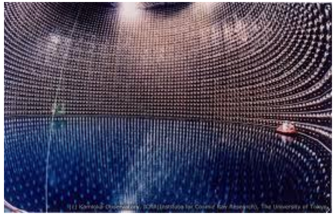
Type-I See-Saw Neutrinos at the Energy Frontier

SSI 2016

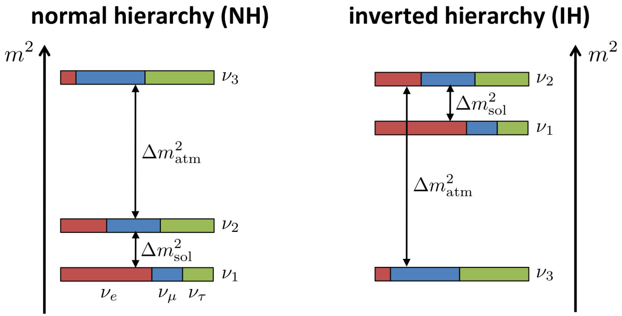
Occam’s Theory of Neutrinos

Neutrinos’ only known interaction is the weak interaction.
Only requires left handed neutrinos. Kinematically very light.
No need for right handed neutrinos, no mass term necessary!



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L’EXCELLENCE

But Neutrino oscillations → Neutrino Masses



So where do we go?

Why not do what all the cool kids are doing? Yukawa Couplings!

I. Introduce right-handed neutrinos
II. Give neutrinos Dirac Masses
III. Keep going?

$$N_{\alpha R}$$

$$\overline{\nu_{\alpha L}} m_{\alpha\beta} N_{\beta R} + h.c.$$

$$N^T_{\beta R} \hat{C} M_{\beta\beta'} N_{\beta' R} + h.c.$$

$$\left(\overline{\nu_{\alpha L}}\, \overline{N^C_{\beta L}}\right) \begin{pmatrix} 0_{3\times 3} & m_{3\times n} \\ m^T_{n\times 3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c_{\alpha' R} \\ N_{\beta' R} \end{pmatrix} + h.c.$$

A Little Sterile Neutrino Never Hurt Anybody

… But in quark sector diagonalizing mass matrices gives CKM, lots of phenomenology, what happens here?

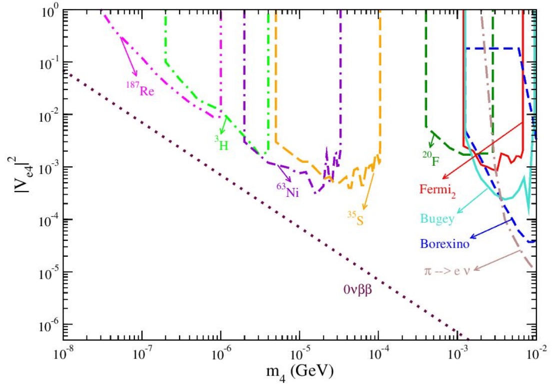
Diagonalize Mass Matrix to get mass eigenstates and rewrite the gauge eigenstates:

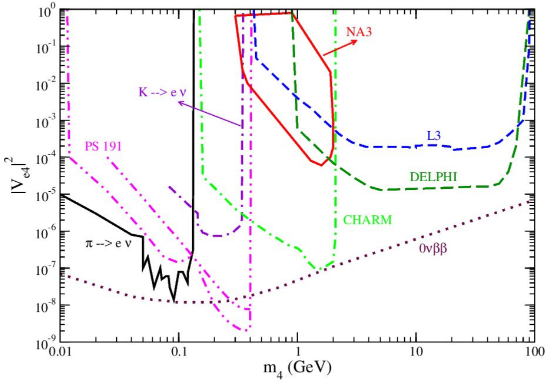
$$\nu_{\alpha L} = U_{\alpha m} \nu_{m L} + V_{\alpha m'} N^{c}_{m' R}$$

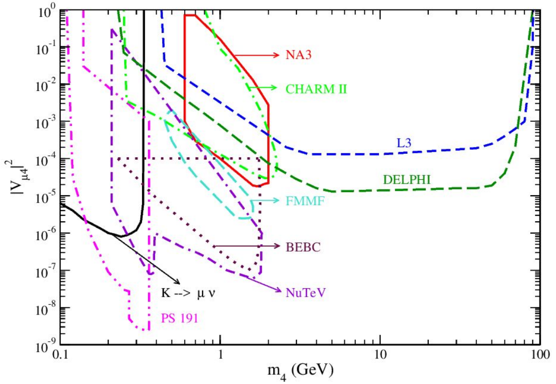
Gauge interactions mix between mass eigenstates!

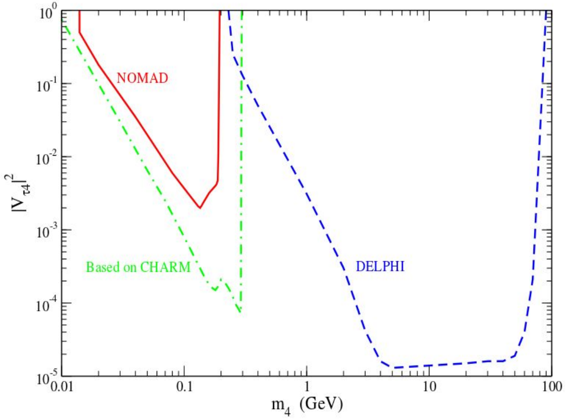
Should be able to see evidence from gauge interaction physics….. But lots of freedom in how we generate masses. Singlets, Triplets, Left-Right Symmetric Models, Mass parameters, Mixing Parameters...

Lots of phase space already ruled out



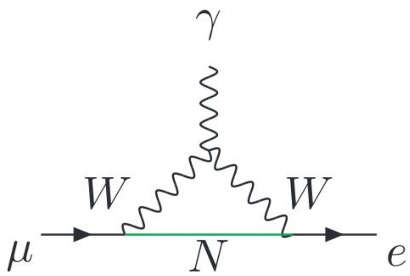






arXiv:0901.3589v2

- Neutrinoless Double Beta Decay
- Neutrino Mixing
- Precision ElectroWeak
- Lepton Universality
- Flavour Changing Currents
- Meson Decays
- Tau Decays



See-Saw

Set sterile Majorana Mass large:

$$m_\nu \sim \frac{m^2_{Yukawa}}{M_{Majorana}} \qquad m_N \sim M_{Majorana}$$

$M \sim M_{GUT}$ → Neutrino Yukawa couplings O(1)

No Planck Scale Colliders (yet) :(

$M \sim TeV$ → Neutrino Yukawa couplings O(charged lep Yukawa)

TeV Scale Colliders are real :)

Experimental Neutrinos Masses, Scale ??

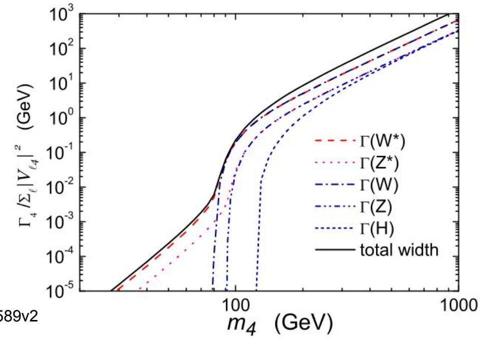
Speculative TeV Scale See-Saw

<u>For Simplicity:</u>

Assume single accessible heavy neutrino. Put bounds on masses, mixing.

Phenomenology

Lots of interesting features depending on parameter choices



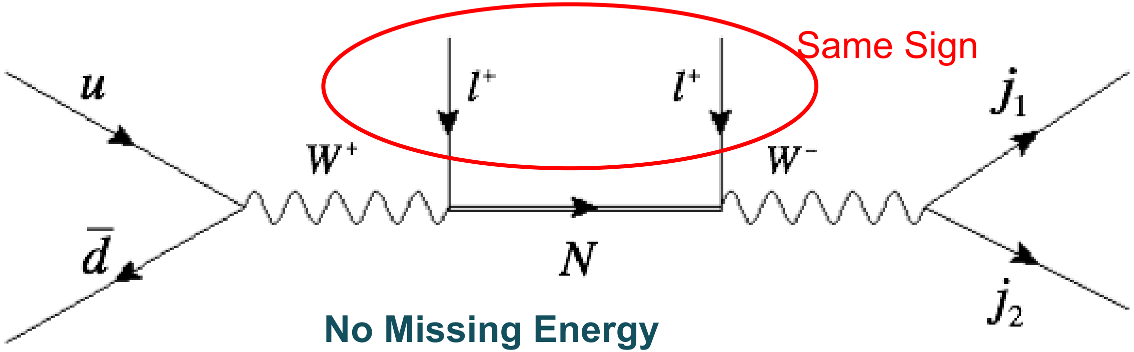
arXiv:0901.3589v2

Higgs Physics

Z Physics

W Physics

Distinctive Lepton Number Violating Processes.

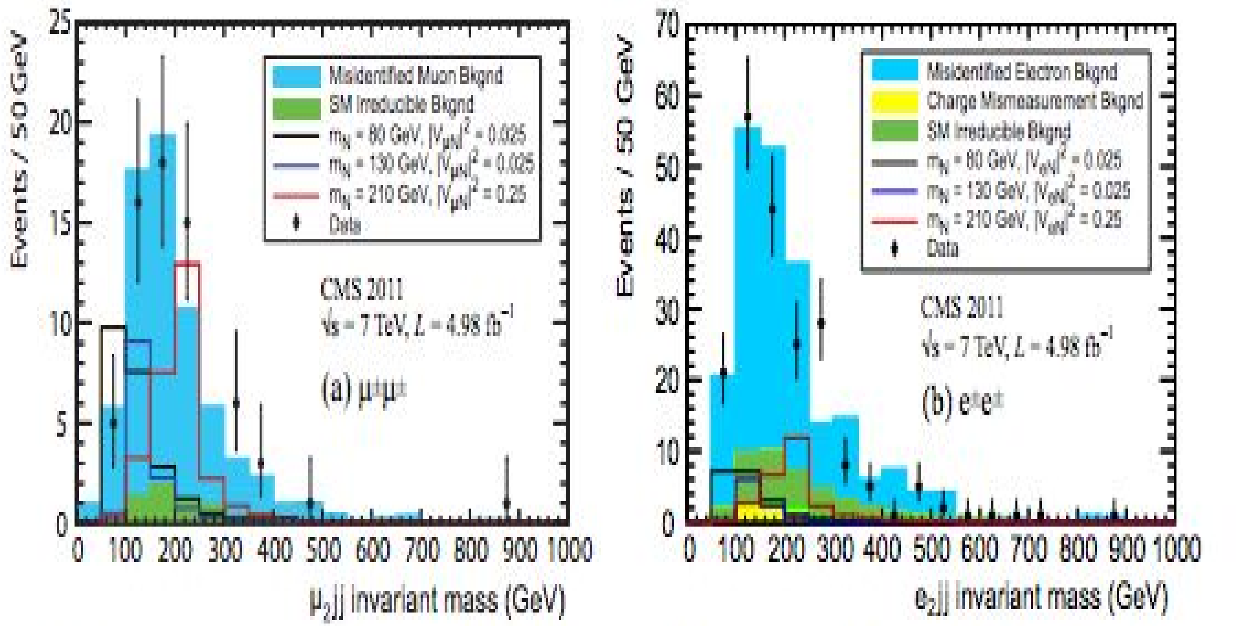


Neutrinos can still hide a little e.g. WWW, ttbar with non prompt.
And can have charge mismeasurements

No Missing Energy
(Almost nowhere to hide!)

Current Results and Constraints

Run I LHC searches by CMS and ATLAS



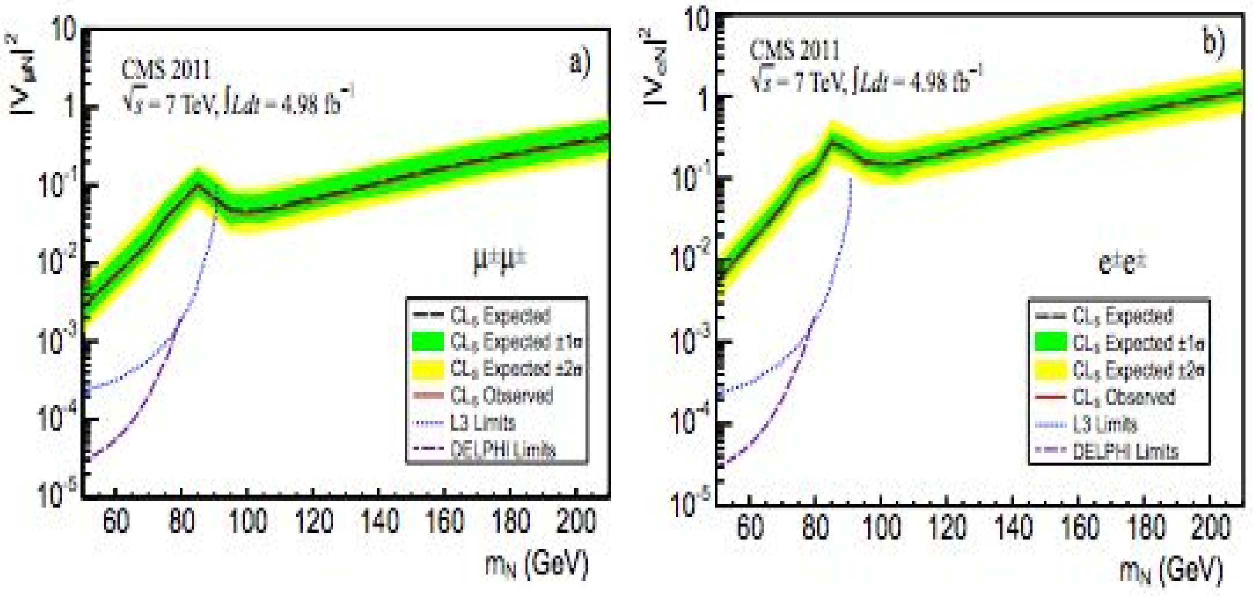
Current Results and Constraints

Run I LHC searches by CMS and ATLAS

Source	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$
Irreducible SM backgrounds:		
WZ	$3.2 \pm 0.3 \pm 0.2$	$4.9 \pm 0.3 \pm 0.3$
ZZ	$1.0 \pm 0.1 \pm 0.1$	$2.1 \pm 0.1 \pm 0.1$
$W\gamma$	$0.75 \pm 0.27 \pm 0.07$	$1.7 \pm 0.4 \pm 0.2$
$t\bar{t}W$	$1.06 \pm 0.05 \pm 0.53$	$0.62 \pm 0.04 \pm 0.31$
W^+W^+qq	$0.76 \pm 0.06 \pm 0.38$	$0.73 \pm 0.07 \pm 0.37$
W^-W^-qq	$0.45 \pm 0.03 \pm 0.23$	$0.27 \pm 0.02 \pm 0.13$
Double-parton $W^{\pm}W^{\pm}$	$0.07 \pm 0.02 \pm 0.04$	$0.19 \pm 0.03 \pm 0.10$
Total irreducible SM background	$7.3 \pm 0.4 \pm 0.7$	$10.6 \pm 0.6 \pm 0.6$
Charge mismeasurement background	$0^{+0.2}_{-0}$	$31.9 \pm 2.7 \pm 8.0$
Misidentified lepton background	$63.1 \pm 4.2 \pm 22.1$	$176.8 \pm 4.7 \pm 61.9$
Total background	$70 \pm 4 \pm 22$	$219 \pm 6 \pm 62$
Data	65	201
Expected signal:		
$m_N = 130\,\mathrm{GeV}/c^2$, $\lvert V_{\ell N}\rvert^2 = 0.1$	$58 \pm 1 \pm 4$	$39 \pm 1 \pm 3$
$m_N = 210\,\mathrm{GeV}/c^2$, $\lvert V_{\ell N}\rvert^2 = 0.1$	$12.0 \pm 0.1 \pm 0.8$	$8.5 \pm 0.1 \pm 0.6$

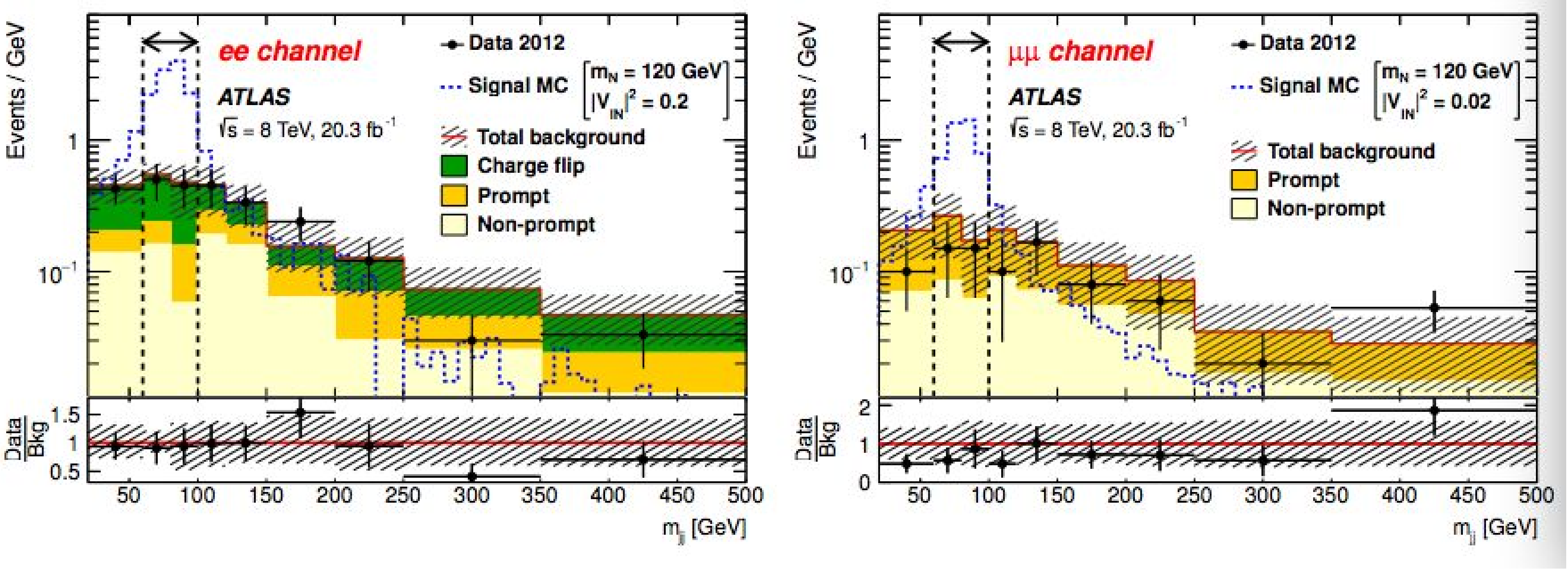
Current Results and Constraints

Run I LHC searches by CMS and ATLAS



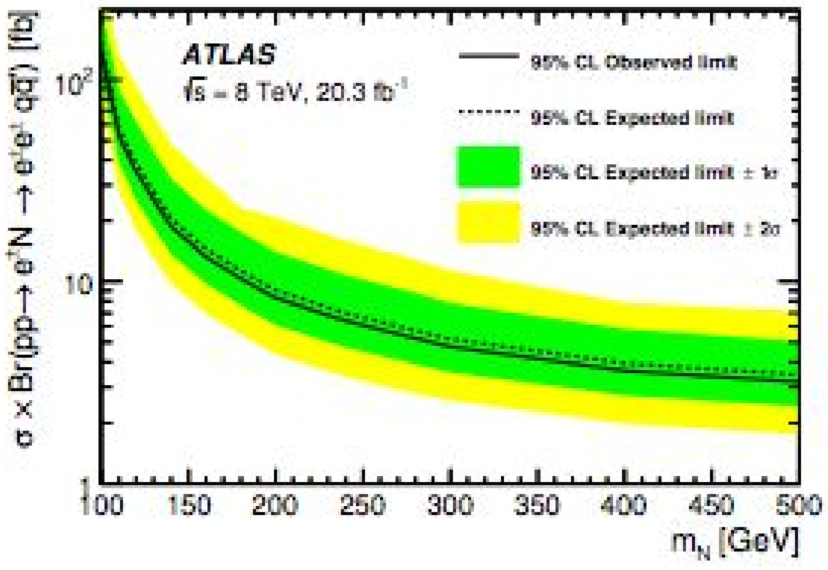
Atlas result for 8 Tev with an integrated luminosity of 20.3 fb^-1

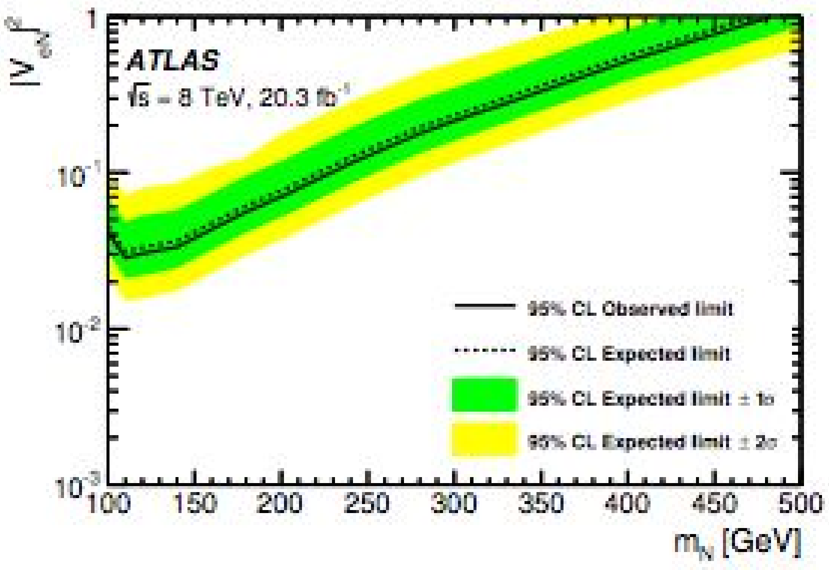
Data satisfy the prediction and no excess of events relative to the expectation



Atlas result for 8 Tev with an integrated luminosity of 20.3 fb^-1

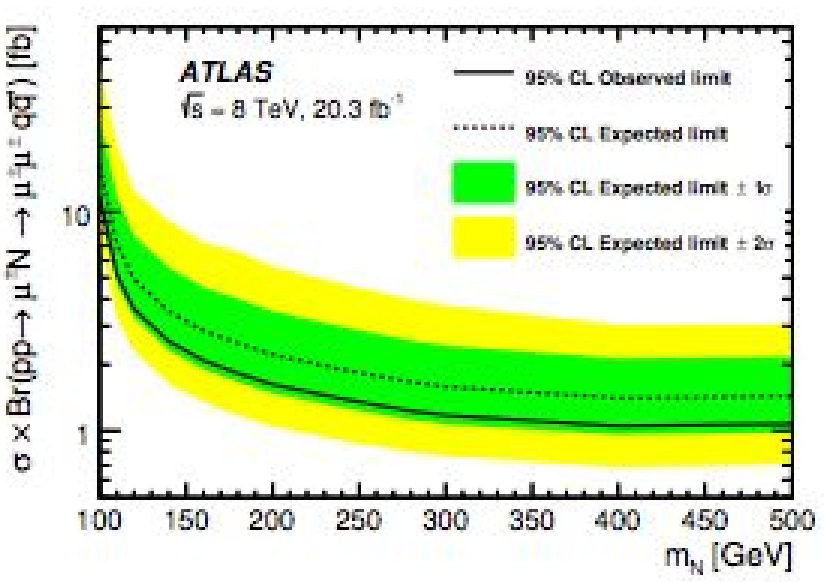
Excluded the mixing parameters as low as |VeN| ^2 = 0.029

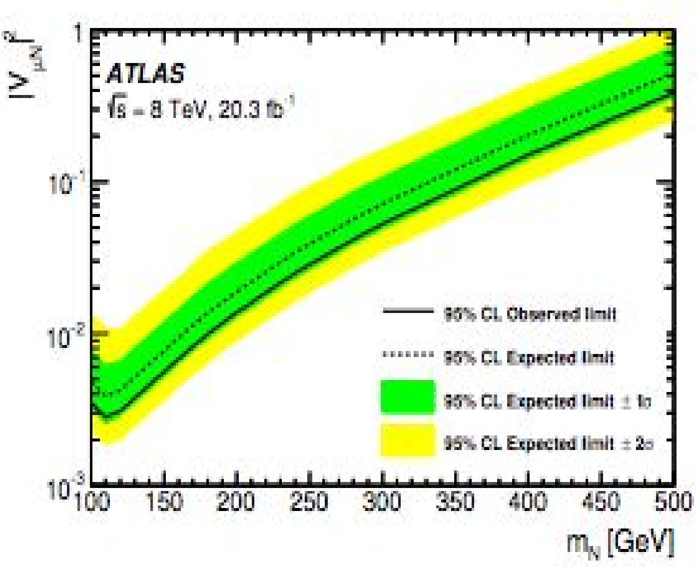




Atlas result for 8 Tev with an integrated luminosity of 20.3 fb^-1

Excluded the mixing parameters as low as |VμN|^ 2 = 0.0028





Current Results and Constraints

Run II LHC searches by CMS and ATLAS (compare to other constraints)

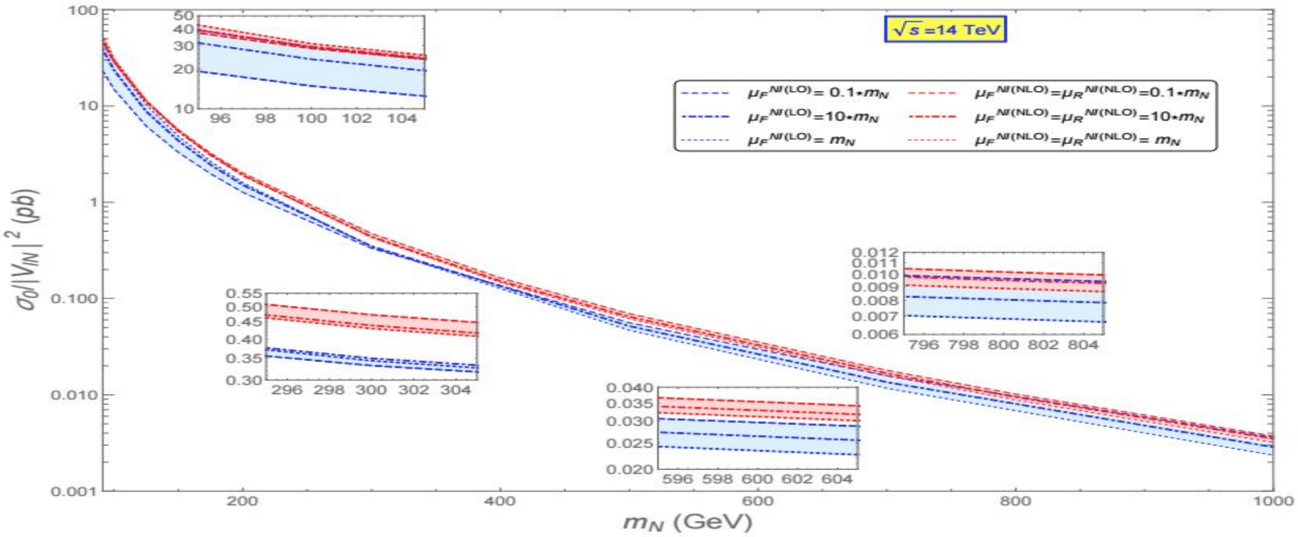
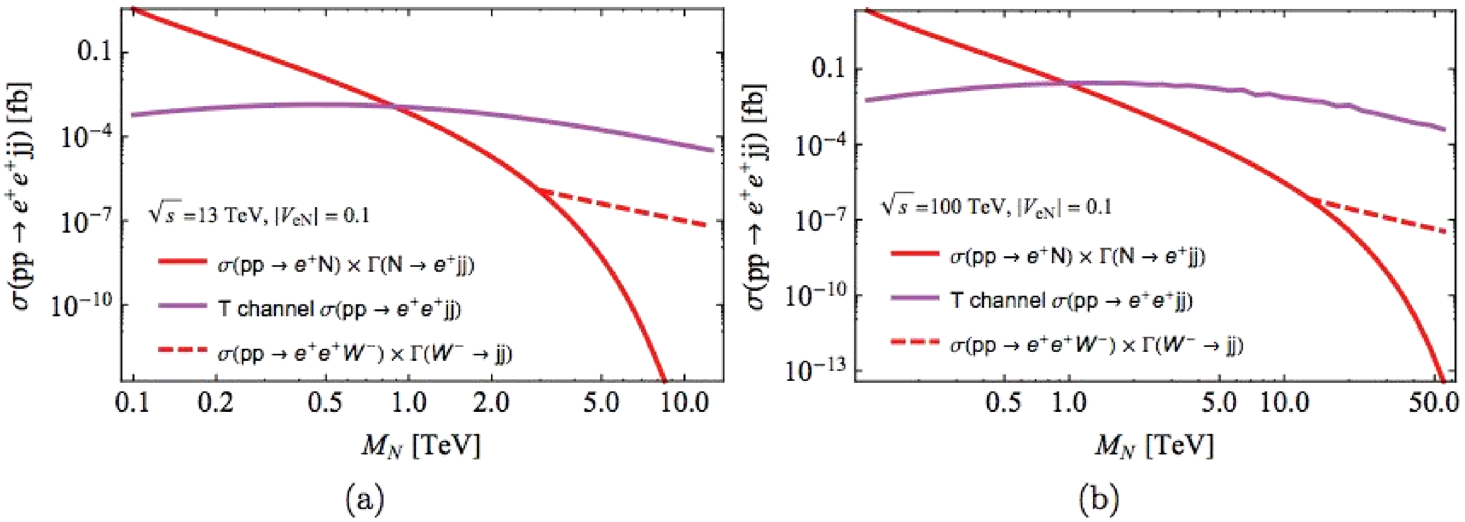


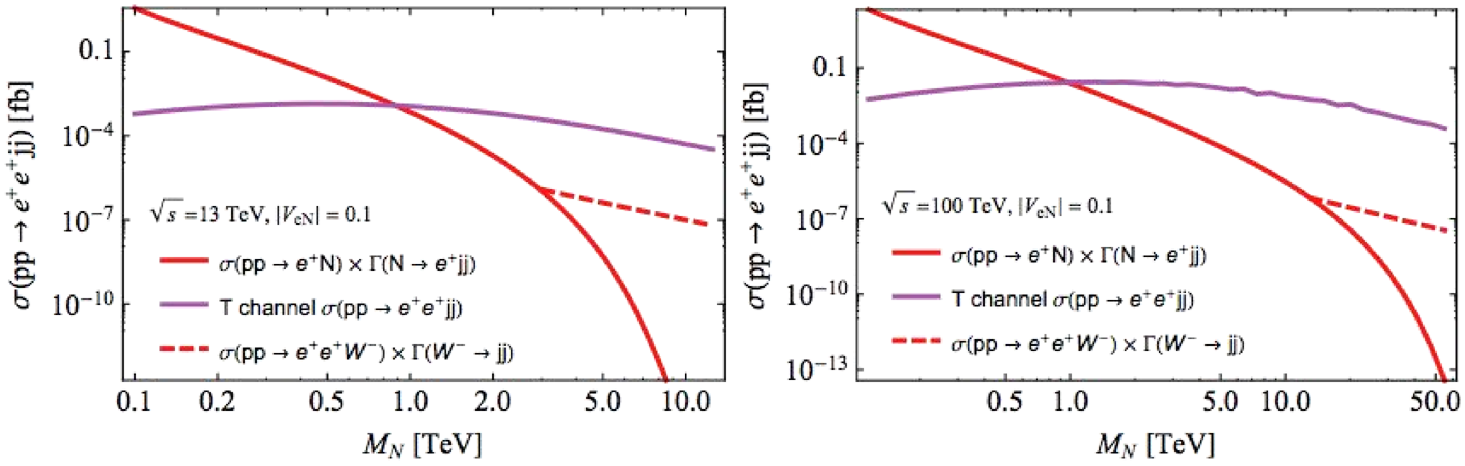
Figure 5. Heavy neutrino production cross-section from $pp \to \ell N$ at the 14 TeV LHC as a function of m_N. Both LO and NLO predictions are shown with the scale variation effect as a band. The cross-sections are normalized by the square of the mixing angles. Inset plots showing with zoomed bands at different masses.

LHC Ultimate reach potential and 100 TeV collider



The s channel and t channel contribution signal by MadGraph default cut at 13 TeV and 100 TeV machine in parton level. The mixing angle here is assumed to be 0.1 and universal to all lepton flavors.

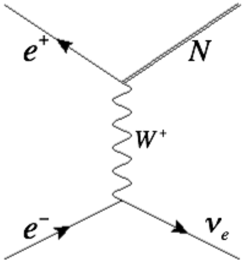
[Ng, J.N., de la Puente, A. & Pan, B.W. J. High Energ. Phys. (2015) 2015: 172.]

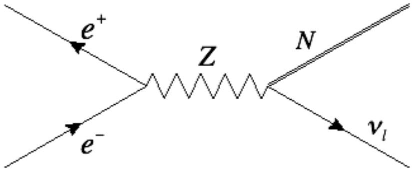


(a) (b)

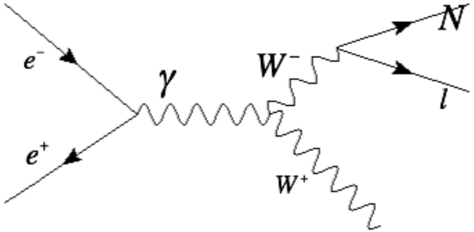
1. The higher energy does not reach significant improvement for s-channel (PDF is universal if we fix the momentum transfer as Mass of N .)
2. If total invariant mass s is less than the mass of Majorana neutrino, we can not produce the on-shell Majorana neutrino through s-channel.
3. T channel dominates when N-mass is greater than 1 TeV

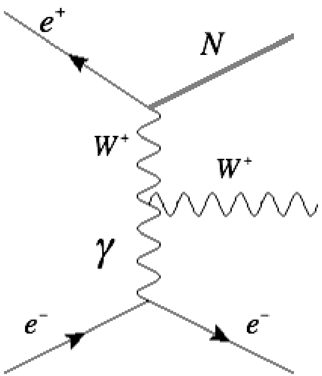
Lepton collider

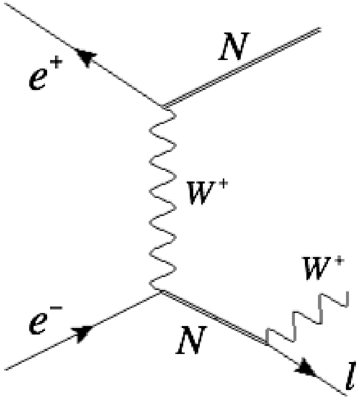


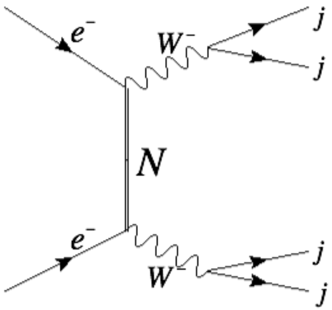


1. $e^+e^- \to N\nu \to ljj\not{E}$ (No LNV final state)
2. $e^+e^- \to N\, l^\pm\, W^\mp \to l^\pm\, W^\mp\, l^\pm\, W^\mp \to l^\pm\, l^\pm 4j$
3. $e^-e^- \to W^-W^- \to 4j$









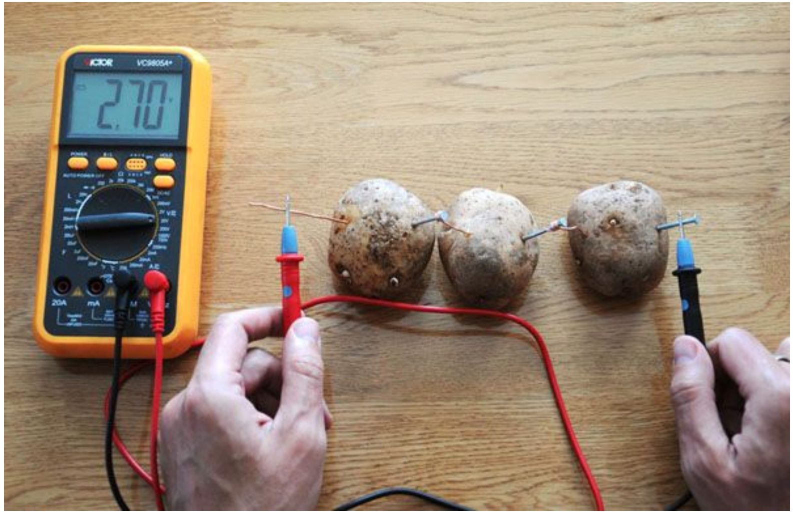
Nearly no SM background

For the second channel , LFV for moun moun final state

[S. Banerjee, P. S. B. Dev, A. Ibarra, T. Mandal and M. Mitra, Phys. Rev. D 92, 075002 (2015)]

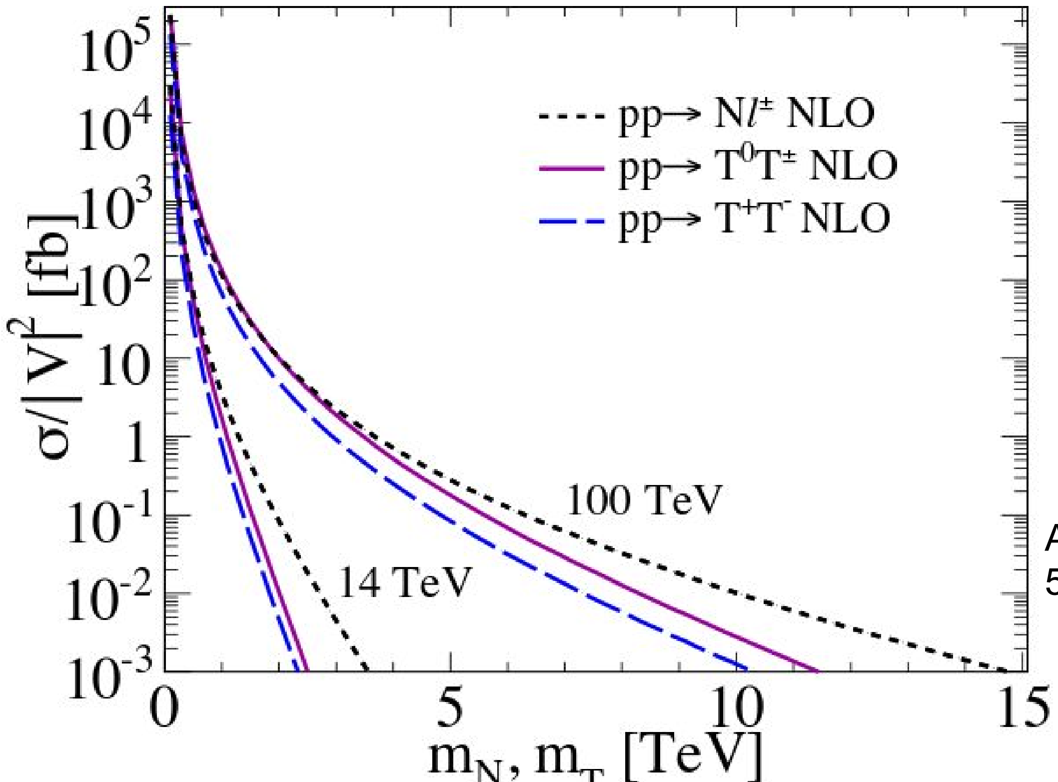
Conclusions

1. Seesaw model produce light and heavy mass for neutrino
2. The mixing angle could be small, but the background is also small.
3. Future collider and Lepton collider can improve search for heavy neutrino.



END

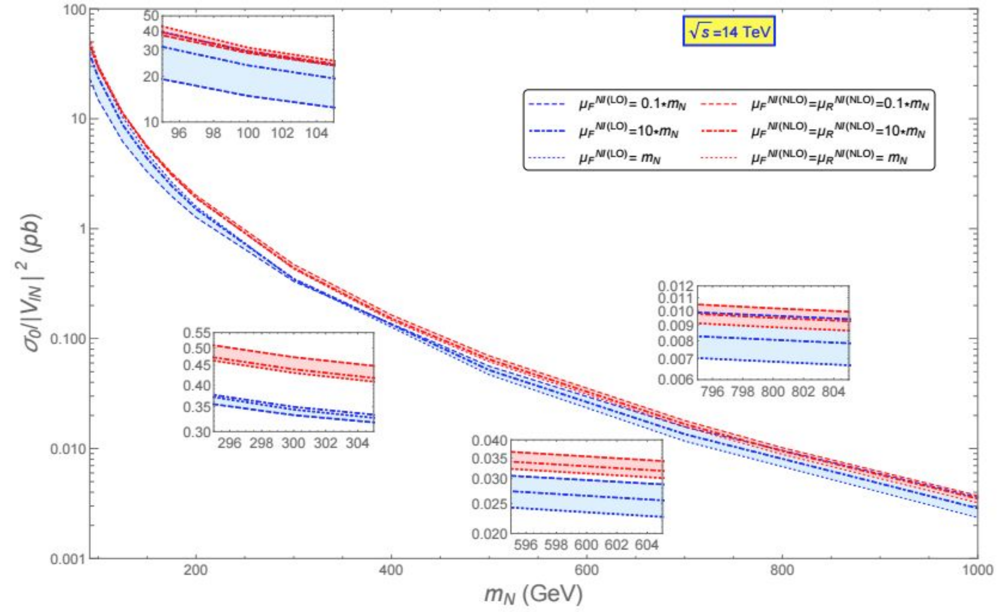
Where does this one comes from ?



Arxiv:1511.06495v1, Section 5.5

https://arxiv.org/pdf/1604.00608v3.pdf

14TeV



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https://arxiv.org/pdf/1604.00608v3.pdf

100TeV

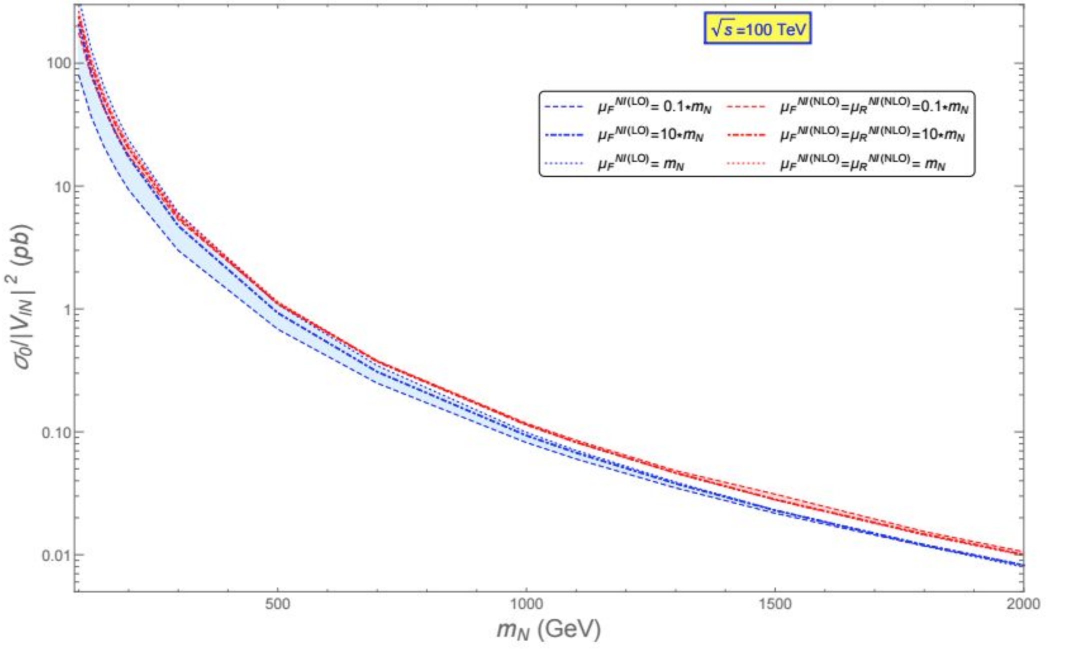
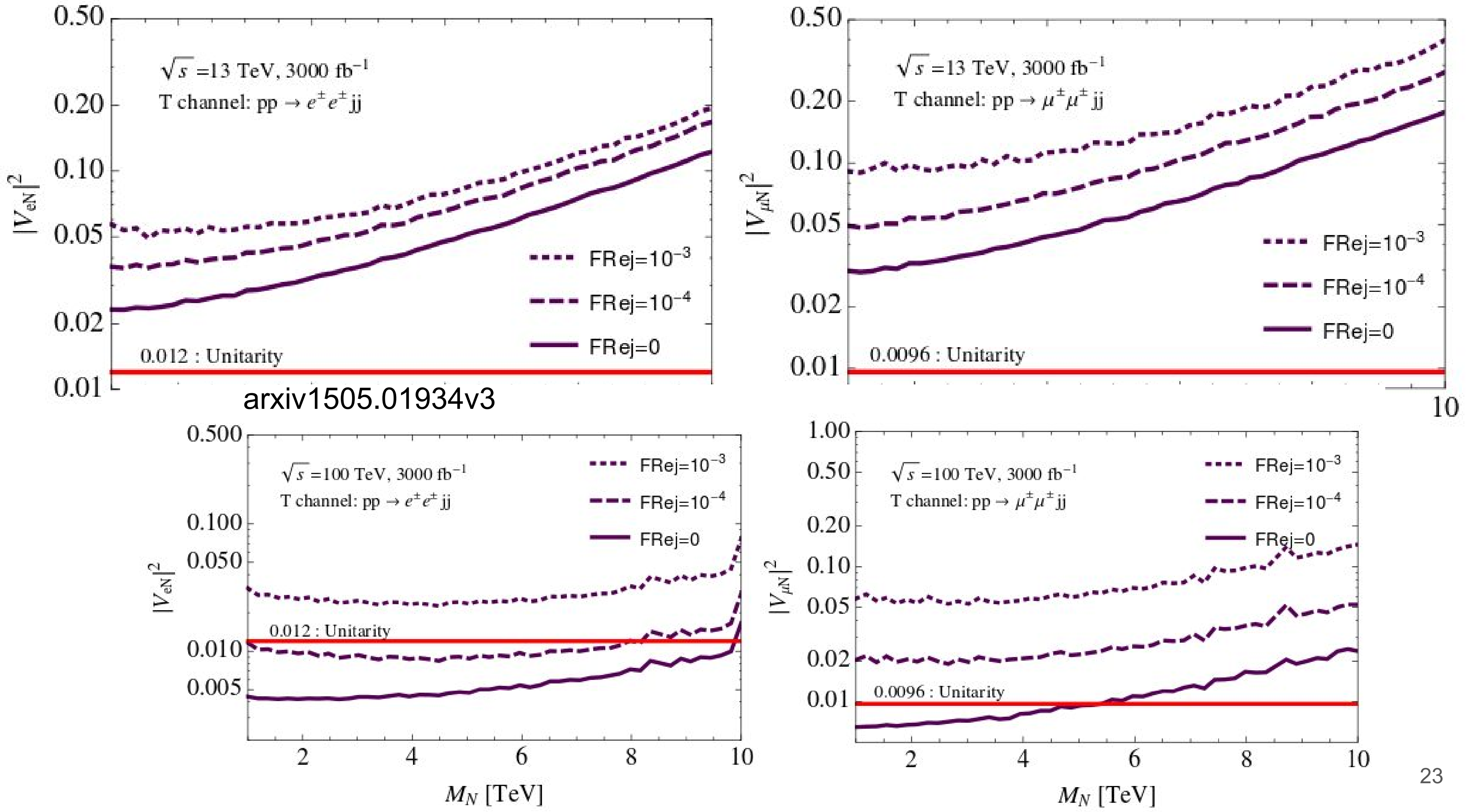
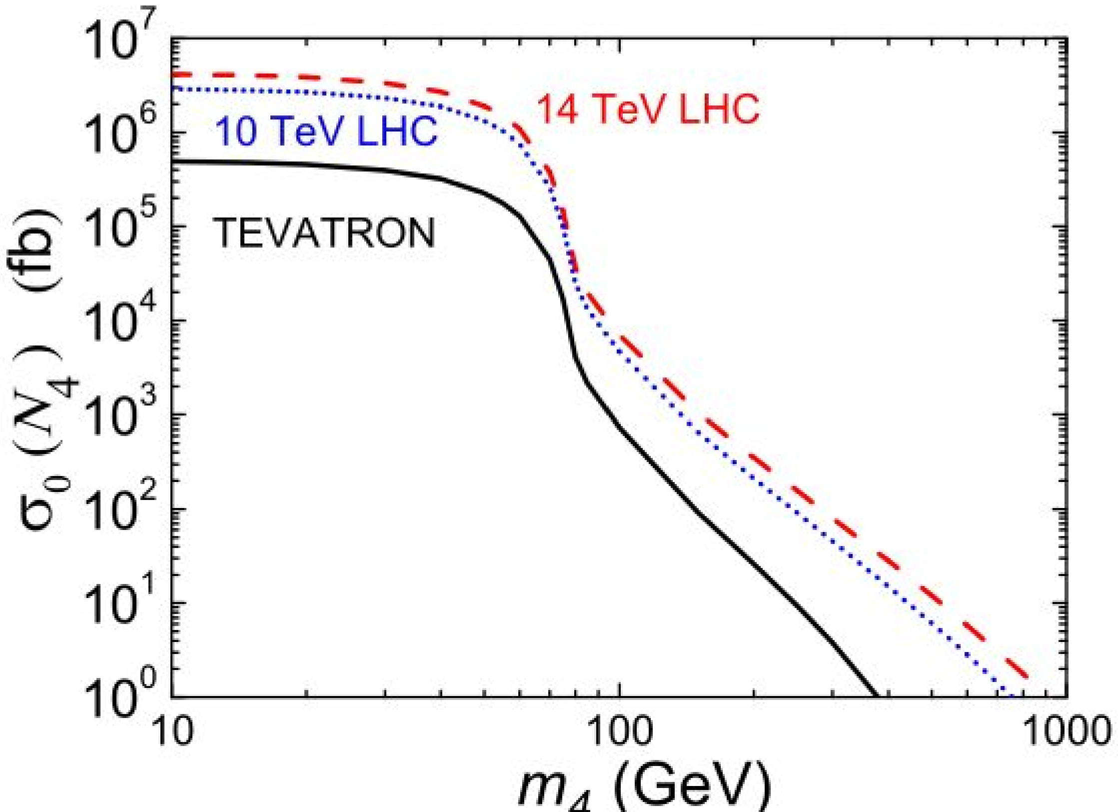


Figure 6. Heavy neutrino production cross-section from $pp \to \ell N$ at the 100 TeV hadron



arxiv1505.01934v3

Arxiv0901.3589v2 page 29



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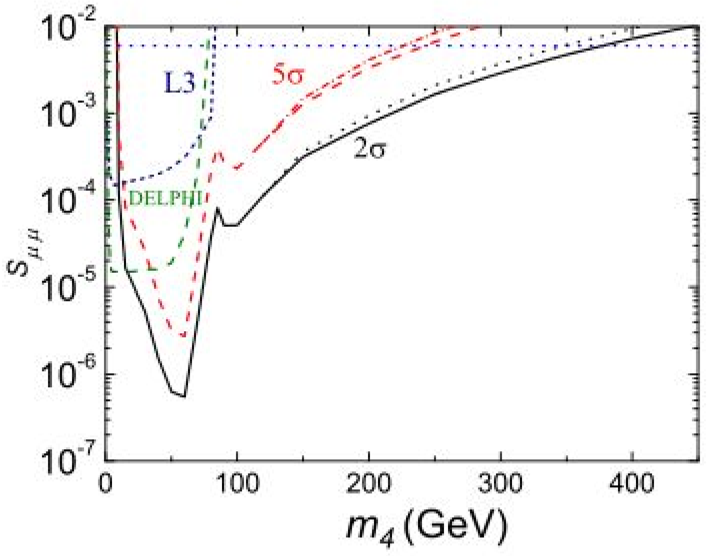

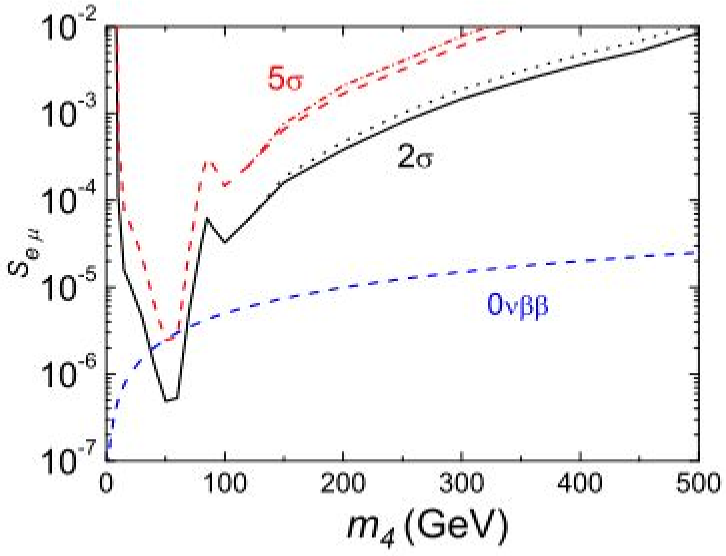

http://arxiv.org/pdf/0901.3589v2.pdf pg 36

Cutflow table