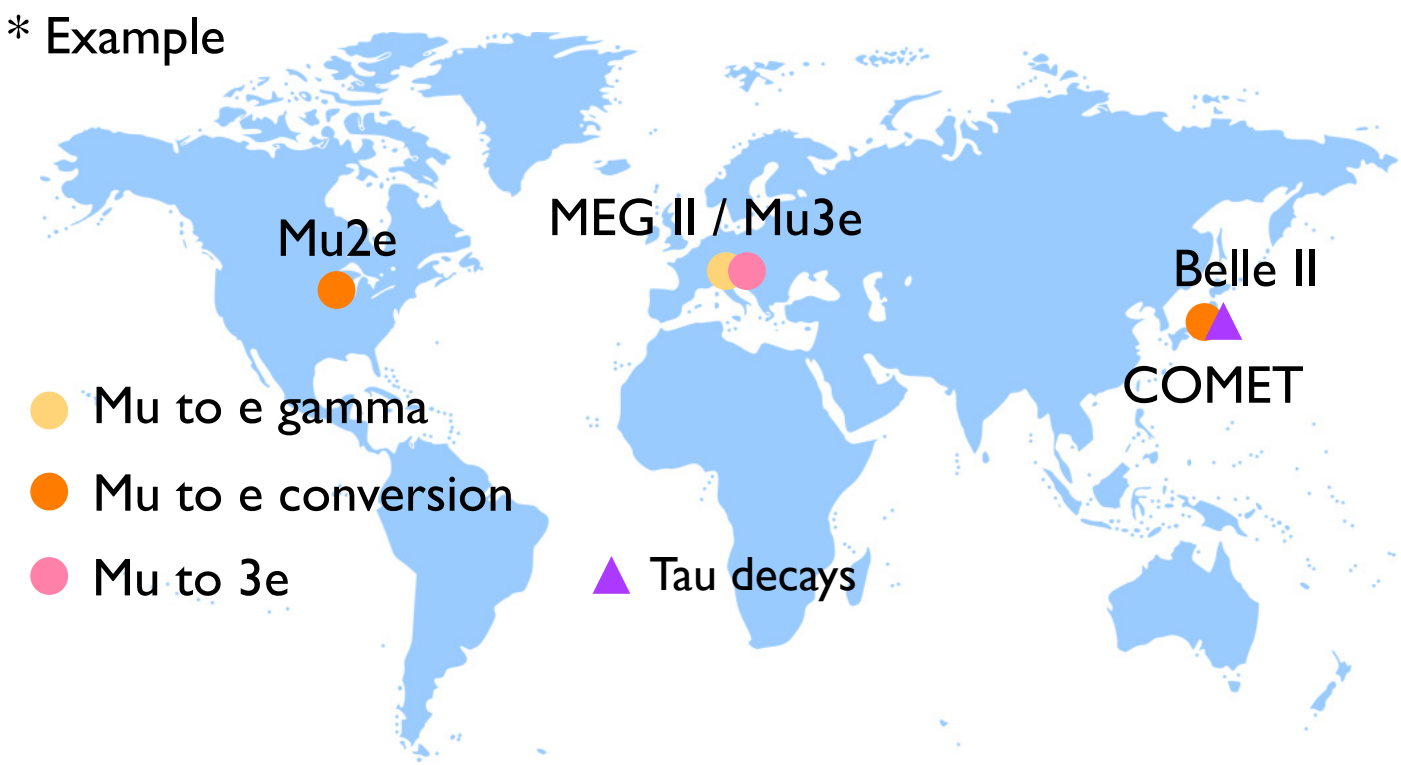
CLFV searches have been ongoing.



Tau-e LFV : Weaker constraints
Rich variety of LFV tau decays

Present searches

CLFV searches have been ongoing.



Tau-e LFV : BR ~ $O(10^{-(9-10)})$ at Belle II

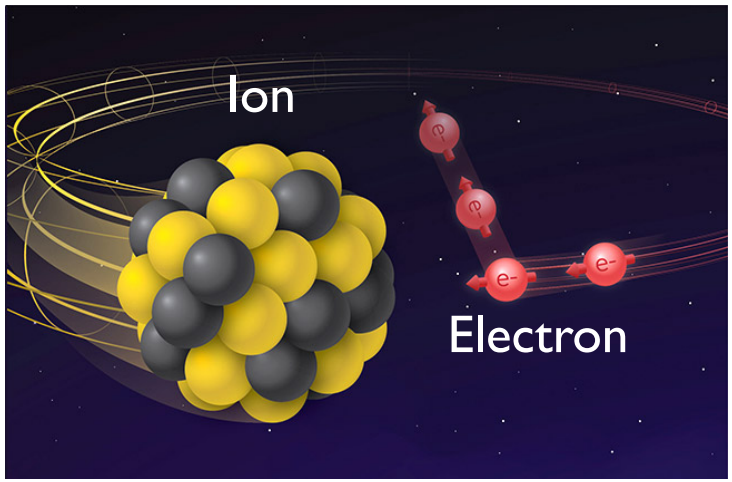
What about high-energy probes?

Electron-Ion Collider

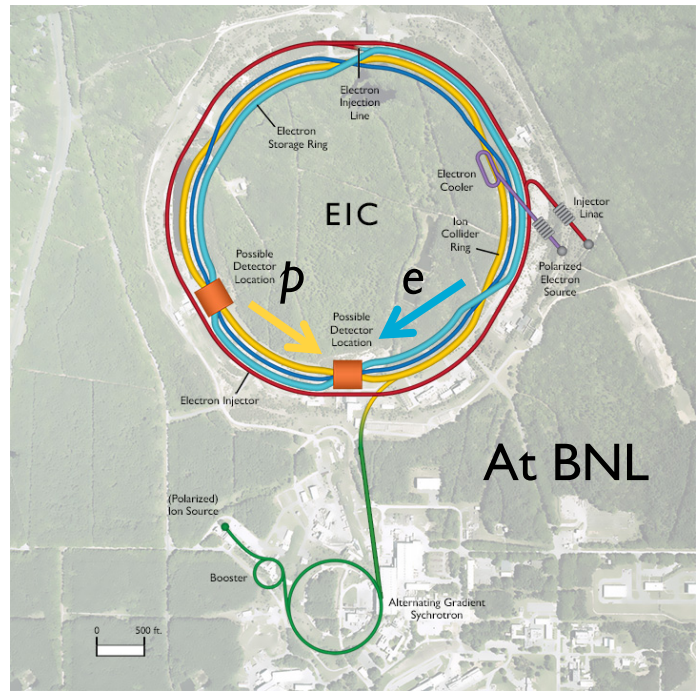
EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

One potential probe : LFV search at the EIC

DOE granted CD-0 to the EIC on January 9, 2020.



Collide electrons and protons/heavy ions



Map the structure of the proton and nuclei

Electron-Ion Collider

EIC Detector Requirements and R&D Handbook
EIC Yellow report, arXiv:2103.05419

- Electrons - protons/heavy ions collisions

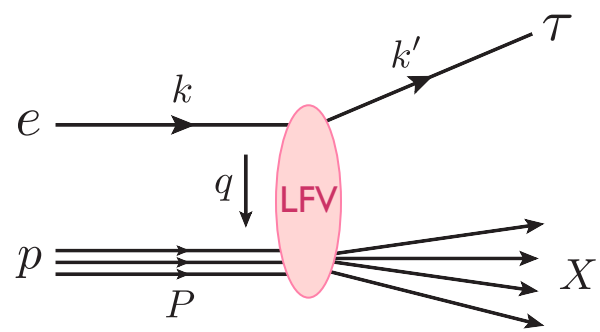
$$\sqrt{S} = 20 \sim 100 \text{ GeV} \quad (\text{Upgradable to } 140 \text{ GeV})$$

- Polarized electron (~70%) and proton (~70%) beams

- High Luminosity

$$\mathcal{L} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$$

(10-100 fb^{-1} per year)



(e.g. HERA $\sqrt{S} = 318 \text{ GeV}, \ \mathcal{L} = 1.4 \times 10^{31} \text{ cm}^{-1}\text{s}^{-1}$)

Another opportunity to search for ep → τ X

Our study

ArXiv: 2102.06176
V. Cirigliano, KF, C. Lee, E. Mereghetti, B. Yan (LANL)

Study the possibility to probe e-tau LFV at the EIC

* Tau-e interactions in SMEFT (d = 6)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2} C_{\tau e}^{(6)} \mathcal{O}^{(6)}$$

Tau-e LFV interaction

Our study

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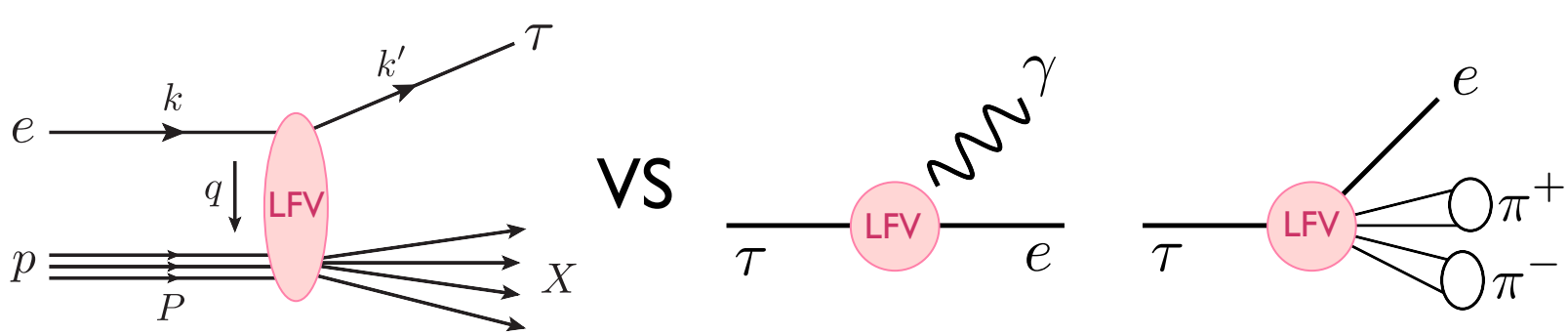
Tau-e LFV interaction

* Current limits on tau-e operators



EFT approach

Total : 16 different LFV operators

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

X : Gauge boson ψ : Fermion φ : Higgs

Results

Total : 16 different LFV operators

Ex) Dipole, Yukawa and 4F vector operators

$$\mathcal{L}_{\rm LFV} \supset -\frac{e}{2v}\left(\Gamma^e_\gamma\right)_{\tau e}\bar{\tau}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$$

Photon dipole

$$-\frac{4G_F}{\sqrt{2}}[C_{Lu}]_{cc}\bar{\tau}_L\gamma^\mu e_L\bar{c}_R\gamma_\mu c_R$$

VLR : cc element

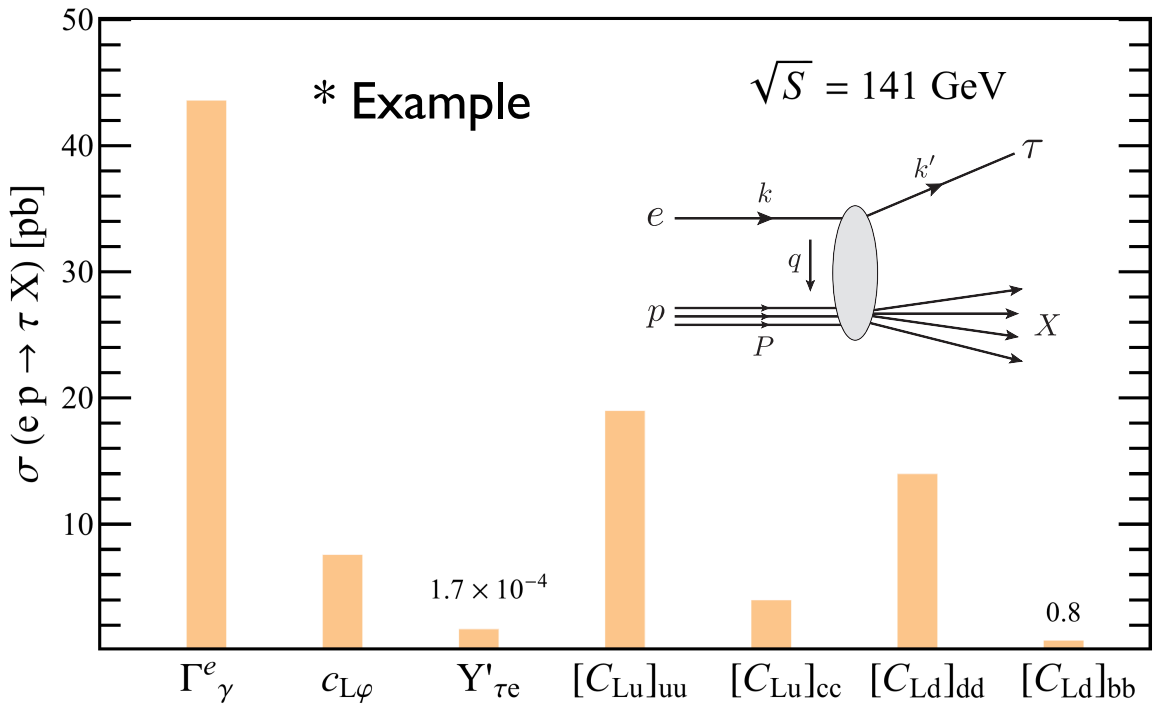
$$-\frac{4G_F}{\sqrt{2}}[C_{Ld}]_{bb}\bar{\tau}_L\gamma^\mu e_L\bar{b}_R\gamma_\mu b_R$$

VLR : bb element

* Single-operator analysis

EIC analysis

Unpolarized cross sections at LO in QCD (C=1)



- Mostly pb range
- Heavy quarks suppressed by PDF

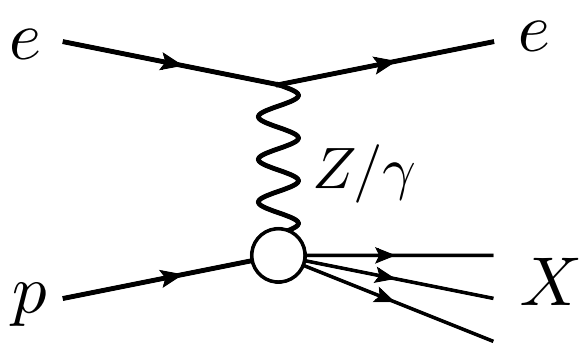
  Larger PDF/scale uncertainties, e.g. 0.8 (0.5) pb for $[C_{Ld}]_{bb}$

EIC analysis

- Major backgrounds

1) Neutral Current : $ep \to ej$

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

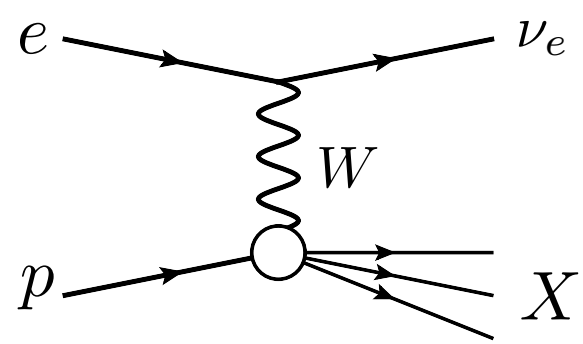


- Tau decays

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

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

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



✔ Consider simple cuts to enhance efficiencies

LFV tau and meson decays

Limits on quark-flavor conserving operators

Decay mode	Upper limit (90% C.L.)
$\tau \to e\gamma$	3.3×10^{-8}
$\tau \to e\pi^+\pi^-$	2.3×10^{-8}
$\tau \to e\pi^0$	8.0×10^{-8}
$\tau \to e\eta$	9.2×10^{-8}
$\tau \to e\eta'$	1.6×10^{-7}
$\tau \to ee^+e^-$	2.7×10^{-8}
$\tau \to e\mu^+\mu^-$	2.7×10^{-8}

BR ~ O(10^{-8})

PDG, PTEP2020 (2020) 083C01.

LFV tau and meson decays

Limits on quark-flavor conserving operators

	Decay mode	Upper limit (90% C.L.)
	$\tau \to e\gamma$	3.3×10^{-8}
Semileptonic (uu/dd/ss)	$\tau \to e\pi^+\pi^-$	2.3×10^{-8}
	$\tau \to e\pi^0$	8.0×10^{-8}
	$\tau \to e\eta$	9.2×10^{-8}
	$\tau \to e\eta'$	1.6×10^{-7}
Leptonic	$\tau \to ee^+e^-$	2.7×10^{-8}
	$\tau \to e\mu^+\mu^-$	2.7×10^{-8}

PDG, PTEP2020 (2020) 083C01.

LFV tau and meson decays

Limits on quark-flavor conserving operators

Decay mode	Upper limit (90% C.L.)
$\tau \to e\gamma$	3.3×10^{-8}
[illegible]	[illegible]
$\tau \to e\eta$	1.6×10 [illegible]
$\tau \to ee^+e^-$	2.7×10^{-8}
$\tau \to e\mu^+\mu^-$	2.7×10^{-8}

What about heavy-quark operators?

Scale running effects based on the RGEs

PDG, PTEP2020 (2020) 083C01.

Scale running effects

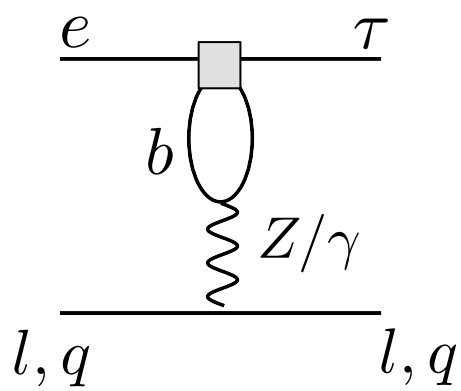
Scale

Λ

GeV

Running to low energy based on the RGEs

Ex) $\mathcal{L}_{\rm LFV} \supset [C_{ed}]_{bb} \bar{\tau}_R \gamma^\mu e_R \bar{b}_R \gamma_\mu b_R$



* Suppression factor ~ 10^{-3}

$$[C_{eu}]_{uu},\ [C_{ed}]_{dd},\ [C_{ee}]_{ll} \sim \frac{g^2}{(4\pi)^2}[C_{ed}]_{bb}$$

Can by constrained by low-energy tau decays!

LEP and LHC

- Z decay $\mathrm{BR}(Z \to \tau e) < 8.1 \times 10^{-6}\ (95\%\mathrm{C.L.})$

OPAL collaboration, Phys. C 67 (1995) 555{564).

- Higgs decay $\mathrm{BR}(H \to e^- \tau^+ + \tau^- e^+) < 4.7 \times 10^{-3}\ (95\%\mathrm{C.L.})$

ATLAS collaboration, PLB 800 (2020) 135069

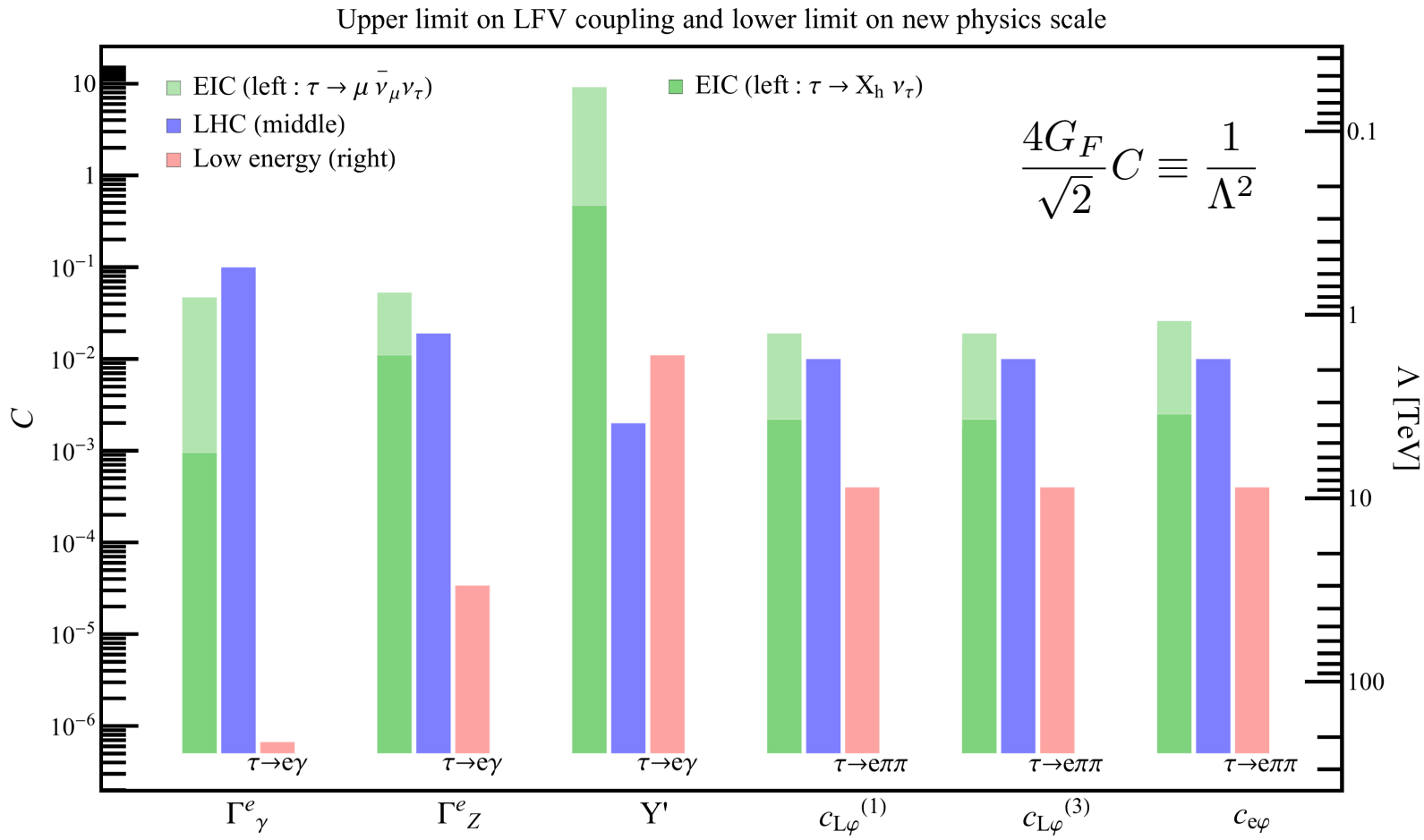
- Top decay $\mathrm{BR}(t \to q\ell\ell') < 1.86 \times 10^{-5}\ (95\%\mathrm{C.L.})$

ATLAS collaboration, ATLAS-CONF-2018-044

- ATLAS Search $pp \to \tau e$ PRD98(2018)092008, [1807.06573]
Eur. Phys. J. C 76 (2016) 541, [1607.08079].

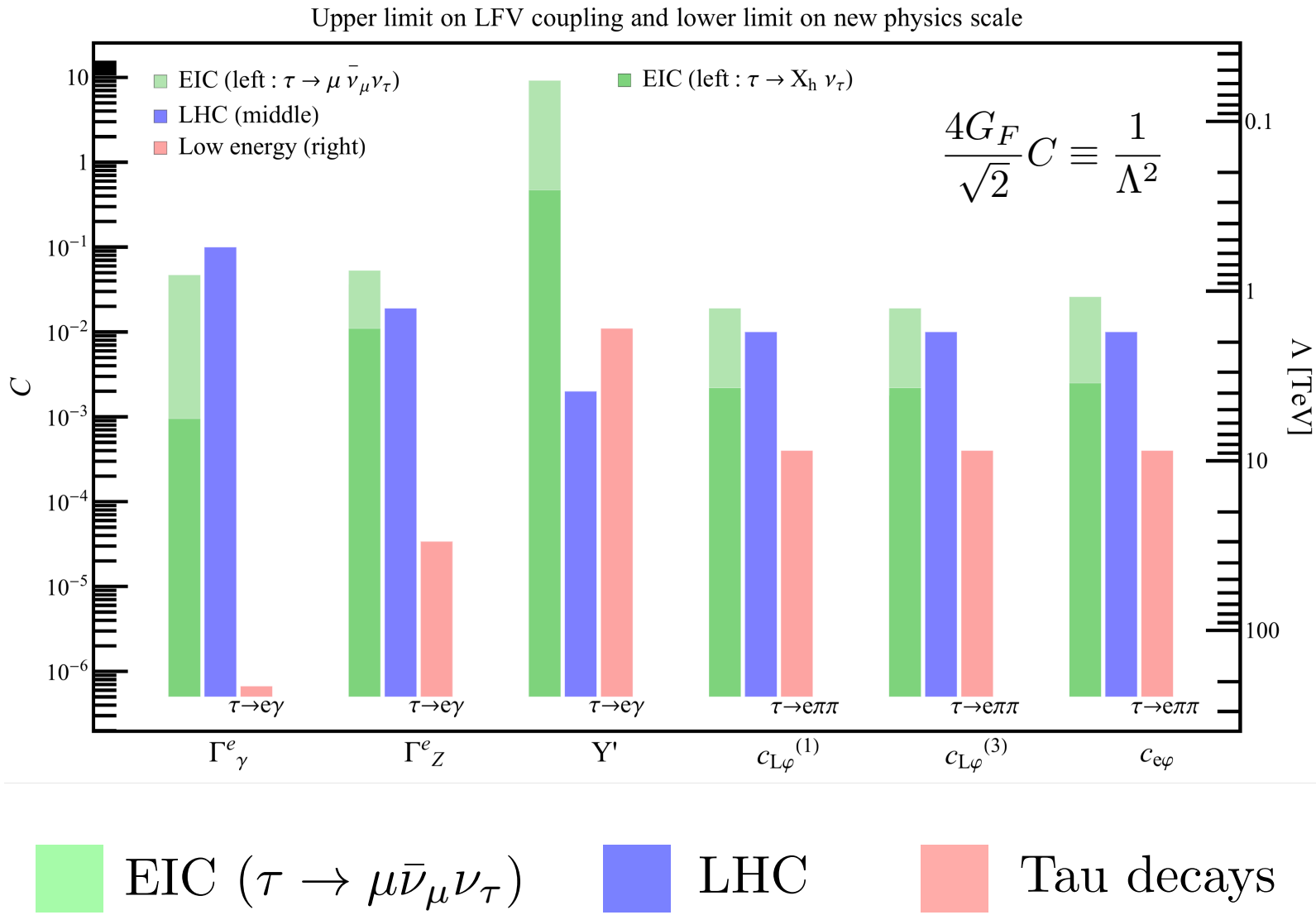
✔ Bound up-type flavor-violating operators

Dipole operator



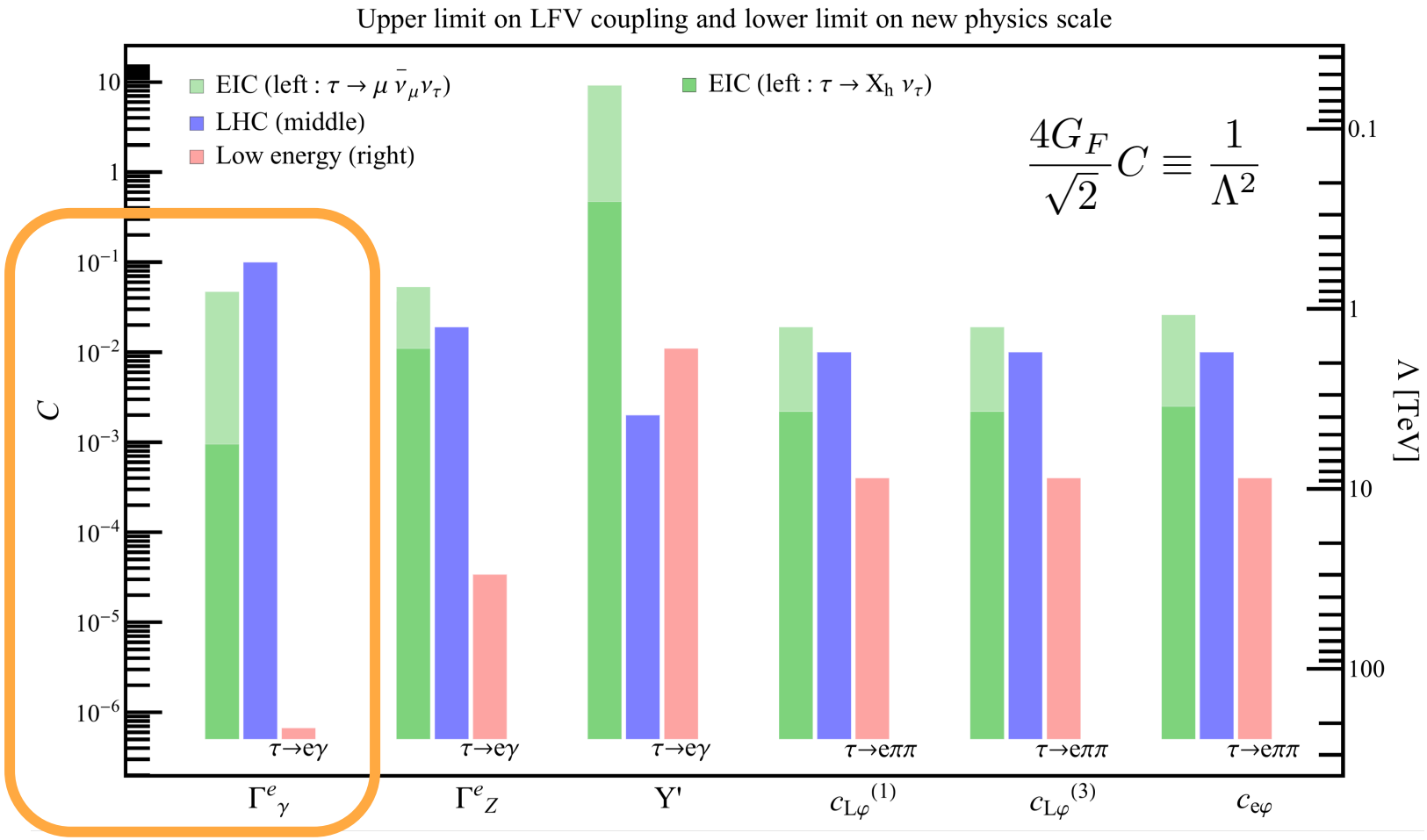
Leftmost (Rightmost) axis : Limit on operator (Λ)

Dipole operator



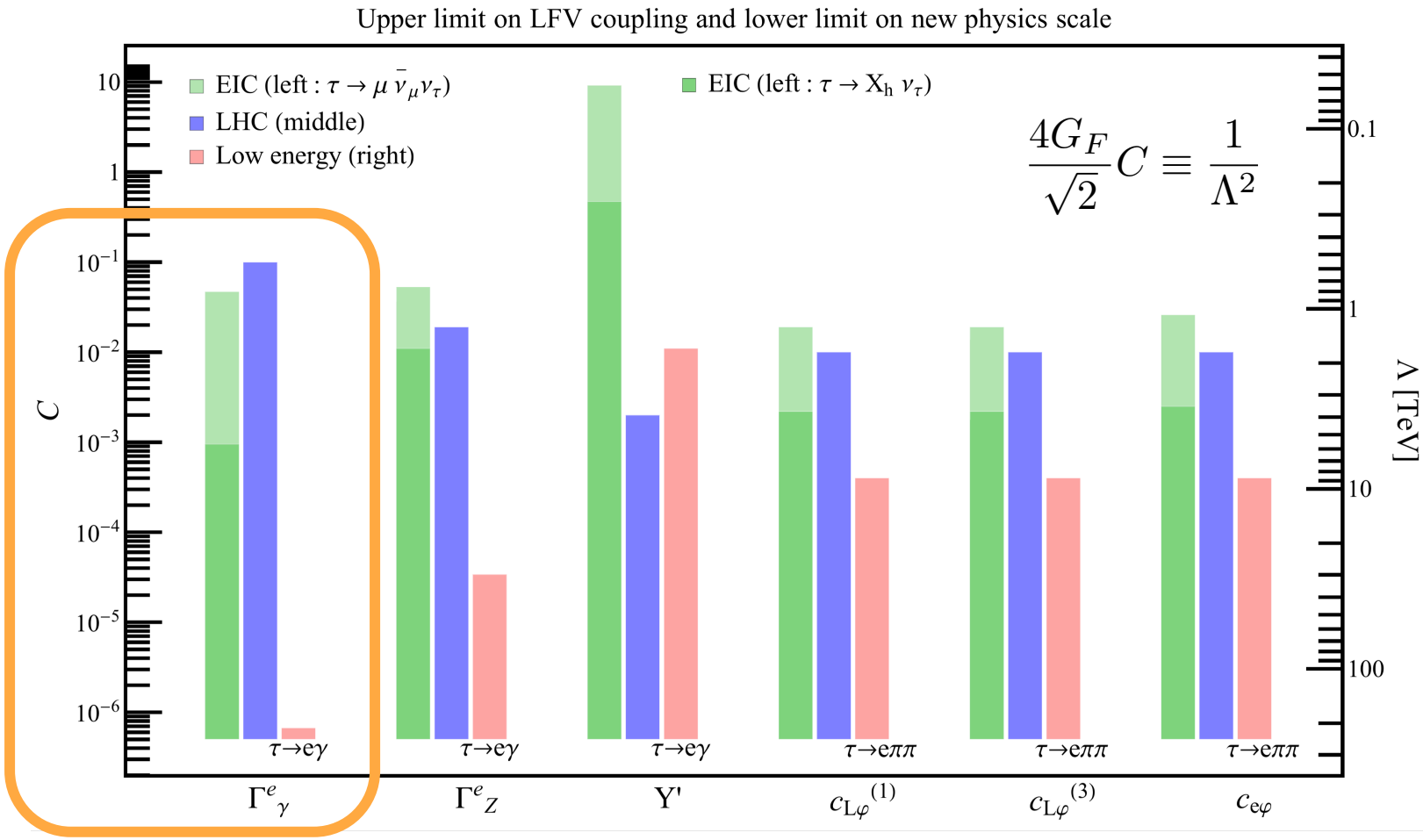
EIC $(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$ LHC Tau decays

Dipole operator



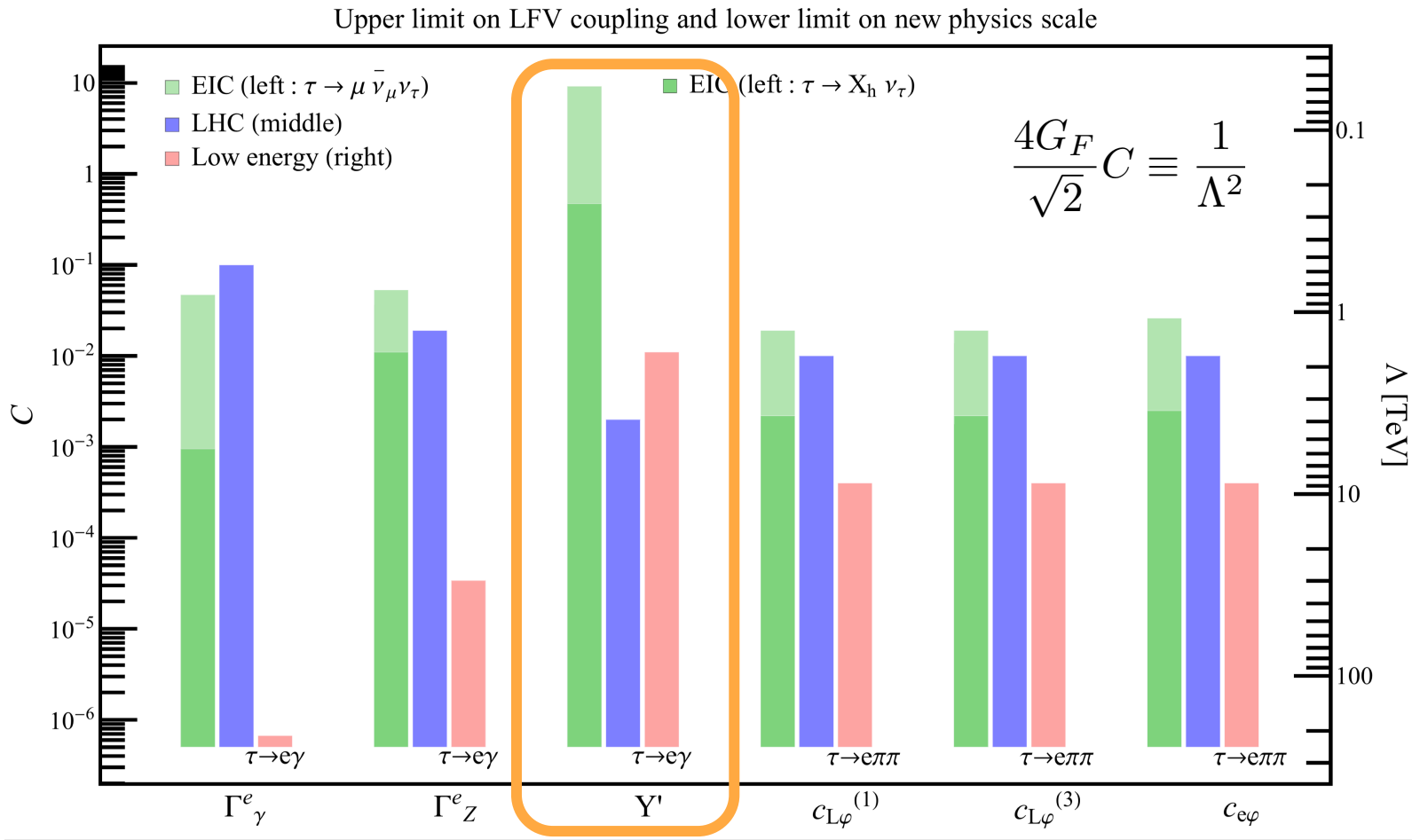
EIC, LHC : $\Gamma^e_\gamma \lesssim 0.1$ Tau e gamma : $\Gamma^e_\gamma < 6.7 \times 10^{-7}$

Dipole operator



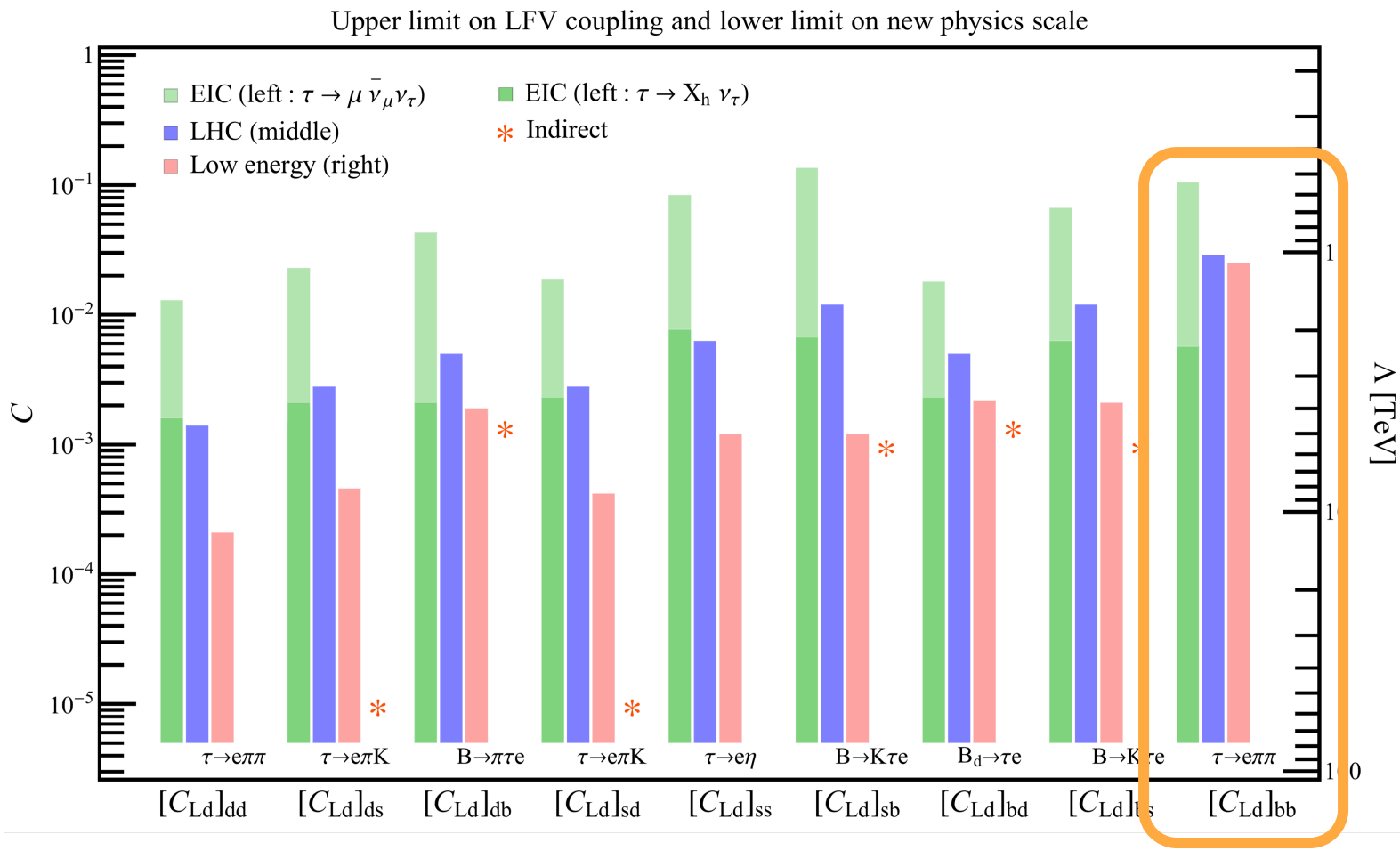
EIC, LHC : $\Gamma^e_\gamma \lesssim 0.1$ Tau e gamma : $\Lambda \gtrsim 200$ TeV

Yukawa



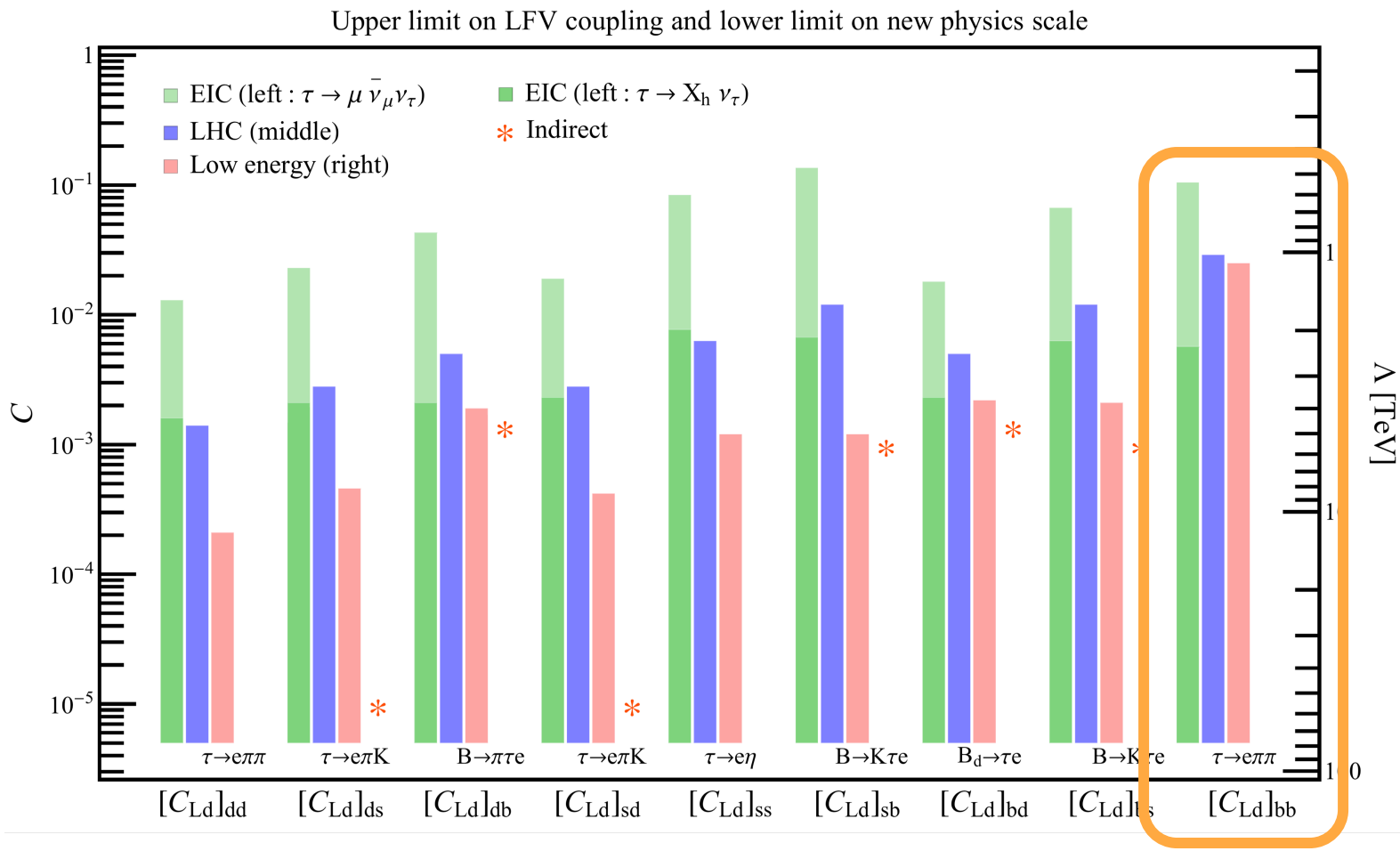
LHC : $[Y'_e]_{\tau e} < 2 \times 10^{-3}$ Tau e gamma : $[Y'_e]_{\tau e} < 1.1 \times 10^{-2}$

VLR bottom



EIC : $[C_{Ld}]_{bb} < 0.1$ LHC, Tau decay : $[C_{Ld}]_{bb} < O(10^{-2})$

VLR bottom



Dark Green

$$\text{EIC } (\tau \to X_h \nu_\tau) \quad [C_{Ld}]_{bb} < 6.8 \times 10^{-3} \ (\epsilon = 1)$$

Multi-operator scenario

See the situation where 8 operators are nonzero

* Z couplings + down-type 4F operators

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

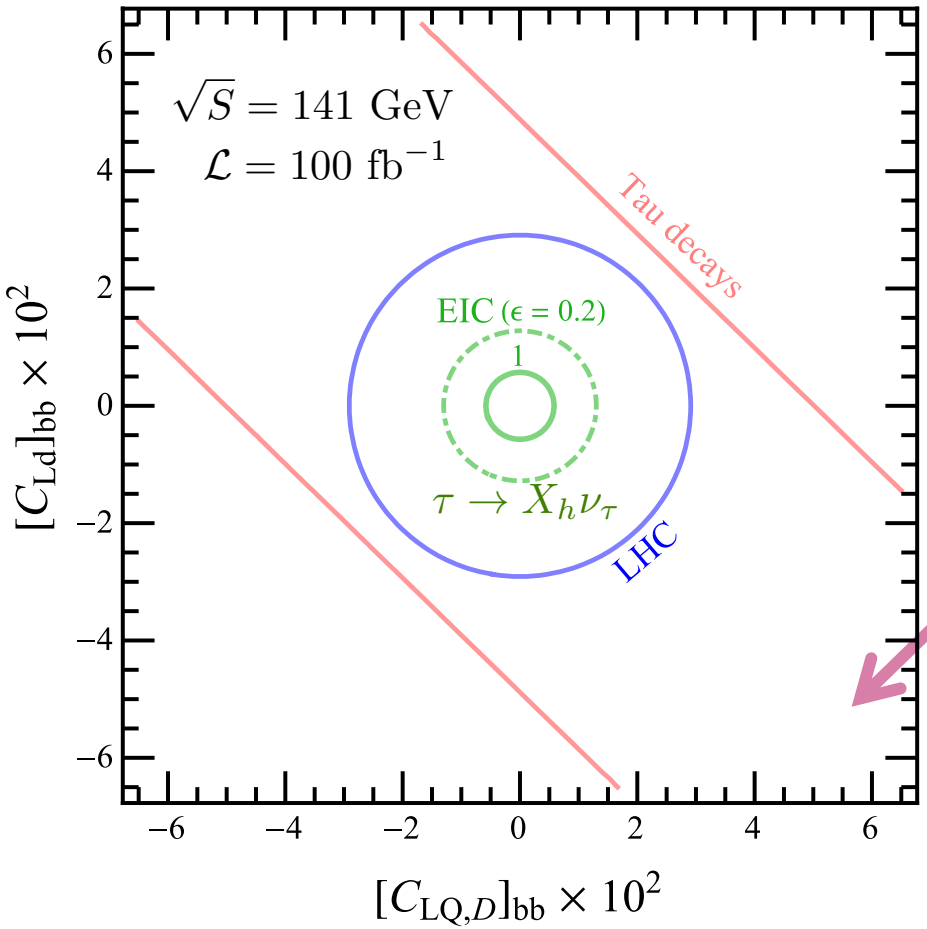
$$-\frac{4G_F}{\sqrt{2}}\sum_{a=d,s,b}[C_{Ld}]_{aa}\bar{\tau}_L\gamma^\mu e_L\bar{d}_{Ra}\gamma_\mu d_{Ra}$$

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

✔ Limits on $[C_{LQ,D}]_{bb}$ and $[C_{Ld}]_{bb}$ at 90% C.L.

The rest is marginalized.

Multi-operator scenario



Free direction appears.

$$[C_{LQ,D}]_{bb} - [C_{Ld}]_{bb}$$

Collider probes are necessary to close the free direction.

Summary

The discovery of neutrino oscillation implies nonzero neutrino mass.

✦ *Key approach : Fundamental symmetry tests*

Ex) Lepton number / flavor violation

Search for neutrinoless double beta decay is a probe of Majorana mass.

Our study : Model-independent analyses with light ν_R

Possible to analyze NDBD in any mass spectrum with interpolation formulae

✔ *Intensity frontier to unravel the neutrino nature will be more advanced.*