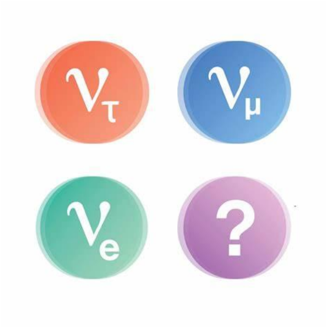


Neutrino Physics at the LHC

-- A subjective overview

Gang Li (李刚)

School of Physics and Astronomy,
Sun Yat-sen University, Zhuhai

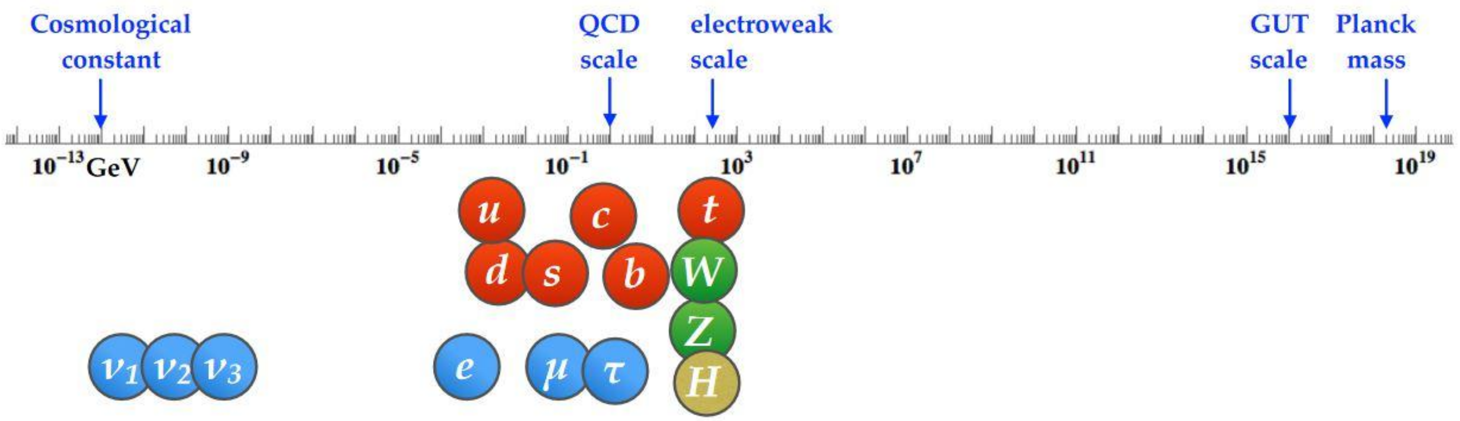
第九届中国LHC物理年会 The 9th China LHC Physics Workshop

(CLHCP2023)

2023年11月19日

Neutrinos & neutrino physics

Neutrinos are the most mysterious particles in the SM

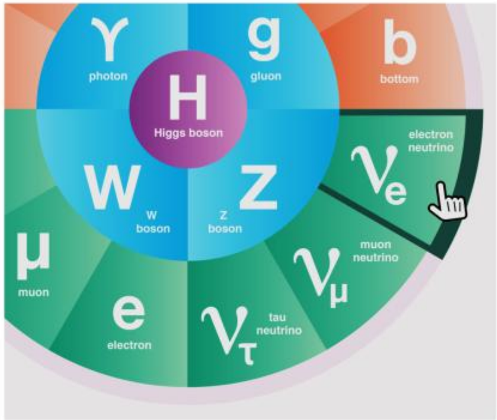


- They are the lightest particles observed
- They have the weakest interaction (except gravity)

Neutrinos & neutrino physics

Open questions in neutrino physics

- Normal or Inverted (sign of Δm^2_{31}?)
- Leptonic CP Violation (δ = ?)
- Octant of θ_{23} (> or < 45°?)
- Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)
- Majorana or Dirac Nature ($\nu = \nu^c$?)
- Majorana CP-Violating Phases (how?)



- Extra Neutrino Species
- Exotic Neutrino Interactions
- Various LNV & LFV Processes
- Leptonic Unitarity Violation

- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM and/or BAU

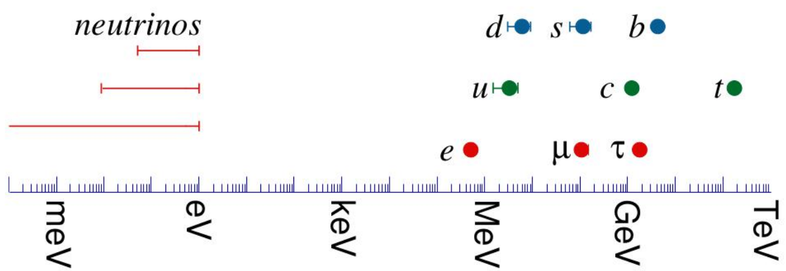
credit: Shun Zhou

Afterall, neutrinos are related to new physics

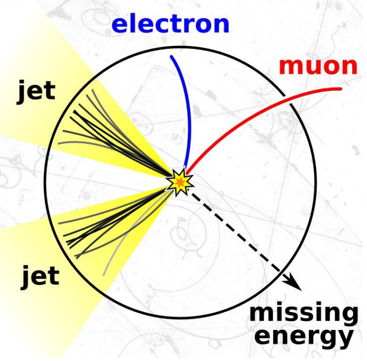
Neutrinos as the probe

- Collider neutrinos

  Neutrinos are the lightest and weakest, so that it is difficult to “catch” them with the LHC detectors



[quark, gluon]



[neutrino]

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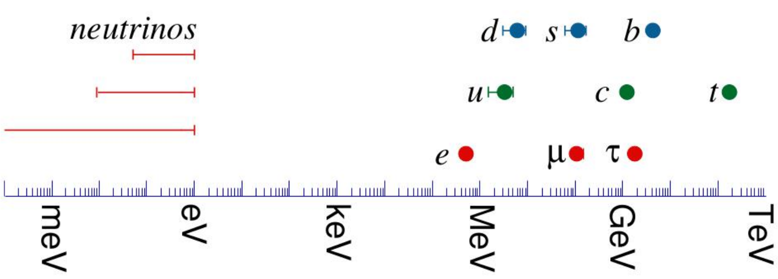
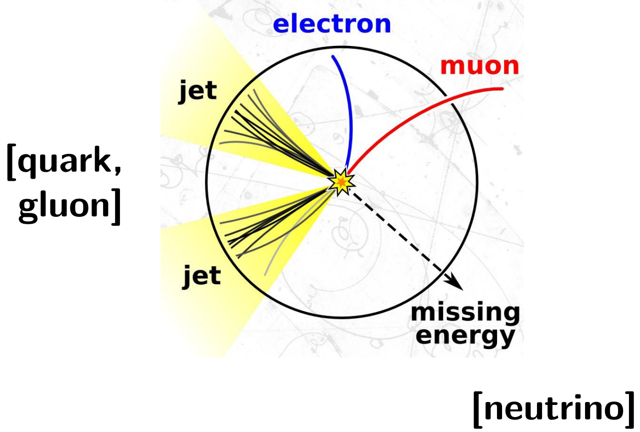
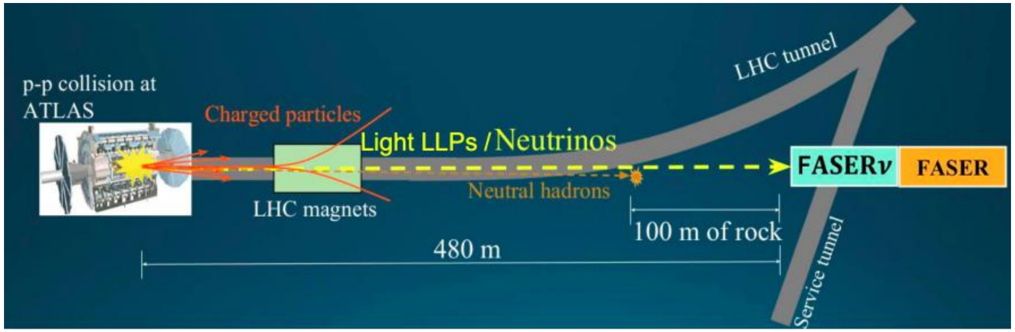




LHC as neutrino source

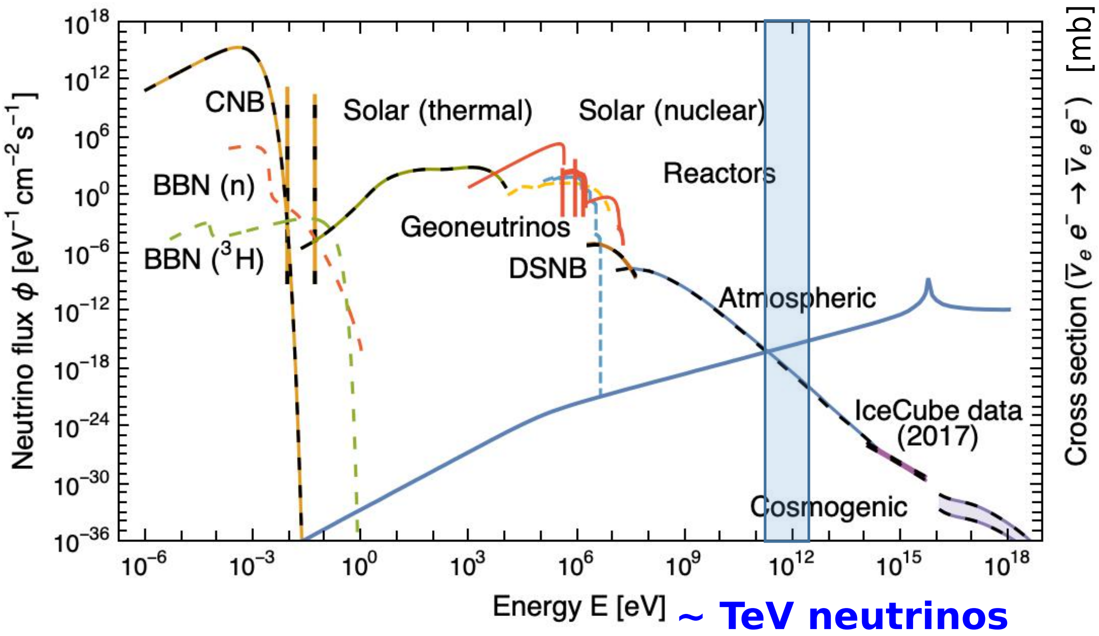


see Jinfeng Liu's talk

Neutrinos as the probe

- Collider neutrinos

Neutrino sources

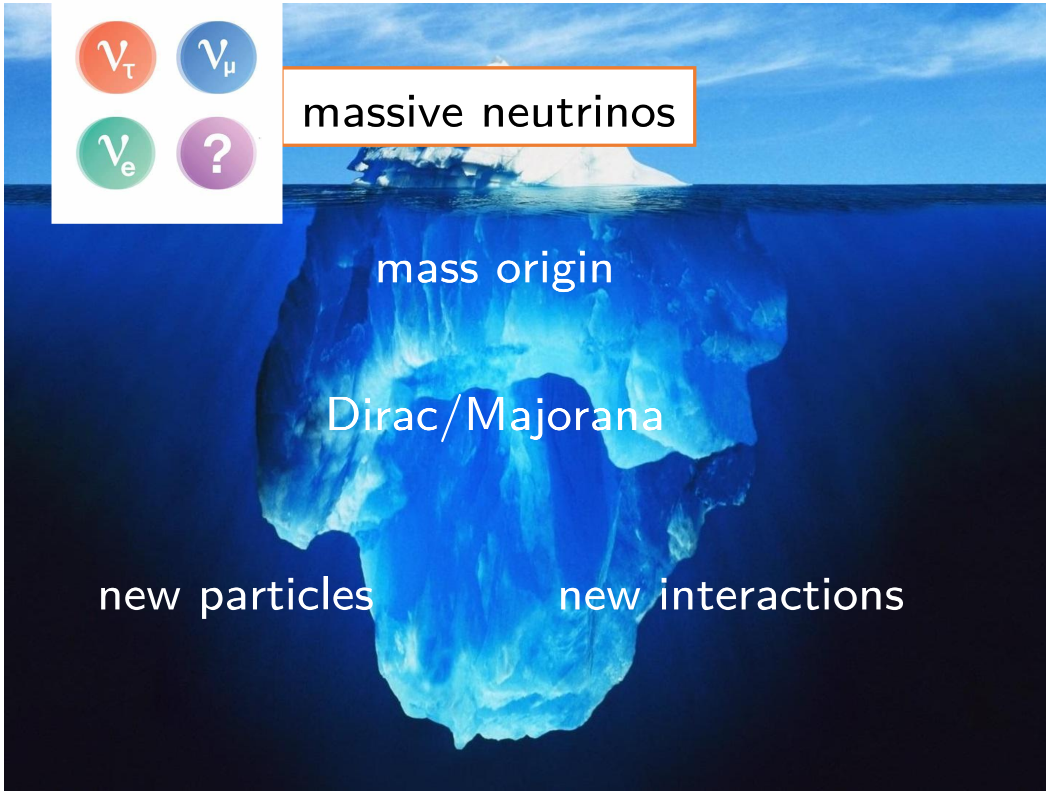


Use neutrinos to probe neutrino interactions and species

FASER, 1908.02310 (EPJC)
Ismail, Abraham, Kling, 2012.10500 (PRD)

Neutrinos as a window to new physics

- New physics related to neutrinos



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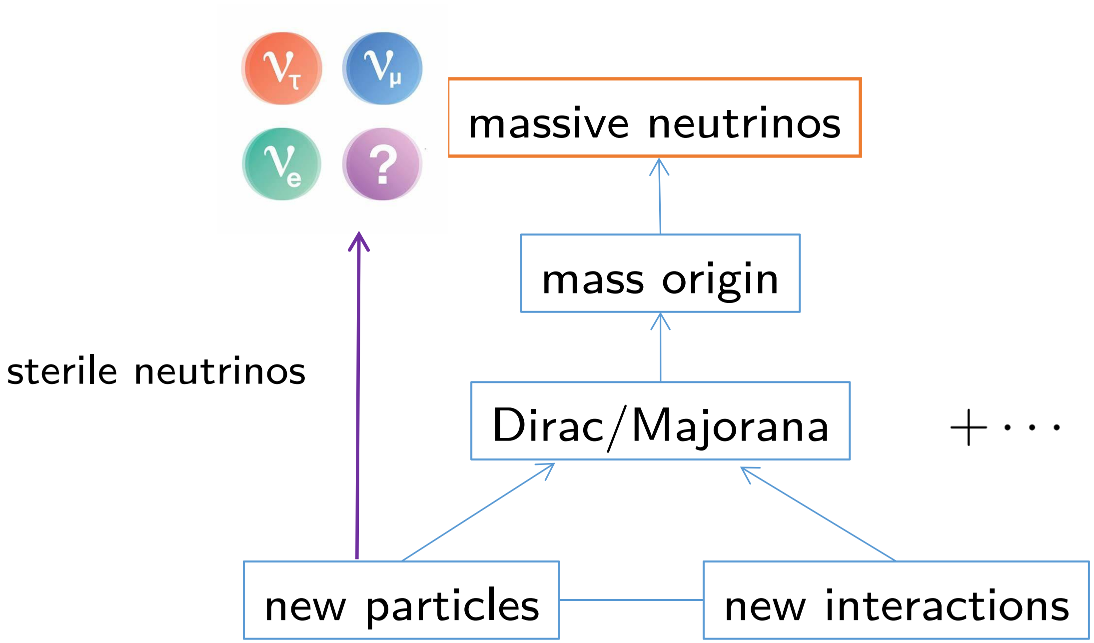

Neutrinos as a window to new physics

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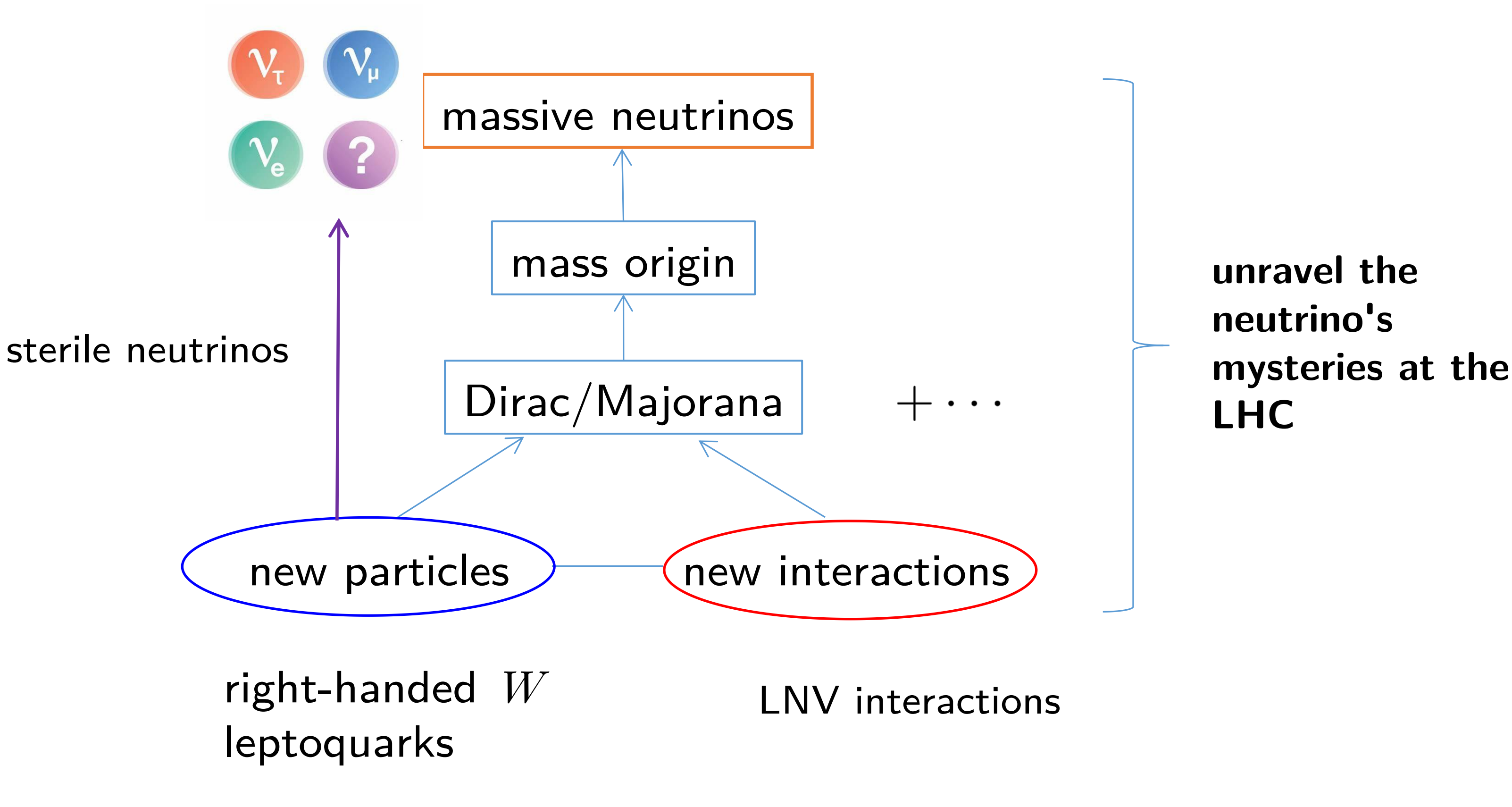


Outline

- Majorana neutrinos and LNV
- $0\nu\beta\beta$ decay and LHC searches for LNV
- TeV scale LNV: EFTs and UV completions

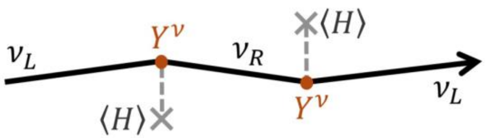
Majorana neutrinos

- Mass origin and Majorana nature -- top-layer questions
  - How do neutrinos get their masses?
  - Are they Dirac or Majorana fermions?

Majorana neutrinos

- Mass origin and Majorana nature
  - **How do neutrinos get their masses?**
  - Are they Dirac or Majorana fermions?

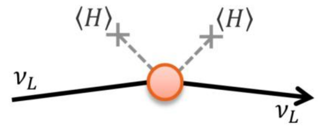
Dirac mass:



$$\mathcal{L}_D = -(Y^\nu \bar{L} H \nu_R + \text{h.c.})$$

very small coupling

Majorana mass:



$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

Weinberg operator

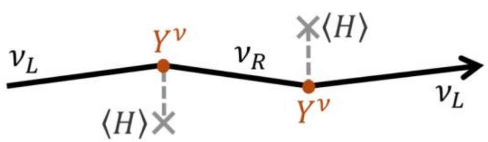
(very) large scale

a la eg. type-I, II, III seesaw

Majorana neutrinos

- Mass origin and Majorana nature
  - **How do neutrinos get their masses?**
  - Are they Dirac or Majorana fermions?

Dirac mass:



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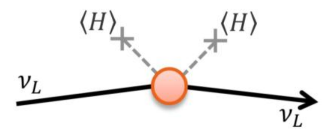
Majorana mass:



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Weinberg operator

(very) large scale

$\Delta L = 2$ lepton numer violation

(LNV)

a la eg. type-I, II, III seesaw

Majorana neutrinos

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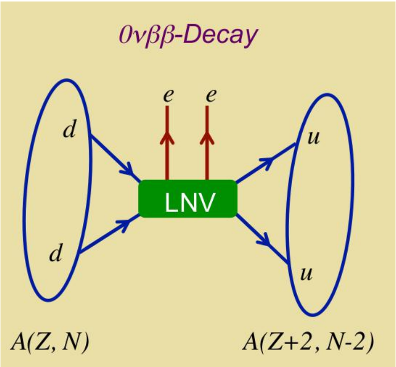
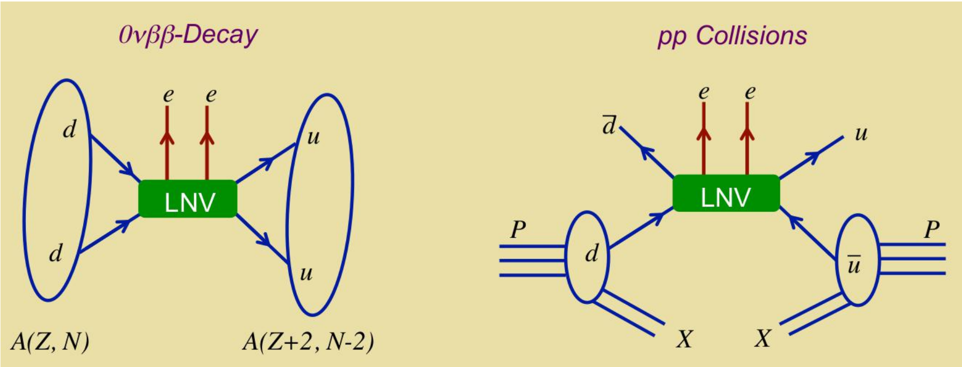
    - $0\nu\beta\beta$ decay is the most sensitive way to assess Majorana nature



Majorana neutrinos

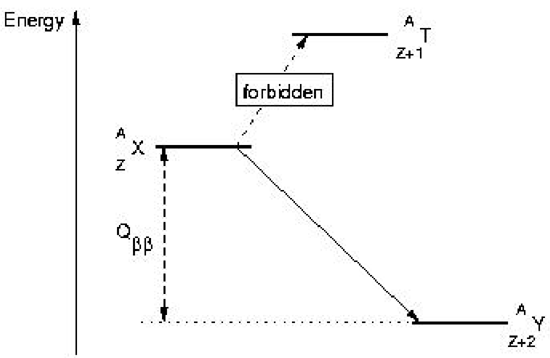
- Mass origin and Majorana nature
  - How do neutrinos get their masses?
  - **Are they Dirac or Majorana fermions?**
    - $0\nu\beta\beta$ decay is the most sensitive way to assess Majorana nature
    - LHC is utilized to diagnose underlying mechanisms of $0\nu\beta\beta$ decay

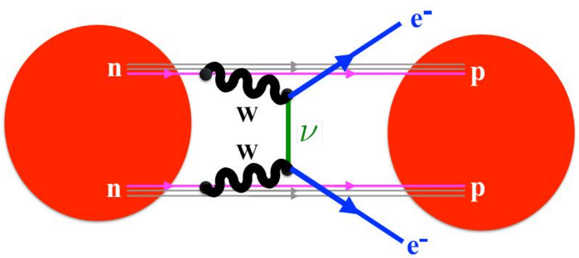


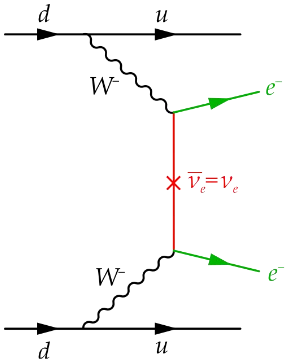
credit: M. J. Ramsey-Musolf

Neutrinoless double beta decay

- $0\nu\beta\beta$ decay in nuclei







nuclear level:

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

nucleon level:

$$nn \to ppe^-e^-$$

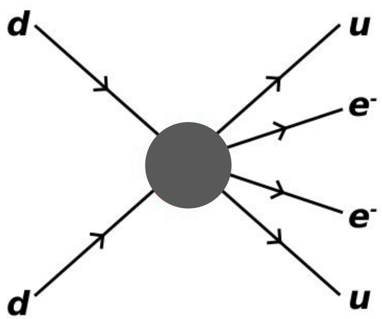
quark level:

$$dd \to uue^-e^-$$

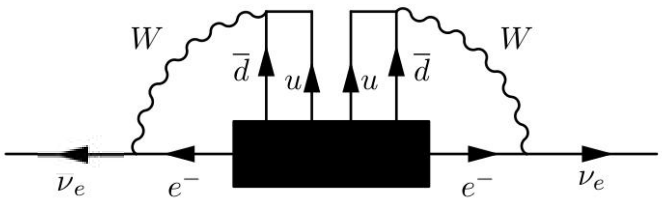
Neutrinoless double beta decay

- $0\nu\beta\beta$ decay in nuclei

  An observation of $0\nu\beta\beta$ decay undoubtedly implies the Majorana nature of neutrinos



various $\Delta L = 2$
LNV interactions



Schechter, Valle, Phys.Rev. D25 (1982) 774

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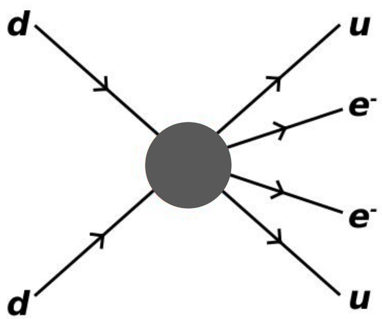

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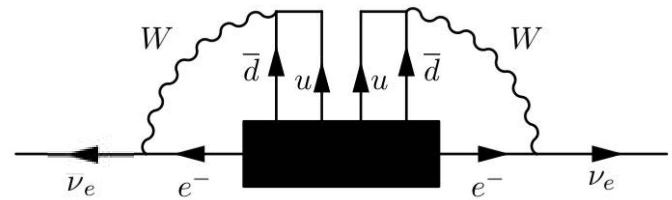
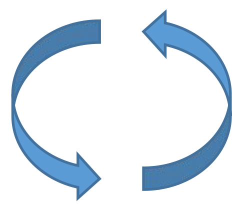


Schechter, Valle, Phys.Rev. D25 (1982) 774

$\nu = \nu^c$

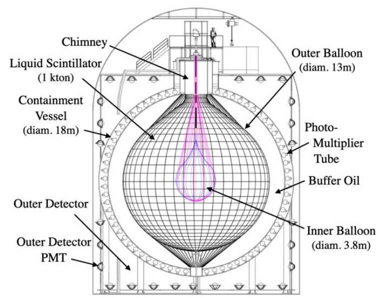


$0\nu\beta\beta$ decay

Neutrinoless double beta decay

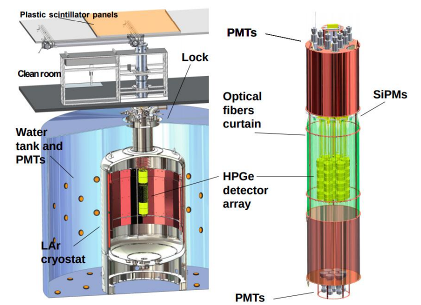
- Experimental searches

KamLAND-Zen: $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + e^{-} + e^{-}$



$$T_{1/2}^{0\nu}(\text{Xe}) > 1.07 \times 10^{26} \text{ year}$$

GERDA: $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + e^{-} + e^{-}$



$$T_{1/2}^{0\nu}(\text{Ge}) > 1.8 \times 10^{26} \text{ year}$$

Neutrinoless double beta decay

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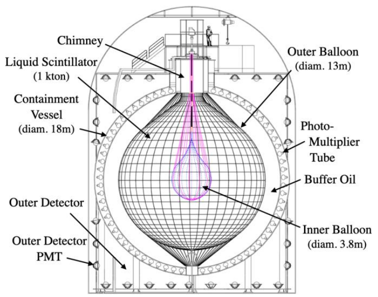

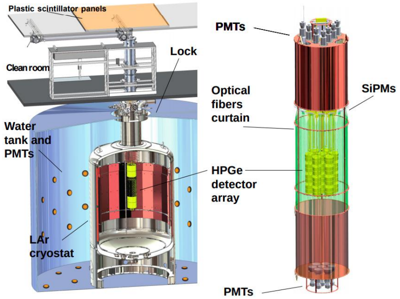

$T^{0\nu}_{1/2}(\text{Xe}) > 1.07 \times 10^{26}$ year

$T^{0\nu}_{1/2}(\text{Ge}) > 1.8 \times 10^{26}$ year

- Theoretical interpretation

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} {M_{0\nu}}^2 \langle m_{\beta\beta} \rangle^2$$

$G_{0\nu}$: phase space factor (atomic physics)

$M_{0\nu}$: nuclear matrix element (nuclear physics)

$\langle m_{\beta\beta} \rangle$: effective Majorana mass (particle physics)

Neutrinoless double beta decay

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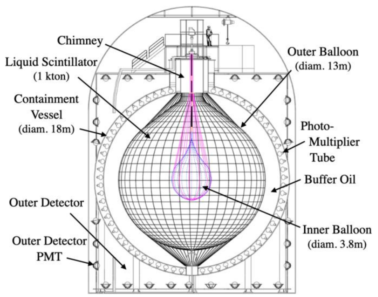

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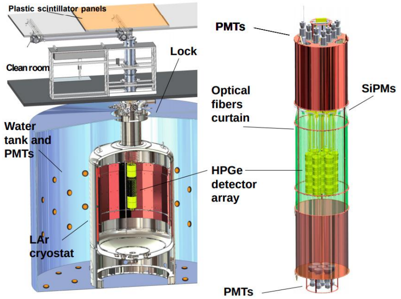

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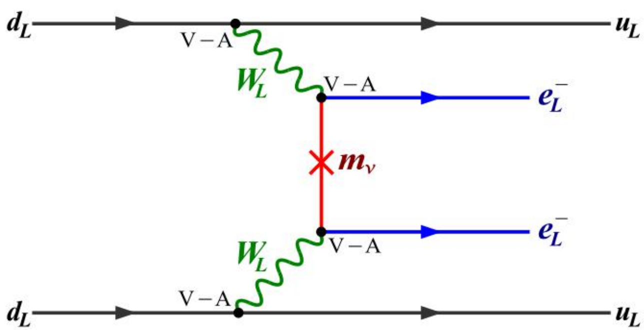
$G_{0\nu}$: phase space factor (atomic physics)
$M_{0\nu}$: nuclear matrix element (nuclear physics)
$\langle m_{\beta\beta} \rangle$: effective Majorana mass (particle physics)

What is $\langle m_{\beta\beta} \rangle$?

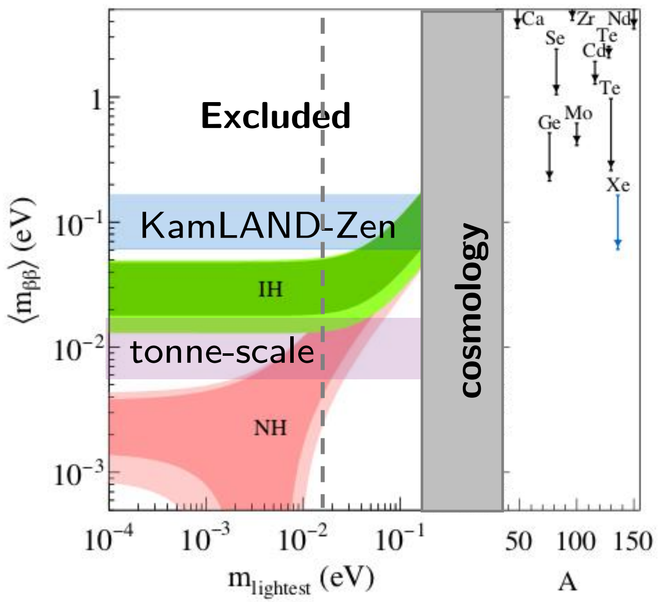
Mechanisms of $0\nu\beta\beta$ decay

- Active neutrinos



$$\langle m_{\beta\beta} \rangle = |\sum_i m_i U_{ei}^2|$$

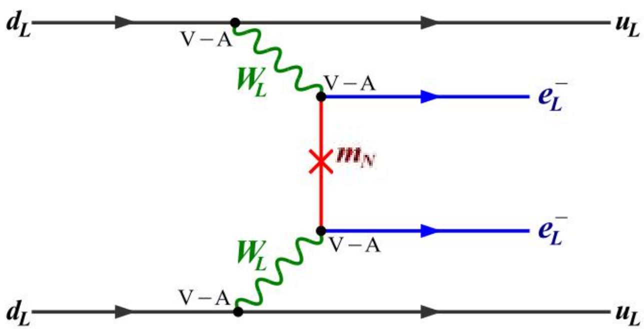
Weinberg operator



Phys.Rev.Lett. 117 (2016) 082503;
Phys.Rev.Lett. 125 (2023) 130, 051801

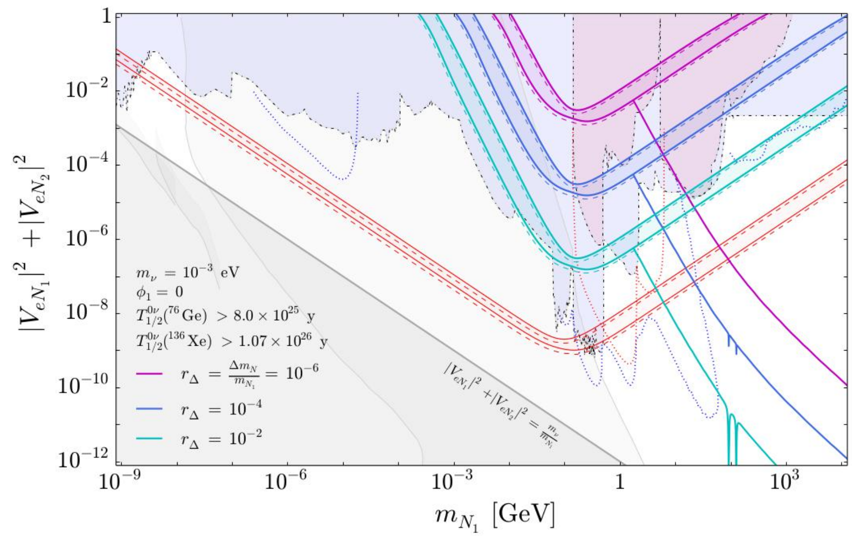
Mechanisms of $0\nu\beta\beta$ decay

- Sterile neutrinos



$$\langle m_{\beta\beta} \rangle = \left| \sum_i \frac{U_{ei}^2}{m_{N_i}} \right|$$

type-I seesaw model

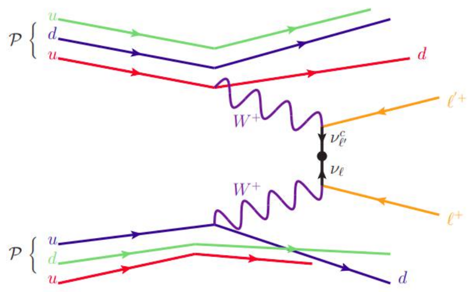


Bolton, Deppisch, Bhupal Dev, 1912.03058 (JHEP)

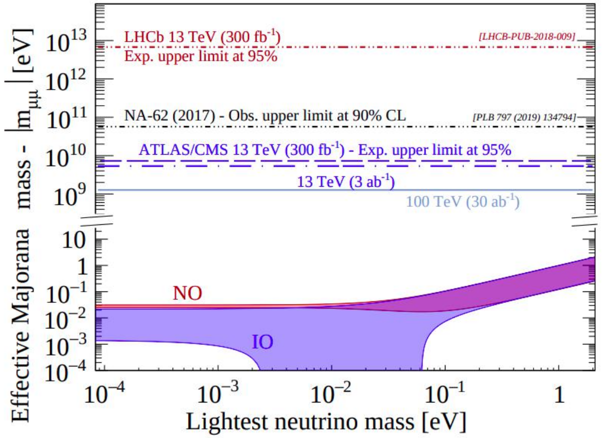
see also
W. Dekens, et al, 2002.07182 (JHEP);
J. de Vries, GL, M.J. Ramsey-Musolf, J.C. Vasquez, 2209.03031 (JHEP)

LHC searches

- Searches for LNV at the LHC



active neutrinos



B. Fuks et al., 2012.09882 (PRD)

LHC Run 2

CMS : $|m_{\mu\mu}| \leq 10.8\ \mathrm{GeV}$

ATLAS : $|m_{\mu\mu}| \leq 16.7\ \mathrm{GeV}$

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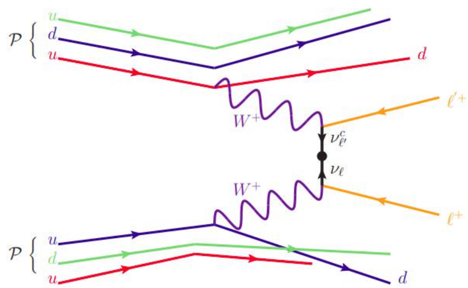

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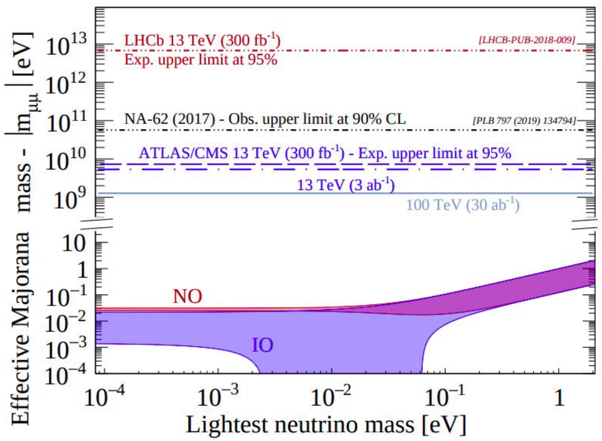

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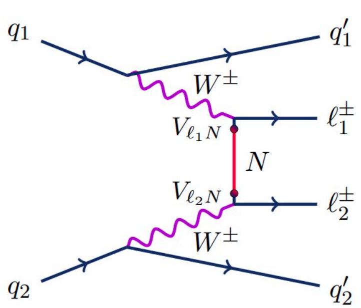
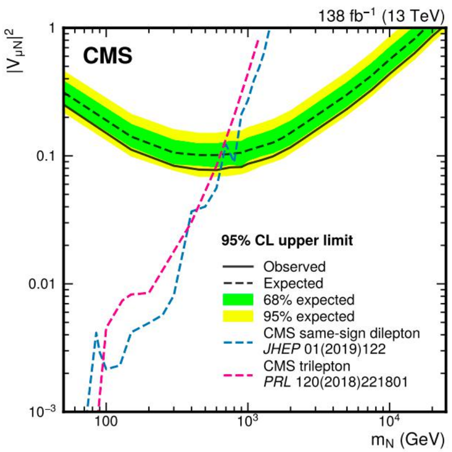
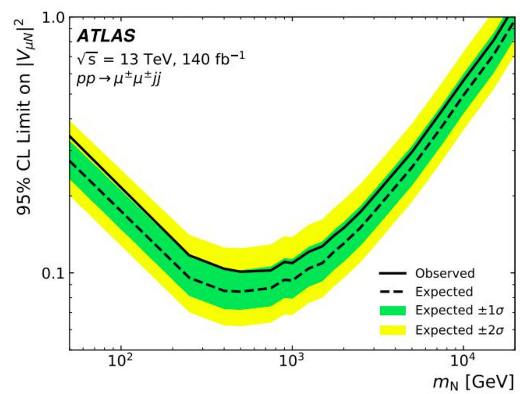


sterile neutrino



CMS, 2206.08956 (PRL)

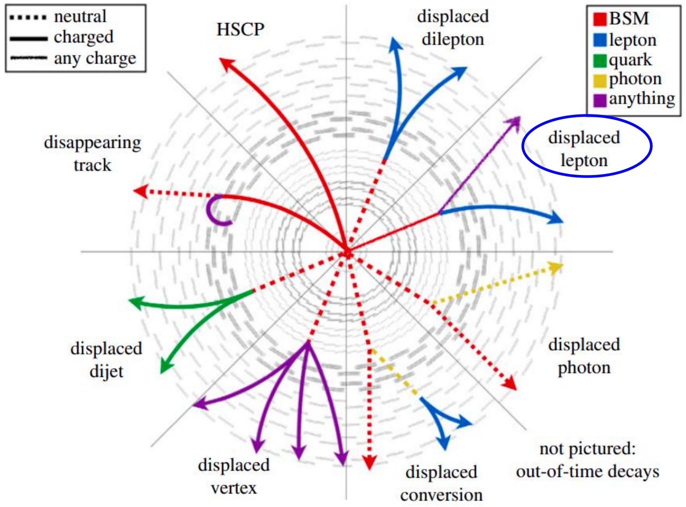


ATLAS, 2305.14931 (EPJC)

LHC searches

- Searches for LNV at the LHC

$$pp \to \ell^{\pm}\ell^{\pm}jj \quad \text{(displaced lepton)}$$



LHC searches

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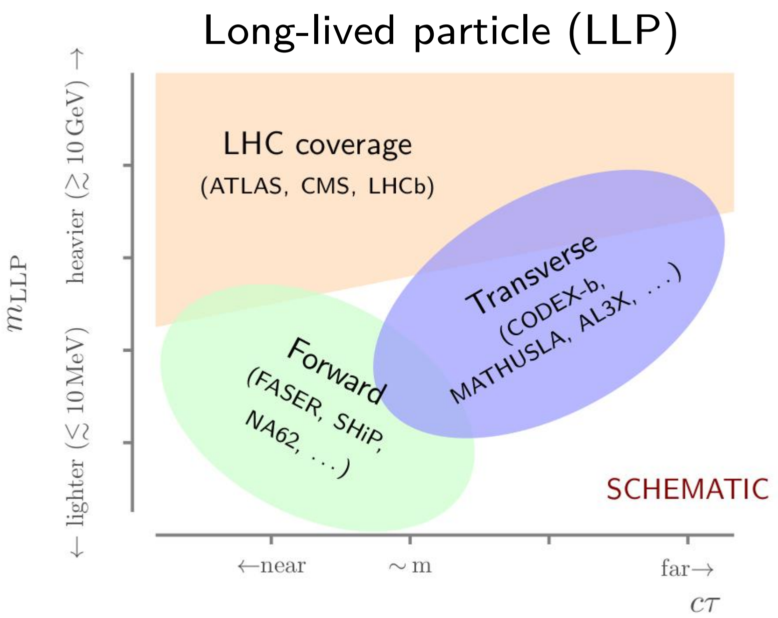
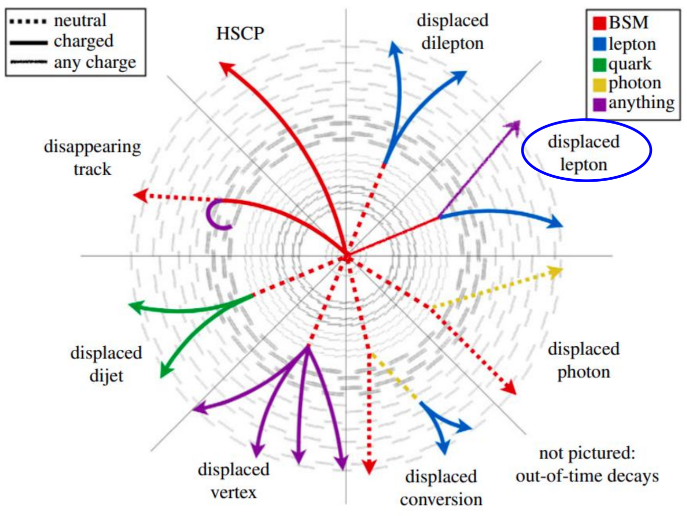
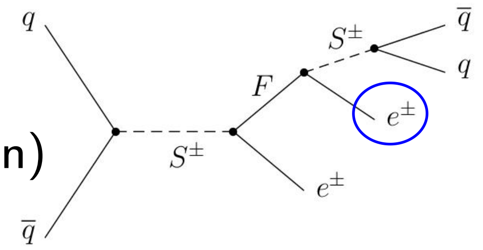




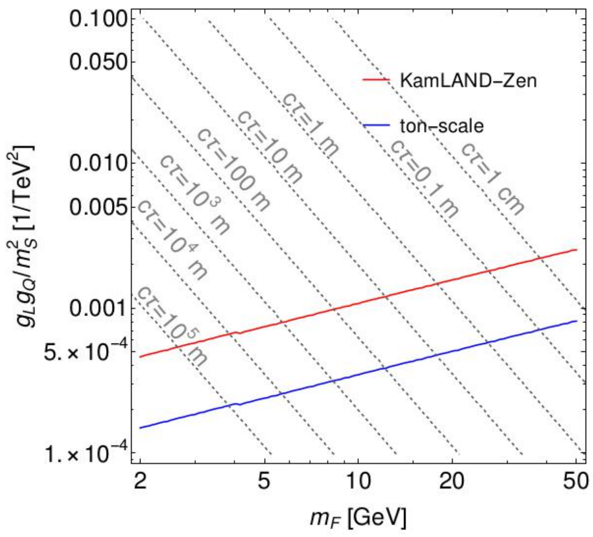
- upgrade of the LHC detectors
- construction of new detectors

LHC searches

- Searches for LNV at the LHC



$pp \to \ell^{\pm}\ell^{\pm}jj$ (displaced lepton)

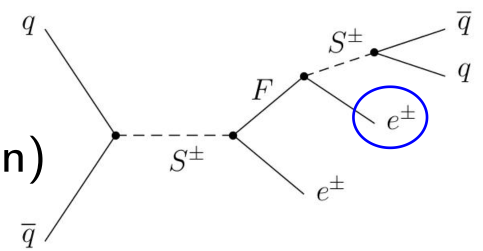


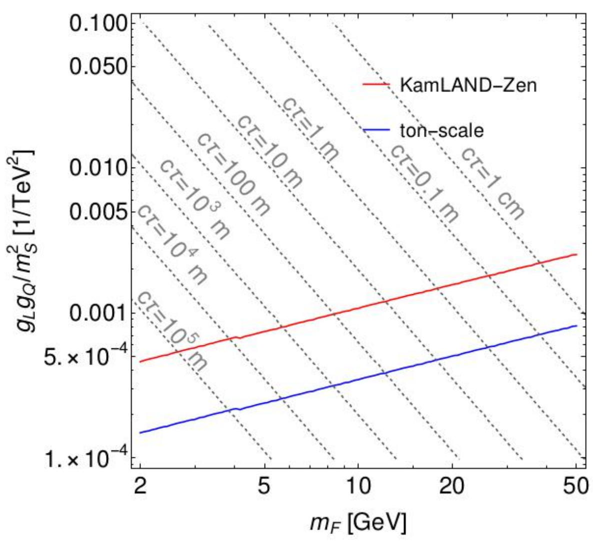
[sterile neutrino mass]

LHC searches

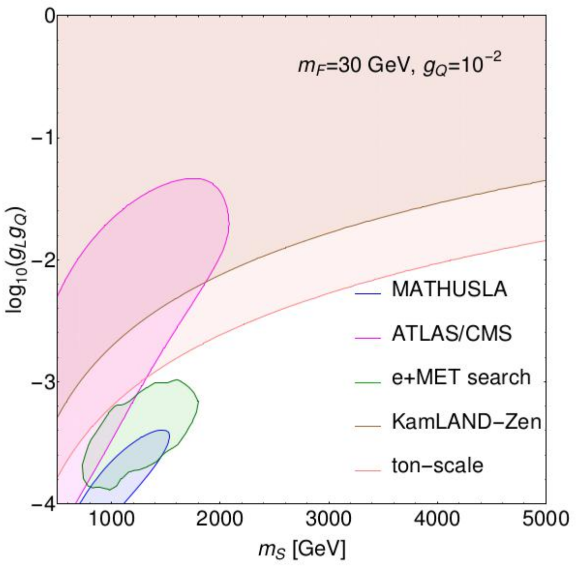
- Searches for LNV at the LHC

$$pp \to \ell^\pm \ell^\pm jj$$ (displaced lepton)





[sterile neutrino mass]



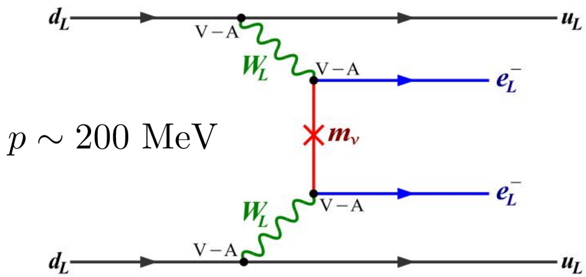
GL, M. J. Ramsey-Musolf, S. Su, J. C. Vasquez, 2109.08172 (PRD)
GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2202.01789 (PRD)
J. de Vries et al., 2010.07305 (JHEP)
J. Helo, M. Hirsch, S. Kovalenko, 1312.2900 (PRD)

TeV scale LNV

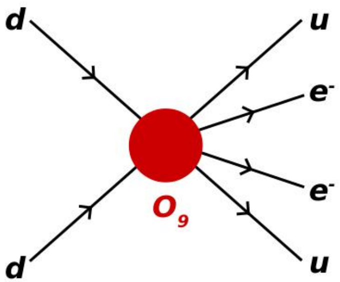
- Why TeV scale LNV?

TeV scale LNV

- Why TeV scale LNV?
  - comparable contribution to $0\nu\beta\beta$ decay



$\sim G_F^2 m_{\beta\beta}/p^2$



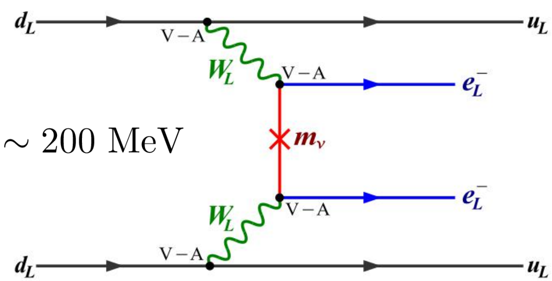
$\sim c/\Lambda^5$

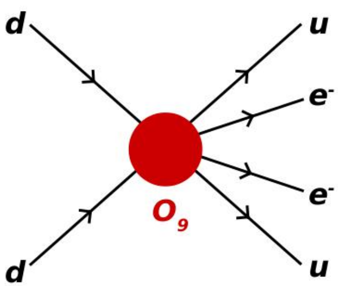
W. Rodejohann, 1106.1334

TeV scale LNV

- Why TeV scale LNV?
  - comparable contribution to $0\nu\beta\beta$ decay

$p \sim 200$ MeV





$\sim G_F^2 m_{\beta\beta}/p^2$

$\sim c/\Lambda^5$

W. Rodejohann, 1106.1334

$$\frac{c/\Lambda^5}{G_F^2 m_{\beta\beta}/p^2} = c\left(\frac{3.3\ \mathrm{TeV}}{\Lambda}\right)^5 \frac{0.1\ \mathrm{eV}}{m_{\beta\beta}}$$

c: new coupling
Λ: new particle mass

TeV scale LNV

- Why TeV scale LNV?
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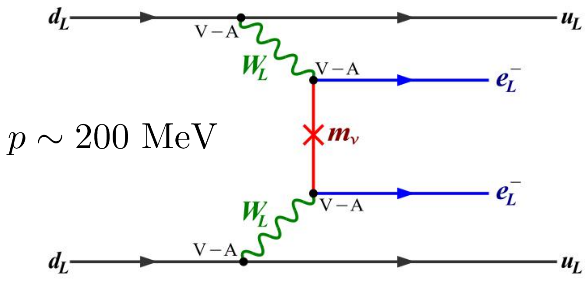

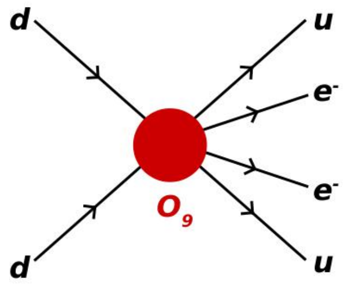

$$\sim G_F^2 m_{\beta\beta}/p^2 \qquad\qquad \sim c/\Lambda^5$$

W. Rodejohann, 1106.1334

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c: new coupling
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  - reachable at the LHC

Helo, Hirsch, Kovalenko, Pas, 1303.0899 (PRD), 1307.4849 (PRD)
Peng, Ramsey-Musolf, Winslow 1508.04444 (PRD)

TeV scale LNV

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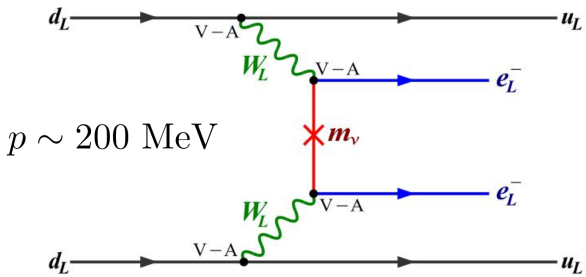

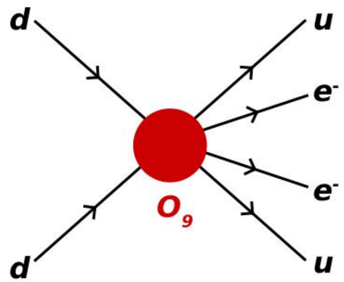

$\sim G_F^2 m_{\beta\beta}/p^2$ $\sim c/\Lambda^5$ **W. Rodejohann, 1106.1334**

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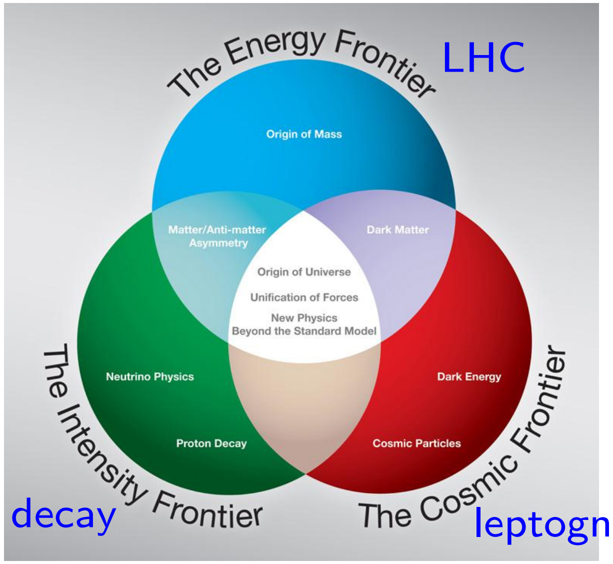
  - a viable leptogenesis **J. Harz, M. J. Ramsey-Musolf, T. Shen, S. Urrutia-Quiroga, 2106.10838**
    F.F. Deppisch, L. Graf, J. Harz, W.-C. Huang, 1711.10432 (PRD)

TeV scale LNV

- Why TeV scale LNV?



LHC

$0\nu\beta\beta$ decay

leptognesis

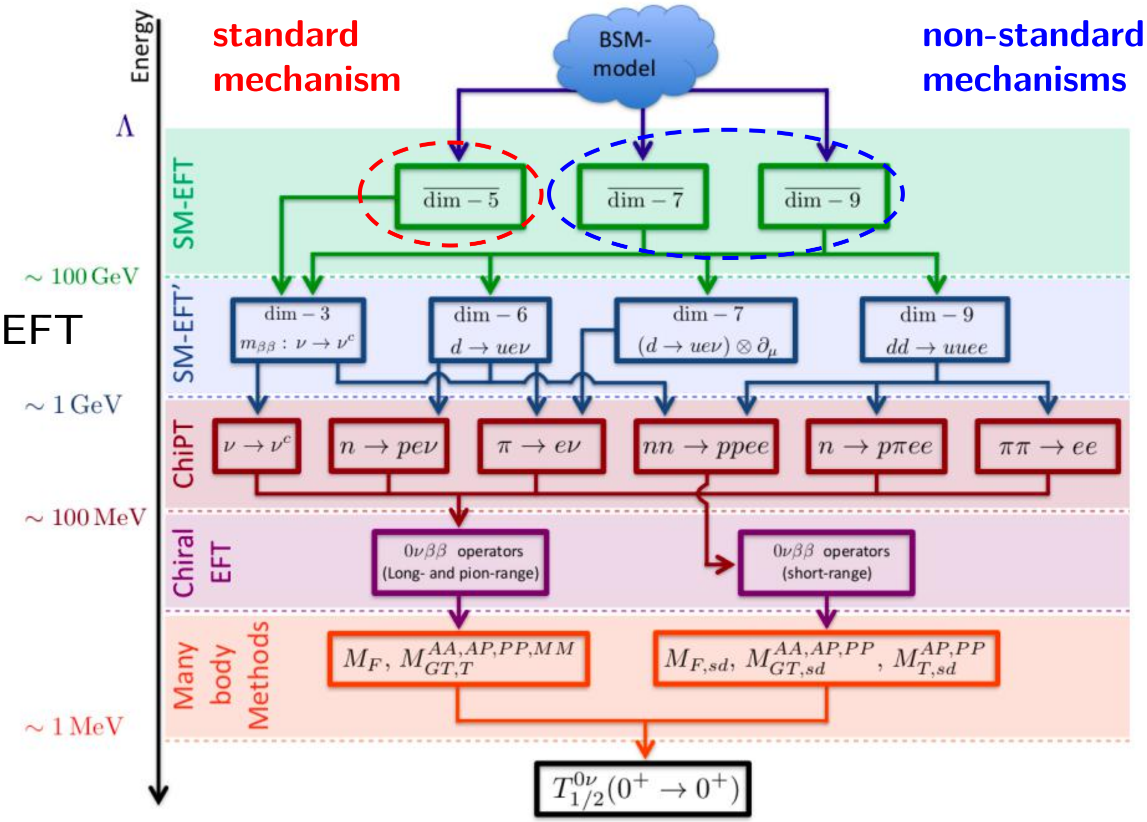
Effective field theory approach

- A systematic description of $\Delta L = 2$ LNV sources

Effective field theory approach

- A systematic description of $\Delta L = 2$ LNV sources

or LEFT



$\mathcal{L}(u, d, \nu, e)$

$\mathcal{L}(N, \pi, \nu, e)$

V. Cirigliano et al., 2203.12169, Snowmass 2021

Effective field theory approach

Inverse half-life for $0\nu\beta\beta$ decay in the EFT approach

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \Big\{ G_{01} \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2$$

$$+2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu + \mathcal{A}_R)\right)\right]$$

$$-2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right]$$

$$+G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\}.$$

G. Prézeau, M. Ramsey-Musolf, P. Vogel, Phys. Rev. D 68, 034016 (2003)
V. Cirigliano et al, 1708.09390 (JHEP), 1806.02780 (JHEP)

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Effective Majorana mass

$\langle m_{\beta\beta}\rangle \sim \sum$ LEC x Wilson Coeff

- non-perturbative QCD
- low-energy constant (LEC) as the weight

Effective field theory approach

LECs are ordered in chiral power counting

$$\frac{p}{\Lambda_\chi} \simeq \frac{200\ \text{MeV}}{1\ \text{GeV}}$$

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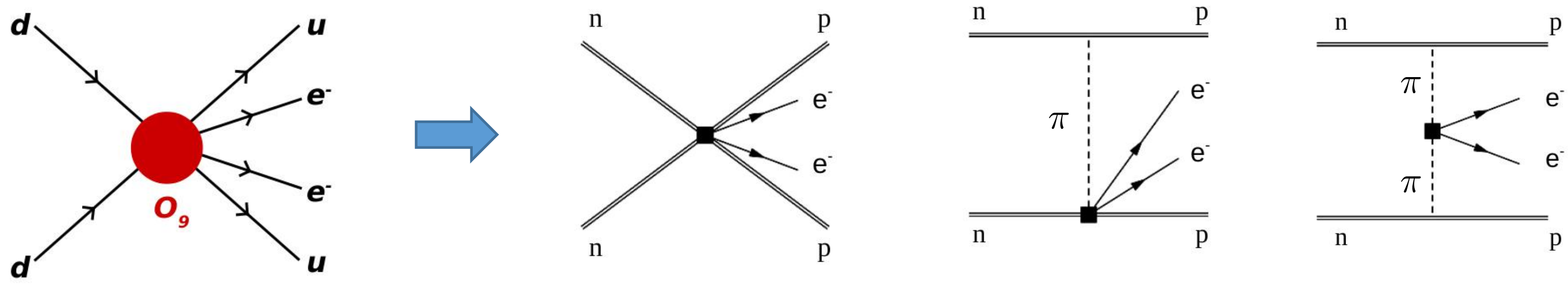


$\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$ $\quad (\bar{p}n)(\bar{p}n)\bar{e}_R e^c_R \quad (\bar{p}S\cdot\partial\pi^- n)\,\bar{e}_R e^c_R \quad \pi^-\pi^-\bar{e}_R e^c_R \quad R \to L$

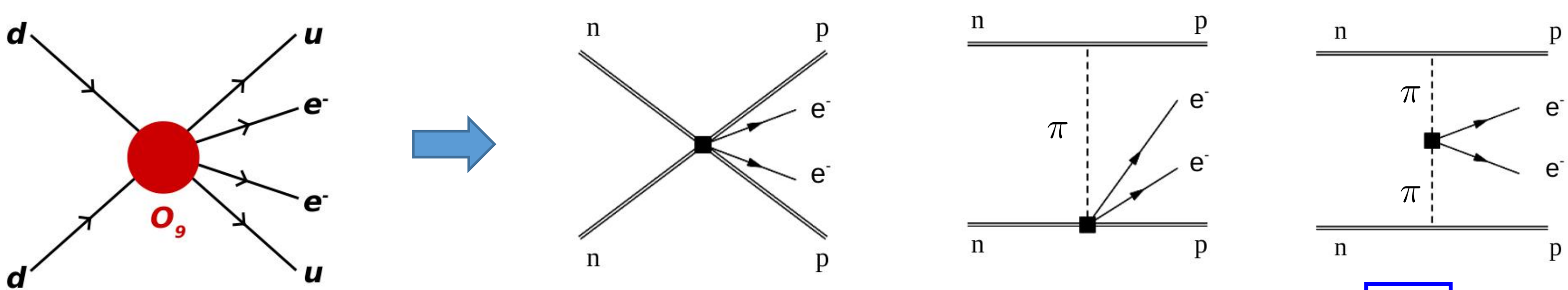
$(\bar{p}n)(\bar{p}n)v^\mu \bar{e}\gamma_\mu\gamma_5 e^c \quad \bar{p}\left(S\cdot\partial\pi^- n\right) v^\mu \bar{e}\gamma_\mu\gamma_5 e^c \quad \partial_\mu\pi^-\partial^\mu\pi^-\bar{e}_R e^c_R$

Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016

Effective field theory approach

LECs are ordered in chiral power counting

$$\frac{p}{\Lambda_\chi} \simeq \frac{200 \text{ MeV}}{1 \text{ GeV}}$$



p^0 $\quad$ p^0 $\quad$ p^{-2}, p^0

$\bar{u}\Gamma_1 d \; \bar{u}\Gamma_2 d \; \bar{e}\Gamma_3 e^c$ $\quad$ $(\bar{p}n)(\bar{p}n)\bar{e}_R e_R^c$ $\quad$ $(\bar{p}S \cdot \partial\pi^- n)\, \bar{e}_R e_R^c$ $\quad$ $\pi^-\pi^-\bar{e}_R e_R^c$ $\quad$ $R \to L$

$(\bar{p}n)(\bar{p}n)v^\mu \bar{e}\gamma_\mu\gamma_5 e^c$ $\quad$ $\bar{p}\,(S \cdot \partial\pi^- n)\, v^\mu \bar{e}\gamma_\mu\gamma_5 e^c$ $\quad$ $\partial_\mu\pi^-\partial^\mu\pi^-\bar{e}_R e_R^c$

Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016

Effective field theory approach

Dim-9 LEFT operators: $\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$

- lepton bilinear

$$\bar{e}\Gamma_3 e^c = \bar{e}_L e_L^c\ , \bar{e}_R e_R^c\ , \bar{e}\gamma_\mu\gamma_5 e^c$$

- quark biliners

M. L. Graesser, 1606.04549 (JHEP)

$$O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\ \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta\,, \qquad O_1' = \bar{q}_R^\alpha \gamma_\mu \tau^+ q_R^\alpha\ \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta\,,$$

$$O_2 = \bar{q}_R^\alpha \tau^+ q_L^\alpha\ \bar{q}_R^\beta \tau^+ q_L^\beta\,, \qquad O_2' = \bar{q}_L^\alpha \tau^+ q_R^\alpha\ \bar{q}_L^\beta \tau^+ q_R^\beta\,,$$

$$O_3 = \bar{q}_R^\alpha \tau^+ q_L^\beta\ \bar{q}_R^\beta \tau^+ q_L^\alpha\,, \qquad O_3' = \bar{q}_L^\alpha \tau^+ q_R^\beta\ \bar{q}_L^\beta \tau^+ q_R^\alpha\,,$$

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\ \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta\,,$$

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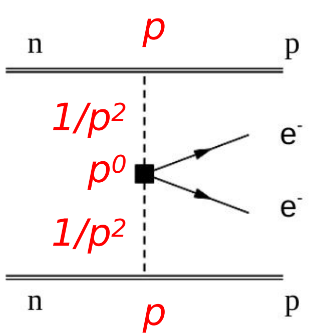

$\sim p^{-2}$

$$O_6^\mu = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L \tau^+ q_R\right)\ , \qquad O_6^{\mu\prime} = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R \tau^+ q_L\right)\ ,$$

$$O_7^\mu = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ , \qquad O_7^{\mu\prime} = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ ,$$

$$O_8^\mu = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R \tau^+ q_L\right)\ , \qquad O_8^{\mu\prime} = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L \tau^+ q_R\right)\ ,$$

$$O_9^\mu = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ , \qquad O_9^{\mu\prime} = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ ,$$

Effective field theory approach

Dim-9 LEFT operators: $\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$

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$$\bar{e}\Gamma_3 e^c = \bar{e}_L e^c_L\ , \bar{e}_R e^c_R\ , \bar{e}\gamma_\mu\gamma_5 e^c$$

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M. L. Graesser, 1606.04549 (JHEP)

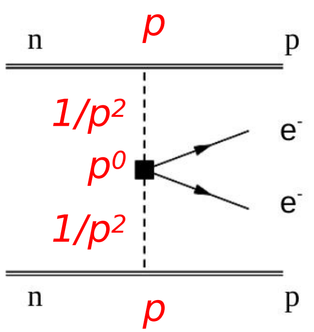
$$O_1 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_L \gamma^\mu \tau^+ q^\beta_L\,, \qquad O'_1 = \bar{q}^\alpha_R \gamma_\mu \tau^+ q^\alpha_R\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_2 = \bar{q}^\alpha_R \tau^+ q^\alpha_L\ \bar{q}^\beta_R \tau^+ q^\beta_L\,, \qquad O'_2 = \bar{q}^\alpha_L \tau^+ q^\alpha_R\ \bar{q}^\beta_L \tau^+ q^\beta_R\,,$$

$$O_3 = \bar{q}^\alpha_R \tau^+ q^\beta_L\ \bar{q}^\beta_R \tau^+ q^\alpha_L\,, \qquad O'_3 = \bar{q}^\alpha_L \tau^+ q^\beta_R\ \bar{q}^\beta_L \tau^+ q^\alpha_R\,,$$

$$O_4 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_5 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\beta_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\alpha_R\,,$$



$\sim p^{-2}$

$$O^\mu_6 = (\bar{q}_L \tau^+ \gamma^\mu q_L)(\bar{q}_L \tau^+ q_R)\ , \qquad O^{\mu\prime}_6 = (\bar{q}_R \tau^+ \gamma^\mu q_R)(\bar{q}_R \tau^+ q_L)\ ,$$

$$O^\mu_7 = (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)(\bar{q}_L t^a \tau^+ q_R)\ , \qquad O^{\mu\prime}_7 = (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)(\bar{q}_R t^a \tau^+ q_L)\ ,$$

$$O^\mu_8 = (\bar{q}_L \tau^+ \gamma^\mu q_L)(\bar{q}_R \tau^+ q_L)\ , \qquad O^{\mu\prime}_8 = (\bar{q}_R \tau^+ \gamma^\mu q_R)(\bar{q}_L \tau^+ q_R)\ ,$$

$$O^\mu_9 = (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)(\bar{q}_R t^a \tau^+ q_L)\ , \qquad O^{\mu\prime}_9 = (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)(\bar{q}_L t^a \tau^+ q_R)\ ,$$

UV completion

- TeV scale LNV correlated with observed neutrino masses

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \qquad \bar{e}_L e_L^c, \bar{e}_R e_R^c$$

UV completion

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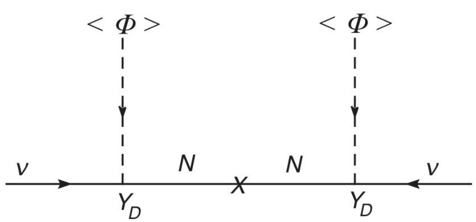
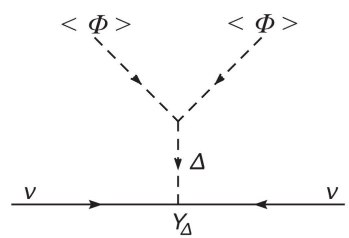
Both left- and right-handed charged currents, thus the most manifest UV realization is the **left-right symmetric model**

Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165



type-I seesaw



type-II seesaw

$$\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta e^{-i\alpha} \\ \sin\zeta e^{i\alpha} & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix}$$

$$\tan\zeta = \frac{M_W^2}{M_{W_R}^2} \sin(2\beta)$$

UV completion

- TeV scale LNV correlated with observed neutrino masses

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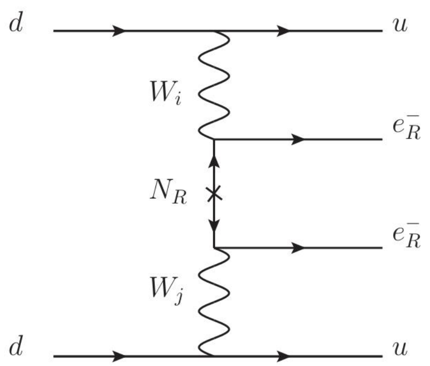

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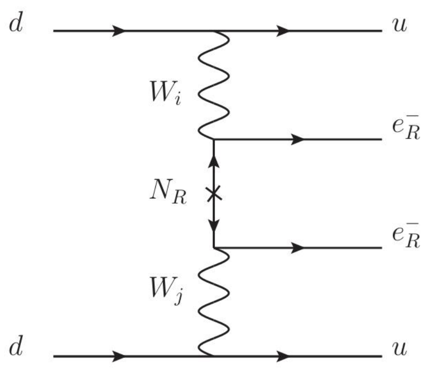

$$(i,j) = (R,R) \qquad \bar{u}_R \gamma_\mu d_R \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_1' \bar{e}_R e_R^c$$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \left(\frac{M_W}{M_{W_R}} \right)^4 p^0$$

$$(i,j) = (1,2) \qquad \bar{u}_L \gamma_\mu d_L \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_4 \bar{e}_R e_R^c$$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \sin 2\beta \left(\frac{M_W}{M_{W_R}} \right)^4 \Lambda_\chi^2 p^{-2}$$

Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016

UV completion

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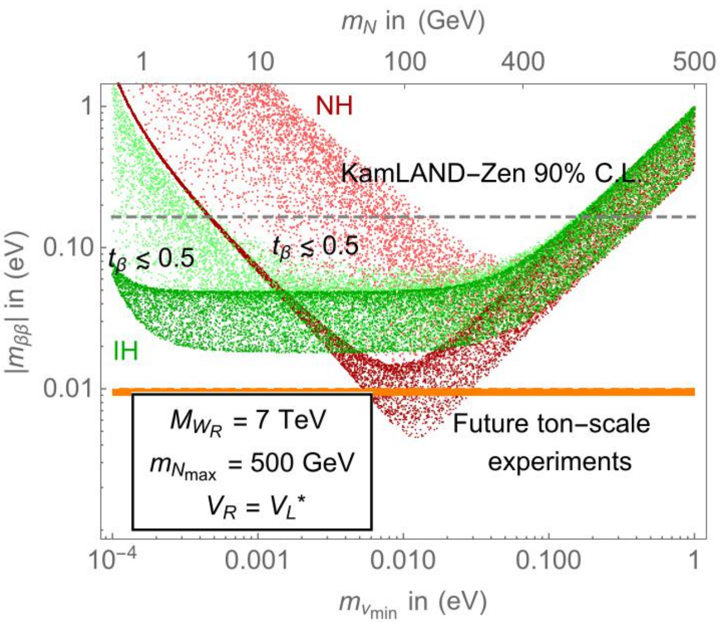

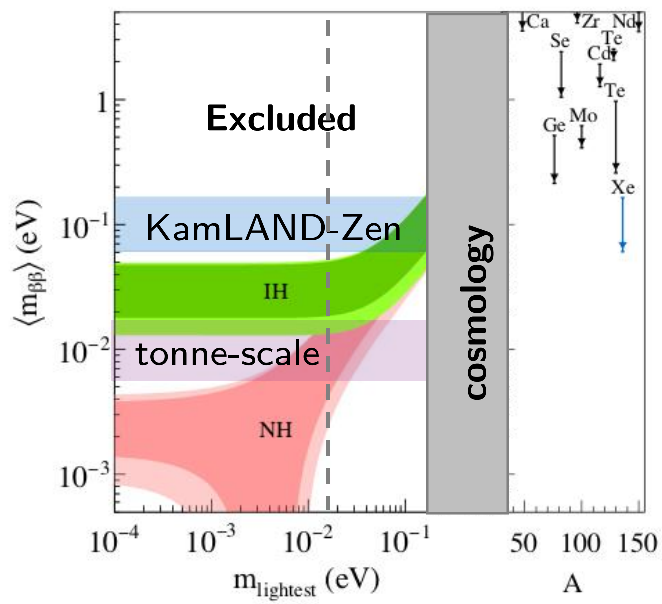

GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL)

UV completion

- TeV scale LNV uncorrelated with observed neutrino masses

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UV completion

- TeV scale LNV uncorrelated with observed neutrino masses

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  - Contributions to Majorana masses of neutrinos are non-zero but **negligible**
  - Possible if neutrino have **different mass origins**
  - Other kinds of UV scenarios that are **reachable** in the $0\nu\beta\beta$ decay experiments and at the LHC

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- Two-step UV completions **Li, Ni, Xiao, Yu, 2204.03660 (JHEP)**

dim-9 LEFT → dim-7, 9 SMEFT → UV models

Lehman 2014; Liao & Ma 2016, 2020; Li et al, 2020

UV completion

- Step 1

O. Scholer, J. de Vries, L. Gráf, 2304.05415 (JHEP)

Dim-7 SMEFT operator:

$$\mathcal{O}^{(7)}_{\bar{d}uLLD} = \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i iD_\mu L_j\right)$$

Dim-9 SMEFT operators:

$$\begin{aligned}
\mathcal{O}^{(9)}_1 &= \epsilon^{ij}\left(\bar{d}_R\gamma^\mu e_R\right)\left(\bar{u}^c_R e_R\right) H_j D_\mu H_i\ ,\\
\mathcal{O}^{(9)}_2 &= \epsilon^{ik}\left(\bar{d}_R L_j\right)\left(\bar{L}^c_i\gamma^\mu u_R\right) H^{\dagger j} D_\mu H_k\ ,\\
\mathcal{O}^{(9)}_3 &= \epsilon^{ij}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{L}^c_i D_\mu L_j\right) H_k H^{\dagger k}\ ,\\
\mathcal{O}^{(9)}_4 &= \epsilon^{ik}(\bar{u}^\alpha_R Q^\beta_j)(\bar{L}^j d^\alpha_R)(\bar{L}_i Q^{\beta c}_k)\ .
\end{aligned}$$

UV completion

- Step 1

O. Scholer, J. de Vries, L. Gráf, 2304.05415 (JHEP)

Dim-7 SMEFT operator:

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Dim-9 SMEFT operators:

$$\mathcal{O}^{(9)}_1 = \epsilon^{ij}\,(\bar{d}_R\gamma^\mu e_R)\,(\bar{u}^c_R e_R)\,H_j D_\mu H_i\,,$$
$$\mathcal{O}^{(9)}_2 = \epsilon^{ik}\,(\bar{d}_R L_j)\,(\bar{L}^c_i\gamma^\mu u_R)\,H^{\dagger j} D_\mu H_k\,,$$
$$\mathcal{O}^{(9)}_3 = \epsilon^{ij}\,(\bar{d}_R\gamma^\mu u_R)\,(\bar{L}^c_i D_\mu L_j)\,H_k H^{\dagger k}\,,$$
$$\mathcal{O}^{(9)}_4 = \epsilon^{ik}(\bar{u}^\alpha_R Q^\beta_j)(\bar{L}^j d^\alpha_R)(\bar{L}_i Q^{\beta c}_k)\,.$$

- Step 2

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UV models:

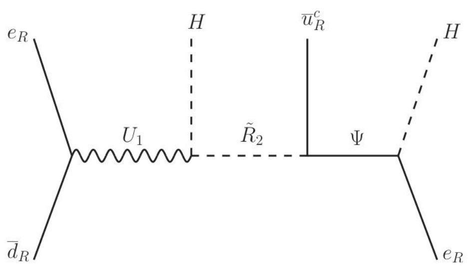
	operator	leptoquark(s)		vector-like fermions	singlet scalar
tree level	$\mathcal{O}^{(9)}_1$	$\tilde{R}_2 \in (3,2,1/6)$	$U_1 \in (3,1,2/3)$	$\Psi_{L,R} \in (1,2,-1/2)$	/
tree level	$\mathcal{O}^{(9)}_2$	$\bar{S}_1 \in (\bar{3},1,-2/3)$	$\tilde{V}_2 \in (\bar{3},2-1/6)$	$E'_{L,R} \in (1,1,-1)$	/
tree level	$\mathcal{O}^{(9)}_3$	$\tilde{R}_2 \in (3,2,1/6)$	/	$\Psi_{L,R} \in (1,2-1/2)$	$S \in (1,1,0)$
tree level	$\mathcal{O}^{(9)}_4$	$\tilde{R}_2 \in (3,2,1/6)$	$S_1 \in (\bar{3},1,1/3)$	$\Psi_{L,R} \in (1,2-1/2)$	/
one-loop level	$O^{(7)}_{\bar{d}uLLD}$	$\tilde{V}_2 \in (\bar{3},2-1/6)$	/	$\Psi_{L,R} \in (1,2,-1/2)$, $d'_{L,R} \in (3,1,-1/3)$	$S \in (1,1,0)$

$v^2/\Lambda^2 \sim 1/16\pi^2$

UV completion

- Indirect searches in $0\nu\beta\beta$ decay experiments

$$\mathcal{L} \supset \lambda_{ed}\left(\bar{d}_R \gamma_\mu e_R\right) U_1^\mu + \lambda_{u\Psi} \tilde{R}_2^* \bar{u}_R^c \Psi_R$$
$$+ \lambda_{DH} U_1^{\mu\dagger} \tilde{R}_2 \epsilon \left(i D_\mu H\right) + f_{\Psi e} \bar{\Psi}_L H e_R + \text{h.c.}$$



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UV completion

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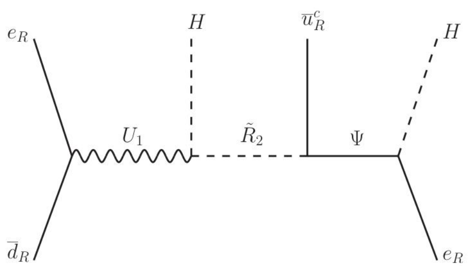

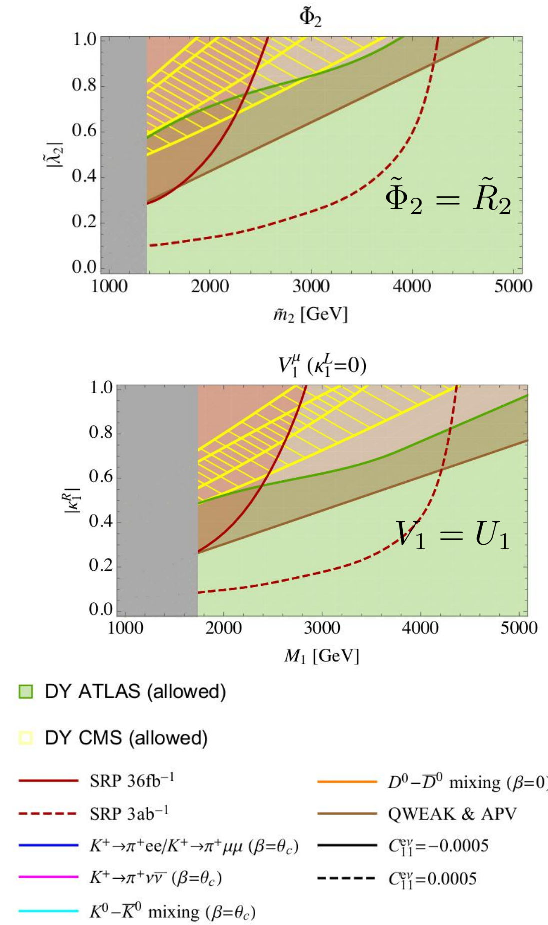

PP (excluded)

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A. Crivellin, L. Schnell, 2104.06417 (PRD)

UV completion

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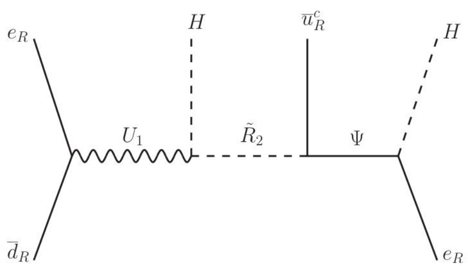

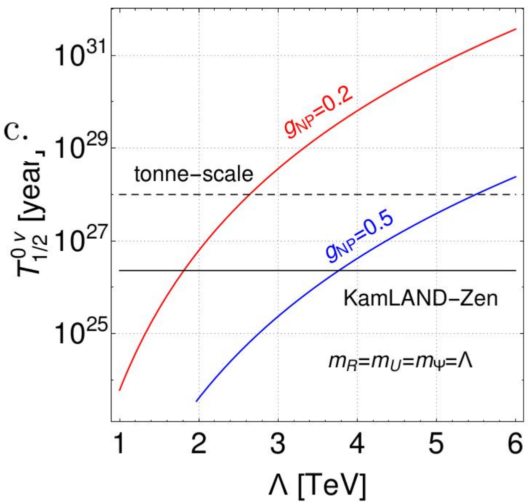

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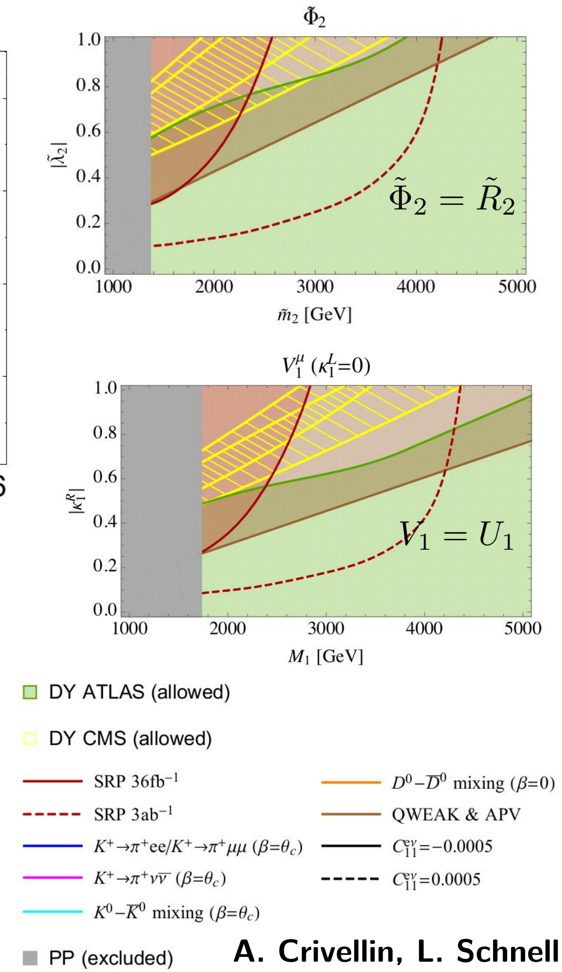

A. Crivellin, L. Schnell, 2104.06417 (PRD)

UV completion

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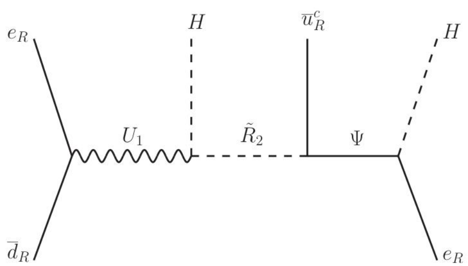

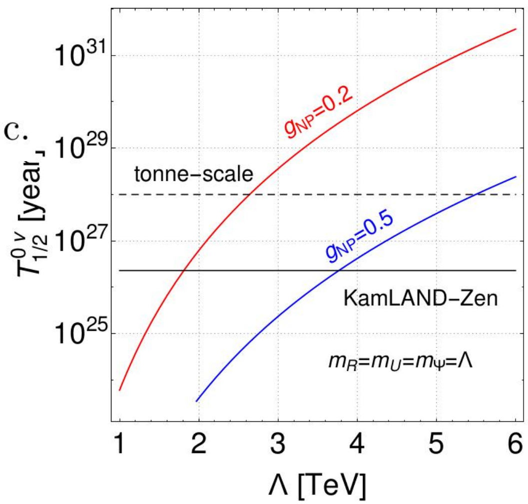

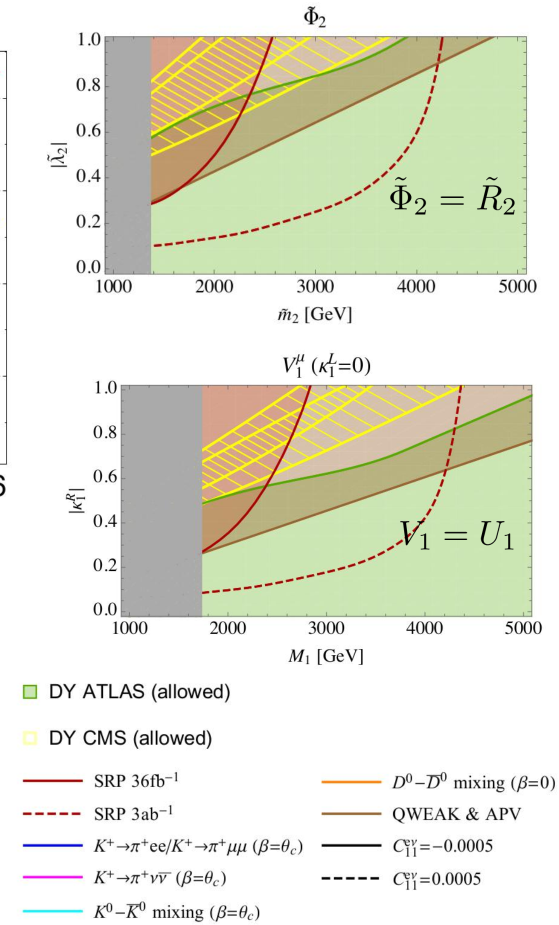

Leptoquarks are good candidates for the UV completions

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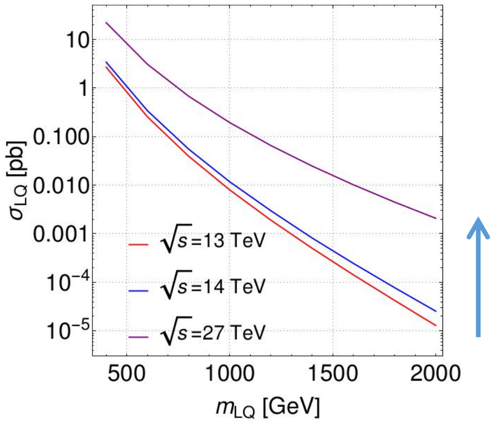
UV completion

- Direct searches at the LHC



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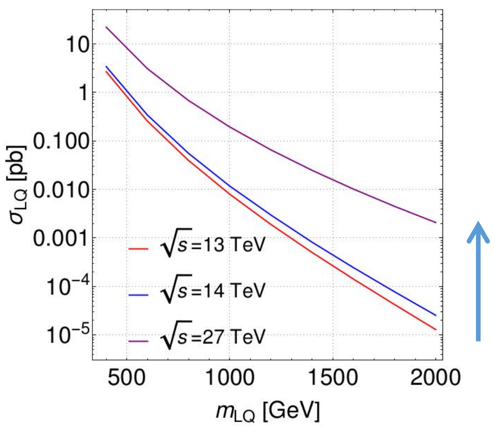
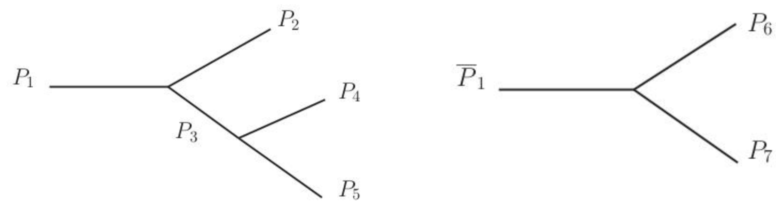
UV completion

- Direct searches at the LHC





operator	P_1	P_2	P_3	P_4	P_5	P_6	P_7
$\mathcal{O}_1^{(9)}$	$\tilde{R}_2^{-1/3}$	W^-	$U_1^{2/3}$	e^+	d	e^+	$\bar{u}$
	$U_1^{-2/3}$	W^-	$\tilde{R}_2^{+1/3}$	e^+	$\bar{u}$	e^+	d

$$pp \to e^\pm e^\pm jjW^\mp$$

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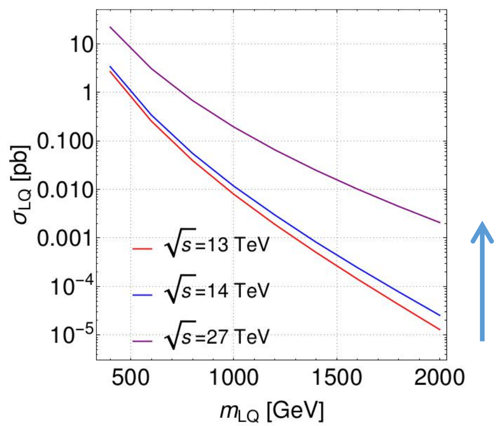
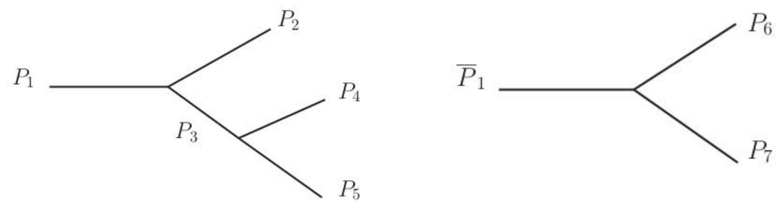
UV completion

- Direct searches at the LHC





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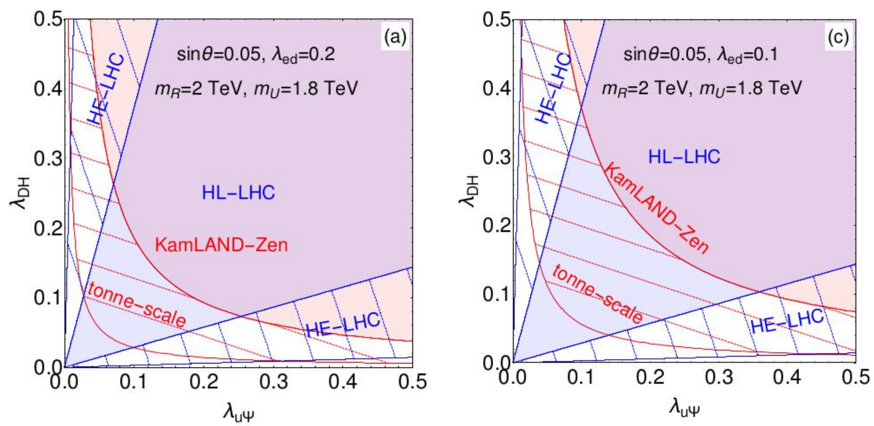

Searches at the LHC and $0\nu\beta\beta$ decay experiments are complementary to test the UV completions

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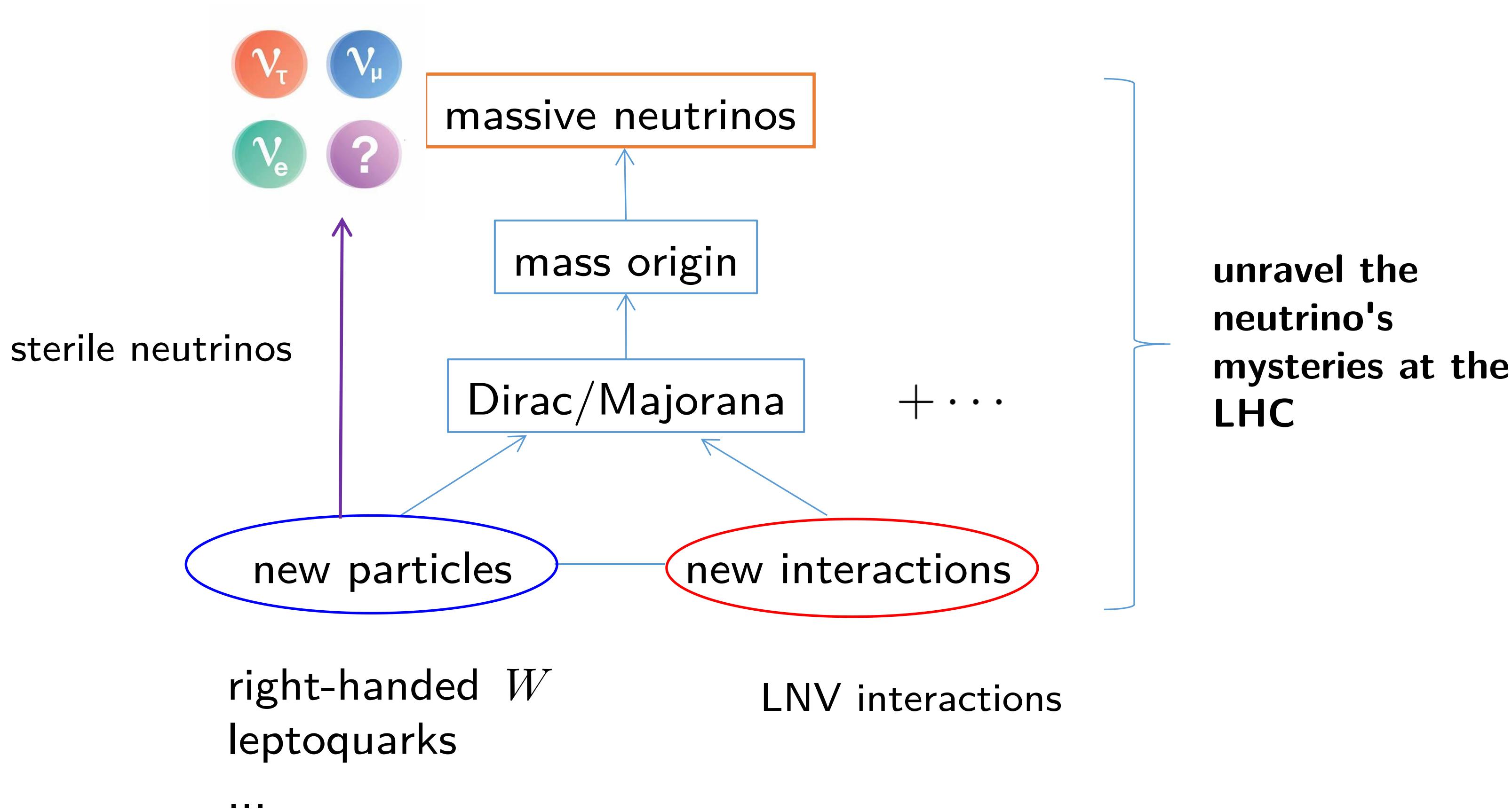
Summary

- New physics related to neutrinos



Summary

- This talk reviews some aspects of neutrino physics
- New physics related to neutrinos -- sterile neutrino, LNV -- is studied at the LHC
- Complementary searches for LNV in the ongoing $0\nu\beta\beta$ decay experiments and at the upgrated LHC (LLP, HL-LHC, HE-LHC)
- The EFT framework is used to study $0\nu\beta\beta$ decay, while promising UV completions are classified -- left-right symmetric model, leptoquark models

Thanks for your attention!