Majorana-Masses of Neutrinos: Origin and Phenomenology

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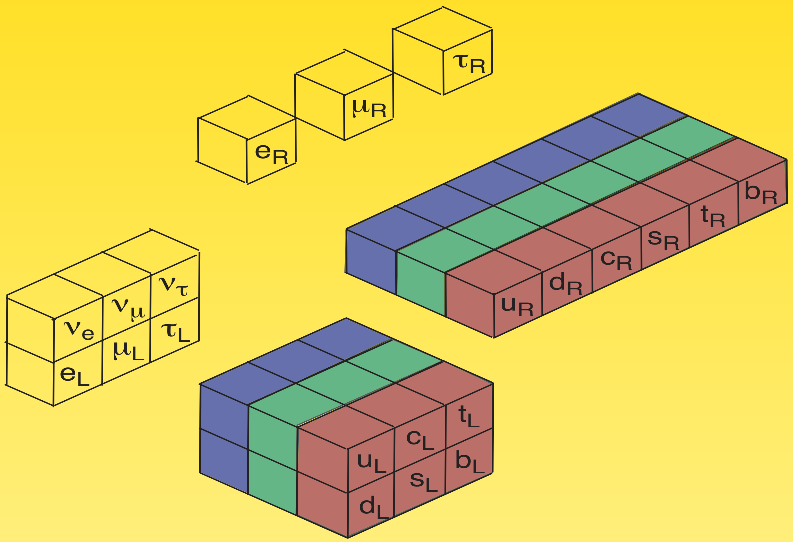
Outline

- Neutrino Physics
- Dirac vs. Majorana masses
- Neutrinoless Double Beta Decay

Neutrino Physics

Standard Model of Elementary Particle Physics: $SU(3)_C \times SU(2)_L \times U(1)_Y$



Species	$\#$	$\sum$
Quarks	10	10
Leptons	3	13
Charge	3	16
Higgs	2	18

18 free parameters...

+ Dark Matter

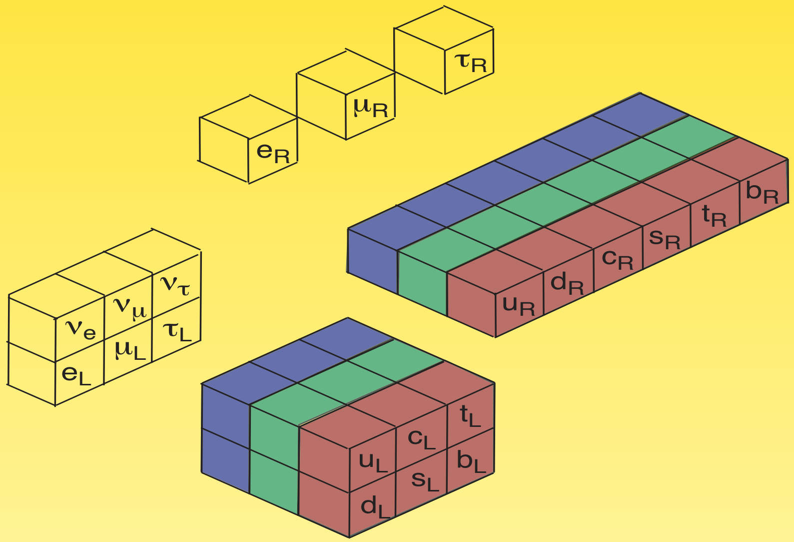
+ Baryon Asymmetry

+ Dark Energy

+ Gravitation

Neutrino Physics

Standard Model of Elementary Particle Physics: $SU(3)_C \times SU(2)_L \times U(1)_Y$



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$+$ Neutrino Mass m_ν

Standard Model of Particle Physics

add neutrino mass matrix m_ν

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Standard Model of Particle Physics

add neutrino mass matrix m_ν

Species	#	$\sum$
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$\longrightarrow$

Species	#	$\sum$
Quarks	10	10
Leptons	12 (10)	22 (20)
Charge	3	25 (23)
Higgs	2	27 (25)

Standard Model* of Particle Physics

add neutrino mass matrix m_ν

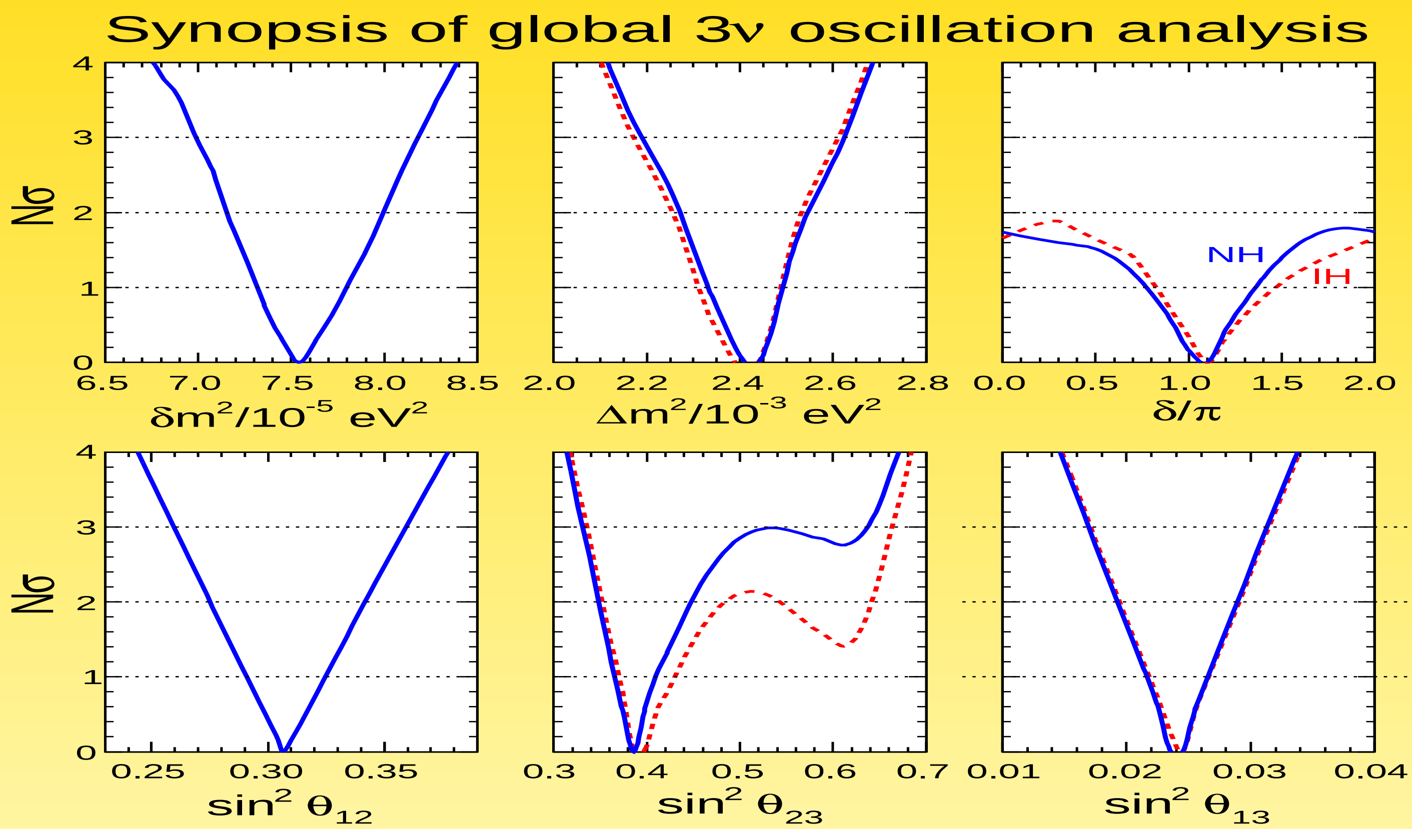
Species	#	$\sum$		Species	#	$\sum$
Quarks	10	10		Quarks	10	10
Leptons	3	13	$\longrightarrow$	Leptons	12 (10)	22 (20)
Charge	3	16		Charge	3	25 (23)
Higgs	2	18		Higgs	2	27 (25)

And: a new energy scale besides Higgs VEV?

Neutrino Physics: 9 parameters (`Talk by Caren Hagner, PV I`)

- 3 masses:
  - $\Delta m^2_\odot \simeq 7 \cdot 10^{-5}$ eV^2
  - $|\Delta m^2_\mathrm{A}| \simeq 2 \cdot 10^{-3}$ eV^2
  - $\Delta m^2_\mathrm{A} > 0$ (normal ordering) or $\Delta m^2_\mathrm{A} < 0$ (inverted ordering)?
  - smallest mass < 2.3 eV
- 3 mixing angles:
  - $\theta_{12} \simeq (34 \pm 1)^0$
  - $\theta_{23} \simeq (39 \pm 1.5)^0$
  - $\theta_{13} \simeq (9 \pm 0.5)^0$
- 3 CP phases:
  - δ
  - α, β

Neutrino Physics



Fogli, Lisi *et al.*

Neutrino Mass: Dirac or Majorana?

SM has no right-handed neutrinos N_R (and only Higgs doublet): $\Rightarrow$ no mass

add right-handed neutrinos N_R: $\Rightarrow$ neutrinos have mass $m_D\,\overline{\nu_L}\,N_R$, but...

$$L \equiv \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \text{vs.} \quad Q \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L$$

why $m_\nu \ll m_e$ while $m_u \sim m_d$?

once you introduce N_R: two terms are allowed!

1) $m_D\,\overline{L}\,\Phi\,N_R$: Dirac mass generated in analogy to other SM masses

2) $M_R\,\overline{N_R^c}\,N_R$: Majorana mass of right-handed neutrinos $\gg m_D$

$\Rightarrow$ neutrinos are **Majorana particles** $m_\nu\,\overline{\nu_L}\,\nu_L^c$ with $m_\nu = m_D^2/M_R$

$$m_\nu = m_D^2/M_R = \frac{m_D}{M_R}\, m_D = \epsilon\, m_{\rm SM}$$

(type I) Seesaw Mechanism

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanović (77-80)

Comments

$$m_\nu = m_D^2/M_R \simeq v^2/M_R$$

- $m_D \leftrightarrow \overline{L}\,\tilde{\Phi}\,N_R$ related to Higgs!
- $M_R\,\overline{N_R^c}\,N_R$ is “bare” mass term **not** related to Higgs!
- with $m_\nu \simeq \sqrt{\Delta m_{\rm A}^2}$ it follows: $M_R \simeq 10^{15}$ GeV
- testable scale? Consequences?

Seesaw Phenomenology

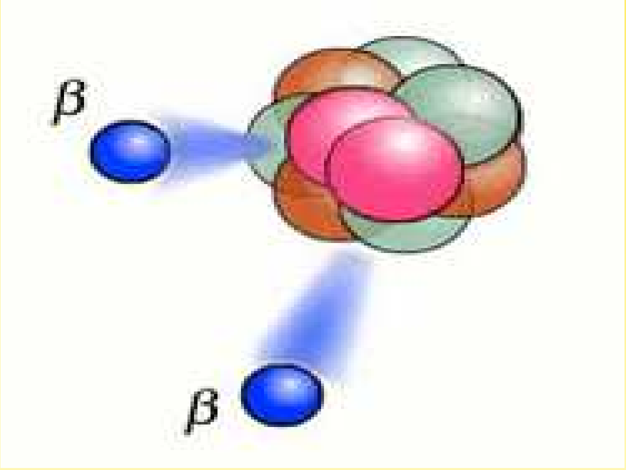
- Leptogenesis
- LFV in supersymmetric seesaw
- TeV seesaw...
- N_R couple to Higgs: $\Rightarrow$ vacuum stability
- **Neutrinoless double beta decay**

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Neutrino mass term $\overline{\nu_L}\,\nu_L^c \propto \nu_L^\dagger\,\nu_L^*$

- two extra CP phases in mixing matrix (no effect in oscillations, only related to:)
- Lepton Number Violation $\Delta L = 2$

$$(A, Z) \to (A, Z+2) + 2\,e^-$$ (e.g. ^{76}Ge $\to^{76}$Se $+2e^-$)



Why to look for Lepton Number Violation

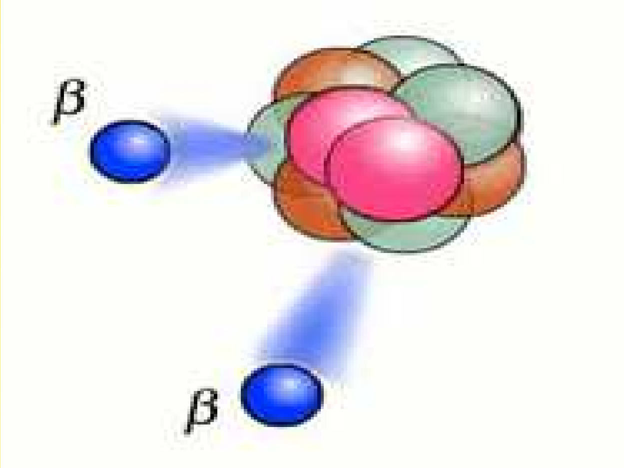
$0\nu\beta\beta$ is much more than a neutrino (mass) experiment!

- L and B *accidentally* conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\,\mathcal{L}_{\rm LNV} + \frac{1}{\Lambda^2}\,\mathcal{L}_{\rm LFV,\,BNV,\,LNV} + \ldots$
- baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majorana neutrinos

$\Rightarrow$ Lepton Number Violation as important as Baryon Number Violation

Small problem. . .

$$\boxed{(A, Z) \to (A, Z + 2) + 2\,e^-}$$ (e.g. ^{76}Ge $\to ^{76}$Se $+2e^-$)

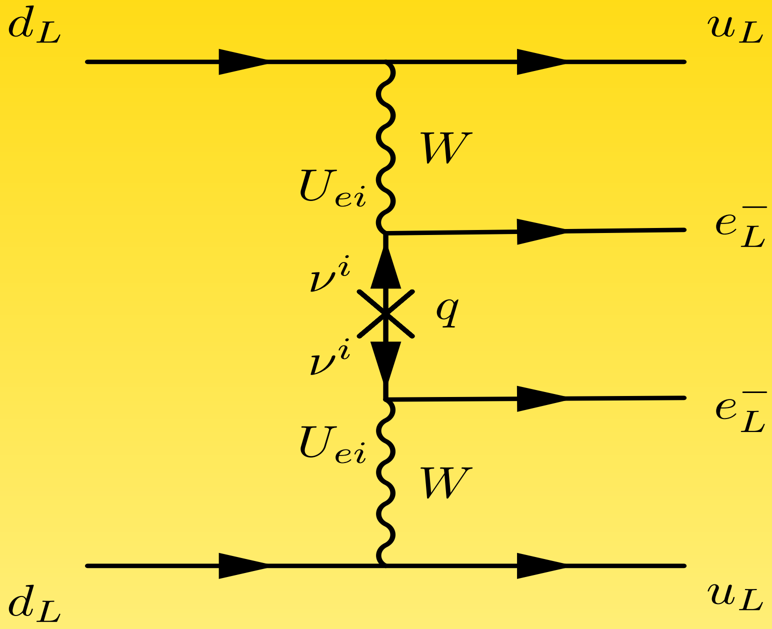


Majorana phenomenology **always** suppressed by $(m_\nu/E)^2$

$\Rightarrow$ Lifetimes start with 10^{25} years. . .

$\Rightarrow$ only N_A can save the day!

What is Neutrinoless Double Beta Decay?



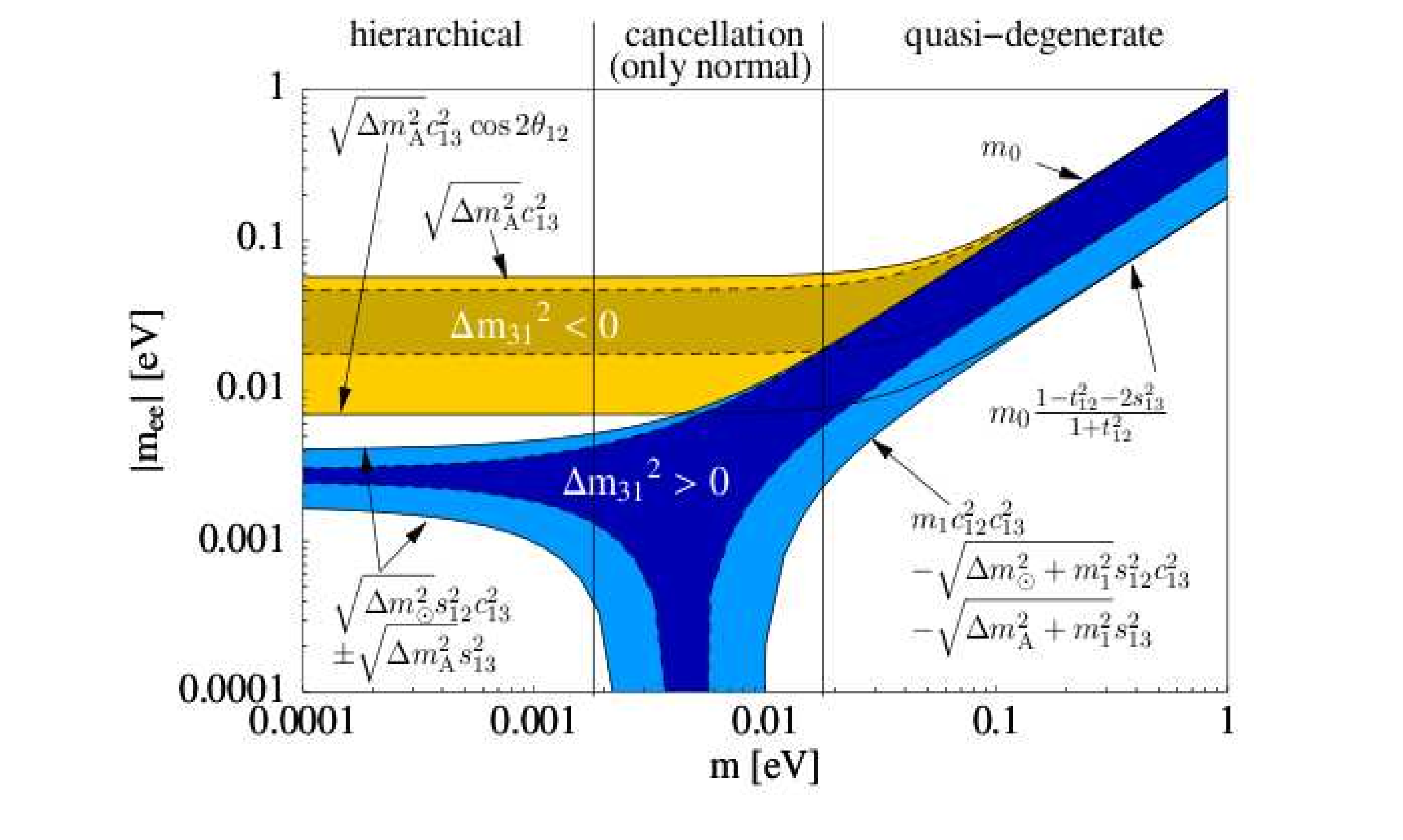
Amplitude proportional to coherent sum (<u>"effective mass"</u>):

$$|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|$$

$$= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m^2_{\mathrm{A}}), \alpha, \beta\right)$$

7 out of 9 parameters of neutrino physics!

The usual plot



horizontally: $0\nu\beta\beta$ experiments

vertically: other neutrino mass approaches. . .

Isotope	$T^{0\nu}_{1/2}$/yrs	Experiment	$\lvert m_{ee}\rvert$ [eV]
^{48}Ca	5.8×10^{22}	CANDLES	10.14
^{76}Ge	1.9×10^{25}	HDM	0.55
^{82}Se	3.2×10^{23}	NEMO-3	2.17
^{100}Mo	1.0×10^{24}	NEMO-3	0.84
^{130}Te	2.8×10^{24}	CUORICINO	0.62
^{136}Xe	5.0×10^{23}	DAMA	2.24
^{136}Xe	1.6×10^{25}	EXO-200	0.40
^{136}Xe	1.9×10^{25}	KamLAND-Zen	0.36
^{136}Xe	3.4×10^{25}	KamLAND-Zen + EXO-200	0.27
^{150}Nd	1.8×10^{22}	NEMO-3	5.68

Upcoming/running experiments: exciting time!!

best limit was from 2001...

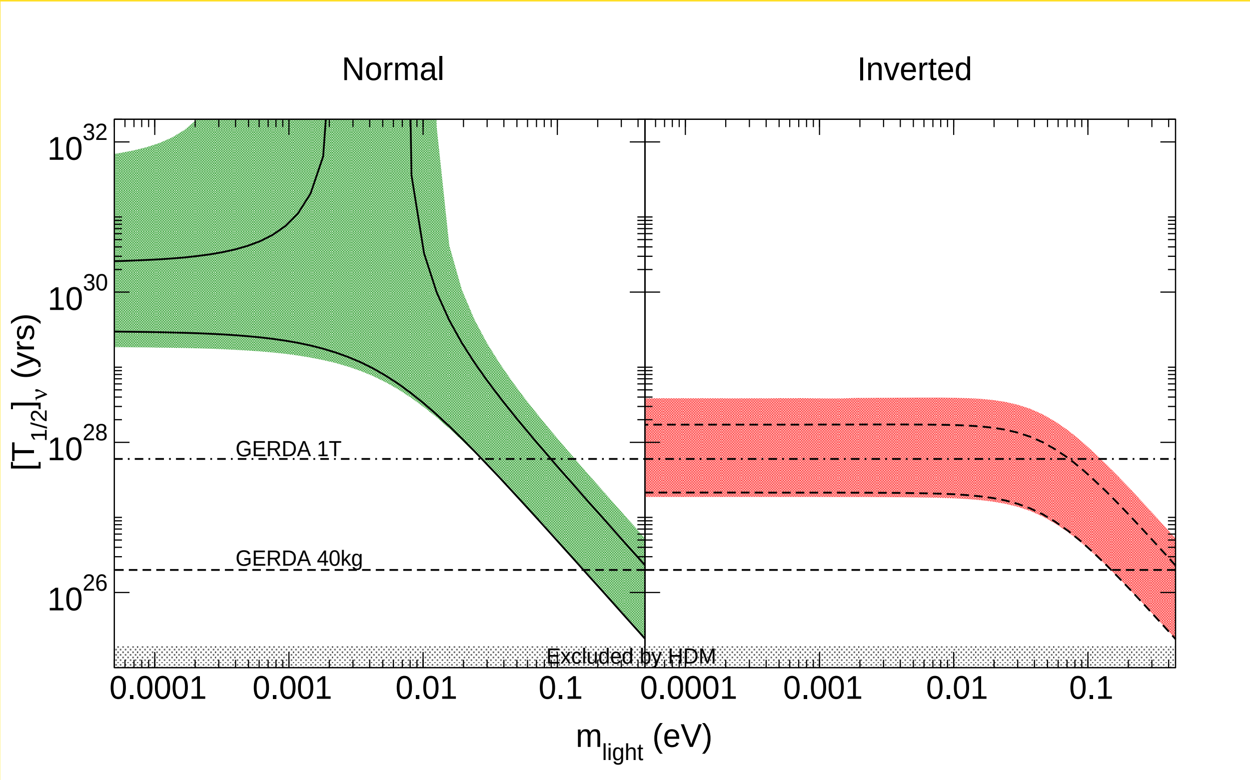
Name	Isotope	source = detector; calorimetric with			source ≠ detector
		high energy res.	low energy res.	event topology	event topology
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA*	^{116}Cd (and ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se or ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA+	^{76}Ge	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LUCIFER	^{82}Se or ^{100}Mo or ^{130}Te	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se or ^{100}Mo or ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+%	^{150}Nd(?)	–	✓	–	–
SuperNEMO	^{82}Se or ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

*: see T 102.1; HK 7.1; +: see T 103.1; HK 43.2; %: see T 103.1; HK 66.1

Recent reviews. . .

- **X. Sarazin**, ***Review of double beta experiments***, 1210.7666
- **B. Schwingenheuer**, ***Status and prospects of searches for neutrinoless double beta decay***, 1210.7432
- **W. Rodejohann**, ***Neutrino-less double beta decay and particle physics***, 1106.1334
- **J.J. Gomez-Cadenas et al.**, ***The search for neutrinoless double beta decay***, 1109.5515
- **J.D. Vergados, H. Ejiri, F. Simkovic**, ***Theory of neutrinoless double beta decay***, 1205.0649
- **S.M. Bilenky, C. Giunti**, ***Neutrinoless double-beta decay. A brief review***, 1203.5250
- **S.R. Elliott**, ***Recent progress in double beta decay***, 1203.1070
- **P. Vogel**, ***Nuclear structure and double beta decay***, J. Phys. G 39, 124002 (2012)
- **S.J. Freeman, J.P. Schiffer**, ***Constraining the $0\nu 2\beta$ matrix elements by nuclear structure observables***, J. Phys. G 39, 124004 (2012)
- **J. Suhonen, O. Civitarese**, ***Review of the properties of the $0\nu\beta^-\beta^-$ nuclear matrix elements***, J. Phys. G 39, 124005 (2012)
- **A. Faessler, V. Rodin, F. Simkovic**, ***Nuclear matrix elements for neutrinoless double beta decay and double electron capture***, J. Phys. G 39, 124006 (2012)
- **F. Deppisch, M. Hirsch, H. Päs**, ***Neutrinoless double beta decay and physics beyond the standard model***, J. Phys. G 39, 124007 (2012)
- **W. Rodejohann**, ***Neutrinoless double beta decay and neutrino physics***, J. Phys. G 39, 124008 (2012)
- **K. Zuber**, ***Double beta decay experiments***, J. Phys. G 39, 124009 (2012)

Life-time instead of $|m_{ee}|$



Inverted Hierarchy cannot fully be covered by current experiments...

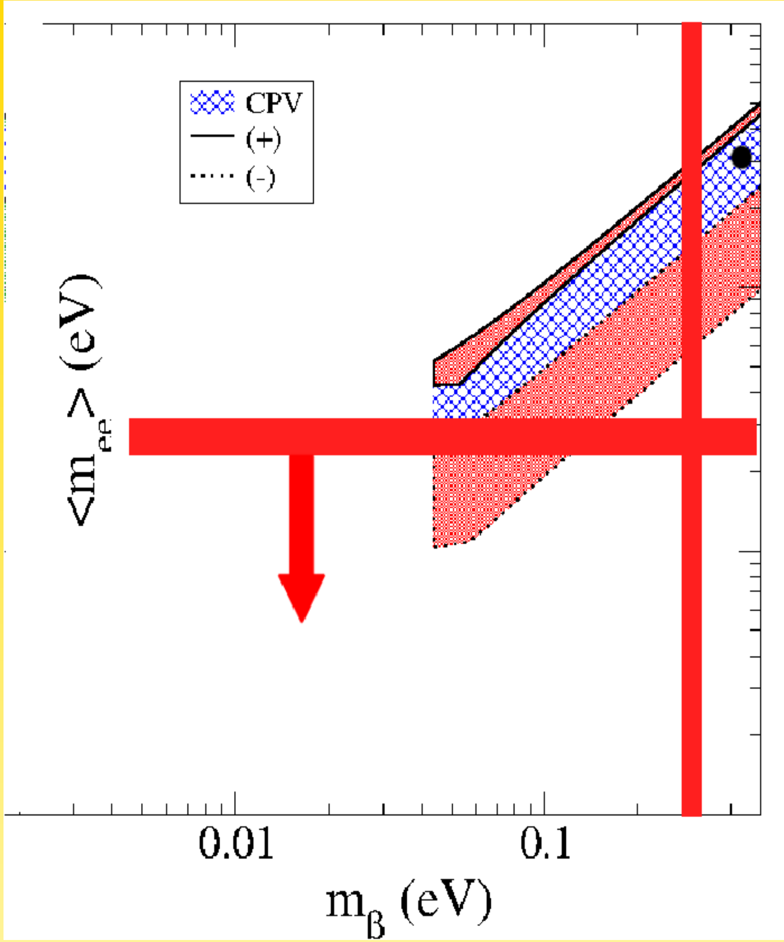
(crucial dependence on $\theta_{12} \leftrightarrow$ more precision required)

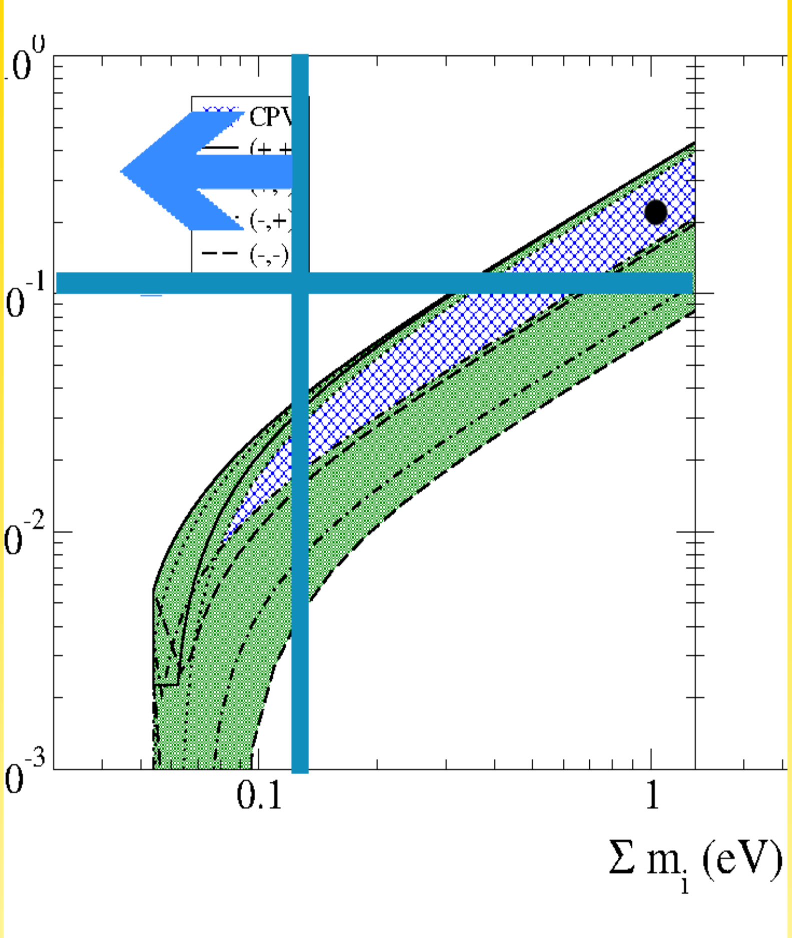
Neutrino Mass

$$m(\text{heaviest}) \gtrsim \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV}$$

3 **complementary** methods to measure neutrino mass:

Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum \|U_{ei}\|^2 m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	1	0.5	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\|\sum U_{ei}^2 m_i\|$	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty





CP violation!

Dirac neutrinos!

Something else does $0\nu\beta\beta$!

Neutrino Mass Matrix

At the end of the decade. . .

		KATRIN		$0\nu\beta\beta$		cosmology	
		yes	no	yes	no	yes	no
KATRIN	yes	–	–	QD + Majorana	QD + Dirac	QD	N-SC
	no	–	–	N-SI	low IH or NH or Dirac	$m_\nu \lesssim 0.1$eV or N-SC	NH
$0\nu\beta\beta$	yes	•	•	–	–	(IH or QD) + Majorana	N-SC or N-SI
	no	•	•	–	–	low IH or (QD + Dirac)	NH
cosmology	yes	•	•	•	•	–	–
	no	•	•	•	•	–	–

Light Sterile Neutrinos??

- reactor anomaly
- Gallium anomaly
- LSND/MiniBooNE
- cosmology
- BBN
- r-process nucleosynthesis in Supernovae

New neutrino state with $\Delta m^2 \sim 1$ eV^2 and $|U_{e4}| \sim 0.1$?

`Talks by Caren Hagner, PV I; Antonio Palazzo, T 6.5`

Light Sterile Neutrinos: A White Paper

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L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63]
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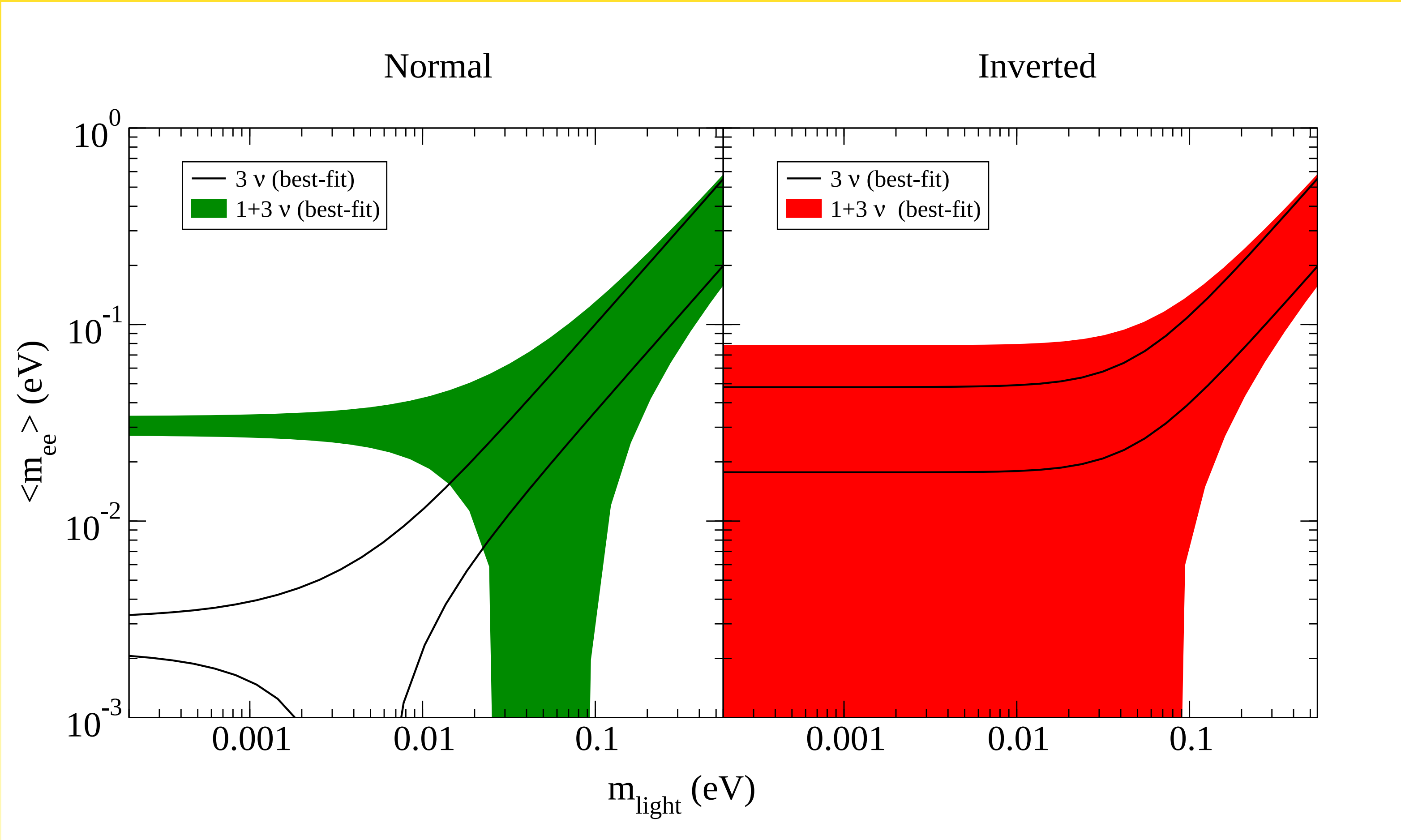
Light Sterile Neutrinos: A White Paper

Strong german contribution: 

- Section I: Theory and Motivation (Barenboim, Rodejohann)
- Section II: Astrophysical Evidence (Abazajian, Wong)
- Section III: Evidence from Oscillation Experiments (Kopp, Louis)
- Section IV: Global Picture (Lassere, Schwetz)
- Section V: Requirements for Future Measurements (Fleming, Formaggio)
- Appendix: Possible Future Experiments (Huber, Link)

Usual plot gets completely turned around!

recall: $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH}$ cannot vanish



Barry, W.R., Zhang, JHEP **1107**

Interpretation of Neutrino-less Double Beta Decay

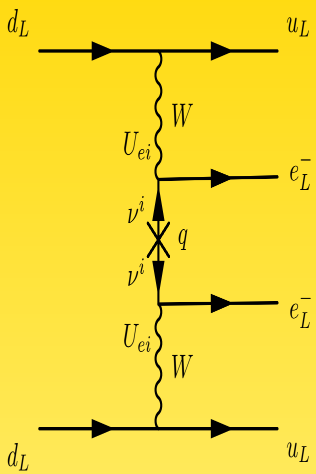
- **Standard Interpretation:**

  Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution

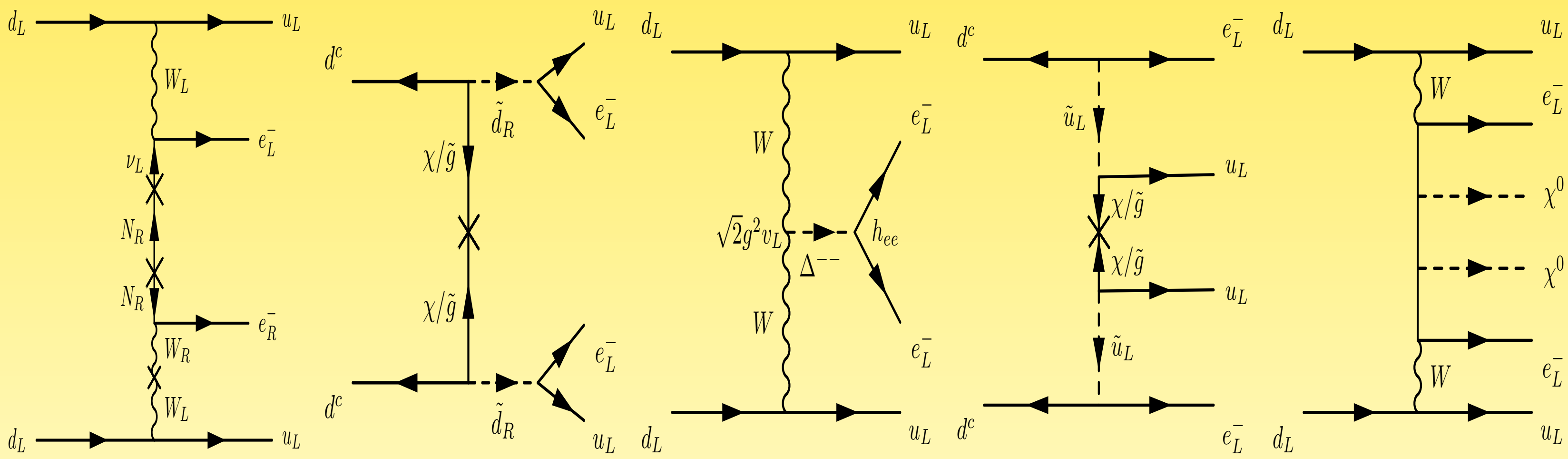
- **Non-Standard Interpretations:**

  There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism

- **Standard Interpretation:**



- **Non-Standard Interpretations:**



$0\nu\beta\beta$ is much more than a neutrino (mass) experiment!

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\lvert U_{ei}^2\, m_i \right\rvert$	0.4 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\lvert \frac{S_{ei}^2}{M_i} \right\rvert$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\lvert \frac{V_{ei}^2}{M_i\, M_{W_R}^4} \right\rvert$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\lvert \frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4} \right\rvert$	10^{-15} GeV^{-5}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\lvert \frac{U_{ei}\, \tilde{S}_{ei}}{M_{W_R}^2} \right\rvert$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta \left\lvert U_{ei}\, \tilde{S}_{ei} \right\rvert$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\left\lvert \lambda'^2_{111} \right\rvert}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\lvert \sin 2\theta^b\, \lambda'_{131}\, \lambda'_{113} \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2} \right) \right\rvert$ $\sim \frac{G_F}{q}\, m_b \frac{\left\lvert \lambda'_{131}\, \lambda'_{113} \right\rvert}{\Lambda_{\rm SUSY}^3}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\lvert\langle g_\chi \rangle\rvert$ or $\lvert\langle g_\chi \rangle\rvert^2$	$10^{-4} \ldots 1$	spectrum, cosmology

Distinguishing Mechanisms

The inverse problem of 0$\nu\beta\beta$

1.) Other observables (LHC, LFV, KATRIN, cosmology,...)

2.) Decay products (individual e^- energies, angular correlations, spectrum,...)

3.) Nuclear physics (multi-isotope, 0νECEC, $0\nu\beta^+\beta^+$,...)

Energy Scale:

Note: *standard amplitude* for light Majorana neutrino exchange:

$$\mathcal{A}_{\rm l} \simeq G_F^2 \, \frac{|m_{ee}|}{q^2} \simeq 7 \times 10^{-18} \left(\frac{|m_{ee}|}{0.5 \text{ eV}} \right) \text{GeV}^{-5} \simeq 2.7 \text{ TeV}^{-5}$$

if new heavy particles are exchanged:

$$\mathcal{A}_{\rm h} \simeq \frac{c}{M^5}$$

$\Rightarrow$ for $0\nu\beta\beta$ holds:

$$\boxed{1 \text{ eV} = 1 \text{ TeV}}$$

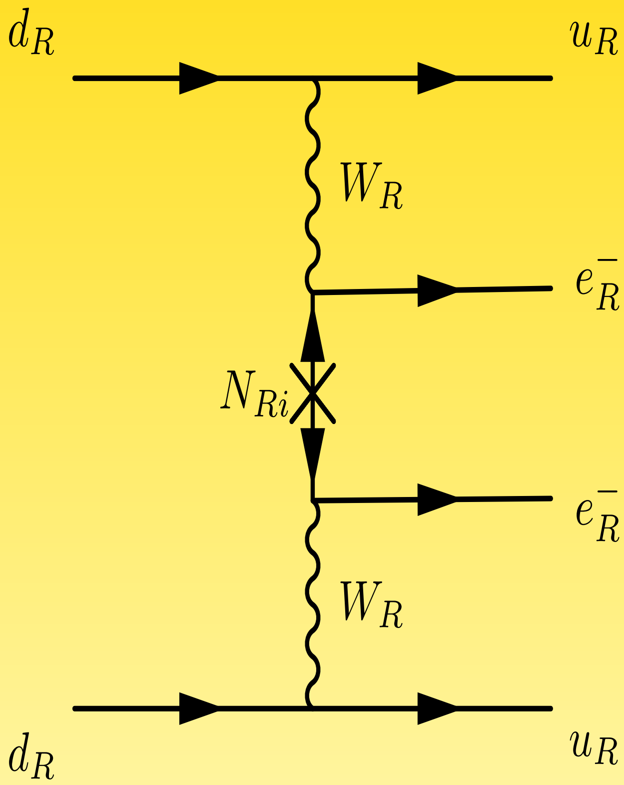
$\Rightarrow$ Phenomenology in colliders, LFV

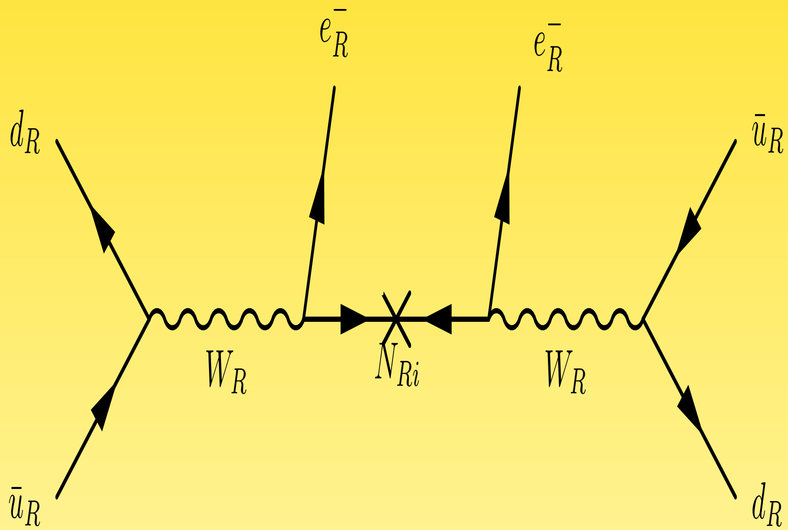
Examples

- R-parity violating supersymmetry (Allanach, Paes, Kom)
- TeV seesaw neutrinos (Ibarra, Petcov *et al.*; Mitra, Senjanovic, Vissani)
- Left-right symmetric theories (Senjanovic *et al.*; Goswami *et al.*; Barry, W.R.)
- Color seesaw (Choubey *et al.*; Kohda *et al.*)
- Higher dimensional operators (Hirsch *et al.*)
- ...

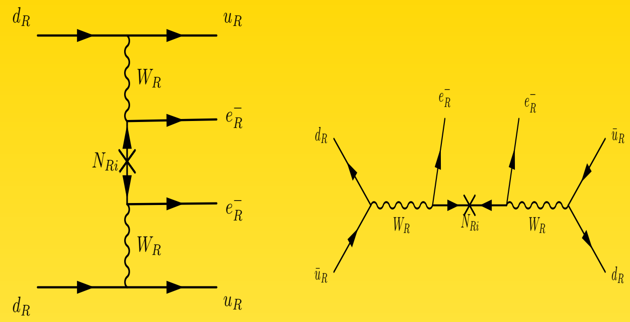
...focus only on one example here...

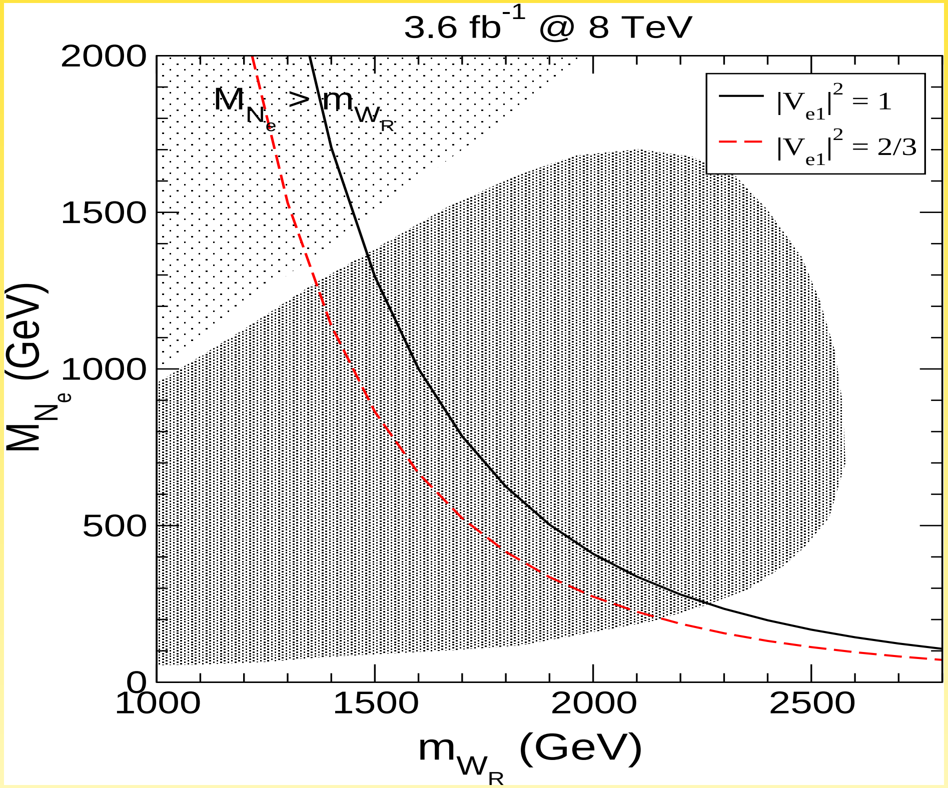
Left-right symmetry





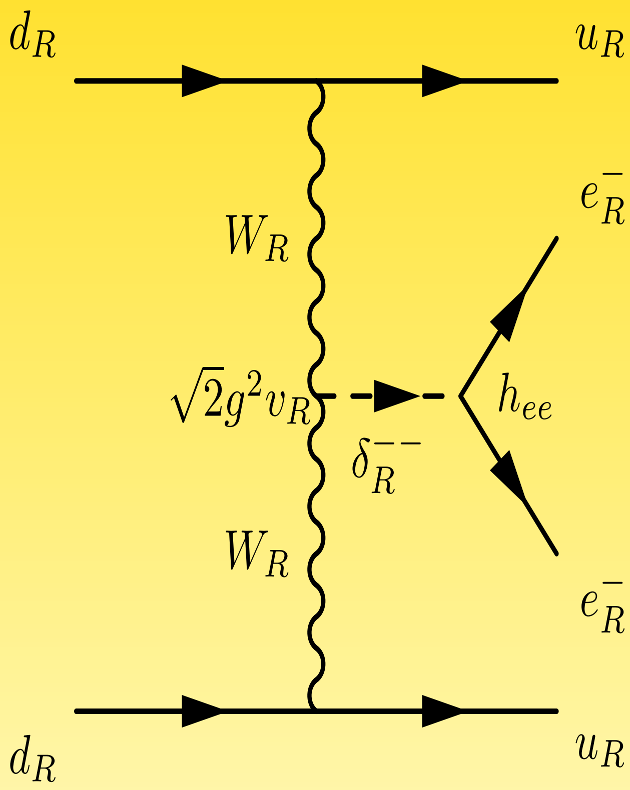
Senjanoviv, Keung, 1983; Senjanovic *et al.*, 1011.3522; 1103.1627

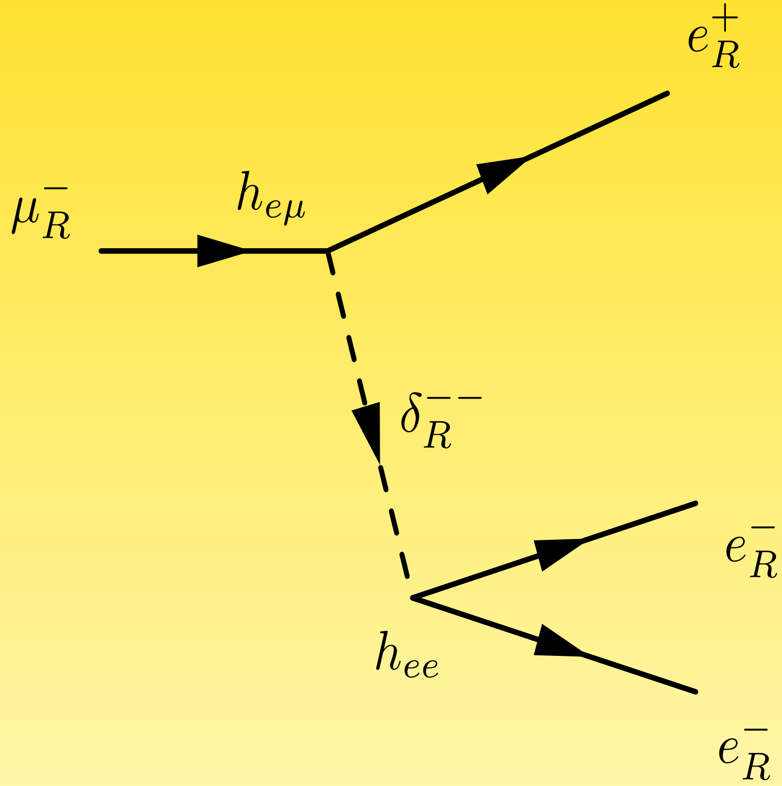

d_R
u_R
W_R
e_R^-
N_{Ri}
e_R^-
W_R
d_R
u_R
d_R
e_R^-
e_R^-
$\bar{u}_R$
W_R
N_{Ri}
W_R
$\bar{u}_R$
d_R


3.6 fb^{-1} @ 8 TeV
$M_{N_e} > m_{W_R}$
$|V_{e1}|^2 = 1$
$|V_{e1}|^2 = 2/3$
M_{N_e} (GeV)
m_{W_R} (GeV)
0
500
1000
1500
2000
1000
1500
2000
2500

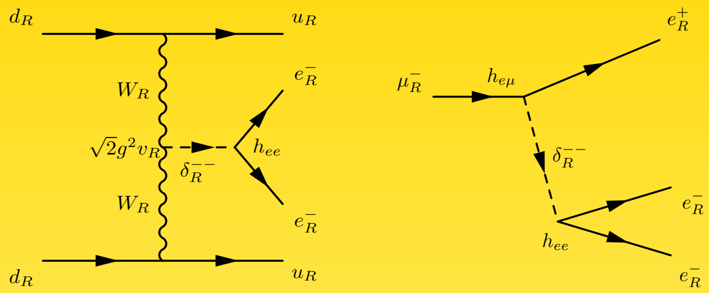
Barry, W.R.

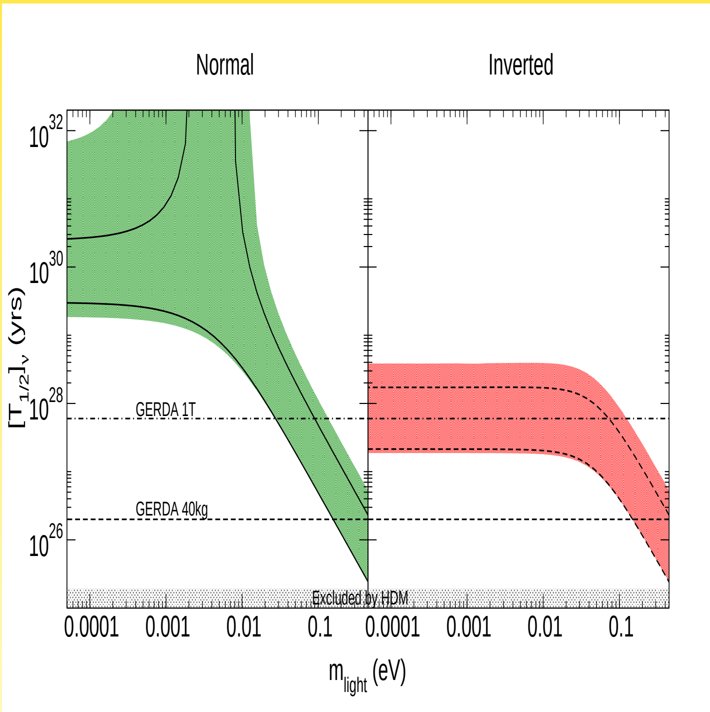
Constraints from Lepton Flavor Violation

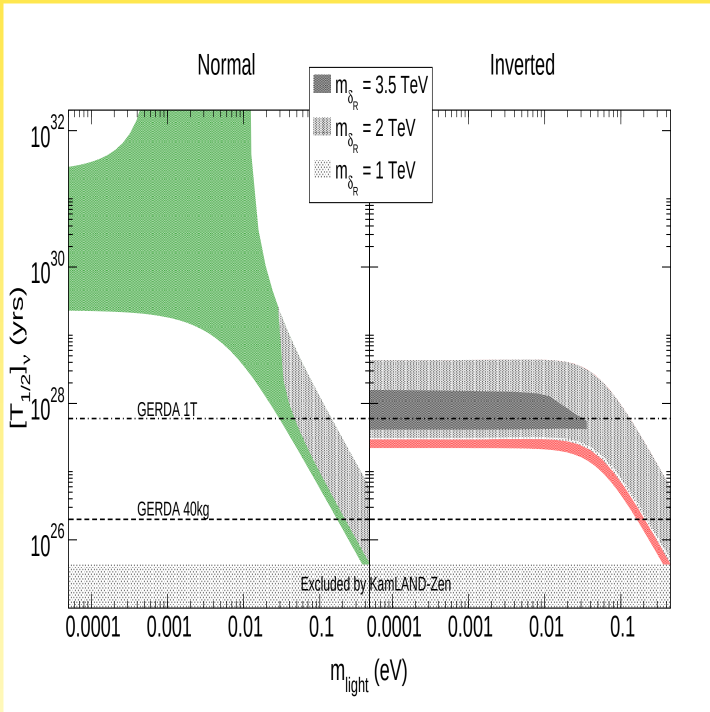




Constraints from Lepton Flavor Violation







Barry, W.R.; talk by James Barry, T 20.1

Summary

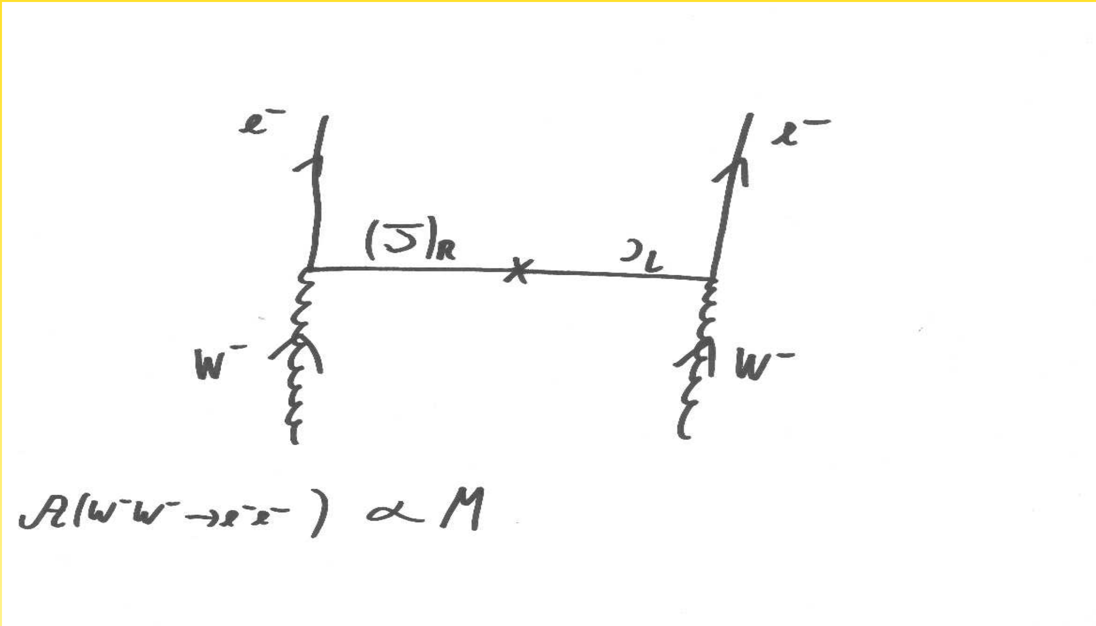
Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Extra Slides from here on

Testing light Majorana Neutrinos

Majorana phenomenology **always** suppressed by $(m_\nu/E)^2$



- RH component can be absorbed *if Majorana particle*
- RH component can be absorbed *if mass is non-zero*

$\Rightarrow$ amplitude $\propto (m_\nu/E) \Rightarrow$ probability $\propto (m_\nu/E)^2$

$\Rightarrow$ only N_A can save the day!

With $0\nu\beta\beta$ one can

- test lepton number violation
- test Majorana nature of neutrinos
- probe neutrino mass scale
- extract Majorana phase
- test flavor symmetry models
- constrain inverted ordering

conceptually, it would increase our believe in

- GUTs
- seesaw mechanism
- leptogenesis

Xe vs. Ge

$$T_{\rm Ge}^{-1} = G_{\rm Ge}\,|\mathcal{M}_{\rm Ge}|^2\,|m_{ee}|^2 \stackrel{?}{=} \left(2.23\times 10^{25}\,{\rm yrs}\right)^{-1}$$

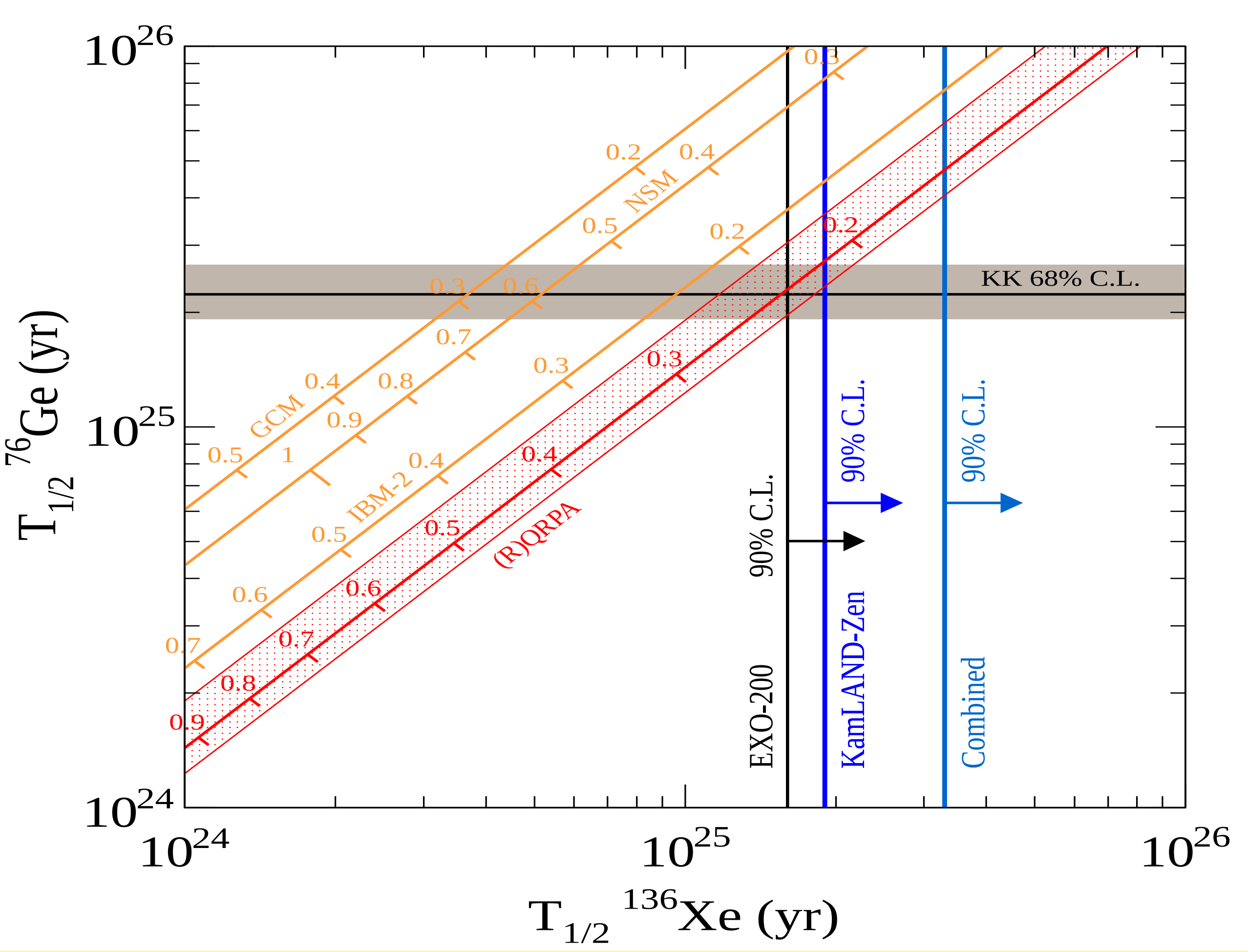
$$T_{\rm Xe}^{-1} = G_{\rm Xe}\,|\mathcal{M}_{\rm Xe}|^2\,|m_{ee}|^2$$

Ge-claim is ruled out when:

$$T_{\rm Xe} \geq 6.5\times 10^{24} \left|\frac{\mathcal{M}_{\rm Ge}}{\mathcal{M}_{\rm Xe}}\right|^2 {\rm yrs}$$

Using available NMEs:

$$\left|\frac{\mathcal{M}_{\rm Ge}}{\mathcal{M}_{\rm Xe}}\right|^2 \simeq \begin{cases} \left|\frac{5.98}{3.67}\right|^2 = 2.66 \Rightarrow T_{\rm Xe} \geq 1.7\times 10^{25}\,{\rm yrs} & \text{IBM-2 (Iachello et al.)} \\ \left|\frac{5.81}{2.78}\right|^2 = 4.37 \Rightarrow T_{\rm Xe} \geq 2.8\times 10^{25}\,{\rm yrs} & \text{QRPA (Tübingen)} \\ \left|\frac{5.18}{3.16}\right|^2 = 2.69 \Rightarrow T_{\rm Xe} \geq 1.7\times 10^{25}\,{\rm yrs} & \text{QRPA (Jyväskulä)} \\ \left|\frac{5.09}{1.89}\right|^2 = 7.25 \Rightarrow T_{\rm Xe} \geq 4.7\times 10^{25}\,{\rm yrs} & \text{QRPA (Engel et al.)} \\ \left|\frac{2.81}{2.19}\right|^2 = 1.65 \Rightarrow T_{\rm Xe} \geq 1.1\times 10^{25}\,{\rm yrs} & \text{NSM (Povez et al.)} \\ \left|\frac{4.60}{4.20}\right|^2 = 1.20 \Rightarrow T_{\rm Xe} \geq 7.8\times 10^{24}\,{\rm yrs} & \text{GCM (Martinez-Pinedo et al.)} \end{cases}$$



KamLAND-Zen, 1211.3863

Sterile Neutrinos and $0\nu\beta\beta$

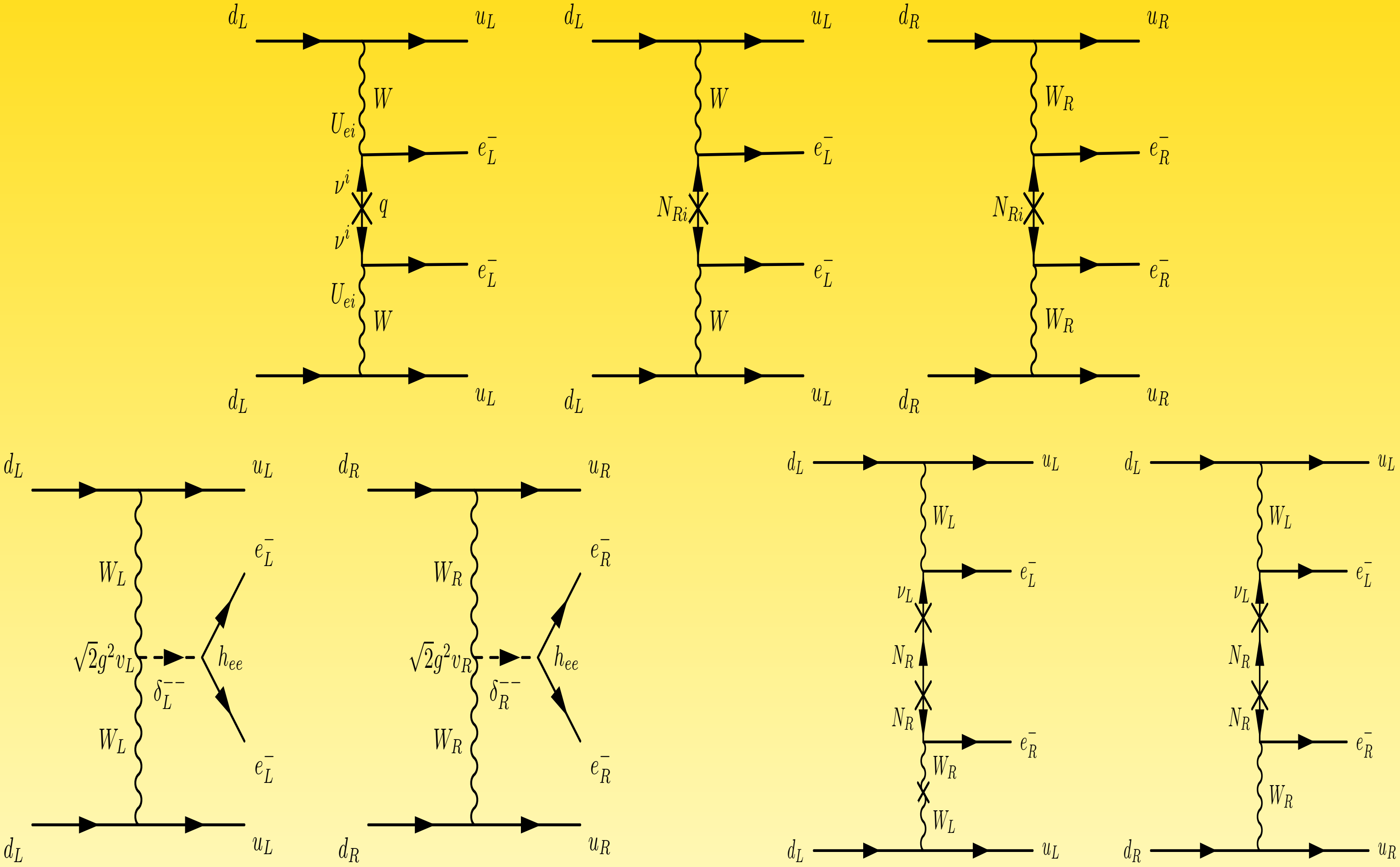
- recall: $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH} \sim 0.03$ eV cannot vanish
- $|m_{ee}| = |\underbrace{|U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}^2|\, m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2\, m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- $\Delta m^2_{\rm st} \simeq 1.8$ eV^2 and $|U_{e4}| \simeq 0.13$
- sterile contribution to $0\nu\beta\beta$ (assuming 1+3):

$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \simeq 0.03 \text{ eV} \left\{ \begin{array}{c} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

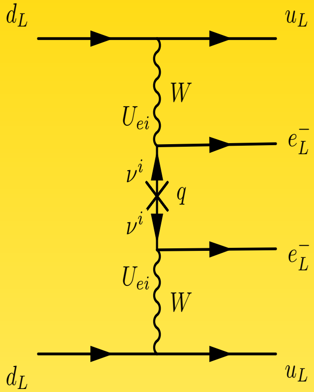
- $\Rightarrow |m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

usual phenomenology gets completely turned around!

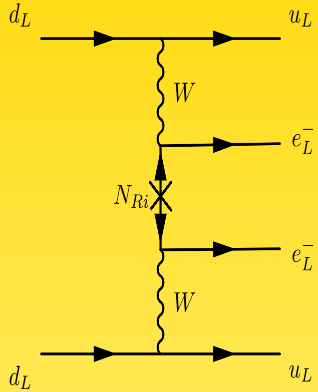
Left-right symmetry



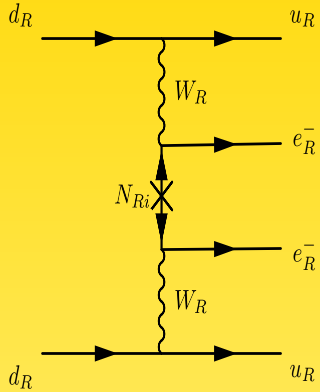
Left-right symmetry



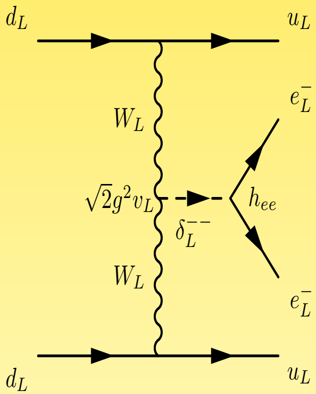
$$U_{ei}^2\, m_i$$



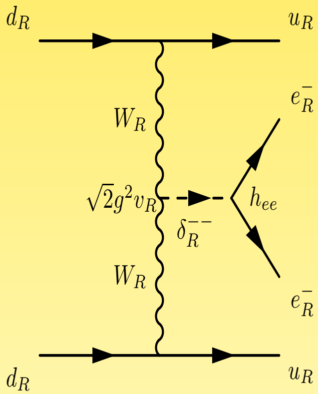
$$\frac{S_{ei}^2}{M_i}$$



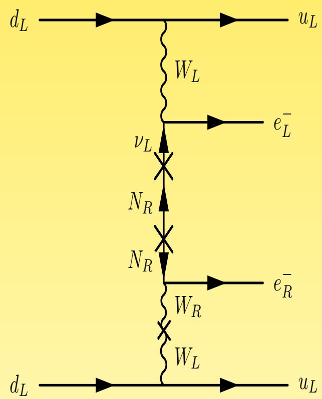
$$\frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



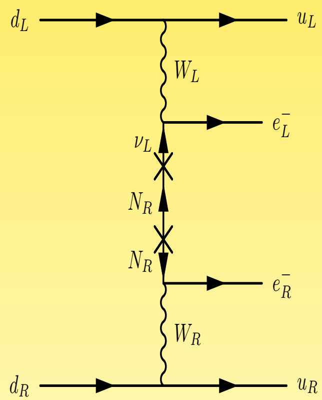
$$\frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$$



$$\frac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2}$$



$$U_{ei}\, T_{ei}\, \tan\zeta$$



$$\frac{U_{ei}\, T_{ei}}{M_{W_R}^2}$$

Alternative processes

$$(A,Z) \to (A,Z+2)^* + 2\,e^- \qquad (0\nu\beta\beta)^*$$

$$(A,Z) \to (A,Z-2) + 2\,e^+ \qquad (0\nu\beta^+\beta^+)$$

$$e_b^- + (A,Z) \to (A,Z-2) + e^+ \qquad (0\nu\beta^+\mathrm{EC})$$

$$2\,e_b^- + (A,Z) \to (A,Z-2)^* \qquad (0\nu\mathrm{ECEC})$$

all depend on the same particle physics parameters, but are more difficult to realize/test

BUT: ratio to $0\nu\beta\beta$ is test of NME calculation and mechanism

precision studies $(0\nu\mathrm{ECEC})$: Klaus Blaum, PV IV

"Inverse $0\nu\beta\beta$"

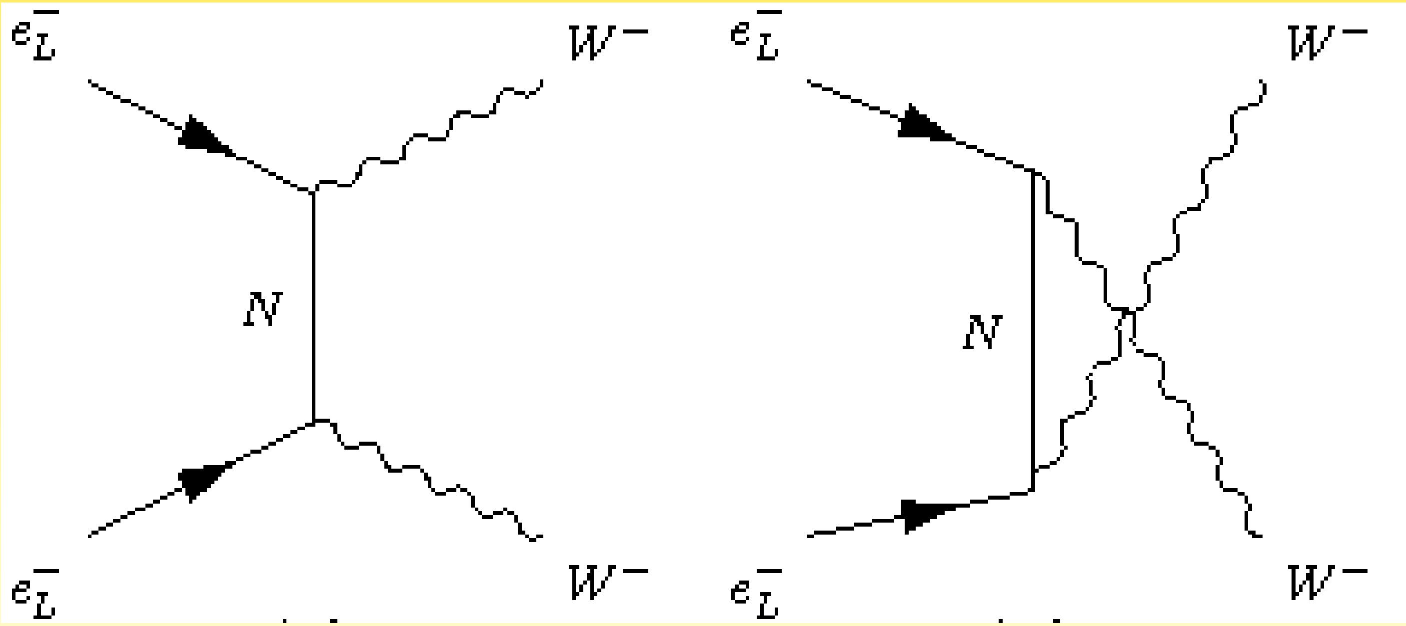
this is not

$$^{76}\mathrm{Se}^{++} + e^- + e^- \to \ ^{76}\mathrm{Ge}$$

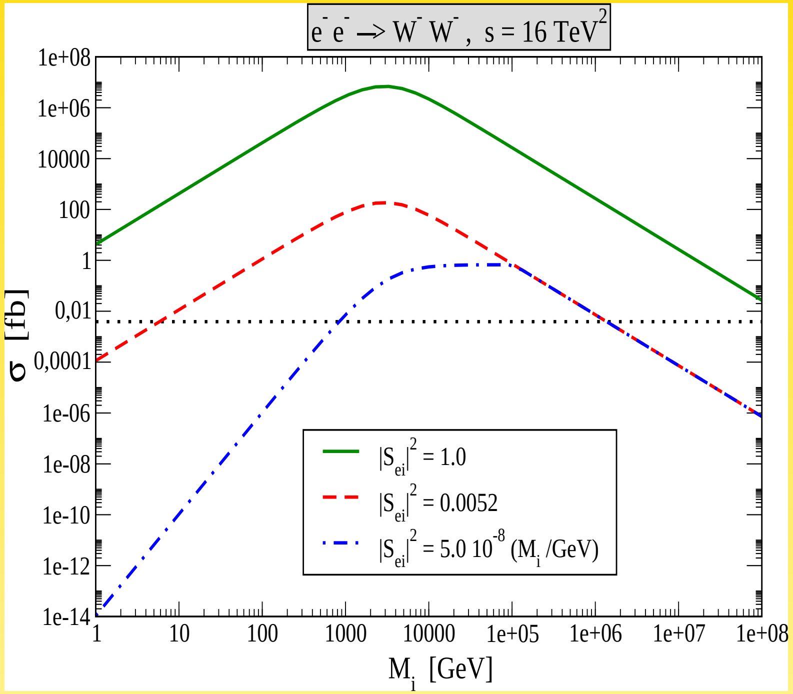
but rather

$$e^- + e^- \to W^- + W^-$$

Rizzo; Heusch, Minkowski; Gluza, Zralek; Cuypers, Raidal;...



Inverse Neutrinoless Double Beta Decay



W.R., PRD **81**

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{32\,\pi}\left\{\sum (m_\nu)_i\,\mathcal{U}_{ei}^2\left(\frac{t}{t-(m_\nu)_i}+\frac{u}{u-(m_\nu)_i}\right)\right\}^2$$

Inverse Neutrinoless Double Beta Decay

Extreme limits:

- light neutrinos:

$$\sigma(e^-e^- \to W^-W^-) = \frac{G_F^2}{4\,\pi}\,|m_{ee}|^2 \leq 4.2 \cdot 10^{-18} \left(\frac{|m_{ee}|}{1\,\mathrm{eV}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ way too small

- heavy neutrinos:

$$\sigma(e^-e^- \to W^-W^-) = 2.6 \cdot 10^{-3} \left(\frac{\sqrt{s}}{\mathrm{TeV}}\right)^4 \left(\frac{S_{ei}^2/M_i}{5 \cdot 10^{-8}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ too small

- $\sqrt{s} \to \infty$:

$$\sigma(e^-e^- \to W^-W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2\,(m_\nu)_i\right)^2$$

$\Rightarrow$ amplitude grows with $\sqrt{s}$? Unitarity??

Unitarity

high energy limit $\sqrt{s} \to \infty$:

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2 \, (m_\nu)_i \right)^2$$

$\leftrightarrow$ amplitude grows with $\sqrt{s}$?

Answer: exact see-saw relation $\mathcal{U}_{ei}^2 \, (m_\nu)_i = 0$

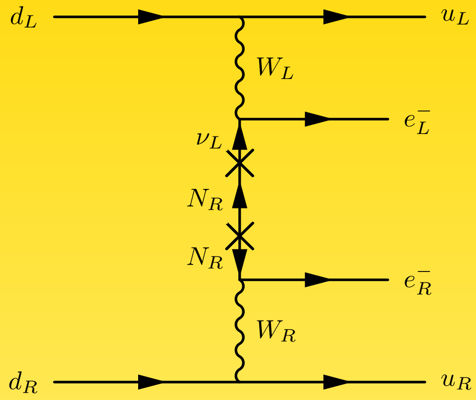
$$\mathcal{M} = \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_R \end{array} \right) = \mathcal{U} \left(\begin{array}{cc} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{array} \right) \mathcal{U}^T$$

if Higgs triplet is present: unitarity also conserved

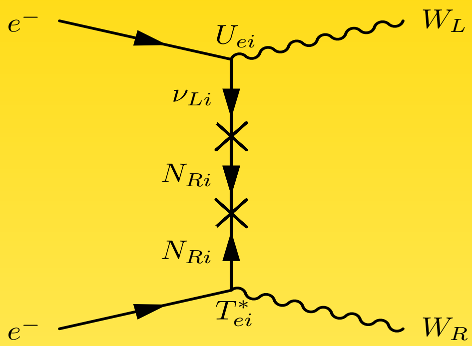
$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left((\mathcal{U}_{ei}^2 \, (m_\nu)_i - (m_L)_{ee} \right)^2 = 0$$

W.R., PRD **81**

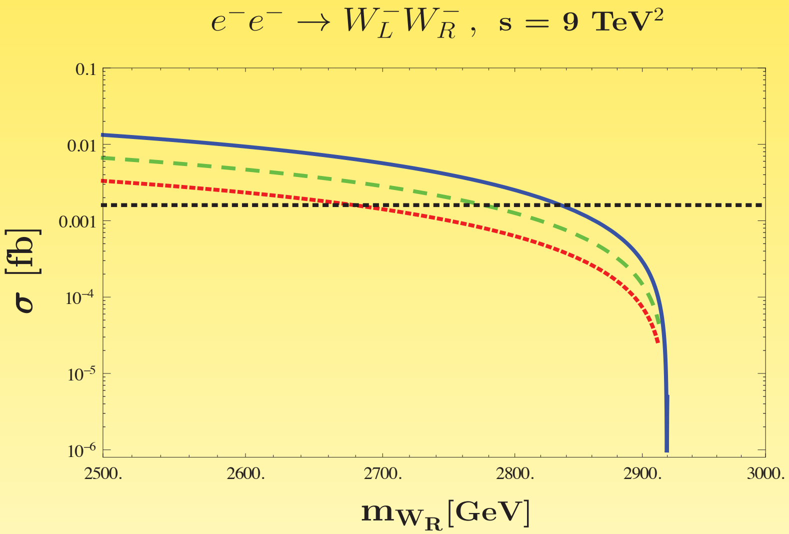
First possibility: λ-diagram in LR symmetry



$0\nu\beta\beta$

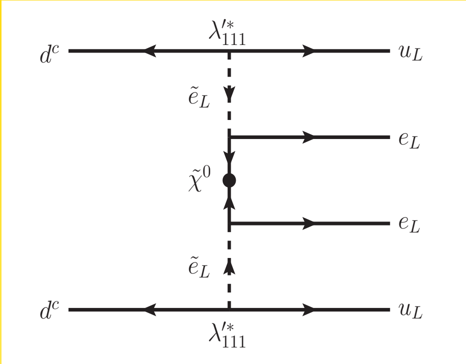


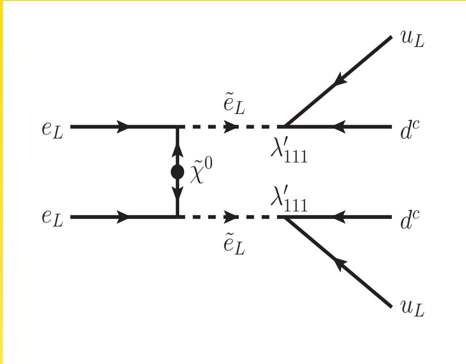
W-W_R production



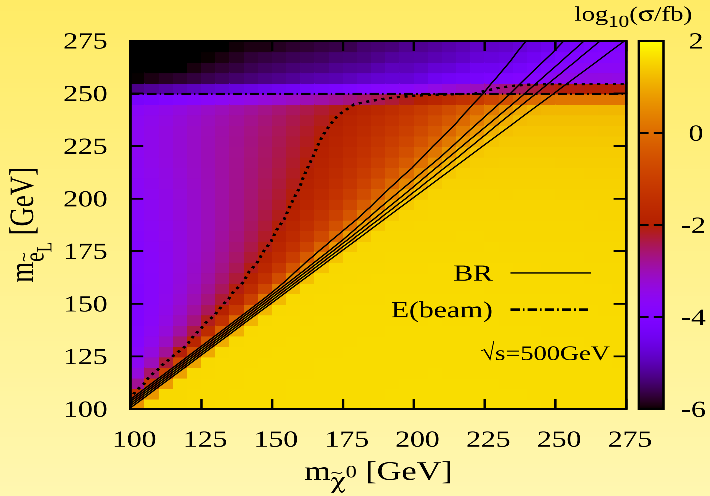
Barry, Dorame, W.R., 1204.3365

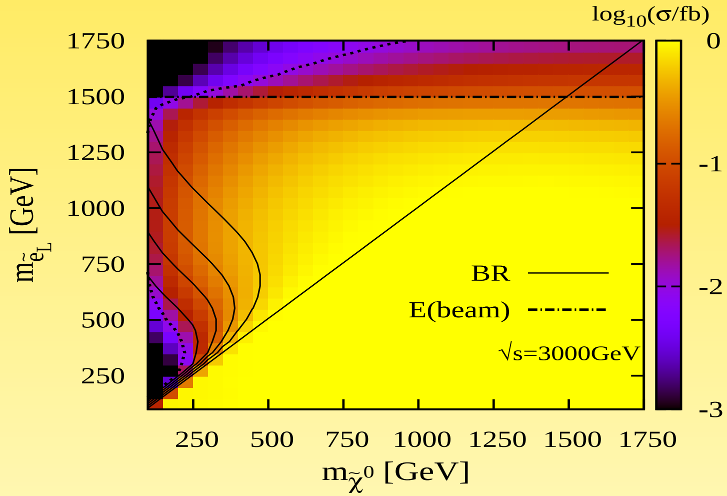
Second possibility: RPV SUSY





$0\nu\beta\beta$ *resonant* $\tilde{e}_L$ production $\to 4j$





Kom, W.R., 1110.3220

3 Reasons for Multi-isotope determination

1.) credibility

2.) test NME calculation

$$\frac{T^{0\nu}_{1/2}(A_1, Z_1)}{T^{0\nu}_{1/2}(A_2, Z_2)} = \frac{G(Q_2, Z_2)}{G(Q_1, Z_1)} \frac{|\mathcal{M}(A_2, Z_2)|^2}{|\mathcal{M}(A_1, Z_1)|^2}$$

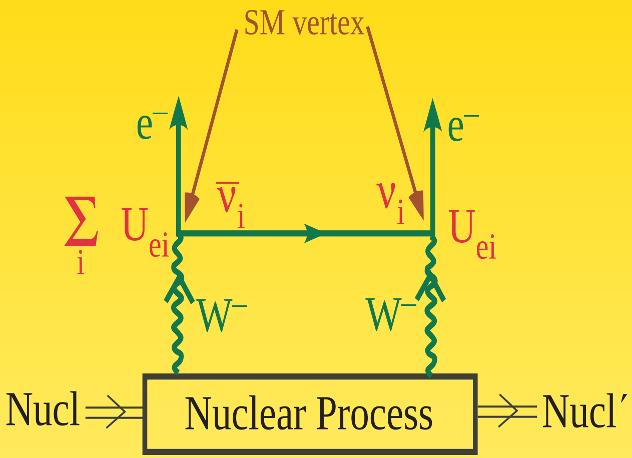
systematic errors drop out, ratio sensitive to NME model

3.) test mechanism

$$\frac{T^{0\nu}_{1/2}(A_1, Z_1)}{T^{0\nu}_{1/2}(A_2, Z_2)} = \frac{G_x(Q_2, Z_2)}{G_x(Q_1, Z_1)} \frac{|\mathcal{M}_x(A_2, Z_2)|^2}{|\mathcal{M}_x(A_1, Z_1)|^2}$$

particle physics drops out, ratio of NMEs sensitive to mechanism

From life-time to particle physics: Nuclear Matrix Elements



- 2 point-like Fermi vertices; "long-range" neutrino exchange; momentum exchange $q \simeq 1/r \simeq 0.1$ GeV
- NME $\leftrightarrow$ overlap of decaying nucleons...
- different approaches (QRPA, NSM, IBM, GCM, pHFB) imply uncertainty
- plus uncertainty due to model details
- plus convention issues (Cowell, PRC **73**; Smolnikov, Grabmayr, PRC **81**; Dueck, W.R., Zuber, PRD **83**)

typical model for NME: set of single particle states with a number of possible wave function configurations; solve $\mathcal{H}$ in a mean background field

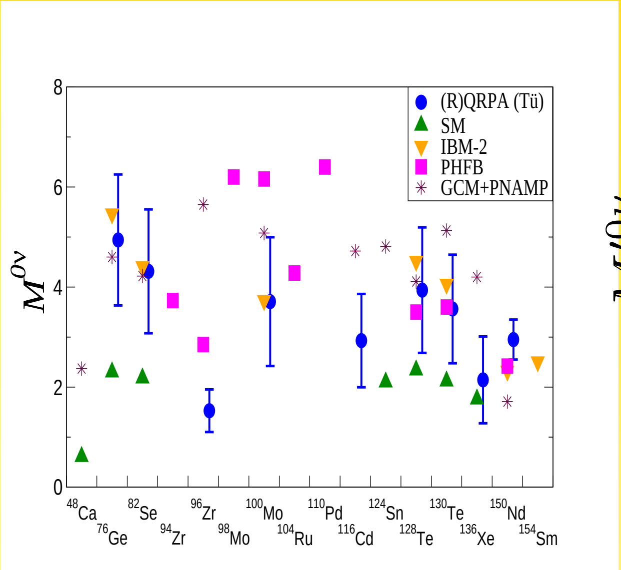
- Quasi-particle Random Phase Approximation (QRPA) (many single particle states, few configurations)
- Nuclear Shell Model (NSM) (many configurations, few single particle states)
- Interacting Boson Model (IBM) (many single particle states, few configurations)
- Generating Coordinate Method (GCM) (many single particle states, few configurations)
- projected Hartree-Fock-Bogoliubov model (pHFB)

tends to overestimate NMEs

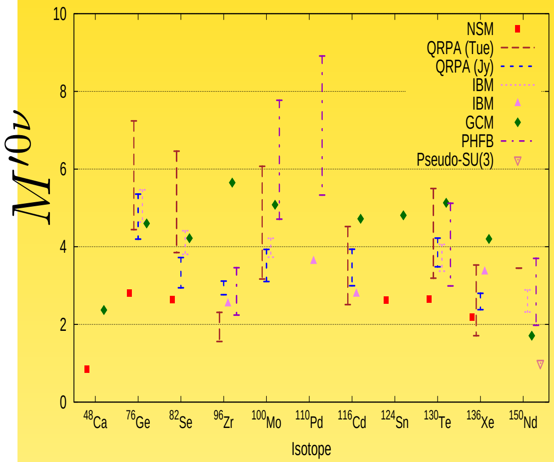
tends to underestimate NMEs

See `Javier Menendez, HK 85.1 (HV)`

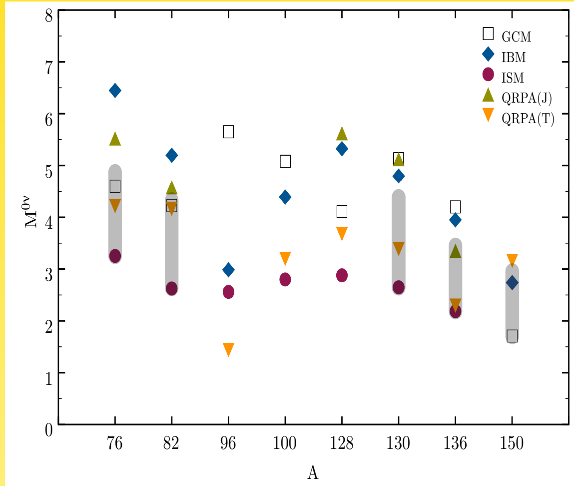
From life-time to particle physics: Nuclear Matrix Elements



Faessler, 1104.3700

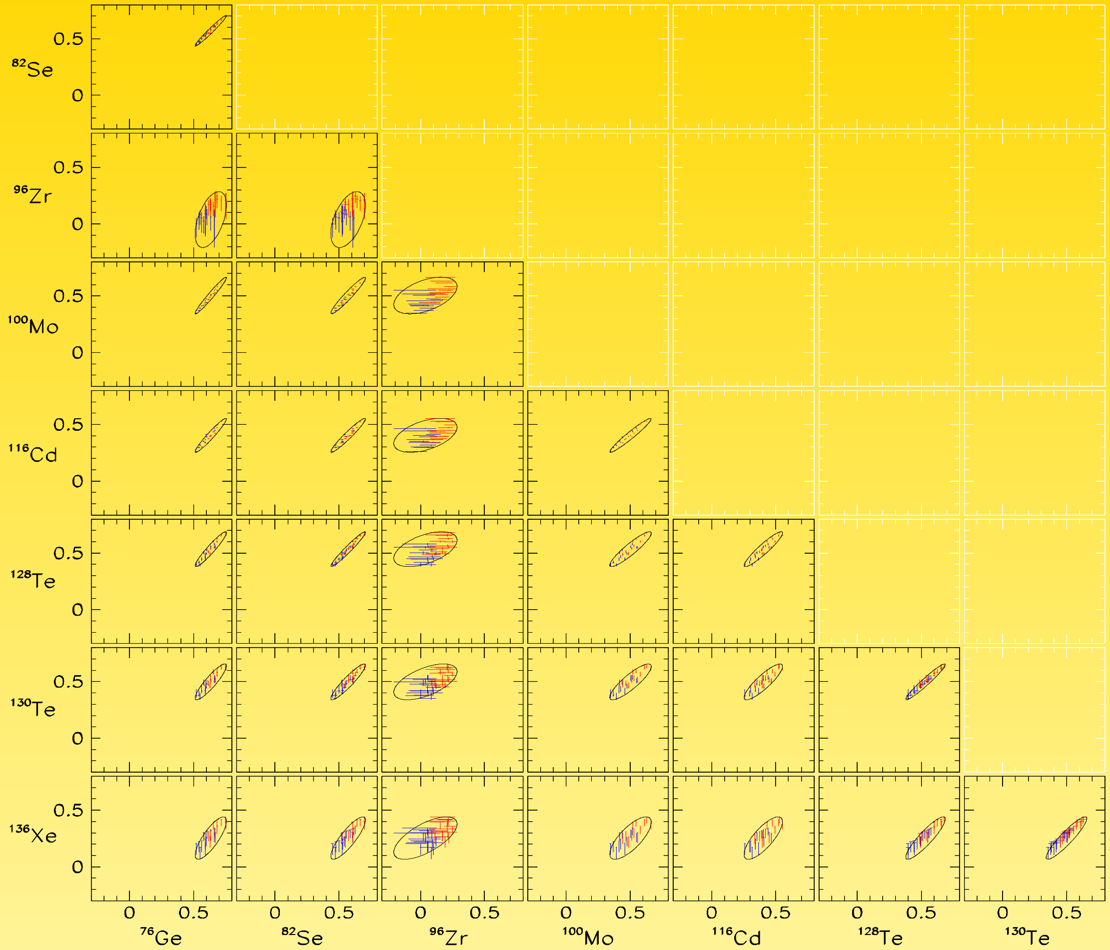


Dueck, W.R., Zuber, PRD **83**



Gomez-Cadenas *et al.*, 1109.5515

to better estimate error range: correlations need to be understood



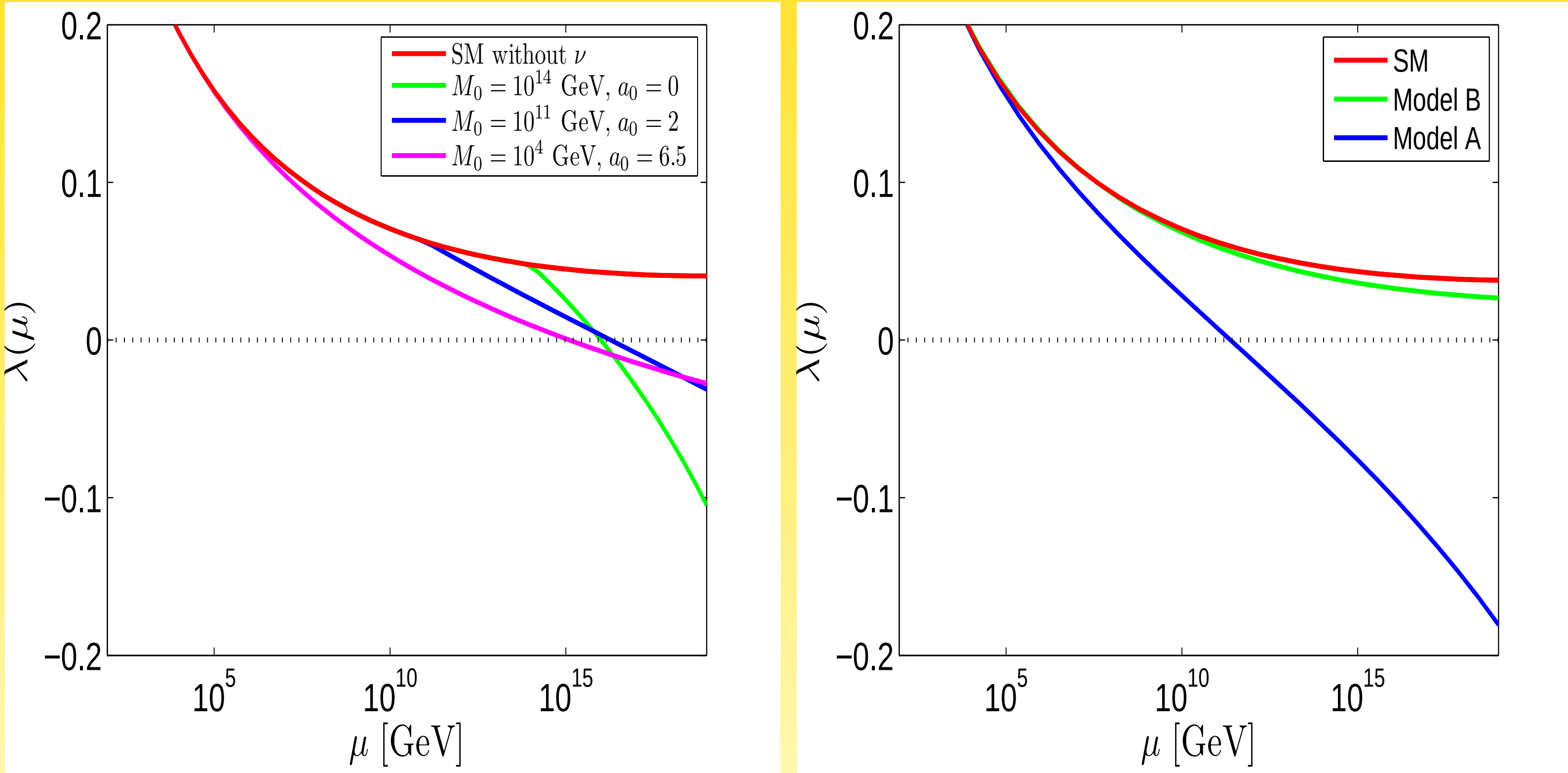
Faessler, Fogli *et al.*, PRD **79**

ellipse major axis: SRC (blue, red) and g_A

ellipse minor axis: g_{pp}

Higgs physics and sterile neutrinos

if neutrinos are made accessible at colliders, Dirac Yukawa is large even for TeV neutrinos ⇒ influences vacuum stability bound



W.R., Zhang

Why we think neutrinos have Majorana masses

- higher-dimensional operators: gauge and Lorentz invariant, only SM fields (Weinberg 1979):

$$\frac{1}{\Lambda}\,\mathcal{O}_5 = \frac{c}{\Lambda}\,\overline{L}\,\Phi\,\Phi\,L^c \stackrel{\text{EWSB}}{\longrightarrow} \frac{c\,v^2}{\Lambda}\,\overline{\nu_L}\,\nu_L^c \equiv M_L\,\overline{\nu_L}\,\nu_L^c$$

- GUTs: $\mathbf{16}_F$ of $SO(10)$ is

$$\mathbf{16}_F = \big((u_{r,g,b})_{L,R}, (d_{r,g,b})_{L,R}, e^{\pm}, \nu_L, N_R\big)$$

coupling with $\mathbf{126}_H$ gives Majorana mass

$M\,\overline{\nu_L}(\nu_L)^c$ is realized in basically all theories beyond the Standard Model!

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$

- $G_x(Q,Z)$: phase space factor
- $\mathcal{M}_x(A,Z)$: nuclear physics
- η_x: particle physics

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$

- $G_x(Q,Z)$: phase space factor; calculable
- $\mathcal{M}_x(A,Z)$: nuclear physics; problematic
- η_x: particle physics; interesting

Testing light Majorana Neutrinos

in $V-A$ theories: difference in rate **always** suppressed by $(m_\nu/E)^2$

- suppose beam from π^+ decays: $\pi^+ \to \mu^+ \nu_\mu$
- can we observe $\nu_\mu \to \overline{\nu}_\mu$ and $\overline{\nu}_\mu + n \to p + \mu^-$?
- emitted particle is not purely left-handed:

$$\nu_\downarrow = \nu_L + \frac{m_\nu}{E} N_R = \begin{cases} \nu_L + \frac{m_\nu}{E} N_R & \text{Dirac} \\ \nu_L + \frac{m_\nu}{E} \overline{\nu}_R & \text{Majorana} \end{cases}$$

- RH component can be absorbed $P_R \nu_\downarrow \neq 0$ if
  - *if Majorana particle*
  - *if mass is non-zero*

$\Rightarrow$ amplitude $\propto (m_\nu/E)$ $\Rightarrow$ probability $\propto (m_\nu/E)^2$

(only N_A can save the day!)

Dirac vs. Majorana

- Z-decay:

$$\frac{\Gamma(Z \to \nu_{\rm D}\nu_{\rm D})}{\Gamma(Z \to \nu_{\rm M}\nu_{\rm M})} \simeq 1 - 3\frac{m_\nu^2}{m_Z^2}$$

- Meson decays

$$\mathrm{BR}(K^+ \to \pi^- \, e^+ \, \mu^+) \propto |m_{e\mu}|^2 = \left|\sum U_{ei} \, U_{\mu i} \, m_i\right|^2 \sim 10^{-30} \, \left(\frac{|m_{e\mu}|}{\mathrm{eV}}\right)^2$$

- neutrino-antineutrino oscillations

$$P(\nu_\alpha \to \bar{\nu}_\beta) = \frac{1}{E^2} \left| \sum_{i,j} U_{\alpha j} U_{\beta j} U_{\alpha i}^* U_{\beta i}^* \, m_i m_j \, \mathsf{e}^{-i(E_j - E_i)t} \right|$$

Neutrino Physics

$$|U| = \begin{pmatrix} 0.795\ldots0.846 & 0.513\ldots0.585 & 0.126\ldots0.178 \\ 0.205\ldots0.543 & 0.416\ldots0.730 & 0.579\ldots0.808 \\ 0.215\ldots0.548 & 0.409\ldots0.725 & 0.567\ldots0.800 \end{pmatrix}$$

looks different to

$$|V| = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

Only 3 tree-level methods for Majorana masses

General remarks: $SU(2)_L \times U(1)_Y$ with $\underline{2} \otimes \underline{2} = \underline{3} \oplus \underline{1}$:

$$\overline{L}\,\tilde{\Phi} \sim (\underline{2}, -1) \otimes (\underline{2}, 1) = (\underline{3}, 0) \oplus (\underline{1}, 0)$$

To make a singlet, couple $(\underline{1}, 0)$ or $(\underline{3}, 0)$, because $\underline{3} \otimes \underline{3} = \underline{5} \oplus \underline{3} \oplus \underline{1}$

Alternatively:

$$\overline{L}\,L^c \sim (\underline{2}, -1) \otimes (\underline{2}, -1) = (\underline{3}, -2) \oplus (1, -2)$$

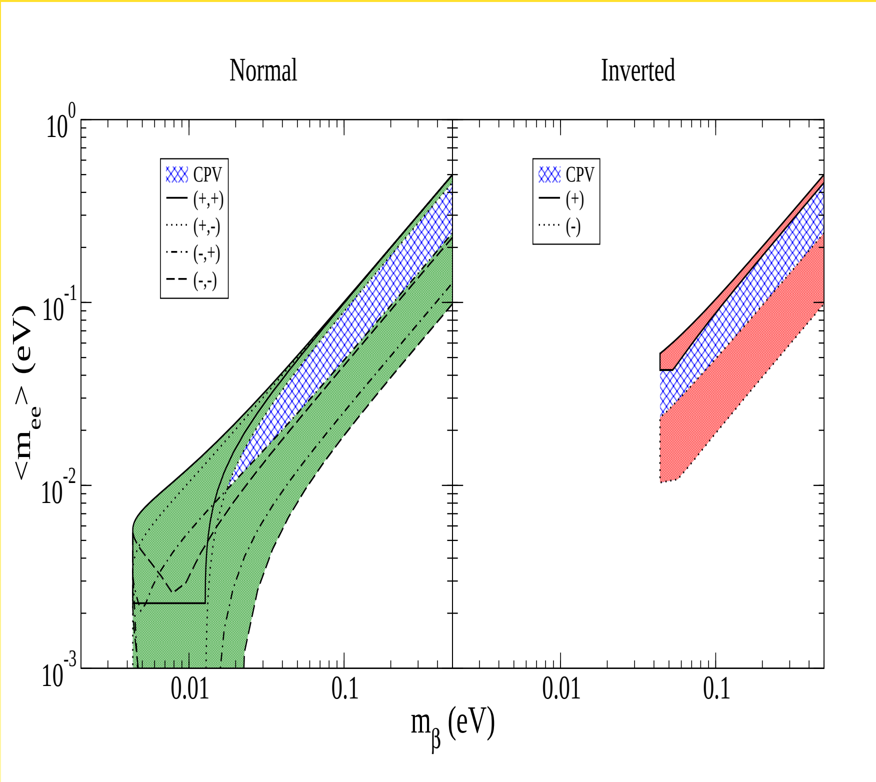
To make a singlet, couple to $(\underline{1}, 2)$ or $(\underline{3}, 2)$. However, singlet combination is $\overline{\nu}\,\ell^c - \overline{\ell}\,\nu^c$, which cannot generate neutrino mass term

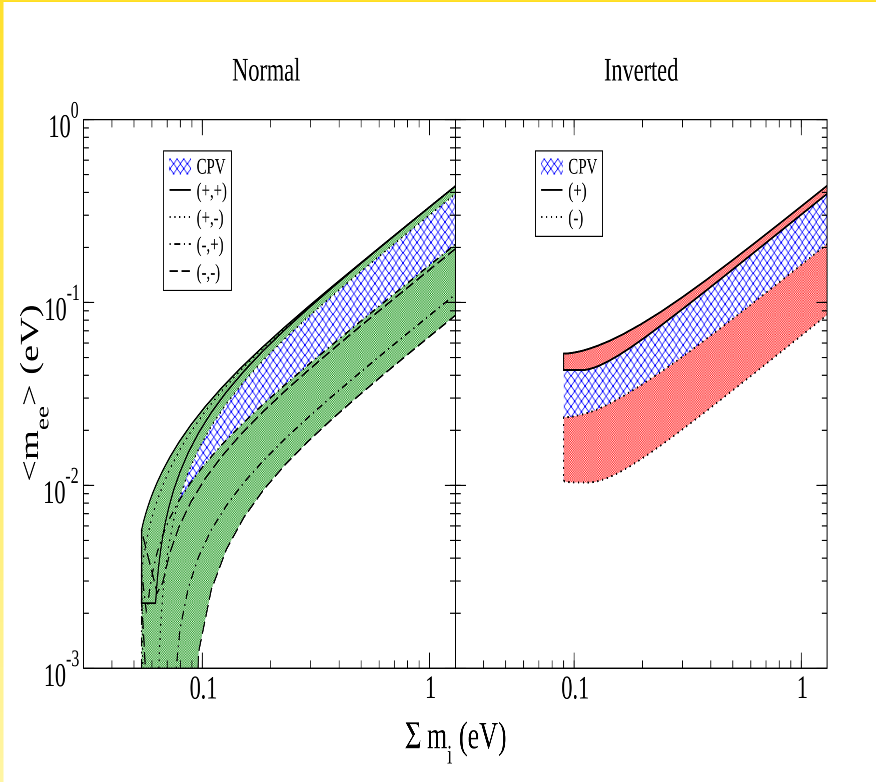
$\Longrightarrow$	$(\underline{1}, 0)$	or	$(\underline{3}, 2)$	or	$(\underline{3}, 0)$
seesaw	type I		type II		type III

Ansatz	content	$\mathcal{L}$	m_ν	scale
"SM" (Dirac mass)	singlet	$y\overline{L}HN_R$	yv	$y = \mathcal{O}(10^{-12})$
"effective" (dim 5 operator)	new scale + LNV	$\frac{1}{\Lambda}\overline{L}HH^TL^c$	$\frac{v^2}{\Lambda}$	$\Lambda = \left(\frac{0.1\text{ eV}}{m_\nu}\right)10^{14}$ GeV
"direct" (Type II See-Saw)	Higgs triplet + LNV	$y\overline{L}\Delta L^c + \mu HH\Delta$	yv_T	$\Lambda = \frac{1}{y\mu}M_\Delta^2$
"indirect 1" (Type I see-saw)	Singlet + LNV	$y\overline{L}HN_R + \overline{N_R^c}M_RN_R$	$\frac{(yv)^2}{M_R}$	$\Lambda = \frac{1}{y}M_R$
"indirect 2" (Type III see-saw)	Fermion triplet + LNV	$y\overline{L}\,\Sigma H + \mathrm{Tr}\overline{\Sigma}M_\Sigma\Sigma$	$\frac{(yv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{y}M_\Sigma$

All theories beyond the Standard Model predict Majorana neutrinos!

Plot against other observables





Complementarity of $|m_{ee}| = U_{ei}^2\, m_i$, $m_\beta = \sqrt{|U_{ei}|^2\, m_i^2}$ and $\Sigma = \sum m_i$

Majorana Particles

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REPORT

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

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ABSTRACT

Majorana fermions are particles identical to their own antiparticles. They have been theoretically predicted to exist in topological superconductors. We report electrical measurements on InSb nanowires contacted with one normal (Au) and one superconducting electrode (NbTiN). Gate voltages vary electron density and define a tunnel barrier between normal and superconducting contacts. In the presence of magnetic fields of order 100 mT, we observe bound, mid-gap states at zero bias voltage. These bound states remain fixed to zero bias even when magnetic fields and gate voltages are changed over considerable ranges. Our observations support the hypothesis of Majorana fermions in nanowires coupled to superconductors.

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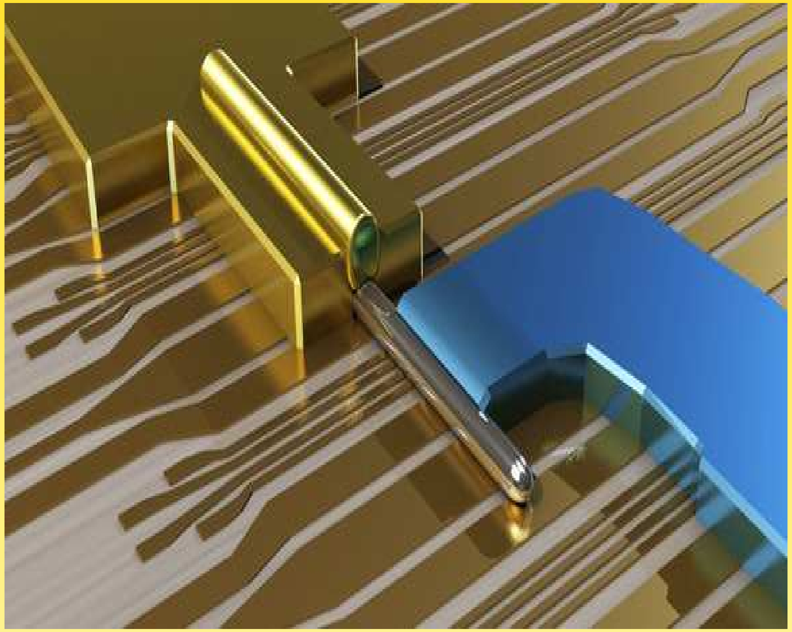


put a semi-conductor nanowire between a gold electrode and a superconductor

observe zero-velocity quasiparticles in the nanowire

(electrons acting collectively as Majorana fermions)

FRANKFURTER ALLGEMEINE SONNTAGSZEITUNG, 22. APRIL 2012, NR. 16 — WISSENSCHAFT 57

SOZIALE SYSTEME

Frauen und Kinder zuerst

VON JÜRGEN KAUBE

Frauen und Kinder zuerst – so lautet die soziale Norm bei Schiffsuntergängen. Wird ihr auch gefolgt? Ein Autorenteam um den Schweizer Ökonomen Bruno S. Frey hat die entsprechenden Daten der „Titanic“- und „Lusitania“-Havarien untersucht. Dabei zeigte sich, dass auf der „Titanic“ Frauen und Passagiere der ersten Klasse die höchsten Überlebenschancen hatten, bei der von einem deutschen Torpedo getroffenen „Lusitania“ hingegen gab es solch ein Muster nicht.

Die Erklärung der Forscher: Die „Titanic“ sank langsam, die „Lusitania“ binnen achtzehn Minuten. Soziale Normen durchzusetzen benötigt auch dann Zeit, wenn sie schon vor ihrem Anwendungsfall bekannt sind und sich nicht erst aus der Gefahrensituation heraus entwickeln. Bemerkenswert aber sei gleichwohl, dass auf der „Titanic“ eine …

Quasi ein Teilchen

Seit Jahrzehnten suchen Physiker eine neue Sorte von Partikeln. Jetzt haben sie solche „Majorana-Teilchen“ aufgespürt – zumindest etwas in der Art.

VON ROBERT GAST

Der Raum war viel zu klein. Gestandene Forscher mussten auf dem Boden Platz nehmen, immer mehr Publikum drängte in den Saal auf dem März-Treffen der amerikanischen Physikervereinigung in Boston. Schließlich präsentierte der Niederländer Leo Kouwenhoven von der Delft University of Technology das heißersehnte Resultat: „Haben wir Majorana-Fermionen gefunden? Ich würde vorsichtig sagen: ja.“ Die Zuhörer lauschten gebannt, berichtet Wolfgang Belzig von der Universität Konstanz. „Es ist sehr selten, dass man bei so einem aufregenden Ereignis dabei sein kann“, sagt er. Etwas Vergleichbares habe es zuletzt vor acht Jahren gegeben, als der Wunderstoff Graphen der Öffentlichkeit präsentiert wurde.

Der Name Ettore Majorana lässt seit Jahrzehnten Forscheraugen leuchten. …

Ettore Majorana fragte sich, ob es Materie gibt, die mit ihrer Antimaterie identisch ist.

Eine Perle für Festkörperphysiker, eine harte Nuss für Philosophen.

A bis Z

Lehm

INS NETZ GEGANGEN

DA LACHT DAS LABOR

IN DEN STERNEN

Chamäleon

VON ULF VON RAUCHHAUPT

…n es denn ein Majo…
…nen ist. Gegenwärtig versu…
…en gleich mehrere Experimente …n abgeschirmten Untergrund-Labors, diesen „neutrinolosen doppelten Beta-Zerfall“ aufzuspüren (*Sonntagszeitung* vom 21.11.2010).

Hat sich das mit der Entdeckung aus Delft nun erledigt? Rodejohann winkt ab: „Das Ergebnis von Kouwenhoven ist leider kein Beweis, dass es auch in der Natur elementare Majoranas gibt.“ Was die Niederländer gezeigt hätten, sei …in spezieller Effekt im Inneren ei… Festkörpers, der ähnliche Eigen…
…n wie die ersehnte Partik…

Non-maximal θ_{23}?

LBL accelerator experiments have octant-asymmetric amplitude (plus higher order terms with sensitivity to δ and sgn$(\Delta m^2_{\rm A})$)

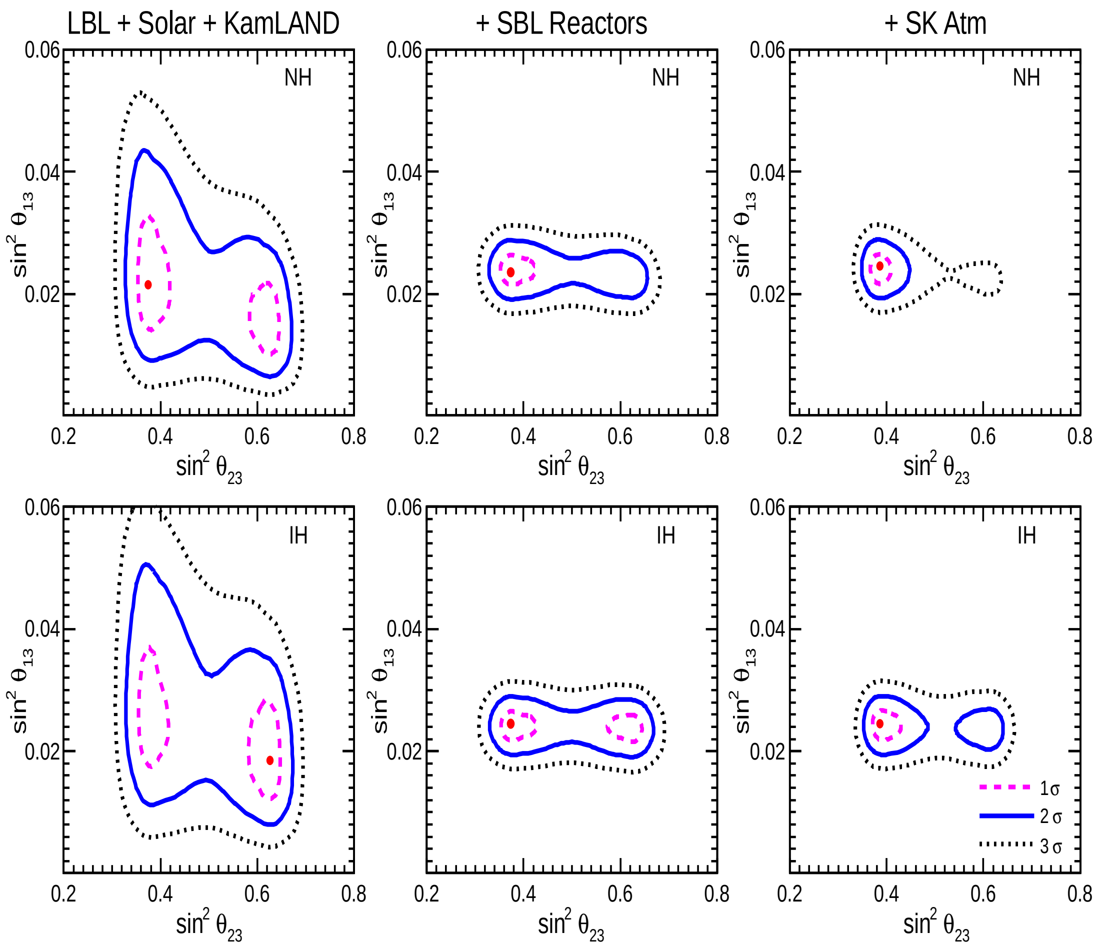
$$P(\nu_\mu \to \nu_\mu) \propto \cos^2\theta_{13}\sin^2\theta_{23}\,(1 - \cos^2\theta_{13}\sin^2\theta_{23})$$
$$P(\nu_\mu \to \nu_e) \propto \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}$$

MINOS and T2K disappearence data most important, preference for $\theta_{23} \neq \pi/4$

atmospheric data:

$$N_e - N_e^0 \propto (R\sin^2\theta_{23} - 1)\, f(\Delta m^2_{\rm A}, \theta_{13}) + (R\cos^2\theta_{23} - 1)\, g(\Delta m^2_\odot, \theta_{12})$$
$$-C\,\sin\theta_{13}\sin\theta_{23}\,\cos\theta_{23}\cos\delta$$

slight electron excess in sub-GeV atmospheric data sets easier explained by $\cos\delta = -1$ and $\theta_{23} < \pi/4$



Fogli, Lisi, *et al.*, June 2012

Dirac vs. Majorana masses

CP-Partner ψ^c of a **neutral fermion** ψ has two options:

$$(i)\ \psi^c = \psi \text{ or } (ii)\ \psi^c \neq \psi$$

Option (i) implies that $\boxed{(\psi_L)^c = \psi_R}$

$\Rightarrow$ left- and right-handed projection are related!

This means for mass term $\overline{L}R$:

$$M_L\, \overline{\psi_L} (\psi_L)^c$$

Such a fermion $\psi = \psi^c$ is a **Majorana fermion**

Phenomenology of heavy singlets

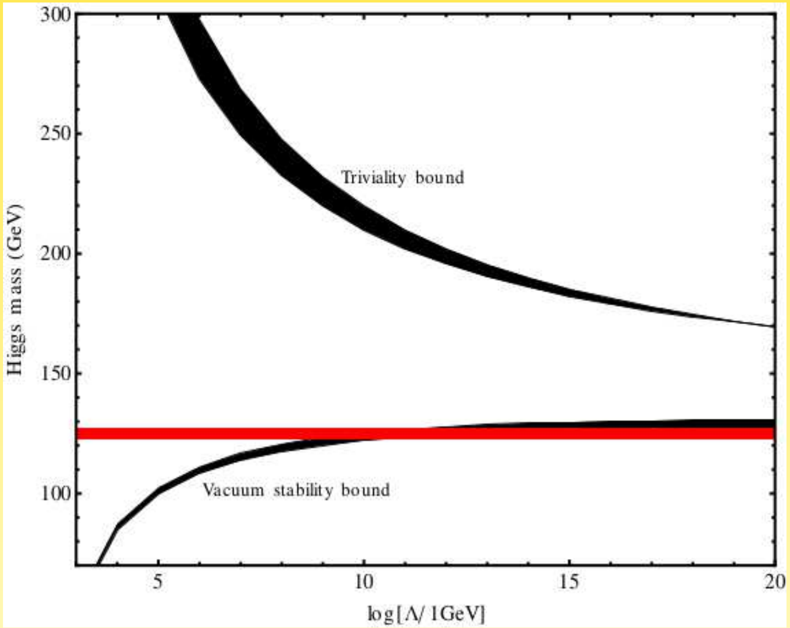
recall: quartic Higgs coupling $\lambda = m_h/(v\sqrt{2})$ is driven negative:

$$\beta_\lambda \propto -24\,\mathrm{Tr}\left(m_{\rm up}^\dagger m_{\rm up}\right)^2 \Rightarrow m_h \geq f(\Lambda)$$

vacuum stability bound

currently unclear situation ($\leftrightarrow$ top mass):

- could be $\lambda(M_{\rm Pl}) = 0$
- vacuum could be stable
- vacuum could be unstable
- vacuum could be metastable



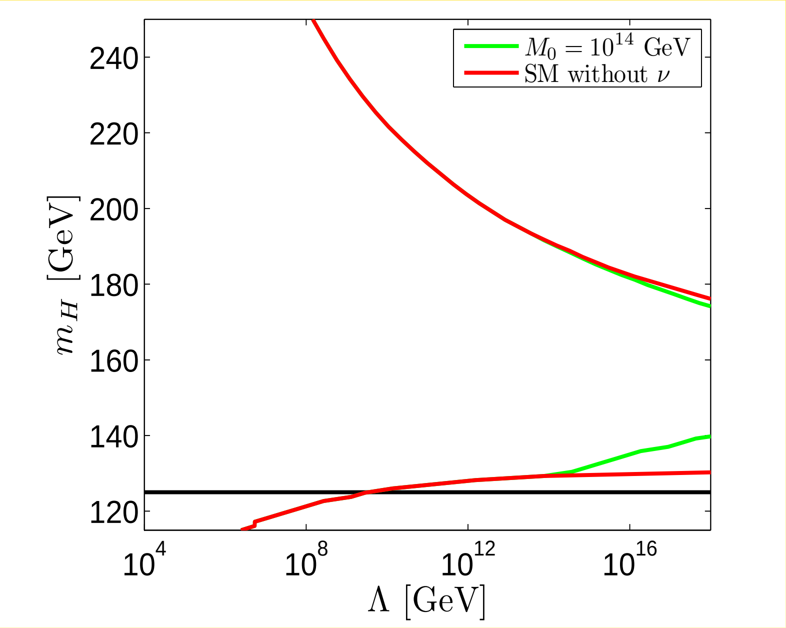
(Holthausen, Lim, Lindner; Bezrukov *et al.*; Strumia *et al.*; Masina)

Phenomenology of heavy singlets

often overlooked: Dirac mass $\overline{\nu_L}\, m_D\, N_R$ contribution to λ:

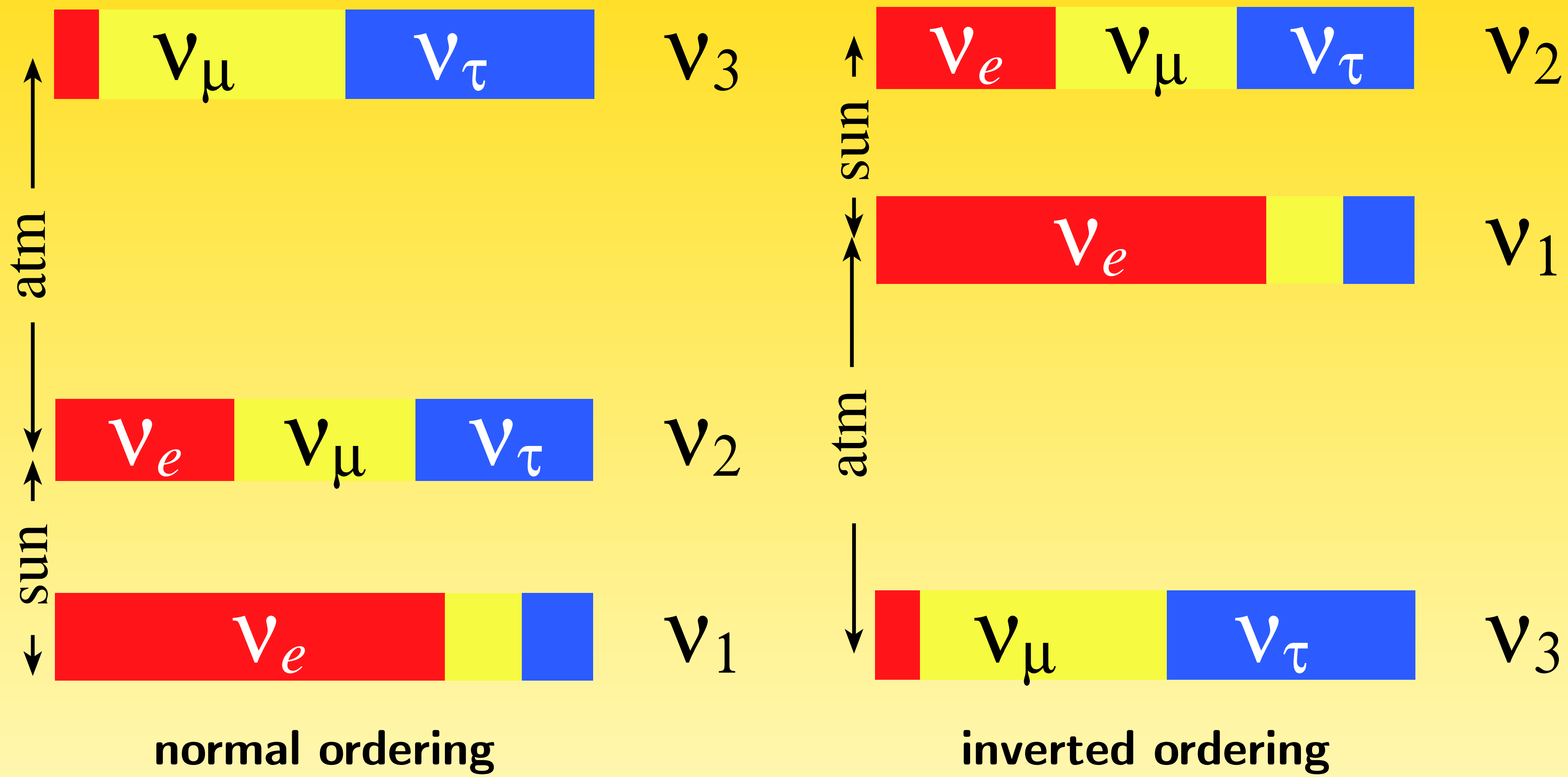
$$\Delta\beta_\lambda \propto -8\,\mathrm{Tr}\left(m_D^\dagger m_D\right)^2$$ (Casas *et al.*; Strumia *et al.*)

makes vacuum stability condition worse!



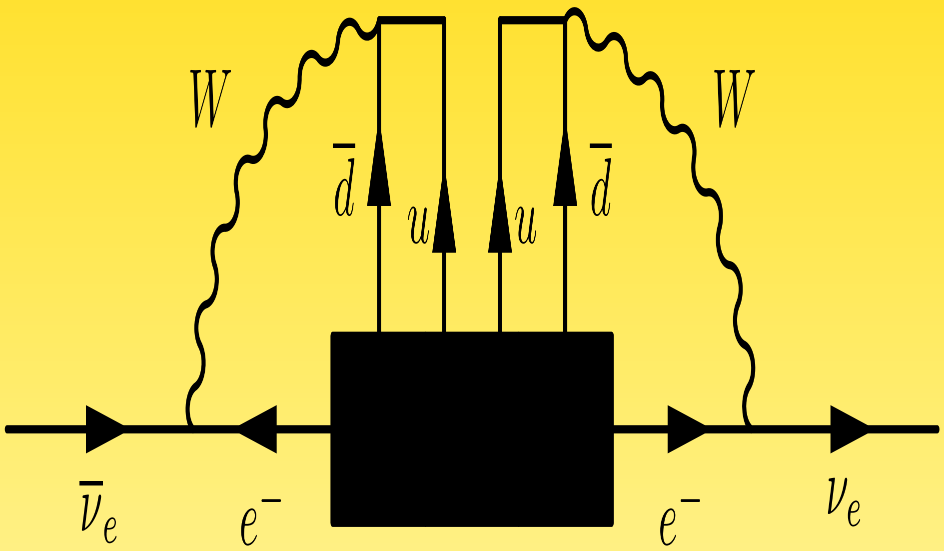
naively, if M_R goes down, m_D goes down and effect is negligible, unless cancellations for testable TeV seesaw (W.R., Zhang, JHEP 1206 (2012) 022)

Neutrino Mass Ordering



Schechter-Valle theorem:

no matter what process, neutrinos are Majorana:



is 4 loop diagram: $m_\nu \sim \frac{G_F^2}{(16\pi^2)^4} \mathrm{MeV}^5 \sim 10^{-25}\,\mathrm{eV}$

explicit calculation: Duerr, Lindner, Merle, JHEP 1106 (2011) 091; talk by Michael Duerr, T 20.2

Dirac vs. Majorana masses

only neutral fermions we know of: neutrinos ν_L

can be **Majorana particles** having **Majorana masses**

$$\nu^c = \nu \quad \text{and} \; M_L \, \overline{\nu_L} \, (\nu_L)^c$$

in terms of Standard Model:

- usual Dirac mass term is generated by gauge invariant interaction with Higgs:

$$y \, \overline{L} \, \tilde{\Phi} \, N_R \to y v \, \overline{\nu_L} \, N_R \equiv m_D \, \overline{\nu_L} \, N_R$$

- a Majorana mass term $M_L \, \overline{\nu_L} \, (\nu_L)^c$ **cannot** stem from Higgs Boson!
- a Majorana mass term $M_R \, \overline{N_R^c} \, N_R$ is possible ("bare mass term")

towards seesaw

introduce N_R, couple to $\overline{L}\,\tilde{\Phi}$ and allow for Majorana mass term for N_R

$$\mathcal{L} = \overline{\nu_L}\, m_D\, N_R + \tfrac{1}{2}\, \overline{N_R^c}\, M_R\, N_R$$

$$= \tfrac{1}{2}\,(\overline{\nu_L},\, \overline{N_R^c}) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$$\equiv \tfrac{1}{2}\, \overline{\Psi}\, \mathcal{M}_\nu\, \Psi^c$$

is a Majorana mass term!

diagonalizing with $m_D \ll M_R$ gives:

heavy fermion N_R: $\quad M_R$

light fermion ν_L: $\quad M_L \equiv m_\nu = m_D^2/M_R$

Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

10_H ($\leftrightarrow H$), $\overline{126}_H$ ($\leftrightarrow F$), 120_H ($\leftrightarrow G$)

Gives relation for mass matrices:

$$
\begin{aligned}
m_{\rm up} &\propto r(H + sF + it_u\, G) \\
m_{\rm down} &\propto H + F + iG \\
m_D &\propto r(H - 3sF + it_D\, G) \\
m_\ell &\propto H - 3F + it_l\, G \\
M_R &\propto r_R^{-1} F
\end{aligned}
$$

Numerical fit including RG, Higgs, Y_B, θ_{13}

`Dueck, W.R.; talk by Alexander Dueck, T 15.8`

Predictions of $SO(10)$ theories

Model	Fit	$\lvert m_{ee}\rvert$ [meV]	m_0 [meV]	M_3 [GeV]	M_2 [GeV]	M_1 [GeV]	χ^2
$10_H + \overline{126}_H$	NH	0.52	2.38	3.62e12	1.97e11	1.39e11	23.5
$10_H + \overline{126}_H$ + SS	NH	0.44	6.52	1.32e12	2.77e10	2.74e10	3.3
$10_H + \overline{126}_H + 120_H$	NH	2.56	1.27	8.82e14	1.07e14	7.86e12	11.5
$10_H + \overline{126}_H + 120_H$ + SS	NH	0.89	7.78	3.71e12	1.66e09	5.88e07	0.2
$10_H + \overline{126}_H + 120_H$	IH	35.43	30.0	1.14e13	3.51e12	5.53e11	13.3
$10_H + \overline{126}_H + 120_H$ + SS	IH	45.72	15.11	1.65e10	1.06e10	1.22e09	20.5

$10_H + \overline{126}_H$: 19 free parameters

$10_H + \overline{126}_H + 120_H$: 18 free parameters

20 (19) observables to be fitted