Lepton Number Violation:

from $0\nu\beta\beta$ Decay to LLP Searches

Gang Li (李刚)

ACFI, University of Massachusetts Amherst

arXiv:2109.08172 in collaboration with

Michael J. Ramsey-Musolf, Shufang Su, Juan Carlos Vasquez

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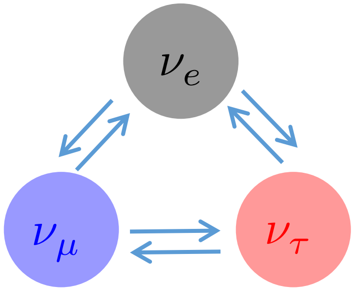
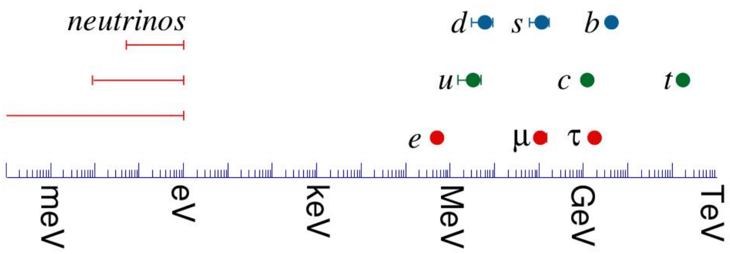
Lepton number violation

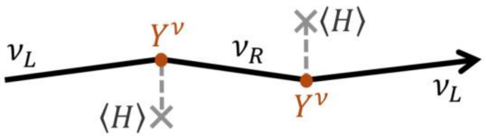
- Neutrinos are massive





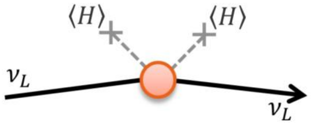
- How do neutrinos obtain tiny masses?

Higgs mechanism:



$Y^\nu < 10^{-13}$

seesaw mechanism (**P. Minkowski 1977**):

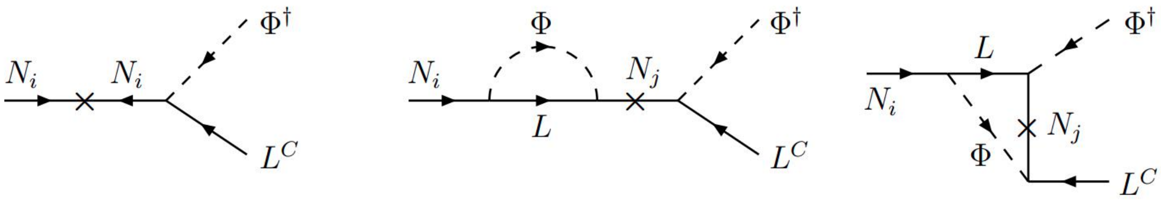


$\Delta L = 2$

seesaw scale can be anywhere

Lepton number violation

- LNV is also motivated by observed baryon asymmetry in the Universe (leptogenesis Fukugita&Yanagida 1986)



- LNV scale may be accessible at colliders and in low-energy experiments

- This talk focuses on the interplay of neutrinoless double beta decay and long-lived particle searches in the tests of LNV $\Delta L = 2$

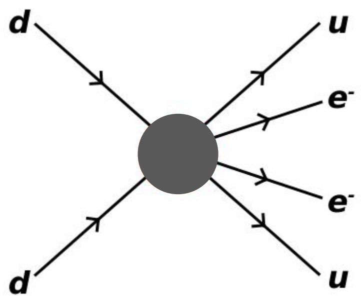
$0\nu\beta\beta$ decay in a nutshell

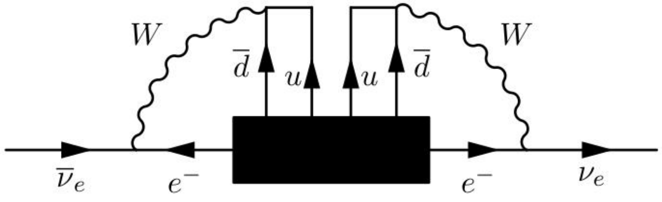
- Neutrinoless double beta ($0\nu\beta\beta$) decay in nuclei ^{136}Xe, ^{76}Ge, et al.

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

A: mass number # of p, n
Z: atomic number # of p

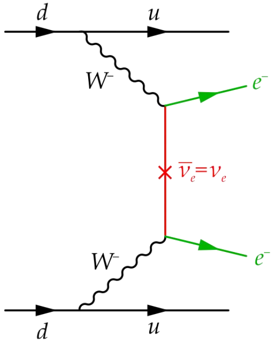
- It can provide direct evidence for Majorana neutrino mass and LNV





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

regardless of the origin of the "black box"



+ other $\Delta L = 2$ LNV interactions

$0\nu\beta\beta$ decay in a nutshell

From kg to tonne scale experiments (PandaX-III, CDEX-1T etc.)

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	300 kg	CaF_2 scint. crystals	Prototype	Kamioka
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating	LNGS
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Operating	SURF
CDEX-1T	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Prototype	CJPL
LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Construction	LNGS
LEGEND-1000	^{76}Ge	ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	5 kg	Zn^{enr}Se scintillating bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2019	Modane
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
CMOS Imaging	^{82}Se		^{enr}Se, CMOS	Development	
AMoRE-Pilot	^{100}Mo	1 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Operation	YangYang
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2019	YangYang
AMoRE-II	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2020	Yemi
CROSS	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$ surface coated Bolometers	Construction - 2020	Canfranc
LUMINEU	^{100}Mo		Li^{enr}MoO$_4$, Zn^{enr}MoO$_4$ scint. bolometers	Development	LNGS, LSM
Aurora	^{116}Cd	1 kg	^{enr}CdWO$_4$ scintillating crystals	Development	LNGS
COBRA-dem	^{116}Cd	0.38 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Tin.Tin	^{124}Sn	1 kg	Tin bolometers	Development	INO
CALDER	^{130}Te		TeO_2 bolometers with Cerenkov Light	Development	LNGS
CUORE	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+	^{130}Te	1.3 t	0.5% ^{enr}Te loaded liq. scint.	Construction - 2020	SNOLab
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100	^{136}Xe	100 kg	gas TPC	Prototype	Canfranc
AXEL	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen	^{136}Xe	800 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
LZ	^{136}Xe		Dual phase Xe TPC	Construction - 2020	SURF
PANDAX-III	^{136}Xe	1 ton	Dual phase Xe TPC	Construction - 2019	CJPL
XENON1T	^{136}Xe	1 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
NuDot	Various		Cherenkov and scint. detection in liq. scint.	Development	
FLARES	Various		Scint. crystals with Si photodetectors	Development	

May 28, 2020 Elliott, BB Theory Workshop

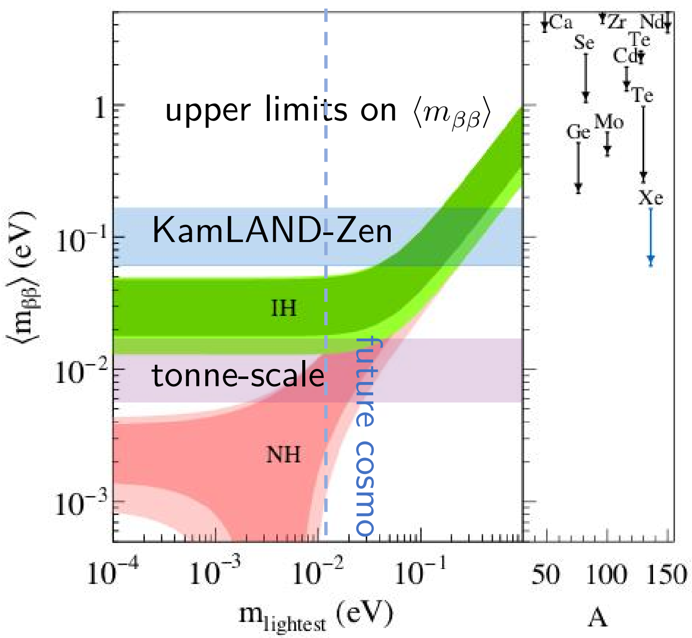
$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ year → $T^{0\nu}_{1/2} \gtrsim 10^{28}$ year

$0\nu\beta\beta$ decay in a nutshell

Interpretation as effective Majorana mass

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

$G_{0\nu}$: phase space factor
$M_{0\nu}$: nuclear matrix element



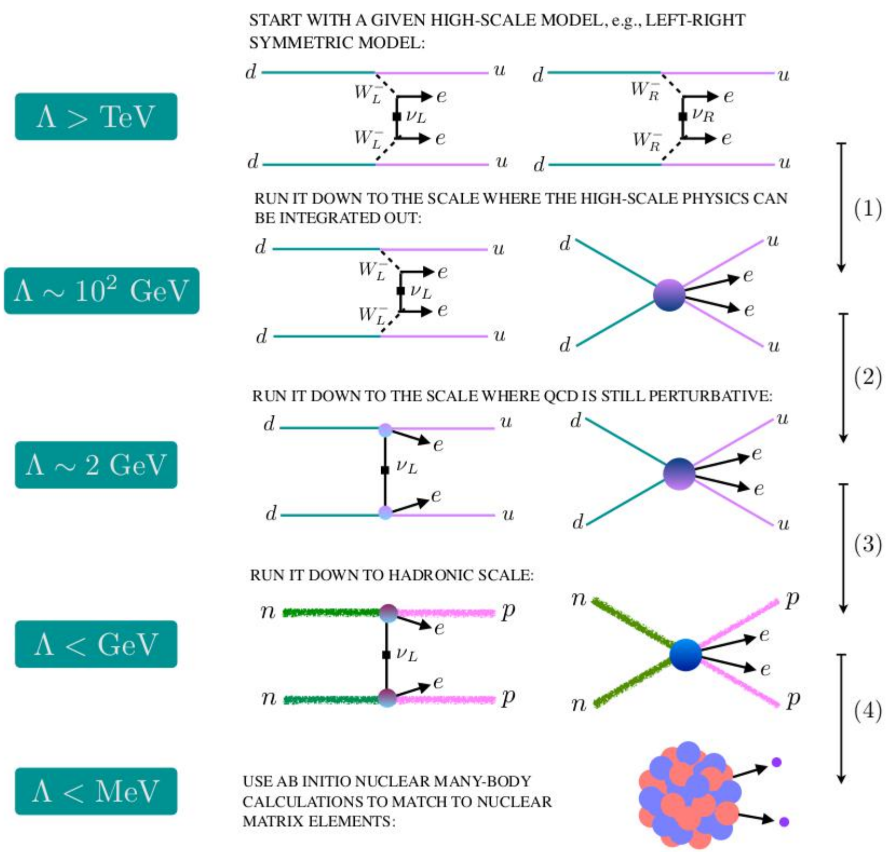
NH is favored over IH at 2.7σ with current neutrino oscillation data

P.F. de Salas et al, 2006.11237 (JHEP)

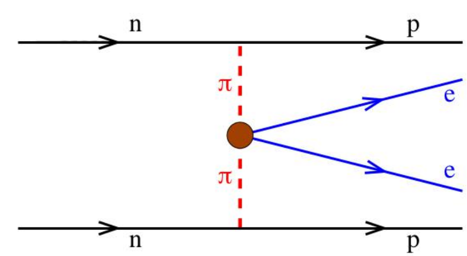
It is plausible that a positive $0\nu\beta\beta$-decay signal would come from other sources of LNV beyond neutrino masses

EFT and UV completion

$0\nu\beta\beta$ decay is insensitive to the underlying mechanism of LNV



- An EFT approach to $0\nu\beta\beta$ decay can include all LNV sources systematically
- Contributions to $0\nu\beta\beta$ decay from different LNV sources are organized in powers of p/Λ_χ (chiral power counting)



Prezeau, Ramsey-Musolf, Vogel, PRD 68, 034016 (2003)
Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP12(2018)097

We will consider the leading-order operators and their UV completion

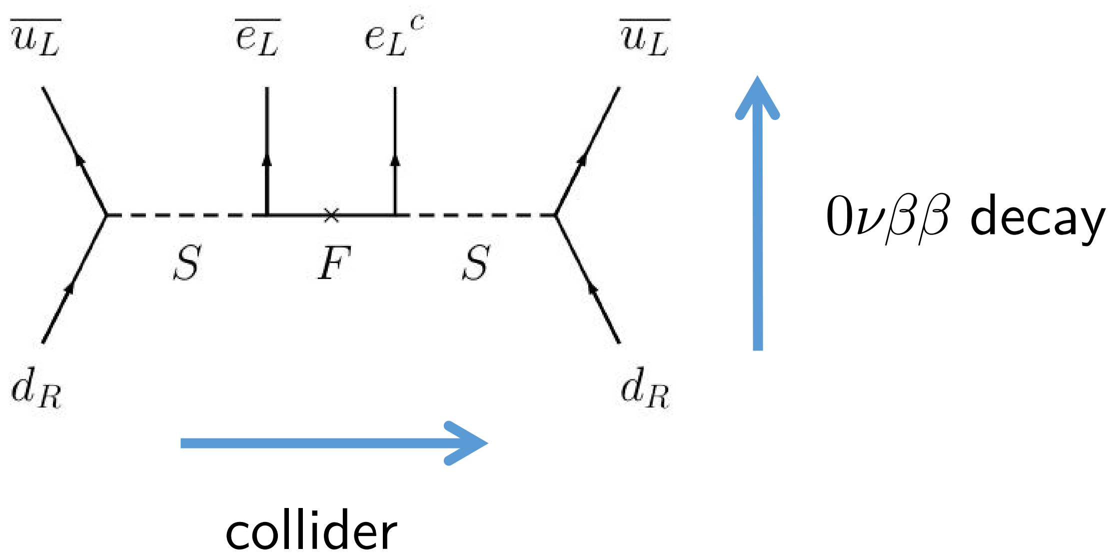
A simplified model

Doublet scalar S, Majorana fermion F

$$\mathcal{L} = (\partial_\mu S)^\dagger \partial^\mu S - m_S^2 S^\dagger S + \frac{1}{2}\bar{F}^c(i\partial\!\!\!/ - m_F)F$$
$$+ g_Q \bar{Q}_L S d_R + g_L \bar{L}\tilde{S}F + \text{h.c.}$$

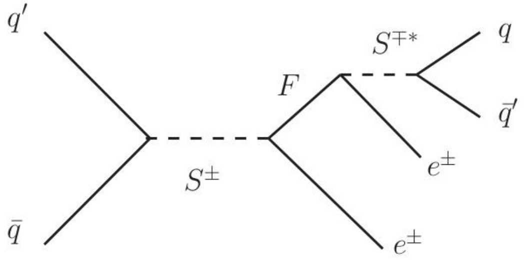
Lepton number is violated by the mass term of F

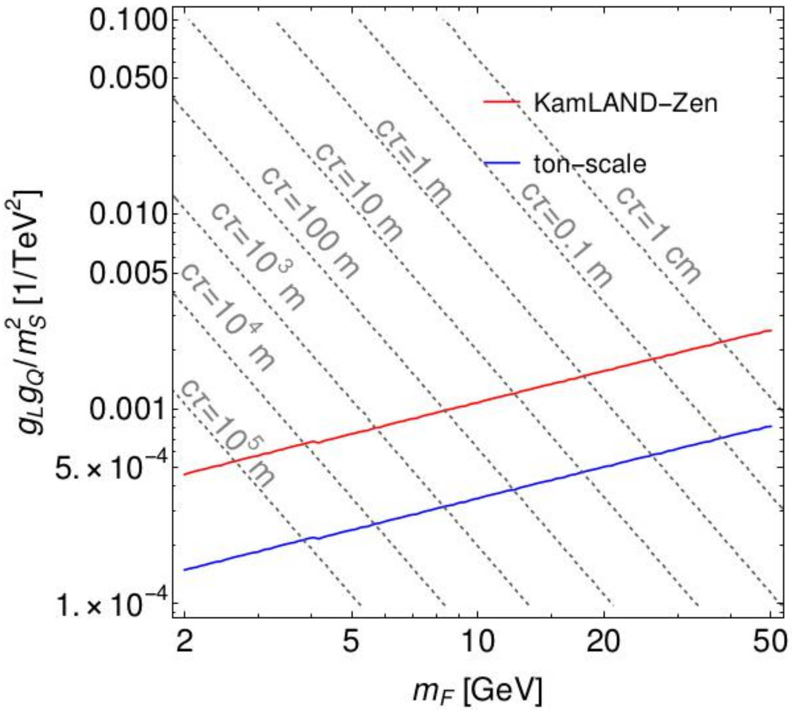
Uncover the mechanism of LNV $\Delta L = 2$

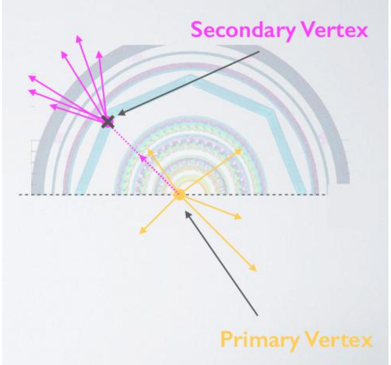


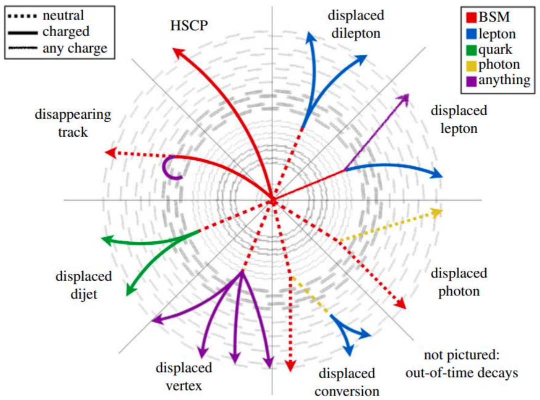
Why LLP searches?

- Almost zero background events
- Prompt searches may fail for small couplings and/or mass





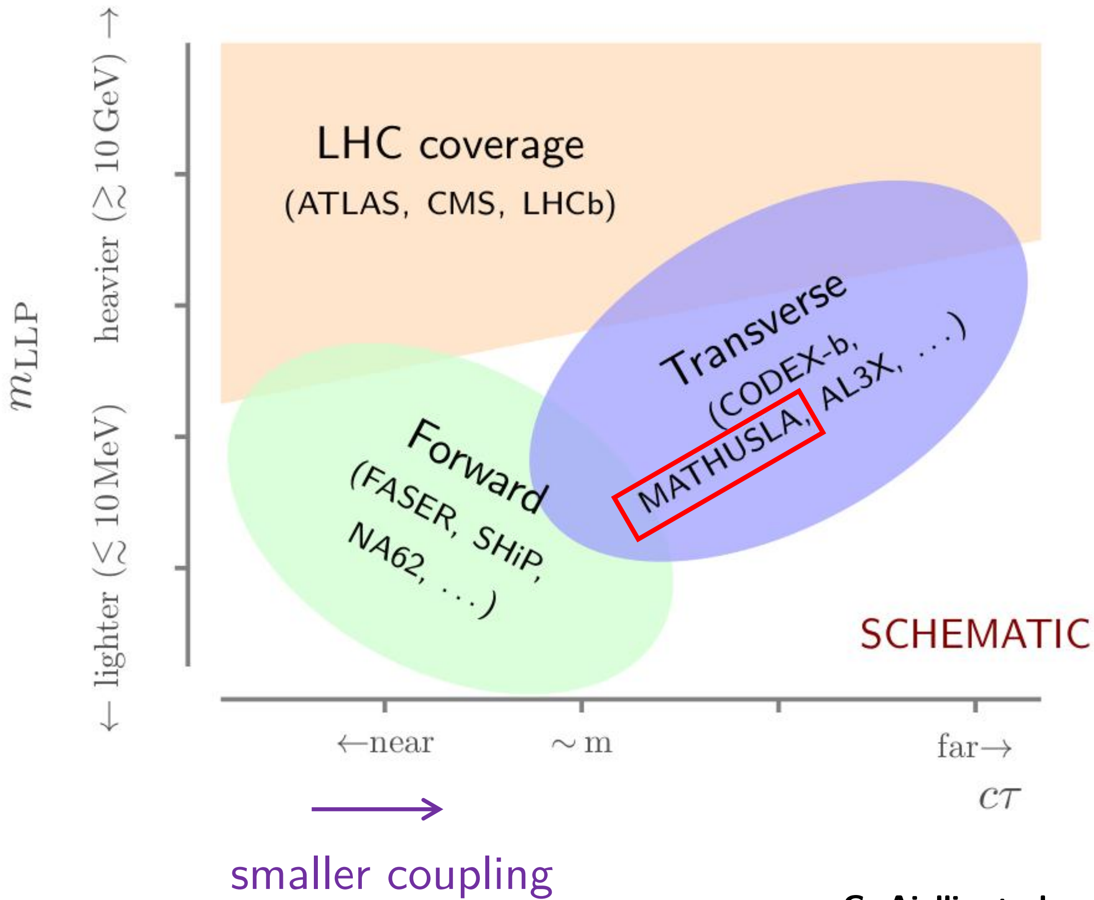


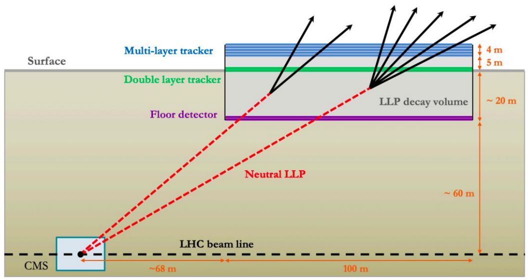


$c\tau = \hbar c/\Gamma$

GL, M. Ramsey-Musolf, S. Su, J. C. Vasquez, 2109.08172

LLP searches: lifetime frontier





G. Aielli, et al, 1911.00481 (EPJC)

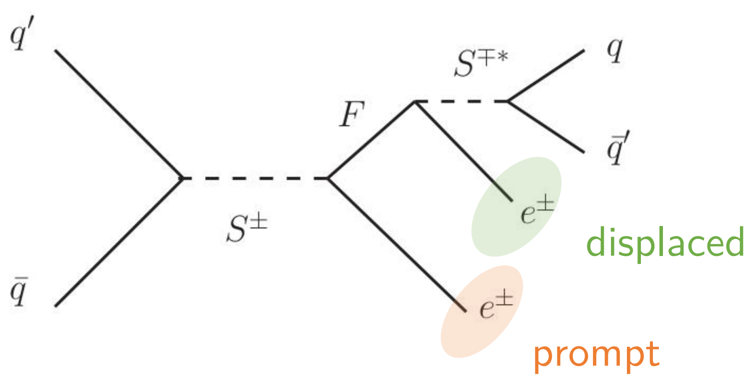
LLP searches at the HL-LHC

Observed numbers of signal events at the detector = ATLAS/CMS, MATHUSLA

$$N_{\rm obs}^{\rm detector} = \sigma_{eF}\ {\rm Br}_{ejj}\ \mathcal{L}\ \epsilon_{\rm LLP}^{\rm detector}\ \epsilon_{\rm prompt}^{\rm detector}\ \mathcal{P}_{\rm decay}$$

$$\mathcal{P}_{\rm decay} \equiv \frac{1}{\sigma_{eF}} \int_{\Delta\Omega} d\Omega \frac{d\sigma_{eF}}{d\Omega} \int_{L_1}^{L_2} dL \frac{1}{d_\perp} e^{-L/d_\perp}$$

$d_\perp$: transverse decay length



We require two same-sign electrons to be reconstructed (dispalced lepton), thus clear LNV signal

Genuine LNV signal in LLP searches

LLP searches at the HL-LHC

Observed numbers of signal events at the detector = ATLAS/CMS, MATHUSLA

$$N_{\rm obs}^{\rm detector} = \sigma_{eF}\ {\rm Br}_{ejj}\ \mathcal{L}\ \epsilon_{\rm LLP}^{\rm detector}\ \epsilon_{\rm prompt}^{\rm detector}\ \mathcal{P}_{\rm decay}$$

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$d_\perp$: transverse decay length

Analytic approach (validated): $P_{\rm decay}(d; L_1, L_2) = e^{-L_1/d} - e^{-L_2/d}$

$$\mathcal{P}_{\rm decay} = P_{\rm decay}$$

$$\mathcal{P}_{\rm decay} = P_{\rm decay}\epsilon_{\rm geometric} \quad \epsilon_{\rm geometric} = 0.05$$

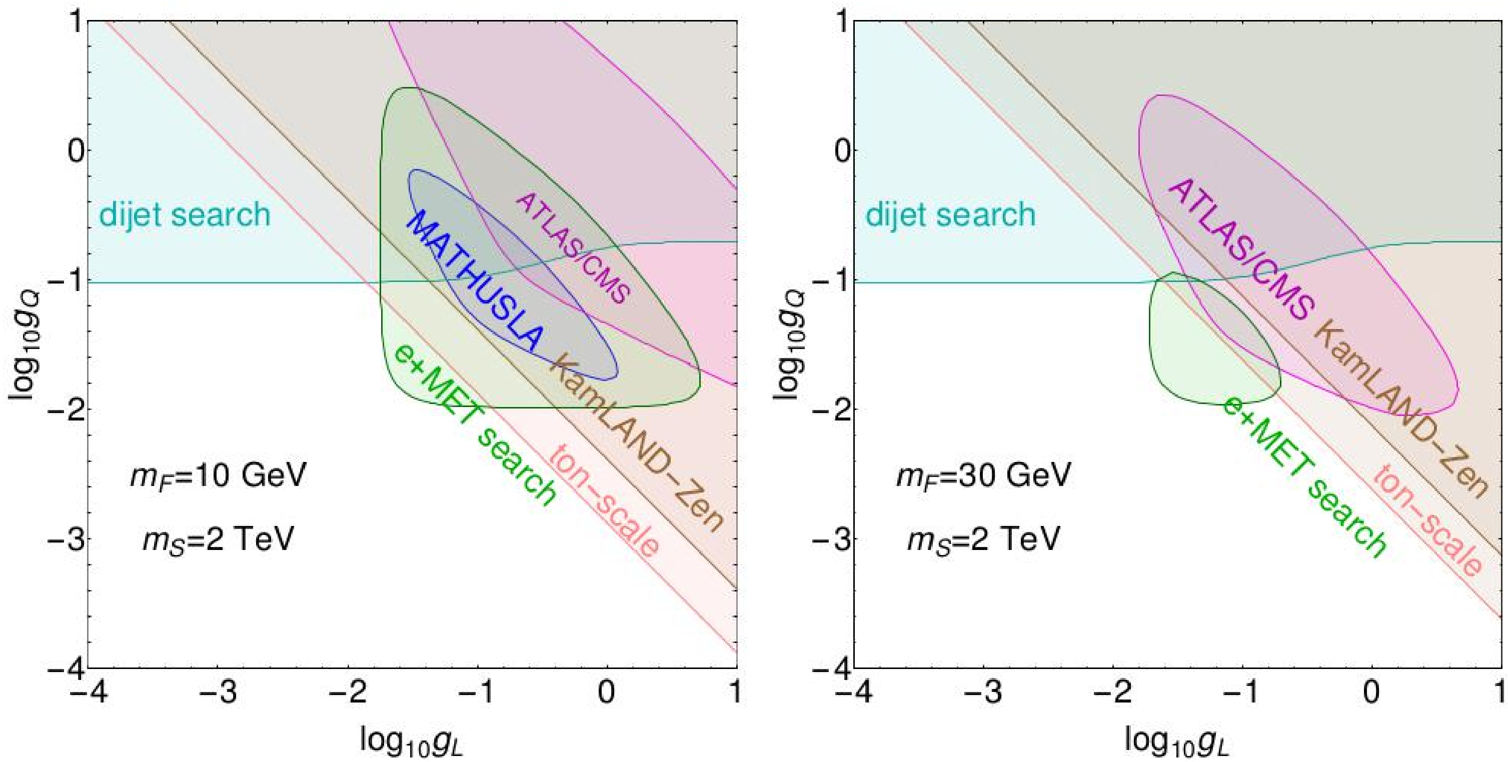
$$\epsilon_{\rm LLP}^{\rm LHC}\epsilon_{\rm prompt}^{\rm LHC} = 0.01$$

$$\epsilon_{\rm LLP}^{\rm MATH} = 1,\ \epsilon_{\rm prompt}^{\rm MATH} = 1$$

(our proposed effciencies)

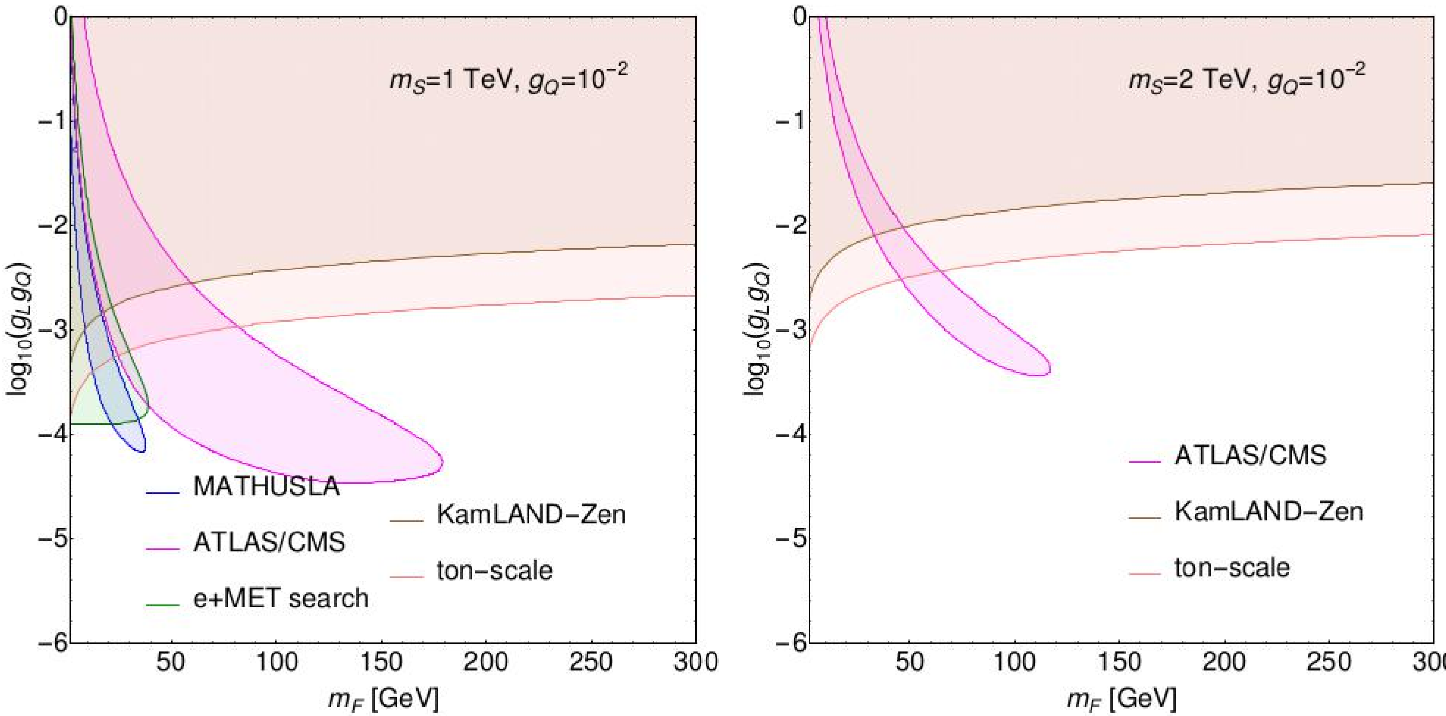
Interplay of LLP searches and $0\nu\beta\beta$ decay

The sensitivities to g_L and g_R



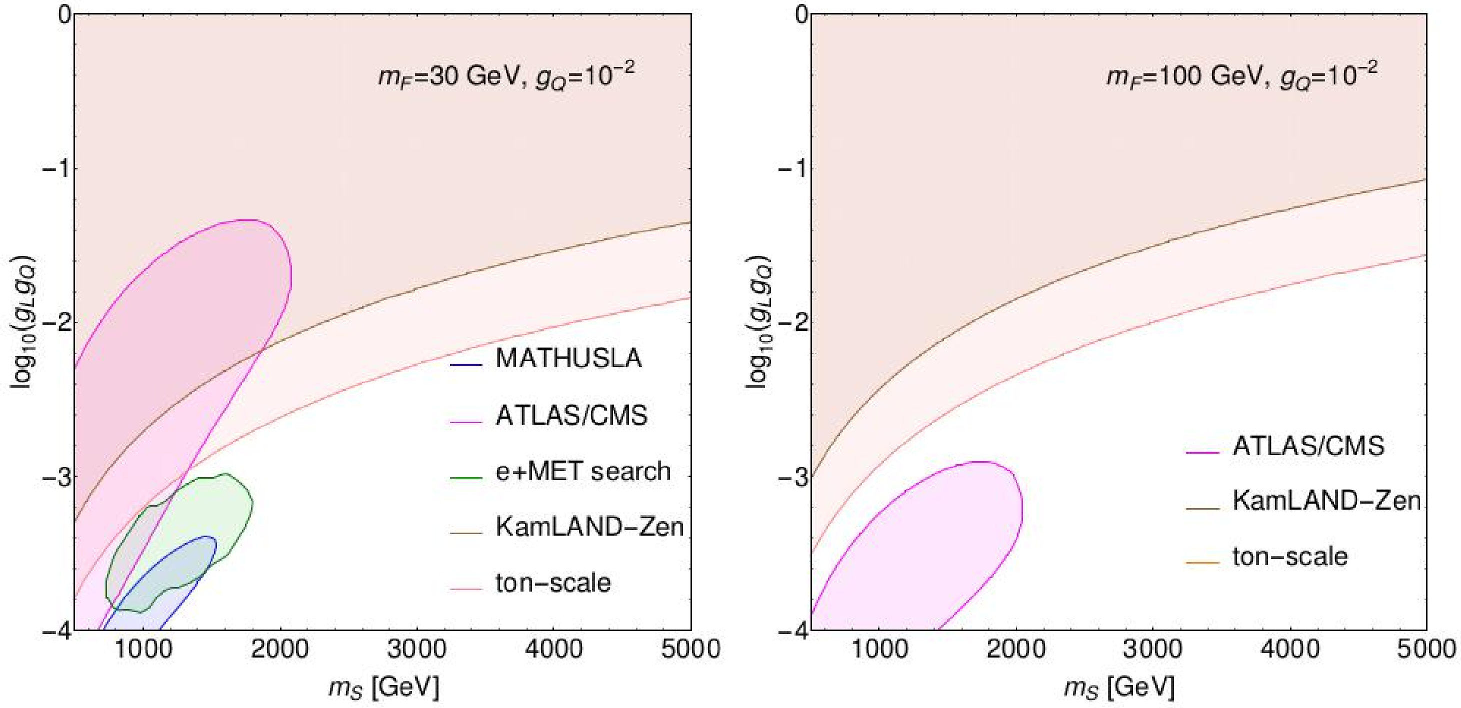
Interplay of LLP searches and $0\nu\beta\beta$ decay

The reaches to m_F



Interplay of LLP searches and $0\nu\beta\beta$ decay

The reaches to m_S



Summary

- $0\nu\beta\beta$ decay, once observed, is a clear and direct evidence for Majorana neutrino masses and LNV $\Delta L = 2$
- While $0\nu\beta\beta$ decay is insensitive to the underlying mechanism, the LHC searches can uncover it if the associated LNV scale is at TeV or smaller
- We propose to search for LNV in LLP searches
- In a simplified model, we show the complementarities between the $0\nu\beta\beta$ decay and LLP searches at HL-LHC with ATLAS/CMS and MATHUSLA detectors