BSM ν Physics @ Colliders

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NF-EF Cross-cutting Topics
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Contents:

- Neutrino mass models & their phenomenological features
- Collider tests & complementarity

ν's: the most elusive/least known particle in the SM:

- How many species: 3 $\boldsymbol{\nu}_L$'s + N_R?
- Absolute mass scale: $m_{\boldsymbol{\nu}} \sim y_{\boldsymbol{\nu}}\, v < 1$ eV?
  or a new physics scale: $M_{majorana} >> v$?
- Mass-ordering?
- Flavor oscillations & CP violation?
- Non-standard interactions?
- Mixing with sterile ν's?
- Portal to dark sector?

→ 6+ Nobel Prizes related to ν's, more than other discoveries, and more excitement to come!

In theory, simplest SM extension for $\boldsymbol{\nu}$ mass:

n N_R's (sterile) → SM-like Yukawa coupling (Dirac)

$$y_\nu\, \bar{L}\ell_R \cdot \tilde{H} N_R \to (m_\nu + \frac{y_\nu}{\sqrt{2}} H)\bar{\nu}_L \nu_R$$

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)

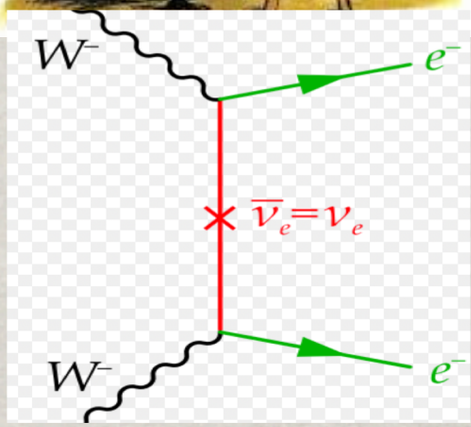
Implications:

- 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:

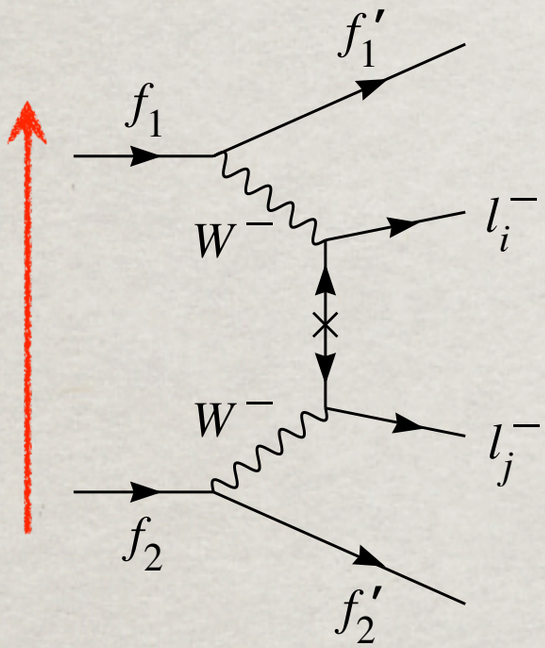
  $\Delta L=2$ → Majorana mass (Majorana neutrinos)

→ 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: $\Delta L=2$

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

Majorana neutrinos:

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

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

<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*)

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

$U_{\ell m},\ \Delta m_\nu$ 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:

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

(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 $\Phi\ (Y=2):\ \phi^{\pm\pm}, \phi^{\pm}, \phi^{0}$ (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
- … …

Typically, they introduce additional Higgs states and thus new (model-dependent) experimental signatures.

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

Non-Standard ν Interactions (NSIs)

First introduced by Wolfenstein in 1978:

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)\,,$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

Or more general interactions:

$$\mathscr{L}_{\rm GNI} = \frac{G_F}{\sqrt{2}} \sum_a (\bar{\nu}\Gamma_a \nu)[\bar{f}\Gamma_a(\epsilon_a + \tilde{\epsilon}_a \gamma^5) f],$$

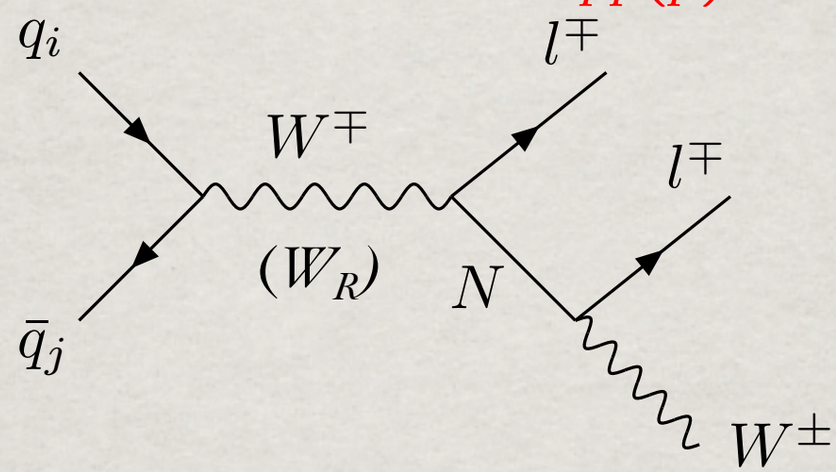
where $\Gamma_a = \{\mathbb{1}, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$

They will impact both oscillation observables as well as collider signals

BSM $\boldsymbol{\nu}$ Whitepaper: arXiv:2203.06131
arXiv:1907.00991

1. N_R at Colliders

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

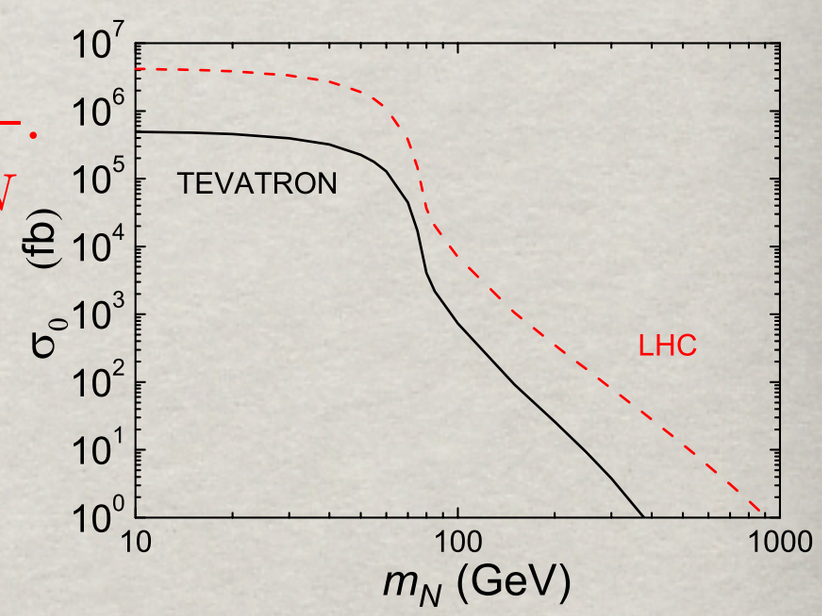


$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2 \, \sigma_0.$$

Factorize out the mixing couplings: [†]

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

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



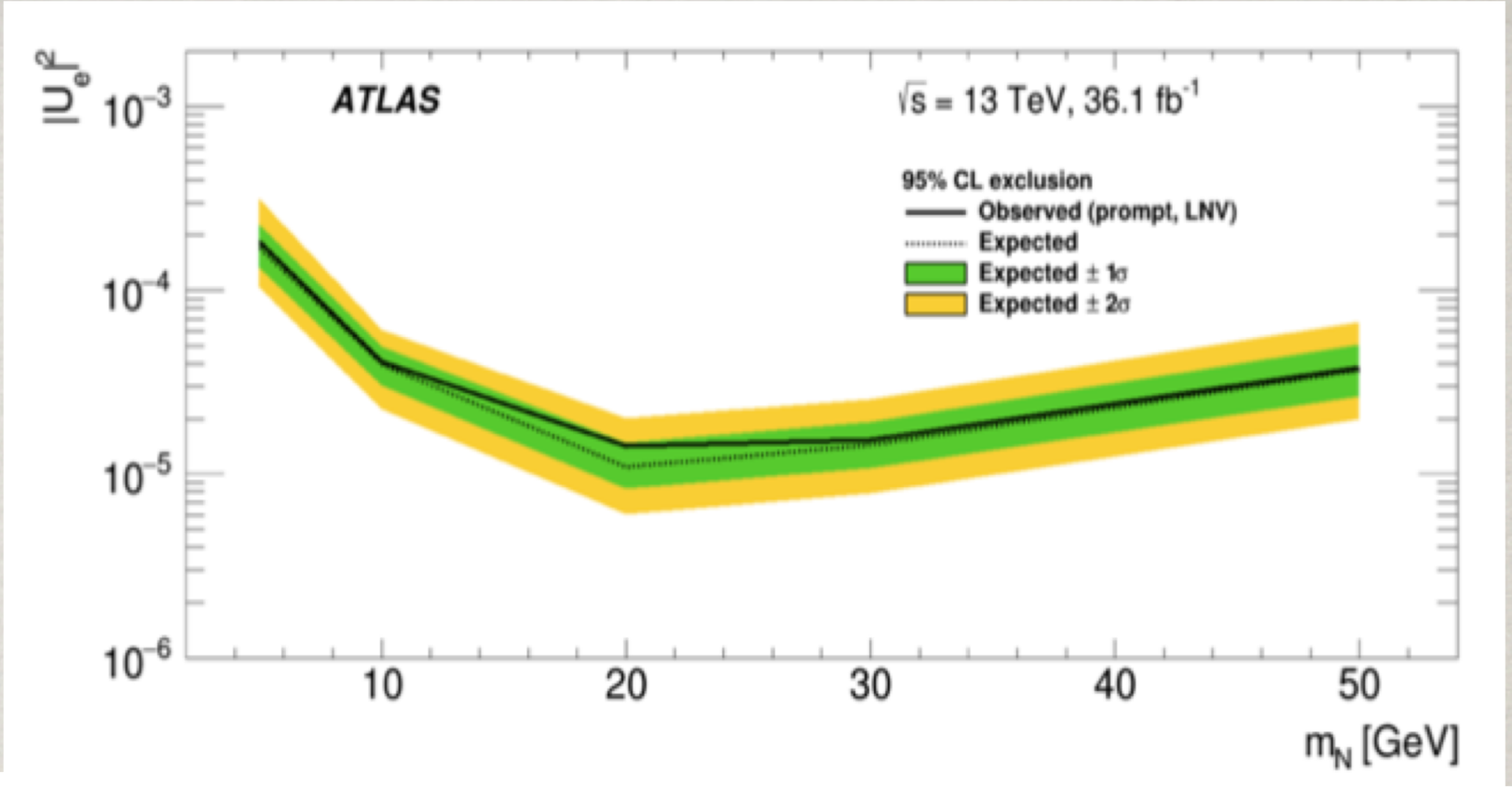
A very clean channel:

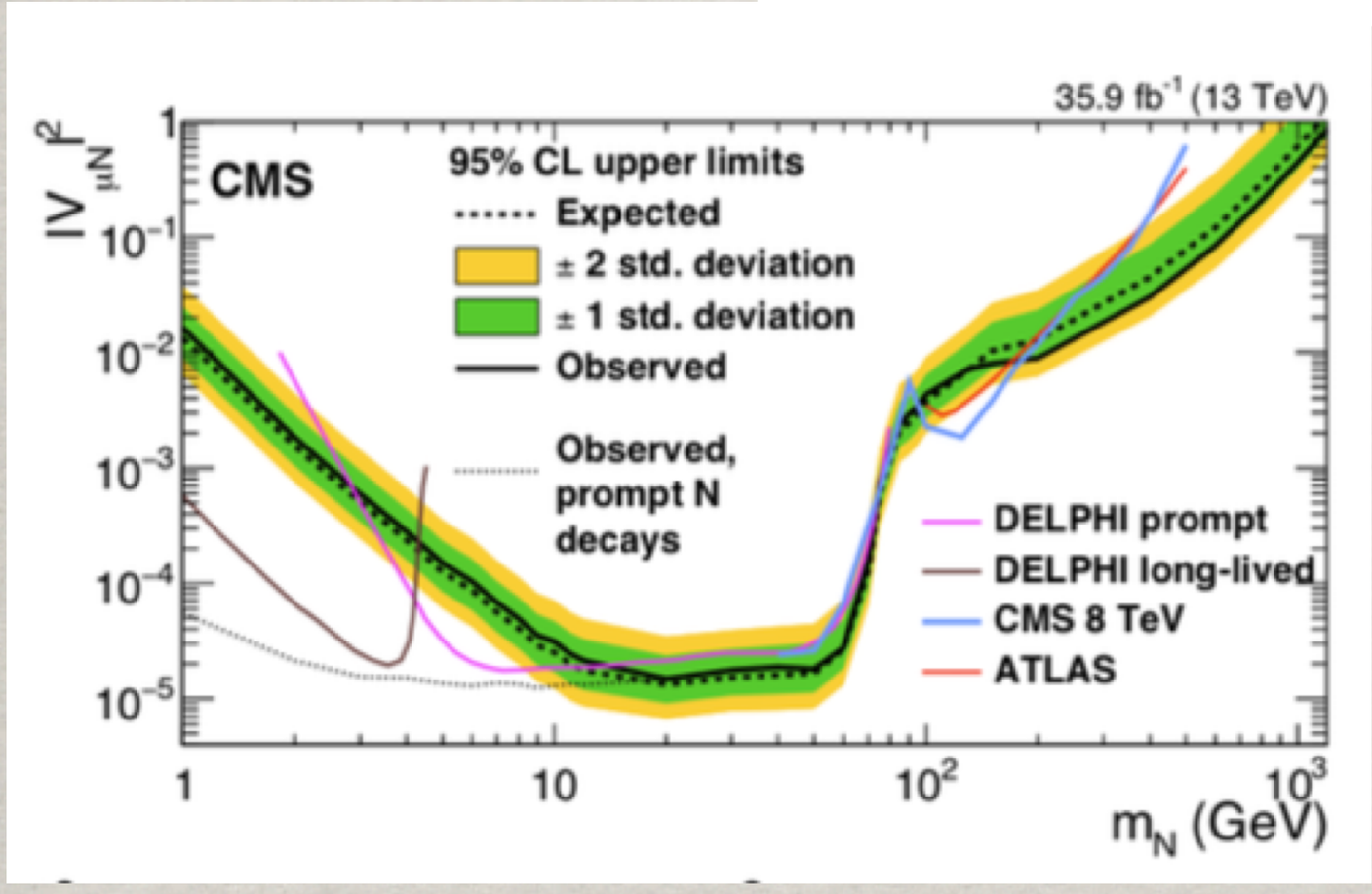
- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W, \; m(jj\mu) = m_N.$

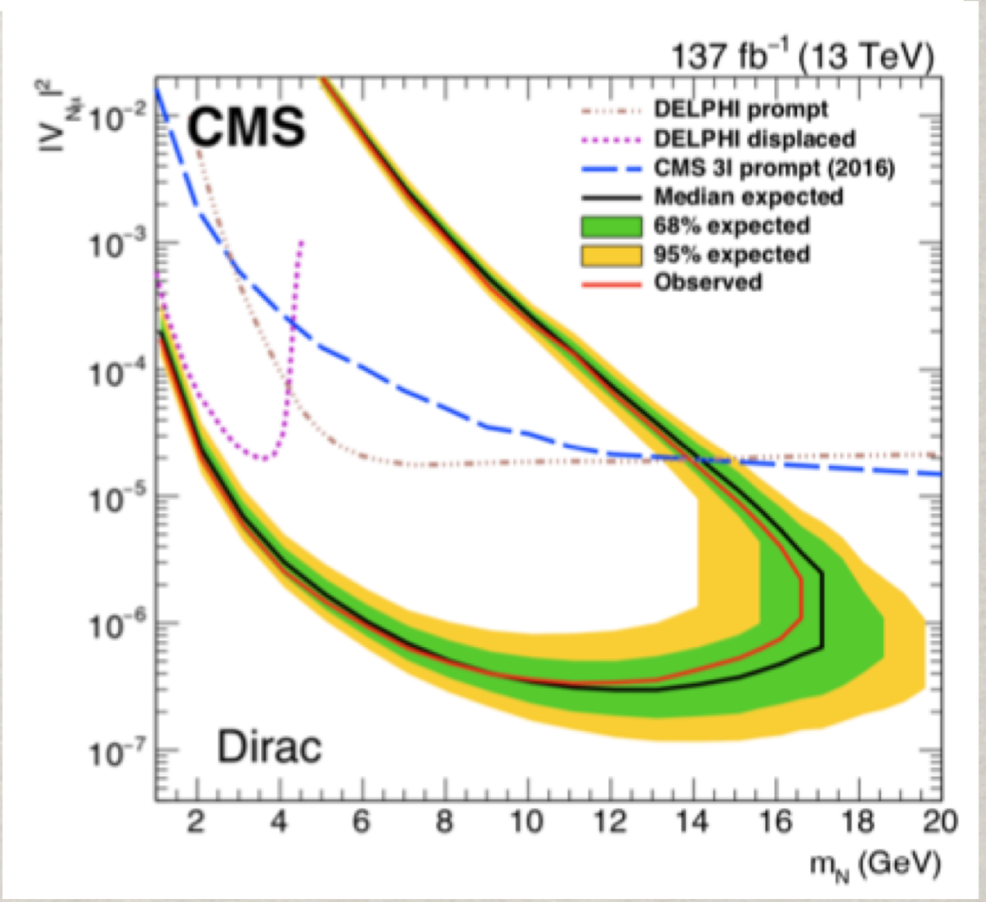
[§] Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

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

Active search @ LHC

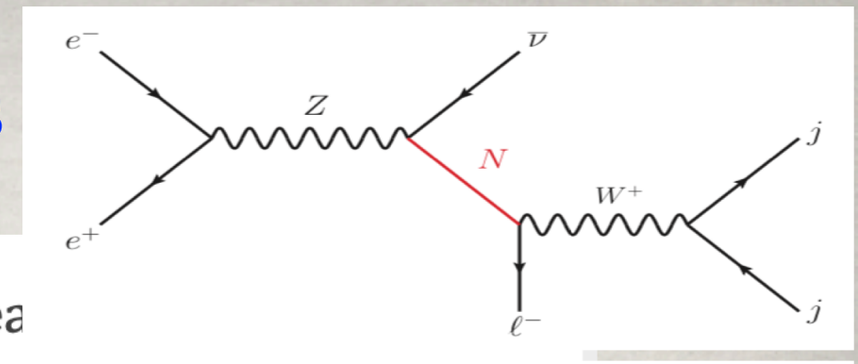




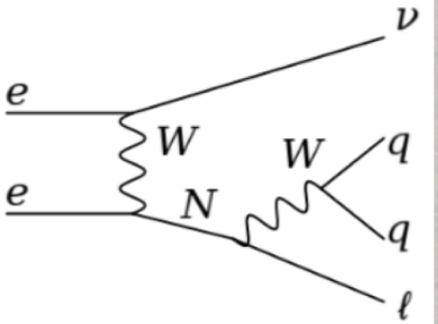


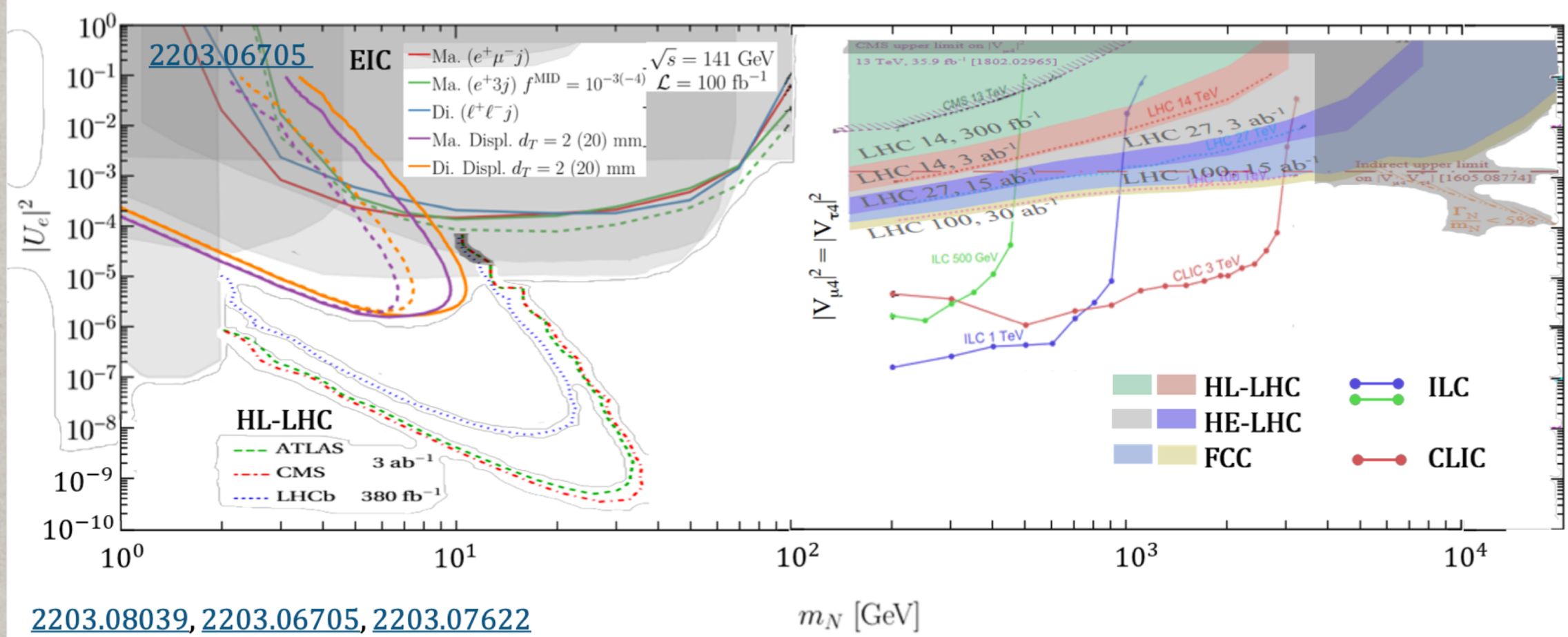
Heavy N Whitepaper: arXiv:2203.08039

Complementarity @ different colliders



- **EIC**: sensitive at low and medium mass ranges, special LFV sea
- **LHC/FCC**: strong potential for low mass displaced searches, consistent couplir reach out to very high mass with increased lumi and energy
- **ILC/CLIC**: can dig more deeply into coupling space where energy allows.
  - Fast-sim study with machine learning



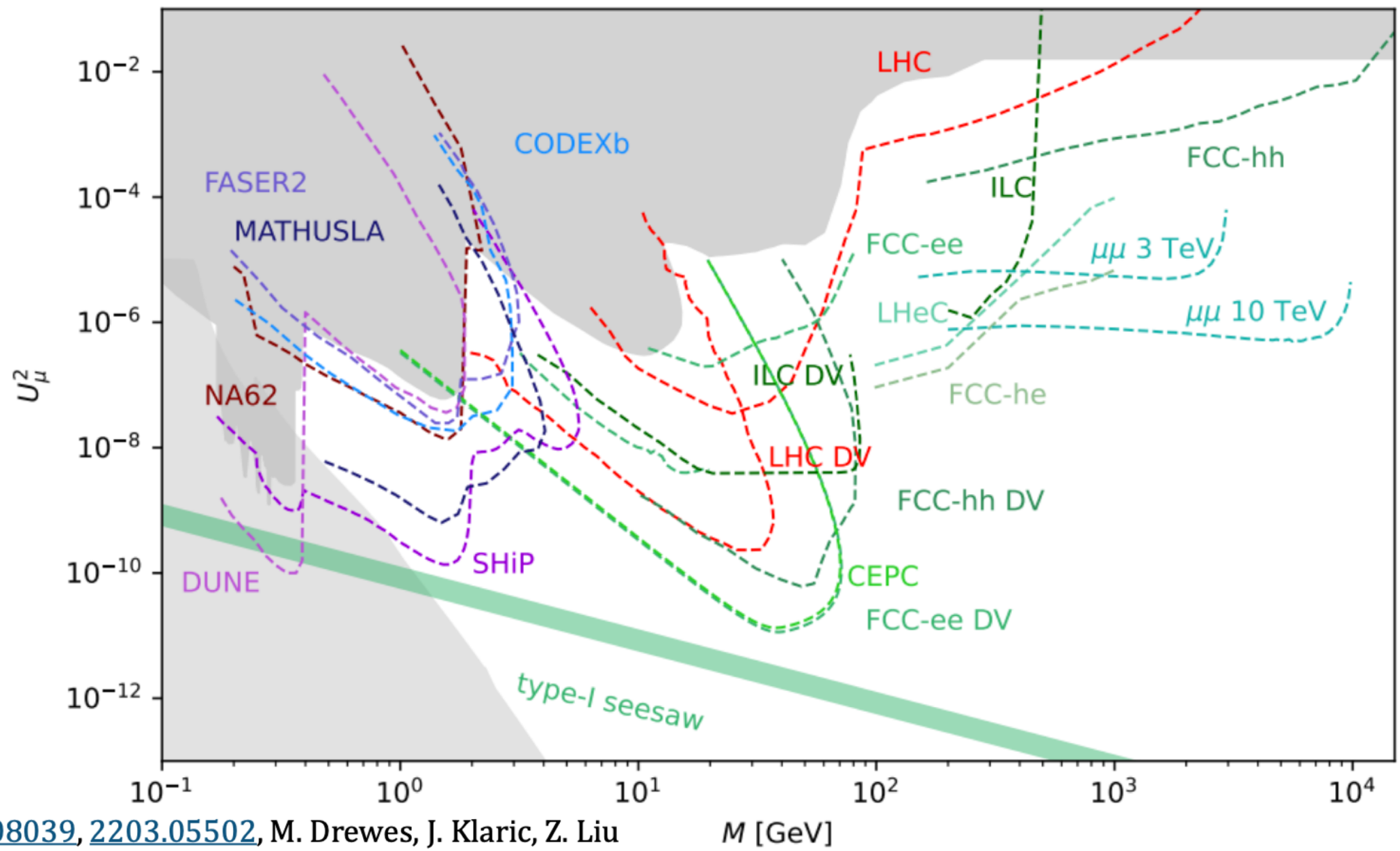


2203.08039, 2203.06705, 2203.07622

ILC Whitepaper: arXiv:2203.06722

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

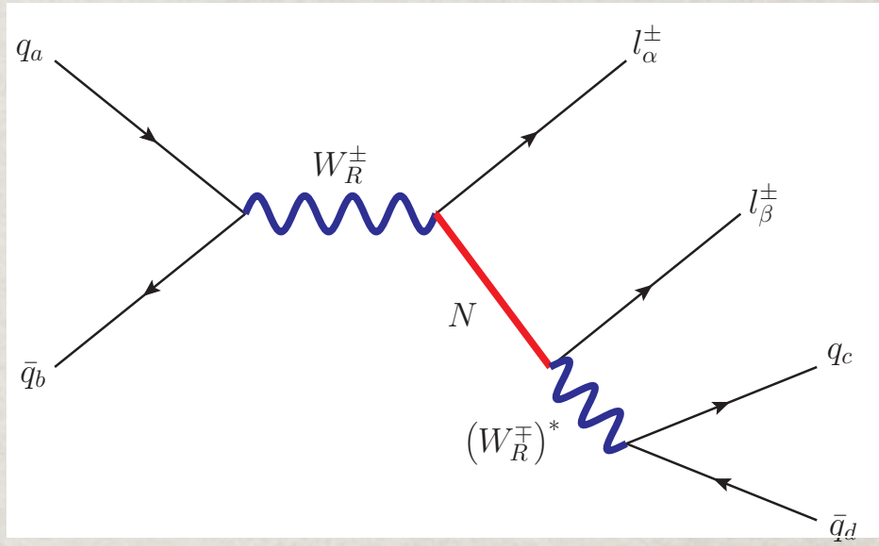


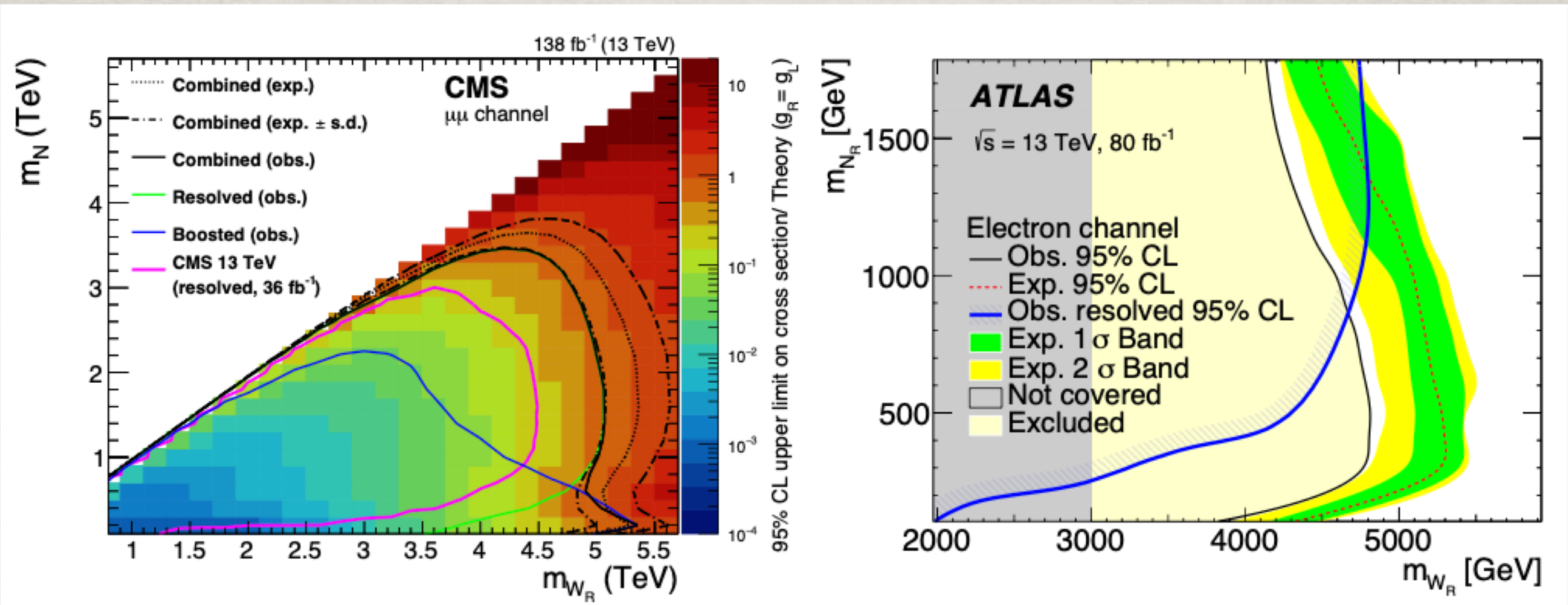
2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

2. N_R & W_R @ Hadron Colliders

In Left-Right symmetric model:

- No mixing suppression
- New unknown mass scale M_R





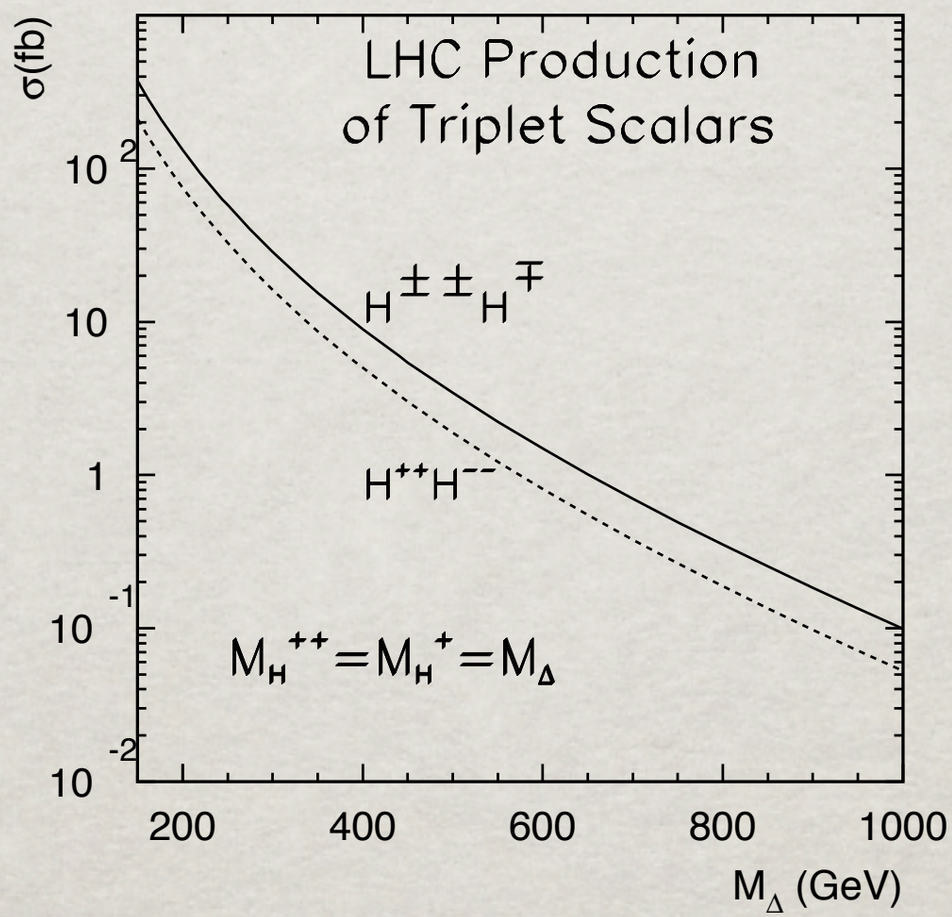
W. Keung & G. Senjanovic, PRL 50 (1983) 1427

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.

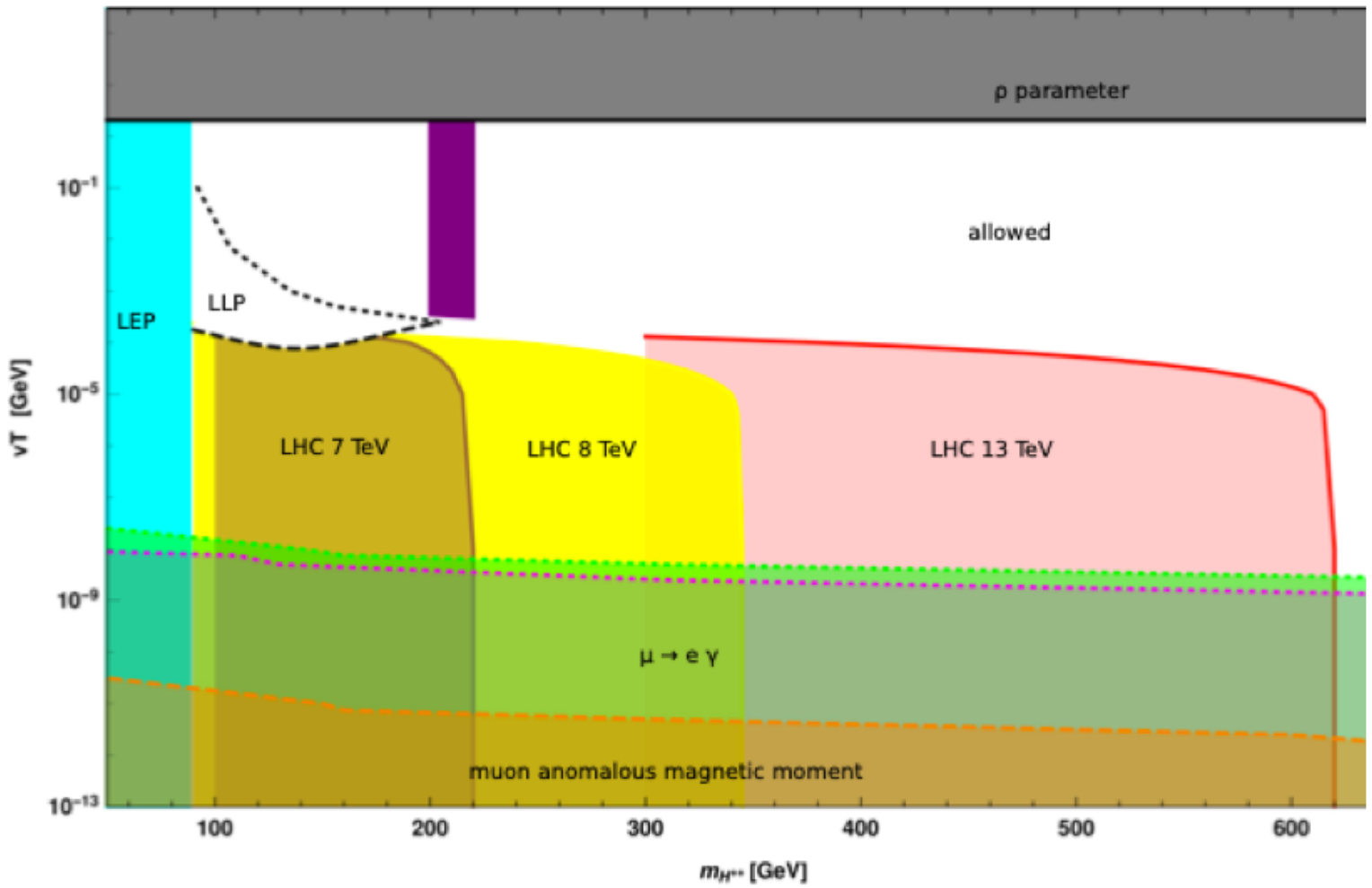
$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY.

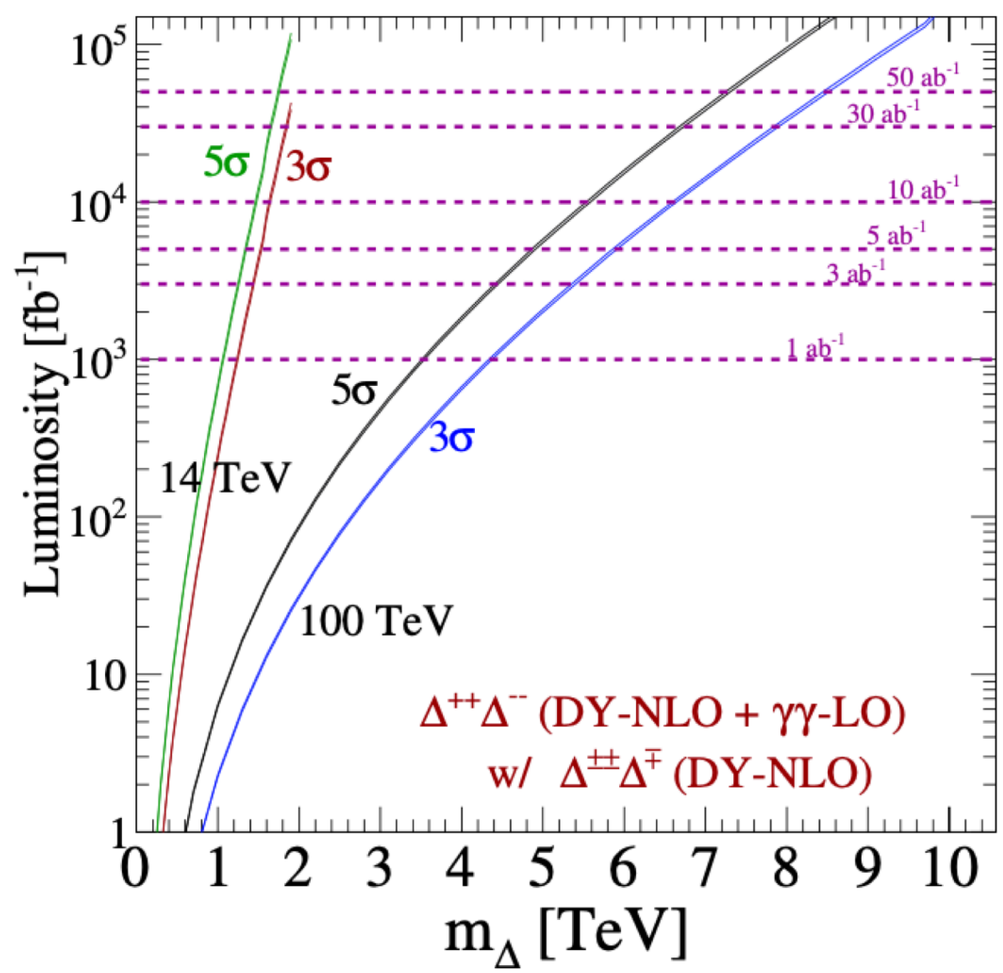
†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

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:

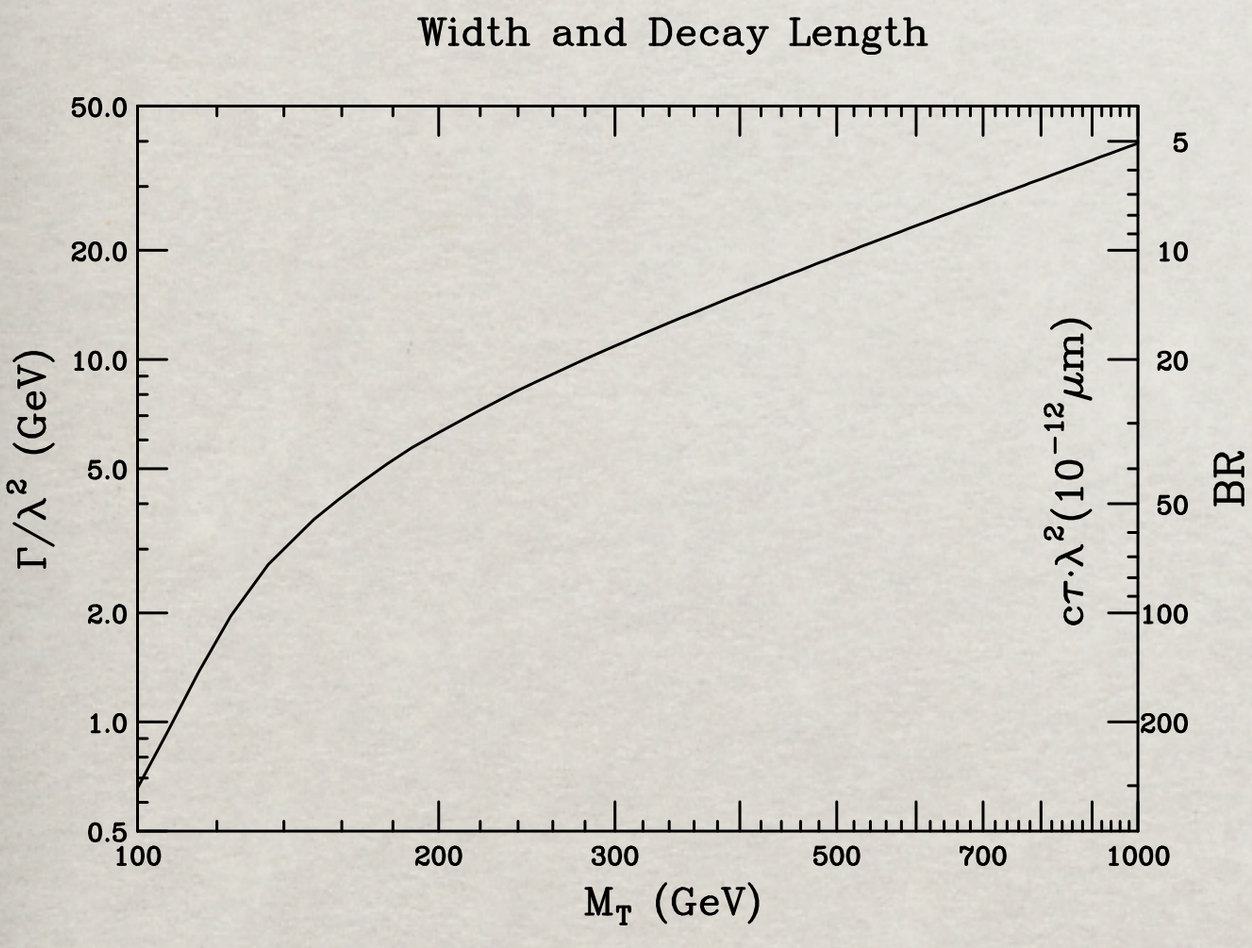
Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	$\mathrm{BR}(H^{++} \to \tau^+\tau^+)$, $\mathrm{BR}(H^{++} \to \mu^+\mu^+) \gg \mathrm{BR}(H^{++} \to e^+e^+)$ $\mathrm{BR}(H^{++} \to \mu^+\tau^+) \gg \mathrm{BR}(H^{++} \to e^+\mu^+)$, $\mathrm{BR}(H^{++} \to e^+\tau^+)$ $\mathrm{BR}(H^+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

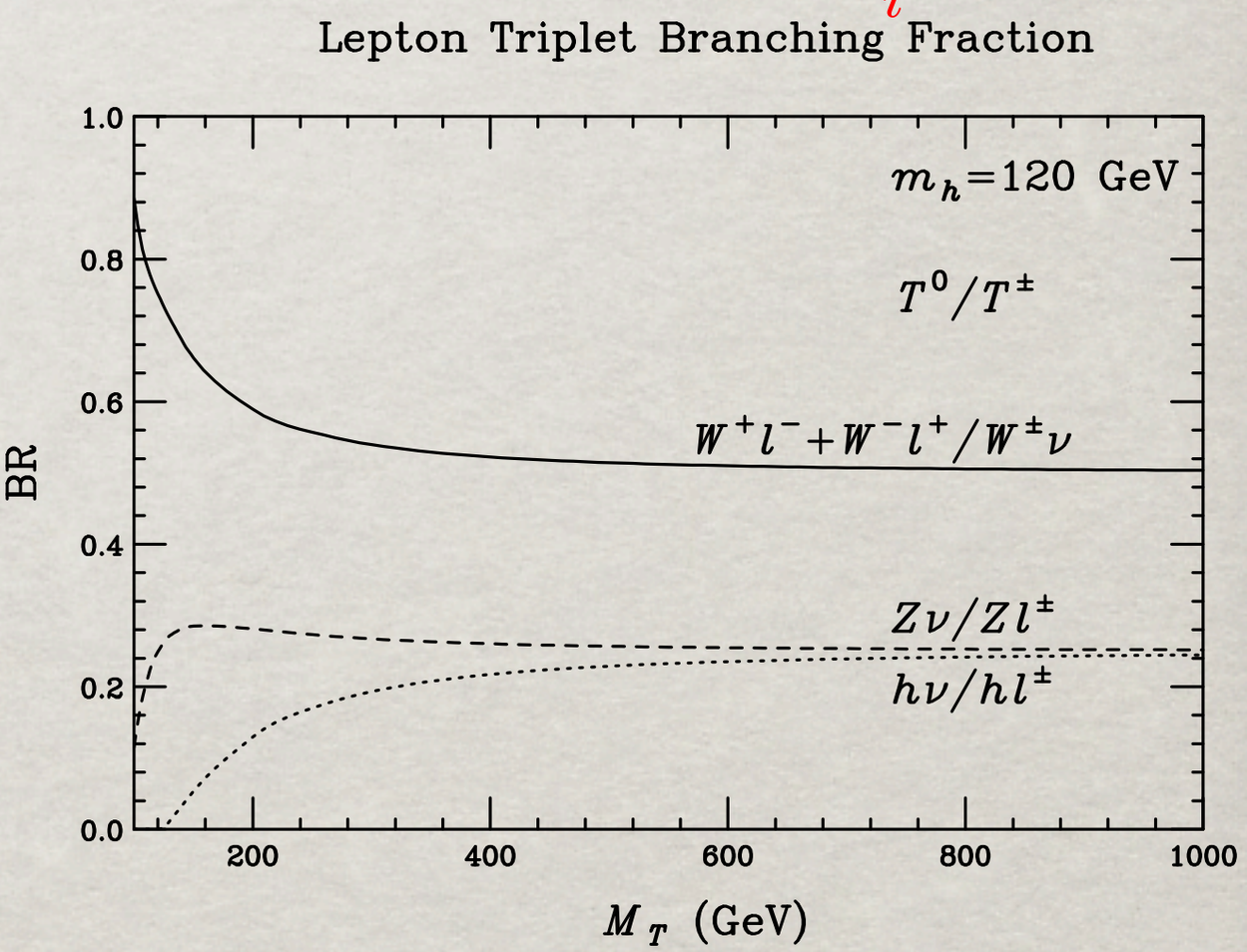
†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

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

Consider their decay length:

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



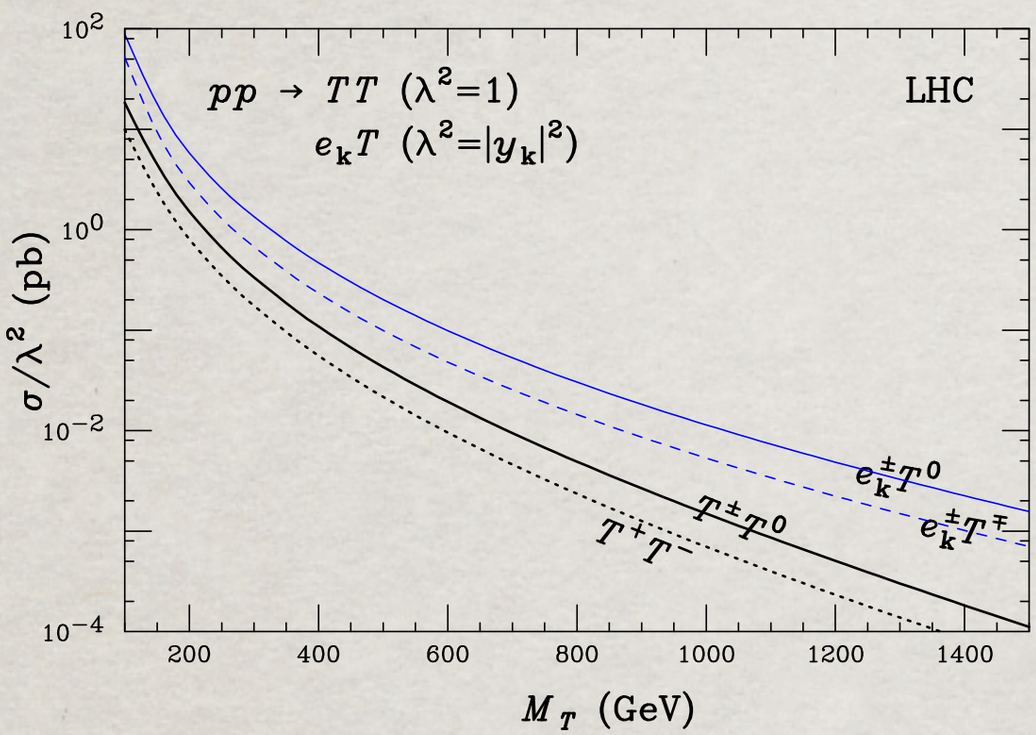


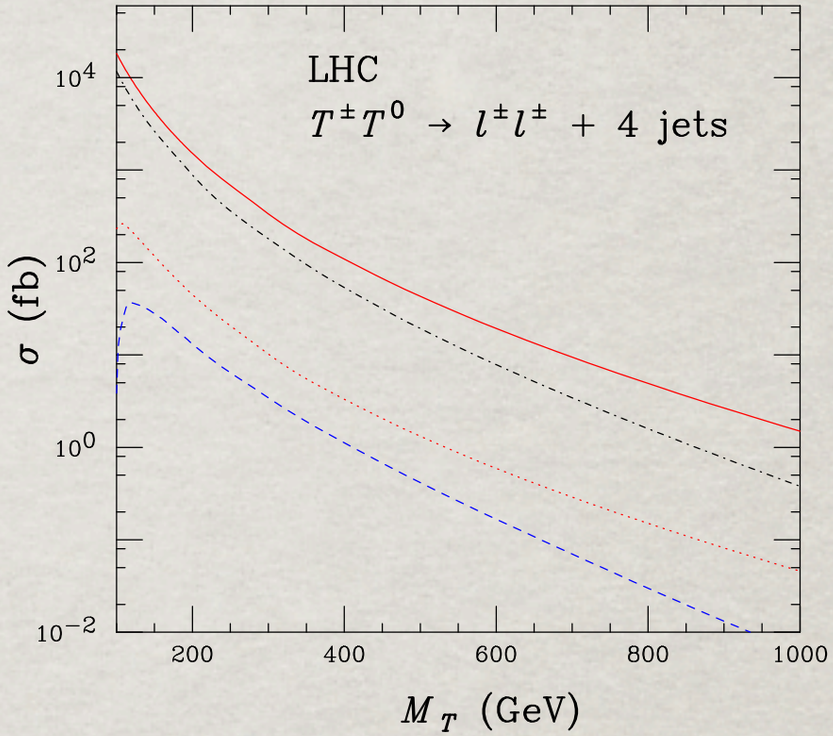
With $\lambda^2 = y_j^2 \sim 10^{-16} - 10^{-12}$, then $c\tau \sim 10^{-2} - 10^{-4}$ m

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

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

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.

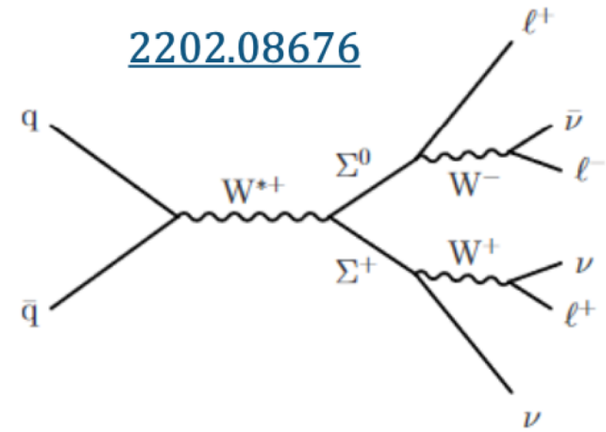
- LHC studies with Minimal Flavor Violation implemented. ‡

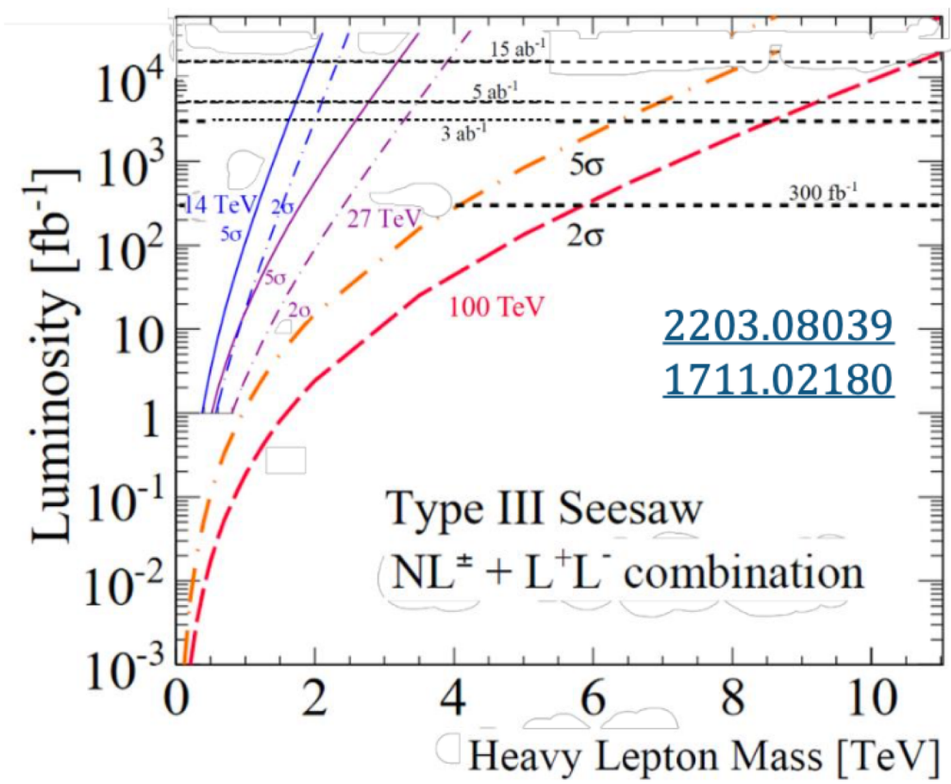
†Similar earlier work: Franceschini, Hambye, Strumia, arXiv:0805.1613.

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

- 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





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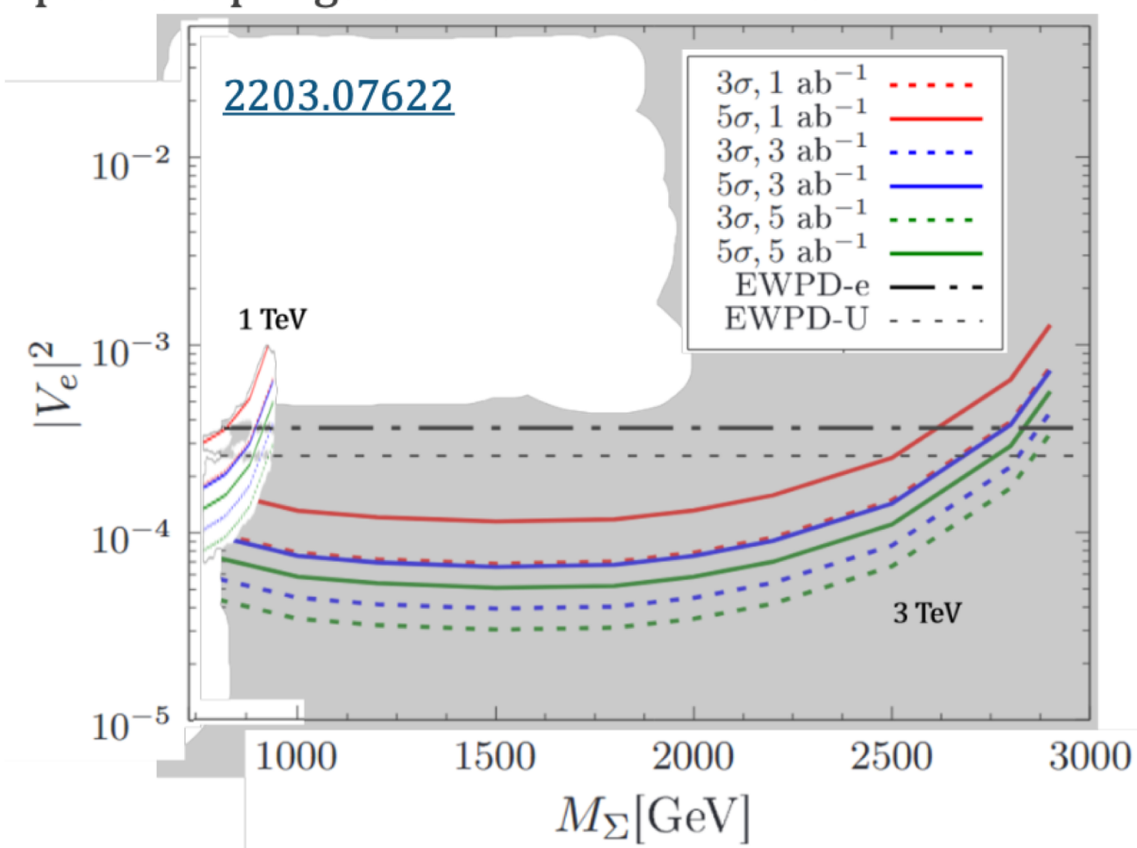


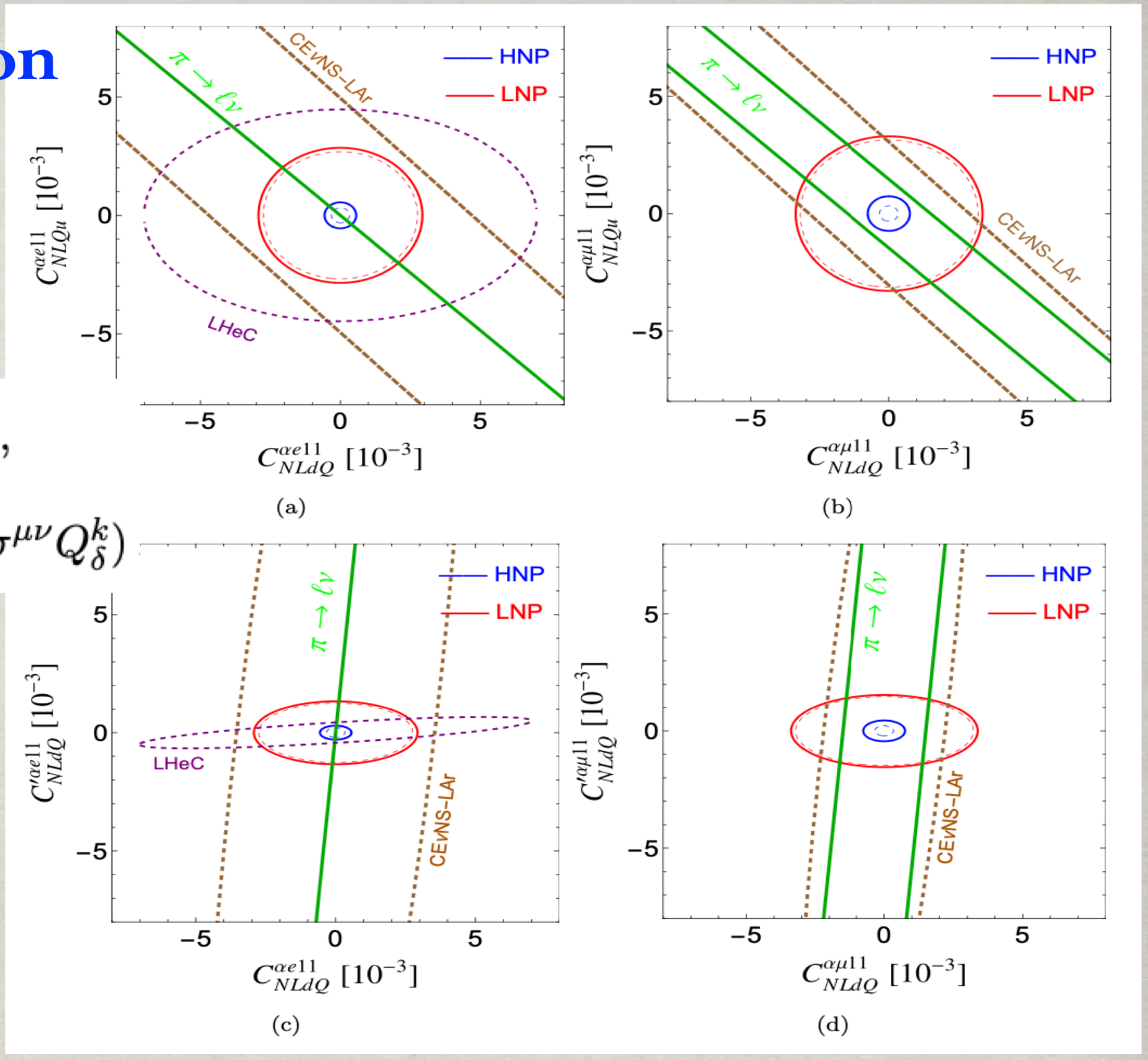
BSM Whitepaper: arXiv:2203.08039

5. NSI: oscillation vs. collider

$$O^{\alpha\beta\gamma\delta}_{NLdQ} = (\overline{N}_\alpha L^j_\beta)\epsilon_{jk}(\overline{d}_\gamma Q^k_\delta)\,,$$

$$O'^{\alpha\beta\gamma\delta}_{NLdQ} = (\overline{N}_\alpha \sigma_{\mu\nu} L^j_\beta)\epsilon_{jk}(\overline{d}_\gamma \sigma^{\mu\nu} Q^k_\delta)$$

BSM $\boldsymbol{\nu}$ Whitepaper:
arXiv:2203.06131;
arXiv:1907.00991;
arXiv:2004.13869.



the projected bounds from HL-LHC with 3 ab^{-1} of data for the LNP and HNP case, respectively. The dashed purple contours in the left panels correspond to the projected bounds from LHeC with 3 ab^{-1}.

A UV complete Z' model:

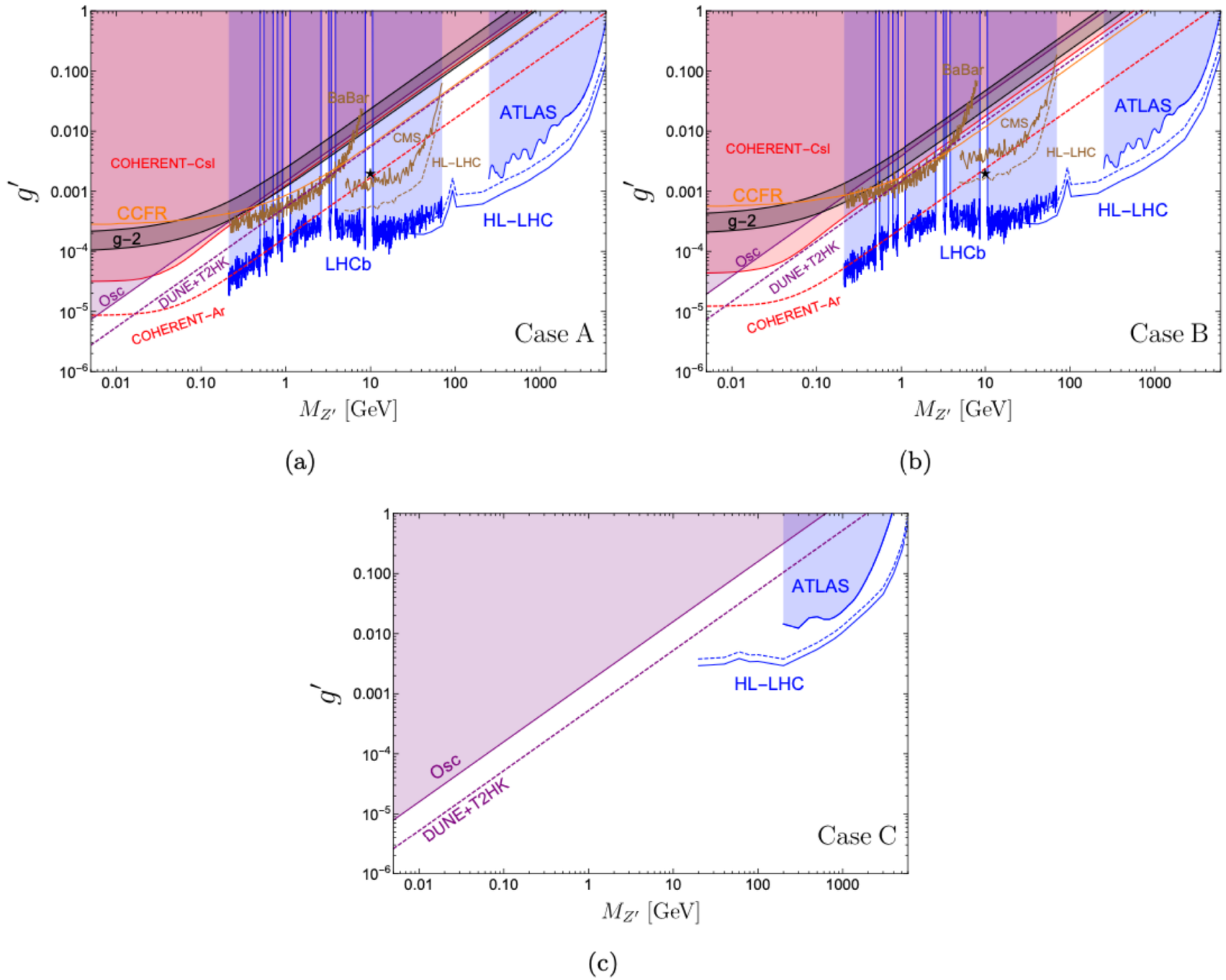


Figure 4. Bounds on g' as a function of $M_{Z'}$ for Cases A (upper left panel), B (upper right panel) and C (lower panel). For details of individual experiment, see Sec. 3.

TH, Liao, Liu, Marfatia: arXiv:1910.03272;
BSM $\boldsymbol{\nu}$ Whitepaper: arXiv:2203.06131

Summary

- Seesaw mechanism well motivated: $m_\nu \sim v^2/M$
- 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 non-standard interactions (NSIs).

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