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Neutrino at Collider - II

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Neutrino at Collider - II

"Parity restored at TeV scale?"

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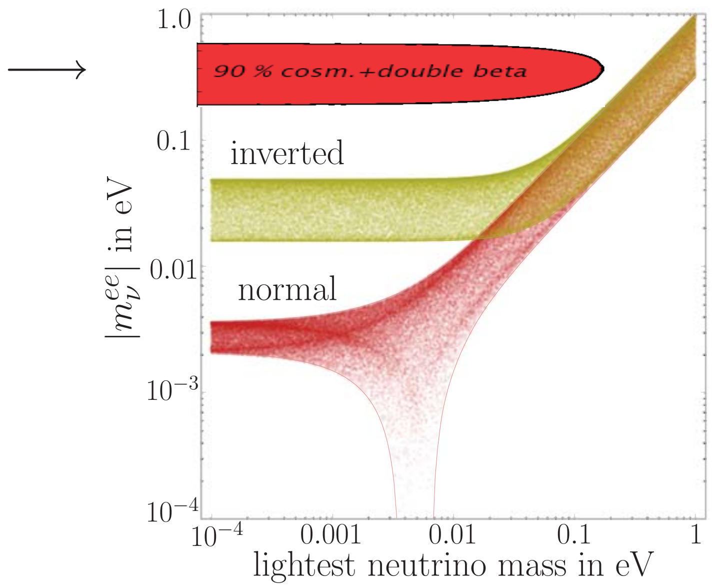
Summer School on Particle Physics

ICTP — April 2011

Future clash, $0\nu\beta\beta$ with cosmology?



- $0\nu\beta\beta$ claim of $m_\nu^{ee} \sim 0.4\,\text{eV}$, versus

(if confirmed!)

- cosmology, limiting the absolute scale $\sum m_\nu \lesssim 0.44 \div 1\,\text{eV}$

(and shrinking)

...may become incompatibile in the near future.

In this case, need new physics beyond light neutrinos!

New Physics - where?

If m_ν^{ee} excluded by cosmology, can New Physics do the job?

Try to guess at the level of effective operators...

- The 'New Physics' operator is dimension 9

$$O_{NP} = \lambda \frac{nnppee}{\Lambda^5}$$

- Require new physics amplitude to saturate $m_\nu^{ee} \sim eV$

$$A_{0\nu}^{NP} = \frac{\lambda}{\Lambda^5} \qquad \leftrightarrow \qquad A_{0\nu}^{m_\nu} = G_F^2 \frac{m_\nu}{p^2}$$

Result, the amplitudes are comparable for (say $\lambda \sim G_F^2 M_W^4$)

$$\Lambda \sim TeV.$$

...something would be expected at collider.

New physics - what?

- Need to generate Majorana neutrino mass

- E.g. type-I seesaw: (y and M quite free)

$$y\,\bar{\ell}H\nu_R + M\nu_R^t\nu_R$$

- So...maybe M hints to something? New interactions?
  ...e.g.: M breaks lepton number, $B-L$, ...

  Let's take it low:

- Maybe we can test a TeV M and new forces at LHC?
  (Yes, because of $\not{L}$ at collider.)

  Which forces?

Hints from quantum numbers...

SM – More symmetric

	Lorentz	Q $(Y+T_{3L})$	Y $(T_{3R}+\frac{(B-L)}{2})$	$SU(2)_L$ T_{3L}	$SU(2)_R$ T_{3R}	$B-L$	$SU(3)$
u_L	**2**	$2/3$	$1/6$	$1/2$	0	$1/3$	**3**
d_L	**2**	$-1/3$	$1/6$	$-1/2$	0	$1/3$	**3**
ν_L	**2**	0	$-1/2$	$1/2$	0	-1	**1**
e_L	**2**	-1	$-1/2$	$-1/2$	0	-1	**1**
u_R	$\bar{\mathbf{2}}$	$2/3$	$2/3$	0	$1/2$	$1/3$	**3**
d_R	$\bar{\mathbf{2}}$	$-1/3$	$-1/3$	0	$-1/2$	$1/3$	**3**
ν_R	$\bar{\mathbf{2}}$	0	0	0	$1/2$	-1	**1**
e_R	$\bar{\mathbf{2}}$	-1	-1	0	$-1/2$	-1	**1**

- Right fermions, SM singlets...
  ...actually doublets of a "right"-isospin group $SU(2)_R$.
- We *needed* the RH neutrino.
- Note, $Y = T_{3R} + (B-L)/2 \;\rightarrow\; Q = T_{3L} + T_{3R} + (B-L)/2$
- $B-L$ clearly anomaly free.

Also the path to unifications

Looking into fermion quantum numbers opens the view on unification setups

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$$

$$q_L \in (\mathbf{2}, \mathbf{1}, 1/3, \mathbf{3}) \qquad q_R \in (\mathbf{1}, \mathbf{2}, 1/3, \mathbf{3})$$
$$\ell_L \in (\mathbf{2}, \mathbf{1}, -1, \mathbf{1}) \qquad \ell_R \in (\mathbf{1}, \mathbf{2}, -1, \mathbf{1})$$

. . . one naturally tries to unify different factors:

- Pati-Salam: $SU(2)_L \times SU(2)_R \times SU(4)$ [Pati Salam '74; Georgi '75]

$$(q_L + \ell_L) = \psi_L \in (\mathbf{2}, \mathbf{1}, \mathbf{4}) \qquad (q_R + \ell_R) = \psi_R \in (\mathbf{1}, \mathbf{2}, \mathbf{4})\,.$$

- GUT: $SO(10)$ [Georgi, '75, Fritzsch Minkowski '75]

$$\psi_L + \psi_R^c \in (\mathbf{2}, \mathbf{1}, \mathbf{4}) + (\mathbf{1}, \mathbf{2}, \bar{\mathbf{4}}) = \mathbf{16}\,.$$

- *Gravi*GUT: $SO(3, 11)$ [FN '07, FN Percacci '09]

$$(\mathbf{2}_{Lorentz}, \mathbf{16}_{SO(10)}) = \mathbf{64}_{MW}\,.$$

Parity restoration?

So: the SM with minimal extension can restore parity!

By restoration of parity here we mean a generalization:
Interchange $\psi_L \leftrightarrow \psi_R$ and also gauge groups $SU(2)_L \leftrightarrow SU(2)_R$.

Left-Right symmetry

[Pati Salam '74, Mohapatra Pati '75, Senjanović Mohapatra '75]

Note: Lee Yang in '56 suggesting $\not{P}$, also hoped for its restoration!

- Need the extension of $U(1)_Y \subset SU(2)_R \times U(1)_{B-L}$
- Need of course an extended Higgs sector, for the breaking.
- The RH neutrino.

To see the predictions, let's look at the model

Left-Right models

- The gauge group:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$$

- Fermions:

Quarks $q_{L,R}$, Leptons $\ell_{L,R}$.

- Gauge bosons

$$W^i_{L\mu} \quad W^i_{R\mu} \quad B_\mu \quad G^a_\mu$$

(with respective coupling constants g_L, g_R, g_{B-L}, g_s)

- Assume $L \leftrightarrow R$ symmetry exact at TeV scale.

so $g_L = g_R$

- Higgs:

complex bidoublet: ϕ
triplets: Δ_L, Δ_R

Breaking

Breaking from: bidoublet $\phi \sim (h_{light}, H_{heavy})$, triplets Δ_L, Δ_R,

$$\langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}, \qquad \langle \phi \rangle = \begin{pmatrix} v' & \\ & v \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

spontaneously with $v_R \gg v > v' \gg v_L$. [Mohapatra Senjanovic '75]

Breaking in two steps:

- v_R breaks $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$
  $W_R^\pm \longrightarrow$ heavy: $M_{W_R} = g v_R$.
  W_R^3, $B \longrightarrow$, heavy Z_R, massless B_Y.

- v & v' break $SU(2)_L \times U(1)_Y \to U(1)_{EM}$
  The standard $W_L^\pm$ becomes massive $M_{W_L} = gv$
  W_L^3, B_Y, become Z massive, and the photon A massless.

(really a general mixing matrix)

For TeV LR-symmetry, $v^2/v_R^2 = M_{W_L}^2/M_{W_R}^2 \simeq 10^{-3}$.

Left + Right models: spectrum

- Bosons: W_R, ν_R, Δ_L, Δ_R heavy. from $v_r \to$ TeV
- Quark masses from two yukawa matrices, $\bar{q}_L(Y\phi + \tilde{Y}\tilde{\phi})q_R$:

$$M_u = |v|\, Y + |\tilde{v}| e^{i\alpha}\, \tilde{Y}$$
$$M_d = |v'|\, Y + |v| e^{i\alpha}\, \tilde{Y}$$

- Similarly, neutrino Dirac masses.

$$M_D = |v|\, h + |\tilde{v}| e^{i\alpha}\, \tilde{h}$$
$$M_\ell = |v'|\, h + |v| e^{i\alpha}\, \tilde{h}$$

- Recall from the triplets, Majorana neutrino masses:

$$M_L = Y_\Delta \langle \Delta_L \rangle \quad \ll \quad M_R = Y_\Delta \langle \Delta_R \rangle$$

Note, proportional by LR symmetry: $M_L \propto M_R$.

There is a new mixing

Diagonalize again quarks as usual with biunitary:

$$M_u = U_{Lu} m_u U_{Ru}\,, \qquad M_u = U_{Lu} m_u U_{Ru}$$

- The Left charged currect contains the usual V_{CKM}:

$$V_L = U^\dagger_{Lu} U_{Ld}\,.$$

- There is also a 'right' charged current:

$$V_R = U^\dagger_{Ru} U_{Rd}\,.$$

- And same in the lepton sector: $U_{PMNS\,L}$ and $U_{PMNS\,R}$.

M_R scale

Again, focus on the scenario

- Low $M_{W_R} \gtrsim$ TeV possible and testable:

  leading to striking signals

  (. . . direct probe of new interactions)
  (. . . of P restoration)
  (. . . of Majorana character)
  (. . . of additional flavour structure)

- Collider signals of W_R and ν_R.

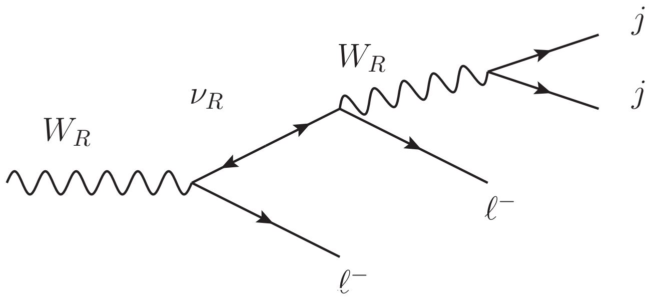
- And, lepton number violation enters in rare processes: i.e. new contributions to $0\nu\beta\beta$

  . . . disentangled from light neutrino masses.

Interesting collider processes

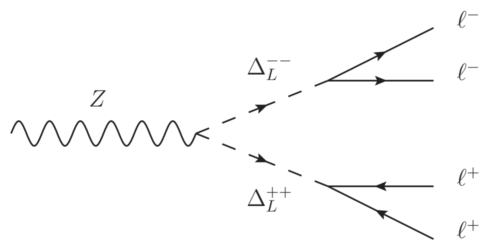
- Premium: W_R-ν_R production

  Same-sign dileptons.

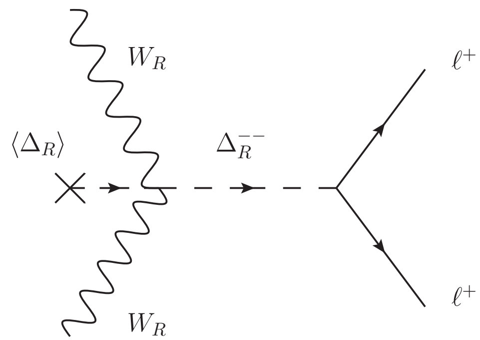


  And:

- $\Delta_L^{\pm\pm}$ production (pairwise)



- $\Delta_R^{\pm\pm}$ production (W fusion)



- W_R-Δ_R pair production

First, are there limits on the RH scale?

Limits

Limits

- Direct limits

  Dijets @ D0: $M_{W_R} \geq 885\,\text{GeV}$ [PRL '96, '04, '08, 1101.0806]

  $W' \to e\nu$ @ CMS: $M_{W_R} \geq 1.35\,\text{TeV}$ [CMS, 1012.5945]

  (see later)

- Limits from quark Flavour? Insurmountable? [see Tarantino's lectures]

  Meson oscillations.

  CP violation.

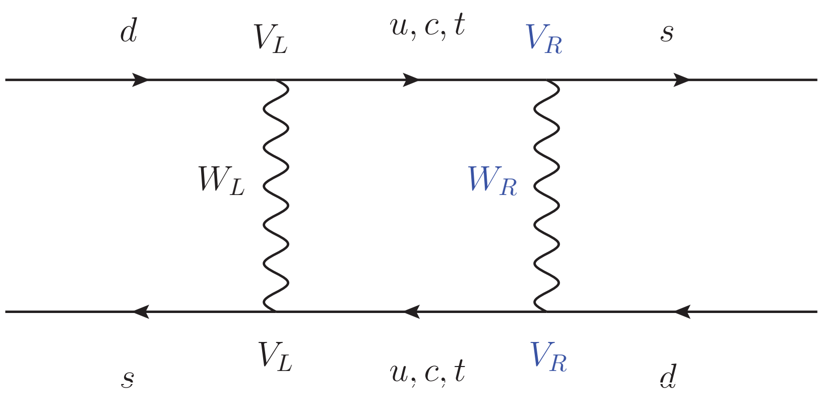
- Limits from leptonic flavour changing.

  (there will be no time!)

Let's see the case of $\Delta F = 2$.

$\Delta F = 2$ processes

$W_R \to$ new boxes for $\Delta F = 2$ — largest is W_L-W_R, e.g.:



Recall the GIM mechanism.

Here, the presence of W_R changes the game:

- $V_R^\dagger V_L$ is not identity.
- W_R current requires chirality flip.

... GIM is modified.

$\Delta F = 2$ Hamiltonians

Effective **Hamiltonians** from the box diagrams:

$$\mathcal{H}_{LL}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2} \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu L d\, \bar{d}'\gamma_\mu L d \sum_{i,j=c,t} \lambda_i^{LL}\lambda_j^{LL} S_{LL}(x_i,x_j)\,\eta_{LL,ij}$$

$$\mathcal{H}_{LR}{}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, \beta \sum_{d,d'=d,s,b} \bar{d}' L d\, \bar{d}' R d \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL}\, 8 S_{LR}(x_i,x_j,\beta)\,\eta_{LR,ij}$$

$$\mathcal{H}_{RR}{}^{\Delta F=2} = \frac{G_F^2 M_{W_L}^2}{4\pi^2}\, \beta \sum_{d,d'=d,s,b} \bar{d}'\gamma_\mu R d\, \bar{d}'\gamma_\mu R d \sum_{i,j=c,t} \lambda_i^{RR}\lambda_j^{RR} S_{RR}(x_i,x_j,\beta)\,\eta_{RR,ij}$$

where

$$\lambda_i^{AB} = V_{id'}^{A*} V_{id}^{B}\,, \quad x_i = m_i^2/M_{W_L}^2\,, \quad \beta = M_{W_L}^2/M_{W_R}^2$$

and chiral enhancement in **Matrix element** for meson M^0-$\overline{M}^0$:

$$\left\langle M^0 \left| \bar{d}'\gamma_\mu L d\, \bar{d}'\gamma_\mu L d \right| \overline{M}^0 \right\rangle = \frac{2}{3} f_M^2 m_M \mathcal{B}_M^{LL}$$

$$\left\langle M^0 \left| \bar{d} L d'\, \bar{d} R d' \right| \overline{M}^0 \right\rangle = \frac{1}{2} f_M^2 m_M \mathcal{B}_M^{LR} \left[\left(\frac{m_M}{m_{d'} + m_d} \right)^2 + \frac{1}{6} \right].$$

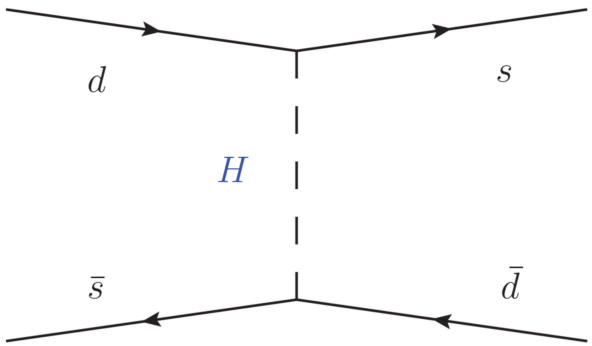
$\Delta F = 2$ FC Higgs

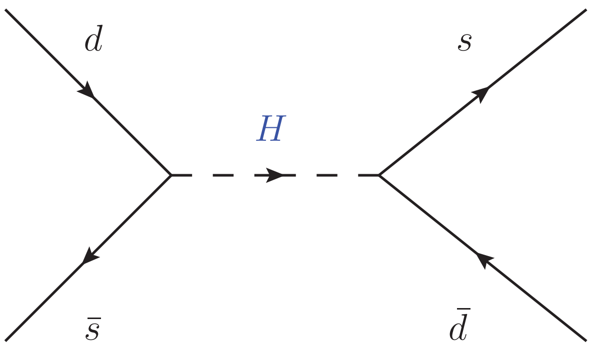
Effective **Hamiltonians** from the tree level Higgs:

$$\mathcal{H}_H^{\Delta F=2} = -\frac{4G_F}{\sqrt{2}M_H^2} \sum_{d,d'=d,s,b} \bar{d}'Ld\,\bar{d}'Rd \sum_{i,j=u,c,t} \lambda_i^{LR}\lambda_j^{RL} m_i m_j\,,$$

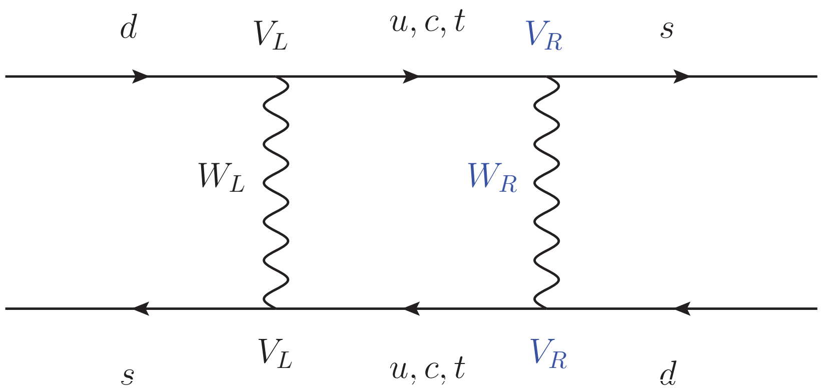
where again

$$\lambda_i^{LR} = V_{id'}^{L*} V_{id}^{R}\,.$$





$K\bar{K}$



- Dominant is c-c loop – Correlated bound V_R-M_{W_R}:

$$M_{W_R}^2 > (2.5\,\text{TeV})^2 \left(\frac{V^*_{R\,cd}}{\lambda_c}\right)\left(\frac{V_{R\,cs}}{1}\right)$$

(With hadronic uncertainty 25–50%)

(and LR long-distance part)

So it is V_R^{CKM} that matters. . .

Good mixing matrices

Good V_R would have thus one of the following forms:

$$V_R = \begin{pmatrix} e^{i\psi} & 0 & 0 \\ 0 & ce^{i\sigma} & -se^{i\gamma} \\ 0 & se^{i\theta} & ce^{i\epsilon} \end{pmatrix}, \quad \begin{pmatrix} 0 & e^{i\psi} & 0 \\ ce^{i\sigma} & 0 & -se^{i\gamma} \\ se^{i\theta} & 0 & ce^{i\epsilon} \end{pmatrix}$$

[Langacker Sarkar '98]

Enough to relax limits from both Δm_K and B_s, B_d.

Then also CP violation bounds can be satisfied, by exploiting phases.

$$\theta_{12\,R} = 0 \quad \text{or} \quad \pi/2$$

Can we reach this form?

- Generically yes, Y, $\tilde{Y}$, α unconstrained, $\rightarrow$ V_R free $\rightarrow$ no limit.
- In minimal models, Y, $\tilde{Y}$, α are constrained. . .

L-R models: the two symmetries

Restrict the yukawa: good for predictivity, bad for constraints.

$\boxed{\mathcal{P}}$ Generalized Parity:

$$f_L \leftrightarrow f_R\,,\;\; \phi \leftrightarrow \phi^\dagger$$

Need $Y,\ \tilde{Y}$ hermitian.

But masses are *not*, due to the 'spontaneous' phase $e^{i\alpha}$.

...what mixings?

$\boxed{\mathcal{C}}$ Generalized Charge conj.

$$f_L \leftrightarrow (f_R)^c\,,\;\; \phi \leftrightarrow \phi^T$$

Need $Y,\ \tilde{Y}$ symmetric.

Therefore, $\Rightarrow$ $V_R = K_1\, V_L^*\, K_2\,,$

with $K_1,\ K_2$ diagonal phases.

(So for $\mathcal{C}$ equal mixings, $\rightarrow$ we already know $M_{W_R} \geq 2.5\,\text{TeV}$)

(Note this is gaugeable symmetry – e.g. embedded in GUT SO(10)

case of $\mathcal{P}$: RH mixings and W_R

- May disentangle V_R and V_L if masses are not hermitian?

$$M_u = v\,Y + v'\,\tilde{Y}\,\mathrm{e}^{i\alpha}$$
$$M_d = v'\,Y + v\,\tilde{Y}\,\mathrm{e}^{i\alpha}$$

Key parameters are α and $x = v'/v$. $(0 < x < 1)$

- For small $x \lesssim m_b/m_t$: one obtains analytically $V_R \simeq V_L$

[Zhang+ '07]

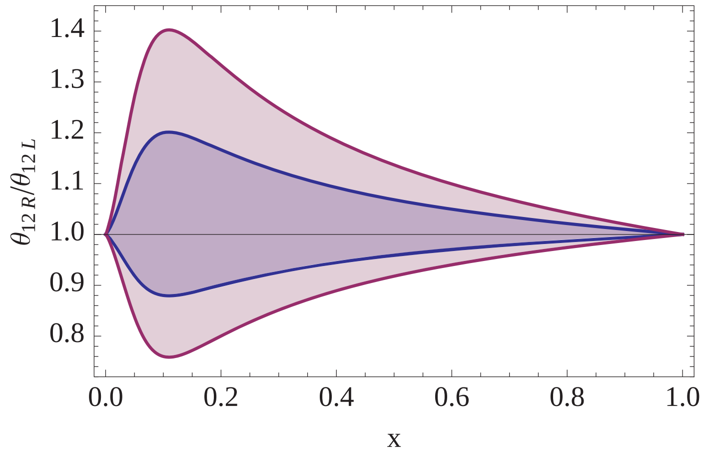
- For $x > m_b/m_t$ there may be cancellations and large angles...

...However α is limited by the need to adjust $m_b \ll m_t$.

So no, in general matrices ∼hermitian and mixings similar...

case of $\mathcal{P}$: limits

Numerical fit to check how robust. [Maiezza+ '10]



Mixings are quite aligned, to 10-20%.

Here $\theta_{12\,R}/\theta_{12\,L}$.

Other angles similarly related.

So, bound from ΔM_K is still at $M_{W_R} \gtrsim 2.5\,\text{TeV}$, at most 20% less.

(And still 25% from matrix element, long distance parts...)

$\mathcal{P}$: summary of bounds on M_{W_R}

Mixings $\sim$ similar $\longrightarrow$ model is predictive, depends only on the scale:

CP conserving:

- Δm_K : $\sim$ 2.5 TeV
- $\Delta m_{B_{d,s}}$: 1.5 $\sim$ 2 TeV

$\mathcal{P}$ is a theory of two phases only ($e^{i\alpha}$ and one phase in the $\tilde{Y}$) so also phases are predicted... Main bound then comes from ϵ, ϵ'..

CP violating:

- ϵ, ϵ': 3.2 $\sim$ 4.2 TeV
- CP in $B_{d,s}$: ? (no solution for the SM tensions [[]see Tarantino])

4 TeV a bit high $\longrightarrow$ $\mathcal{P}$ Marginally detectable at LHC.

Case of $\mathcal{C}$: Charge Conjugation

Mass matrices symmetric: same angles, only extra phases (5)

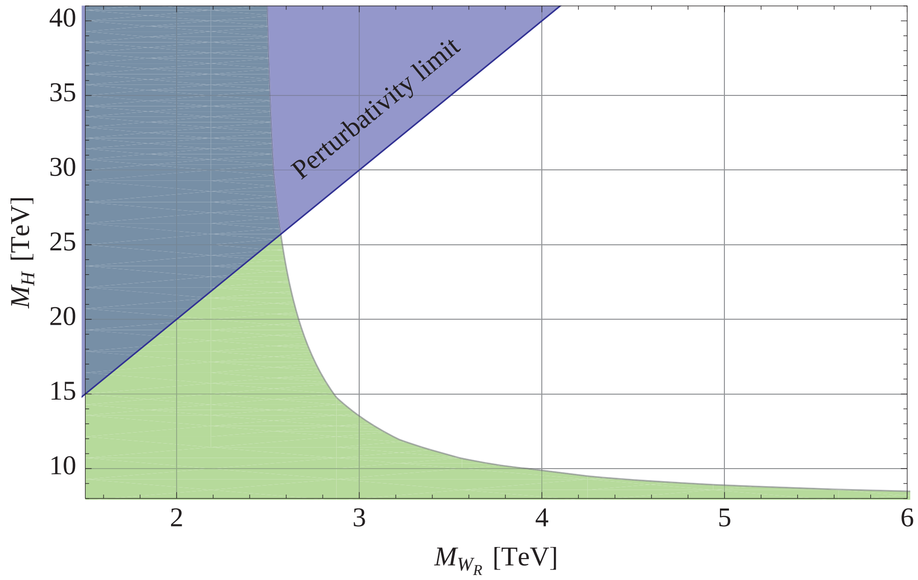
$$V_R = K_u\, V_L^*\, K_d$$

$$(K_u = \mathrm{diag}\{e^{i\theta_u}, e^{i\theta_c}, e^{i\theta_t}\},\ K_d = \mathrm{diag}\{e^{i\theta_d}, e^{i\theta_s}, e^{i\theta_b}\})$$

- So again, from Δm_K:

  $$M_{W_R} > 2.5\,\mathrm{TeV}.$$

  Correlated bound w/ heavy FC higgs:



- No constraint from Δm_{B_d}, Δm_{B_d}, but

  CP violations?

$\mathcal{C}$, cont'd: ϵ_K

Possible new physics in ϵ is at most ∼15–30%:

$$\frac{\epsilon_{LR}}{\epsilon_{SM}} \simeq \mathrm{Im}\left[e^{i(\theta_d-\theta_s)} A_{cc}\right] < 0.3$$

where $\beta = -\arg(V_{Ltd})$ and the c-c term is:

$$A_{cc} \simeq \left[150 + 8.2 \ln\left(\frac{M_{W_R}}{2.5\,\text{TeV}}\right)\right]\left(\frac{2.5\,\text{TeV}}{M_{W_R}}\right)^2 + 84\left(\frac{15\,\text{TeV}}{M_H}\right)^2$$

Quite large contribution from LR! However,

- For Zero phases $\theta_{d,s}$, no CP violation

In fact this is general, with $\mathcal{C}$.

So, *no bounds*, we only conclude that we need:

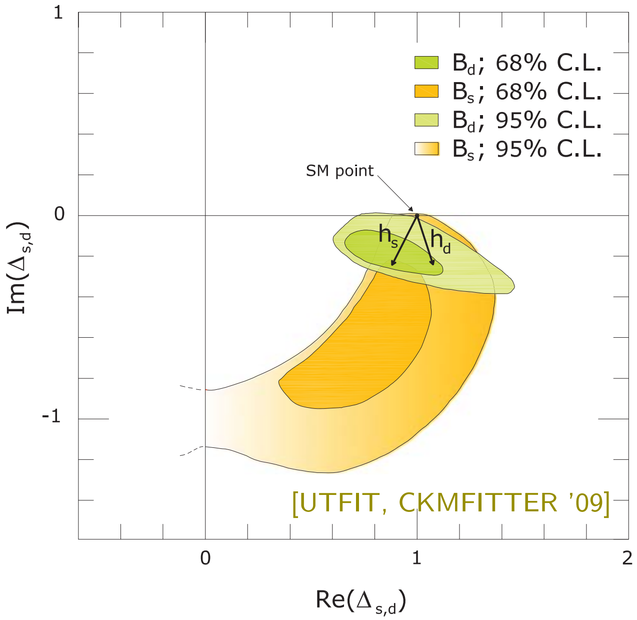
$$\theta_d - \theta_s \simeq 0\,.$$

Finally, situation with CP violation in $B_{d,s}$ is still curious...

$\mathcal{C}$, cont'd, $B_{d,s}$

[Maiezza+'10]

New Physics in B^0-$\overline{B}^0$:



$$h_q = \frac{\langle B_q | \mathcal{H}_{LR} | \overline{B}_q \rangle}{\langle B_q^0 | \mathcal{H}_{SM} | \overline{B}_q^0 \rangle}, \qquad (q = d, s)$$

Need the last nonzero phase θ_b:

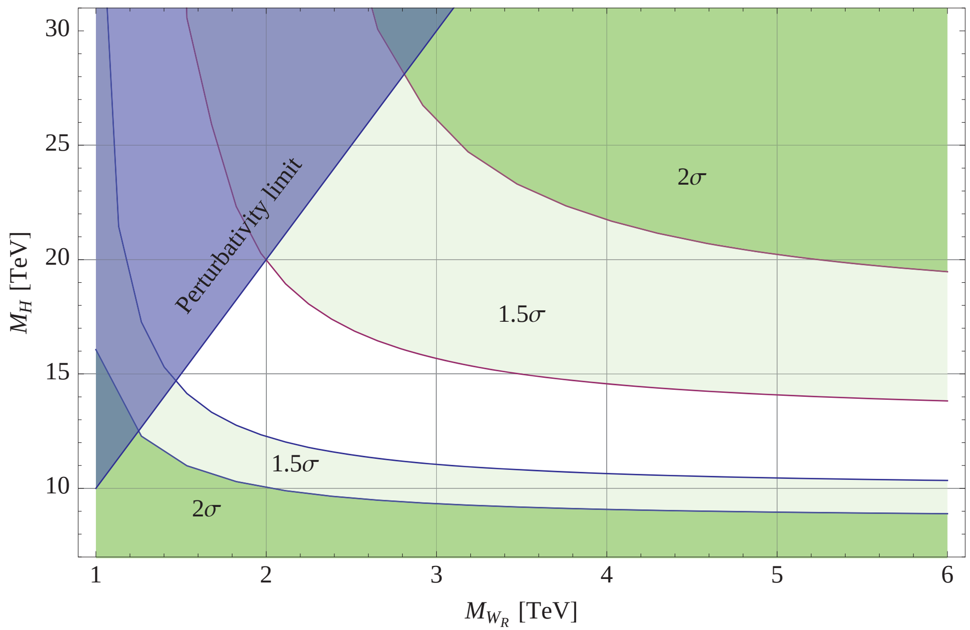
$$\theta_b - \theta_d \simeq \theta_b - \theta_s$$

(recall $\theta_d \simeq \theta_s$)

$\rightarrow h_{d,s}$ point toward same region.

Correlated bound:

In the interesting zone for LHC



Summary of theoretical limits

- Important limit comes only from $K^0\overline{K}^0$ mass difference,
  - In general models, $V_{CKM\,R} \neq V_{CKM\,L}$ then no limit on M_{W_R}.
  - In minimal models, $V_{CKM\,R} \simeq V_{CKM\,L}$, we need $M_{W_R} > 2.5\,\text{TeV}$
- In general ϵ, ϵ' harmless, due to free phases.
- Lepton Flavour violation ($\mu \to eee$, $\mu \to e\gamma$), require heavy Δ_R or light M_{ν_R}.

In conclusion, restoring $\mathcal{C}$ gives a predictive theory at TeV scale, which is nontrivially passing all tests of flavour.

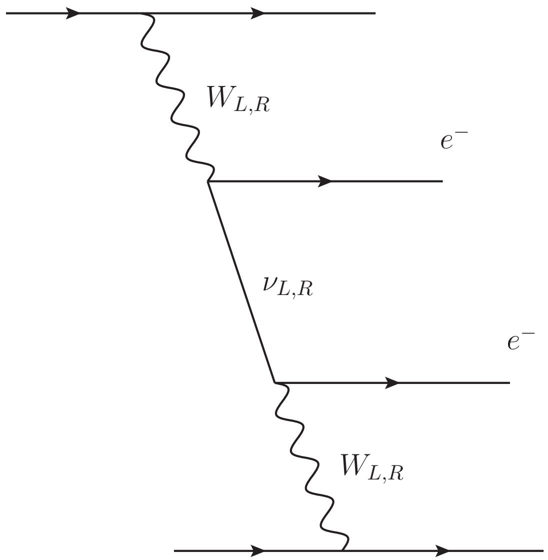
[see Tarantino]

Finally, back to $0\nu\beta\beta$

Back to $0\nu\beta\beta$

Back to $0\nu\beta\beta$

New contributions!



- LL - the standard.
- LR hardly important.
  (need Dirac cancelations)
- RR important for:

  $$\left(\frac{M_{W_R}}{\mathrm{TeV}}\right)^4\left(\frac{m_{\nu_R}}{\mathrm{TeV}}\right) < 2\,. \qquad \text{(Yukawa free)}$$

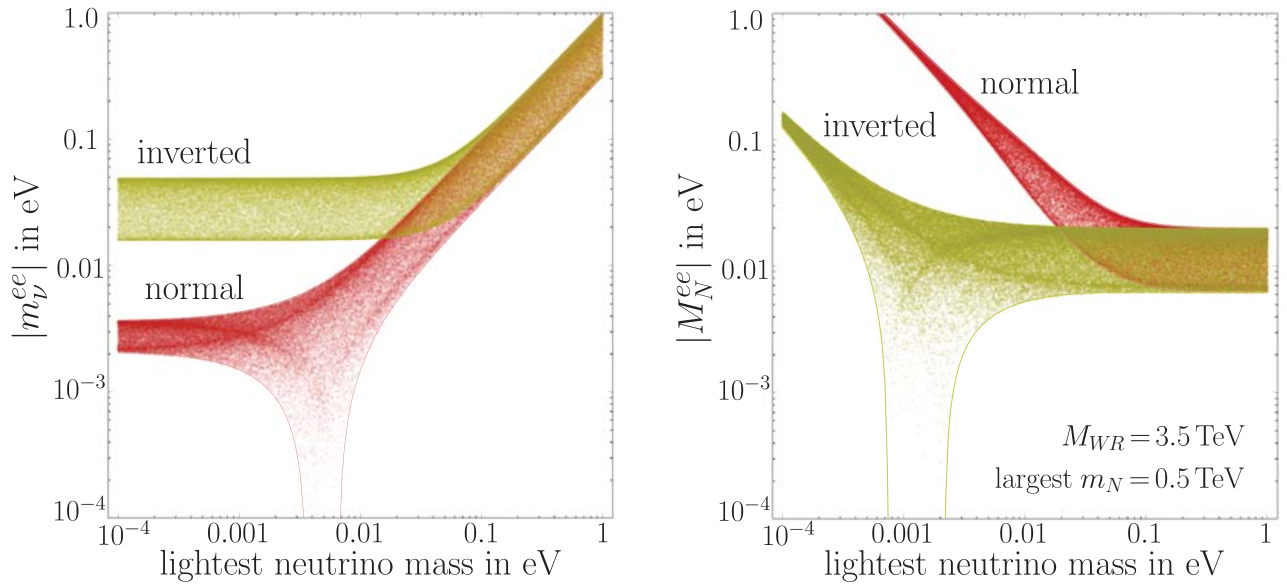
  E.g. $M_{W_R} \simeq 3\,\mathrm{TeV}$, $m_{\nu_R} \simeq 25\,\mathrm{GeV}$!

  Remember the estimate of New Physics scale? This is a realization.

$0\nu\beta\beta$ cont'd

[Tello+ '11]

Sample case of type-II seesaw: $U_{PMNS\,L} = U_{PMNS\,R}$, and proportional masses. Light and heavy ν competing:

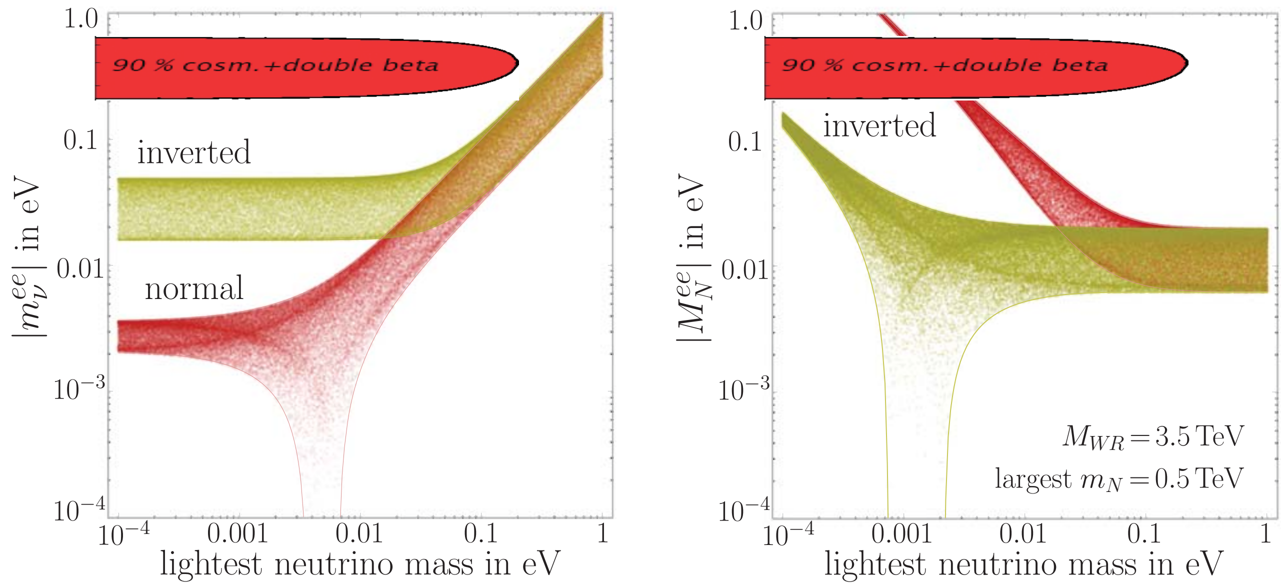


Summing the two: never vanishing.

$0\nu\beta\beta$ cont'd

[Tello+ '11]

Sample case of type-II seesaw: $U_{PMNS\,L} = U_{PMNS\,R}$, and proportional masses. Light and heavy ν competing:

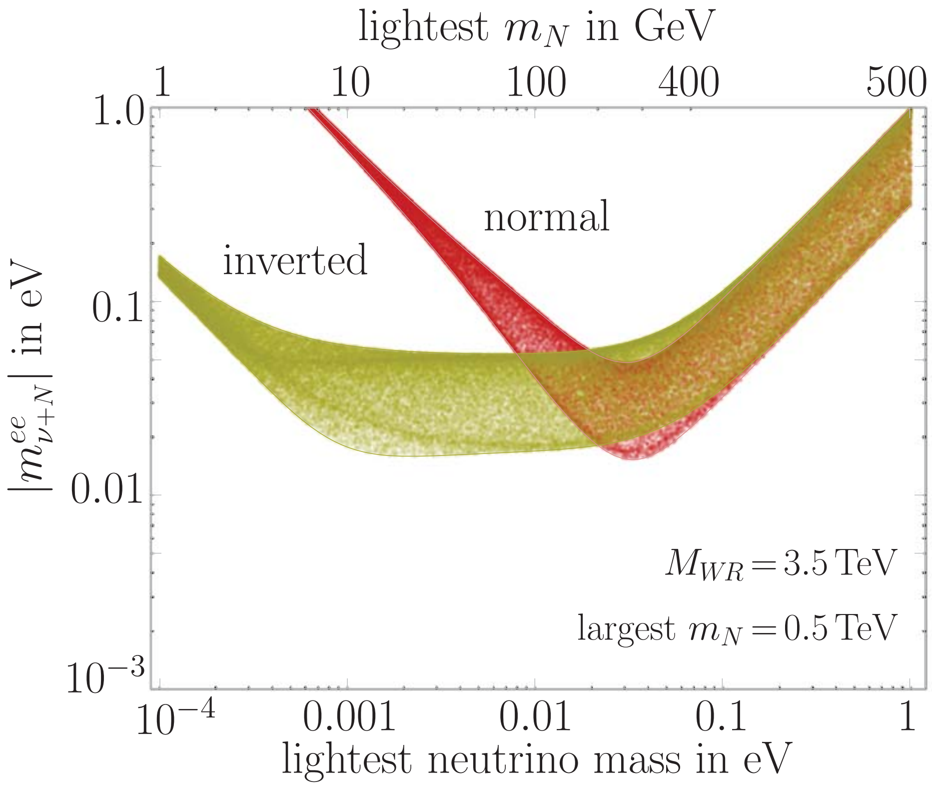


Summing the two: never vanishing.

Check now the possible $0\nu\beta\beta$ evidence versus cosmology :

- LR an example of new physics in $0\nu\beta\beta$ avoiding the clash.

$0\nu\beta\beta$: type-II sum



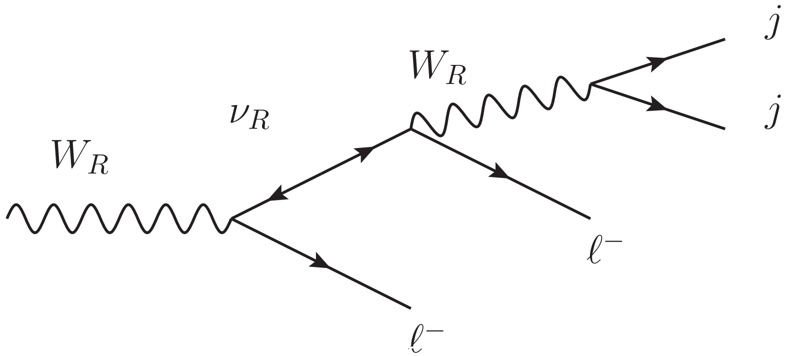
- Never vanishing: $0\nu\beta\beta$ probe can exclude this scenario.
- Or confirm it, with a hint for $M_{\nu_R} \sim 20\,\text{GeV}$.

Let's finally turn this prediction to collider.

Collider

W_R-ν_R

Lepton number violation @ collider: W_R, ν_R on-shell.



[Keung Senjanović '83]

Half the decays in same-sign dileptons (Majorana!)

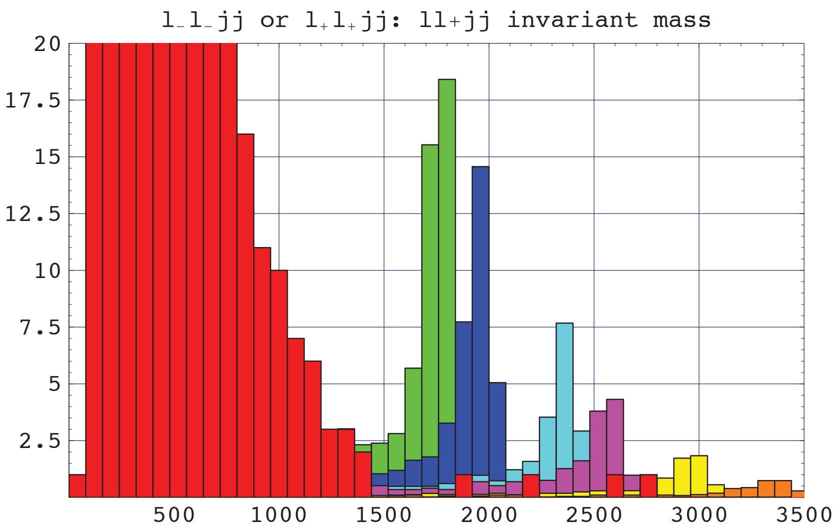
Reconstruct W_R and ν_R invariant masses:

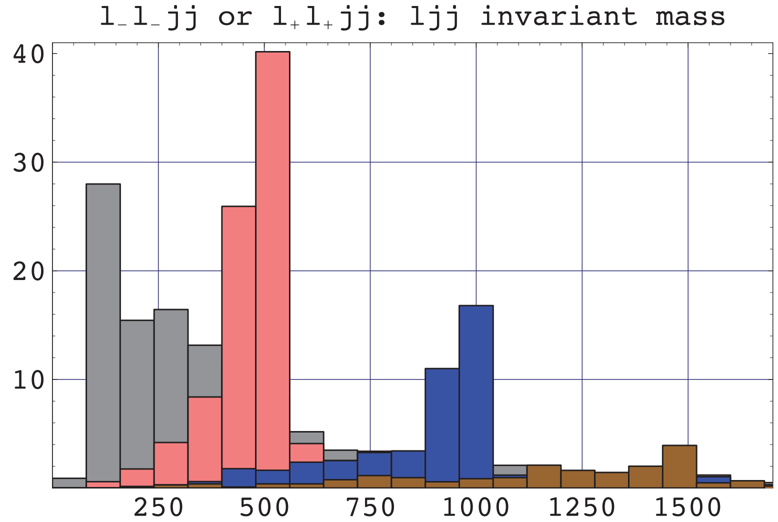
- Two leptons and two jets $\rightarrow M_{W_R}$.
- Second lepton and two jets $\rightarrow M_{\nu_R}$.
- Yukawa-free
- Probing RH neutrino flavour pattern (e-e, e-μ, μ-μ, τ?)

Is it feasible experimentally?

W_R-ν_R cont'd

Pythia already implements a minimal L-R model - can play with it.
Detector - e.g. PGS (Pretty Good Simulator) is pretty good.





$10 fb^{-1}$ @ 14 TeV, PT cuts 20GeV, $t\bar{t}$ background

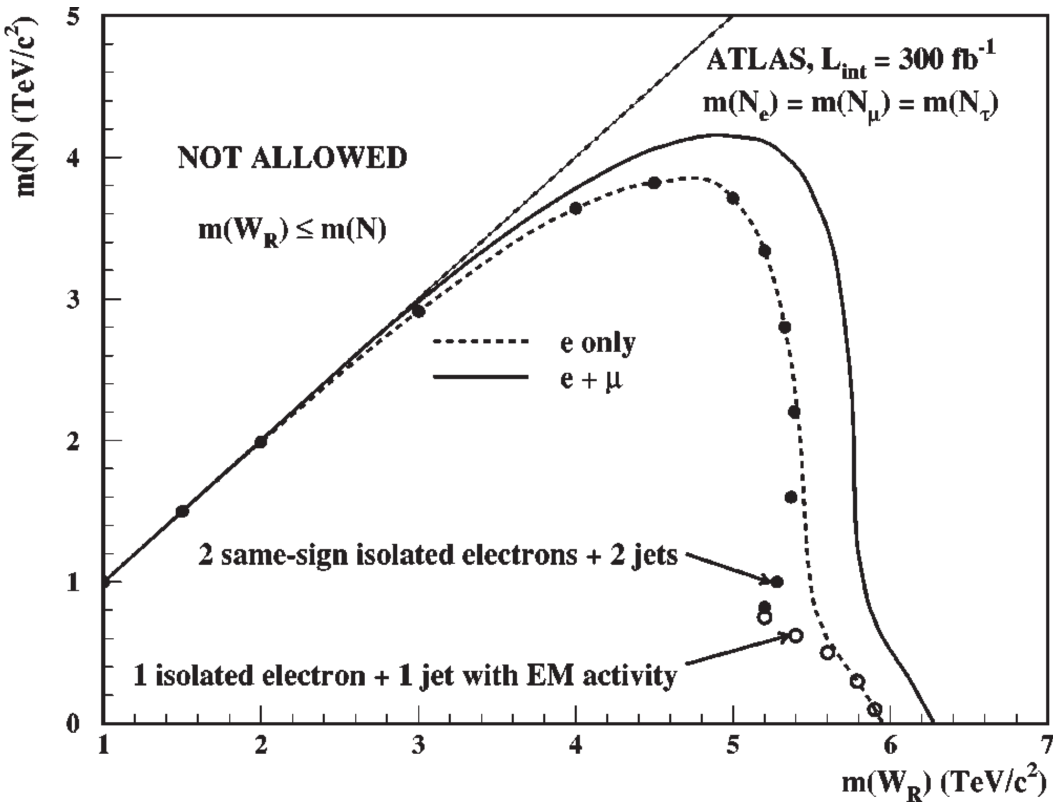
Gift of LNV: no background above 1.5TeV. Good both for M_{W_R}, M_{ν_R}.

- Note, width of W_R, is roughly $1/100$ of its mass $\rightarrow$ few GeV. The energy resolution will probably be not enough to measure it!
- M_{ν_R} has to be below M_{W_R}, kinematically.

W_R-ν_R cont'd

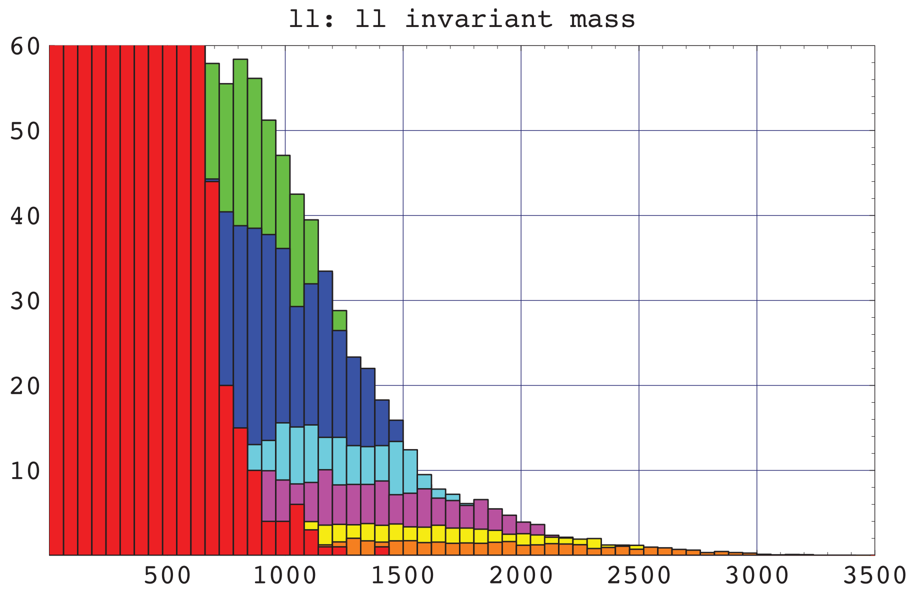
- LHC reach?

$M_{W_R}[TeV]$	m_{ν_R} [TeV]	$\int L$	energy	
4 (2)	2 (1)	30 /fb	14(7) TeV	Ferrari et al '00, Gninenko et al '07
2.1 (1.5)	2.1	100/pb	14(10) TeV	Kirsanov '09



dileptons

- And: early signal through $\ell^\pm\ell^\pm$ large energy (wrt to $t\bar{t}$ ones)...



- Neutrino masses and flavour:
  Yukawa-free, but probing RH neutrino matrix.
  Need channels, e-e, e-μ, μ-μ, τ(?)

  (and need updated MC)

- Displaced Vertex?

$$\tau_{\nu_R} \gtrsim 1\,\text{cm} \text{ for } m_{\nu_R} \lesssim 10\,\text{GeV} \quad (M_{W_R} = 2.5\,\text{TeV})$$

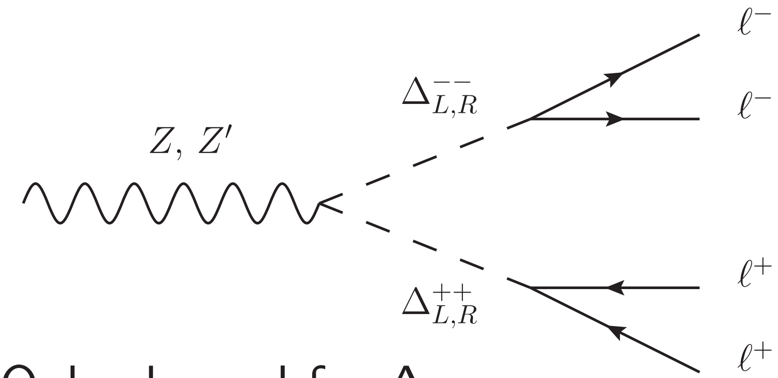
How right is W_R?

LHC is a pp symmetric machine, so it is not possible to use the simple A_{FB} asymmetry of W_R, to look for chirality of its interactions.

- One has to use the first decay $W_R \to eN$.
  - Determine the W_R direction (from the full event!)
  - Identify the first lepton. (the more energetic)
  - Its asymmetry wrt the W_R direction gives the 'Right' chirality.
- It is necessary to efficiently distinguish the two leptons. (More difficult for $M_N \neq 0.6 \div 0.8\, M_{W_R}$ [Ferrari '00])
- Also the subsequent decay $N \to \ell jj$ may be used.

Polarization seems to be visible in a wide range of masses M_{ν_R}, M_{W_R}.

$\Delta_{L,R}$

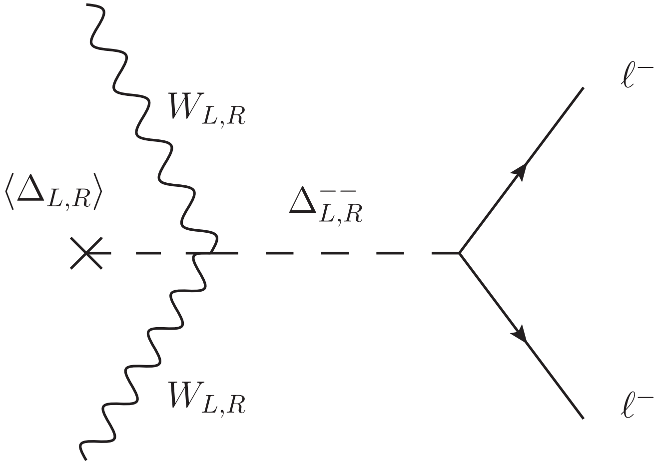


$\propto (Y_\Delta)_{ij}(Y^*_\Delta)_{kl}$

Only channel for Δ_L (except for $y_\Delta \ll 1$!)

Can probe neutrino masses, assuming type-II seesaw. . .

[Kadastik Raidal Rebane '07, del Aguila et al '07, Han et al]



$\propto (Y_\Delta)_{ij}$

large VEV for Δ_R but suppressed for heavy W_R

[Azuelos '05]

VEV suppressed for Δ_L

Reach $< 1\,\text{TeV}$ $(100\,\text{fb}^{-1})$

Direct Limits

Current probes:

- $W' \to tb$: dijets @ D0: [PRL '96, '04, '08, 1101.0806]

$$M_{W_R} \geq 885\,\text{GeV}$$

- $W' \to e\nu$: $e+ \not{E}$ @ CMS: [CMS, 1012.5945]

$$M_{W_R} \geq 1.35\,\text{TeV} \text{ for very light } m_{\nu_R} \sim \text{GeV} \qquad (36\,\text{pb}^{-1})$$

(superseding $M_{W_R} \geq 1.12\,\text{TeV}$ from Tevatron)

- Limit on $Z' \to \mu^+\mu^-$

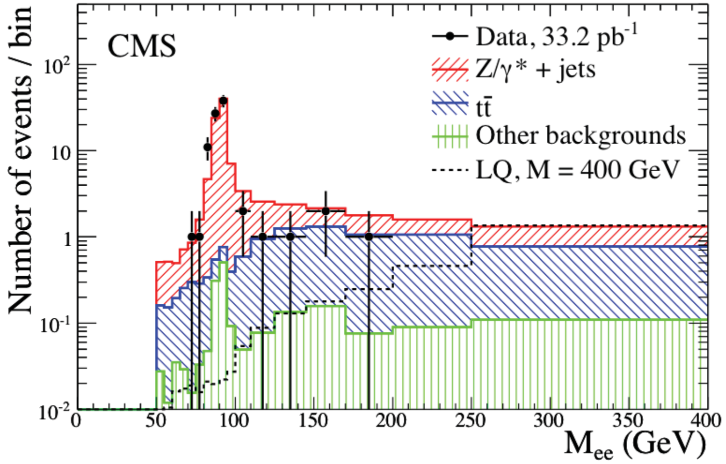
$$M_{Z'} > 1050\,\text{GeV}$$ [CMS, 1103.0981]

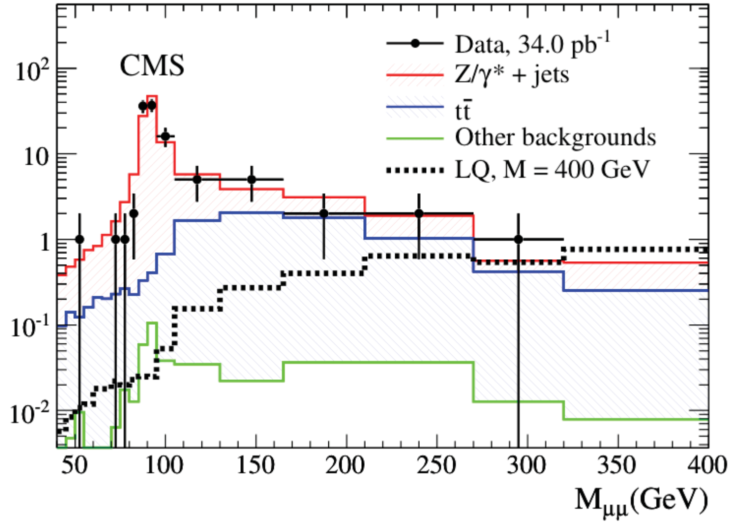
(superseding $M_{Z'} > 959\,\text{GeV}$ (CDF) [Erler+, 1010.3097])

Recent data. . .

CMS dileptons dijets

Published data from Leptoquark search :) [CMS, 1012.4031/33]





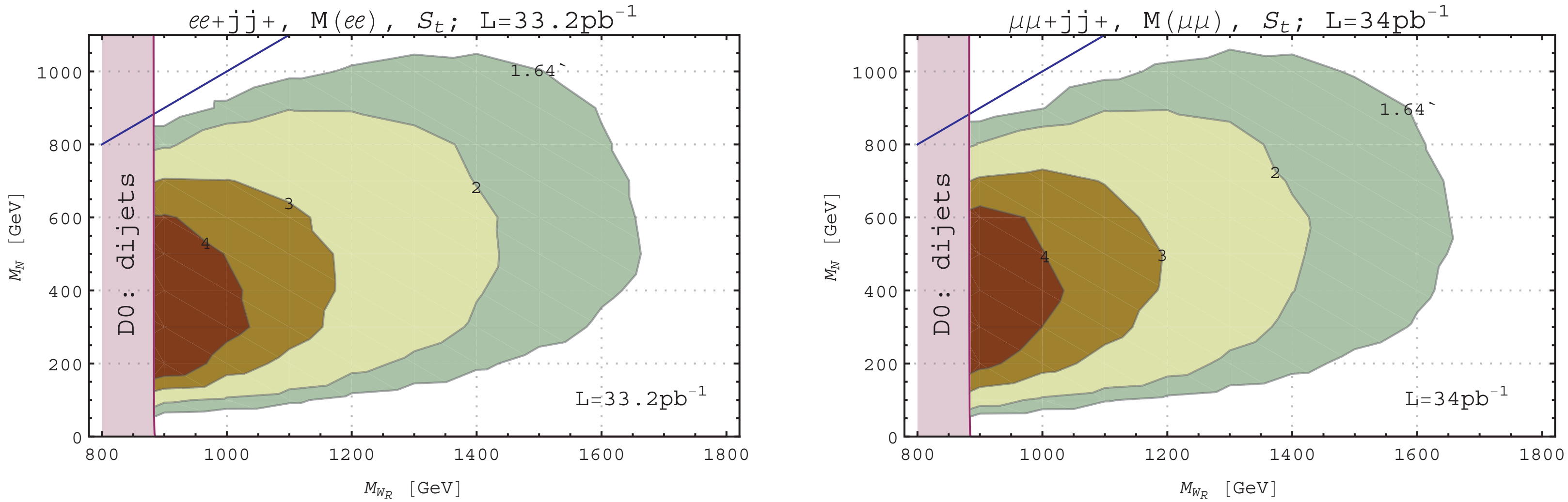
- Using tight lepton isolation. and cuts on:
  - $M_{\ell\ell}$: Invariant mass of dileptons
  - S_t: sum of total p_t of dileptons, dijets
- No $ee(\mu\mu)$ events above:

$$M_{\ell\ell} > 200(320)\,\text{GeV or } S_t > 620(560)\,\text{GeV}$$

...using the same cuts and background, exclude W_R-ν_R...

CMS dileptons dijets, cont'd

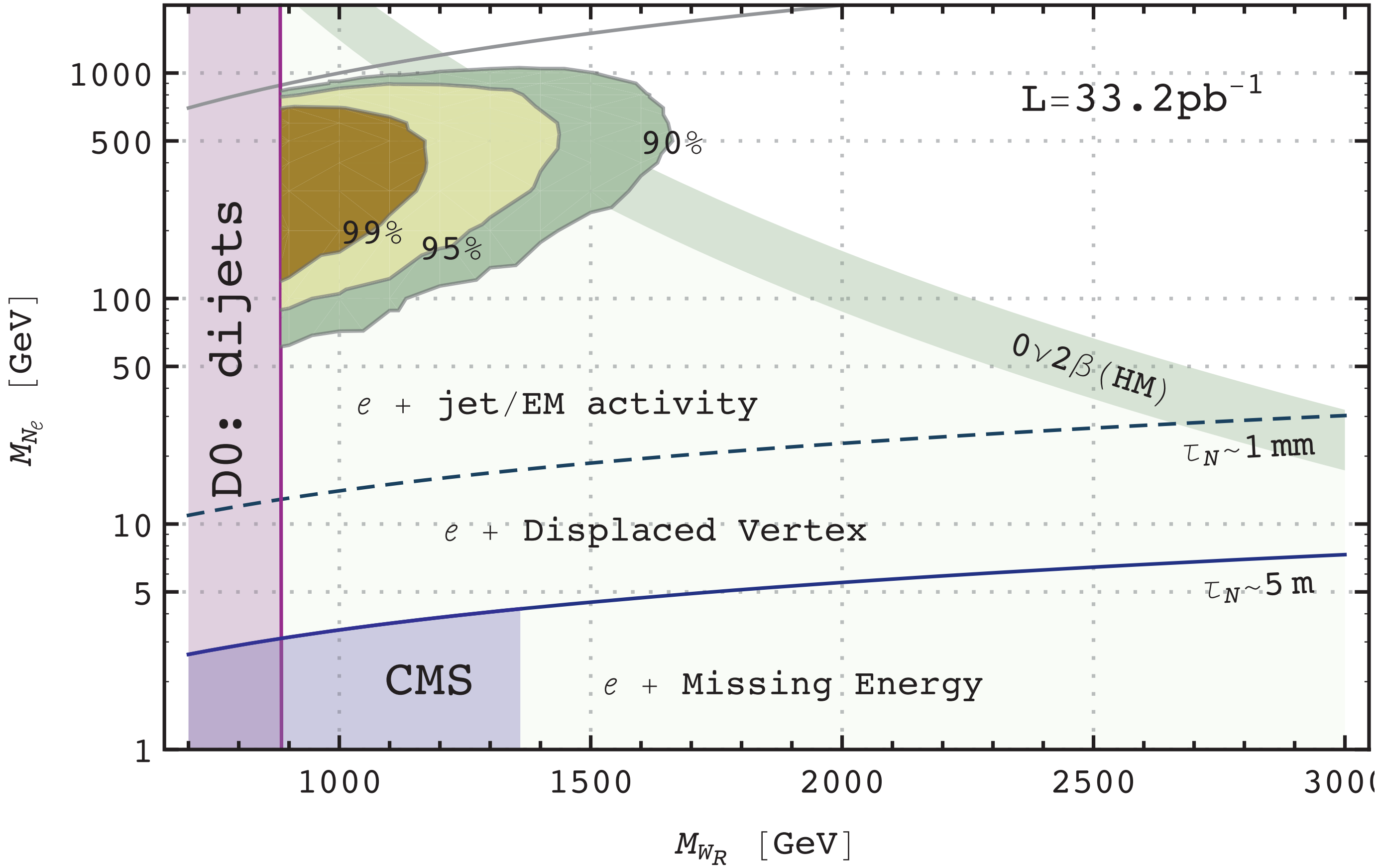
Result of exclusion $[\sigma]$ for $ee{+}jj{+}$ and $\mu\mu{+}jj{+}$:



- Electron and muon channels give similar limits
- A new limit of $M_{W_R} \gtrsim 1.4\,\text{TeV}$ (95% CL)
- Holding in a good part of the parameter space
- $L = 100\text{pb}^{-1}$: $M_{W_R} > 1.6\,\text{TeV}$, $\qquad L = 1\text{fb}^{-1}$: $M_{W_R} > 2.2\,\text{TeV}$.

High or very low M_{ν_R} unaccessible to this probe. . .

On a global plot [Nemevšek+ '11]



The interesting $0\nu\beta\beta$ region waiting for us...
Looking forward for jets with EM activity...
...and displaced vertices.

Summary

Neutrino physics leading us to TeV scale parity restoration.

- Needs Majorana (If $0\nu\beta\beta$ claim true)
- Beyond a simple RH neutrino (if clash with cosmology)
- A symmetric extension BSM,
- LR Symmetry at low scale.
- Leading to a connection between neutrino masses,$0\nu\beta\beta$, collider.
- TeV scale tailor-fit for $0\nu\beta\beta$.
- And for W_R-ν_R @ LHC.
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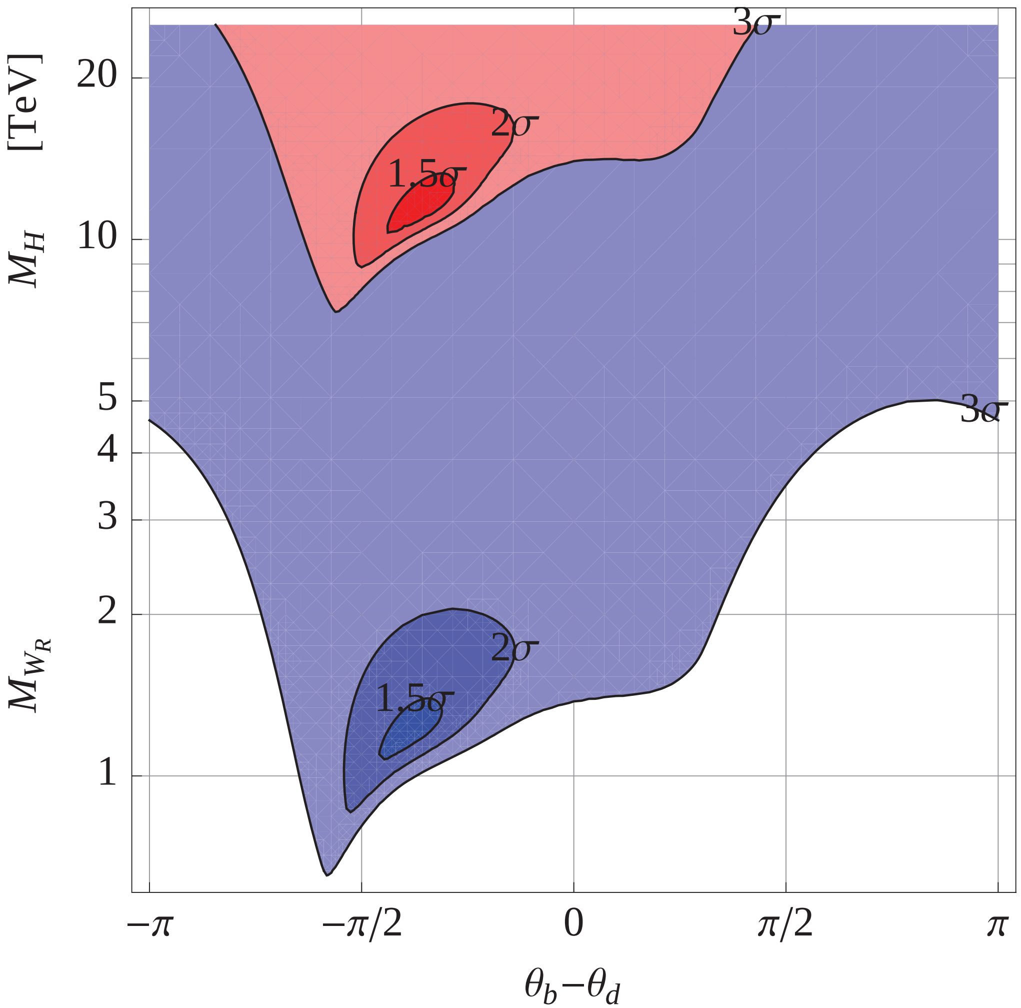
$\mathcal{C}$: B CP violation

The last free phase is constrained:



Lepton Flavour Violation constraints

Leptons less predictive. . . (neutrinos have Dirac and Majorana mass)

. . . but the collider flavour structure enters, via $M_{\nu_R} \propto Y_\Delta$, e.g.:

- $\mu \to 3e$: $$\left|\frac{(M_{\nu_R})_{\mu e}(M_{\nu_R})^*_{ee}}{M_\Delta^2}\right|^2 \lesssim \left(\tfrac{1}{2}\right)^4 \div \left(\tfrac{1}{10}\right)^4$$
- $\mu \to e\gamma$: $$\left|\frac{(M^2_{\nu_R})_{\mu e}}{M_\Delta^2}\right|^2 \lesssim 1$$
- $\mu \to e$ in nuclei . . .

[w/ V. Tello, M. Nemevšek, G. Senjanović, F. Vissani, 1011.3522]

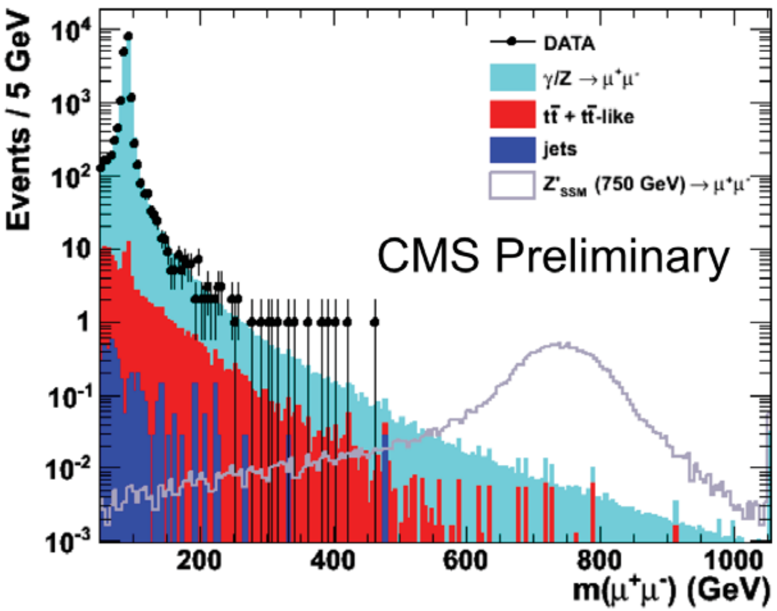
So, $M_{\nu_R} < M_\Delta/2 \div 10$ . . . light M_{ν_R} is favoured.

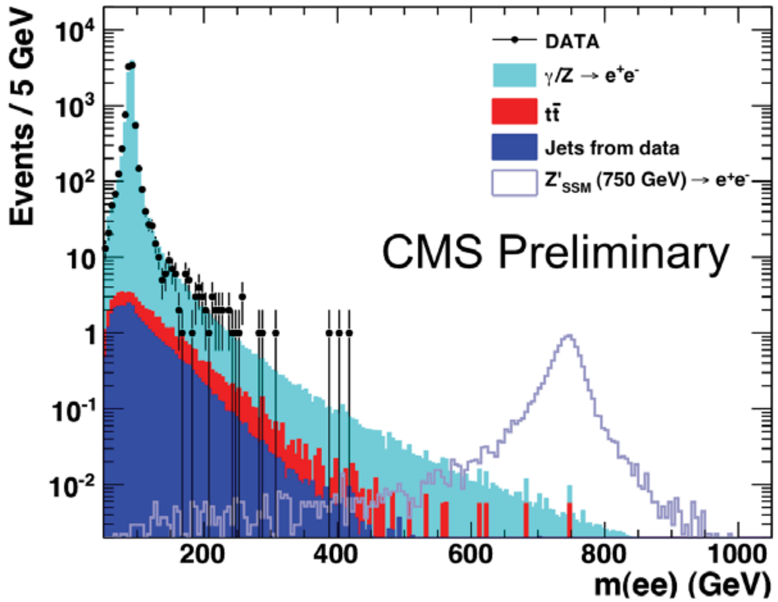
Again in type-II seesaw, we already have information from $M_{\nu_R} \propto M_\nu$.

LHC verifying connections between light and heavy neutrino mass.

(Need to observe different neutrino peaks – statistics, resolution. . . luck.)

Other data: CMS dileptons ? [CMS 1103.0981, Landsberg, 24/1/'11]

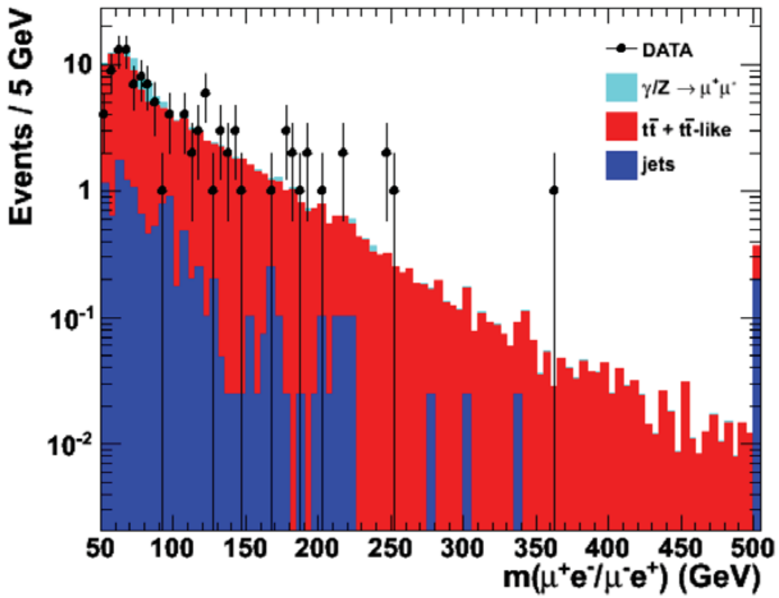




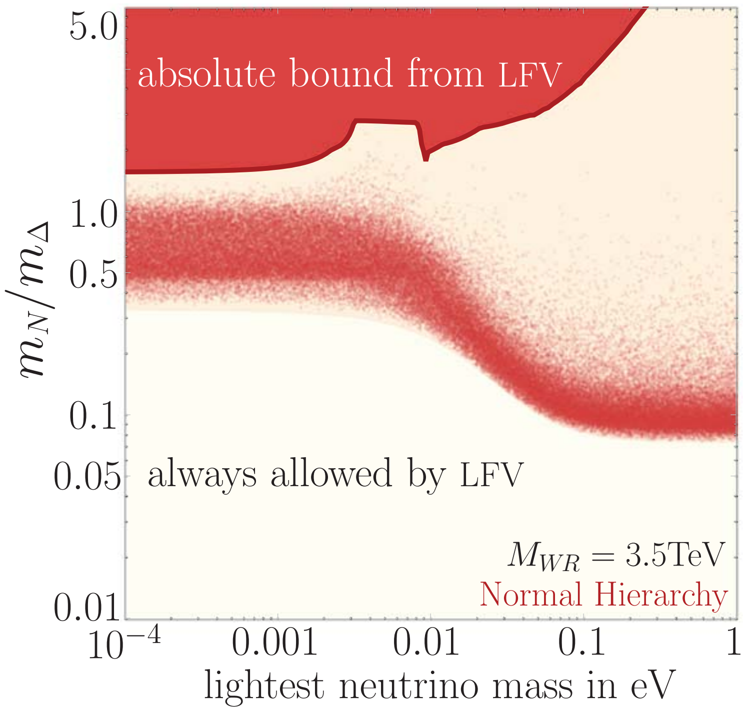
$$\int L = 35\text{–}40\,\text{pb}^{-1}$$

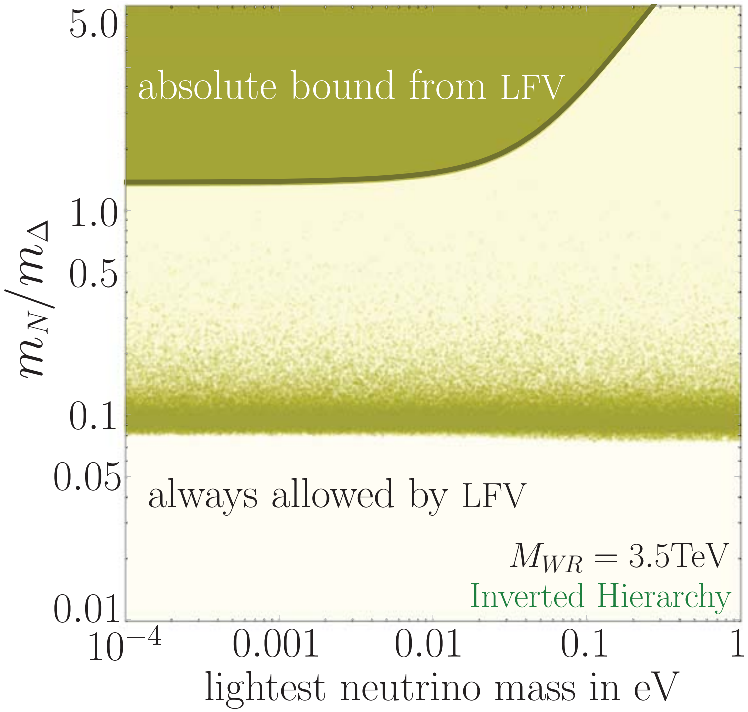
Already sensitive.

Implement same cuts. . .



LFV constraints





Including $\mu \to 3e$, $\tau \to 3e$, $\mu \to e$ in nuclei.

This tells us just $m_\Delta > m_N$.

L-R Lagrangian

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{fermion} + \mathcal{L}_{Yuk} + \mathcal{L}_{Maj}$$

$$\begin{aligned}\mathcal{L}_{Higgs} &= \mathrm{Tr}[(D_\mu\Delta_L)^\dagger(D^\mu\Delta_L)] + \mathrm{Tr}[(D_\mu\Delta_R)^\dagger(D^\mu\Delta_R)] \\ &+ \mathrm{Tr}[(D_\mu\phi)^\dagger(D^\mu\phi)] + V(\phi,\Delta_L,\Delta_R)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{Fermion} &= \overline{q}_{Li}\, i\not{D} q_{Li} + \overline{\ell}_{Li}\, i\not{D}\ell_{Li} + (L\leftrightarrow R) \\ \mathcal{L}_{Yukawa\, q} &= \overline{q}_{Li}(Y_{ij}\phi + \tilde{Y}_{ij}\tilde{\phi})q_{Rj} + h.c. \\ \mathcal{L}_{Yukawa\, \ell} &= \overline{\ell}_{Li}(h_{ij}\phi + \tilde{h}_{ij}\tilde{\phi})\ell_{Rj} + h.c. \\ \mathcal{L}_{Majorana} &= Y^{ij}[\overline{\ell}^t_{Li} C\, \tau_2 \Delta_L\, \ell_{Lj} + (L\leftrightarrow R)] + h.c.\end{aligned}$$

$$\mathcal{L}_{M_W} = \begin{pmatrix} W^-_{L\mu} & W^-_{R\mu}\end{pmatrix}\begin{pmatrix} \frac{1}{2}g^2(v^2+v'^2+2v_L^2) & -g^2 vv' e^{-i\alpha} \\ -g^2 vv' e^{i\alpha} & g^2 v_R^2\end{pmatrix}\begin{pmatrix} W_L^{+\mu} \\ W_R^{+\mu}\end{pmatrix}$$

$$\begin{array}{ccc} W_{3L} & W_{3R} & B \end{array}$$
$$\begin{pmatrix} g^2/2(\kappa^2+\kappa'^2+4v_L^2) & -g^2/2(\kappa^2+\kappa'^2) & -2gg'v_R^2 \\ -g^2/2(\kappa^2+\kappa'^2) & g^2/2(\kappa^2+\kappa'^2+4v_R^2) & -2gg'v_R^2 \\ -2gg'v_L^2 & -2gg'^2v_R^2 & 2g'^2(v_L^2+v_R^2)\end{pmatrix}$$

$$\begin{aligned} D_\mu\phi &= \partial_\mu\phi + ig_L W_{L\mu}\,\phi - ig_R\phi\, W_{R\mu} \\ D_\mu\psi &= \partial_\mu\phi + ig_L W_{L,R\mu}\psi_{L,R} + ig'(B-L)/2B_\mu\psi_{L,R} \\ D_\mu\Delta_{(L,R)} &= \partial_\mu\Delta_{(L,R)} + ig_{(L,R)}\left[W_{(L,R)\mu},\ \Delta_{(L,R)}\right] + ig' B_\mu\Delta_{(L,R)}\end{aligned}$$

Left-Right: scalar potential

$$
\begin{aligned}
V(\phi,\Delta_L,\Delta_R) = &\\
& -\mu_1^2 \mathrm{Tr}(\phi^\dagger\phi) - \mu_2^2\left[\mathrm{Tr}(\tilde\phi\phi^\dagger)+\mathrm{Tr}(\tilde\phi^\dagger\phi)\right] - \mu_3^2\left[\mathrm{Tr}(\Delta_L\Delta_L^\dagger)+\mathrm{Tr}(\Delta_R\Delta_R^\dagger)\right]\\
& +\lambda_1\left[\mathrm{Tr}(\phi^\dagger\phi)\right]^2 + \lambda_2\left\{\left[\mathrm{Tr}(\tilde\phi\phi^\dagger)\right]^2+\left[\mathrm{Tr}(\tilde\phi^\dagger\phi)\right]^2\right\}\\
& +\lambda_3\mathrm{Tr}(\tilde\phi\phi^\dagger)\mathrm{Tr}(\tilde\phi^\dagger\phi) + \lambda_4\mathrm{Tr}(\phi^\dagger\phi)\left[\mathrm{Tr}(\tilde\phi\phi^\dagger)+\mathrm{Tr}(\tilde\phi^\dagger\phi)\right]\\
& +\rho_1\left\{\left[\mathrm{Tr}(\Delta_L\Delta_L^\dagger)\right]^2+\left[\mathrm{Tr}(\Delta_R\Delta_R^\dagger)\right]^2\right\}\\
& +\rho_2\left[\mathrm{Tr}(\Delta_L\Delta_L)\mathrm{Tr}(\Delta_L^\dagger\Delta_L^\dagger)+\mathrm{Tr}(\Delta_R\Delta_R)\mathrm{Tr}(\Delta_R^\dagger\Delta_R^\dagger)\right]\\
& +\rho_3\mathrm{Tr}(\Delta_L\Delta_L^\dagger)\mathrm{Tr}(\Delta_R\Delta_R^\dagger) + \rho_4\left[\mathrm{Tr}(\Delta_L\Delta_L)\mathrm{Tr}(\Delta_R^\dagger\Delta_R^\dagger)+\mathrm{Tr}(\Delta_L^\dagger\Delta_L^\dagger)\mathrm{Tr}(\Delta_R\Delta_R)\right]\\
& +\alpha_1\mathrm{Tr}(\phi^\dagger\phi)\left[\mathrm{Tr}(\Delta_L\Delta_L^\dagger)+\mathrm{Tr}(\Delta_R\Delta_R^\dagger)\right]\\
& +\left\{\alpha_2 e^{i\delta_2}\left[\mathrm{Tr}(\tilde\phi\phi^\dagger)\mathrm{Tr}(\Delta_L\Delta_L^\dagger)+\mathrm{Tr}(\tilde\phi^\dagger\phi)\mathrm{Tr}(\Delta_R\Delta_R^\dagger)\right]+\mathrm{h.c.}\right\}\\
& +\alpha_3\left[\mathrm{Tr}(\phi\phi^\dagger\Delta_L\Delta_L^\dagger)+\mathrm{Tr}(\phi^\dagger\phi\Delta_R\Delta_R^\dagger)\right] + \beta_1\left[\mathrm{Tr}(\phi\Delta_R\phi^\dagger\Delta_L^\dagger)+\mathrm{Tr}(\phi^\dagger\Delta_L\phi\Delta_R^\dagger)\right]\\
& +\beta_2\left[\mathrm{Tr}(\tilde\phi\Delta_R\phi^\dagger\Delta_L^\dagger)+\mathrm{Tr}(\tilde\phi^\dagger\Delta_L\phi\Delta_R^\dagger)\right] + \beta_3\left[\mathrm{Tr}(\phi\Delta_R\tilde\phi^\dagger\Delta_L^\dagger)+\mathrm{Tr}(\phi^\dagger\Delta_L\tilde\phi\Delta_R^\dagger)\right]
\end{aligned}
$$

Higgs spectrum

Higgs state	m^2
$h^0 = \sqrt{2}\,\mathrm{Re}\,\left(\phi_1^{0*} + xe^{-i\alpha}\phi_2^0\right)$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1}\right) v^2 + \alpha_3 v_R^2 x^2$
$H_1^0 = \sqrt{2}\,\mathrm{Re}\,(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0)$	$\alpha_3 v_R^2$
$A_1^0 = \sqrt{2}\,\mathrm{Im}\,(-xe^{i\alpha}\phi_1^{0*} + \phi_2^0)$	$\alpha_3 v_R^2$
$H_2^0 = \sqrt{2}\,\mathrm{Re}\,\delta_R^0$	$4\rho_1 v_R^2$
$H_2^+ = \phi_2^+ + xe^{i\alpha}\phi_1^+ + \frac{1}{\sqrt{2}}\epsilon\delta_R^+$	$\alpha_3\left(v_R^2 + \frac{1}{2}v^2\right)$
δ_R^{++}	$4\rho_2 v_R^2 + \alpha_3 v^2$
$H_3^0 = \sqrt{2}\,\mathrm{Re}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$A_2^0 = \sqrt{2}\,\mathrm{Im}\,\delta_L^0$	$(\rho_3 - 2\rho_1)v_R^2$
$H_1^+ = \delta_L^+$	$(\rho_3 - 2\rho_1)v_R^2 + \frac{1}{2}\alpha_3 v^2$
δ_L^{++}	$(\rho_3 - 2\rho_1)v_R^2 + \alpha_3 v^2$

Leading order in $\epsilon = v/v_R$ and $x = v'/v$, and assuming $v_L = 0$.
The SM Higgs is identified with h^0.

W_L-W_R mixing

In the minimal model, the tree level W_L-W_R mixing angle is

$$\tan 2\zeta = \frac{2vv'}{v_r^2 + v^2} \simeq \frac{v'}{v}\frac{M_{W_L}^2}{M_{W_R}^2}$$

This is bound by 'Left' weak decays, $\zeta < 10^{-2}$ $(3\,10^{-3})$.

Thus, this translates into a limit on the W_R mass:

$$M_{W_R} > 1.5\,\text{TeV}\sqrt{\frac{2x}{1+x^2}}\,,$$

...However, since $M_{W_R} > 2.$ TeV (see later), this bound is quite harmless.

Note: a *different* way to restore parity

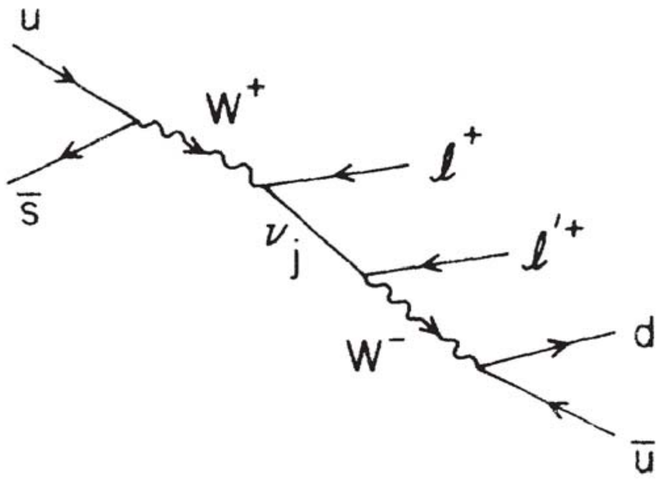
Instead of symmetrizing the gauge group, symmetrize the fermions.

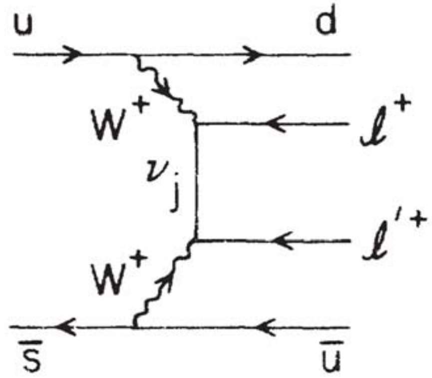
- add mirror fermions: three families of opposite chirality
  q'_R, ℓ'_R, u'_L, d'_L, e'_L. (No ν'_L here!)
- Possible mass terms like $\bar{q}_L q'_R$ must be forbidden.
- And, being (anti)chiral families, they can (only) get mass from SU(2) breaking: Yukawa. Then, not arbitrarily heavy (perturbativity).
- But mirror families *must* be heavy – from direct searches:
  $m_{q'} > 350$ GeV $m_{e'} \gtrsim 100$ GeV $m_{\nu'} \gtrsim 45$ GeV
  So, low perturbativity cutoff.

Hence: no connection with neutrino masses here.

But predictive, and on the way to be excluded by LHC?
LHC search for 4^{th} and further generations.

Neutrinoless decays: $K \longrightarrow \pi e^+ e^+$





Extremely rare, e.g. estimate

$$B(K^+ \to \pi^- \ell^+ \ell'^+) \sim 10^{-13} \left[\left(\frac{m_{\nu ee}}{100\text{MeV}} \right)^2 + U_{eR}^2 \left(\frac{100\text{MeV}}{m_R} \right)^2 \right] r_{\ell\ell'}$$