“Neutrinos @ the LHC”

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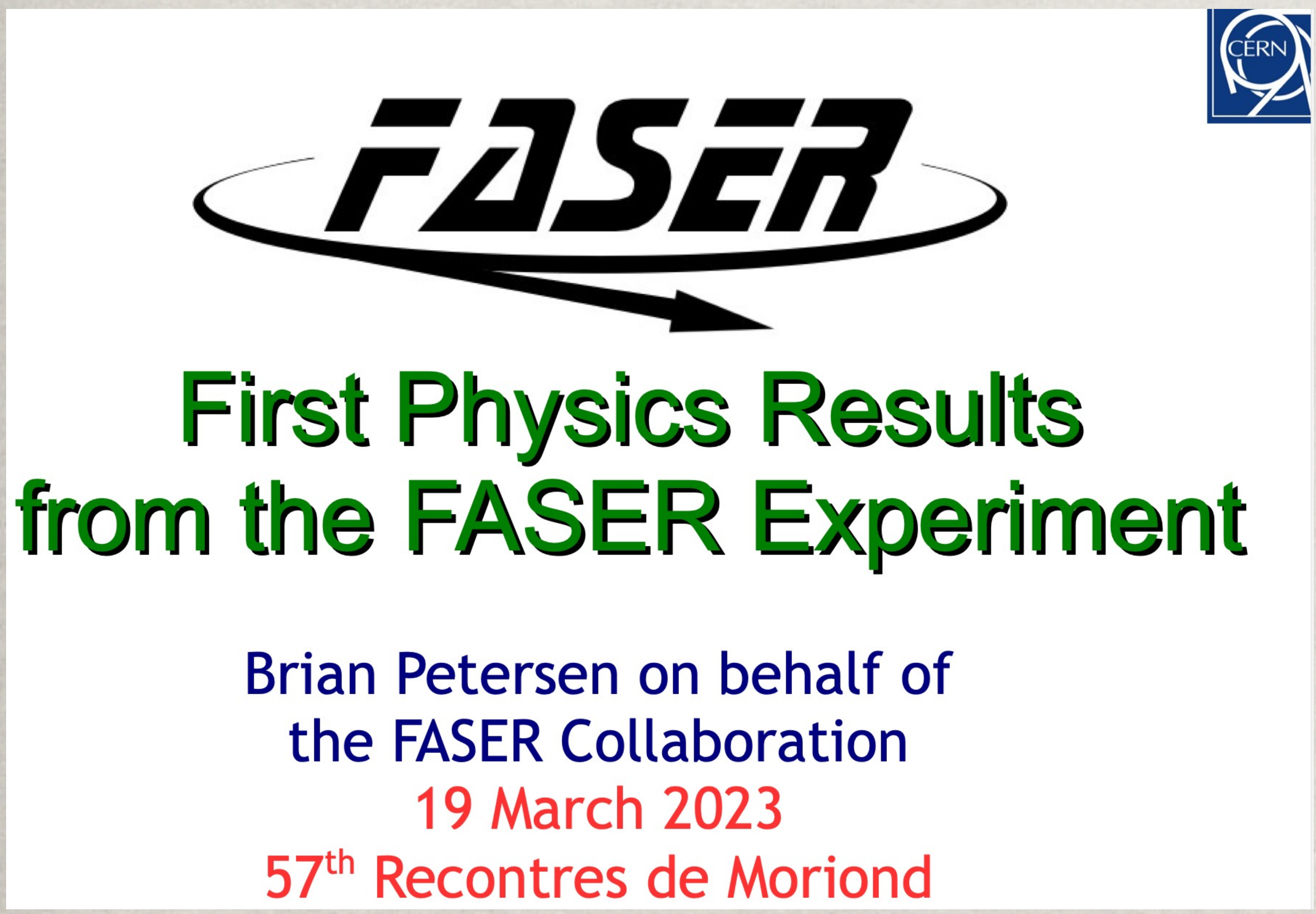
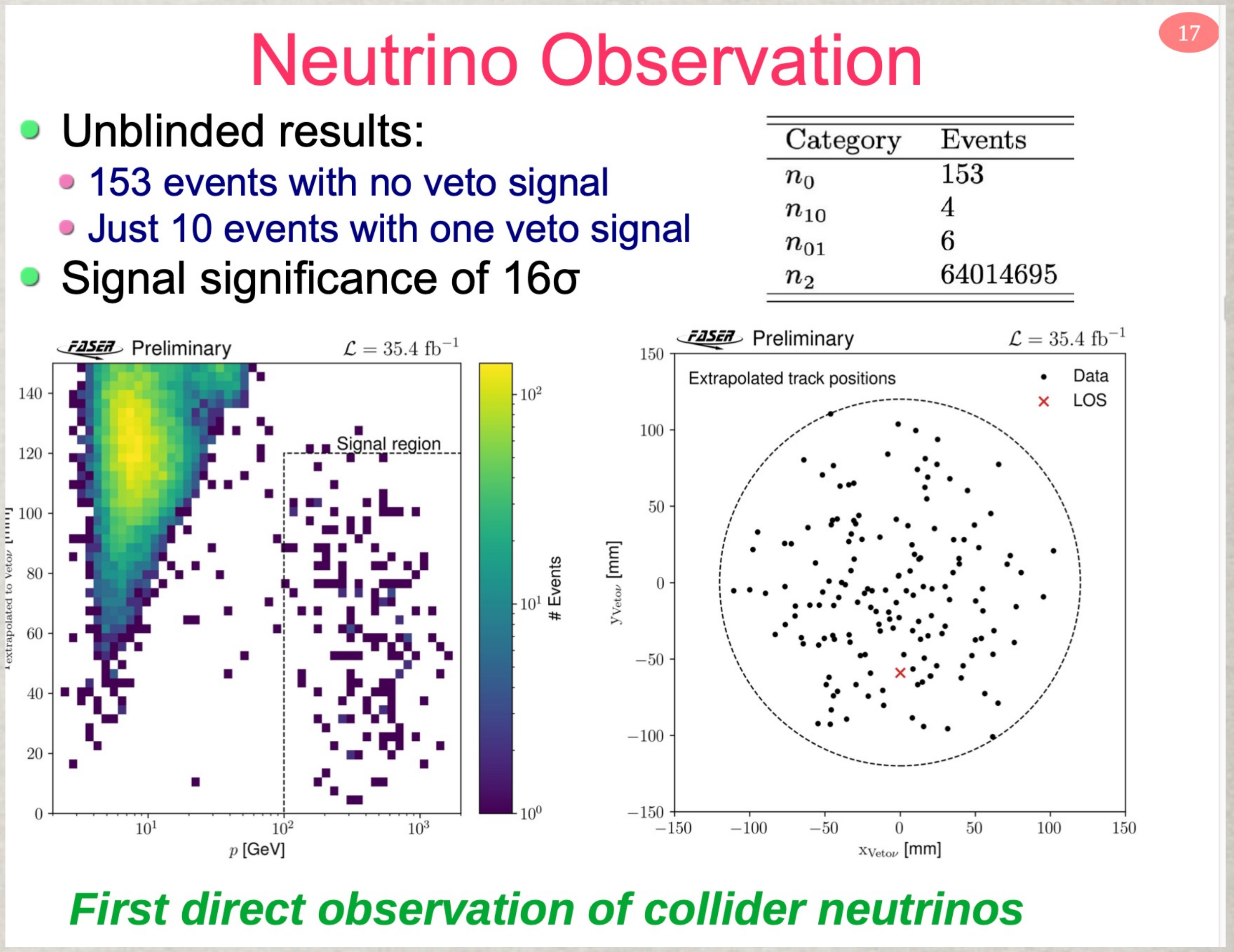
Neutrinos @ Colliders (?)

They Are All Gone!

-- as "missing energies"

Time has changed: They are "seen"!





Category	Events
n_0	153
n_{10}	4
n_{01}	6
n_2	64014695

More, see Jonathan Feng's talk this evening

Testing Neutrino Mass Models @ Colliders

Contents:

- Representative neutrino mass models & their phenomenological features
- Collider tests & complementarity

Most straightforward on $\mathbf{m}_\nu$: add N_R's – like all the other SM fermions

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

$$\begin{aligned} -\mathcal{L}_Y &= \sum_{a=1}^{3} \sum_{b=1}^{n} f^\nu_{ab} \, \overline{L_{aL}} \, \hat{H} N_{bR} + h.c. \\ &\Rightarrow \sum_{a=1}^{3} \sum_{b=1}^{n} \overline{\nu_{aL}} \, m^\nu_{ab} \, N_{bR} + h.c. \end{aligned}$$

- Dirac mass terms:
  Yukawa couplings arbitrary & tiny: $y_\nu < 10^{-11}$

- N_R a gauge singlet: "sterile neutrino"
  Why not a Majorana mass term?

$$\sum_{b,b'=1}^{n\geq 2} \overline{N^c{}_{bL}} \, M_{bb'} \, N_{b'R} + h.c.$$

SM as a low-energy effective field theory:

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)

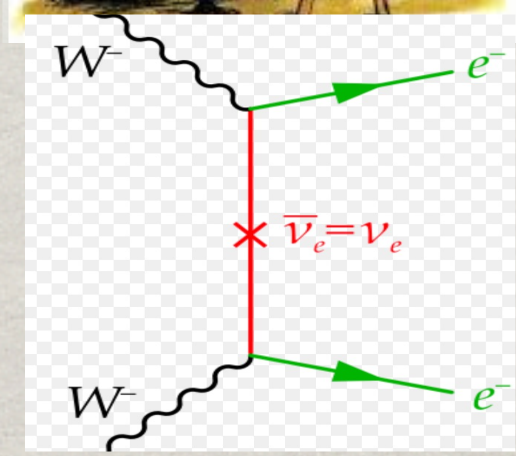
Implications:

- Theoretical: ***Λ*** → new scale / particles, implies an underlying (UV) theory!

The See-saw spirit: †

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

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



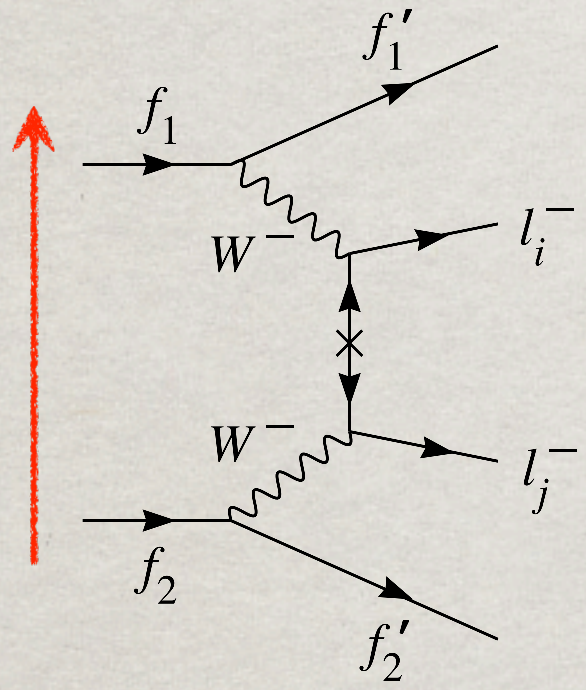
- Observational:
  ΔL=2 → Majorana mass (Majorana neutrinos)

→ Opens the door to BSM *ν* physics at low & high energies!

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

Observational Aspects:
the most-wanted process: ΔL=2

The fundamental diagram:



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

The crossing diagrams can probe different processes and new physics of N/T^0, W^+_R, H^{++}

The transition rates are proportional to

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

UV-complete theoretical Models:

The Weinberg operator non-renormalizable
→ Need Ultra-Violet completion at/above Λ .

Group representations based on SM $SU_L(2)$ doublets:

$$2 \otimes 2 = 1(\text{singlet}) + 3(\text{triplet})$$

→ There are three possibilities:

- Type I: Fermion singlets $\otimes (L\ H)_S$
- Type II: Scalar triplet $\otimes (L\ L)_T$
- Type III: Fermion triplets $\otimes (L\ H)_T$

E. Ma: PRL 81, 1771 (1998).
For recent reviews: Z.Z. Xing: arXiv:1406.7739;
Y. Cai, TH, T. Li & R. Ruiz: arXiv:1711.02180.

Type I Seesaw: Singlet N_R's – Sterile neutrinos

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

Dirac plus Majorana mass terms: $\left(\overline{\nu_L} \;\; \overline{N^c{}_L}\right) \begin{pmatrix} 0_{3\times3} & D^\nu_{3\times n} \\ D^{\nu T}_{n\times3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c{}_R \\ N_R \end{pmatrix}$

Majorana neutrinos:

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

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

<u>The charged currents:</u>

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

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

Type I Seesaw features:

😀 Existence of N_R (possibly 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: could be accessible!

🙁 But difficult to see N_R:

The mixing is typically small, mass wide open:

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

(Fine-tune or hybrid could 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).

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:#

$W^\pm_R \to N_R\, e^\pm$

(* 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.

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. ...

Other Models & Phenomenology

Thus far, we considered tree-level Type I, II, III seesaw models

Many models to account for the neutrino mass.*
Another class of well-motivated models:
Radiative (loop) generation of neutrino masses.

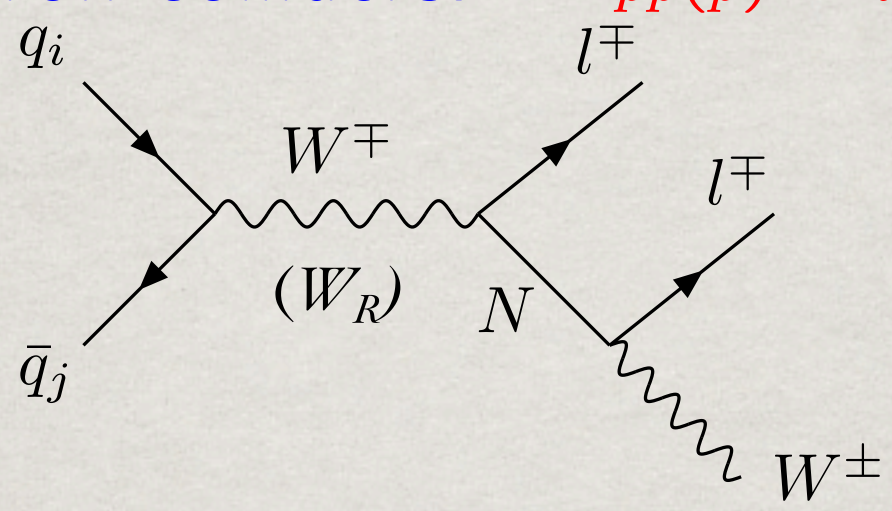
- Zee (1986)-Babu (1988) Model:
  add singlet scalar fields m_ν generate at 2-loop
  → change Higgs physics
- Ma Models (2006):
  add singlet scalars + Z_2 symmetry
  → Dark matter

- Other rich phenomenology:
  - Neutrino portal to the dark sector (Brian Batell)
  - Non-Standard ν–interactions (NSIs)

* For a review, see, M.C. Chen & J.R. Huang, arXiv:1105.3188v2.

1. N_R at Colliders

At hadron colliders: § $pp(\bar{p}) \to \ell^\pm \ell^\pm jjX$

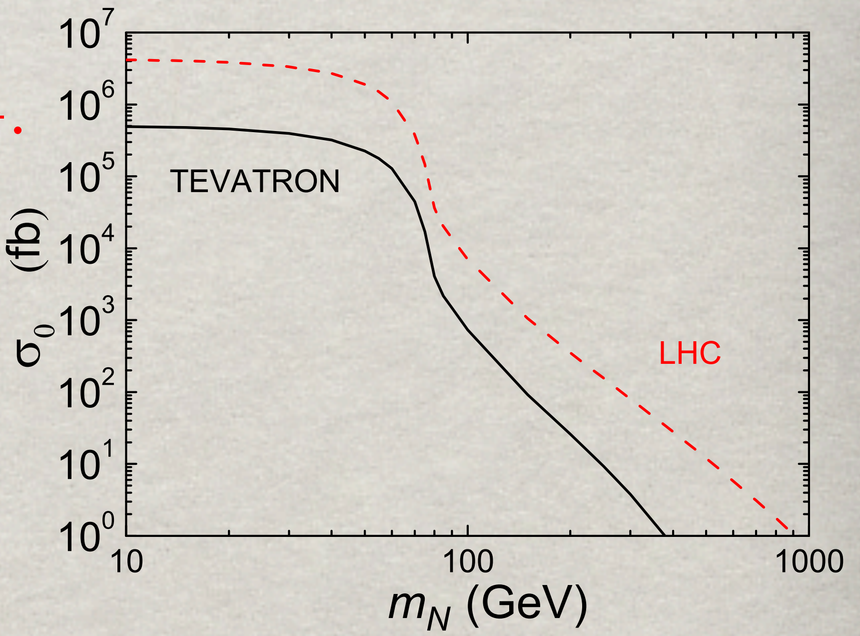


Factorize out the mixing couplings: †

$$\sigma(pp \to \mu^\pm\mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2\ \sigma_0.$$

$$\sigma(pp \to \mu^\pm\mu^\pm W^\mp) \equiv S_{\mu\mu}\ \sigma_0,$$

$$S_{\mu\mu} = \frac{V_{\mu N}^4}{\sum_l |V_{\ell N}|^2} \approx \frac{V_{\mu N}^2}{1 + V_{\tau N}^2/V_{\mu N}^2}.$$



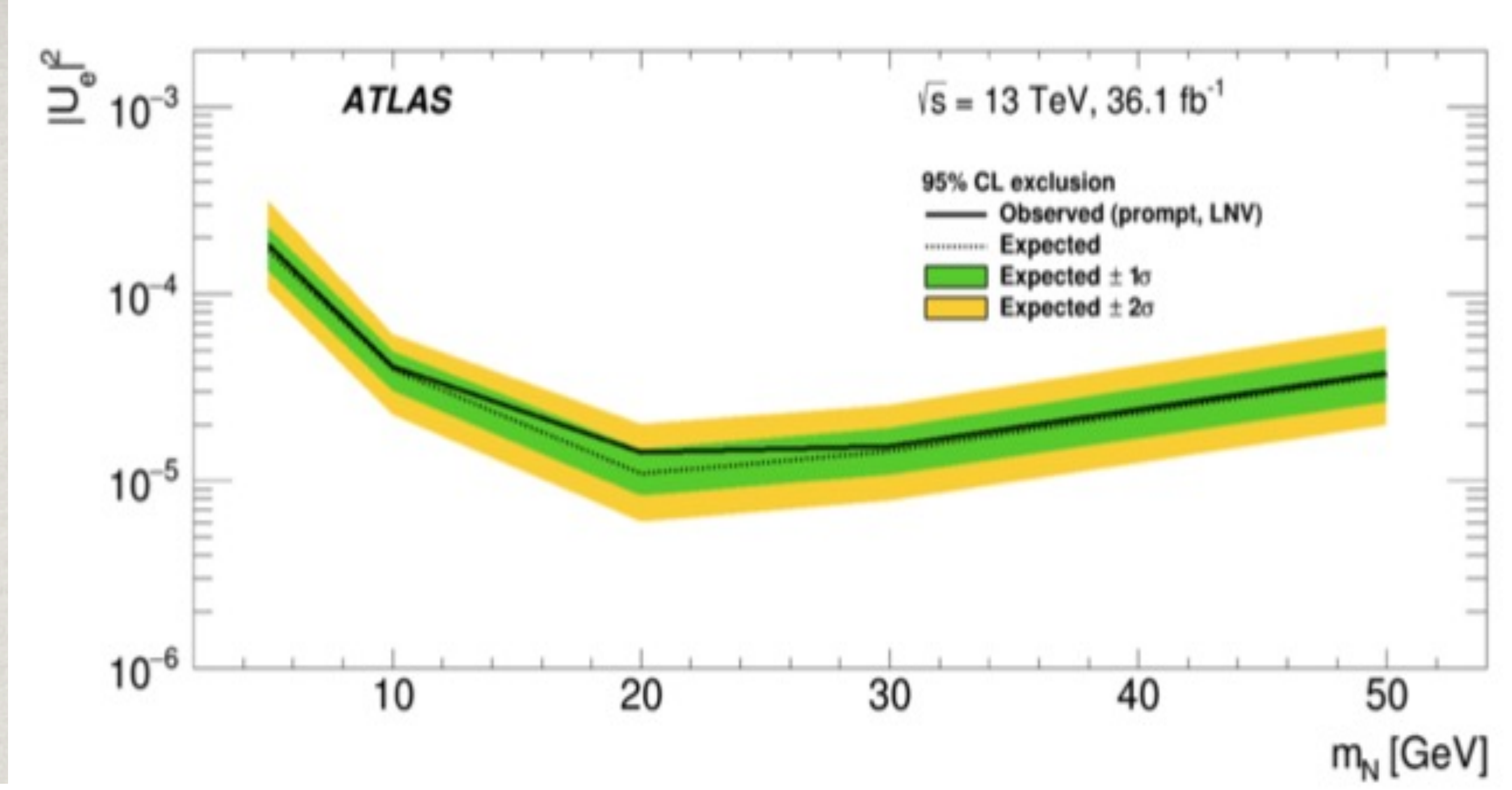
A very clean channel:

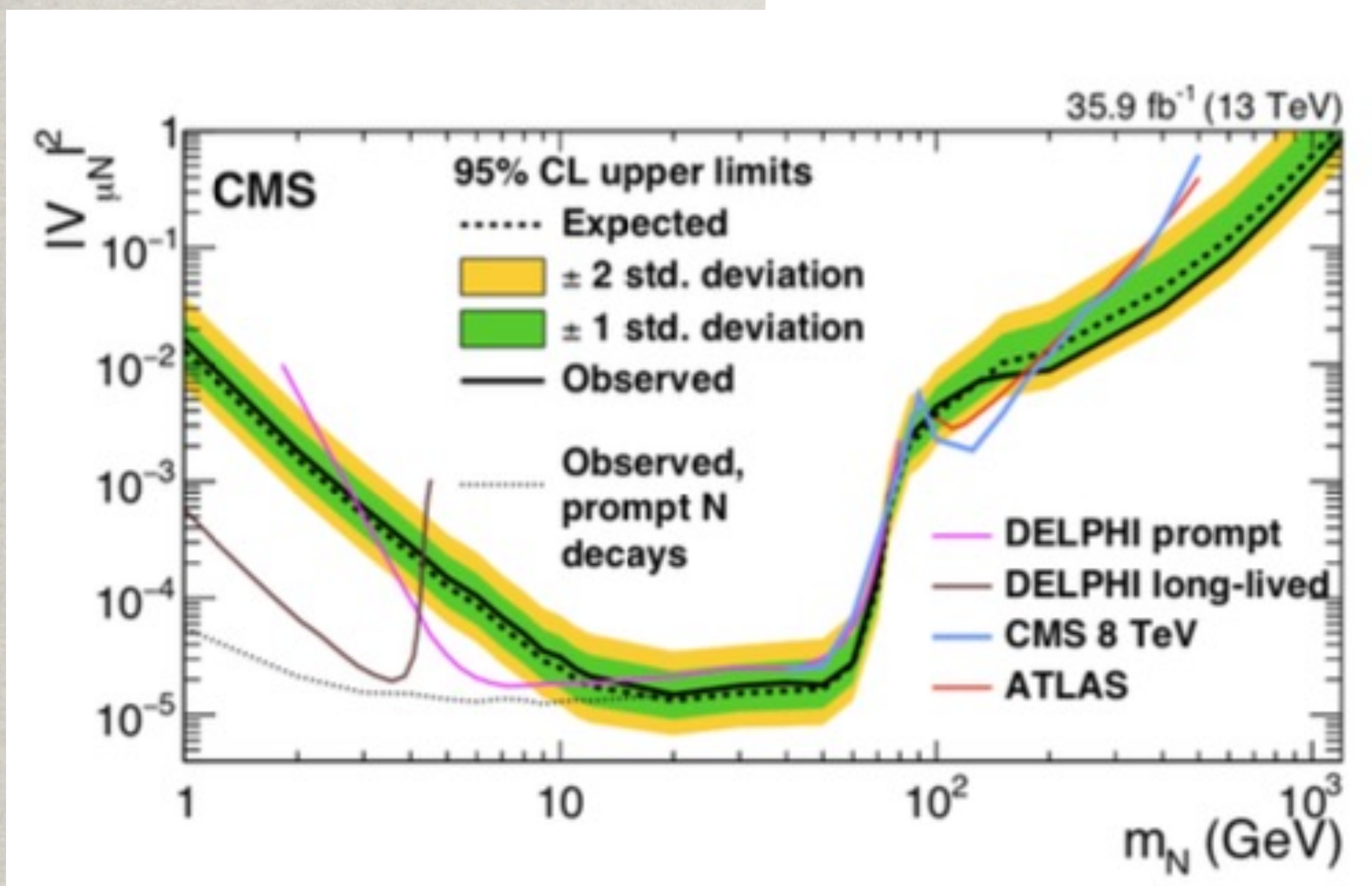
- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W,\ m(jj\mu) = m_N$.

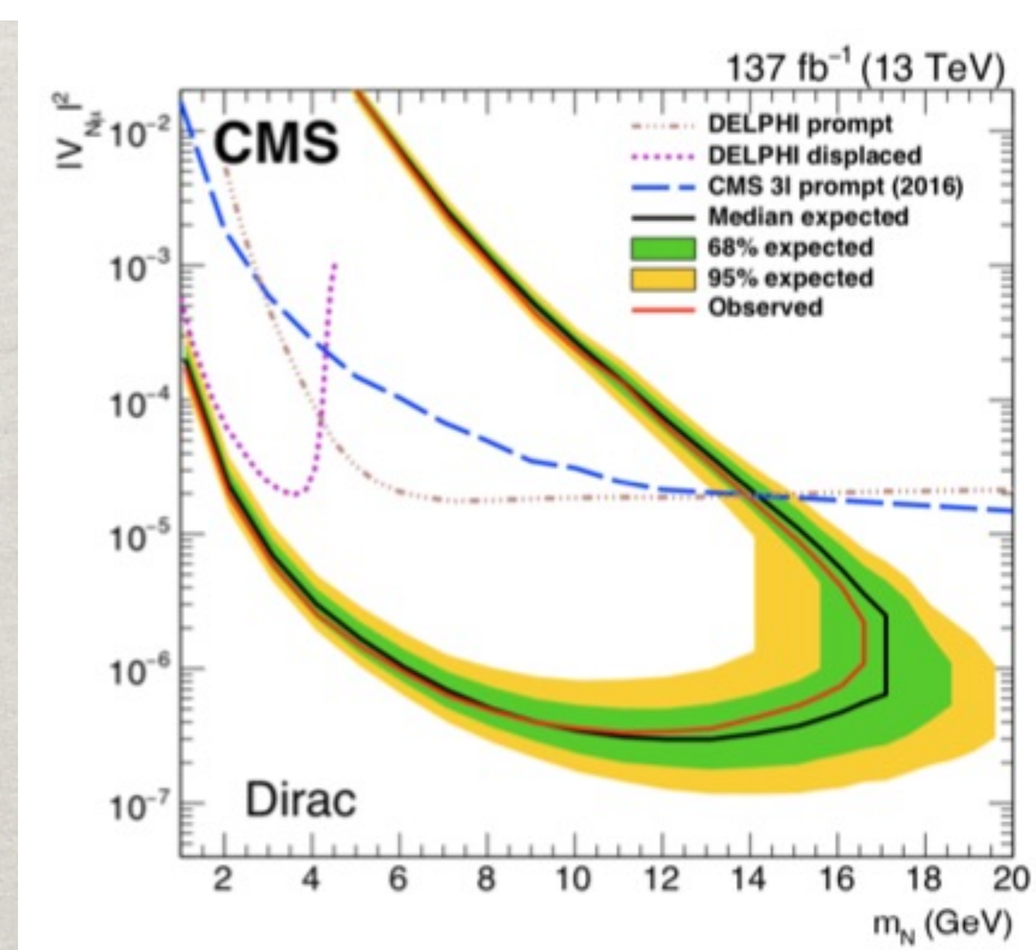
§Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

†T. Han and B. Zhang, hep-ph/0604064, PRL (2006).

Active search @ LHC



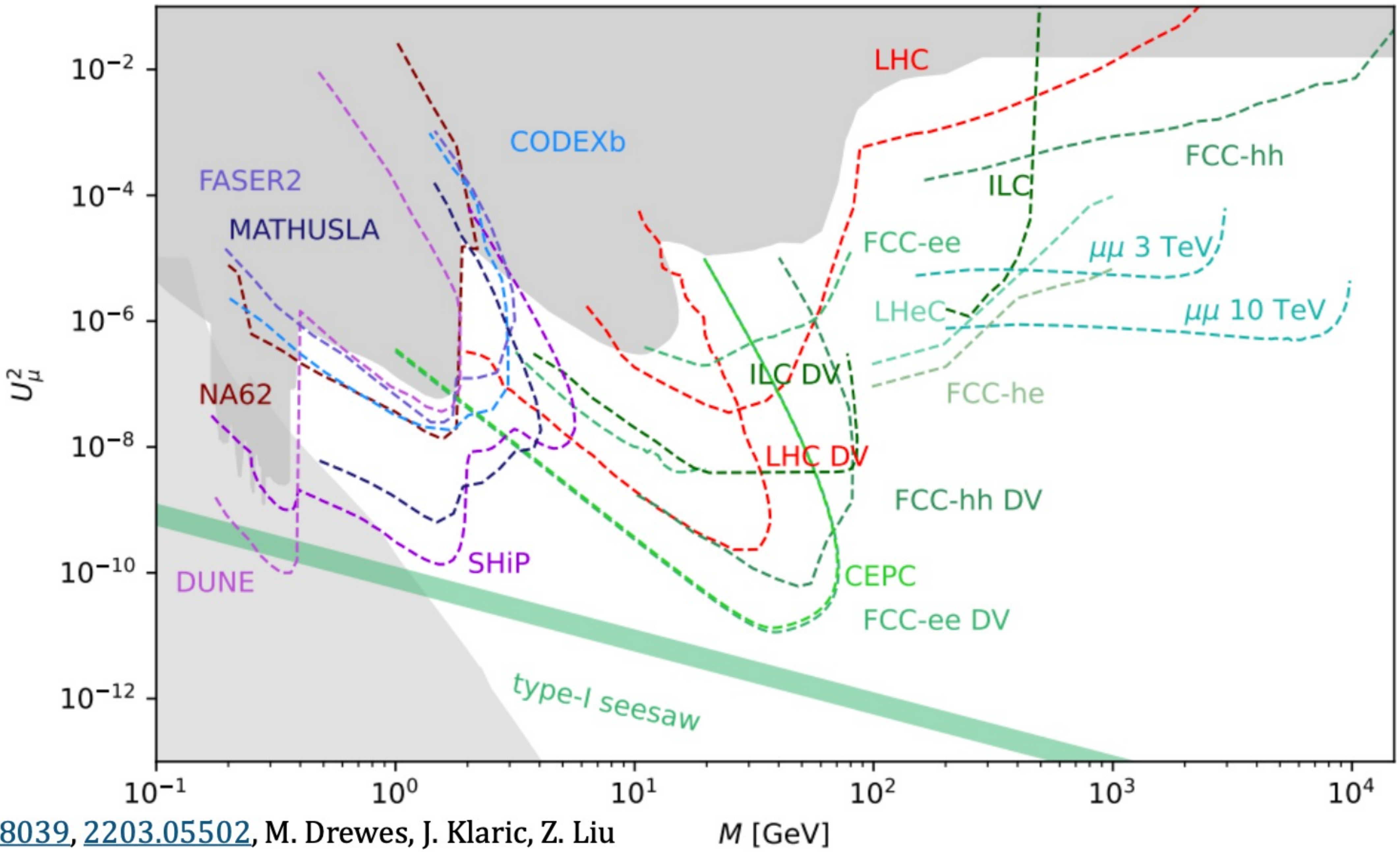




Heavy N Whitepaper: arXiv:2203.08039

Complementarity @ high & low masses

- **For displaced HNL signatures, more experiments can join the search**
- HL-LHC timescale: FASER2, MATHUSLA, CODEXb, DUNE can probe low masses



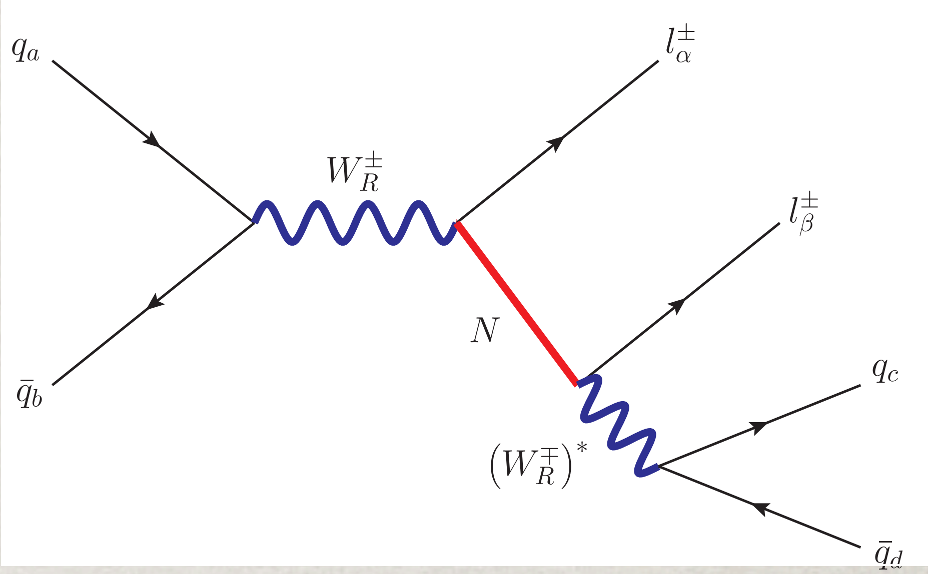
2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

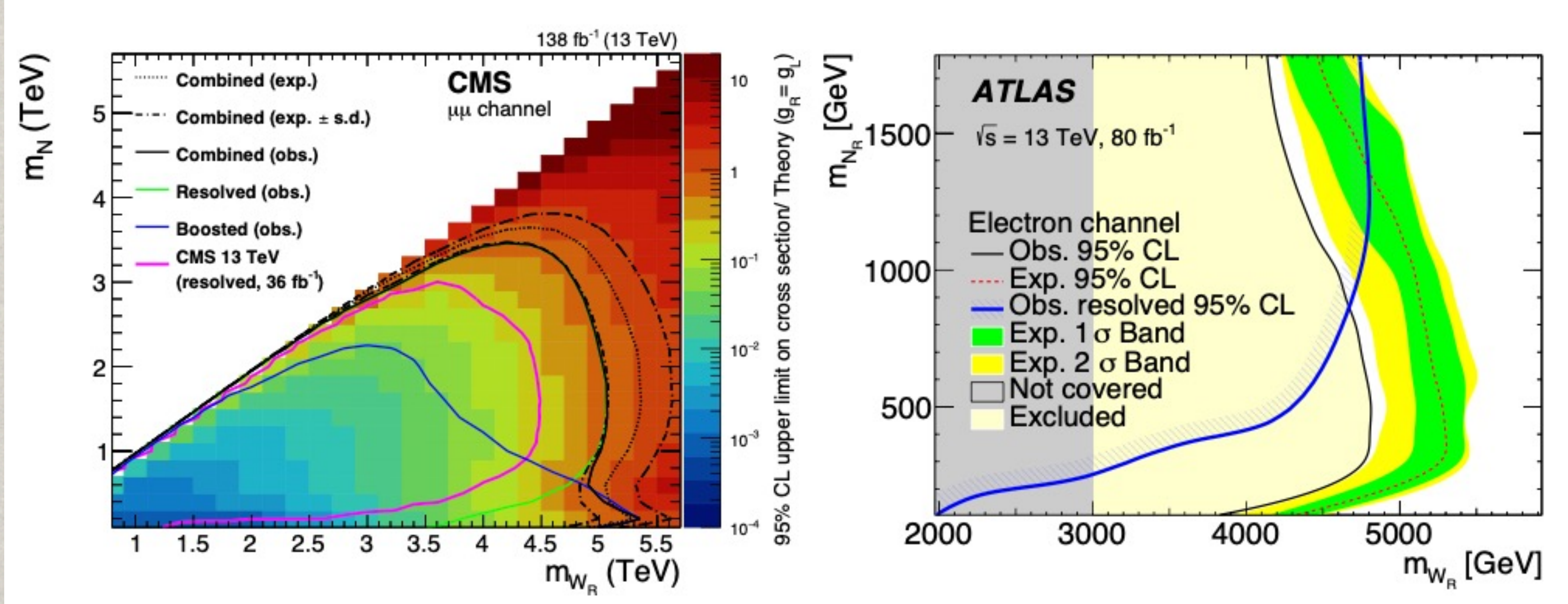
J. Hogan

2. N_R & W_R @ Hadron Colliders

In Left-Right symmetric model:

- No mixing suppression
- New unknown mass scale M_R





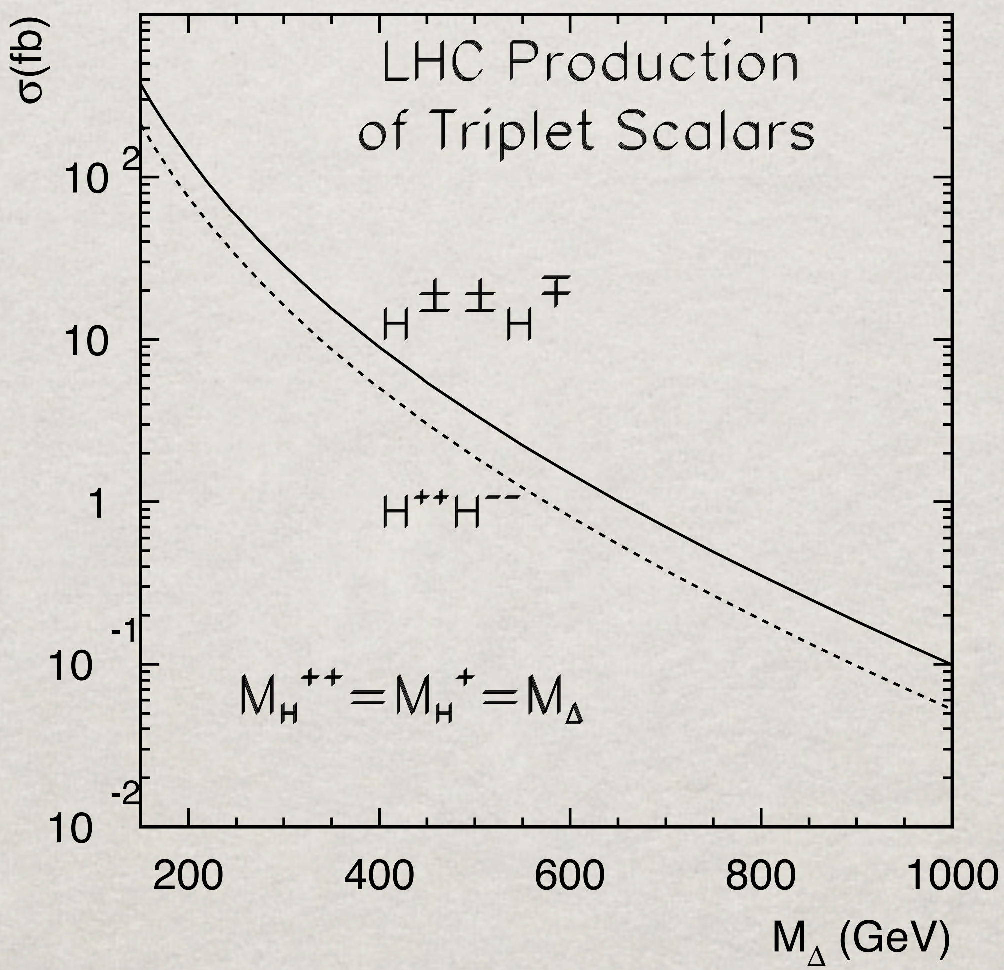
W. Keung & G. Senjanovic, PRL 50 (1983) 1427

Heavy N Whitepaper: arXiv:2203.08039

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

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

Pure electroweak gauge interactions



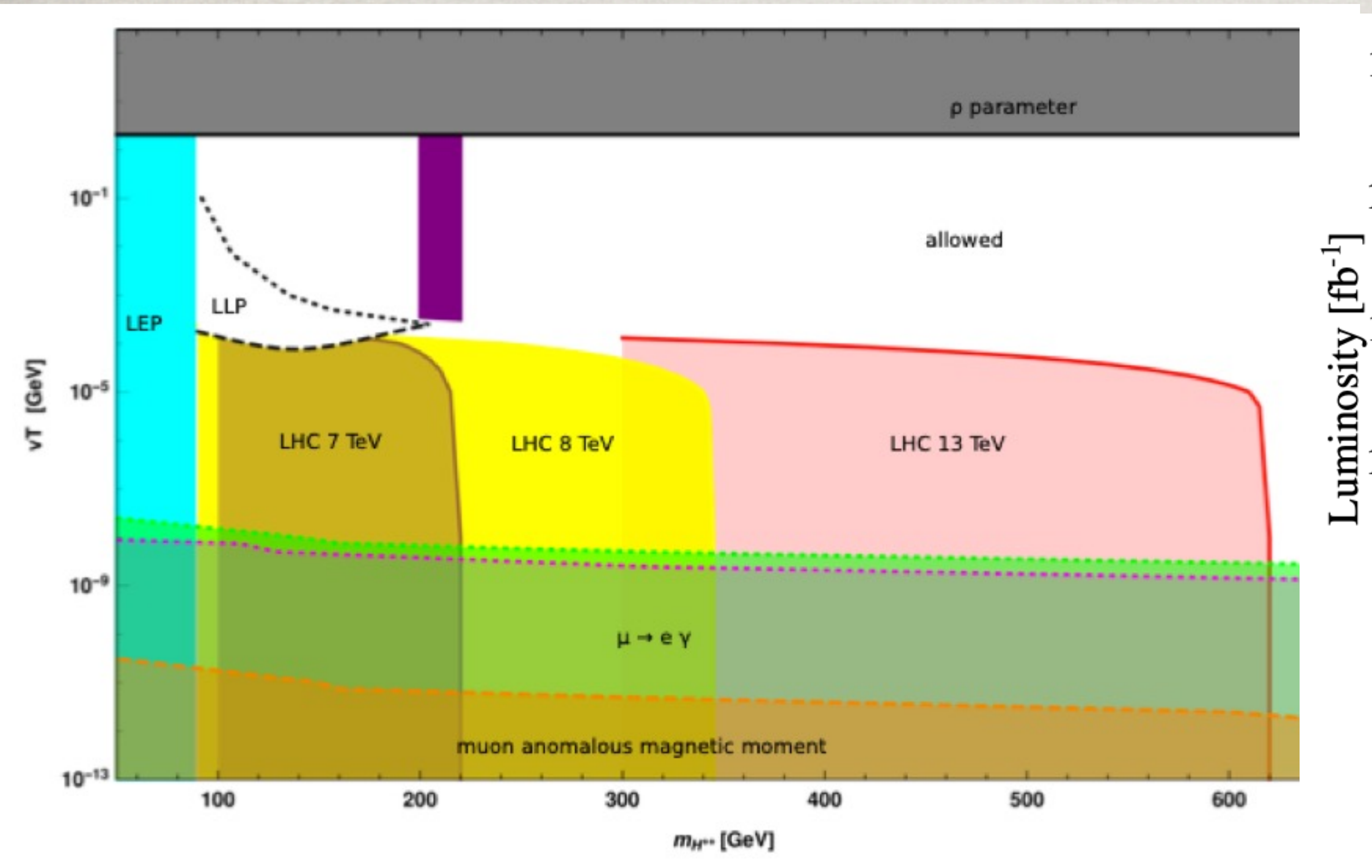
Akeroyd, Aoki, Sugiyama, 2005, 2007.

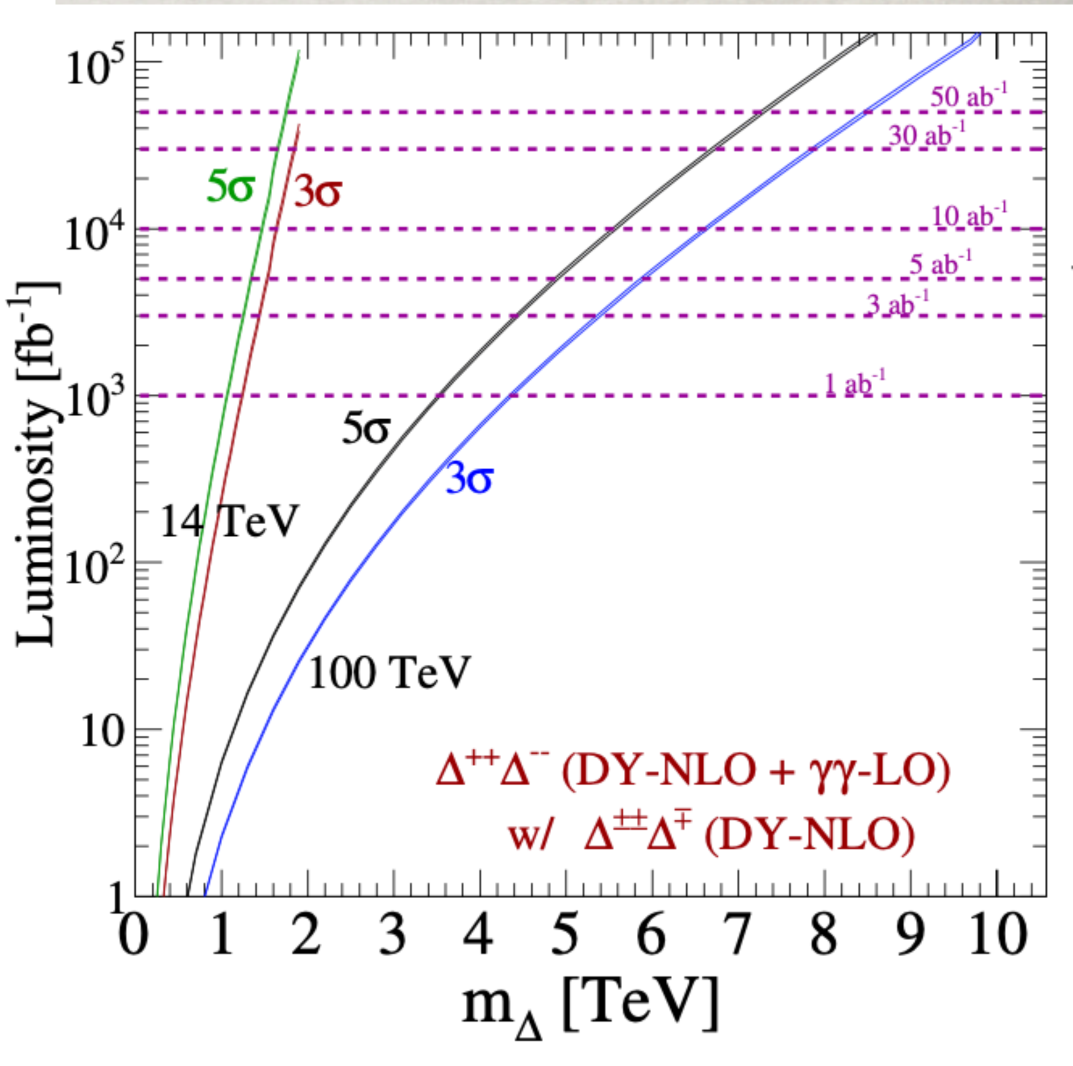
$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY.

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

Z.L. Han, R. Ding, Y. Liao, arXiv:1502.05242; 1506.08996;
J. Gehrlein, D. Goncalves, P. Machado, Y. Perez-Gonzalez: arXiv:1804.09184.

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





BSM Whitepaper: arXiv:2203.08039

Neutrino – charged lepton correlations

Summarize the discovery modes:

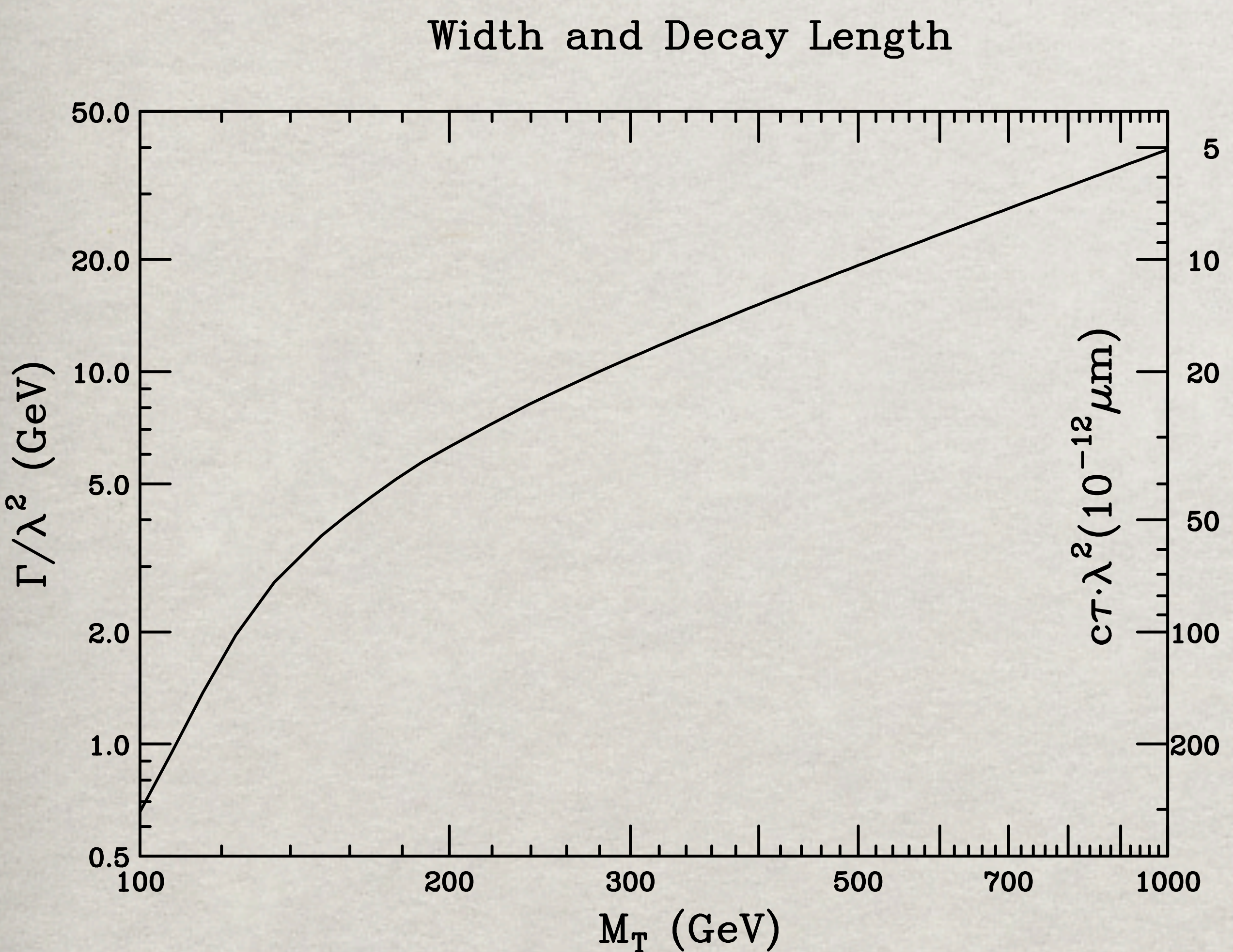
Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	BR($H^{++} \to \tau^+\tau^+$), BR($H^{++} \to \mu^+\mu^+$) $\gg$ BR($H^{++} \to e^+e^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\mu^+$), BR($H^{++} \to e^+\tau^+$) BR($H^+ \to \tau^+\bar{\nu}$), BR($H^+ \to \mu^+\bar{\nu}$) $\gg$ 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($H^+ \to \tau^+\bar{\nu}$) $\approx 1/3$

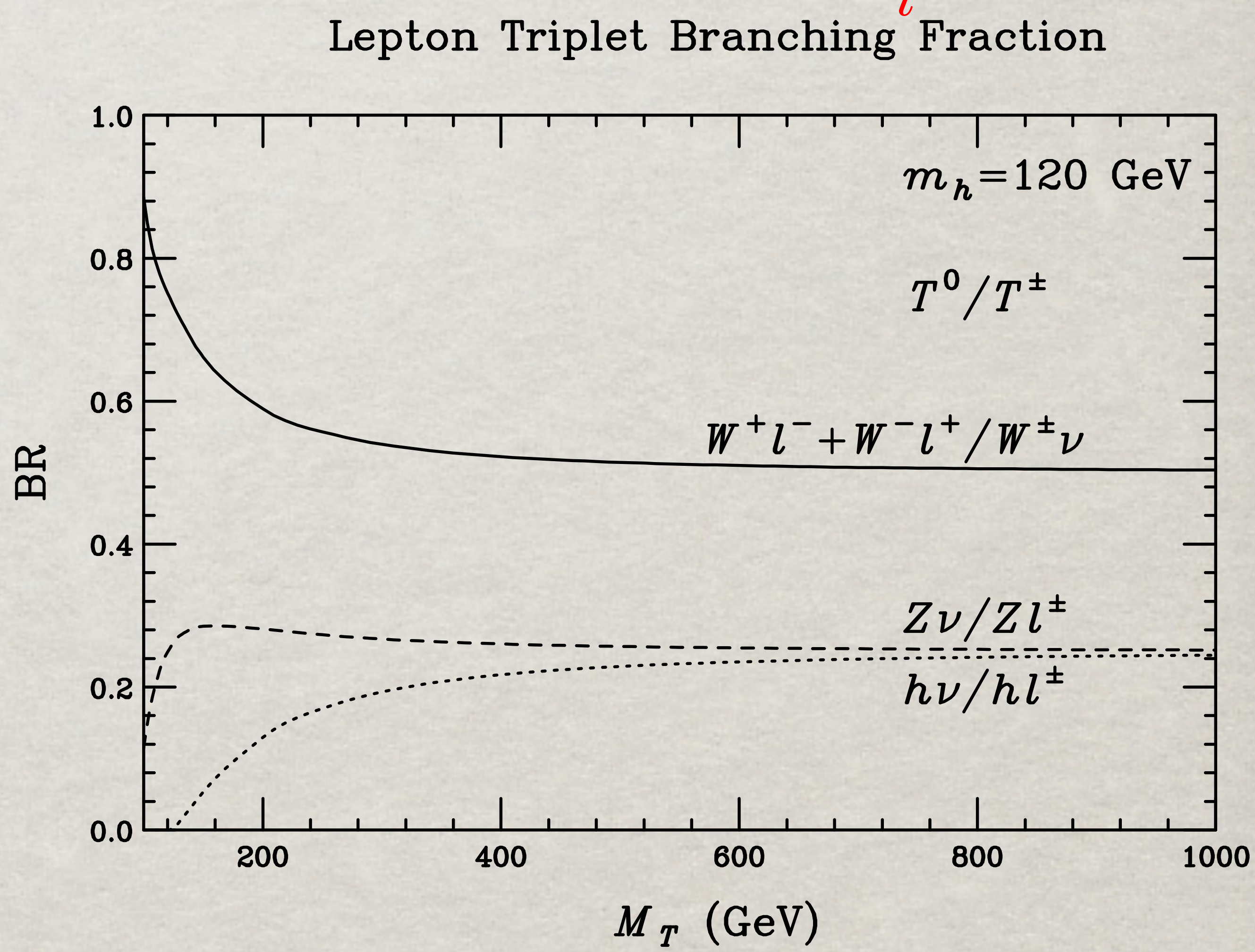
†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

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

Consider their decay length:

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





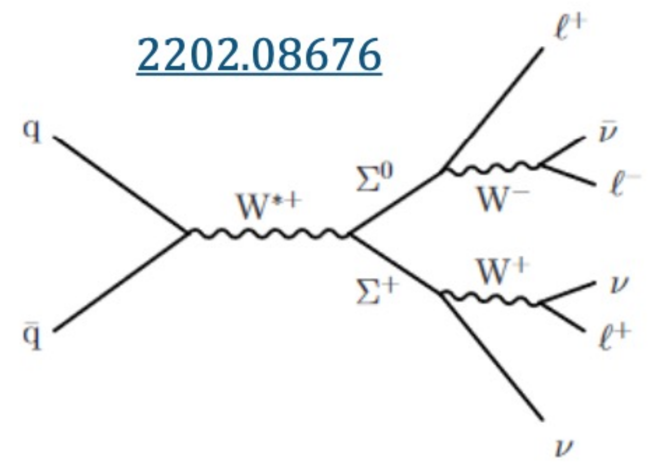
With $\lambda^2 = y_j^2 \sim 10^{-16} - 10^{-12}$, then $c\tau \sim 10^{-2} - 10^{-4}$ m

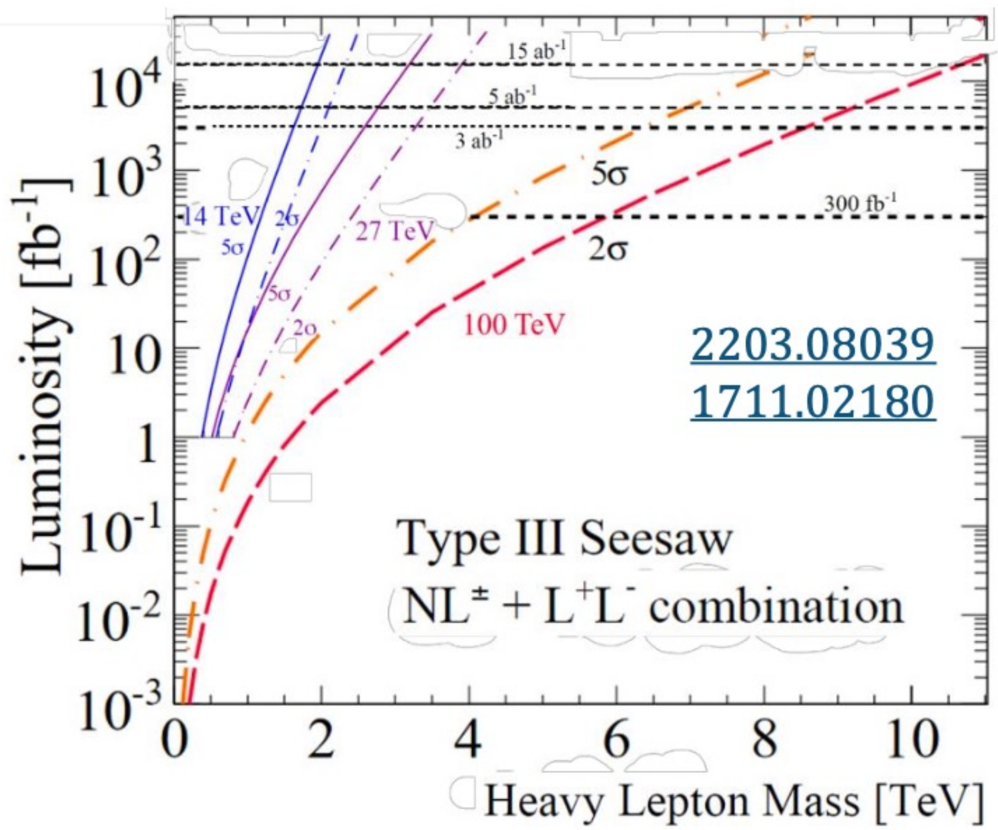
Still not too long-lived, but possibly large displaced vertices.

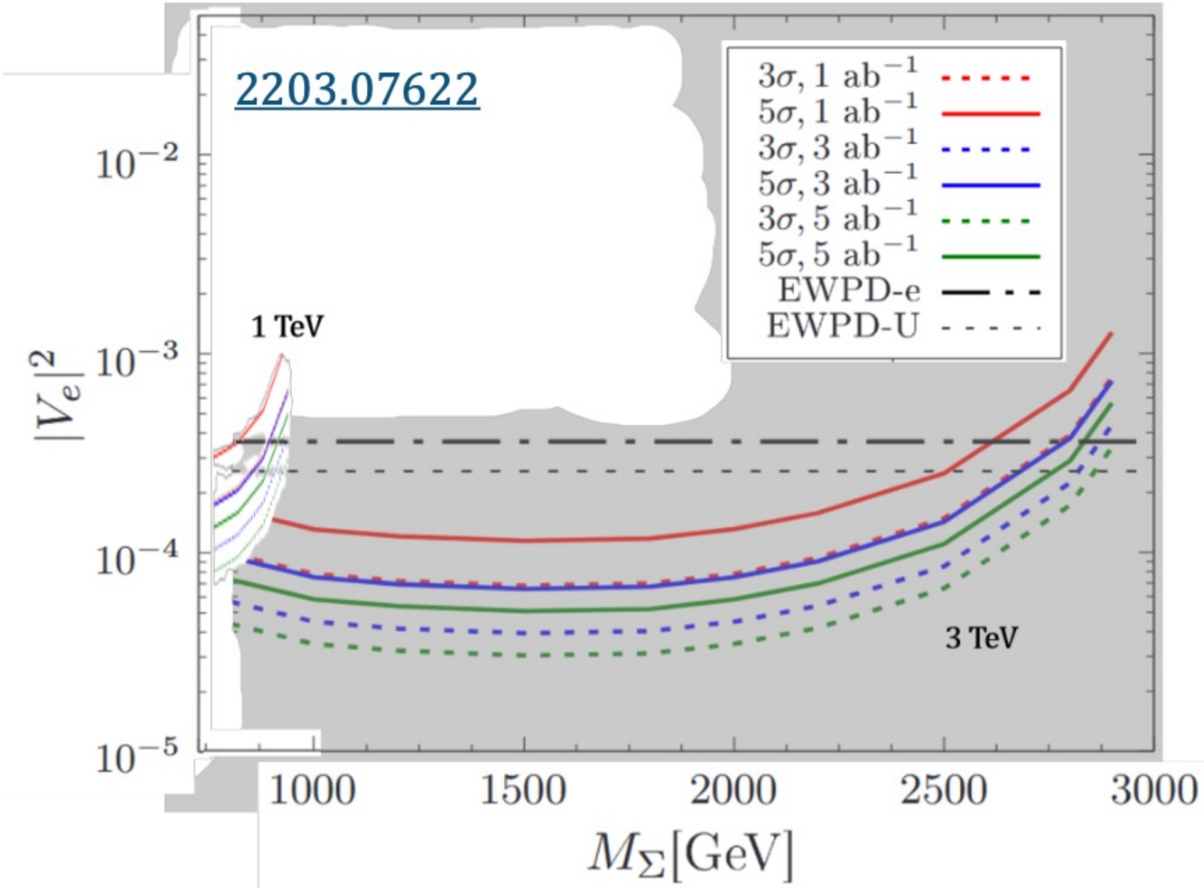
Tong Li & X.G. He, hep-ph/0907.4193.

- N → Wℓ gives multilepton or boosted-jet final states
- **pp**: pair production of neutral + charged heavy leptons
  - HL-LHC will not reach far beyond ~1 TeV Run 2 bounds
  - 100 TeV could quickly out to 6 TeV, discover past 3 TeV
- **ee**: single production of neutral lepton
  - Below their thresholds, ee colliders can push couplings below EWPD bounds.

2202.08676





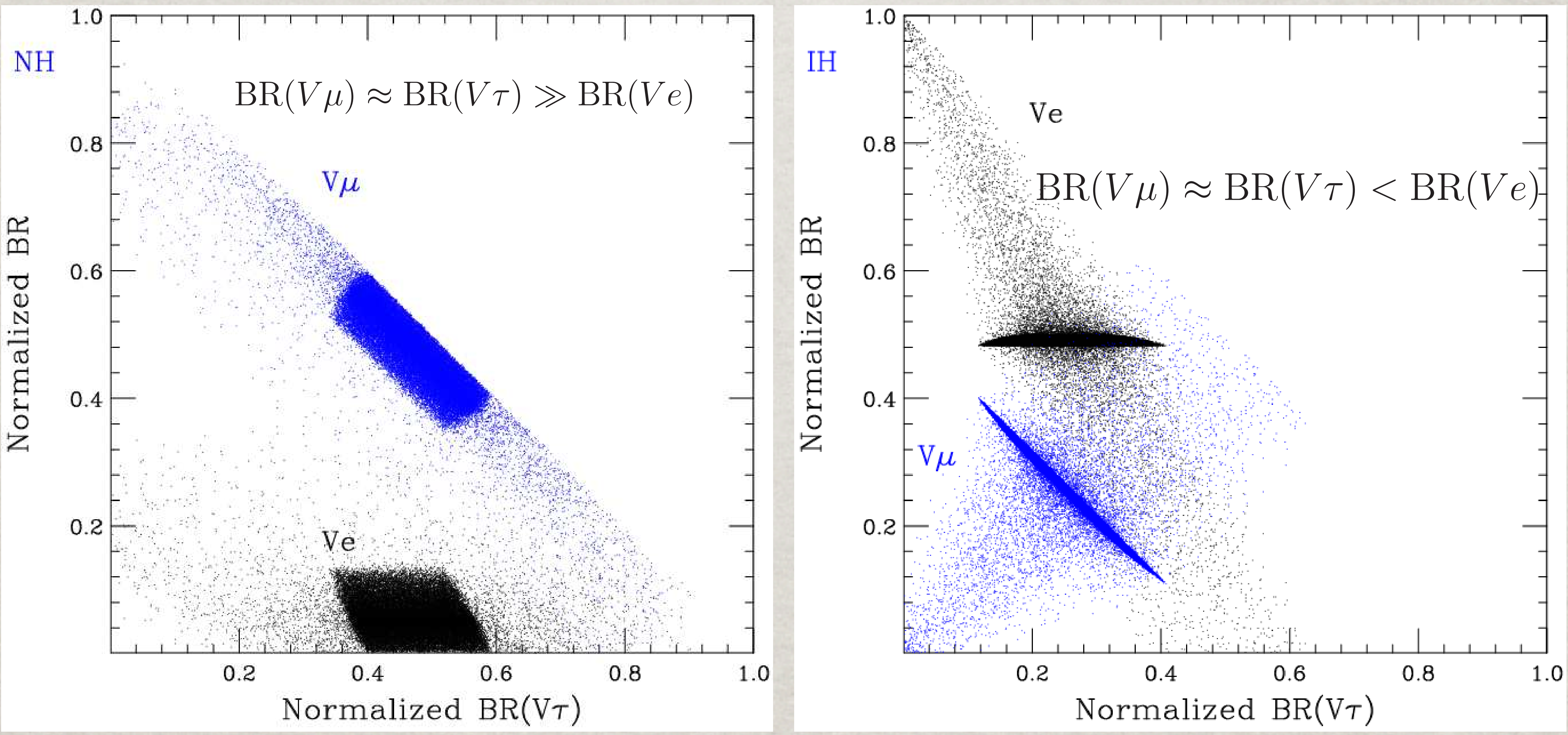


BSM Whitepaper: arXiv:2203.08039

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.

Summary

- Seesaw mechanism well motivated: $m_\nu \sim y^2 v^2/M$
- Collider experiments complement the oscillations experiments to explore ν physics.

- Collider experiments reach higher mass threshold and thus probe the dynamical origin.

  - Type I-like: $N_R \sim 1$ TeV, $U_\nu \sim 10^{-6}$
  - Type II: $H^{++} \sim 1$ TeV
  - Type III: T^+, $T^0 \sim 1$ TeV

  - Radiative mass models: scalar mass a few 100 GeV.
  - Test ν-portal to DM; NSIs.

Collider experiments may discover the neutrino mass generation mechanism (with luck)!