Lepton Number Violation and Scalar Searches at LHC

Francisco del Águila
M. Chala, A. Santamaría and J. Wudka

CENTRO ANDALUZ DE FISICA DE PARTICULAS ELEMENTALES
Universidad de Granada

Trieste 2013, October 4

arXiv:1305.3904 [hep-ph]
arXiv:1307.0510 [hep-ph]
arXiv:1310.xxxx [hep-ph]

Outline

- Introduction: Up to now the tiny neutrino masses are the only direct observation of Lepton Number Violation (LNV), if they are actually Majorana [and the observed baryon asymmetry of the universe is not generated by leptogenesis]. At the LHC era the question is if LNV is observable at the LHC.

- Present limits on di-lepton decays can be easily extrapolated to LNV processes.

- But H++ can be a component of a generic scalar multiplet, generalizing the see-saw of type II model [with a heavy scalar triplet (Δ^{++} Δ^{+} Δ^{0}) giving Majorana masses to neutrinos]. What can be determined sampling appropriately 4 and 3 isolated lepton signals because their production rate does depend on T and Y.

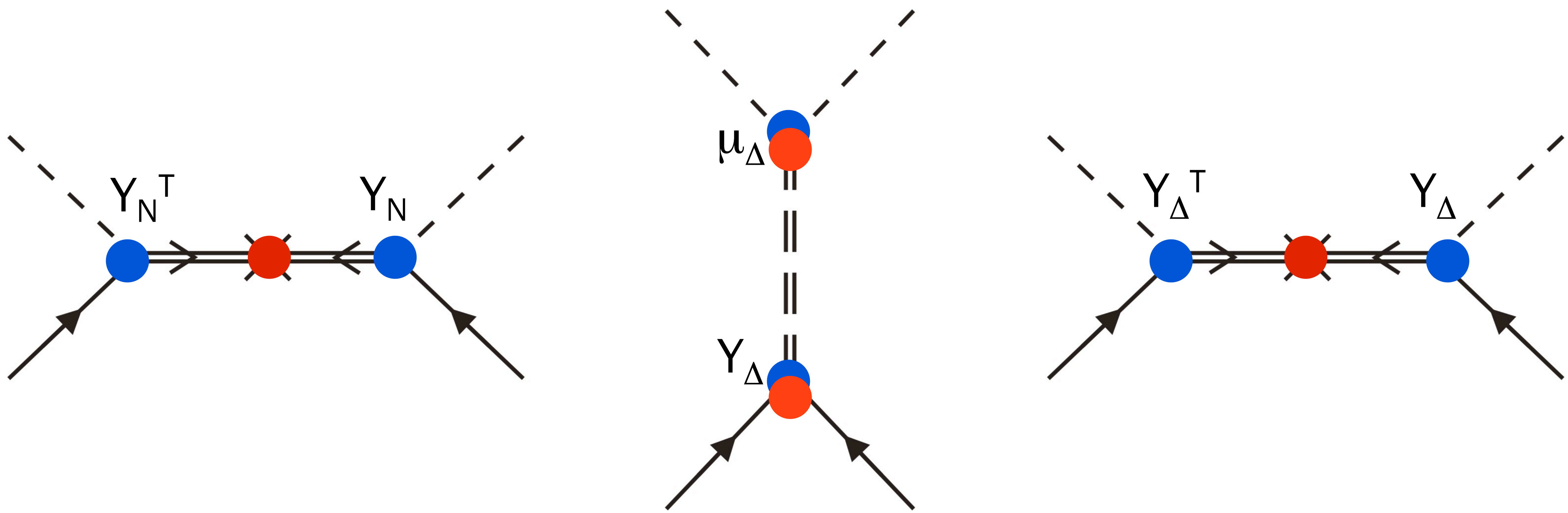
- Conclusions

$$(m_\nu)_{ij} = x_{ij} v^2/\Lambda \sim 0.1\,\mathrm{eV}$$

$$\mathcal{O}^{(5)} = (\overline{L_L^c}\tilde{\phi}^*)(\tilde{\phi}^\dagger L_L)$$

$$\mathcal{L}^{(5)}_{m_\nu} = -x_{ij}\mathcal{O}^{(5)}_{ij}/\Lambda + \mathrm{h.c.} \rightarrow -(x_{ij}v^2/2\Lambda)\overline{\nu^c_{Li}}\nu_{Lj} + \mathrm{h.c.}$$

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



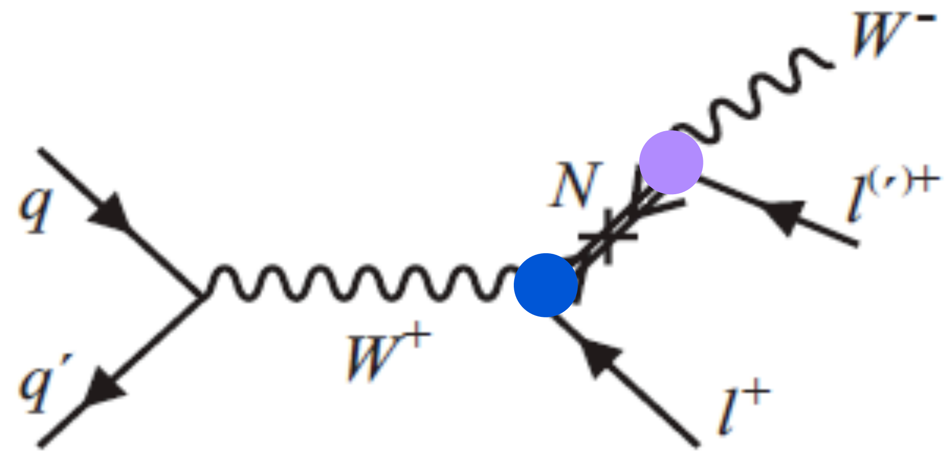
$\frac{1}{2} Y_N^T M_N^{-1} Y_N$ — Phase cancellation or small couplings

$-2\, Y_\Delta \mu_\Delta M_\Delta^{-2}$ — small coupling(s)

$\frac{1}{2} Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$ — Phase cancellation or small couplings

The three mechanisms must violate Lepton Number (LN) for they are assumed to generate Majorana masses. I and III involve fermions: singlets N (I) or triplets Σ (III), and II scalar triplets: Δ.

TeV signatures of see-saw messengers: Multilepton signals



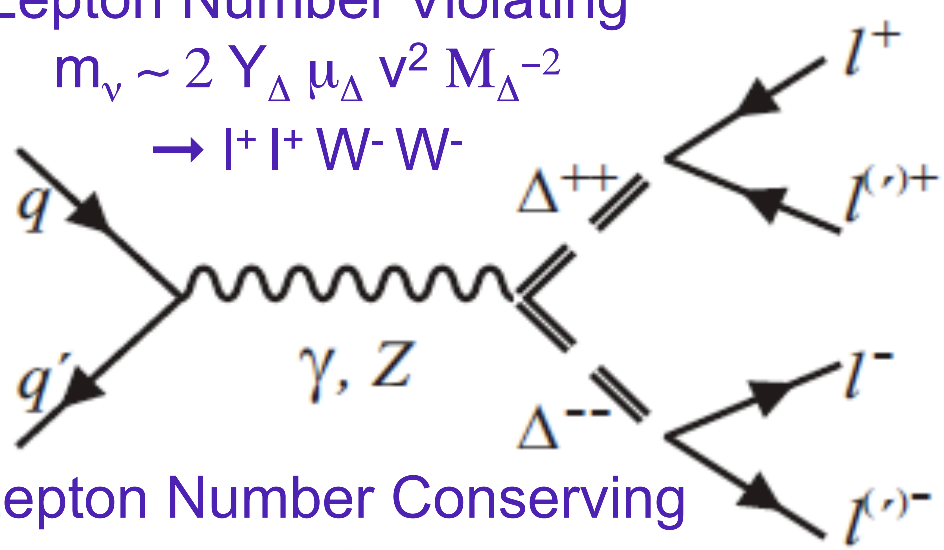
(I)

W.Y. Keung and G. Senjanovic, Phys. Rev. Lett. 50 (1983) 1427

Lepton Number Violating

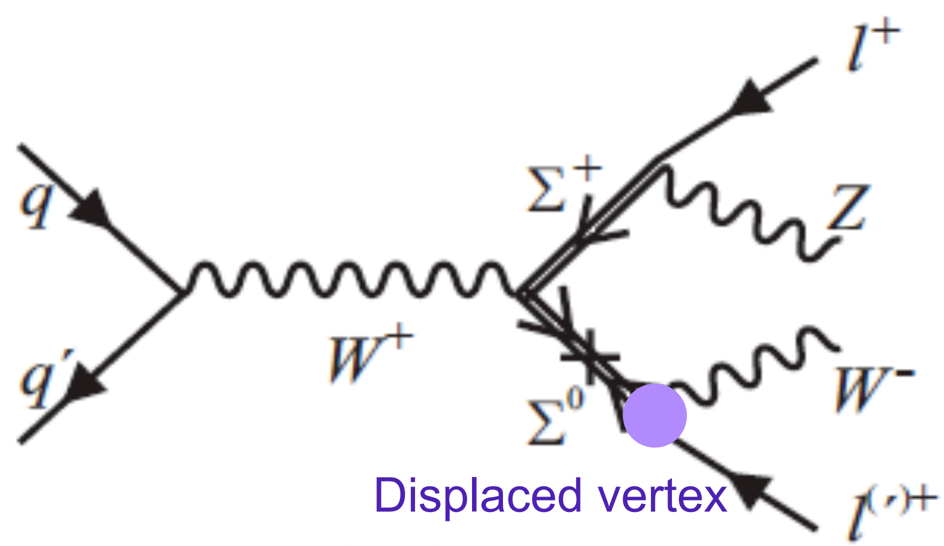
$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$

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



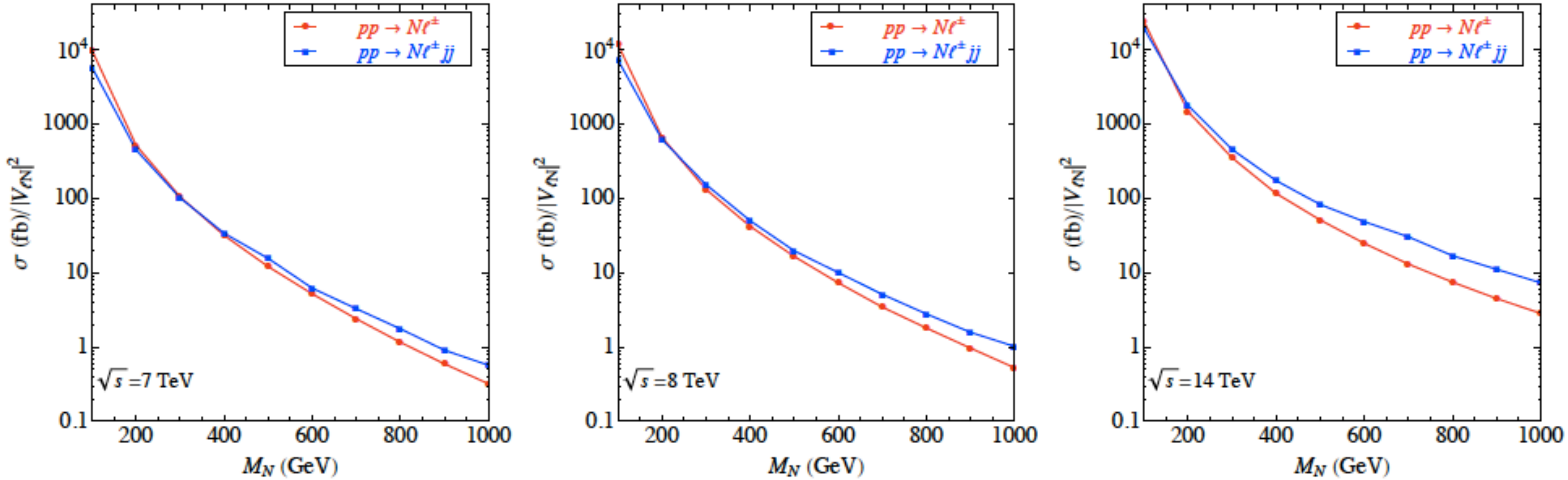
Lepton Number Conserving

(II)

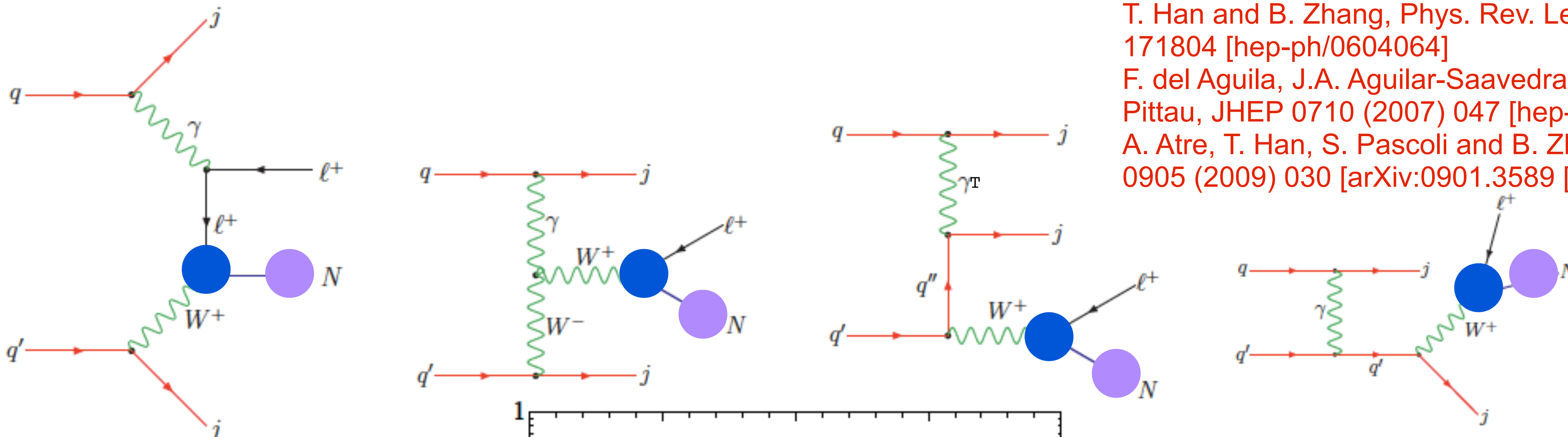


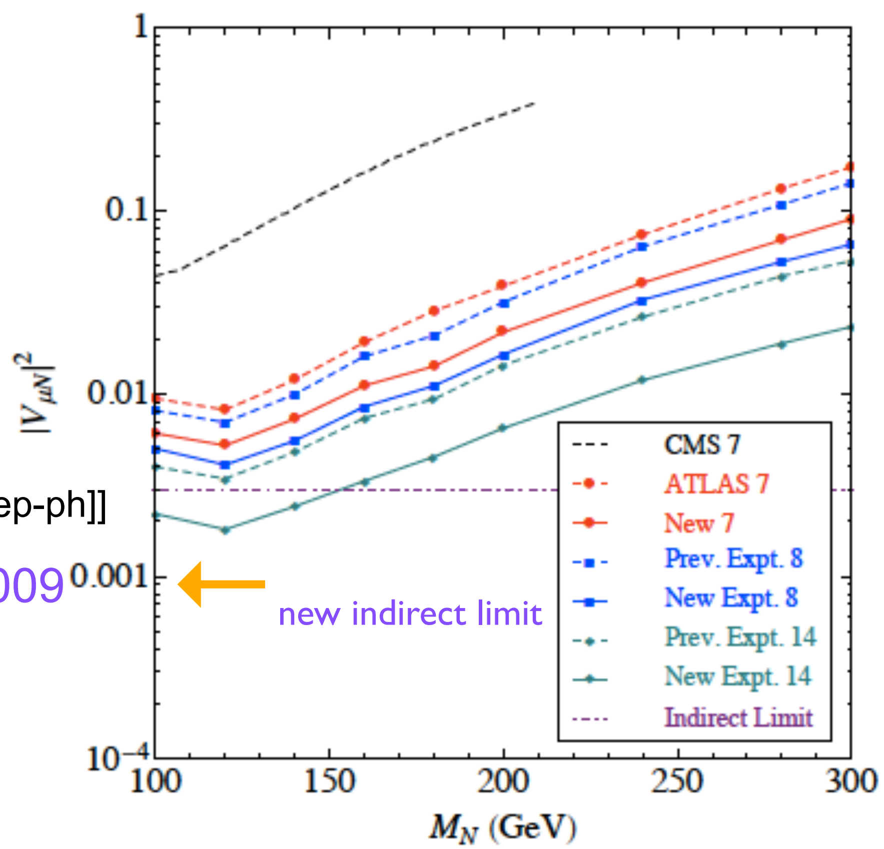
(III)

R. Franceschini, T. Hambye and A. Strumia, Phys. Rev. D 78 (2008) 033002 [arXiv:0805.1613 [hep-ph]]



T. Han and B. Zhang, Phys. Rev. Lett. 97 (2006) 171804 [hep-ph/0604064]
F. del Aguila, J.A. Aguilar-Saavedra and R. Pittau, JHEP 0710 (2007) 047 [hep-ph/0703261]
A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905 (2009) 030 [arXiv:0901.3589 [hep-ph]]

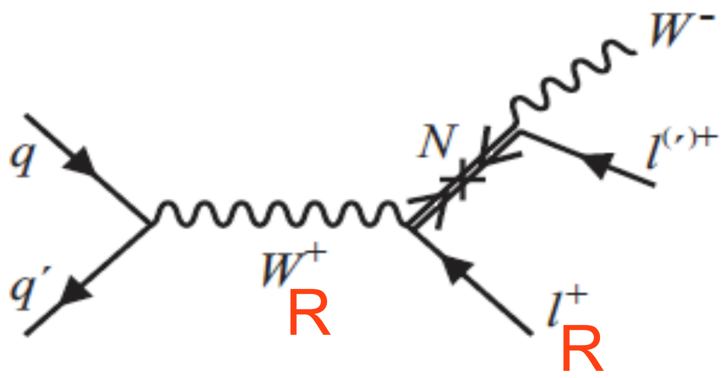




P.S.B. Dev, A. Pilaftsis and U. Yang, arXiv:1308.2209 [hep-ph]

F. del Aguila, J. de Blas and M. Perez-Victoria, Phys. Rev. D 78(2008) 013010 [arXiv:0803.4008 [hep-ph]]

J. de Blas, arXiv:1307.6173 [hep-ph]: 0.0009



(I)

S.N. Gninenko, M.M. Kirsanov, N.V. Krasnikov and V.A. Matveev, Phys. Atom. Nucl. 70 (2007) 441

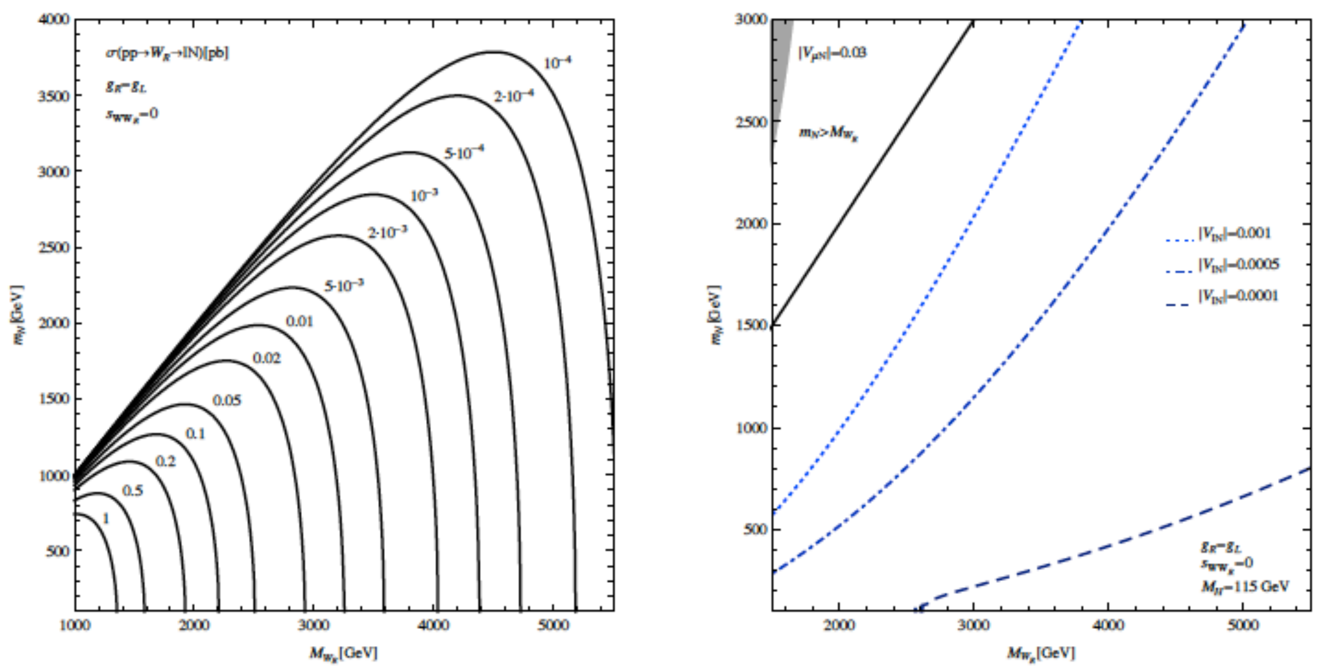


Fig. 2. Left: $pp \to W_R \to lN$ cross section at LHC. Right: N decay branching ratio to W_R^* and SM bosons (see the text).

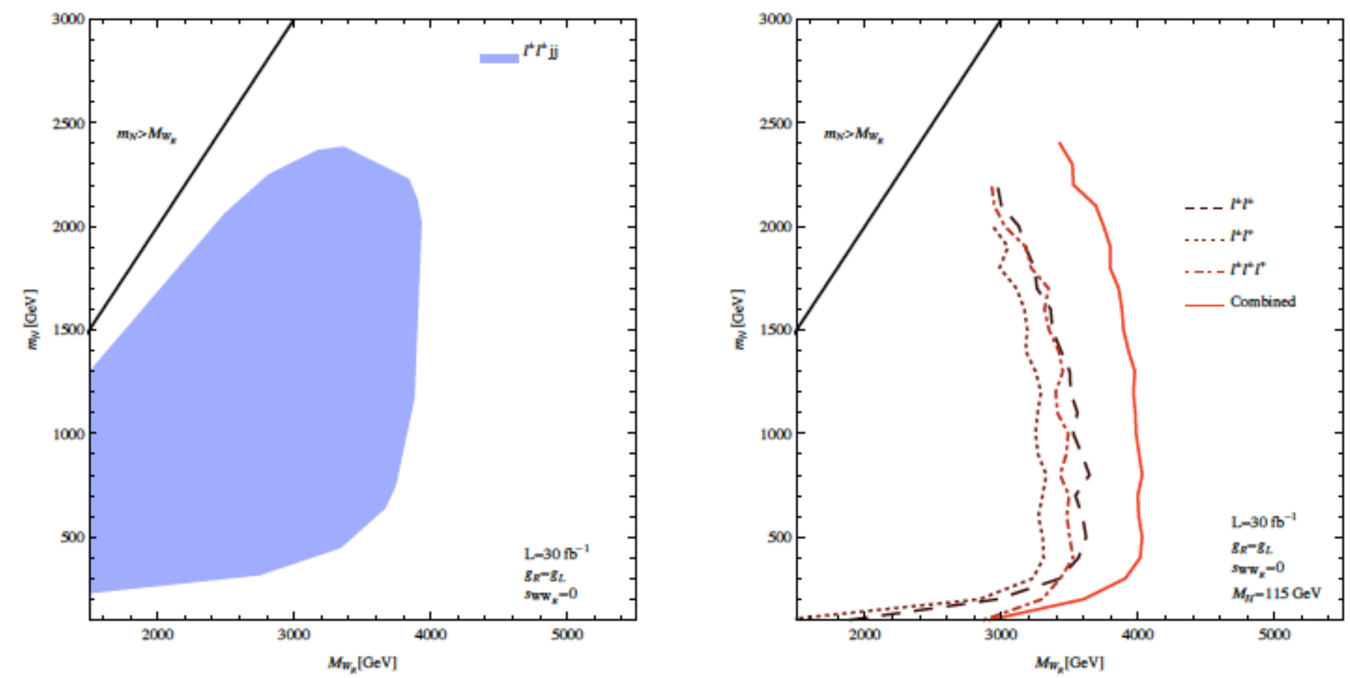


Fig. 3. Left: Discovery limits for 30 fb^{-1} as a function of M_{W_R} and m_N, assuming that N only decays into $l^{\pm}W_R^* \to ljj$, from Ref. [11]. Right: The same, assuming that N decays into SM bosons.

F. del Aguila, J.A. Aguilar-Saavedra and J. de Blas, Acta Phys. Polon. B 40 (2009) 2901 [arXiv:0910.2720 [hep-ph]]

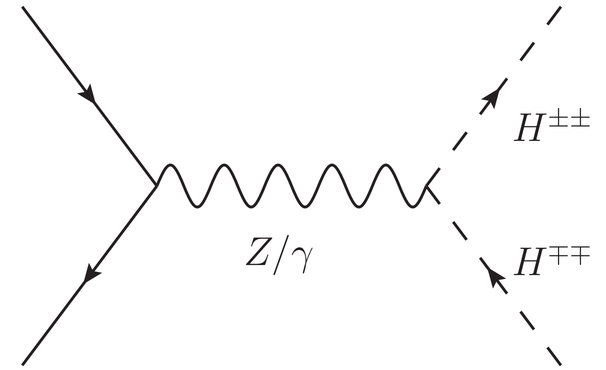
CMS and ATLAS have set stringent limits on doubly-charged scalars $H^{\pm\pm}$ decaying into two same-sign leptons ~ 400 GeV with only 5 fb^{-1} at 7 TeV.

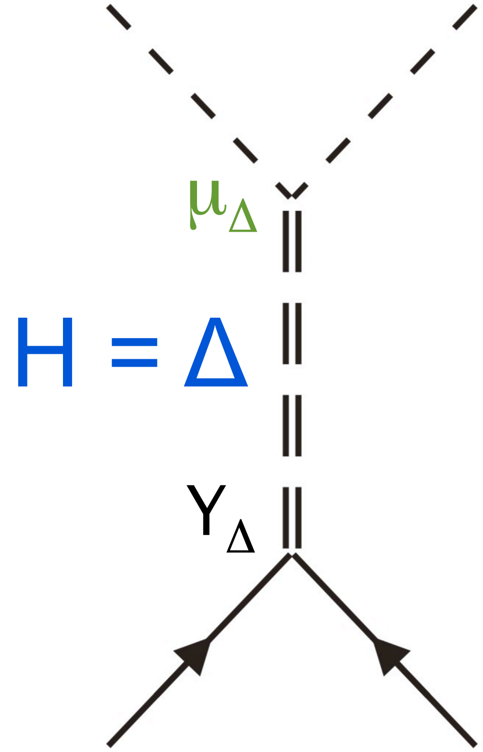
But they very much depend on the assumed di-leptonic branching ratios, in particular, into τs, and especially into gauge bosons. For instance, if the new scalar muliplet has a neutral component getting a v.e.v., through the gauge coupling $g^2\langle H^0\rangle H^{++}W^-W^-$. On the other hand, if both $H^{\pm\pm}$ decays are observed, $pp \to H^{++} H^{--} \to l^+ l^+ W^- W^-$, LN will have been proved to be violated at the LHC.

- The most popular Standard Model extension of this class is the see-saw of type II with a heavy scalar triplet (Δ^{++} Δ^{+} Δ^{0}) giving Majorana masses to neutrinos.
- Present limits on di-lepton decays can be easily extrapolated to LNV processes.
- But H++ can be a component of a generic scalar multiplet with

$$T^H \geq T_3^{H++} = 2 - Y^H$$

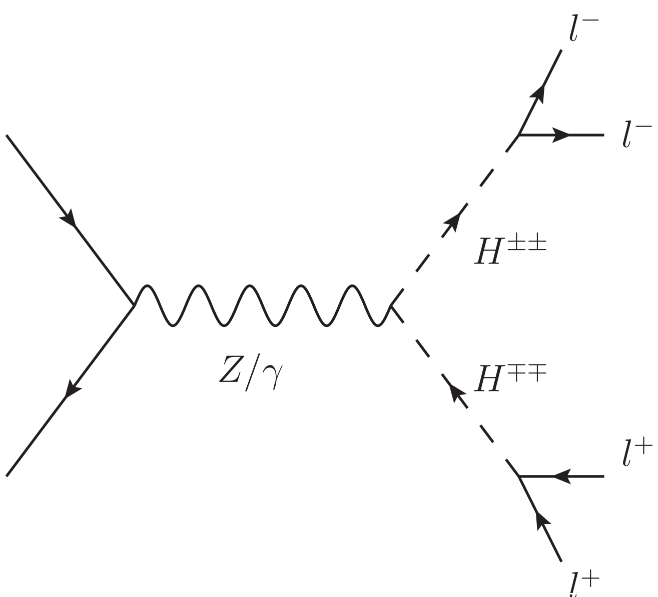
- What can be determined sampling appropriately 4 and 3 isolated lepton signals because their production rate does depend on T and Y.





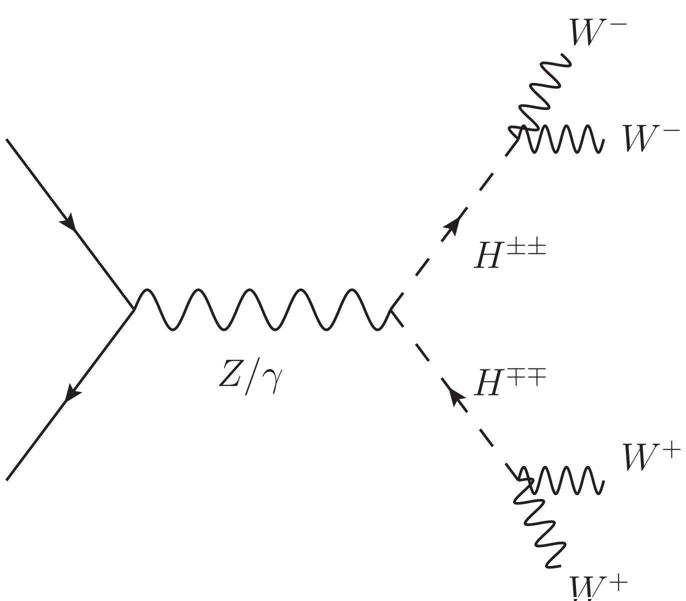
$$g^2 < \Delta^0 > W^{\mp\mu} W^{\mp}_{\mu} \Delta^{\pm\pm}$$

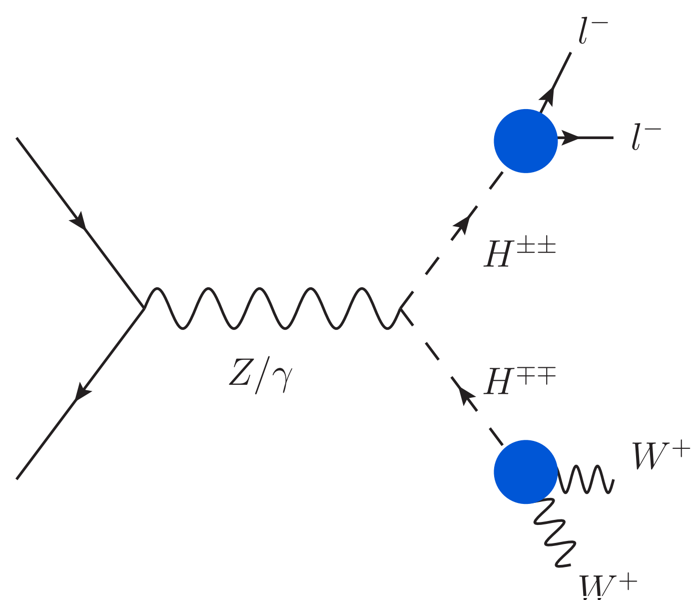
$$(\overline{\tilde{L}_L} \tau^a L_L)\Delta^{-a}$$



$-2Y_\Delta \mu_\Delta v^2 M_\Delta^{-2} \sim$ meV with $\sqrt{2} <\Delta^0> = \mu_\Delta v^2 M_\Delta^{-2}$

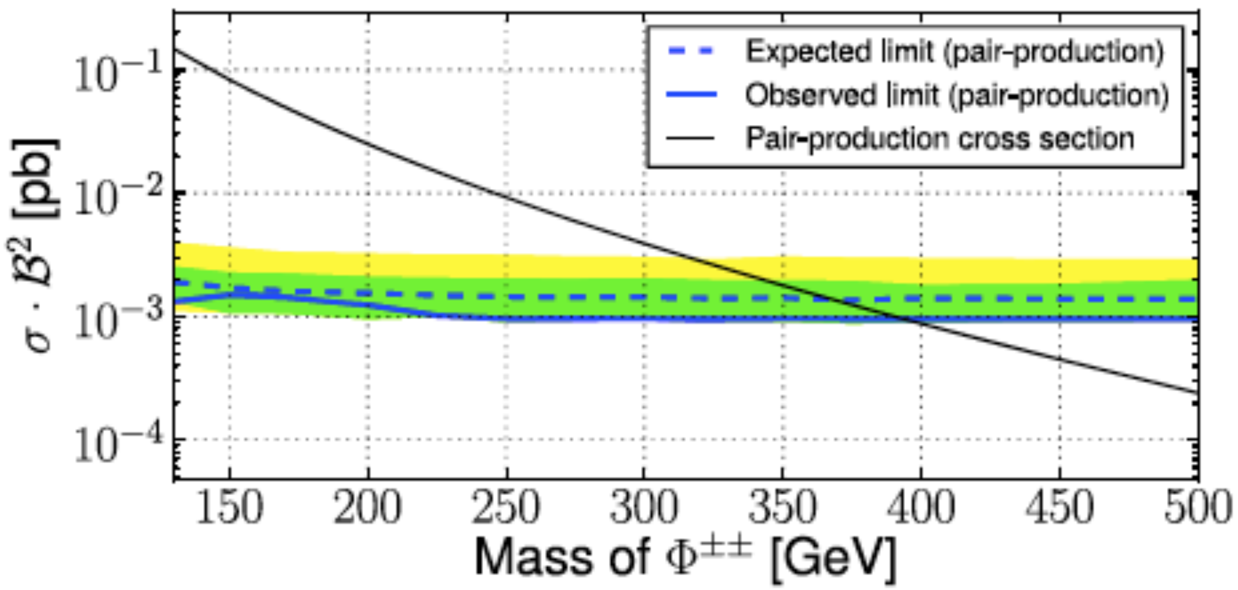
if $M_\Delta \sim$ TeV: $Y_\Delta \mu_\Delta \sim 10^{-11}$ GeV

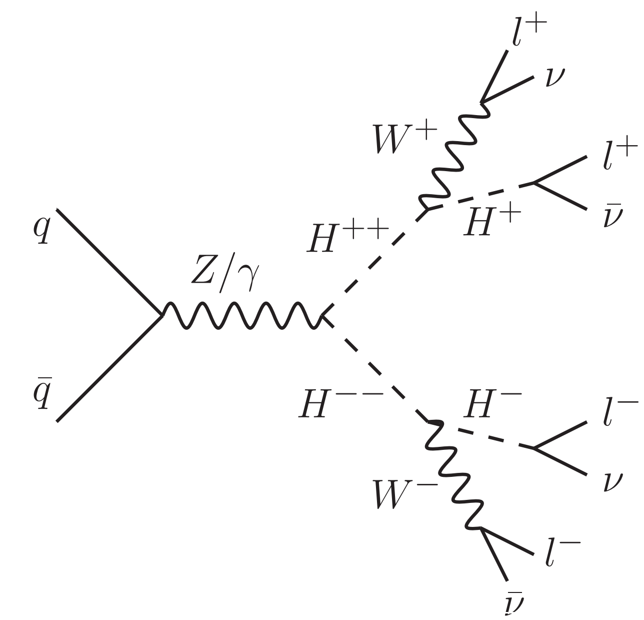




$$\left[\sum_{i,j=e,\mu,\tau} \Gamma(\Delta \to l_i l_j)\Gamma(\Delta \to WW)\right]^{-1} \approx 10^{-15} \left[\sum_{i=1,2,3} m_{\nu_i}^2\right]^{-1} \frac{m_W^4}{m_\Delta^4} > 10^5 \frac{m_W^4}{m_\Delta^4} \mu\text{m}^2$$

e and μ only





S. Chatrchyan et al. [CMS Collaboration]
Eur. Phys. J. C 72 (2012) 2189 [arXiv:1207.2666 [hep-ex]]

No τ decays
G. Aad et al. [ATLAS Collaboration],
Eur. Phys. J. C 72 (2012) 2244 [arXiv:1210.5070 [hep-ex]]

H^{+++} K.S. Babu, S. Nandi and Z. Tavartkiladze, Phys. Rev. D 80, 071702 (2009) [arXiv:0905.2710 [hep-ph]]

F^{++} K.L. McDonald, arXiv:1310.0609 [hep-ph]

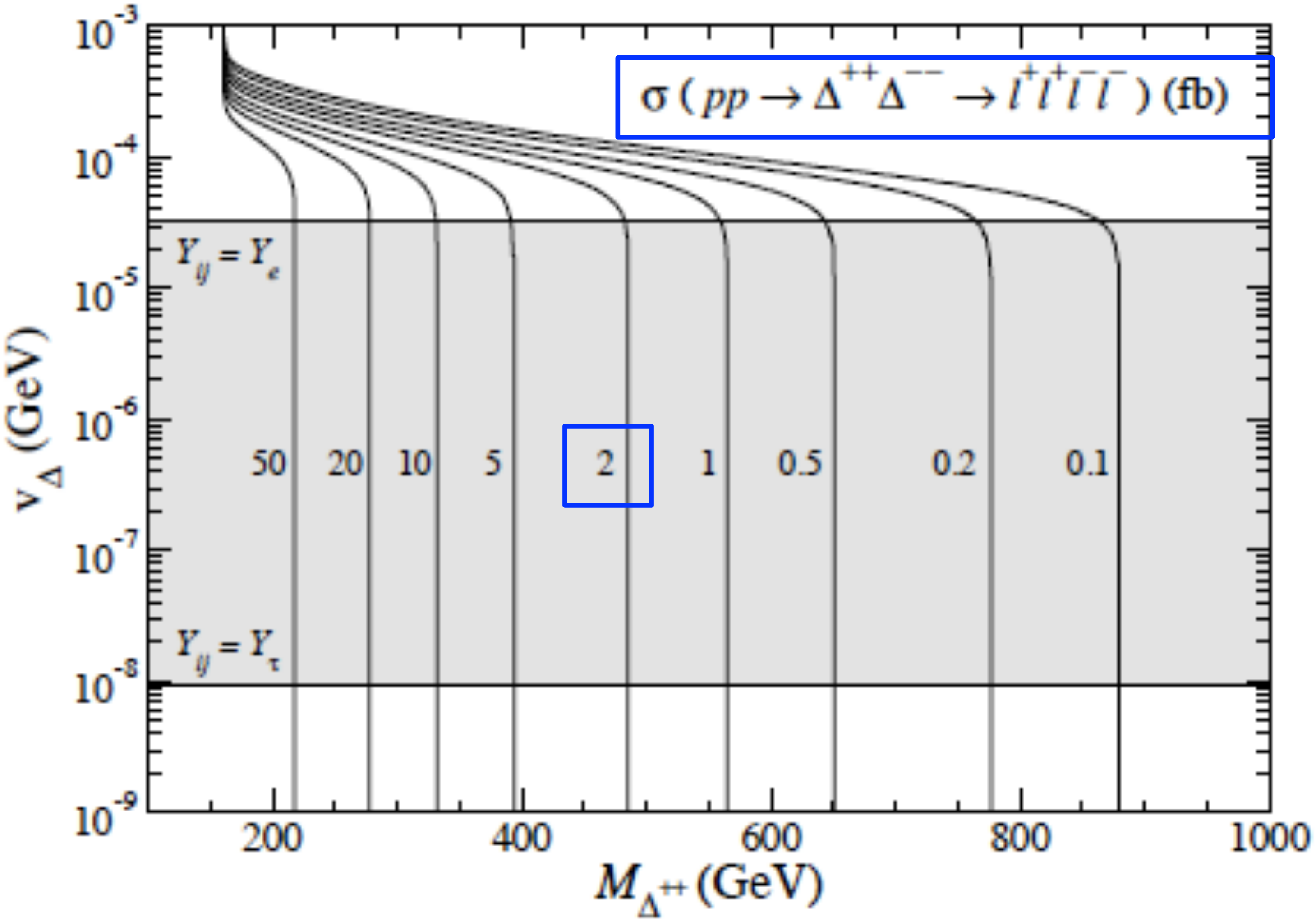
	6ℓ	5ℓ	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm$
Σ (M)	0.6	10.6	17.4	55.7	10.2	110.3	177.8	178.7	232.4
Σ (D)	1.9	21.4	9.1	173.4	2.9	194.4	4.4	607.0	314.9
SM Bkg	0.0	0.9	2.5	14.3	1.9	15.9	19.5	548.3	1328

Table 2: Number of events with 30 fb^{-1} for the fermion triplet signals with Majorana (M) and Dirac (D) neutrinos, and SM background in different final states.

F. del Aguila and J.A. Aguilar-Saavedra, Phys. Lett. B 672 (2009) 158 [arXiv:0809.2096 [hep-ph]]

LHC reach (30 fb^{-1} and 14 TeV):

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



F.A and J.A. Aguilar-Saavedra,
Nucl. Phys. B813 (2009) 22 [arXiv:0808.2468 [hep-ph]]

Lepton Number Violating

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

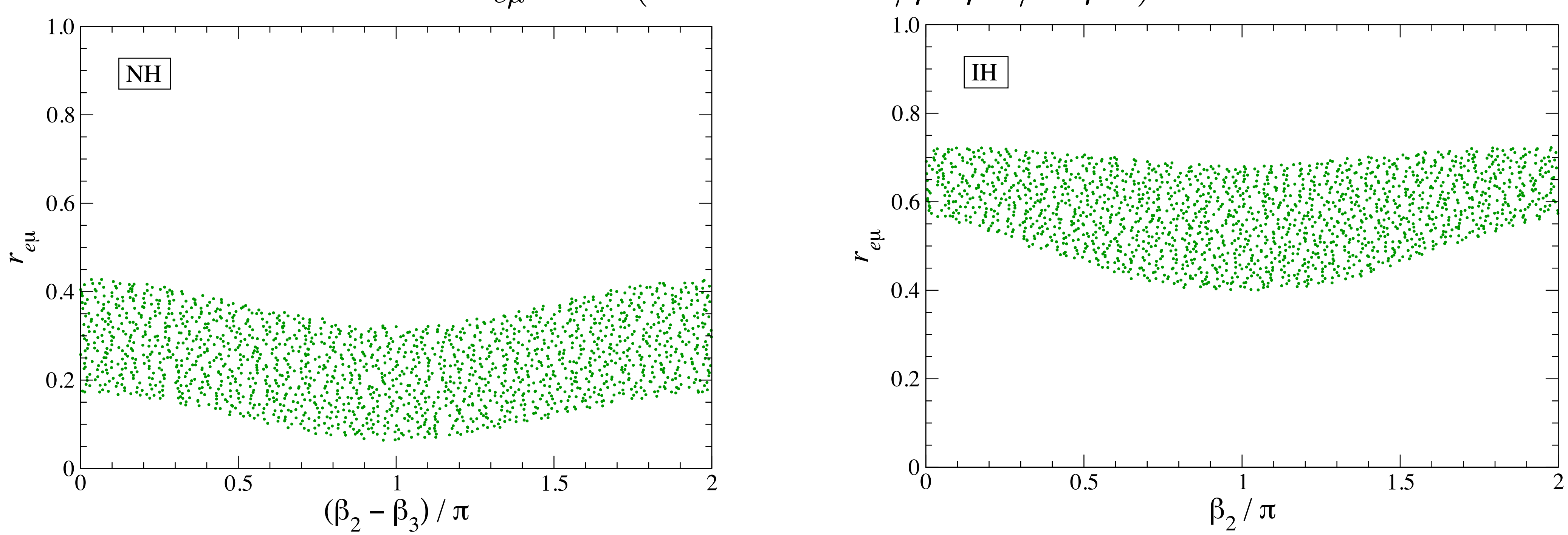
$\rightarrow l^+ l^+ W^- W^-$

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

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

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).

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



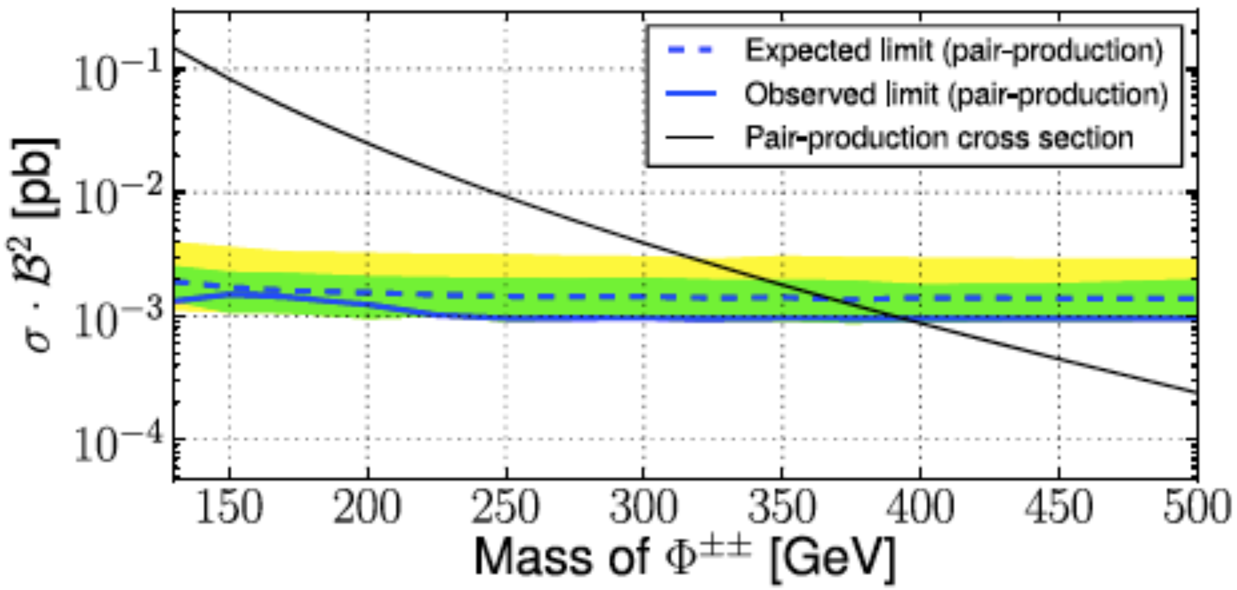
--- K.S. Babu, Phys. Lett. B 203 (1988) 132

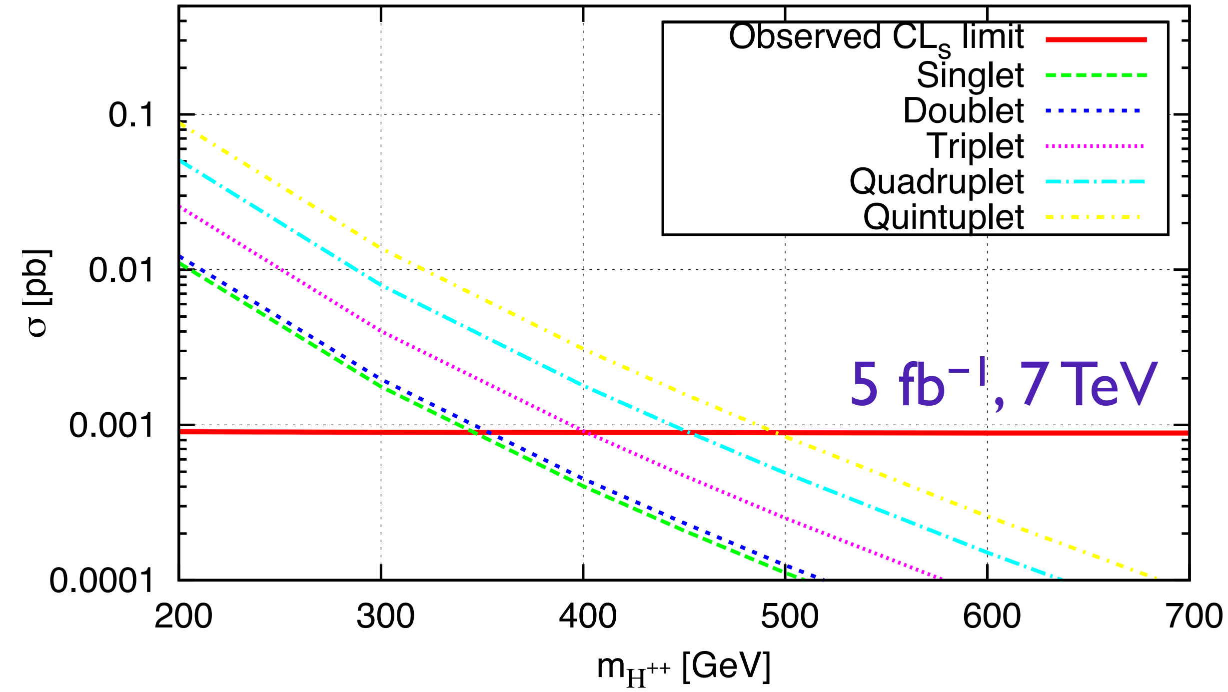
--- F.A., A. Aparici, S. Bhattacharya, A. Santamaria and J. Wudka, JHEP 1205 (2012) 133 [arXiv:1111.6960 [hep-ph]]

-·- K.S. Babu, S. Nandi and Z. Tavartkiladze, Phys. Rev. D 80, 071702 (2009) [arXiv:0905.2710 [hep-ph]]

Y: 1/2 → 3/2 ⇒ NC: coupling → doublet, CC: √3/2 → √2

e and μ only





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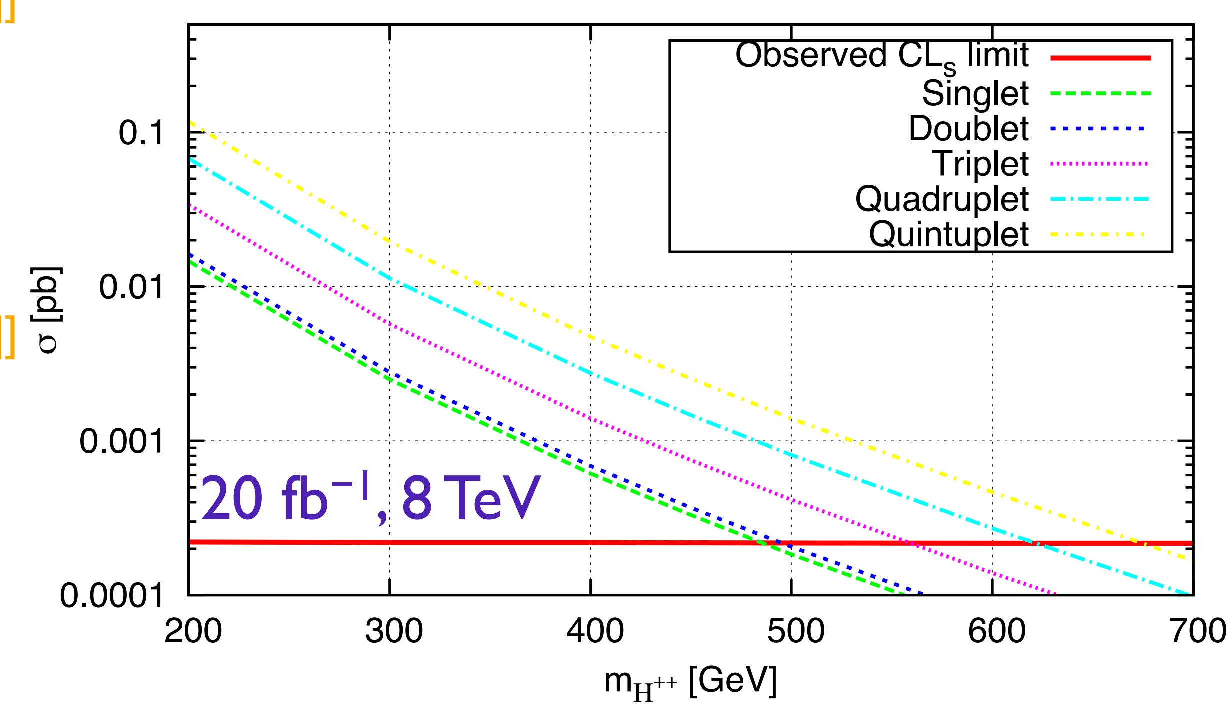
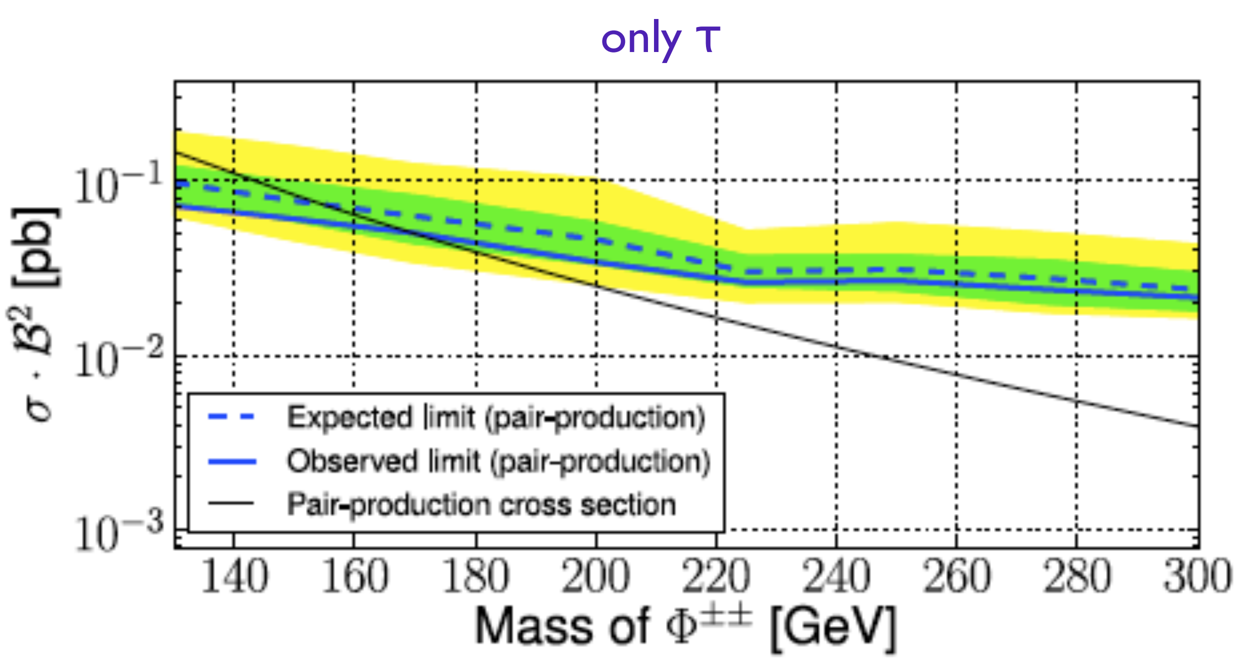
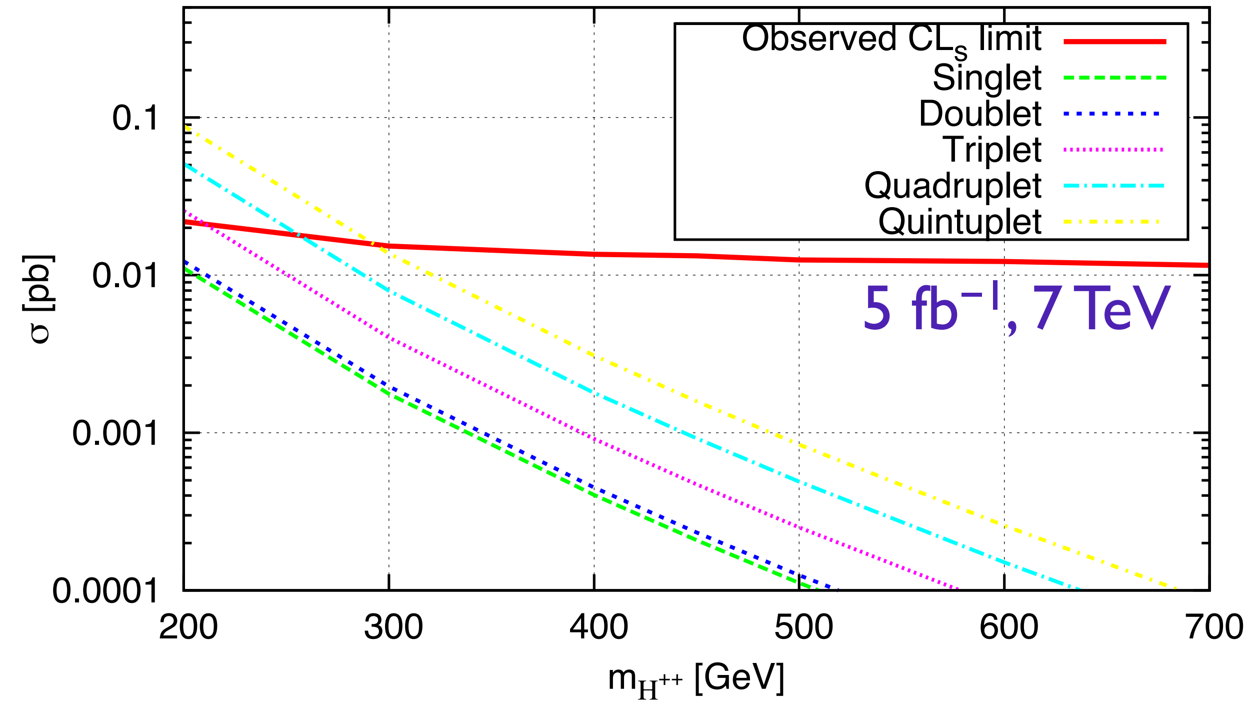
Eur. Phys. J. C 72 (2012) 2189 [arXiv:1207.2666 [hep-ex]]



No τ decays
G. Aad et al. [ATLAS Collaboration],
Eur. Phys. J. C 72 (2012) 2244 [arXiv:1210.5070 [hep-ex]]





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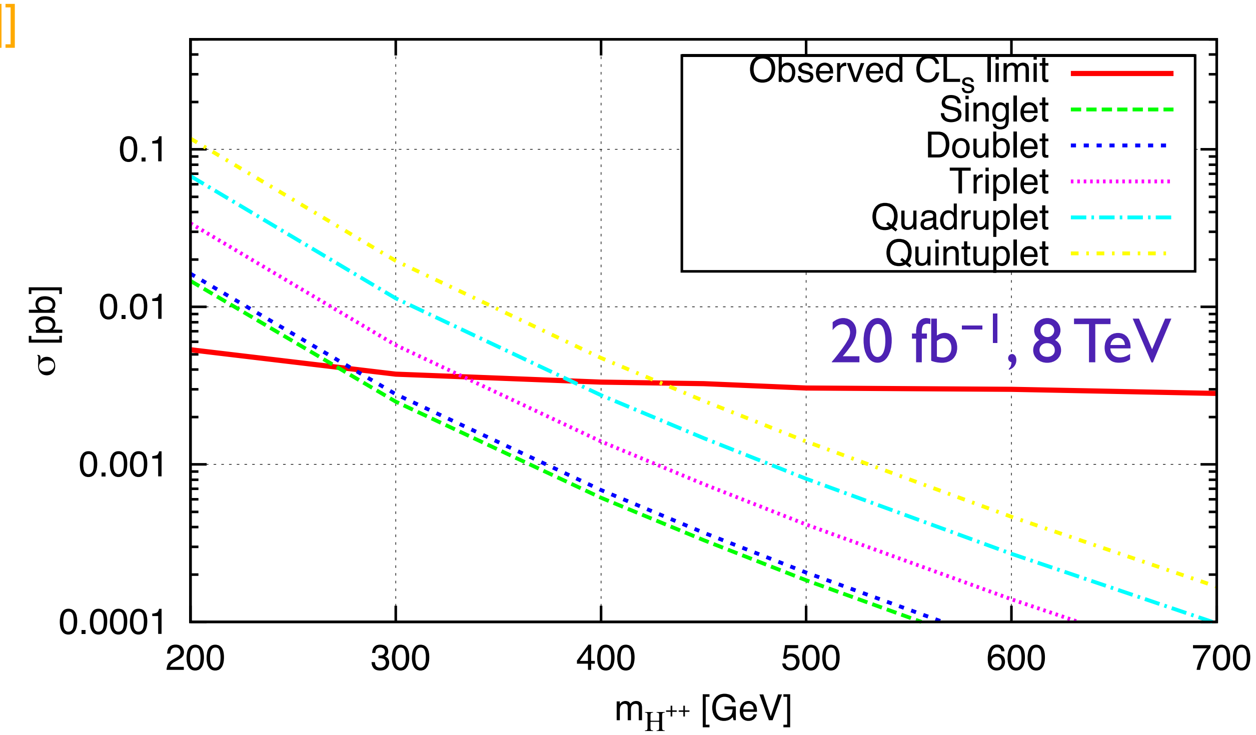
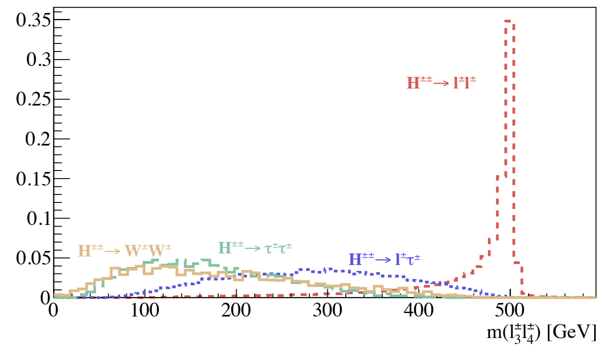
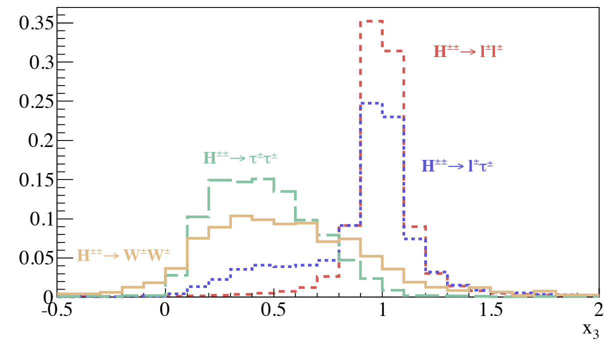
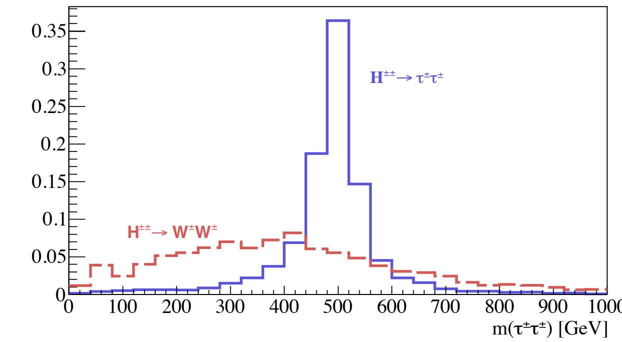
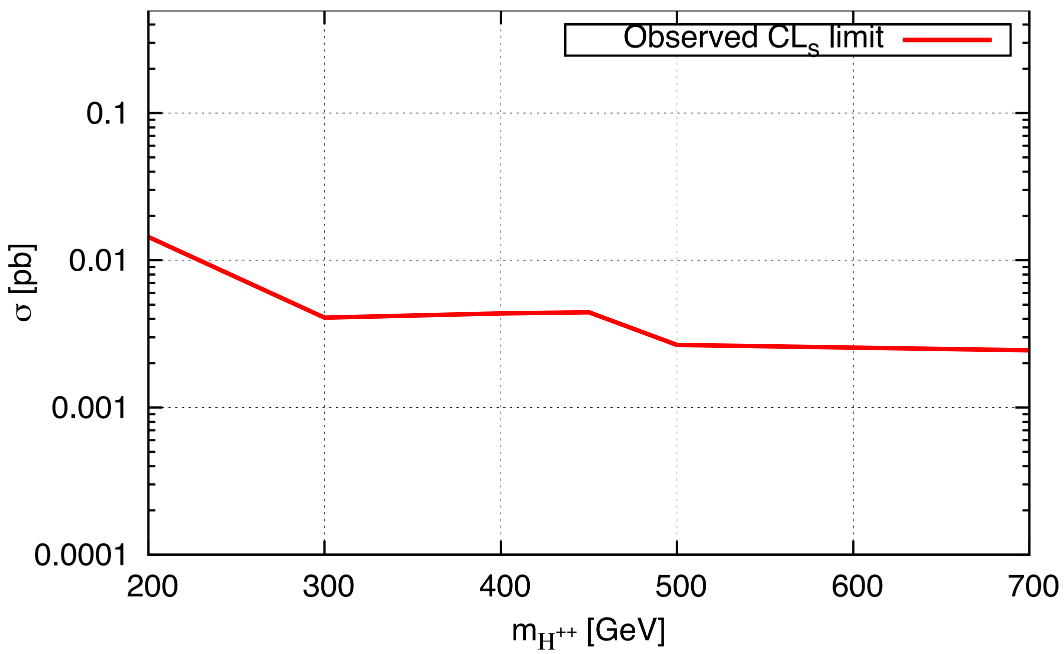


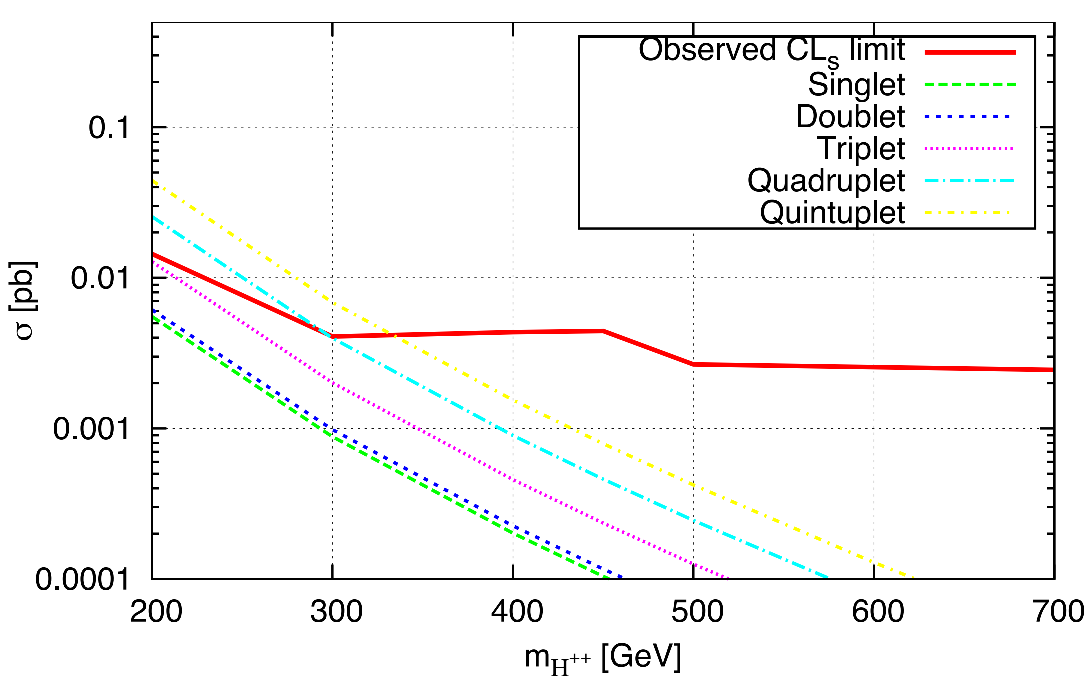




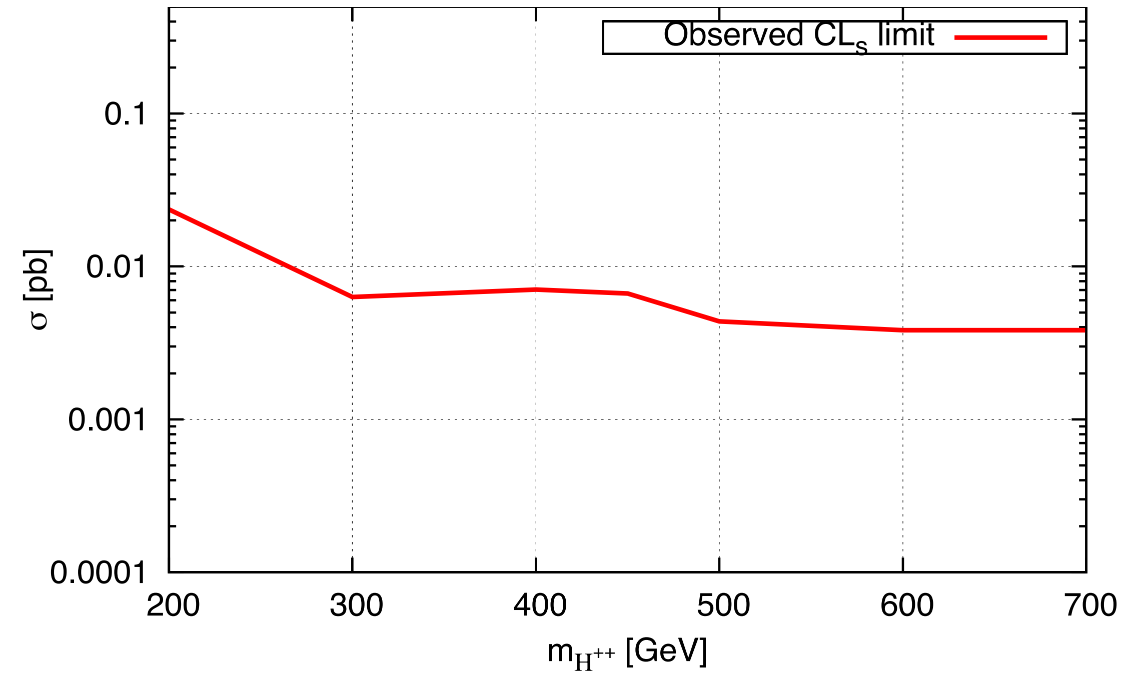


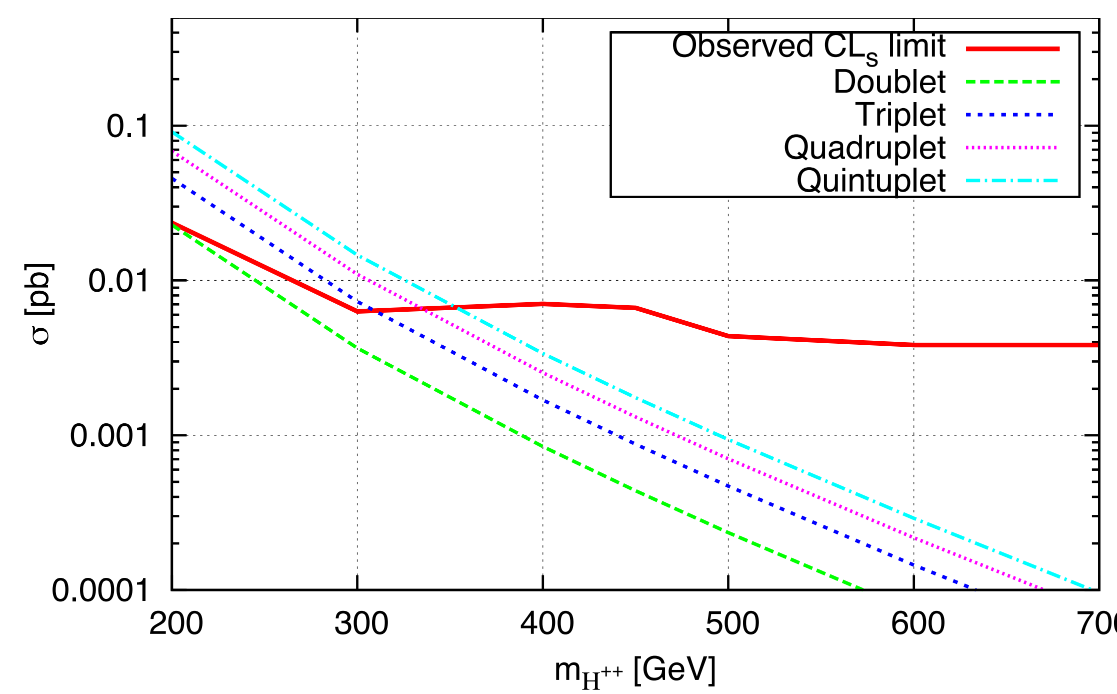
pair production
5 fb^{-1}, 7 TeV
50 % ll + 50 % WW





associated production
5 fb^{-1}, 7 TeV
$H^{\pm\pm} \rightarrow l^\pm l^\pm$ and $H^\pm \rightarrow W^\pm Z$





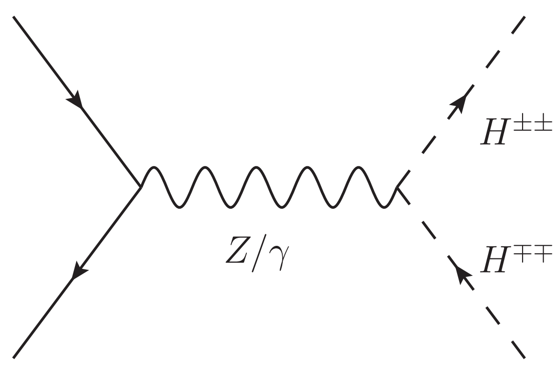
	Multiplet	Operator
Dimension 4	$\begin{pmatrix}\Delta^{++}\\ \Delta^{+}\\ \Delta^{0}\end{pmatrix}$	$(\overline{\tilde{L}_L}\tau^a L_L)\Delta^{-a}$
	κ^{++}	$\overline{l^c_R} l_R \kappa$
Dimension 5	$\begin{pmatrix}\Sigma^{++}\\ \Sigma^{+}\\ \Sigma^{0}\\ \Sigma'^{-}\end{pmatrix}$	$(-1)^{\frac{1}{2}-b} C^{1\times\frac{1}{2}\to\frac{3}{2}}_{a,b}(\overline{\tilde{L}_L}\tau^a L_L)\phi^b \Sigma^{-a-b}$
	$\begin{pmatrix}\chi^{++}\\ \chi^{+}\end{pmatrix}$	$(-1)^{1-a}(\overline{\tilde{L}_L}\tau^a L_L)(\phi^\dagger \tau^{-a}\chi)$, $\overline{l^c_R} l_R (\tilde{\phi}^\dagger \chi)$
Dimension 6	$\begin{pmatrix}\Omega^{++}\\ \Omega^{+}\\ \Omega^{0}\\ \Omega^{-}\\ \Omega^{--}\end{pmatrix}$	$C^{1\times 1\to 2}_{a,b}(\overline{\tilde{L}_L}\tau^a L_L)(\tilde{\phi}^\dagger \tau^b \phi)\Omega^{-a-b}$

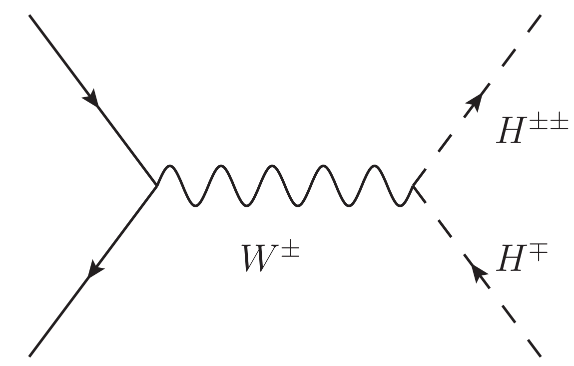
$$\overline{e^c_L} e_L \mathrm{H}^{++}$$

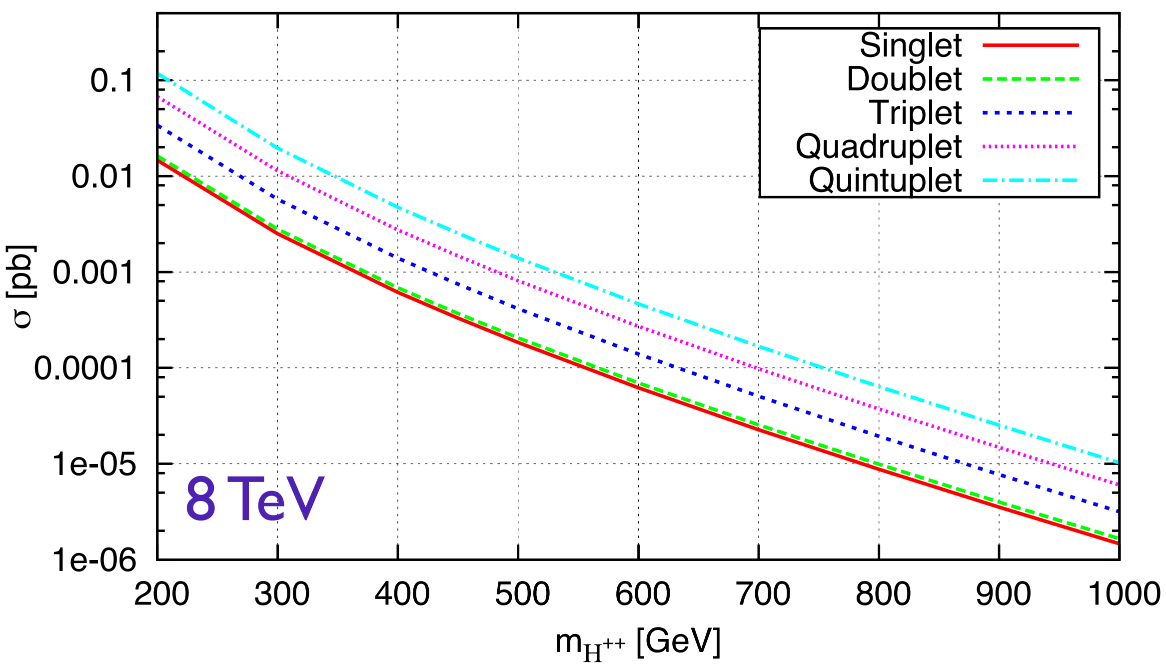
$$\overline{e^c_R} e_R \mathrm{H}^{++}$$

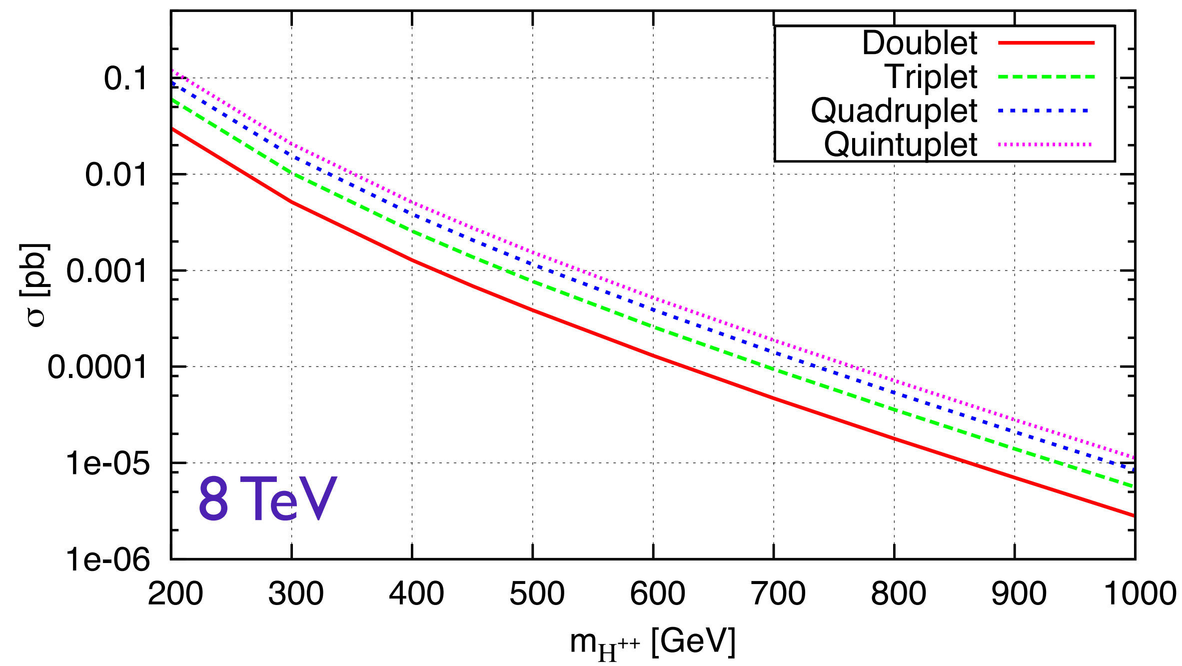
$$T^{\mathrm{H}} \geq T_3^{\mathrm{H}^{++}} = 2 - Y^{\mathrm{H}}$$

$$T^{\mathrm{H}} = T_3^{\mathrm{H}^{++}} \leq 2$$





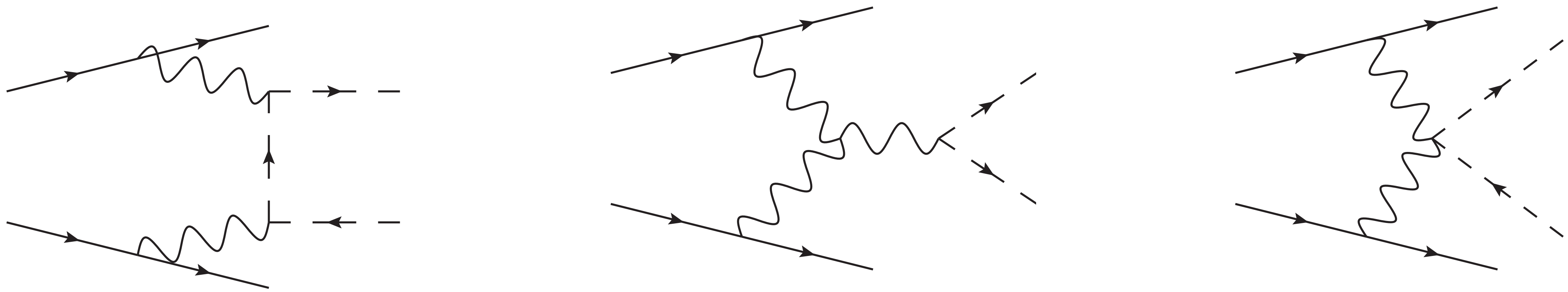


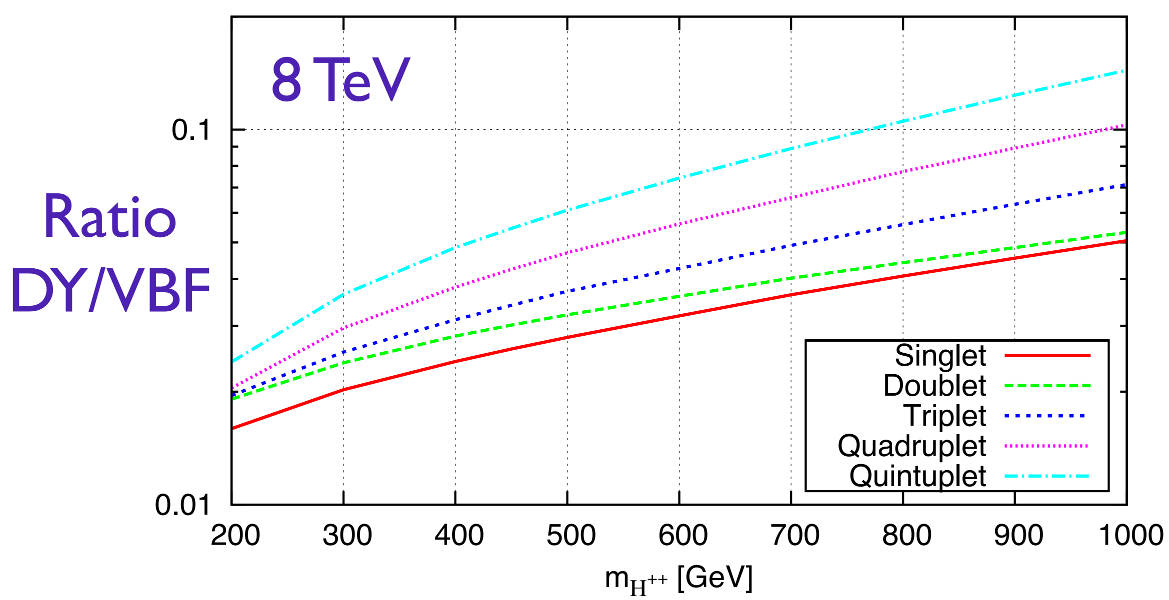


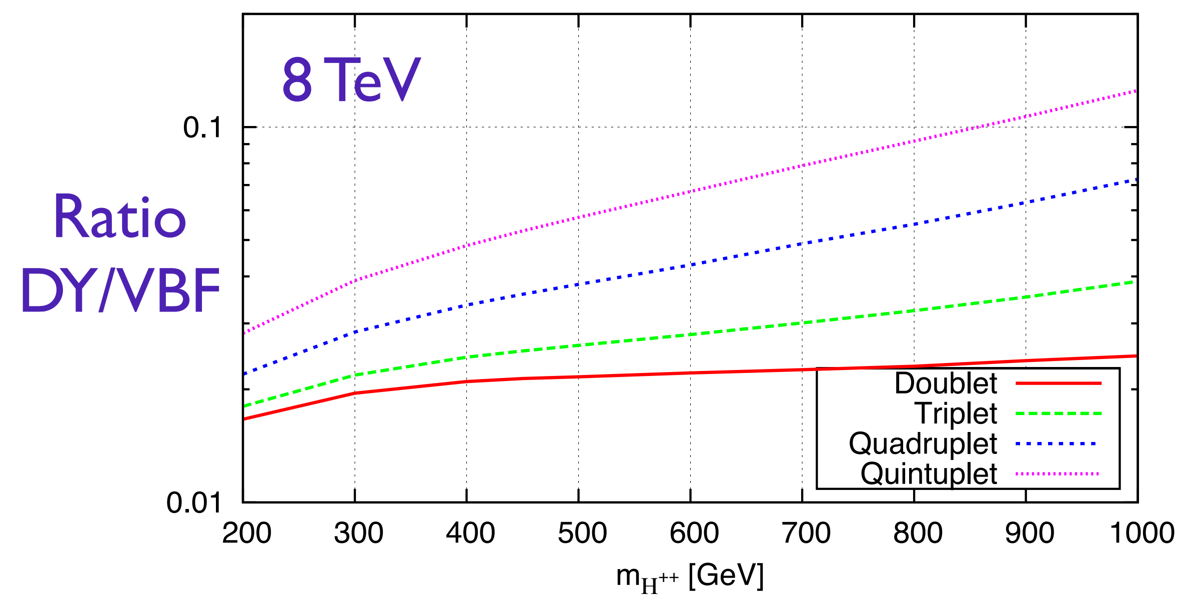
$$\mathcal{L}_{\gamma}^{\mathrm{H}^{\pm\pm}} = ieQ(\partial^{\mu}\mathrm{H}^{--})\mathrm{H}^{++}A_{\mu} + \mathrm{h.c.}\,,$$

$$\mathcal{L}_{Z}^{\mathrm{H}^{\pm\pm}} = \frac{ig}{c_W}(T_3 - Qs_W^2)(\partial^{\mu}\mathrm{H}^{--})\mathrm{H}^{++}Z_{\mu} + \mathrm{h.c.}$$

$$\mathcal{L}_{W}^{\mathrm{H}^{\pm\pm}} = \frac{ig}{\sqrt{2}}\sqrt{(T-T_3+1)(T+T_3)}[\mathrm{H}^{++}(\partial^{\mu}\mathrm{H}^{-}) - (\partial^{\mu}\mathrm{H}^{++})\mathrm{H}^{-}]W_{\mu}^{-} + \mathrm{h.c.}$$







γγ contribution

T. Han, B. Mukhopadyaya, Z. Si and K. Wang,
Phys. Rev. D76 (2007) 075013 [arXiv:0706.0441]

		$(1, 0, 0)$	$(\frac{1}{2}, \frac{1}{2}, 0)$	$(\frac{1}{2}, 0, \frac{1}{2})$	$(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$
Quintuplet	$(l^{\pm}l^{\pm})l^{\mp}l^{\mp}p_T^{miss}$	1307 ± 38	501 ± 25	362 ± 22	238 ± 19
	$(l^{\pm}l^{\pm})(l^{\mp}l^{\mp})$	1046 ± 32	261 ± 16	261 ± 16	116 ± 11
Quadruplet	$(l^{\pm}l^{\pm})l^{\mp}l^{\mp}p_T^{miss}$	765 ± 30	293 ± 20	212 ± 18	139 ± 16
	$(l^{\pm}l^{\pm})(l^{\mp}l^{\mp})$	612 ± 24	153 ± 12	153 ± 12	68 ± 8
Triplet	$(l^{\pm}l^{\pm})l^{\mp}l^{\mp}p_T^{miss}$	383 ± 22	147 ± 16	106 ± 15	70 ± 13
	$(l^{\pm}l^{\pm})(l^{\mp}l^{\mp})$	306 ± 18	77 ± 9	77 ± 9	34 ± 6
Doublet	$(l^{\pm}l^{\pm})l^{\mp}l^{\mp}p_T^{miss}$	189 ± 17	73 ± 14	53 ± 13	35 ± 12
	$(l^{\pm}l^{\pm})(l^{\mp}l^{\mp})$	151 ± 12	38 ± 6	38 ± 6	17 ± 4
Singlet	$(l^{\pm}l^{\pm})l^{\mp}l^{\mp}p_T^{miss}$	168 ± 17	64 ± 13	47 ± 13	31 ± 12
	$(l^{\pm}l^{\pm})(l^{\mp}l^{\mp})$	135 ± 12	34 ± 6	34 ± 6	15 ± 4

$(l^{\pm}l^{\pm})(l^{\mp}p_T^{miss})$	$(1, 0, 0)$	$(\frac{1}{2}, \frac{1}{2}, 0)$	$(\frac{1}{2}, 0, \frac{1}{2})$	$(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$
Quintuplet	1011 ± 34	283 ± 21	261 ± 20	130 ± 17
Quadruplet	592 ± 27	166 ± 18	153 ± 17	76 ± 15
Triplet	296 ± 21	83 ± 15	77 ± 15	38 ± 14
Doublet	146 ± 17	41 ± 13	38 ± 14	19 ± 13
Singlet	0 ± 12	0 ± 12	0 ± 12	0 ± 12

$$\sigma_{lla} \equiv 2\sigma z_{ll} z_a, a \neq ll$$

$$\sigma_{lllp_T^{miss}} = \sigma_{llll} + 2\sum_{a=l\tau,\tau\tau,WW} \sigma z_{ll} z_a Br(a \to ll + p_T^{miss})$$

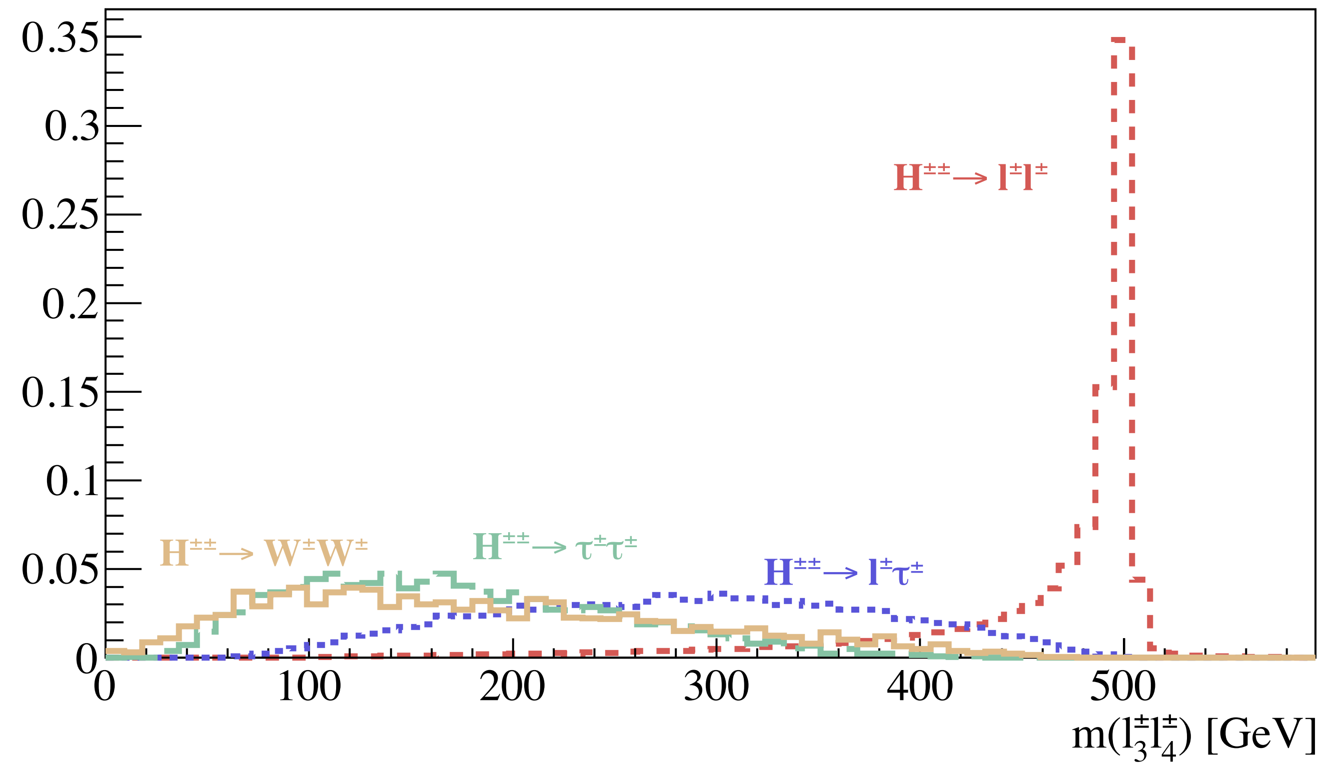
How well can we measure the total cross-section ?

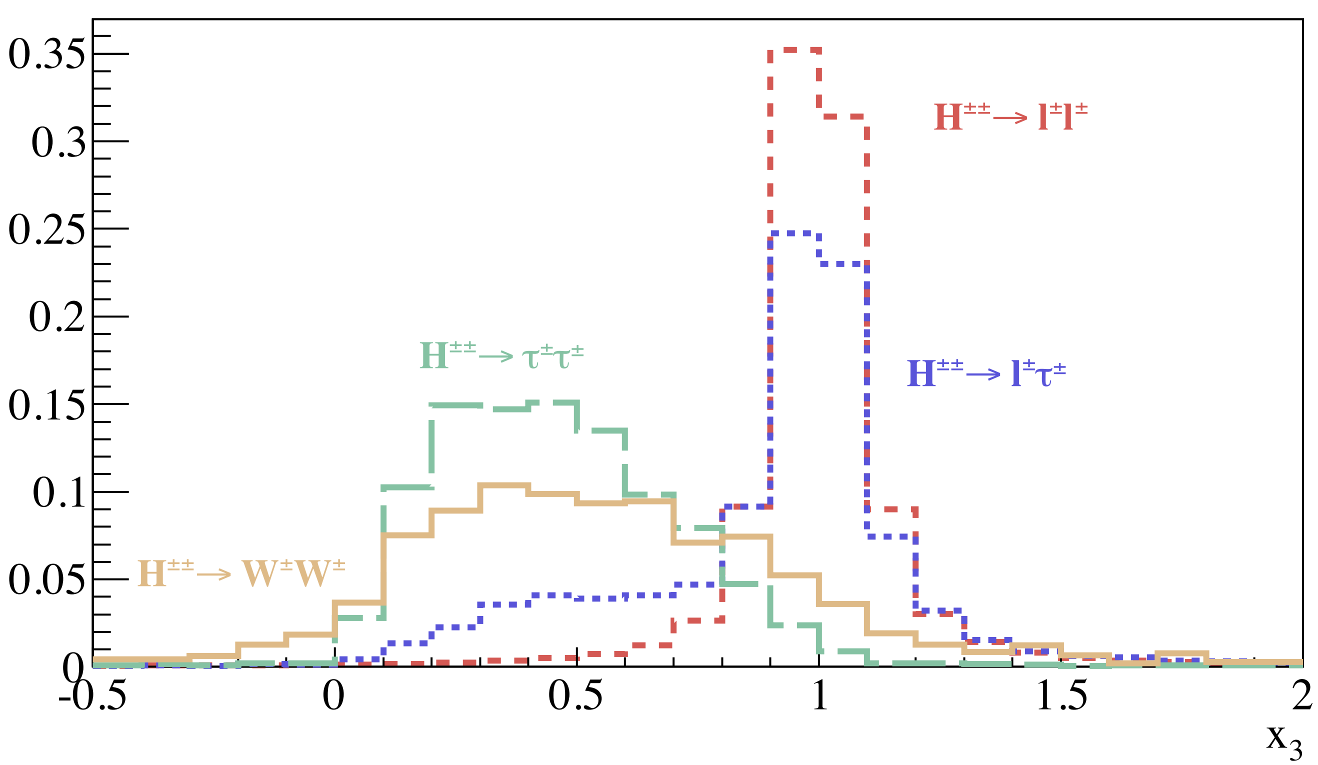
$$\sigma = \left(\sigma_{llll} + \frac{1}{2}\sum_{a\neq ll} \sigma_{lla}\right)^2 / \sigma_{llll}$$

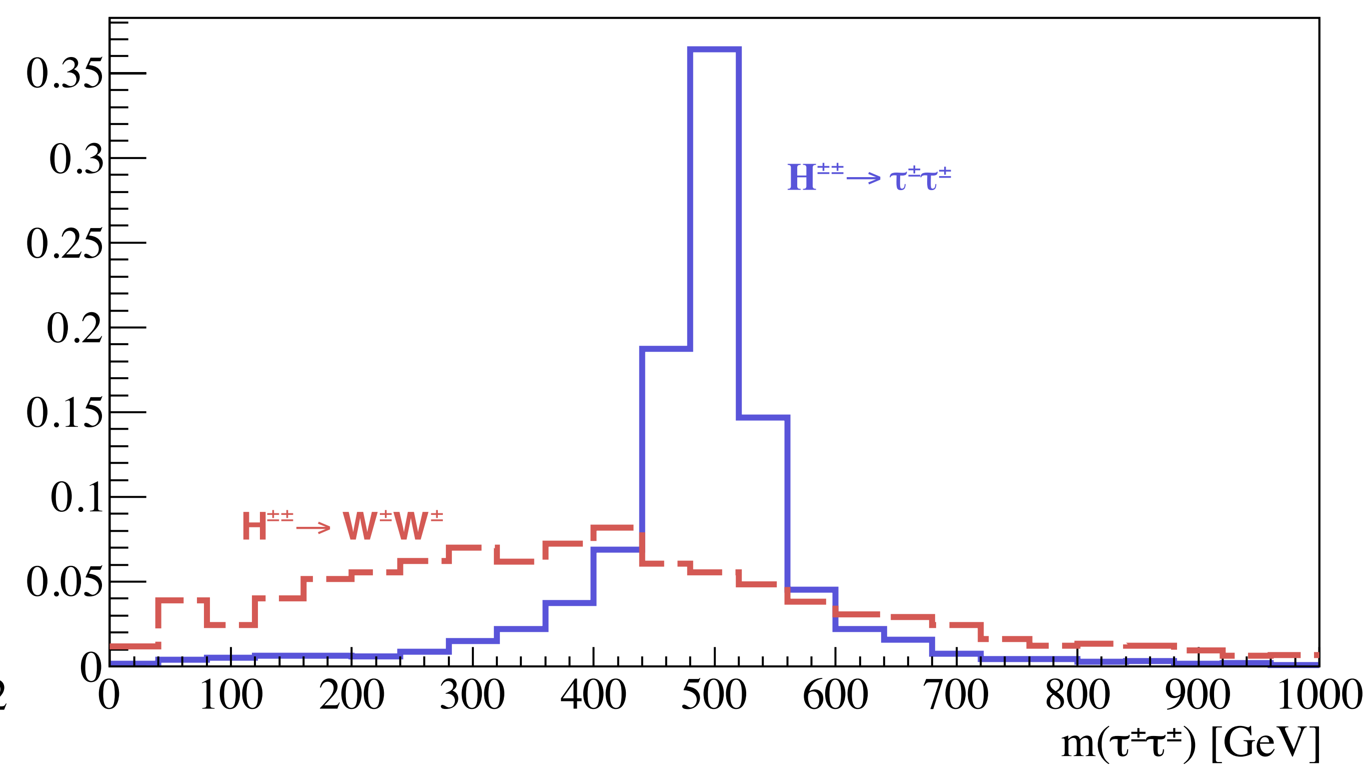
$$1 = \sum_{a=ll,l\tau,\tau\tau,WW} z_a, z_a \equiv Br(H \to a)$$

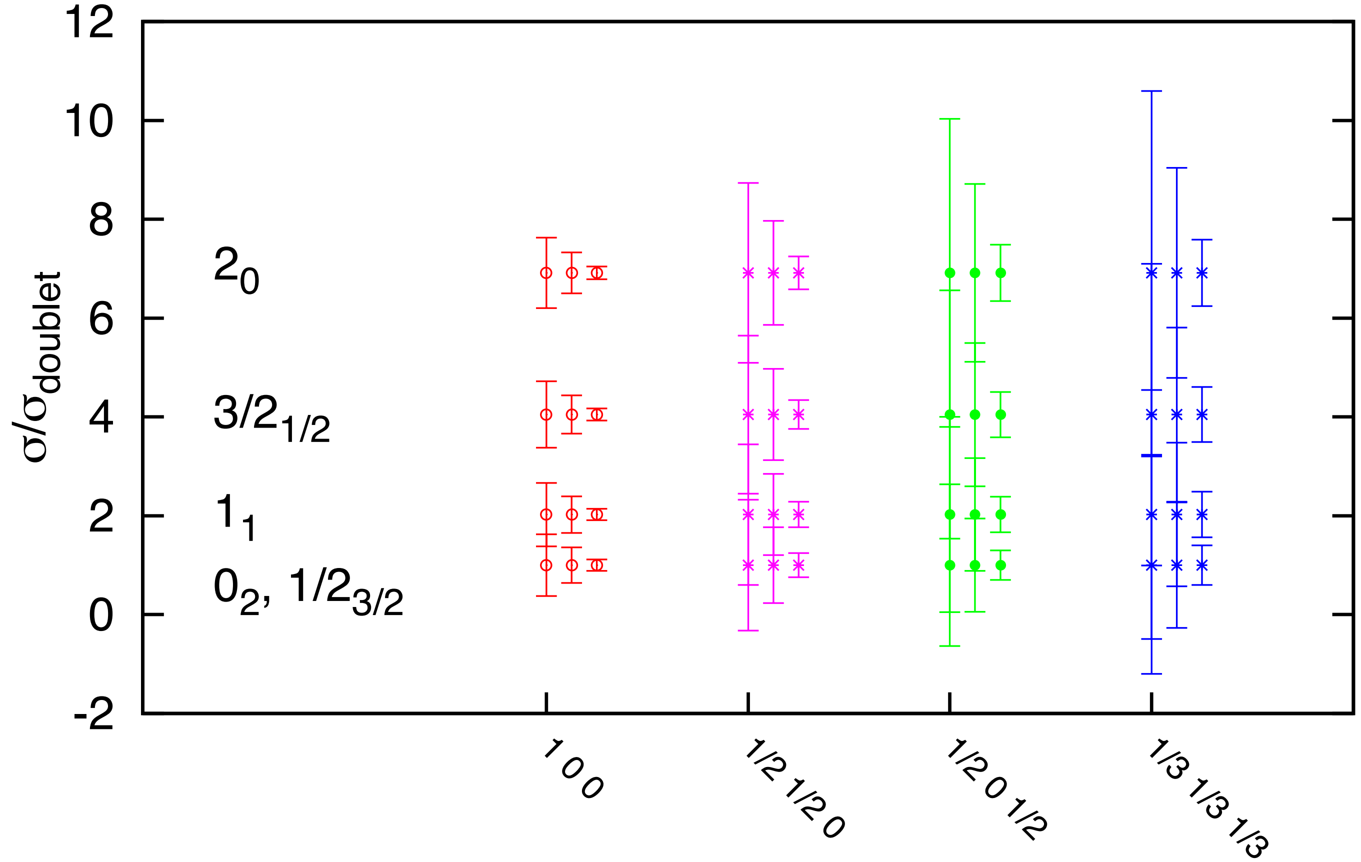
It is enough to group the sample with four charged leptons in three sub-sets:

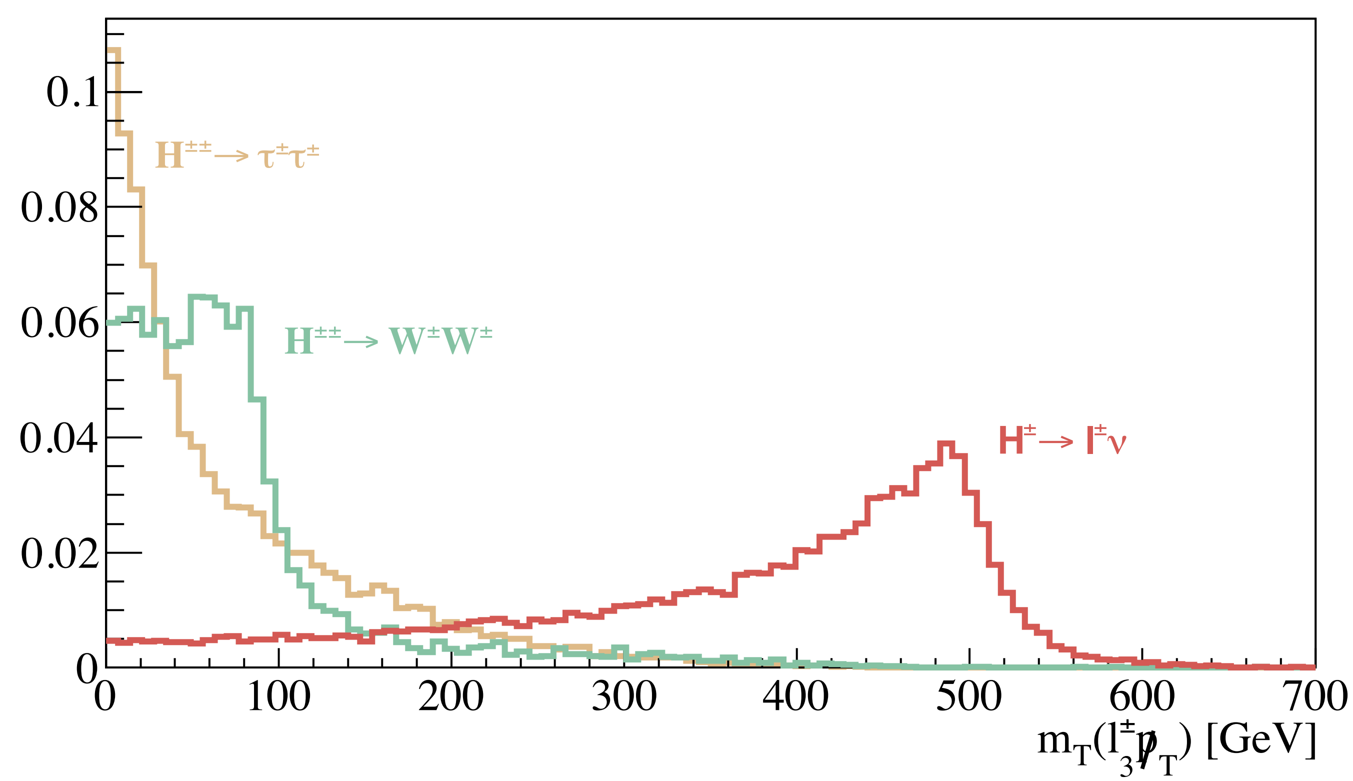
$$\left(z_{ll}\,,\,z_{l\tau}\,,\,z_{\tau\tau}\;+\;z_{WW}\right)$$








σ/σdoublet
2_0
3/2_1/2
1_1
0_2, 1/2_3/2
1 0 0
1/2 1/2 0
1/2 0 1/2
1/3 1/3 1/3


H±± → τ±τ±
H±± → W±W±
H± → l±ν
m_T(l±_3 p̸_T) [GeV]

Summary

arXiv:1305.3904 [hep-ph]
arXiv:1307.0510 [hep-ph]
arXiv:1310.xxxx [hep-ph]

- LNV processes are rare ($m_\nu \sim 0$) and require a physical enhancement (cancelling contributions to m_ν or rather slow decays) and an efficient reconstruction to be observable at the LHC.
- Present limits on doubly-charged scalar masses mediating the see-saw of type II (triplet) and decaying into leptons only can be extended to more general multiplets and decays.
- If observed in the same-sign charged di-lepton channel, the type of multiplet can be determined using events with four and three isolated leptons, independently of the size of LNV.

From Majorana to LHC: Workshop on the Origin of Neutrino Mass

Thanks for your attention

Universidad de Granada