On the Origin of Neutrino Mass and Lepton Number Violating Searches

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Outline:

- Experimental observations
- Seesaw and massive neutrinos
- Lepton number violating searches
- Neutrinoless double beta decay
- Underlying mechanisms
  - canonical and beyond standard model interpretations
- Complementarity with collider searches
- Seesaw and astroparticle probe
- Summary

Experimental Observation:

Non-zero eV neutrino masses m_i and mixing U from oscillation and non-oscillation experiments

- Cosmological bound on the sum of light neutrino masses

$$\sum_i m_i < 0.23 - 1.08 \text{ eV}$$

Planck collaboration, 2013

$$\Delta m^2_{21} = (7.0 - 8.09) \times 10^{-5}\,\mathrm{eV}^2$$
$$\Delta m^2_{31} = (2.27 - 2.69) \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{12} = 0.27 - 0.34$$
$$\sin^2\theta_{23} = 0.34 - 0.67$$
$$\sin^2\theta_{13} = 0.016 - 0.030$$

Schwetz et al., 2012

Also Fogli., et al., 2012

Super Kamiokande, Long Baseline $\sim$ T2K, MINOS, K2K

Reactor $\sim$ DAYA BAY, RENO, Double CHOOZ,...

Solar $\sim$ SNO, Borexino, SAGE, GALLEX...

List of Don't Knows

Neutrino Mass

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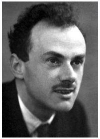

Dirac or Majorana?

- Dirac mass, $m_D \bar{\nu}_L N_R \rightarrow$ lepton number is conserved
- Majorana mass, $m \nu^T C^{-1} \nu \rightarrow$ lepton number is violated by two units

Lepton number is a Global $U(1)$ symmetry of the standard model

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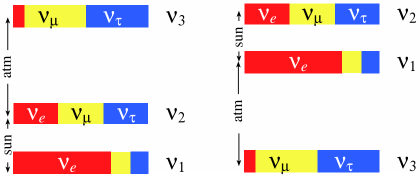
Normal or Inverted?

$$\Delta m^2_{12} \sim 10^{-5}\mathrm{eV}^2 \text{ and } \Delta m^2_{13} \sim 10^{-3}\mathrm{eV}^2$$



Lightest neutrino state ν_1 or ν_3 ??

Oscillation Experiments

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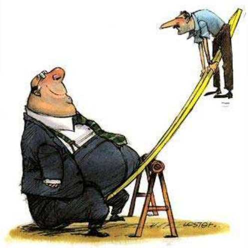
- Majorana phases $\boxed{\alpha,\ \beta\ ?}$ $\rightarrow$ Neutrinoless double beta decay
- CP violation in leptonic sector $\boxed{\text{phase } \delta\ ?}$ $\rightarrow$ Oscillation experiments?
- Lightest mass scale $\boxed{m_0?}$ $\rightarrow$ Low energy observable, like beta decay, neutrinoless double beta decay with cosmology
- Precision in the mixing angles $\boxed{\theta_{23},\ \theta_{12} \text{ and } \theta_{13}?}$ $\rightarrow$ Oscillation experiments

Behind neutrino mass:

Neutrinos $\sim$ eV mass?? Top to neutrino mass ratio 10^{12}



Seesaw

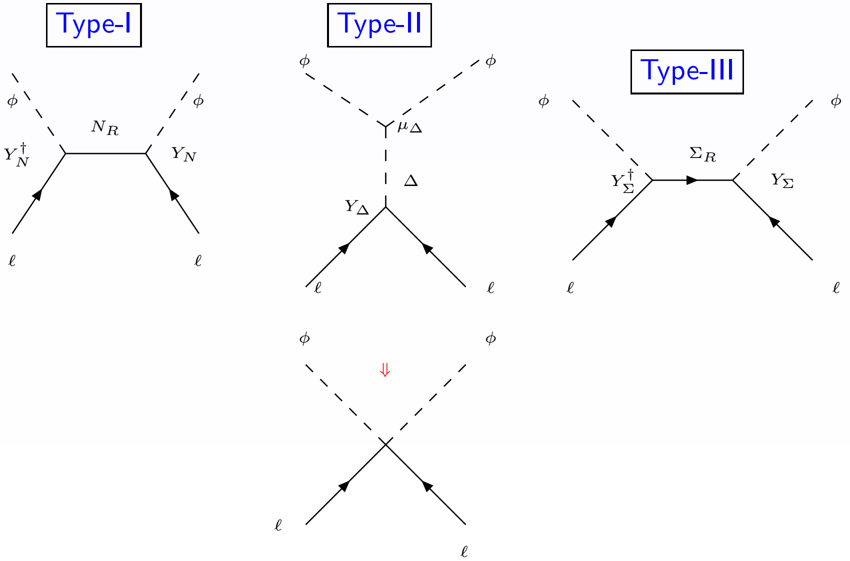
Gell-mann, Raymond, Slansky, Minkowski

- Heavy modes integrated out $\Rightarrow \hat{O} = \frac{LL\phi\phi}{M} \Rightarrow$ Weinberg *d*=5 operator
- $\frac{y^2 LL\langle\phi\rangle\langle\phi\rangle}{M} \Rightarrow m_\nu \Rightarrow$ Neutrino Mass
- For $M = 10^{15}$ GeV, neutrino mass of eV is generated with $y \sim \mathcal{O}(1)$

Tree Level Mass Generation

- Type-II $\leftarrow$ Seesaw $\rightarrow$ Type-I or Type-III
- Intermediate state bosonic/fermionic
- Type-I seesaw: Intermediate state fermionic gauge singlet
- Type-III seesaw: $SU(2)$ triplet fermion with $Y = 0$
- Type-II seesaw: $SU(2)$ triplet scalar with $Y = -2$

Contd:


Type-I
ϕ
ϕ
N_R
$Y_N^\dagger$
Y_N
ℓ
ℓ
Type-II
ϕ
ϕ
μ_Δ
Δ
Y_Δ
ℓ
ℓ
Type-III
ϕ
ϕ
Σ_R
$Y_\Sigma^\dagger$
Y_Σ
ℓ
ℓ
ϕ
ϕ
$\Downarrow$
ℓ
ℓ

Type-I/III Seesaw

Add gauge singlet fermionic field N_R or $SU(2)$ triplet fermion Σ

Lagrangian:

$$-\mathcal{L}_\nu = Y_\nu \overline{L}\tilde{H}N_R + \frac{1}{2}\overline{\mathbf{N^c_R}}\mathbf{M}\mathbf{N_R} + \mathrm{h.c}$$

Lagrangian:

$$-\mathcal{L}_Y = \left[Y_{lij}\bar{l}_{R_i}H^\dagger L_j + Y_{\Sigma ij}\tilde{H}^\dagger\overline{\Sigma}_{R_i}L_j + h.c.\right] + \frac{1}{2}M_{\Sigma_{ij}}Tr\left[\overline{\Sigma}_{R_i}\Sigma^{C'}_{R_j} + h.c.\right]$$

$SU(2)$ triplet, $Y=0$ fermion field, $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

- Lepton Number Violation $\rightarrow$ $M, \ M_\Sigma$
- $m_\nu \sim m_D^T M^{-1} m_D$ where $m_D = Y_\nu v$
- For $M \sim 10^{15}$ GeV, $m_\nu \simeq 1$ eV is generated without any fine tuning of yukawa. For $M \sim 1\,\mathrm{TeV}$, we need $Y_\nu \sim 10^{-6}$
- Fits within $SO(10)$, $SU(5)$ Grand Unified Theory

Type-II Seesaw

- Higgs triplet, Δ (3,2), $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$
- Lagrangian,

Lagrangian:

$$-\mathcal{L}_Y = y_\Delta l_L^T C i\tau_2 \Delta l_L + \mu_\Delta \phi^T i\tau_2 \Delta^\dagger \phi + M_\Delta Tr(\Delta^\dagger \Delta) + \text{h.c} + ...$$

- Integrating out heavy Higgs triplet $\rightarrow$ $C_{\alpha\beta}(\overline{l^c_{L\alpha}}\widetilde{\phi^*})(\widetilde{\phi}^\dagger l_{L\beta})$
- $C \propto y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$
- $M_\nu \propto y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$
- Light neutrino mass is proportional to μ

Inverse Seesaw

Add singlet fermionic fields N, S.

. Small lepton number violating scale μ

$$M_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix}$$

Mohapatra, PRL, 86

- For $\mu \ll m_D < M \rightarrow$ $m_\nu \sim m_D^T {M^T}^{-1} \mu M^{-1} m_D$

$\mu \rightarrow$ Lepton number violation. $\mu \rightarrow 0 \implies M_\nu \rightarrow 0$ and enhanced lepton number symmetry. Inverse seesaw

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Loop generated mass? Radiative inverse seesaw (Dev, Pilaftsis, 2012)

Supersymmetry (R-parity violation) and neutrino mass

Phenomenologies

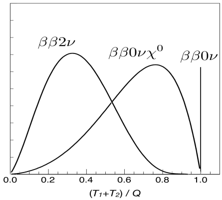
Astroparticle Physics → leptogenesis, dark matter, ...

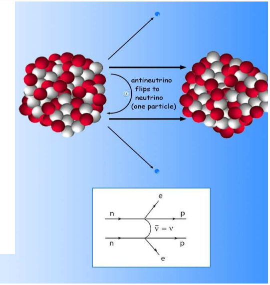
Collider Phenomenologies → lepton number and flavor violation

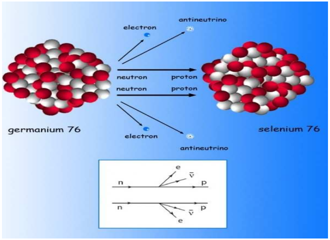
Low Energy Experiments → lepton number and flavor violation

Lepton Number Violating Searches

Neutrinoless double beta decay



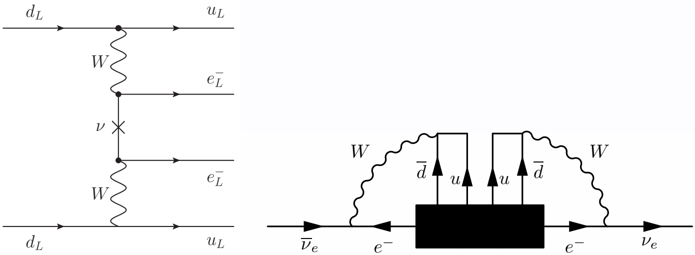




The process is $(A, Z) \to (A, Z+2) + 2e^-$

Probing lepton number violation

Why important?



Schechter-Valle, PRD, 82

Information about the effective mass m_{ee}^{ν}

Majorana Nature of Light Neutrinos

L and B numbers are accidental symmetries of the standard model

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- Chiral anomalies $\partial_\mu j^\mu_{B,L} \neq 0$
- The low energy effective Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \xi_1 \frac{\mathcal{O}_5}{M} + \xi_2 \frac{\mathcal{O}_6}{M^2} + ...$$

- $\mathcal{O}_5 \rightarrow$ LNV, $\mathcal{O}_6 \rightarrow$ LFV, BNV
- Lepton and Baryon number violation might originate from high scale theory

Not only mass measurement!

$0\nu2\beta$ is a probe of lepton number violation

Experimental Results

Experimental Results for $^{76}\mathrm{Ge}$

- Heidelberg-Moscow, $T^{0\nu}_{1/2} > 1.9 \times 10^{25}\mathrm{yr}$, 90% C.L
  H. V. Klapdor-Kleingrothaus *et al.*, 2001
- GERDA, $T^{0\nu}_{1/2} > 2.1 \times 10^{25}\mathrm{yr}$, 90% C.L
- GERDA combined (IGEX+Heidelberg-Moscow) $T^{0\nu}_{1/2} > 3.0 \times 10^{25}\mathrm{yr}$, 90% C.L
  GERDA collaboration, 2013

Experimental Results for $^{136}\mathrm{Xe}$

- EXO-200, $T^{0\nu}_{1/2} > 1.6 \times 10^{25}\mathrm{yr}$ at 90% C.L EXO collaboration, 2012
- KamLAND-Zen, $T^{0\nu}_{1/2} > 1.9 \times 10^{25}\mathrm{yr}$ at 90% C.L
- KamLAND-Zen combined, $T^{0\nu}_{1/2} > 3.4 \times 10^{25}\mathrm{yr}$ at 90% C.L
  KamLAND-Zen collaboration, 2012

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Positive Claim

- The half-life for $^{76}\mathrm{Ge}$, $T_{1/2}^{0\nu} = 1.19^{+037}_{-0.23} \times 10^{25}$ yr, 68% CL.

H. V. Klapdor-Kleingrothaus *et al.*, 2004

- The half-life for $^{76}\mathrm{Ge}$, $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr, 68% CL.

H. V. Klapdor-Kleingrothaus *et al.*, 2006

slide courtesy: W. Rodejohann

Experimental Aspects: existing limits

Isotope	$T_{1/2}^{0\nu}$ [yrs]	Experiment
^{48}Ca	5.8×10^{22}	CANDLES
^{76}Ge	1.9×10^{25}	HDM
	2.1×10^{25}	GERDA
	3.0×10^{25}	GERDA+HDM+IGEX
^{82}Se	3.2×10^{23}	NEMO-3
^{100}Mo	1.0×10^{24}	NEMO-3
^{130}Te	2.8×10^{24}	CUORE
^{136}Xe	1.6×10^{25}	EXO
^{136}Xe	1.9×10^{25}	KamLAND-Zen
^{136}Xe	3.4×10^{25}	EXO+KamLAND-Zen
^{150}Nd	1.8×10^{22}	NEMO-3

Future Experiments

Future limits

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011
		40	2×10^{26}	in progress	$\sim$ 2012
		1000	6×10^{27}	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	$\sim$ 2013
			$2.1 \times 10^{26**}$		
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013
		1000	6×10^{27}	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	in progress	$\sim$ 2011
		1000	8×10^{26}	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-15
KamLAND-Zen	^{136}Xe	400	4×10^{26}	in progress	$\sim$ 2011
		1000	10^{27}	R&D	$\sim$ 2013-15
SNO+	^{130}Te	800	$\sim 10^{26}$	in progress	$\sim$ 2014
		8000	$\sim 10^{27}$	R&D	$\sim$ 2017

Slide courtesy: W. Rodejohann

Future experiments $\rightarrow$ expected sensitivity $T_{1/2}^{0\nu} \sim 10^{26}/10^{27}$ yrs

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$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}|\mathcal{M}(A,Z)\,\eta|^2$$

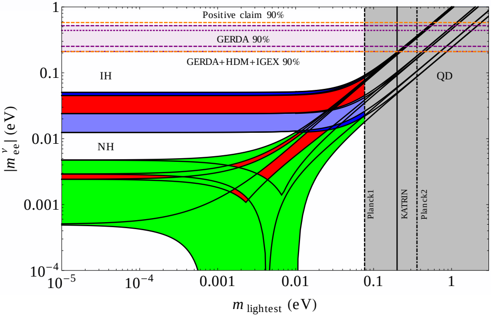
- $G_{0\nu} \rightarrow$ Phase space factor
- $\mathcal{M}(A,Z) \rightarrow$ Nuclear matrix element
- $\eta \rightarrow$ Particle physics parameter

$\frac{1}{T_{1/2}^{0\nu}} \propto \eta^2 \rightarrow$ Quadratic in particle physics parameter

Improvement of η by $\mathcal{O}(0.1)$ requires improvement of half life $T_{1/2}^{0\nu}$ by $\mathcal{O}(10^2)$

The light neutrino contribution

The half-life → $\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^\nu}{m_e}\right|^2$



- $G_{0\nu}$ → phase-space
- $\mathcal{M}_\nu$→ nuclear matrix element
- $m_{ee}^\nu = \Sigma m_i U_{ei}^2$ effective mass of $0\nu 2\beta$

$$|m_{ee}^\nu| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha} + m_3 U_{e3}^2 e^{2i\beta}|$$

- α, β → Majorana phase, m_i → light neutrino masses
- Unknown → neutrino mass spectra, absolute mass scale, CP phases

Comparison of experimental results

NME	Limit on m^{ν}_{ee} (eV)				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
EDF(U)	0.32	0.27	0.27-0.35	0.15	0.11
ISM(U)	0.52	0.44	0.44-0.58	0.28	0.21
IBM-2	0.27	0.23	0.23-0.30	0.19	0.14
pnQRPA(U)	0.28	0.24	0.24-0.31	0.20	0.15
SRQRPA-B	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA	0.29	0.24	0.24-0.32	0.33	0.25

DeV, Goswami, Mitra and Rodejohann, PRD, 2013

- Individual bound from GERDA does not rule out the positive claim
- Tension between the GERDA combined and positive claim
- Experiments using $^{136}\mathrm{Xe} \rightarrow$ A complimentary way to test the positive claim
- The constraint on the effective mass from $^{136}\mathrm{Xe}$ is stronger than $^{76}\mathrm{Ge}$

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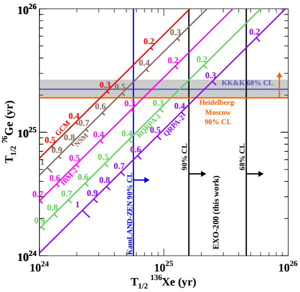
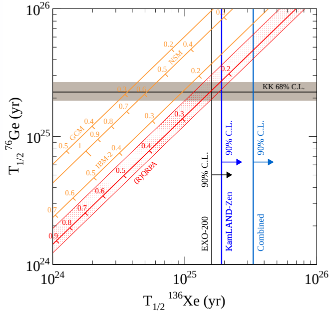
- The correlation between the half-lives

$$T^{0\nu}_{1/2}({}^{136}\text{Xe}) = \frac{G^{\text{Ge}}_{0\nu}}{G^{\text{Xe}}_{0\nu}} \left(\frac{\mathcal{M}_{0\nu}({}^{76}\text{Ge})}{\mathcal{M}_{0\nu}({}^{136}\text{Xe})}\right)^2 T^{0\nu}_{1/2}({}^{76}\text{Ge})$$

- The positive claim for ${}^{76}\text{Ge}$ will be ruled out for $T^{0\nu}_{1/2}(\text{predicted}) < \text{T}^{0\nu}_{1/2}(\text{exp})$ for ${}^{136}\text{Xe}$.





From A. Gando et al., 2012

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	NME		$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$
Method	$\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})$	$\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})$	$[10^{25}$ yr]
EDF(U)	4.60	4.20	0.33 - 0.57
ISM(U)	2.81	2.19	0.46 - 0.79
IBM-2	5.42	3.33	0.74 - 1.27
pnQRPA(U)	5.18	3.16	0.75 - 1.29
SRQRPA-B	5.82	3.36	0.84 - 1.44
SRQRPA-A	4.75	2.29	1.20 - 2.06
QRPA-B	5.57	2.46	1.43 - 2.46
QRPA-A	5.16	2.18	1.56 - 2.69
SkM-HFB-QRPA	5.09	1.89	2.02 - 3.47

DeV, Goswami, Mitra and Rodejohann, PRD, 2013

- The positive claim is ruled out from the combined bound of KamLAND-Zen ($T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr) for all but one, NME calculation. However, is consistent with individual limits for $^{136}\mathrm{Xe}$

Future predictions

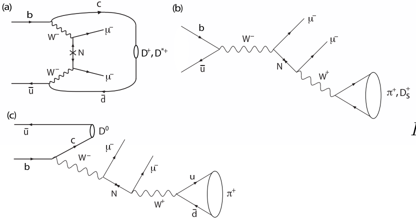
Implications for GERDA phase-II ($T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.50 \times 10^{26}$ yr)

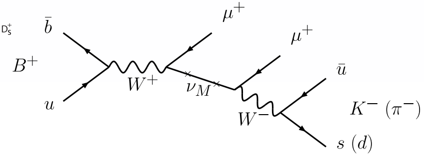
- The half-life of $^{136}\mathrm{Xe}$ $T^{0\nu}_{1/2} = 2.92 \times 10^{25} - 1.76 \times 10^{26}$ yr
- The lower value is incompatible with the combined limit from KamLAND-Zen $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr
- The range will be incompatible with the future EXO-1T limit $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 8 \times 10^{26}$

Meson decay and Collider Searches

Lepton number violation in meson system

$B^- \to D^+/\pi^+\mu^-\mu^-$, $B^- \to D^{*+}\mu^-\mu^-$, $B^- \to D^0\pi^+\mu^-\mu^-$, $B^+ \to K^-/\pi^-\mu^+\mu^+$

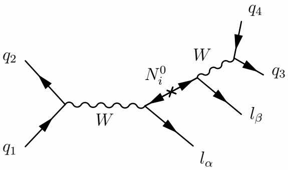




LHCb collaboration, 2012; LHCb collaboration, 2011; BELLE collaboration, O. Seon et al., 2011.

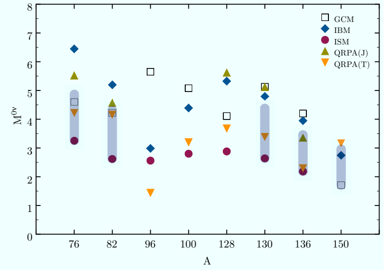
Also lepton number violating τ decays by BABAR, LHCb

Collider searches → same sign dilepton/multilepton signature



Limited by kinematics

———— $0\nu 2\beta$ ————



Limited by NME uncertainty

Underlying mechanisms

BSM Contributions!

- Sterile neutrino
- Left-Right symmetry
- R-parity violating supersymmetry

Additional contributions?

$0\nu2\beta \iff$ light Majorana neutrinos?

The effective Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \xi_1 \frac{llHH}{M} + \xi_2 \frac{qqql}{M^2} + \xi_3 \frac{(q\bar{d}l)^2}{M^5} + \ldots$$

Weinberg, PRL 43, 1979

- $\xi_1 \frac{llHH}{M} \rightarrow$ d-5 operator. Generates neutrino mass
- $\xi_2 \frac{qqql}{M^2} \rightarrow$ d-6. Relevant for proton decay
- $\xi_3 \frac{(u\bar{d}e)^2}{M^5} \rightarrow$ d-9. Relevant for neutrinoless double beta decay

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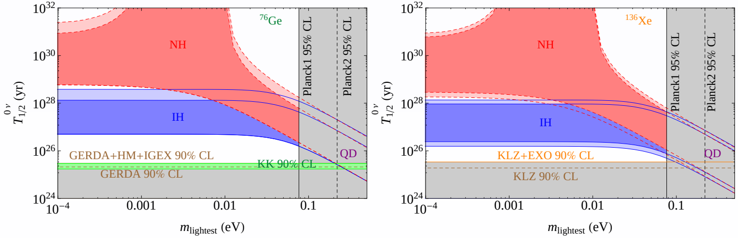
Dimension 5 and Dimension 9 operators are uncorrelated

Confronting with cosmology!



- The most stringent bound from Planck $\rightarrow \Sigma_i m_i < 0.23$ eV.
- The light neutrino contribution saturates the $0\nu2\beta$ in quasi degenerate region

Strong tension with cosmology!! (Fogli et al., 2008; Mitra et al., 2012, 2013)

More than one order of magnitude improvement in half-life is required $\rightarrow$ Additional contributions!!!

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Previous and recent studies

- R parity violating supersymmetry (Mohapatra 1986; Hirsch et al, 1995; Choi et al, 2002; Allanach et al, 2009.)
- Left Right symmetry (Hirsch et al., PLB, 96, Tello et al., PRL, 2011, Goswami et al., JHEP, 2012, Barry et al., JHEP, 2013, Vogel et al., PRD, 2003; Awasthi et al., JHEP, 2013)
- Quasidirac neutrinos (Petcov, Ibarra, 2010)
- Sterile neutrinos (S. Pascoli et al., 2012; M. Blennow et al., 2010; M. Mitra, F. Vissani, G. Senjanović, 2012; Meroni et al, 2012)

Heavy Sterile Neutrino Exchange in Type I seesaw

- Saturating contribution from sterile neutrino sector?
- Light and sterile contribution decoupled?

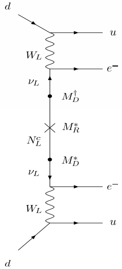
Heavy sterile neutrino exchange

n_h heavy Majorana neutrinos N_i → mixing V_{li} → mass M_i.

$M_i^2 > p^2 \sim (200)^2 \mathrm{MeV}^2$; p → intermediate momentum

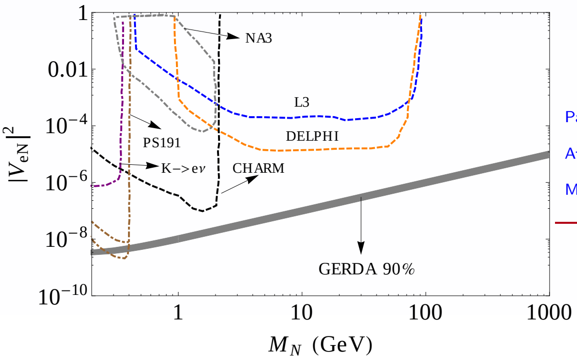
$$\text{Half-life } \frac{1}{T_{1/2}} = G_{0\nu} \left|\mathcal{M}_\nu \eta_\nu + \mathcal{M}_N \eta_N\right|^2$$

- $\eta_\nu = U_{ei}^2 m_i / m_e$, $\eta_N = V_{ei}^2 m_p / M_i$,
- $\mathcal{M}_\nu$ and $\mathcal{M}_N$ → nuclear matrix elements for light and heavy exchange



Bounds on active-sterile mixing

Bounds on active-sterile mixing angle from meson decays, sterile neutrino decays and neutrinoless double beta decay



Pascoli et al, 2013 ;

Atre et al., JHEP **0905**, 030 (2009);

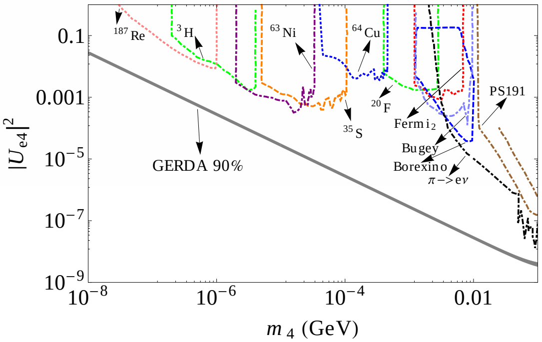
Mitra at el, , NPB **856**, 26 (2012)

$0\nu2\beta \to$ most stringent bound

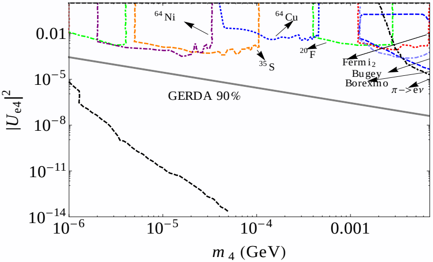
For light sterile $m_4 < 100\,\mathrm{MeV}$, the half-life

$$\frac{1}{T_{1/2}} = G_{0\nu} \left|\mathcal{M}_\nu \eta_\nu\right|^2$$

where $\eta_\nu \propto \Sigma_i m_i U^2 ei + \Sigma_i m_{4_i} U^2_{e4_i}$



S. Pascoli, M. Mitra, S. Wong, 2013



Bound from X-ray observation

(Dolgov, Hansen, 00; Abazajian, Fuller, Tucker, 01; Boyarsky, Ruchaysky, Shaposhnikov, 2006; etc.)

$$N \to \nu\,\gamma \Longrightarrow U_{e4}^2 \leq 1.8 \times 10^{-5} \left(\frac{1\,\mathrm{keV}}{M_1}\right)^5$$

$$0\nu 2\beta \to U_{e4}^2 \leq \frac{1}{m_4} \frac{1}{\sqrt{T_{1/2}^{0\nu} G_{0\nu} \mathcal{M}_\nu^2}}$$

(Benes et al., 2005; Bezrukov, 2005; Merle et al., 2013)

The bound from X-ray observation is stronger than $0\nu 2\beta$

$M \sim 1$ KeV, $m_{ee}^N \sim 0.01$ eV

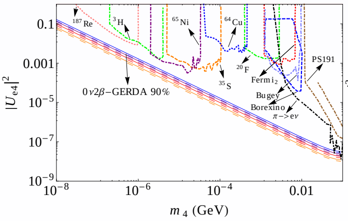
Within the reach of next generation experiments

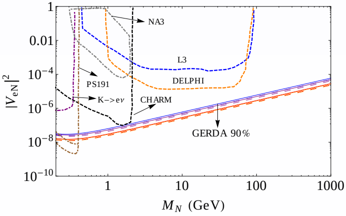
In preparation with E. J. Chun

Interference!

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu \eta_\nu + \mathcal{M}_h \eta_h|^2 \rightarrow$$ Interference (Meroni et al., 2011, 2012; Faessler et al., 2011)

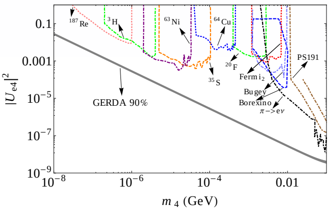
Cancellation between active and sterile neutrino for $^{136}\mathrm{Xe}$. Implications for $^{76}\mathrm{Ge}$

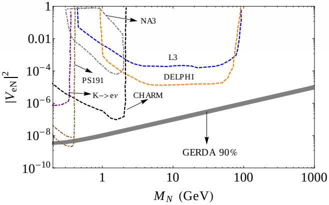




Pascoli, Mitra, Wong, 2013

Bound on mass-mixing plane becomes weaker in the presence of cancellation !!





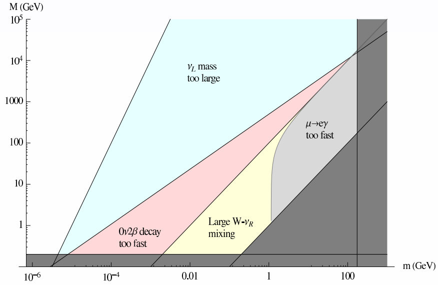
Expectation from Type-I Seesaw

Heavy sterile neutrinos N_i with Majorana mass matrix M_R

Kersten, Smirnov, 2007; Ibarra et al., 2010; Blennow et al., 2010; Pascoli et al., 2012

Mass matrix $M_n = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$

- $M_R \gg M_D$, the light Majorana mass $M_\nu = M_D^T M_R^{-1} M_D$
- Active-sterile mixing, $V = M_D^\dagger M_R^{-1*}$



Scale of $M_D \to m$, and Scale of M_R as M; $M_\nu = \frac{m^2}{M}$ and $V = \frac{m}{M}$

Constraints from small neutrino mass kills out any dominant sterile neutrino contribution in neutrinoless double beta decay

Naive seesaw expectation for neutrino mass has to be altered

Multiflavor scenario

Vanishing seesaw condition $M_D^T M_R^{-1} M_D = 0$

Smirnov, Kersten, 2007; Adhikari et al. 2010

- Neutrino mass as a perturbation of the vanishing seesaw condition $M_\nu = M_D^T M_R^{-1} M_D = 0$
- Light and sterile neutrino contributions in neutrinoless double beta decay are decoupled

For $M_i^2 \gg |p^2| \sim (200)^2$ MeV^2,

Amplitude

$$\mathcal{A}^* = \left[\frac{M_\nu}{p^2} - M_D^T M_R^{-1} M_R^{-1*} M_R^{-1} M_D + \mathcal{O}(M_R^{-5}) \right]_{ee}$$

Perturbations

In Dirac diagonal basis

Case A

$$M_D = m \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix}; M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix}$$

The light neutrino mass matrix in Dirac diagonal basis

$$M_\nu \Rightarrow \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon^2 & \epsilon \\ 0 & \epsilon & \epsilon \end{pmatrix}$$

- ϵ is the perturbing element
- In the limit $\epsilon \to 0$, $M_\nu \to 0$
- The above generates one massless and two massive light neutrinos

Contd:

The sterile contribution in flavor basis is

For normal hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e3}^* \sqrt{m_3})^2}{m_2 + m_3}$$

For inverted hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e1}^* \sqrt{m_1})^2}{m_1 + m_2}$$

Numerator and denominator depend same way on light neutrino mass

Sterile contribution is not suppressed by the light neutrino mass scale.

Additional Questions!

- Fine tuning of the parameter ϵ?
- Radiative stability of the light neutrino mass matrix?

In a pure Type-I seesaw scenario the radiative stability imposes

The heavy sterile mass $M \leq 10$ GeV

Mitra, Vissani, Senjanović, 2012

Type-I seesaw

- The light neutrino contribution $\frac{m^2}{M}\frac{1}{p^2}$. The heavy sterile contribution $\frac{m^2}{M^3}$
- For heavy sterile $M^2 > |p^2|$. The naive dimensional analysis implies a small heavy sterile contribution
- Vanishing seesaw condition $M_D^T M_R^{-1} M_D = 0$
- light neutrino mass $\rightarrow$ perturbation of the seesaw condition
- Fine tuning of the parameter ϵ?
- Radiative stability of the light neutrino mass matrix?

The heavy sterile mass $M \leq 10$ GeV

Mitra, Senjanović, Vissani, NPB, 2012

Fine tuning can be avoided if sterile neutrino is embedded in Left-Right symmetry.

The gauge boson W_R participates in neutrinoless double beta decay.

Left-Right symmetric theory

Pati; Salam; Mohapatra, Senjanović, 74, 75

Enlarged gauge sector $\rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- Parity symmetry restoration at high scale
- Two Higgs triplet $\Delta_L = (3,1,2)$, $\Delta_R = (1,3,2)$
- Sterile neutrino N is part of the gauge multiplet $\begin{pmatrix} N \\ e \end{pmatrix}_R$
- The vacuum expectation value of Δ_R breaks the symmetry
- Additional gauge bosons W_R and Z'. $M_{W_R} \propto \langle \Delta_R \rangle$
- Natural way to embed the sterile neutrinos

Contd

- The Lagrangian

$$\mathcal{L}_Y = f_\nu \bar{L}_L \Phi L_R + \widetilde{f}_\nu \bar{L}_L \widetilde{\Phi} L_R + f_L L_L^{\mathsf{T}} C i\sigma_2 \Delta_L L_L + f_R L_R^{\mathsf{T}} C i\sigma_2 \Delta_R L_R + \text{h.c.}$$

- Bi-doublet vev $\langle \Phi \rangle = v$. Higgs triplet vevs $\langle \Delta_{L,R} \rangle = v_{L,R}$
- Dirac mass $m_D = f_\nu v$. Heavy neutrino mass $M_R = f_R v_R$ and $m_L = f_L v_L$
- The neutrino mass matrix $\begin{pmatrix} f_L v_L & f_\nu v \\ f_\nu^T v & f_R v_R \end{pmatrix}$
- The light neutrino mass

$$\boxed{m_\nu \simeq m_L - m_D^{\mathsf{T}} M_R^{-1} m_D = f_L v_L - \frac{v^2}{v_R^2} y_\nu^T f_R^{-1} y_\nu}$$

Charged current Lagrangian

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(\bar{\nu}_L V_L^\dagger W_L e_L + \bar{N}_R V_R^\dagger W_R e_R \right) + \text{h.c.} \,.$$

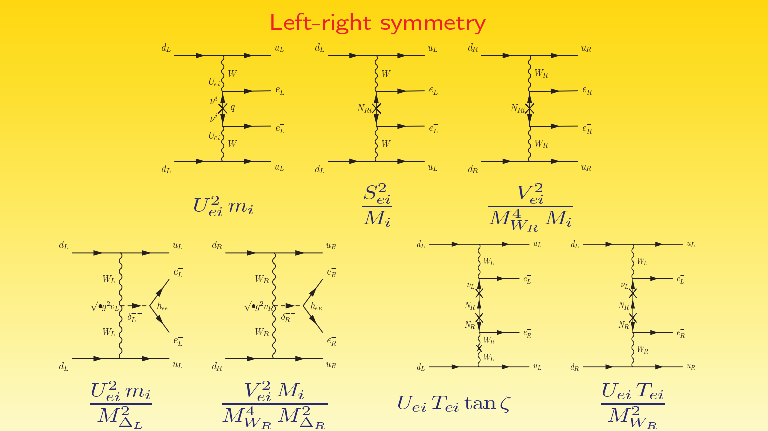
$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3} \Big[\overline{\ell}_{\alpha\, L}\, \gamma_\mu \, \{ (U_L)_{\alpha i} \nu_{Li} + (T)_{\alpha i} N^c_{Ri} \} W_L^\mu + \overline{\ell}_{\alpha\, R}\, \gamma_\mu \, \{ (S)^*_{\alpha i} \nu^c_{Li} + (U_R)^*_{\alpha i} N_{Ri} \} W_R^\mu \Big] + \text{h.c.}$$

$S, T \sim m_D/M_R \rightarrow$ active-sterile neutrino mixing

- The mass $M_{W_R} \propto v_R$. For v_R TeV scale, M_{W_R} will be at TeV
- The experimental limits: $K_L - K_S$ mass difference $M_{W_R} > 1.6$ TeV (Beall, Bander, Soni, PRL, 1982)
- ATLAS and CMS $\rightarrow M_{W_R} \geq 2.5$ TeV (CMS, ATLAS, 2012)

Large contribution can be obtained from TeV scale W_R and M_R. (Hirsch et al., PLB, 96, Tello et al., PRL, 2011, Goswami et al., JHEP, 2012, Barry et al., JHEP, 2013, Vogel et al., PRD, 2003) slide courtesy: Srubabati Goswami

$0\nu\beta\beta$ in Type-I LR model : Additional Diagrams



slide courtsey: W. Rodejohann

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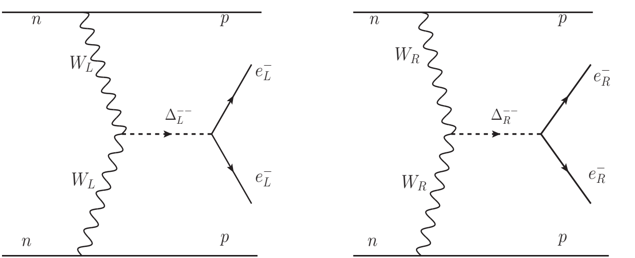


- Lepton flavor violation $l_i \to l_j l_k l_p \to M_\Delta > M_N$ in most of the parameter space (Tello et al., PRL, 2011)
- Small contribution in $0\nu 2\beta$

Type-II dominance and Heavy Neutrinos

- Neutrino mass $M_\nu = Y_\Delta v_L + m_D^T M_R^{-1} m_D$
- Type-II dominance, m_D is negligible $\to M_\nu \simeq Y_\Delta v_L$

(Tello et al., PRL, 2011)

Heavy right handed neutrinos are heavy

- $W_R - W_R$ mode is dominant. The decay width

$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left|\frac{\mathcal{M}_\nu}{m_e}\right|^2 \left(|m_\nu^{ee}|^2 + \left|p^2 \frac{M_{W_L}^4}{M_{W_R}^4} \frac{V_{ej}^2}{M_j}\right|^2\right)$$

- The effective mass for right handed neutrino contribution

$$m_{ee}^N = \langle p^2 \rangle \frac{M_{W_L}^4}{M_{W_R}^4} \sum_j \frac{V_{ej}^2}{M_j}$$

- The exchanged momentum $\langle p^2 \rangle = -m_e m_p \mathcal{M}_N / \mathcal{M}_\nu$

Contd

- Symmetry between Left and Right sector $\rightarrow f_L = f_R$. $M_R = f_R v_R$

$$M_\nu = (v_L/v_R) M_R \rightarrow \text{light neutrino mass } m_i \propto M_i$$

- For normal ordering, $M_1 < M_2 \ll M_3$
- $M_i \rightarrow$ right handed neutrino mass

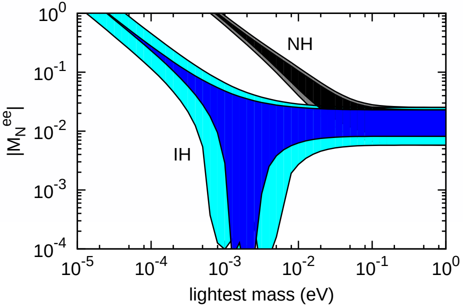
The effective mass for the heavy neutrino exchange

$$|m_{ee}^N|_{\rm nor} = \frac{C_N}{M_3}\left(\frac{m_3}{m_1} c_{12}^2 c_{13}^2 + \frac{m_3}{m_2} s_{12}^2 c_{13}^2 e^{2i\alpha_2} + s_{13}^2 e^{2i\alpha_3}\right)$$

- The factor $C_N = \langle p^2 \rangle M_{W_L}^4 / M_{W_R}^4$

- For inverted ordering, M_2 will be the largest

$$|m_{ee}^N|_{\rm inv} = \frac{C_N}{M_2}\left(\frac{m_2}{m_1}c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{2i\alpha_2} + \frac{m_2}{m_3}s_{13}^2 e^{2i\alpha_3}\right)$$

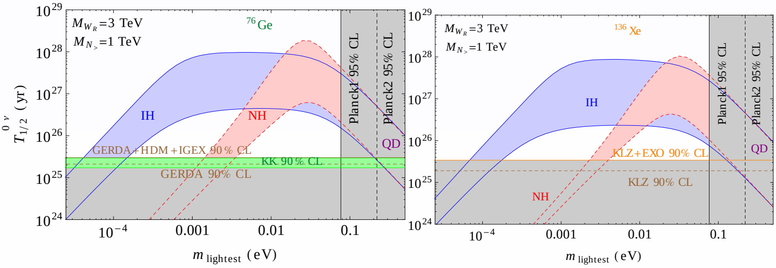


From J. Chakrabortty, H. J Devi, S. Goswami and S. Patra, JHEP, 2012

Total contribution:

- The half-life $\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^{(\nu+N)}}{m_e}\right|^2$
- The total effective mass $\rightarrow$ $\left|m_{ee}^{(\nu+N)}\right|^2 = |m_{ee}^{\nu}|^2 + |m_{ee}^{N}|^2$
- The sterile contribution $m_{ee}^{N} = \langle p^2\rangle \frac{M_{W_L}^4}{M_{W_R}^4} \sum_j \frac{V_{ej}^2}{M_j}$
- $\langle p^2\rangle = -m_e m_p \mathcal{M}_N/\mathcal{M}_\nu$
- For $^{76}\mathrm{Ge}$ the momentum exchange $p^2 = -(157 - 185)^2 \mathrm{MeV}^2$
- For $^{136}\mathrm{Xe}$ the momentum exchange $p^2 = -(153 - 184)^2 \mathrm{MeV}^2$

Contd



(DeV, Goswami, Mitra and Rodejohann, PRD, 2013)

- The heaviest right handed neutrino $M_{N>} = 1$ TeV. $M_i \propto m_i$. The lightest right handed neutrino mass $M_{N<} > 490$ MeV
- Even for hierarchical light neutrino mass, saturating limit can be obtained
- All the sterile neutrinos are heavy, $m_{\text{lightest}} = (10^{-5} - 1)$ eV. Lower limit on light neutrino mass
- For the positive claim $\rightarrow$ 1-4 meV (NH) and 0.03-0.2 meV (IH)
- For normal hierarchy, it is $2 - 4$ meV and 0.07-0.2 meV for Inverted hierarchy

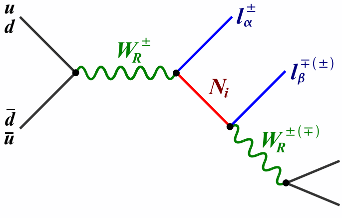
Relating with Collider Searches

Complementarity to LHC

Collider search $\rightarrow$ same sign dilepton+jets

Keung, Senjanović, PRL, 83

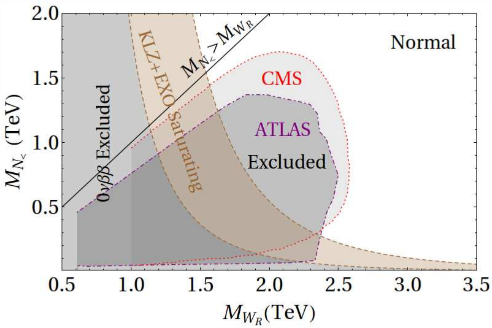
S. P. Das, F .F. Deppisch, O. Kittel, J. W. F. Valle, PRD, 2012



From S. P. Das, F .F. Deppisch, O. Kittel, J. W. F. Valle, PRD, 2012

Bound from LHC on W_R mass $\rightarrow M_{W_R} \geq 2.5$ TeV (CMS, ATLAS, 2012)

Complementarity to LHC



The contour is $M_{N_<} = \frac{p^2}{M^4_{W_R}} \frac{\Phi(\text{oscillation parameters})}{\sqrt{m^{\nu}_{exp} - m^{\nu}_{ee}}}$

- The band is due to the 3σ oscillation uncertainty
- $m_{\text{lightest}} \sim 10^{-5} - 0.077$ eV. Most stringent limit from Planck

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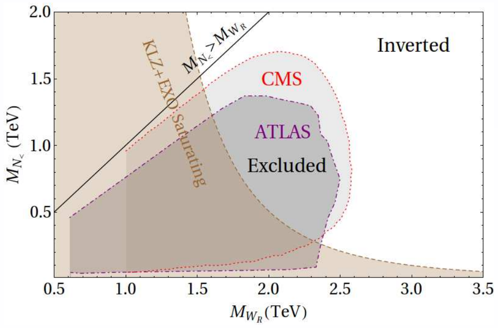


From DeV, Goswami, Mitra and Rodejohann, PRD, 2013

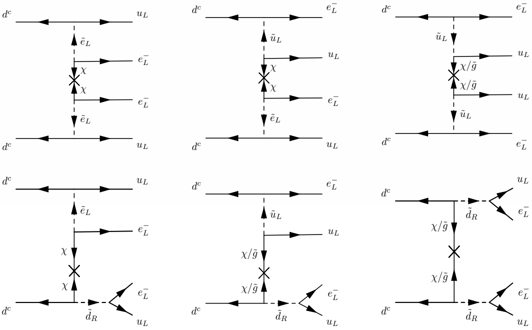
- Complementary to LHC (DeV et al., 2013; Rodejohann et al., 2013; S. P. Das et al., 2012)
- For Inverted hierarchy $\rightarrow$ no additional constraint
- For Normal hierarchy part of parameter space is restricted

R-parity violating contributions

- R-parity violating MSSM $\rightarrow$ L and B number violation
- $W = \epsilon L H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' Q Q D^c$

The states gluino, neutralino and squark can mediate the process

λ'_{111} mediated diagrams



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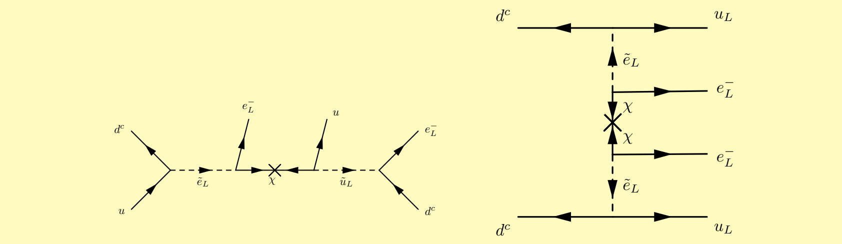
- ${\lambda'_{111}}^2 \to$ Like sign dilepton signal from single selectron production at LHC

Interesting correlation!!



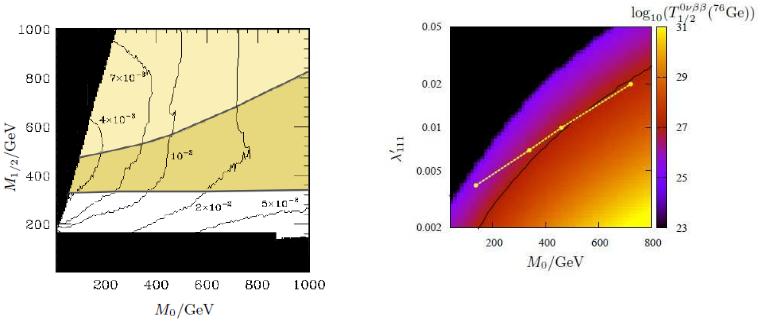
$$\sigma(pp \to \tilde{l}) \propto \frac{|\lambda'_{111}|^2}{m^3_{\tilde{e}_L}},\ T^{0\nu}_{1/2}(Ge)^{-1} \propto \frac{|\lambda'_{111}|^4}{\Lambda^{10}_{susy}}$$

Contd

- mSUGRA, $m_{0,1/2} = [40 - 1000]\,\mathrm{GeV}$, $tan\beta = 10$, $A_0 = 0$ and $sgn(\mu) = +$
- Black $\rightarrow$ stau LSP, direct constraints, White: $T^{0\nu}_{1/2} < 10^{25}$ yrs
- Dark-gray: $T^{0\nu}_{1/2} \sim 10^{25} - 10^{27}$ yrs, Light-gray: $T^{0\nu}_{1/2} > 10^{27}$ yrs

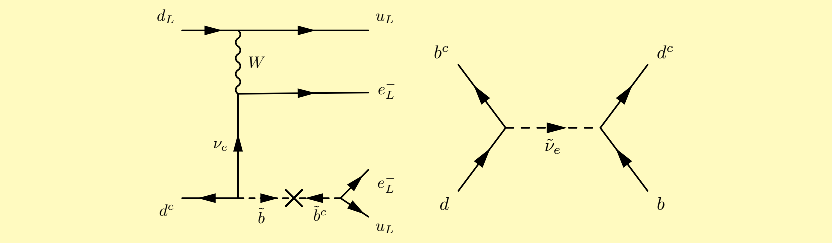
Signal in next generation of $0\nu 2\beta \rightarrow 5\sigma$ discovery of single slepton production

(Allanach, Kom, Pas, PRL, 2009)



$0\nu 2\beta$ and $B-\bar{B}$ mixing $\rightarrow \lambda'_{113}\lambda'_{131}$

$$\lambda'_{113}\lambda'_{131} \leq 2\times 10^{-8}\left(\frac{\Lambda}{100GeV}\right)^3 \,, \quad \lambda'_{113}\lambda'_{131} \leq 4\times 10^{-8}\frac{m^2_{\tilde{\nu}_e}}{(100GeV)^2}$$

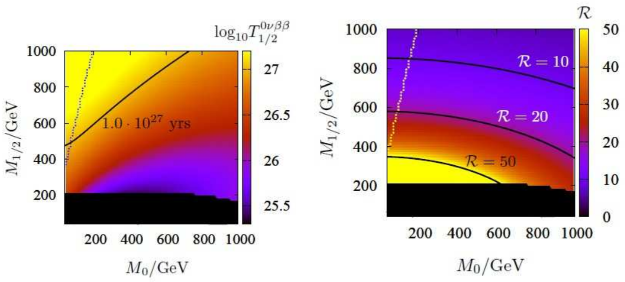


After LHC, half-life $T^{0\nu}_{1/2} \sim 10^{25}$ yrs is challenging!

In preparation with Subhadeep Mondal, Sourov Roy, Sanjoy Biswas

$T^{0\nu}_{1/2}$ within the reach of $10^{25} - 10^{27}$ yrs, after taking the bound from $B - \bar{B}$ mixing

(Allanach, Kom, Pas, JHEP, 2009)



Search for Multilepton states

Higgs triplet $\Delta^{++} \to l^+ l^+$, $pp \to l^+ N \to l^+ W^- l^+ \to l^+ l^+ jj$

Light Neutrino Mass $\to$ Small Yukawa $Y_N \sim 10^{-6}$ for TeV seesaw

Displaced Vertices!!

- Previous and recent references for Type-I and Type-II (Aguilar-Saavedra et al., 2009, 2013; Arhrib et al., 2010; Chun et al., 2012, 2013; Perez et al., 2009, 2008; Melfo et al., 2012; Nemesvek, Senjanovic, Tello, 2012)
- Previous and recent references for Type-III seesaw (Bandyopadhyay, Choubey, Mitra, 2009; Bandyopadhyay et al., 2010, 2012)
- Collider signature of Type-III seesaw for 2HDM (Bandyopadhyay, Choubey, Mitra, JHEP, 2009)
- Collider studies for Left-Right symmetry (Das et al., 2012; Chen et al., 2013; DeV et al., 2013, 2012; Tello et al., 2010)

Contd

Seesaw in Astroparticle Physics

Massive degrees of freedom participate in

Leptogenesis, Inflation

Dark matter candidate,...

Matter-Antimatter Asymmetry!

The baryon to photon number density

$$\frac{n_B}{n_\gamma} \sim 10^{-10}$$

From WMAP, BBN measurements

- **Leptogenesis!**..... and **Massive Neutrinos!**

  Fukugita, Yanagida, 86

- Lepton asymmetry from the decay of right handed neutrino
- Non perturbative sphaleron effects $\Longrightarrow$ Baryon Asymmetry

  Kuzmin, Rubakov, Shaposhnikov, 85

- Sakharov's conditions (Sakharov, 67)
  - Baryon number violation
  - C and CP violation
  - Out of equilibrium dynamics

Contd:

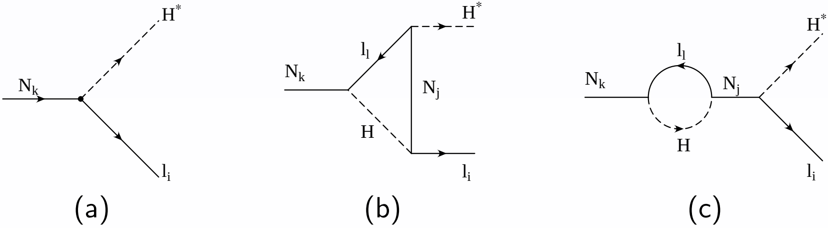
- Right handed neutrino ($SU(2)$ triplet Σ) decay

$$\epsilon_i^\alpha = \frac{\Gamma(N_i \to \phi\,\bar{l}_\alpha) - \Gamma(N_i \to \phi^\dagger\, l_\alpha)}{\sum_\beta \left[\Gamma(N_i \to \phi\,\bar{l}_\beta) + \Gamma(N_i \to \phi^\dagger\, l_\beta)\right]}$$

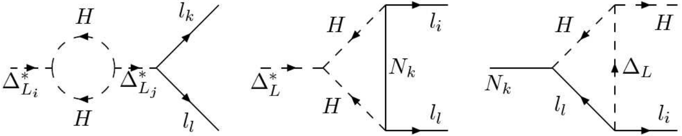
- Similarly other fields, scalar triplet or fermionic triplet can also participate in the process

Contd:

Leptogenesis due to right handed neutrino decay



Leptogenesis due to scalar triplet decay



Contd

- CP asymmetry is not enough!
- Washout factors!! decay and scattering can dilute the CP asymmetry $\rightarrow$ need to solve Boltzmann Equation
- Bound from neutrino mass

The baryon asymmetry

$$\boxed{Y_{\Delta B} \sim 10^{-3} \epsilon \, \eta}$$

$\epsilon \rightarrow$ CP asymmetry, $\eta \rightarrow$ washout factor

Contd

Interesting possibilities!

- Leptogenesis falsifiable at LHC!! (Deppisch et al., 1312.4447, Frere et al., 2009, Blanchet et al., 2010)
- Family symmetry and leptogenesis $\rightarrow$ the structure of m_D is determined in flavor models
- Form Dominance and leptogenesis (Choubey, King, Mitra, PRD, 2010)

Form Dominance $m_D \sim U \rightarrow R = I \rightarrow \epsilon \rightarrow 0$

Vanishing CP asymmetry!

Summary

The search for seesaw $\rightarrow$ lepton number and lepton flavor violation

$0\nu 2\beta$, Collider Searches, Other Laboratory Searches

- The updated positive claim is consistent with GERDA individual limit. Although strong tension with the combined GERDA+HM+IGEX. Next generation experiments $T^{0\nu}_{1/2} \sim 10^{26} - 10^{27}$ yrs
- A positive signal in $0\nu 2\beta$-decay from the 3 light neutrino $\rightarrow$ conflict with the most stringent limit from PLANCK
- Interesting beyond standard model features
- Sterile neutrino in Type-I seesaw, $M < 10$ GeV. In left-right symmetry, large sterile contribution can be obtained even for hierarchical light neutrino mass limit
- Lower bound on light neutrino mass
- Interesting correlations with collider searches $\rightarrow$ model dependent
- Massive states contribute in Leptogenesis, Inflation, can work as dark matter $\rightarrow$ astroparticle probe!

Thank You

R matrix

- Yukawa: $-\mathcal{L}_Y = Y_e \overline{L} H l_R + Y_\nu \overline{L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^c} M N_R + \text{h.c}$
- $m_\nu \sim m_D M^{-1} m_D^T$, $U^\dagger m_\nu U^* = D_k$, $U_M^\dagger M U_M^* = D_M$
- R matrix $R = D^{-1}_{\sqrt{M}} U_M^\dagger m_D^T U^* D^{-1}_{\sqrt{k}}$
- R complex orthogonal matrix, $RR^T = R^T R = I$
- $m_D \to 15$, $U{+}m_i \to 9$, $R \to 6$

CP asymmetry and Form Dominance

- Flavored CP asymmetry $\Longrightarrow \epsilon_i^{\alpha} = -\frac{3\,M_i}{16\pi v^2} \frac{\mathrm{Im}\left[\sum_{j,k} m_j^{1/2}\, m_k^{3/2}\, U_{\alpha j}^*\, U_{\alpha k}\, R_{ij}^*\, R_{ik}^*\right]}{\sum_j m_j\, |R_{ij}|^2}$
- $\epsilon_i = -\frac{3\,M_i}{16\pi v^2} \frac{\mathrm{Im}\left[\sum_j m_j^2\, (R_{ij}^*)^2\right]}{\sum_j m_j\, |R_{ij}|^2}$
- R real $\rightarrow \varepsilon_i = 0$
- Subclass of R real $\Rightarrow R = R_d \Longrightarrow R_d = diag(\pm 1, \pm 1, \pm 1)$
- ϵ_i^{α}, $\epsilon_i \rightarrow \mathbf{0}$
- $m_D = U.D' \rightarrow$ **Form Dominance**
- $D' = diag(\pm\sqrt{m_1}\sqrt{M_1}, \pm\sqrt{m_2}\sqrt{M_2}, \pm\sqrt{m_3}\sqrt{M_3})$
- $D'^2 = I \Longrightarrow$ unitary m_D
- **Form Dominance** and 0 Lepton Asymmetry irrespective of mixing matrix U
- Vialotaion of Form Dominance and Leptogenesis.

Experimental Measurements

Number of events $N = log2 \frac{N_A}{W} \frac{t\,M}{T^{0\nu}_{1/2}}$

- $M \rightarrow$ mass of the isotope, $t \rightarrow$ time of data taking
- $\epsilon \rightarrow$ efficiency factor, $W \rightarrow$ atomic weight
- $N_A \rightarrow$ Avogadro number, $T^{0\nu} \rightarrow$ half-life
- $c =$ no of events , $\Delta E \rightarrow$ energy resolution

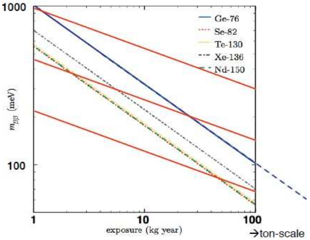


Figure courtesy: M. Lindner

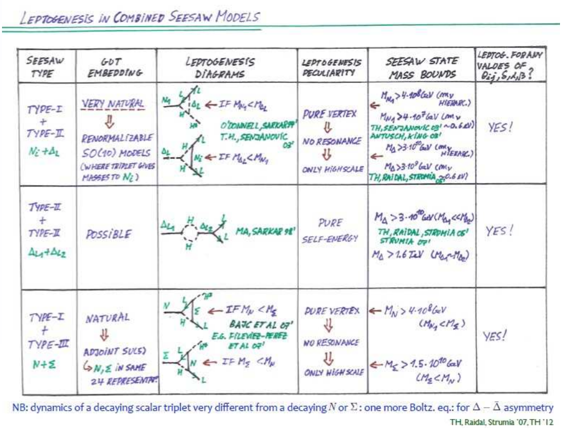
$\sqrt{\frac{1}{T^{0\nu}_{1/2}}} \sim m_{\beta\beta} = K_1 \sqrt{\frac{N}{\epsilon M t}}$ without background

$\sqrt{\frac{1}{T^{0\nu}_{1/2}}} \sim m_{\beta\beta} = K_2 \frac{1}{\epsilon} (\frac{c \Delta E}{M t})^{1/4} \rightarrow$ with background

sensitivity reduces due to background

Contd

Slide Courtesy: T. Humbye



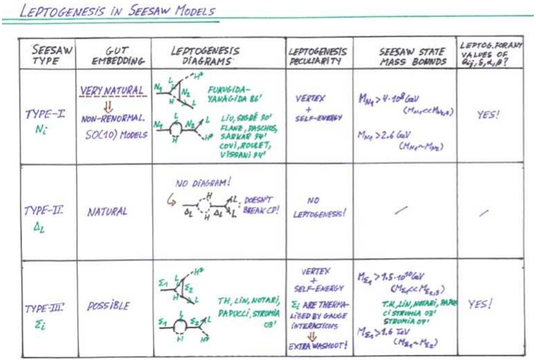
LEPTOGENESIS IN COMBINED SEESAW MODELS

SEESAW TYPE	GUT EMBEDDING	LEPTOGENESIS DIAGRAMS	LEPTOGENESIS PECULIARITY	SEESAW STATE MASS BOUNDS	LEPTOG. FOR ANY VALUES OF $\theta_{ij}, \delta, \alpha, \beta$?
TYPE-I + TYPE-II $N_i + \Delta_L$	VERY NATURAL ⇓ RENORMALIZABLE SO(10) MODELS (WHERE TRIPLET GIVES MASSES TO N_i)	← IF $M_{N_1} < M_{\Delta_L}$ O'DONNELL, SARKAR 94' T.H., SENJANOVIC 03' ← IF $M_{\Delta_L} < M_{N_1}$	PURE VERTEX ⇓ NO RESONANCE ⇓ ONLY HIGH SCALE	← $M_{N_1} > 4 \cdot 10^8$ GeV (m_ν HIERARC.) $M_{N_1} > 4 \cdot 10^7$ GeV ($m_\nu \sim 0.6$ eV) TH, SENJANOVIC 03' ANTUSCH, KING 03' ← $M_\Delta > 3 \cdot 10^{10}$ GeV (m_ν HIERARC.) $M_\Delta > 3 \cdot 10^9$ GeV ($m_\nu \simeq 0.6$ eV) TH, RAIDAL, STRUMIA 05'	YES!
TYPE-II + TYPE-II $\Delta_{L_1} + \Delta_{L_2}$	POSSIBLE	MA, SARKAR 98'	PURE SELF-ENERGY	$M_\Delta > 3 \cdot 10^{10}$ GeV ($M_{\Delta_1} \ll M_{\Delta_2}$) TH, RAIDAL, STRUMIA 05' STRUMIA 07' $M_\Delta > 1.6$ TeV ($M_{\Delta_1} \sim M_{\Delta_2}$)	YES!
TYPE-I + TYPE-III $N + \Sigma$	NATURAL ⇓ ADJOINT SU(5) ↳ N, Σ IN SAME 24 REPRESENTAT.	← IF $M_N < M_\Sigma$ BAJC ET AL 07' E.G. FILEVIEZ-PEREZ ET AL 07' ← IF $M_\Sigma < M_N$	PURE VERTEX ⇓ NO RESONANCE ⇓ ONLY HIGH SCALE	← $M_N > 4 \cdot 10^8$ GeV ($M_{N_1} < M_\Sigma$) ← $M_\Sigma > 1.5 \cdot 10^{10}$ GeV ($M_\Sigma < M_N$)	YES!

NB: dynamics of a decaying scalar triplet very different from a decaying N or Σ: one more Boltz. eq.: for $\Delta - \bar{\Delta}$ asymmetry

TH, Raidal, Strumia '07, TH '12

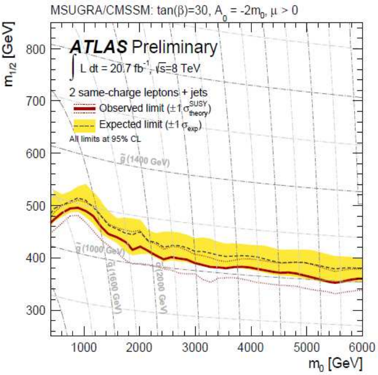
Slide Courtesy: T. Humbye

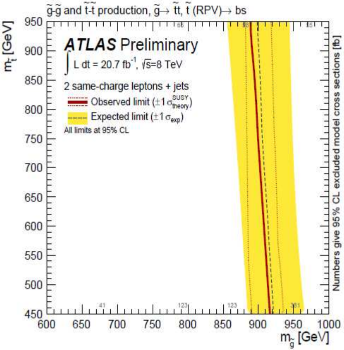


LEPTOGENESIS IN SEESAW MODELS

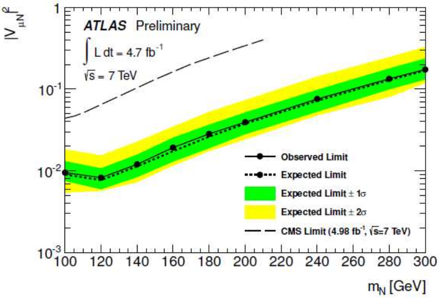
SEESAW TYPE	GUT EMBEDDING	LEPTOGENESIS DIAGRAMS	LEPTOGENESIS PECULIARITY	SEESAW STATE MASS BORNDS	LEPTOG. FOR ANY VALUES OF $\theta_{ij}, \delta, \alpha, \beta$?
TYPE-I N_i	VERY NATURAL ⇓ NON-RENORMAL. SO(10) MODELS	FUKUGIDA-YANAGIDA 86'; LIU, SEGRÉ 90' FLANZ, PASCHOS, SARKAR 94' COVI, ROULET, VISSANI 94'	VERTEX + SELF-ENERGY	$M_{N_1} > 4 \cdot 10^8$ GeV ($M_{N_1} \ll M_{N_{2,3}}$); $M_{N_1} > 2.6$ GeV ($M_{N_1} \sim M_{N_2}$)	YES!
TYPE-II Δ_L	NATURAL	NO DIAGRAM! DOESN'T BREAK CP!	NO LEPTOGENESIS!	/	/
TYPE-III Σ_i	POSSIBLE	TH, LIN, NOTARI, PAPUCCI, STRUMIA 03'	VERTEX + SELF-ENERGY; Σ_i ARE THERMALIZED BY GAUGE INTERACTIONS ⇓ EXTRA WASHOUT!	$M_{\Sigma_1} > 1.5 \cdot 10^{10}$ GeV ($M_{\Sigma_1} \ll M_{\Sigma_{2,3}}$) T.H, LIN, NOTARI, PAPUCCI STRUMIA 03' STRUMIA 07'; $M_{\Sigma_1} > 1.6$ TeV ($M_{\Sigma_1} \sim M_{\Sigma_2}$)	YES!

Contd

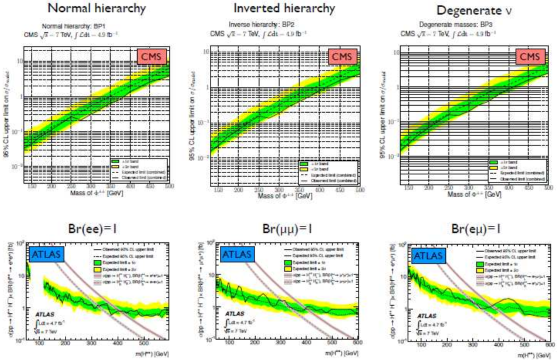

MSUGRA/CMSSM: tan(β)=30, A0 = -2m0, μ > 0
ATLAS Preliminary
∫ L dt = 20.7 fb-1, √s=8 TeV
2 same-charge leptons + jets
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
All limits at 95% CL
m1/2 [GeV]
m0 [GeV]


g̃-g̃ and t̃-t̃ production, g̃→ t̃t, t̃ (RPV)→ bs
ATLAS Preliminary
∫ L dt = 20.7 fb-1, √s=8 TeV
2 same-charge leptons + jets
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
All limits at 95% CL
m t̃ [GeV]
m g̃ [GeV]
Numbers give 95% CL excluded model cross sections [fb]

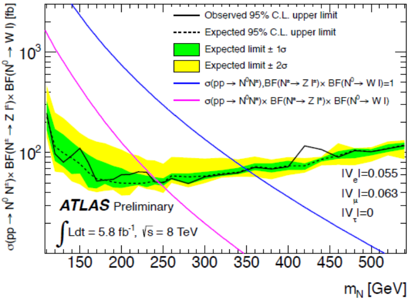
Contd


ATLAS Preliminary
∫ L dt = 4.7 fb-1
√s = 7 TeV
Observed Limit
Expected Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
CMS Limit (4.98 fb-1, √s=7 TeV)
|VμN|2
mN [GeV]
100 120 140 160 180 200 220 240 260 280 300
1
10-1
10-2
10-3

Limits on type II seesaw



Contd



Observed 95% C.L. upper limit
Expected 95% C.L. upper limit
Expected limit ± 1σ
Expected limit ± 2σ
ATLAS Preliminary
∫Ldt = 5.8 fb⁻¹, √s = 8 TeV
m_N [GeV]

Contd

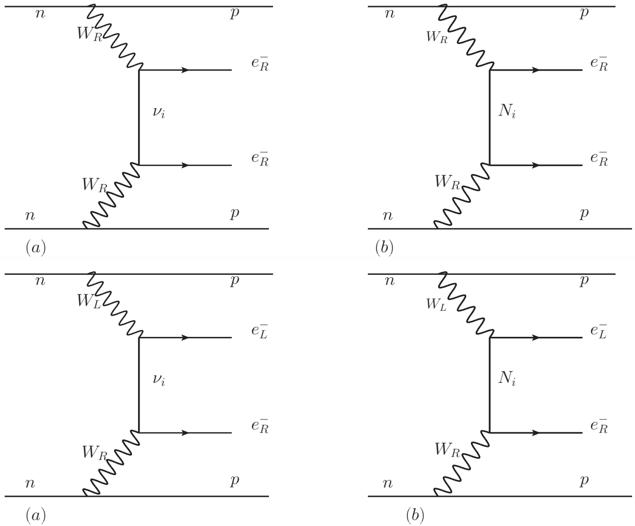
- The effective mass $m_{ee}^N \sim \frac{1}{M_{W_R}^4}$
- The effective mass $m_{ee}^N \sim \frac{1}{M_N}$

The range is sensitive to the right handed gauge boson and sterile neutrino masses M_{W_R} and M_N

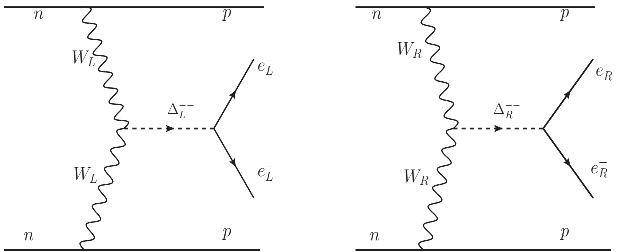
Contd

SRQRPA NME method	Limit on $M_{W_R}^{-4} \sum_j V_{ej}^2/M_j$ (TeV^{-5})				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
Argonne intm	0.30	0.25	0.24-0.33	0.18	0.13
Argonne large	0.26	0.22	0.22-0.29	0.18	0.14
CD-Bonn intm	0.20	0.16	0.17-0.22	0.17	0.13
CD-Bonn large	0.17	0.14	0.14-0.18	0.17	0.13

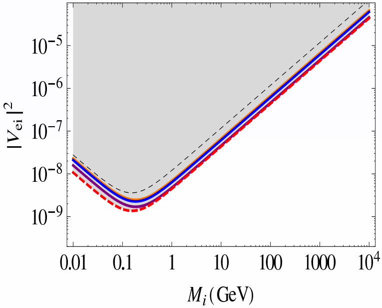
- The positive claim is consistent with the individual bounds of $^{136}\mathrm{Xe}$
- Inconsistent with the combined bound


n
p
W_R
e^-_R
ν_i
e^-_R
W_R
n
p
(a)
n
p
W_R
e^-_R
N_i
e^-_R
W_R
n
p
(b)
n
p
W_L
e^-_L
ν_i
e^-_R
W_R
n
p
(a)
n
p
W_L
e^-_L
N_i
e^-_R
W_R
n
p
(b)

Contd:



Contd:



- Nuclear matrix element

  Simkovic et al., Phys. Rev. **D82**, 113015 (2010), Meroni et al., 2012

- Heidelberg-Moscow, EX0-200,KamLAND-Zen and EXO-200+KamLAND-Zen bound

Active-sterile mixing $\frac{V_{ei}^2}{M_i} \leq (4-7) \times 10^{-9}\ \mathrm{GeV}^{-1}$

Perturbations

In Dirac diagonal basis

Case A

$$M_D = m \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix}; M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix}$$

The light neutrino mass matrix in Dirac diagonal basis

$$M_\nu \Rightarrow \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon^2 & \epsilon \\ 0 & \epsilon & \epsilon \end{pmatrix}$$

- ϵ is the perturbing element
- In the limit $\epsilon \to 0$, $M_\nu \to 0$
- The above generates one massless and two massive light neutrinos

Contd:

The sterile contribution in flavor basis is

For normal hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e3}^* \sqrt{m_3})^2}{m_2 + m_3}$$

For inverted hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e1}^* \sqrt{m_1})^2}{m_1 + m_2}$$

Numerator and denominator depend same way on light neutrino mass

Sterile contribution is not suppressed by the light neutrino mass scale.

Contd

However, Small neutrino mass $\epsilon \frac{m^2}{M} < 0.1$ eV demands $\epsilon = 10^{-9}$

Extreme fine-tuning condition

- Simple scaling of M, m and ϵ by $\alpha < 1$

$$M \to \alpha \times M;\ m \to \alpha^{3/2} \times m;\ \epsilon \to \alpha^{-2} \times \epsilon$$

- Light neutrino mass $\epsilon \frac{m^2}{M}$ and the sterile contribution $\frac{m^2}{M^3}$ remains unchanged
- ϵ can be relatively large $\longrightarrow$ fine-tuning reduces

With lower value of sterile neutrino mass scale M, the fine tuning reduces

Radiative stability

- The light neutrino mass $M_\nu \sim \epsilon \frac{m^2}{M}$
- For $M < M_{ew} \to \delta M_\nu \sim \frac{g^2}{(4\pi)^2} \frac{m^2}{M} \frac{M^2}{M_{ew}^2}$
- For $M > M_{ew} \to \delta M_\nu \sim \frac{g^2}{(4\pi)^2} \frac{m^2}{M} \log(M_1/M_2)$
- From radiative stability,
  - $\epsilon \gtrsim (M/1 \text{ TeV})^2$ for $M < M_{ew}$
  - $\epsilon \gtrsim 10^{-2}$ for $M > M_{ew}$

Contd:

Figure: One loop correction to the ν_L mass

Upper bound

- $T_{1/2} = 1.9 \times 10^{25}$ yr
- Saturating sterile contribution $\to \kappa m^2/M^3 = 7.6 \times 10^{-9}$ GeV^{-1}
- Small neutrino mass, $\to \frac{\epsilon m^2}{M} < 0.1$ eV

- Upper bound on $\epsilon \to \epsilon \lesssim \kappa \left(\frac{100 \text{ MeV}}{M}\right)^2$
- Including radiative stability $\to M \lesssim \kappa^{1/4} \times 10$ GeV
- Satisfies small neutrino mass constraint, radiative stability
- $0\nu 2\beta$ provides stringent bound

Perturbations

Preferred choice of basis $\rightarrow$ Dirac diagonal basis

$$M_D = m \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} ; M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix} \rightarrow M_\nu \Rightarrow \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon^2 & \epsilon \\ 0 & \epsilon & \epsilon \end{pmatrix}$$

$$M_D = m\,\text{diag}(\epsilon, \epsilon, 1); M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix} \rightarrow M_\nu = \frac{m^2}{M} \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon & \epsilon & \epsilon \end{pmatrix}$$

- In the limit $\epsilon \rightarrow 0$, $M_\nu \rightarrow 0$
- For the first case, one massless and two massive light neutrinos
- Elements are $\mathcal{O}(\epsilon)$, determinant is $\mathcal{O}(\epsilon^4)$
- Lightest neutrino mass $\rightarrow \mathcal{O}(\epsilon^2)$

Two flavor

- Simple two flavor example
- $M_R = M \begin{pmatrix} \epsilon & 1 \\ 1 & 1 \end{pmatrix}$; $M_D = m \begin{pmatrix} \epsilon & 0 \\ 0 & 1 \end{pmatrix} \Longrightarrow$ Dirac diagonal basis
- Light neutrino mass and contact term,

$$M_\nu = \frac{\epsilon m^2}{M} \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}; \;\; M_D M_R^{-3} M_D = \frac{m^2}{M^3} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

- M_ν depends on ϵ, while the contact term is ϵ independent

Contd:

- Rotation by $\tan\theta = \sqrt{\frac{m_1}{m_2}}$
- From Dirac diagonal basis $\rightarrow$ mass basis $\rightarrow$ Flavor basis
- Light neutrino contribution,

$$(M_\nu)_{ee} = \sin^2\theta_\odot \; m_2 - \cos^2\theta_\odot \; m_1 \; e^{i2\phi}$$

- The contact term in flavor basis,

$$(M_D^T M_R^{-3} M_D)_{ee}^{(\mathrm{Fl.})} = \xi \frac{m^2}{M^3} \frac{(\sin\theta_\odot \; \sqrt{m_2} + \cos\theta_\odot \; \sqrt{m_1} \; e^{i\phi})^2}{m_1 + m_2}$$

- Numerator and denominator depend same way on light neutrino mass $\Longrightarrow$ independent of the light neutrino mass scale

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- ξ is a combination of order 1 coefficients in M_R^{-1}

Contd:

- For ϕ=0 or π, light neutrino contribution vanishes, for
  - $m_2 = \sqrt{\Delta m^2_{\odot}} \frac{\cos^2 \theta_{\odot}}{\sqrt{\cos 2\theta_{\odot}}}$; $m_1 = \sqrt{\Delta m^2_{\odot}} \frac{\sin^2 \theta_{\odot}}{\sqrt{\cos 2\theta_{\odot}}}$
- Contact term is unsuppressed for $\phi = 0$
- $0\nu2\beta$ transition is *entirely* due to heavy neutrino exchange
- Schechter-Valle theorem?

Three flavor scenario

The contact term in Dirac diagonal basis,

$$M_D^T M_R^{-3} M_D = \xi \ \frac{m^2}{M^3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\downarrow$$

Contact term in flavor basis

- Contact term in flavor basis,

$$(M_D^T M_R^{-3} M_D)_{ee}^{(\mathrm{Fl.})} \equiv (U^* O^T M_D^T M_R^{-3} M_D O U^\dagger)_{ee}$$

- O and U are two mixing matrices
  - Dirac diagonal $\rightarrow$ mass $\rightarrow$ flavor
- Contact term $(M_D^T M_R^{-3} M_D)_{ee} = \kappa \ \frac{m^2}{M^3}$
- κ is $\kappa = \xi \times \varphi^2$, with $\varphi = \sum_{i=1}^3 U_{ei}^* O_{3i}$

Contd:

- For case A and B, the contact term in flavor basis,

For normal hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U^*_{e2}\sqrt{m_2} + U^*_{e3}\sqrt{m_3})^2}{m_2 + m_3}$$

For inverted hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U^*_{e2}\sqrt{m_2} + U^*_{e1}\sqrt{m_1})^2}{m_1 + m_2}$$

- For normal and inverted mass hierarchy,

$|(M_\nu)_{ee}| = |m_3 U_{e3}^2 - m_2 U_{e2}^2|; \quad |(M_\nu)_{ee}| = |m_2 U_{e2}^2 - m_1 U_{e1}^2|$

Contd:

- $\frac{m^2}{M^3} \sim 7.6 \times 10^{-9}\ \mathrm{GeV}^{-1}$ to saturate $0\nu2\beta$ bound
- $\Delta m^2_{12} = 7.7 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\theta_{12} = 34^\circ$, $\theta_{23} = 42^\circ$ and $\theta_{13} = 8^\circ$
  - $\varphi^2 \to$ 0.12-0.007 for normal hierarchy;
  - $\varphi^2 \to$ 0.94-0.03 for inverted hierarchy