Neutrinoless Double Beta Decay and particle physics: an overview

Heisenberg-Programm
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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

- Lepton Number Violation: Why look for it?
- Neutrinoless Double Beta Decay $(A,Z) \to (A,Z+2) + 2\,e^-$:
  - Standard Interpretation
  - Non-Standard Interpretations
- Majorana neutrinos outside *V-A*

Why look for Lepton Number Violation?

- L and B accidentally conserved in SM
- $\mathcal{L} = \mathcal{L}_{SM} + 1/\Lambda\, \mathcal{L}_5 + 1/\Lambda^2\, \mathcal{L}_6 + \ldots$, with $\mathcal{L}_5 = L^c\phi\, \phi L \to m_\nu\, \nu_L{}^c\, \nu_L$
- Baryogenesis: B is violated
- B, L often connected in BSM, GUTs
- GUTs have seesaw and Majorana neutrinos
- (B and L non-perturbatively violated by 3 units in SM…)

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Lepton Number as important as Baryon Number

Neutrinoless Double Beta Decay

best limit from 2002, improved since 2012 by one order of magnitude!

Name	Isotope	Source = Detector; calorimetric with			Source ≠ Detector
		high ΔE	low ΔE	topology	topology
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA	^{116}Cd (and ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
CUPID	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LEGEND	^{76}Ge	✓	–	–	–
LUCIFER	^{82}Se / ^{100}Mo / ^{130}Te	✓	–	–	–
LUMINEU	^{100}Mo	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se / ^{100}Mo / ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+	^{130}Te	–	✓	–	–
SuperNEMO	^{82}Se / ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

Neutrinoless Double Beta Decay

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

- Master Formula: $$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$
  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME)
  - η_x : particle physics parameter

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  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$ calculable
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME) problematic
  - η_x : particle physics parameter interesting

Interpretations

- 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

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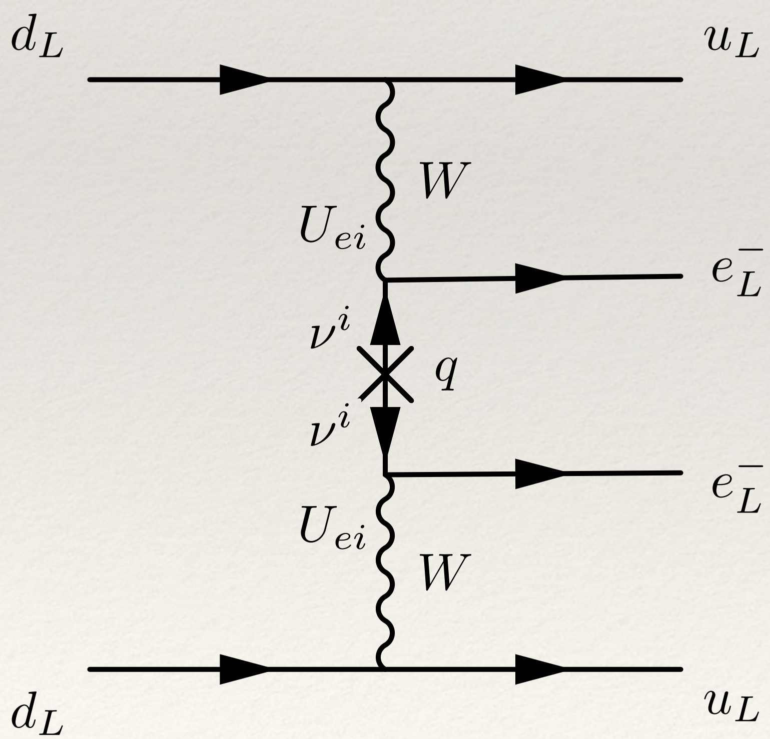
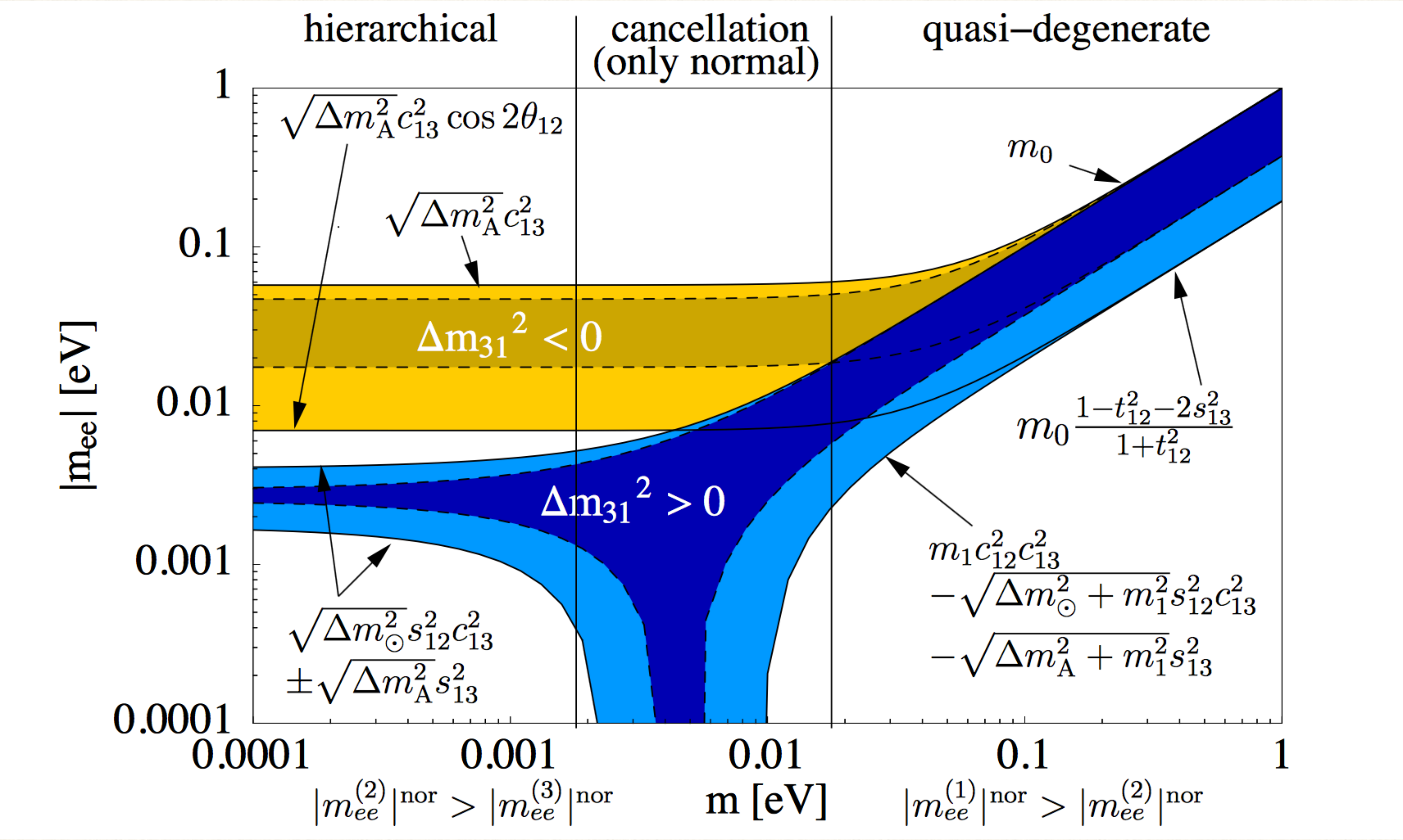


amplitude proportional to „effective mass“:

$$|m_{ee}| = |\sum U_{ei}^2\, m_i| = |U_{e1}^2\, m_1 + U_{e2}^2\, m_2 e^{i\alpha} + U_{e3}^2\, m_3 e^{i\beta}|$$
$$= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m_{\rm A}^2), \alpha, \beta\right)$$

See talk by Bilenky

The usual plot



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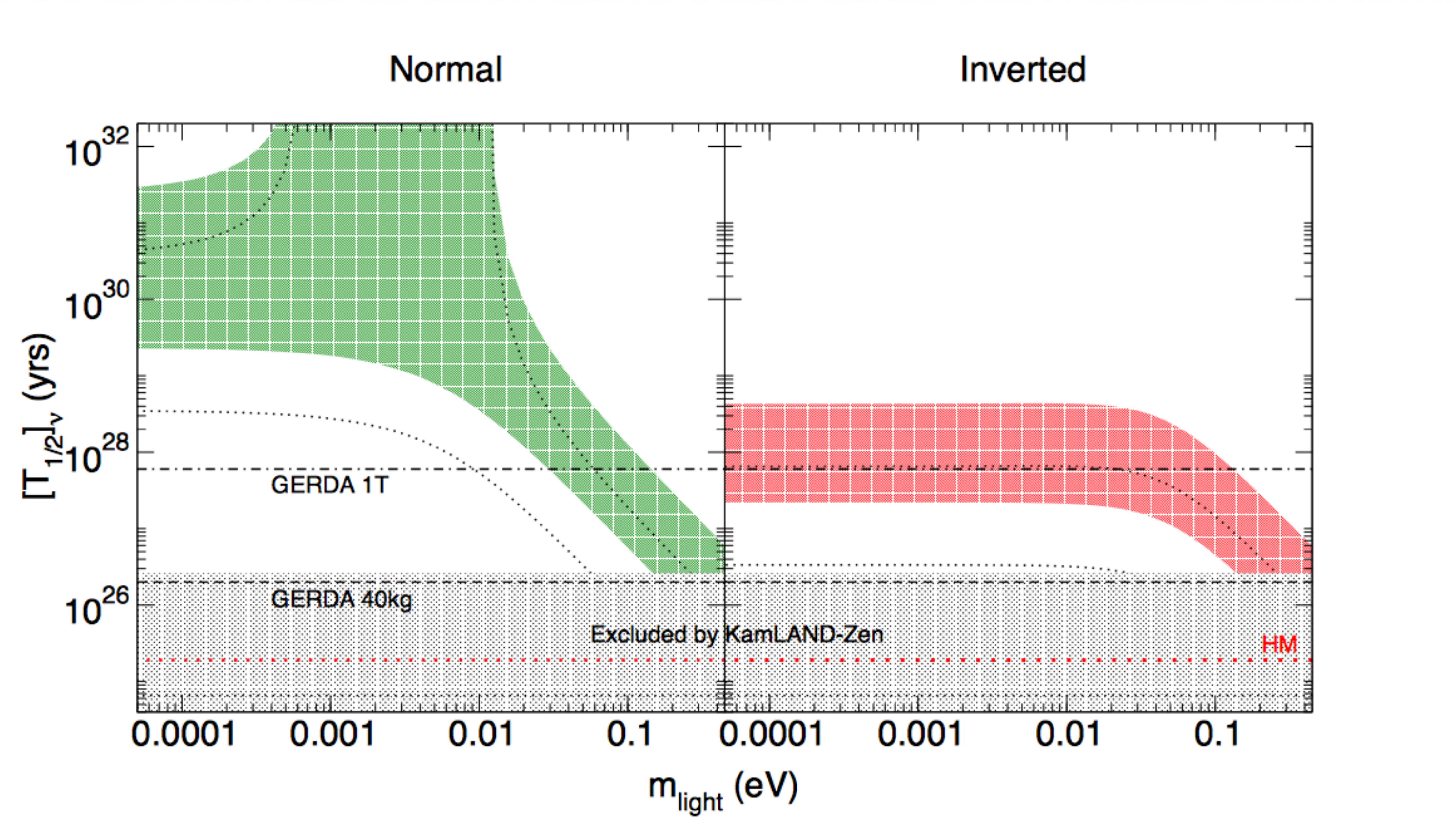
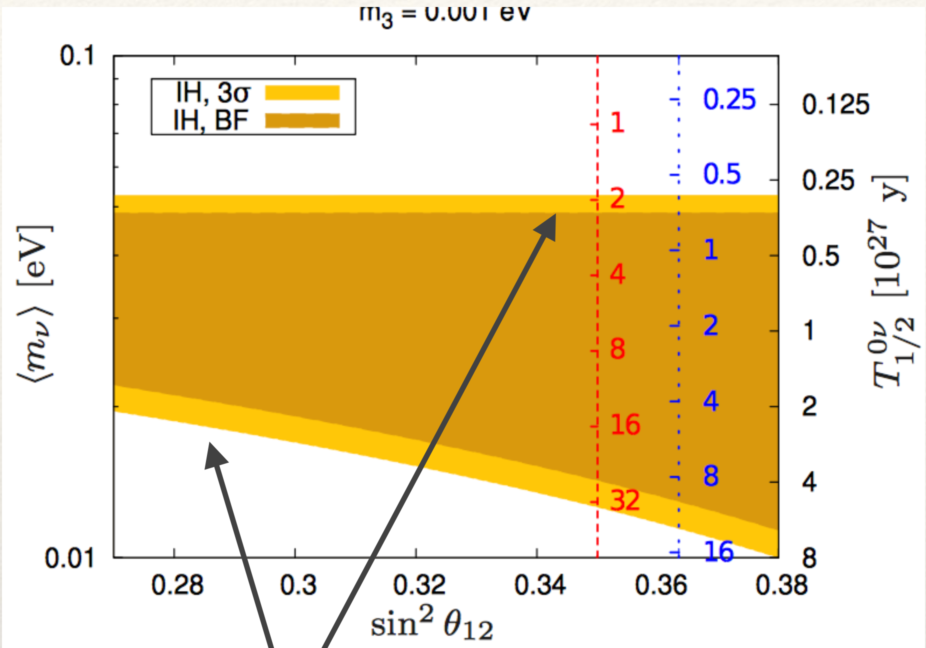


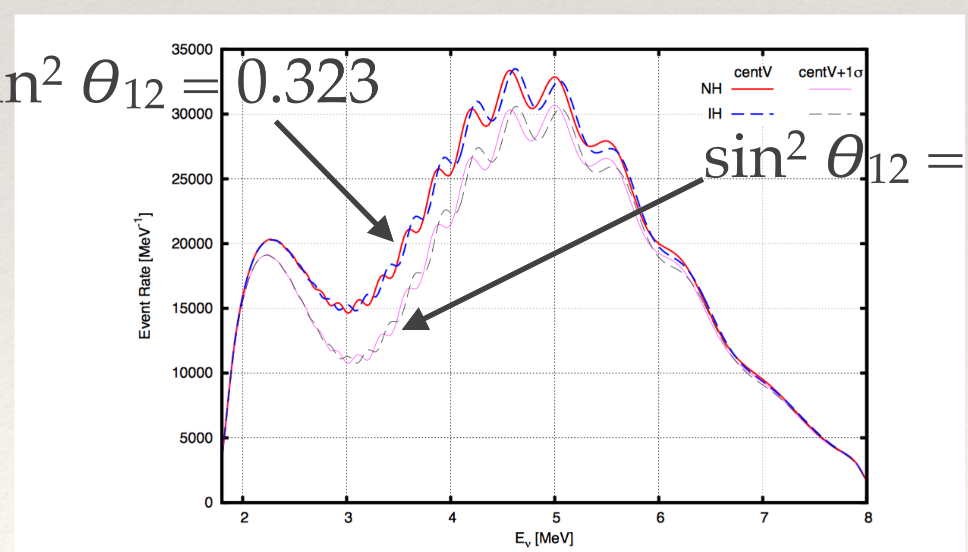
Connections to Oscillation Experiments



Nature gives us two scales

Factor 2 uncertainty of minimal m_{ee} in IH, mostly from θ_{12}

$\sin^2\theta_{12} = 0.323$



$\sin^2\theta_{12} = 0.339$

JUNO will fix θ_{12} and remove uncertainty in value of minimal m_{ee} in IH

Dueck, WR, Zuber, 1103.4152; Ge, WR, 1507.05514

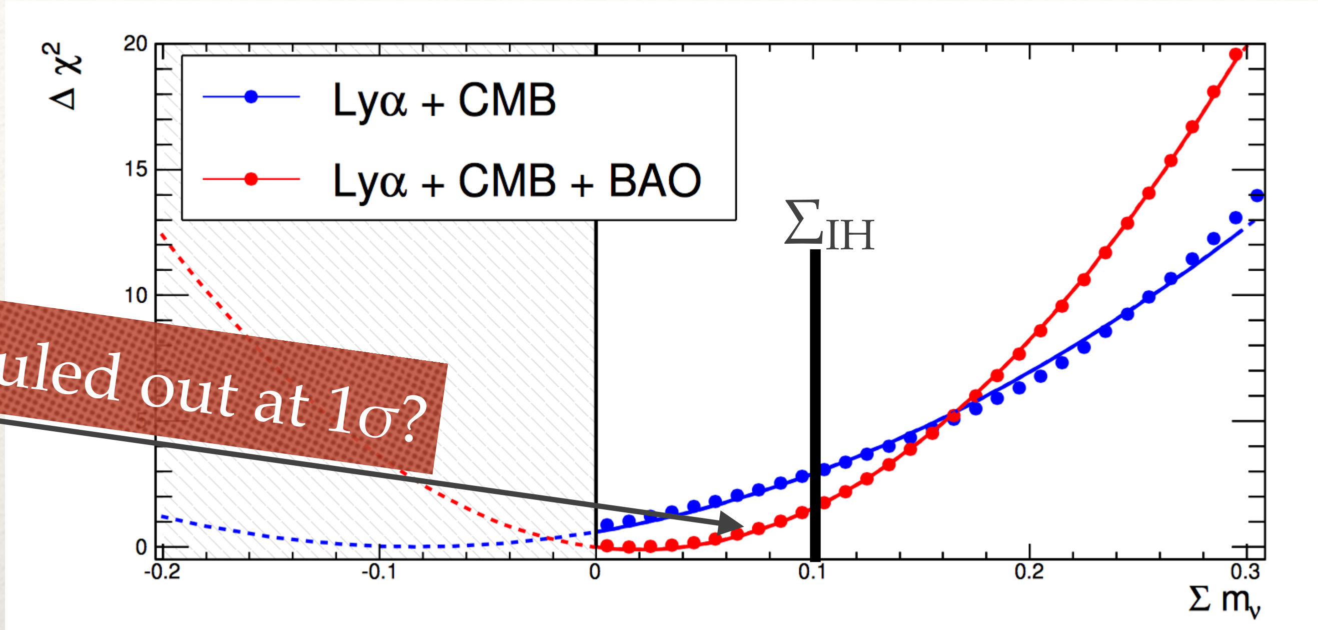
Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$\sum \vert U_{ei}\vert^2 m_i$	2.3 eV	0.3 eV	0.1 eV?	model-indep.; clean	final; weakest
cosmo	$\sum m_i$	0.5 eV	0.1 eV	0.05 eV?	best; NH/IH	model-dep.; systematics
$0\nu\beta\beta$	$\sum U_{ei}^2 m_i$	0.2 eV	0.05 eV	0.01 eV?	fundamental; NH/IH	model-dep.; NMEs

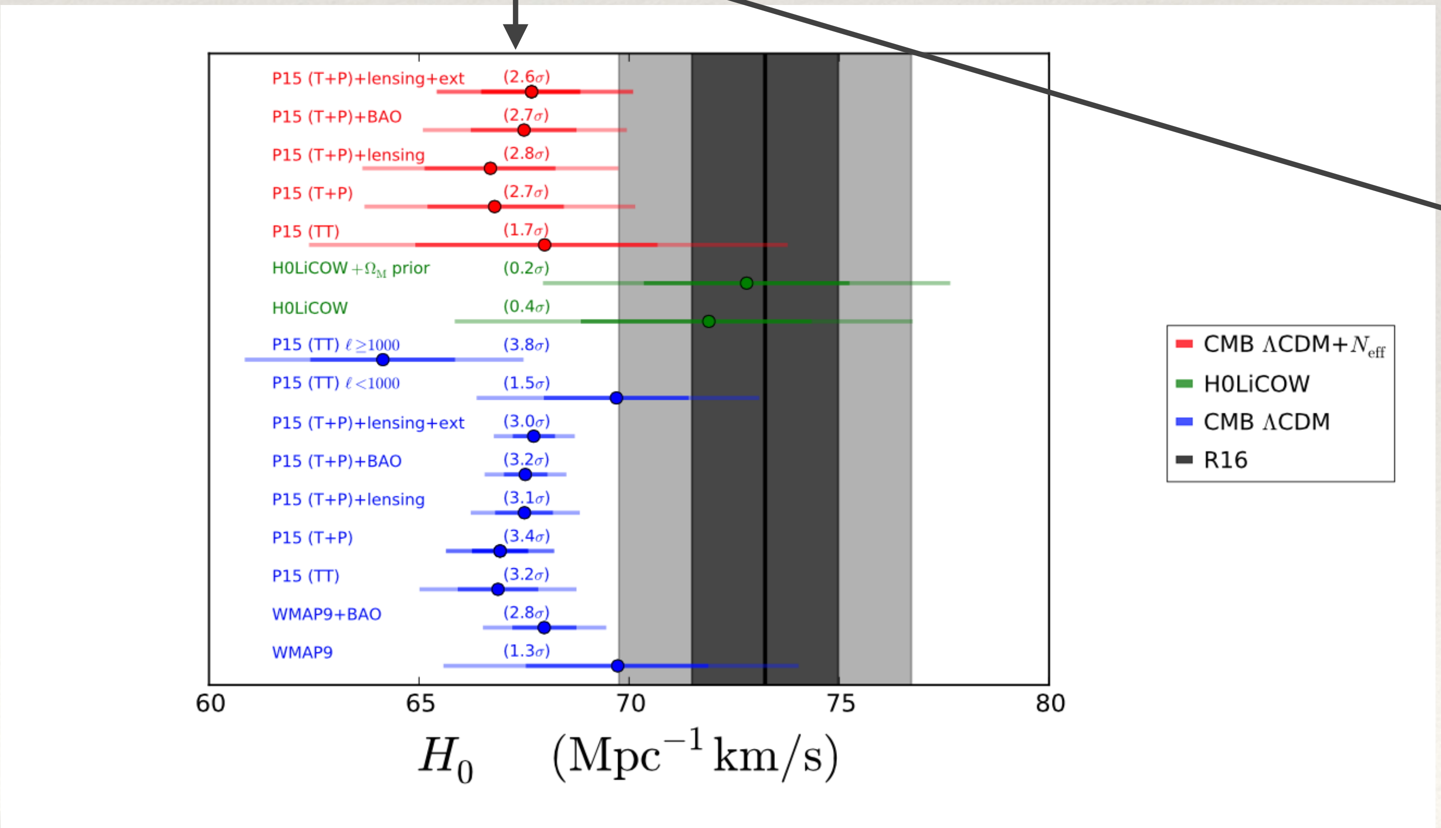
Cosmological Mass Limits

- adding more and more data sets: breaks degeneracies and improves limits
- BUT: can introduce systematics?

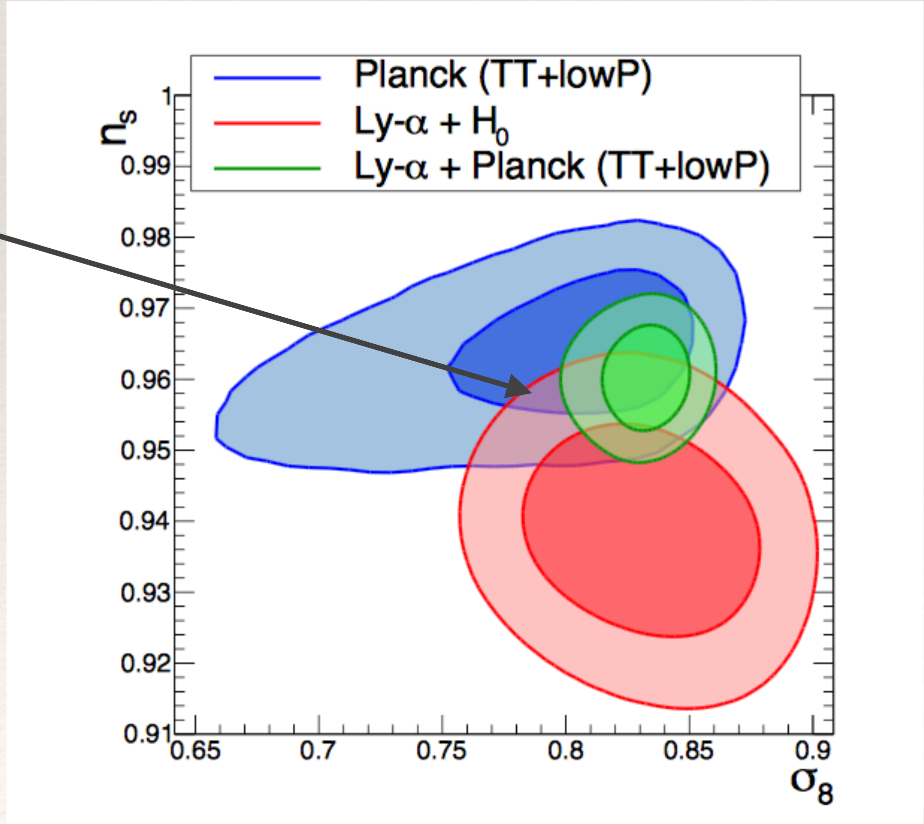
IH ruled out at 1σ?



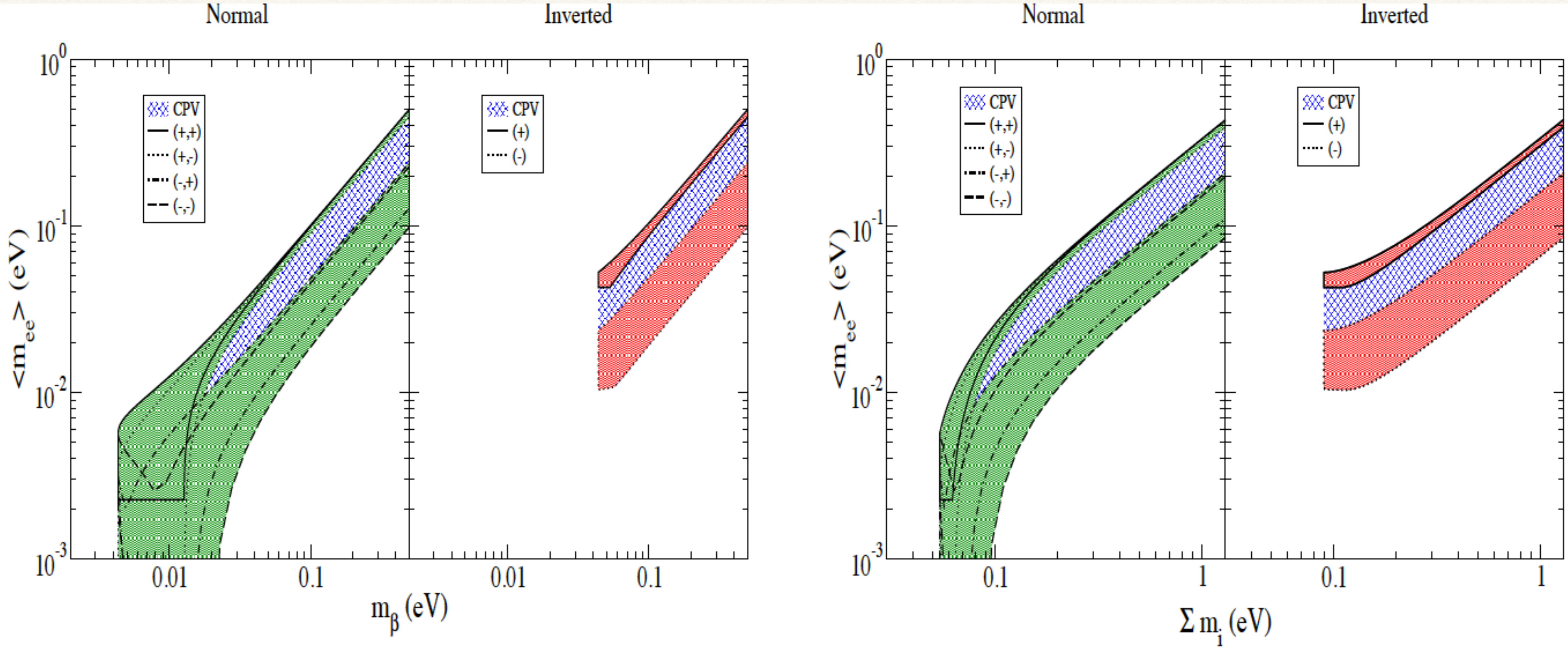
Palanque-Delabrouille et al., 1410.7244 + 1506.05976



Bernal, Verde, Riess, 1607.05617



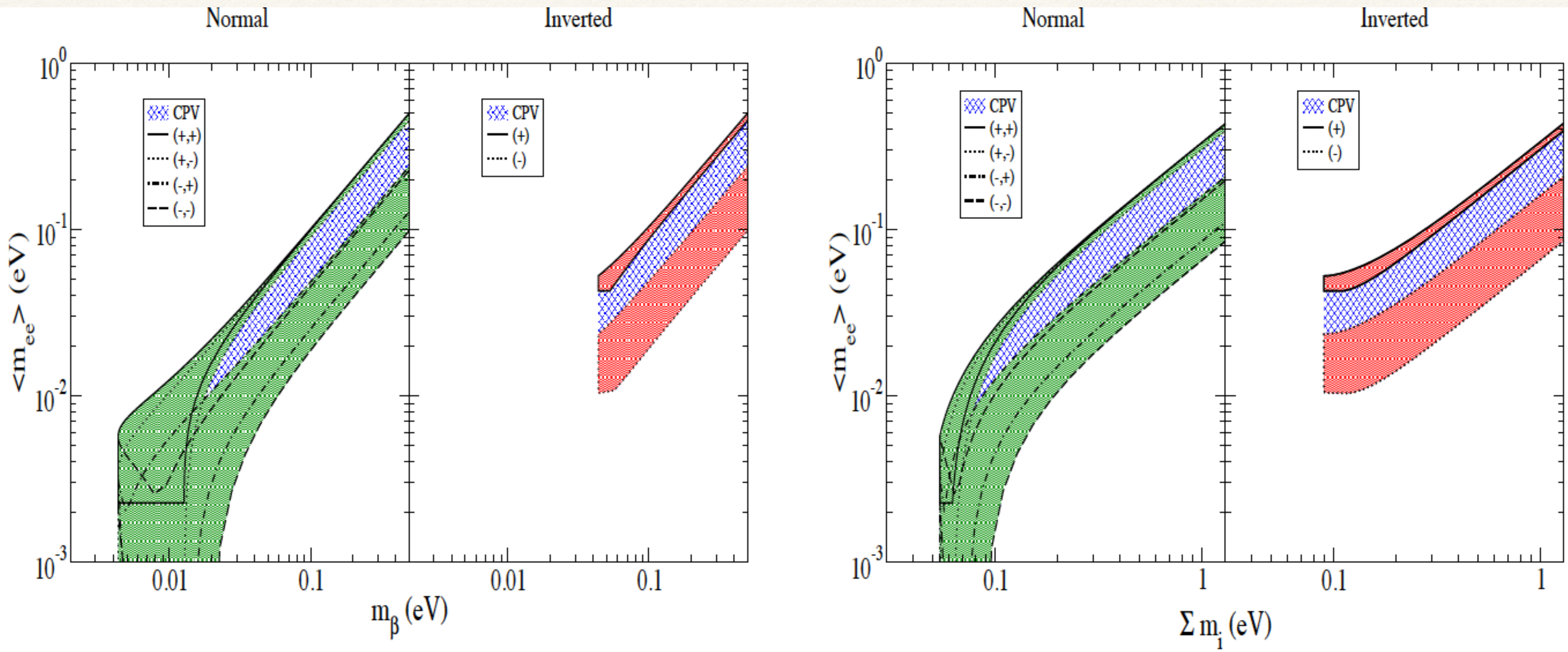
Neutrino Mass Observables



complete complementarity of observables

- $0\nu\beta\beta$ rules out that neutrinos saturate Mainz-limit
- $0\nu\beta\beta$ and cosmology currently roughly the same
- cosmology strongly disfavors a signal in KATRIN

Neutrino Mass Observables



complete complementarity of observables

- 0νββ rules out that neutrin… e Mainz-limit
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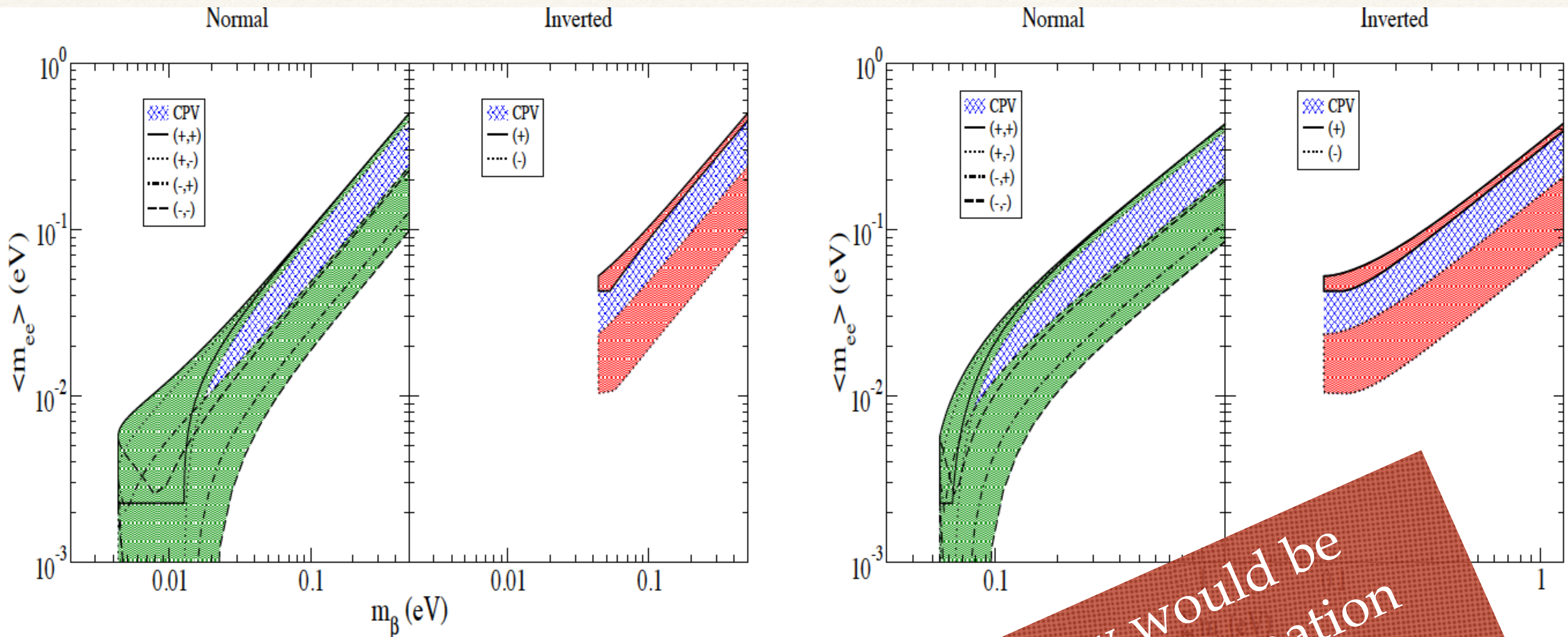
- cosmo… ngly disfavors a signal in KATRIN

All need to be pursued!

Neutrino Mass Observables

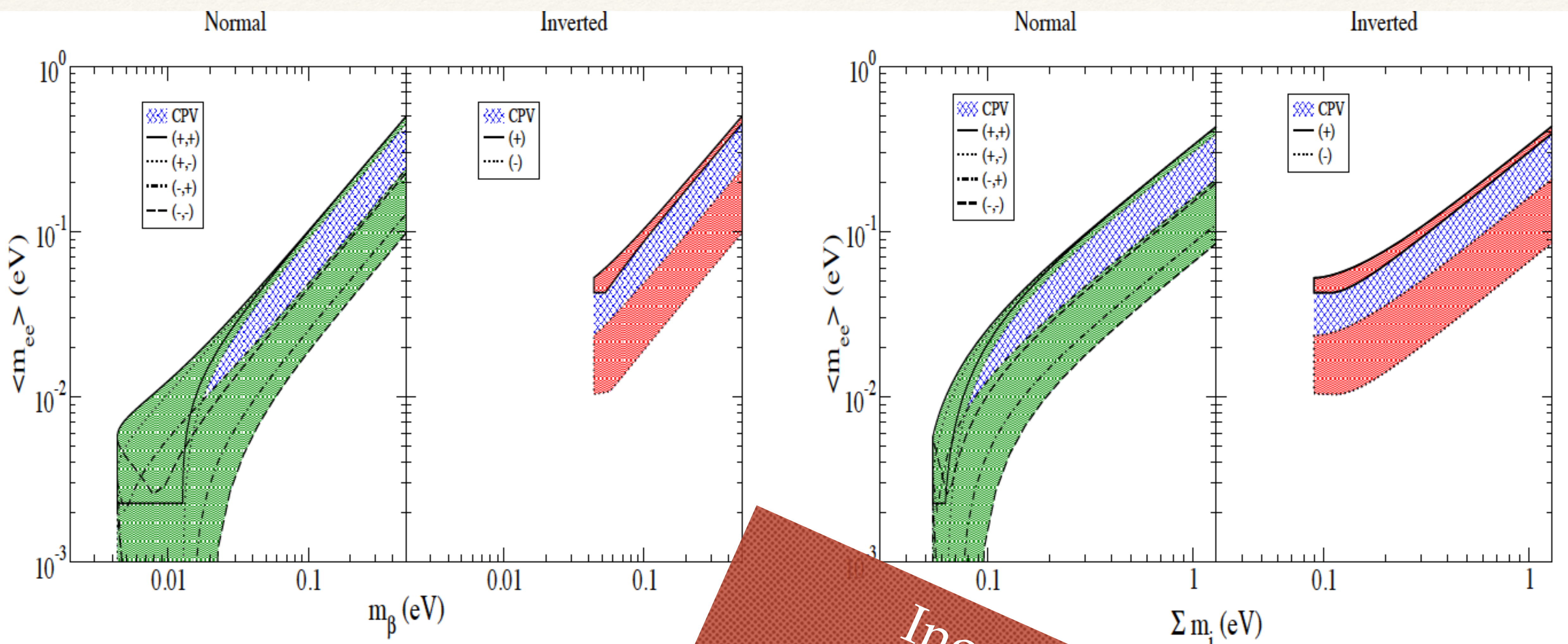


complete complementarity of observables

- 0νββ rules … t
- 0νββ and cos… the same
- cosmology … rs a signal in KATRIN

Consistency would be spectacular confirmation of <u>3 Majorana neutrino paradigm</u>

Neutrino Mass Observables

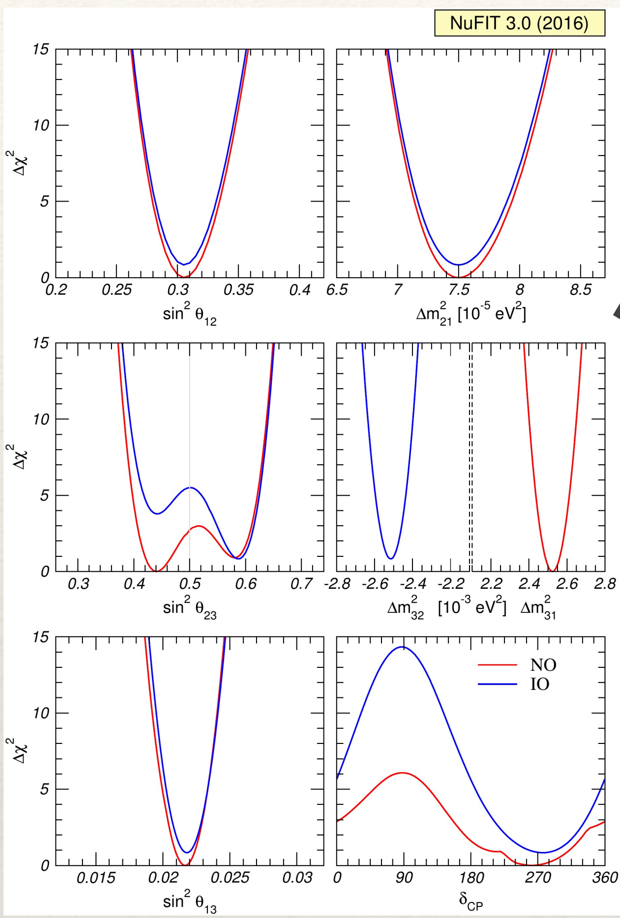


complete complementarity of observables

- 0νββ ru... Mainz-limit
- 0νββ and cosmolog... me
- cosmology strongly disfavors a ... ATRIN

Inconsistencies would be major discovery!

Expectations of lifetimes



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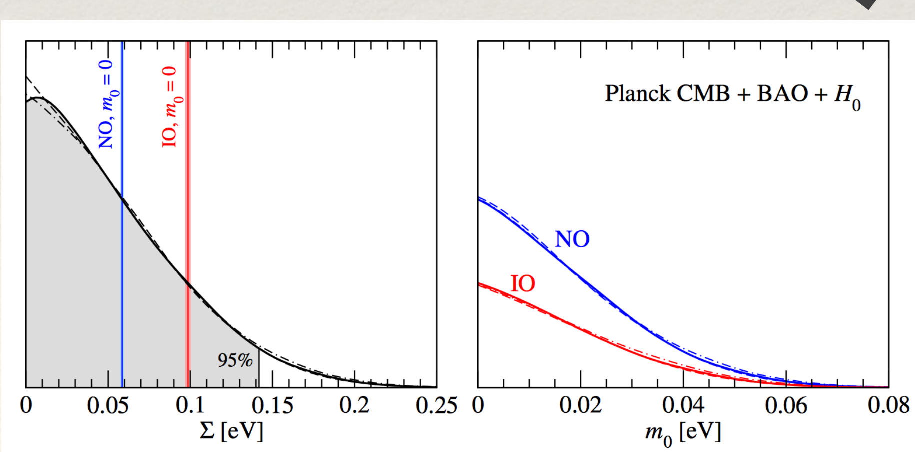
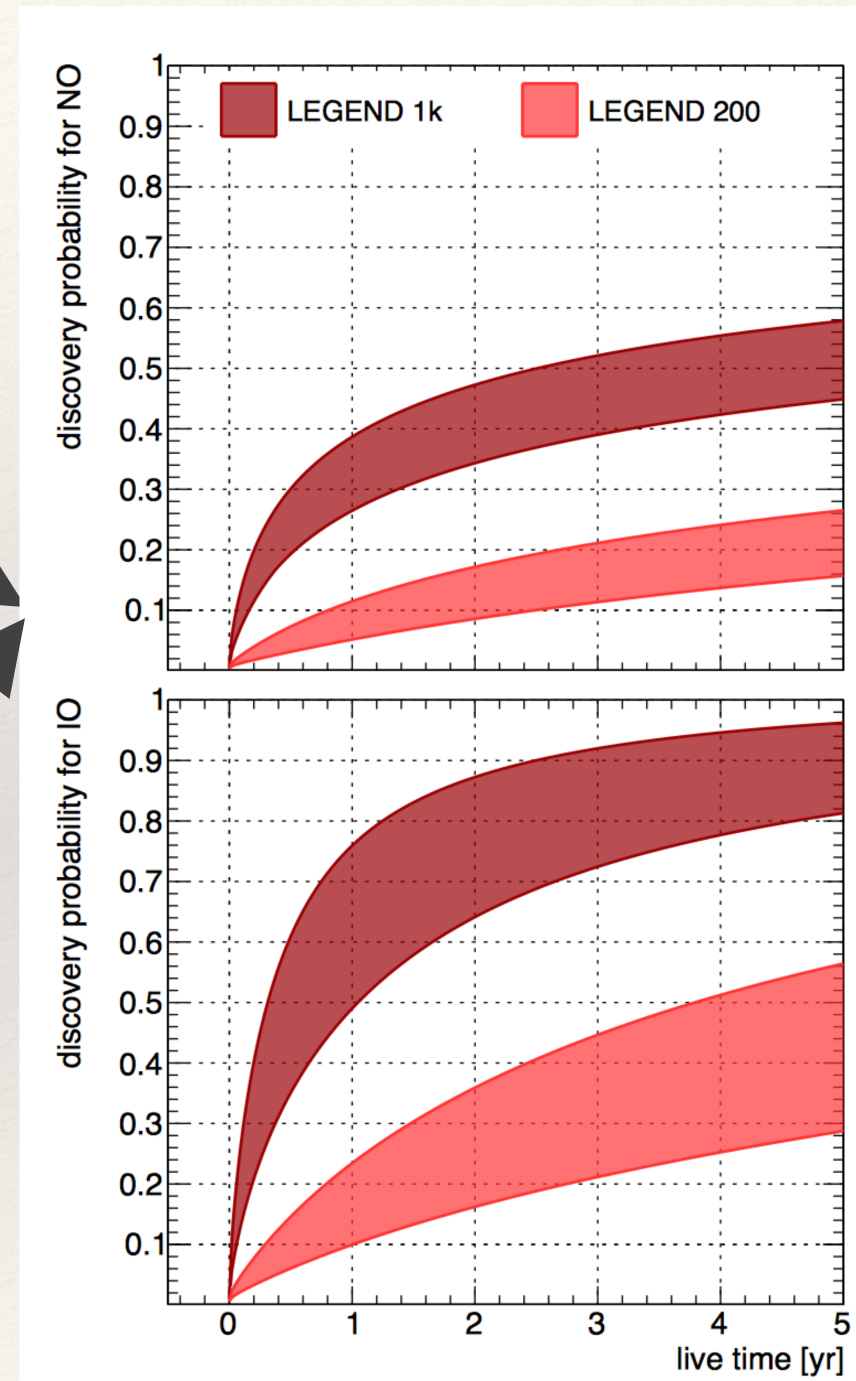




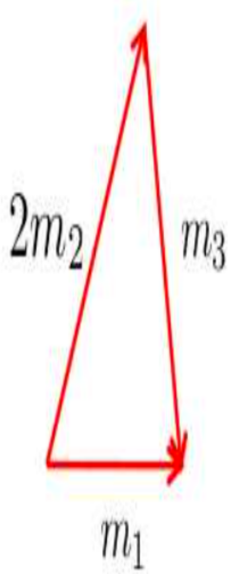
Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

Agostini et al, 1705.02996; also Caldwell et al., 1705.01945

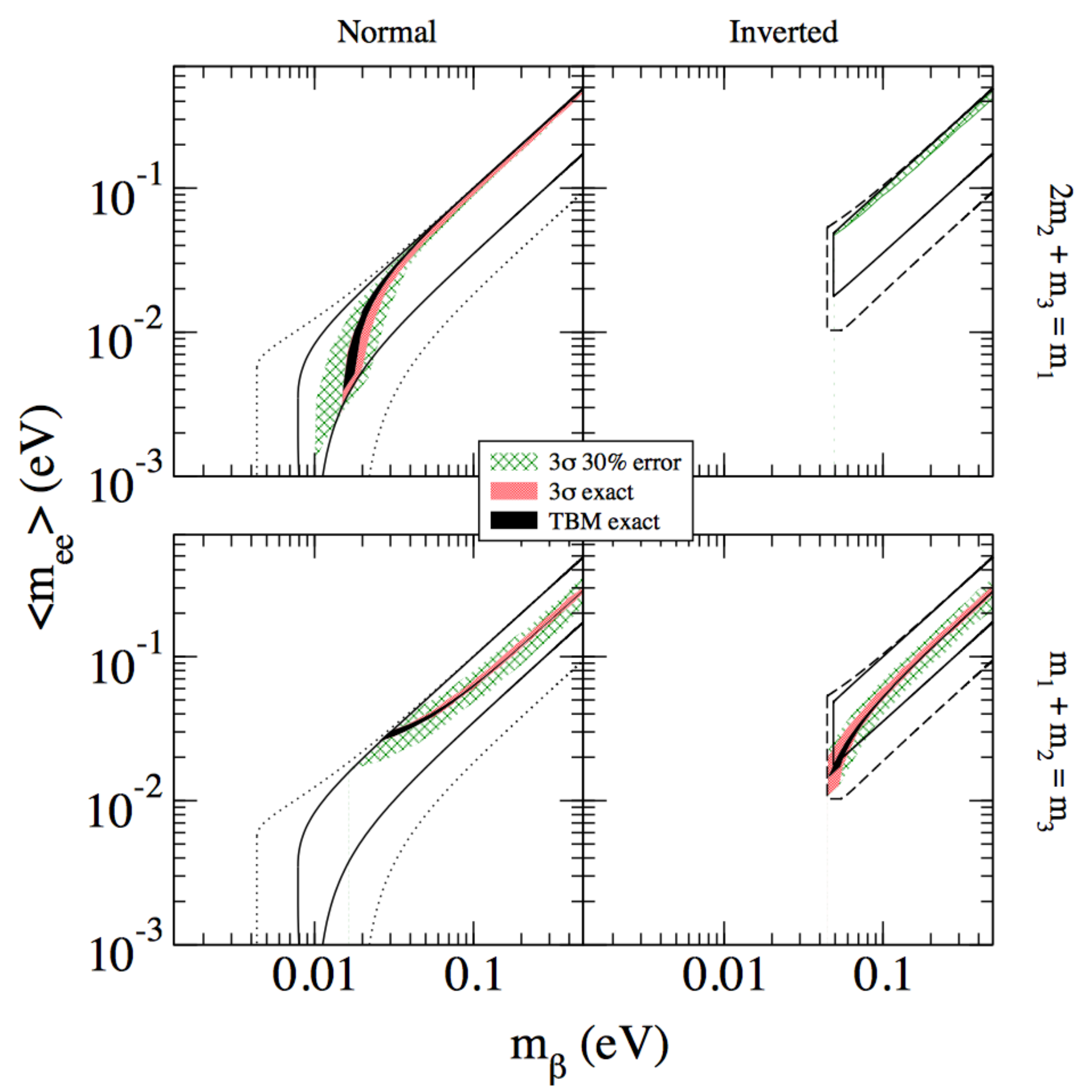
Neutrino Mass Sum-Rules

Flavor Symmetry models can not predict masses,
but relations between them:

Barry, WR, 1007.5217

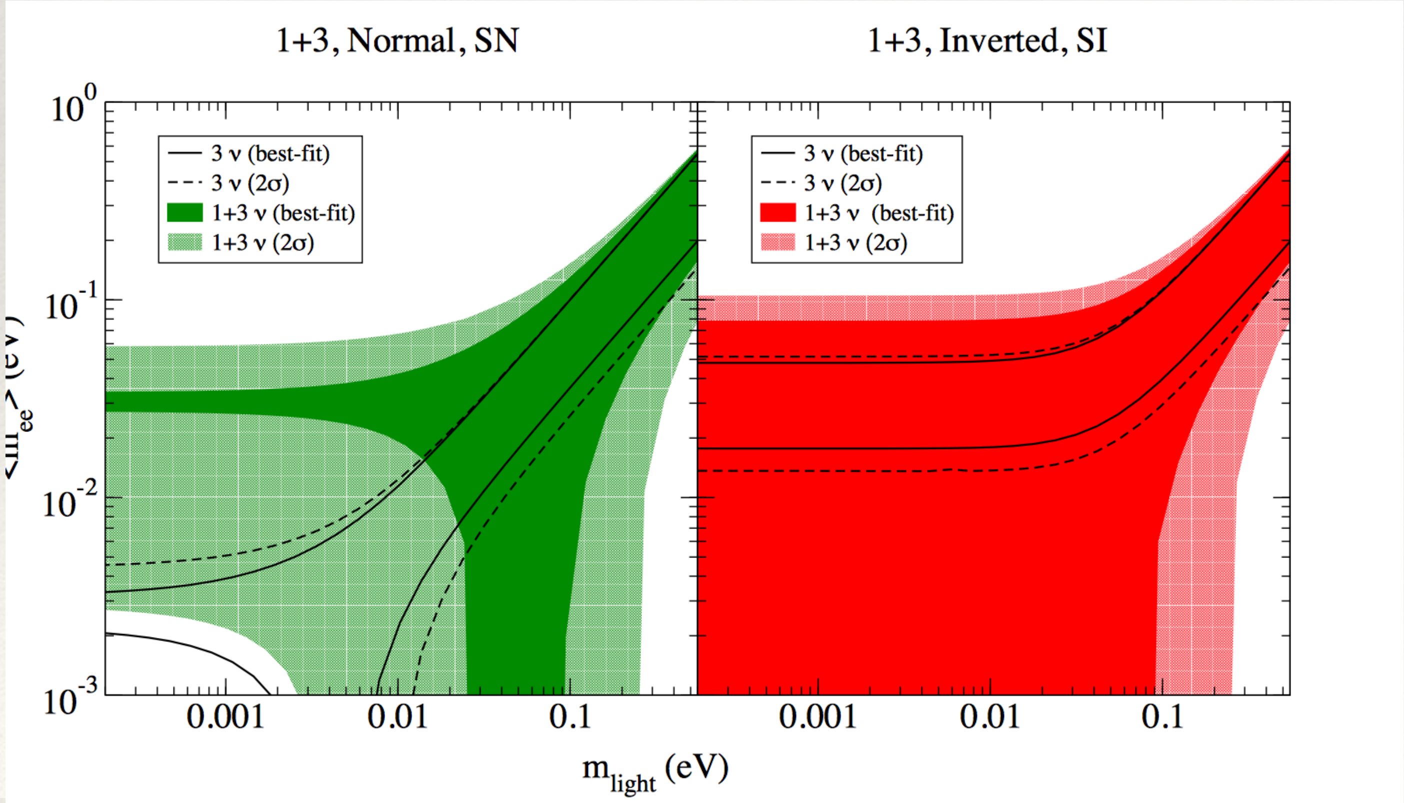


Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4



Sterile Neutrinos

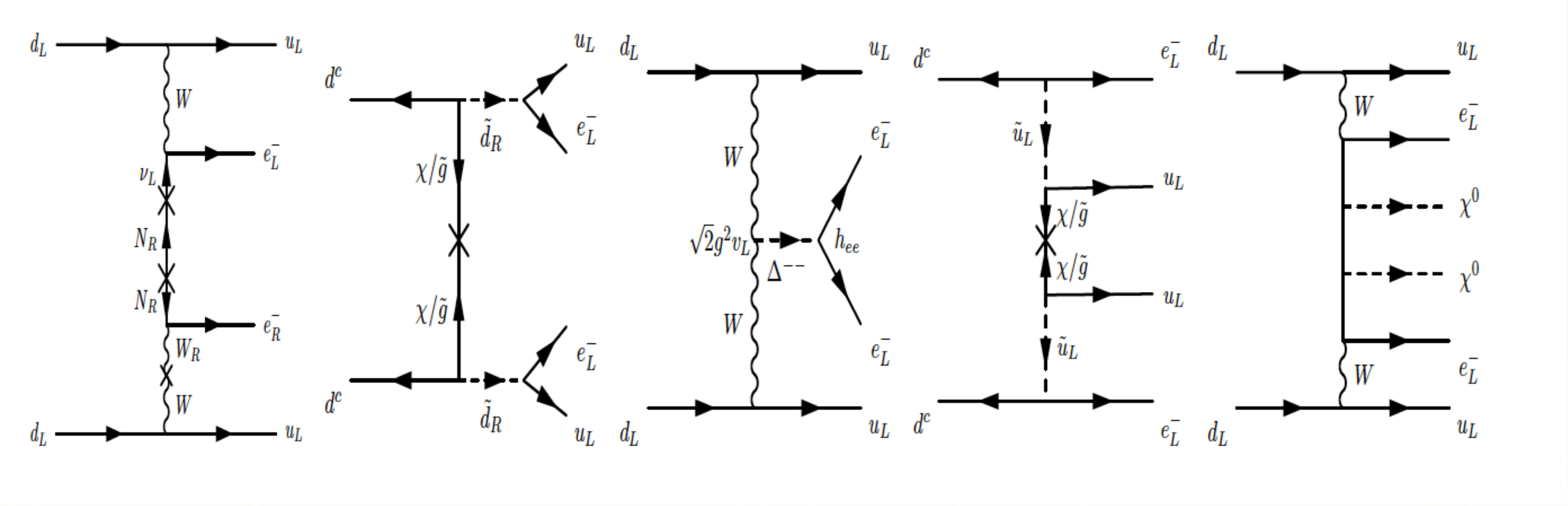
- are there sterile states (LSND / reactor / etc.) with mass $\Delta m^2 \simeq eV^2$ and mixing $U_{e4} \simeq 0.1$?
- would make m_{ee} sum of 4 terms with sterile contribution $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel contribution of IH!
- usual pheno completely turned around!



Barry, WR, Zhang; Petcov et al., Giunti et al.

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



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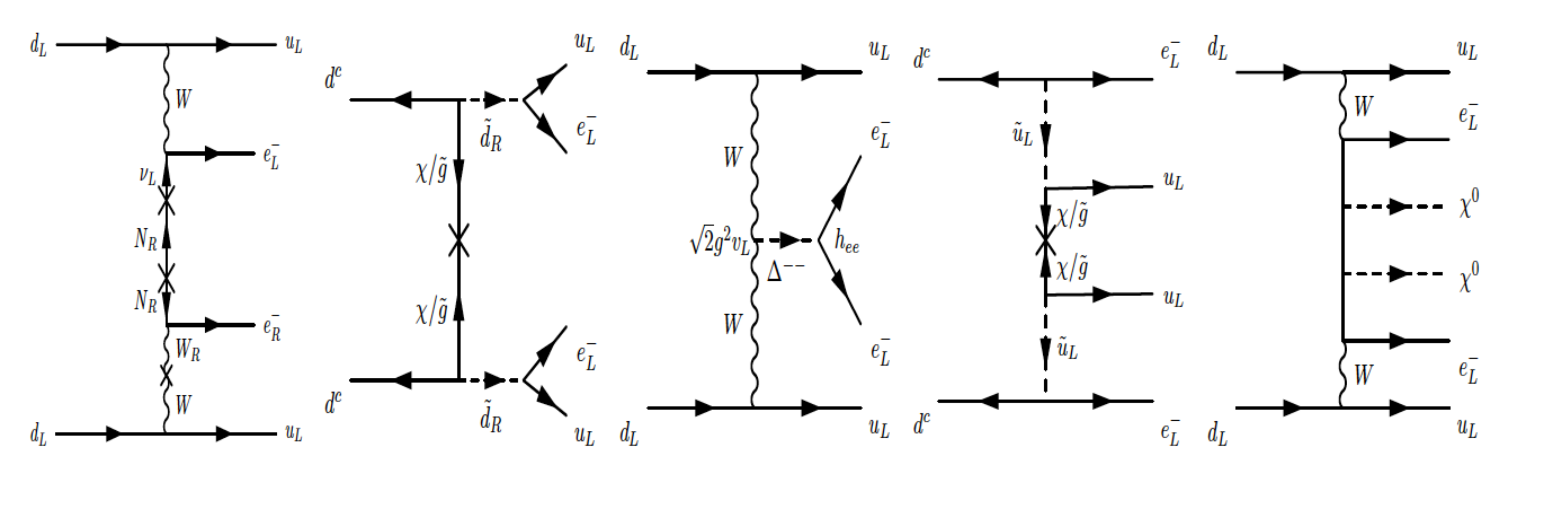

⇒ 0νββ is not a neutrino mass experiment!

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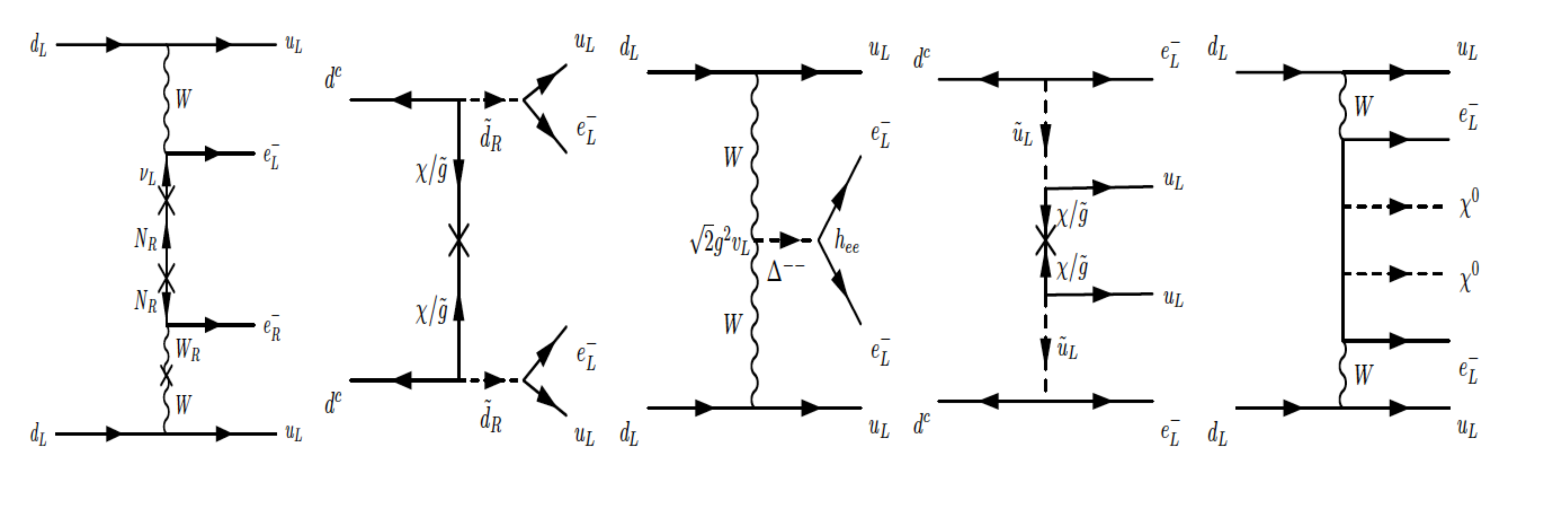


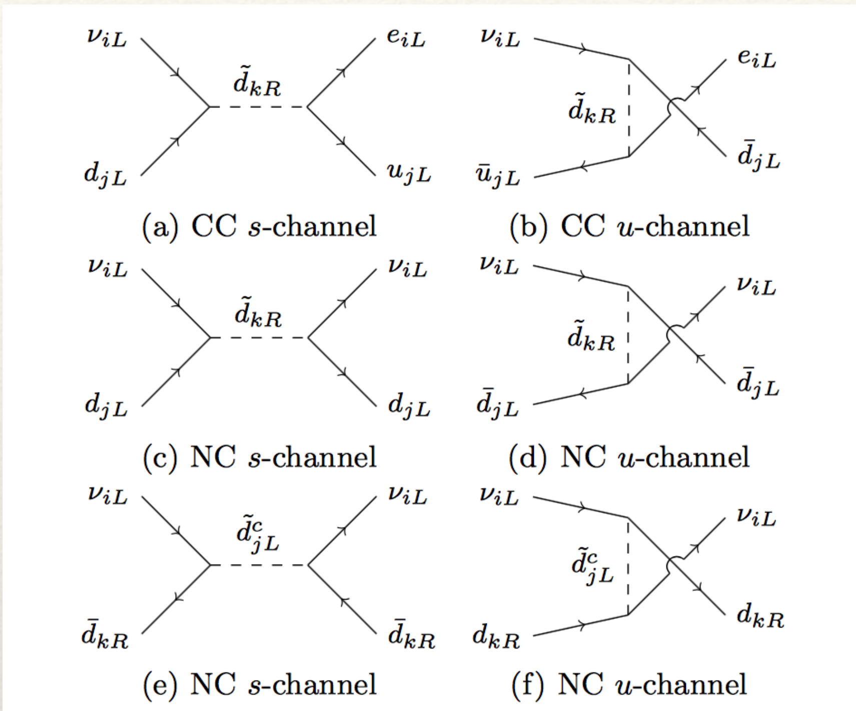
$\Rightarrow$ need to solve the „inverse problem“

Non-Standard Interpretations

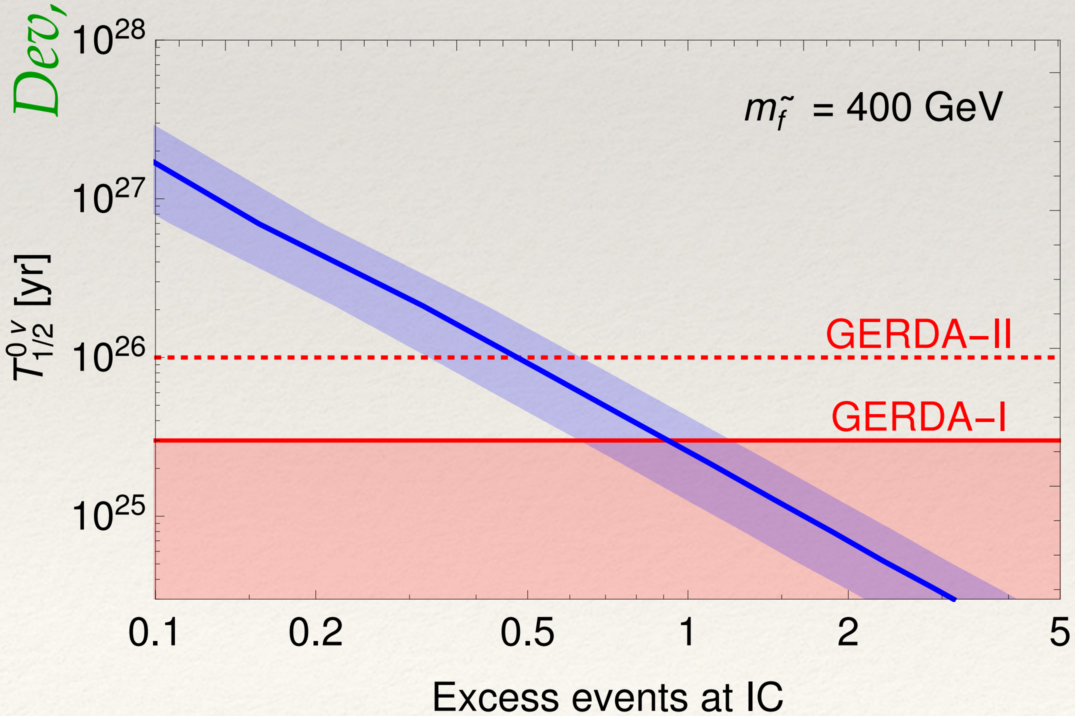
mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\|U_{ei}^2\, m_i\right\|$	0.2 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\|\frac{S_{ei}^2}{M_i}\right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\|\frac{V_{ei}^2}{M_i\, M_{W_R}^4}\right\|$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\|\frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4}\right\|$	10^{-15} GeV^{-1}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\|\frac{U_{ei}\, \tilde{S}_{ei}}{M_{W_R}^2}\right\|$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta \left\|U_{ei}\, \tilde{S}_{ei}\right\|$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\|\lambda_{111}'^2\|}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\|\sin 2\theta^b\, \lambda_{131}'\, \lambda_{113}' \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda_{131}'\, \lambda_{113}'\|}{\Lambda_{\rm SUSY}^3}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\|\langle g_\chi \rangle\|$ or $\|\langle g_\chi \rangle\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

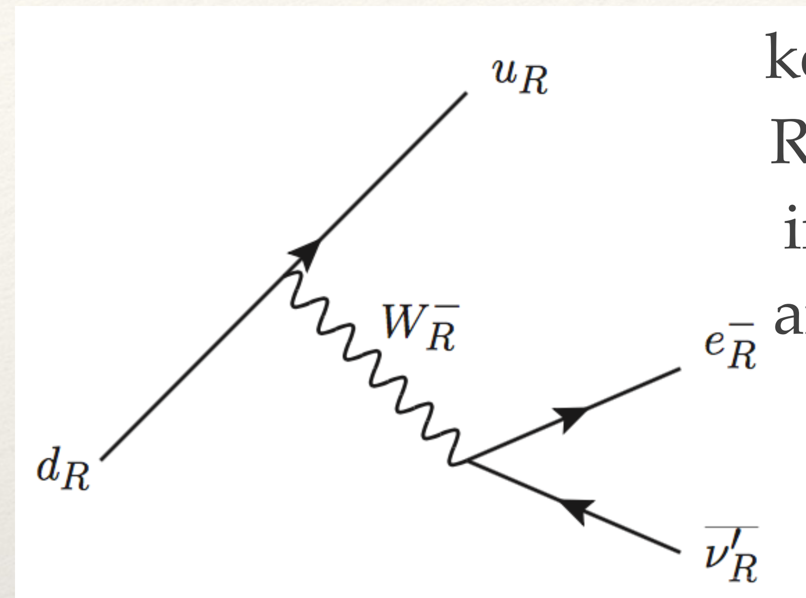
Unexpected Correlations with other Experiments

Dev, Ghosh, WR, 1605.09743



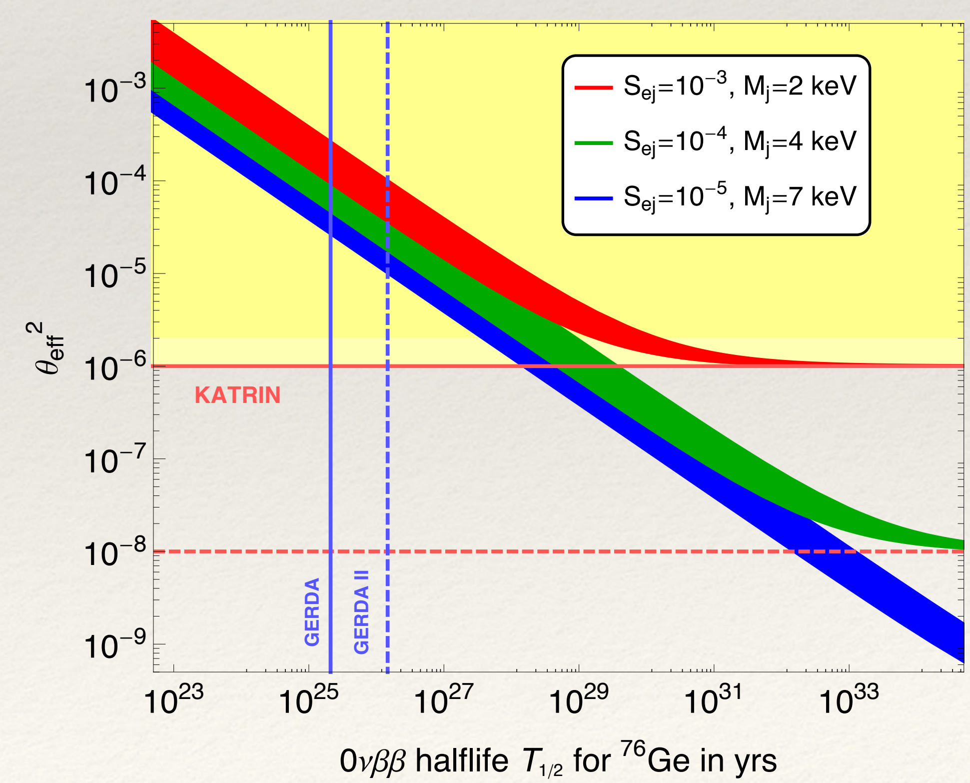
RPV SUSY at IceCube and in 0νββ



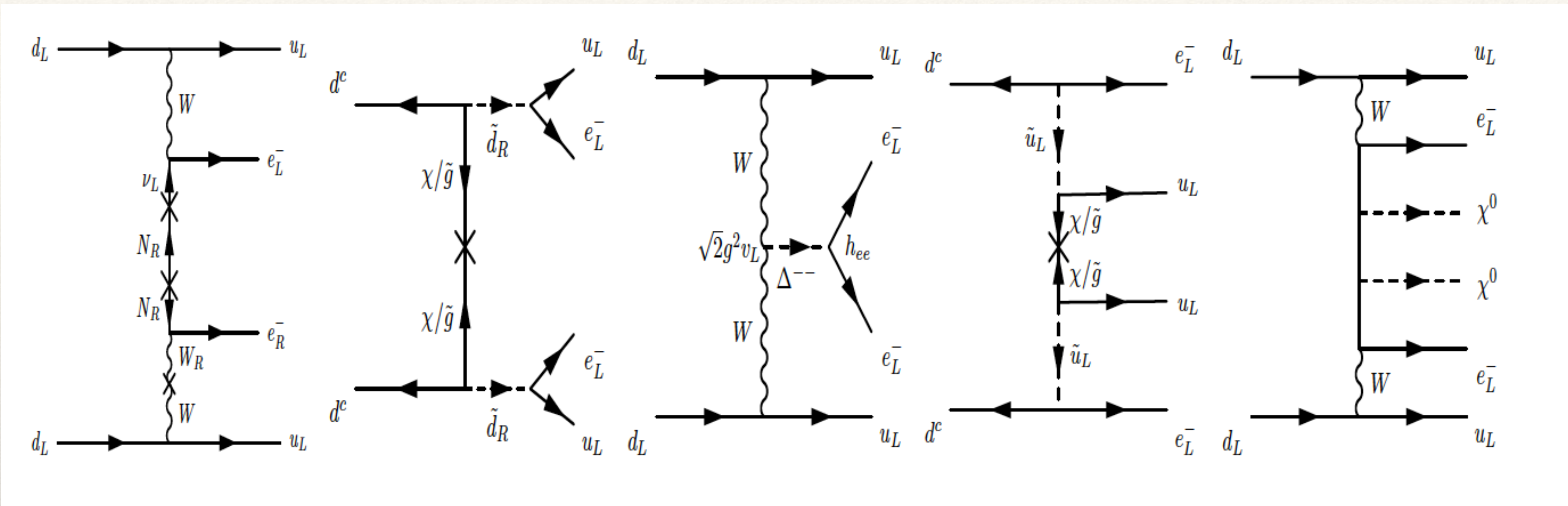


keV nus and RH currents in KATRIN and in 0νββ

Barry, Heeck, WR, 1404.5955



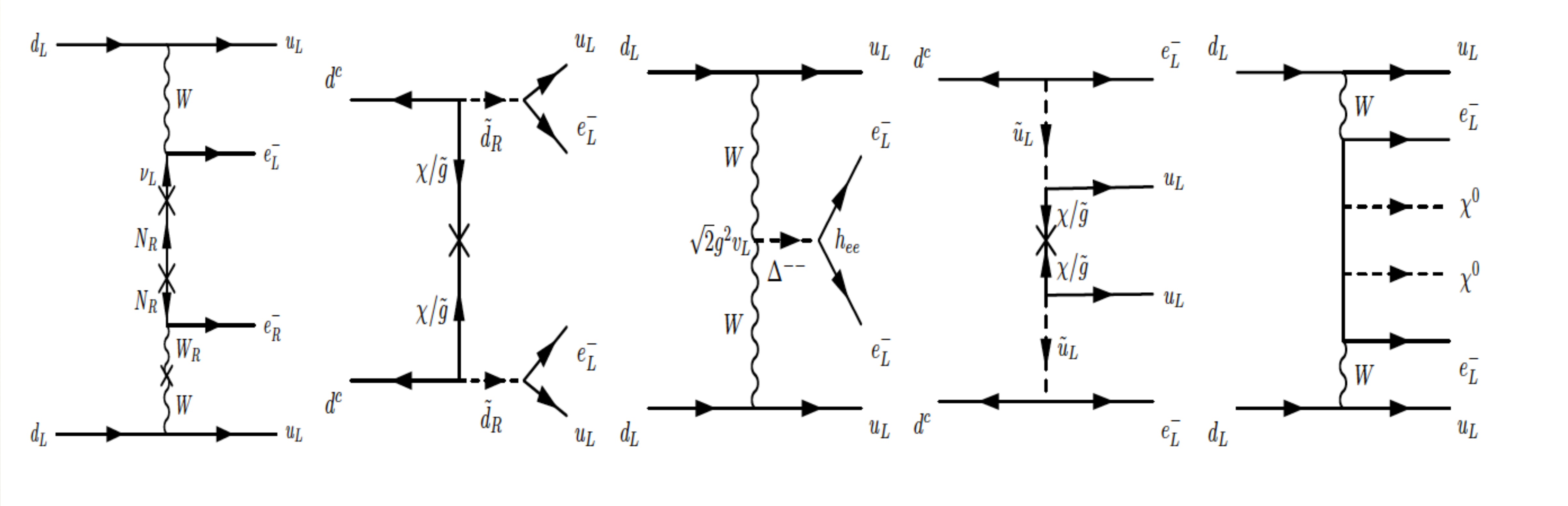
Non-Standard Interpretations



- decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \quad \text{versus} \quad \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

Non-Standard Interpretations



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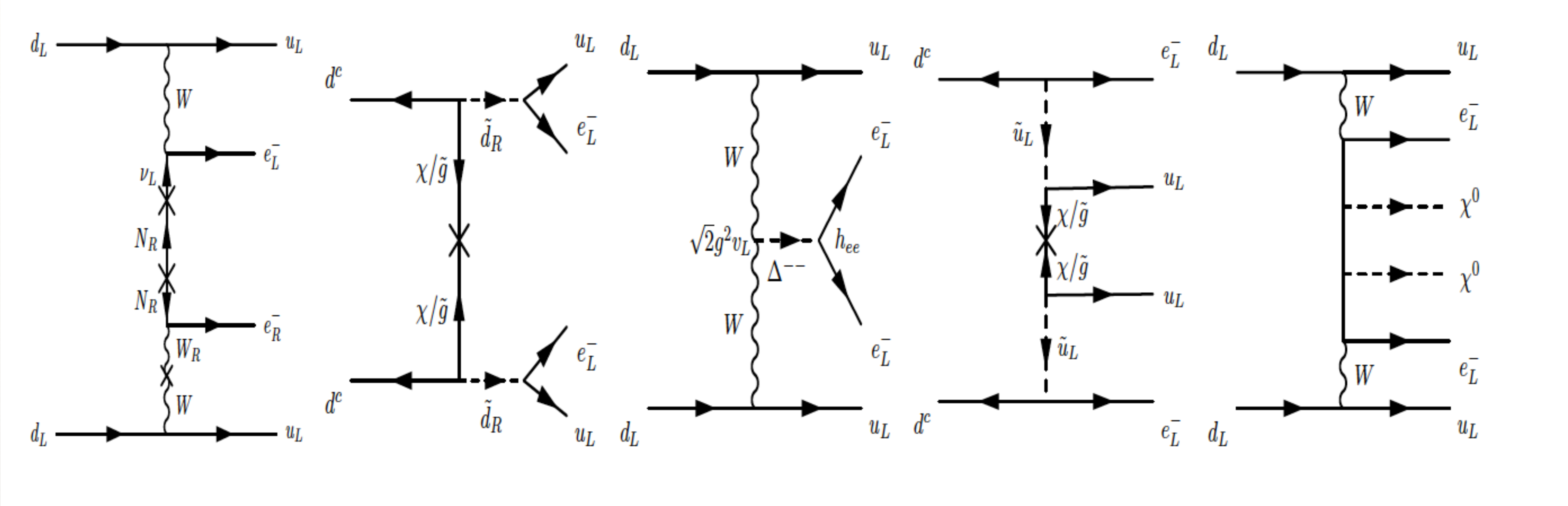
Therefore:
$T(\text{eV}) = T(\text{TeV})$

Non-Standard Interpretations



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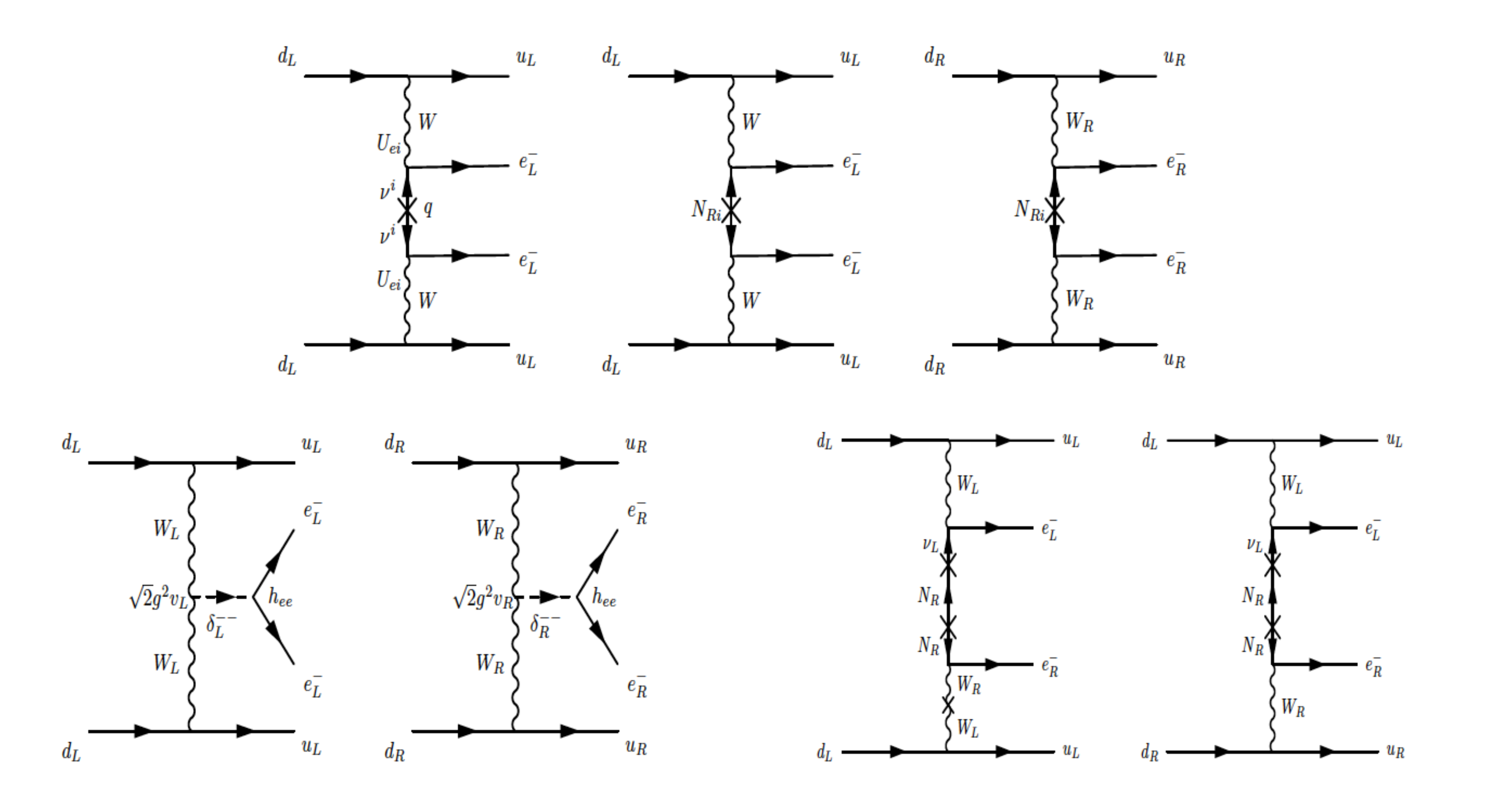
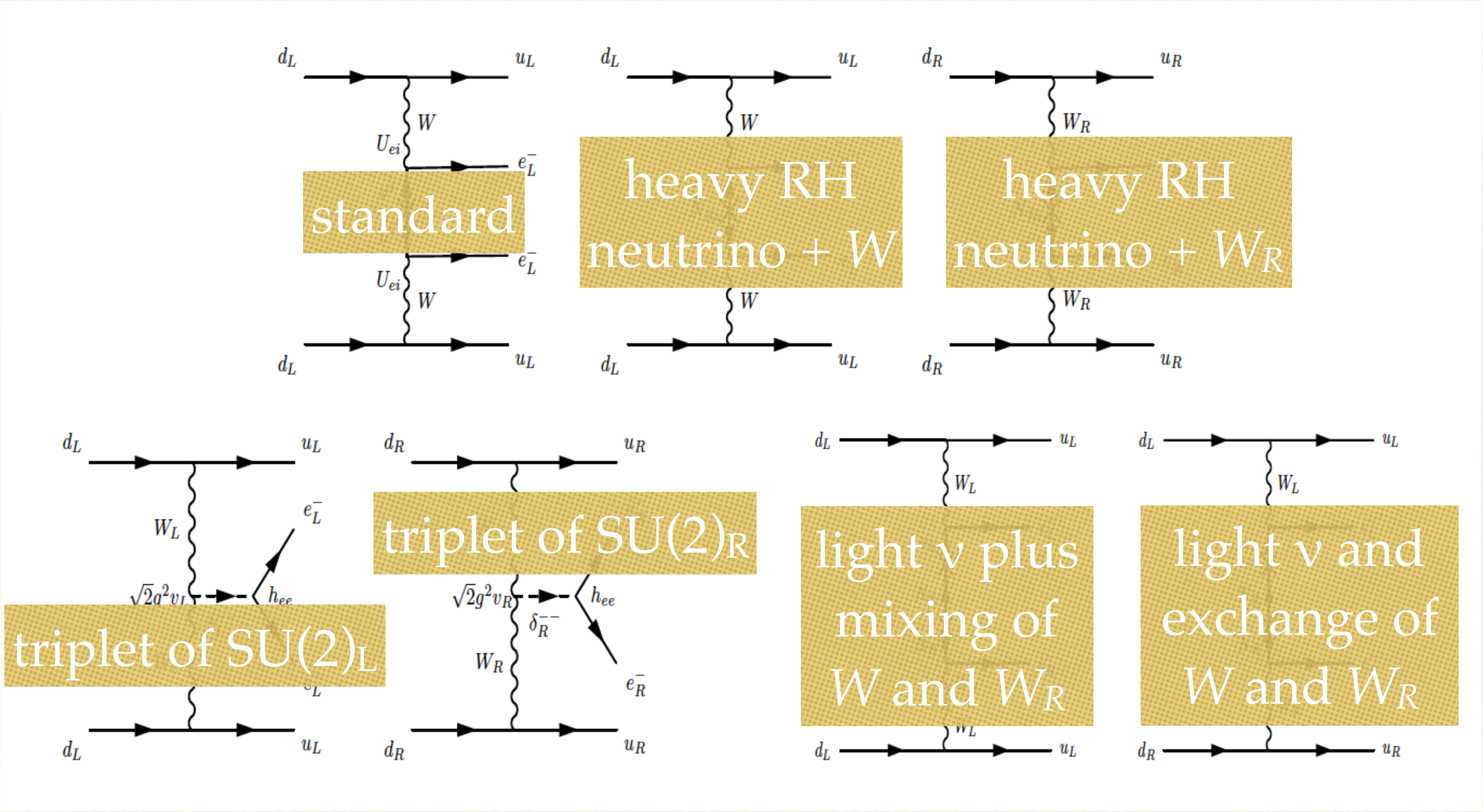
Therefore:
T(eV) = T(TeV)

$\Rightarrow$ Tests with LHC, LFV, etc.

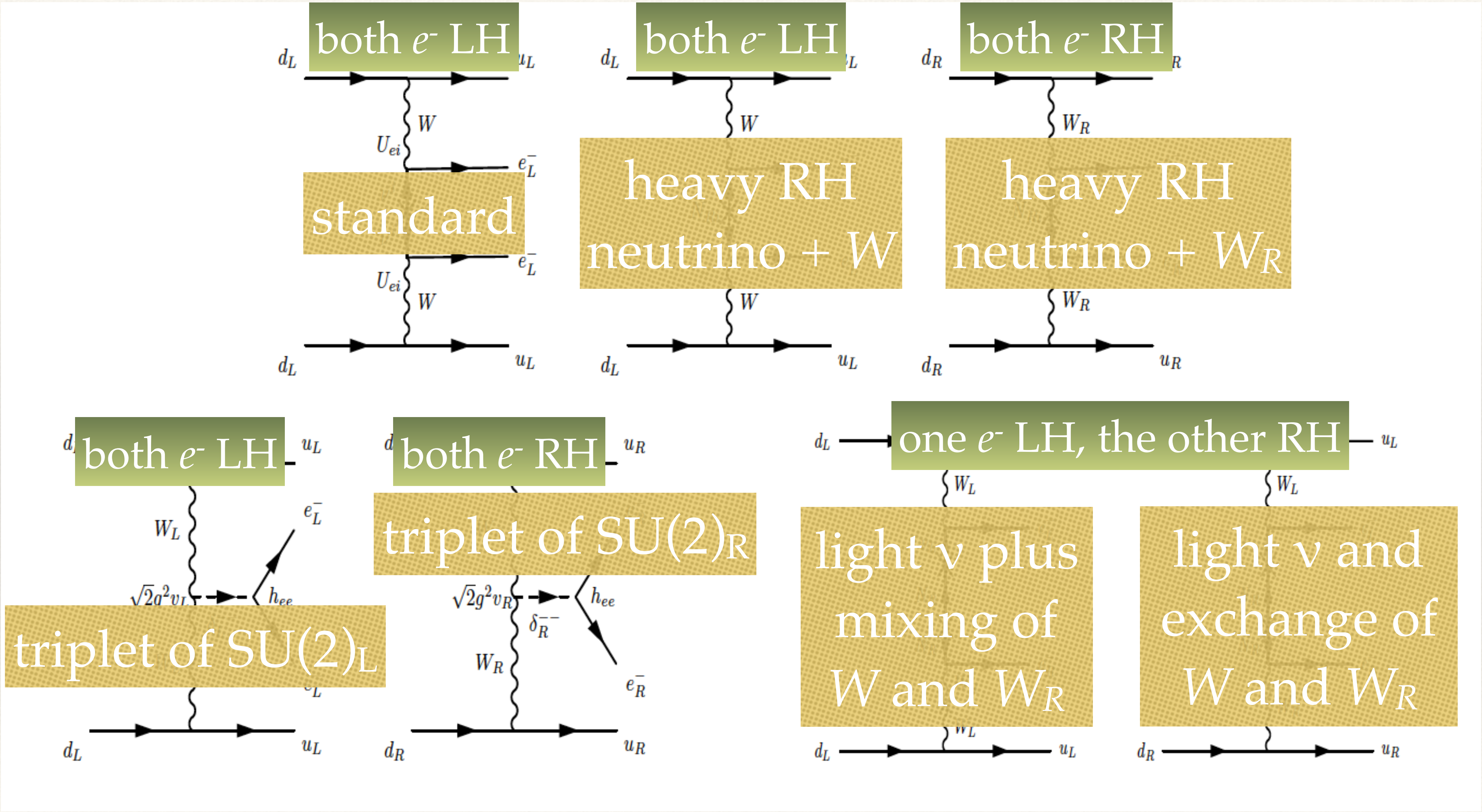
Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



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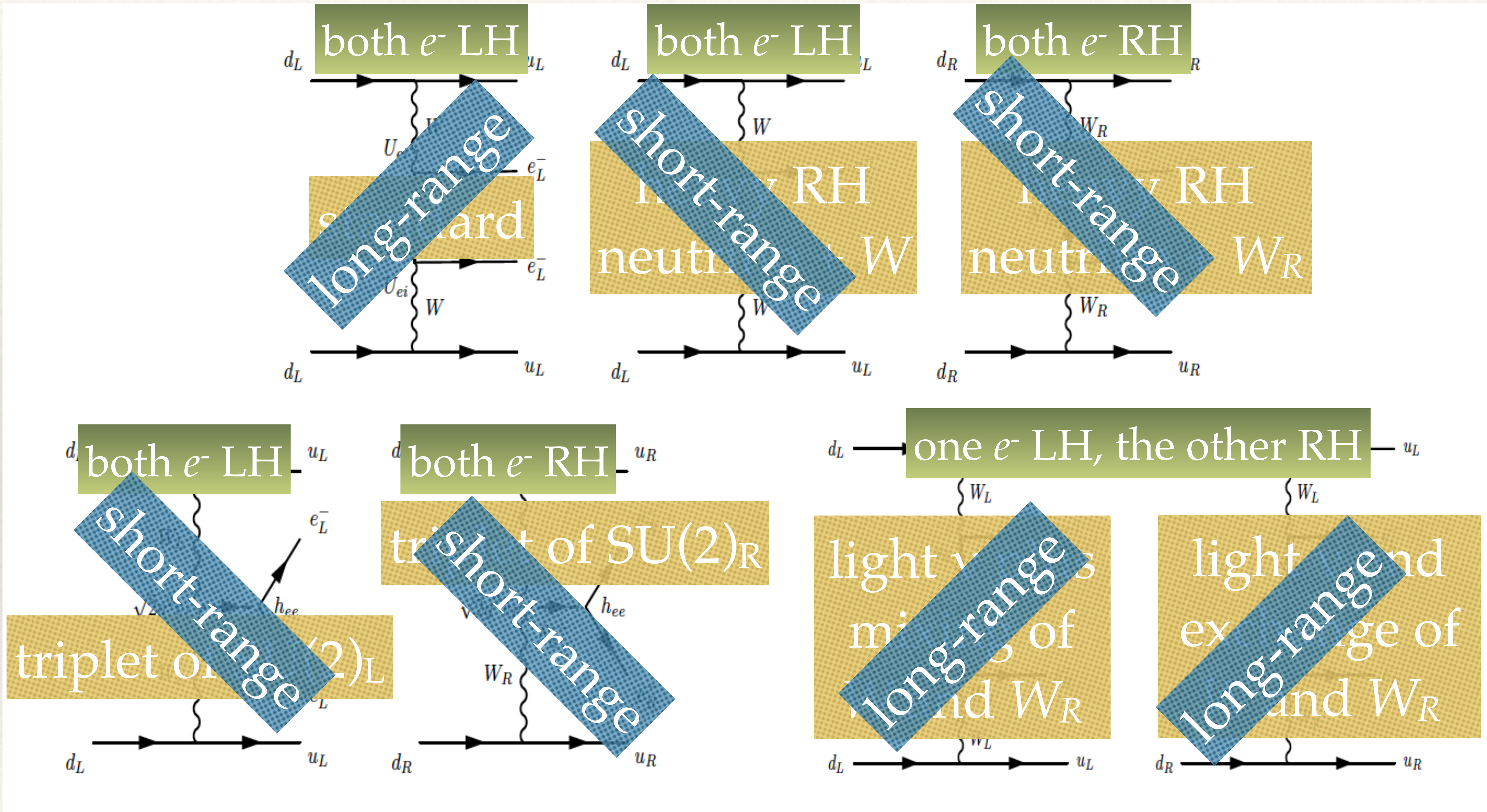

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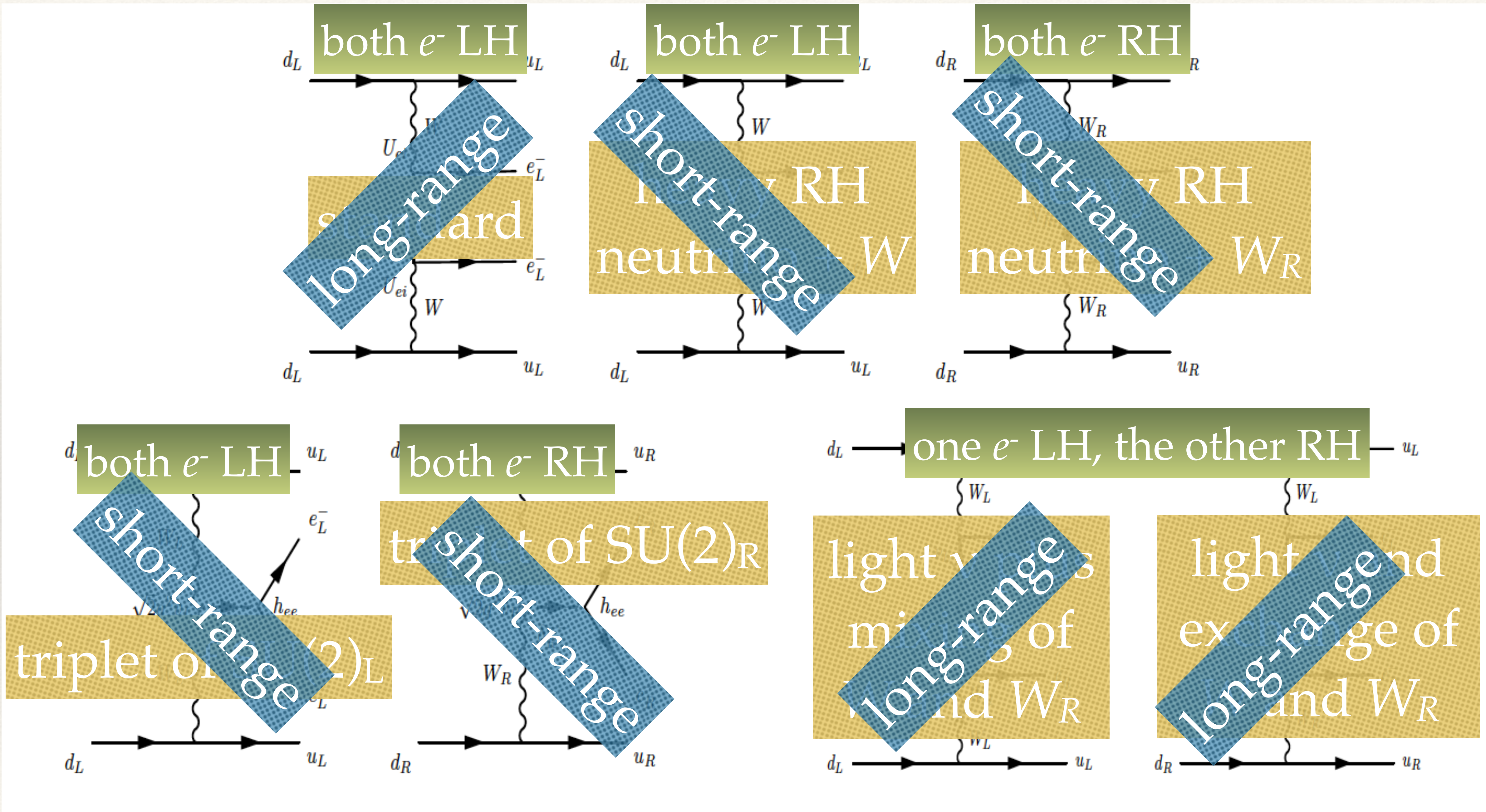
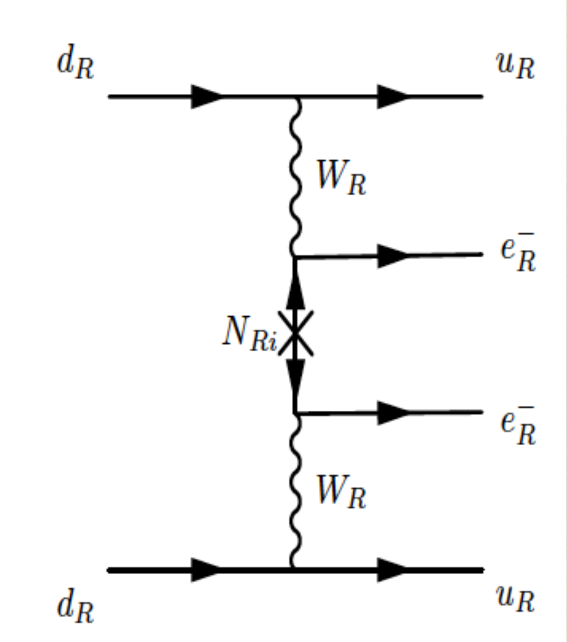


simultaneous presence / interference / ...

Double Beta Decay and LR-Symmetry

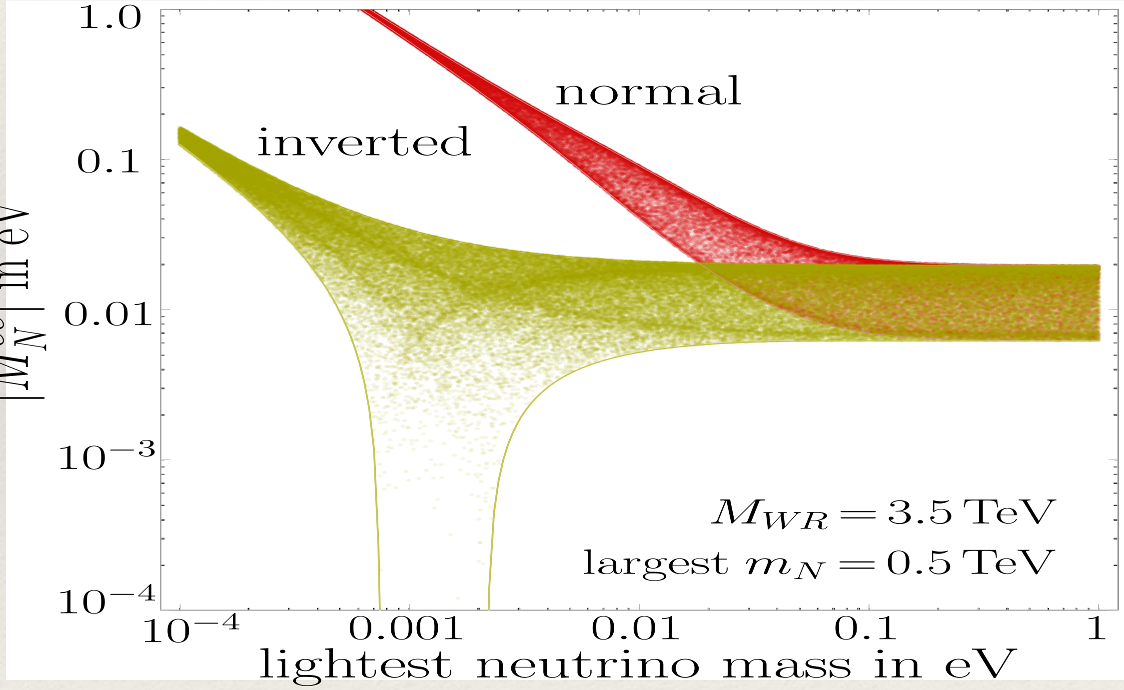
Type II dominance: $m_\nu = m_L - M_D^2/M_R \to m_L$ with $m_L \propto M_R$

$\Rightarrow$ right-handed neutrinos diagonalized by PMNS matrix!



$$\mathcal{A} \propto \frac{V_{ei}^2}{M_i} \propto \frac{U_{ei}^2}{m_i}$$

amplitude determined by PMNS, but $\propto 1/m_\nu$

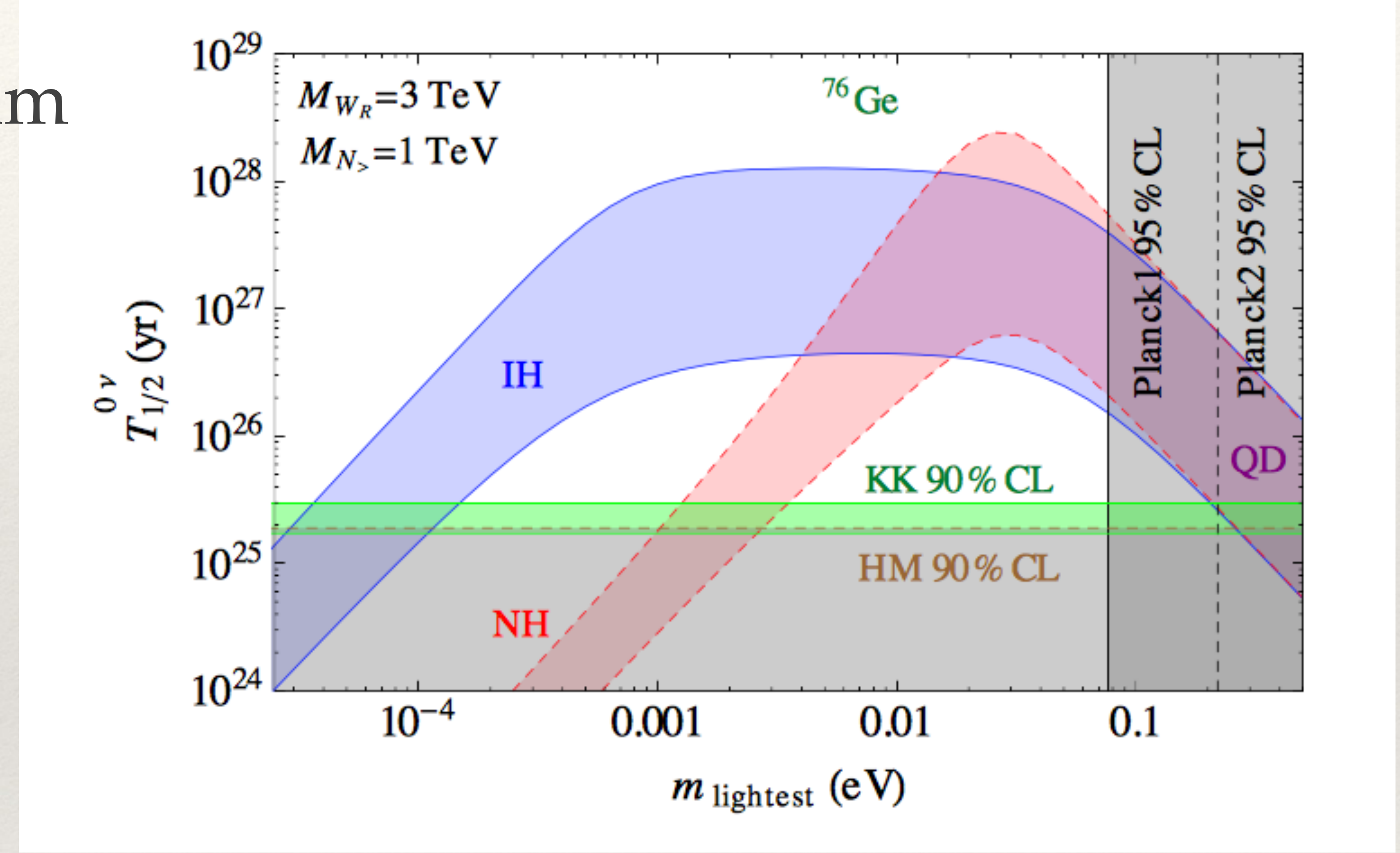


Senjanovic et al., 1011.3522

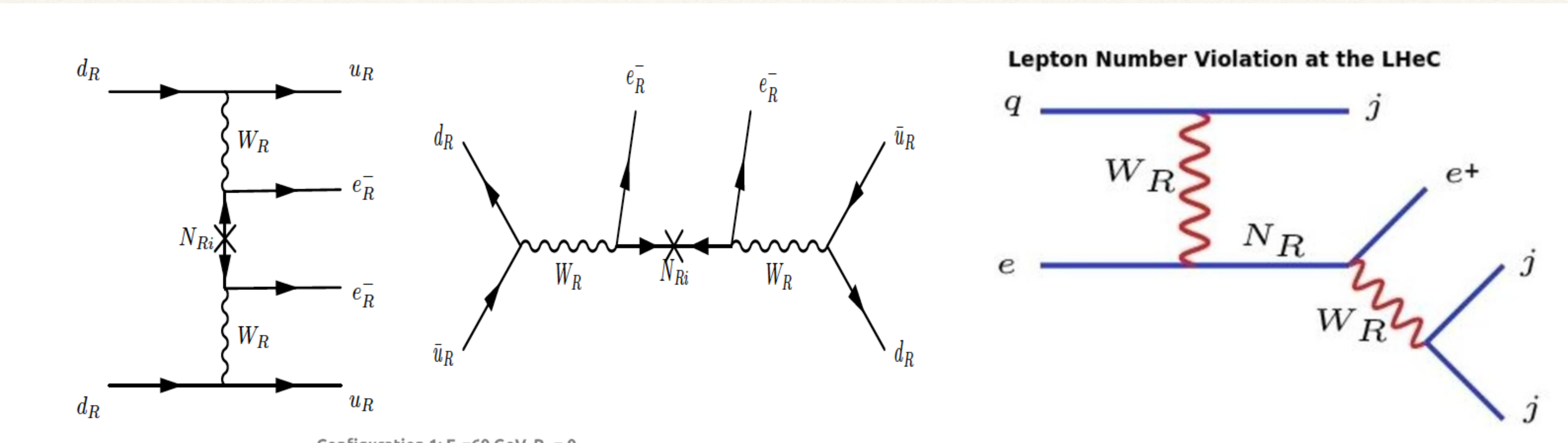
again, NH/IH turned around…

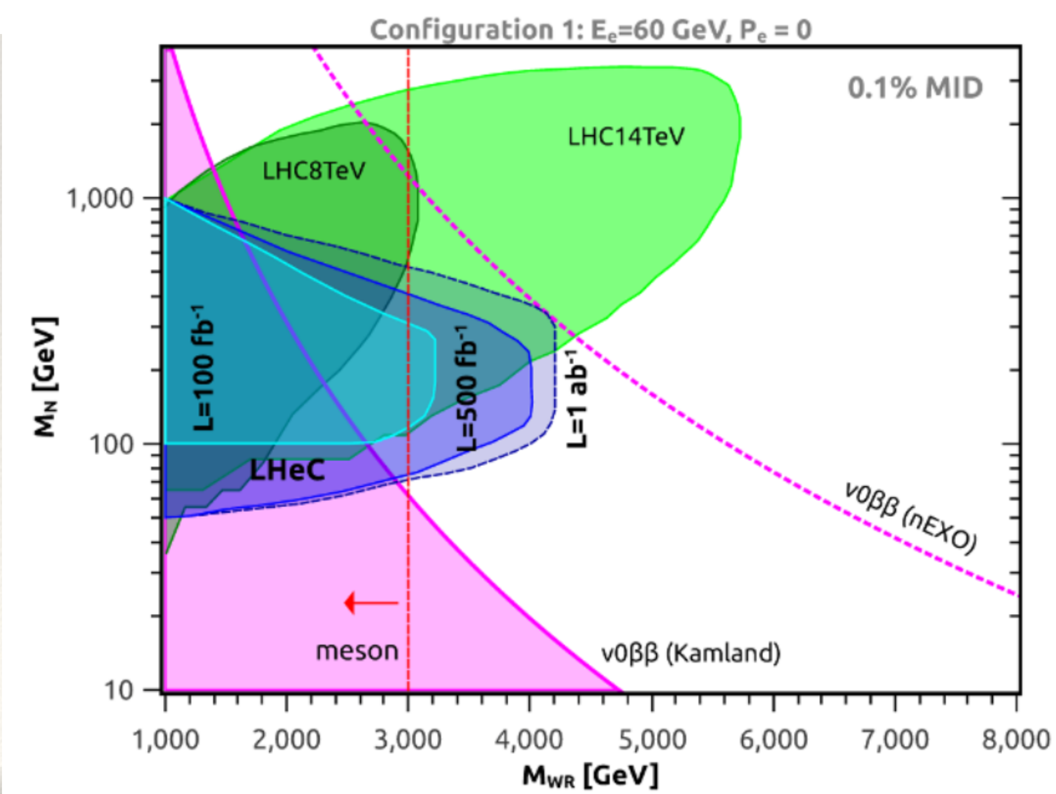
Double Beta Decay and LR-Symmetry

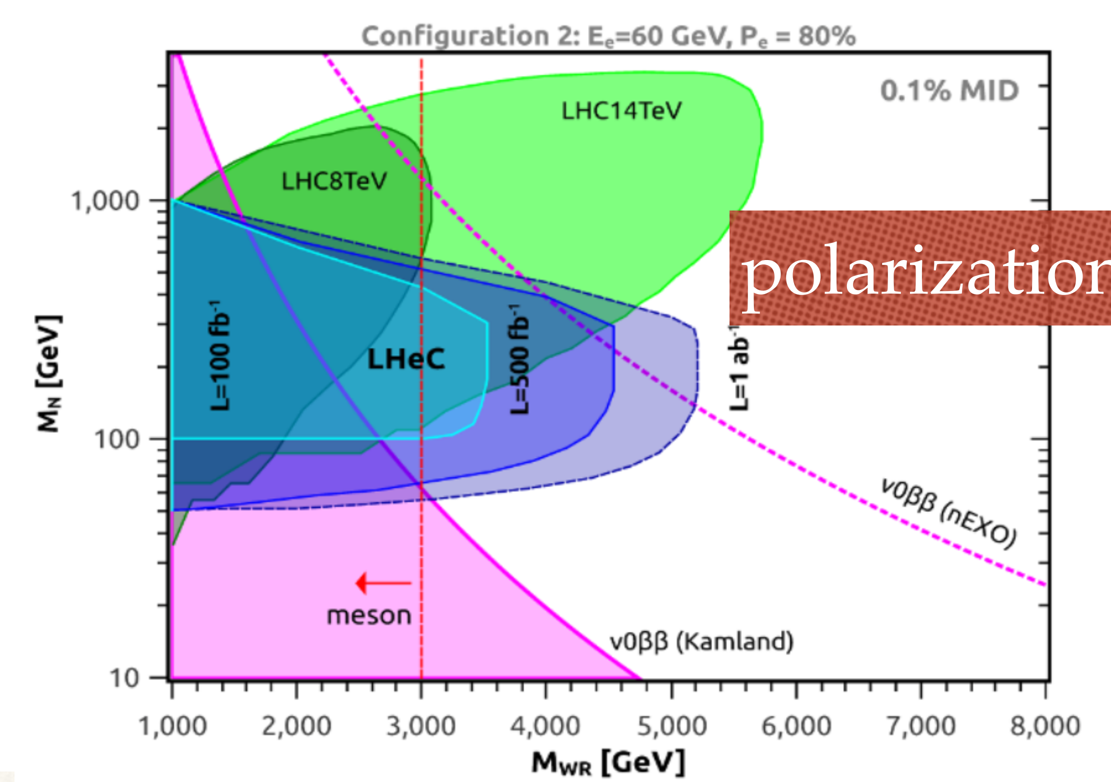
- add Standard and LR-diagram
- $T_{\rm St} \propto 1/m_\nu^2$ and $T_{\rm LR} \propto m_\nu^2$
- gives ***lower limit*** on m_ν



LHC and Double Beta Decay



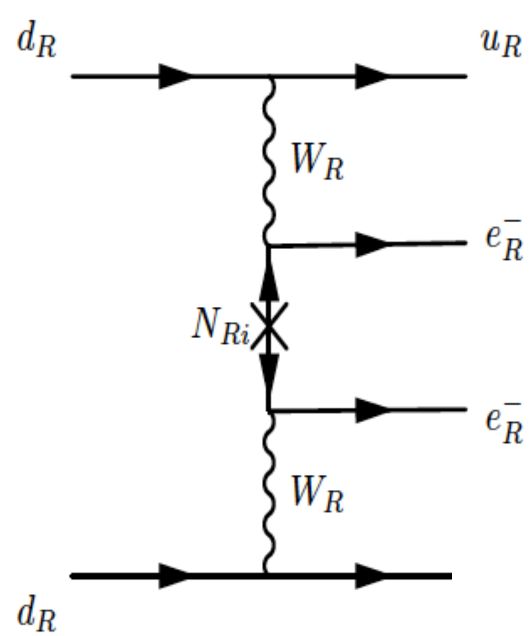


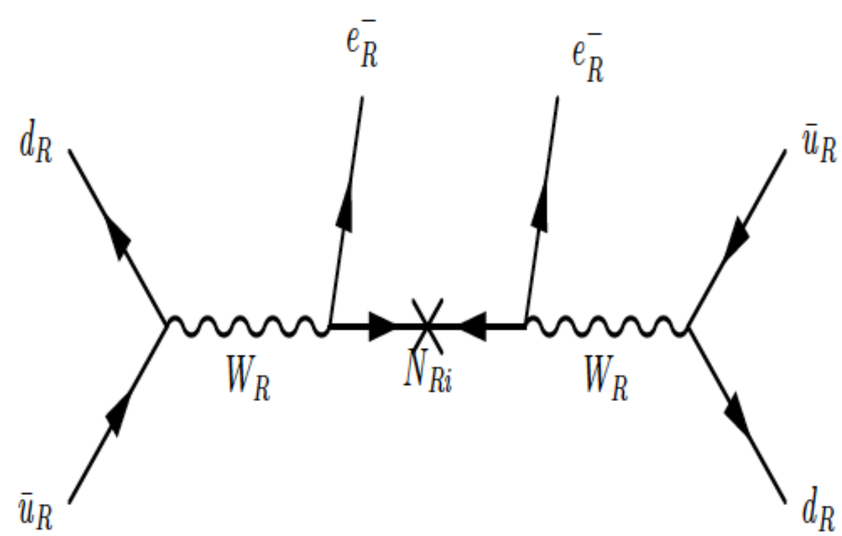


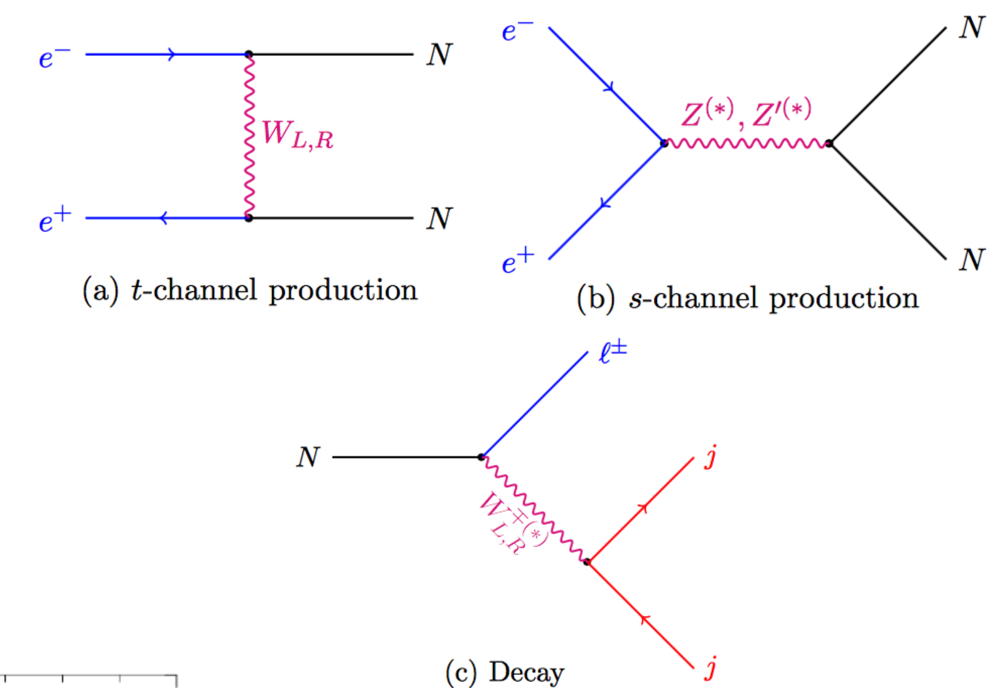
polarization at LHeC

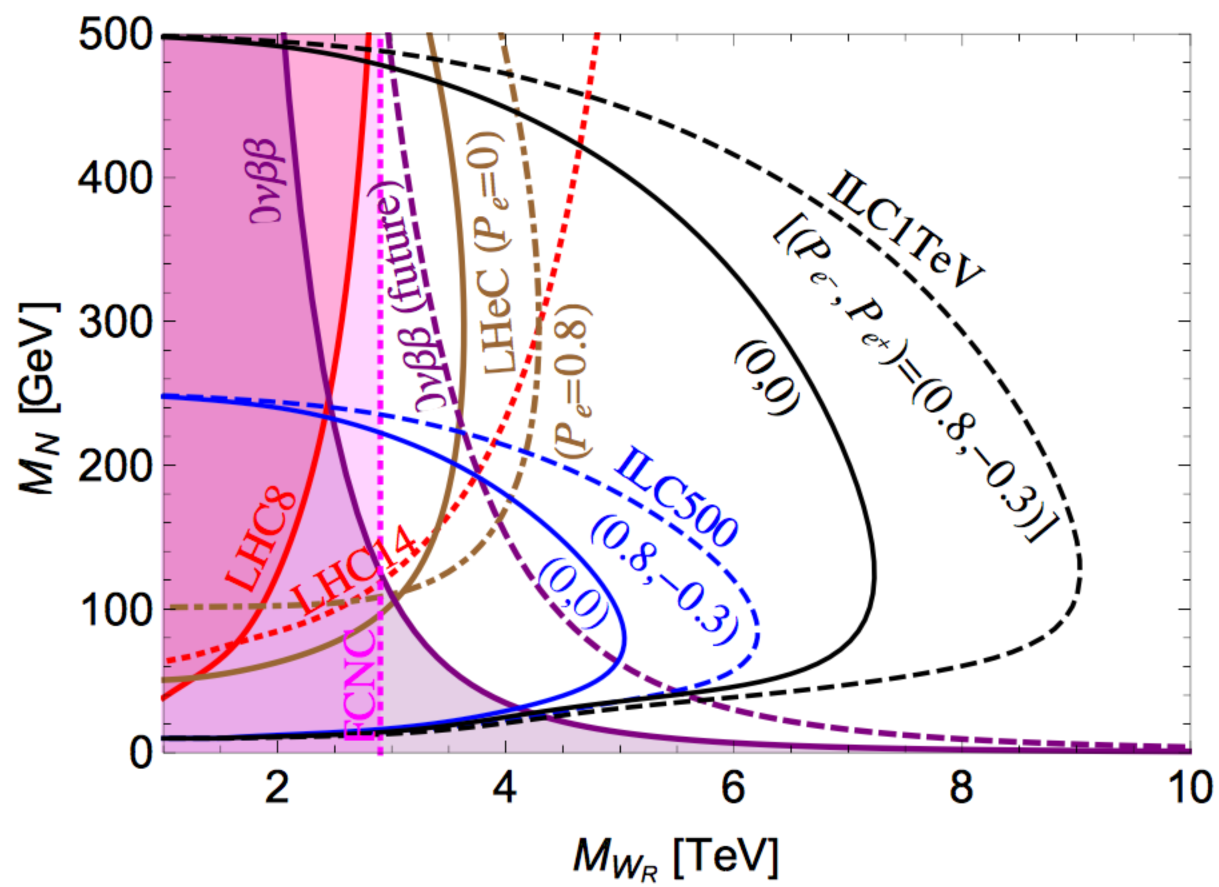
Lindner, Queiroz, WR, Yaguna, 1604.08596

LHC and Double Beta Decay





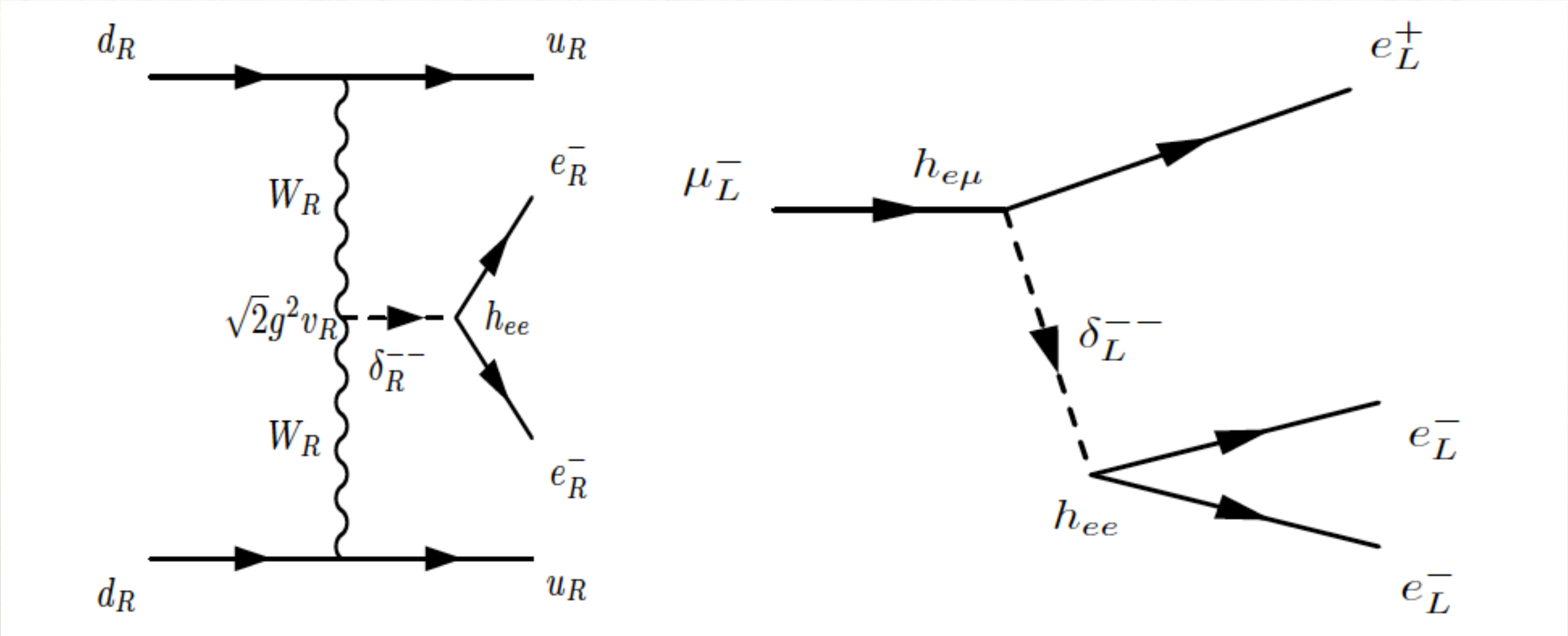


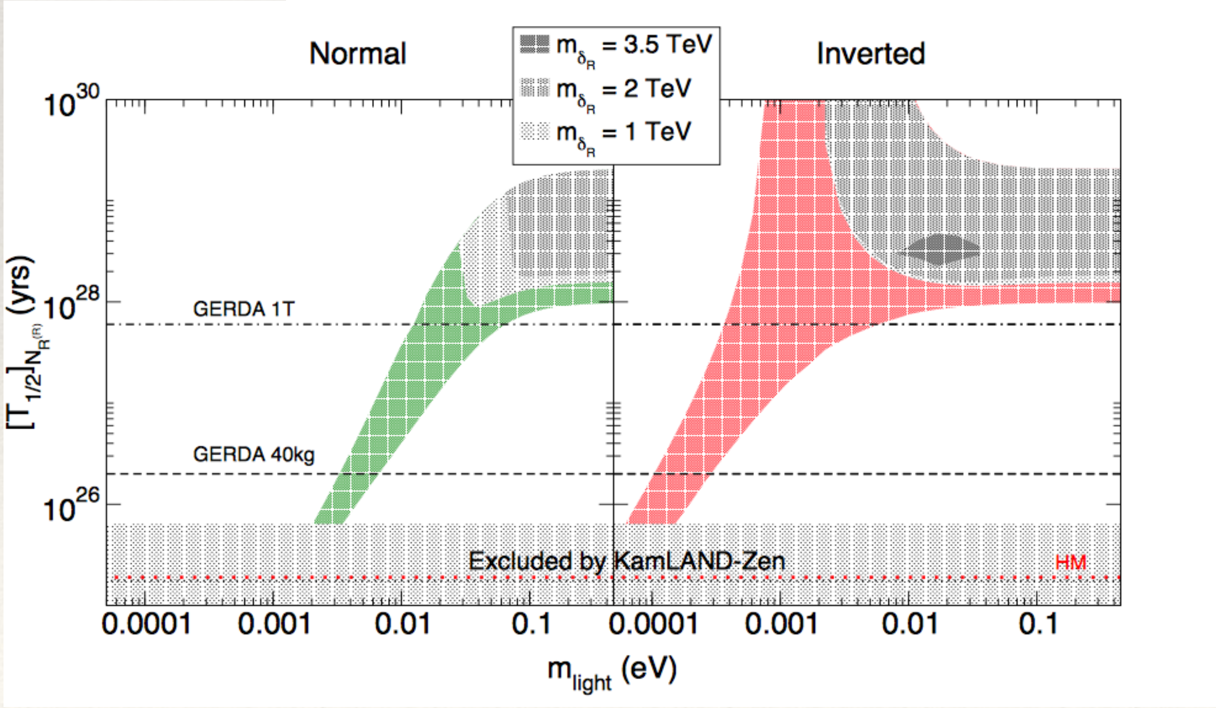


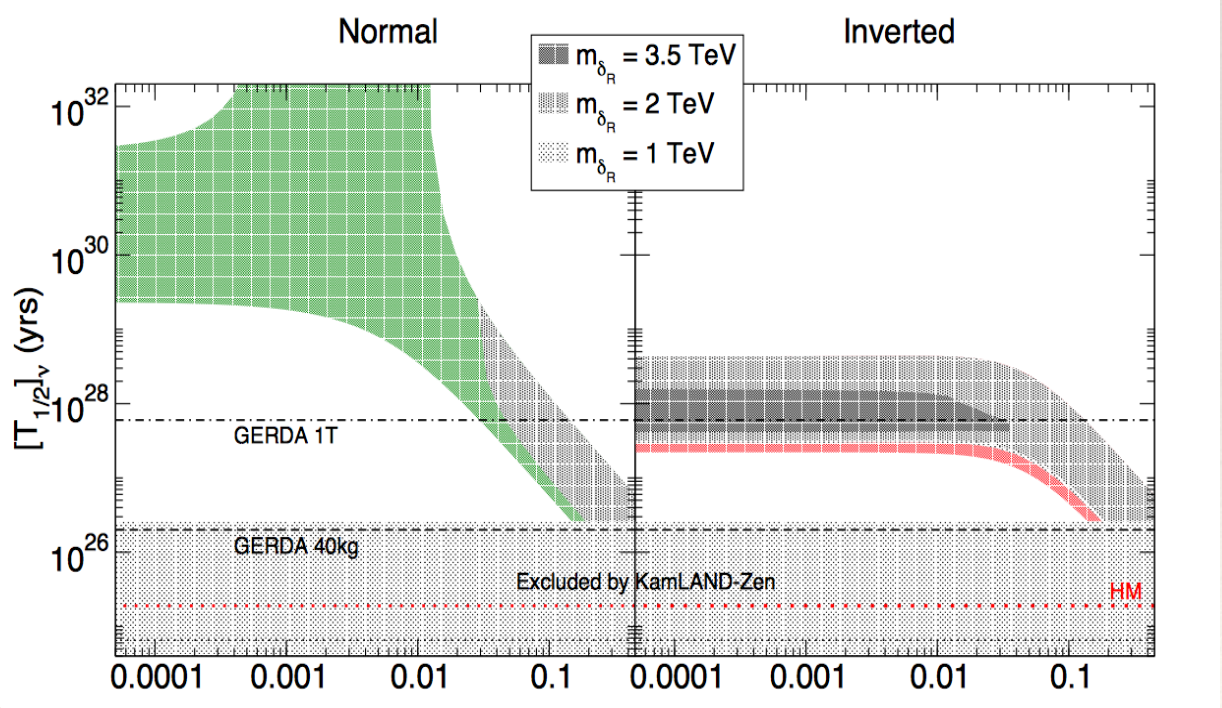
polarization at ILC

Biwal, Bhupal Dev, 1701.08751

LFV and Double Beta Decay



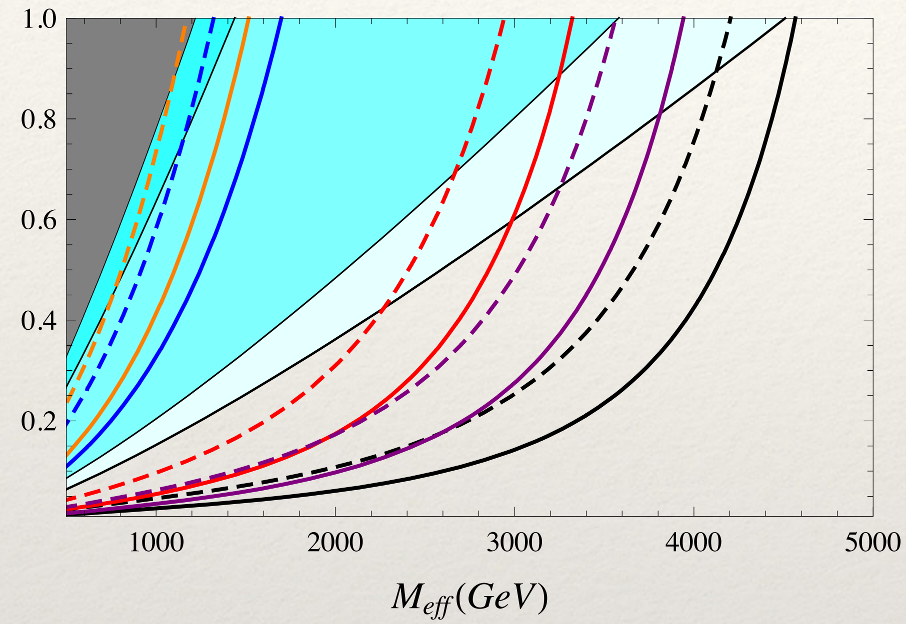




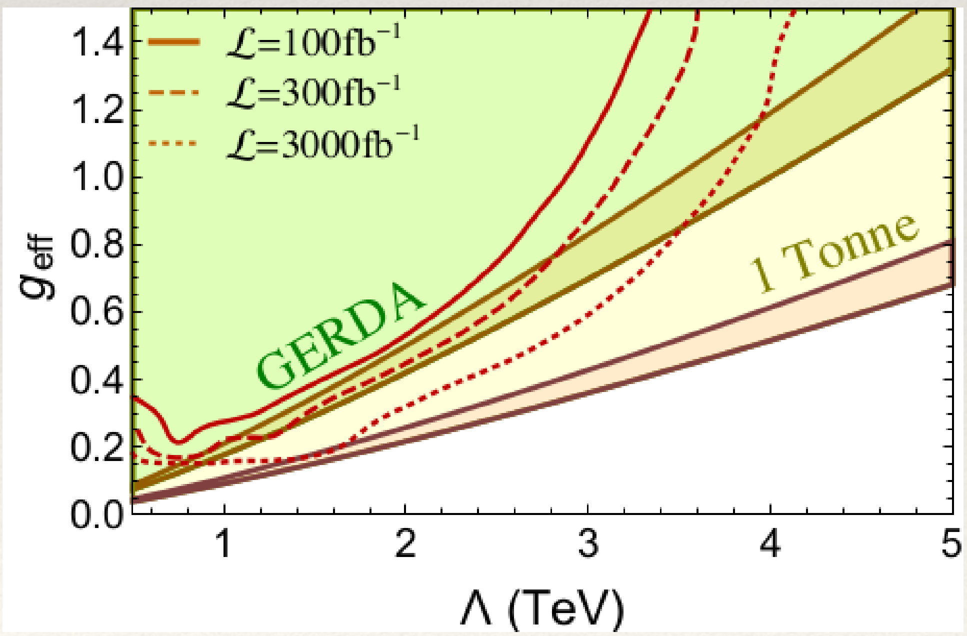
Barry, WR, 1303.6324

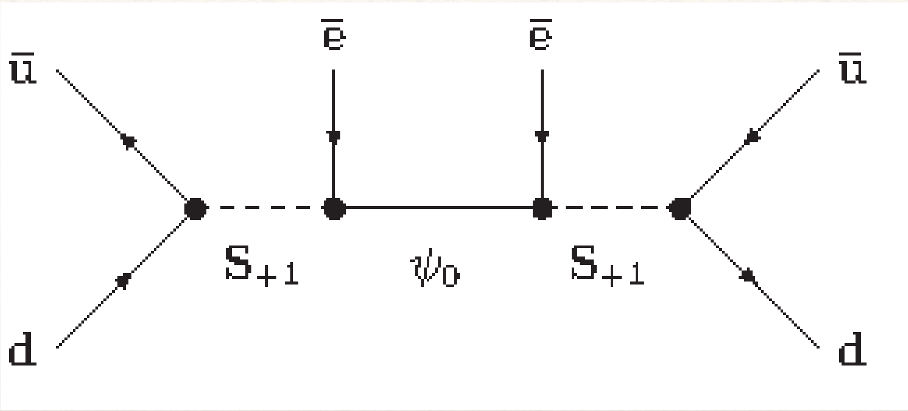
Complementarity of LHC and 0νββ

Hirsch et al., 1511.03945



Ramsey-Musolf et al., 1508.04444





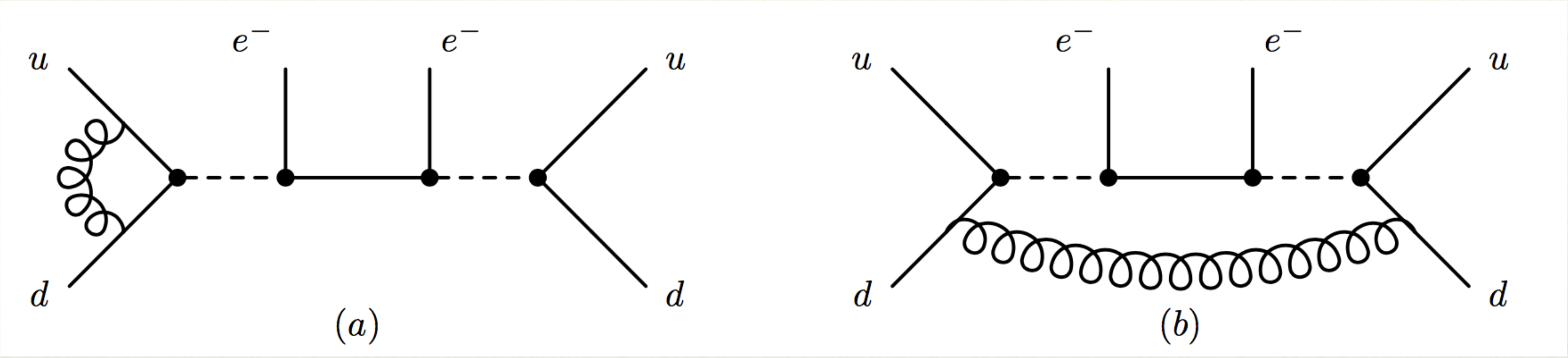
S~(1,2)

ψ~(1,0)

- LHC needs $M_S > M_\psi$
- LHC has low sensitivity for small M_ψ
- include jet-fake rate, charge mis-ID, QCD corrections in 0νββ, etc.
- ⇒ complementary

See talk by Ramsey-Musolf

QCD Corrections



- naive size $(\alpha_s/4\pi)\ln(M_W/100\text{ MeV})^2 \simeq 10\%$, true for standard diagram
- creates in non (V-A) $\otimes$ (V-A) short-range mechanisms color non-singlets, Fierzing to singlets gives different operators with vastly different NMEs
- $\Rightarrow$ can give effect exceeding NME uncertainty…

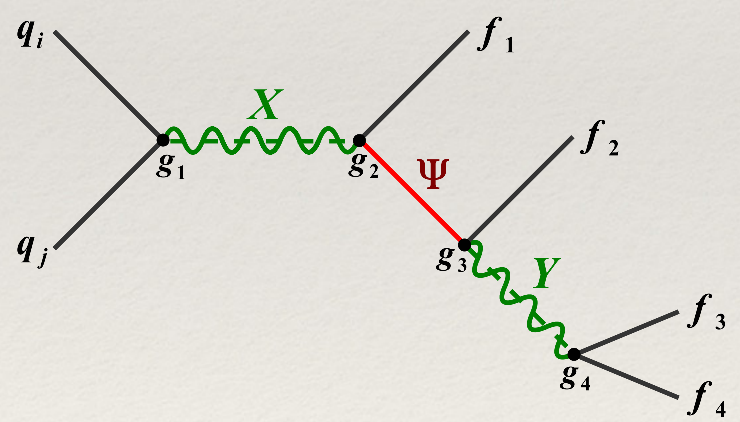
Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93;

Peng, Ramsey-Musolf, Winslow, PRD 93

TeV-scale LNV and Baryogenesis

- Example TeV-scale W_R: leads to washout in early Universe via $e_R\, e_R \leftrightarrow W_R\, W_R$ and $e_R\, W_R \leftrightarrow W_R\, e_R$; processes stay long in equilibrium *(Frere, Hambye, Vertongen; Bhupal Dev, Mohapatra; Sarkar et al.)*

- more model-independent *(Deppisch, Harz, Hirsch)*:



wash-out:

$$\log_{10} \frac{\Gamma_W(qq \to \ell^+ \ell^+ qq)}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}$$

(⟺ need for high-scale baryogengesis if TeV-scale LNV is present…?)

Dirac vs. Majorana beyond *V-A*

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_a \overline{\nu}\Gamma^a \nu \left[\overline{\ell}\Gamma^a (C_a + \overline{D}_a i\gamma^5)\ell\right]$$

Rosen, PRL48 (1982)
WR, Xu, Yaguna, 1702.05721

- gives cross section for elastic neutrino-electron scattering:

$$\frac{d\sigma}{dT}(\nu + \ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2\right]$$

$$\frac{d\sigma}{dT}(\overline{\nu} + \ell) = \frac{G_F^2 M}{2\pi}\left[C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2\right]$$

$$T = \frac{2ME_\nu^2 c_\theta^2}{(M + E_\nu)^2 - E_\nu^2 c_\theta^2}$$

with:

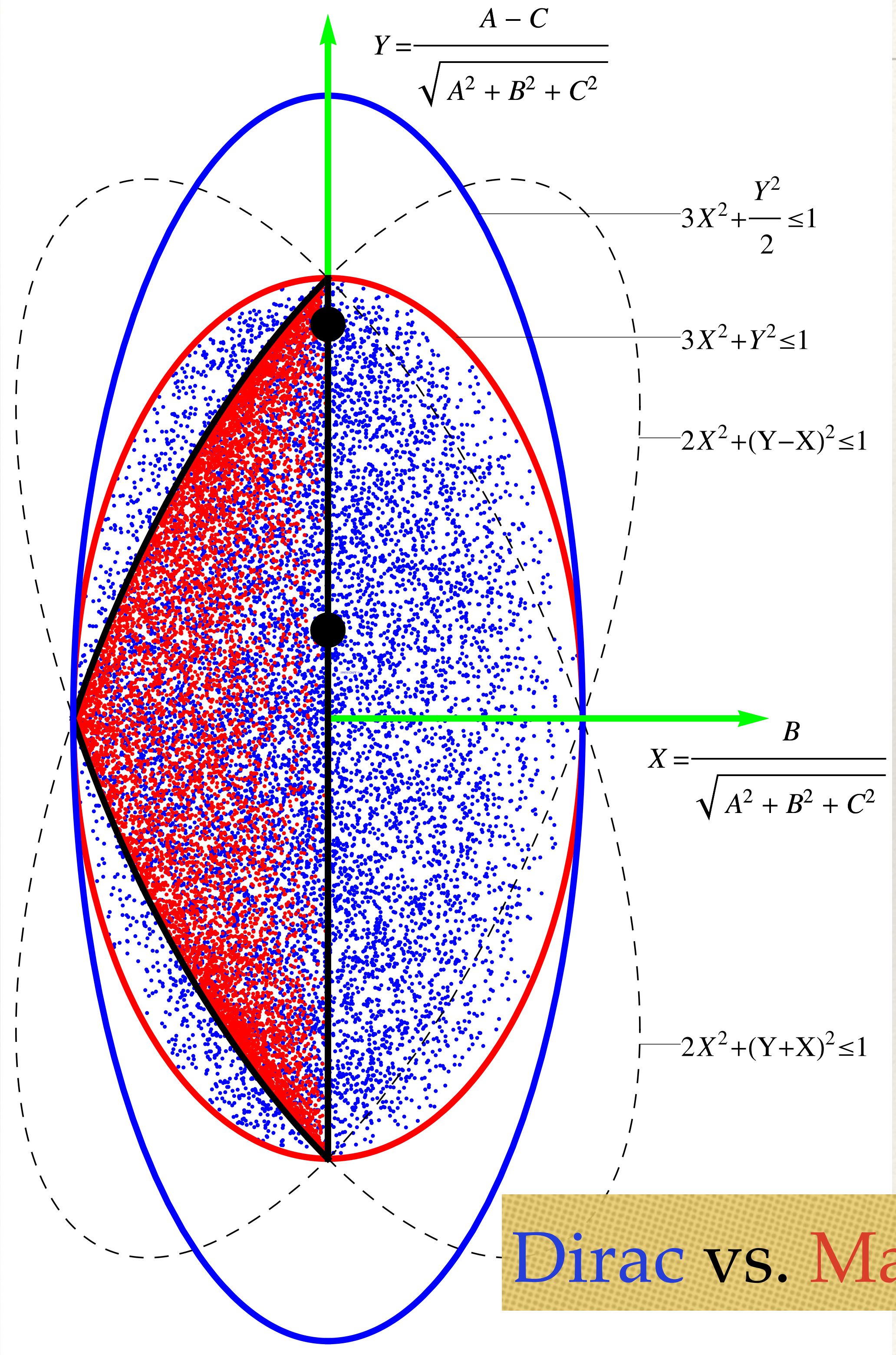
$$A \equiv \frac{1}{4}\left(C_A - D_A + C_V - D_V\right)^2 + \frac{1}{2}C_P C_T + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) - \frac{1}{2}C_S C_T + C_T^2 + \frac{1}{2}D_P D_T - \frac{1}{2}D_S D_T + D_T^2$$

$$B \equiv -\frac{1}{8}\left(C_P^2 + C_S^2 + D_P^2 + D_S^2\right) + C_T^2 + D_T^2\,,$$

$$C \equiv \frac{1}{4}\left(C_A + D_A - C_V - D_V\right)^2 - \frac{1}{2}C_P C_T + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) + \frac{1}{2}C_T C_S + C_T^2 - \frac{1}{2}D_P D_T + \frac{1}{2}D_S D_T + D_T^2$$

- **For Majorana neutrinos: $C_V = D_V = C_T = D_T = 0$**

Dirac vs. Majorana beyond *V-A*



can only demonstrate Dirac nature!

$$X \equiv \frac{B}{R}, \; Y \equiv \frac{A - C}{R}$$

$$R \equiv \sqrt{A^2 + B^2 + C^2}$$

Dirac neutrinos:

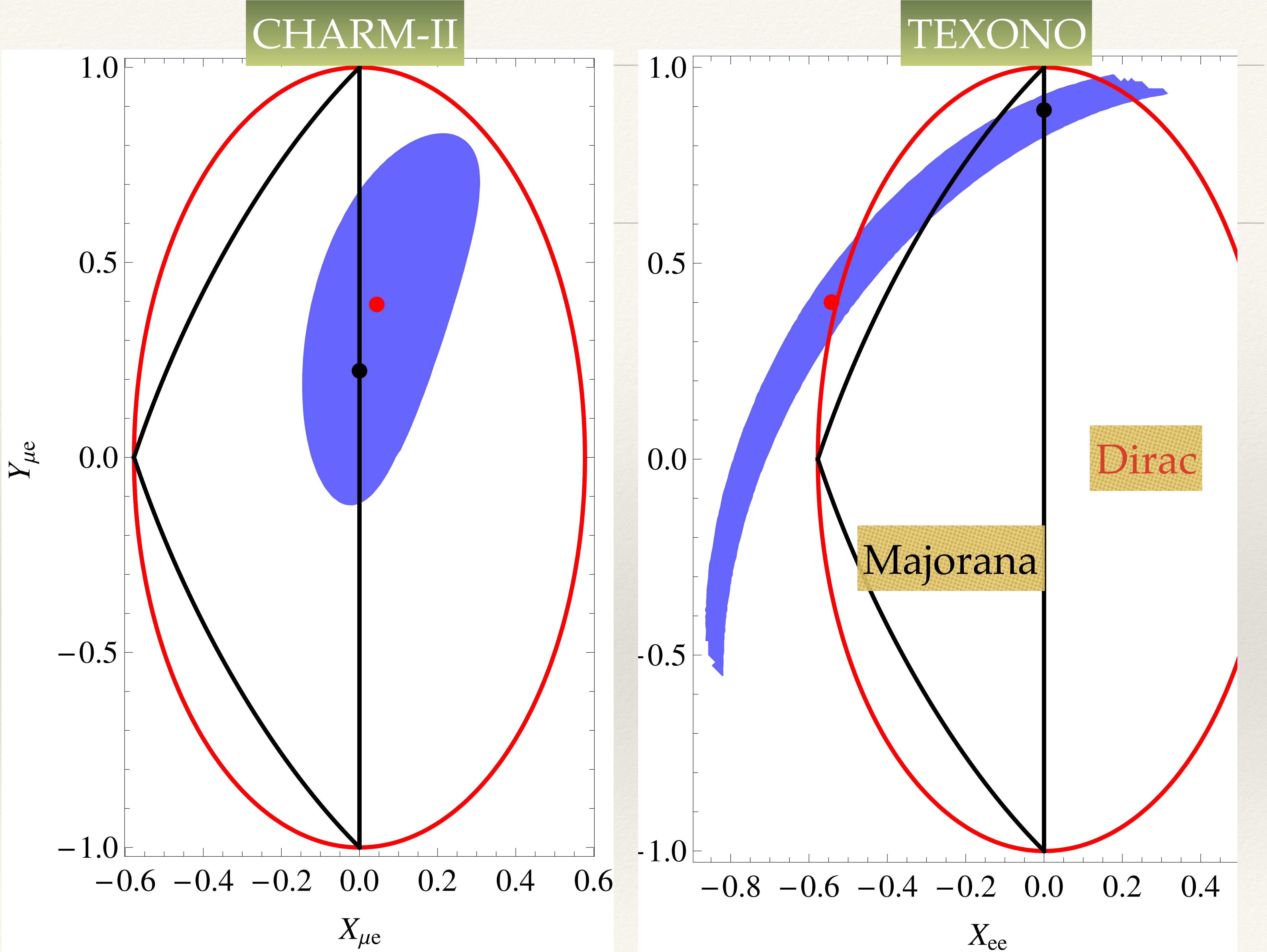
$$3X^2 + Y^2 \leq 1$$

Majorana neutrinos:

$$2X^2 + (Y \pm X)^2 \leq 1 \quad \text{and} \quad X \leq 0$$

Dirac vs. Majorana

WR, Xu, Yaguna, 1702.05721



CHARM-II
1.0
0.5
0.0
-0.5
-1.0
$Y_{\mu e}$
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
$X_{\mu e}$
TEXONO
1.0
0.5
0.0
-0.5
-1.0
Dirac
Majorana
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
X_{ee}

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.