LFV and Dirac-ness of massive neutrinos composed of Majorana states

Janusz Gluza (Silesia U.)

In collaboration with:

Tomasz Jeliński, Magdalena Kordiaczyńska (Silesia U.)
Robert Szafron (Alberta U.)

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Introduction

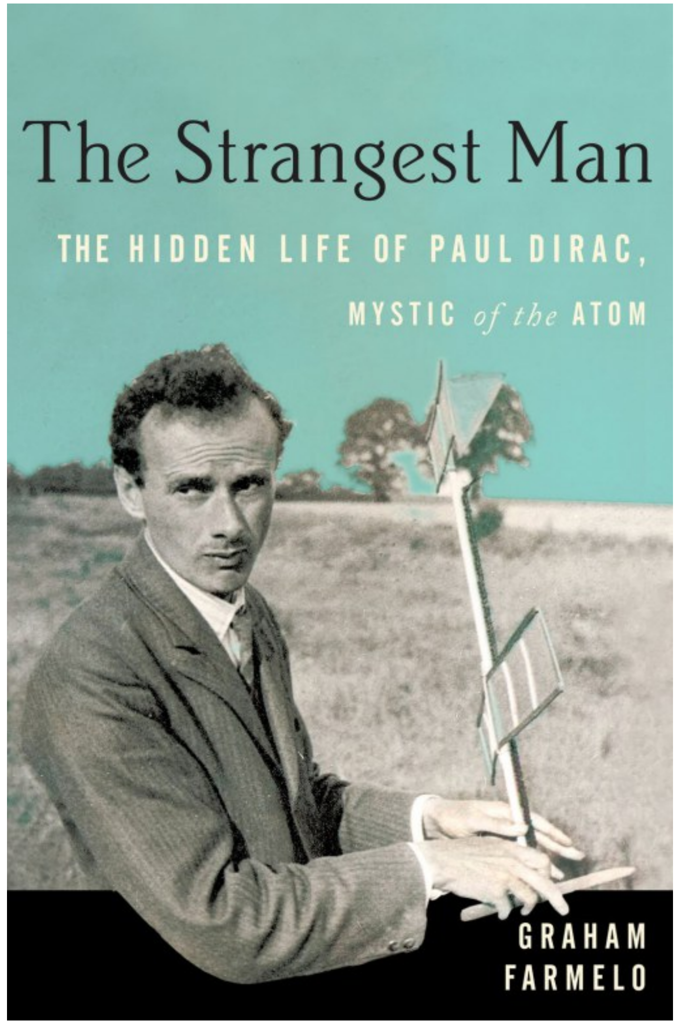
1. Introduction: Dirac vs Majorana

2. Neutrinos with masses below M_W, M_Z

3. Heavy neutrinos (HN) and right-handed currents (RHC) in $pp \to lljj$ (LHC, ...)

4. $pp \to lljj$ and low energy constraints

5. HN, RHC and the Universe.



"... I felt extremely embarrassed, like I was witnessing a friend pouring out his most terrible secrets to his psychiatrist", Kurt Hofer

Majorana

Majorana returns, Frank Wilczek, Nature Physics 5, 614 - 618 (2009)

Today: Majorana fermions in particle physics ($\beta\beta_{0\nu}$, supersymmetry, dark matter), solid state, quantum statistics (qubits)

Fermi:
”... there are the geniuses, like Galileo and Newton. Well Ettore Majorana was one of them.”

”Majorana had greater gifts than anyone else in the world. Unfortunately he lacked one quality which other men generally have: plain common sense.”

and more...

FIELDS:

Weyl, Dirac, Majorana - textbooks

pseudo/quasi-Dirac, sterile, active, schizophrenic, vanilla ... - specialized papers

MASS generation mechanisms:

see-saw type-I [Minkowski (1977), Gell-Mann et al (1979), Yanagida, Mohapatra (1980)],
type-II [Magg, Wetterich, ... (1980)]
type-III [Foot et al (1989)]
type-IV [Type-IV Seesaw Mechanism and CP Violation for Leptogenesis, E.T. Franco, arXiv:1510.06240],
inverse see-saw [Mohapatra, PRL, 1986],
radiative generation (last Nobel prize: that neutrinos are massive does not mean that other heavy neutrino states exist!)

A few words on Majorana vs Dirac in theory

- Bilenky, Petcov, Rev. Mod.Phys. (1986), plus textbooks

- "For the left-handed interacting neutrino, differences in all observables for the Dirac and Majorana neutrino smoothly vanish for $m_\nu \to 0$".
  "Practical Dirac-Majorana Confusion Theorem", Kayser, Shrock (1982)

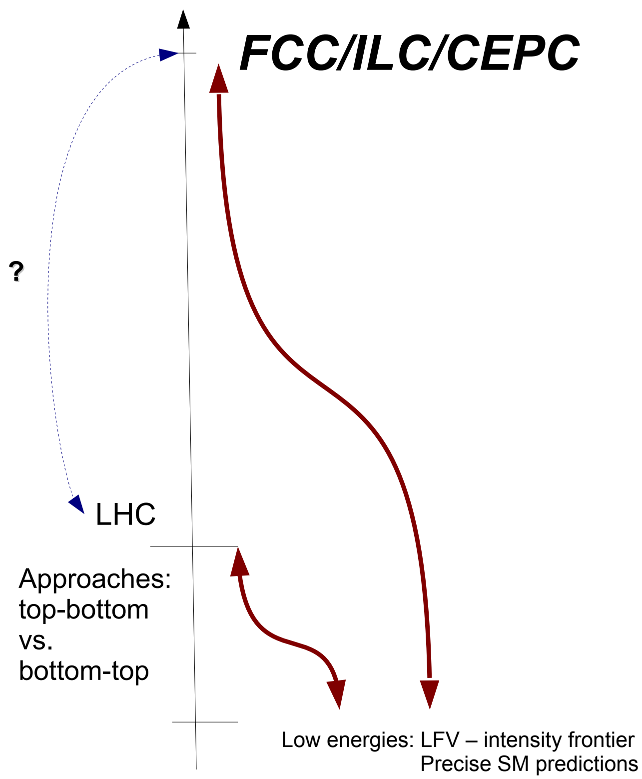
  In other words, in "terrestrial" experiments, non standard effects (NP) (e.g. connected with "wrong" helicity")

$$\mathrm{NP} \propto \frac{m_\nu}{M_W, E}$$

  also:
  Czakon, JG, Zralek, APPB (1999)
  Zralek, APPB (1997)

Dirac, Majorana $\to$ Weyl with $m_\nu \to 0$

Neutrino masses:
From the lowest to the high(est) energies and back



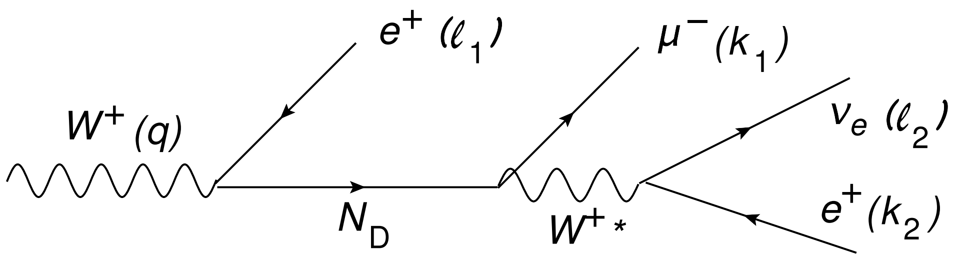
What matters in dynamical processes (scatterings): $m_\nu >> MeV \to GeV \to TeV$

This talk: $pp \to lljj$

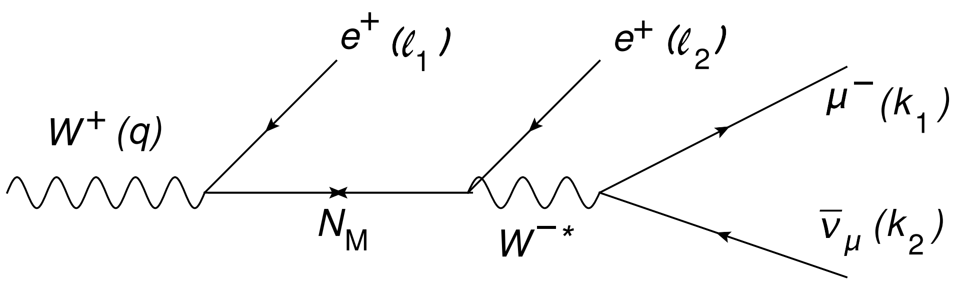
Discovering sterile Neutrinos ligther than M_W at the LHC

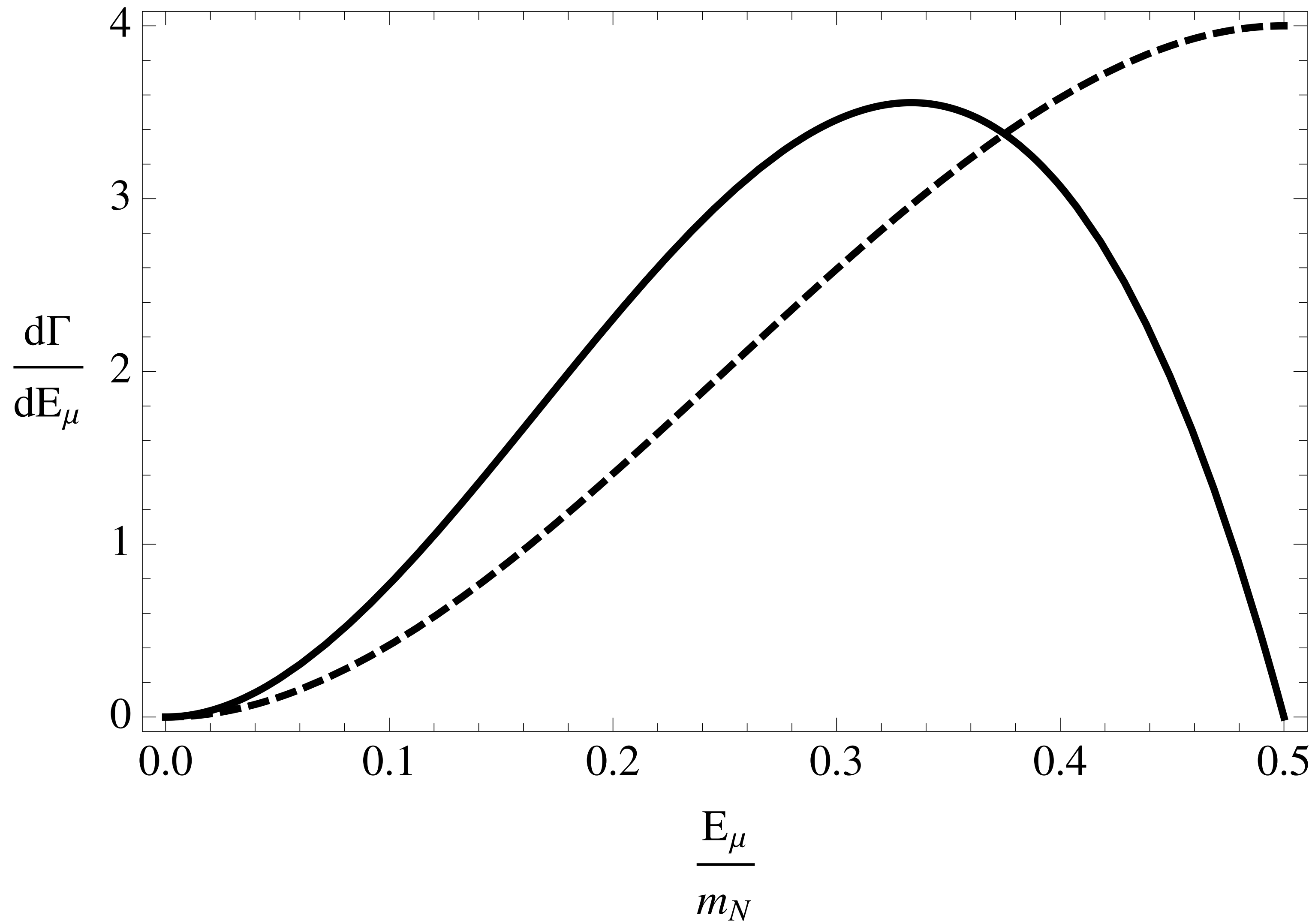
Dib, Kim, arXiv:1509.05981

- $W^+ \to e^+\mu^- e^+\nu_e$ (Dirac) - LFV, not LNV



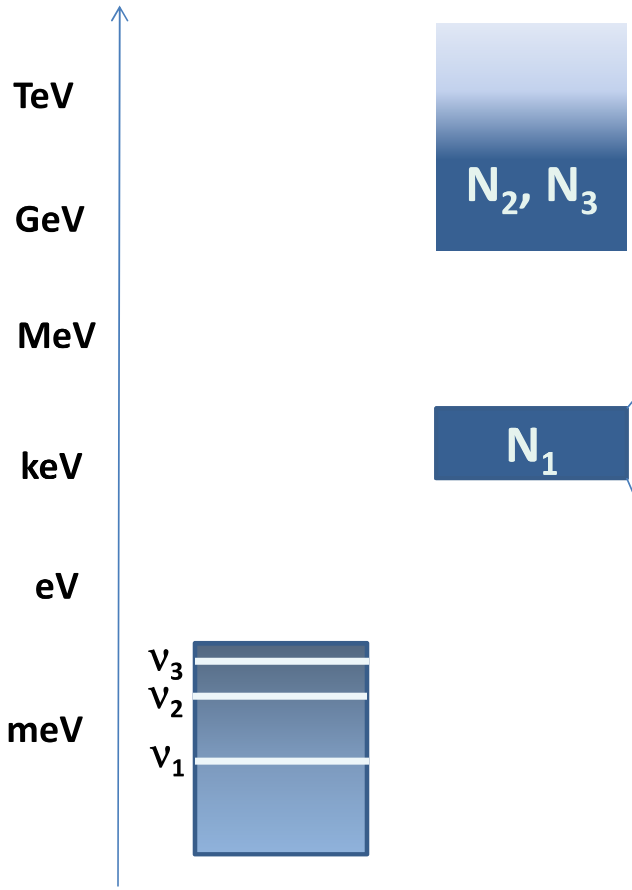
- $W^+ \to e^+e^+\mu^-\bar{\nu}_\mu$ (Majorana) - LFV and LNV





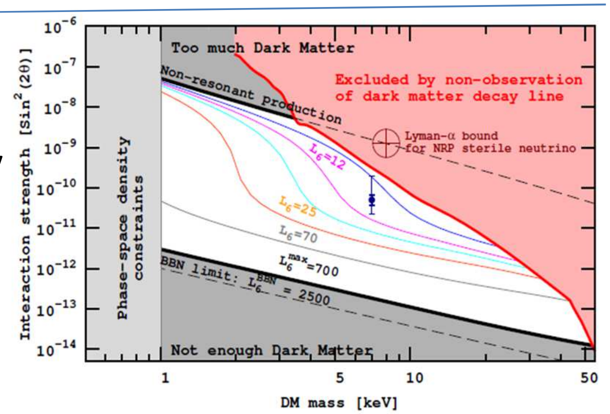
4
3
2
1
0
$\frac{d\Gamma}{dE_\mu}$
0.0
0.1
0.2
0.3
0.4
0.5
$\frac{E_\mu}{m_N}$

Another spectrum: GigaZ



can generate Baryon Asymmetry of Universe
if $m_{N2,N3}$ > 140 MeV

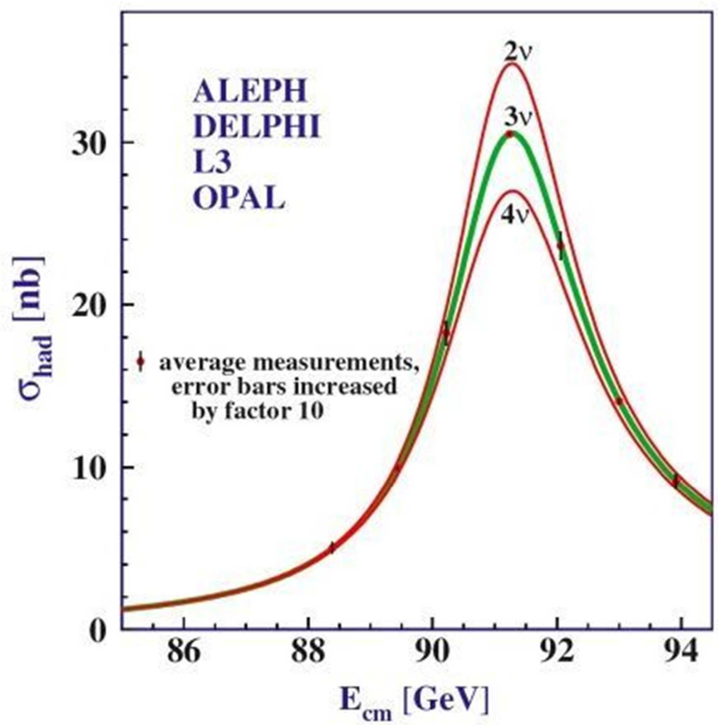
constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$



$N_1 \rightarrow \nu\,\gamma$ *may* have been seen:
arxiv:1402:2301 and arxiv:1402.4119

Blondel et al 1411.5230

$$n_\nu \equiv \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)^{meas} \Big/ \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{lept}}\right)^{SM}$$



$$N_\nu = 2.9840 \pm 0.0082 \quad ALEPH,\ 2005$$

LHC-1 excess data

A few deviations from the SM predictions in invariant mass distributions near 2 TeV:

(i) a 3.4σ excess at ∼2 TeV in the ATLAS search interpreted as a W' boson decaying into $WZ \to jj$, The mass range with significance above 2σ is ~ 1.9–2.1 TeV; the global significance is 2.5σ - see pdf.

(ii) A CMS search for jj resonances without distinguishing between the W- and Z-tagged jets, a 1.4σ excess at ∼1.9 TeV - see pdf

(iii)

a 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search for a W' and a heavy "right-handed" neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process - see pdf

(iv) a 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$ - see pdf

(v) a $\sim 2\sigma$ excess at ~ 1.8 TeV in the CMS dijet resonance search - see pdf. The ATLAS search in the same channel has yielded only a 1σ excess at 1.8 TeV - see pdf

Theory vs experiment

Three examples:

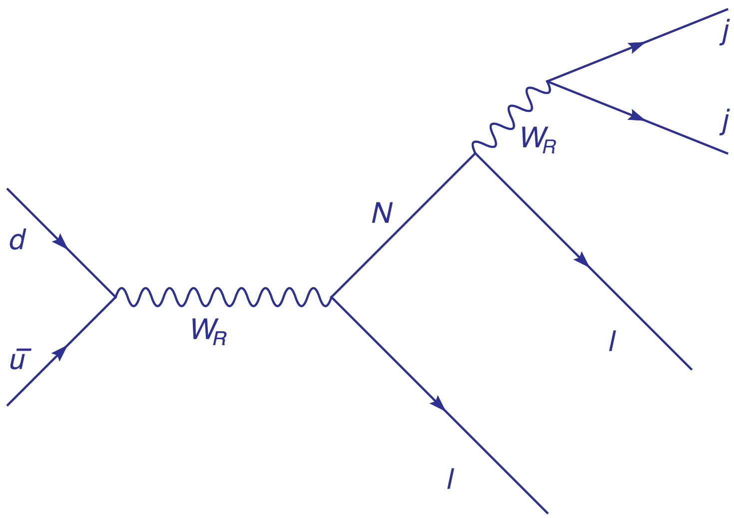
(i) "Symmetry Restored in Dibosons at the LHC?" [Brehmer et al., arXiv:1507.00013]

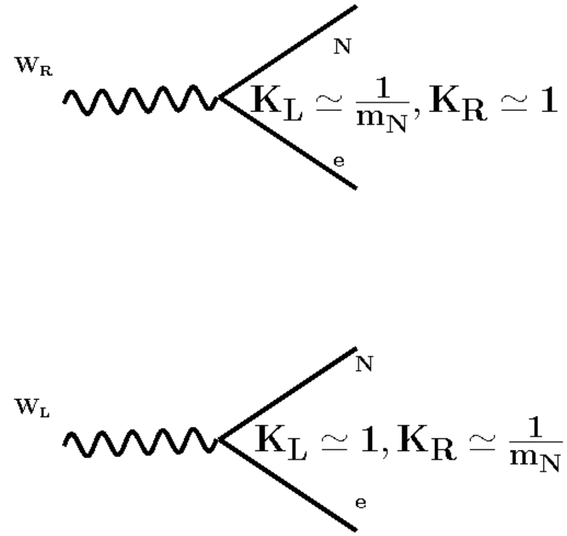
(ii) "Reconciling the 2 TeV Excesses at the LHC in a Linear Seesaw Left-Right Model" [Deppisch et al., arXiv:1508.05940]

(iii) "Unified explanation of the $eejj$, diboson and dijet resonances at the LHC" [Bhupal Dev and Mohapatra, arXiv:1508.02277]

In (ii) linear see-saw is favorable, in (iii) inverse see-saw is favorable over type I see-saw

Extra gauge bosons, heavy neutrinos: Golden Event





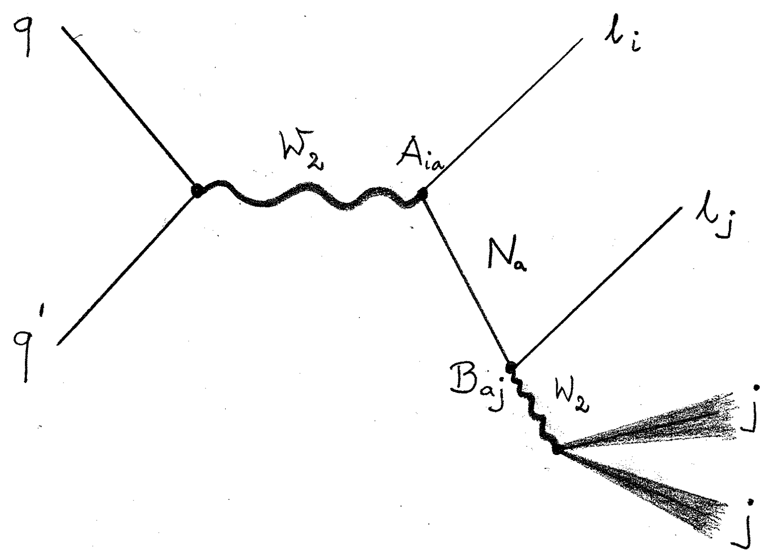
For right-handed charged currents there is no damping factors like $\sin(\ xi)$
$[W_L - W_R$ mixing]
and/or [light state]-[heavy neutrino] mixing, K_R right- (~ 1)

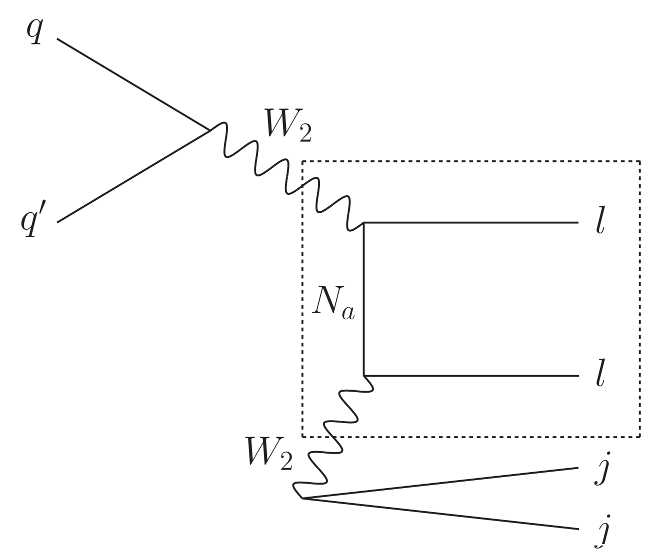
for more discussion on couplings, see e.g. JG, Zralek, PRD48, 1993, JG, APPB33, 2002

What is surprising about the CMS LHC1 data on $pp \to lljj$?

1. Ratio of opposite-sign (OS) $pp \to e^{\pm}e^{\mp}jj$ to the same-sign (SS) $pp \to e^{\pm}e^{\pm}jj$ leptons:

$$r_{CMS} = \frac{N_{SS}}{N_{OS}} = \frac{1}{13},$$





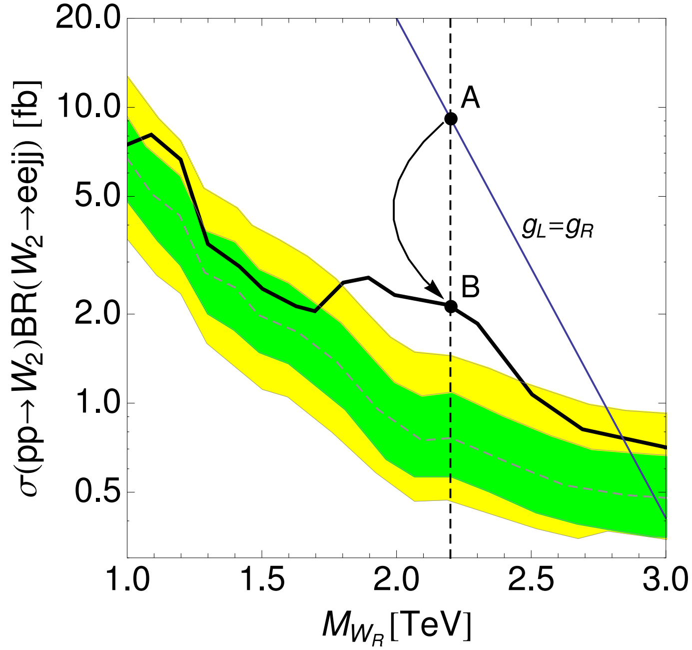
Almost no lepton number violation! Dirac/Pseudo-Dirac heavy neutrinos

Q: What should we expect for Majorana/Dirac neutrinos?

In addition:

2. No excess in the $\mu\mu$ channel

3. Overall excess in $eejj$ production (point B), interpreted by CMS with $g_L = g_R$ (point A)



ATLAS case!

Only SS leptons considered - assumption of Majorana neutrinos

Keung, Senjanovic 1983 paper ...

For Majorana neutrinos the same number of SS and OS events is expected,
and
as CMS indicates strongly that $r << 1$,
then
Dirac-type of neutrinos must be involved.

ATLAS casus:

If no SS signals are found, then possibility that neutrinos are of Dirac type is missed.

And this seems to be exactly the ATLAS collaboration case.

see, Dobrescu et al, arXiv:1508.04129
- they assume $r = 0$ and pure Dirac neutrinos

How to explain CMS excess data with/without RHC?

However, in this way conclusions can be distorted or even some interesting and natural scenarios can be overlooked.

- supersymmetric models,...
- RHC, $A \to B$: $g_R < g_L$
- RHC, $A \to B$: take into account interferences among neutrino states

At LHC analysis are simplified: degenerated heavy neutrinos, no HN mixings

Our point of view:

'Heavy neutrinos and the $pp \to lljj$ CMS data," JG and T. Jeliński,
PLB **748** (2015) 125, e-Print: arXiv:1504.05568

All the above facts can be reconciled with data if RHC with heavy neutrinos with CP phases and mixings are taken into account

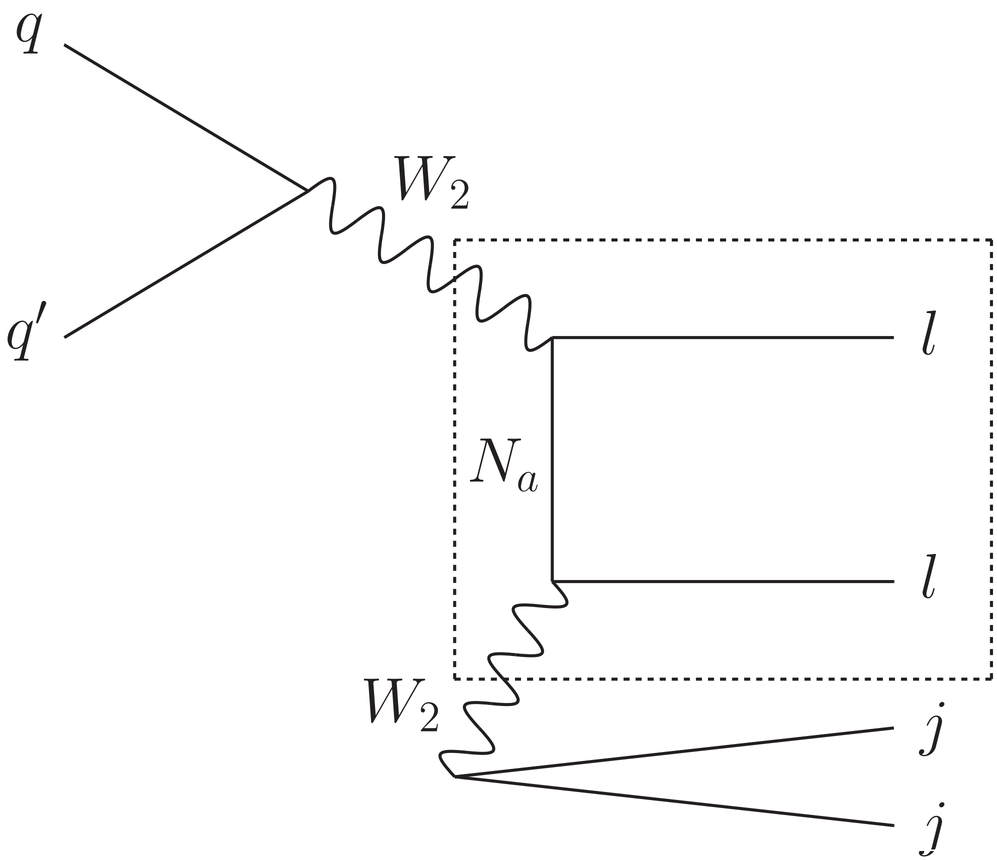
$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \sum_{a=1}^{3} \overline{\nu}_a \gamma^\mu P_L (U_{PMNS})_{aj} l_j W_{1\mu}^+ + \text{h.c.}$$
$$+ \frac{\tilde{g}}{\sqrt{2}} \sum_{a=1}^{3} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W_{2\mu}^+ + \text{h.c.}$$

e.g.

$$M_{N_{1,3}} = 0.925\,\text{TeV}, \quad M_{N_2} = 10\,\text{TeV}, \quad K_R = \begin{pmatrix} \cos\theta_{13}\ [1] & 0 & \sin\theta_{13} [0] \\ 0 & 1 & 0 \\ -e^{i\phi_3}\sin\theta_{13}\ [0] & 0 & e^{i\phi_3}\cos\theta_{13}\ [1] \end{pmatrix}.$$

$$\mathcal{L}_{\mathcal{RHC}} = \overbrace{\left(\cos\theta_{13}\overline{N}_1 - e^{i\phi_3}\sin\theta_{13}\overline{N}_3\right)}^{N_{eff}} \frac{\tilde{g}}{\sqrt{2}} \gamma^\mu P_R (K_R)_{aj} l_j W_{2\mu}^+$$

Dirac composed of Majorana

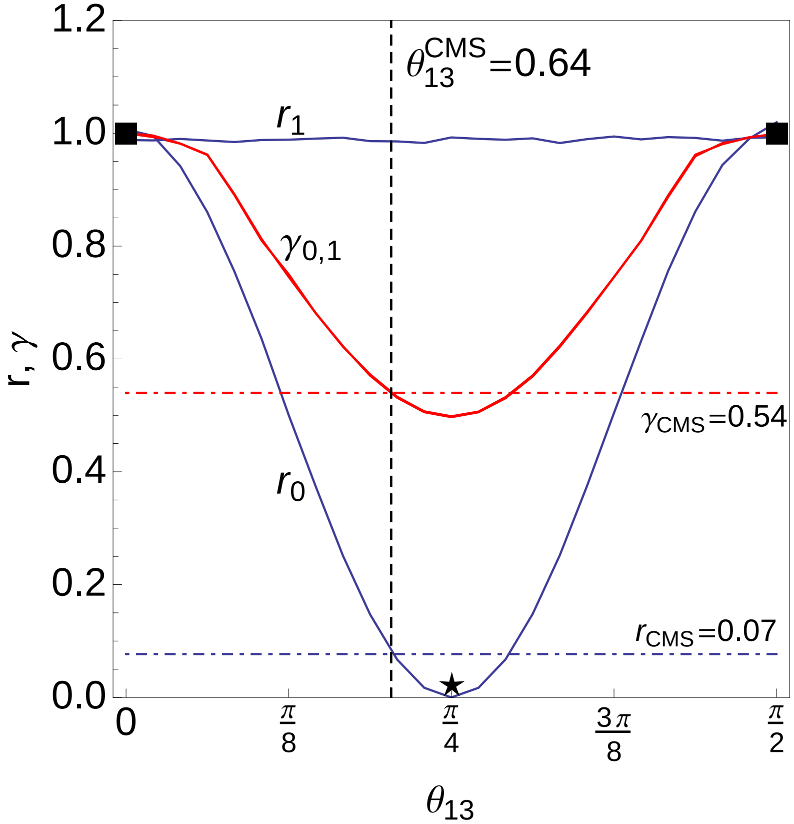


$$N_D = \frac{1}{\sqrt{2}}(N_1 + iN_2)$$

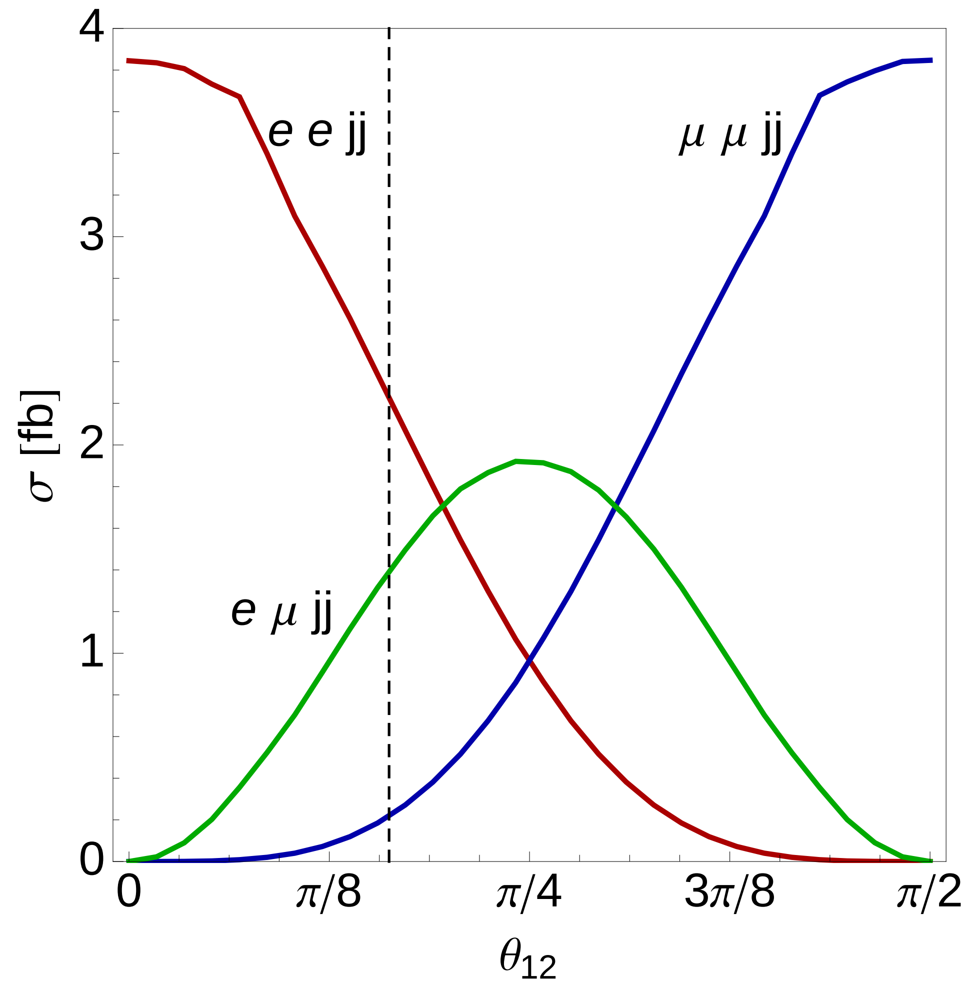
Destructive interferences among Majorana neutrinos (mixings and CP-phases) lead to LFC

$$\text{Amplitude} \sim \sum_i K_R^2 \, \text{FUN}(M_i, ...) \longrightarrow 0$$

$$pp \to eejj, \quad \Gamma_{N_{1,3}} = \mathcal{O}(MeV), M_{N_{1,3}}\mathcal{O}(TeV), \phi = \pi/2$$



γ - a factor by which LR cross section has to be reduced to fit the CMS data
$r = SS/OS$
r_1: $\Delta M_{13} = 1$ GeV mass splitting between M_{N_1} and M_{N_3}



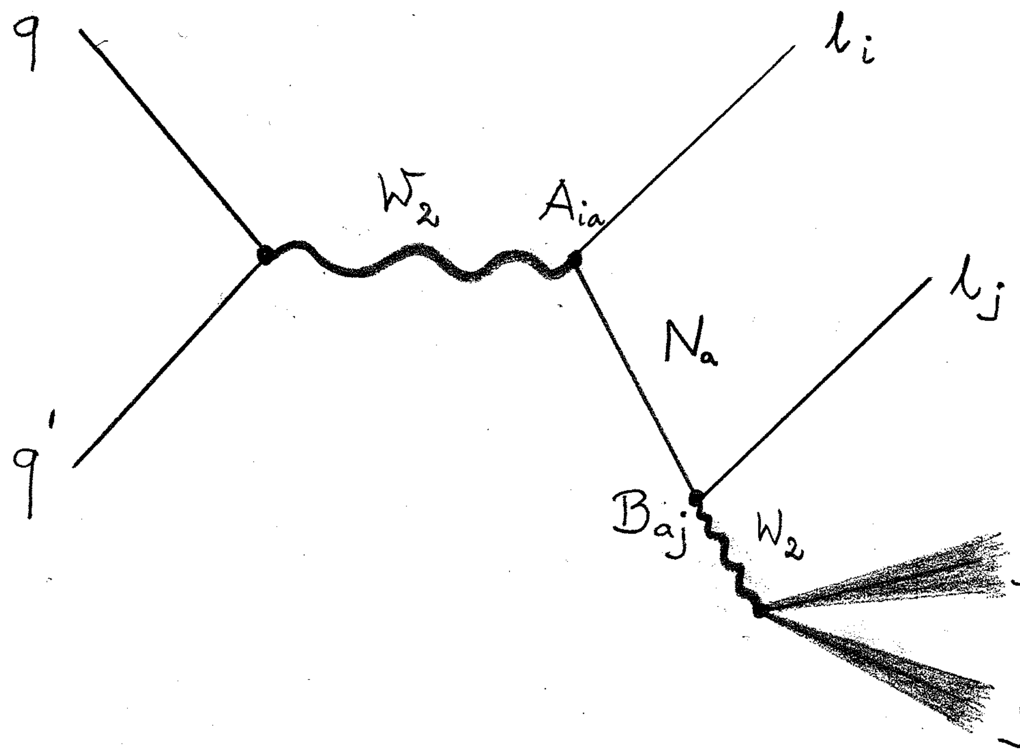
Here example with supressed $\mu\mu jj$ and too big $e\mu jj$.

Dirac-ness of neutrino states composed of Majorana massive states measured by r parameter in $pp \to lljj$

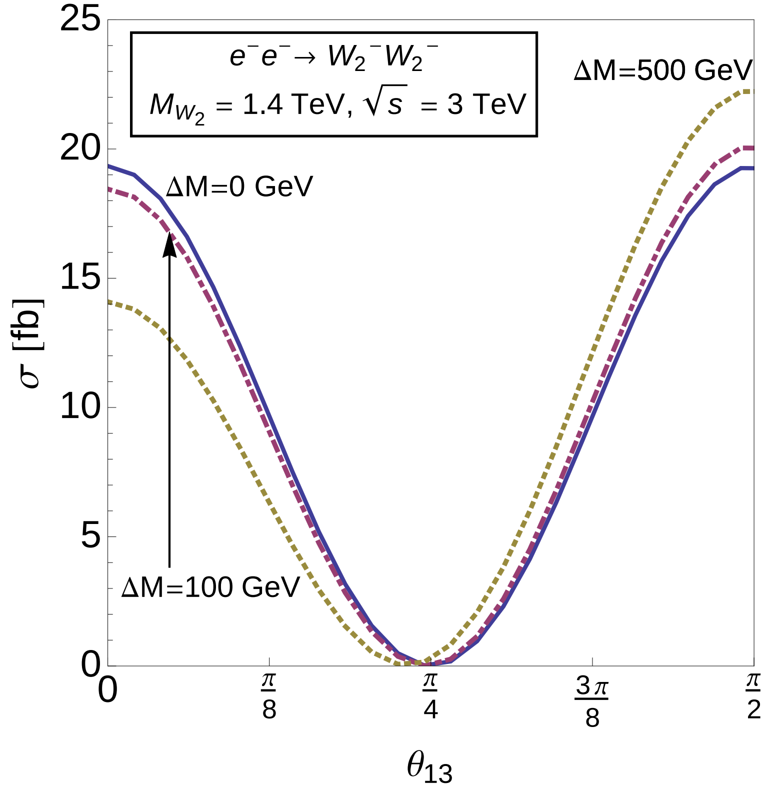
$\epsilon = \frac{\Delta M_{ij}}{max(\Gamma_i, \Gamma_j)}$	r	ΔL violation	Nature
0	0	0	Dirac
$<< 1$	small	moderate	pseudo-Dirac
~ 1	large	substantial	Majorana
$>> 1$	1	maximal	Majorana

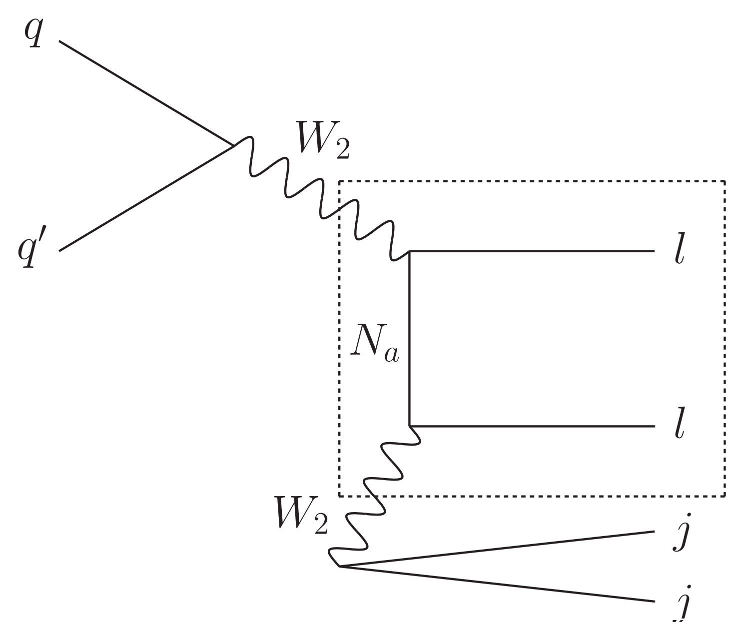
What about stable neutrinos? E.g. light, active neutrinos?

$pp \to lljj$ is s-channel dominated (no interference for mass splitings, it was a surprised to me!). What, if a t-channel is dominated?



$e^-e^- \to W^-W^-$ and the $pp \to lljj$





Here interferences can be substantial even for very large Majorana neutrino mass splittings because the signal is not dominated by the pole contribution. Large interference can lead effectively to restoration of the lepton flavour.

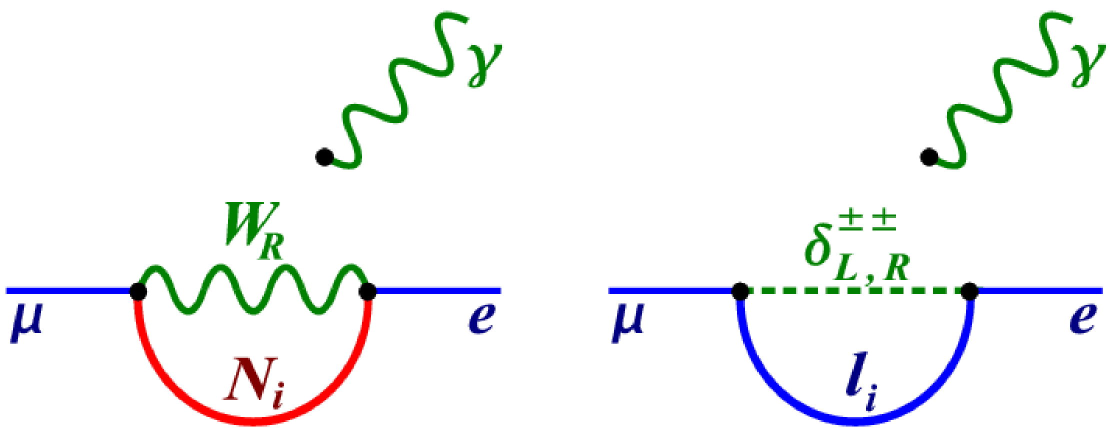
$\mu \to e\gamma$ - MEG,Mu2e, Comet,...

Probe NP up to 10 000 TeV!

Current and planned limits on Lepton CFLV

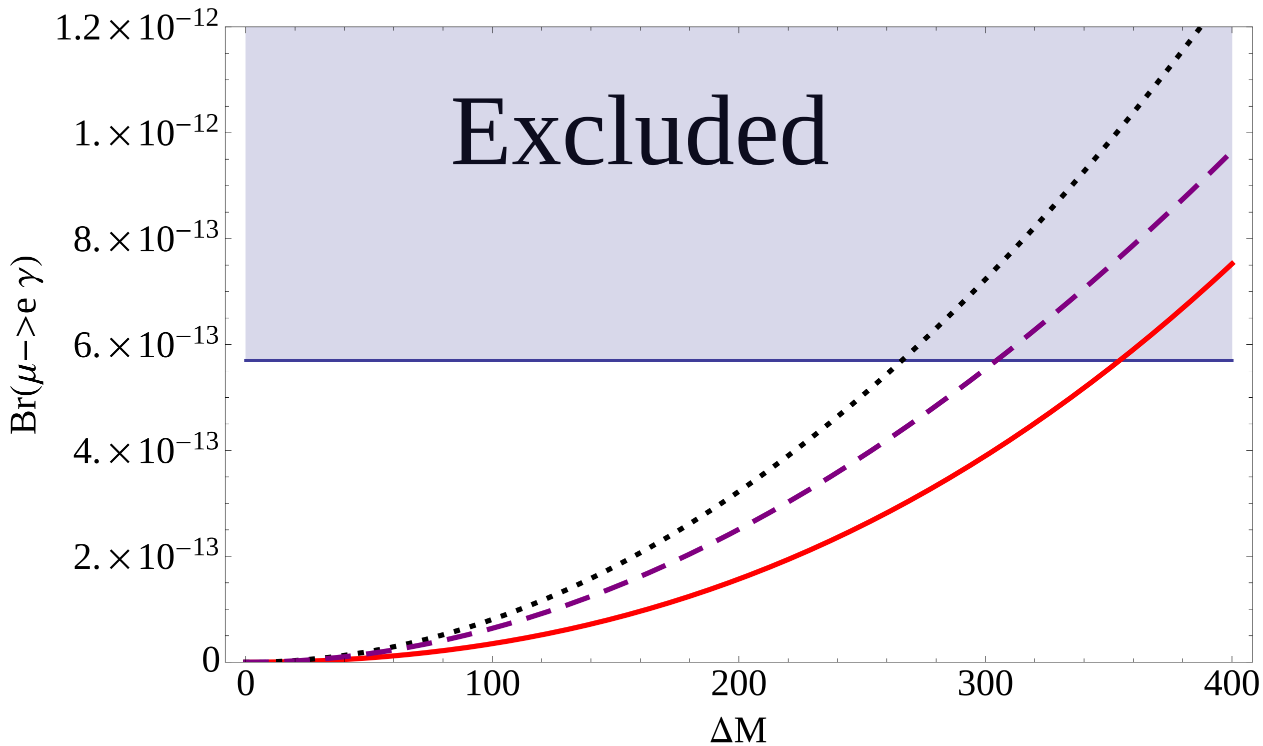
Process	Current Limit	Planned Limit
$\tau \to \mu\gamma$	6.8E-8	1.0E-9
$\tau \to e\gamma$	1.2E-7	
$\tau \to \mu\mu\mu$	3.2E-8	1.0E-9
$\tau \to eee$	3.6E-8	1.0E-9
$\mu \to e\gamma$	5.7E-13	1.0E-14
$\mu N \to eN$	7.0E-13	1.0E-17
$\mu \to eee$	1.0E-12	1.0E-16

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{m_W}{m_{W_R}}\right)^4 \left(\sin\theta\cos\theta\frac{\Delta M^2}{m_{W_R}^2}\right)^2 .$$



Small mass splittings allowed

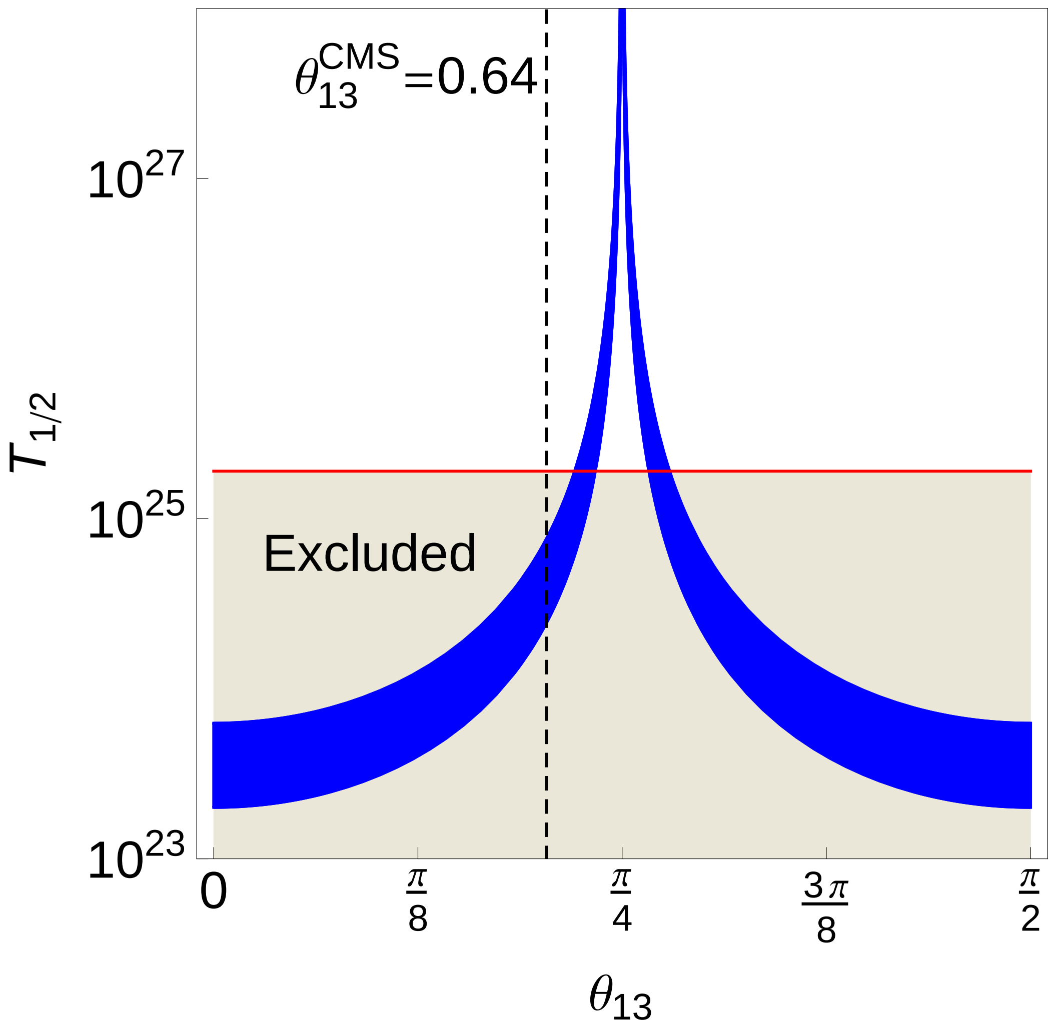
$m_{N_1} = 500$GeV (solid); $m_{N_1} = 1500$GeV (dotted);
$m_{N_1} = 2500$GeV (dashed)
$\theta = \pi/4$ (maximal)

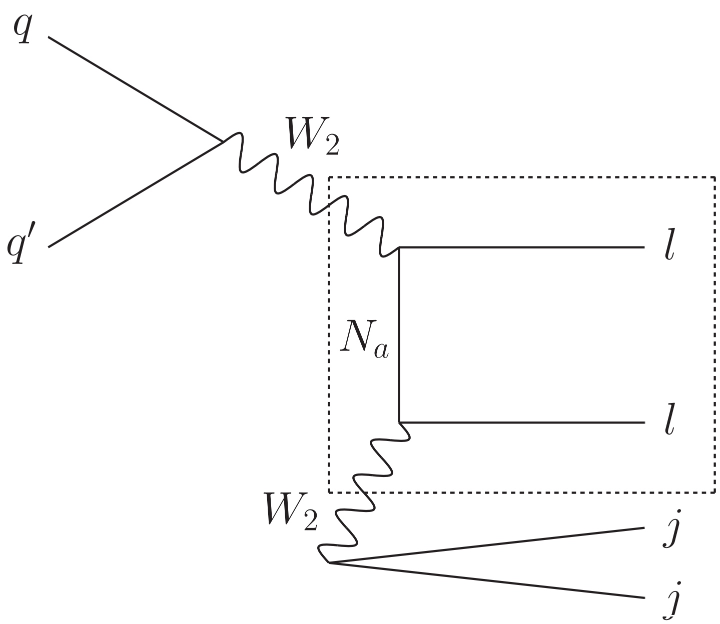


Neutrinoless doubly beta decay

$$
\begin{aligned}
T^{0\nu}_{1/2} &> 3 \cdot 10^{25} \text{ years (GERDA phase} - \text{I)} \\
T^{0\nu}_{1/2} &> 10^{28} \text{ years (future)} \\
\frac{1}{T^{0\nu}_{1/2}} &= G_{0\nu} g_A^4 |\mathcal{M}_\nu|^2 \left| \frac{m^\nu_{ee} + m^N_{ee}}{m_e} \right|^2 \\
m^N_{ee} &= |p^2| \left(\frac{g_R}{g_L} \right)^4 \left(\frac{M_{W_L}}{M_{W_R}} \right)^4 \sum_j \frac{V^2_{ej} M_j}{|p^2| + M_j^2}, \quad |p^2|
\end{aligned}
$$

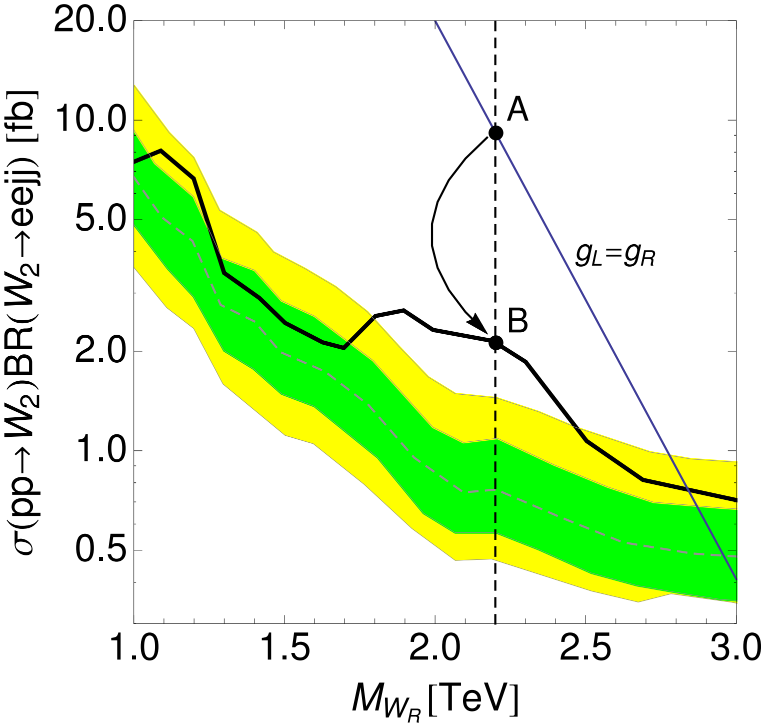
Very strong constrain (for chosen HN masses, CP-phase,...)

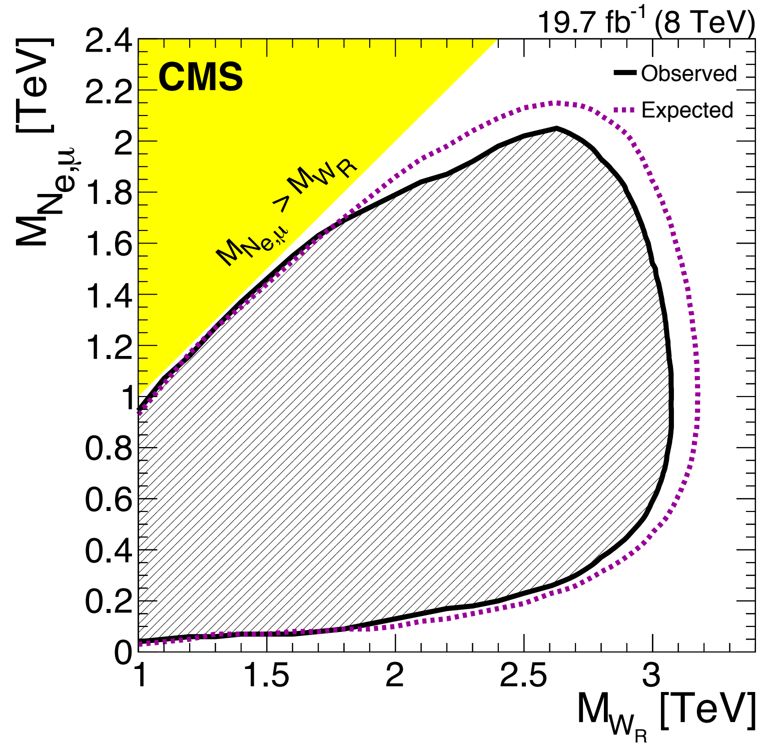




Consequences of our findings

Importance of Majorana mixings, CP-phases, masses.





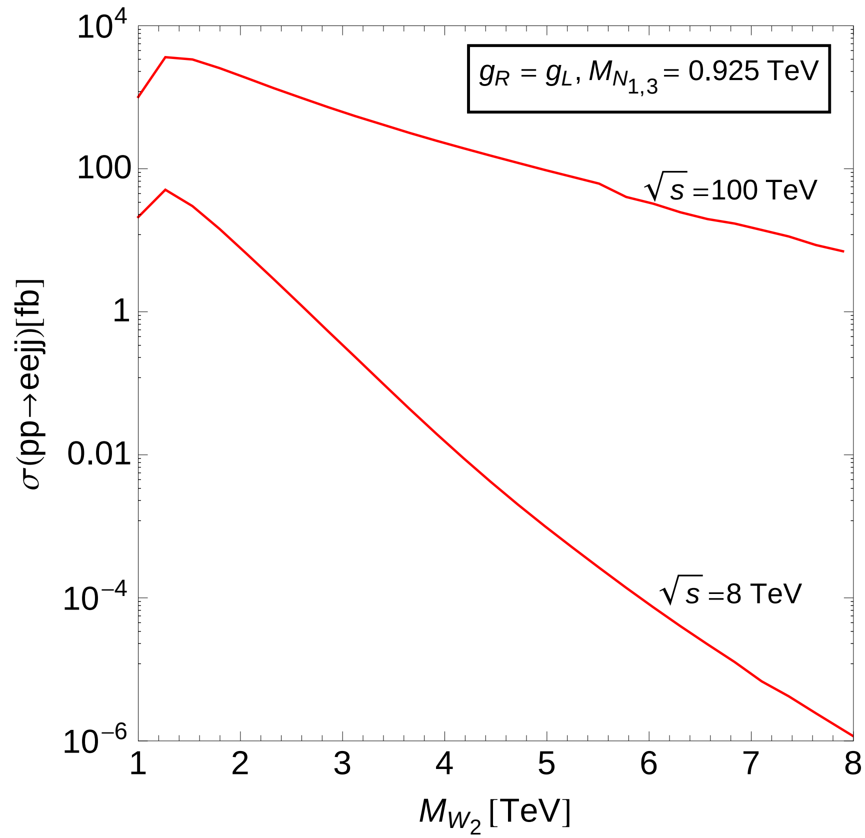
Degenerate heavy neutrino masses without neutrino mixings is a very narrow option (leading to simplified exclusion plots).

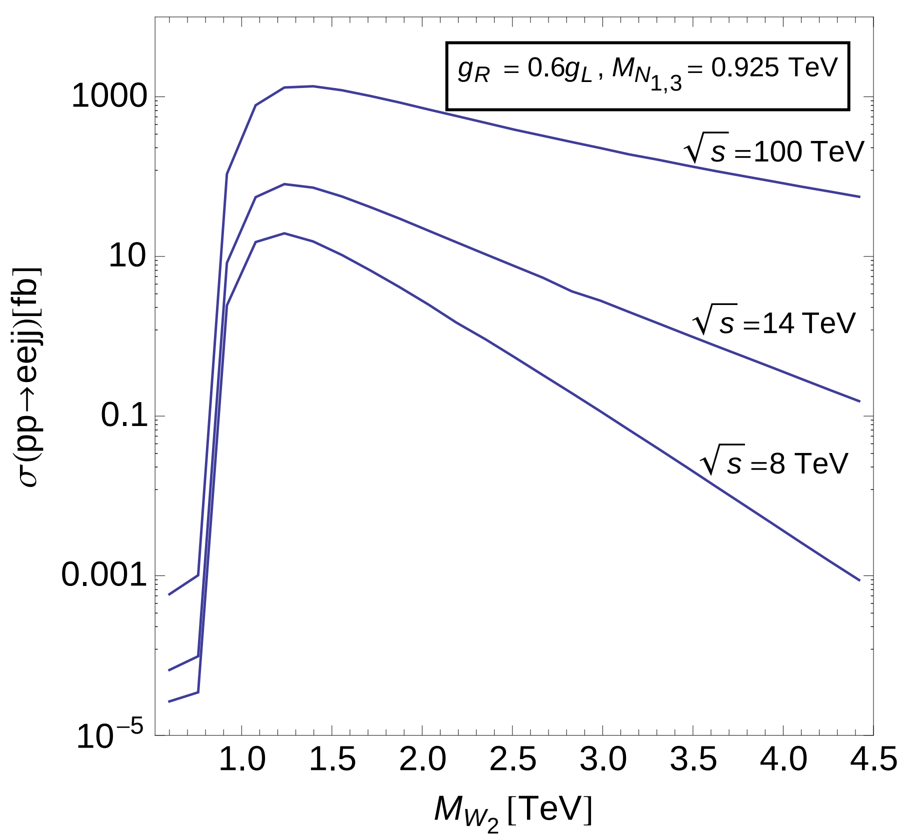
Simple speaking

CMS, ATLAS:

Departing from trivial scenarios gives a way, in connection with low energy measurements, for much deeper insight into theory and a structure of a heavy neutrino sector.

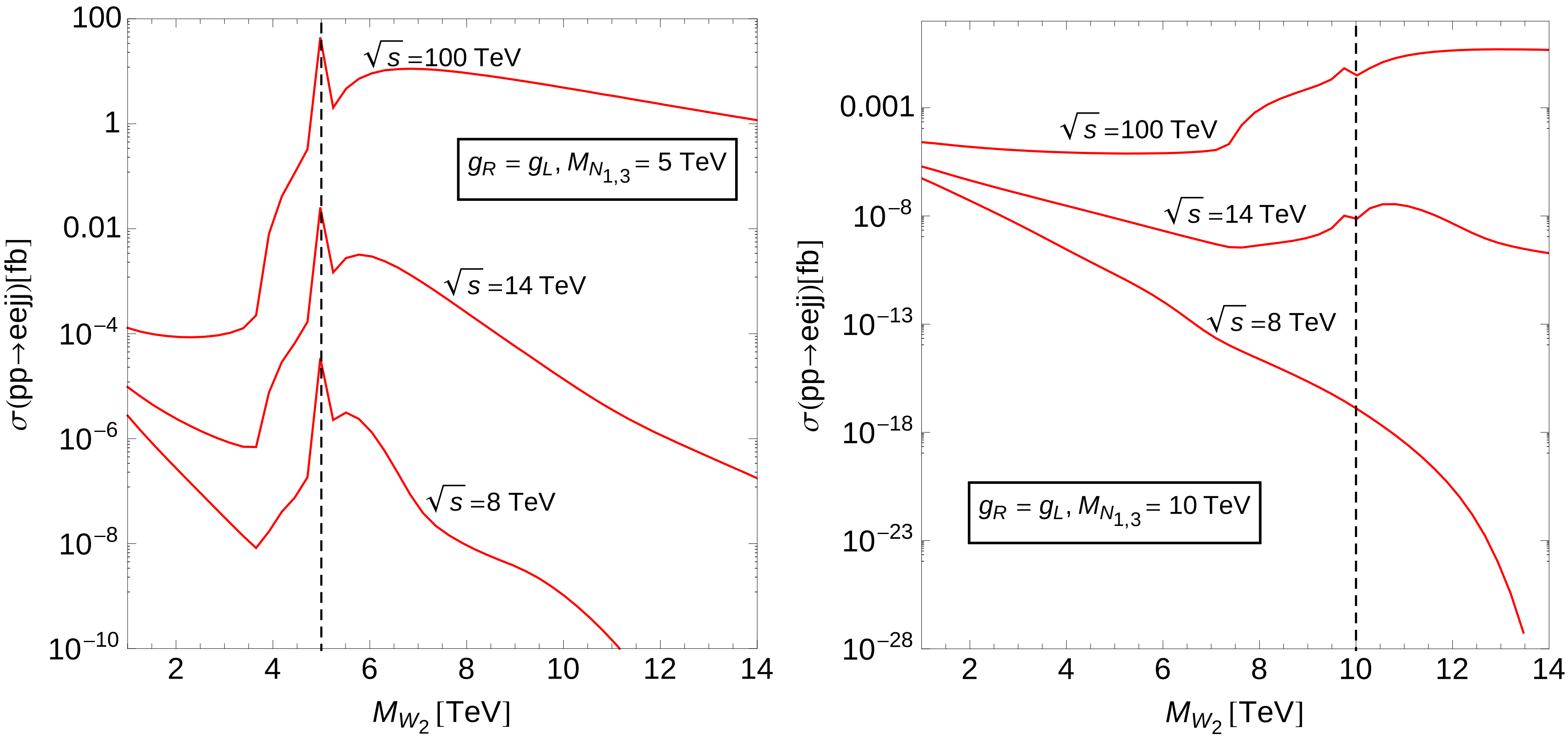
HN and RHC at higher energies, LHC2, FCC



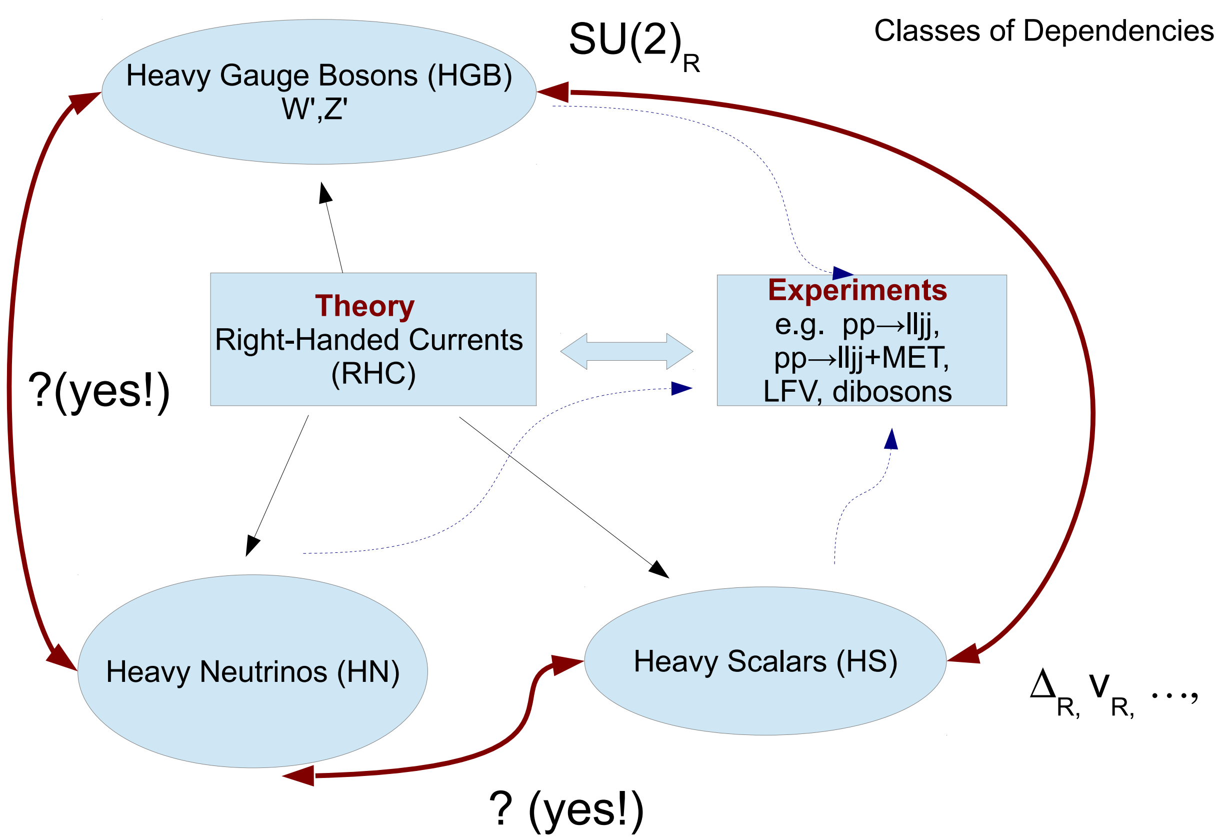


Solid: $g_R = 0.6 g_L$, Dashed: $g_R = g_L$

HN and RHC at higher energies, LHC2, FCC



Summary: RHC includes plenty of connected issues



What about mass mechanisms leading to Majorana/Dirac neutrinos?

In our case θ_{13} controls amount of LFV.

Another look is through a neutrino mass matrix, not a mixing matrix

(Our approach is more suitable for phenomelogical studies and experimental analysis, considering mass textures and possible symmetries goes deeper into theory).

Traditional see-saw (type-I)

Seesaw I: right handed singlets

$$
\begin{aligned}
\mathcal{L}_{\mathsf{Y}} &= -Y_{ij}\,\overline{L'_{iL}}N'_{jR}\,\tilde{\phi} + \mathsf{H.c.} \\
\mathcal{L}_{\mathsf{M}} &= -\frac{1}{2}M_{ij}\overline{N'_{iL}}N'_{jR} + \mathrm{H.c.}\,, \\
\mathcal{L}_{\mathrm{mass}} &= -\frac{1}{2}\,(\bar{\nu}'_L\ \bar{N}'_L)\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}\begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \mathrm{H.c.}\,.
\end{aligned}
$$

The neutrino mass matrix

$$
M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R(v_R) \end{pmatrix}
$$

with $M_D \ll M_R$.

$$
\begin{aligned}
m_N &\sim M_R \\
m_{\mathrm{light}} &\sim M_D^2/M_R
\end{aligned}
$$

Inverse see-saw

Dev, Mohapatra:

In the original inverse seesaw proposal, the lepton number violation is small, being directly proportional to the light neutrino masses.

The generalized inverse seesaw neutrino mass matrix in the flavor basis $\{\nu^C, N, S^C\}$ is given by

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^{\mathsf{T}} & \mu_R & M_N^{\mathsf{T}} \\ 0 & M_N & \mu_S \end{pmatrix}$$

$$M_{N_{1,2}} \simeq \frac{1}{2}\left[\mu_R \pm \sqrt{\mu_R^2 + 4M_N^2}\right] ,$$

For $\mu_R \ll M_N$, $N_{1,2}$ - pseudo-Dirac pair

For $\mu_R \gg M_N$, N_1 - purely Majorana with $M_{N_1} = \mu_R$

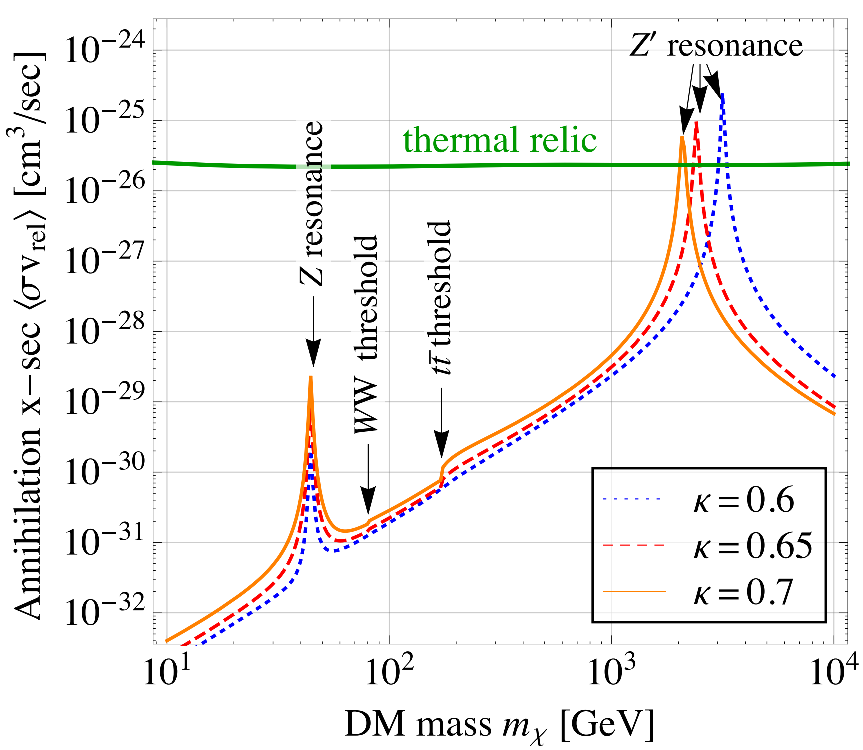
Thus, for intermediate values of μ_R, we can have scenarios with varying degree of lepton number breaking.

HN, RHC and the Universe

- Dark matter
- Baryon asymmetry
- GUT

Dark matter, [Brehmer et al., arXiv:1507.00013]

The total DM annihilation cross section as a function of the DM mass for different values of $\kappa = g_R/g_L$. Only for $m_\chi \sim m_{Z_R}/2$, the cross section can be large enough to avoid DM overproduction in the simplest thermal freeze-out scenarios.



Baryon asymmetry, [Bhupal Dev and Mohapatra, arXiv:1508.02277]

Baryon asymmetry of the Universe can be explained via leptogenesis through the out-of-equilibrium decay of the heavy Majorana neutrinos...

GUT with no intermediate scales, if $g_R \sim 0.51 g_L$ (however, additional symmetries: D-parity])

See also recent Ko, Nomura for similar issues, arXiv:1510.07872.

Backup slides

Seesaw II (scalar triplets)

$$\mathcal{L}_{\mathsf{Y}} = \frac{1}{\sqrt{2}} Y_{ij}\, \overline{\tilde{L}_{iL}}\, (\vec{\tau}\cdot\vec{\Delta})\, L_{jL} + \mathrm{H.c.}\,,$$

$$\Delta^{++} = \frac{1}{\sqrt{2}}(\Delta^1 - i\Delta^2)\,, \quad \Delta^{+} = \Delta^3\,, \quad \Delta^0 = \frac{1}{\sqrt{2}}(\Delta^1 + i\Delta^2)$$

can be left and right handed triplets
possible messengers at LHC

$$q\bar{q} \to Z^*\,/\,\gamma^* \to \Delta^{++}\Delta^{--}\,,$$
$$q\bar{q}' \to W^* \to \Delta^{\pm\pm}\Delta^{\mp}\,,$$
$$q\bar{q} \to Z^*\,/\,\gamma^* \to \Delta^{+}\Delta^{-}\,.$$

Seesaw III (3 leptonic triplets)

$$\mathcal{L}_{\mathsf{Y}} = -Y_{ij}\,\bar{L}'_{iL}(\vec{\Sigma}_j\cdot\vec{\tau})\,\tilde{\phi} + \text{H.c.}\,,$$

$$\mathcal{L}_{\mathsf{M}} = -\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}^c_i}\cdot\vec{\Sigma}_j + \text{H.c.}\,,$$

$$\Sigma^+_j = \frac{1}{\sqrt{2}}(\Sigma^1_j - i\Sigma^2_j)\,,\quad \Sigma^0_j = \Sigma^3_j\,,\quad \Sigma^-_j = \frac{1}{\sqrt{2}}(\Sigma^1_j + i\Sigma^2_j)$$

$$\mathcal{L}_{\nu,\mathrm{mass}} = -\frac{1}{2}\,(\bar{\nu}'_L\ \bar{N}'_L)\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}\begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \mathrm{H.c.}$$

possible messengers at LHC

$$q\bar{q} \to Z^*\,/\,\gamma^* \to E^+E^-\,,$$

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

Type IV seesaw

[Type-IV Seesaw Mechanism and CP Violation for Leptogenesis, E.T. Franco, arXiv:1510.06240]

Parity restoration, a lot of theoretical and experimental activity (triggered by LHC)

Start: 1973-1974,

Pati, Salam, Senjanovic, Mohapatra

gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
(i) restores left-right symmetry to e-w interactions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \qquad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

(ii) hypercharge interpreted as a difference of baryon and lepton numbers

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$\begin{array}{ccc} W_L^{\pm}, W_L^0 & & W_1^{\pm}, W_2^{\pm} \\ W_R^{\pm}, W_R^0 & \rightarrow [SSB] & Z_1, Z_2 \\ B^0 & & \gamma \end{array}$$

The minimal Higgs sector consists of two triplets and one bidoublet

$$\Delta_{L,R} = \begin{pmatrix} \delta^{+}_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^{0}_{L,R} & -\delta^{+}_{L,R}/\sqrt{2} \end{pmatrix},$$

$$\Phi = \begin{pmatrix} \phi^{0}_{1} & \phi^{+}_{1} \\ \phi^{-}_{2} & \phi^{0}_{2} \end{pmatrix}.$$

with vacuum expectation values allowed for the neutral particles

$$\frac{v_L}{\sqrt{2}} = \langle \delta^0_L \rangle,$$

$$\text{new HE scale}: \frac{v_R}{\sqrt{2}} = \langle \delta^0_R \rangle,$$

$$\text{SM VEV scale}: \sqrt{\kappa_1^2 + \kappa_2^2}$$

$$\frac{\kappa_1}{\sqrt{2}} = \langle \phi^0_1 \rangle,$$

$$\frac{\kappa_2}{\sqrt{2}} = \langle \phi^0_2 \rangle.$$

Right-handed currents

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W^+_{2\mu} + \text{h.c.} \sin\xi + \text{h.c.}$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}, \qquad U \approx \begin{pmatrix} 1 & 0 \\ 0 & K_R^\dagger \end{pmatrix},$$

- heavy gauge bosons $Z_2, W_2^\pm$,
  $M_{Z_2} = 0.783 v_R$, $M_{W_2} = 0.461 v_R$.
- heavy neutrinos N_i, $m_{N_i} = \sqrt{2} h_{M_i} v_R$,
- Higgs particles, neutral, charged and doubly charged.
  $\Rightarrow$ one bidoublet and two triplets.
- Right triplet gets VEV: $v_R \Rightarrow$ LR symmetry broken to SM symmetry.
- v_R determines the energy scale. Usually it is assumed to be of order of few TeV.

Mohapatra, Senjanovic (1980); Deshpande, Gunion, Kayser, Olness, 1991

$$
\begin{aligned}
&\mathcal{L}_{Higgs} = \\
&-\mu_1^2 Tr[\Phi^\dagger \Phi] - \mu_2^2 (Tr[\tilde{\Phi}\Phi^\dagger] + Tr[\tilde{\Phi}^\dagger \Phi]) - \mu_3^2 (Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger]) \\
&+\lambda_1 Tr[\Phi\Phi^\dagger]^2 + \lambda_3 (Tr[\tilde{\Phi}\Phi^\dagger] Tr[\tilde{\Phi}^\dagger \Phi]) \\
&+\rho_1 (Tr[\Delta_L \Delta_L^\dagger]^2 + Tr[\Delta_R \Delta_R^\dagger]^2) \\
&+\rho_2 (Tr[\Delta_L \Delta_L] Tr[\Delta_L^\dagger \Delta_L^\dagger] + Tr[\Delta_R \Delta_R] Tr[\Delta_R^\dagger \Delta_R^\dagger]) \\
&+\rho_3 (Tr[\Delta_L \Delta_L^\dagger] Tr[\Delta_R \Delta_R^\dagger]) \\
&+\alpha_3 (Tr[\Phi\Phi^\dagger \Delta_L \Delta_L^\dagger] + Tr[\Phi^\dagger \Phi \Delta_R \Delta_R^\dagger]) + \ldots i^\dagger \Delta_L \tilde{\Phi} \Delta_R^\dagger]),
\end{aligned}
$$

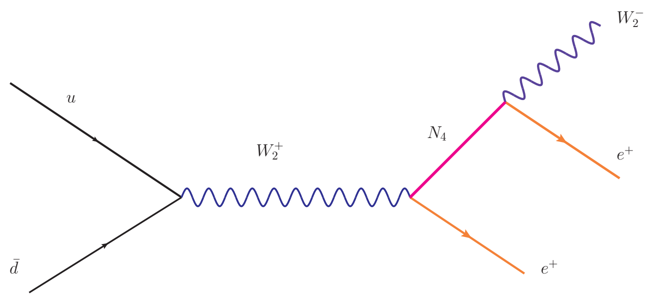
invariant under the symmetry $\Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger$.

Physical scalars

- 4 neutral scalars: H_0^0, H_1^0, H_2^0, H_3^0,
  (the first can be considered to be the light Higgs of the SM),
- 2 neutral pseudo-scalars: A_1^0, A_2^0,
- 2 charged scalars: $H_1^\pm, H_2^\pm$,
- 2 doubly-charged scalars: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

Remark, models consistency, radiative corrections

"Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data", J. Chakrabortty et al, JHEP 1207 (2012) 038

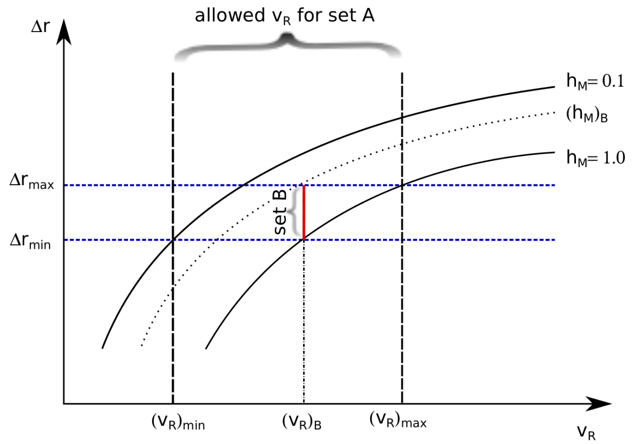


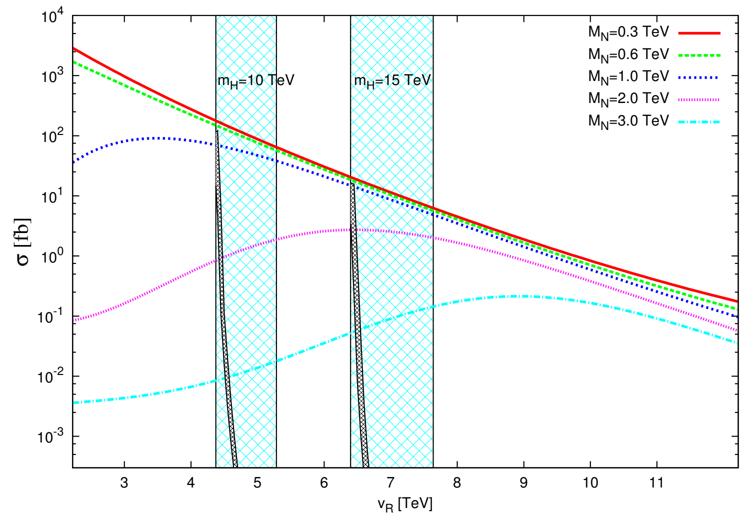
Muon decay constrain parameter space of a model

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1 - M_W^2/M_Z^2)M_W^2}(1 + \Delta r[M_N, M_H, M_{W_2}]).$$

⇒ calculate Δr in LR
⇒ do the matching with SM
⇒ compare with data
M. Czakon, J. Gluza,M. Zrałek, Nucl. Phys. **B573** (2000) 57 and
M. Czakon, J. Gluza, J. Hejczyk, Nucl. Phys. **B642** (2002) 157-172.

Corrections narrow parameter space, $\sqrt{s} = 14$ TeV





$pp \rightarrow eeW_2$