Neutrino physics

- Neutrino evidence: Standard Model
- Neutrino oscillations: Neutrino masses and mixing
- New physics beyond the neutrino Standard Model:
See-saw mechanisms, A_4 models

- Dirac and Majorana mass effects
- TeV signatures of see-saw messengers:
Multilepton signals
- Non-standard neutrino interactions

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Some (recent) reviews

PDG: B. Kayser, ``Neutrino Mass, Mixing, and Flavor Change'', arXiv:0804.1497 [hep-ph].

G. Altarelli, ``Lectures on Models of Neutrino Masses and Mixings", arXiv:0711.0161 [hep-ph].

S. King, ``Neutrino Mass Models: a road map'', arXiv:0810.0492 [hep-ph].

E. Ma, ``Neutrino Mass: Mechanisms and Models'', arXiv:0905.0221 [hep-ph].

Some global fits

M.C. Gonzalez-Garcia and M. Maltoni, ``Phenomenology with Massive Neutrinos'', Phys. Rept. 460 (2008) 1 [arXiv:0704.1800 [hep-ph]].

T. Schwetz, M. Tortola and J.W.F. Valle, ``Three-flavour neutrino oscillation update", New J. Phys. 10 (2008) 113011 [arXiv:0808.2016 [hep-ph]].

M. Maltoni and T. Schwetz, ``Three-flavour neutrino oscillation update and comments on possible hints for a non-zero theta_{13}", arXiv:0812.3161 [hep-ph].

G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A.M. Rotunno, ``What we (would like to) know about the neutrino mass", arXiv:0809.2936 [hep-ph].

Neutrino evidence: Standard Model

Pauli postulated the ν in 1933, a particle approximately massless and of spin ½; and Fermi formulated β decay in 1934. $\pi^+ \to \mu^+\nu$, $\nu n \to \mu^- p$; $\mu^- \to e^-\gamma$; ...:

Left-handed neutrinos and no Lepton Flavour Violation

Left-Handed doublets	Q	L_e	L_μ	L_τ
ν_e	0	1	0	0
e	-1	1	0	0
ν_μ	0	0	1	0
μ	-1	0	1	0
ν_τ	0	0	0	1
τ	-1	0	0	1

with total Lepton Number $L = \sum_i L_i$

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	I	II	III
$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$
$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	u_R	c_R	t_R
$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	d_R	s_R	b_R
$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu_L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau_L} \\ \tau_L \end{pmatrix}$
$(\mathbf{1}, \mathbf{1}, -1)$	e_R	μ_R	τ_R

Neutrinos are massless within the minimal Standard Model for they have no Right-Handed counterparts, and L_i are conserved:

$$\mathcal{L}_{K.T.} = \sum_{\alpha=e,\mu,\tau} (\bar{L}_{L\alpha}\gamma^{\lambda} i D_{\lambda} L_{L\alpha} + h.c.)$$

$$\mathcal{L}_{K.T.} = \sum_{\alpha=e,\mu,\tau}(\bar{L}_{L\alpha}\gamma^\lambda iD_\lambda L_{L\alpha} \ + \ \bar{l}_{R\alpha}\gamma^\lambda iD_\lambda l_{R\alpha} \ + \ h.c.) \ ,$$

$$\mathcal{L}_Y = -Y^l_{\alpha\beta}\bar{L}_{L\alpha}Hl_{R\beta} + h.c.$$

$$H \ (\equiv \phi) \sim (\mathbf{1}, \mathbf{2}, \tfrac{1}{2})$$

$$L_{L\beta} \rightarrow U^l_{L\beta\alpha}L_{L\alpha} \ , \ l_{R\beta} \rightarrow U^l_{R\beta\alpha}l_{R\alpha}$$

$$Y^l_{\alpha\beta} \ = \ U^{l\dagger}_{L\alpha\rho} \ y^l_{\rho\rho} \ \delta_{\rho\eta} \ U^l_{R\eta\beta}$$

$$\mathcal{L}_Y = -y^l_{\alpha\alpha}\bar{L}_{L\alpha}Hl_{R\alpha} + h.c.$$

$$\mathcal{L}_{K.T.} = \sum_{\alpha=e,\mu,\tau}(\bar{L}_{L\alpha}\gamma^\lambda iD_\lambda L_{L\alpha} + h.c.) \rightarrow$$

$$-\frac{g}{\sqrt{2}}\sum_{\alpha=e,\mu,\tau}(\bar{l}_{L\alpha}\gamma^\lambda \nu_{L\alpha}W^-_\lambda + h.c.) \ ,$$

However, if neutrinos are massive as required by neutrino oscillations, we can not rotate them arbitrarily:

$$l_{L\beta} \rightarrow U^l_{L\beta\alpha}l_{L\alpha} \ , \ \nu_{L\beta} \rightarrow U^\nu_{L\beta\alpha}\nu_{L\alpha}$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}}(\bar{l}_{L\alpha}\gamma^\lambda \boxed{U_{\alpha i}}\nu_{Li}W^-_\lambda + h.c.)$$

$$U \equiv U^{l\dagger}_L \ U^\nu_L$$

$V_{CKM} \rightarrow U_{PMNS}$

$$\mathbf{V} = \begin{bmatrix} \mathbf{V}_{ud} & \mathbf{V}_{us} & \mathbf{V}_{ub} \\ \mathbf{V}_{cd} & \mathbf{V}_{cs} & \mathbf{V}_{cb} \\ \mathbf{V}_{td} & \mathbf{V}_{ts} & \mathbf{V}_{tb} \end{bmatrix}$$

CKM mixing matrix V is unitary but the field phases are unphysical

$\overline{\mathbf{u}}_L \mathbf{V} \, \mathbf{d}_L$

$u_i \to e^{i\phi_i} u_i$ $\quad d_j \to e^{i\theta_j} d_j$ $\quad \mathbf{V}_{ij} \to \mathbf{V}_{ij} e^{i(\theta_j - \phi_i)}$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{13}} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & c_{23}\,c_{13} \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$ $\quad s_{ij} \equiv \sin\theta_{ij} \;\; (i,j = 1,2,3)$

$c_{ij} \geq 0\,,\; s_{ij} \geq 0$ $\quad 0 \leq \delta_{13} \leq 2\pi$

$n^2 - 2n + 1 \rightarrow \; 4 = 3 + 1$

3 angles and 1 phase

$$\mathbf{U} = \begin{bmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{bmatrix}$$

PMNS mixing matrix U is unitary but the ℓ phases are unphysical

$$\bar{\ell}_\alpha \gamma^\mu (1-\gamma_5) \mathbf{U}_{\alpha i} \nu_i$$

$n^2 - n \rightarrow 6 = 3 + 3$: 3 angles and 3 phases

$$= \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Non-zero phases in general stand for CP violation, with two of them only present for Majorana neutrinos, $\alpha_{1,2}$.
If $| U_{e3} | = 0, 1$, CP is conserved for Dirac neutrinos.

If Majorana $\nu_i = \nu_i^c$ and α_i have a physical meaning but not in the Dirac case

$$\mathbf{U} = \begin{bmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{bmatrix}$$

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$n^2 - n \rightarrow 6 = 3 + 3$: 3 angles and 3 phases

$$= \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, \mathrm{e}^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, \mathrm{e}^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, \mathrm{e}^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, \mathrm{e}^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, \mathrm{e}^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix} \begin{bmatrix} \mathrm{e}^{i\alpha_1} & 0 & 0 \\ 0 & \mathrm{e}^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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If $| U_{e3} | = 0, 1$, CP is conserved for Dirac neutrinos.

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \rightarrow 0.86 & 0.50 \rightarrow 0.63 & 0.00 \rightarrow 0.22 \\ 0.22 \rightarrow 0.56 & 0.44 \rightarrow 0.73 & 0.57 \rightarrow 0.80 \\ 0.21 \rightarrow 0.55 & 0.40 \rightarrow 0.71 & 0.59 \rightarrow 0.82 \end{pmatrix}$$

No possible evidence up to now for (Dirac) CP violation

$$\mathbf{U} = \begin{bmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{bmatrix}$$

PMNS mixing matrix U is unitary
but the ℓ phases are unphysical

$$\bar{\ell}_\alpha \gamma^\mu (1-\gamma_5) \mathbf{U}_{\alpha i} \nu_i$$

$n^2 - n \rightarrow 6 = 3 + 3$: 3 angles and 3 phases

$$= \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

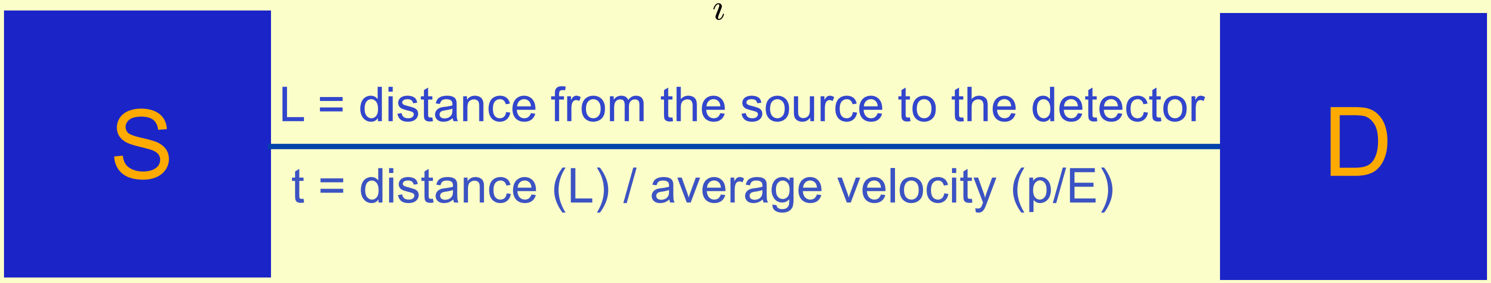
No possible evidence up to now for (Dirac) CP violation

Neutrino oscillations: Neutrino masses and mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle \quad , \qquad \sum_{i=1}^{3} U_{\beta i} U^*_{\alpha i} = \delta_{\beta\alpha} \quad , \qquad |\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i}|\nu_\alpha\rangle \quad .$$

Neutrino propagation in vacuum

Production $\mathcal{A}\left(\nu_\alpha \to \nu_\beta\right) = \sum_i U^*_{\alpha i} e^{-i m_i^2\, L/2E} U_{\beta i}$ Detection



$$\mathrm{P}(\nu_\alpha \to \nu_\beta) \;=\; \left|\mathcal{A}\left(\nu_\alpha \to \nu_\beta\right)\right|^2$$

CP conserving $= \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2(\Delta m^2_{ij} L/4E)$

CP violating $+ 2 \sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin(\Delta m^2_{ij} L/2E)$

$\Delta m^2_{ij} = m^2_i - m^2_j$

t = $L/\bar{v}$ (distance / average velocity),

with $\bar{v} \equiv \dfrac{p_1 + p_2}{E_1 + E_2}$

$$
\begin{aligned}
\delta\phi(12) &= (E_2 t - p_2 L) - (E_1 t - p_1 L) \\
&= (p_1 - p_2)L - (E_1 - E_2)t \\
&\cong \frac{p_1^2 - p_2^2}{p_1 + p_2} L - \frac{E_1^2 - E_2^2}{p_1 + p_2} L \\
&= (m_2^2 - m_1^2)\frac{L}{p_1 + p_2} \cong (m_2^2 - m_1^2)\frac{L}{2E}
\end{aligned}
$$

$$\mathrm{P}(\overline{\nu_\alpha} \to \overline{\nu_\beta};\ U) = \mathrm{P}(\nu_\beta \to \nu_\alpha;\ U) = \mathrm{P}(\nu_\alpha \to \nu_\beta;\ U^*)$$

CPT

Probability amplitude

Then, a phase in U given a different P for neutrinos and antineutrinos stands for CP violation

Neutrino propagation in matter

$$i\frac{\partial}{\partial t}\Psi(t) = \mathcal{H}\Psi(t)$$

$$\mathcal{H} = \frac{1}{2E_\nu}U^* \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^T + \frac{1}{2E_\nu}\begin{pmatrix} A+A' & 0 & 0 \\ 0 & A' & 0 \\ 0 & 0 & A' \end{pmatrix},$$

Coherent forward scattering {

- CC piece $A = \pm\frac{2\sqrt{2}G_F Y \rho E_\nu}{m_n}$ + for neutrino in matter
- NC piece (involving the quarks) is universal A'

Neutrinos	Experiment	
Atmospheric	SK	ν_μ disappearance
Accelerator	K2K, MINOS	ν_μ disappearance
Solar	Gallex, SNO Borexino	ν_e disappearance (CC) and $\sum_\alpha \nu_\alpha$ (NC) [^{8}B] ^{7}B
Reactor	Palo Verde, CHOOZ KamLAND	No $\bar{\nu}_\mu \to \bar{\nu}_e$ $\bar{\nu}_e$ disappearance
LSND (Stopped μ+ decay) $\bar{\nu}_e$ excess	KARMEN MiniBooNE	No $\bar{\nu}_\mu \to \bar{\nu}_e$ Search for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

In the Sun + H_M ⇒ heaviest neutrino has lowest energy (opposite sign H_V)

$$P(\nu_e \to \nu_e) = \sin^2\theta_\odot$$

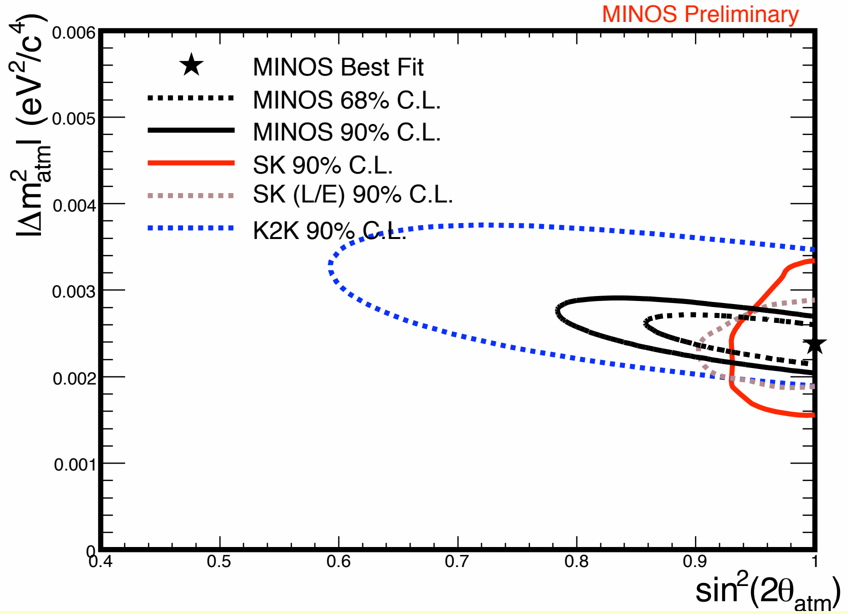
SNO:

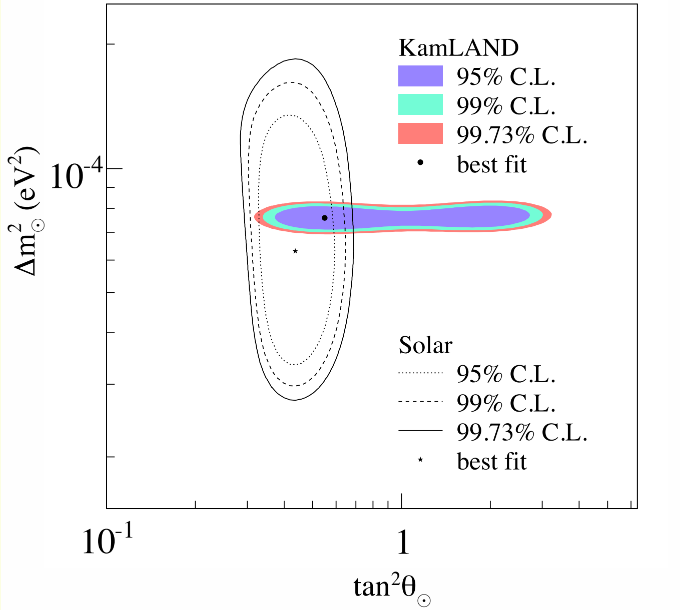
$$\nu + d \to e^- + p + p\ ,$$

$$\nu + d \to \nu + p + n\ ,$$

$$\nu + e^- \to \nu + e^-$$

$$\frac{\phi(\nu_e)}{\phi(\nu_e)+\phi(\nu_{\mu,\tau})} = 0.340 \pm 0.023\,(\mathrm{stat})\ {}^{+0.029}_{-0.031}\,(\mathrm{syst})$$



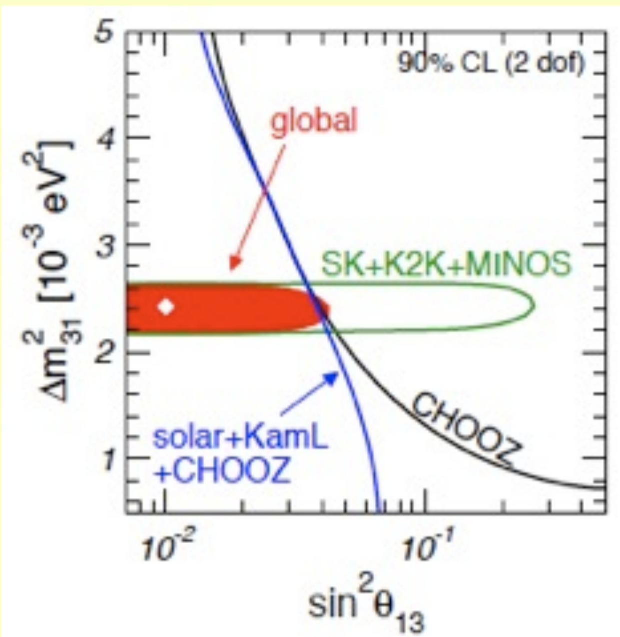


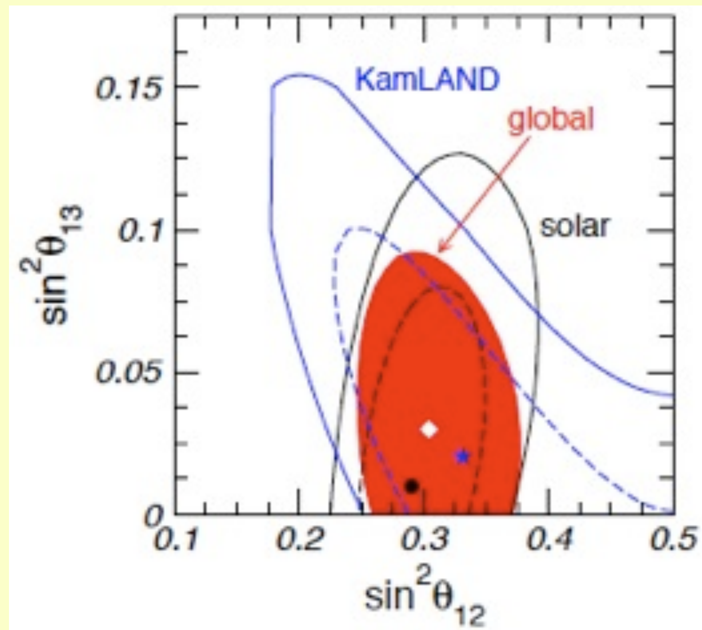
$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2\,,$$

$$\Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12\,\left(^{+0.37}_{-0.40}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}\,, \\ +2.49 \pm 0.12\,\left(^{+0.39}_{-0.36}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}\,, \end{cases}$$

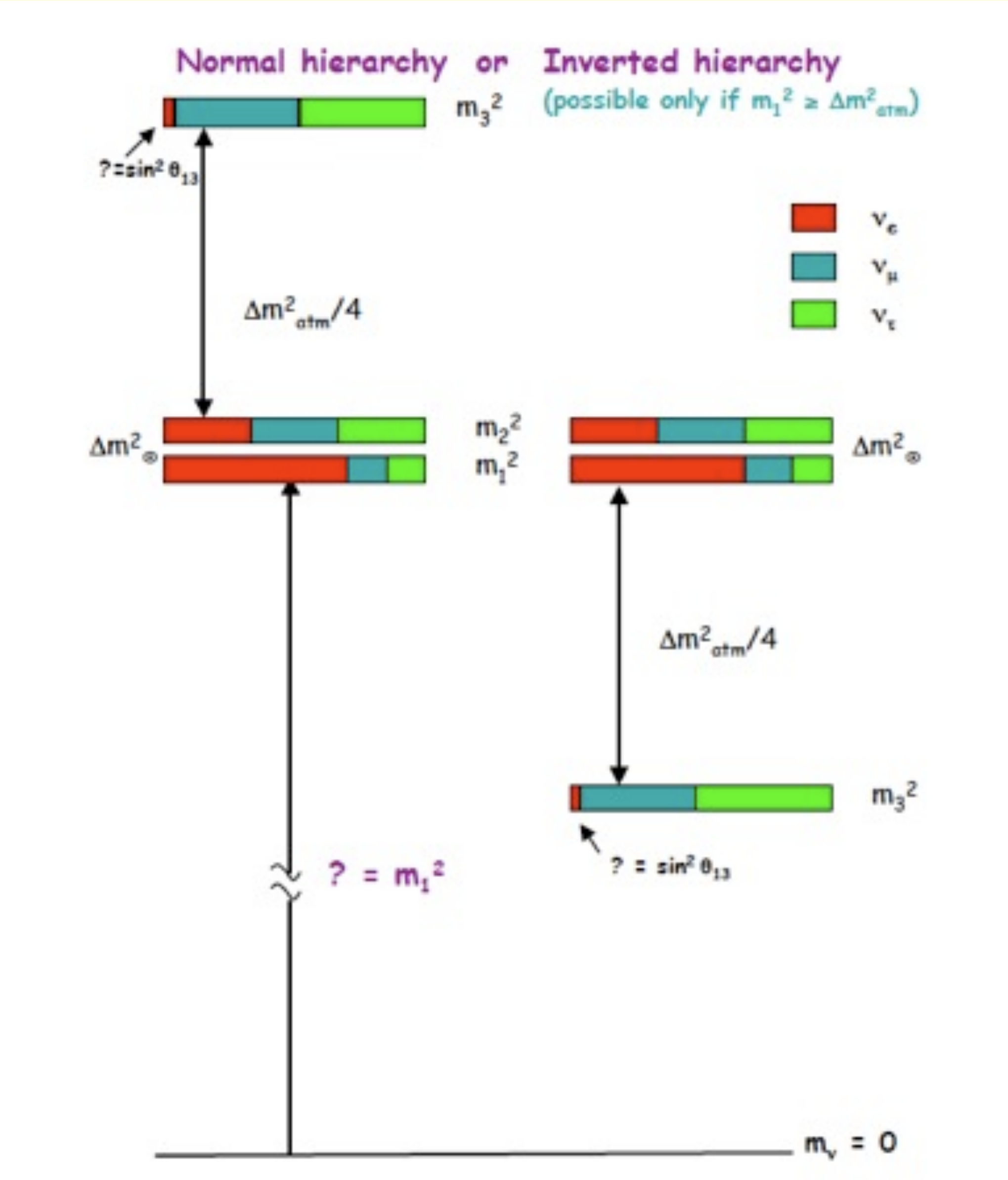
1σ (3σ)

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.00 \to 0.22 \\ 0.22 \to 0.56 & 0.44 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.40 \to 0.71 & 0.59 \to 0.82 \end{pmatrix}\,.$$





Accelerator	Experiment	
	On going	A factor of 3
	NuFact	3 orders of magnitude



$$| < \nu_\alpha | \nu_i > |^2 = |U_{\alpha i}|^2$$

degenerate:

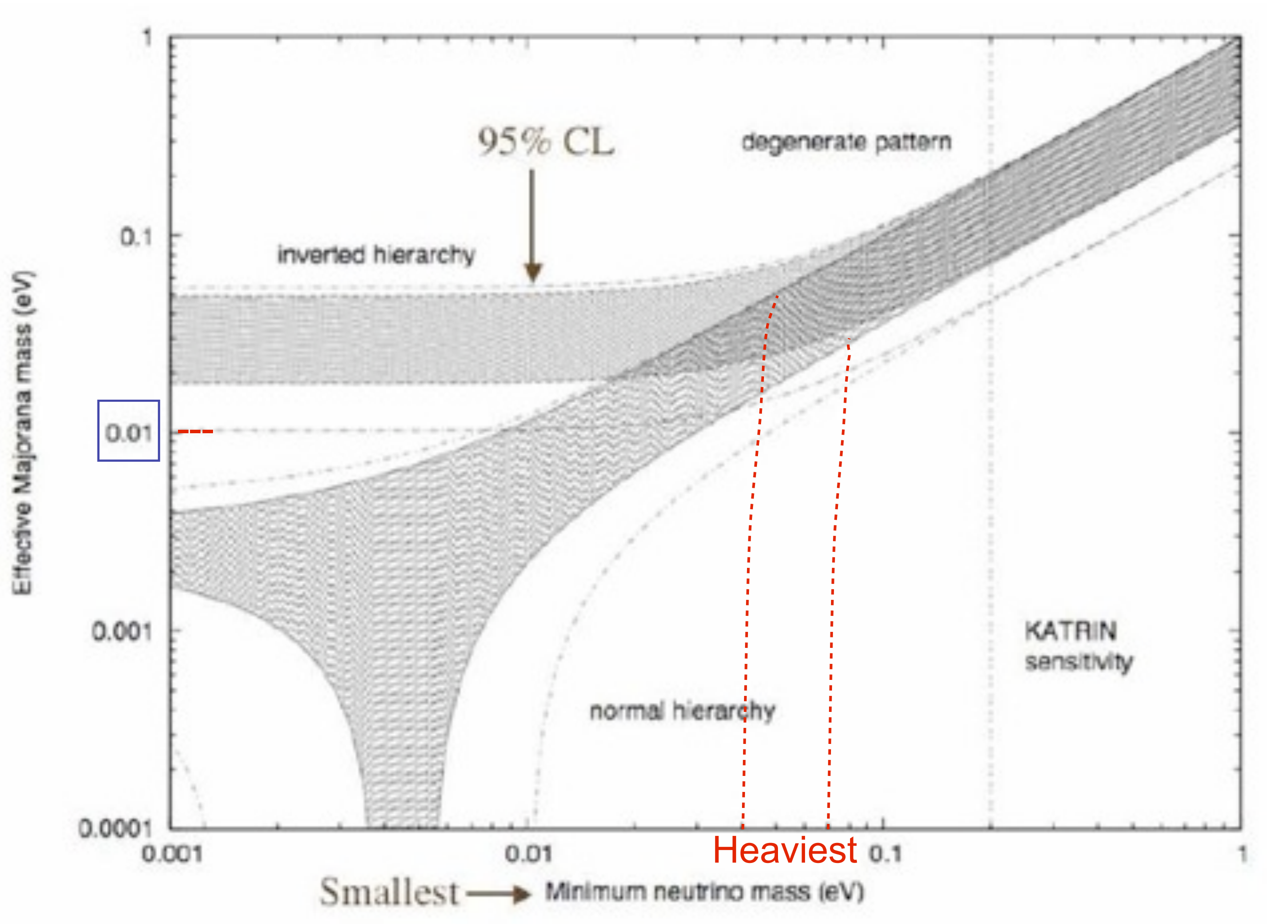
$$m_1 \sim m_2 \sim m_3 >> |m_i - m_j|$$

If light neutrinos are Majorana, they can mediate double beta decay

$$\left|\sum_i m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

$$\geq \sqrt{\Delta m^2_{\rm atm}} \cos 2\theta_\odot$$

≥10 meV for inverted hierarchy

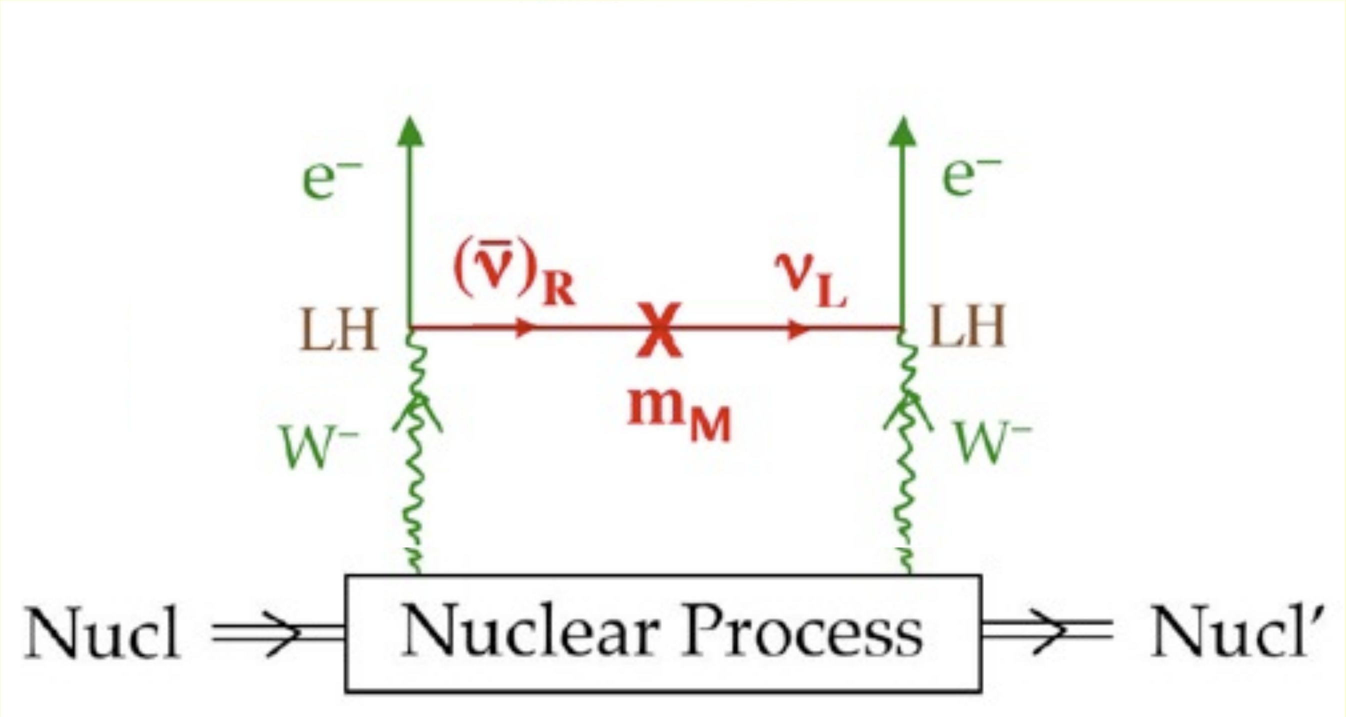


0.04 < m(heaviest ν) < 0.07-0.7 eV

$\sqrt{\Delta m^2_{atm}}$ $\sum m_\nu$ (cosmology)

Subir S.'s lectures

$$|m_{11}| = |(1 - s_{13}^2)(m_1 c_{12}^2 e^{-2i\alpha_1} + m_2 s_{12}^2 e^{-2i\alpha_2}) + m_3 s_{13}^2 e^{2i\delta_{13}}|$$



Both vertices must be the same. Then, if light neutrinos are Majorana, $\nu_i = \nu_i^c$, and the process is proportional to the ee entry of

$$M = U^* M_{diag} U^\dagger$$

Dirac neutrinos can not mediate such a process.

	lower limit (2σ)	best value	upper limit (2σ)
$(\Delta m^2_{sun})_{LA}$ (10^{-5} eV^2)	7.2	7.9	8.6
Δm^2_{atm} (10^{-3} eV^2)	1.8	2.4	2.9
$\sin^2\theta_{12}$	0.27	0.31	0.37
$\sin^2\theta_{23}$	0.34	0.44	0.62
$\sin^2\theta_{13}$	0	0.009	0.032

$0.304^{+0.022}_{-0.016}$	$0.326^{+0.050}_{-0.040}$ $[2\sigma]$
$0.50^{+0.07}_{-0.06}$	$0.45^{+0.16}_{-0.09}$ $[2\sigma]$
$0.010^{+0.016}_{-0.011}$	0.016 ± 0.010

$$U_{HPS} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \rightarrow \left\{ \begin{array}{l} 0.33 \\ 0.50 \\ 0.00 \end{array} \right.$$

What do we need ?

- Double beta decay
- TB, s_{13} and CP violation
- Surprises (NP) in LFV processes or oscillation experiments
- Collider signals

Neutrino physics

- Neutrino evidence: Standard Model
- Neutrino oscillations: Neutrino masses and mixing
- New physics beyond the neutrino Standard Model:

See-saw mechanisms, A_4 models

- Dirac and Majorana mass effects
- TeV signatures of see-saw messengers:

Multilepton signals

- Non-standard neutrino interactions

Models of neutrino masses and mixing

Within the SM ν masses are zero for 3 reasons:

• No ν_R's	$-Y^{\nu}_{\alpha\beta}\overline{L_{L\alpha}}\tilde{H}N_{R\beta}+h.c.$	LNC [NR RH counterpart (D)]
• Only Higgs doublets	$\frac{1}{\sqrt{2}}Y^{\nu}_{\alpha\beta}\overline{\tilde{L}_{L\alpha}}(\vec{\tau}\cdot\vec{\Delta})L_{L\beta}+h.c.$	$L_\Delta=-2$ but $m_\nu\neq0$ ⇒ LNV
• Renormalizable theory	$\frac{x_{5\alpha\beta}}{\Lambda}\overline{L^c_{L\alpha}}\tilde{H}^*\tilde{H}^\dagger L_{L\beta}+h.c.$	LNV

$$\mathcal{L}_M=-\frac{1}{2}m_{\alpha\beta}\overline{\nu_{L\alpha}}\nu^c_{L\beta}-Y^{\nu}_{\alpha\beta}\frac{v}{\sqrt{2}}\overline{\nu_{L\alpha}}N_{R\beta}-\frac{1}{2}M_{\alpha\beta}\overline{N^c_{R\alpha}}N_{R\beta}+h.c.$$

$$\mathcal{M}=\begin{pmatrix} m & m_D \\ m_D^T & M \end{pmatrix}$$

Light neutrino masses can be Dirac or Majorana

Which is the problem ?

$$-Y^{\nu}_{\alpha\beta}\overline{L_{L\alpha}}\tilde{H}N_{R\beta} + h.c.$$

if $m_\nu \sim$ eV, Y $\sim 10^{-11}$
[N_R RH counterpart (D)]

$$\frac{1}{\sqrt{2}}Y^{\nu}_{\alpha\beta}\overline{\tilde{L}_{L\alpha}}(\vec{\tau}\cdot\vec{\Delta})L_{L\beta} + h.c.$$

introduce scalar triplet and explain small v_Δ and/or Y

$$\frac{x_{5\alpha\beta}}{\Lambda}\overline{L^c_{L\alpha}}\tilde{H}^*\tilde{H}^\dagger L_{L\beta} + h.c.$$

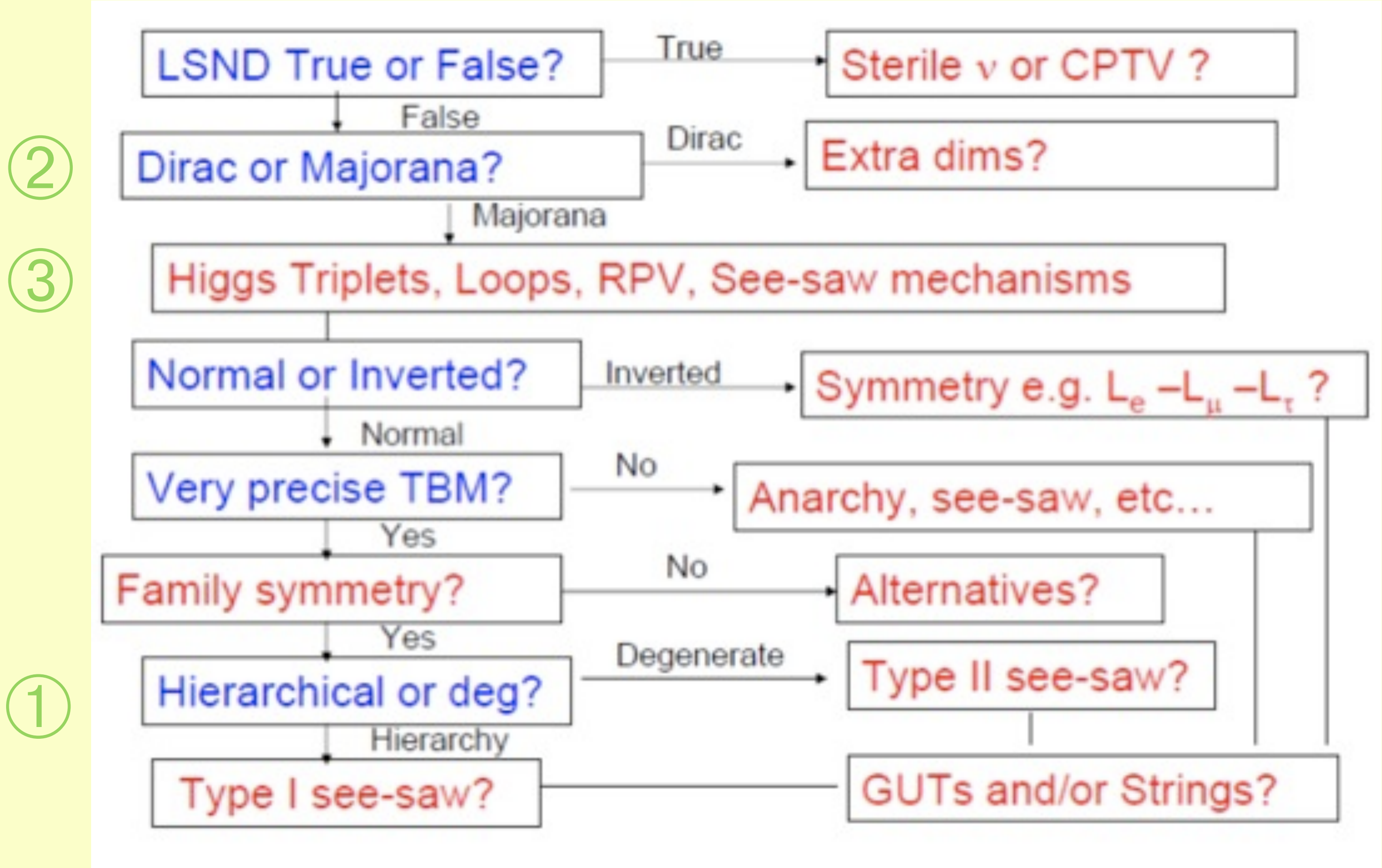
if x $\sim$ 1, $\Lambda \sim 10^{14}$ GeV

Bonus new heavy physics (NR): Leptogenesis

Margarida R.'s talk

A Dirac neutrino mass matrix, which is an arbitrary complex matrix, can accommodate some constraints (like special zeroes) that a Majorana neutrino mass matrix, which is complex but symmetric, can not. Although if we do not impose further constraints both can describe the same physics at low energy.

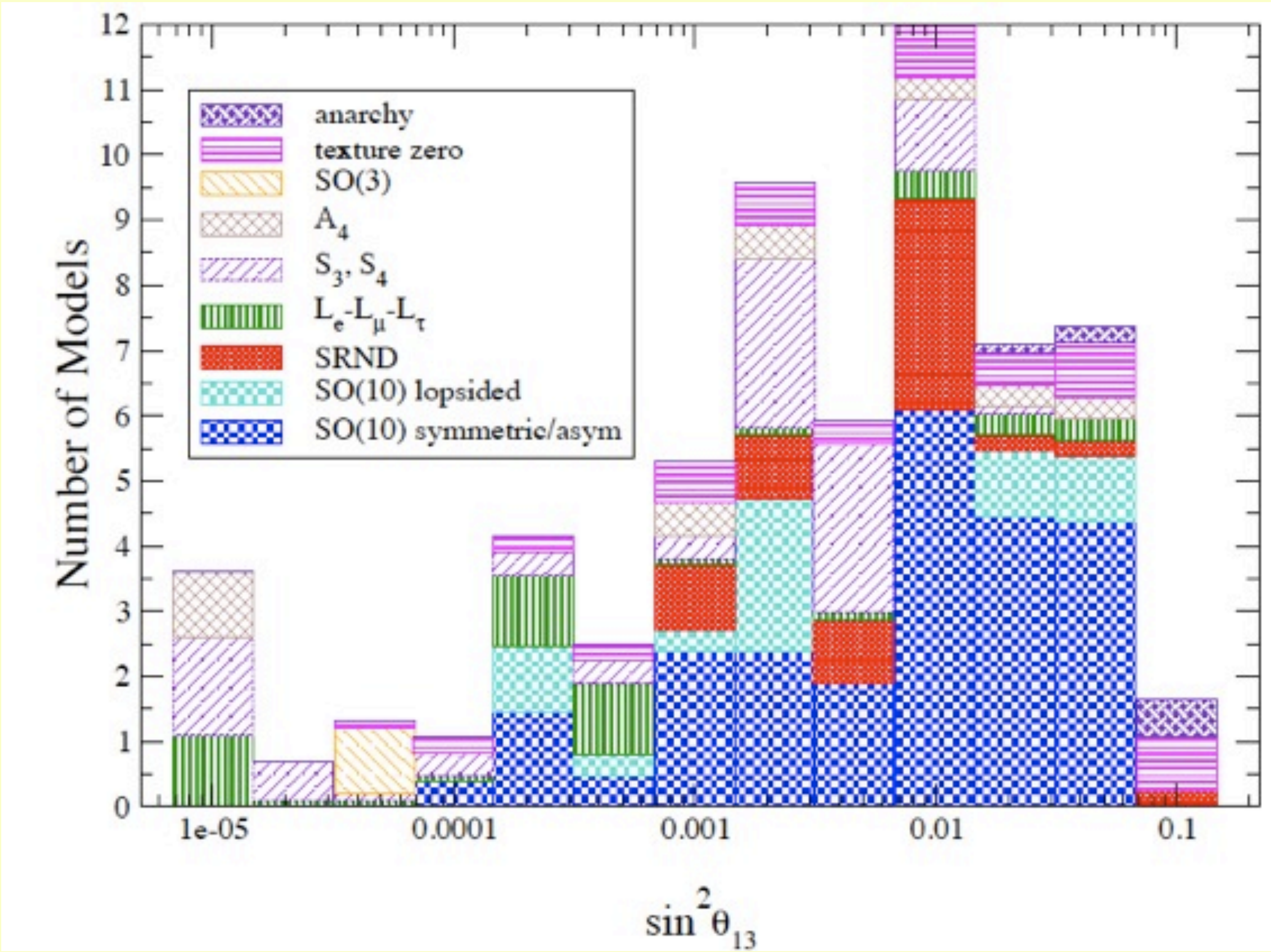
Harald F.'s talk



① Scale versus mixing

② Dirac or Majorana

③ See-saw mechanisms



Berthold S.'s talk

See-saw mechanisms (messengers of type I, II, III)

$$\mathcal{L} = \mathcal{L}_\ell + \mathcal{L}_h + \mathcal{L}_{\ell h} \rightarrow \mathcal{O}_5 = \overline{l_L^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$$

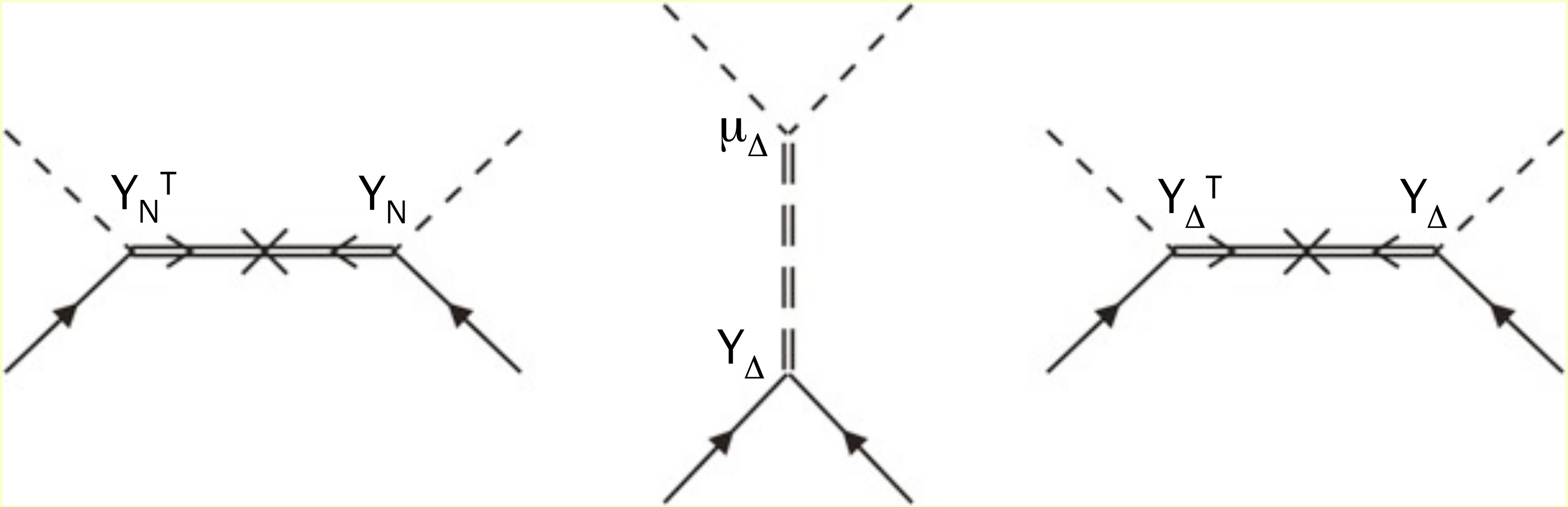
In the fermionic case: heavy neutrinos in singlets N (type I) or triplets Σ (type III)

$$\mathcal{L}_\ell \supset \overline{l_L^i} i \not{D}\, l_L^i + \overline{e_R^i} i \not{D}\, e_R^i - \left((\lambda_e)_i \overline{l_L^i}\, \phi\, e_R^i + \text{h.c.} \right)$$

$$\mathcal{L}_h = \eta_L \overline{L^I} i \not{D}\, L^I - \eta_L M_I \overline{L^I} L^I$$

Change of notation
$L_L \rightarrow l_L$, $Y^\dagger = \lambda \rightarrow Y^*$

$$\mathcal{L}_{\ell h} = -\left(\lambda_{Le}\right)_{Ij} \overline{L_L^I} \Phi_{Le} e_R^j - \left(\lambda_{Ll}\right)_{Ij} \overline{L_R^I} \Phi_{Ll} l_L^j + \text{h.c.}$$



$^1/_2 Y_N^T M_N^{-1} Y_N$ | $-2\, Y_\Delta \mu_\Delta M_\Delta^{-2}$ | $^1/_2 Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$

Phase cancellation or small couplings

small coupling(s)

Phase cancellation or small couplings

The three mechanisms must violate Lepton Number for they are assumed to generate Majorana masses, $\mathcal{O}_5 = \overline{l_L^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$. I and III involve fermions: singlets N (I) or triplets Σ (III), and II scalar triplets: Δ.

Type I

Dimension	Operator	Coefficient
5	$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$\frac{1}{2}Y_N^T M_N^{-1} Y_N$
6	$\mathcal{O}_{\phi l}^{(1)} = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\frac{1}{4}Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$
	$\mathcal{O}_{\phi l}^{(3)} = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a\gamma^\mu l_L\right)$	$-\frac{1}{4}Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N$

Belén G.'s talk

Type II

Dimension	Operator	Coefficient
4	$\mathcal{O}_4 = \left(\phi^\dagger\phi\right)^2$	$2\left\|\mu_\Delta\right\|^2/M_\Delta^2$
5	$\mathcal{O}_5 = \overline{l^c_L}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$-2\,Y_\Delta \mu_\Delta / M_\Delta^2$
6	$\mathcal{O}_{ll}^{(1)} = \frac{1}{2}\left(\overline{l^i_L}\gamma^\mu l^j_L\right)\left(\overline{l^k_L}\gamma_\mu l^l_L\right)$	$2(Y_\Delta)_{jl}(Y_\Delta^\dagger)_{ki}/M_\Delta^2$
	$\mathcal{O}_\phi = \frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$-6\left(\lambda_3+\lambda_5\right)\left\|\mu_\Delta\right\|^2/M_\Delta^4$
	$\mathcal{O}_\phi^{(1)} = \left(\phi^\dagger\phi\right)\left(D_\mu\phi\right)^\dagger D^\mu\phi$	$4\left\|\mu_\Delta\right\|^2/M_\Delta^4$
	$\mathcal{O}_\phi^{(3)} = \left(\phi^\dagger D_\mu\phi\right)\left(D^\mu\phi^\dagger\phi\right)$	$4\left\|\mu_\Delta\right\|^2/M_\Delta^4$

Type III

Dimension	Operator	Coefficient
5	$\mathcal{O}_5 \quad = \overline{l_L^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L$	$\frac{1}{2}Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$
6	$\mathcal{O}_{\phi l}^{(1)} \quad = \left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L}\gamma^\mu l_L\right)$	$\frac{3}{4}Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma$
	$\mathcal{O}_{\phi l}^{(3)} \quad = \left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L}\sigma_a\gamma^\mu l_L\right)$	$\frac{1}{4}Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma$
	$\mathcal{O}_{e\phi} \quad = \left(\phi^\dagger \phi\right)\overline{l_L}\phi e_R$	$Y_\Sigma^\dagger (M_\Sigma^\dagger)^{-1} M_\Sigma^{-1} Y_\Sigma Y_e$

There is a question about the relative size of the coefficients of the operators of dimension 5 and 6:

Can the dimension 5 operator coefficient be negligible but dimension 6 operator coefficients sizeable ?

The answer is positive, for instance, if Lepton Number is (quasi-)conserved.

$$\begin{array}{c} \\ \nu_L \\ N \end{array}\begin{array}{c} \begin{array}{cc} \nu_L & N \end{array} \\ \begin{pmatrix} 0 & Y_N^T \frac{v}{\sqrt{2}} \\ Y_N \frac{v}{\sqrt{2}} & M_N \end{pmatrix} \end{array} \longrightarrow \begin{array}{c} \\ \nu_L \\ N_L \\ N_R^c \end{array}\begin{array}{c} \begin{array}{ccc} \nu_L & N_L & N_R^c \end{array} \\ \begin{pmatrix} 0 & 0 & \frac{y_N v}{\sqrt{2}} \\ 0 & 0 & m_N \\ \frac{y_N v}{\sqrt{2}} & m_N & 0 \end{pmatrix} \end{array}$$

Type I and III: Light neutrinos are massless.

$$\begin{array}{c|ccc} & \nu_L & N_L & N_R^c \\ \nu_L & 0 & 0 & \frac{y_N v}{\sqrt{2}} \\ N_L & 0 & \mu & m_N \\ N_R^c & \frac{y_N v}{\sqrt{2}} & m_N & 0 \end{array}$$

Type I and III:
Light neutrinos get a mass proportional to the LN breaking parameter μ. [If μ is in the (1,1) entry, the light neutrino masses are ~ μ, and 0 –up to r.c.– if it is in the position (3,3)].

$$-Y_N^T M_N^{-1} Y_N \frac{v^2}{2} \simeq -\frac{y_N^2}{2}\left[\frac{(1-\frac{\mu}{4m_N})^2}{m_N+\frac{\mu}{2}} - \frac{(1+\frac{\mu}{4m_N})^2}{m_N-\frac{\mu}{2}}\right]\frac{v^2}{2} \simeq \frac{\mu y_N^2}{m_N^2}\frac{v^2}{2}$$

$$Y_N^\dagger (M_N^\dagger)^{-1} M_N^{-1} Y_N \simeq \frac{|y_N|^2}{2}\left[\frac{(1-\frac{\mu}{4m_N})^2}{(m_N+\frac{\mu}{2})^2} + \frac{(1+\frac{\mu}{4m_N})^2}{(m_N-\frac{\mu}{2})^2}\right] \simeq \frac{|y_N|^2}{m_N^2}$$

(Neutrino models based on) A_4

$$M = U^* M_{diag} U^\dagger$$

If U is the HPS matrix (which is real):

$$U_{HPS} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$M = \frac{1}{6} \begin{pmatrix} 4m_1 + 2m_2 & -2m_1 + 2m_2 & -2m_1 + 2m_2 \\ -2m_1 + 2m_2 & m_1 + 2m_2 + 3m_3 & m_1 + 2m_2 - 3m_3 \\ -2m_1 + 2m_2 & m_1 + 2m_2 - 3m_3 & m_1 + 2m_2 + 3m_3 \end{pmatrix} = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix},$$

$$x = \tfrac{1}{3}(2m_1 + m_2),\ y = \tfrac{1}{3}(-m_1 + m_2),\ v = \tfrac{1}{2}(-m_1 + m_3)$$

Neglecting Majorana phases, otherwise $m_{1,2} \to m_{1,2} e^{-2i\alpha_{1,2}}$

They form a group relevant for $m_D^T M^{-1} m_D$

A_4 = {Even permutations of 4 objects} $\subset S_4$

generated by $\begin{cases} S = (4321) \\ T = (2314) \end{cases}$

$C1 \;: I = (1234)$

$C2 \;: T = (2314), ST = (4132), TS = (3241), STS = (1423)$

$C3 \;: T^2 = (3124), ST^2 = (4213), T^2S = (2431), TST = (1342)$

$C4 \;: S = (4321), T^2ST = (3412), TST^2 = (2143)$

Class	χ^1	$\chi^{1'}$	$\chi^{1''}$	χ^3
C_1	1	1	1	3
C_2	1	ω	ω^2	0
C_3	1	ω^2	ω	0
C_4	1	1	1	-1

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

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

$\underline{(ll)_{symmetric}}$:

$(3X3)_{symm}$ =

C.G.'s:

(up to global factors)

$$a=\begin{pmatrix}1&&\\&&1\\&1&\end{pmatrix},\ b=\begin{pmatrix}&&1\\&1&\\1&&\end{pmatrix},\ c=\begin{pmatrix}&1&\\1&&\\&&1\end{pmatrix},$$

1+1'+1''+

$$d=\begin{pmatrix}2&&\\&&-1\\&-1&\end{pmatrix},\ e=\begin{pmatrix}&&-1\\&2&\\-1&&\end{pmatrix},\ f=\begin{pmatrix}&-1&\\-1&&\\&&2\end{pmatrix}$$

3_{symm}

In the basis where the charged lepton masses are diagonal $a,\ b+c,\ d+e+f$

$$3\begin{pmatrix}x&y&y\\y&x+v&y-v\\y&y-v&x+v\end{pmatrix}=(x+2y-2v)\begin{pmatrix}1&&\\&&1\\&1&\end{pmatrix}+(x+2y+v)\begin{pmatrix}&1&1\\1&1&\\1&&1\end{pmatrix}+(x-y+v)\begin{pmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{pmatrix}$$

They form a group

<1>

It is not in A_4: <1'>=<1''>

<3>~(1,1,1)

$$\mathcal{L}_Y = y_e e^c(\varphi l) + y_\mu \mu^c(\varphi l)'' + y_\tau \tau^c(\varphi l)' + x_a \xi(ll) + x_d(\varphi' ll) + h.c. + \ldots$$

- No φ ↔ φ' exchange (extra symmetries)
- $h_{u,d} = \Lambda = 1$
- < > dynamically generated

$$<\varphi>=\begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}, \quad <\varphi'>=\frac{1}{3}\begin{pmatrix} v' \\ v' \\ v' \end{pmatrix}, \quad <\xi>=u$$

- with $\frac{<>}{\Lambda} < 0.05$ giving the size of the corrections

$$m_\nu = \frac{v_u^2}{\Lambda}\begin{pmatrix} a+2d/3 & -d/3 & -d/3 \\ -d/3 & 2d/3 & a-d/3 \\ -d/3 & a-d/3 & 2d/3 \end{pmatrix}$$

$$a \equiv x_a \frac{u}{\Lambda} \quad , \quad d \equiv x_d \frac{v'}{\Lambda}$$

Review summary

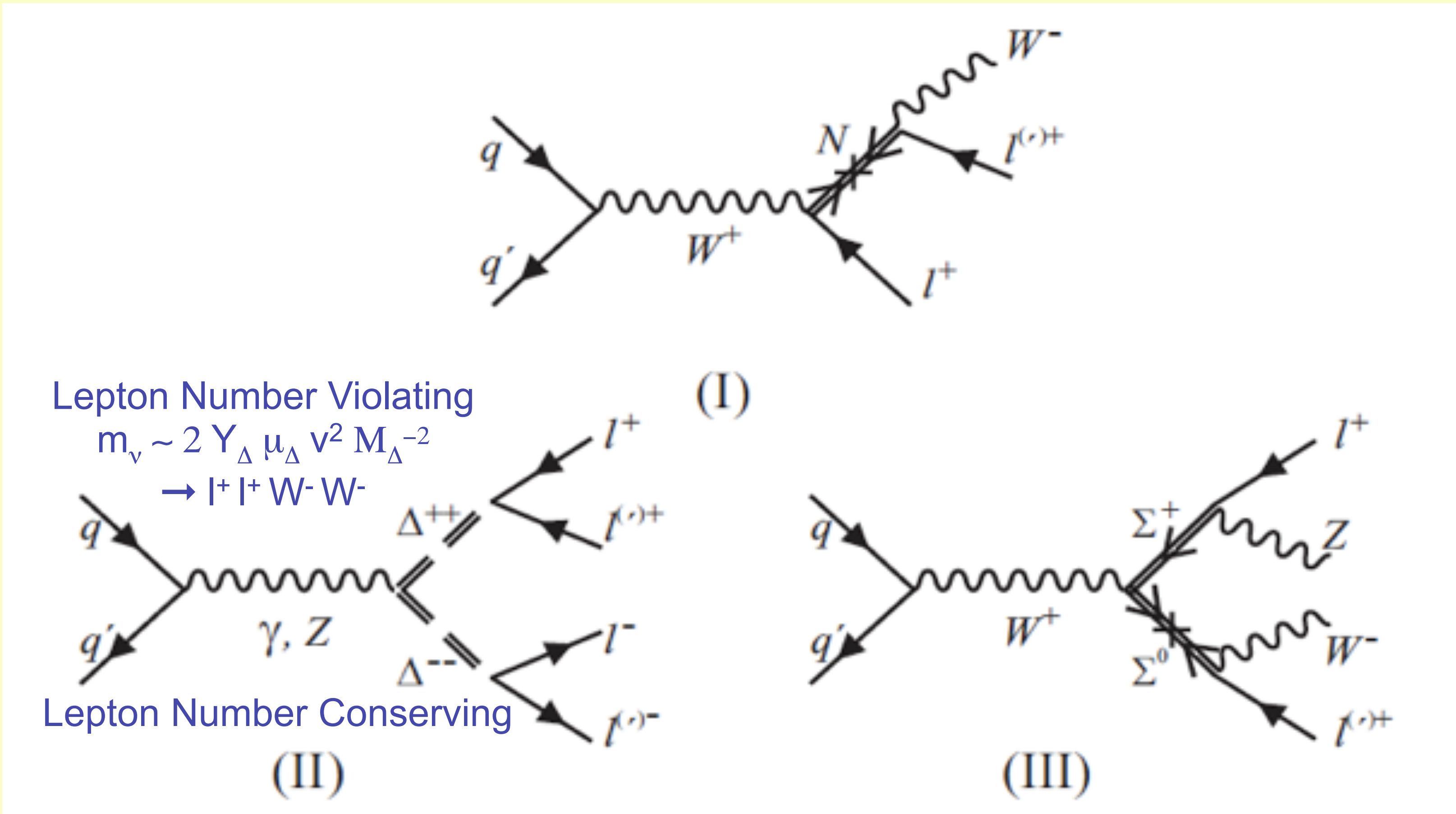
- Many experiments give a consistent picture of non-zero neutrino masses and charged Lepton Flavour transitions

- In contrast with the quark sector the mixing angles are large, and the neutrino masses tiny

- A bottom-up approach leave many questions open, giving further motivation to new experiments

- There are many models which do accommodate the observed pattern, with no apparently favoured scenario

TeV signatures of see-saw messengers: Multilepton signals



Lepton Number Violating

$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$

$\rightarrow l^+ l^+ W^- W^-$

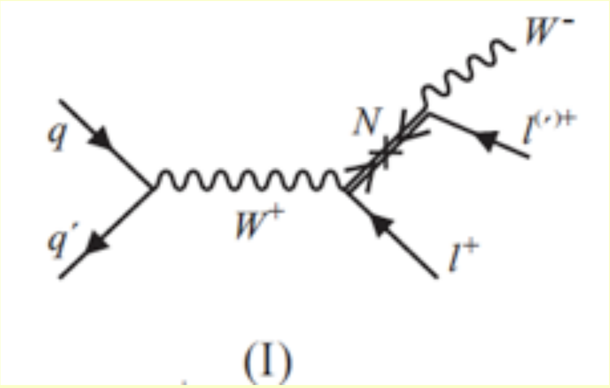
Lepton Number Conserving

LNV signals have smaller backgrounds than LNC ones BUT for a fixed number of final particles. As a matter of fact the significance of trilepton LNC signals is similar to the significance of LNV dilepton signals.

At any rate, multilepton signals are complementary in order to discriminate between models. Scalar and fermion triplets mediating the see-saw mechanism have final states with many leptons (up to 6), as many other new particles at the TeV scale (as, for example, heavy leptons or quarks, or new neutral gauge bosons decaying into them).

Fermion singlet N

$$V_{lN} \simeq \frac{Y_{lN} v}{\sqrt{2} m_N}$$



$$m_\nu \simeq - V_{lN_i}^{*2}\, m_{N_i}$$

The production mechanism is proportional to the mixing between the light leptons and the new heavy neutrino N, as there are the light neutrino masses (if they have a see-saw origin as in the usual MAJORANA case). BUT in the first case enters the specific mixing matrix element and in the second one the combination of all of them and cancellations are possible. Although this can be considered arbitrary in the absence of a symmetry, and unstable because corrections may be large.

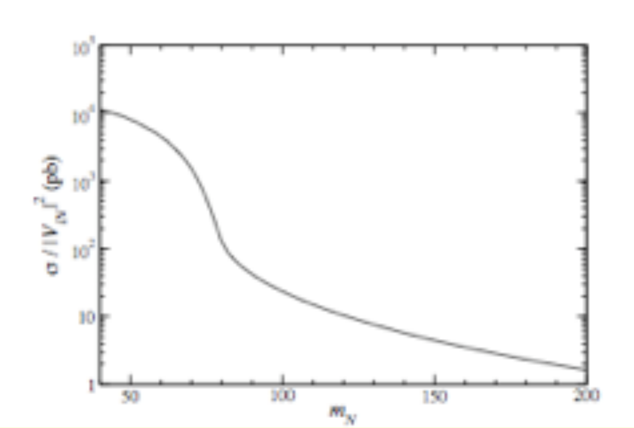
$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left(V_{lN}\, \bar{l} \gamma^\mu P_L N\, W_\mu^- + V_{lN}^*\, \bar{N} \gamma^\mu P_L l\, W_\mu^+\right),$$
$$\mathcal{L}_Z = -\frac{g}{2c_W} \left(V_{lN}\, \bar{\nu}_l \gamma^\mu P_L N + V_{lN}^*\, \bar{N} \gamma^\mu P_L \nu_l\right) Z_\mu,$$
$$\mathcal{L}_H = -\frac{g\, m_N}{2M_W} \left(V_{lN}\, \bar{\nu}_l P_R N + V_{lN}^*\, \bar{N} P_L \nu_l\right) H,$$

90 % C.L.

$|V_{eN}|^2 < 0.003$

$|V_{\mu N}|^2 < 0.0032$

$|V_{\tau N}|^2 < 0.0062$ unobservable



Total cross sections are the same, although the total width for a Majorana neutrino is twice than for a Dirac one

$$q\bar{q}' \to W^* \to l^\pm N,$$

$$q\bar{q} \to Z^* \to \nu N,$$
$$gg \to H^* \to \nu N$$

Overwhelming background

$$N \to \ell W \quad \left\{ \begin{array}{l} \ell^+ N \to \ell^+ \ell^- W^+ \\ \ell^+ N \to \ell^+ \ell^+ W^- \end{array} \right. \left(\begin{array}{l} \to \ell^+ \ell^- \ell^+ \bar{\nu} \\ \to \ell^+ \ell^+ \ell^- \nu \end{array} \right)$$

$\ell^\pm \ell^\pm$ $\ell^\pm \ell^\pm \ell^\mp$

$$q\bar{q} \to Z^* \to NN$$

Too small cross section

Majorana particles give LNV as well as LNC signals, whereas Dirac particles only give LNC ones. In any case there are SM backgrounds.

LNC signals may be more significant than LNV ones

m_N = 100 GeV
$|V|^2$ = 0.003

	$\ell^\pm\ell^\pm\ell^\mp$ (2e)	$\ell^\pm\ell^\pm\ell^\mp$ (2μ)	$\ell^\pm\ell^\pm$ (2e)	$\ell^\pm\ell^\pm$ (2μ)
N (S1,M)	28.6	0	(11.3)	0
N (S1,D)	44.8	0	0.4	0
N (S2,M)	0	29.6	0	(13.4)
N (S2,D)	0	45.8	0	0.5
SM Bkg	116.4	45.6	36.1	20.2

Difference due to kinematics

Table 1: Number of events with 30 fb^{-1} for the Majorana (M) and Dirac (D) neutrino singlet signals in scenarios S1 and S2, and SM background in different final states.

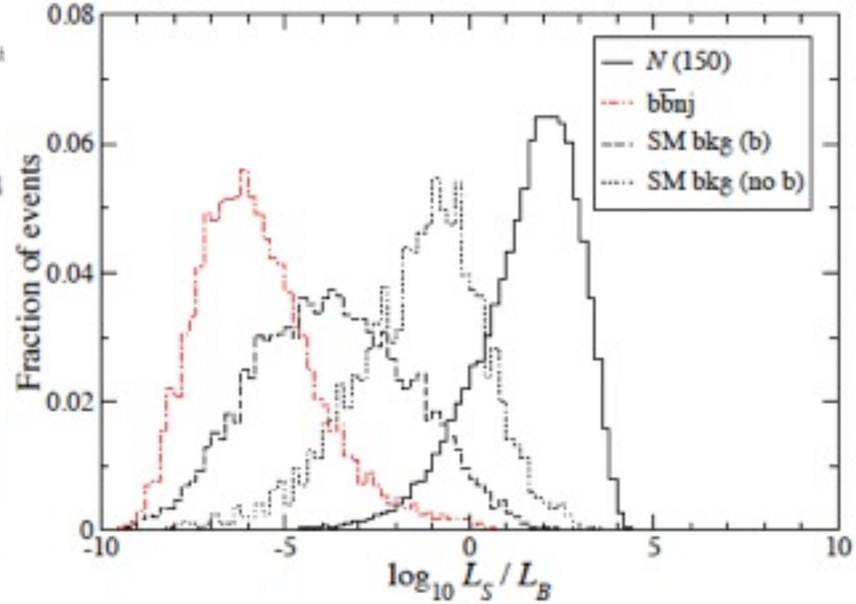
Coupling to e and μ, respectively

Broad dilepton invariant mass distributions

A case for MULTILEPTON searches

	Pre-selection			Selection		
	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$
N (a)	113.6	0	0	(59.1)	0	0
N (b)	0	72.0	0	0	(17.6)	0
N (c)	78.4	25.5	82.6	41.6	4.7	22.4
$b\bar{b}nj$	14800	52000	82000	0	0	0
$c\bar{c}nj$	(11)	300	200	(0)	0	0
$t\bar{t}nj$	1162.1	8133.0	15625.3	2.4	8.3	7.7
tj	60.8	176.5	461.5	0.0	0.0	0.1
$Wb\bar{b}nj$	124.9	346.7	927.3	0.4	0.6	0.3
$Wt\bar{t}nj$	75.7	87.2	166.9	0.3	0.0	0.0
$Zb\bar{b}nj$	12.2	68.9	117.0	0.0	0.2	0.0
$WWnj$	82.8	89.0	174.8	0.5	0.1	0.7
$WZnj$	162.4	252.0	409.2	4.8	1.8	2.3
$ZZnj$	3.8	13.3	12.9	0.0	0.6	0.1
$WWWnj$	31.9	30.1	64.8	0.9	0.1	0.0

Table 1: Number of $\ell^\pm\ell^\pm jj$ events at LHC for 30 fb^{-1}, at the pre-selection and selection levels. The heavy neutrino signal is evaluated assuming $m_N = 150$ GeV and coupling (a) to the muon, $V_{\mu N} = 0.098$; (b) to the electron, $V_{eN} = 0.073$; (c) to both, $V_{eN} = 0.073$ and $V_{\mu N} = 0.098$.



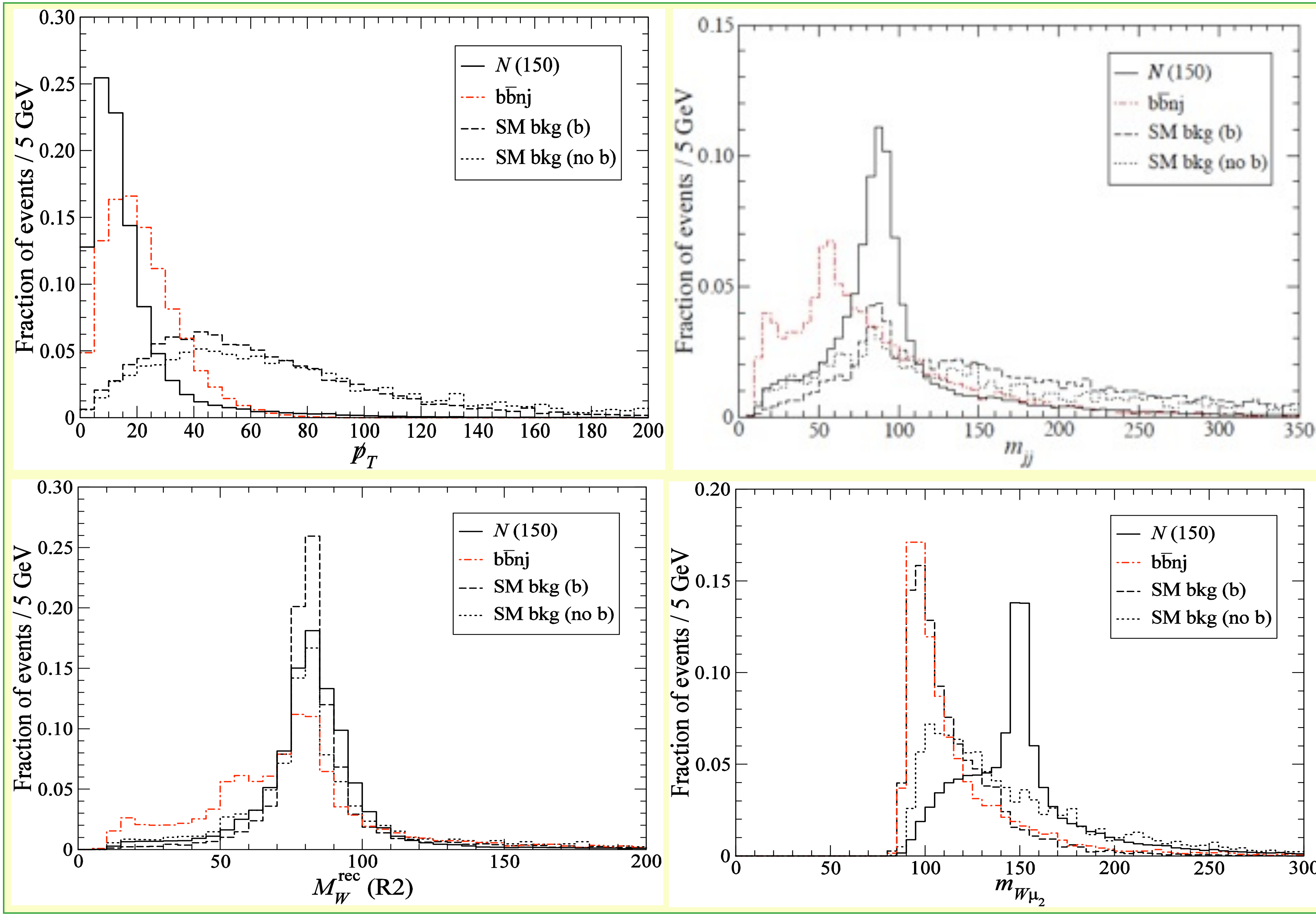
Large backgrounds

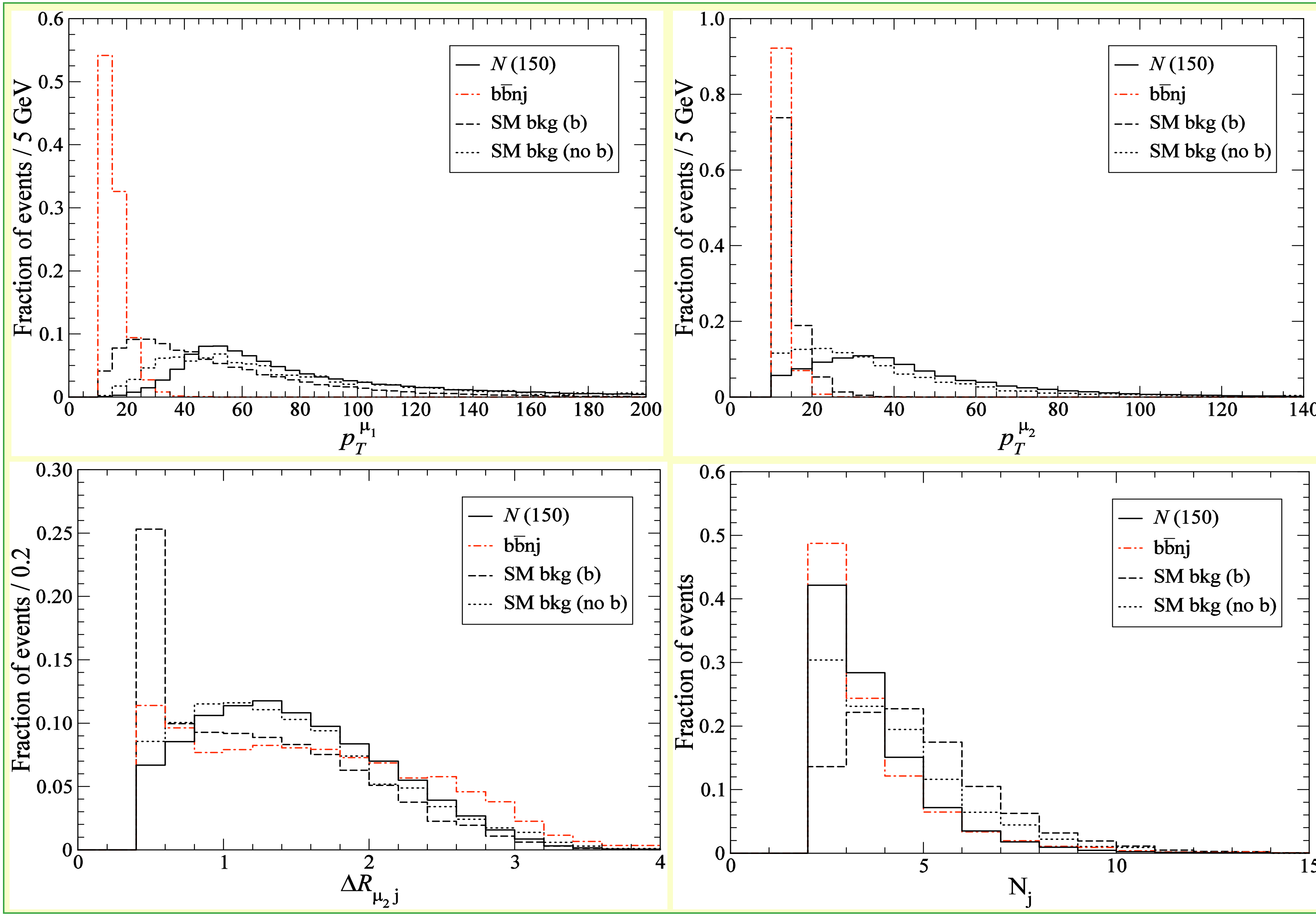
Likelihood analysis with many distributions

Limit on their mass
~ 120 (150) GeV for D (M)

CLIC does better

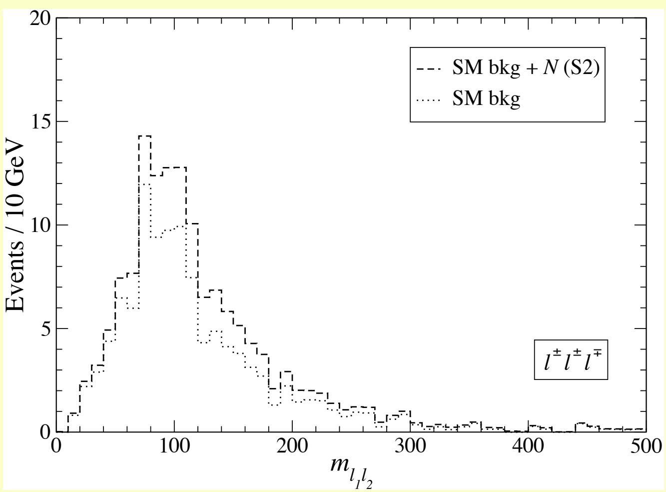
60 GeV neutrino coupling to the muon up to $|V_{\mu N}|^2 = 4.9 \times 10^{-5}$


N (150)
bb̄nj
SM bkg (b)
SM bkg (no b)
Fraction of events / 5 GeV
$\not{p}_T$
m_{jj}
M_W^{rec} (R2)
$m_{W\mu_2}$


N (150)
$b\bar{b}nj$
SM bkg (b)
SM bkg (no b)
Fraction of events / 5 GeV
$p_T^{\mu_1}$
$p_T^{\mu_2}$
Fraction of events / 0.2
$\Delta R_{\mu_2 j}$
Fraction of events
N_j

	Pre-selection		Selection		Impr. selection	
	$2e$	2μ	$2e$	2μ	$2e$	2μ
N (S1)	37.1	0	32.4	0	28.6	0
N (S2)	0	37.8	0	33.1	0	29.6
$t\bar{t}nj$	244.8	78.0	159.8	52.4	58.4	16.3
tW	14.8	3.0	10.5	1.7	6.5	0.6
$Wt\bar{t}nj$	25.6	19.9	20.6	14.5	3.8	2.6
$Zb\bar{b}nj$	17.1	16.2	1.1	0.9	0.5	0.1
$Zt\bar{t}nj$	82.5	69.9	10.3	6.5	2.6	1.1
$WZnj$	2166.4	1947.3	49.2	24.3	36.8	17.8
$ZZnj$	141.0	135.0	2.8	1.4	1.6	1.2
$WWWnj$	10.8	12.0	7.9	8.9	4.7	5.3
$WWZnj$	23.9	18.8	1.1	0.7	0.8	0.4

Preselection



Preselection:

- Three charged leptons (e or μ)
- Same sign leptons with $p_T > 30$ GeV (to reduce b's)

Selection:

- Invariant mass of opposite sign pairs differing from the Z boson mass by at least 10 GeV

Improved selection:

- No b jets
- Like sign leptons back-to-back ($> \pi/2$)

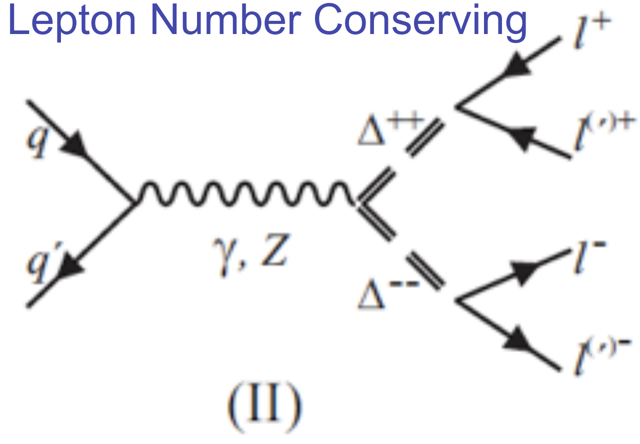
Process	Decay
$t\bar{t}nj$, $n = 0, \ldots, 6$	semileptonic
$t\bar{t}nj$, $n = 0, \ldots, 6$	dileptonic
$b\bar{b}nj$, $n = 0, \ldots, 3$	all
$c\bar{c}nj$, $n = 0, \ldots, 3$	all
tj	$W \to l\nu$
$t\bar{b}$	$W \to l\nu$
tW	all
$t\bar{t}t\bar{t}$	all
$t\bar{t}b\bar{b}$	all
Wnj, $n = 0, 1, 2$	$W \to l\nu$
Wnj, $n = 3, \ldots, 6$	$W \to l\nu$
$Wb\bar{b}nj$, $n = 0, \ldots, 4$	$W \to l\nu$
$Wc\bar{c}nj$, $n = 0, \ldots, 4$	$W \to l\nu$
$Wt\bar{t}nj$, $n = 0, \ldots, 4$	$W \to l\nu$
$Z/\gamma\, nj$, $n = 0, 1, 2$, $m_{ll} < 120$ GeV	$Z \to l^+l^-$
$Z/\gamma\, nj$, $n = 3, \ldots, 6$, $m_{ll} < 120$ GeV	$Z \to l^+l^-$
$Z/\gamma\, nj$, $n = 0, \ldots, 6$, $m_{ll} > 120$ GeV	$Z \to l^+l^-$
$Zb\bar{b}nj$, $n = 0, \ldots, 4$	$Z \to l^+l^-$
$Zc\bar{c}nj$, $n = 0, \ldots, 4$	$Z \to l^+l^-$
$Zt\bar{t}nj$, $n = 0, \ldots, 4$	$Z \to l^+l^-$
$WWnj$, $n = 0, \ldots, 3$	$W \to l\nu$
$WZnj$, $n = 0, \ldots, 3$	$W \to l\nu$, $Z \to l^+l^-$
$ZZnj$, $n = 0, \ldots, 3$	$Z \to l^+l^-$
$WWWnj$, $n = 0, \ldots, 3$	$2W \to l\nu$
$WWZnj$, $n = 0, \ldots, 3$	all
$WZZnj$, $n = 0, \ldots, 3$	all
$ZZZnj$, $n = 0, \ldots, 3$	$2Z \to l^+l^-$

ALPGEN for the backgrounds (interfaced to PYTHIA using the MLM prescription)

Signals calculated with a Monte Carlo generator (TRIADA -for triplets-, ALPGEN -for singlets-) using HELAS (width and spin), VEGAS (phase space integration), interface to PYTHIA (ISR and FSR, pile-up, and hadronisation), and AcerDET (fast LHC detector simulation)

Scalar triplet Δ

Lepton Number Conserving



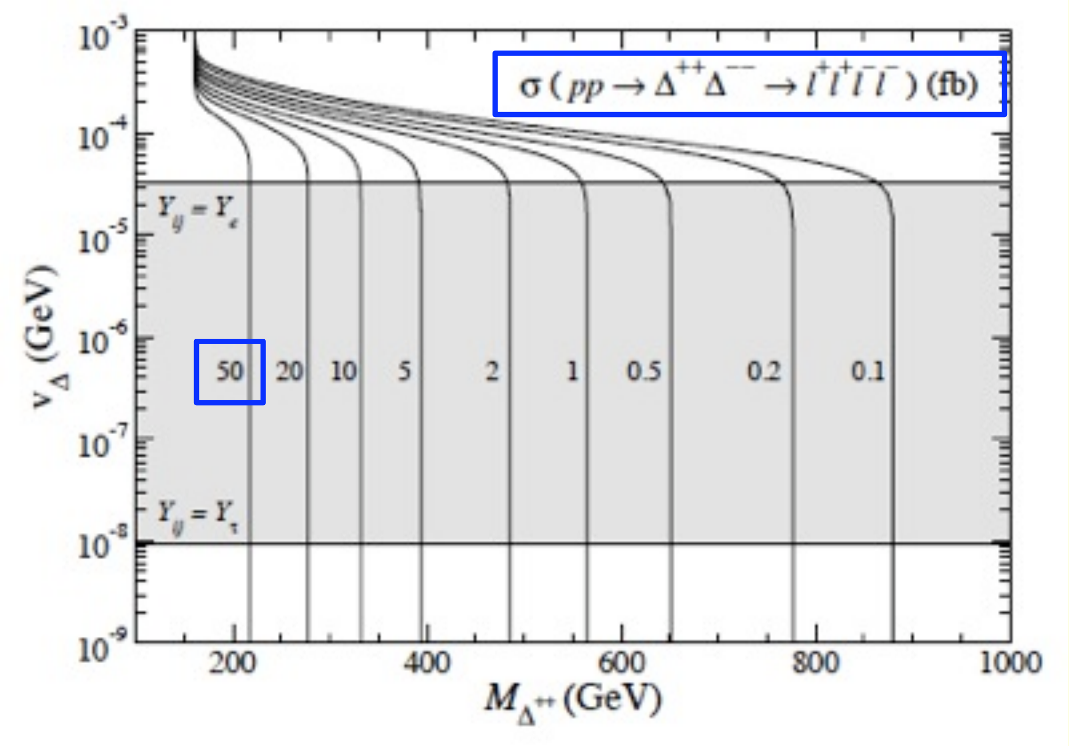
$$v_\Delta = \frac{v^2|\mu_\Delta|}{\sqrt{2}M_\Delta^2} < 2 \text{ GeV}$$

EWPD

Lepton Number Violating

$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$

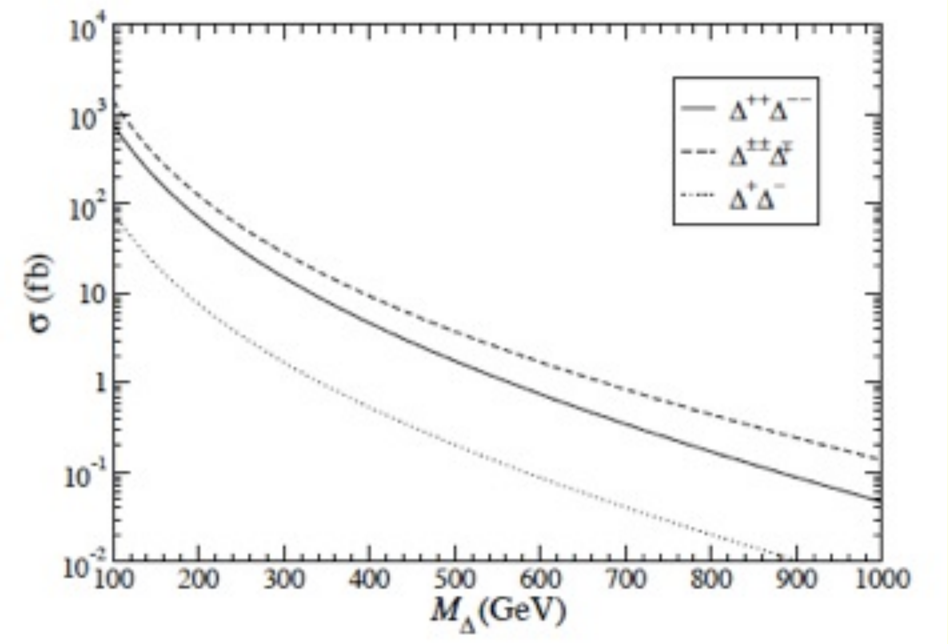
$\rightarrow l^+ l^+ W^- W^-$



F. del Águila
Universidad de Granada

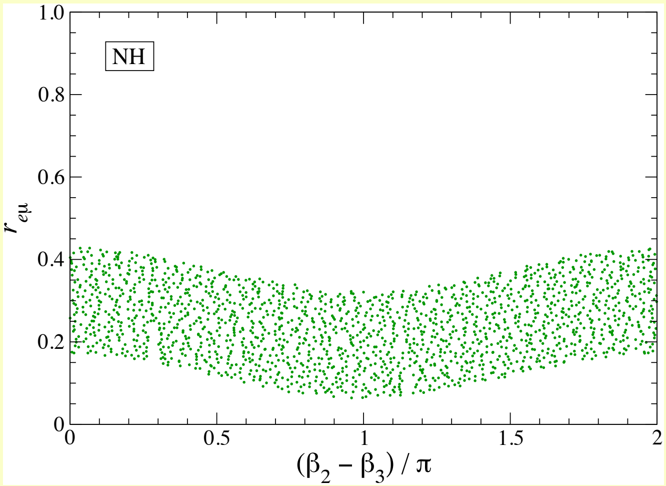
$$\mathcal{L}_{K.T.} = (D^\mu \vec{\Delta})^\dagger \cdot (D_\mu \vec{\Delta}) \ \rightarrow$$

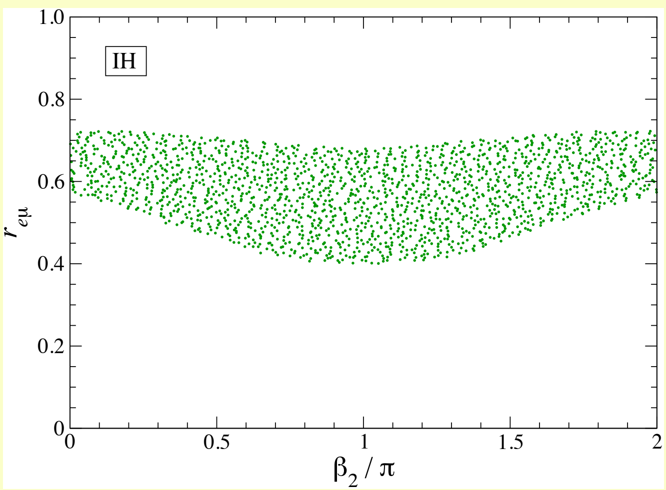
$$\begin{aligned}
\mathcal{L}_W &= -ig\left[(\partial^\mu \Delta^{--})\Delta^{+} - \Delta^{--}(\partial^\mu \Delta^{+})\right] W^+_\mu\,, \\
&\quad -ig\left[(\partial^\mu \Delta^{-})\Delta^{++} - \Delta^{-}(\partial^\mu \Delta^{++})\right] W^-_\mu\,, \\
\mathcal{L}_Z &= \frac{ig}{c_W}(1-2s_W^2)\left[(\partial^\mu \Delta^{--})\Delta^{++} - \Delta^{--}(\partial^\mu \Delta^{++})\right] Z_\mu \\
&\quad -\frac{ig}{c_W}s_W^2\left[(\partial^\mu \Delta^{-})\Delta^{+} - \Delta^{-}(\partial^\mu \Delta^{+})\right] Z_\mu\,, \\
\mathcal{L}_\gamma &= i2e\left[(\partial^\mu \Delta^{--})\Delta^{++} - \Delta^{--}(\partial^\mu \Delta^{++})\right] A_\mu \\
&\quad +ie\left[(\partial^\mu \Delta^{-})\Delta^{+} - \Delta^{-}(\partial^\mu \Delta^{+})\right] A_\mu\,.
\end{aligned}$$



Δ BR's into leptons are a high energy window to neutrino masses and mixings, and may even allow for reconstructing the MNS matrix.

$$r_{e\mu} \equiv \mathrm{Br}(\Delta^{\pm\pm} \to e^\pm e^\pm / \mu^\pm \mu^\pm / e^\pm \mu^\pm)$$





They depend on the neutrino masses and mixings, being the main dependance on α_2 (in the plots $\beta_2 - \beta_3$ and β_2, respectively. We assume in our simulations:

F.A. and J.A. Aguilar-Saavedra,
Nucl. Phys. B813 (2009) 22

	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$\mu^\pm \tau^\pm$	$\tau^\pm \tau^\pm$
NH	0.00	0.20	0.49	0.29
IH	0.50	0.15	0.25	0.10

A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane,
B. Nucl. Phys. B787 (2007) 198

J. Garayoa and T. Schwetz,
JHEP 0803 (2008) 009

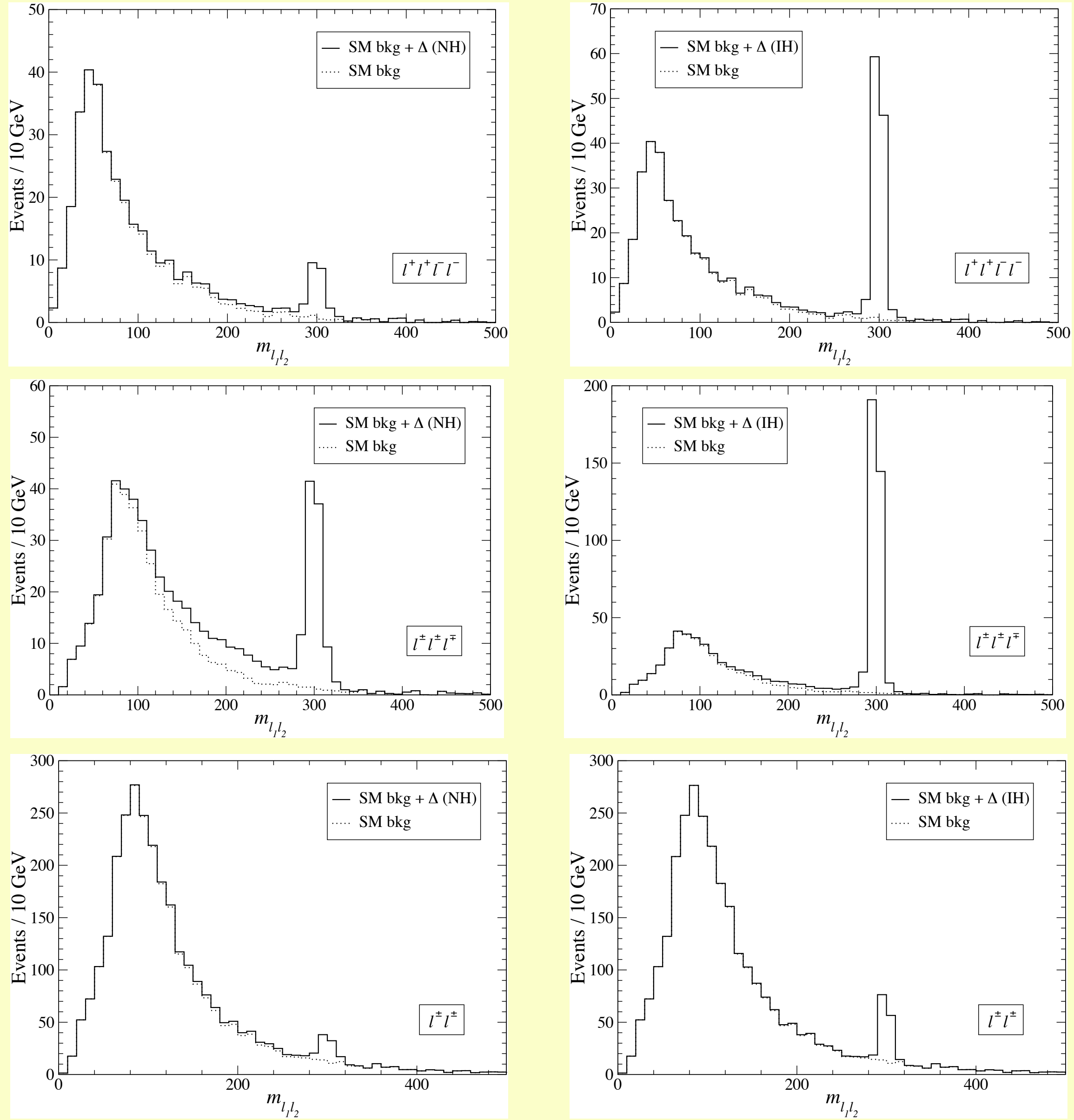
P. Fileviez Perez, T. Han, G.-Y. Huang, T. Li and K. Wang,
Phys. Rev. D78 (2008) 015018

$\ell_1\ell_2$ invariant mass distribution for the SM and the SM plus the triplet signal in the cases of NH (left) and IH (right).

30 fb^{-1} for m_Δ = 300 GeV

LHC reach

Δ: 600 (800) GeV for NH (IH)



Fermion triplet Σ

See Juan Antonio A.-S.'s talk for this case and comparison with other new particles

Summary of the LHC reach (30 fb^{-1} and 14 TeV)

N: 120 (150) GeV for D / M coupling to e (μ)

Δ: 600 (800) GeV for NH (IH)

Σ: 750 (700) GeV for Majorana (Dirac) coupling to e or μ

Non-standard neutrino interactions

$$\mathcal{L}^{M}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}[\bar{f}\gamma^\mu P f][\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta]$$

$$|\varepsilon^{\mu e}_{\alpha\beta}| < \begin{pmatrix} 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \end{pmatrix},$$

$$|\varepsilon^{ud}_{\alpha\beta}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \begin{smallmatrix}1.8\cdot 10^{-6}\\ 0.026\end{smallmatrix} & 0.078 & 0.013 \\ \begin{smallmatrix}0.11\\ 0.13\end{smallmatrix} & \begin{smallmatrix}0.016\\ 0.022\end{smallmatrix} & 0.13 \end{pmatrix},$$

$$|\varepsilon^{e}_{\alpha\beta}| < \begin{pmatrix} \begin{smallmatrix}0.06\\ 0.14\end{smallmatrix} & 0.10 & \begin{smallmatrix}0.4\\ 0.27\end{smallmatrix} \\ 0.10 & 0.03 & 0.10 \\ \begin{smallmatrix}0.4\\ 0.27\end{smallmatrix} & 0.10 & \begin{smallmatrix}0.16\\ 0.4\end{smallmatrix} \end{pmatrix},$$

In general the dimension 6 operators must have coefficients not much larger than 1 % (taking one at a time)

See Belén G.'s talk (and collaborators)

$\varepsilon^{\mu e}_{\alpha\beta}$	**Kin.** G_F (L,R)	**CKM unit.** (V)	**Lept. univ.** (A)	**Oscillation** (L,R)
$\varepsilon^{\mu e}_{ee}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{e\mu}$	$(-1.4 \pm 1.4) \cdot 10^{-3} (\mathbb{R}, L)$ < 0.030	$< 4 \cdot 10^{-4} (\mathbb{R})$ < 0.030	$(-0.4 \pm 3.5) \cdot 10^{-3} (\mathbb{R})$ < 0.080	-
$\varepsilon^{\mu e}_{e\tau}$	< 0.030	< 0.030	< 0.080	< 0.087
$\varepsilon^{\mu e}_{\mu e}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{\mu\mu}$	< 0.030	< 0.030	< 0.080	-
$\varepsilon^{\mu e}_{\mu\tau}$	< 0.030	< 0.030	< 0.080	< 0.087
$\varepsilon^{\mu e}_{\tau e}$	< 0.030	< 0.030	< 0.080	< 0.025
$\varepsilon^{\mu e}_{\tau\mu}$	< 0.030	< 0.030	< 0.080	-
$\varepsilon^{\mu e}_{\tau\tau}$	< 0.030	< 0.030	< 0.080	< 0.087

$$|\varepsilon^u_{\alpha\beta}| < \begin{pmatrix} \substack{1.0 \\ 0.7} & 0.05 & 0.5 \\ 0.05 & \substack{0.003 \\ 0.008} & 0.05 \\ 0.5 & 0.05 & \substack{1.4 \\ 3} \end{pmatrix}$$

$$|\varepsilon^d_{\alpha\beta}| < \begin{pmatrix} \substack{0.3 \\ 0.6} & 0.05 & 0.5 \\ 0.05 & \substack{0.003 \\ 0.015} & 0.05 \\ 0.5 & 0.05 & \substack{1.1 \\ 6} \end{pmatrix}$$

$\varepsilon^{ud}_{\alpha\beta}$	CKM unit. (V)	Lept. univ. (A)	Oscillation	Loop (L)
ε^{ud}_{ee}	$< 8.6 \cdot 10^{-4}(\mathbb{R})$ < 0.041	$(-2.1 \pm 2.6) \cdot 10^{-3}(\mathbb{R})$ < 0.045	-	-
$\varepsilon^{ud}_{e\mu}$	< 0.041	< 0.045	$< 0.028(A)$ $< 0.059(V)$ $< 0.032(L)$ $< 0.045(R)$	-
$\varepsilon^{ud}_{e\tau}$	< 0.041	< 0.045	-	-
$\varepsilon^{ud}_{\mu e}$	-	< 0.078	$< 0.026(A)$	$< 1.8 \cdot 10^{-6}$
$\varepsilon^{ud}_{\mu\mu}$	-	$(2.1 \pm 2.6) \cdot 10^{-3}(\mathbb{R})$ < 0.078	-	-
$\varepsilon^{ud}_{\mu\tau}$	-	< 0.078	$< 0.013(A)$	-
$\varepsilon^{ud}_{\tau e}$	-	< 0.13	$< 0.11(L)$ $< 0.15(R)$	- -
$\varepsilon^{ud}_{\tau\mu}$	-	< 0.13	$< 0.016(L)$ $< 0.022(R)$	- -
$\varepsilon^{ud}_{\tau\tau}$	-	$(3.0 \pm 5.5) \cdot 10^{-3}(\mathbb{R})$ < 0.13	-	-

Summary

• Many experiments give a consistent picture of non-zero neutrino masses and charged Lepton Flavour transitions

• In contrast with the quark sector the mixing angles are large, and the neutrino masses tiny

• A bottom-up approach leave many questions open, giving further motivation to new experiments

• There are many models which do accommodate the observed pattern, with no apparently favoured scenario given the preferred hipotheses

• LHC may observed see-saw messengers below ~ 700 GeV studying multilepton channels, which are the main signatures for many other new particles

• Indirect limits constrain new physics relevant for neutrino oscillation experiments typically below 1 % (at the amplitude level), making their effects hardly visible

Thanks for your attention