Neutrino Physics @ LHC

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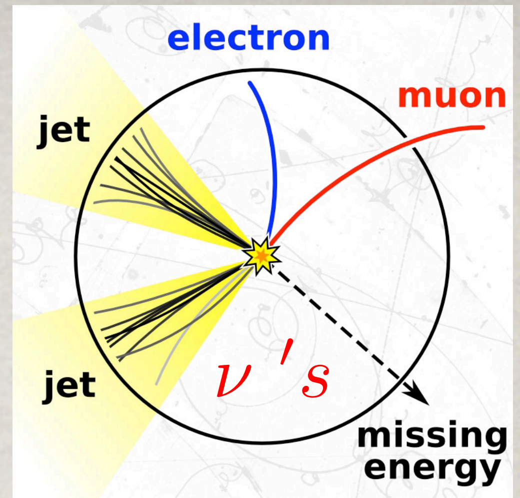
CERN Theory Institute:
Neutrinos: the quest for a new physics scale
March 28, 2017

“Neutrinos @ the LHC”



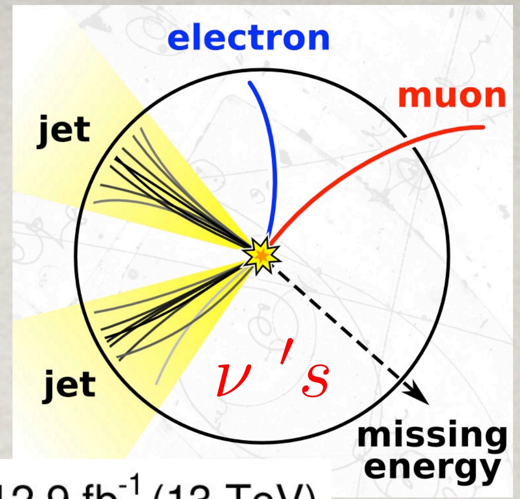
They are all gone !

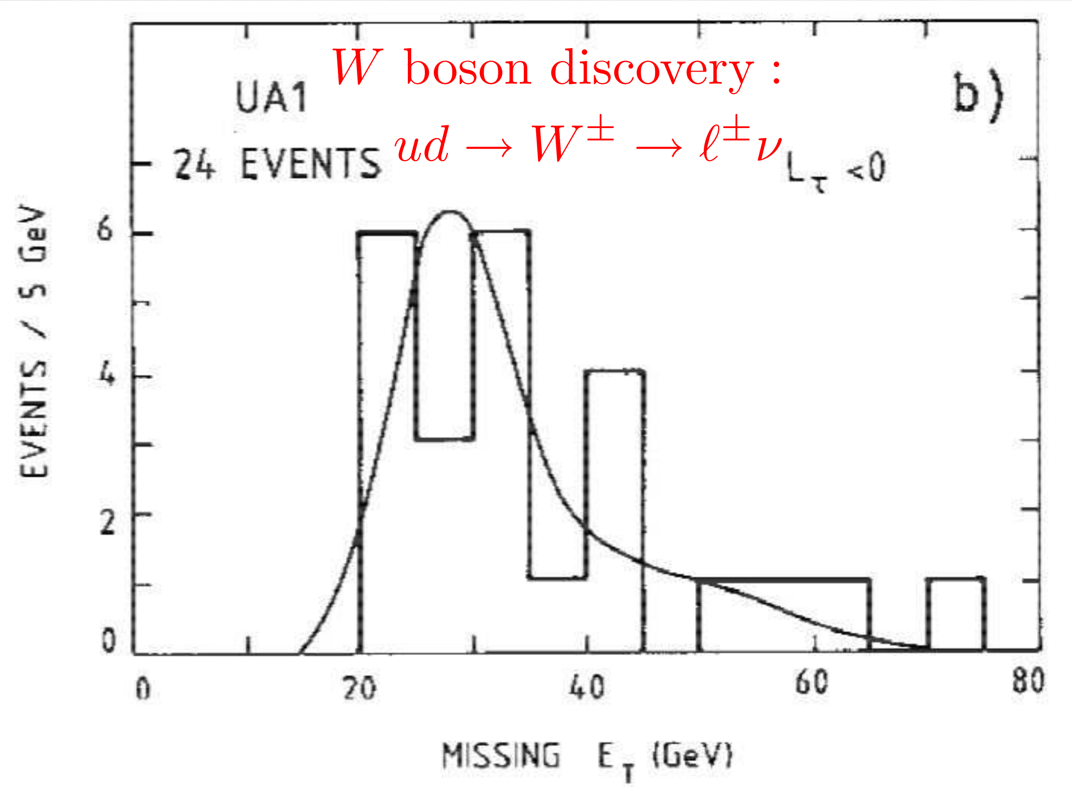
“Much Ado About Nothing”?

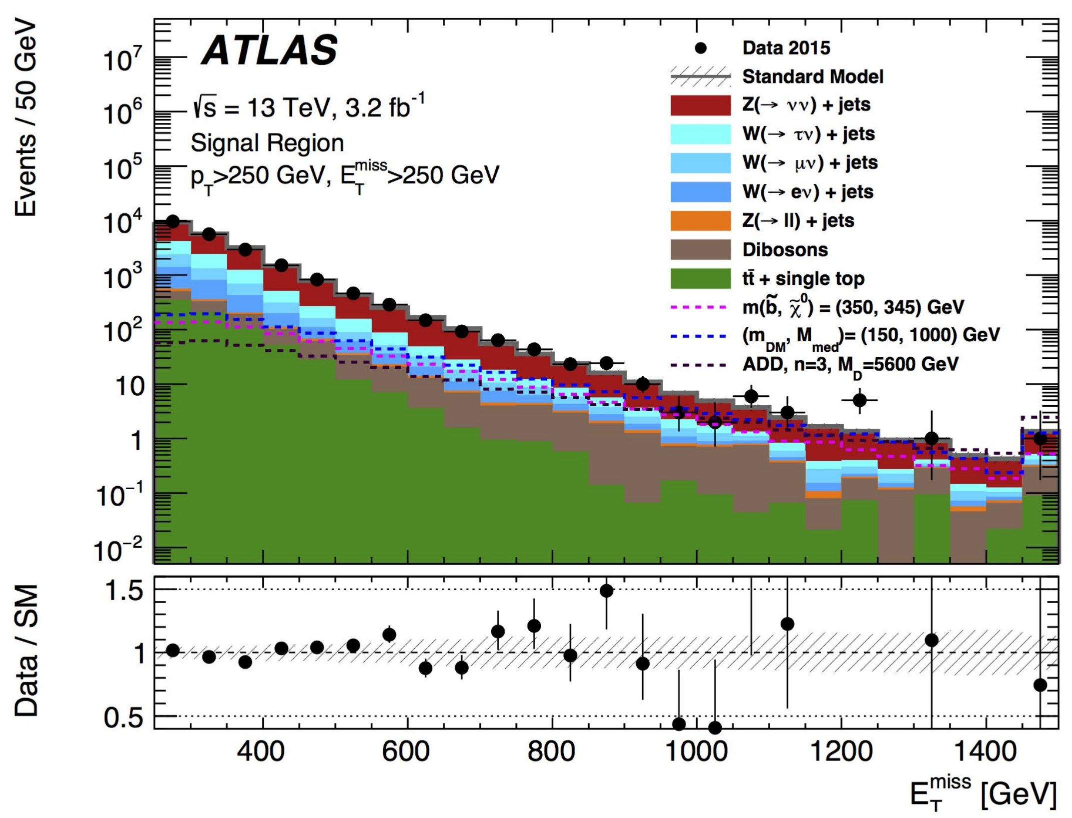
“Neutrinos @ the LHC”

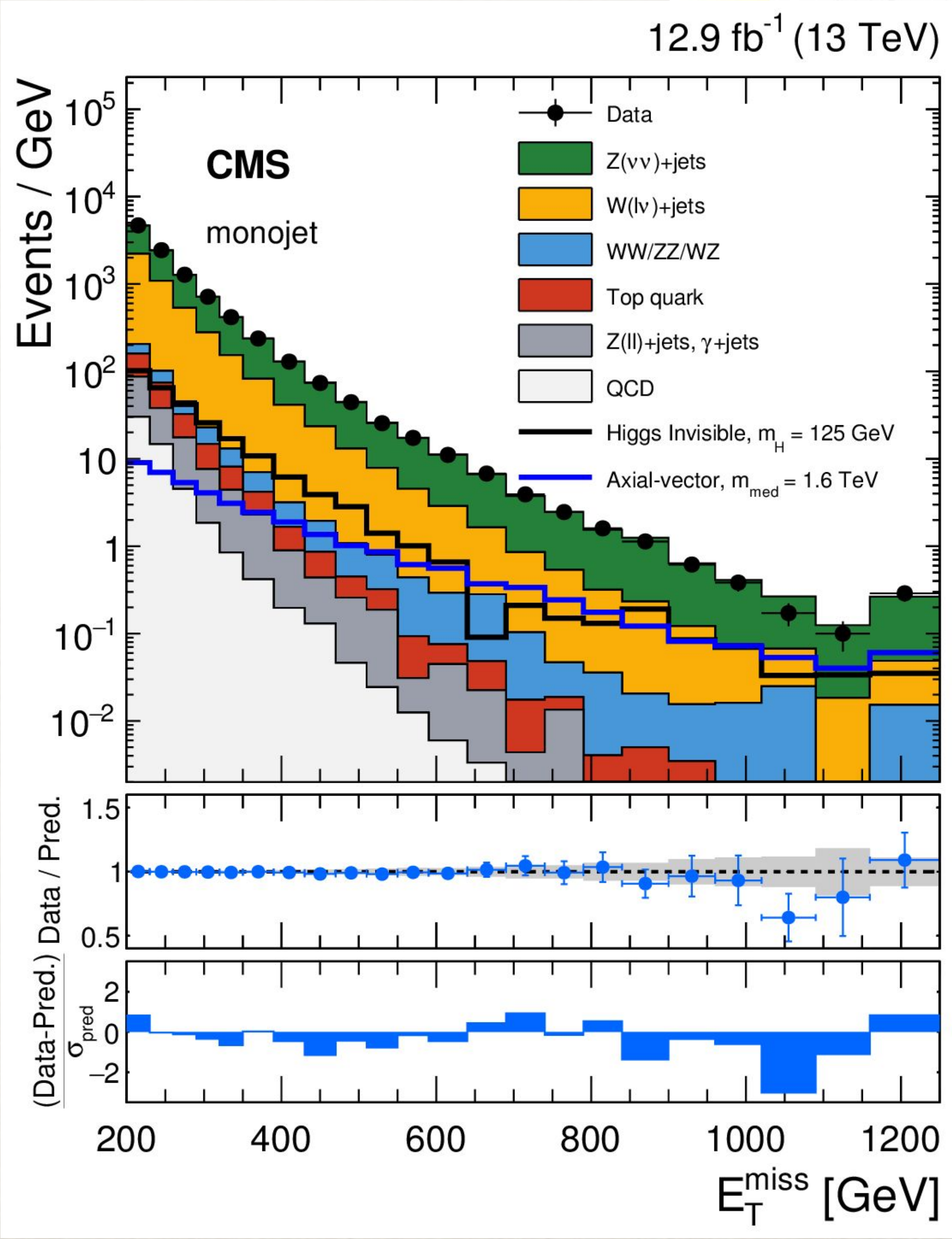
They are all gone !

“Much Ado About Nothing”?



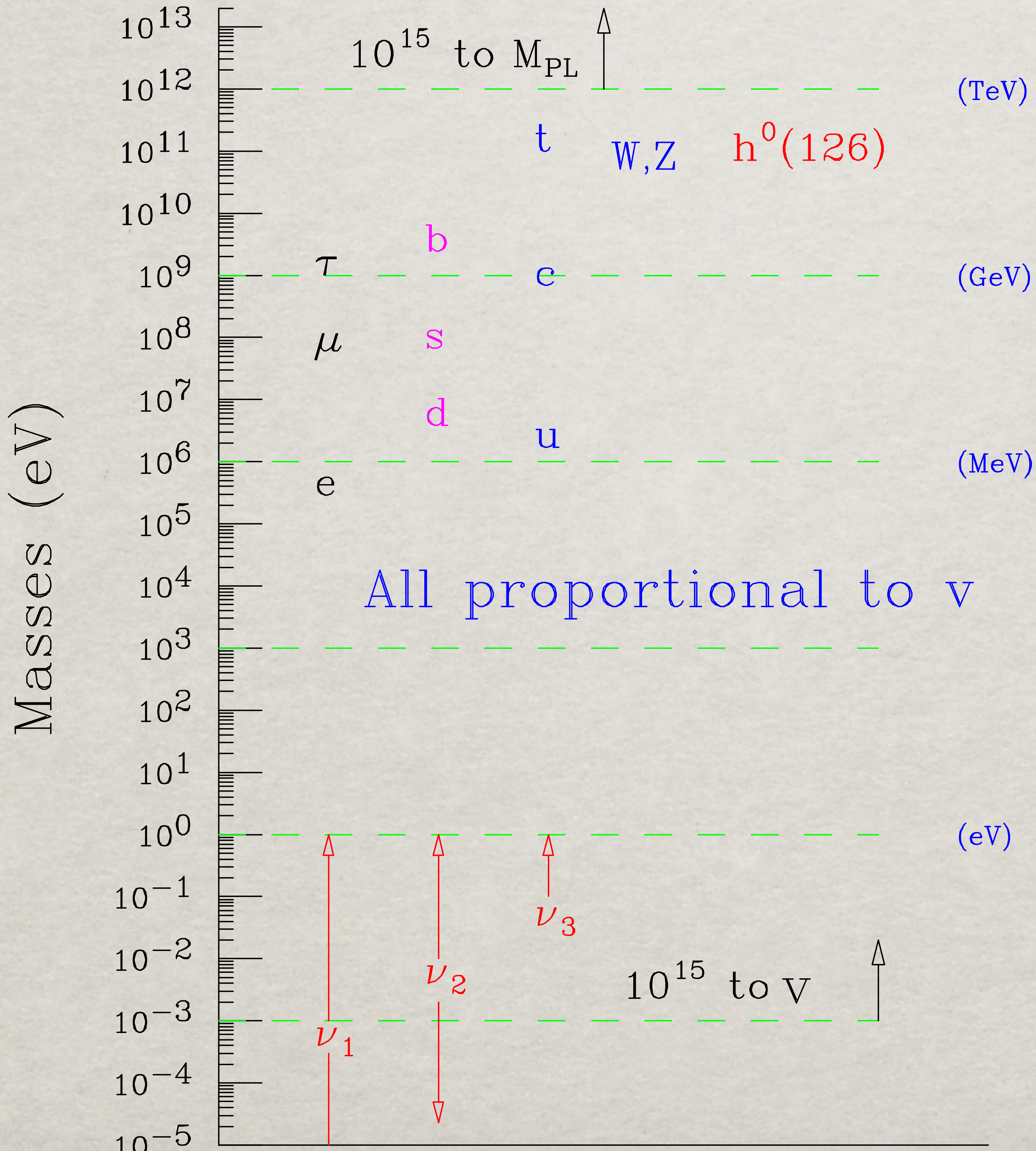






Search for BSM new physics!

Neutrinos Are Massive & the masses are tiny!



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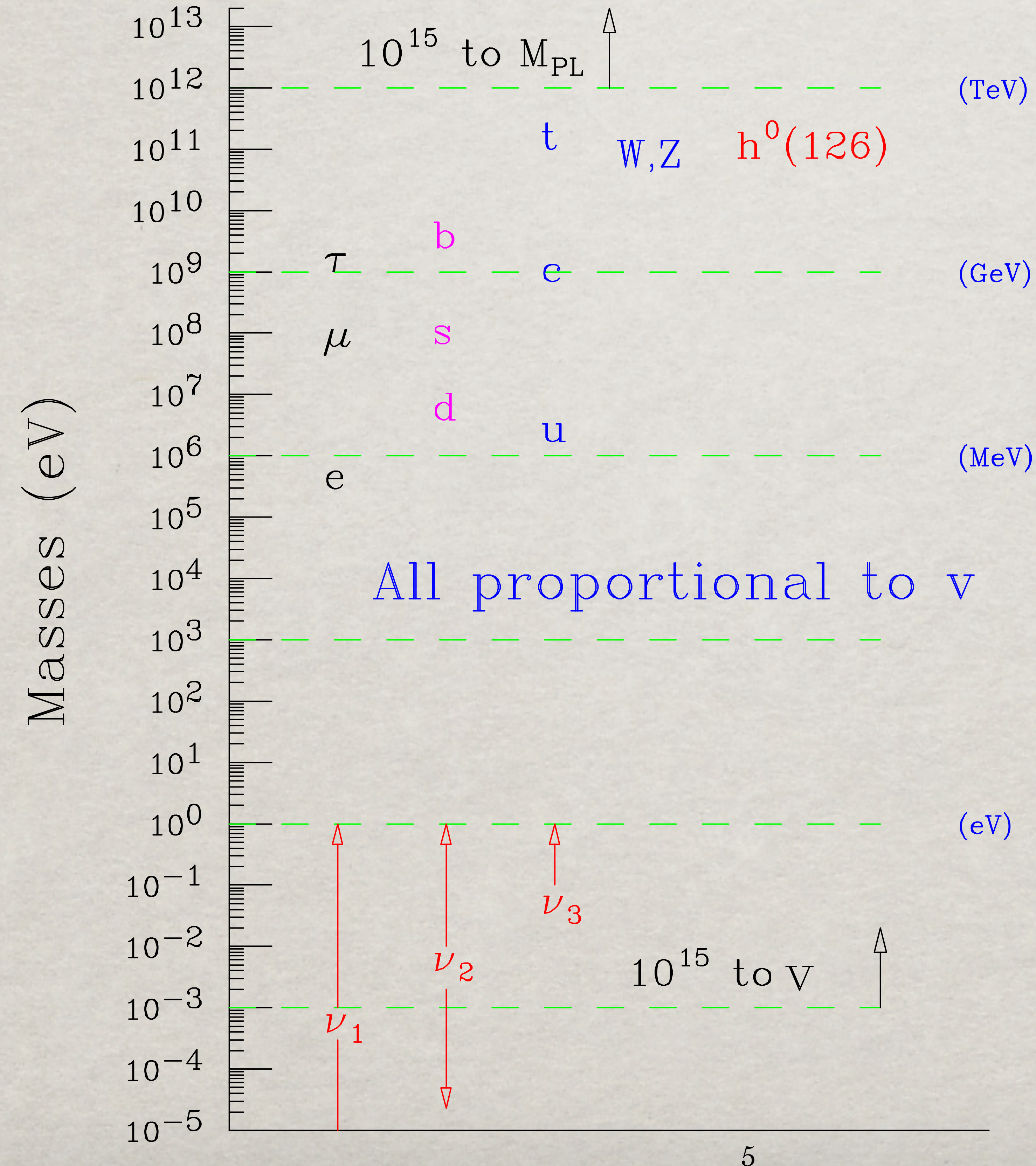

$$m_\nu \sim y_\nu^{eff}\ v$$

$$y_\nu^{eff} < 10^{-12}.$$

Small Neutrino masses

- "Technically natural" in the 't Hooft sense.
- Suppression by integrating out heavy states:

β-decay is "weak" because $(m_n\text{-}m_p)^2/M_W^2 < 10^{-10}$!

the higher dimension $1/\Lambda^n$, the lower Λ can be.

- Suppression by loop radiative generation:

the higher loops $1/(16\pi^2)^n$, the lower m_ν can be.

One would need to introduce:

--- new states of heavy mass M

--- new weak couplings, mixings k, V_{ij}

Their values may be subject to some expt. constraints, but wide open in theory space.

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From phenomenological/experimental point of view:

- Will search EVERY WHERE
- Explore the LHC sensitivity without theory prejudice.

(A). The Models

In the context of the Standard Model:

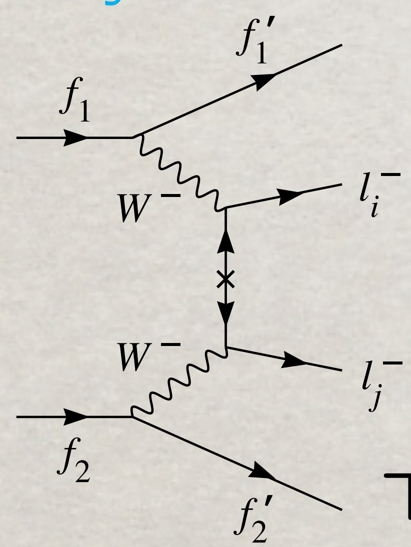
$$L_a = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3$$

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda}(y_\nu LH)(y_\nu LH) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\, \overline{\nu_L}\, \nu_R^c.$$

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

$0\nu 2\beta$ decay: (Thursday's sessions)



The See-saw spirit: †

If $m_\nu \sim$1 eV, then $\Lambda \sim y_\nu^2$ (10^{14} GeV).

$$\Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$

These are the *"most wanted"* processes to

- Discover Majorana neutrinos
- Access the new mass scale
- Probe the lepton flavor structure $y_\nu \sim U_{\ell m}$

†Yanagita (1979); Gell-Mann, Ramond, Slansky (1979), Minkowski (1976); S.L. Glashow (1980); Mohapatra, Senjanovic (1980) ...

Type I Seesaw: Singlet N_R 's

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1,2,3; \qquad N_{bR}, \quad b = 1,2,3,...n \geq 2.$$

Dirac plus Majorana mass terms: $\begin{pmatrix} \overline{\nu_L} & \overline{N^c}_L \end{pmatrix} \begin{pmatrix} 0_{3\times 3} & D^\nu_{3\times n} \\ D^{\nu T}_{n\times 3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} {\nu^c}_R \\ N_R \end{pmatrix}$

Majorana neutrinos:

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'} N^c_{m'L},$$

$$N^c_{aL} = \sum_{m=1}^{3} X_{am}\nu_{mL} + \sum_{m'=4}^{3+n} Y_{am'} N^c_{m'L},$$

The charged currents:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m} \, \overline{\nu_m} \gamma^\mu P_L \ell + h.c.$$

$$+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'} \, \overline{N^c_{m'}} \gamma^\mu P_L \ell + h.c.$$

Type I Seesaw features: Existence of N_R (low mass*)

$$U^2_{\ell m} \sim V^2_{PMNS} \approx \mathcal{O}(1); \;\; V^2_{\ell m} \approx m_\nu/m_N.$$

$U_{\ell m}, \;\; \Delta m_\nu$ are from oscillation experiments

m_N a free parameter

The mixing is typically small:

$$V^2_{\ell m} \approx (m_\nu/eV)/(m_N/GeV) \times 10^{-9}$$
$$< 6 \times 10^{-3} (low\ energy\ bound)$$

(Fine-tuned to make it sizeable.)

* Casas and Ibarra (2001);
A. Y. Smirnov and R. Zukanovich Funchal (2006);
A. de Gouvea, J. Jenkins and N. Vasudevan (2007);
W. Chao, Z. G. Si, Z. Z. Xing and S. Zhou (2008).

A Variation: Inverse seesaw [#]

Inverse Seesaw: (ν_L, N_R^c, S_L)

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M^T \\ 0 & M & \mu_S \end{pmatrix} \qquad \begin{aligned} m_\nu &\simeq \left(\frac{M_D}{M}\right) \mu_S \left(\frac{M_D}{M}\right)^T ; \\ M_H &\simeq \begin{pmatrix} 0 & M^T \\ M & \mu_S \end{pmatrix} . \end{aligned}$$

Small Majorana mass μ_s renders the Dirac mass M_D Yukawa couplings & N mixings sizable!

$$V_{\ell m}^2 \approx (M_D/M_N)^2 \approx m_\nu/\mu_s$$

* **ν** Majorana-like; N Dirac-like.

R. Mohapatra, J. Valle (1986)

Type II Seesaw: No need for N_R, with Φ-triplet*

With a scalar triplet Φ $(Y=2)$: $\phi^{\pm\pm}, \phi^{\pm}, \phi^0$ (many representative models).
Add a gauge invariant/renormalizable term:

$$Y_{ij} L_i^T C(i\sigma_2)\Phi L_j + h.c.$$

That leads to the Majorana mass:

$$M_{ij}\nu_i^T C\nu_j + h.c.$$

where

$$M_{ij} = Y_{ij}\langle\Phi\rangle = Y_{ij}v' \lesssim 1 \text{ eV},$$

Very same gauge invariant/renormalizable term:

$$\mu H^T(i\sigma_2)\Phi^\dagger H + h.c.$$

predicts

$$v' = \mu\,\frac{v^2}{M_\phi^2},$$

leading to the Type II Seesaw. †

*Magg, Wetterich (1980); Lazarides, Shafi (1981); Mohapatra, Senjanovic (1981). ...

†In Little Higgs model: T.Han, H.Logan, B.Mukhopadhyaya, R.Srikanth (2005).

Type II Seesaw features*

- Triplet vev → Majorana mass → neutrino mixing pattern!

$H^{\pm\pm} \to \ell_i^{\pm} \ell_i^{\pm}$ → neutrino mixing pattern!

$H^{\pm\pm} \to W^{\pm} W^{\pm}.$ Competing channel

Variations

Naturally embedded in L-R symmetric model:#

$W^{\pm}{}_R$ → $N_R\ e^{\pm}$

(* Large Type I signals via W_R-N_R)

† Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

Mohapatra, Senjanovic (1981). ...

Type III Seesaw: with a fermionic triplet*

With a lepton triplet T $(Y = 0)$: $T^+ \; T^0 \; T^-$, add the terms:

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + h.c.$$

These lead to the Majorana mass:

$$M_{ij} \approx y_i y_j \frac{v^2}{2M_T}.$$

Again, the seesaw spirit: $m_\nu \sim v^2/M_T$.

Features:

Demand that $M_T \lesssim 1$ TeV, $M_{ij} \lesssim 1$ eV,
Thus the Yukawa couplings:†

$$y_j \lesssim 10^{-6},$$

making the mixing $T^{\pm,0} - \ell^\pm$ very weak.

Could utilize "inverse seesaw" to boost y_i

T^0 a Majorana neutrino;
Decay via mixing (Yukawa couplings);
$T\overline{T}$ Pair production via EW gauge interactions.

*Foot, Lew, He, Joshi (1989); G. Senjanovic et al. ...

Higher dim ΔL=2 Operators*

d=7 (4 fermions):

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_3 = \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\}$$

$$\mathcal{O}_4 = \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\}$$

$$\mathcal{O}_5 = L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km}$$

$$\mathcal{O}_6 = L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl}$$

$$\mathcal{O}_7 = L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm}$$

$$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$

d=9 (6 fermions):

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_{10} = L^i L^j L^k e^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_{11} = \{L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}\}$$

$$\mathcal{O}_{12} = \{L^i L^j \bar{Q}_i \bar{u^c} \bar{Q}_j \bar{u^c}, \quad L^i L^j \bar{Q}_k \bar{u^c} \bar{Q}_l \bar{u^c} \epsilon_{ij}\epsilon^{kl}\}$$

$$\mathcal{O}_{13} = L^i L^j \bar{Q}_i \bar{u^c} L^l e^c \epsilon_{jl}$$

$$\mathcal{O}_{14} = \{L^i L^j \bar{Q}_k \bar{u^c} Q^k d^c \epsilon_{ij}, \quad L^i L^j \bar{Q}_i \bar{u^c} Q^l d^c \epsilon_{jl}\}$$

$$\mathcal{O}_{15} = L^i L^j L^k d^c \bar{L}_i \bar{u^c} \epsilon_{jk}$$

$$\mathcal{O}_{16} = L^i L^j e^c d^c \bar{e^c} \bar{u^c} \epsilon_{ij}$$

$$\mathcal{O}_{17} = L^i L^j d^c d^c \bar{d^c} \bar{u^c} \epsilon_{ij}$$

$$\mathcal{O}_{18} = L^i L^j d^c u^c \bar{u^c} \bar{u^c} \epsilon_{ij}$$

$$\mathcal{O}_{19} = L^i Q^j d^c d^c \bar{e^c} \bar{u^c} \epsilon_{ij}$$

$$\mathcal{O}_{20} = L^i d^c \bar{Q}_i \bar{u^c} \bar{e^c} \bar{u^c}$$

* Babu & Leung, (2001).

Radiative Seesaw Models*

Close the loops: Quantum corrections could generate m_ν.

Suppressions (up to 3-loops) make both m_ν and M low:

$$m_\nu \sim (\frac{1}{16\pi^2})^\ell (\frac{v}{M})^k \ \mu$$

With (Majorana) mass scale μ

Generic features:

- New scalars: φ^0, $H^\pm$, $H^{\pm\pm}$, …

→ BSM Higgs physics, possible flavor relations

- Additional Z_2 symmetry → Dark Matter η

$h^0 \to \eta\eta$ invisible!

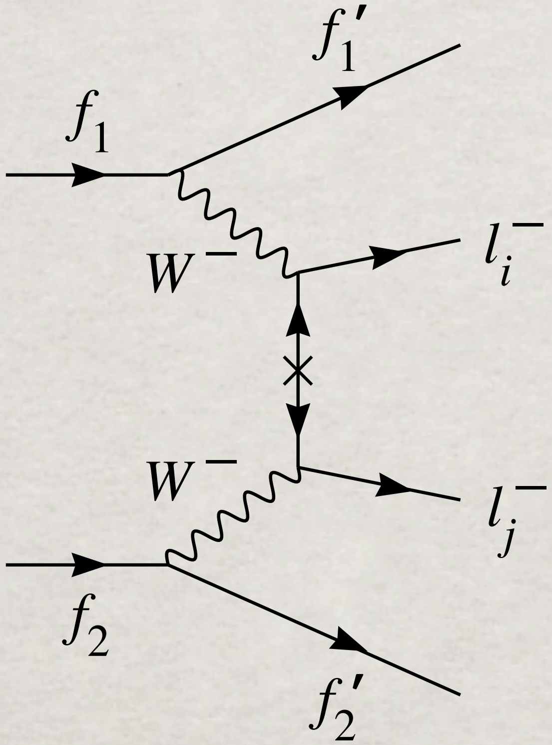
(See Raymond Volkas talks.)

* Zee (1980, 1986); Babu (1988); Ma (2006), Aoki et al. (2009).

(B). The search for Seesaw

Type I Seesaw: Search for N

The fundamental diagram:



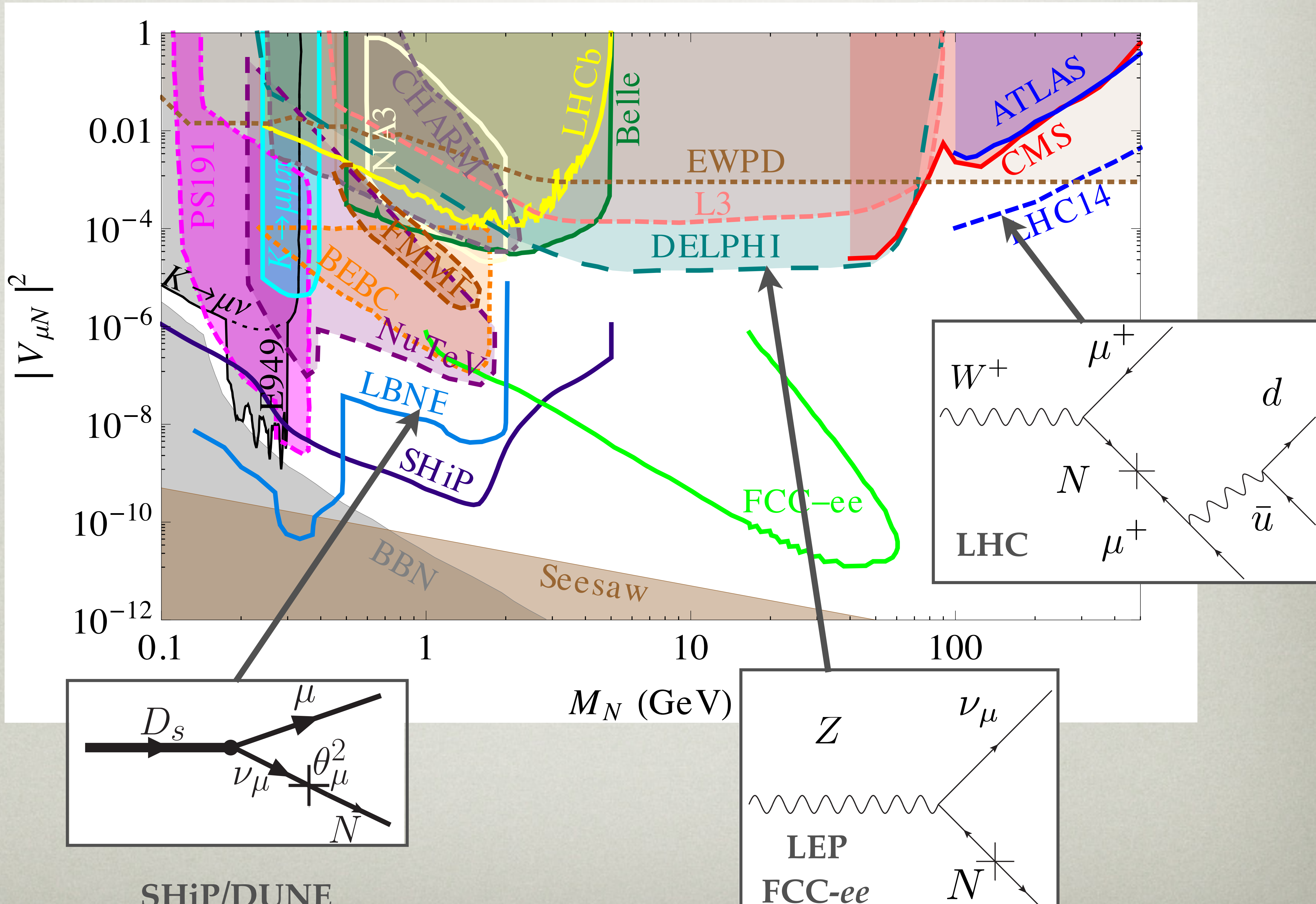
$$U_{iN} \frac{\not{p}+m_N}{p^2-m_N^2+i\epsilon} U_{jN}.$$

The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m \rangle^2_{\ell_1\ell_2} = \left| \sum_{i=1}^{3} U_{\ell_1 i} U_{\ell_2 i} m_i \right|^2 & \text{for light } \nu; \\ \frac{\left| \sum_i^n V_{\ell_1 i} V_{\ell_2 i} \right|^2}{m_N^2} & \text{for heavy } N; \\ \frac{\Gamma(N \to i)\ \Gamma(N \to f)}{m_N \Gamma_N} & \text{for resonant N production.} \end{cases}$$

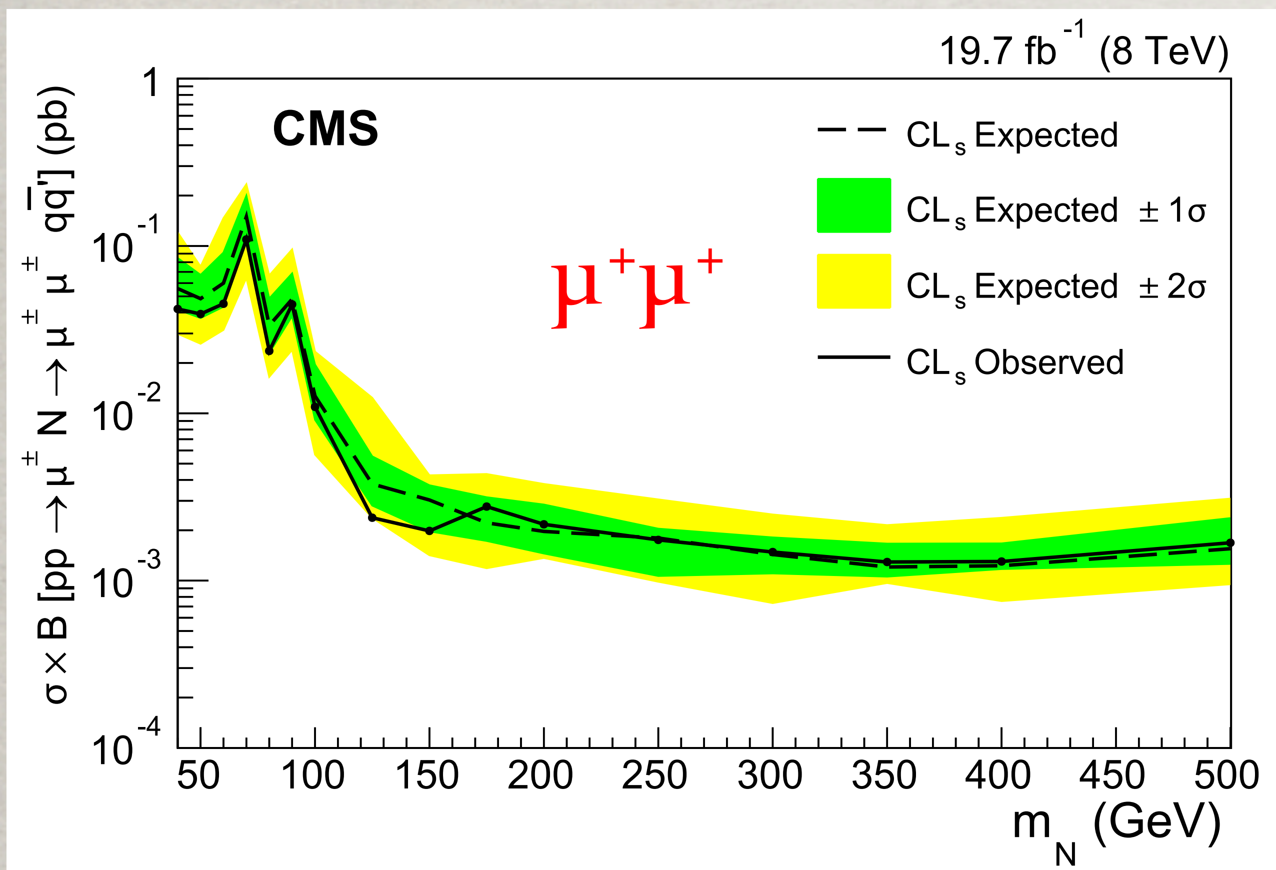
(1). Search for low mass N

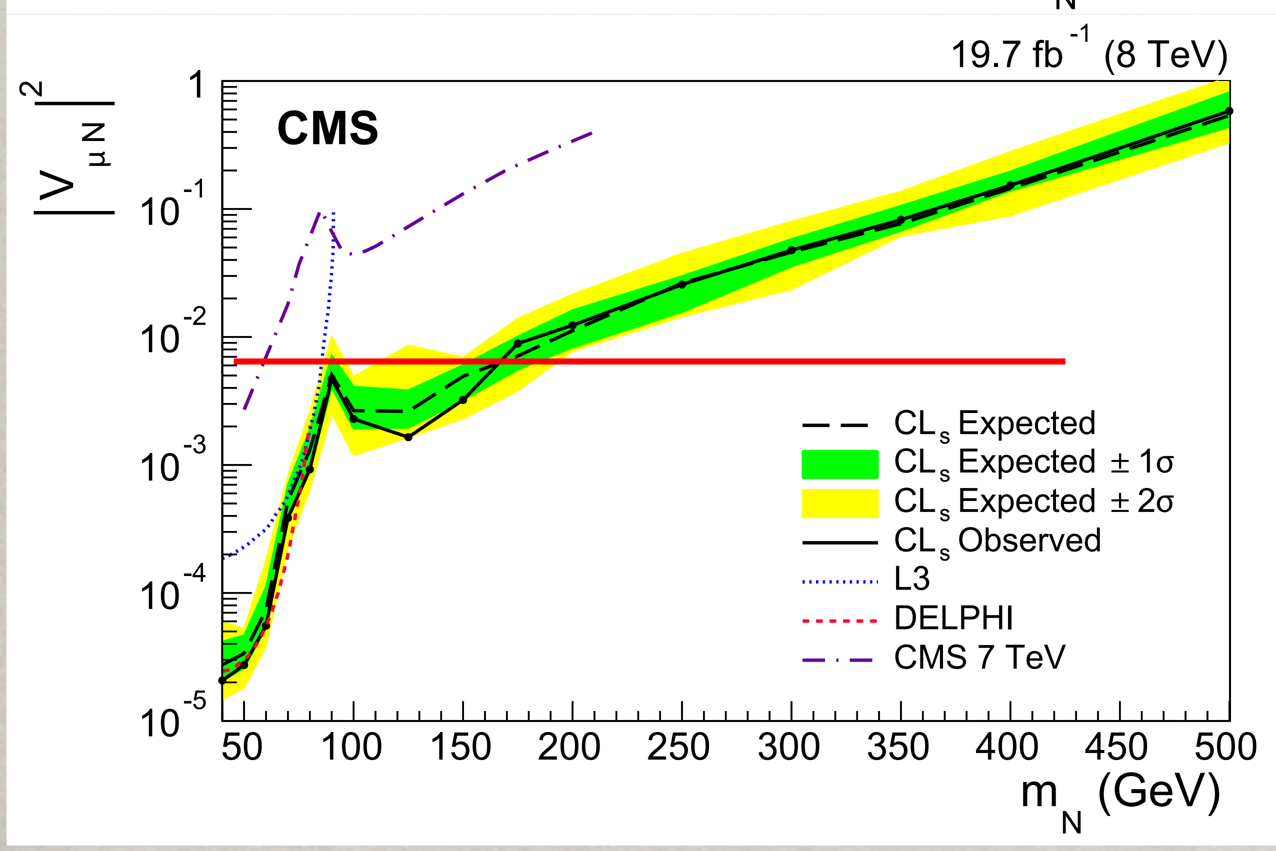
plot taken from Deppisch, Dev, Pilaftsis, 2015
see also Gorbunov and Shaposhnikov, 2007; Atre, Han, Pascoli, Zhang, 2009; …



CMS:

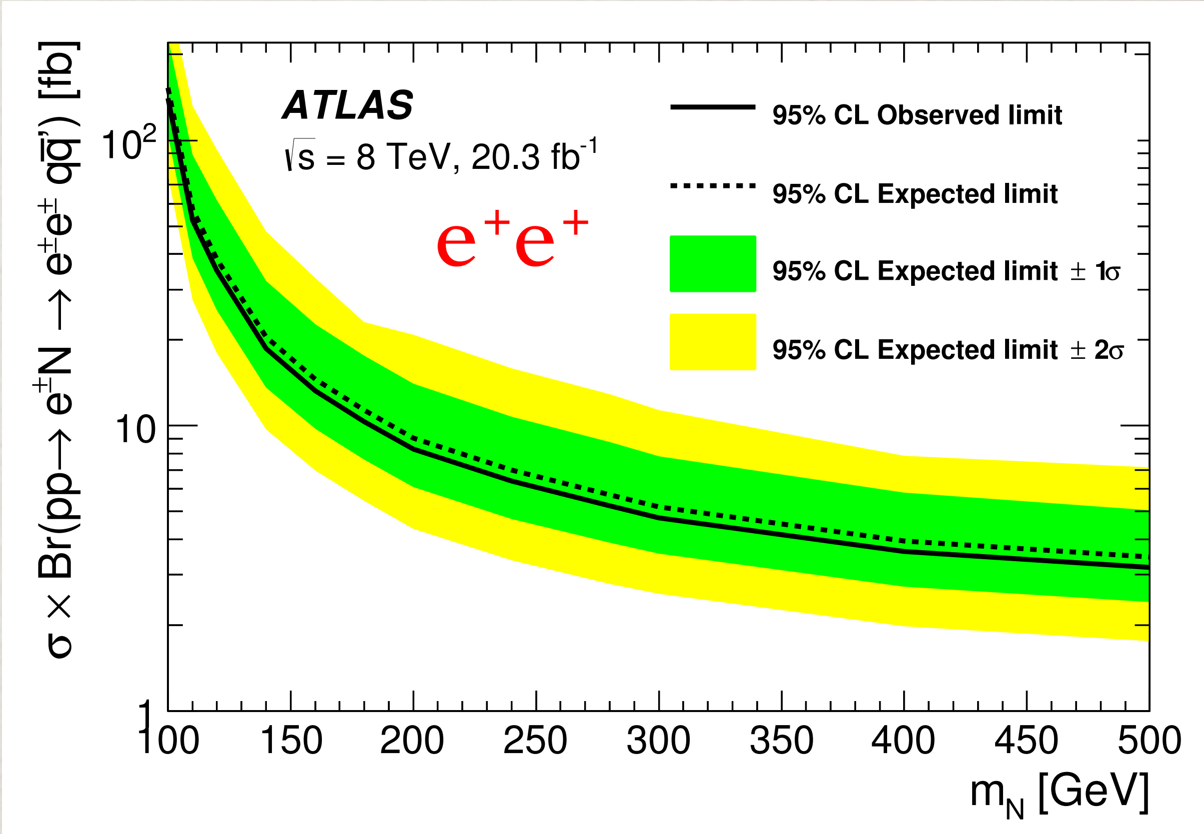
CMS collaboration: arXiv:1501.05566v1.

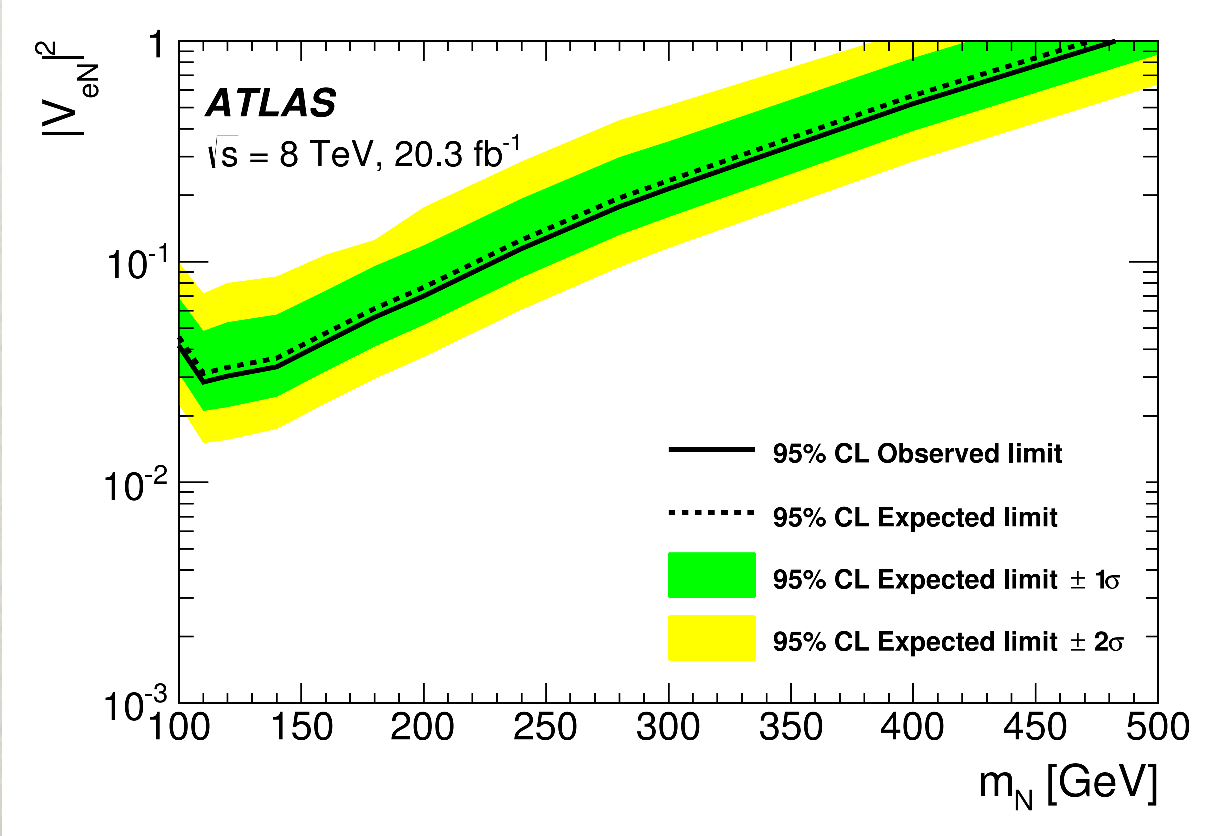




ATLAS:

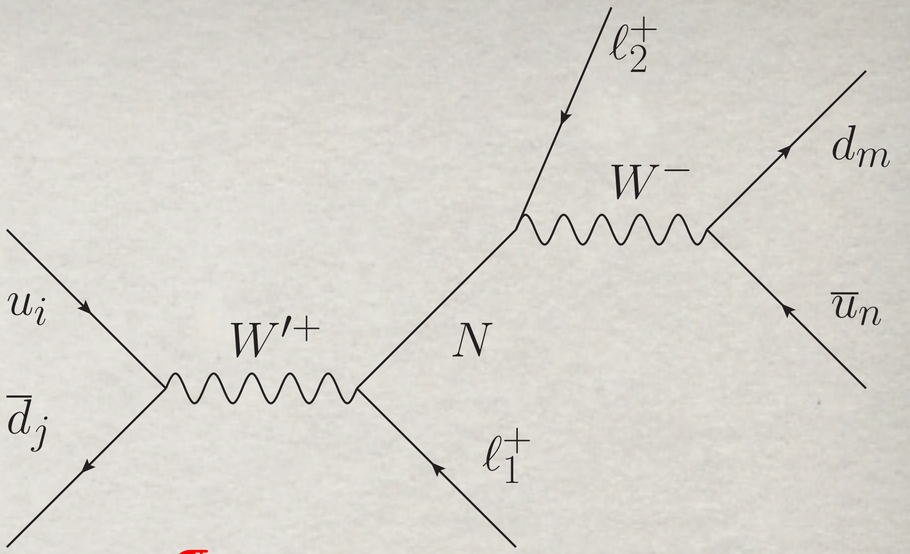
ATLAS collaboration: arXiv:1506.06020v2.





(2). W_R & N_R:

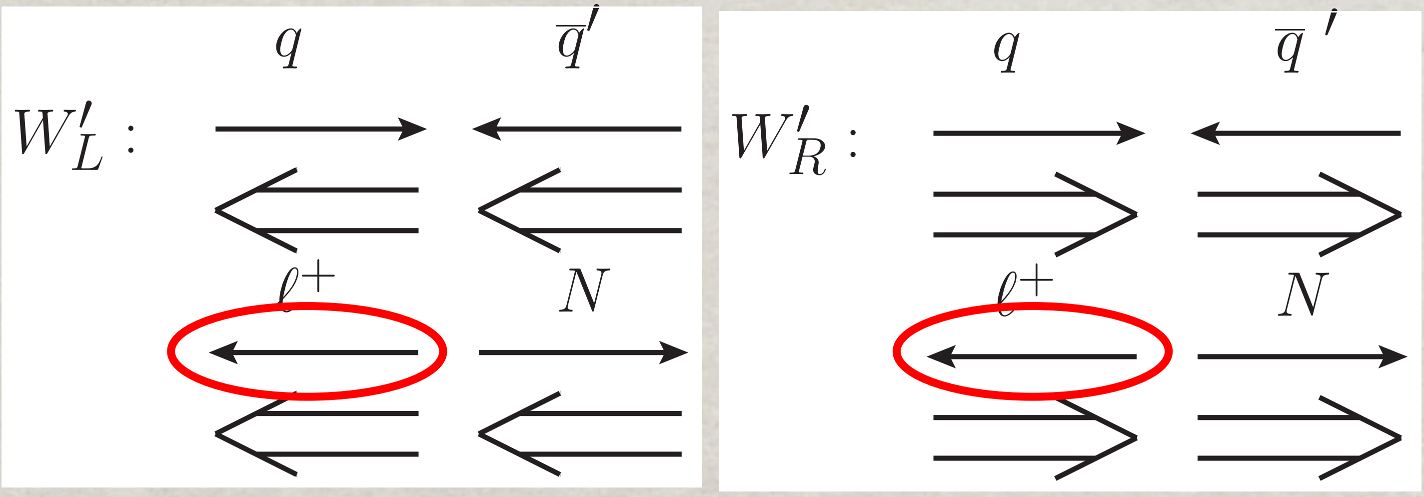
$SU(2)_L \otimes SU(2)_R$ symmetric model:

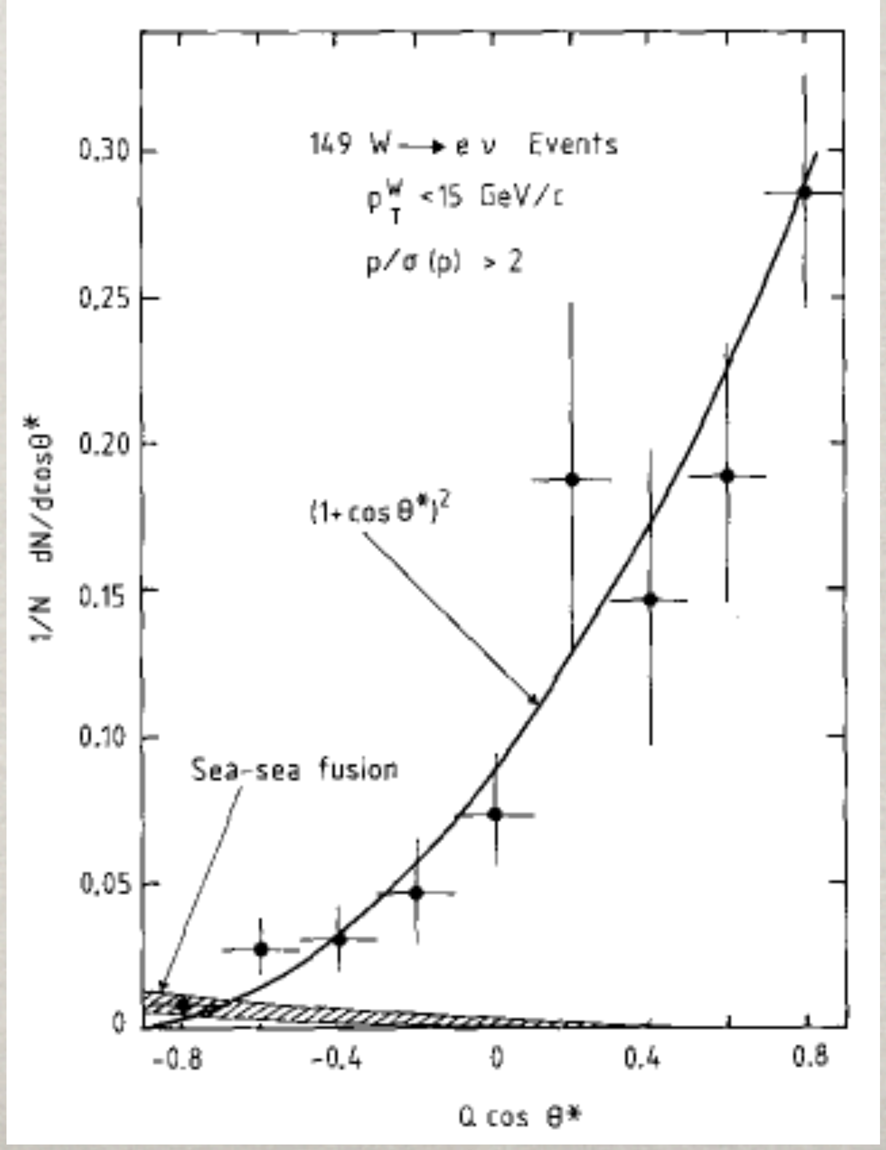


A clean channel with rich physics:†

- Significantly enhanced rate at W_R resonance; ¶
- If observed, determine N's nature: $\Delta L = 2$, azimuthal angle ...
- and determine W' chiral coupling to $\ell - N_{R,L}$ and $q - \bar{q}$.

The primary lepton does not provide L-R discrimination:

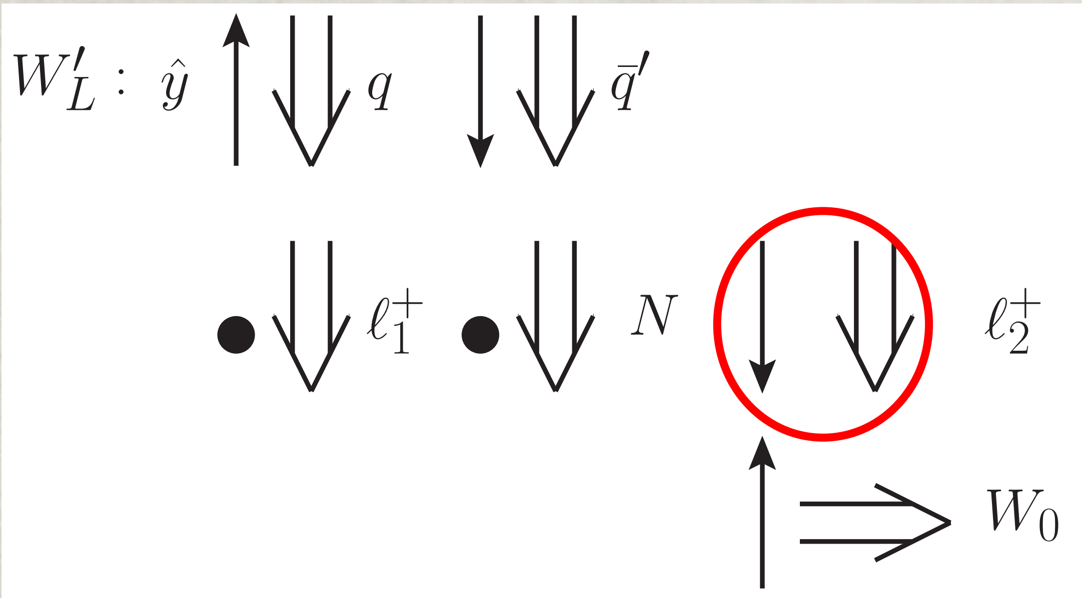


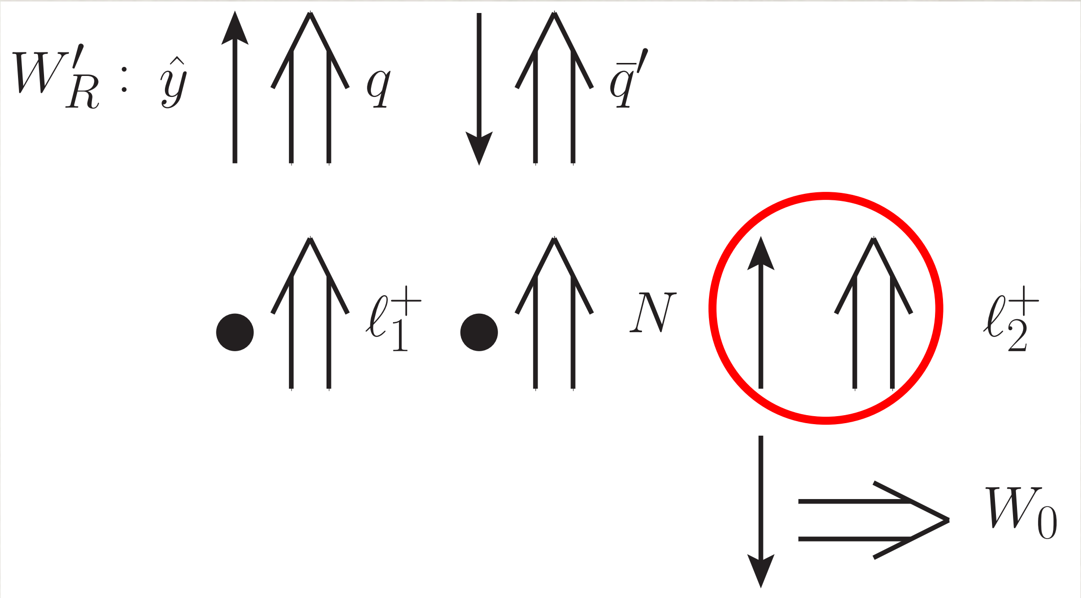


Keung & Senjanovic, PRL (1983).

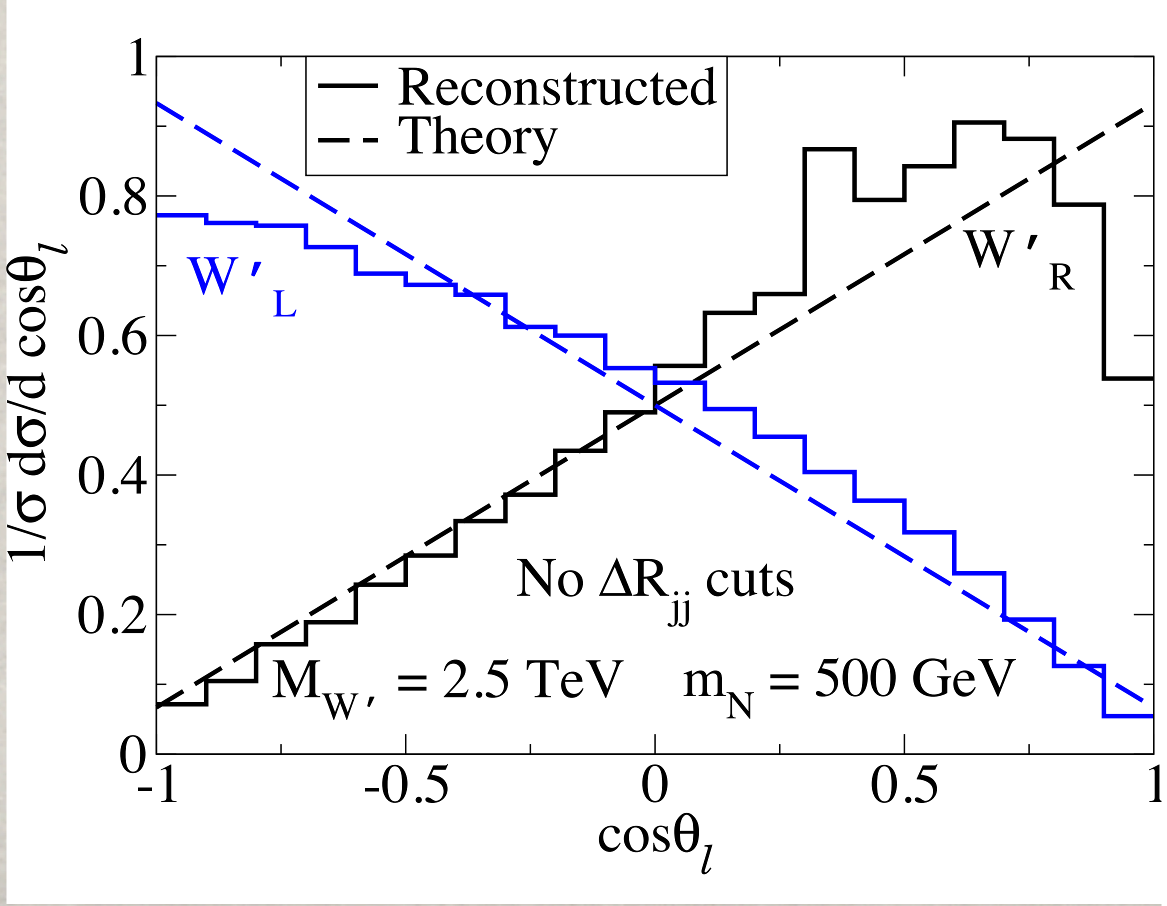
T. Han, I. Lewis, R. Ruiz, Z. Si, arXiv:1211.6447v2

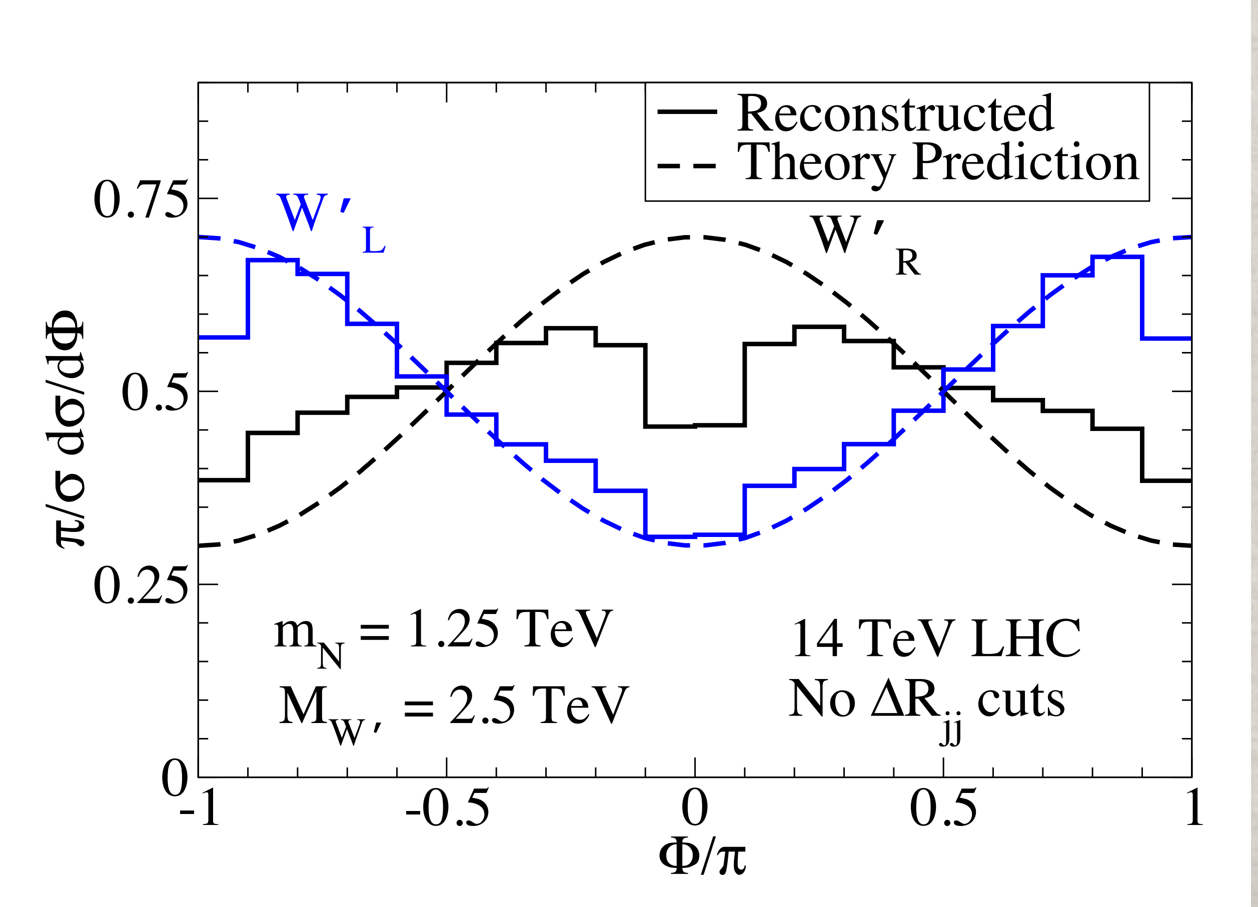
$W_{L,R}$ Discrimination via $N_{L,R}$ Decay:



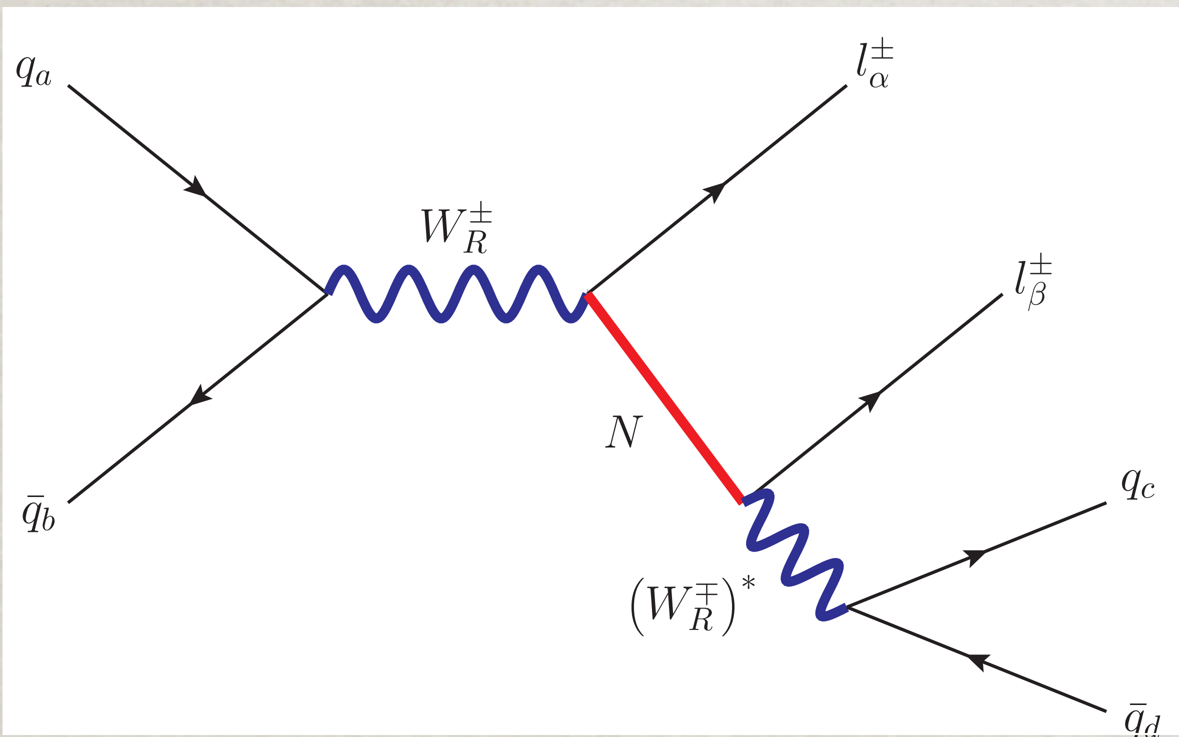


$$N_{L,R} \to \ell^+ W^- \to \ell^+ q\bar{q}'$$

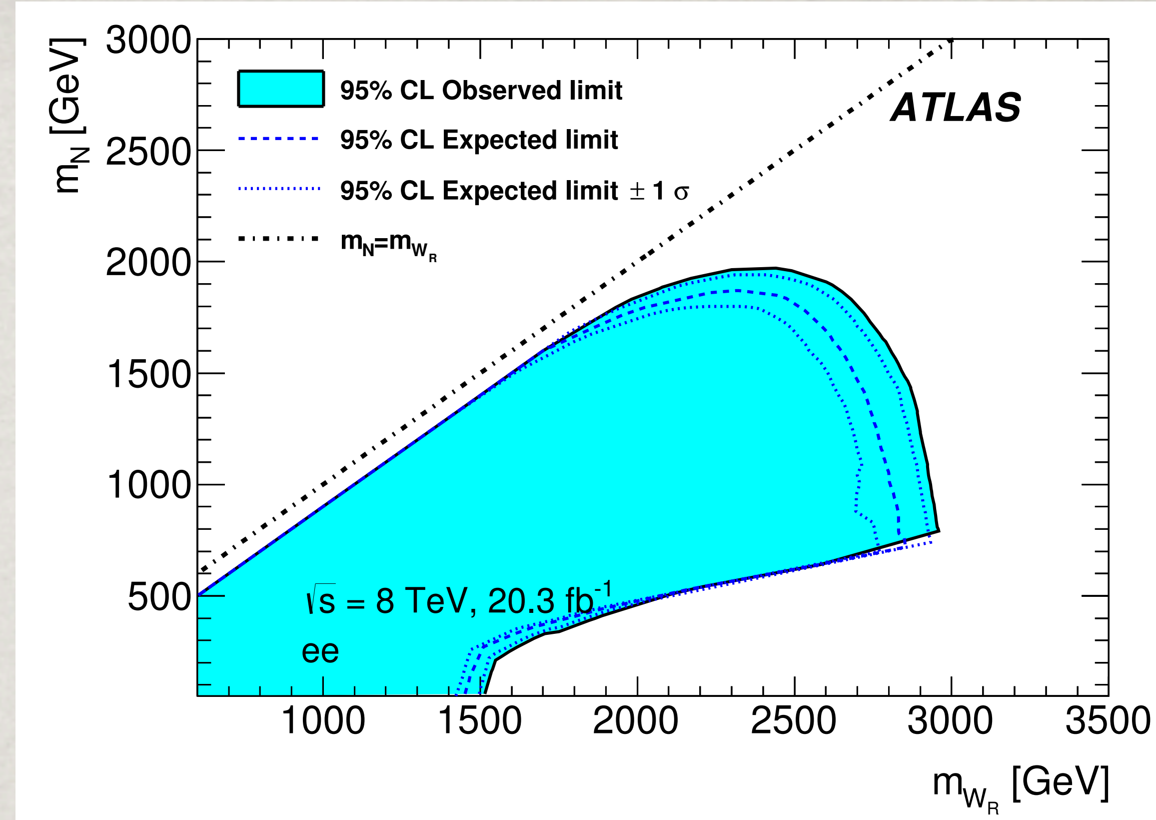




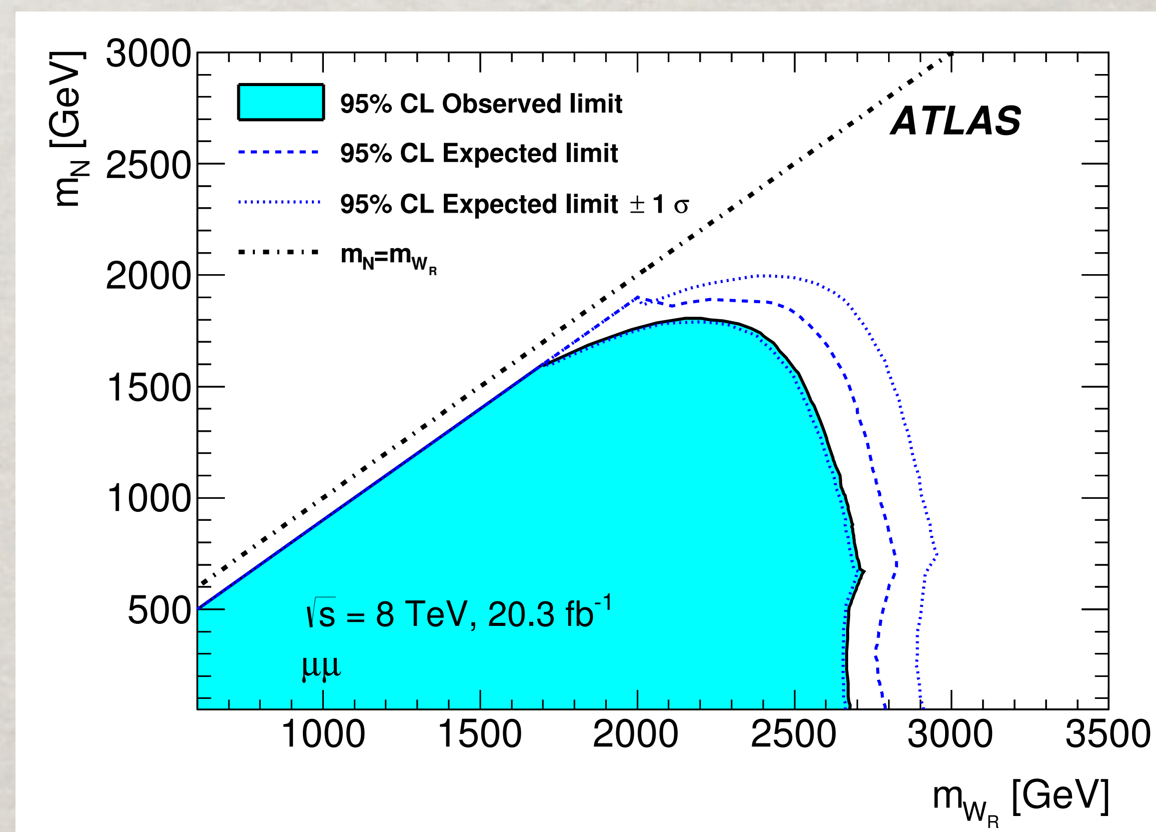
W_R & N @ ATLAS



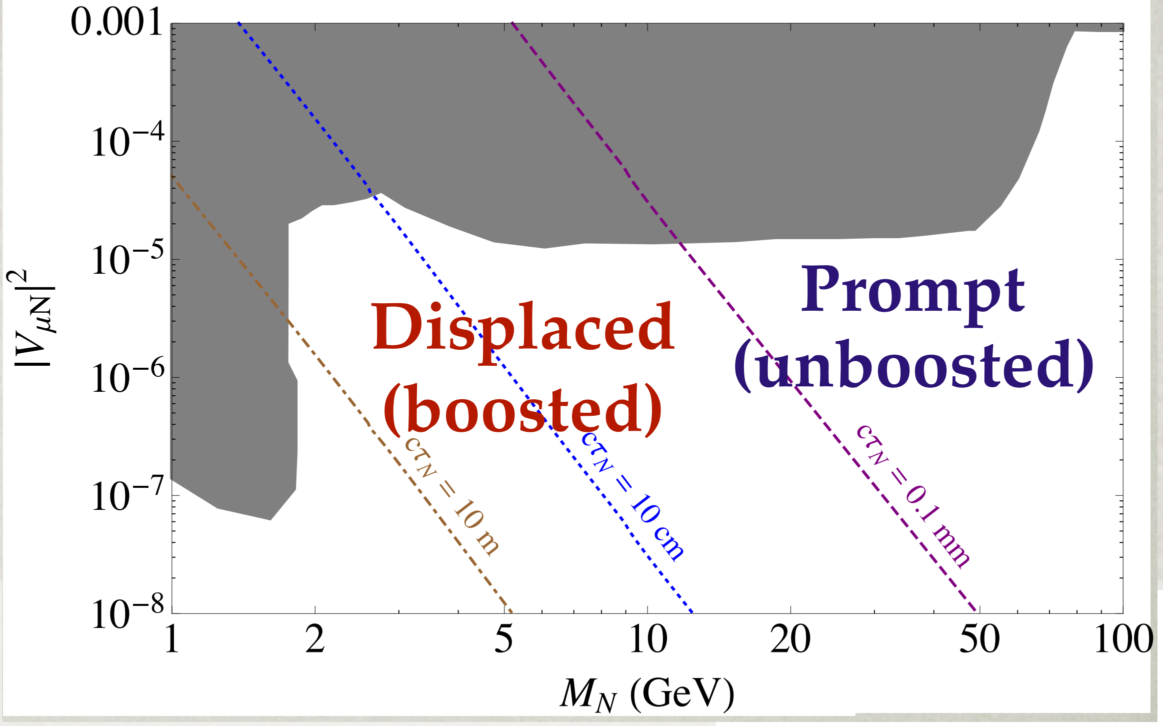
ATLAS collaboration: arXiv:1506.06020v2.



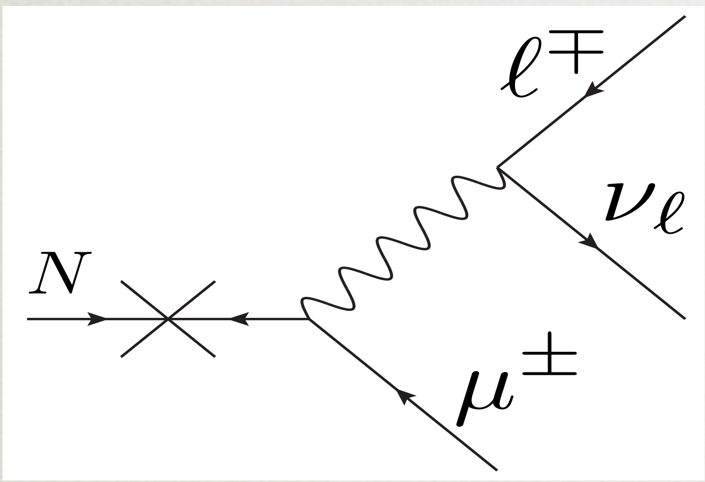
(a)



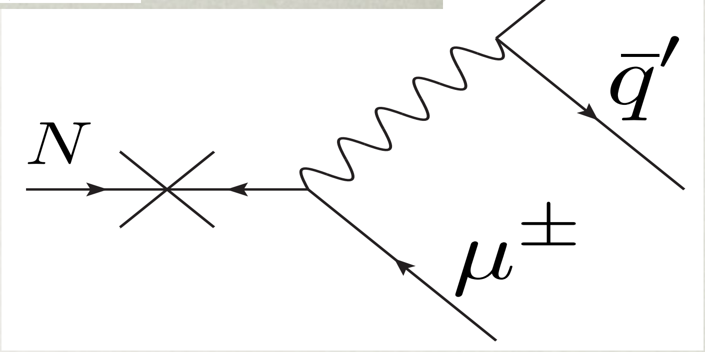
(3). Watch out the unconventional decay topology:



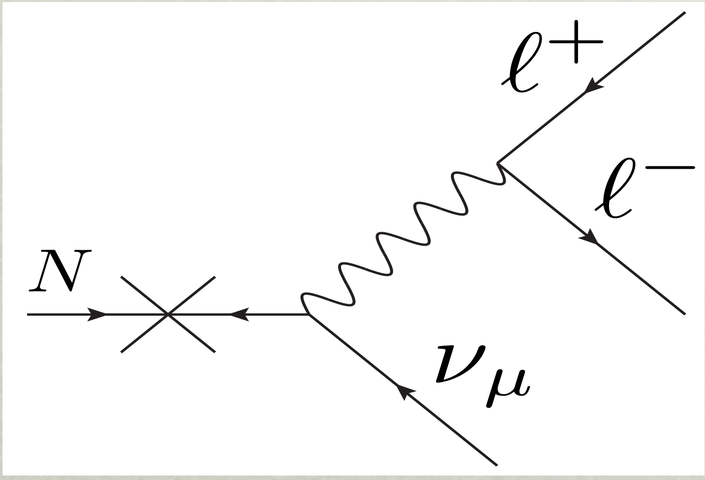
Izaguirre, Shuve (2015)



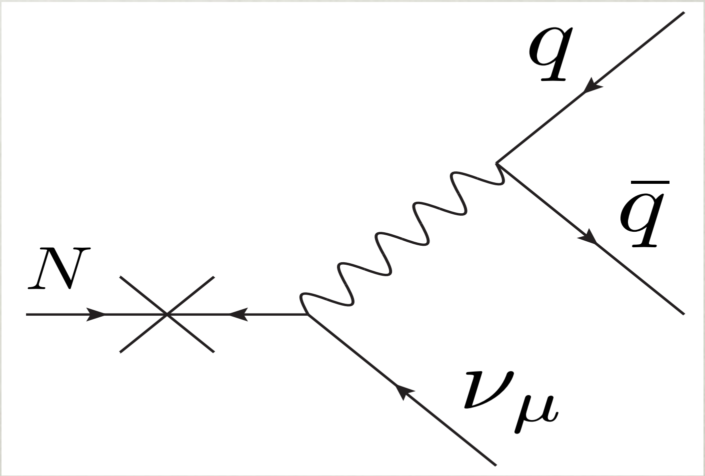
ATLAS displaced dilepton (1504.05162)
CMS displaced dilepton (1411.6977)
CMS "displaced SUSY" (1409.4789)



ATLAS displaced lepton + tracks (1504.05162)
ATLAS displaced jets (1504.03634)
CMS displaced jets (1411.6530)
CMS "displaced SUSY"



ATLAS displaced dilepton
CMS displaced dilepton
CMS "displaced SUSY"



ATLAS displaced jets
CMS displaced jets

(4). Many complementary channels:

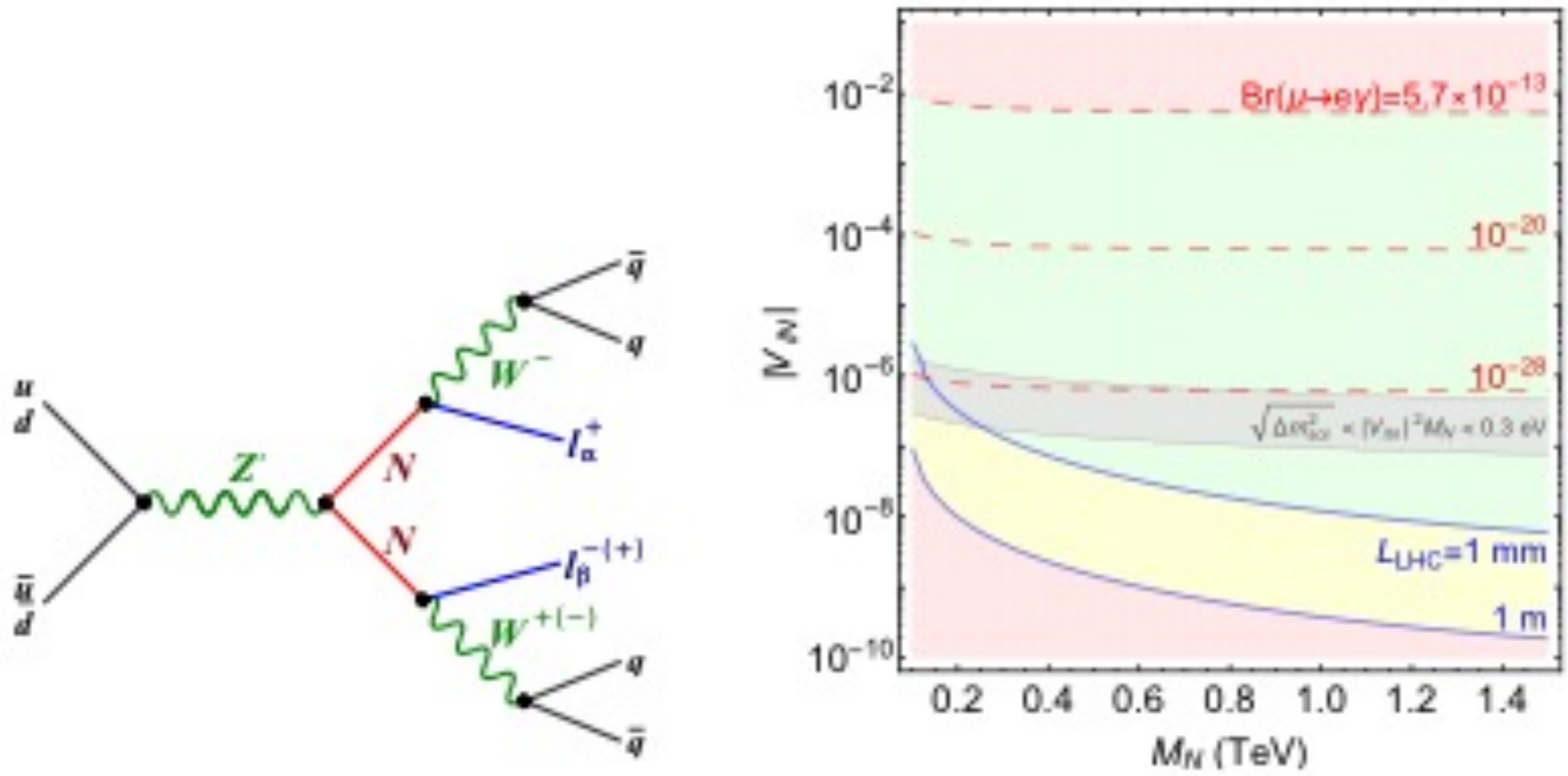


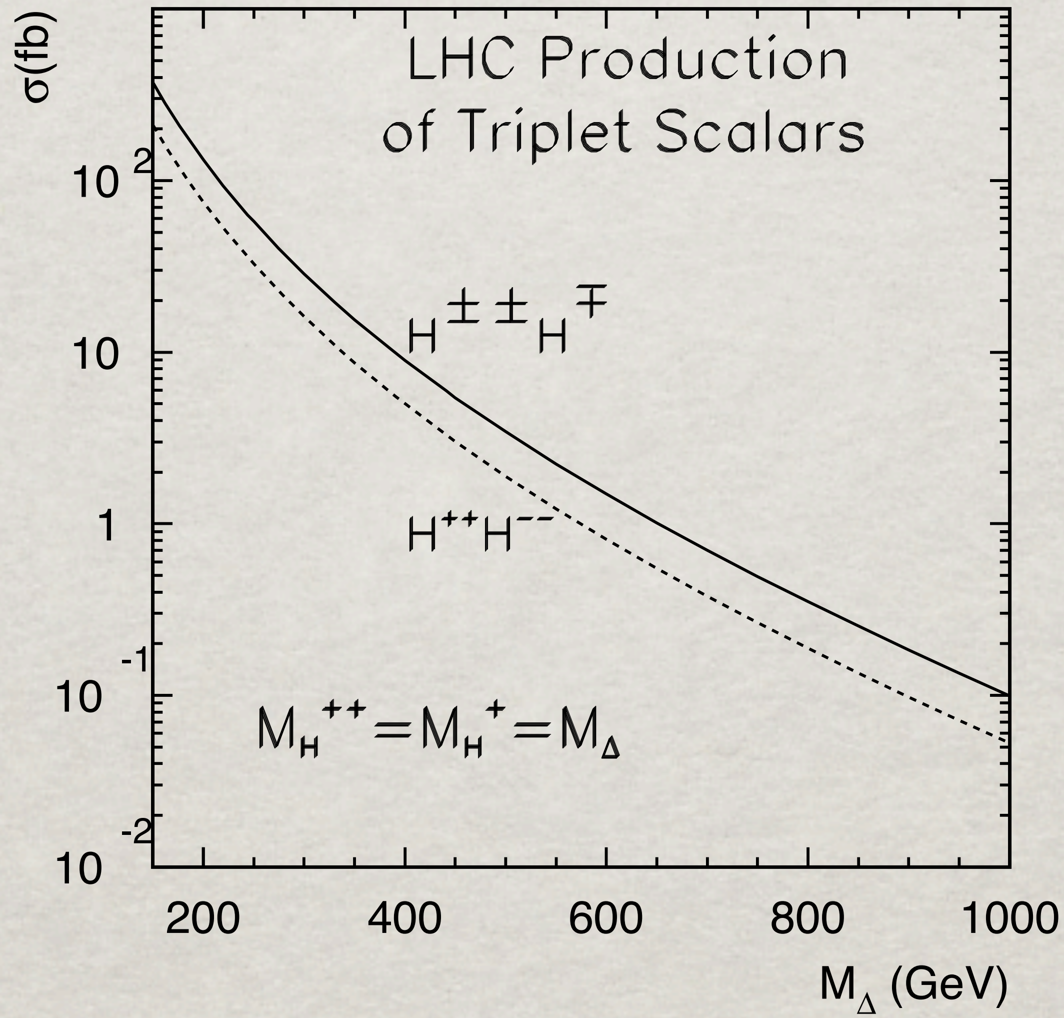
Figure 9. *Left:* Feynman diagram for heavy neutrino production via the Z' resonance. Right: Heavy neutrino decay length as a function of its mass M_N and mixing $V_{\ell N}$ (solid blue contours). The dashed red contours denote $\mathrm{Br}(\mu \to e\gamma)$, with the shaded red region on top excluded by the current MEG limit [294]. The gray shaded band highlights the parameter range where light neutrino mass scales between $\sqrt{\Delta m^2_{\rm sol}}$ and 0.3 eV are generated within the canonical type-I seesaw mechanism.

Deppisch, Dev, Pilaftsis (2015); Datta, Guchait, Pilaftsis (1994); del Aguila, Aguilar-Saavedra, Pittau (2007)

Type II Seesaw: $H^{\pm\pm}$ & $H^{\pm}$

$H^{++}H^{--}$ production at hadron colliders: †

Pure electroweak gauge interactions



$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY.

†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

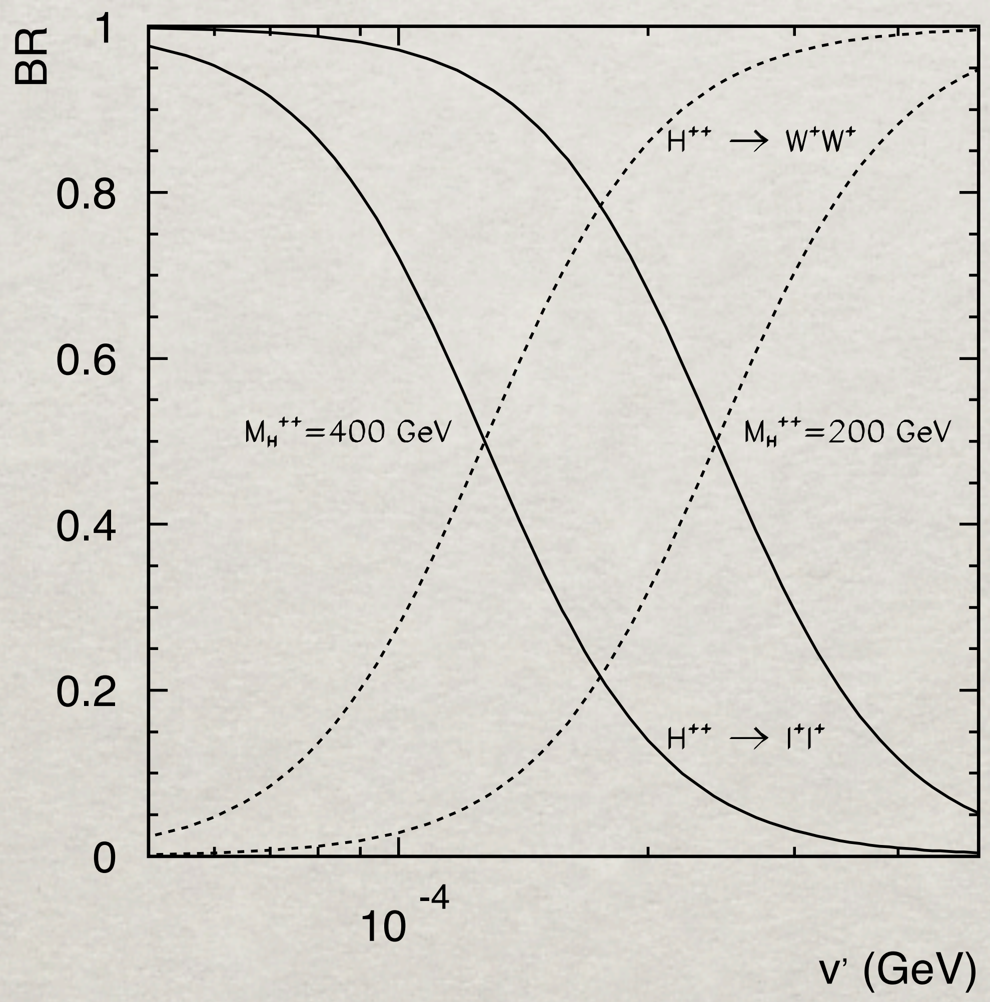
Akeroyd, Aoki, Sugiyama, 2005, 2007.

Type II Seesaw: Complimentary Decays

$\Gamma(\phi^{++} \to \ell^+\ell^+) \propto Y_{ij}^2 M_\phi$

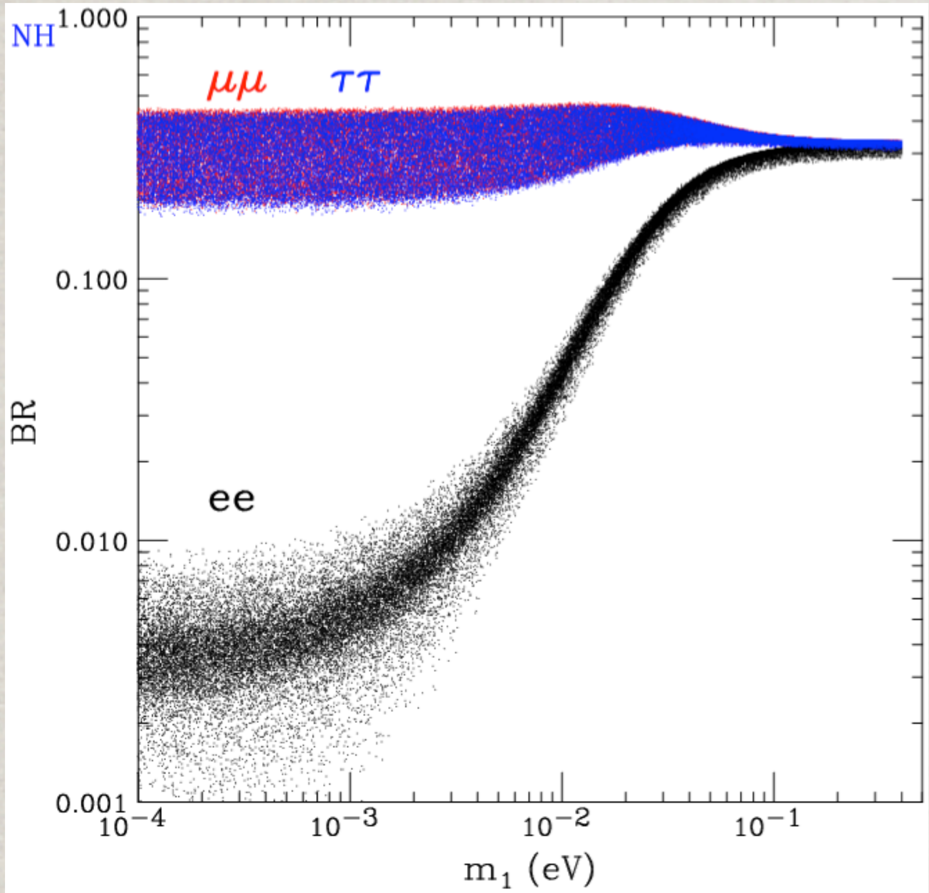
$\Gamma(\phi^{++} \to W^+W^+) \propto \frac{v'^2 M_\phi^3}{v^4},$

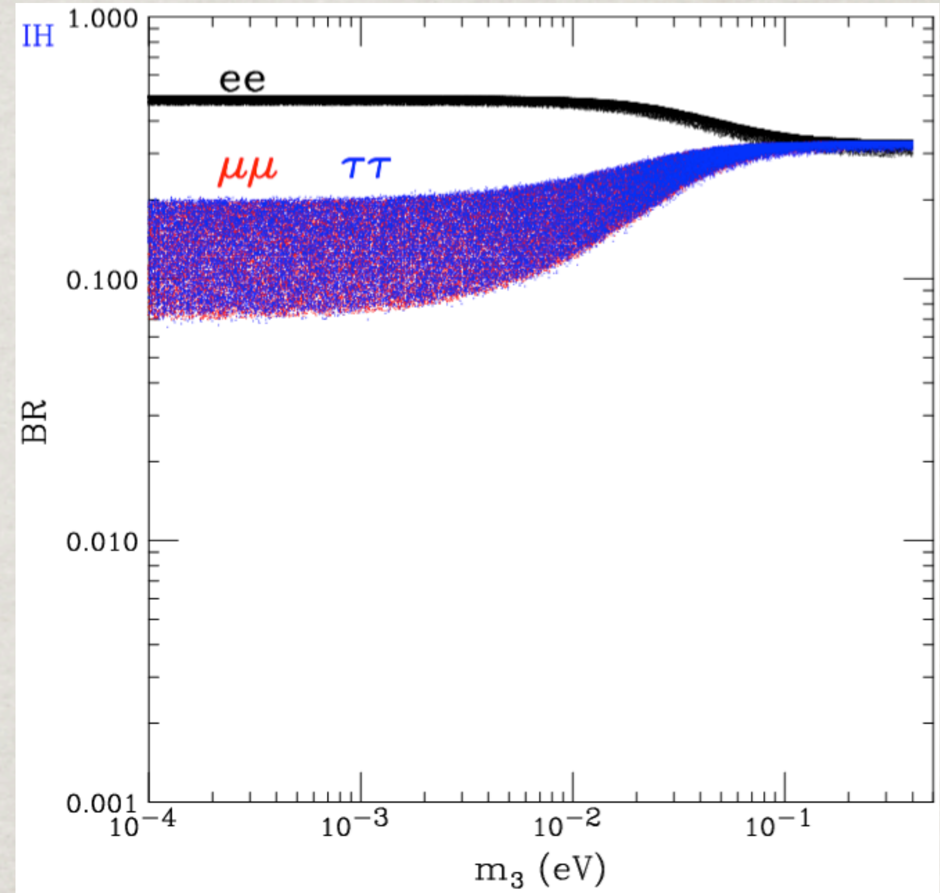
with $\quad Y_{ll}v' \approx m_\nu\ (eV) \Rightarrow v' \approx 2 \times 10^{-4}$ GeV the division.

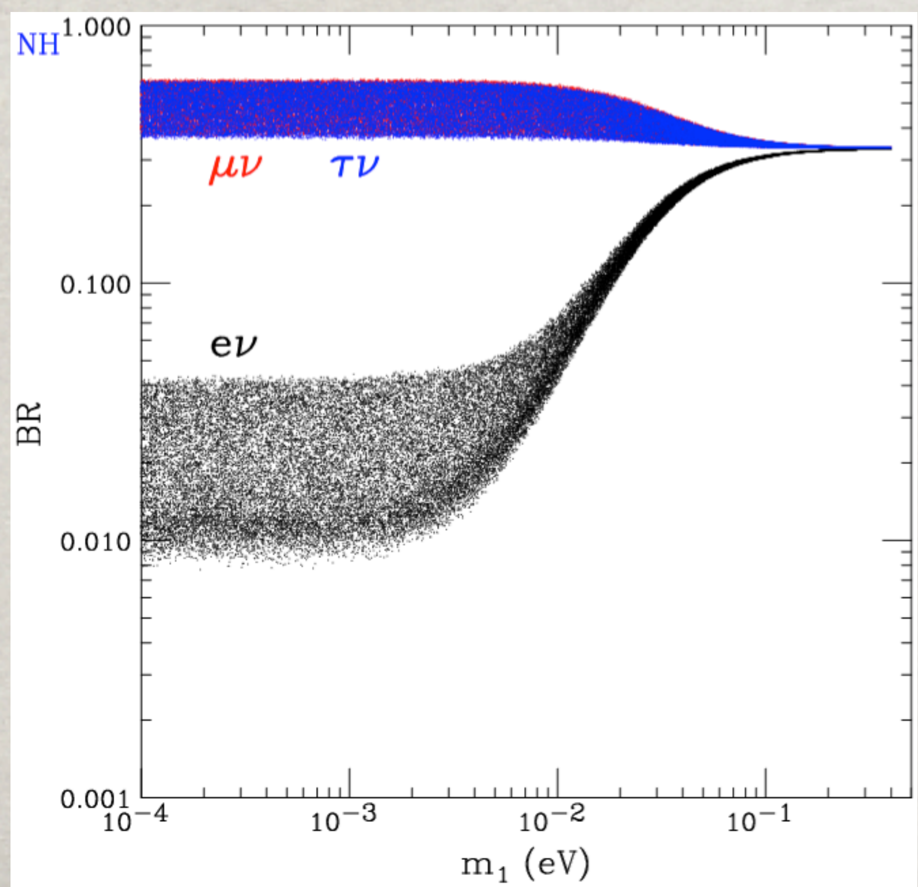


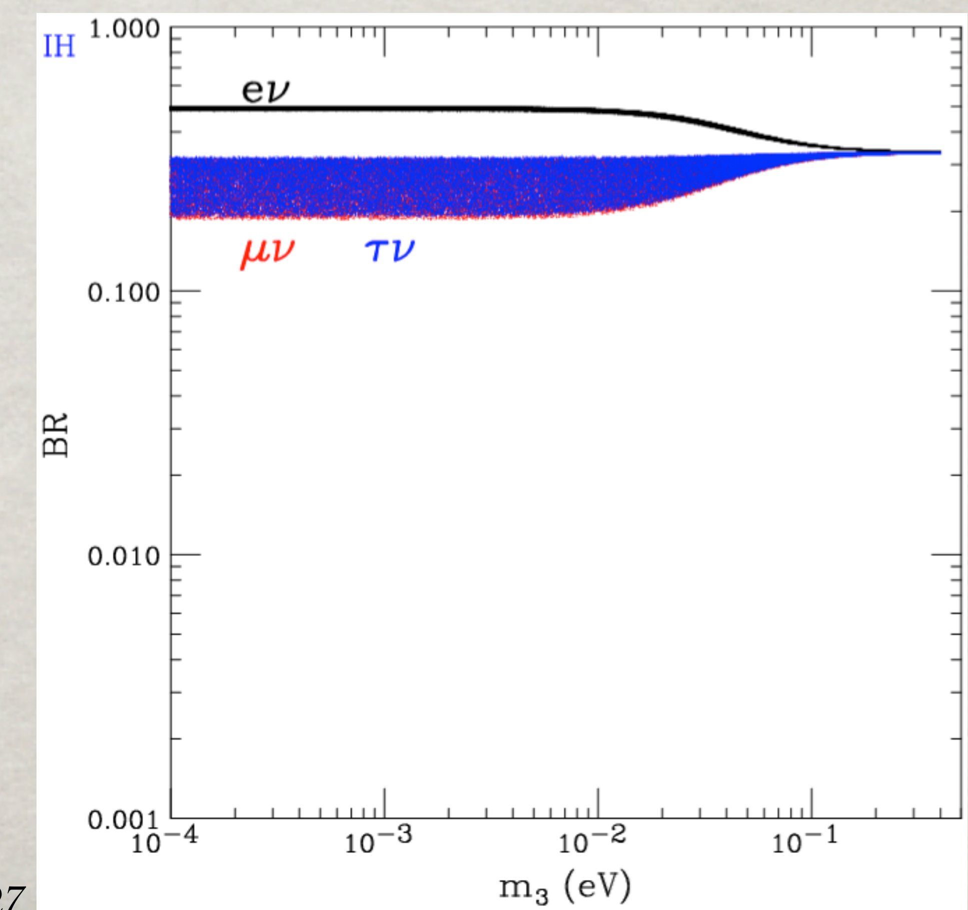
We will focus on the leptonic decays, with a small v'.

$H^{++,--}$, $H^{+,-}$ Decays: Revealing the flavor pattern



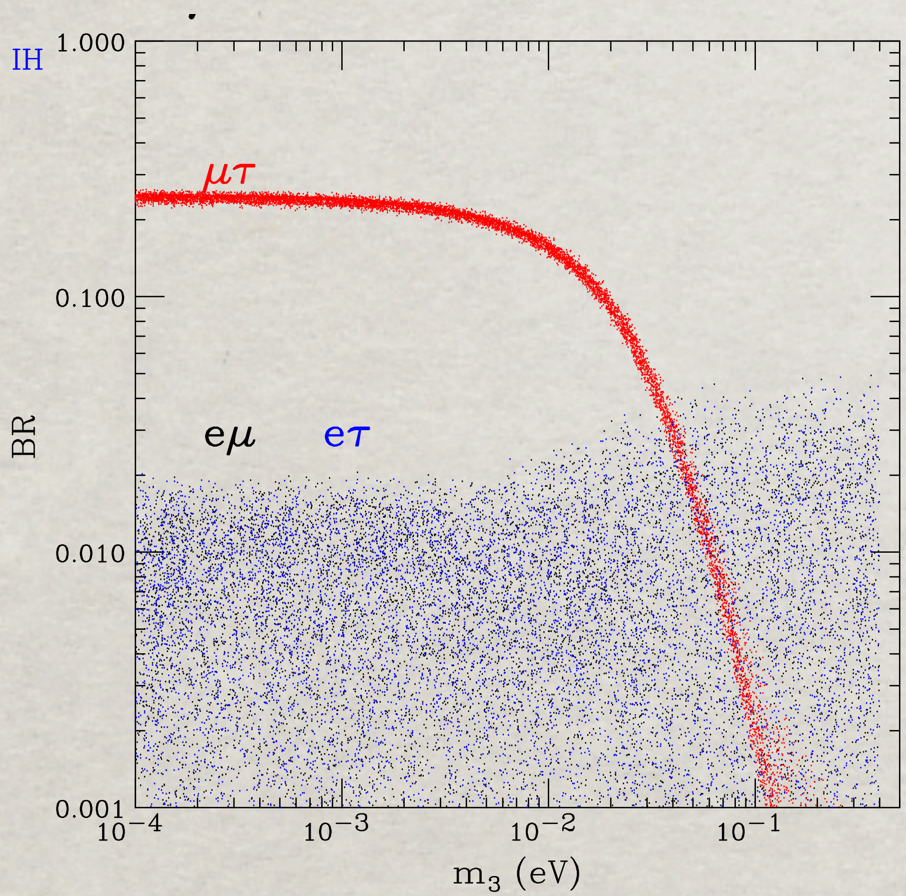




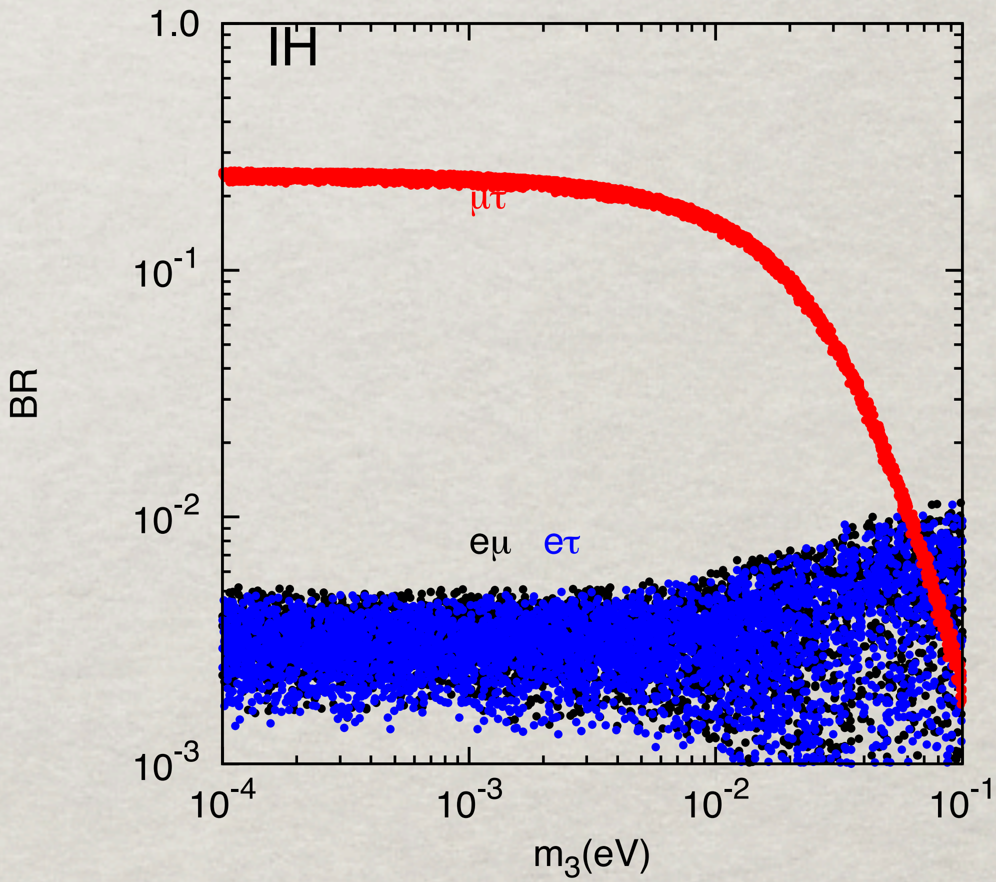


Low-energy/High energy complementarity:

Before DayaBay



With DayaBay



†TH, Gui-Yu Huang, Tong Li, to appear.

Neutrino – charged lepton correlations

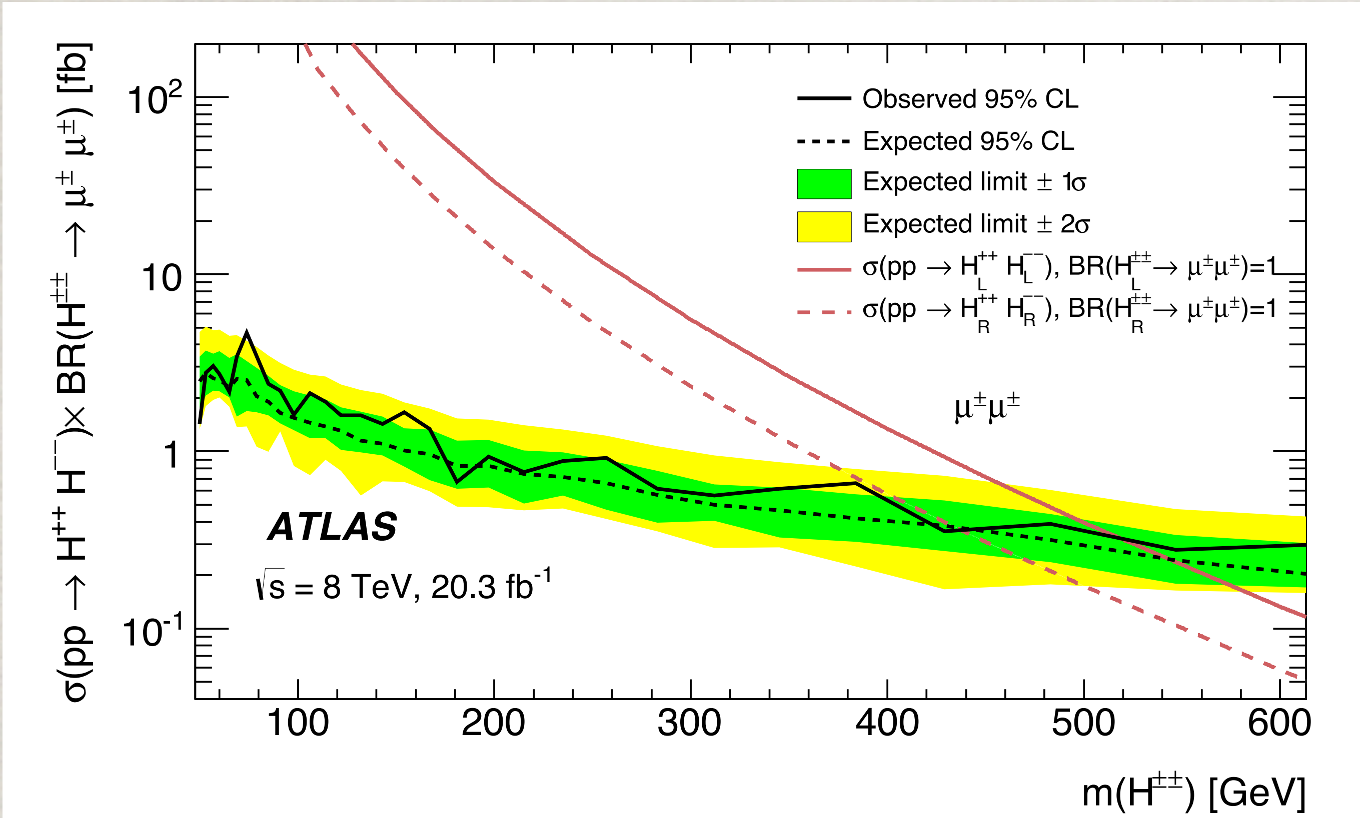
Summarize the discovery modes:

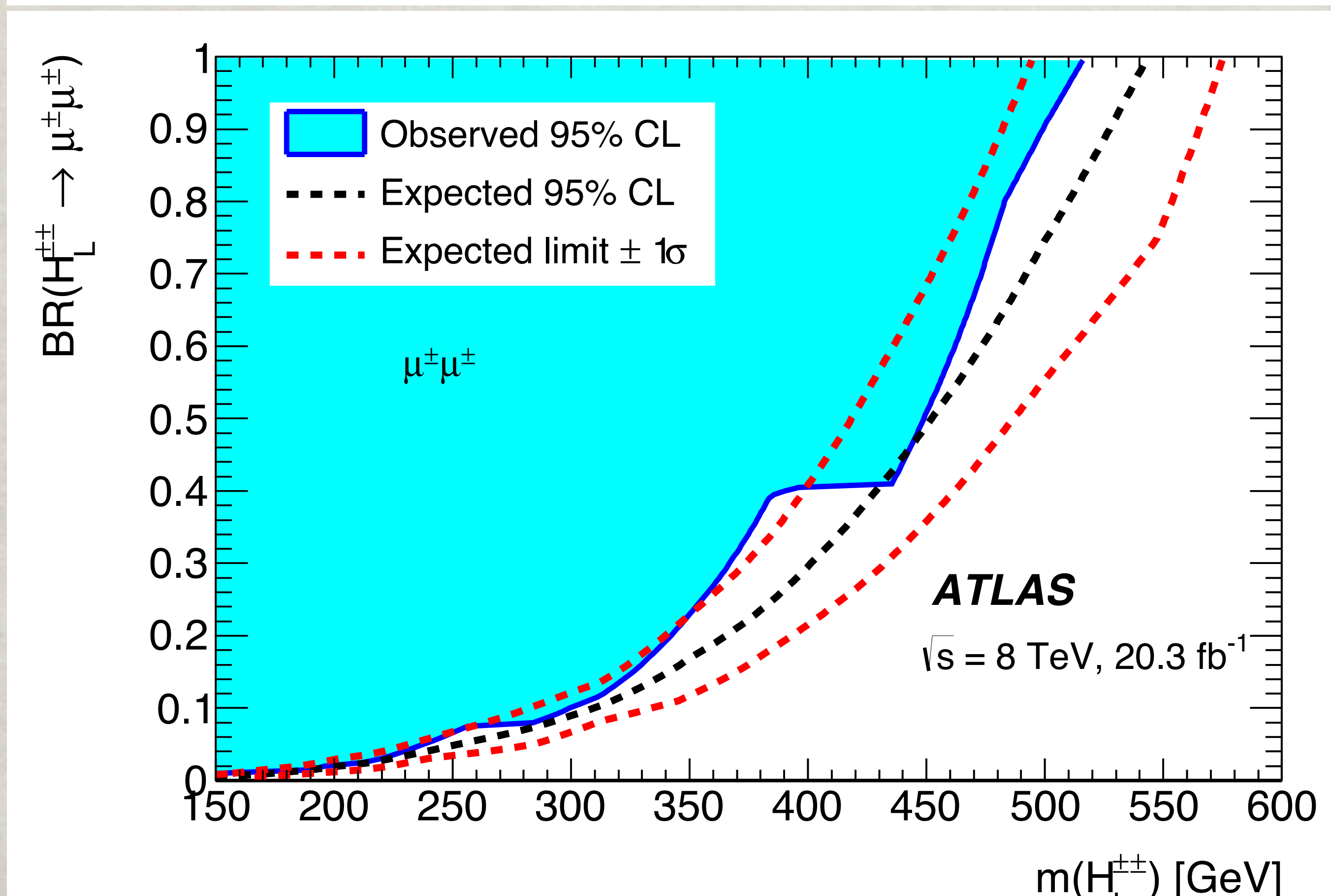
Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	BR($H^{++} \to \tau^+\tau^+$), BR($H^{++} \to \mu^+\mu^+$) $\gg$ BR($H^{++} \to e^+e^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\mu^+$), BR($H^{++} \to e^+\tau^+$) BR($H^{+} \to \tau^+\bar{\nu}$), BR($H^{+} \to \mu^+\bar{\nu}$) $\gg$ BR($H^{+} \to e^+\bar{\nu}$)
Inverted Hierarchy ($\Delta m^2_{31} < 0$)	BR($H^{++} \to e^+e^+$) $>$ BR($H^{++} \to \mu^+\mu^+$), BR($H^{++} \to \tau^+\tau^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\tau^+$), BR($H^{++} \to e^+\mu^+$) BR($H^{+} \to e^+\bar{\nu}$) $>$ BR($H^{+} \to \mu^+\bar{\nu}$), BR($H^{+} \to \tau^+\bar{\nu}$)
Quasi-Degenerate ($m_1, m_2, m_3 > \|\Delta m_{31}\|$)	BR($H^{++} \to e^+e^+$) $\sim$ BR($H^{++} \to \mu^+\mu^+$) $\sim$ BR($H^{++} \to \tau^+\tau^+$) $\approx 1/3$ BR($H^{+} \to e^+\bar{\nu}$) $\sim$BR($H^{+} \to \mu^+\bar{\nu}$) $\sim$BR($H^{+} \to \tau^+\bar{\nu}$) $\approx 1/3$

† Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

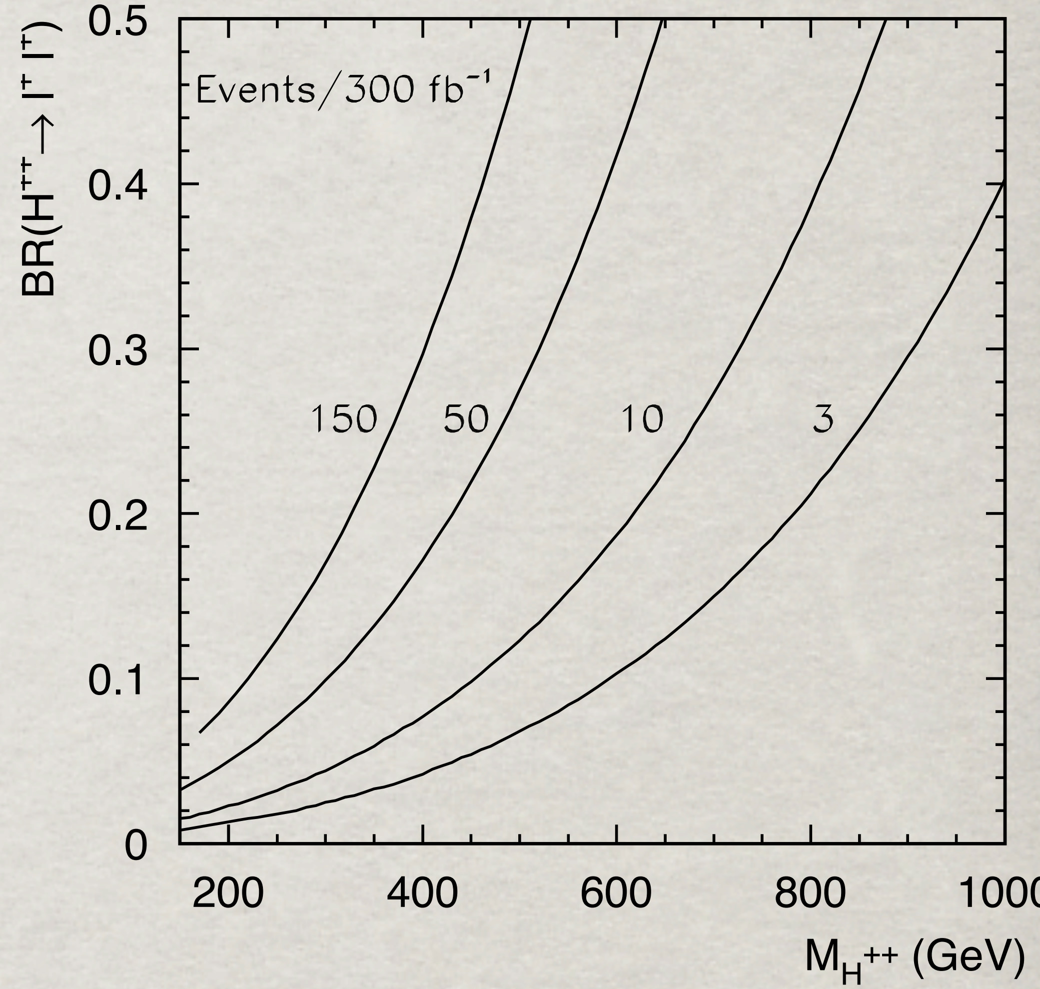
ATLAS Bounds:

ATLAS collaboration: arXiv:1412.0237v2.





Nearly background-free.



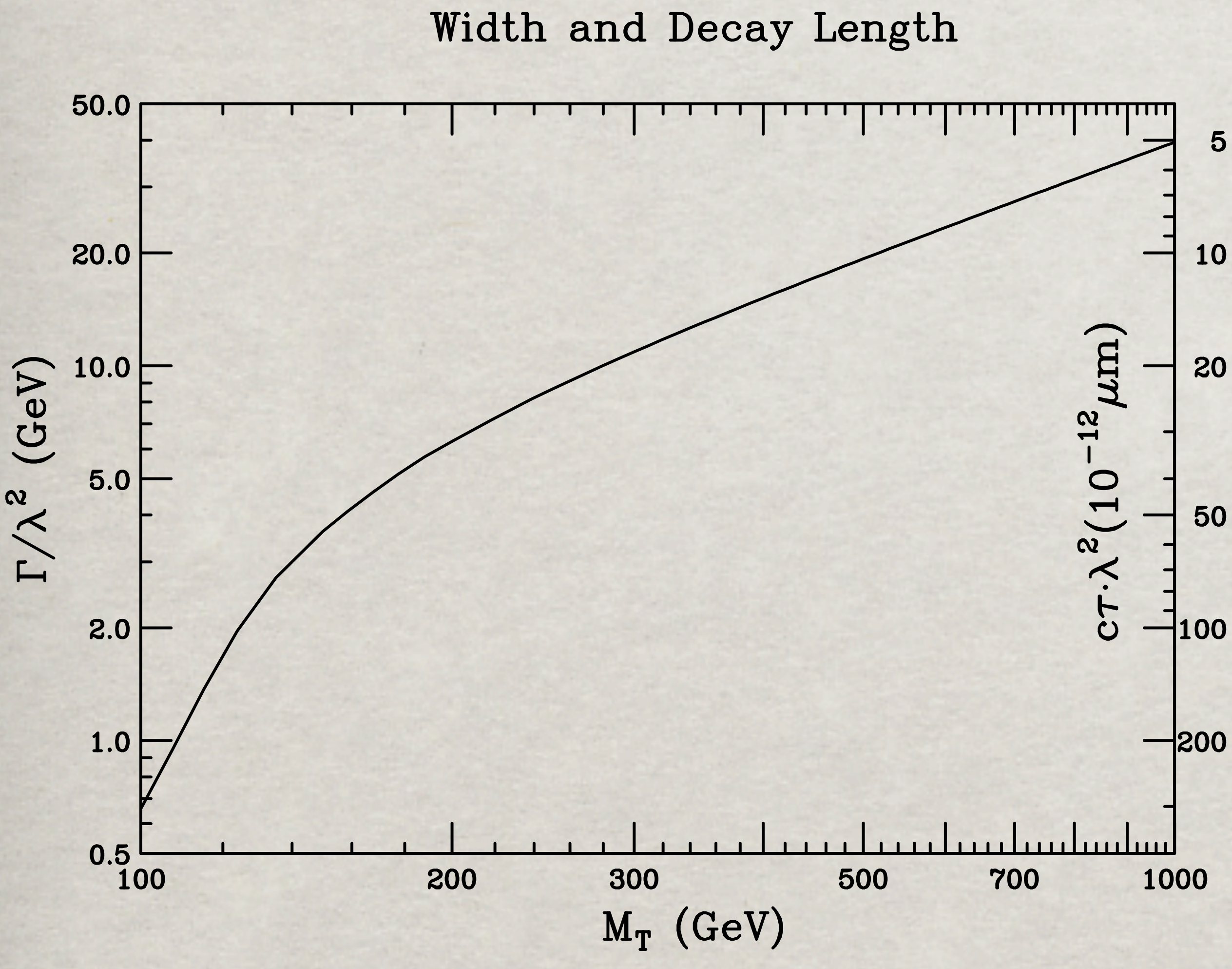
With 300 fb^{-1},

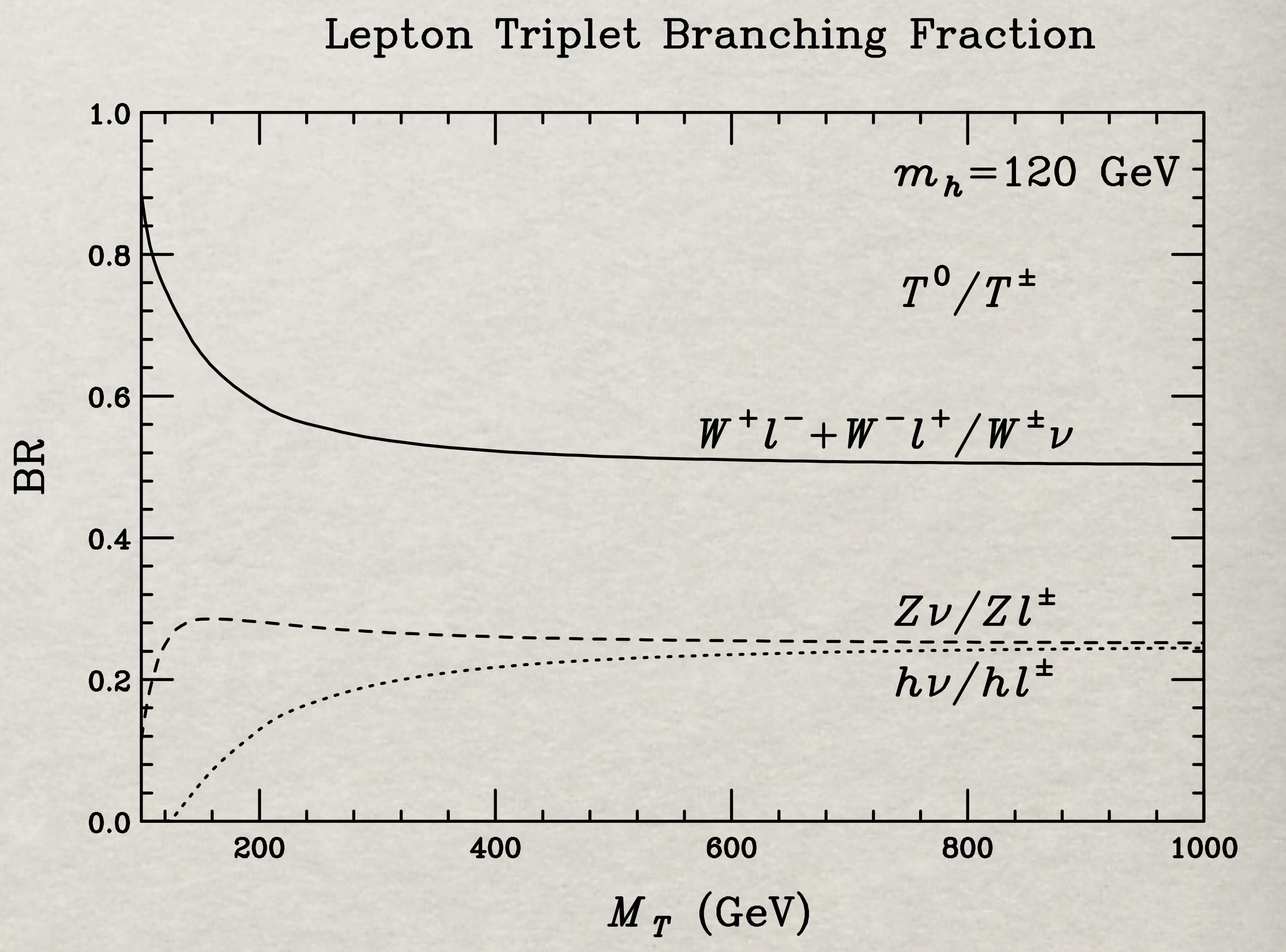
M_H~1 TeV with BR~ 40%

Type III Seesaw: $T^{\pm}$ & T^0

Consider their decay length:

$$\Gamma(T^+ \to W^+\nu) \approx 2\Gamma(T^+ \to Z\ell^+) \approx 2\Gamma(T^+ \to h\ell^+)$$
$$\approx \Gamma(T^0 \to W^+\ell^- + W^-\ell^+) \approx \frac{M_T}{16\pi}\sum_i |y_i|^2.$$





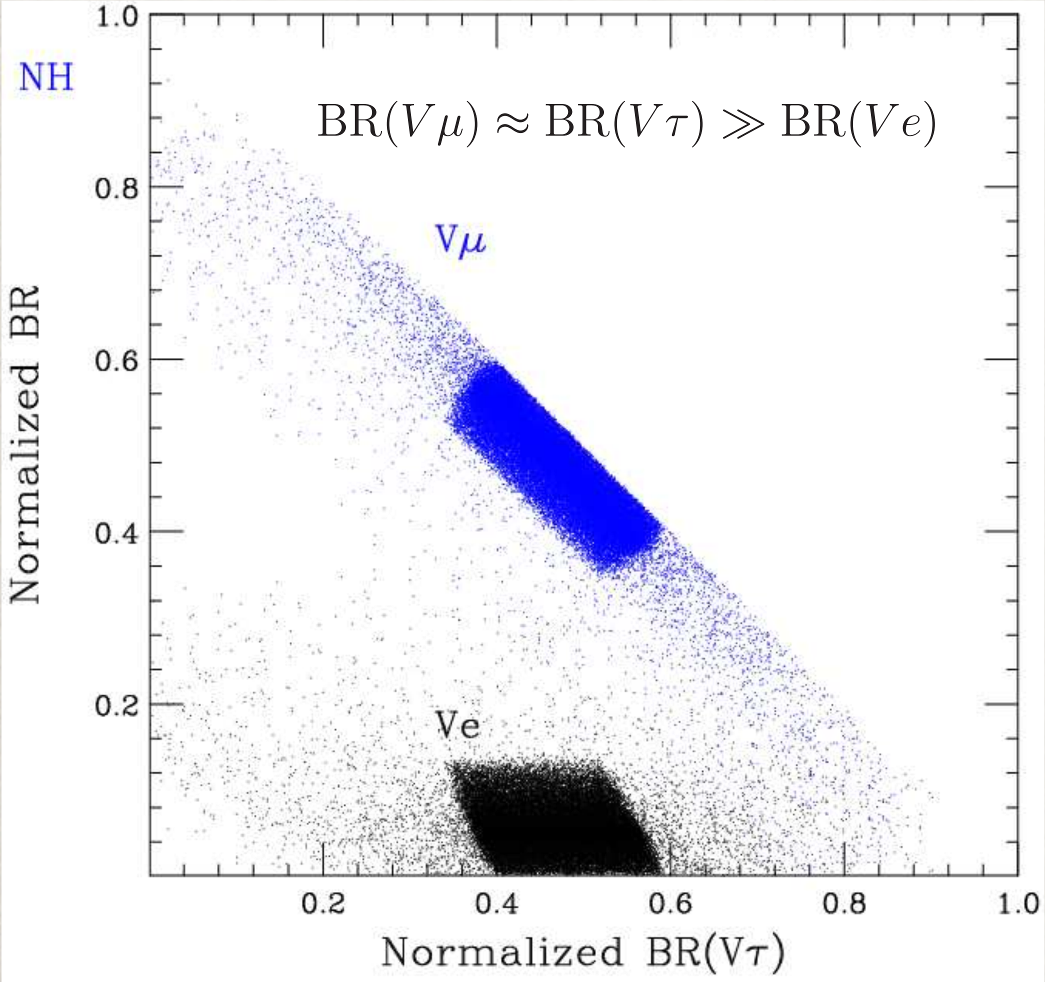
With $\lambda^2 = y_j^2 \sim 10^{-16} - 10^{-12}$, then $c\tau \sim 10^{-2} - 10^{-4}$ m

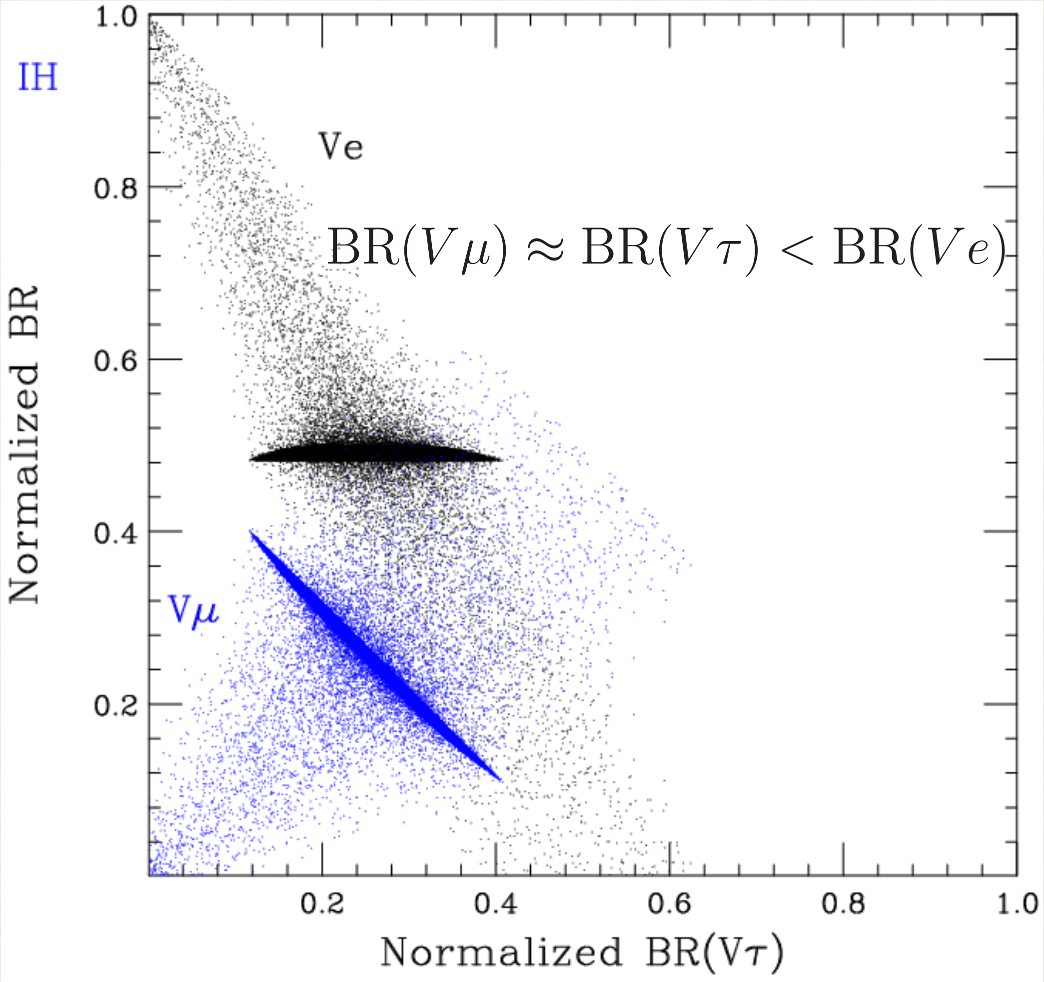
Still not too long-lived, but possibly large displaced vertices.

Type III Seesaw: $T^{\pm}$ & T^0

Lepton flavor combination determines the ν mass pattern: †

$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \quad BR(T^{\pm,0} \to W^{\pm}\ell,\ Z\ell) \sim y_T^2 \sim V_{PMNS}^2\ \frac{M_T m_\nu}{v^2}.$$

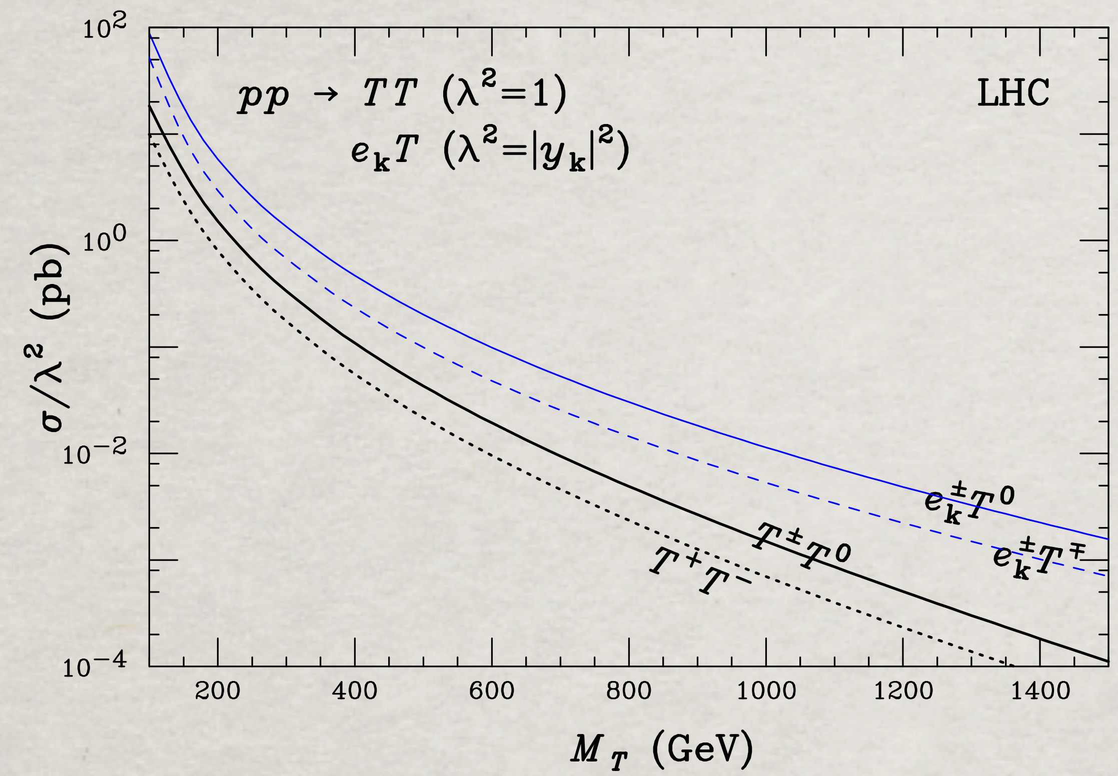


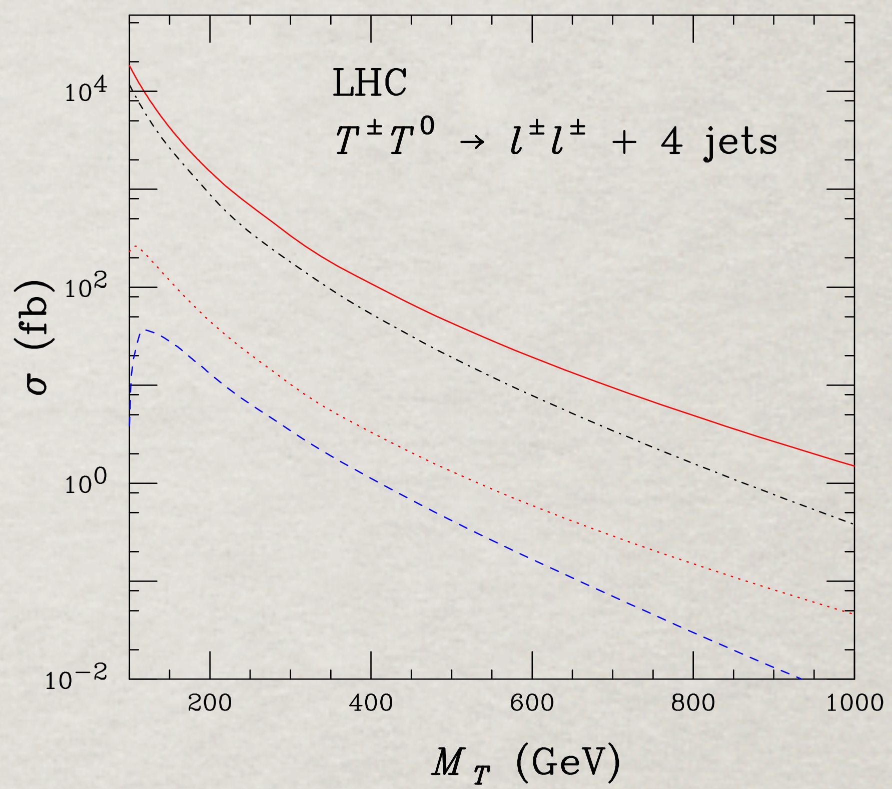


Lepton flavors correlate with the ν mass pattern.

†Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, Ivica Puljak, Goran Sejanovic, arXiv:0904.2390.

Type III Seesaw: $T^{\pm}$ & T^0





- Single production $T^{\pm}\ell^{\mp}$, $T^0\ell^{\pm}$:

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

Example: $T^{\pm} + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj$.
Low backgrounds.

- LHC studies with Minimal Flavor Violation implemented. ‡

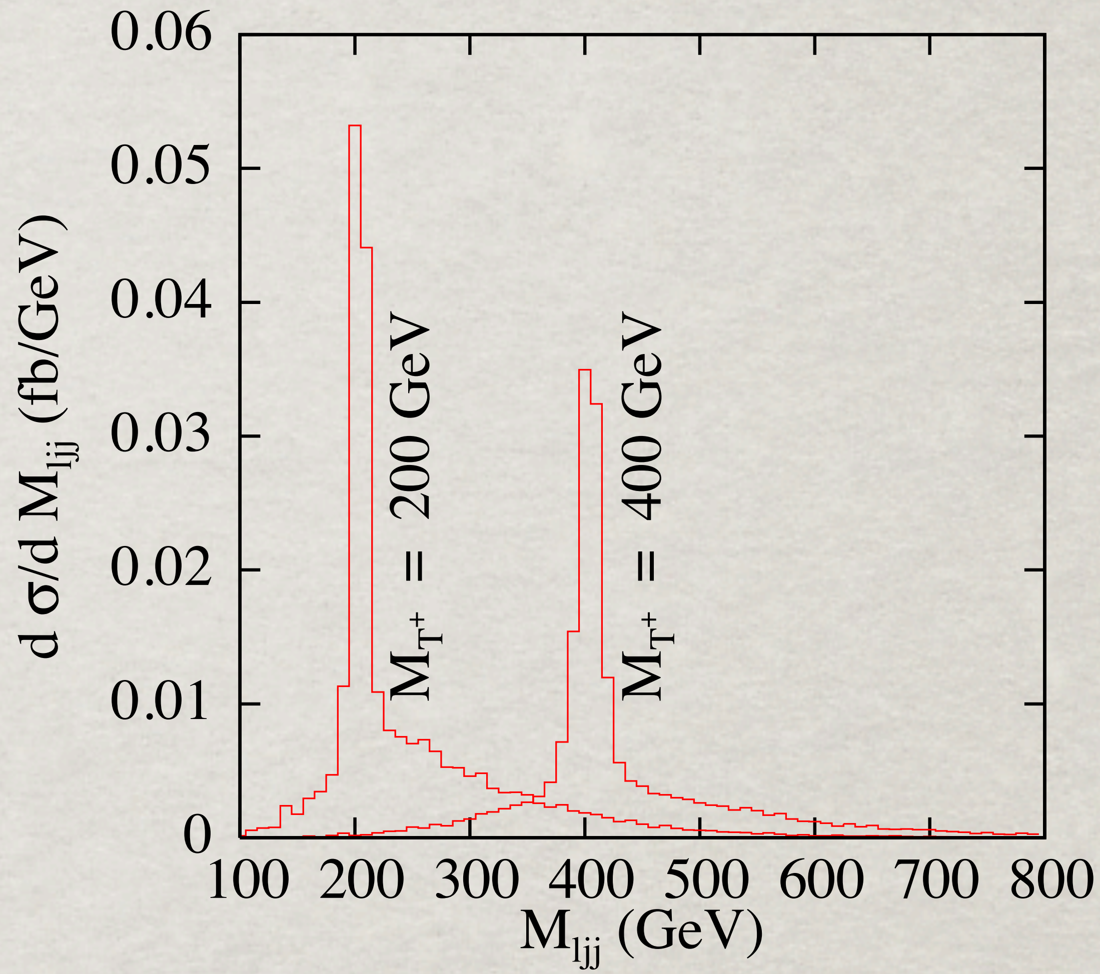
†Similar earlier work: Franceschini, Hambye, Strumia, arXiv:0805.1613.

‡O. Eboli, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia, arXiv:1108.0661 [hep-ph].

$\Delta L=2$ & mass reconstruction for $T^{\pm}$ & T^0

LHC with 14 TeV, 300 fb^{-1}

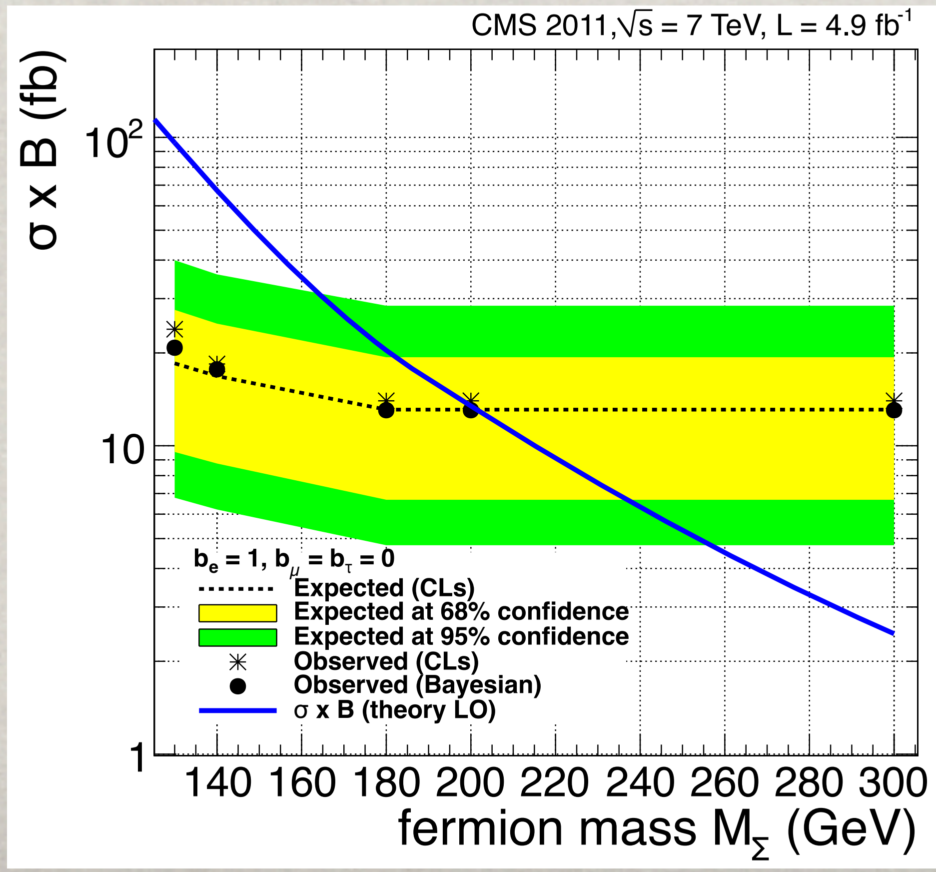
→ mass coverage 800 GeV

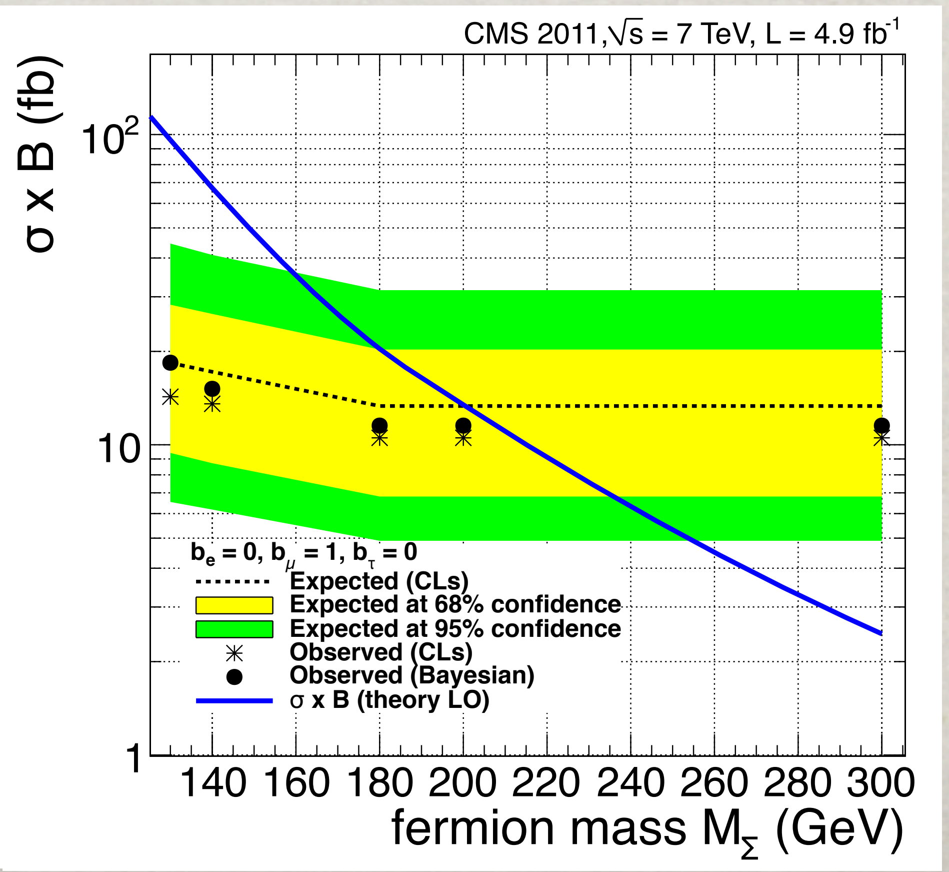


Current LHC bounds:

M_{T+-} > 200 GeV @ 95% CL

CMS: arXiv:1210.1797





Summary

- It is of fundamental importance to test the Majorana nature of ν's.
  - Type I See-saw:
    - $\tau,\ K,\ D,\ B$ rare decays sensitive to

      $140\ \text{MeV} < m_4 < 5\ \text{GeV},\ 10^{-9} < |V_{\ell 4}|^2 < 10^{-2}$;
    - LHC sensitive: $10\ \text{GeV} < m_4 < 400\ \text{GeV},\ 10^{-6} < |V_{\mu 4}|^2 < 10^{-2}$.
    - Difficulty! May be helped with the "inverse seesaw" mechanism.
  - Type II See-saw: for a scalar triplet $\Phi^{\pm\pm}$
    - LHC sensitive: $M_\phi \sim 600 - 1000$ GeV ($\ell^\pm\ell^\pm$ *or* $W^\pm W^\pm$).
    - Distinguish Normal/Inverted Hierarchy; Probe Majorana phases.
    - With $W'^\pm \to N\ell^\pm$, reach $M_N < M_{W'} \sim 4-5$ TeV.
  - Type III See-saw: for a lepton triplet $T^\pm,\ T^0$
    - LHC sensitive: $M_T \sim 800$ GeV.
    - Also distinguish Normal/Inverted Hierarchy.

Radiative seesaw → rich physics in extended Higgs sector.

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Radiative seesaw → rich physics in extended Higgs sector.

IF lucky, hadron colliders may serve
as the discovery machine for Majorana nature of ν's.

A recent update:

NNLO QCD effects; VBF (Wγ) contributions

Alva, TH, Ruiz: arXiv:1411.7305

Bev, Pilaftsis,