Lepton Flavor and Number Physics

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Desy-Th 2015

30/09/15

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ν

$m_\nu = m_L - m_D^T M_R^{-1} m_D$

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

DESY THEORY WORKSHOP

29 September - 02 October 2015

HELMHOLTZ ASSOCIATION

Physics at the LHC and beyond

DESY

DESY Hamburg, Germany

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Outline

- Neutrinos and the Standard Model
- Lepton Flavor Symmetries
  - Residual Symmetries
  - CP
  - Higgs $\to \mu\tau$
- Lepton Number
  - How to generate m_ν
  - Neutrinoless Double Beta Decay: Neutrinos
  - Neutrinoless Double Beta Decay: not Neutrinos

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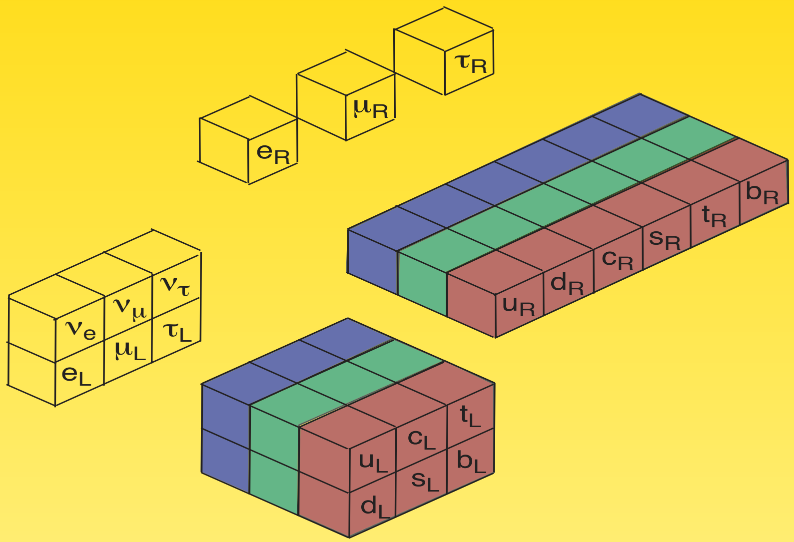
Neutrinos and the Standard Model



Species	#	$\sum$
Quarks	10	10
Leptons	3	13
Charge	3	16
Higgs	2	18
strong CP	1	19

19 free parameters. . .

+ Gravitation

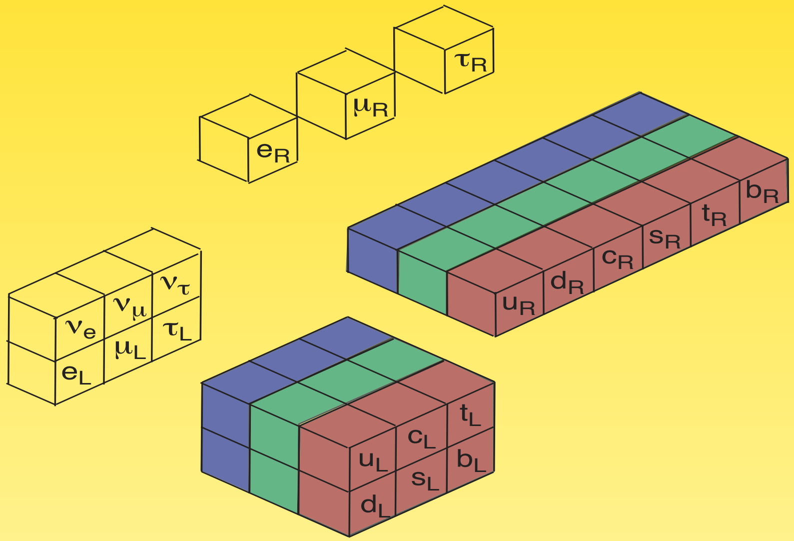
+ Dark Energy

+ Conservation laws

+ Dark Matter

+ Baryon Asymmetry

Neutrinos and the Standard Model



Species	#	$\sum$
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$+$ Neutrino Mass m_ν

Standard Model

add m_ν

Species	#	$\sum$
Quarks	10	10
Leptons	3	13
Charge	3	16
Higgs	2	18
strong CP	1	19

$\longrightarrow$

Species	#	$\sum$
Quarks	10	10
Leptons	12 (10)	22 (20)
Charge	3	25 (23)
Higgs	2	27 (25)
strong CP	1	28 (26)

Standard Model*

Species	#	$\sum$
Quarks	10	10
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$\longrightarrow$

Species	#	$\sum$
Quarks	10	10
Leptons	12 (10)	22 (20)
Charge	3	25 (23)
Higgs	2	27 (25)
strong CP	1	28 (26)

- **new features!**
- **plus new energy scale!**
- **plus new representation!**
- **plus new concepts!**
- **plus**. . .

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Neutrino Physics: Current Situation

at low energies (assuming Majorana neutrinos):

$$\mathcal{L} = \frac{1}{2}\, \nu^T\, m_\nu\, \nu \quad \text{with} \quad m_\nu = U\, \mathrm{diag}(m_1, m_2, m_3)\, U^T$$

with PMNS matrix

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

with $P = \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ ($\leftrightarrow$ Majorana, lepton number violation)

$\Rightarrow$ 3 angles, 3 phases, 3 masses

"three Majorana neutrino paradigm"

Status 2015

9 physical parameters in m_ν

- θ_{12} and $m_2^2 - m_1^2$
- θ_{23} and $|m_3^2 - m_2^2|$
- θ_{13}
- m_1, m_2, m_3
- sgn$(m_3^2 - m_2^2)$
- Dirac phase δ
- Majorana phases α and β

Flavor Symmetries

PMNS-Matrix:

$$|U| = \begin{pmatrix} 0.801\ldots0.845 & 0.514\ldots0.580 & 0.137\ldots0.158 \\ 0.225\ldots0.517 & 0.441\ldots0.699 & 0.614\ldots0.793 \\ 0.246\ldots0.529 & 0.464\ldots0.713 & 0.590\ldots0.776 \end{pmatrix}$$

CKM-Matrix:

$$|V| = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355^{+0.00015}_{-0.00014} \\ 0.22522 \pm 0.00061 & 0.97341 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

Why so different? $\leftrightarrow$ Flavor symmetries!

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Strategy

- choose group (usually discrete non-Abelian) G_f
- SM and new particles are multiplets under G_f
- new scalars ("flavons") acquire VEVs and break G_f such that
  - neutrinos invariant under subgroup of G_f, e.g. $Z_2 \times Z_2$

$$S^T \, m_\nu \, S = m_\nu \quad \text{with} \quad U_\nu^T \, m_\nu \, U_\nu = m_\nu^{\rm diag}$$

  - charged leptons invariant under subgroup of G_f, e.g. Z_3

$$T^\dagger \, m_\ell m_\ell^\dagger \, T = m_\ell m_\ell^\dagger \quad \text{with} \quad U_\ell^\dagger \, m_\ell^\dagger m_\ell \, U_\ell = (m_\ell^{\rm diag})^2$$

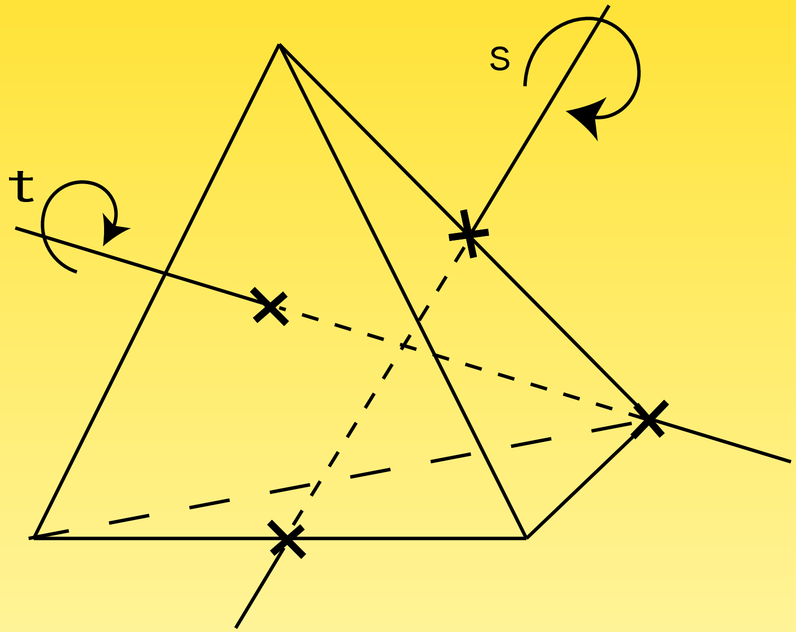
it follows (Lam, PRL101)

$$U_\nu^\dagger \, S \, U_\nu = S^{\rm diag} \quad \text{and} \quad U_\ell^\dagger \, T \, U_\ell = T^{\rm diag} \Rightarrow U = U_\ell^\dagger U_\nu$$

gives $\delta = 0, \pi$ unless smaller residual symmetries, or including CP (see later)

Holthausen, Lim, Lindner; Joshipura, Patel; Feruglio, Hagedorn; Grimus, Fonseca; Smirnov, Hernandez; King, Neder;...

Smallest group with 3-dim irrep: A_4



generators are $S^2 = T^3 = (ST)^3 = \mathbb{1}$

3-dim irreps ($\omega^3 = 1$):

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}$$

$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}$$

$S^2 = \mathbb{1}$ and $T^3 = \mathbb{1}$ are Z_2 and Z_3 subgroups

A role model (Altarelli, Feruglio)

Field	l	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	ξ	φ_0	φ'_0	ξ_0	θ
A_4	3	1	$1''$	$1'$	1	3	3	1	3	3	1	1
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω	1	ω	ω	1
$U(1)_R$	1	1	1	1	0	0	0	0	2	2	2	0

Due to VEV alignment, A_4 is broken to

- Z_2 in m_ν from $\langle\varphi'\rangle = (v', v', v')$ **(eigenvector of S)**
- Z_3 in m_ℓ from $\langle\varphi\rangle = (v, 0, 0)$ **(eigenvector of T)**
- mixing is caused by mismatch of subgroups!
- μ–τ symmetry is accidental from VEVs
- can be explained in larger groups, e.g. S_4

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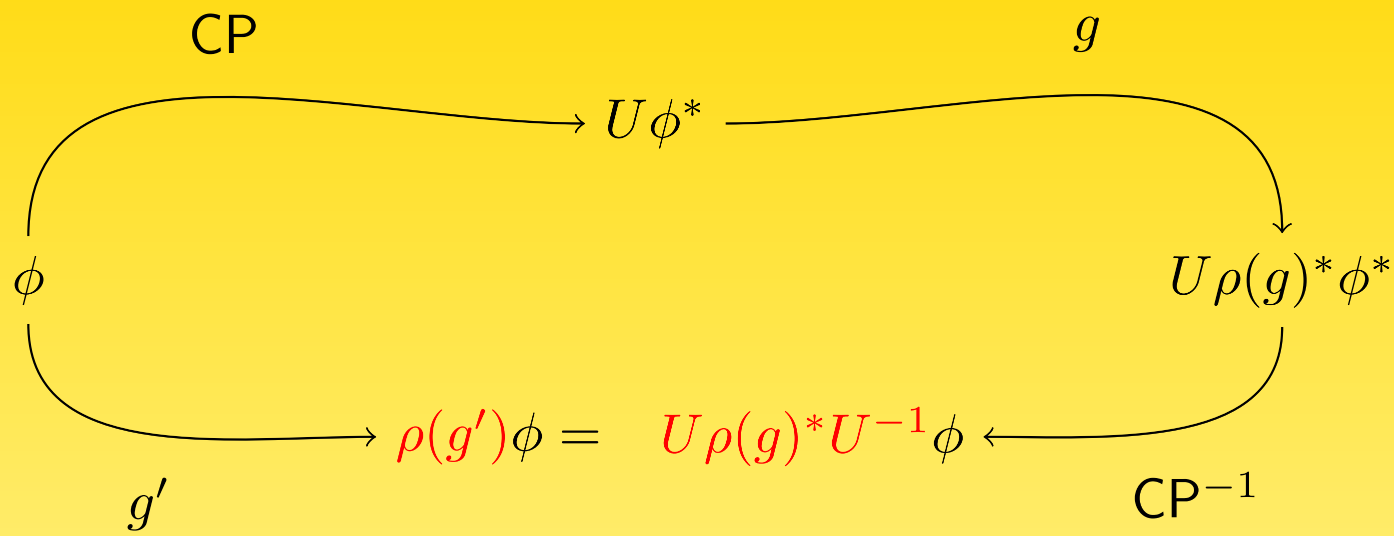
Combining Flavor and CP Symmetries



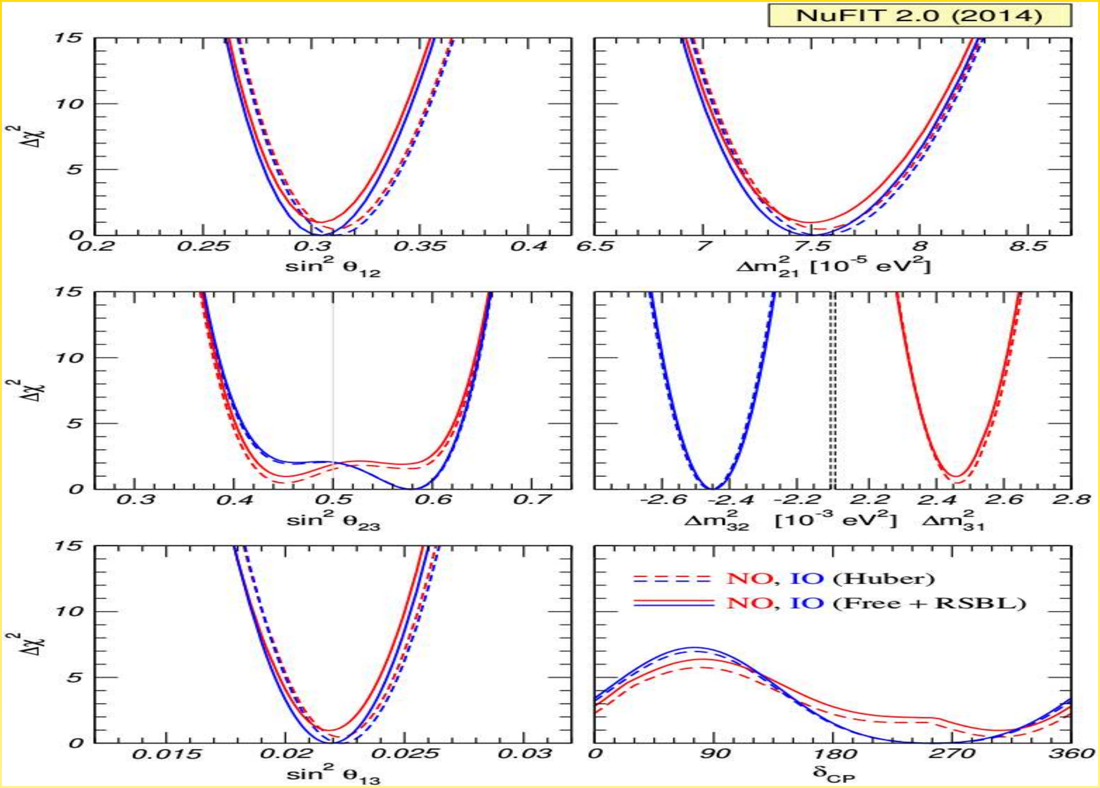
consistency relation for U

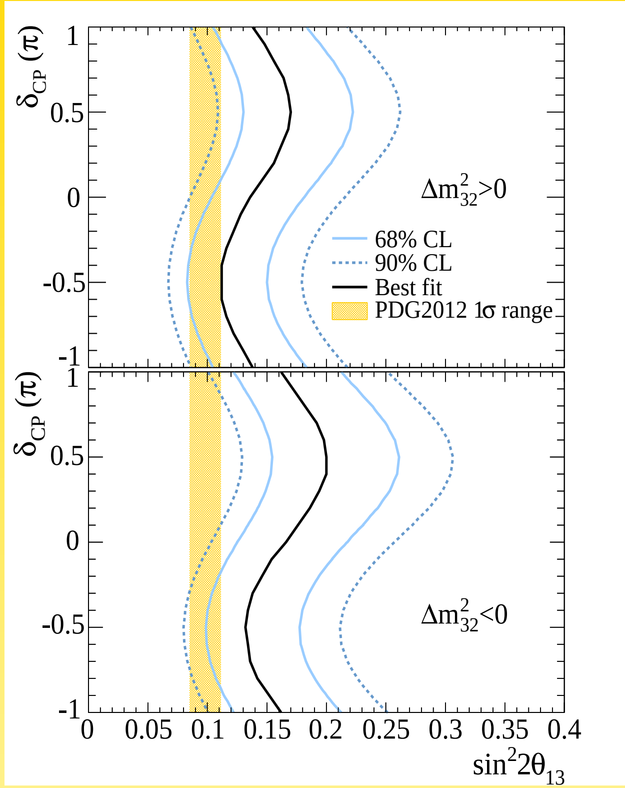
CP is outer automorphisms of the symmetry group, possible U form a representation of the automorphism group

can break $G_f \times \mathrm{CP}$ in $G_\nu = Z_2 \times \mathrm{CP}$ and $G_\ell = Z_3$, can get $\delta = \pi/2$

Grimus; Chen; Feruglio, Hagedorn, Ziegler; Holthausen, Schmidt, Lindner; Ding, King, Stuart; Meroni, Petcov; Branco, King, Varzielas;...

Current Situation





$$P(\nu_\mu \to \nu_e)_{\rm T2K} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}$$

$$- \quad \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{\rm CP}$$

$$+ \quad (\text{CP even term, solar term, matter effect term})$$

"Constrained Maximal CP Violation"

data seems to want $\delta = -\pi/2$ and $\theta_{23} = \pi/4$, equivalent to

- $J_{\rm CP}$ maximal when first row of PMNS is fixed
- column unitary triangles are isosceles triangles
- **second row of PMNS is (third row)***

"If residual symmetries are real and fully determine the mixing pattern, then $\delta = \pm\pi/2$ and $\theta_{23} = \pi/4$ follows."

He, W.R., Xu, 1507.03541

contains subgroups of $O(3)$, such as A_4, S_4, A_5 (Joshipura, Patel, PLB749)

and μ-τ reflection symmetry (Ma; Grimus, Lavoura)

$$\nu_e \to \nu_e^*,\ \nu_\mu \to \nu_\tau^*,\ \nu_\tau \to \nu_\mu^*$$

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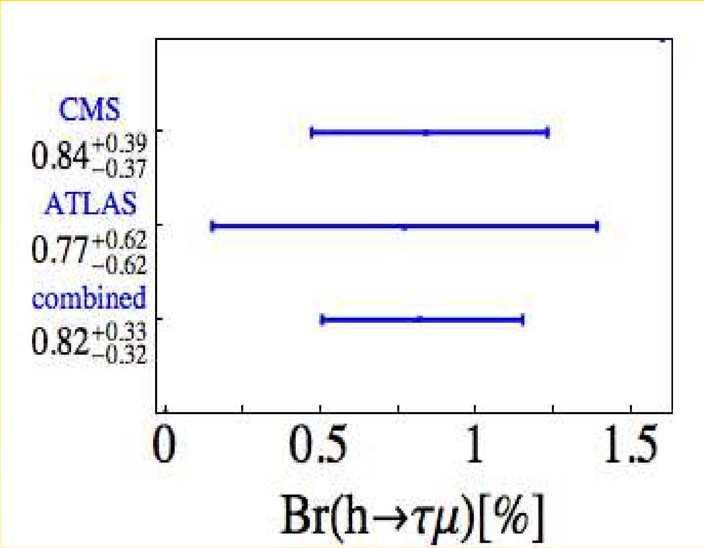
Higgs $\to \mu\gamma$



if real, could be 2HDM:

$$Y_1 \bar{L} \Phi_1 e_R + Y_2 \bar{L} \Phi_2 e_R$$

$$\to m_i \bar{e}_i \, e_i + (Y \neq \mathbb{1})_{ij} \bar{e}_i \, e_j \, h$$

implies $\sqrt{Y_{\mu\tau}^2 + Y_{\tau\mu}^2} \simeq 0.003$

studied before

Bjorken, Weinberg; Han, Marfatia; Giudice, Lebedev; Davidson, Grenier; Celis, Cirigliano, Passemar; Harnik, Kopp, Zupan. . .

and after

Campos, Hernandez, Päs, **Schumacher**; Heeck, Holthausen, Rodejohann, Shimizu; Crivellin, D'Ambrosio, Heeck; Dorsner, Fajfer; de Medeiros Varzielas, Hiller; Aristizabal Sierra, Staub, Vicente; Yue, Pang, Guo;. . .

Gauged $L_\mu - L_\tau$

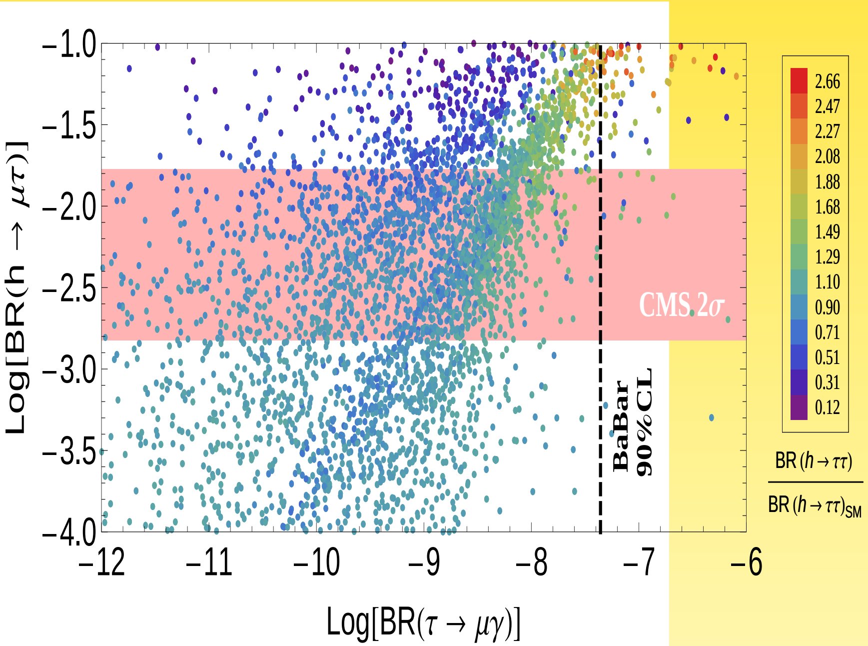
	L_e	L_μ	L_τ	e_R	μ_R	τ_R	N_e	N_μ	N_τ	Φ_1	Φ_2	S
$U(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	1	-1	-2	0	1
$SU(2)_L$	2	2	2	1	1	1	1	1	1	2	2	1

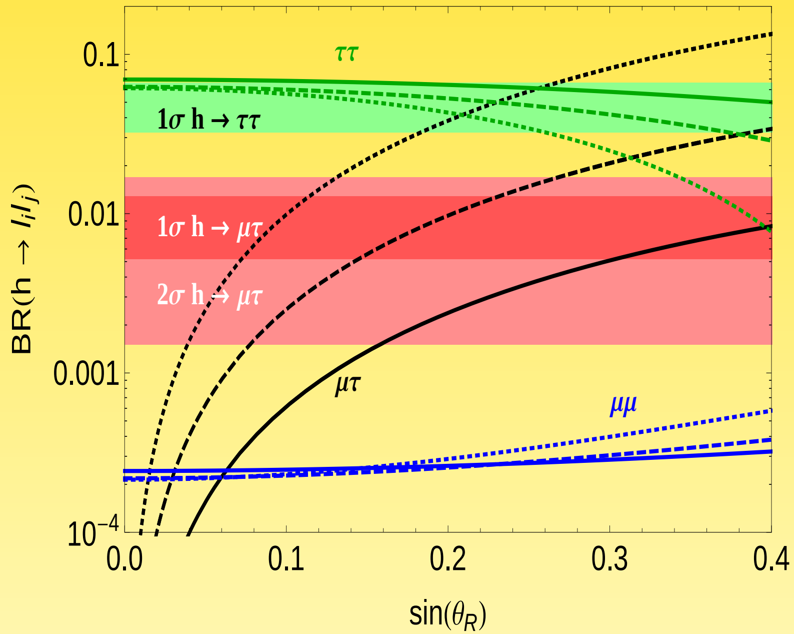
$$\mathcal{L} = y_\alpha \, \overline{L^\alpha} \, \delta_{\alpha\beta} \, \ell_R^\beta \, \Phi_2 + \xi_{\tau\mu} \, \overline{\tau_L} \, \mu_R \, \Phi_1$$

Holthausen, Heeck, W.R., Shimizu, NPB896

Gauged $L_\mu - L_\tau$

	L_e	L_μ	L_τ	e_R	μ_R	τ_R	N_e	N_μ	N_τ	Φ_1	Φ_2	S
$\mathrm{U}(1)_{L_\mu - L_\tau}$	0	1	-1	0	1	-1	0	1	-1	-2	0	1
$\mathrm{SU}(2)_L$	2	2	2	1	1	1	1	1	1	2	2	1





Holthausen, Heeck, W.R., Shimizu, NPB896

Gauged $L_\mu - L_\tau$

- $L_e - L_\mu$ or $L_e - L_\tau$ or $L_\mu - L_\tau$ can be gauged **without anomaly** in the Standard Model (Foot, 1991)
- If symmetry exact: neutrino mass matrix looks like

$$m_\nu = \begin{pmatrix} a & 0 & 0 \\ \cdot & 0 & b \\ \cdot & \cdot & 0 \end{pmatrix} \Rightarrow U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

  masses a, $\pm b$: close-to-degeneracy and μ–τ symmetry! gauge $\leftrightarrow$ flavor

- add in 2HDM vector-like quarks OR make quarks charged under $L_\mu - L_\tau$ in 3HDM to explain BR$(B \to K^* \mu^+ \mu^-)$ and BR$(B \to K \mu^+ \mu^- / B \to K e^+ e^-)$

  Crivellin, D'Ambrosio, Heeck, PRL114

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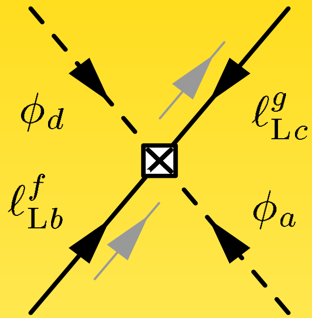
Origin of small masses?

$$\mathcal{L} = \frac{c}{\Lambda}\,\overline{L^c}\,\tilde{\Phi}^*\,\tilde{\Phi}^\dagger\,L$$



has only 3 tree-level realizations

- $N_R \sim (1,0)$ type I seesaw
- $\Delta \sim (3,2)$ type II seesaw
- $\Sigma \sim (3,0)$ type III seesaw

seesaws include new representations, new energy scales, new concepts

Seesaw Formalism

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} \stackrel{M_R \gg m_D}{\Longrightarrow} m_\nu = m_D^T M_R^{-1} m_D$$

arbitrary 6×6 matrix (???)

with new aspects:

- fermionic singlets $N_R \sim (1,0)$
- new energy scale M_R ($\propto 1/m_\nu$)
- lepton number violation

Seesaw tests?

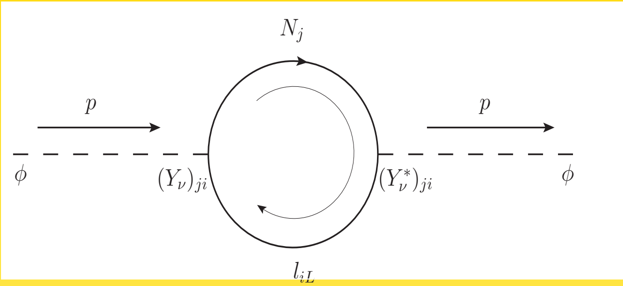
Seesaw portal: $\bar{L}\,\Phi\,N_R \longrightarrow m_D$:

Vertex with Lepton-Doublet L, Higgs Φ, Singlet N_R!

- $N_R \to L\,\Phi$: leptogenesis
- $L_\alpha \to N_R\,\Phi \to L_\beta$: lepton flavor violation
- $\Phi \to N_R\,L \to \Phi$: vacuum stability, hierarchy problem

(plus unitarity violation and neutrinoless double beta decay)

Naturalness issues (Vissani, PRD57; Volkas *et al.* PRD91)

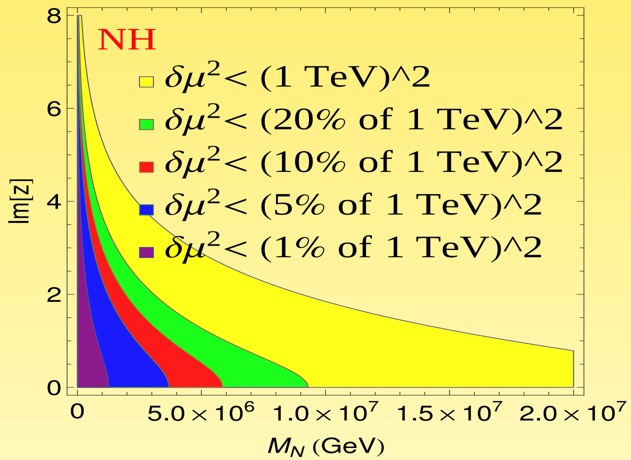


$$\delta\mu^2 \approx \frac{1}{4\pi^2 v^2} \mathrm{Tr}\left[m_D^\dagger \,\mathrm{diag}(M_1^2, M_2^2, M_3^2)\, m_D\right]$$

$$\overset{!}{\lesssim} \mathrm{TeV}^2 \Rightarrow M_R \lesssim 10^7\,\mathrm{GeV}$$

most minimal case $M_1 = M_2 = M$, parametrize m_D as

$$m_D = \sqrt{M}\, R\, \mathrm{diag}(0, \sqrt{m_2}, \sqrt{m_3})\, U^\dagger \quad \text{with } R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}$$



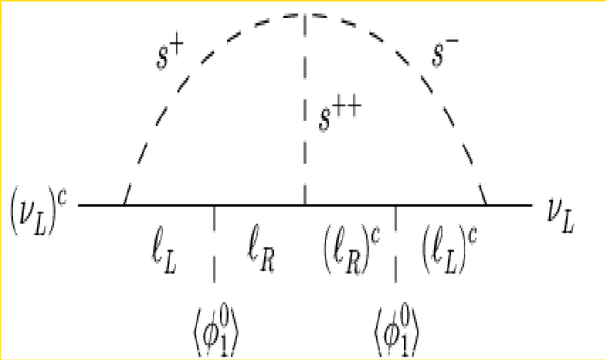
Goswami, W.R., *et al.*, 151x.yyyyy

Seesaw Phenomenology

	LFV	LHC	vacuum stability
type I	loops $\frac{\mathrm{BR}(\alpha\to\beta\gamma)}{\mathrm{BR}(\alpha\to3\beta)} = f(M_i)$	$pp \to \alpha^\pm\beta^\pm\, jj$ $20.3\,\mathrm{fb}^{-1}$ $M_N \gtrsim 100\ldots500\,\mathrm{GeV}$	worse
type II	$\alpha \to 3\beta$ tree $\frac{\mathrm{BR}(1)}{\mathrm{BR}(2)} = f(m_\nu)$	$pp \to H^{++}H^{--} \to 4\ell$ $4.7\,\mathrm{fb}^{-1}$ $M_\Delta \gtrsim 100\ldots600\,\mathrm{GeV}$ (unrealistic BRs)	better
type III	$\alpha \to 3\beta$ tree $\alpha \to \beta$ tree $\frac{\mathrm{BR}(1)}{\mathrm{BR}(2)} = c$	$pp \to \Sigma^+\Sigma^0 \to 3\ell + E_T^{\mathrm{mis}}$ $20.3\,\mathrm{fb}^{-1}$ $M_\Sigma \gtrsim 325\ldots540\,\mathrm{GeV}$ (no LNV)	better/worse

Other ways to generate mass

- loops, e.g. (Zee, Babu)



$$m_\nu \simeq \frac{y^3}{(16\pi^2)^2}\frac{\mu\, m_\tau^2}{M^2}$$
$$\simeq 0.06\left(\frac{y}{0.05}\right)^3\left(\frac{\mu}{100\,\mathrm{GeV}}\right)\left(\frac{500\,\mathrm{GeV}}{M}\right)^2 \mathrm{eV}$$

- n-dim operators
- seesaw variants, e.g. inverse seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_{RS}^T \\ 0 & m_{RS} & M_S \end{pmatrix} \text{ with } m_{RS} \geq m_D \gg M_S$$

gives $m_\nu = (m_D/m_{RS})^2\, M_S \simeq (10^2\,\mathrm{GeV}/\mathrm{TeV})^2\,(M_S/0.1\,\mathrm{keV})\,\mathrm{eV}$

- and combinations of all of the above...

Paths to Neutrino Mass

approach	ingredient	quantum number of messenger	$\mathcal{L}$	m_ν	scale
"SM" (Dirac mass)	RH ν	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L$	$h v$	$h = \mathcal{O}(10^{-12})$
"effective" (dim 5 operator)	new scale + LNV	–	$h\, \overline{L^c}\, \Phi\, \Phi\, L$	$\frac{h\, v^2}{\Lambda}$	$\Lambda = 10^{14}$ GeV
"direct" (type II seesaw)	Higgs triplet + LNV	$\Delta \sim (3,-2)$	$h \overline{L^c} \Delta L + \mu \Phi \Phi \Delta$	$h v_T$	$\Lambda = \frac{1}{h \mu} M_\Delta^2$
"indirect 1" (type I seesaw)	RH ν + LNV	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L + \overline{N_R} M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h} M_R$
"indirect 2" (type III seesaw)	fermion triplets + LNV	$\Sigma \sim (3,0)$	$h \overline{\Sigma}\, L \Phi + \mathrm{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

plus seesaw variants: linear, double, inverse,...

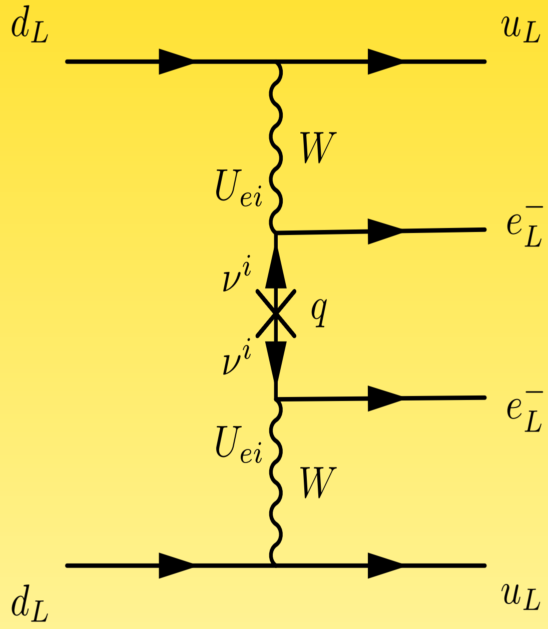
plus radiative mechanisms

plus higher dimensional operators

plus extra dimensions

plusplusplus

Common prediction



Neutrinoless Double Beta Decay $(A, Z) \to (A, Z+2) + 2e^-$

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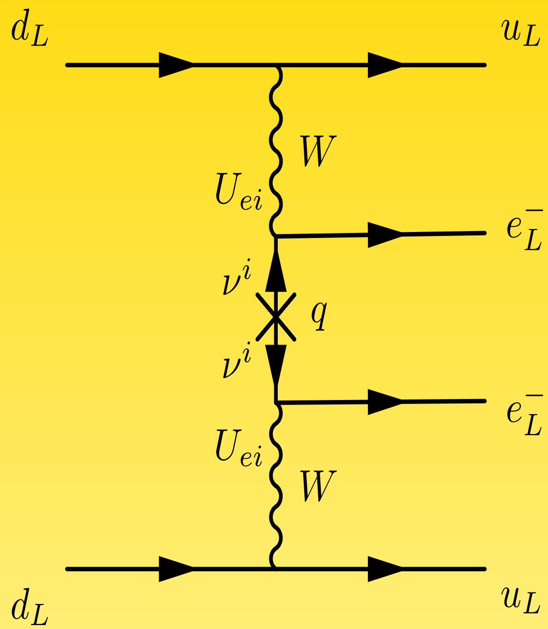


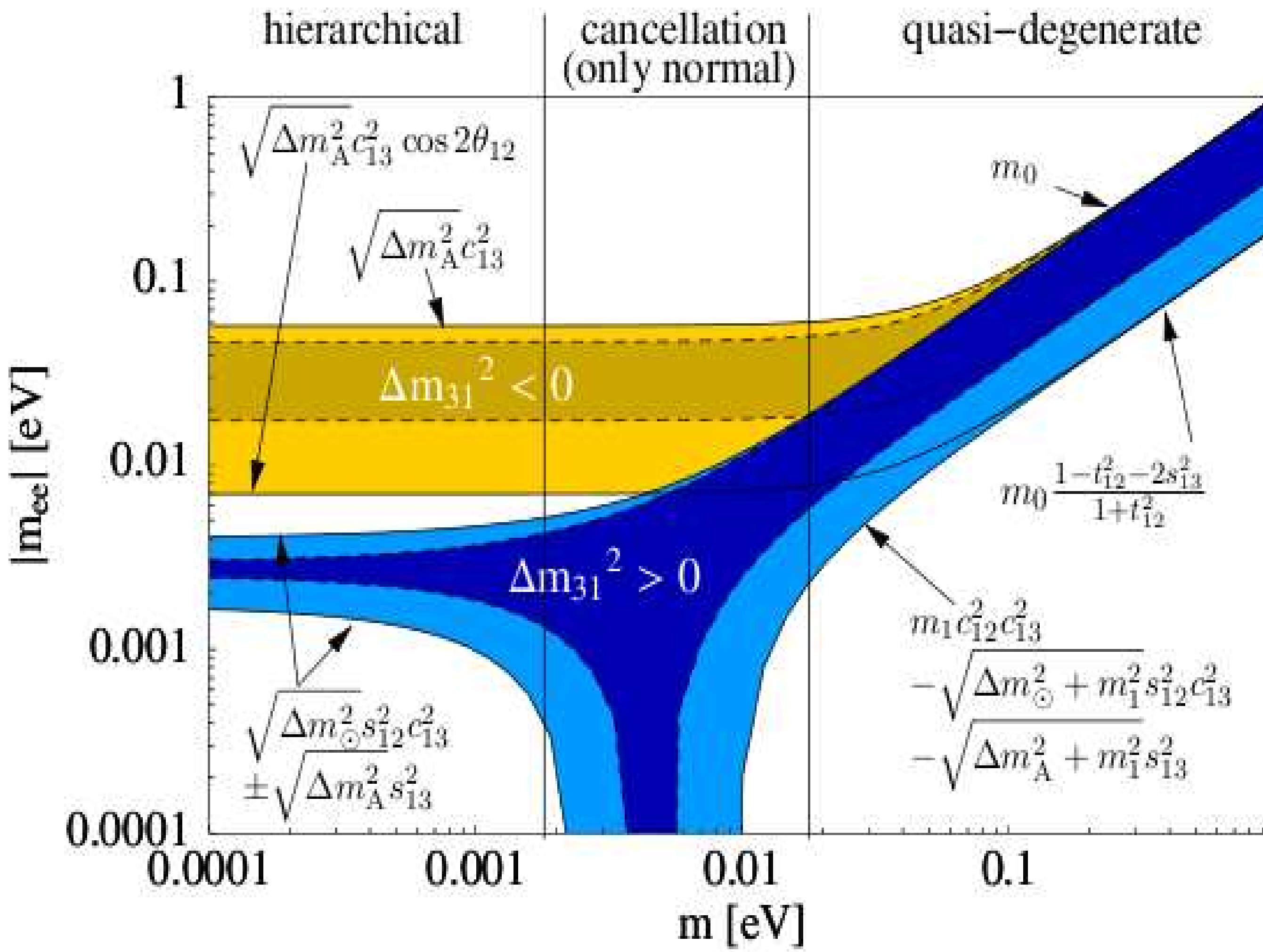
amplitude proportional to coherent sum **("effective mass")**

$$|m_{ee}| = \left|\sum U_{ei}^2\, m_i\right|$$

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

7 out of 9 parameters of neutrino physics!

The usual plot



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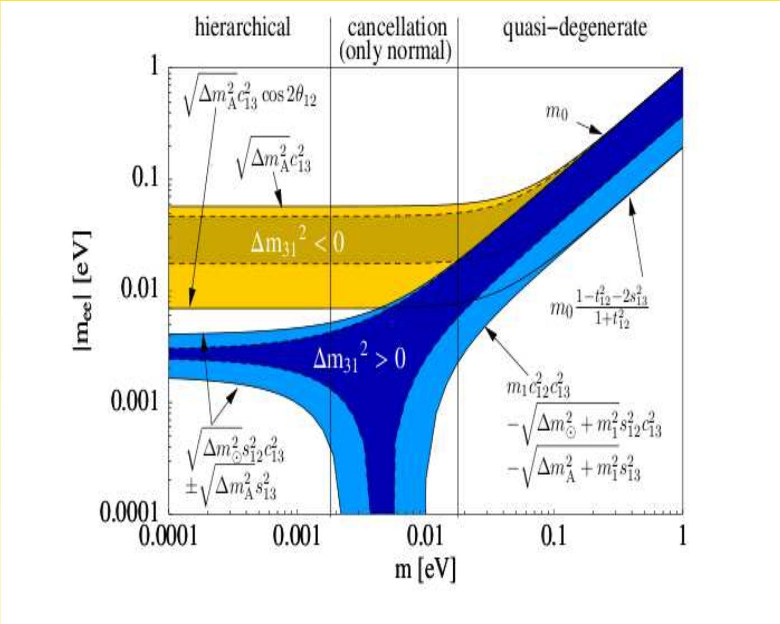
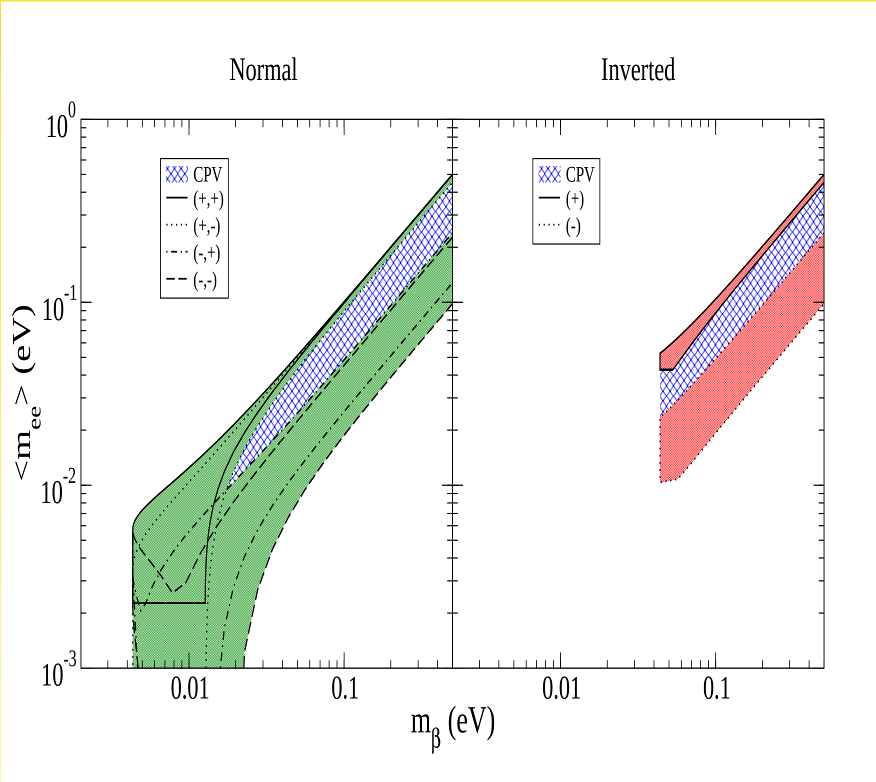
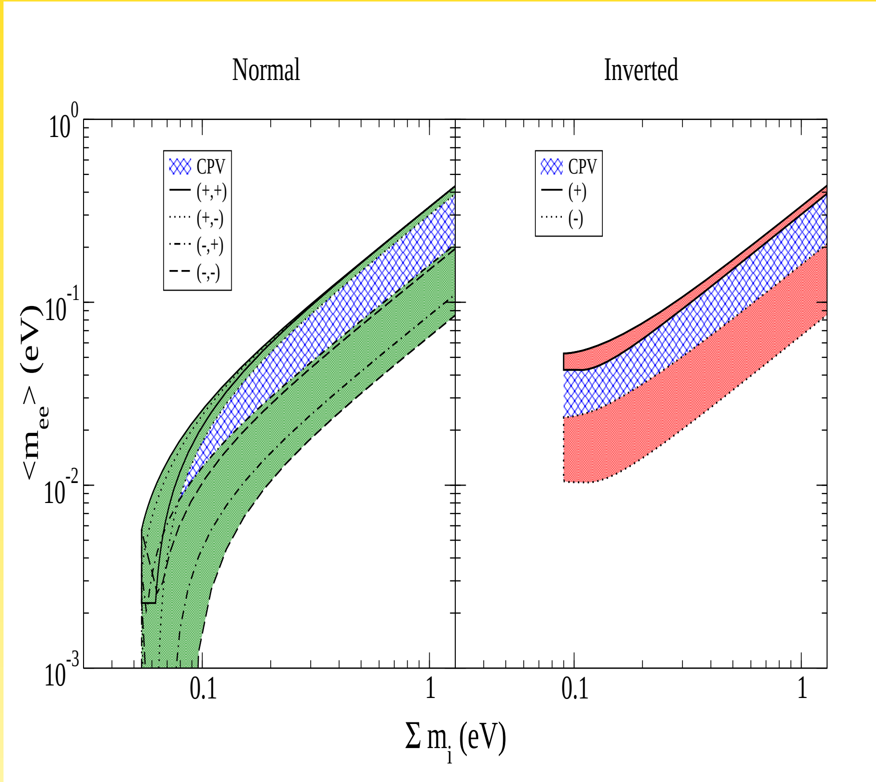


- lower limit on $|m_{ee}|^{\rm IH}_{\rm min}$ varies by factor 2 ($\leftrightarrow \theta_{12}$)
- $T_{1/2}^{0\nu} \propto 1/|m_{ee}|^2 \propto \sqrt{Mt}$
  $\Rightarrow 2 = 16$
- θ_{12} will be fixed in future by JUNO (`Shao-Feng Ge, W.R., 1507.05514`)

Plot against other observables





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

Outline

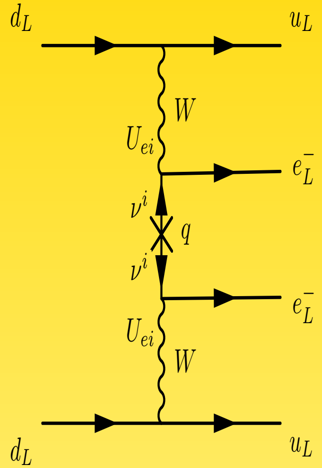
- Neutrinos and the Standard Model
- Lepton Flavor Symmetries
  - Residual Symmetries
  - CP
  - Higgs $\to \mu\tau$
- Lepton Number
  - How to generate m_ν
  - Neutrinoless Double Beta Decay: Neutrinos
  - **Neutrinoless Double Beta Decay: not Neutrinos**

Neutrinoless Double Beta Decay

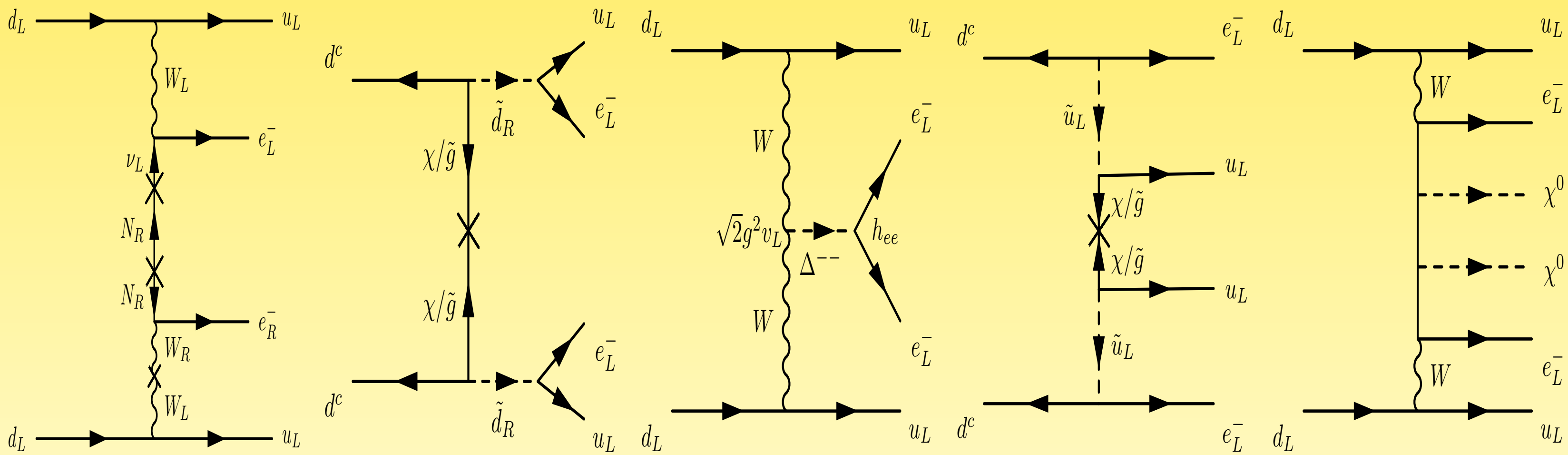
$(A,Z) \to (A,Z+2) + 2\,e^- \quad (0\nu\beta\beta) \Rightarrow$ Lepton Number Violation

- **Standard Interpretation** (neutrino physics)
- **Non-Standard Interpretations** (BSM $\neq$ neutrino physics)

- **Standard Interpretation:**



- **Non-Standard Interpretations:**



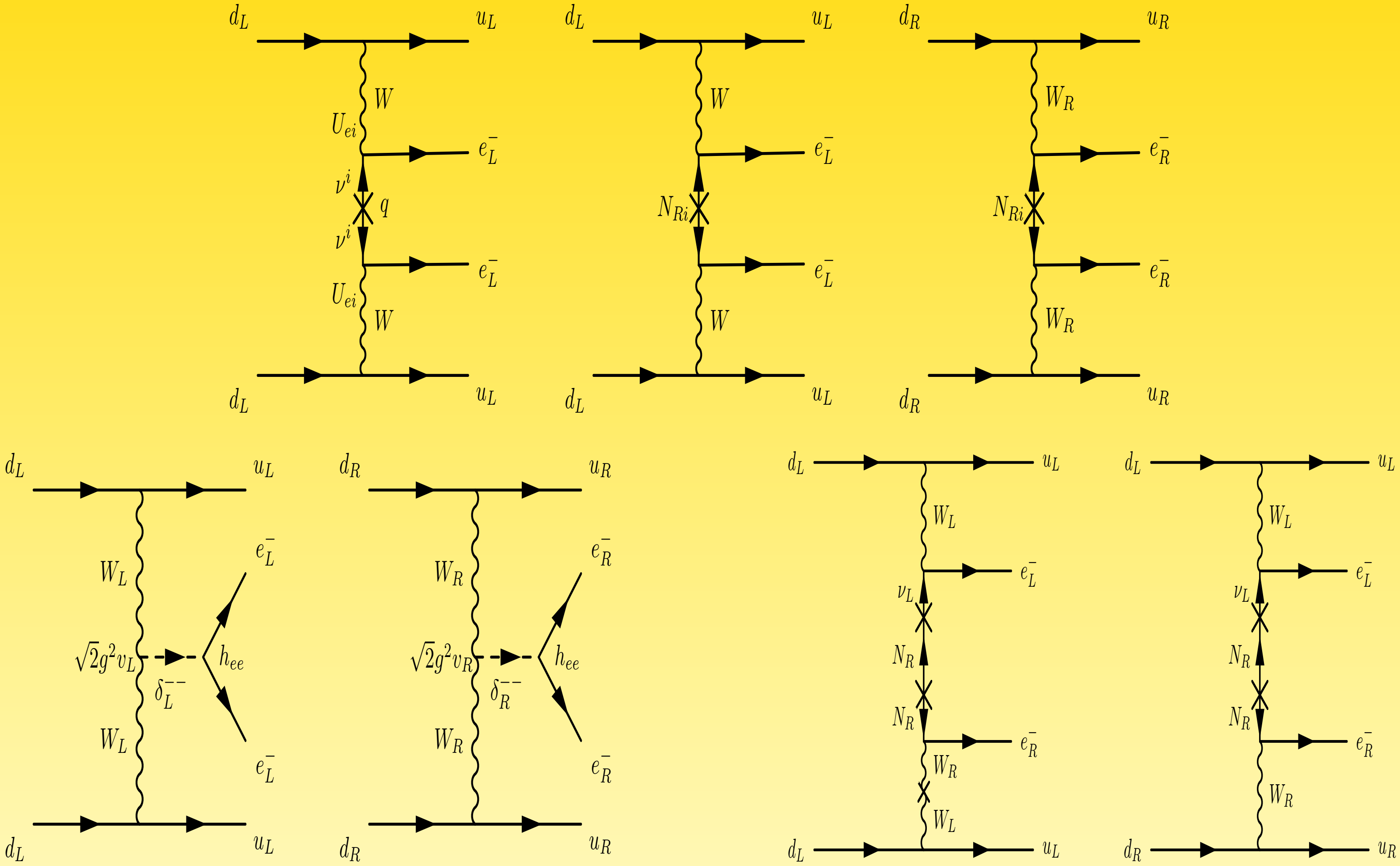
$$T^{0\nu}(1\ \mathrm{eV}) = T^{0\nu}(1\ \mathrm{TeV})$$

- RPV Supersymmetry
- left-right symmetry
- heavy neutrinos
- color octets
- leptoquarks
- effective operators
- extra dimensions
- ...

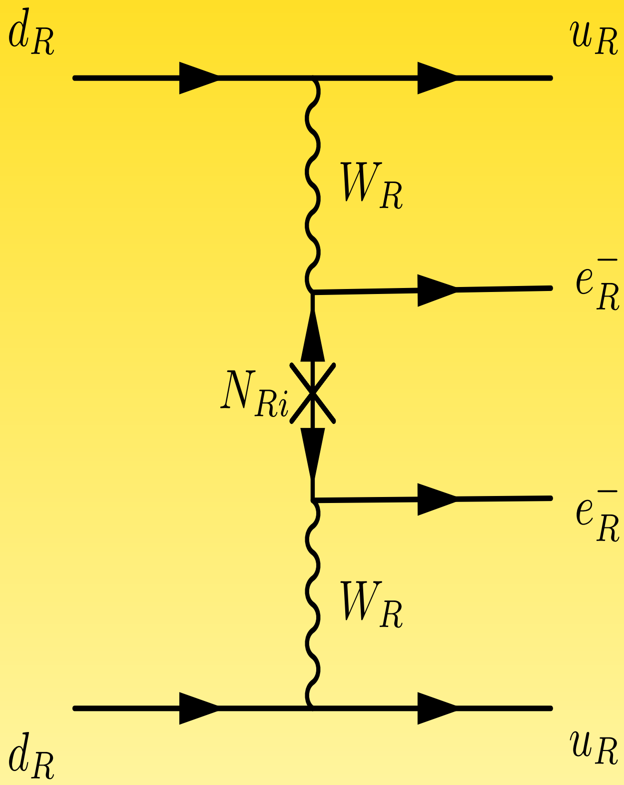
$\Rightarrow$ need to solve the inverse problem...

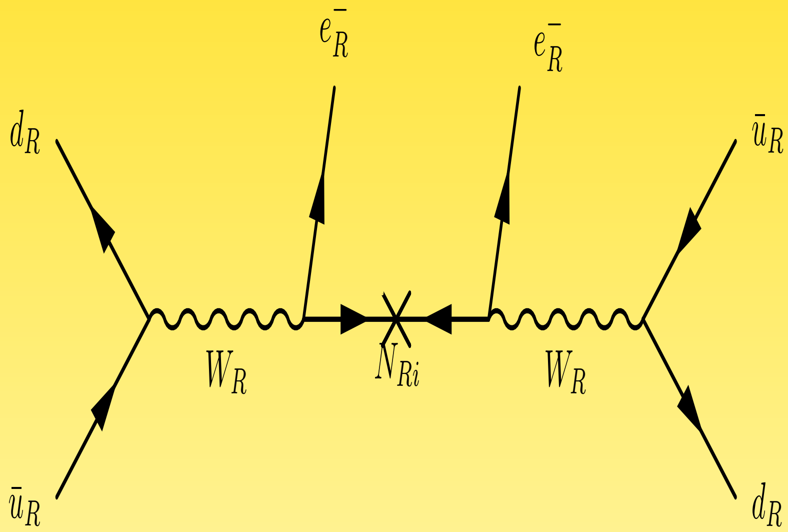
W.R., Int. J. Mod. Phys. E20 (2011) 1833-1930; Päs, W.R., 1507.00170

Left-right symmetry

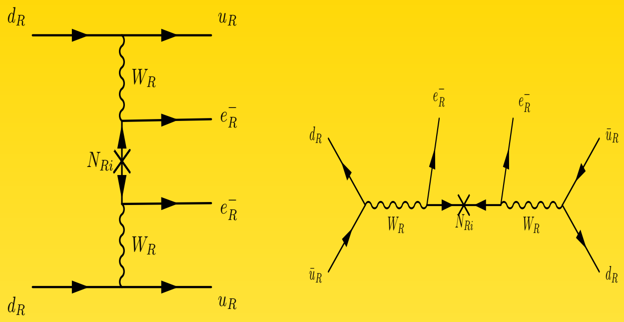


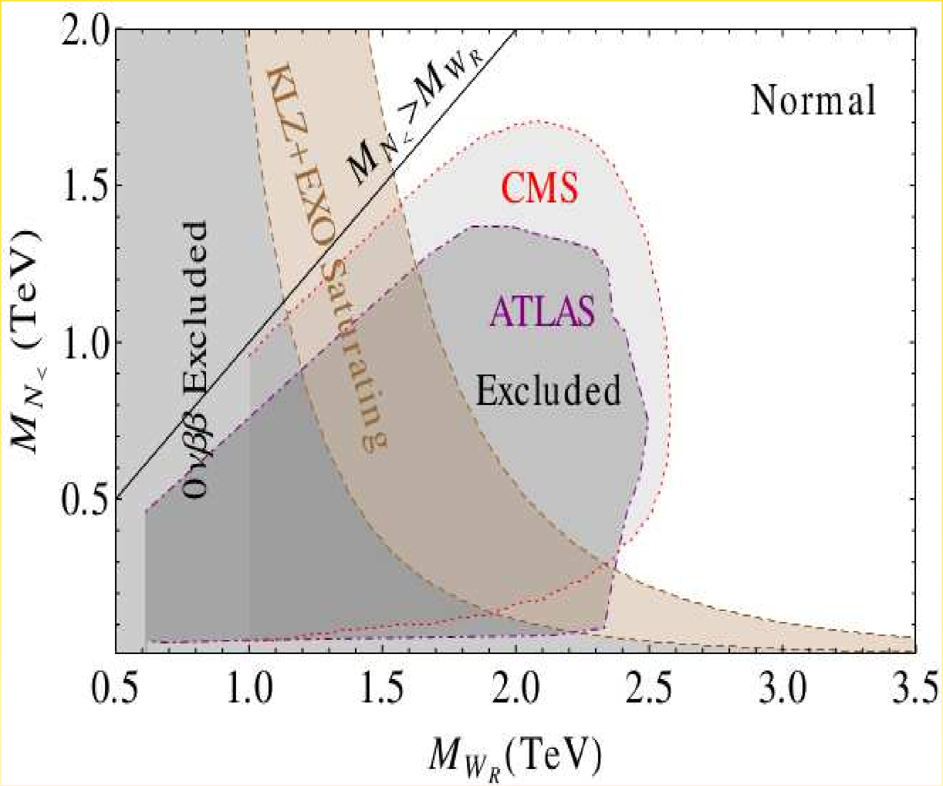
Left-right symmetry





Senjanovic, Keung, 1983; Tello *et al.*; Nemevsek *et al.*





Bhupal Dev, Goswami, Mitra, W.R., PRD88

Neues aus dem Sommerloch

various (local) hints around 2 TeV

- di-bosons, WW, **WZ**, ZZ in hadrons
- **WH**
- **di-jets**
- **eejj**

could be W_R with $\tan\zeta_{\rm LR} \simeq 0.002$ and $g_R/g_L \simeq 0.6$ (**Brehmer** *et al.*; 1507.00013) and Pseudo-Dirac N (Deppisch *et al.*, 1508.05940)

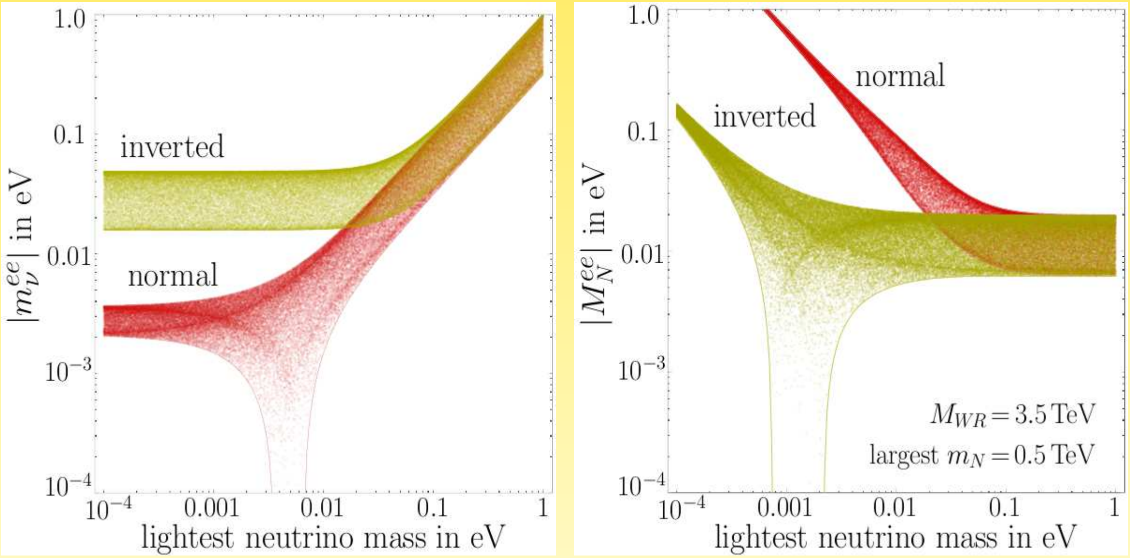
($g_R \neq g_L$: separating breaking of $SU(2)_R$ from discrete LR-symmetry)

Type II dominance (`Tello` *et al.*, `1011.3522`)

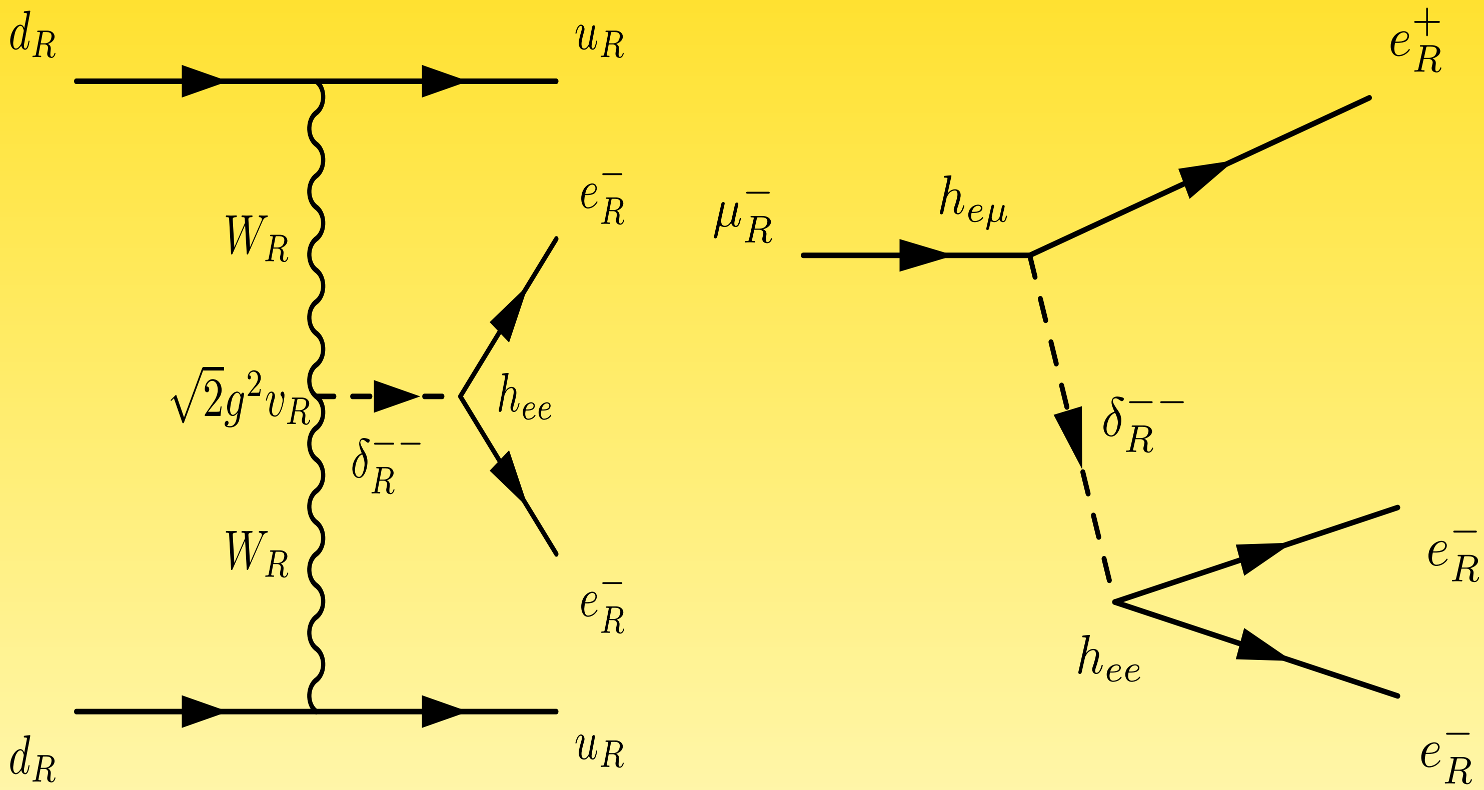
$$m_\nu = m_L - m_D\, M_R^{-1}\, m_D^T = v_L\, f - \frac{v^2}{v_R}\, Y_D\, f^{-1}\, Y_D^T \xrightarrow{*} v_L\, f$$

$\Rightarrow m_\nu$ fixes M_R and exchange of N_R with W_R fixed in terms of PMNS:

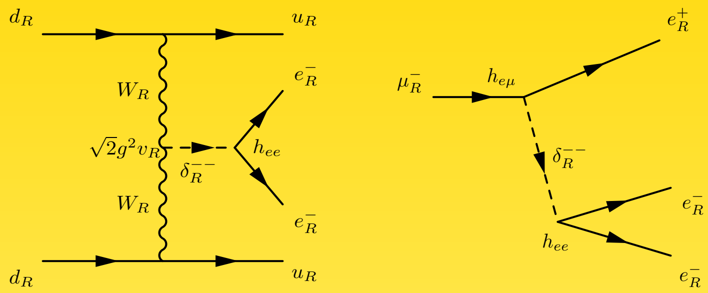
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$

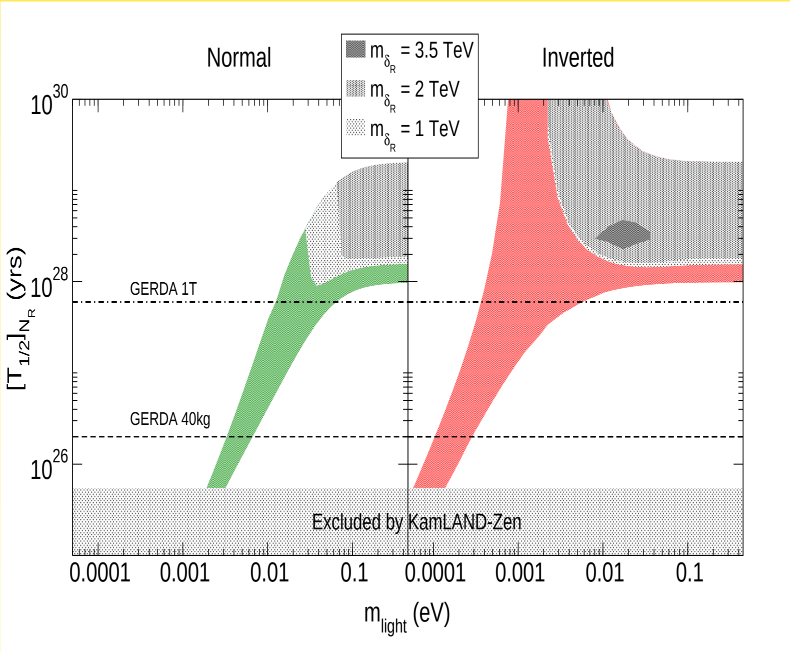


Constraints from Lepton Flavor Violation



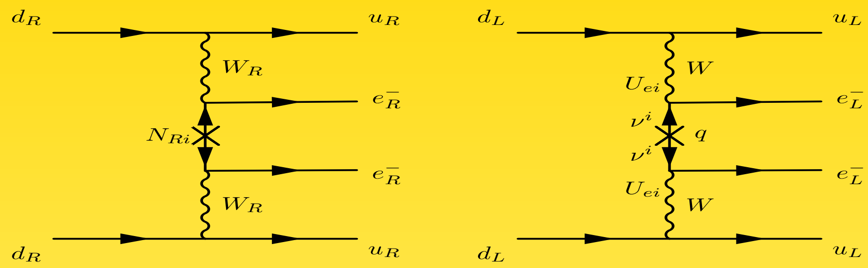
Constraints from Lepton Flavor Violation

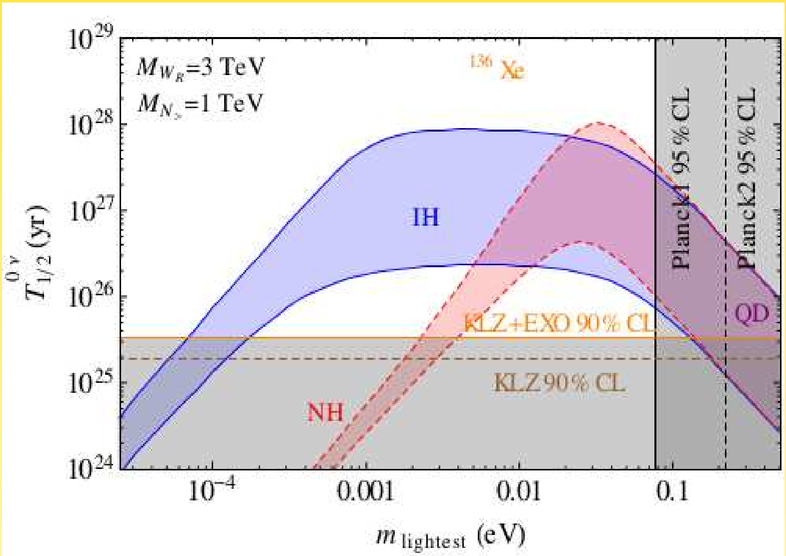




Barry, W.R., JHEP1309

Adding diagrams

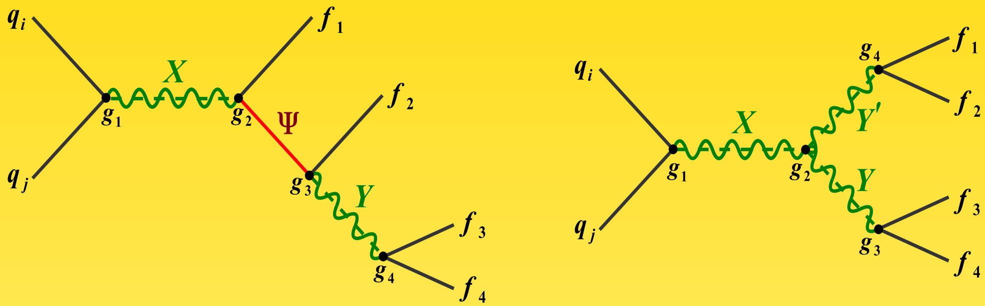




⇒ can vanish for IH! Lower bound on $m(\text{lightest}) \gtrsim$ meV!

Bhupal Dev, Goswami, Mitra, W.R., PRD88; Ge, Patra, Lindner, 1508.07286

Lepton Number Violation at the LHC and Leptogenesis



$$\sigma_{\mathsf{LHC}} = \frac{4\pi^2}{9s}(2J_X+1)\frac{\Gamma_X}{M_X} f_{q_1 q_2}\left(\frac{M_X}{\sqrt{s}}, M_X^2\right) \times \mathsf{Br}(X \to q_1 q_2)\mathsf{Br}(X \to 4f)$$

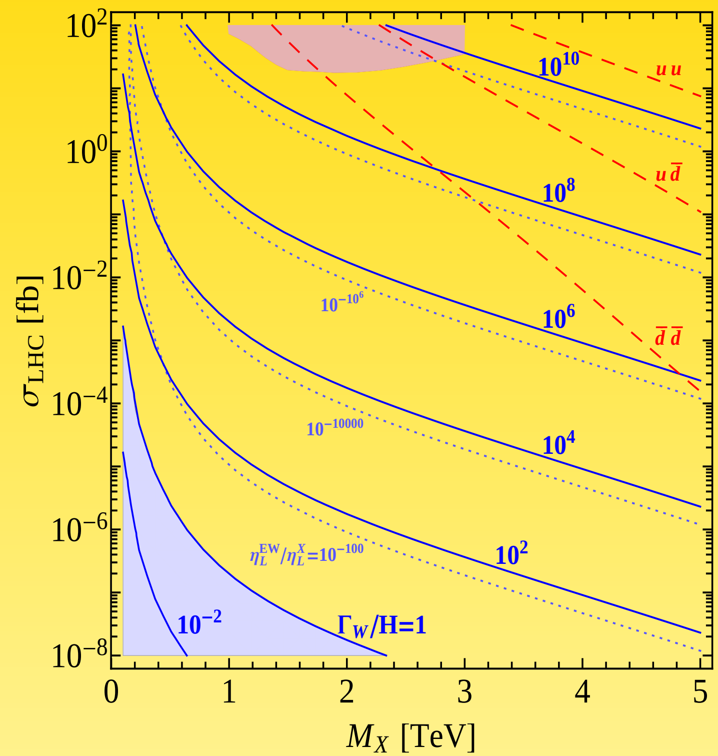
wash-out: $\Gamma_W(qq \leftrightarrow l^\pm l^\pm qq) = \frac{T}{32\pi^4 n_\gamma}\int_0^\infty ds\ s^{3/2}\sigma(s)K_1\left(\frac{\sqrt{s}}{T}\right)$

related via (suppression goes with $10^{-\Gamma_W}$!)

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

`Deppisch, Harz, Hirsch, PRL112`

Lepton Number Violation at the LHC and Leptogenesis



Deppisch, Harz, Hirsch, PRL112

- loopholes: low scale baryogenesis, hide everything in tau leptons,. . .
- example: $M(W_R) \gtrsim 18\,(3)$ TeV without (with) cancellation (Frere, Hambye, Vertonge, JHEP0901; Dev, Lee, Mohapatra, PRD90; Sarkar *et al.*, PRD92)

Summary

- CP?!
- mass scale?!
- Dirac/Majorana?!
- scale of mass generation?!
- new physics?!
  - sterile neutrinos?!
  - NSIs?!
  - extra forces?!
  - Lorentz invariance?!
  - ...?!

many ideas floating around, data will come in!

Combining Flavor and CP Symmetries

Example $G_f = S_4 \times$ CP broken to $G_\nu = S \times$ CP, $G_\ell = T$

$$S^2 = \mathbb{1}\ ,\ \ T^3 = \mathbb{1}\ ,\ \ U^2 = \mathbb{1}$$

$$(ST)^3 = \mathbb{1}\ ,\ \ (SU)^2 = \mathbb{1}\ ,\ \ (TU)^2 = \mathbb{1}\ ,\ \ (STU)^4 = \mathbb{1}$$

$\ell \sim \mathbf{3}'$, with $\mathbf{3}'$ irrep:

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix},\quad T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega^2 & 0 \\ 0 & 0 & \omega \end{pmatrix},\quad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$S m_\nu S = m_\nu$ and $X_{3'} m_\nu X_{3'} = m_\nu^*$, consistency is $X_{3'} S^* - S X_{3'} = 0$:

$$X_{\mathbf{3}'} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

gives $\delta = \pm\pi/2$ (Hagedorn, Feruglio, Ziegler, EPJC74)

Proof

G_ℓ and G_ν real symmetries, hence rotations R in 3-dim space; most general R which rotates the space around an axis $\mathbf{n} = (n_1,\, n_2,\, n_3)^T$ ($\mathbf{n}.\mathbf{n} = 1$) by angle ϕ:

$$R(\boldsymbol{n}, \phi) = \begin{pmatrix} n_1^2 + c\left(n_2^2 + n_3^2\right) & (1-c)n_1 n_2 + s n_3 & -s n_2 + (1-c) n_1 n_3 \\ (1-c) n_1 n_2 - s n_3 & c + n_2^2 - c n_2^2 & s n_1 + (1-c) n_2 n_3 \\ s n_2 + (1-c) n_1 n_3 & -s n_1 + (1-c) n_2 n_3 & c + n_3^2 - c n_3^2 \end{pmatrix}$$

diagonalized by $U_R^\dagger R U_R$ with $U_R = \begin{pmatrix} n_1 & -\frac{\sqrt{1-n_1^2}}{\sqrt{2}} & -\frac{\sqrt{1-n_1^2}}{\sqrt{2}} \\ n_2 & \frac{n_1 n_2 - i n_3}{\sqrt{2(1-n_1^2)}} & \frac{n_1 n_2 + i n_3}{\sqrt{2(1-n_1^2)}} \\ n_3 & \frac{i n_2 + n_1 n_3}{\sqrt{2(1-n_1^2)}} & \frac{n_1 n_3 - i n_2}{\sqrt{2(1-n_1^2)}} \end{pmatrix}$

has two columns conjugate to each other

property not different when multiplied with orthogonal matrix to the right

Example μ-τ reflection symmetry (Ma; Grimus, Lavoura)

defined as $\nu_e \to \nu_e^*$, $\nu_\mu \to \nu_\tau^*$, $\nu_\tau \to \nu_\mu^*$, gives

$$\tilde{M}_\nu = \begin{pmatrix} r_1 & z_1 & z_1^* \\ . & z_2 & r_2 \\ . & . & z_2^* \end{pmatrix}, \qquad \tilde{M}_\ell \tilde{M}_\ell^\dagger = \begin{pmatrix} m_e^2 & & \\ & m_\mu^2 & \\ & & m_\tau^2 \end{pmatrix}$$

rotate $M_\nu = U_\ell \tilde{M}_\nu U_\ell^T$ and $M_\ell M_\ell^\dagger = U_\ell \tilde{M}_\ell \tilde{M}_\ell^\dagger U_\ell^\dagger$

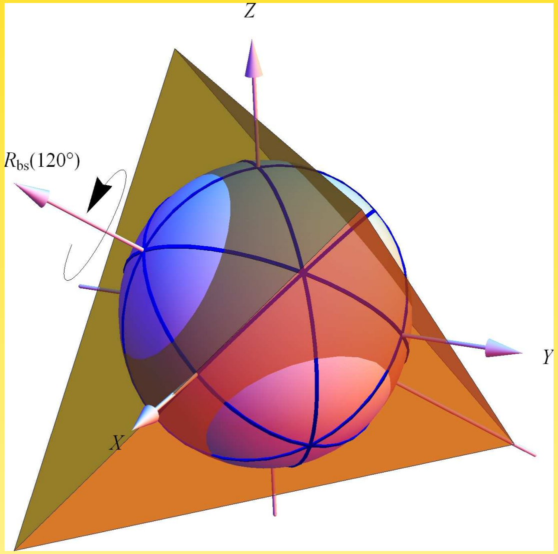
$$U_\ell = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{i}{\sqrt{2}} & \frac{i}{\sqrt{2}} \end{pmatrix}$$

gives real M_ν and $M_\ell M_\ell^\dagger$ diagonalized by real orthogonal R

$\Rightarrow \delta = \pm\pi/2$ and $\theta_{23} = \pi/4$

Symmetric PMNS Matrix?

"If an $SO(3)$ subgroup G is broken such that $G_\nu \sim Z_2 \times Z_2$ and G_ℓ bisects the $Z_2 \times Z_2$, then G generates a symmetric PMNS matrix."



$S_1 = S_x = \text{diag}(1, -1, -1)$,
$S_2 = S_y = \text{diag}(-1, 1, -1)$ and

$$R_{\text{bs}} = \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & 0 & 0 \end{pmatrix}$$

results in $U_\nu = \mathbb{1}$ and $U_\ell = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & \omega & \omega^2 \\ -1 & -\omega^2 & -\omega \\ 1 & 1 & 1 \end{pmatrix}$

`W.R., Xu, Phys. Rev. D91`

The Zoo (of A_4 models)

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
A1				-	[1–14] [15]$^{\#}$
A2	$\underline{3}$	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	-	$\underline{1}$, $\underline{1}'$, $\underline{1}''$, $\underline{3}$	[16–18]
A3				$\underline{1}$, $\underline{3}$	[19]
B1	$\underline{3}$	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	$\underline{3}$	-	[4, 20–27]$^{\#}$ [28–30]* [31–45]
B2				$\underline{1}$, $\underline{3}$	[46]$^{\#}$
C1				-	[2, 47, 48]
C2	$\underline{3}$	$\underline{3}$	-	$\underline{1}$	[49, 50] [51]$^{\#}$
C3				$\underline{1}$, $\underline{3}$	[52]
C4				$\underline{1}$, $\underline{1}'$, $\underline{1}''$, $\underline{3}$	[53]
D1				-	[54, 55]$^{\#}$ [56, 57]* [58]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[59] [60]*
D3				$\underline{1}'$	[61]*
D4				$\underline{1}'$, $\underline{3}$	[62]*
E	$\underline{3}$	$\underline{3}$	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	-	[63, 64]
F	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$	[65]
G	$\underline{3}$	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	-	[66]
H	$\underline{3}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	-	-	[67]
I	$\underline{3}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	-	[68]*
J	$\underline{3}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	$\underline{3}$	-	[12, 39, 69, 70]
K	$\underline{3}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	$\underline{1}$, $\underline{1}$	$\underline{1}$	[71]*
L	$\underline{3}$	$\underline{1}$, $\underline{1}$, $\underline{1}$	$\underline{1}$	-	[72]*
M	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	$\underline{1}$, $\underline{1}''$, $\underline{1}'$	$\underline{3}$, $\underline{1}$	-	[73, 74]
N	$\underline{1}$, $\underline{1}'$, $\underline{1}''$	$\underline{1}$, $\underline{1}''$, $\underline{1}'$	$\underline{3}$, $\underline{1}'$, $\underline{1}''$	-	[75]

Left-Right Symmetric Flavor Model:
$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times A_4 \times Z_2$

	A_4	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	Z_2
ℓ_L	3	2	1	-1	0
ℓ_R	3	1	2	-1	0
Φ	1	2	2	0	1
ϕ^ℓ	3	1	1	0	1
ϕ^ν	3	1	1	0	0
ξ	1	1	1	0	1
Δ_L	1	3	1	2	0
Δ_R	1	1	3	2	0

- LH and RH doublets and triplets transform identically
- even with (v', v', v'), $(v, 0, 0)$ alignment no conserved subgroups:

$$m_D = \kappa\, Y_1 + \kappa'\, Y_2$$

$$m_\ell = \kappa'\, Y_1 + \kappa\, Y_2$$

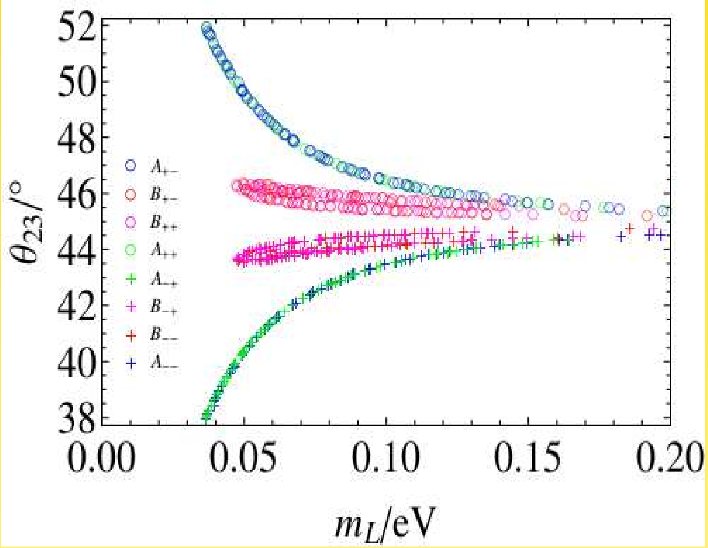
$\Rightarrow$ mixing depends on mass

W.R., Xu, 1509.03265

(used here parity as discrete LR symmetry, for charge conjugation: complications similar to CP + flavor)

Left-Right Symmetric Flavor Model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times A_4 \times Z_2$

	A_4	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	Z_2
ℓ_L	3	2	1	-1	0
ℓ_R	3	1	2	-1	0
Φ	1	2	2	0	1
ϕ^ℓ	3	1	1	0	1
ϕ^ν	3	1	1	0	0
ξ	1	1	1	0	1
Δ_L	1	3	1	2	0
Δ_R	1	1	3	2	0



$$M^\nu = \frac{m}{3(1+z)} \begin{pmatrix} 3+z & zr_2 & -zr_3 \\ . & \frac{z(2+z)r_2^2}{z-1} & \frac{(3+z-z^2)r_2 r_3}{z-1} \\ . & . & \frac{z(2+z)r_3^2}{z-1} \end{pmatrix}$$

Y_1 and Y_2 simultaneously diagonlizable: no FCNC from bi-doublet!

Residual Symmetries

Example $\Delta(96)$, 2 generators S and T with

$$S^2 = T^8 = (ST)^3 = (ST^{-1}ST)^3 = \mathbb{1}$$

can form subgroups $G_\nu = \left\{S,\, ST^4ST^4\right\}$ and $G_\ell = ST$ (Toorop, Feruglio, Hagedorn, PLB703)

$$U = \sqrt{\frac{1}{3}} \begin{pmatrix} \frac{1}{2}(\sqrt{3}+1) & 1 & \frac{1}{2}(\sqrt{3}-1) \\ \frac{1}{2}(\sqrt{3}-1) & 1 & \frac{1}{2}(\sqrt{3}+1) \\ 1 & 1 & 1 \end{pmatrix}$$

typically $\delta = 0, \pi$

(other groups, other residual symmetries allows other phases, as does CP)

See-Saw Scale

$$m_\nu = m_D^2/M_{13} \simeq v^2/M_{13}$$

with $m_\nu \simeq \sqrt{\Delta m_\mathrm{A}^2}$ it follows $M_{13} \simeq 10^{15}$ GeV and mixing

$$m_D/M_{13} = \sqrt{m_\nu/M_{13}} \simeq 10^{-13}$$

can make M_{13} TeV, but then mixing $\sqrt{m_\nu/M_{13}} \simeq 10^{-7}$

Note: not necessarily correct, m_D and M_{13} are matrices...

e.g. $m_D = v \begin{pmatrix} h_1 & h_2 & h_3 \\ \omega\, h_1 & \omega\, h_2 & \omega\, h_3 \\ \omega^2\, h_1 & \omega^2\, h_2 & \omega^2\, h_3 \end{pmatrix}$ and $M_{13} = M_0 \mathbb{1}$

gives $m_\nu = 0$, add (very) small corrections...

$m_D = v$, $M_{13} =$ TeV, mixing m_D/M_{13} large

Inverse Seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_{RS}^T \\ 0 & m_{RS} & M_{12} \end{pmatrix} \text{ with } m_{RS} \gg m_D \gg M_{12}$$

simply use seesaw calculations by identifying

$$\mathbb{M}_D := \begin{pmatrix} m_D \\ 0 \end{pmatrix}, \; \mathbb{M}_{13} := \begin{pmatrix} 0 & m_{RS}^T \\ m_{RS} & M_{12} \end{pmatrix} \Rightarrow \mathcal{M} = \begin{pmatrix} 0 & \mathbb{M}_D^T \\ \mathbb{M}_D & \mathbb{M}_{13} \end{pmatrix}$$

gives light neutrino mass matrix

$$m_\nu = m_D^T \, m_{RS}^{-1} \, M_{12} \, (m_{RS}^T)^{-1} \, m_D \simeq \left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2 \left(\frac{M_{12}}{0.1\,\mathrm{keV}}\right) \mathrm{eV}$$

and unitarity violation $N = U\,(1+\eta)$

$$\eta \simeq -\frac{1}{2} m_D^\dagger \, (m_{RS}^*)^{-1} \, (m_{RS}^T)^{-1} \, m_D \simeq 10^{-2} \left(\frac{m_D}{10^2\,\mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2$$

Inverse Seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_{RS}^T \\ 0 & m_{RS} & M_{12} \end{pmatrix} \text{ with } m_{RS} \geq m_D \gg M_{12}$$

gives light neutrino mass matrix

$$m_\nu = m_D^T \, m_{RS}^{-1} \, M_{12} \, (m_{RS}^T)^{-1} \, m_D \simeq \left(\frac{m_D}{10^2 \, \mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2 \left(\frac{M_{12}}{0.1 \, \mathrm{keV}}\right) \mathrm{eV}$$

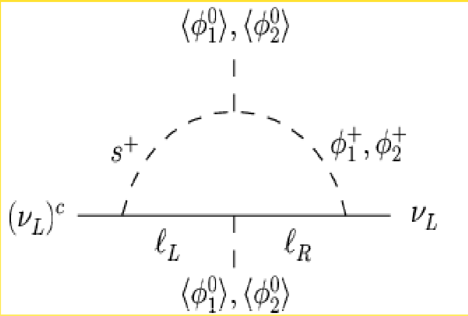
and unitarity violation $N = U \, (1 + \eta)$

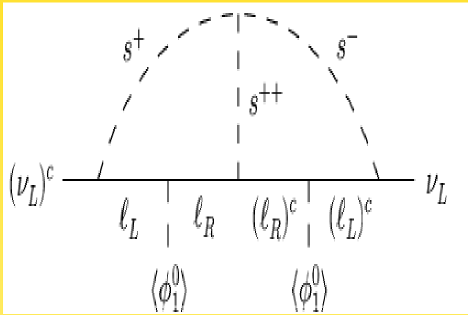
$$\eta \simeq -\frac{1}{2} m_D^\dagger \, (m_{RS}^*)^{-1} \, (m_{RS}^T)^{-1} \, m_D \simeq 10^{-2} \left(\frac{m_D}{10^2 \, \mathrm{GeV}}\right)^2 \left(\frac{\mathrm{TeV}}{m_{RS}}\right)^2$$

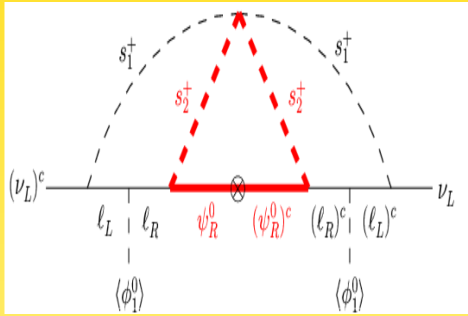
- sizable unitarity violation through moderate mass hierarchy in mass matrix
- light neutrino mass small because of $M_{12} \to 0$

a) radiative mechanisms

can be bought coming with 1, 2 or 3 loops







Zee	Zee-Babu	Krauss-Nasri-Trodden
1-loop	2-loop	3-loop

E.g., Zee-Babu model has

$$m_\nu \simeq \frac{y^3}{(16\pi^2)^2}\frac{\mu\, m_\tau^2}{M^2} \simeq 0.06\left(\frac{y}{0.05}\right)^3\left(\frac{\mu}{100\,\mathrm{GeV}}\right)\left(\frac{500\,\mathrm{GeV}}{M}\right)^2 \mathrm{eV}$$

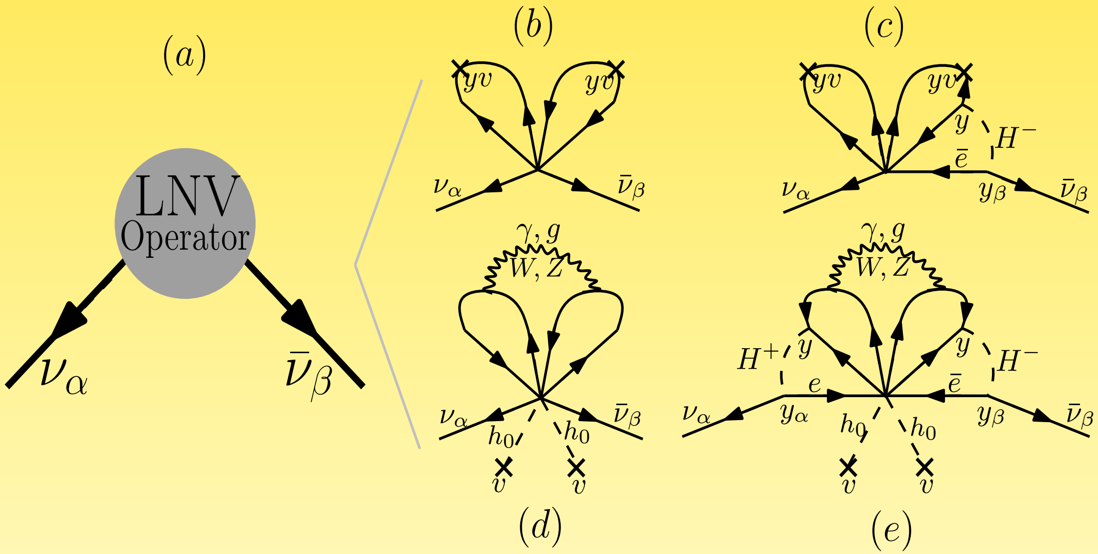
			ψ_R^0	s^0	s^+	s^{++}	Φ_2	Δ
		Spin	1/2	0	0	0	0	0
		$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$
		$U(1)_Y$	0	0	1	2	1/2	1
Majorana ν	Zee Model [4]	1-loop			✓		✓	
	Zee-Babu Model [5]	2-loop			✓	✓		
	Ma Model [6]	1-loop	†				†	
	Krauss-Nasri-Trodden Model [7]	3-loop	†		✓ †			
	Aoki-Kanemura-Seto Model [8]	3-loop	†	†	†		✓	
	Gustafsson-No-Rivera Model [9]	3-loop			†	✓	†	
	Kanemura-Sugiyama Model [10]	1-loop			✓ †		†	✓
Dirac ν	Nasri-Moussa Model [11]	1-loop	✓		✓ ✓			
	Gu-Sarkar Model [12]	1-loop	✓ † †	✓ †			†	
	Kanemura-Matsui-Sugiyama Model [13]	1-loop	✓	✓ †			✓ †	

Sugiyama, 1505.01738

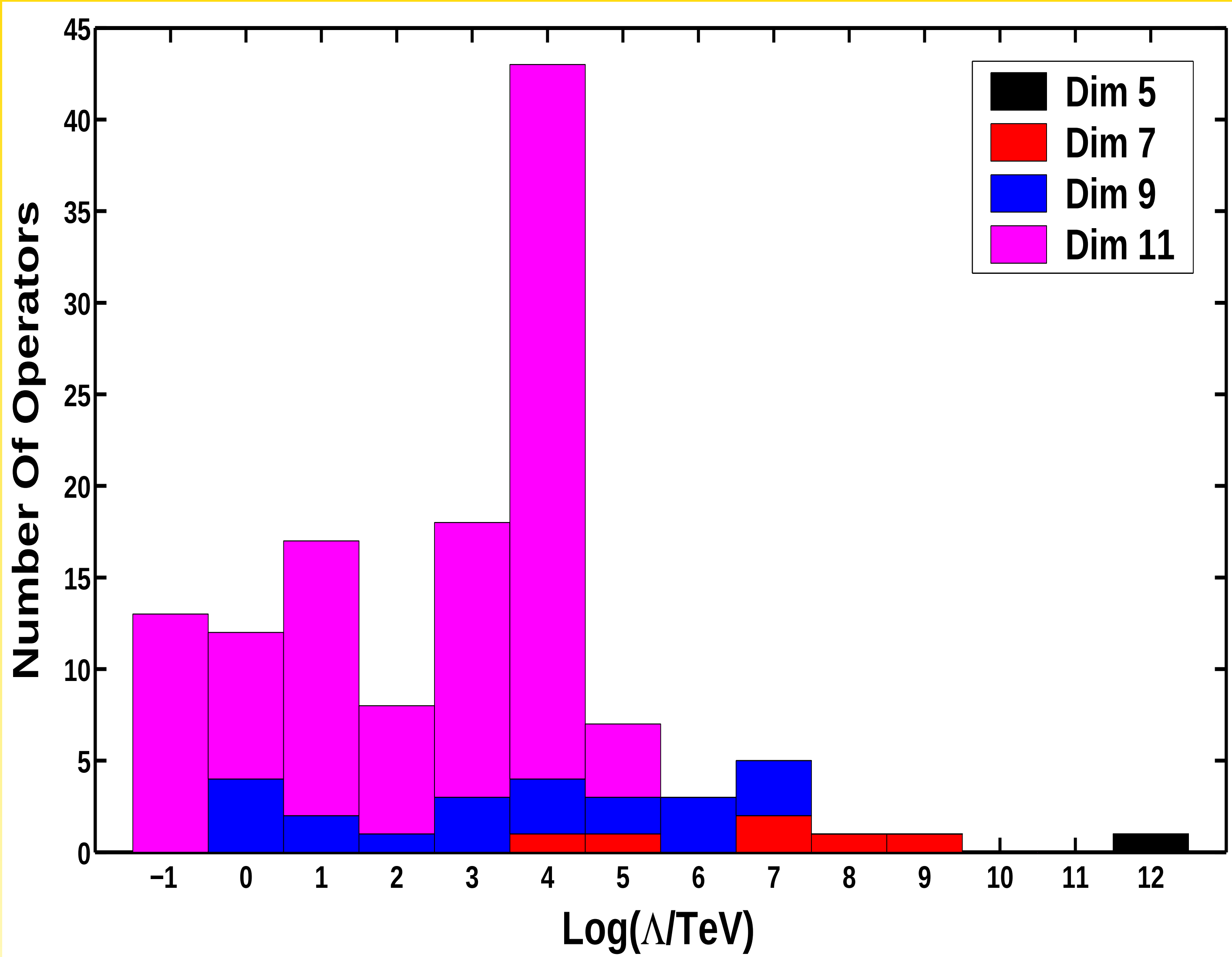
higher dimensional operators

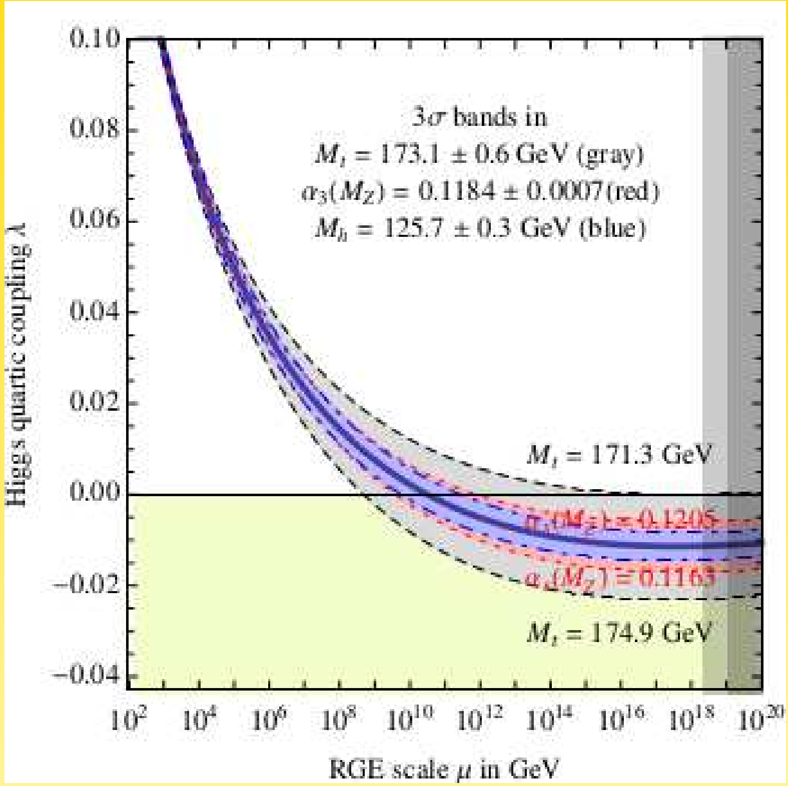
There are 129 higher-dimensional operators up to dimension 11..., e.g.

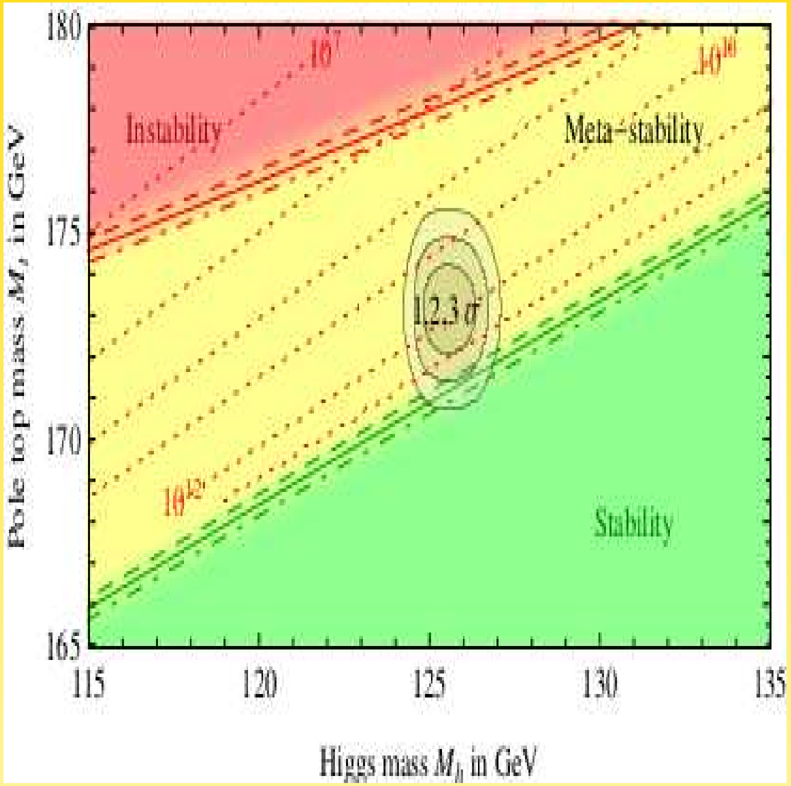
- $\mathcal{L}_7 = LLLe^cH/\Lambda^3 \Rightarrow m_\nu = v^2/\Lambda\, y_\ell/(16\pi^2) \Rightarrow \Lambda \simeq 10^{10}$ GeV
- $\mathcal{L}_9 = LLQd^cQd^c/\Lambda^5 \Rightarrow m_\nu = v^2/\Lambda\, y_d^2/(16\pi^2)^2 \Rightarrow \Lambda \simeq 10^{10}$ GeV (b)
- $\mathcal{L}_9 = LQd^cd^ce^cu^c/\Lambda^5 \Rightarrow m_\nu = v^2/\Lambda\, y_d^2 y_u y_\ell/(16\pi^2)^3 \Rightarrow \Lambda \simeq 10^3$ GeV (c)
- $\mathcal{L}_{11} = LLLe^cLe^cHH/\Lambda^7 \Rightarrow m_\nu = v^2/\Lambda\, g^2/(16\pi^2)^3 \Rightarrow \Lambda \simeq 10^7$ GeV (d)



Babu, Leung NPB **619**; deGouvea, Jenkins, PRD **77**


Number Of Operators
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
45
40
35
30
25
20
15
10
5
0
−1
0
1
2
3
4
5
6
7
8
9
10
11
12





Elias-Miro *et al.*, JHEP **1208**

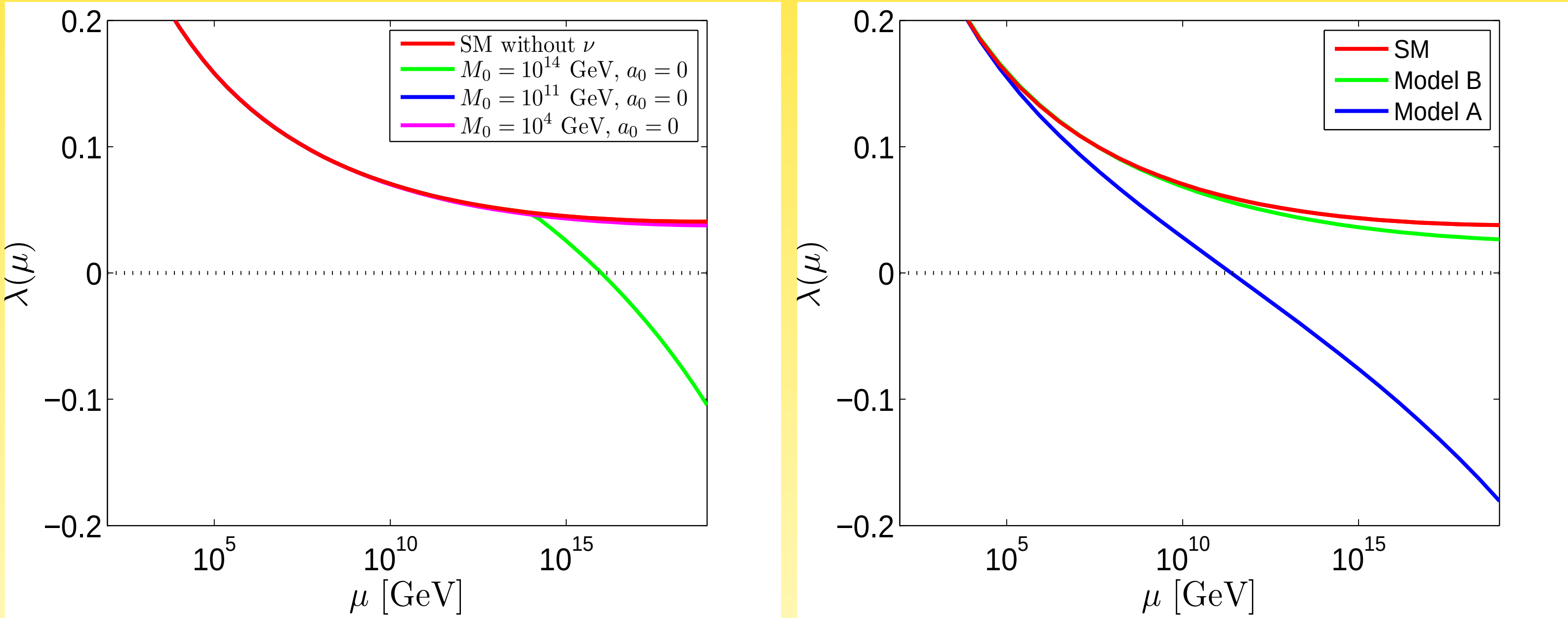
Phenomenology of heavy singlets: Higgs

often overlooked: Dirac $\bar{L}\,\Phi\,N_{13}$ contribution to λ:

$$\Delta\beta_\lambda \propto -8\,m_D^4$$

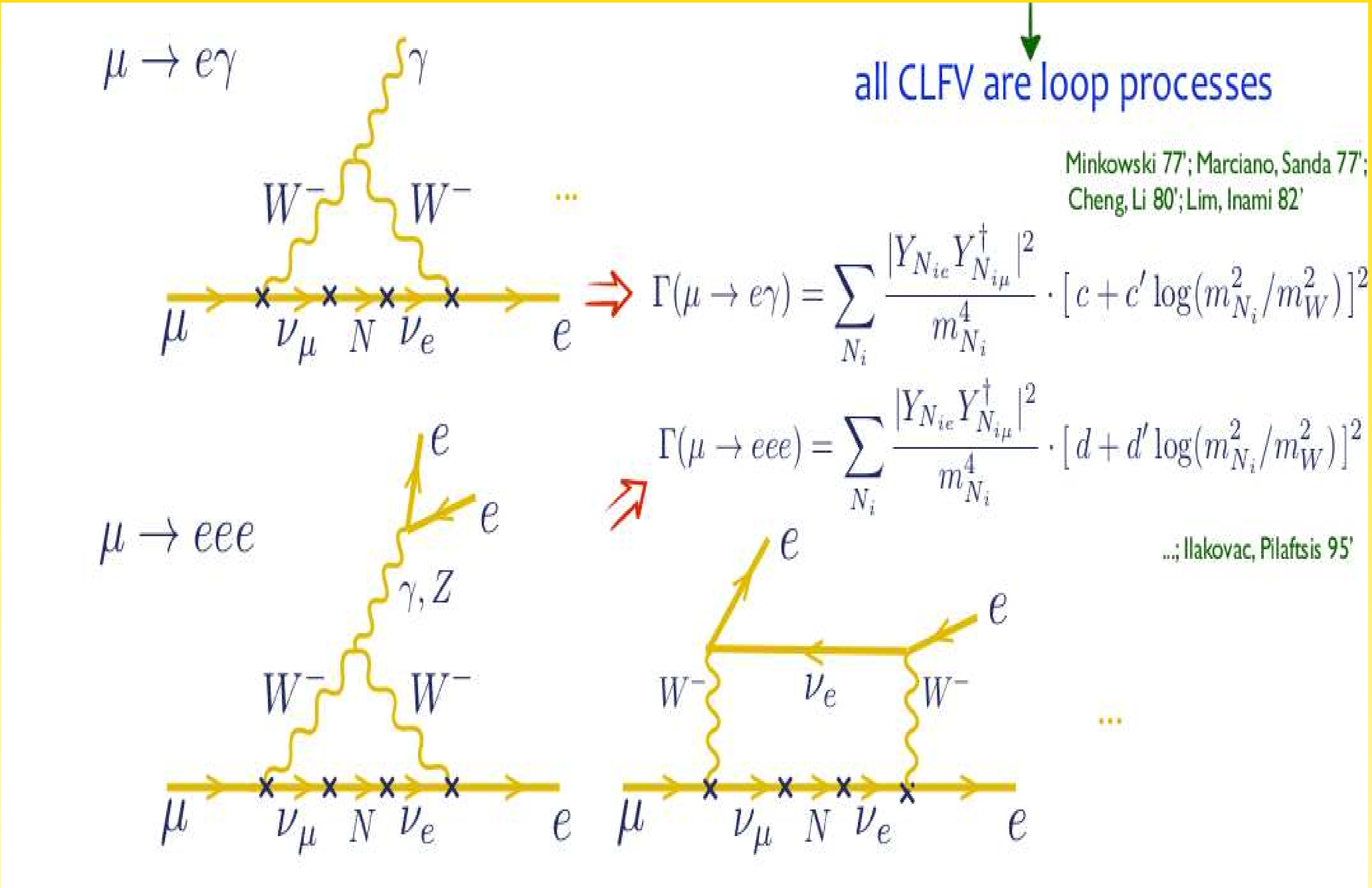
Casas *et al.*; Strumia *et al.*; W.R., Zhang

makes vacuum stability condition worse!



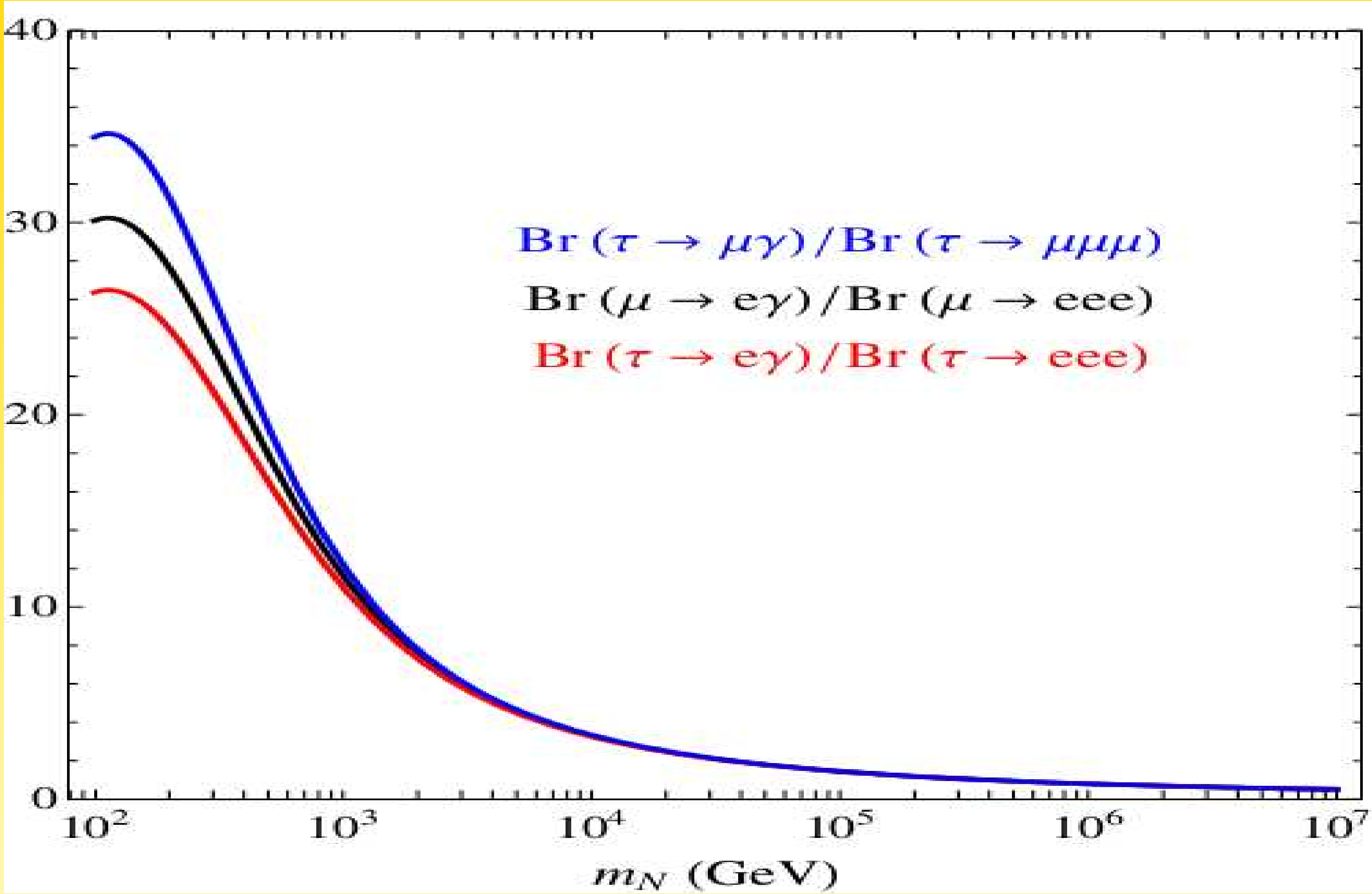
also for neutrinos at TeV scale when producable at colliders!

Lepton Flavor Violation Type I



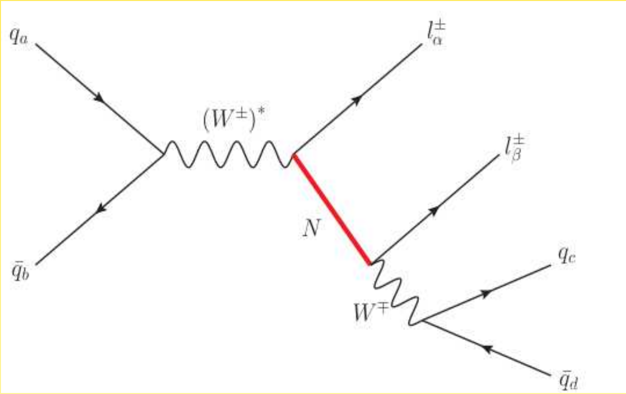
slide by Thomas Hambye

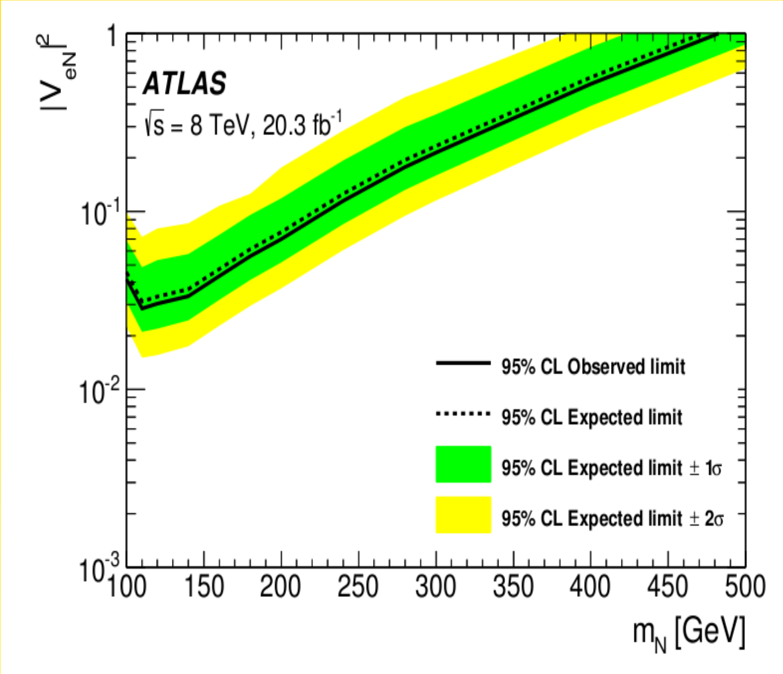
Lepton Flavor Violation Type I



Chu, Dhen, Hambye, JHEP **1111**

LHC Type I

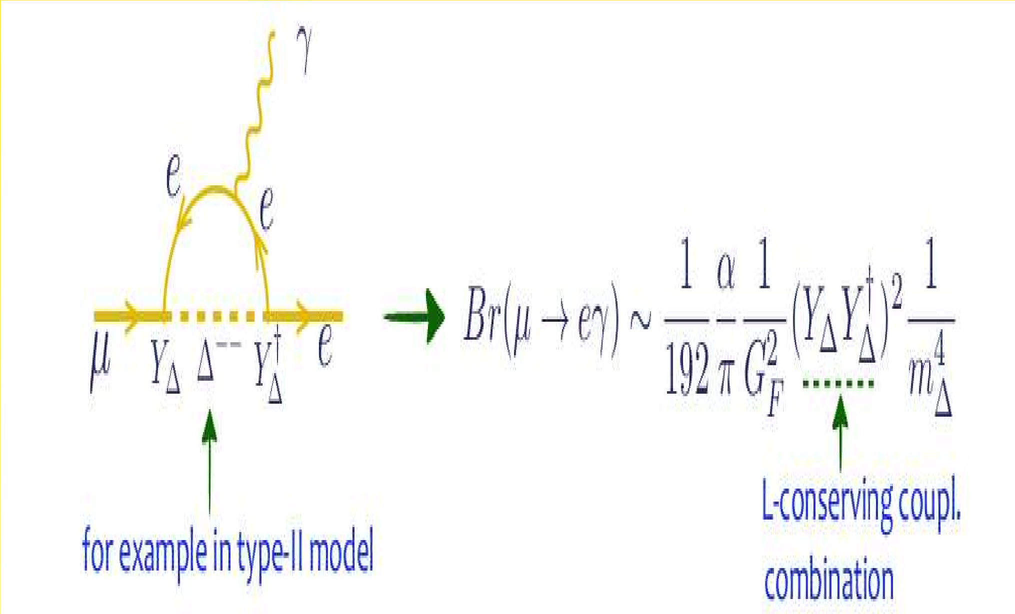


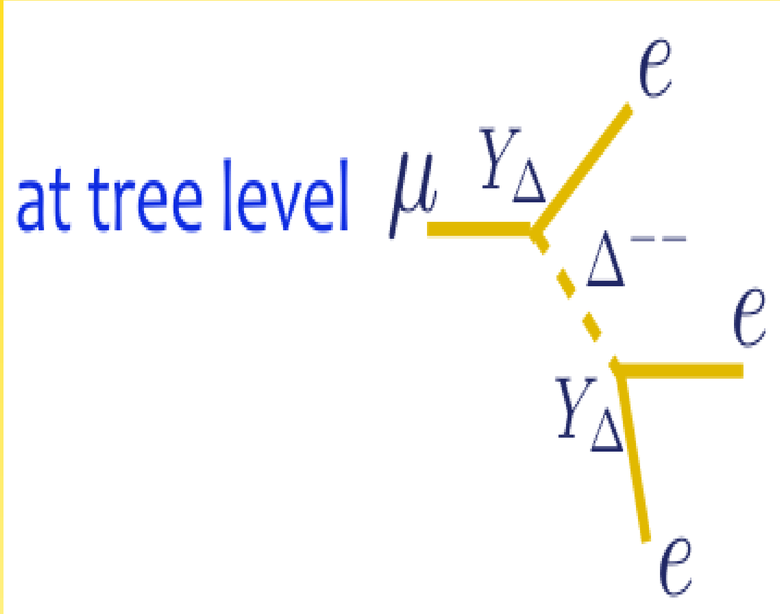


ATLAS, 1506.06020

Lepton Flavor Violation Type II

(minimal flavor violation...)





$$\frac{\mathrm{BR}(\tau \to e\gamma)}{\mathrm{BR}(\tau \to \mu\gamma)} \sim \frac{\mathrm{BR}(\mu \to e\gamma)}{\mathrm{BR}(\tau \to \mu\gamma)} \propto \frac{|(m_\nu m_\nu^\dagger)_{12}|^2}{|(m_\nu m_\nu^\dagger)_{23}|^2} \simeq \frac{|U_{e3}|^2}{\cos^2\theta_{23}}$$

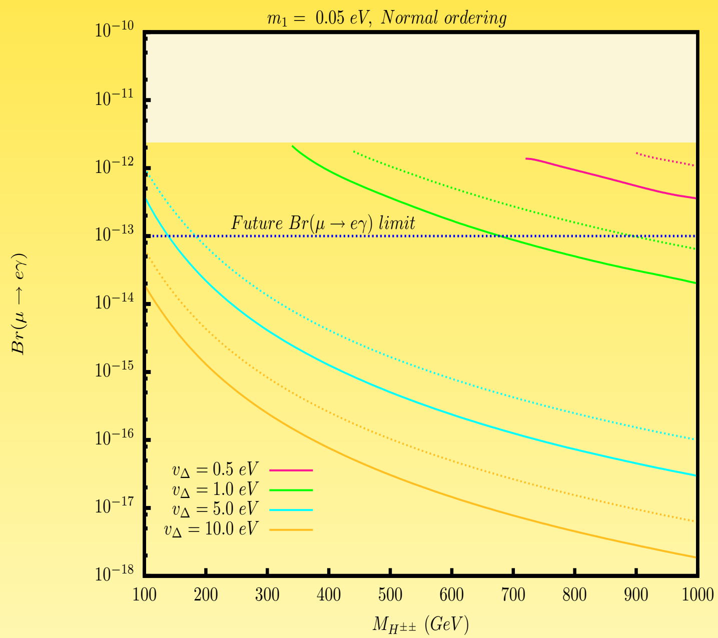
$$\mathrm{BR}(\mu \to 3e) \propto |(m_\nu)_{ee}|^2 \, |(m_\nu)_{e\mu}|^2$$

Lepton Flavor Violation Type II

$\mathrm{BR}(\mu \to e\gamma) \propto |(m_\nu m_\nu^\dagger)_{e\mu}|^2$ can vanish for

$$|U_{e3}| = \frac{1}{2}\,\frac{R\,\sin 2\theta_{12}\,\cot\theta_{23}}{1 \mp R\,\sin^2\theta_{12}} \simeq 0.014$$

$\Rightarrow$ for larger U_{e3} the decay is guaranteed!! $\Rightarrow$ lower bound!

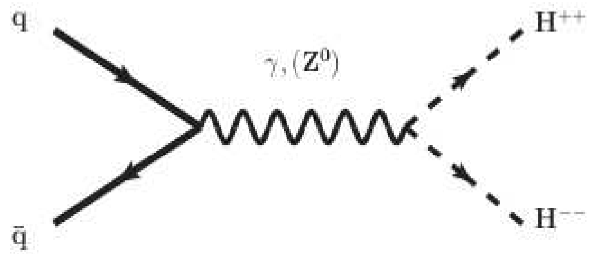


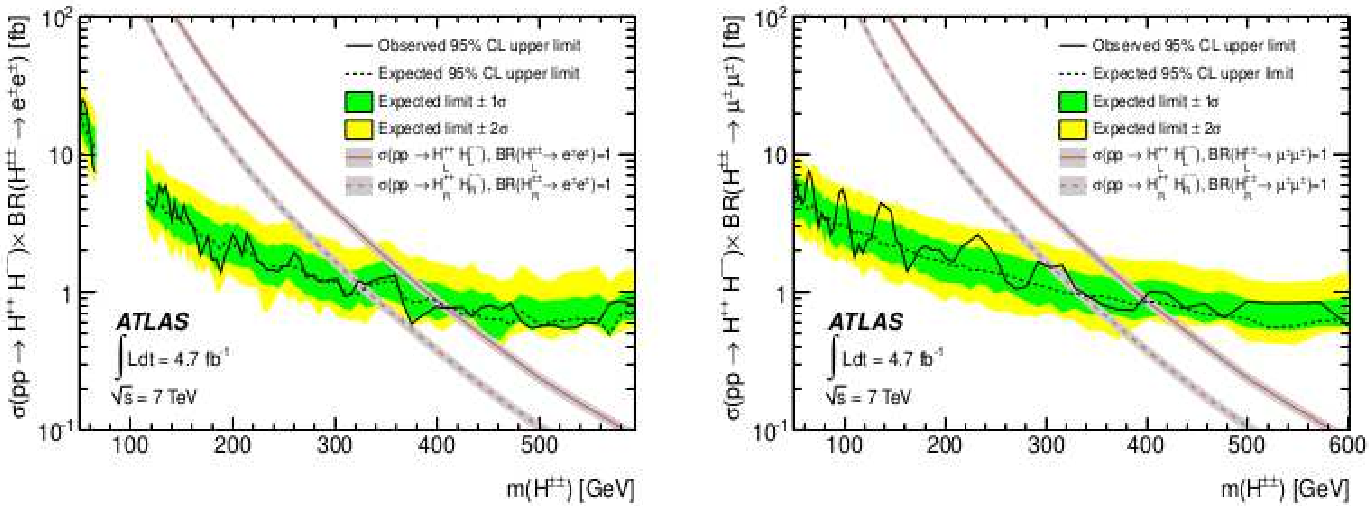
Chakrabortty, Ghosh, W.R., Phys. Rev. **D86**

LHC Type II

Pair production of doubly charged scalar:

Decay: $H^{++} \to l^+ l^+$





$\Rightarrow$ To the left: Br$(H^{++}H^{--} \to e^+e^+e^-e^-) = 1$,

to the right: Br$(H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-) = 1$

Not realistic!

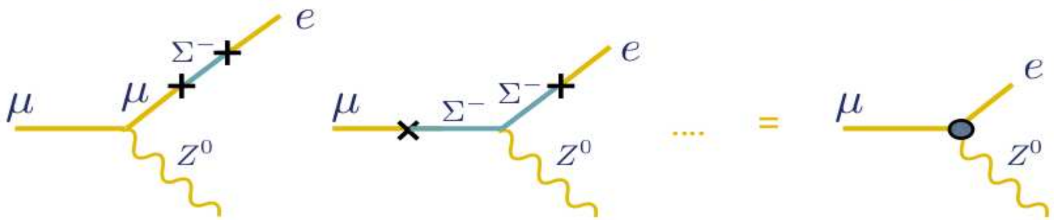
If related to m_ν

Br$(H^{++} \to e^+\mu^+) \neq 0$

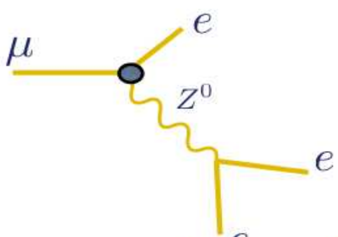
slide by Martin Hirsch

Lepton Flavor Violation Type III

crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states



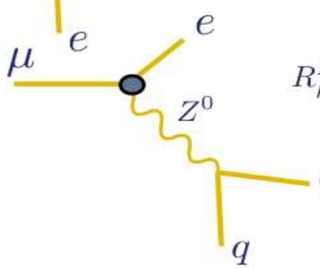
⇒ $\mu \to eee$: tree level



$$\Gamma(\mu \to eee) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^{\dagger}_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot d^2$$

Abada, Biggio, Bonnet, Gavela, TH 07', 08'

$\mu \to e$ conversion : tree level

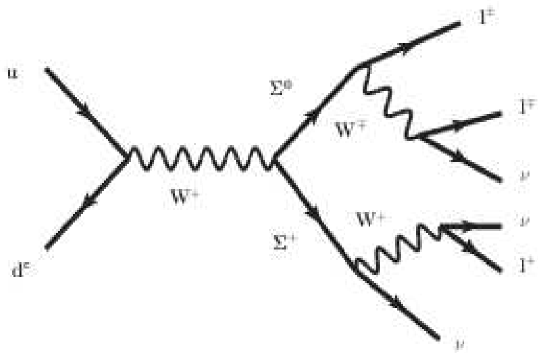


$$R^N_{\mu\to e} = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^{\dagger}_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot (b^N)^2$$

$$Br(\mu \to e\gamma) = 1.3 \cdot 10^{-3} \cdot Br(\mu \to eee) = 3.1 \cdot 10^{-4} \cdot R^{\mu\to e}_{Ti}$$
$$Br(\tau \to \mu\gamma) = 1.3 \cdot 10^{-3} \cdot Br(\tau \to \mu\mu\mu) = 2.1 \cdot 10^{-3} \cdot Br(\tau^- \to e^- e^+ \mu^-)$$
$$Br(\tau \to e\gamma) = 1.3 \cdot 10^{-3} \cdot Br(\tau \to eee) = 2.1 \cdot 10^{-3} \cdot Br(\tau^- \to \mu^- \mu^+ e^-)$$

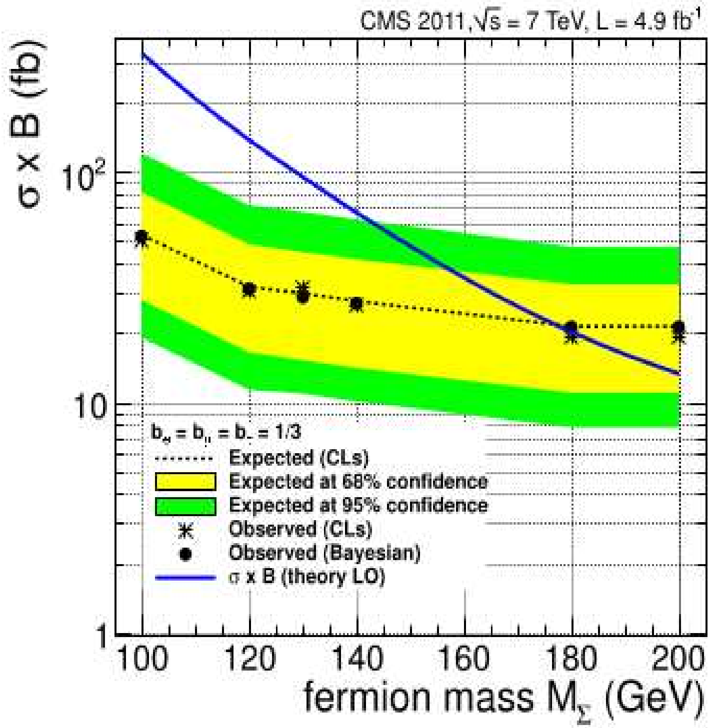
LHC Type III

Production:



⇒ Plot assumes:

Br(e)=Br(μ)=Br(τ)=$1/3$



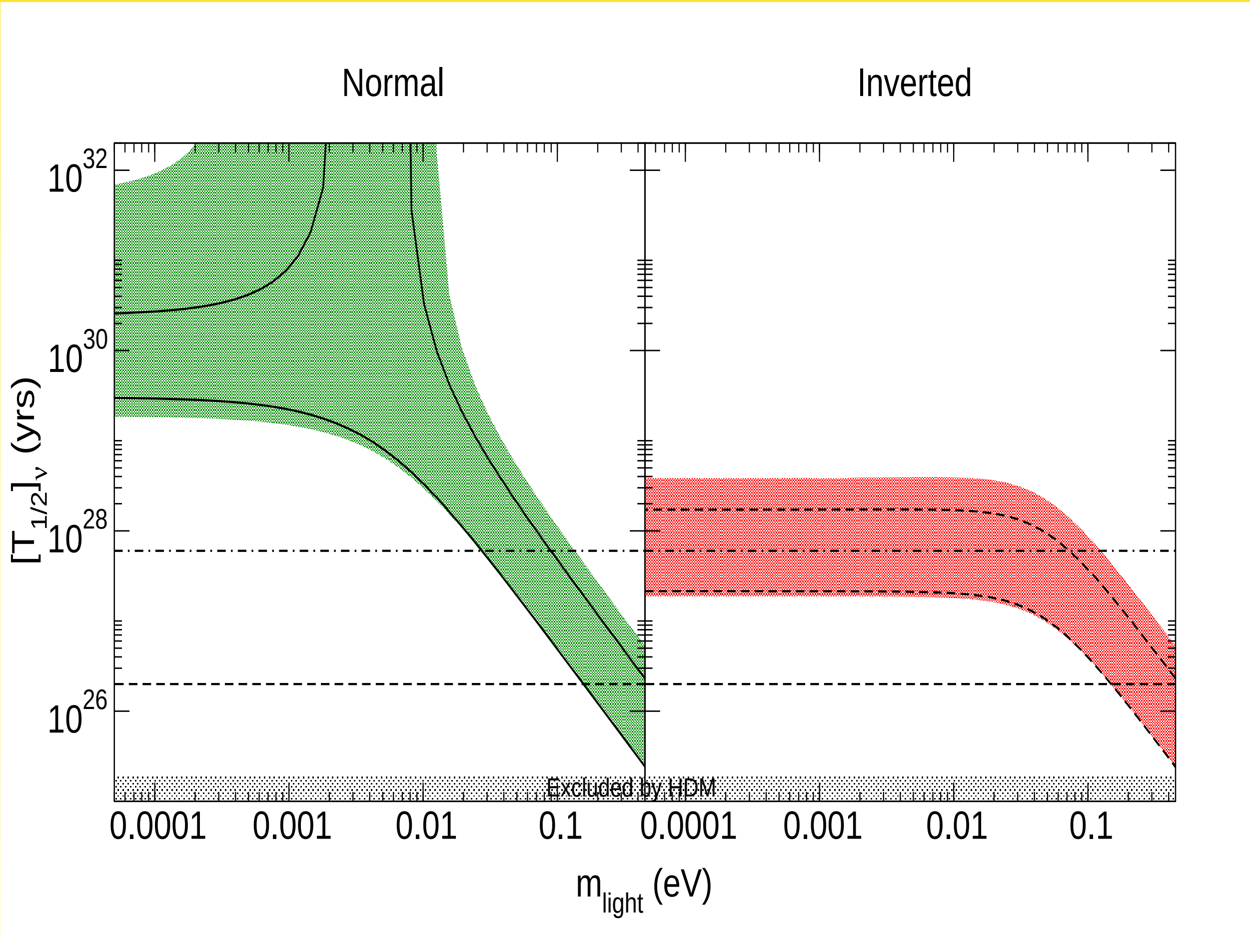
Note: Final state has missing $\not{E}_T$

no proof of lepton number violation!

slide by Martin Hirsch

The usual plot

(life-time instead of $|m_{ee}|$)



Experimental Aspect

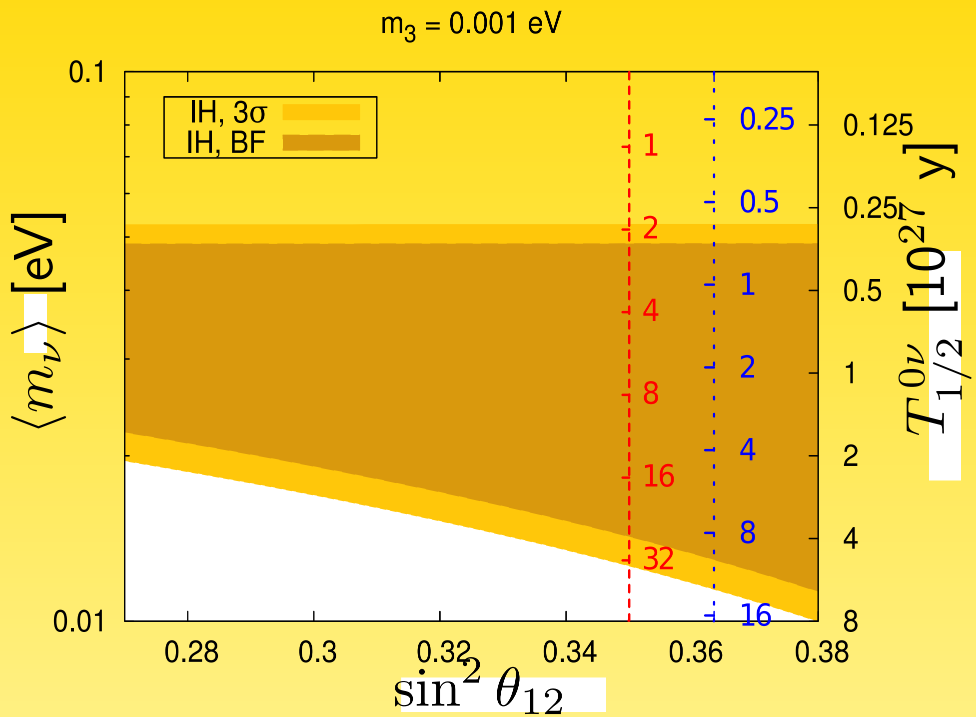
$$(T^{0\nu}_{1/2})^{-1} \propto \begin{cases} a\, M\, \varepsilon\, t & \text{without background} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background} \end{cases}$$

with

- B is background index in counts/(keV kg yr)
- ΔE is energy resolution
- ϵ is efficiency
- $(T^{0\nu}_{1/2})^{-1} \propto$ (particle physics)^2

  factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

Inverted Hierarchy



Current 3σ range of $\sin^2\theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|^{\rm IH}_{\rm min}$

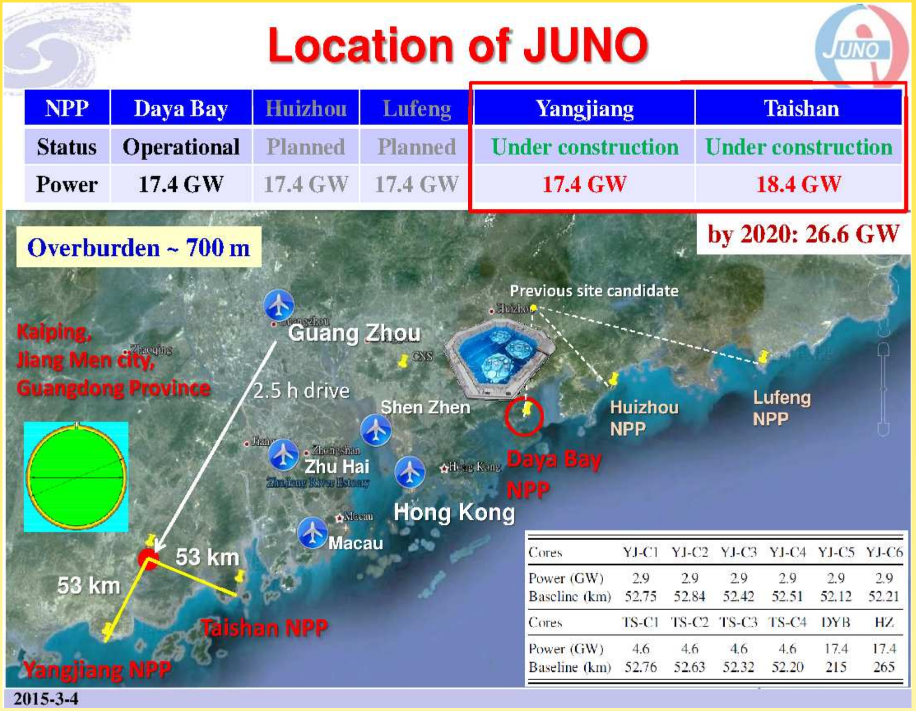
$$T^{0\nu}_{1/2} \propto 1/|m_{ee}|^2 \propto \sqrt{Mt} \Rightarrow 2 = 16$$

$\Rightarrow$ need precision determination of θ_{12}! $\leftrightarrow$ JUNO

`Dueck, W.R., Zuber, PRD83`

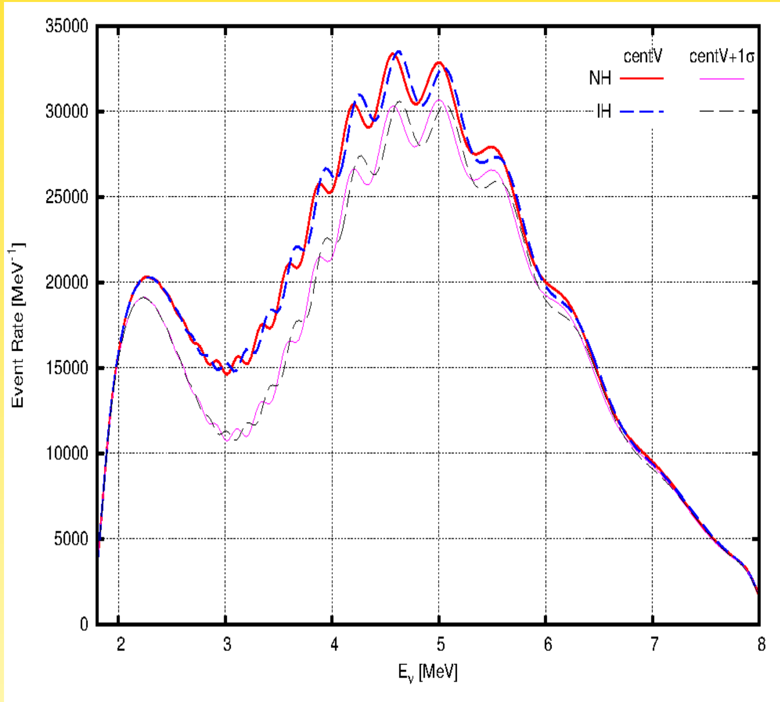
JUNO

$$P_{ee} = 1 - 4c_{13}^4 c_{12}^2 s_{12}^2 \sin^2 \Delta_{21} - 4c_{13}^2 s_{13}^2 \sin^2 |\Delta_{31}|$$
$$- 4s_{12}^2 c_{13}^2 s_{13}^2 \sin^2 \Delta_{21} \cos(2|\Delta_{31}|) \pm 2s_{12}^2 c_{13}^2 s_{12}^2 \sin(2\Delta_{21}) \sin(2|\Delta_{31}|)$$

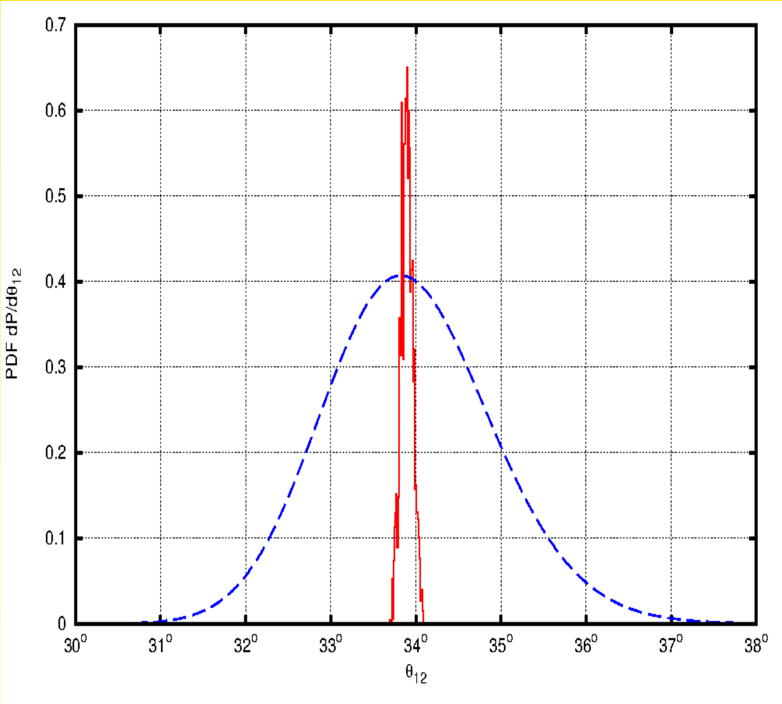


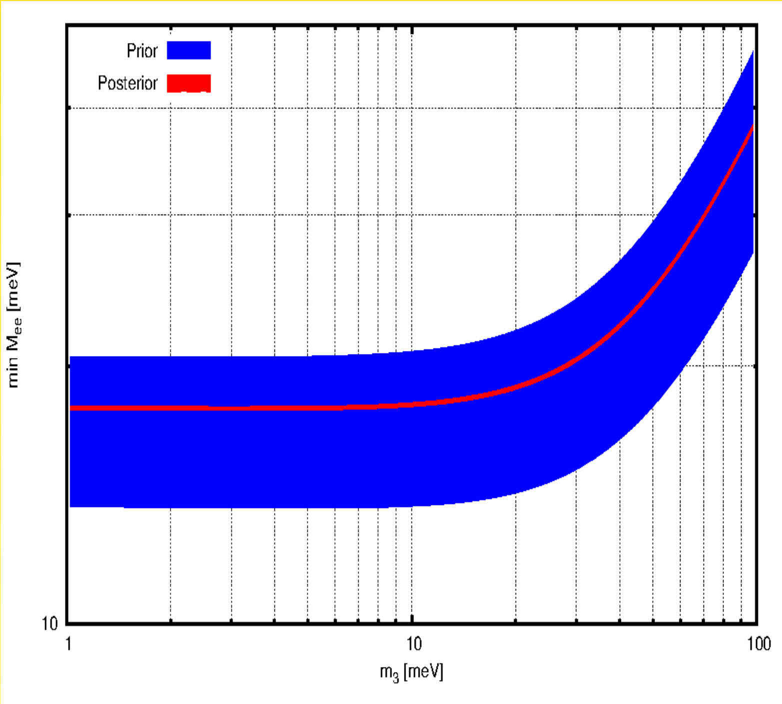
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265



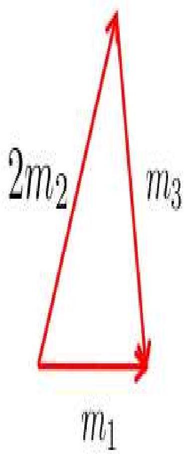
$\sin^2\theta_{12} = 0.323$ and 0.339



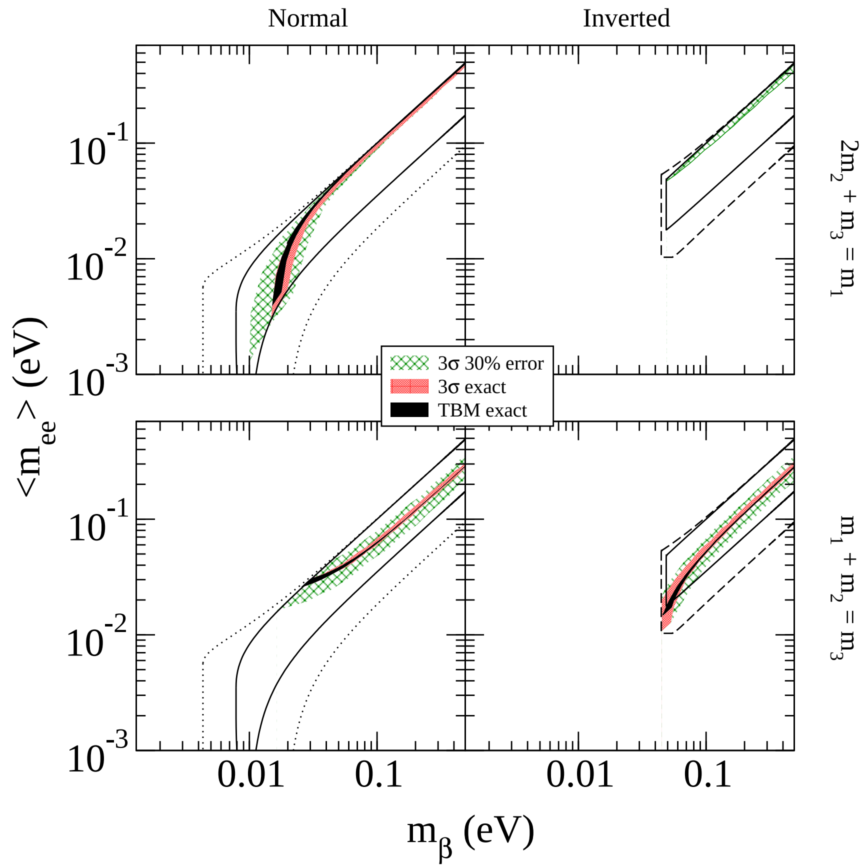


Shao-Feng Ge, W.R., 1507.05514

Flavor Symmetry Models: sum-rules



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



constraints on masses and Majorana phases

Barry, W.R., NPB842

Right-handed Currents in Double Beta Decay

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

$$\mathcal{L}_{CC}^{\rm lep} = \frac{g}{\sqrt{2}} \sum_{i=1}^{3} \Big[\overline{e_L} \gamma^\mu (U_{ei} \nu_{Li} + S_{ei} N_{Ri}^c)(W_{1\mu}^- + \xi e^{i\alpha} W_{2\mu}^-)$$

$$+ \overline{e_R} \gamma^\mu (T_{ei}^* \nu_{Li}^c + V_{ei}^* N_{Ri})(-\xi e^{-i\alpha} W_{1\mu}^- + W_{2\mu}^-) \Big]$$

$$\mathcal{L}_Y^\ell = -\overline{L}_L^{\prime c} i\sigma_2 \Delta_L f_L L_L^\prime - \overline{L}_R^{\prime c} i\sigma_2 \Delta_R f_R L_R^\prime$$

classify diagrams:

- mass dependent diagrams (same helicity of electrons)
- triplet exchange diagrams (same helicity of electrons)
- momentum dependent diagrams (different helicity of electrons)

Neutrino Mass

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

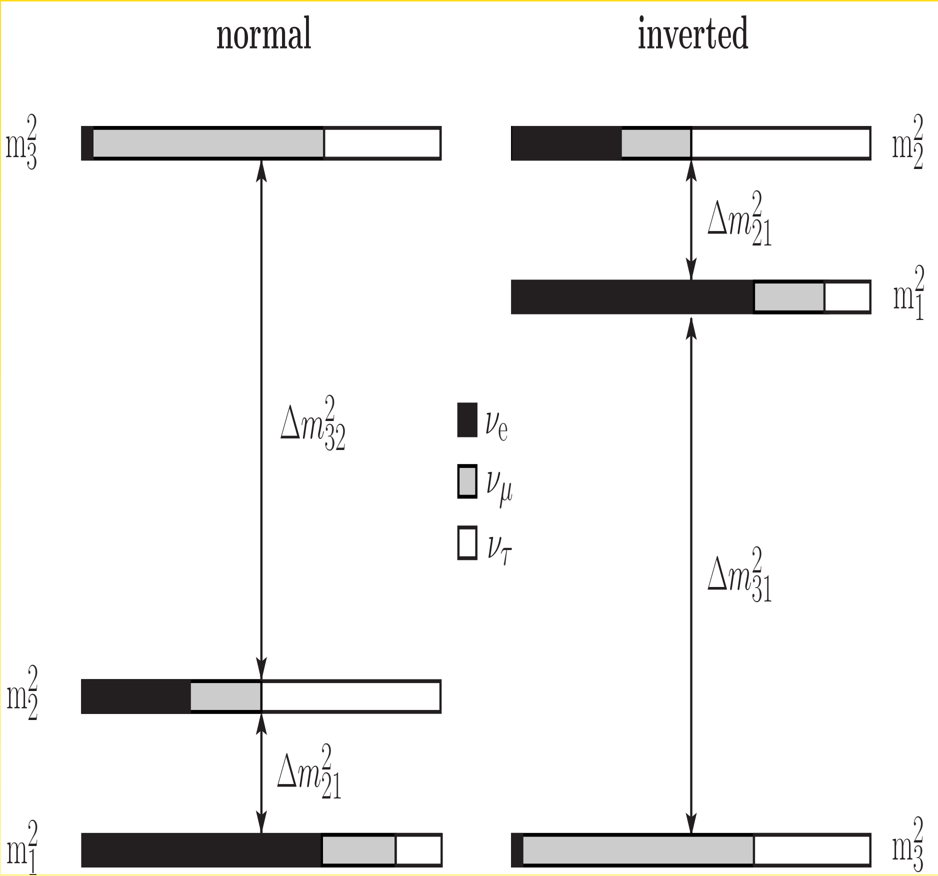
3 **complementary** methods to measure neutrino mass:

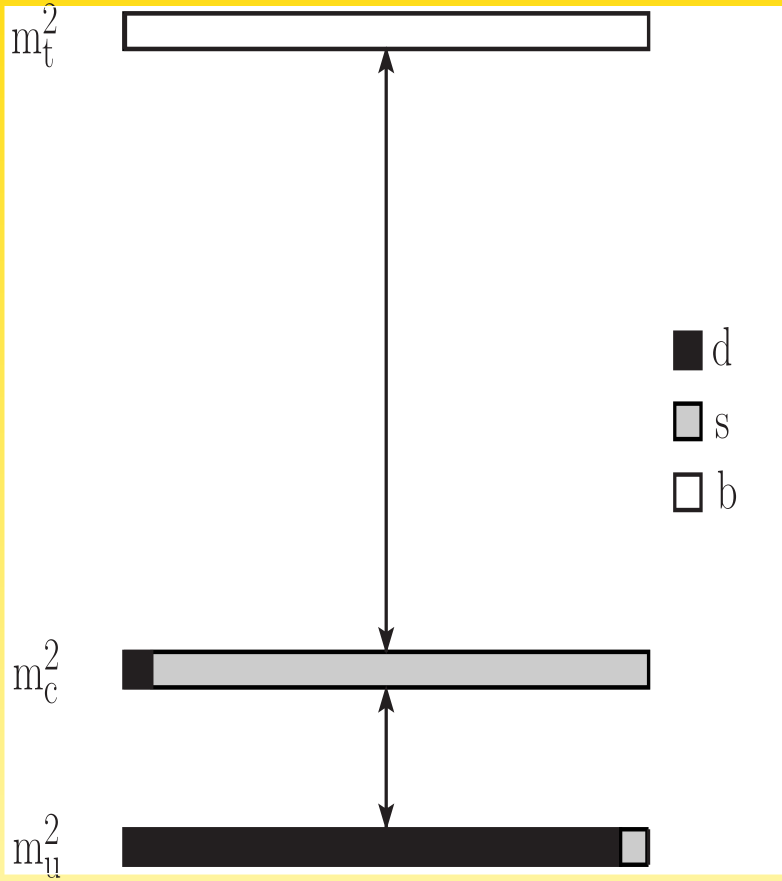
Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 \, m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	0.7	0.3	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\lvert \sum U_{ei}^2 m_i \rvert$	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

Upcoming/running experiments: exciting time!!

best limit was from 2001, improved 2012

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	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
CUPID	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
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	–	✓	–	–





Why so different? $\leftrightarrow$ Flavor symmetries!