Four lepton signals of new physics at large colliders

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CENTRO ANDALUZ DE FISICA DE PARTICULAS ELEMENTALES

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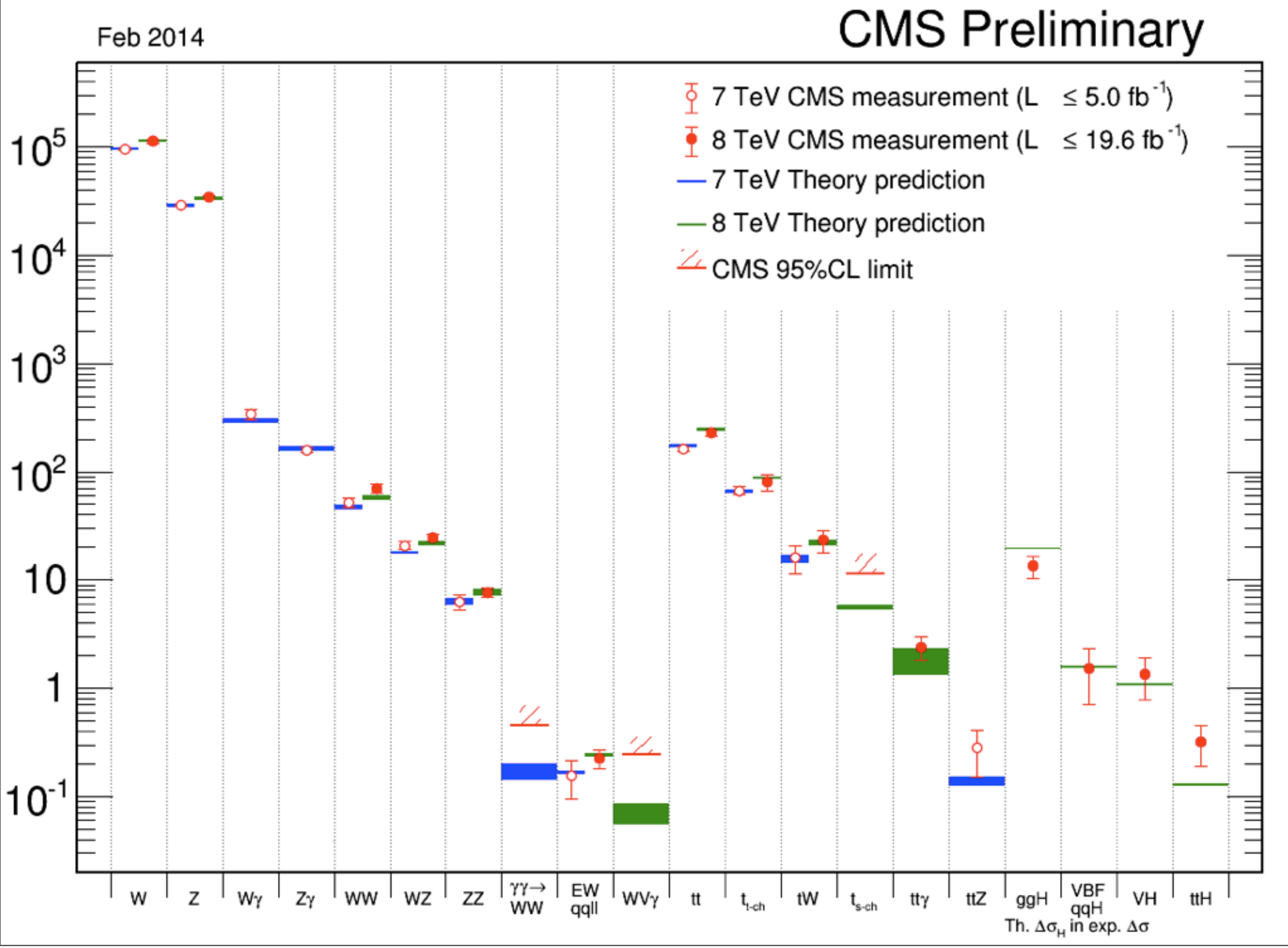
Outline: a phenomenological approach only

- Introduction: New Physics (NP) searches at the LHC benefit of smaller backgrounds when larger the number of leptons in the final state, *ll* , *llll* , ... [Fermion Number is conserved, as it is Lepton Number (LN) to a high degree.]

- Popular Standard Model (SM) extensions can manifest in these modes: new gauge interactions (*Z'*, *W'*), supersymmetric extensions (*sleptons*), etc. ALTHOUGH no NP signal has been detected -neither in other channels, nor indirectly-, yet. This seems to indicate that any departure from the SM (NP) must be (have a) **small** (**cross-section**) and hence, can only show up in samples with small SM backgrounds, being *llll* a prime example. For instance, *SUSY*.

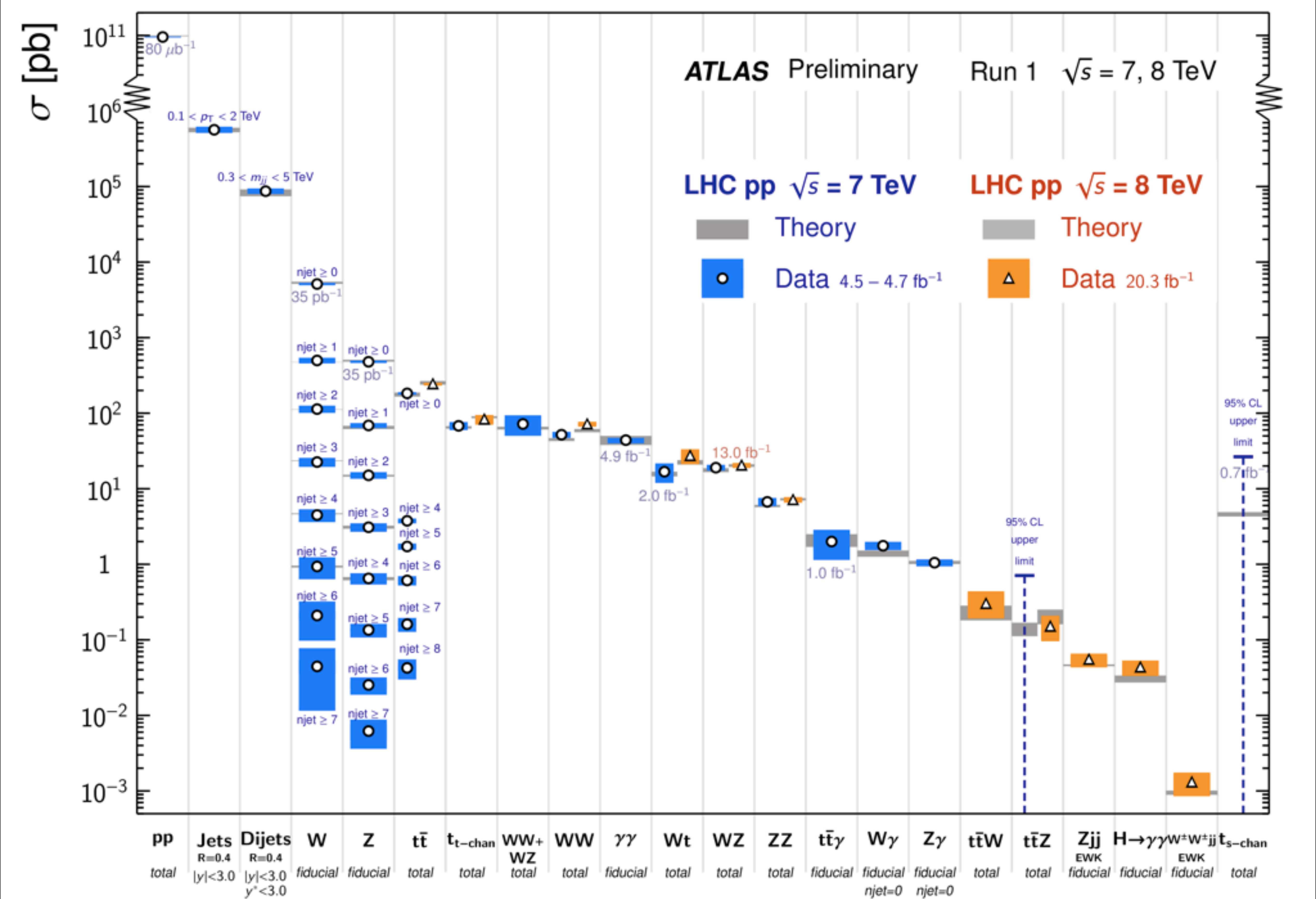
- We want to address two questions: **Will some room for discovery (or for more precise measurements) at the ILC be left after the LHC program is over ? Does any NP mediated by new particles with relatively large couplings and small masses have a small enough cross-section to have avoided detection at the LHC up to now ?** -Obviously, you can never exclude that NP is around the corner, and it has not been observed because the couplings are too small or the masses too large.

- Summary



miércoles 10 de septiembre de 2014

Standard Model Production Cross Section Measurements



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- We do not have any other physical motivation: hierarchy problem -fine tuning-, etc. This would come later.

- *ll, llll*, what is equivalent to W (ATLAS at Run I ~ 5×10^3 pb) or Z (ATLAS at Run I ~ 5×10^2 pb) production, or WW (~ 60 pb), WZ (~ 20 pb), ZZ (~ 7 pb) production

- An alternative is NP coupling only to leptons (*LEPTOPHILIC*) and maybe also to electro-weak (EW) bosons. We will discuss the lowest order realization of the first alternative -which provides another example of the **complementarity** of LHC and ILC- and an example of NP naturally/effectively **suppressed** and based on the only physics beyond the SM observed up to now, neutrino masses: *LN Violation.*

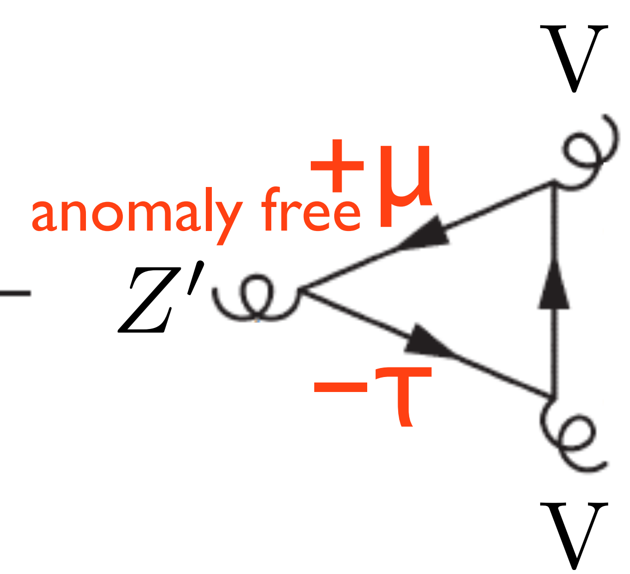
In preparation
CAFPE-183/14, UG-FT-313/14

- A resonance coupled to two SM lepton multiplets: **Higgs quantum numbers** -and we are not interested in- **or neutral** if LN conserving. But then it must be a *vector boson* to have a non-renormalizable coupling -otherwise, chirally suppressed-. [If LN $\neq$ 0, a doubly-charged scalar component.]

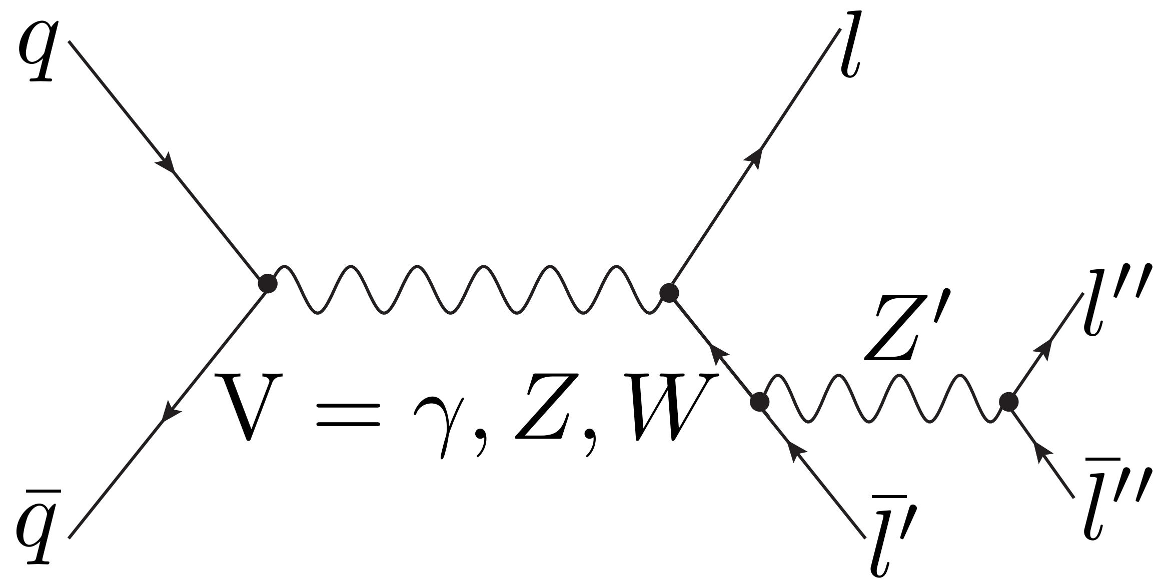
$$(g_{\mathrm{L}}^{\prime ij}\overline{L}_{\mathrm{L}i}\gamma^{\mu}L_{\mathrm{L}j} + g_{\mathrm{R}}^{\prime ij}\overline{l}_{\mathrm{R}i}\gamma^{\mu}l_{\mathrm{R}j})Z'_{\mu}$$

- Even for leptophilic interactions, only the *couplings to muons and taus* can be large enough to be observable at the LHC (LFV, LEP).

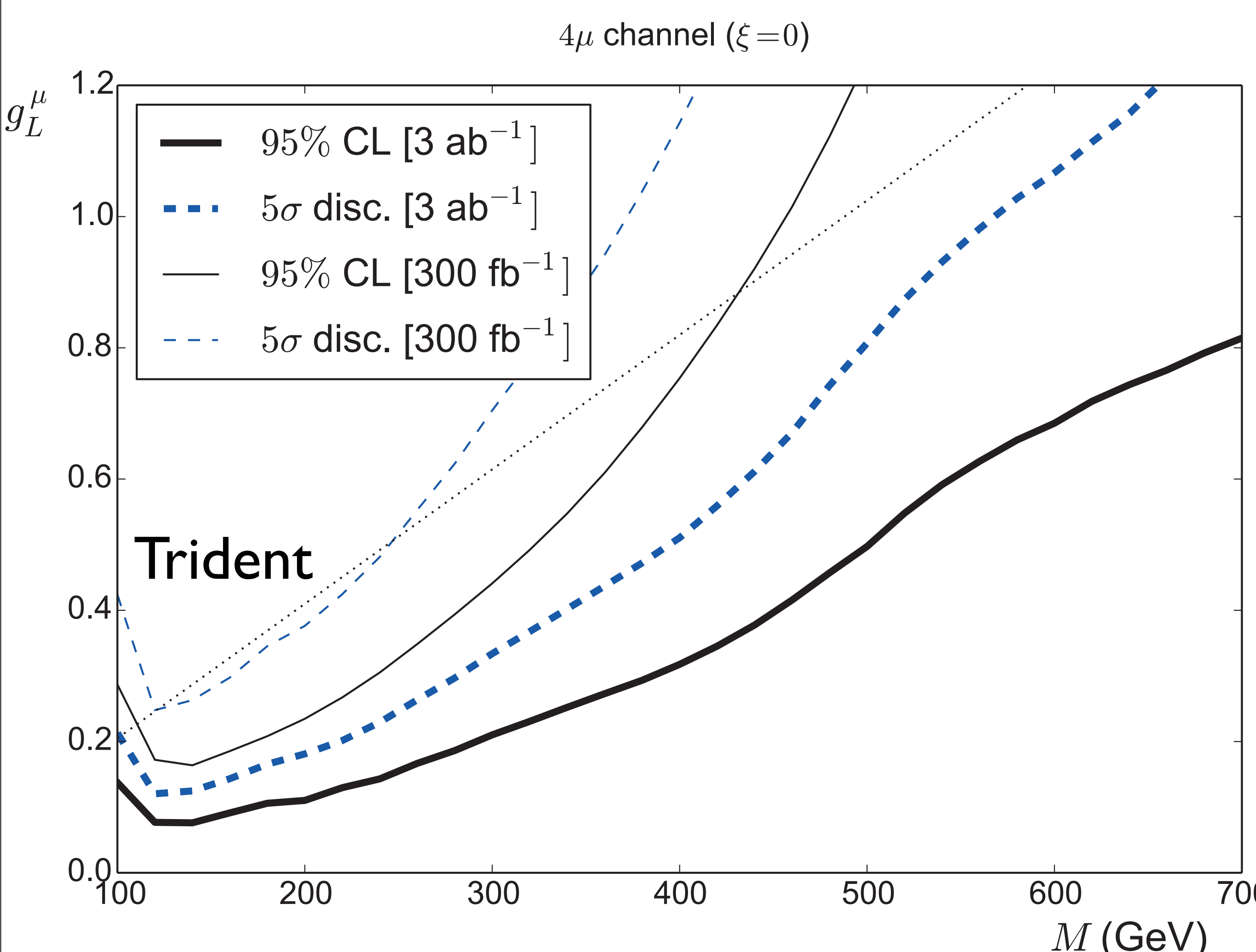
Multiplet	$L_{\mathrm{L}\mu} = \begin{pmatrix} \nu_{\mathrm{L}\mu} \\ \mu_{\mathrm{L}} \end{pmatrix}$	μ_{R}	$L_{\mathrm{L}\tau} = \begin{pmatrix} \nu_{\mathrm{L}\tau} \\ \tau_{\mathrm{L}} \end{pmatrix}$	τ_{R}
Charge	1	1	-1	-1

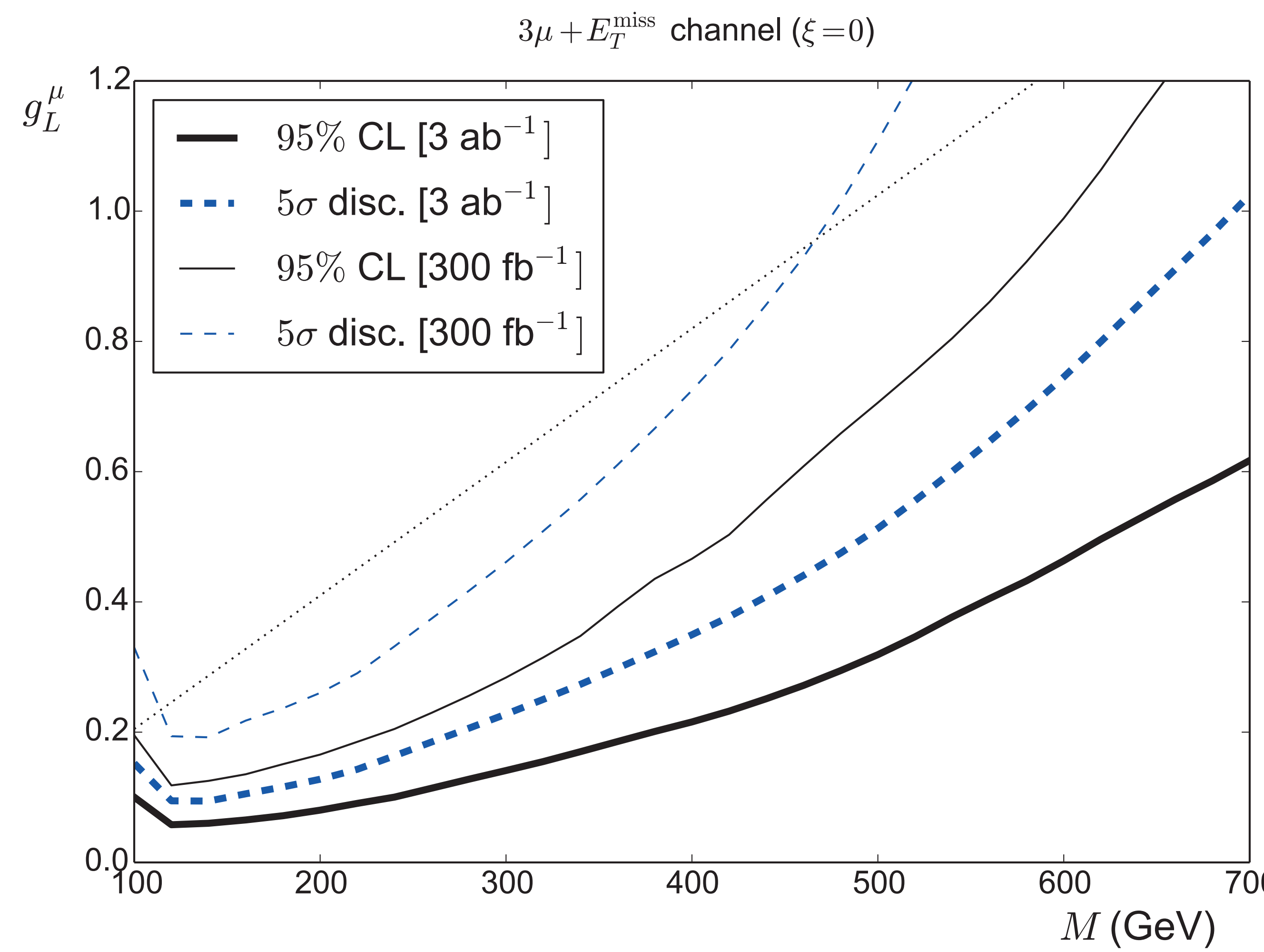


R.Foot, X.G. He, H. Lew and R.R. Volkas, PR D50 (1994) 4571 [hep-ph/9401250]



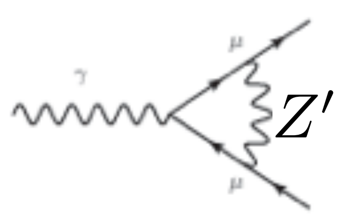
Few fb





$$\nu \mathrm{N} \to \nu \mu^+ \mu^- \mathrm{N}$$

arXiv:1406.2332 [hep-ph]



E. Ma, D.P. Roy and S. Roy, PLB 525 (2002) 101 [hep-ph/0110146]

K. Harigaya, et al., JHEP 1403 (2014) 105 [arXiv:1311.0870 [hep-ph]]

0.3 for 80GeV

MADGRAPH (UFO model) parton level

http://cafpe.ugr.es/index.php/pages/other/software

PYTHIA radiation

DELPHES fast detector simulation

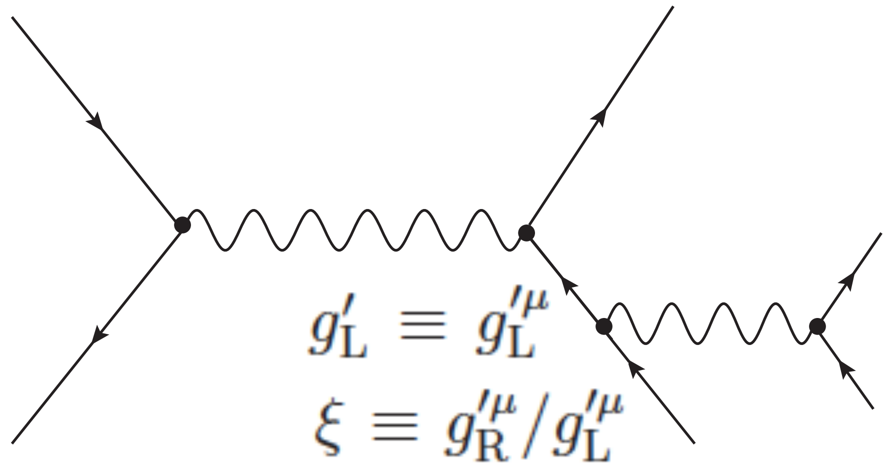
FAST JET reconstruction

MAD ANALYSIS

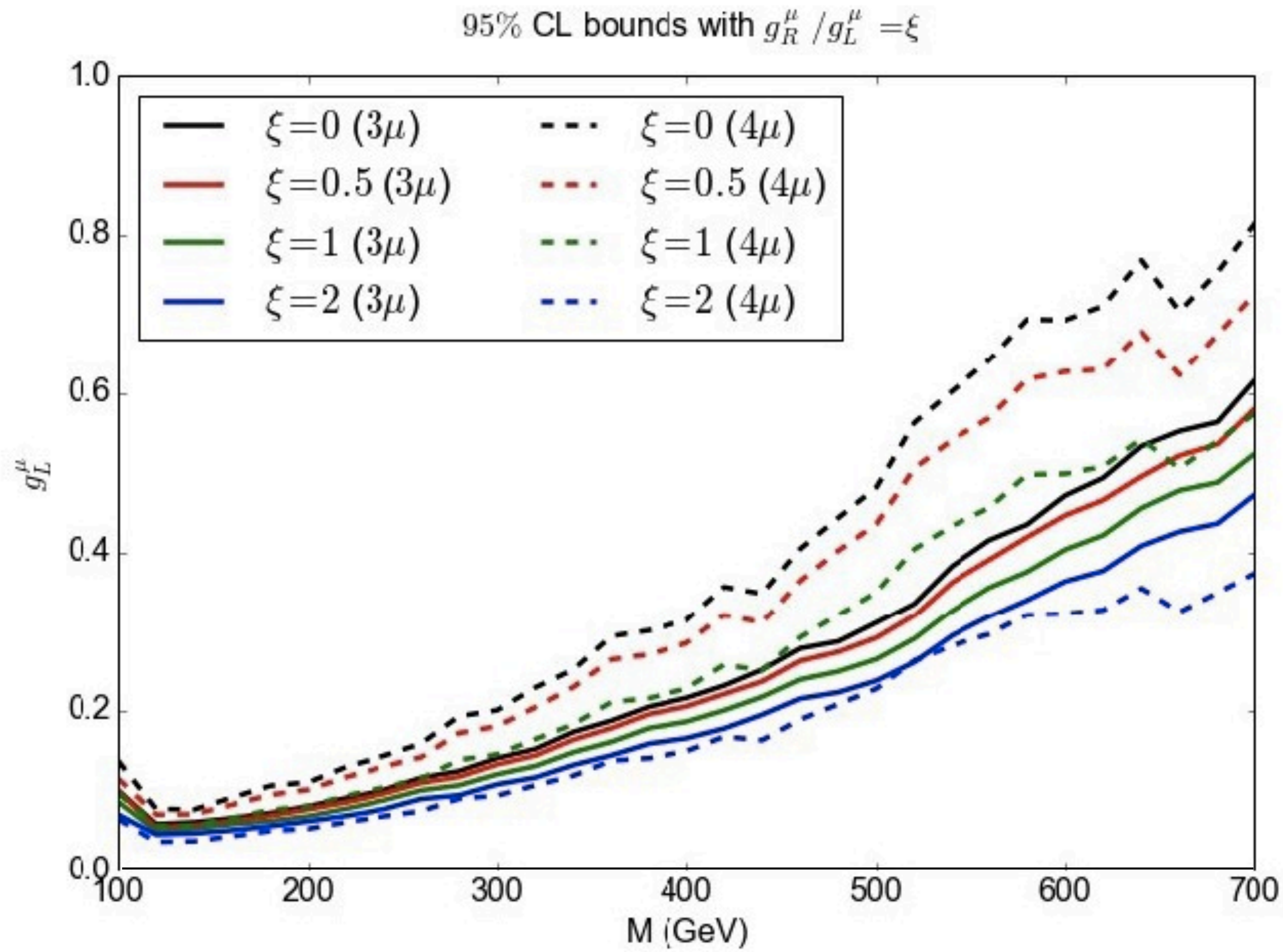
Background: Main irreducible: VV, scaled to SM estimates by ATLAS, for instance

ATLAS-CONF-2013-035 (charginos and neutralinos)
ATLAS-CONF-2013-070 (new phenomena)

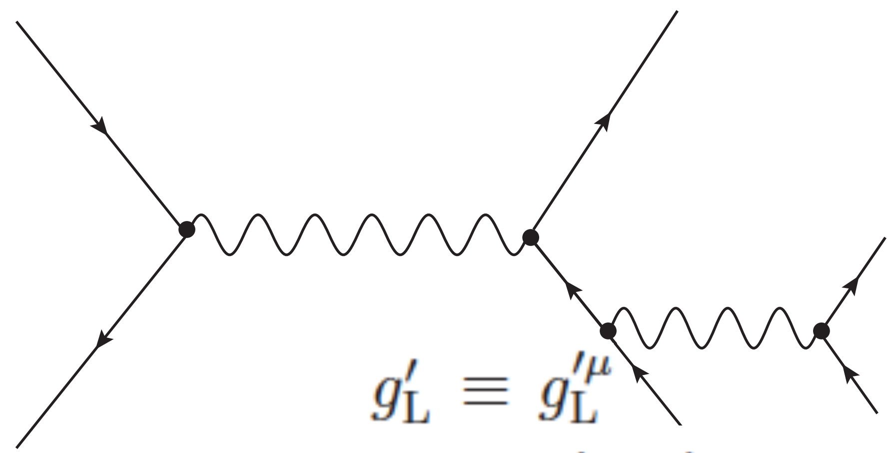
Basic cuts	$p_T^\ell > 10$ GeV, $\eta_\ell < 2.47$, $\Delta R(j\ell) > 0.4$
Number of muons	$N_\mu = 3$ (4)
Z veto	$\lvert m_{\mu^+\mu^-} - m_Z \rvert > 10$ GeV
Mass window	$\lvert m_{\mu^+\mu^-} - m_{Z'} \rvert < 0.1 m_{Z'}$
Missing p_T	$p_T^{miss} > 100$ GeV (No)



$g'_{\rm L} \equiv g'^{\mu}_{\rm L}$
$\xi \equiv g'^{\mu}_{\rm R} / g'^{\mu}_{\rm L}$



95% CL bounds with $g^{\mu}_{R}\ / g^{\mu}_{L}\ = \xi$
ξ=0 (3μ)
ξ=0.5 (3μ)
ξ=1 (3μ)
ξ=2 (3μ)
ξ=0 (4μ)
ξ=0.5 (4μ)
ξ=1 (4μ)
ξ=2 (4μ)
g^{μ}_{L}
M (GeV)



4μ

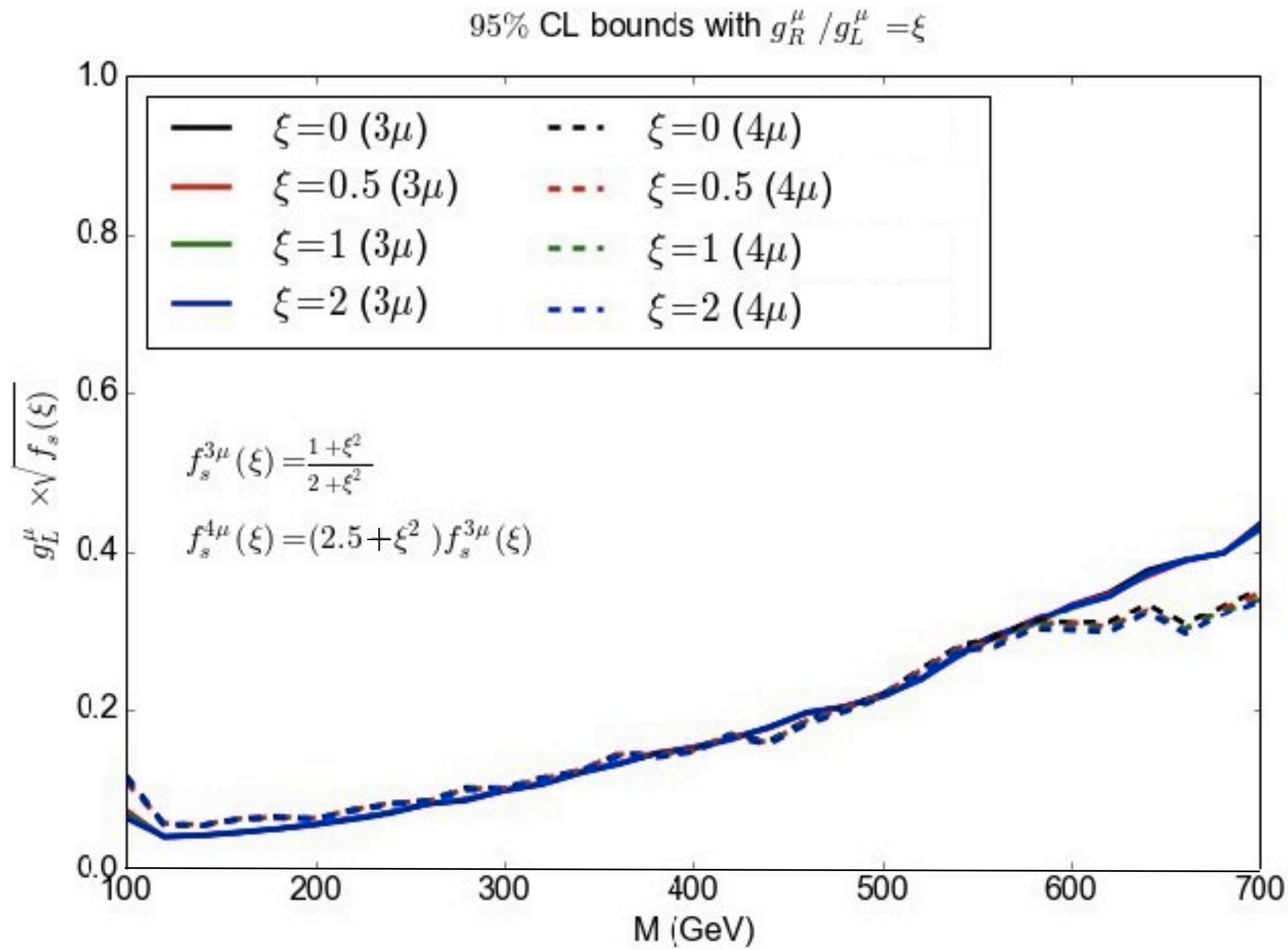
$3\mu 1\nu_\mu$

$2\mu 2\nu_\mu$ No sensitivity

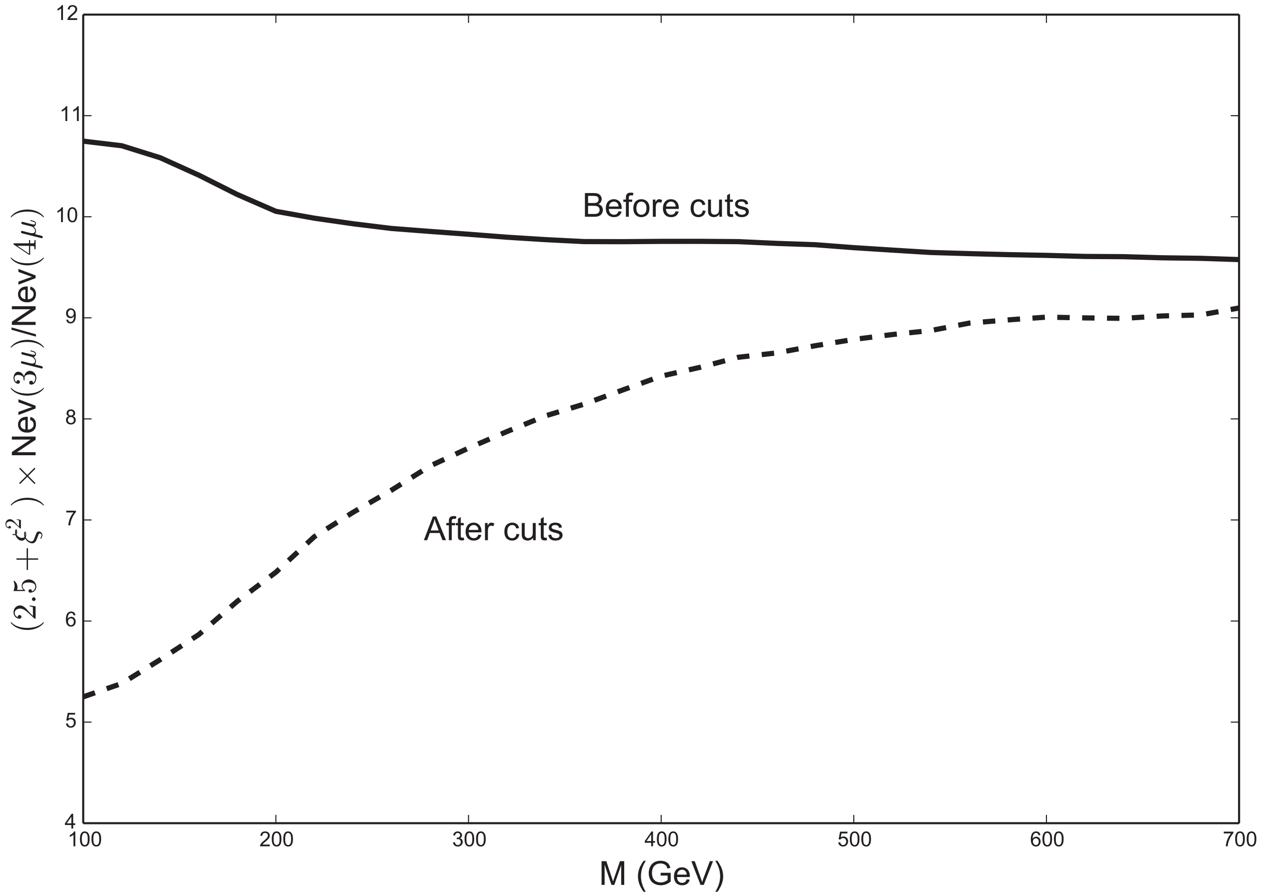
Depends on the Weinberg angle
(u and μ couplings)

$$\sigma_{Z'}(pp \to 4\mu) \approx f_{4\mu}^{\gamma+Z}(M_{Z'})g'^2_{\rm L}(2.5+\xi^2)\frac{g'^2_{\rm L}(1+\xi^2)}{g'^2_{\rm L}(2+\xi^2)+W^{i\neq\mu}}$$

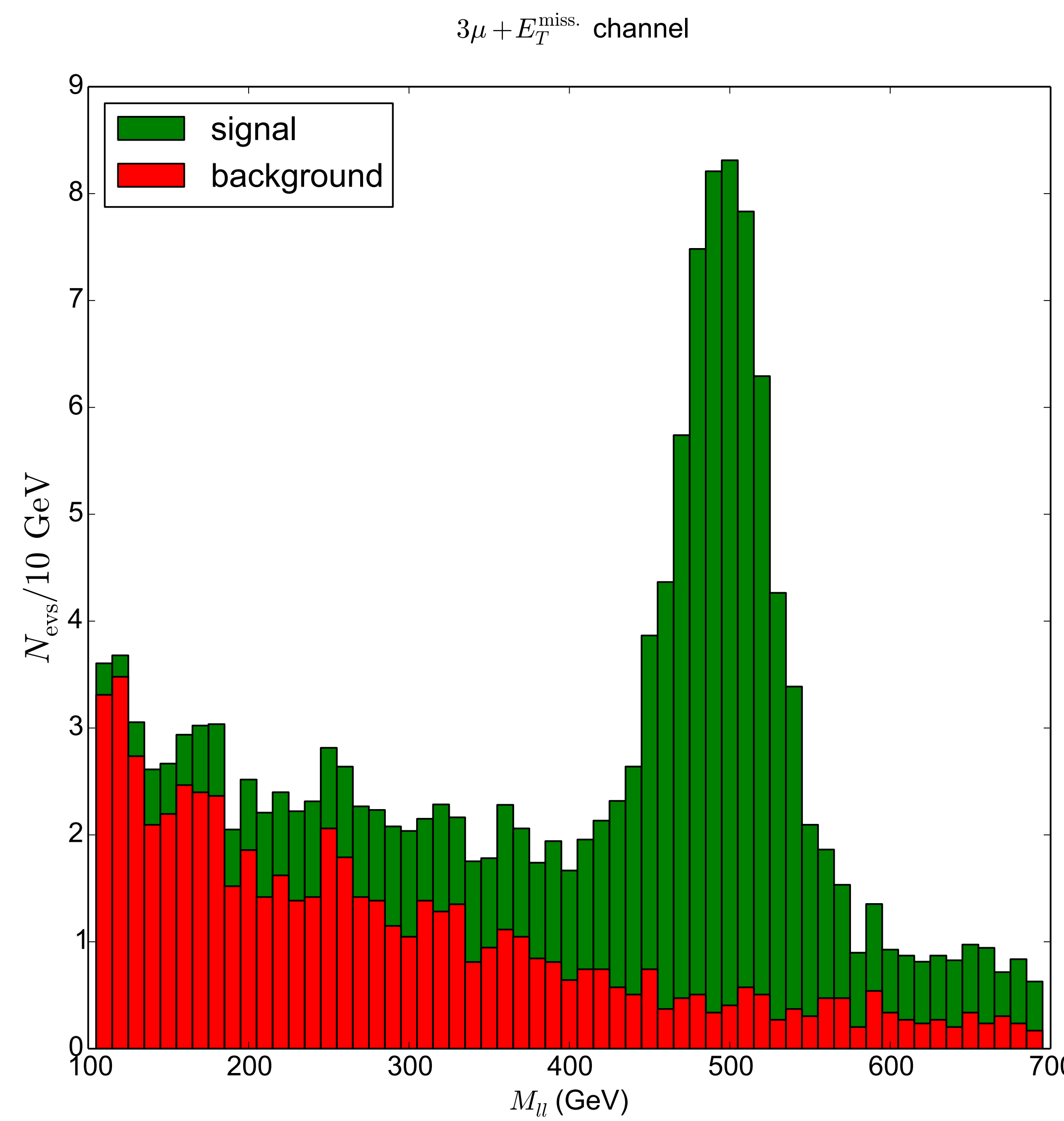
$$\sigma_{Z'}(pp \to 3\mu + p_{\rm T}^{\rm miss}) \approx f^{W}_{3\mu+p_{\rm T}^{\rm miss}}(M_{Z'})g'^2_{\rm L}\frac{g'^2_{\rm L}(1+\xi^2)}{g'^2_{\rm L}(2+\xi^2)+W^{i\neq\mu}}$$



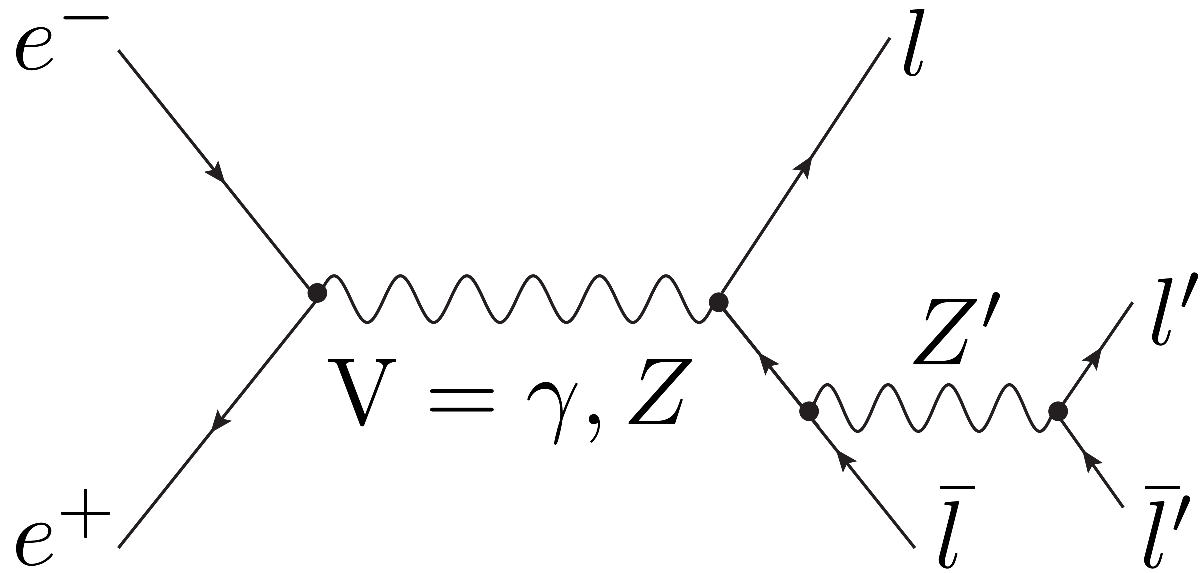
95% CL bounds with $g_R^\mu / g_L^\mu = \xi$
$\xi = 0$ (3μ)
$\xi = 0.5$ (3μ)
$\xi = 1$ (3μ)
$\xi = 2$ (3μ)
$\xi = 0$ (4μ)
$\xi = 0.5$ (4μ)
$\xi = 1$ (4μ)
$\xi = 2$ (4μ)
$f_s^{3\mu}(\xi) = \frac{1+\xi^2}{2+\xi^2}$
$f_s^{4\mu}(\xi) = (2.5+\xi^2)\, f_s^{3\mu}(\xi)$
$g_L^\mu \times \sqrt{f_s(\xi)}$
M (GeV)
0.0
0.2
0.4
0.6
0.8
1.0
100
200
300
400
500
600
700

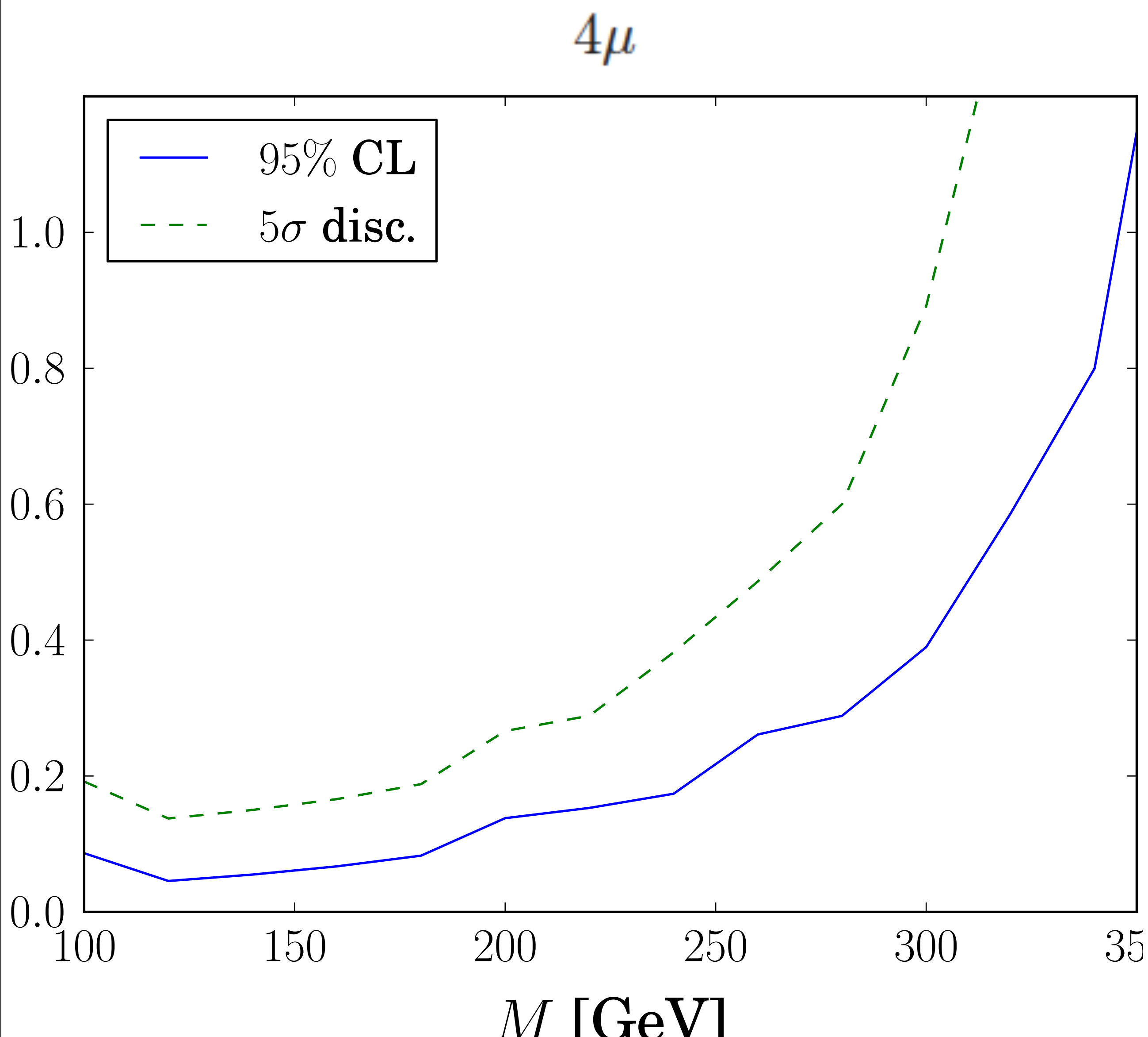


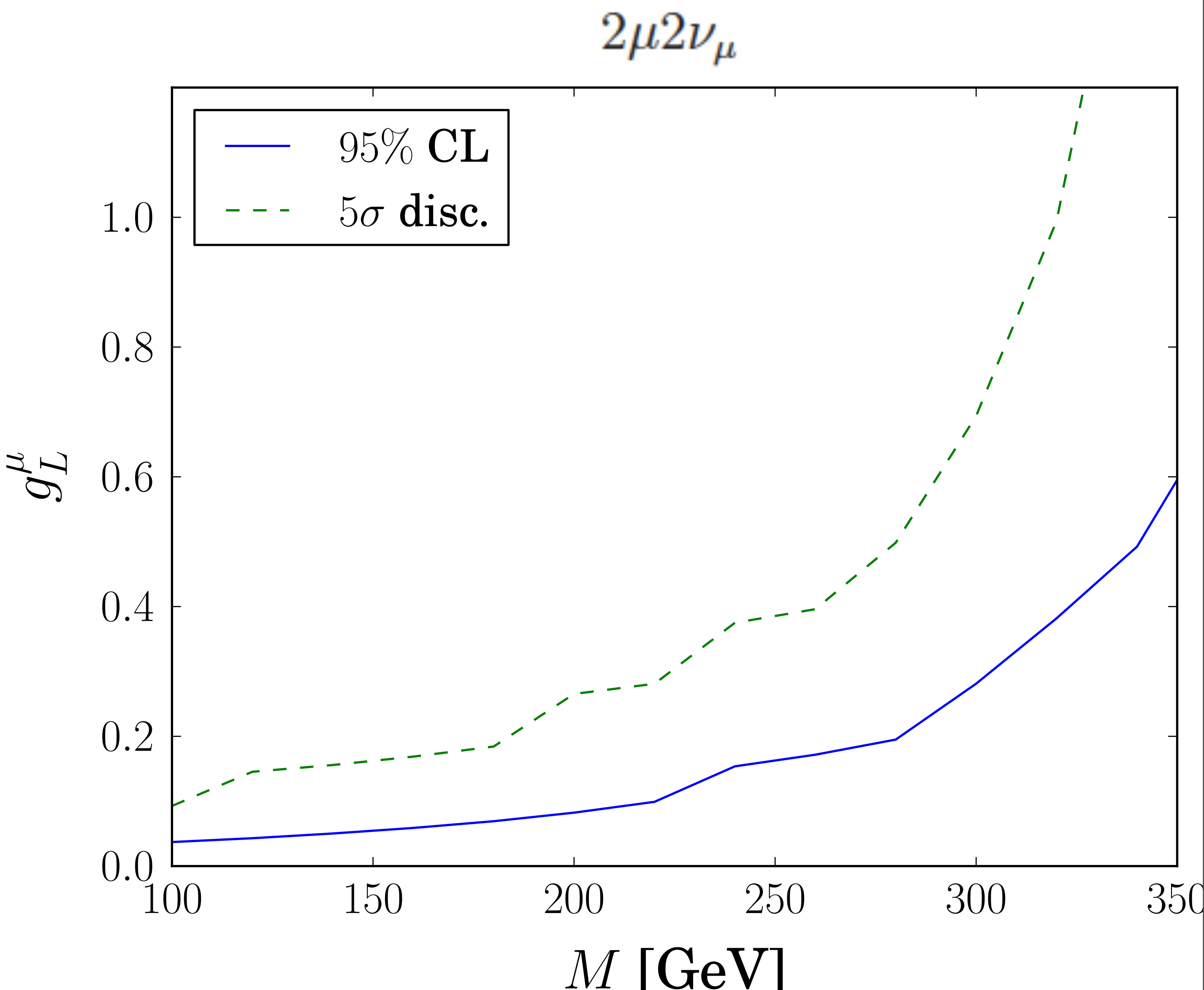
$$\frac{\sigma_{Z'}(pp \to 3\mu + p_{\mathrm{T}}^{\mathrm{miss}})}{\sigma_{Z'}(pp \to 4\mu)} \approx \frac{9.4}{2.5+\xi^2}$$



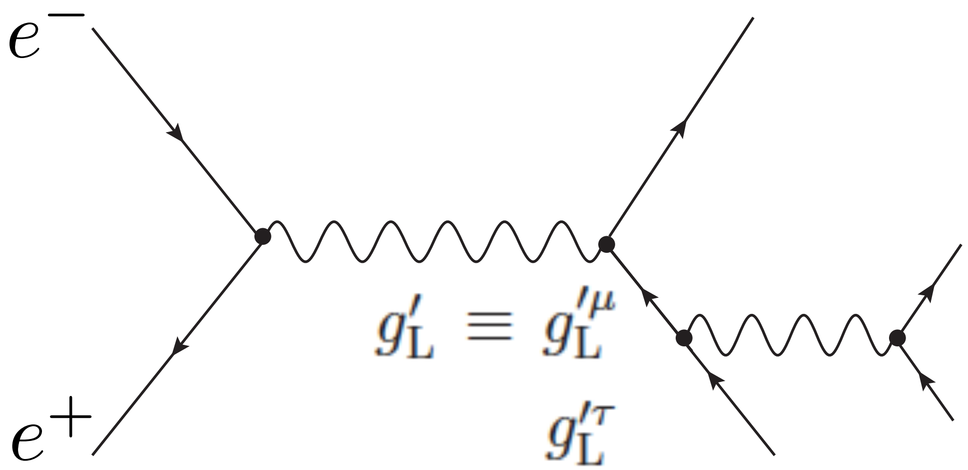
$$\Gamma_{Z'} = \frac{g_{\mathrm{L}}'^2(2+\xi^2) + W^{i\neq\mu}}{24\pi} M_{Z'}$$ ~10 GeV


e^-
e^+
l
$\bar{l}$
Z'
l'
$\bar{l}'$
$\mathrm{V} = \gamma, Z$


4μ
95% CL
5σ disc.
0.0
0.2
0.4
0.6
0.8
1.0
100
150
200
250
300
35
M [GeV]


$2\mu 2\nu_\mu$
95% CL
5σ disc.
g_L^μ
0.0
0.2
0.4
0.6
0.8
1.0
100
150
200
250
300
350
M [GeV]

$$(g_{\rm L}^{\prime ij}\overline{L}_{{\rm L}i}\gamma^\mu L_{{\rm L}j} + g_{\rm R}^{\prime ij}\overline{l}_{{\rm R}i}\gamma^\mu l_{{\rm R}j})Z'_\mu$$



4μ

$2\mu 2\nu_\mu$ $\quad 2\mu 2\nu_{\mu,\tau}$

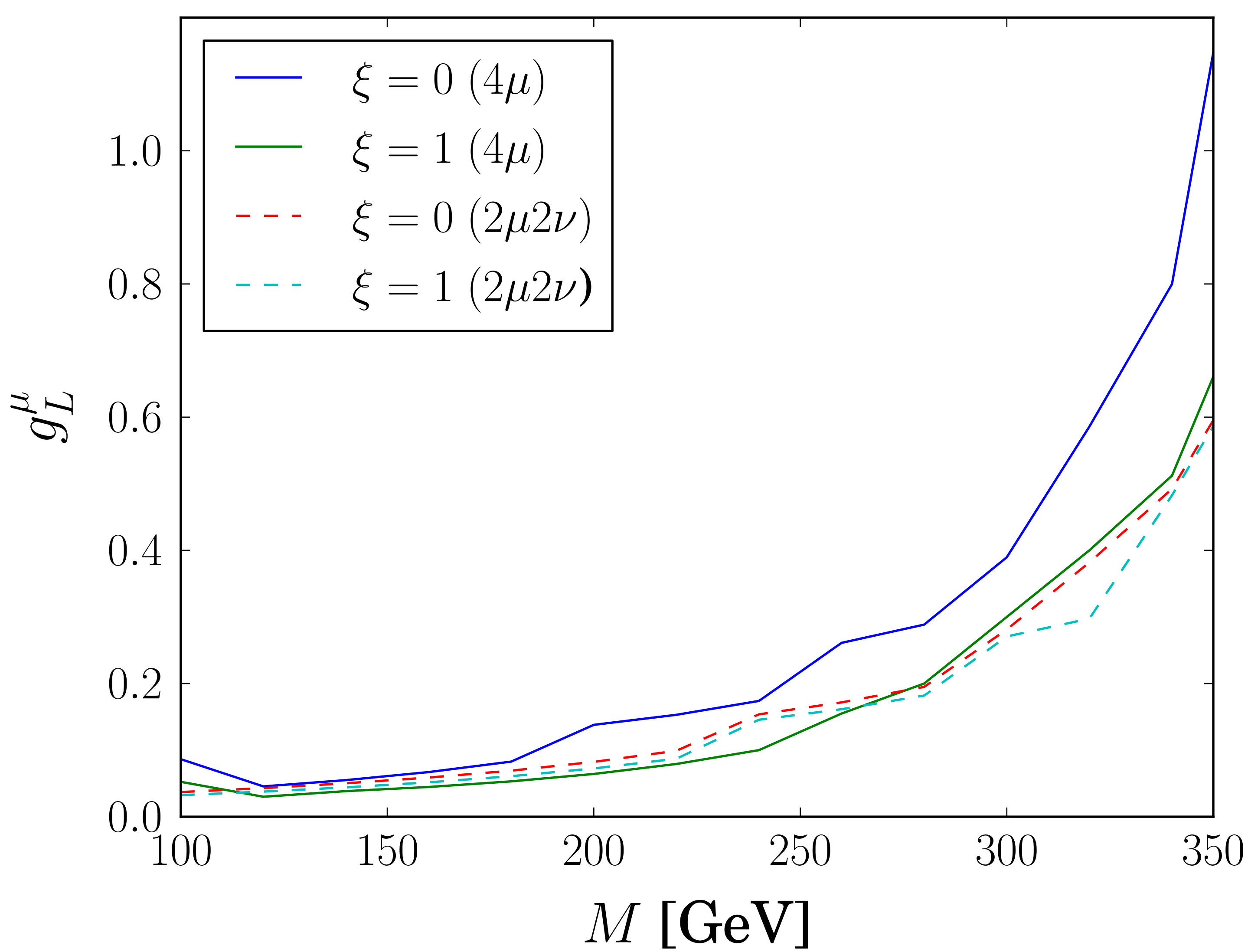
$2\mu 2\tau_{\rm h}$

$g'_{\rm L} \equiv g_{\rm L}^{\prime\mu}$

$g_{\rm L}^{\prime\tau}$

$\xi \equiv g_{\rm R}^{\prime\mu}/g_{\rm L}^{\prime\mu}$

$\xi_\tau g_{\rm L}^{\prime\tau}$



(depends on the value
of the Weinberg angle)

$$\sigma_{Z'}(e^+e^- \to 4\mu) \approx f_{4\mu}^{\prime\gamma+Z}(M_{Z'}) g_{\rm L}^{\prime 2}(1.15+\xi^2)\frac{g_{\rm L}^{\prime 2}(1+\xi^2)}{g_{\rm L}^{\prime 2}(2+\xi^2)+W^{i\neq\mu}}$$

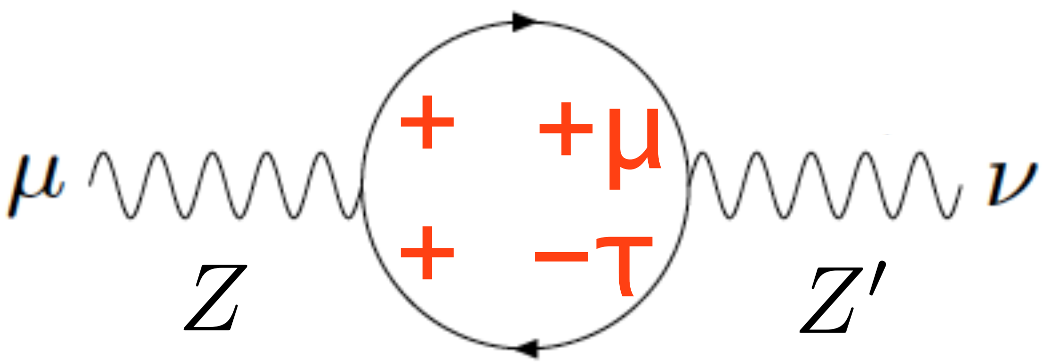
$$\sigma_{Z'\to\bar{\mu}\mu}(e^+e^- \to 2\mu + p^{\rm miss}) \approx f_{2\mu+p^{\rm miss}}^{\prime\gamma+Z}(M_{Z'})(g_{\rm L}^{\prime 2}+g_{\rm L}^{\prime\tau 2})\frac{g_{\rm L}^{\prime 2}(1+\xi^2)}{g_{\rm L}^{\prime 2}(2+\xi^2)+W^{i\neq\mu}}$$

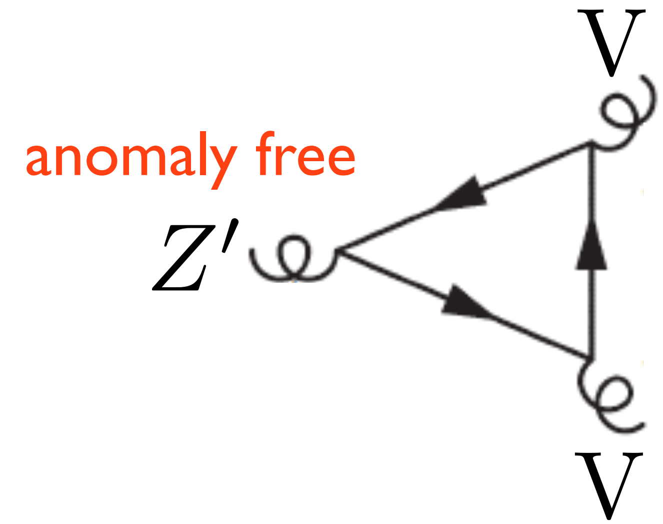
rather similar

$$\sigma_{Z'\to\bar{\nu}\nu}(e^+e^- \to 2\mu + p^{\rm miss}) \approx f_{2\mu+p^{\rm miss}}^{\prime\prime\gamma+Z}(M_{Z'}) g_{\rm L}^{\prime 2}(1.15+\xi^2)\frac{g_{\rm L}^{\prime 2}+g_{\rm L}^{\prime\tau 2}}{g_{\rm L}^{\prime 2}(2+\xi^2)+W^{i\neq\mu}}$$

$$\sigma_{Z'}(e^+e^- \to 2\mu + 2\tau_{\rm h}) \approx f_{2\mu+2\tau_{\rm h}}^{\prime\gamma+Z}(M_{Z'}) g_{\rm L}^{\prime\tau 2}(1.15+\xi_\tau^2)\frac{g_{\rm L}^{\prime 2}(1+\xi^2)}{g_{\rm L}^{\prime 2}(2+\xi^2)+W^{i\neq\mu}}$$

An arbitrary set of Z' couplings will generate a ZZ' mixing δ, except for the muon minus tau combination

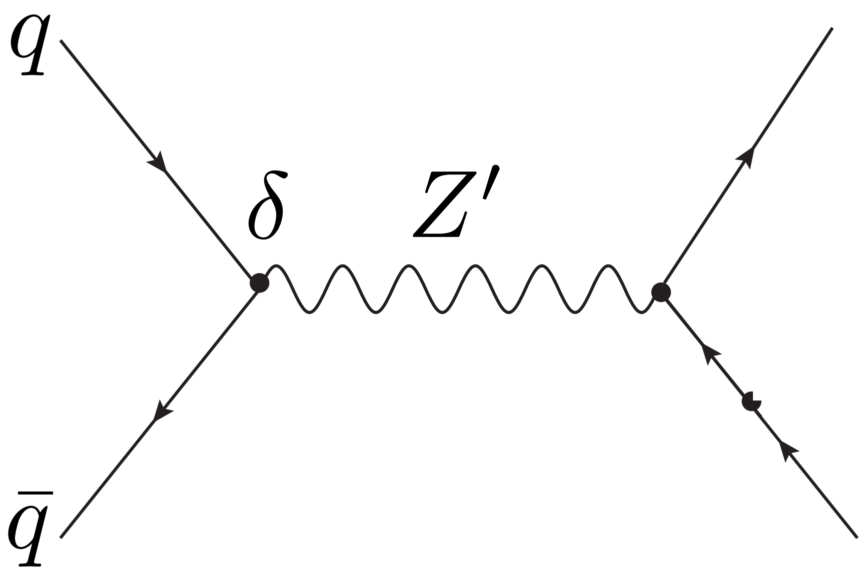




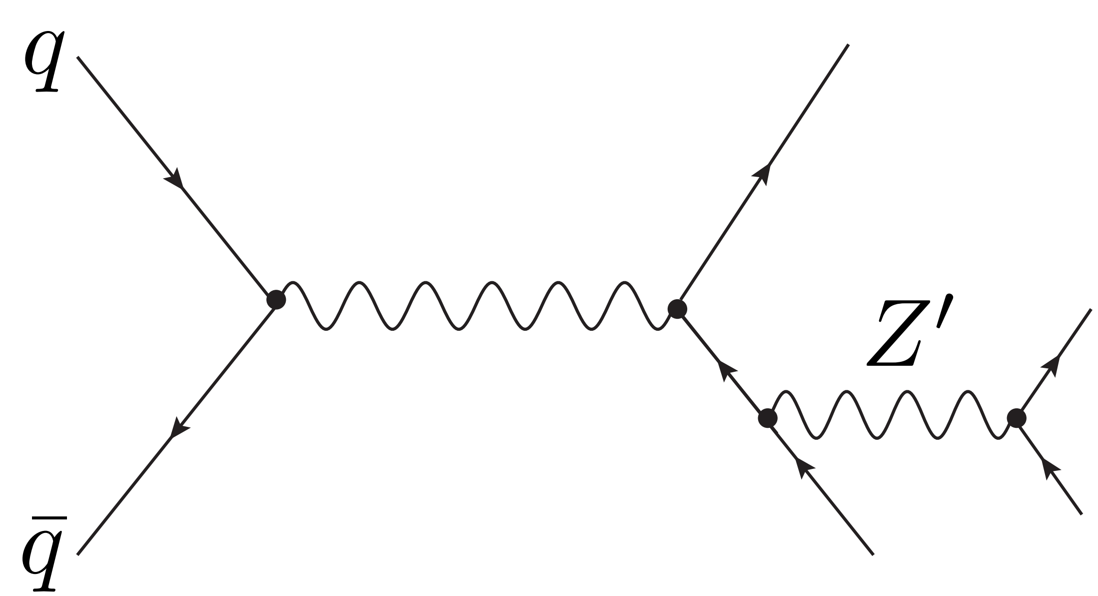
F. del Aguila, G.D. Coughlan and M. Quirós, NP B307 (1988) 633
B. Holdom PLB 259 (1991) 329
F. del Aguila, M. Masip and M. Pérez-Victoria, NP B456 (1995) 531

Although small (δ is squared in the cross-section $\sim \delta^2$) several orders of magnitude in precision give for relatively small values, too: Look in Drell-Yan for a relatively light Z' coupling only to muons with a coupling apparently quite small

$$q\bar{q} \to l\bar{l}$$

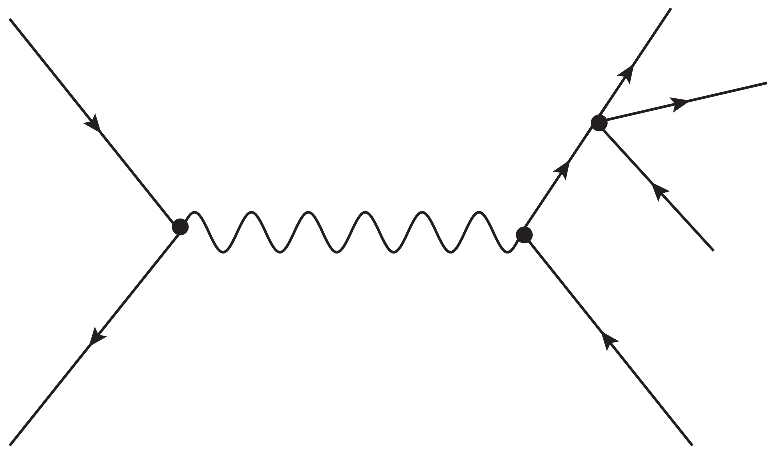


$$q\bar{q} \to V \to l\bar{l}Z' \to l\bar{l}'l''\bar{l}''$$



$$(\mathcal{O}_{LL}^{(1)})_{\mu\mu\mu\mu} = \tfrac{1}{2}(\overline{L_{\mathrm{L}\mu}}\gamma_\alpha L_{\mathrm{L}\mu})(\overline{L_{\mathrm{L}\mu}}\gamma^\alpha L_{\mathrm{L}\mu})$$
$$(\mathcal{O}_{LL}^{(1)})_{\mu\mu\tau\tau} = \tfrac{1}{2}(\overline{L_{\mathrm{L}\mu}}\gamma_\alpha L_{\mathrm{L}\mu})(\overline{L_{\mathrm{L}\tau}}\gamma^\alpha L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{LL}^{(1)})_{\mu\tau\mu\tau} = \tfrac{1}{2}(\overline{L_{\mathrm{L}\mu}}\gamma_\alpha L_{\mathrm{L}\tau})(\overline{L_{\mathrm{L}\mu}}\gamma^\alpha L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{LL}^{(1)})_{\tau\tau\tau\tau} = \tfrac{1}{2}(\overline{L_{\mathrm{L}\tau}}\gamma_\alpha L_{\mathrm{L}\tau})(\overline{L_{\mathrm{L}\tau}}\gamma^\alpha L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{ll})_{\mu\mu\mu\mu} = \tfrac{1}{2}(\overline{\mu_{\mathrm{R}}}\gamma_\alpha \mu_{\mathrm{R}})(\overline{\mu_{\mathrm{R}}}\gamma^\alpha \mu_{\mathrm{R}})$$
$$(\mathcal{O}_{ll})_{\mu\mu\tau\tau} = \tfrac{1}{2}(\overline{\mu_{\mathrm{R}}}\gamma_\alpha \mu_{\mathrm{R}})(\overline{\tau_{\mathrm{R}}}\gamma^\alpha \tau_{\mathrm{R}})$$
$$(\mathcal{O}_{ll})_{\mu\tau\mu\tau} = \tfrac{1}{2}(\overline{\mu_{\mathrm{R}}}\gamma_\alpha \tau_{\mathrm{R}})(\overline{\mu_{\mathrm{R}}}\gamma^\alpha \tau_{\mathrm{R}})$$
$$(\mathcal{O}_{ll})_{\tau\tau\tau\tau} = \tfrac{1}{2}(\overline{\tau_{\mathrm{R}}}\gamma_\alpha \tau_{\mathrm{R}})(\overline{\tau_{\mathrm{R}}}\gamma^\alpha \tau_{\mathrm{R}})$$
$$(\mathcal{O}_{Ll})_{\mu\mu\mu\mu} = (\overline{L_{\mathrm{L}\mu}}\mu_{\mathrm{R}})(\overline{\mu_{\mathrm{R}}}L_{\mathrm{L}\mu})$$
$$(\mathcal{O}_{Ll})_{\mu\mu\tau\tau} = (\overline{L_{\mathrm{L}\mu}}\mu_{\mathrm{R}})(\overline{\tau_{\mathrm{R}}}L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{Ll})_{\mu\tau\mu\tau} = (\overline{L_{\mathrm{L}\mu}}\tau_{\mathrm{R}})(\overline{\mu_{\mathrm{R}}}L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{Ll})_{\mu\tau\tau\mu} = (\overline{L_{\mathrm{L}\mu}}\tau_{\mathrm{R}})(\overline{\tau_{\mathrm{R}}}L_{\mathrm{L}\mu})$$
$$(\mathcal{O}_{Ll})_{\tau\mu\mu\tau} = (\overline{L_{\mathrm{L}\tau}}\mu_{\mathrm{R}})(\overline{\mu_{\mathrm{R}}}L_{\mathrm{L}\tau})$$
$$(\mathcal{O}_{Ll})_{\tau\tau\tau\tau} = (\overline{L_{\mathrm{L}\tau}}\tau_{\mathrm{R}})(\overline{\tau_{\mathrm{R}}}L_{\mathrm{L}\tau})$$

19 more with electrons



$\frac{g'^2}{\Lambda^2} <$ Few TeV^{-2} $\Rightarrow$ no

weakly coupled resonance interpretation $\Lambda \sim \mathrm{M}_{Z'}$
but phenomenological limits can be derived (although less stringent because the events do not accumulate around the new particle mass)

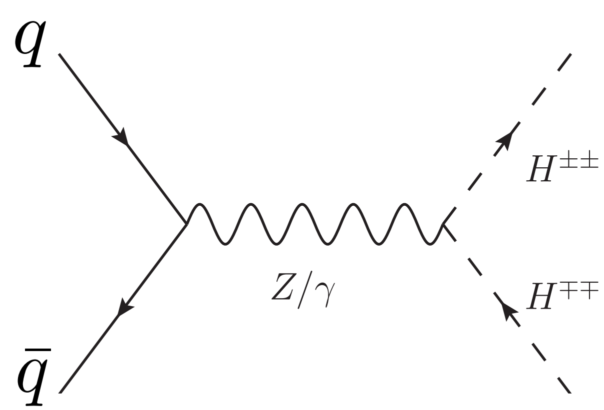
Once we allow for other new physics contributing to four-lepton operators, the other (resonant) possibility is a particle (which can be reconstructed) coupling to the doubly-charged channel ($|LN| = 2$)

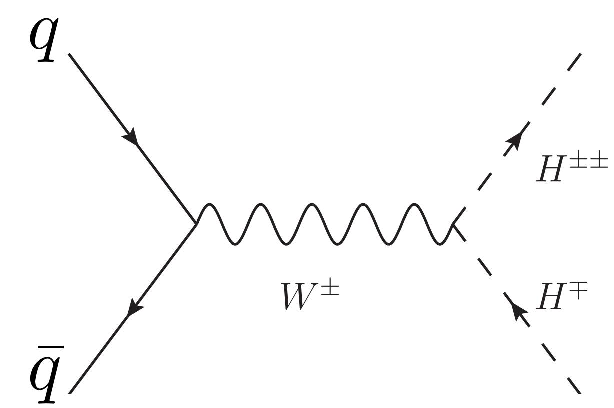
F. del Aguila, M. Chala, A. Santamaría and J. Wudka, PLB 725 (2013) 310
F. del Aguila and M. Chala, JHEP 1403 (2014) 027

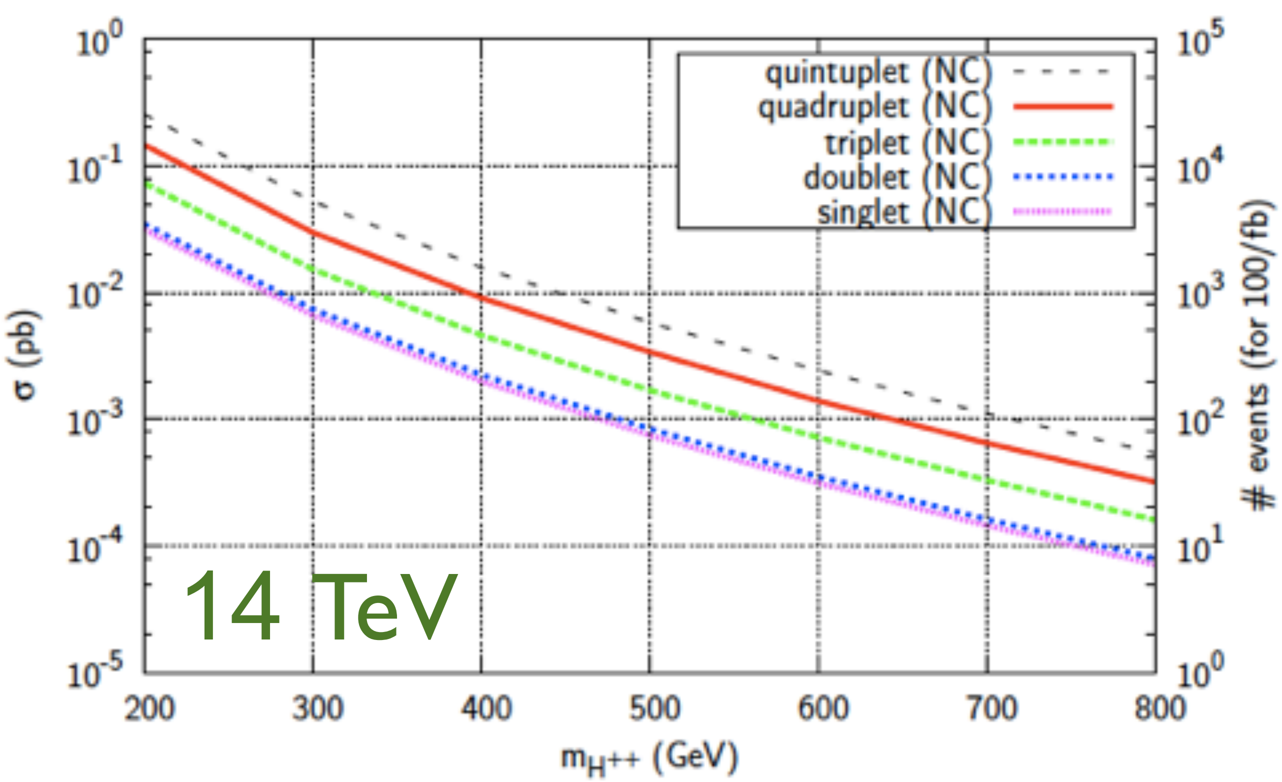
$$\text{Dimension 4} \left\{ \begin{array}{c|l} \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} & (\overline{\tilde{L}_L} \tau^a L_L)\Delta^{-a} \\ \kappa^{++} & \overline{l^c_R} l_R \kappa \end{array} \right.$$

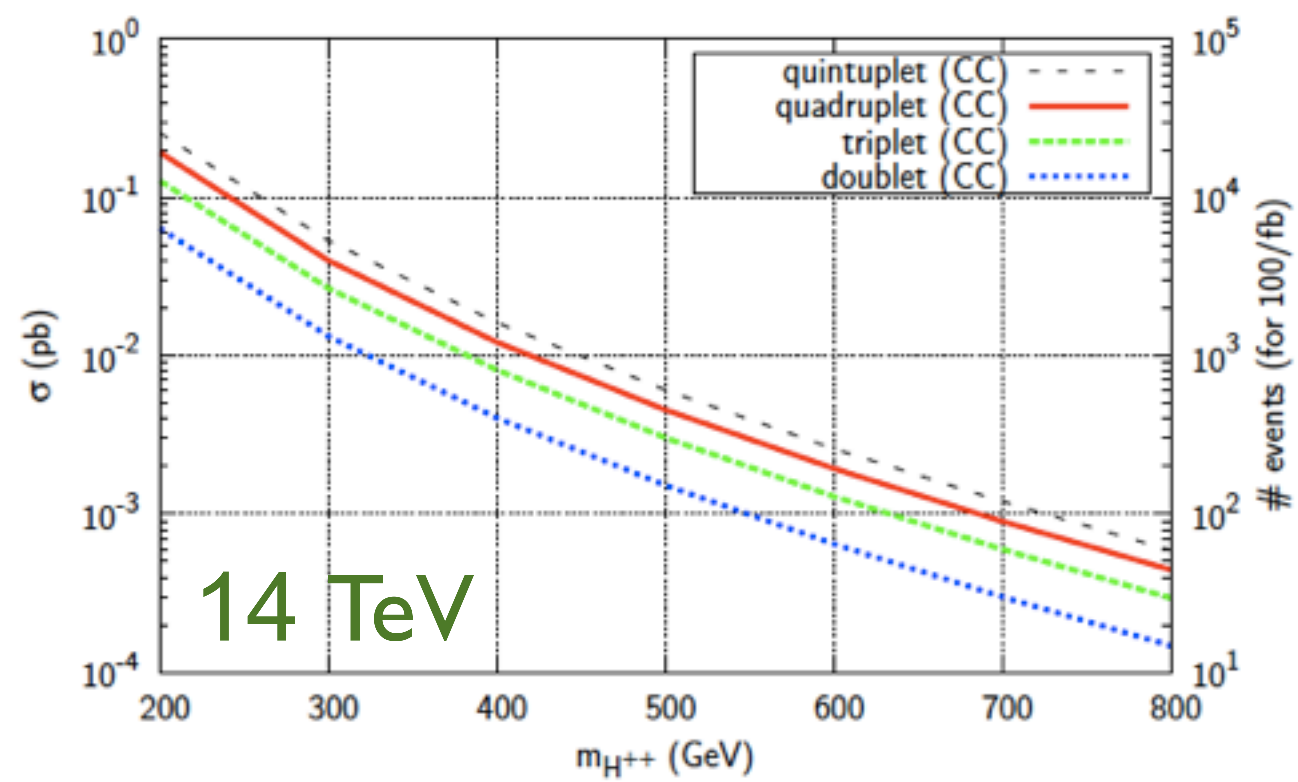
$$\overline{e^c_L} e_L H^{++}$$

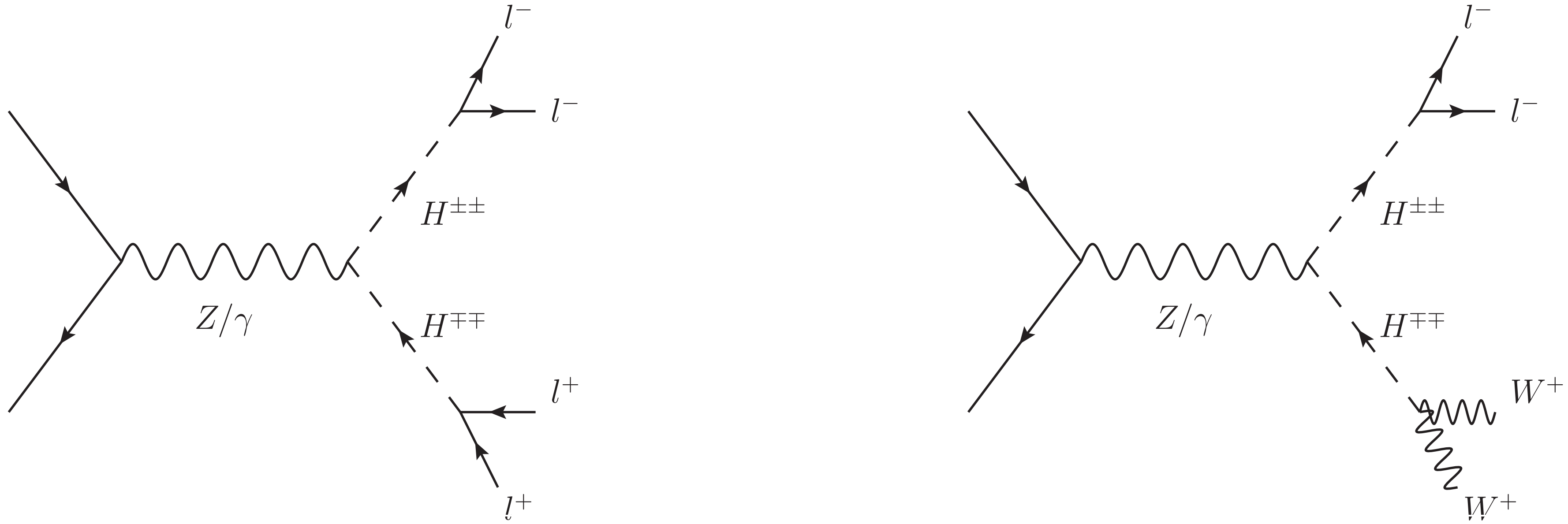
$$\overline{e^c_R} e_R H^{++}$$

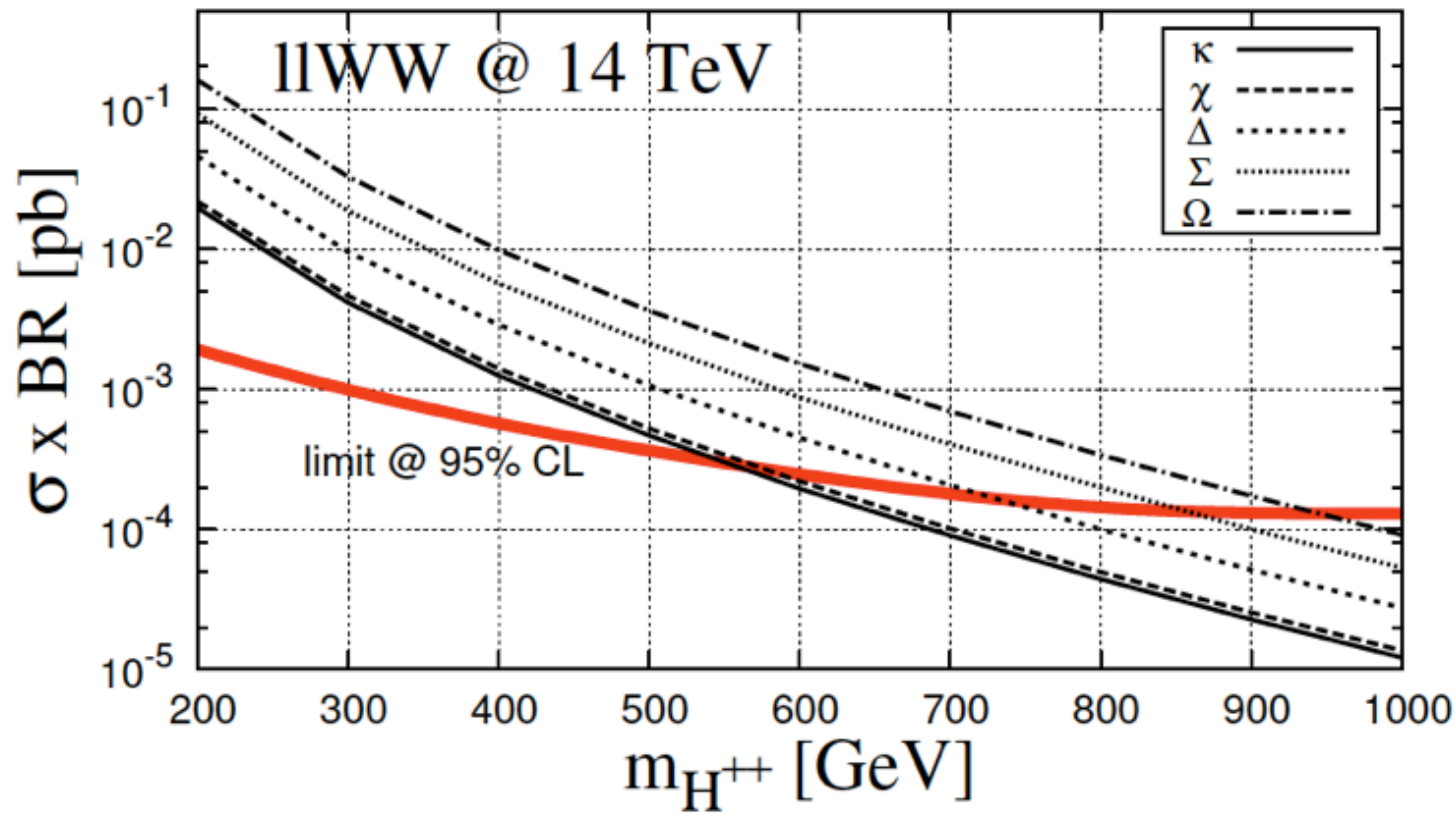








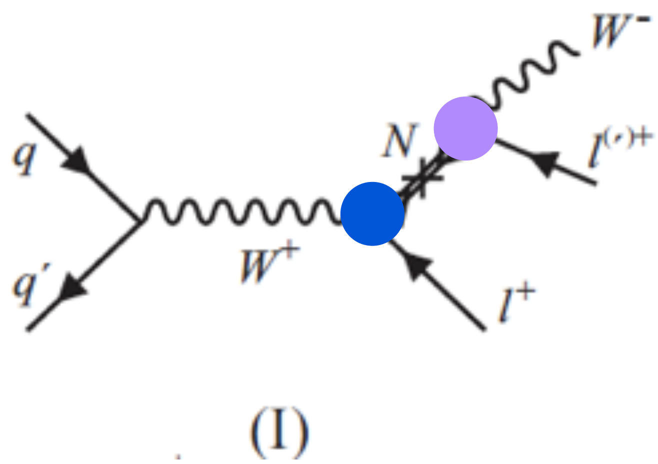




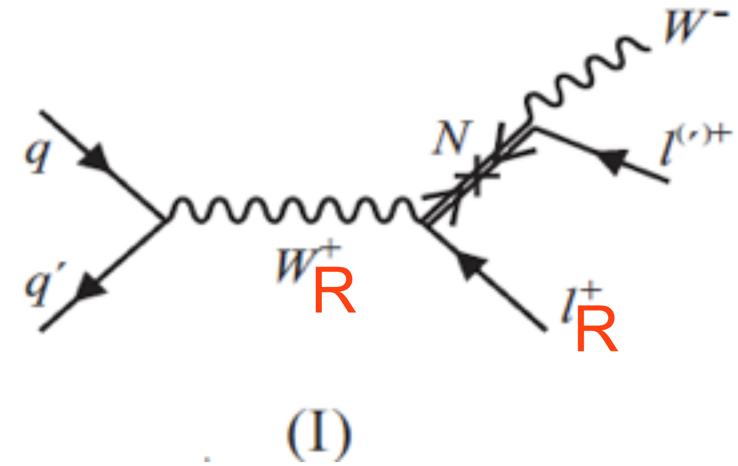
displaced vertices (μm)

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

When one allows for couplings to EW gauge bosons there are many other SM extensions with processes producing 4 leptons in the final state: mixing heavy neutrino (SUSY: sleptons, RPV, ...)



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



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

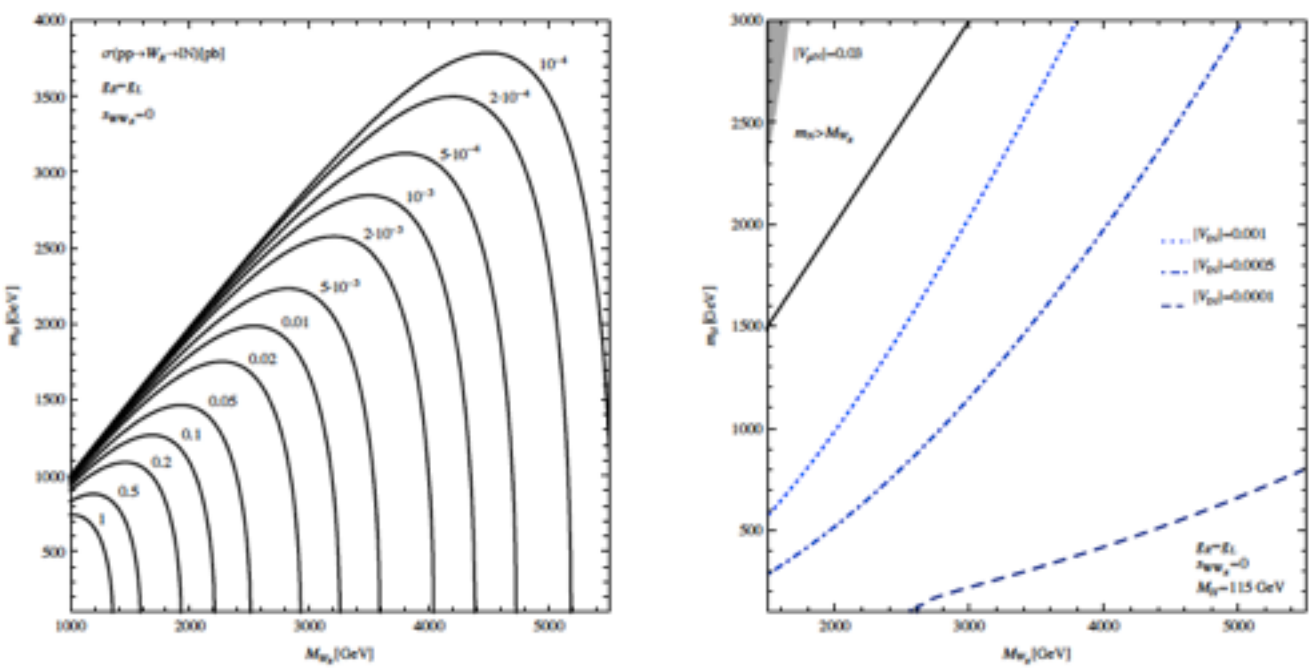


Fig. 2. Left: $pp \to W_R \to lN$ cross section at LHC. Right: N decay branching ratio to W_R^* and SM bosons (see the text).

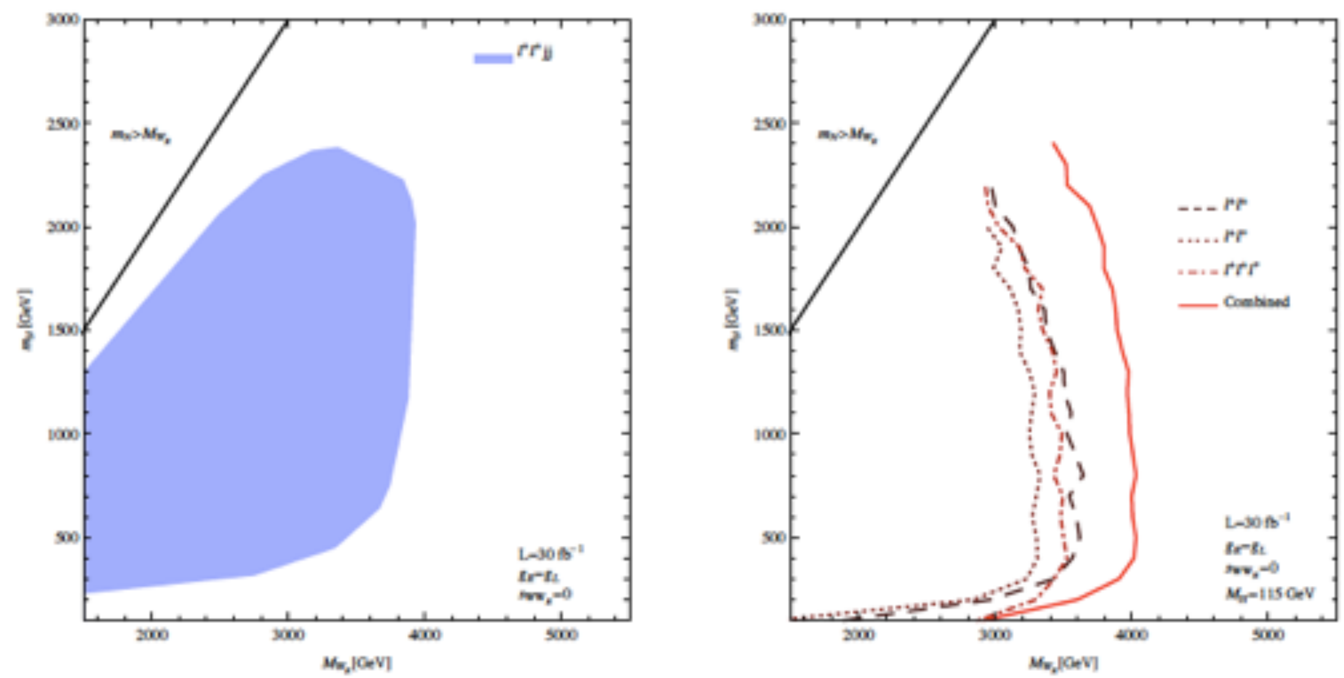
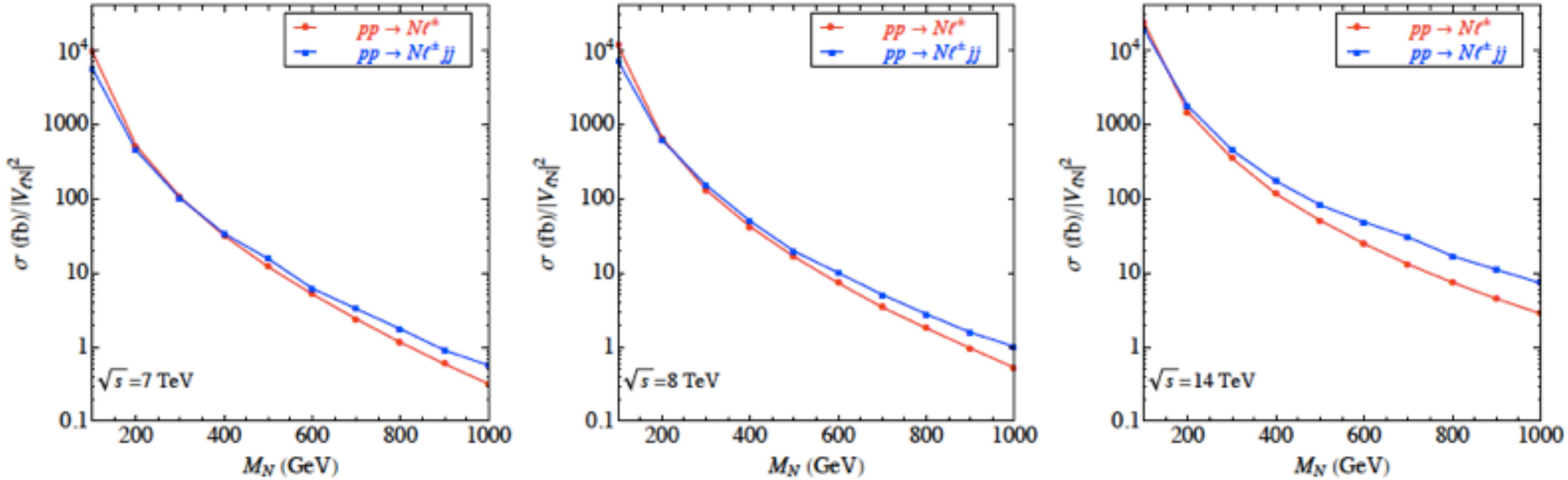
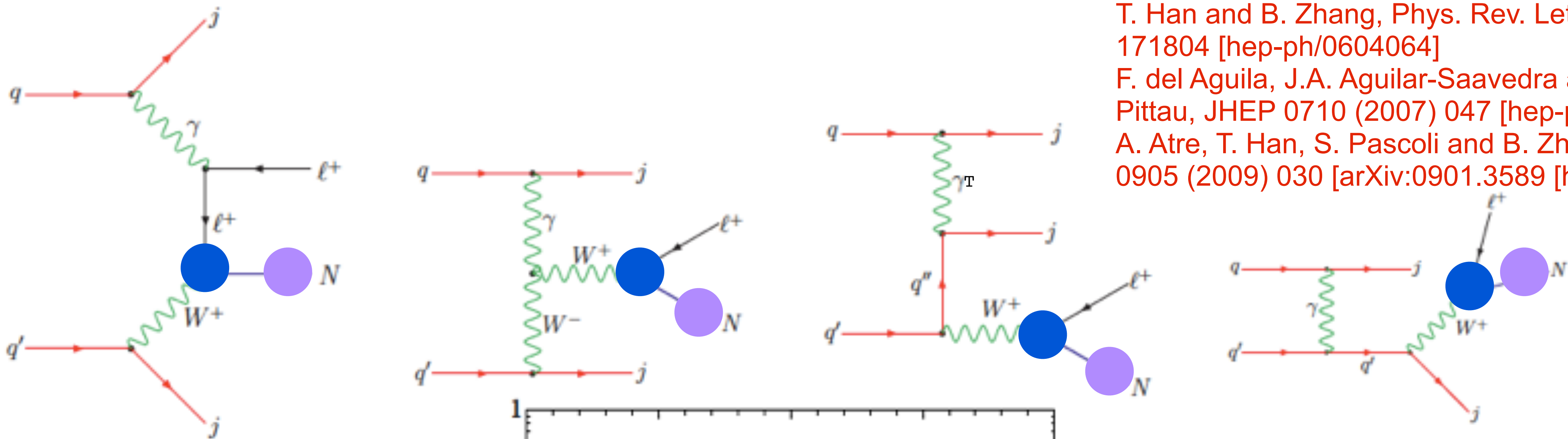


Fig. 3. Left: Discovery limits for 30 fb^{-1} as a function of M_{W_R} and m_N, assuming that N only decays into $l^\pm W_R^* \to ljj$, from Ref. [11]. Right: The same, assuming that N decays into SM bosons.

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

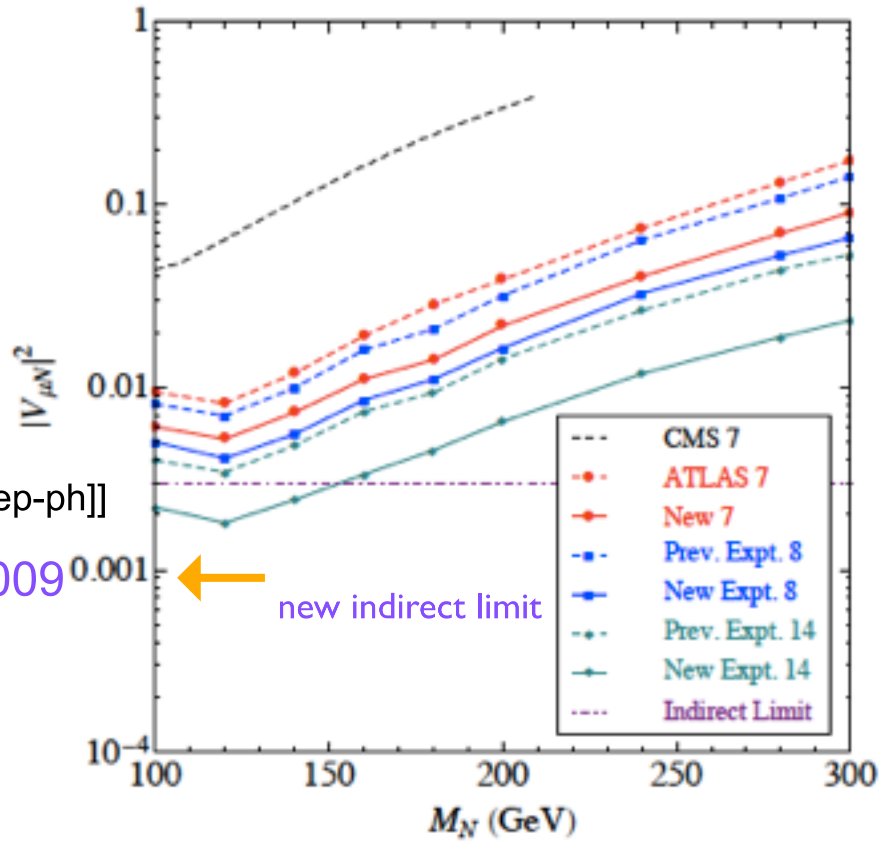


T. Han and B. Zhang, Phys. Rev. Lett. 97 (2006) 171804 [hep-ph/0604064]
F. del Aguila, J.A. Aguilar-Saavedra and R. Pittau, JHEP 0710 (2007) 047 [hep-ph/0703261]
A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905 (2009) 030 [arXiv:0901.3589 [hep-ph]]



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



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

Summary

- The excellent agreement of the LHC data with the SM predictions indicates that any NP waiting for being discovered can not produce large departures from these predictions, implying that the new processes must have relatively small cross sections. What is always possible reducing the couplings or increasing the masses of the new spectrum.

- One may then wonder if there are SM additions involving new particles with small cross sections at the LHC but large couplings and low masses. A candidate is NP coupling only to leptons (LEPTOPHILIC), and maybe also to electro-weak (EW) bosons. The cross sections in this case are at most of few fb, with coupling order 1 and masses several hundreds of GeV.

- For the same token we can ask if such a NP can be better explored at the ILC. In this case processes involving taus can emerge from the background only at the ILC -which provides another example, besides the Higgs boson, of the **complementarity** of LHC and ILC- but the reach is only comparable to the LHC for new particles with low masses.

EISA

European Institute for Sciences and Their Applications

Thank for your attention

CENTRO ANDALUZ DE FISICA DE PARTICULAS ELEMENTALES

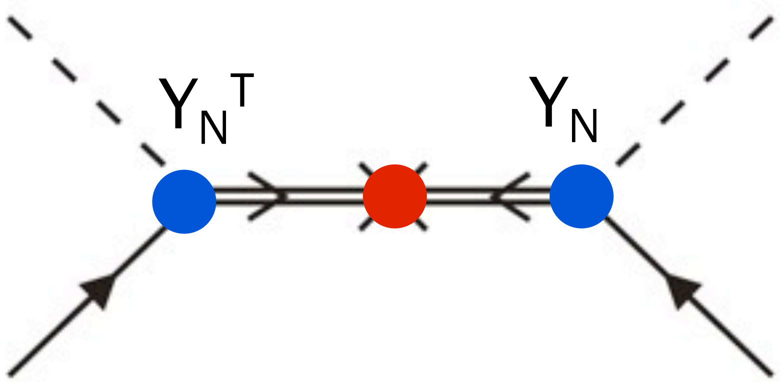
Universidad de Granada

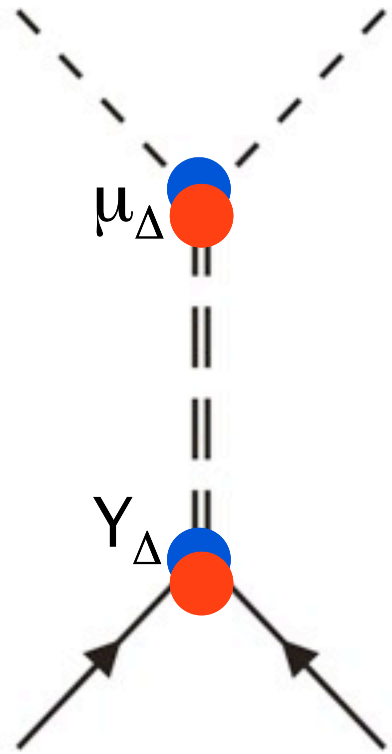
$$(m_\nu)_{ij} = x_{ij} v^2/\Lambda \sim 0.1\,\mathrm{eV}$$

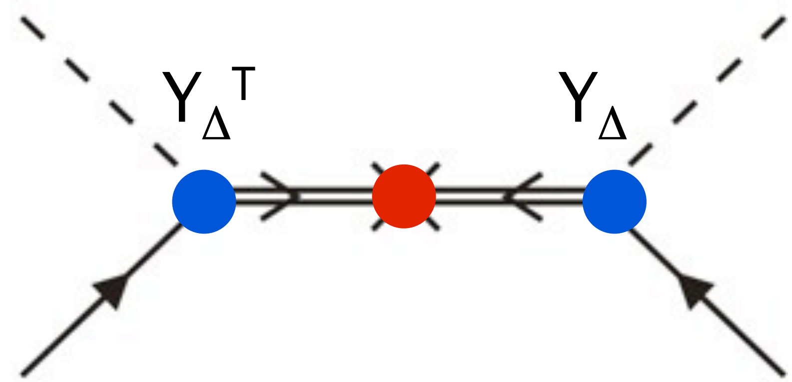
$$\mathcal{O}^{(5)} = (\overline{L_L^c}\tilde{\phi}^*)(\tilde{\phi}^\dagger L_L)$$

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

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







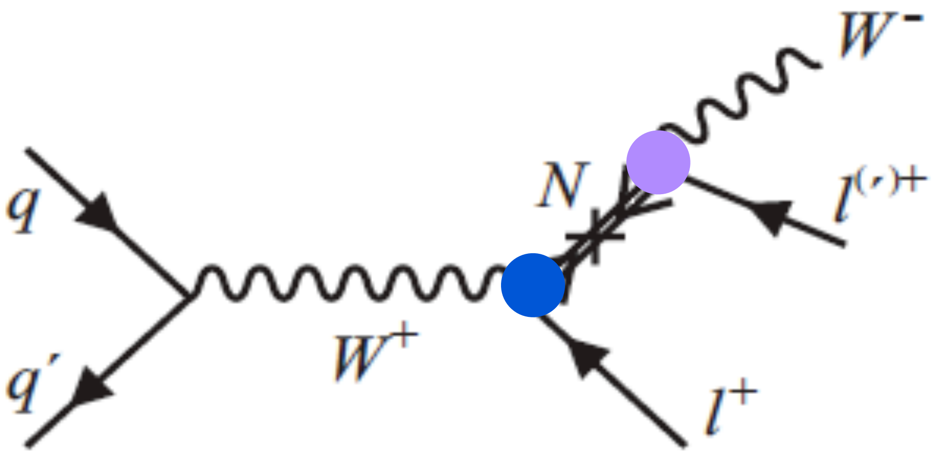
$^1/_2 Y_N^T M_N^{-1} Y_N$ — Phase cancellation or small couplings

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

$^1/_2 Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$ — 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



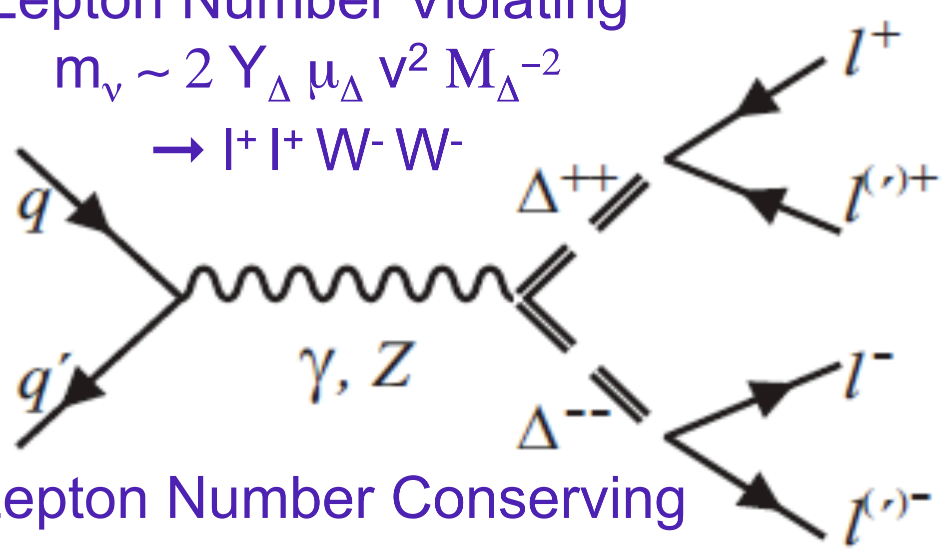
(I)

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

Lepton Number Violating

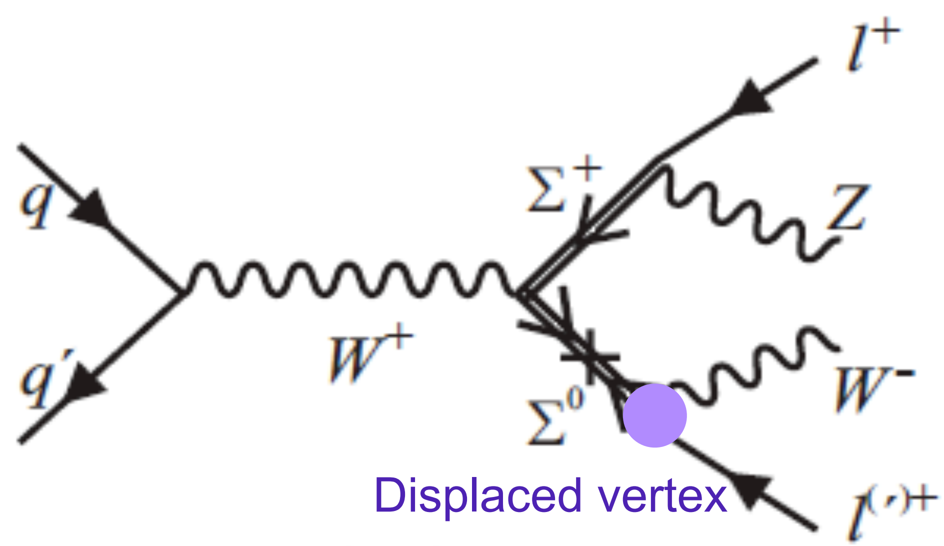
$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$

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



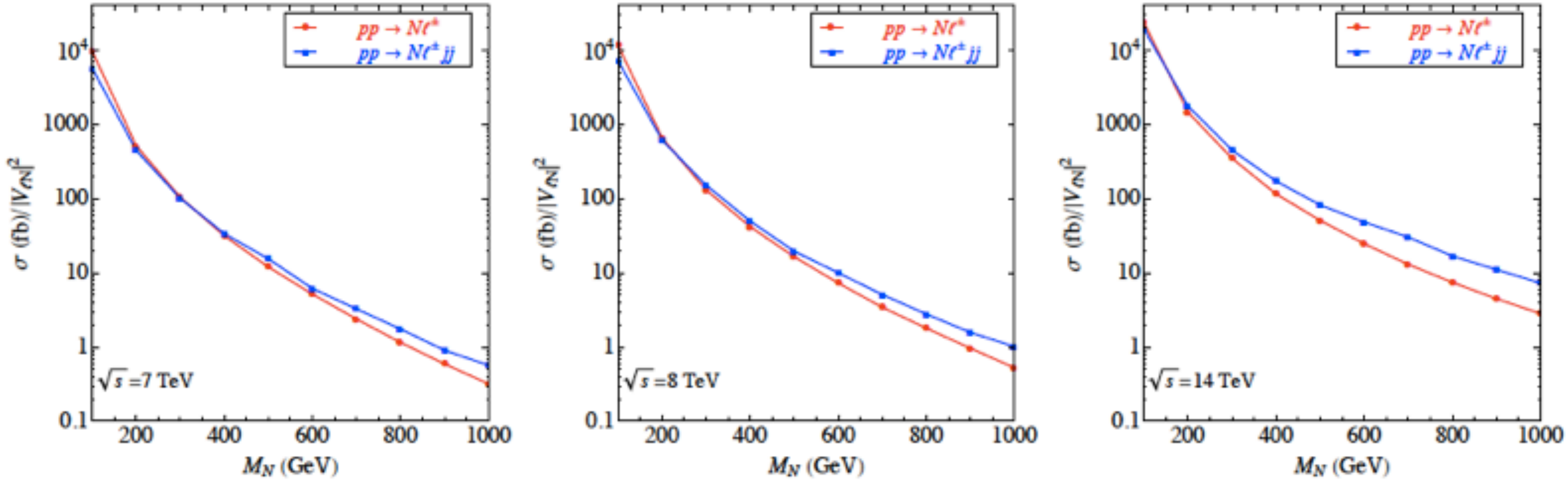
Lepton Number Conserving

(II)



(III)

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



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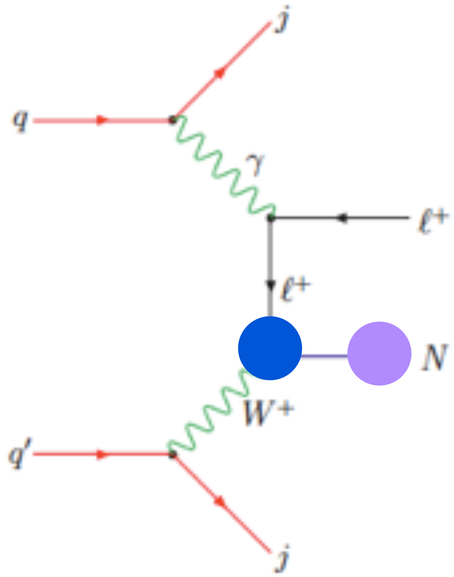
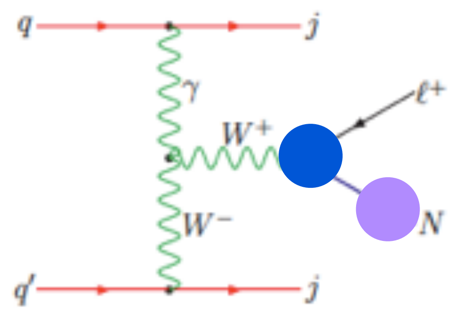
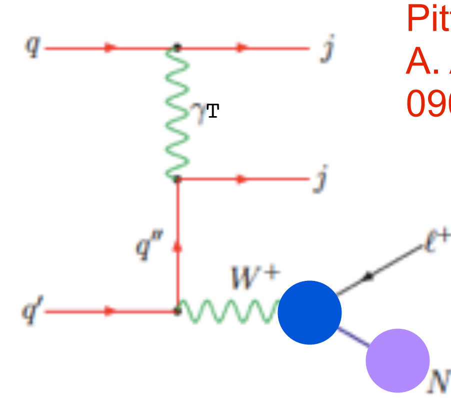
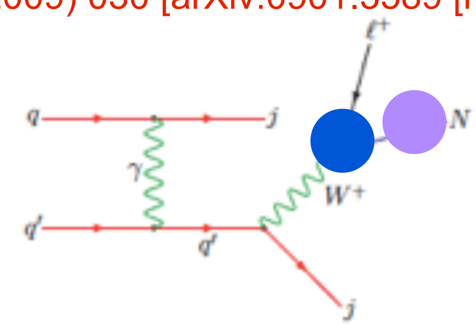
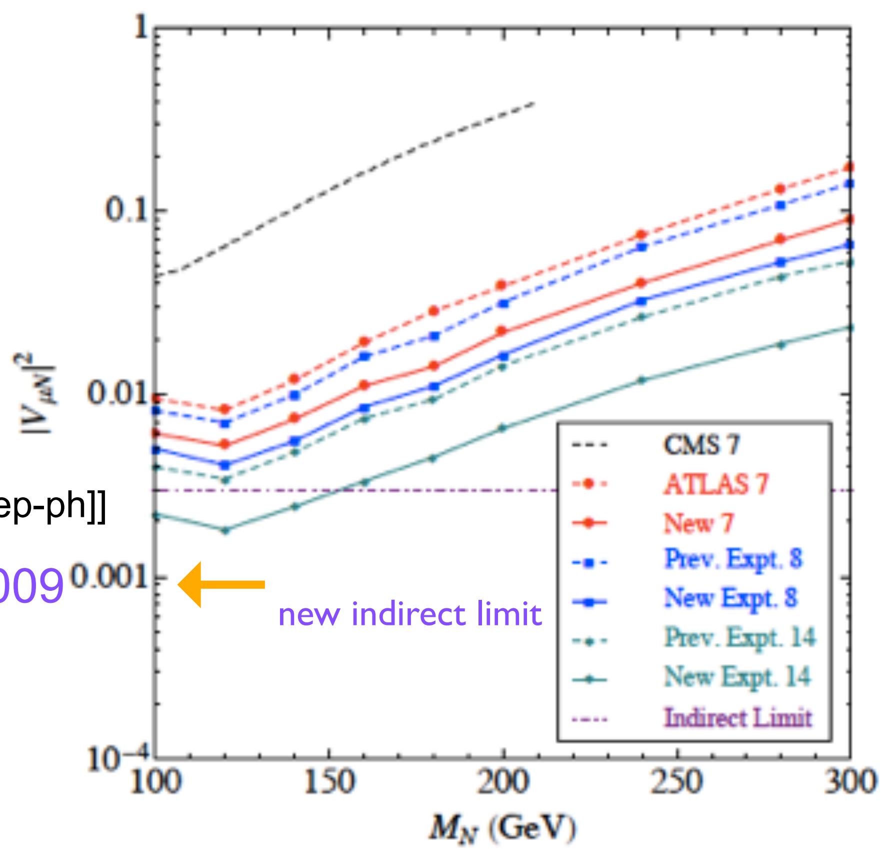






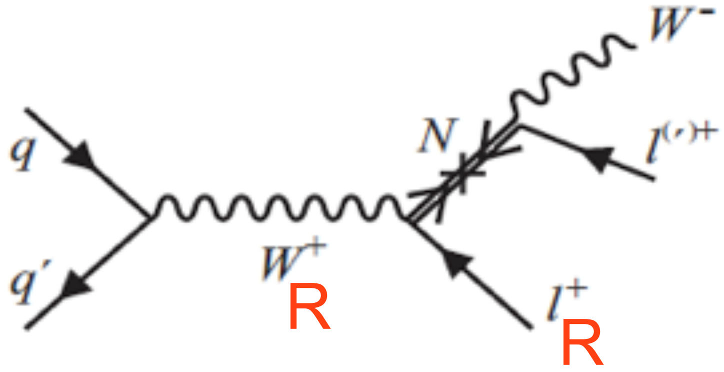




P.S.B. Dev, A. Pilaftsis and U. Yang, arXiv:1308.2209 [hep-ph]

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

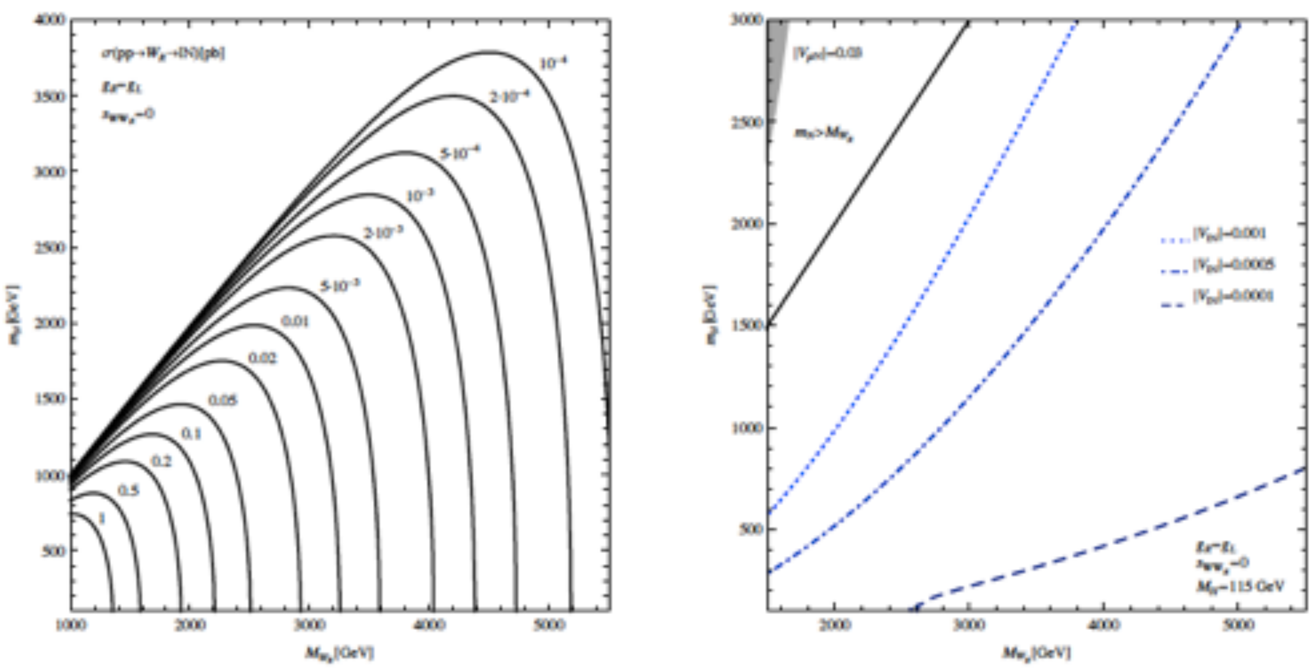


Fig. 2. Left: $pp \to W_R \to lN$ cross section at LHC. Right: N decay branching ratio to W_R^* and SM bosons (see the text).

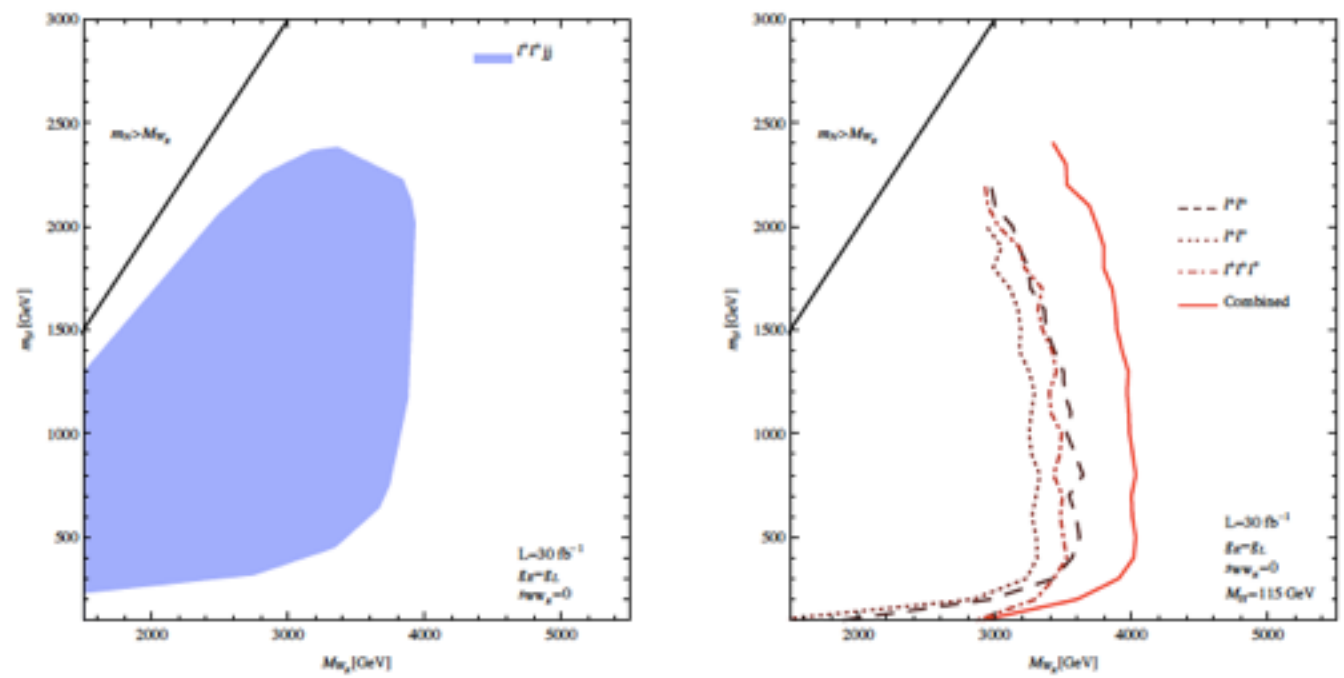


Fig. 3. Left: Discovery limits for 30 fb^{-1} as a function of M_{W_R} and m_N, assuming that N only decays into $l^\pm W_R^* \to ljj$, from Ref. [11]. Right: The same, assuming that N decays into SM bosons.

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

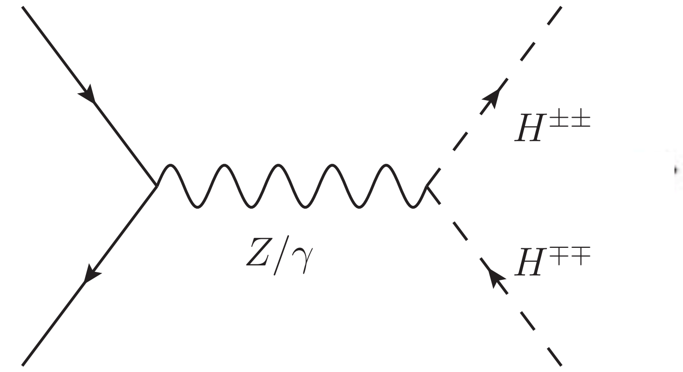
CMS and ATLAS have set stringent limits on doubly-charged scalars $H^{\pm\pm}$ decaying into two same-sign leptons ~ 400 GeV with only 5 fb^{-1} at 7 TeV.

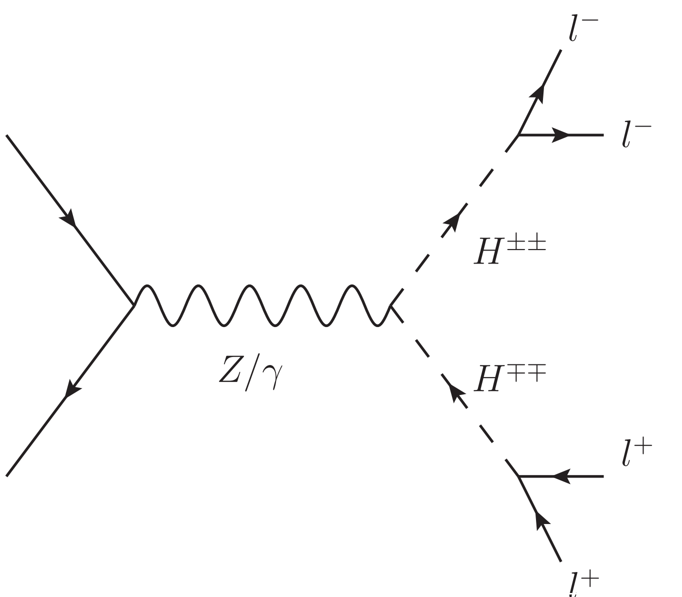
But they very much depend on the assumed di-leptonic branching ratios, in particular, into τs, and especially into gauge bosons. For instance, if the new scalar muliplet has a neutral component getting a v.e.v., through the gauge coupling $g^2\langle H^0\rangle H^{++}W^-W^-$. On the other hand, if both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

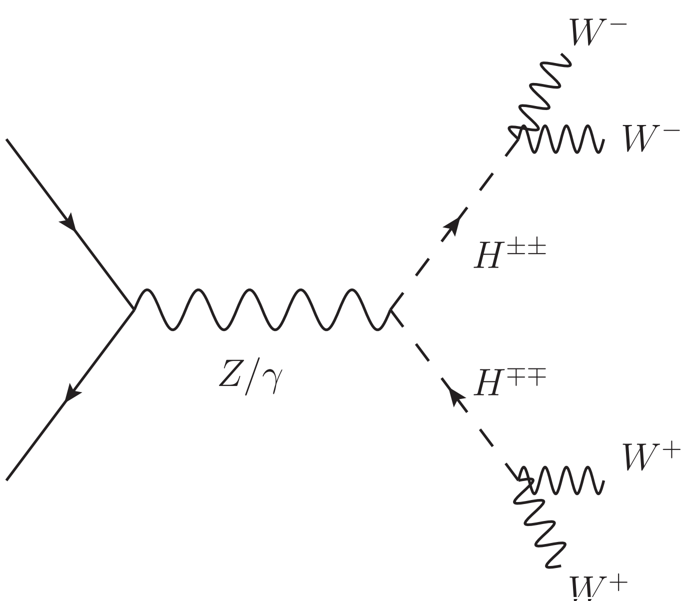
- The most popular Standard Model extension of this class is the see-saw of type II with a heavy scalar triplet (Δ^{++} Δ^+ Δ^0) giving Majorana masses to neutrinos.
- Present limits on di-lepton decays can be easily extrapolated to LNV processes.
- But H++ can be a component of a generic scalar multiplet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

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

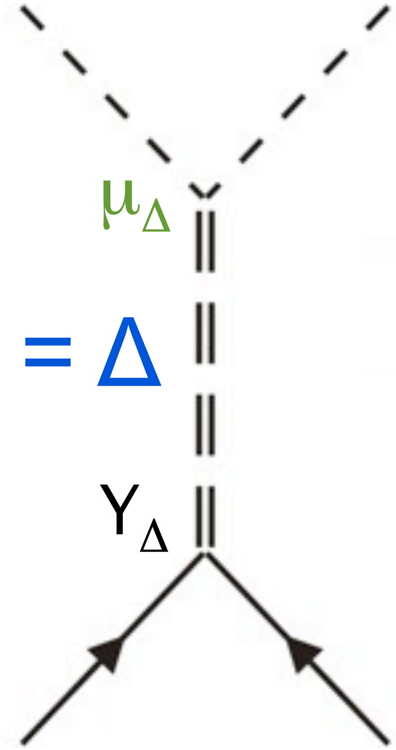
- What can be determined sampling appropriately 4 and 3 isolated lepton signals because their production rate does depend on T and Y.







H = Δ

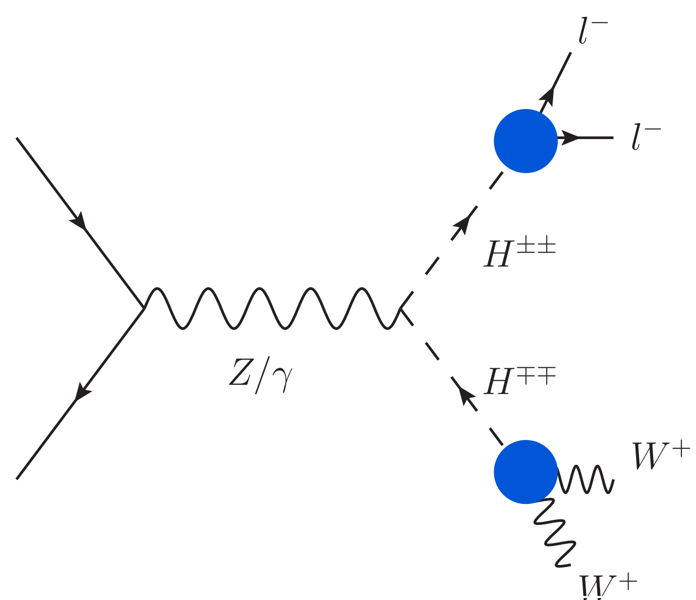


$g^2 \boxed{< \Delta^0 >} W^{\mp\mu} W^{\mp}_{\mu} \Delta^{\pm\pm}$

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

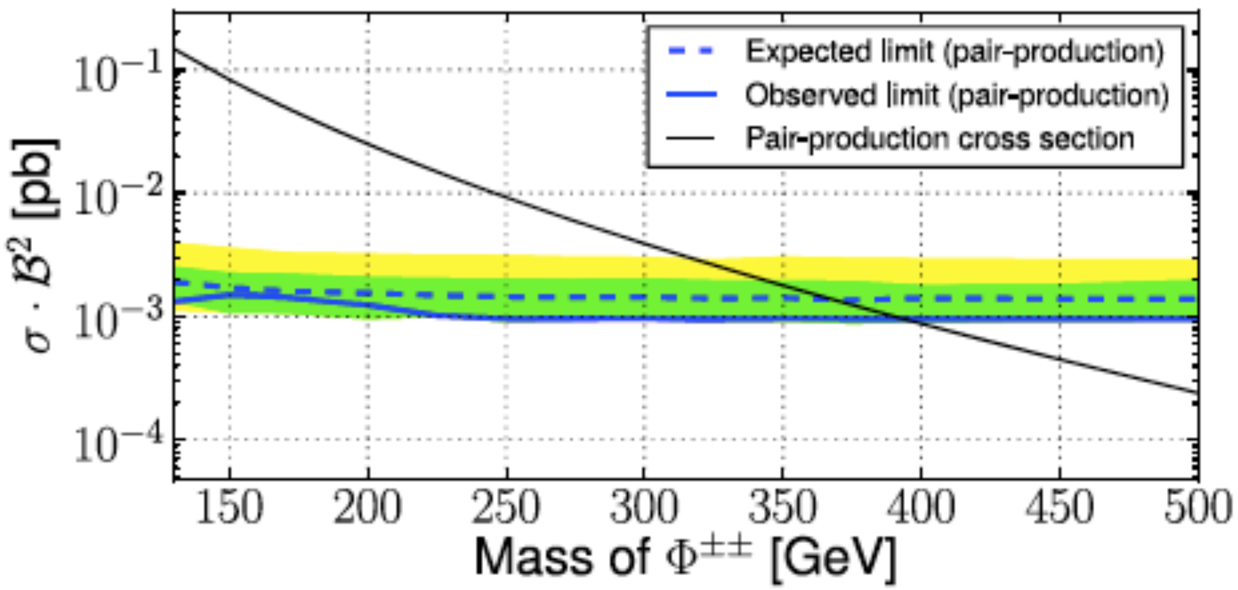
$-2Y_\Delta \mu_\Delta v^2 M_\Delta^{-2} \sim$ meV with $\boxed{\sqrt{2} <\Delta^0> = \mu_\Delta v^2 M_\Delta^{-2}}$

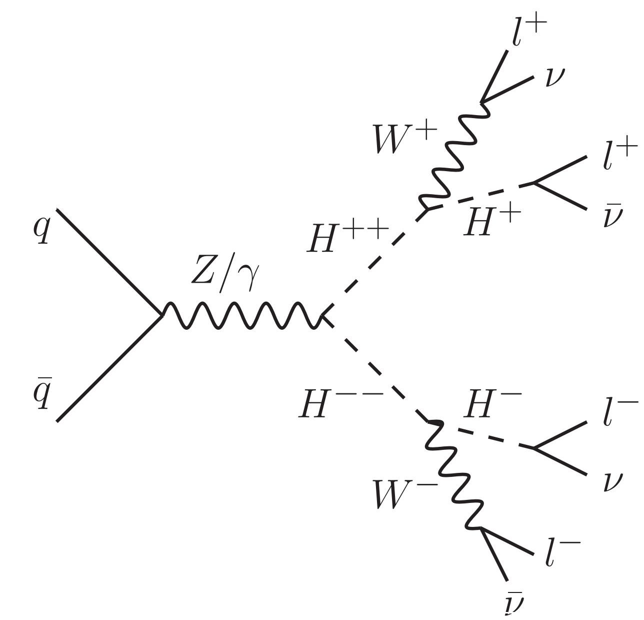
if $M_\Delta \sim$ TeV: $Y_\Delta \mu_\Delta \sim 10^{-11}$ GeV



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

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]

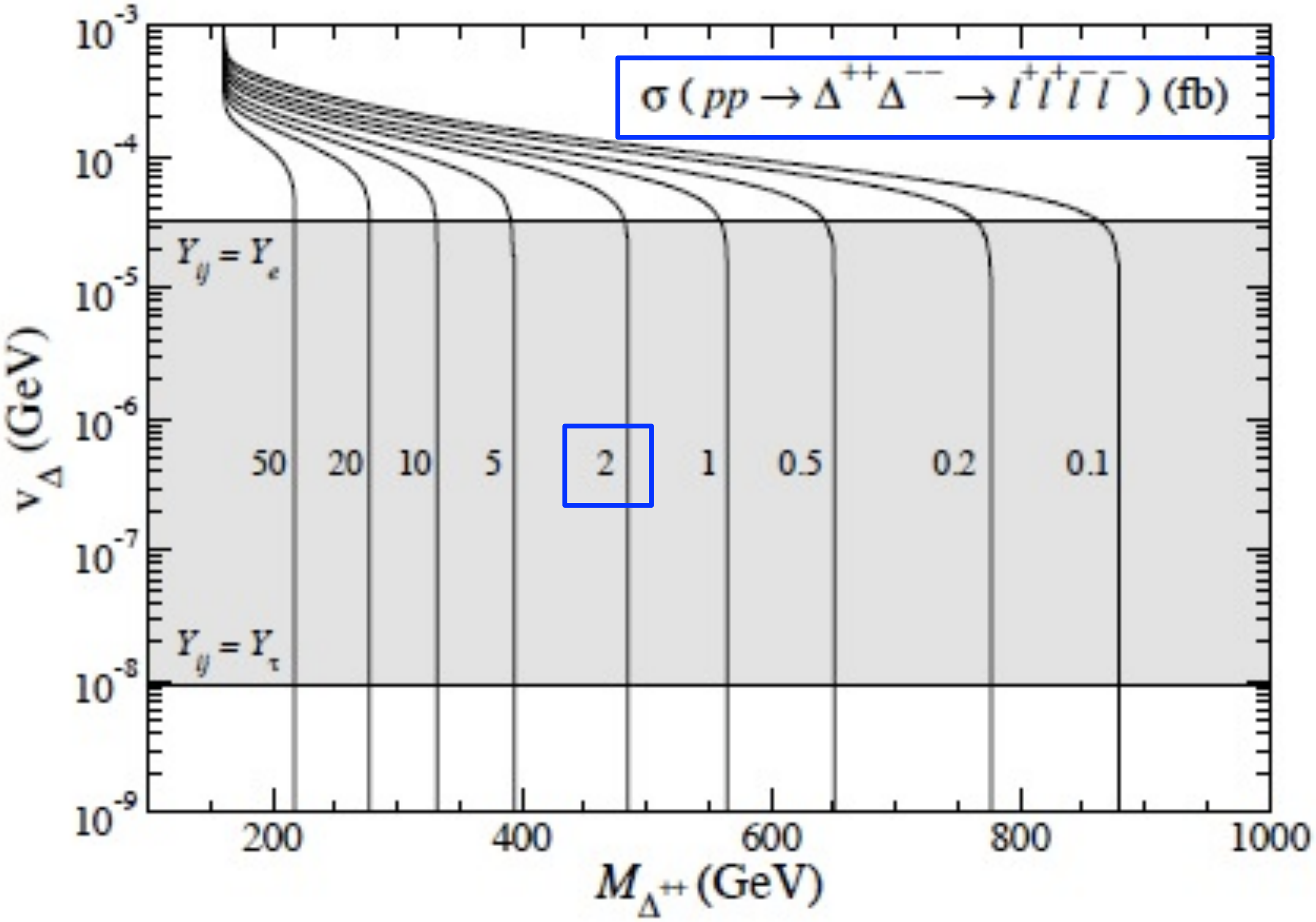
	6ℓ	5ℓ	$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^\pm$	$\ell^\pm\ell^\pm\ell^\mp$	$\ell^\pm\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm$
Σ (M)	0.6	10.6	17.4	55.7	10.2	110.3	177.8	178.7	232.4
Σ (D)	1.9	21.4	9.1	173.4	2.9	194.4	4.4	607.0	314.9
SM Bkg	0.0	0.9	2.5	14.3	1.9	15.9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

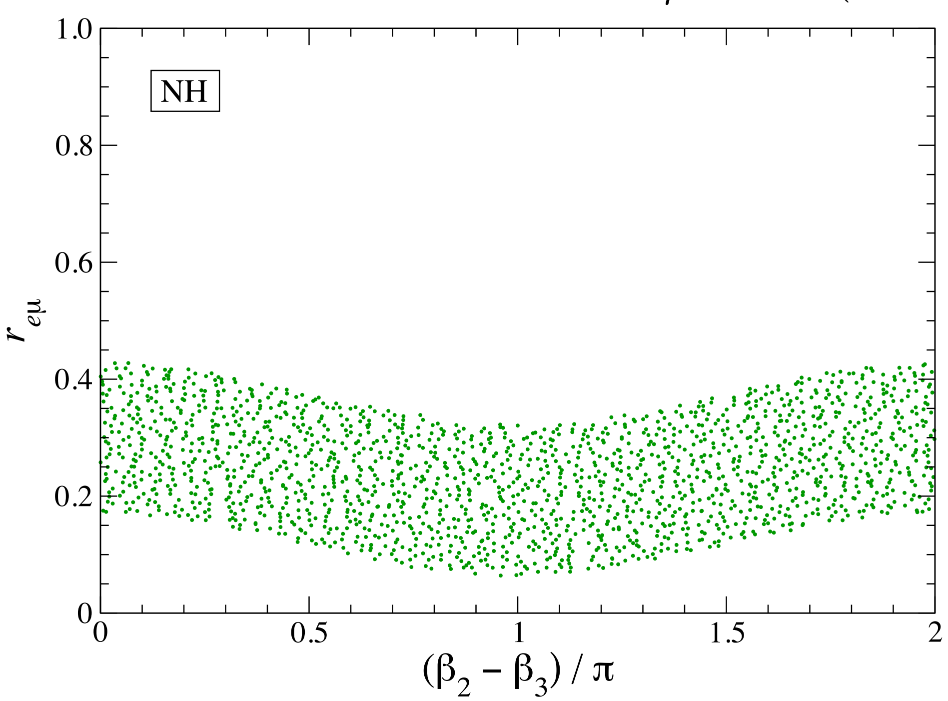
Lepton Number Violating
$m_\nu \sim 2\, Y_\Delta\, \mu_\Delta\, v^2\, M_\Delta^{-2}$
$\rightarrow l^+ l^+ W^- W^-$

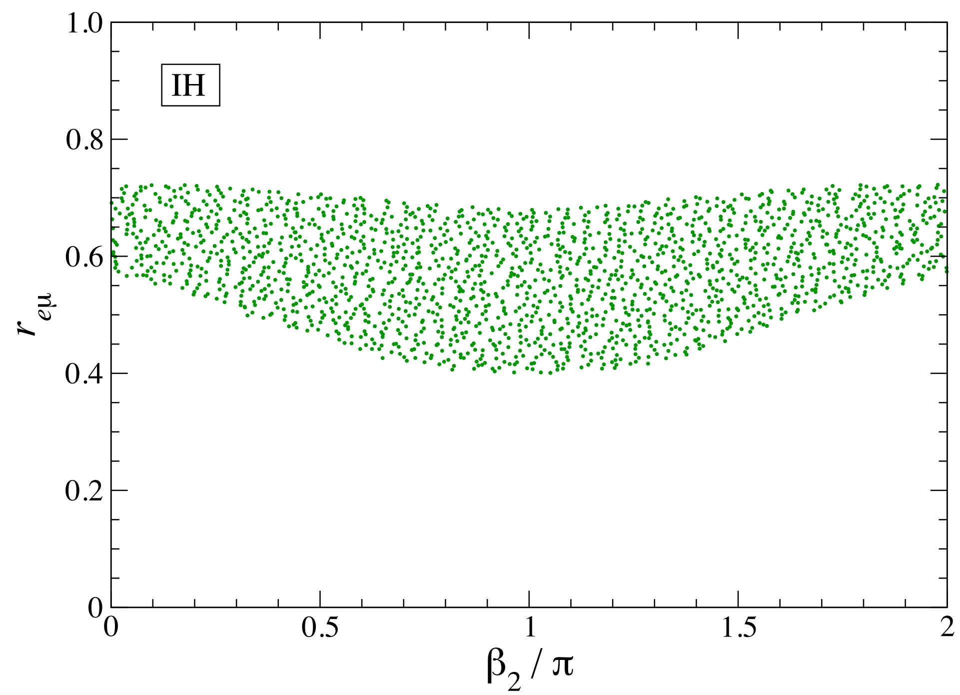
$$v_\Delta = \frac{v^2 |\mu_\Delta|}{\sqrt{2} M_\Delta^2} < 2 \text{ GeV}$$ EWPD

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).

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





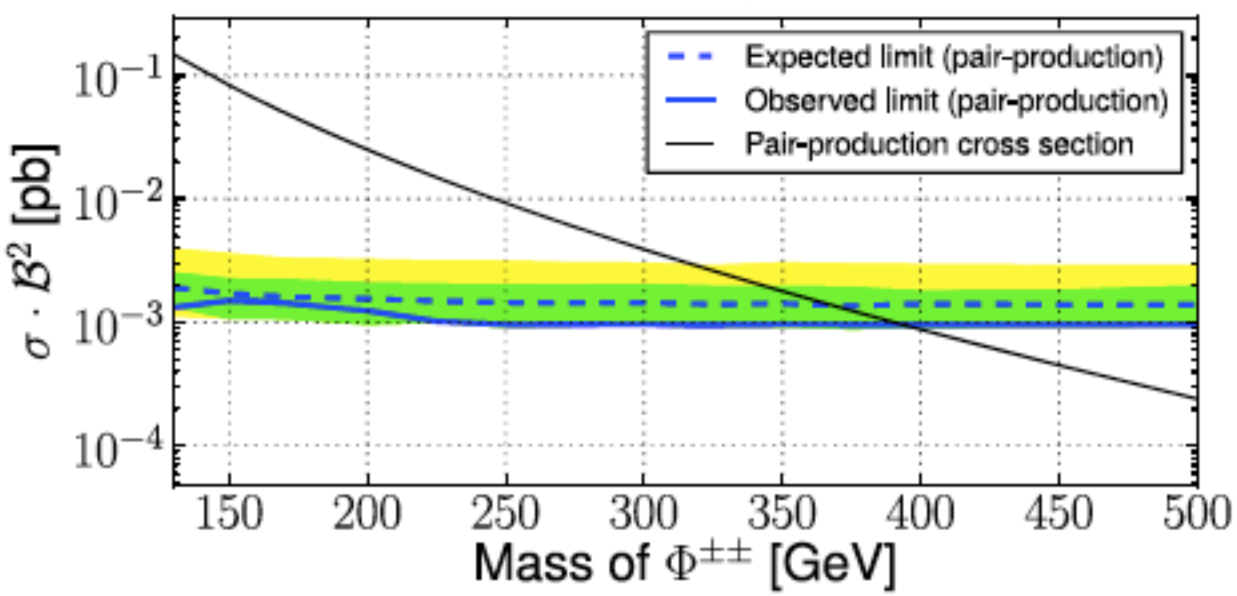
--- K.S. Babu, Phys. Lett. B 203 (1988) 132

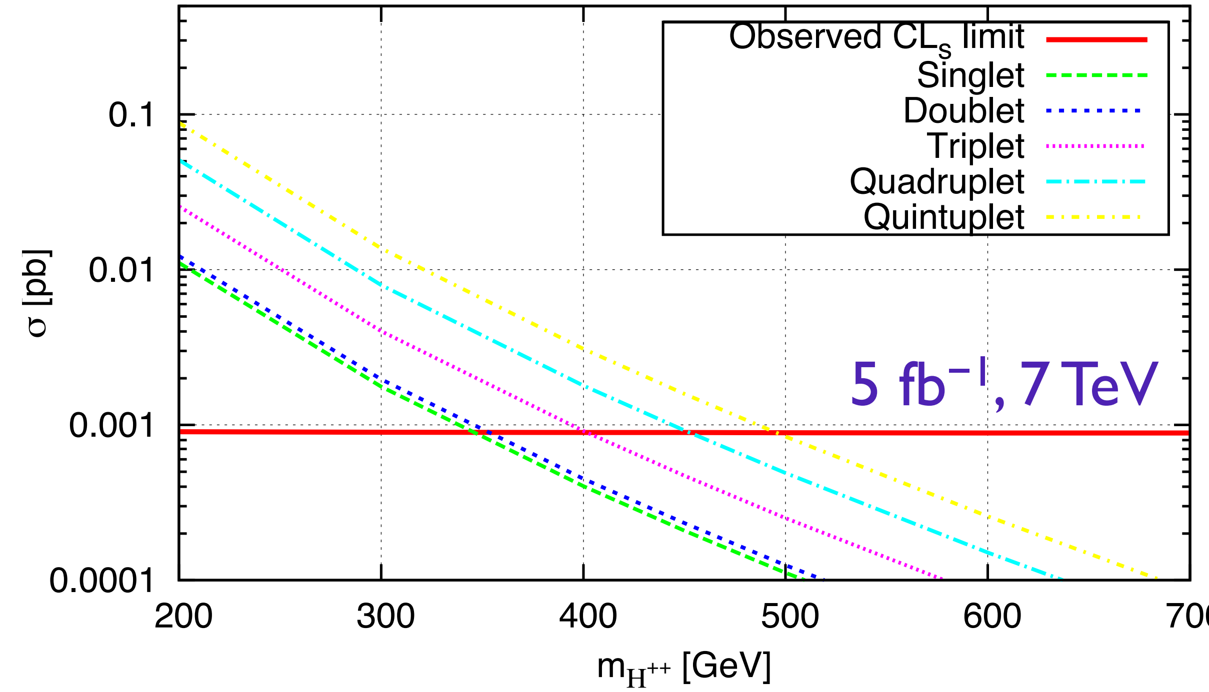
--- F.A., A. Aparici, S. Bhattacharya, A. Santamaria and J. Wudka, JHEP 1205 (2012) 133 [arXiv:1111.6960 [hep-ph]]

-·- 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: $\sqrt{3}/2 \to \sqrt{2}$

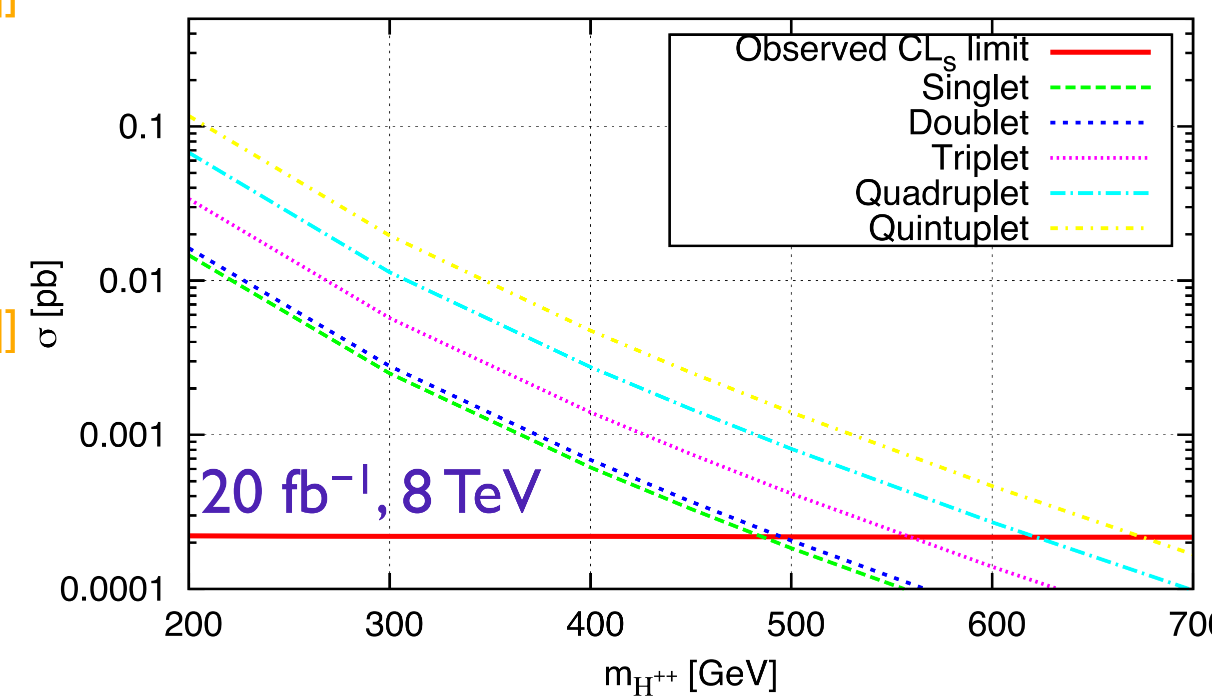
e and μ only



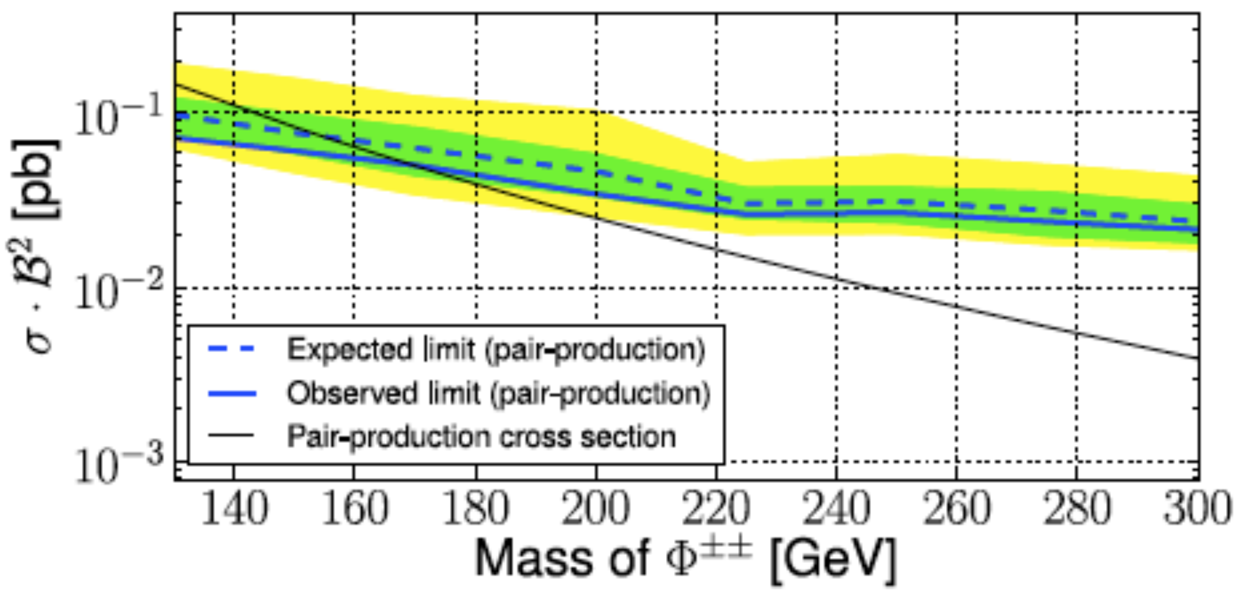


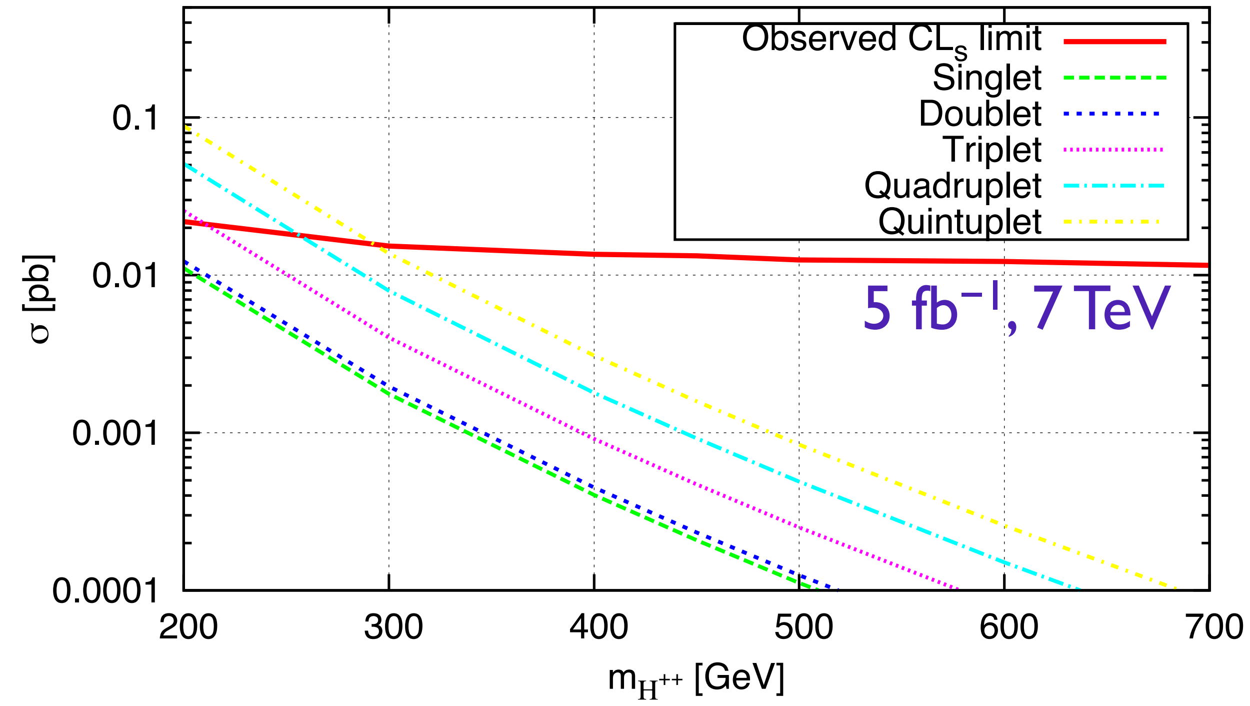
S. Chatrchyan et al. [CMS Collaboration]
Eur. Phys. J. C 72 (2012) 2189 [arXiv:1207.2666 [hep-ex]]

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



only τ





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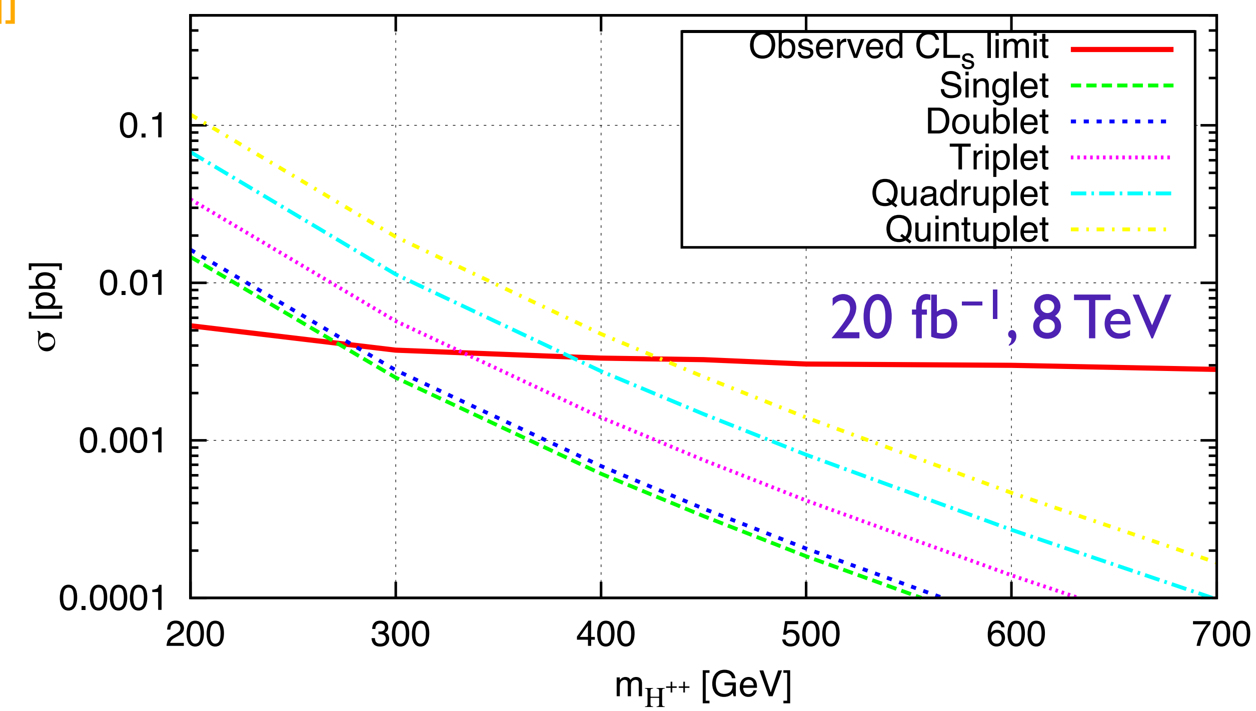
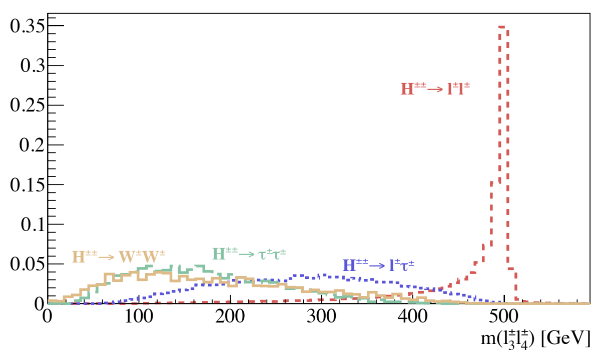
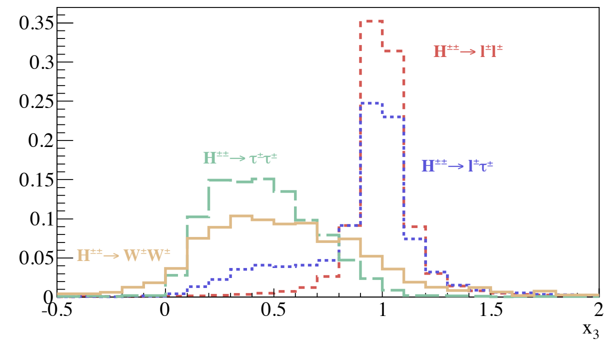
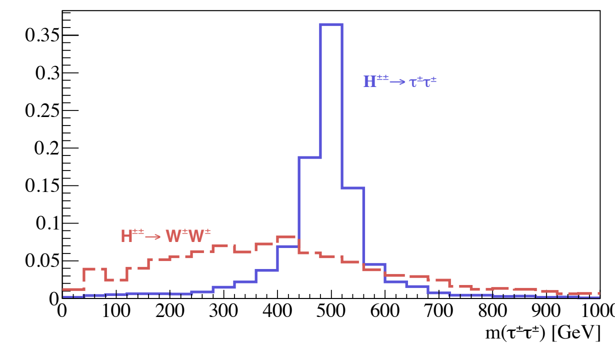
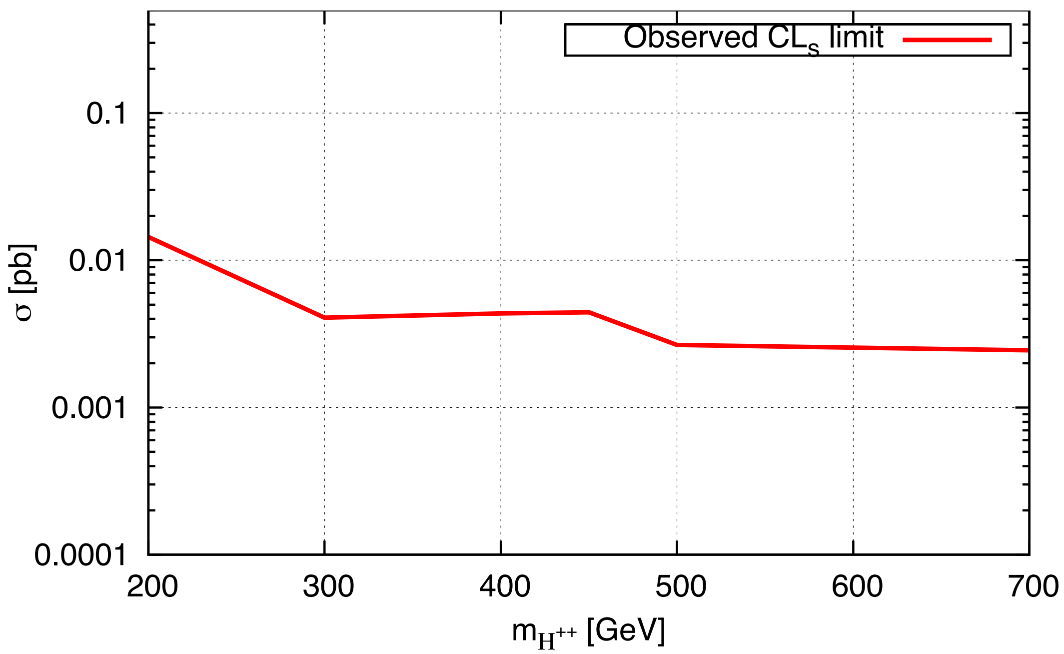


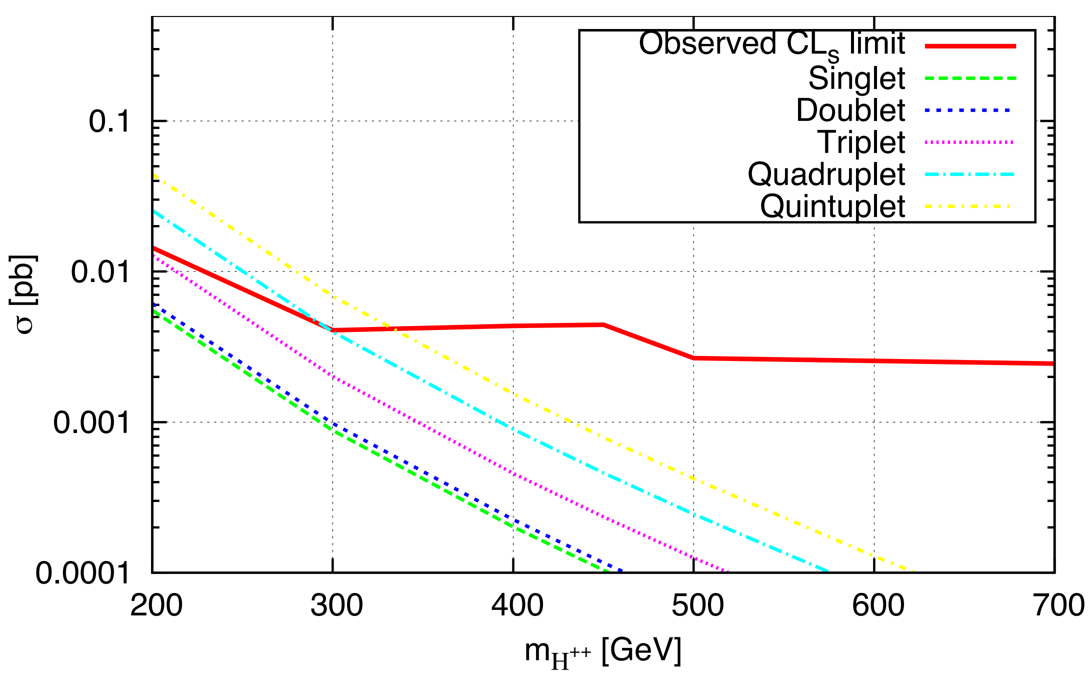




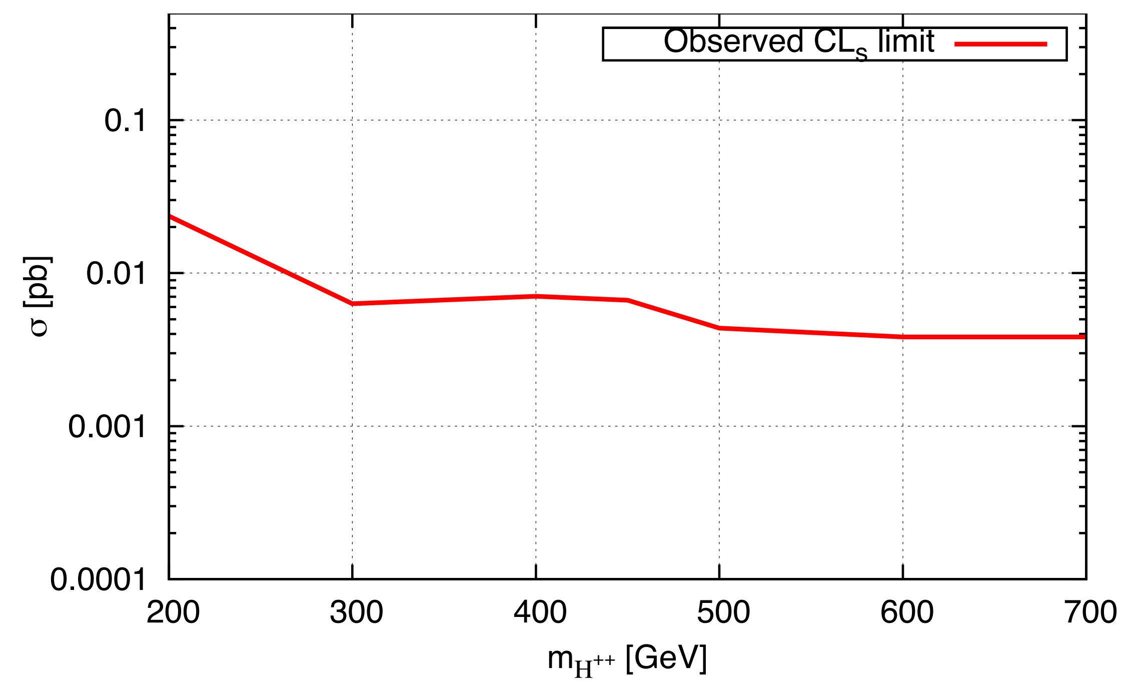


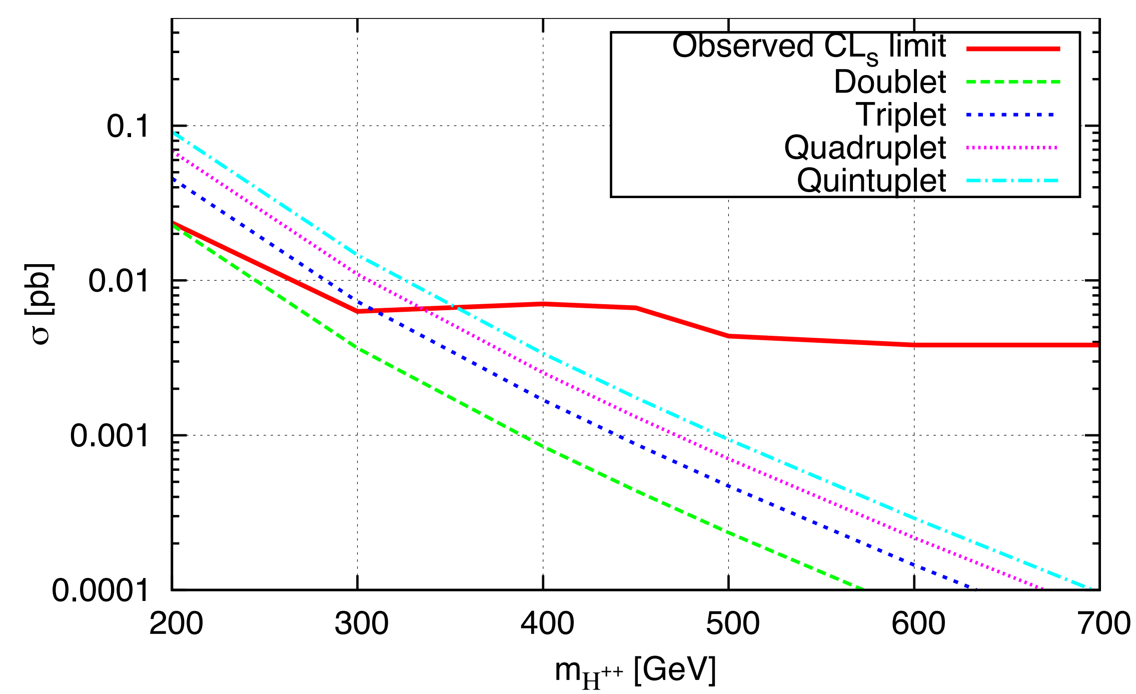
pair production
5 fb^{-1}, 7 TeV
50 % ll + 50 % WW





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





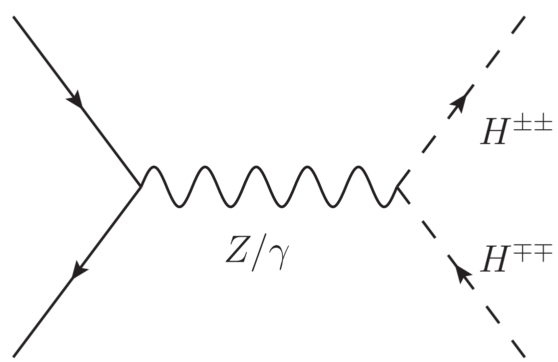
Dimension 4	$\begin{pmatrix}\Delta^{++}\\ \Delta^{+}\\ \Delta^{0}\end{pmatrix}$	$(\overline{\tilde{L}_L}\tau^a L_L)\Delta^{-a}$
	κ^{++}	$\overline{l_R^c}\, l_R \kappa$
Dimension 5	$\begin{pmatrix}\Sigma^{++}\\ \Sigma^{+}\\ \Sigma^{0}\\ \Sigma'^{-}\end{pmatrix}$	$(-1)^{\frac{1}{2}-b}\mathrm{C}_{a,b}^{1\times\frac{1}{2}\to\frac{3}{2}}(\overline{\tilde{L}_L}\tau^a L_L)\phi^b\Sigma^{-a-b}$
	$\begin{pmatrix}\chi^{++}\\ \chi^{+}\end{pmatrix}$	$(-1)^{1-a}(\overline{\tilde{L}_L}\tau^a L_L)(\phi^\dagger\tau^{-a}\chi)$, $\overline{l_R^c}\, l_R(\tilde{\phi}^\dagger\chi)$
Dimension 6	$\begin{pmatrix}\Omega^{++}\\ \Omega^{+}\\ \Omega^{0}\\ \Omega^{-}\\ \Omega^{--}\end{pmatrix}$	$\mathrm{C}_{a,b}^{1\times1\to2}(\overline{\tilde{L}_L}\tau^a L_L)(\tilde{\phi}^\dagger\tau^b\phi)\Omega^{-a-b}$

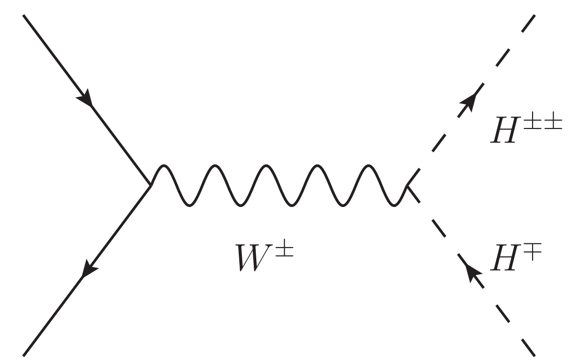
$$\overline{e_L^c}\, e_L \mathrm{H}^{++}$$

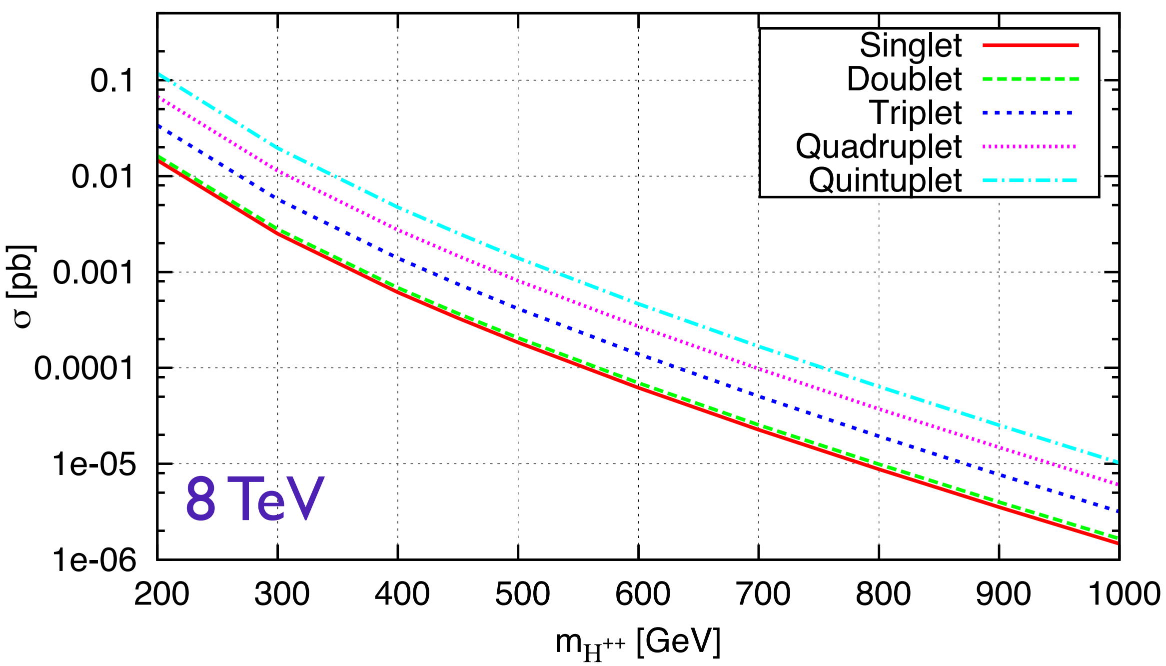
$$\overline{e_R^c}\, e_R \mathrm{H}^{++}$$

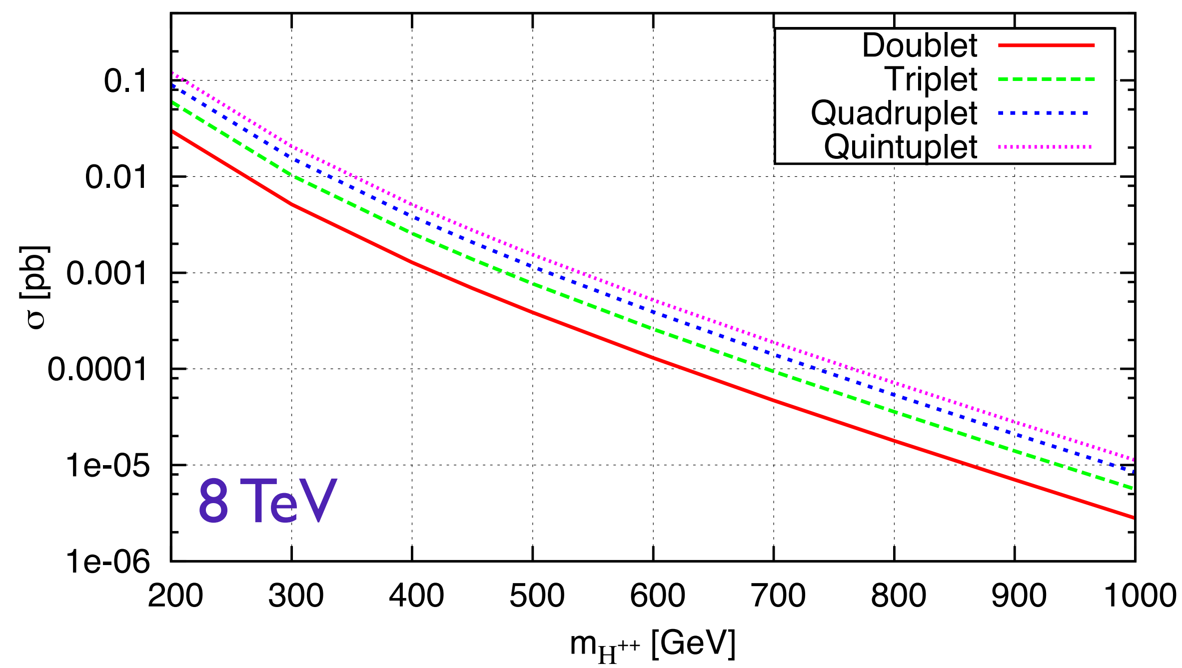
$$T^{\mathrm{H}} \geq T_3^{\mathrm{H}^{++}} = 2 - Y^{\mathrm{H}}$$

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





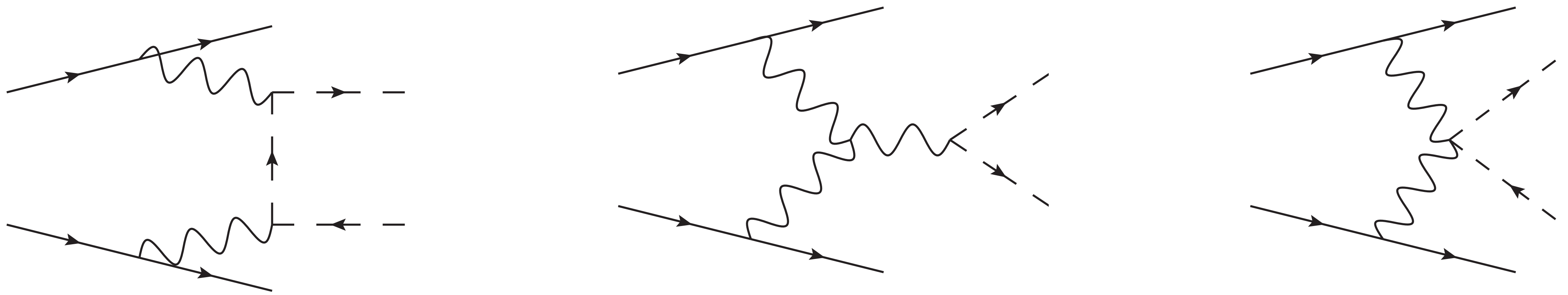


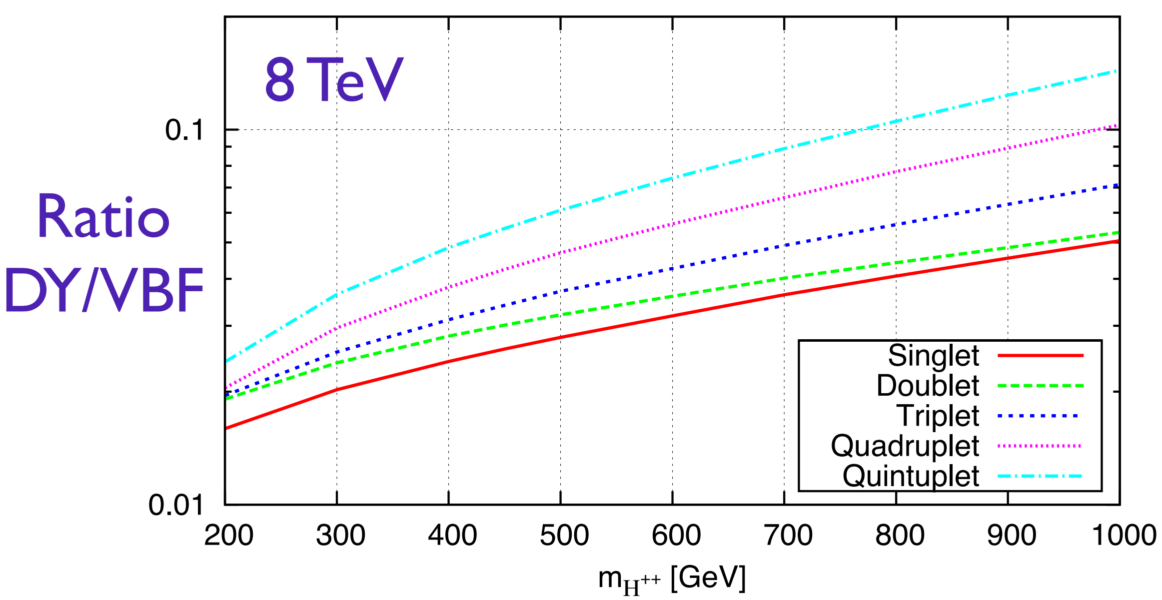


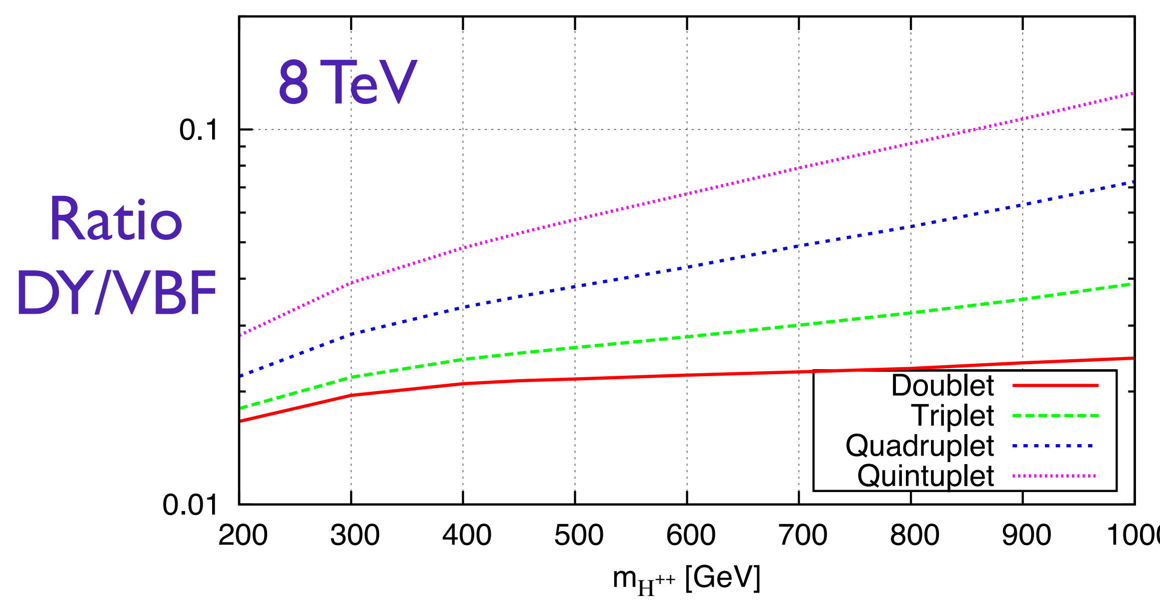
$$\mathcal{L}_{\gamma}^{\mathrm{H}^{\pm\pm}} = ieQ(\partial^{\mu}\mathrm{H}^{--})\mathrm{H}^{++}A_{\mu} + \mathrm{h.c.}\,,$$

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

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







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

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

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

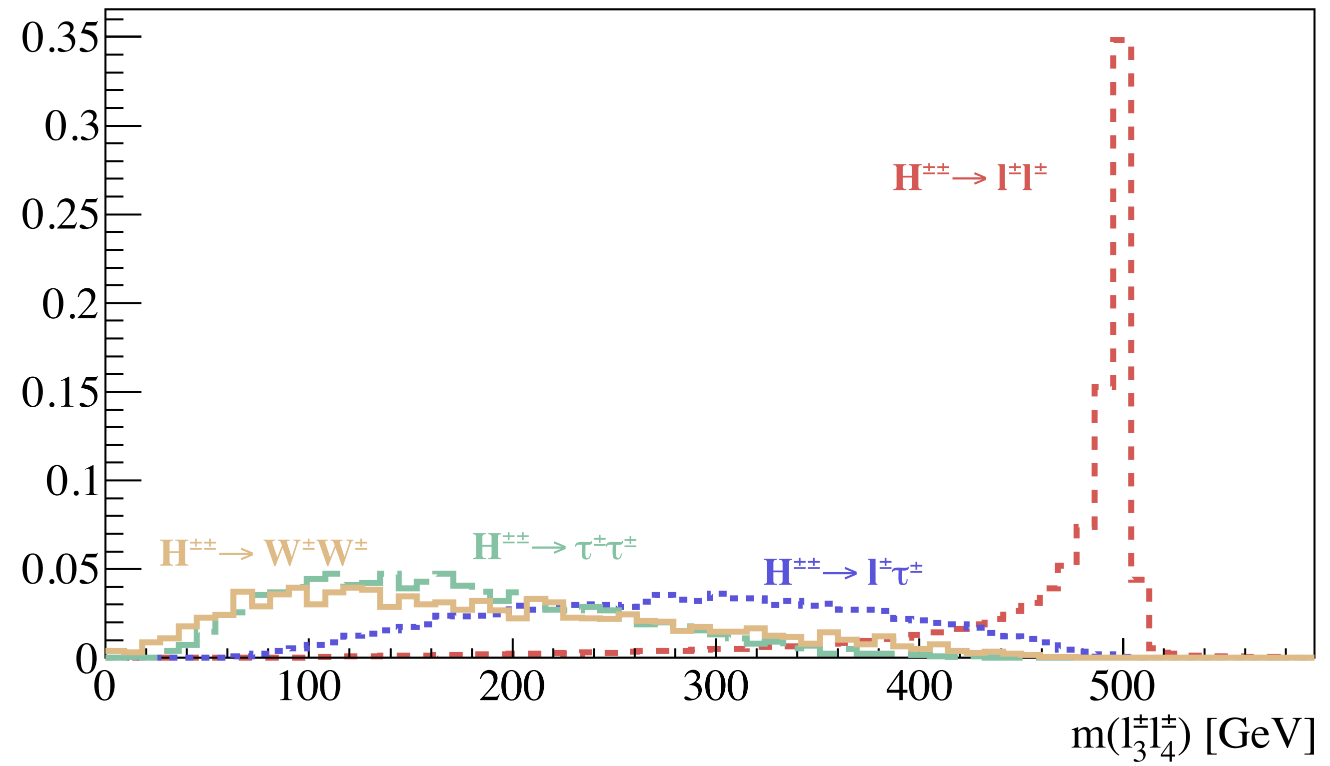
How well can we measure the total cross-section ?

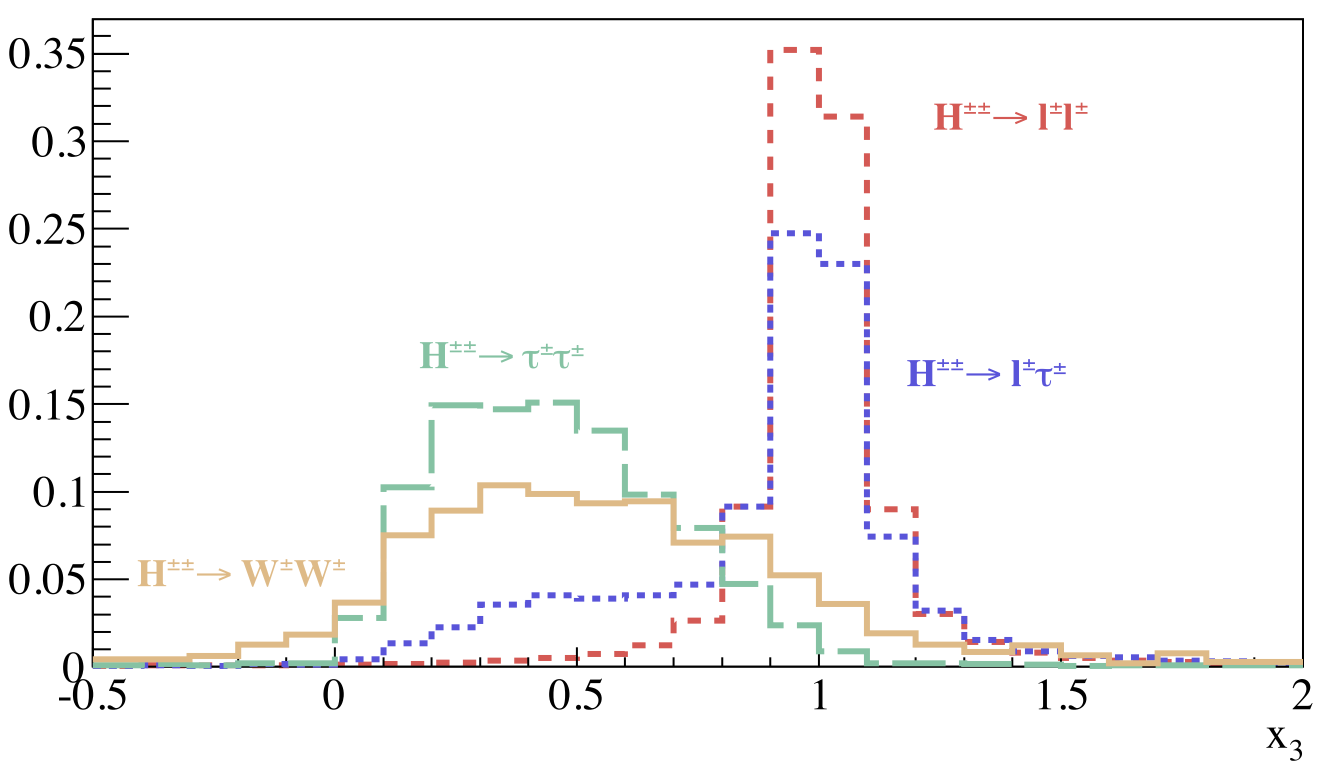
$$\boxed{\sigma = \left(\sigma_{llll} + \frac{1}{2}\sum_{a\neq ll} \sigma_{lla}\right)^2 / \sigma_{llll}}$$

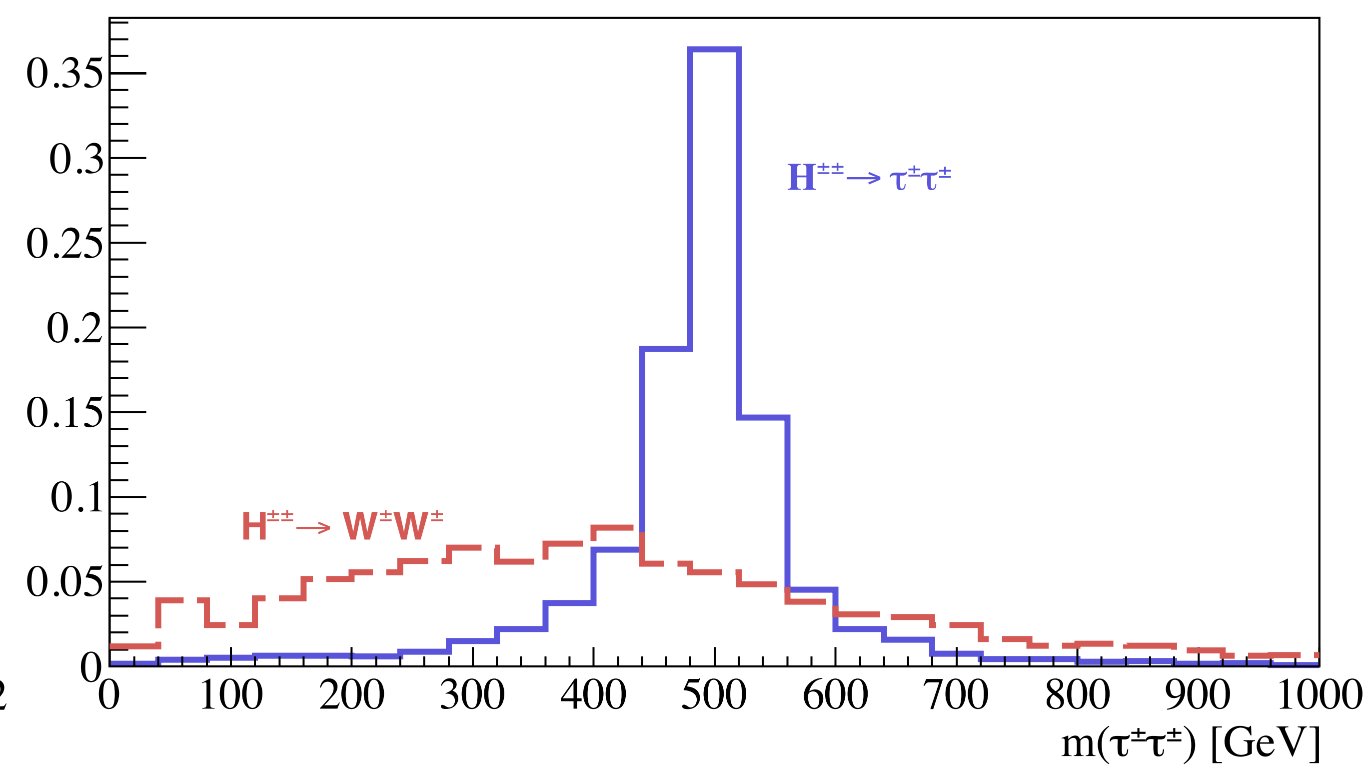
$$1 = \sum_{a=ll,l\tau,\tau\tau,WW} z_a, \; z_a \equiv Br(H \to a)$$

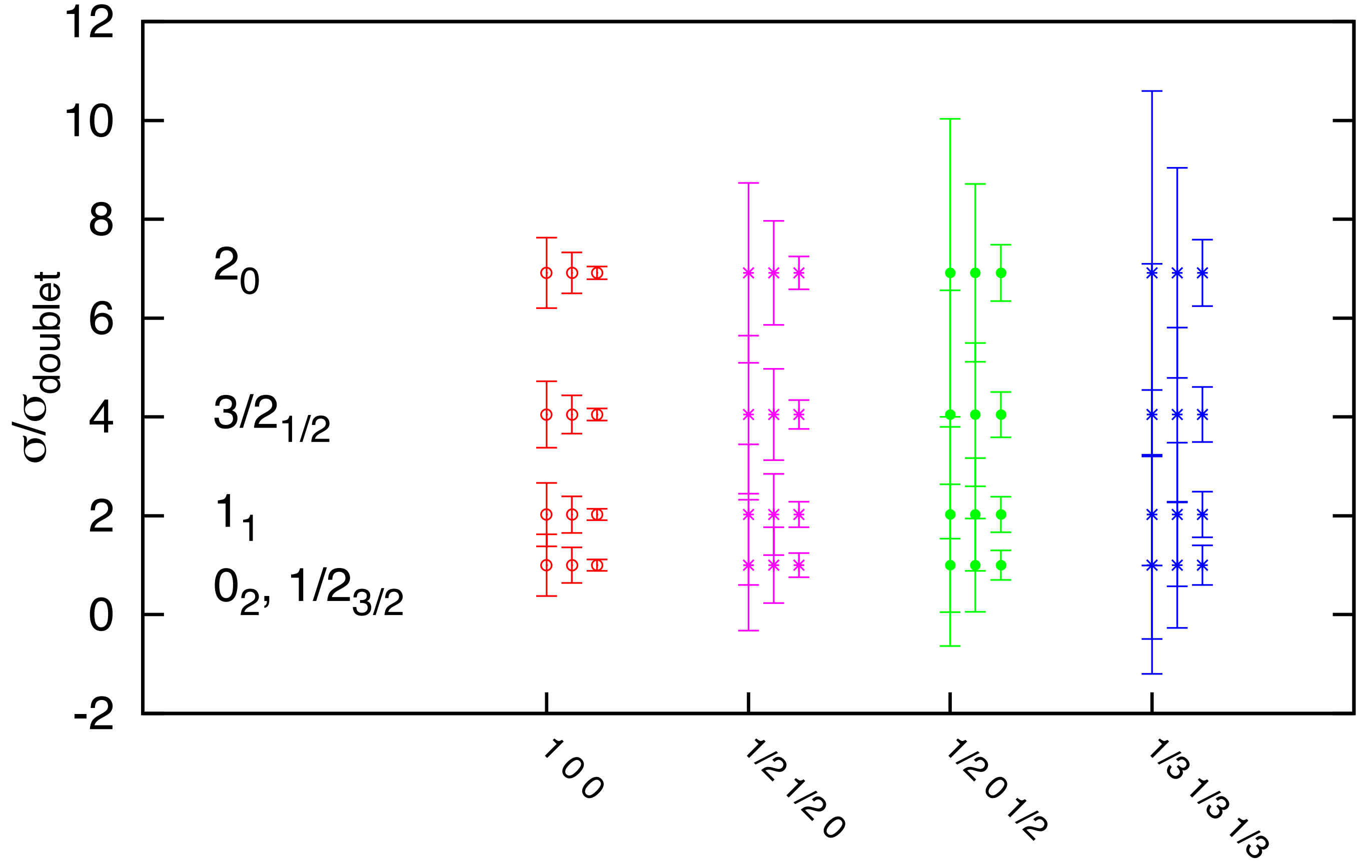
It is enough to group the sample with four charged leptons in three sub-sets:

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

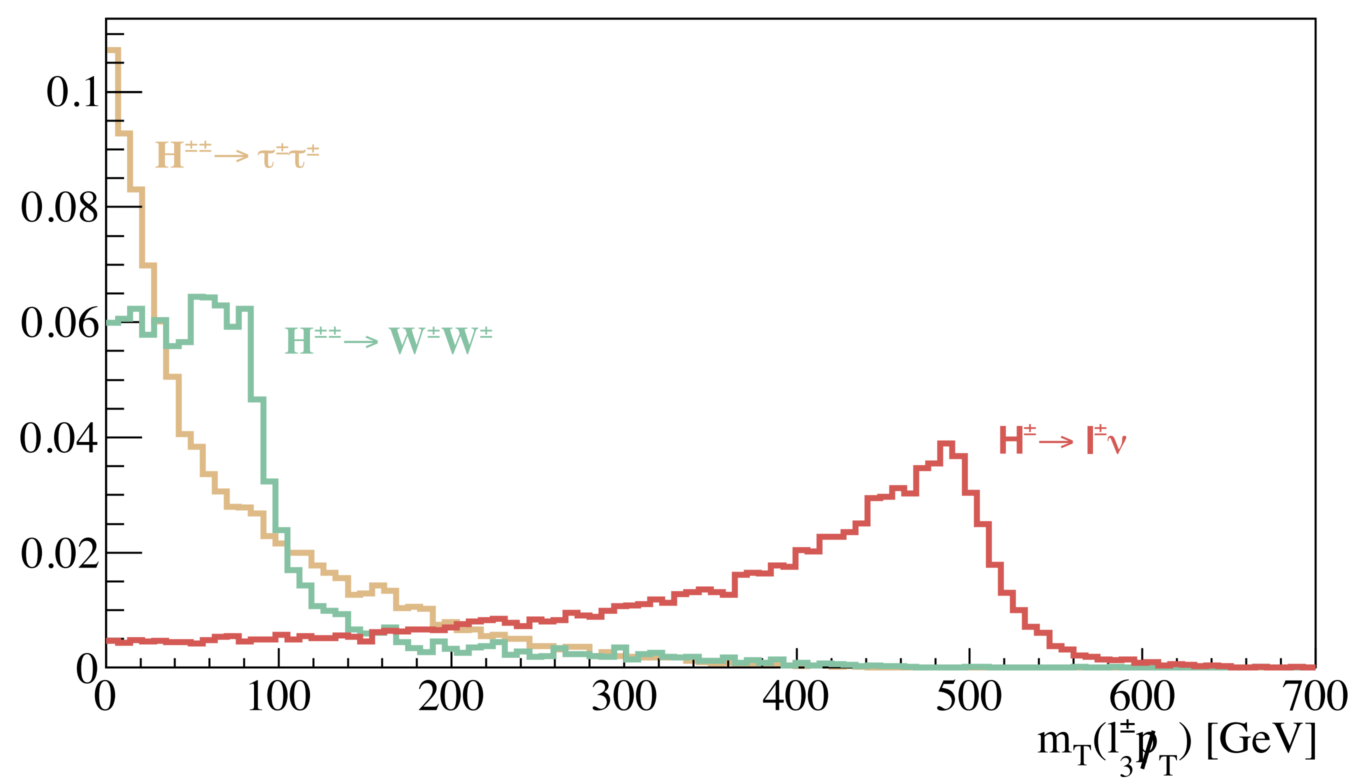








12
10
8
6
4
2
0
-2
$\sigma/\sigma_{doublet}$
2_0
$3/2_{1/2}$
1_1
0_2, $1/2_{3/2}$
1 0 0
1/2 1/2 0
1/2 0 1/2
1/3 1/3 1/3



0.1
0.08
0.06
0.04
0.02
0
$H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$
$H^{\pm\pm} \to W^{\pm}W^{\pm}$
$H^{\pm} \to l^{\pm}\nu$
0
100
200
300
400
500
600
700
$m_T(l_3^{\pm}\not{p}_T)$ [GeV]

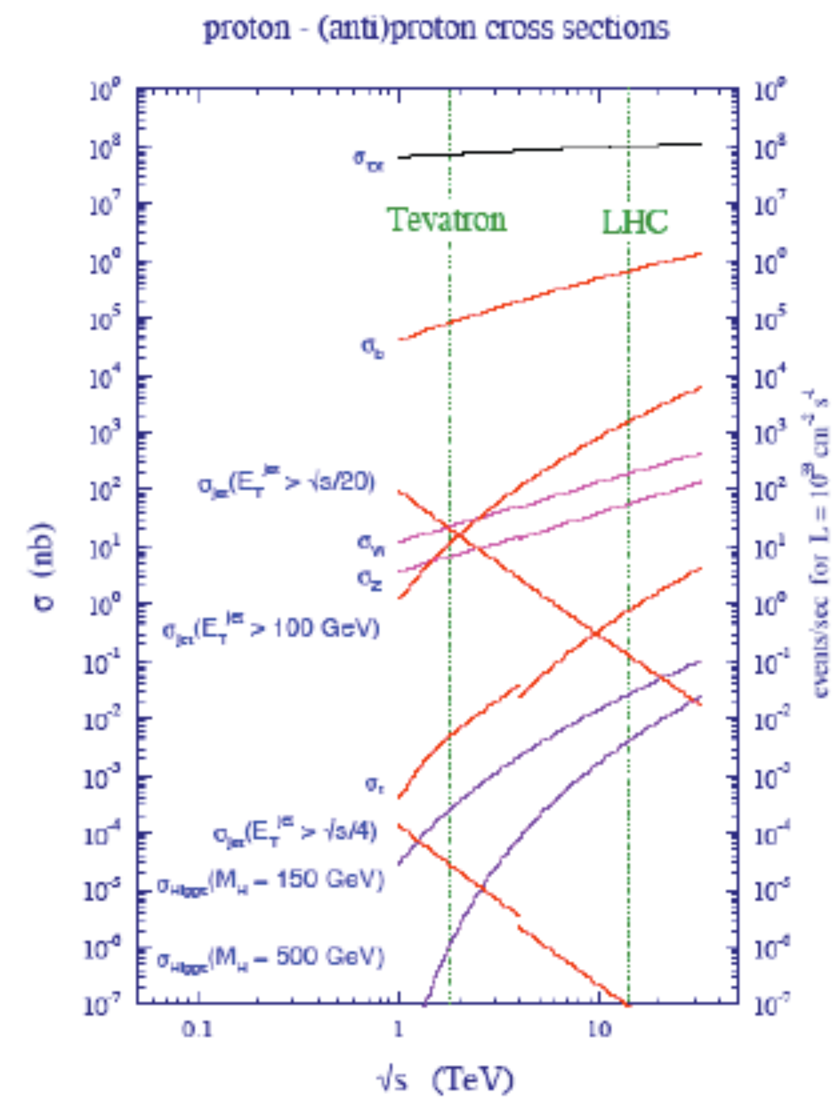
Summary

- 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.

F. del Aguila, M. Chala, A. Santamaría and J. Wudka, PLB 725 (2013) 310
F. del Aguila and M. Chala, JHEP 1403 (2014) 027



proton - (anti)proton cross sections
Tevatron
LHC
σ (nb)
√s (TeV)
events/sec for L = 10^33 cm^-2 s^-1
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)