Low scale Left Right symmetry theoretical and first LHC limits

Fabrizio Nesti

The role of Heavy Fermions in Fundamental Physics

Portoroz — 11th April 2011

w/ A. Maiezza, M. Nemevšek, G. Senjanović, V. Tello, F. Vissani, Y. Zhang

[PRD 82 (2010) 055022 [1005.5160], PRL (2011) [1011.3522], hep-ph/1103.1627]

The LR MSSM (More Symmetric Standard Model)

	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	$\overline{\mathbf{2}}$	$2/3$	$2/3$	0	$1/2$	$1/3$	**3**
d_R	$\overline{\mathbf{2}}$	$-1/3$	$-1/3$	0	$-1/2$	$1/3$	**3**
ν_R	$\overline{\mathbf{2}}$	0	0	0	$1/2$	-1	**1**
e_R	$\overline{\mathbf{2}}$	-1	-1	0	$-1/2$	-1	**1**

Plenty of symmetries toward unification, starting from the simplest, Left-Right symmetry, restoring a "Parity" at some scale:

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

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

(Then Pati-Salam, SO(10), etc, even with Lorentz bringing Gravity into the game)

[Pati Salam '74; Georgi '75] [FN '07, FN Percacci '09, ...]

M_R scales

Can we see it?

- High M_{W_R} up to $\sim 10^{14}$ GeV: ok with GUT.
  Still M_{ν_R} can be low – but hard to see. [Kersten Smirnov 07, etc]
- 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.
  - Also, lepton number violation enters in rare processes: e.g. new contributions to $0\nu\beta\beta$

  . . . disentangled from neutrino masses
  and their (cosmological) bound. . .

M_R scales

Can we see it?

- High M_{W_R} up to $\sim 10^{14}$ GeV: ok with GUT.
  Still M_{ν_R} can be low – but hard to see. [Kersten Smirnov 07, etc]
- Low $M_{W_R} \gtrsim$ TeV possible and testable:

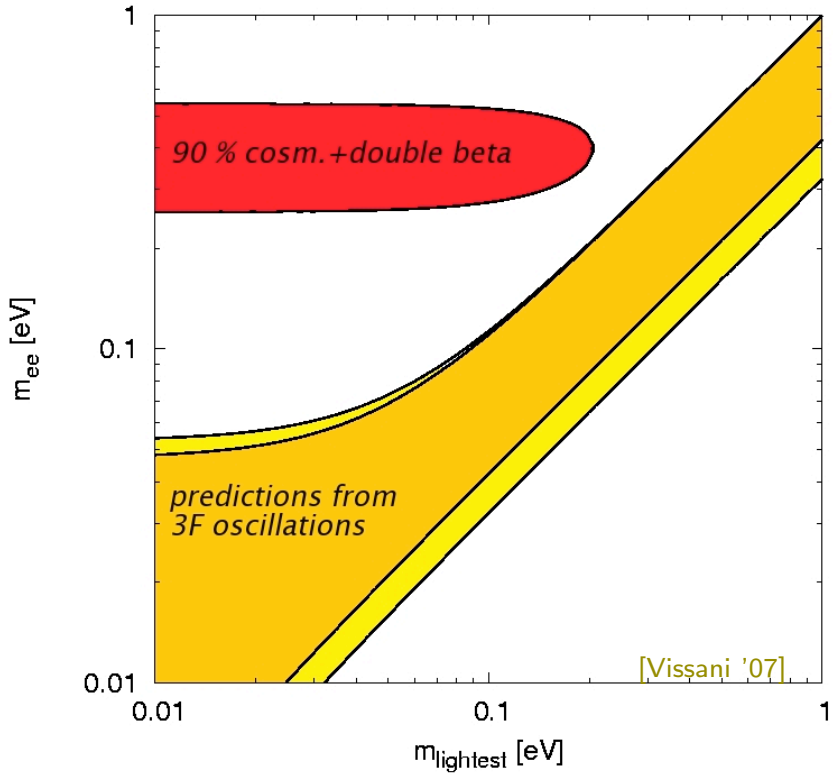
  leading to striking signals

  (. . . direct probe of new interactions)
  (. . . of P restoration)
  (. . . of Majorana character)
  (. . . of additional flavour structure)
- Collider signals of W_R and ν_R.
- Also, lepton number violation enters in rare processes: e.g. new contributions to $0\nu\beta\beta$

  . . . disentangled from neutrino masses
  and their (cosmological) bound. . .

$0\nu\beta\beta$

- Recall: cosmology $\sum m_\nu \lesssim 1(0.6)\,\text{eV}$ [Hannestad+'08, Hamann+'10]
  ...shrinks towards incompatibility with evidences of $0\nu\beta\beta$
  I.e. with claim of $m_{ee} \sim 0.4\,\text{eV}$, from Heidelberg-Moscow.



see talk by Nemevshek

$0\nu\beta\beta$

- Recall: cosmology $\sum m_\nu \lesssim 1(0.6)\,\text{eV}$ [Hannestad+'08, Hamann+'10]
  ...shrinks towards incompatibility with evidences of $0\nu\beta\beta$
  I.e. with claim of $m_{ee} \sim 0.4\,\text{eV}$, from Heidelberg-Moscow.

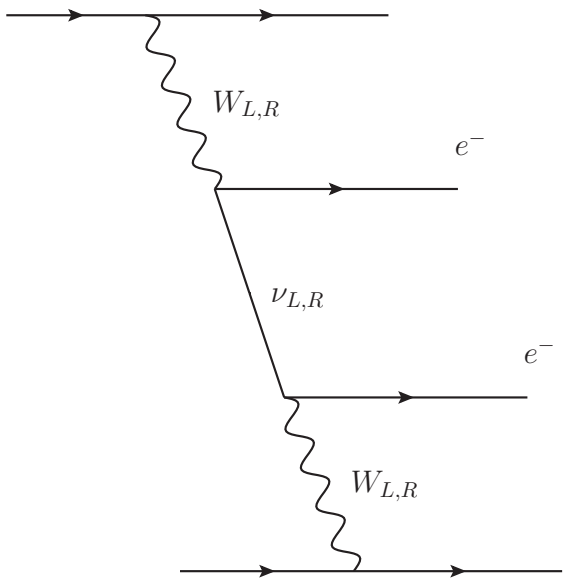
New contributions, that can compete with the standard LL $0\nu\beta\beta$ amplitude $\propto m_{ee}/p^2$ with $m_{ee} \sim 0.1\,\text{eV}$:

- LR hardly important.
  (need Dirac cancelations)

- RR important for:

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

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



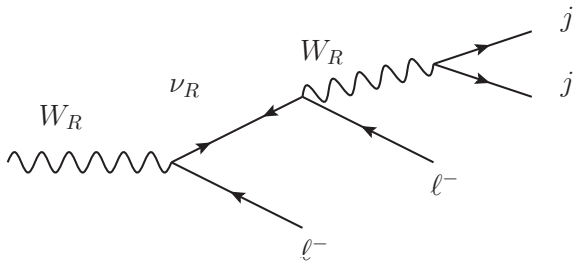
LR @ LHC a case of new physics avoiding the clash.

see talk by Nemevshek

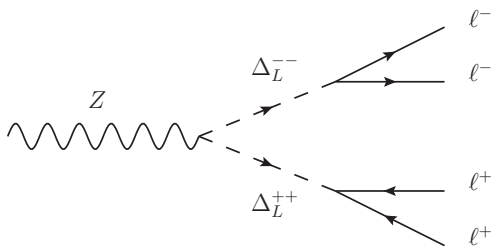
Interesting processes

- Premium: W_R-ν_R production

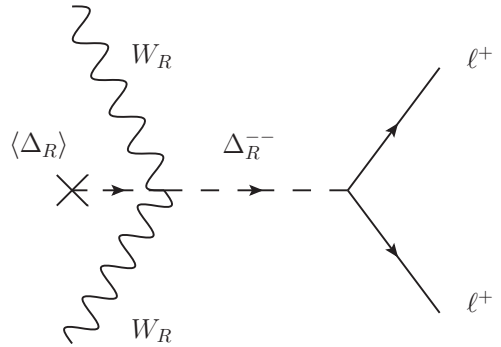
  Same-sign dileptons.



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



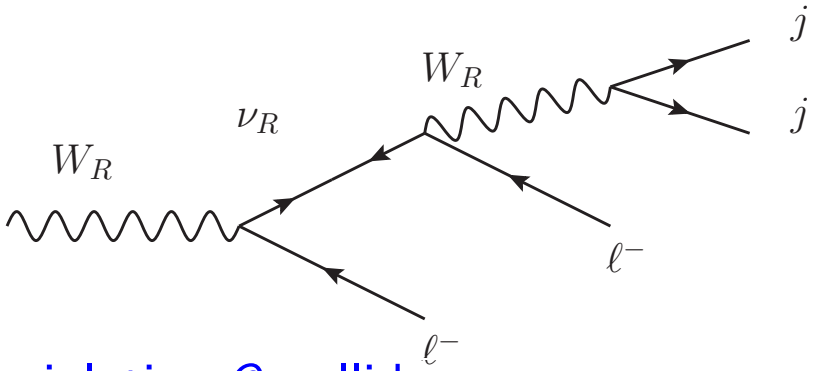
- $\Delta_R^{\pm\pm}$ production (W fusion)
- W_R-Δ_R pair production
- $0\nu 2\beta$ (LL vs RR)
- $\mu \longrightarrow e\gamma$, ... see talk by M. Nemevshek



... depends of course on which particles lie at low scale.

W_R-ν_R

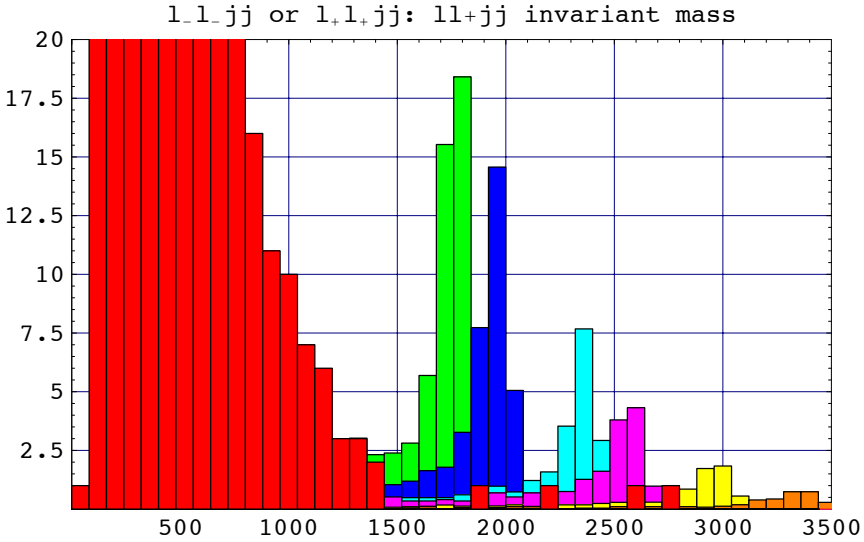
Yukawa-free production of W_R, ν_R possibly on-shell.

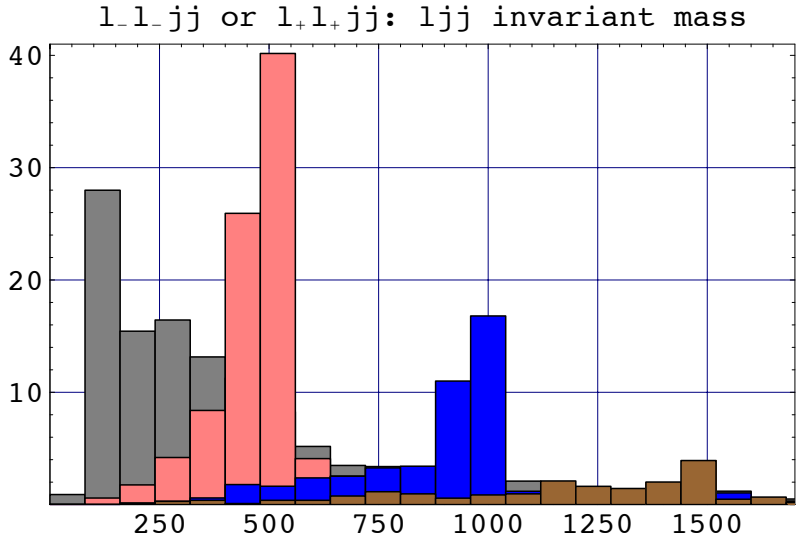


[Keung Senjanovic '83]

Lepton number violation @ collider.

Reconstruct W_R and ν_R invariant masses, probing neutrino flavour pattern





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

W_R-ν_R cont'd

- LHC reach?

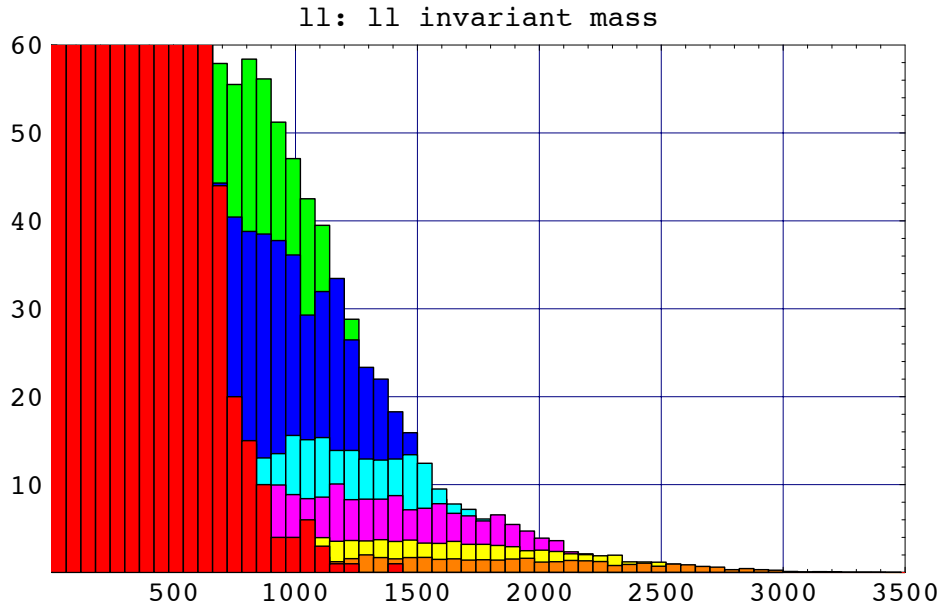
$M_{W_R}[TeV]$	m_{ν_R} [TeV]	$\int L$	energy	
4 (2)	2 (1)	30 /fb	14(7) TeV	Ferrari et al '00, Gninenko et al '07
2.1 (1.5)	2.1	100/pb	14(10) TeV	Kirsanov '09

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

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



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

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

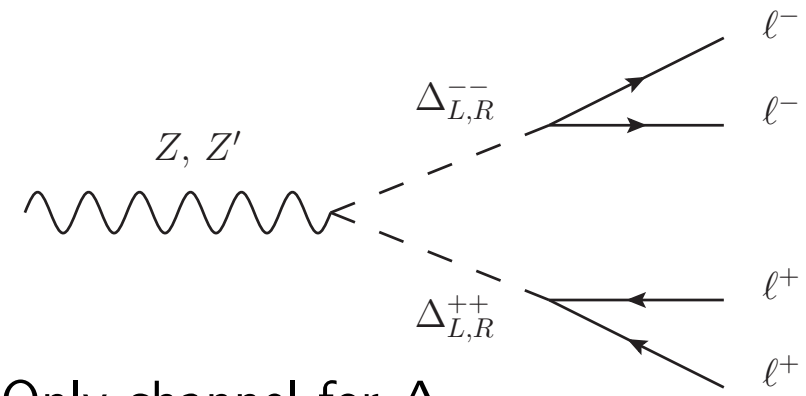
- Neutrino masses and flavour:
  Yukawa-free, but probing RH neutrino matrix.
  Need channels, e-e, e-μ, μ-μ, τ(?)

  (and need updated MC)

- Displaced Vertex?

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

$\Delta_{L,R}$

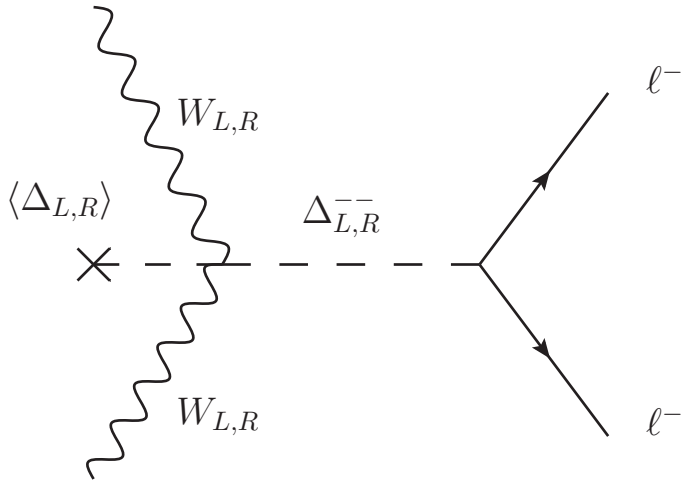


$$\propto (Y_\Delta)_{ij}(Y^*_\Delta)_{kl}$$

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

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)

- Theory: Strongest limit comes from $K^0\overline{K}^0$ mass difference,
  - If disentangled $V_{CKM\,R} \neq V_{CKM\,L}$ then no limit on M_{W_R}.
  - In models where $V_{CKM\,R} \simeq V_{CKM\,L}$, we need $M_{W_R} > 2.5\,\text{TeV} \pm \ldots$

    [Beall+ '81, ..., Zhang+ '07]

- In general ϵ, ϵ' harmless, due to phases. (also in minimal models)

New physics in $\Delta m_K \ldots$

$\Delta F = 2$ 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-$\overline{M}^0$:

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

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

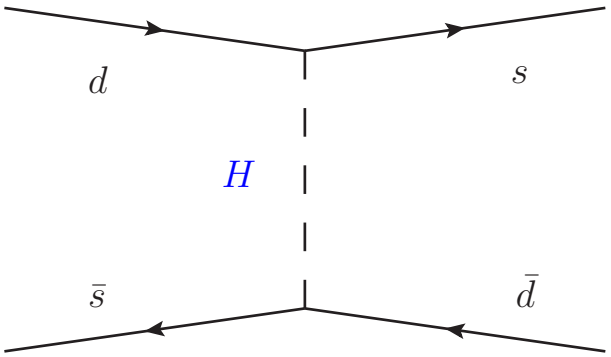
$\Delta F = 2$ FC Higgs

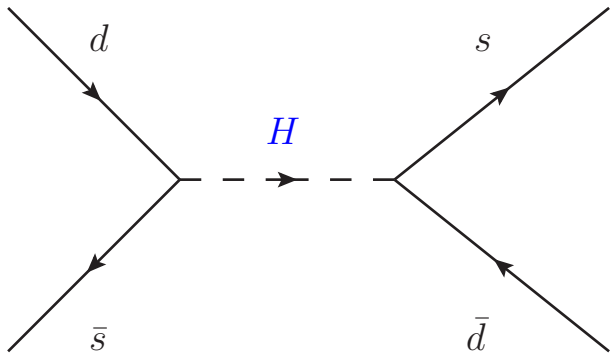
Effective **Hamiltonians** from the tree level Higgs:

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

where again

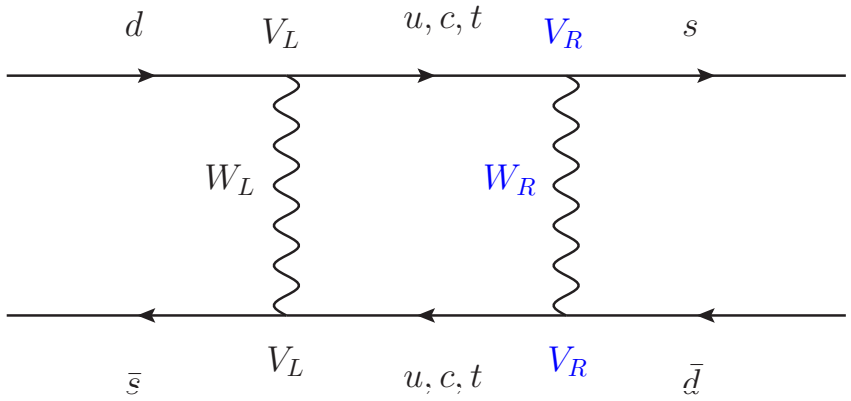
$$\lambda_i^{LR} = V_{id'}^{L*} V_{id}^{R} \,.$$





$K\bar{K}$

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



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

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

(With hadronic uncertainty 25–50%) [Baremboim+ '96, Babich+ '06]

(and LR chiral 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:

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

[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...

Left + Right models

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

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

spontaneously with $v_L \ll v' < v \ll v_R$. [Mohapatra Senjanovic '75]

- Quark masses from two yukawa matrices, $\bar{\psi}_L(Y\phi + \tilde{Y}\tilde{\phi})\psi_R$:

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

- Majorana neutrino masses $m_{LL} \propto m_{RR}$: (in addition to Dirac)

$$m_{LL} = Y_\Delta \langle \Delta_L \rangle \quad \ll \quad m_{RR} = Y_\Delta \langle \Delta_R \rangle$$

- Spectrum: W_R, ν_R, $\Delta_{L,R}$ may be near TeV
- H has to be very heavy (tree-level FC)

[Senjanovič Senjanovič '80, ..., Zhang et al '07]

L-R models: the two symmetries

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

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

Y, $\tilde{Y}$ hermitian, but not masses...

...due to the 'spontaneous' phase $\mathrm{e}^{i\alpha}$.

Complete numerical study $\Rightarrow$ $V_R \simeq V_L$ ($\pm 25\%$)

[w/ A. Maiezza, M. Nemevšek, G. Senjanović, PRD 2010]

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

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

Y, $\tilde{Y}$ symmetric and $\Rightarrow$ $V_R = K_1\, V_L^*\, K_2\,,$

with K_1, K_2 diagonal phases. So equal mixings, and from Δm_K,

$$M_{W_R} \geq 2.5\,\mathrm{TeV}$$

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 in general matrices ∼hermitian and mixings similar...

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

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

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

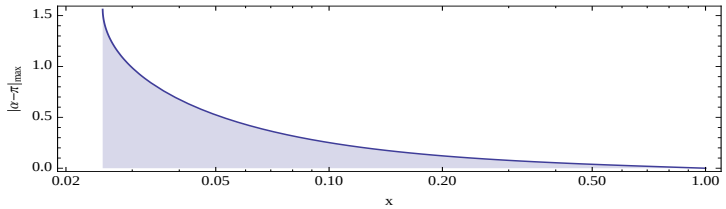
  Key parameters are α and $x = v'/v$. $(0 < x < 1)$

- 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...

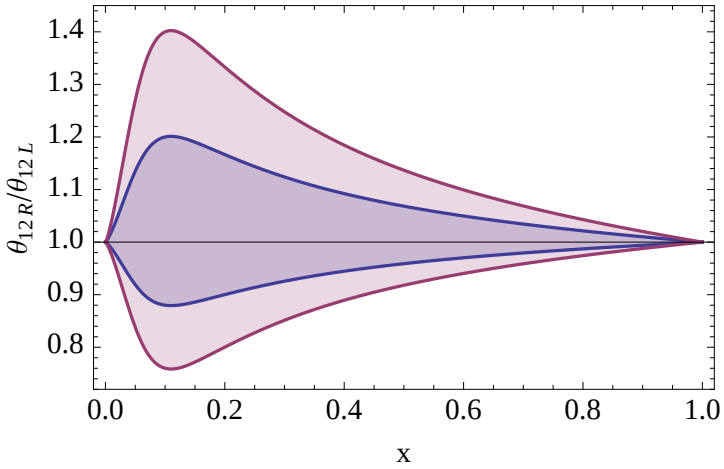
  ...However α is limited by the need to adjust $m_b \ll m_t$.



So in general matrices ∼hermitian and mixings similar...

Completing the landscape for $\mathcal{P}$

Need numerical fit (13 parameters).
A complete numerical analysis: [W/ Maiezza, Nemevšhek, Senjanović PRD10]



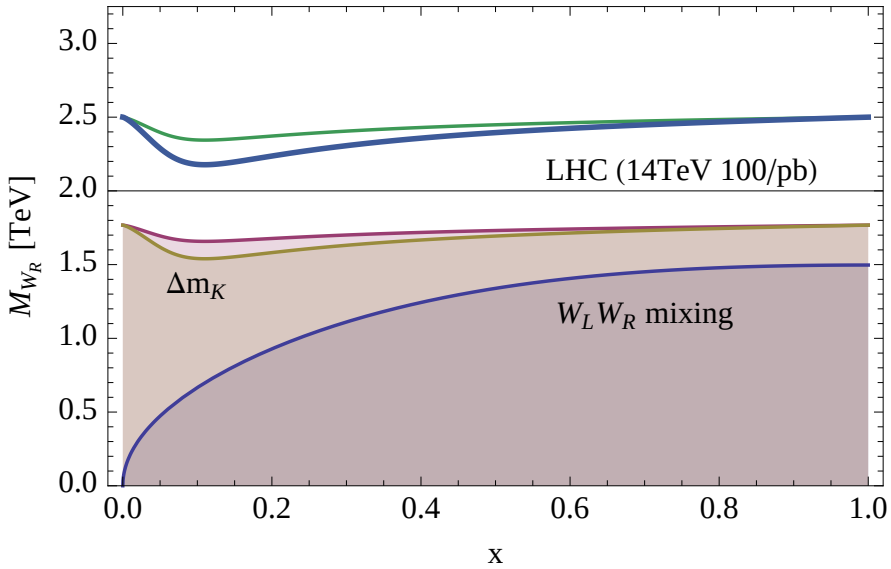
Mixings are quite aligned again.

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

Other angles similarly related.

Bound is maybe bound to stay.

(Still 25%(?) from matrix element, long distance parts...)



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

Mixings $\sim$ similar $\rightarrow$ 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 phases are predicted... ϵ, ϵ'?

CP violating:

- ϵ, ϵ': 3.2 $\sim$ 4.2 TeV
- *nEDM*: 4 TeV (but after having fine-tuned $\bar{\theta}$!)
- CP in $B_{d,s}$: ? (here no solution for the present tensions)

$\rightarrow$ $\mathcal{P}$ Marginally detectable at LHC.

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

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

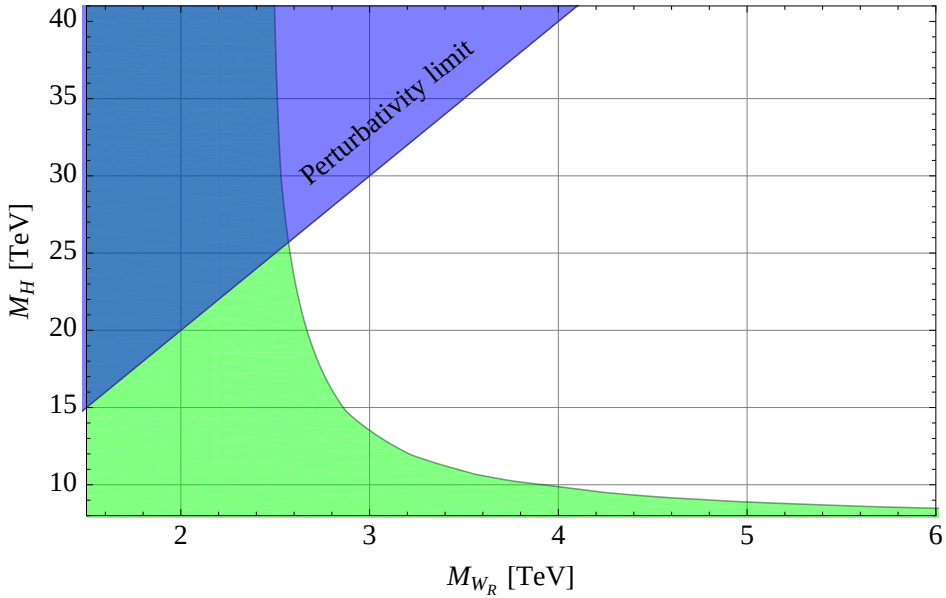
$$V_R = K_u\, V_L^*\, K_d$$

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

- 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 $\sim$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:

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

Quite large contribution from LR, however:

- For Zero phases $\theta_{d,s}$, no CP violation (general in LR with $\mathcal{C}$)
- So, *no bounds*, we only conclude:

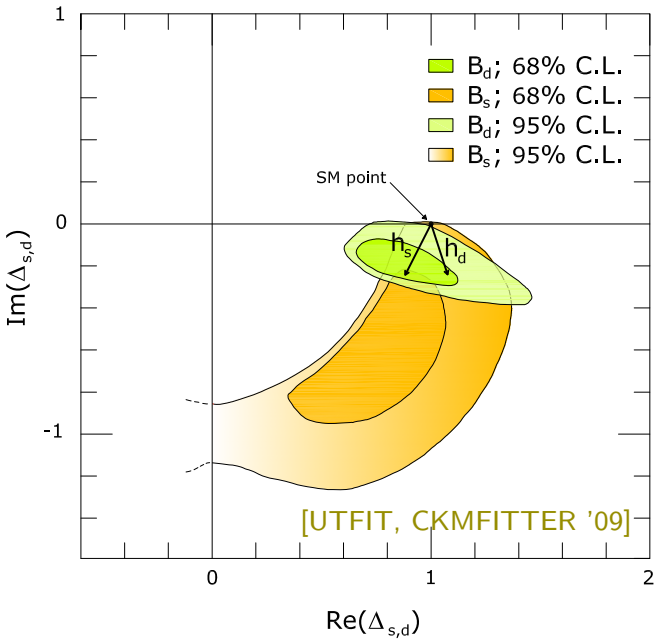
$$\theta_d - \theta_s \simeq 0\,.$$

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

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

[Maiezza, FN, Nemevshek, Senjanovic PRD'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 a nonzero phase θ_b:

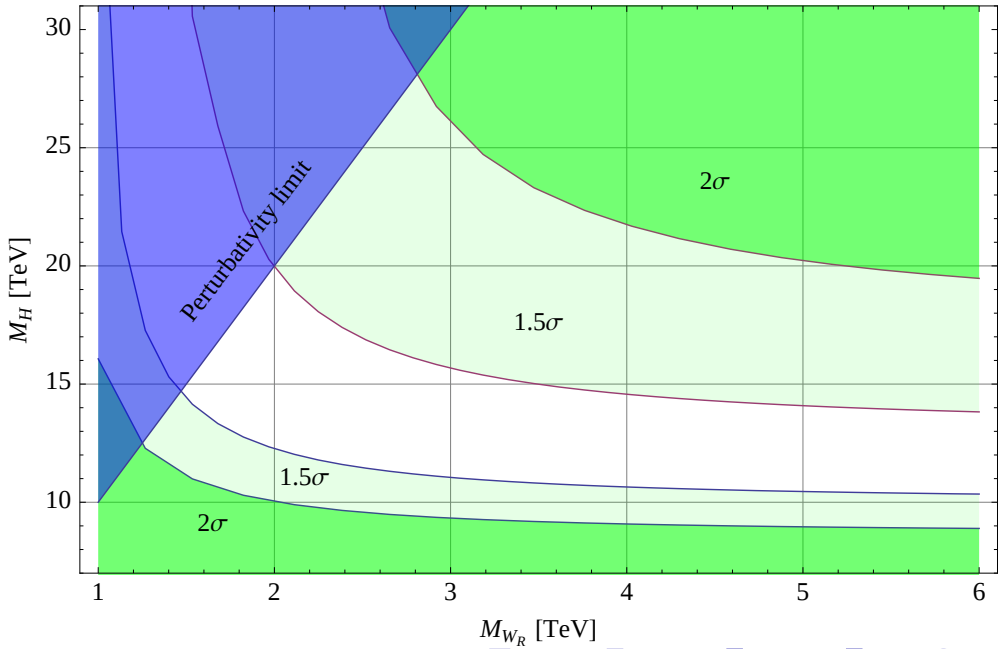
$$\theta_b - \theta_d \simeq \theta_b - \theta_s$$

(recall $\theta_d \simeq \theta_s$)

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

Correlated bound:

In the interesting zone for LHC



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]

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

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

(Note: these limits given for equality of couplings $g_R = g_L$ and $W\nu e$ mixings, which is simplistic.)

- Limit on $Z' \to \mu^+\mu^-$, again for equal couplings

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

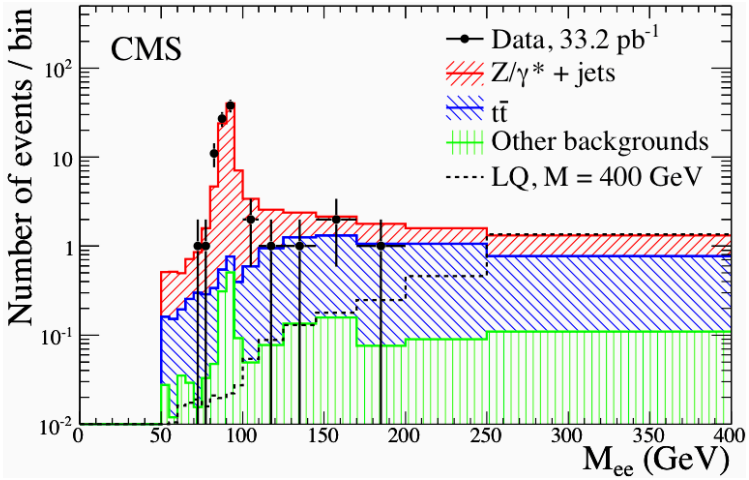
(superseding $M_{Z'} > 959\,\text{GeV}$ (CDF) [Erler+, 1010.3097])

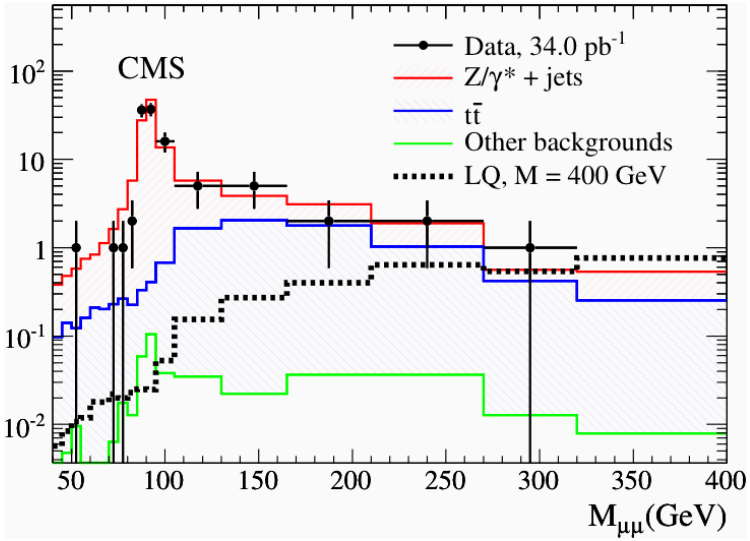
Recent data...

CMS dileptons dijets

Published data:

[CMS LQ search 1012.4031/33]





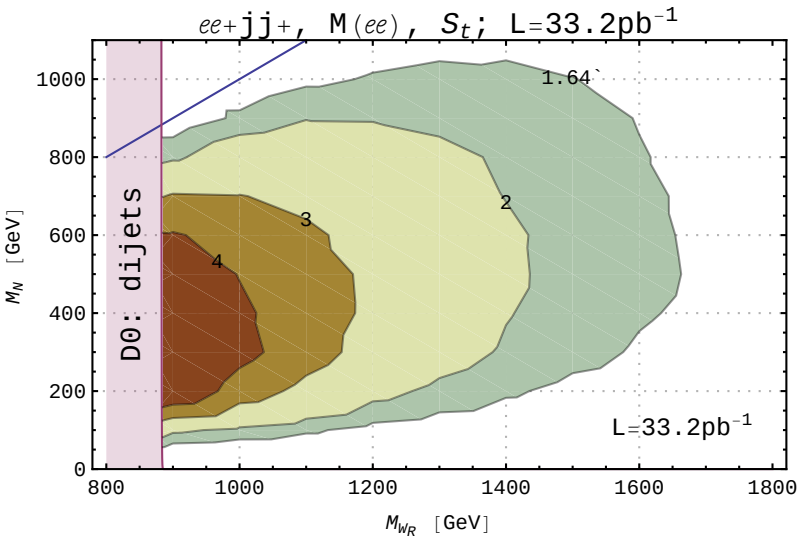
- Using tight lepton isolation. and cuts on:
  - $M_{\ell\ell}$: Invariant mass of dileptons
  - S_t: sum of total p_t of dileptons, dijets
- No $ee(\mu\mu)$ events above:

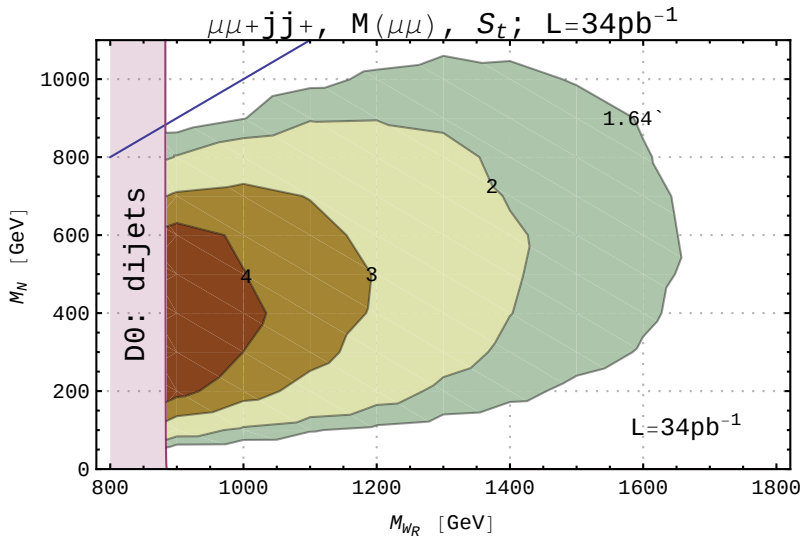
$$M_{\ell\ell} > 200(320)\,\text{GeV} \text{ or } S_t > 620(560)\,\text{GeV}$$

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

CMS dileptons dijets, cont'd

Result of exclusion [σ] for ee+jj+ and $\mu\mu$+jj+:



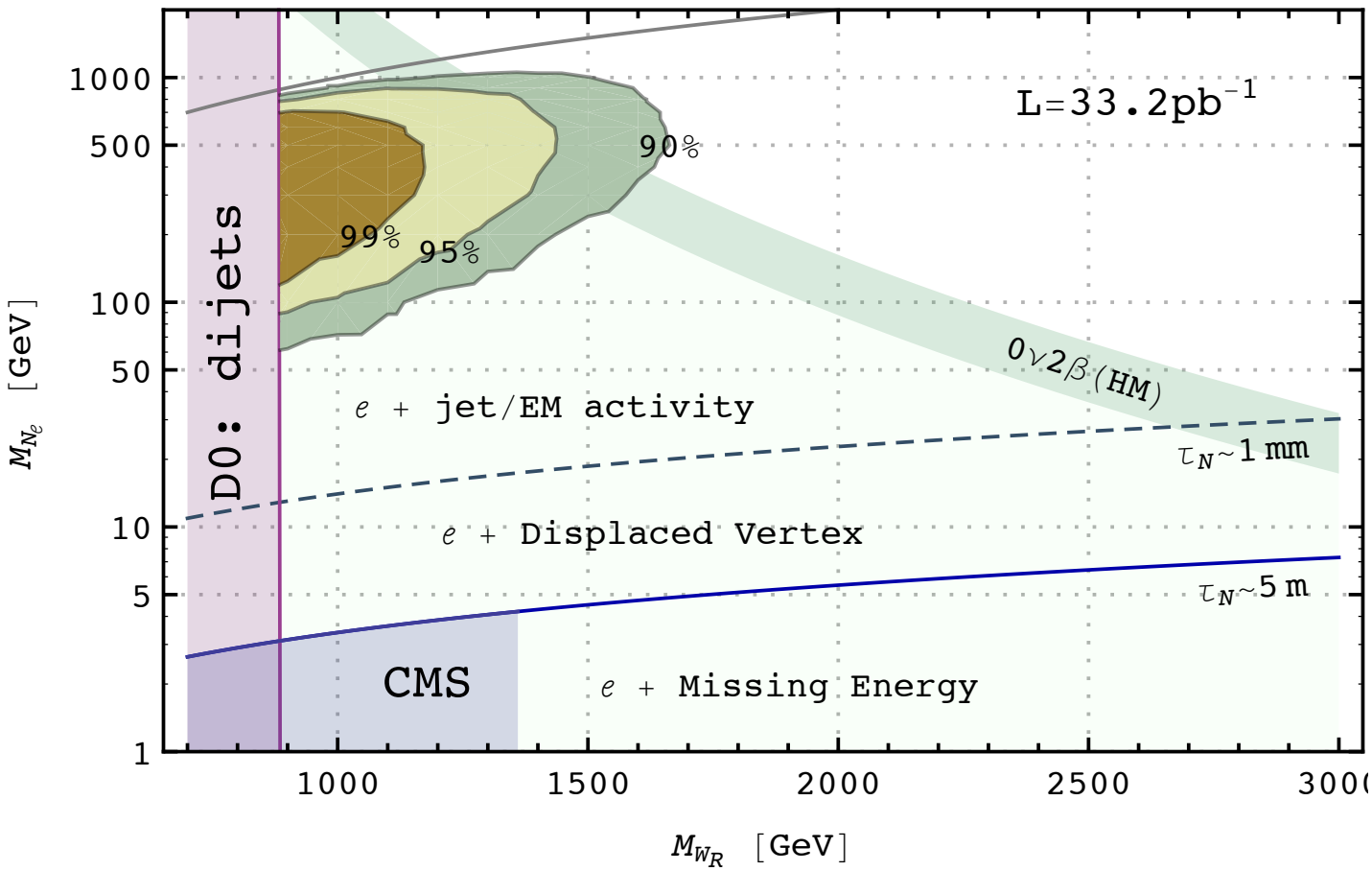


- Electron and muon channels give similar limits
- A new limit of $M_{W_R} \gtrsim 1.4\,\text{TeV}$ (95% CL)
- Holding in a good part of the parameter space
- $L = 100\text{pb}^{-1}$: $M_{W_R} > 1.6\,\text{TeV}$, $L = 1\text{fb}^{-1}$: $M_{W_R} > 2.2\,\text{TeV}$.

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

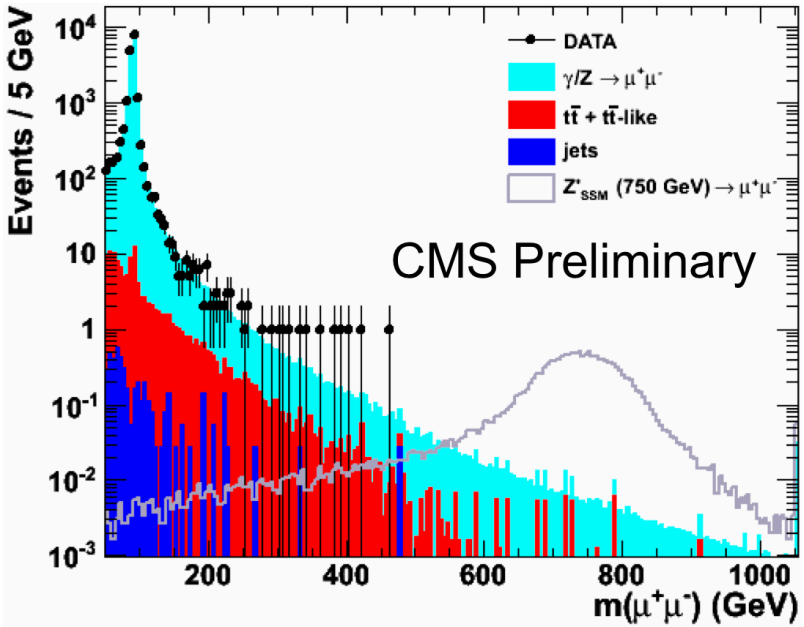
On a global plot

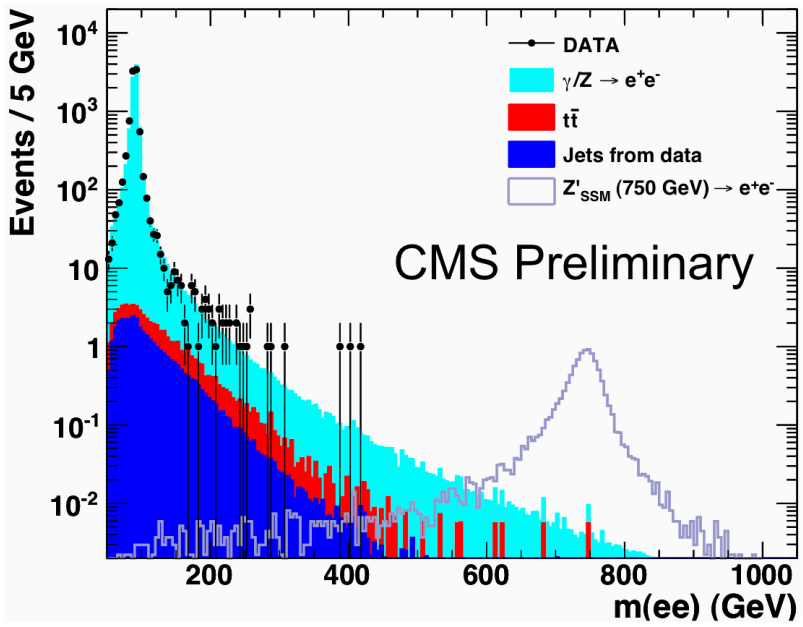
[Nemevshek FN Senjanovic Zhang 1103.1627v2]



Looking forward for jets with EM activity...
...and displaced vertices.

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

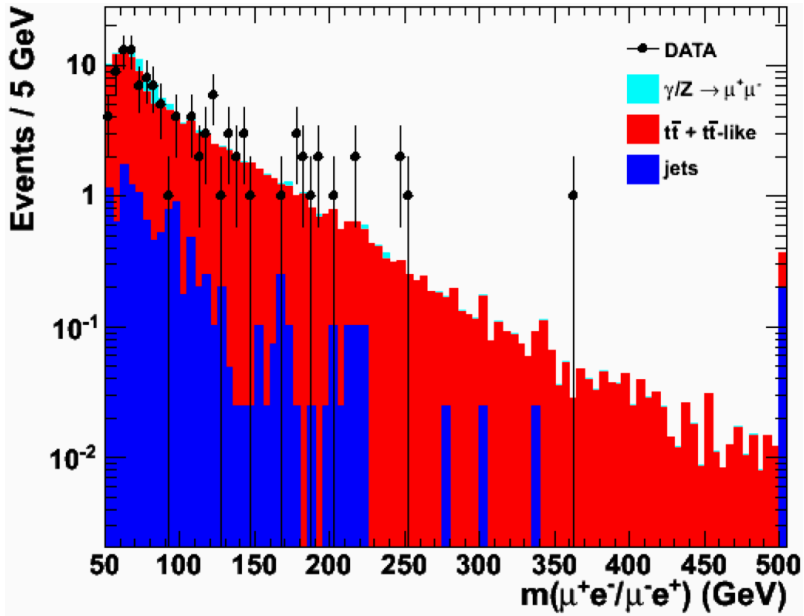




$$\int L = 35\text{–}40\,\text{pb}^{-1}$$

Already sensitive.

Implement same cuts. . .



Outlook

The interesting case of TeV-scale L-R symmetry: (with $\mathcal{C}$)

- A symmetric extension of the SM. (embeddable in GUT)
- LR Parity restored, at low scale.
- Premium channel still on-shell W_R-ν_R @ LHC.
- Lepton Number Violation. ($0\nu\beta\beta$ vs Cosmology)
- Possibly very rich phenomenology. (W_R, ν_R, Δ_L, Δ_R)
- Minimal theories: Lower bound $M_{W_R} \gtrsim 2.5\ TeV$ (from K^0-$\overline{K}^0$)
- No bounds from CP violation... (solution of $B_{d,s}$ CP tension)
- LHC rapidly competitive:
  Missing energy $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (small M_{ν_R})
  Dilepton dijets $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (large M_{ν_R})
- Need to look for lepton+EMjet and displaced vertices.
- Expect 2.2TeV limit with 1/fb, this year.
- Thanks!

Outlook

The interesting case of TeV-scale L-R symmetry: (with $\mathcal{C}$)

- A symmetric extension of the SM. (embeddable in GUT)
- LR Parity restored, at low scale.
- Premium channel still on-shell W_R-ν_R @ LHC.
- Lepton Number Violation. ($0\nu\beta\beta$ vs Cosmology)
- Possibly very rich phenomenology. (W_R, ν_R, Δ_L, Δ_R)
- Minimal theories: Lower bound $M_{W_R} \gtrsim 2.5\ TeV$ (from K^0-$\overline{K}^0$)
- No bounds from CP violation... (solution of $B_{d,s}$ CP tension)
- LHC rapidly competitive:
  Missing energy $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (small M_{ν_R})
  Dilepton dijets $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (large M_{ν_R})
- Need to look for lepton+EMjet and displaced vertices.
- Expect 2.2TeV limit with 1/fb, this year.

- Thanks!

Outlook

The interesting case of TeV-scale L-R symmetry: (with $\mathcal{C}$)

- A symmetric extension of the SM. (embeddable in GUT)
- LR Parity restored, at low scale.
- Premium channel still on-shell W_R-ν_R @ LHC.
- Lepton Number Violation. ($0\nu\beta\beta$ vs Cosmology)
- Possibly very rich phenomenology. (W_R, ν_R, Δ_L, Δ_R)
- Minimal theories: Lower bound $M_{W_R} \gtrsim 2.5\ TeV$ (from K^0-$\overline{K}^0$)
- No bounds from CP violation... (solution of $B_{d,s}$ CP tension)
- LHC rapidly competitive:

  Missing energy $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (small M_{ν_R})

  Dilepton dijets $\longrightarrow M_{W_R} > 1350\,\text{GeV}$ (large M_{ν_R})
- Need to look for lepton+EMjet and displaced vertices.
- Expect 2.2TeV limit with 1/fb, this year.
- Thanks!

L-R Lagrangian

$$L = R$$

W_L-W_R mixing

In the minimal models, tree level W_L-W_R mixing angle ζ is bound by weak decays, $\zeta < 10^{-2}$ $(3\,10^{-3})$.

This translates into a limit on the W_R mass:

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

. . . quite harmless.

Long distance $K^0\bar{K}^0$: complete $\Delta S = 1$ operators

$$Q_1^{LL} = (\bar{s}_\alpha u_\beta)_L(\bar{u}_\beta d_\alpha)_L \qquad Q_1^{RR} = (\bar{s}_\alpha u_\beta)_R(\bar{u}_\beta d_\alpha)_R$$
$$Q_2^{LL} = (\bar{s}u)_L(\bar{u}d)_L \qquad Q_2^{RR} = (\bar{s}u)_R(\bar{u}d)_R$$
$$Q_3 = (\bar{s}d)_L(\bar{q}q)_L \qquad Q_3' = (\bar{s}d)_R(\bar{q}q)_R$$
$$Q_4 = (\bar{s}_\alpha d_\beta)_L(\bar{q}_\beta q_\alpha)_L \qquad Q_4' = (\bar{s}_\alpha d_\beta)_R(\bar{q}_\beta q_\alpha)_R$$
$$Q_7 = \tfrac{3}{2}(\bar{s}d)_L e_q(\bar{q}q)_L \qquad Q_7' = \tfrac{3}{2}(\bar{s}d)_R e_q(\bar{q}q)_R$$
$$Q_8 = \tfrac{3}{2}(\bar{s}_\alpha d_\beta)_L e_q(\bar{q}_\beta q_\alpha)_L \qquad Q_8' = \tfrac{3}{2}(\bar{s}_\alpha d_\beta)_R e_q(\bar{q}_\beta q_\alpha)_R$$

$$Q_1^{RL} = (\bar{s}_\alpha u_\beta)_R(\bar{u}_\beta d_\alpha)_L \qquad Q_1^{LR} = (\bar{s}_\alpha u_\beta)_L(\bar{u}_\beta d_\alpha)_R$$
$$Q_2^{RL} = (\bar{s}u)_R(\bar{u}d)_L \qquad Q_2^{LR} = (\bar{s}u)_L(\bar{u}d)_R$$
$$Q_5 = (\bar{s}d)_L(\bar{q}q)_R \qquad Q_5' = (\bar{s}d)_R(\bar{q}q)_L$$
$$Q_6 = (\bar{s}_\alpha d_\beta)_L(\bar{q}_\beta q_\alpha)_R \qquad Q_6' = (\bar{s}_\alpha d_\beta)_R(\bar{q}_\beta q_\alpha)_L$$
$$Q_9 = \tfrac{3}{2}(\bar{s}d)_L e_q(\bar{q}q)_R \qquad Q_9' = \tfrac{3}{2}(\bar{s}d)_R e_q(\bar{q}q)_L$$
$$Q_{10} = \tfrac{3}{2}(\bar{s}_\alpha d_\beta)_L e_q(\bar{q}_\beta q_\alpha)_R \qquad Q_{10}' = \tfrac{3}{2}(\bar{s}_\alpha d_\beta)_R e_q(\bar{q}_\beta q_\alpha)_L$$

$$Q_{11}^{RL} = \bar{s}_R\sigma_{\mu\nu}d_L G^{\mu\nu} \qquad Q_{11}^{LR} = \bar{s}_L\sigma_{\mu\nu}d_R G^{\mu\nu} \qquad \textit{LR top enhanced}$$
$$Q_{12}^{RL} = \bar{s}_R\sigma_{\mu\nu}d_L F^{\mu\nu} \qquad Q_{12}^{LR} = \bar{s}_L\sigma_{\mu\nu}d_R F^{\mu\nu}$$

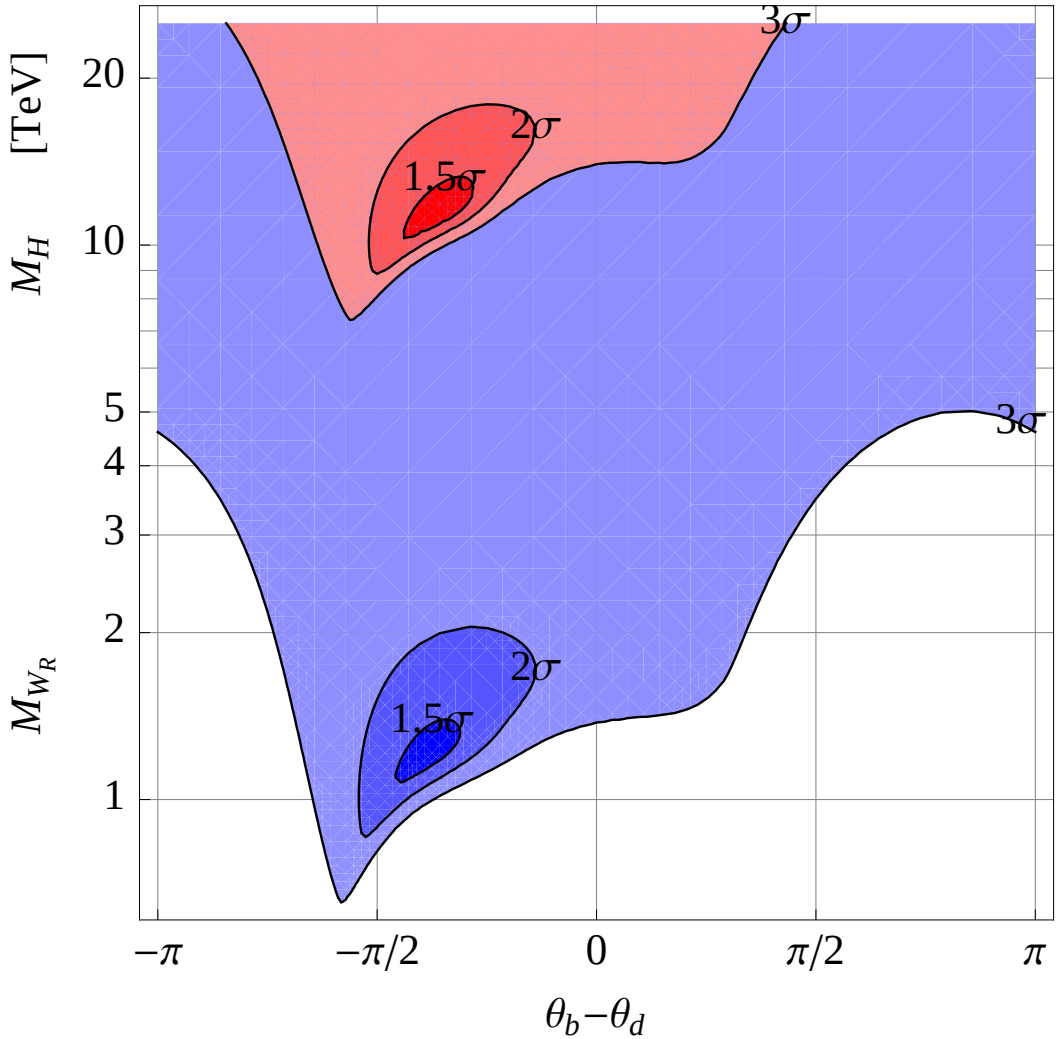
Higgs spectrum

Higgs state	m^2
$h^0 = \sqrt{2}\ \mathrm{Re}\ \left(\phi_1^{0*} + x e^{-i\alpha}\phi_2^0\right)$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1}\right) v^2 + \alpha_3 v_R^2 x^2$
$H_1^0 = \sqrt{2}\ \mathrm{Re}\ \left(-x e^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$A_1^0 = \sqrt{2}\ \mathrm{Im}\ \left(-x e^{i\alpha}\phi_1^{0*} + \phi_2^0\right)$	$\alpha_3 v_R^2$
$H_2^0 = \sqrt{2}\ \mathrm{Re}\ \delta_R^0$	$4\rho_1 v_R^2$
$H_2^+ = \phi_2^+ + x e^{i\alpha}\phi_1^+ + \frac{1}{\sqrt{2}}\epsilon\delta_R^+$	$\alpha_3\left(v_R^2 + \frac{1}{2}v^2\right)$
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.

$\mathcal{C}$: B CP violation

The last free phase is constrained:



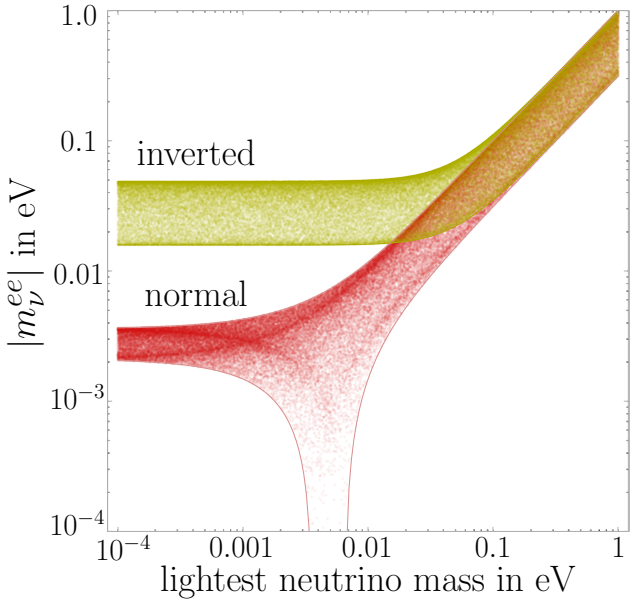
$0\nu\beta\beta$ cont'd [Tello Nemevšek FN Senjanović Vissani PRL 1011.3522]

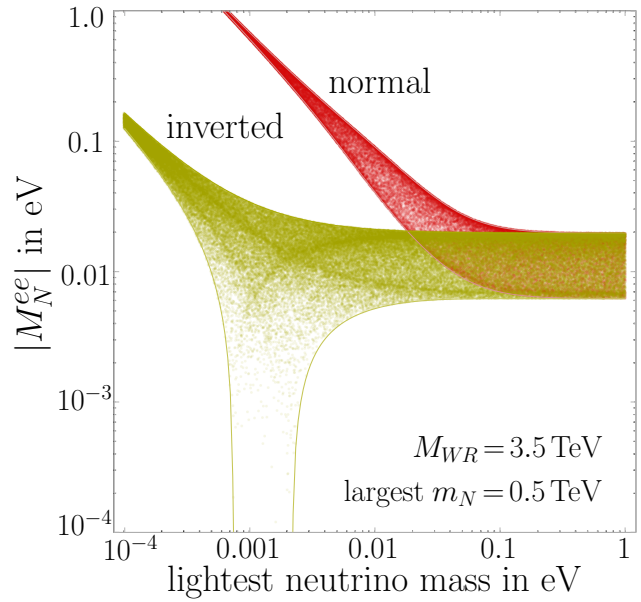
- Recall cosmology, $\sum m_\nu \lesssim 1(0.6)\,\text{eV}$ [Hannestad+ '08, Hamann+ '10]

. . . shrinking toward incompatibility with evidences of $0\nu\beta\beta$, i.e. claim of $m_{ee} \sim 0.4\,\text{eV}$, Heidelberg-Moscow.

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

Sample case of type-II seesaw: $V_{leptonR} = V_{leptonL}$, testable at LHC, and proportional masses. Light and heavy ν competing:





Summing the two: never vanishing.

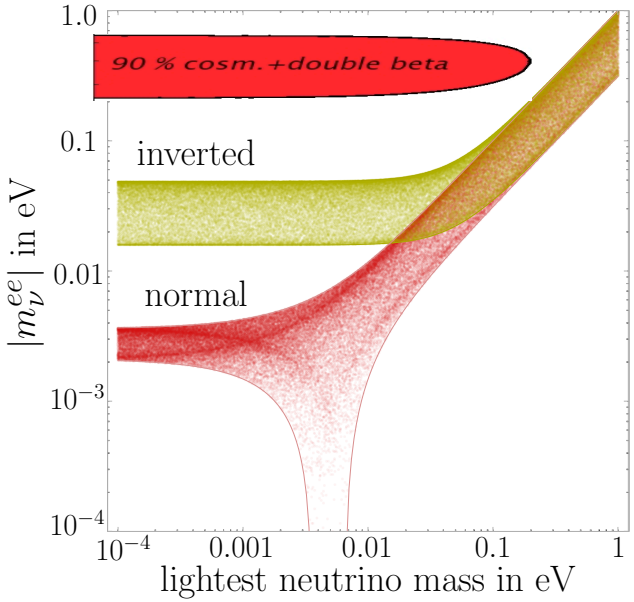
$0\nu\beta\beta$ cont'd [Tello Nemevšek FN Senjanović Vissani PRL 1011.3522]

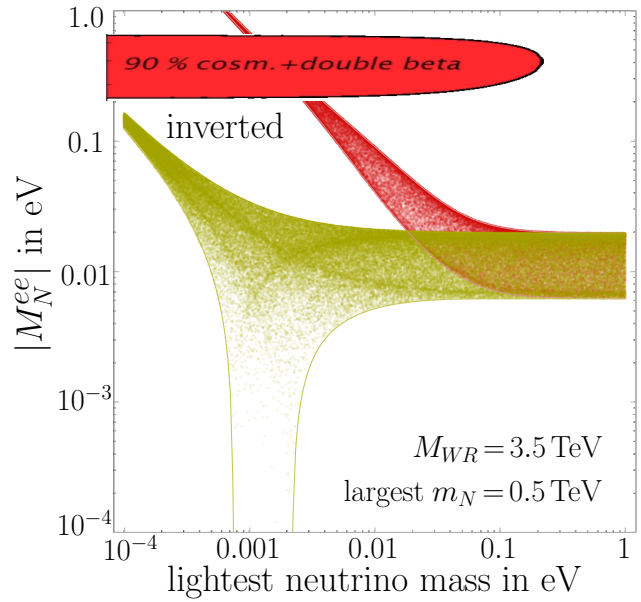
- Recall cosmology, $\sum m_\nu \lesssim 1(0.6)\,\text{eV}$ [Hannestad+ '08, Hamann+ '10]

. . . shrinking toward incompatibility with evidences of $0\nu\beta\beta$, i.e. claim of $m_{ee} \sim 0.4\,\text{eV}$, Heidelberg-Moscow.

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

Sample case of type-II seesaw: $V_{leptonR} = V_{leptonL}$, testable at LHC, and proportional masses. Light and heavy ν competing:





Summing the two: never vanishing.