BSM ν Physics @ Colliders

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Contents:

- Neutrino mass models & their phenomenological features
- Searches at colliders:
  The strategies & results

Henry of Germany giving a lecture to university students in Bologna. Laurentius de Voltolina, *Liber ethicorum des Henricus de Alemannia*, Berlin, Kupferstichkabinett SMPK, min. 1233.

NEUTRINOS

the most elusive/least known particles in the SM

Talks by E. Lisi; S. Petcov; P. Coloma

- How many species: $3\ \nu_L$'s + N_R?
- Absolute mass scale: $m_\nu \sim y_\nu\, v < 1$ eV?

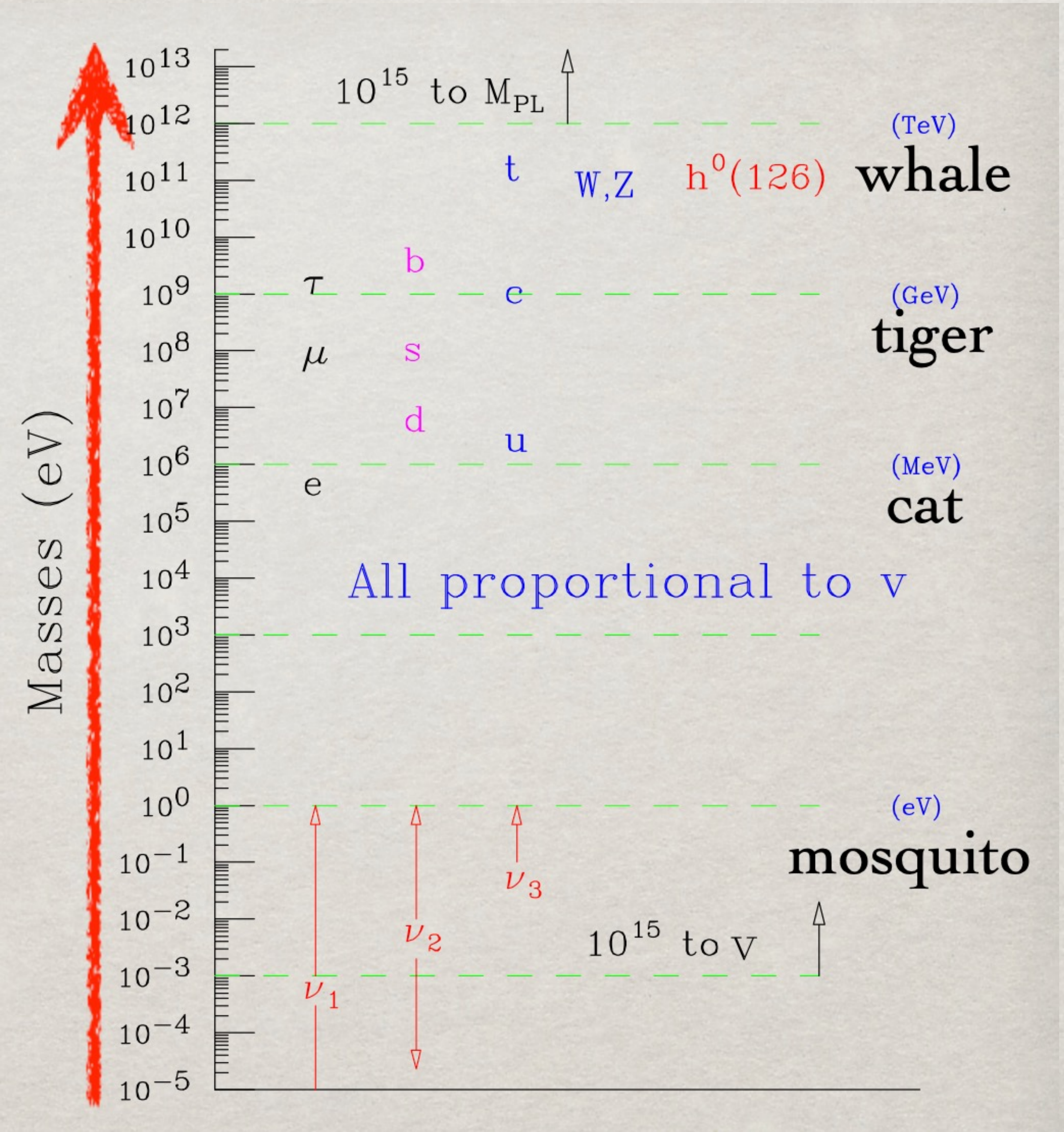
  or a new physics scale: $M_{majorana} >> v$?
- Mass-ordering?
- Flavor oscillations & CP violation?
- Non-standard interactions?
- Mixing with sterile ν's?
- Portal to dark sector?

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

Simplest SM extension for ν mass:

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

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



Lectures by E. Lisi;
S. Petcov

$y_e \sim 10^{-5}$

$y_\nu < 10^{-6}\, y_e$

We must miss something (big)!

SM as a low-energy effective field theory:

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

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

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

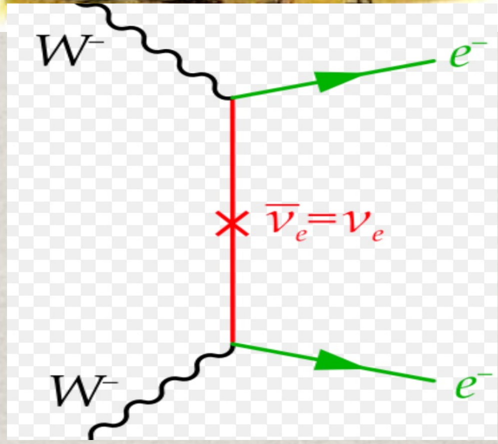
Implications:

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

The See-saw spirit: †

If m_ν ~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!

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

UV-complete theoretical Models:

Lectures by S. Petcov

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

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

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

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>

$$\begin{aligned} -\mathcal{L}_{CC} &= \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m}\ \overline{\nu_m}\gamma^\mu P_L \ell + h.c. \\ &+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'}\ \overline{N^c_{m'}}\gamma^\mu P_L \ell + h.c. \end{aligned}$$

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.
- "Inverse seesaw"

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)

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

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. [†]

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[*] 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.

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. ...

Radiative Seesaw Models*

- New fields + (Z_2) symmetry → no tree-level mass terms
- 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!

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

Non-Standard ν Interactions (NSIs)

Lectures by P. Coloma

First introduced by Wolfenstein in 1978:

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

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

Or more general interactions:

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

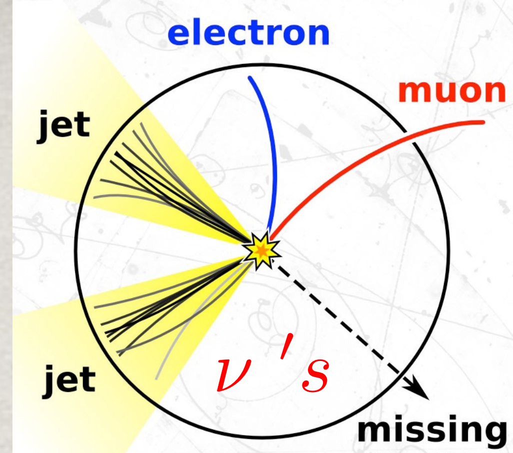
where $\Gamma_a = \{\mathbb{1}, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$

They will impact both oscillation observables
as well as collider signals

So many ideas: Embarrassment of riches!

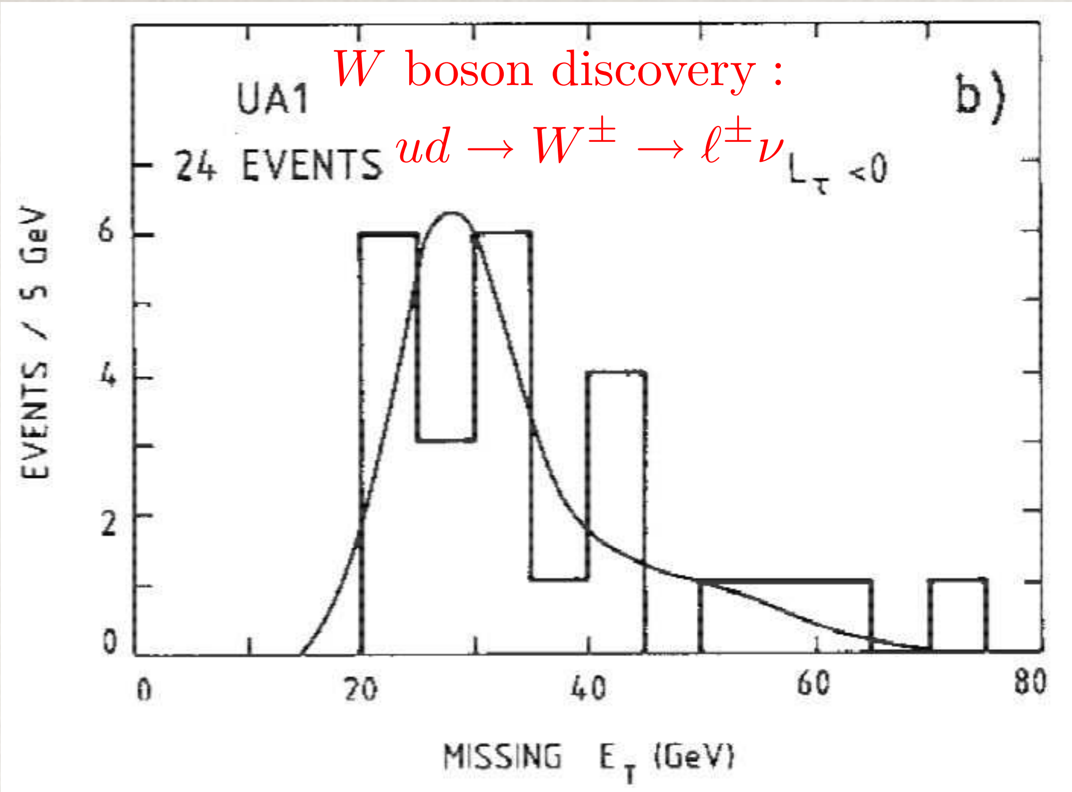
BSM ν Whitepaper: arXiv:2203.06131; arXiv:1907.00991

“NEUTRINOS @ COLLIDERS”

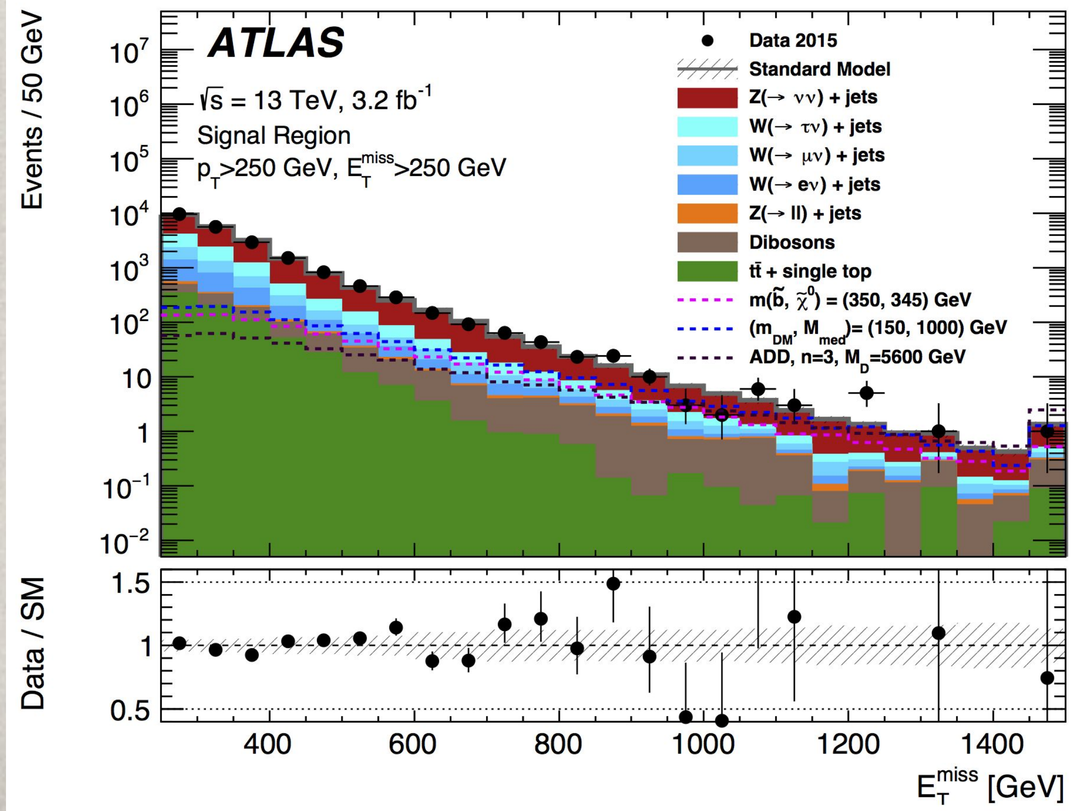


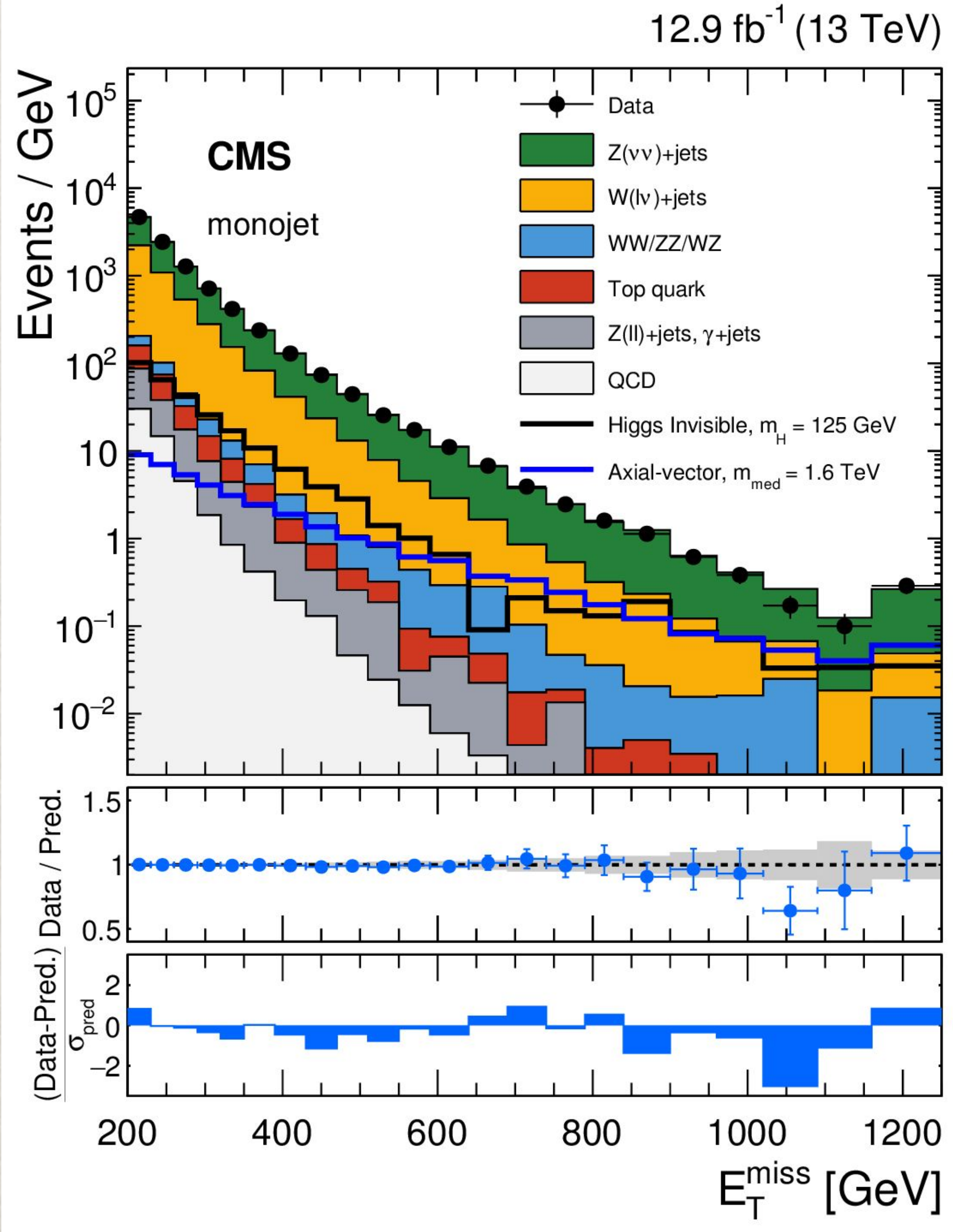
They are all gone !

“Much Ado About Nothing”?



W boson discovery : $ud \rightarrow W^\pm \rightarrow \ell^\pm \nu$



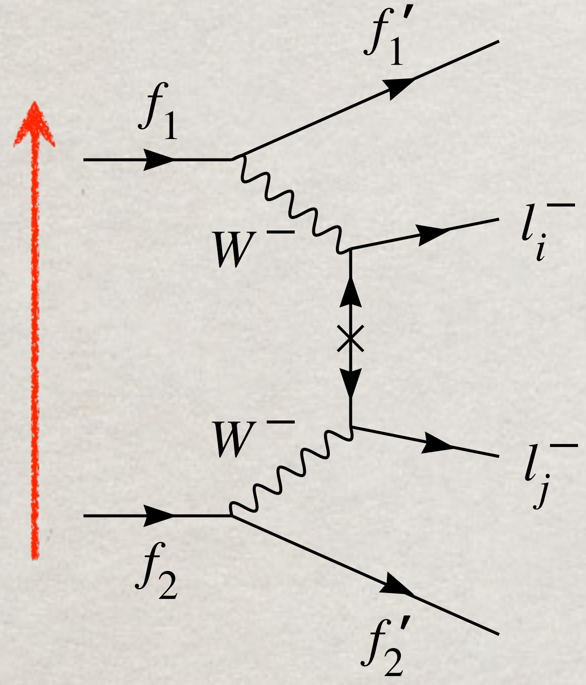


Search for BSM new physics!

Observational Aspects:

the most-wanted process: ΔL=2

The fundamental diagram:



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

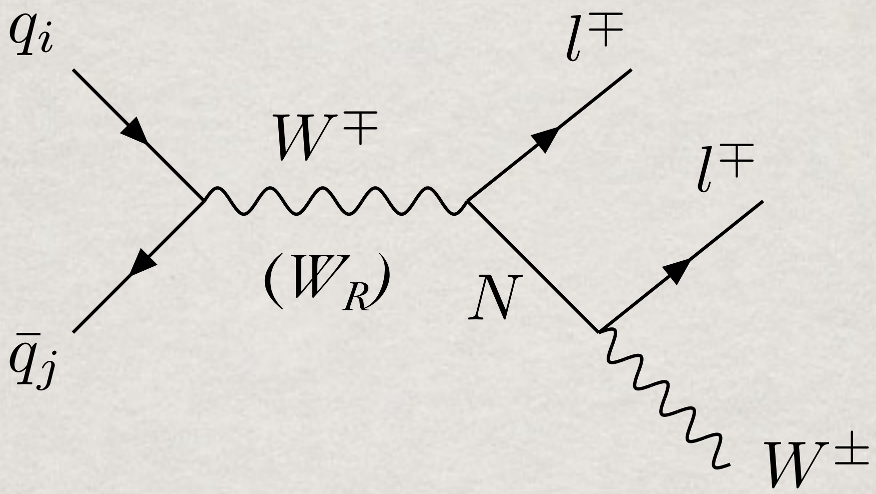
The crossing diagrams can probe different processes and new physics of N/T^0, W^+_R, H^{++}

The transition rates are proportional to

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

1. N_R at Colliders

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



Factorize out the mixing couplings: [†]

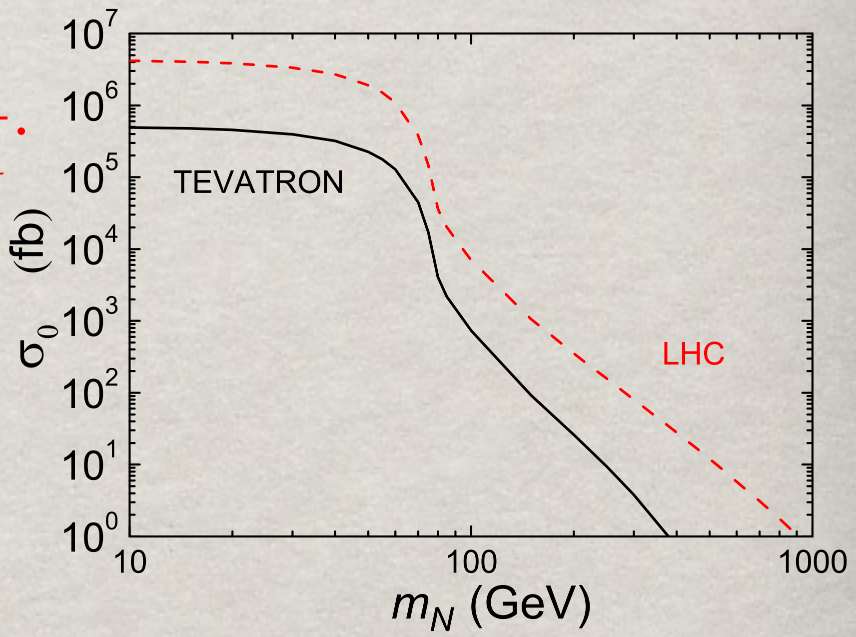
$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2 \ \sigma_0.$$

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

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

A very clean channel:

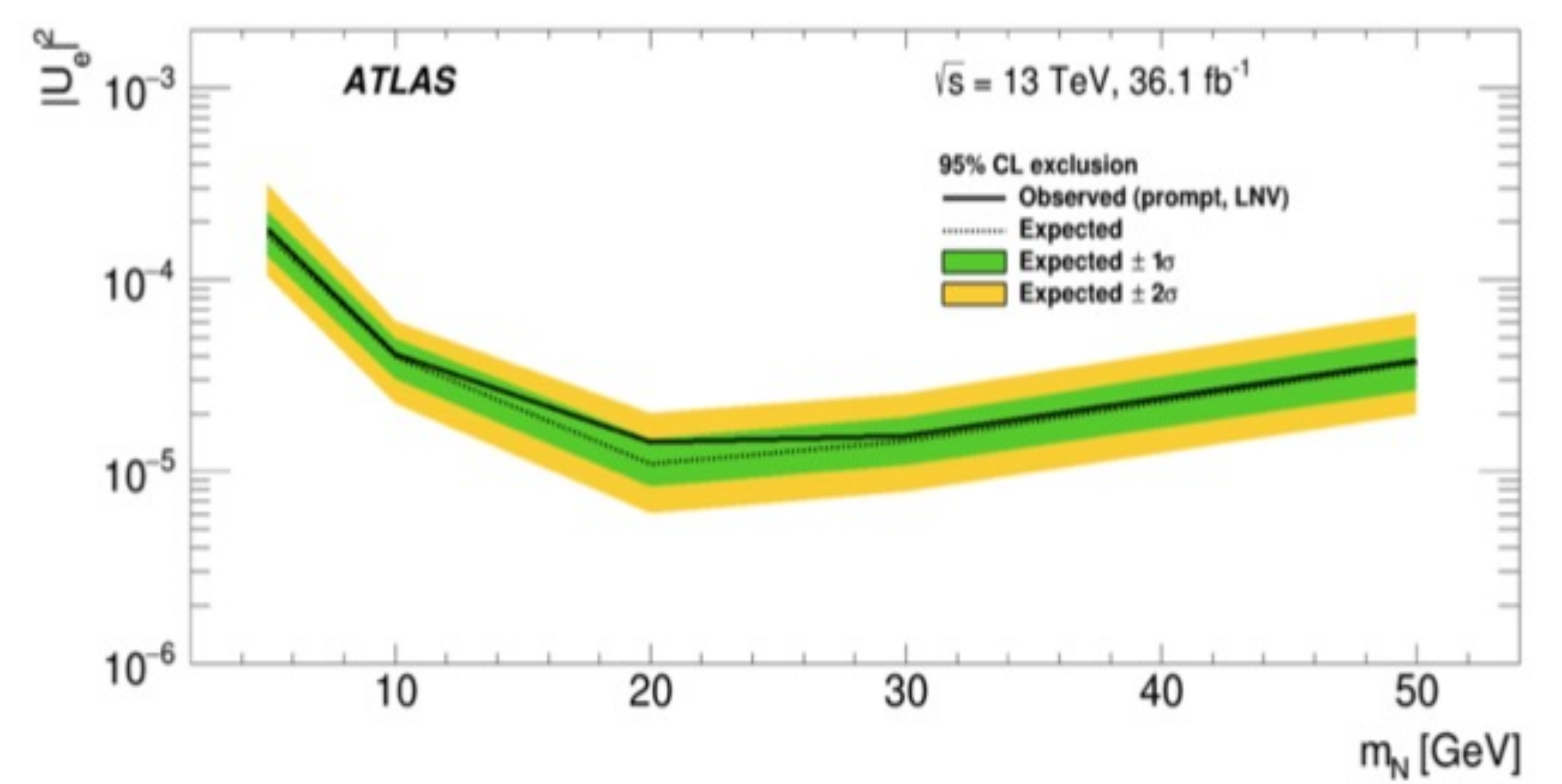
- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W, \ m(jj\mu) = m_N$.

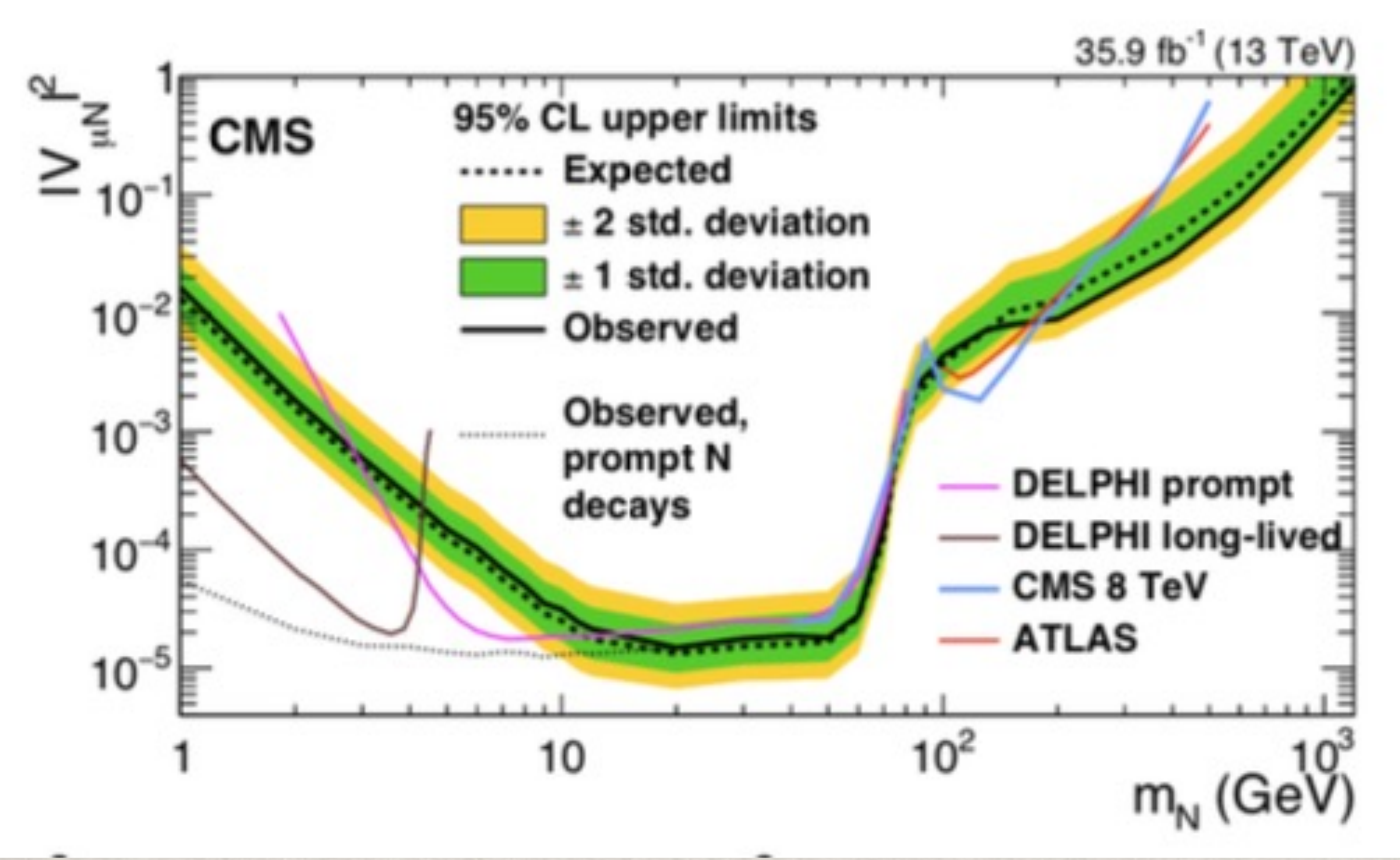


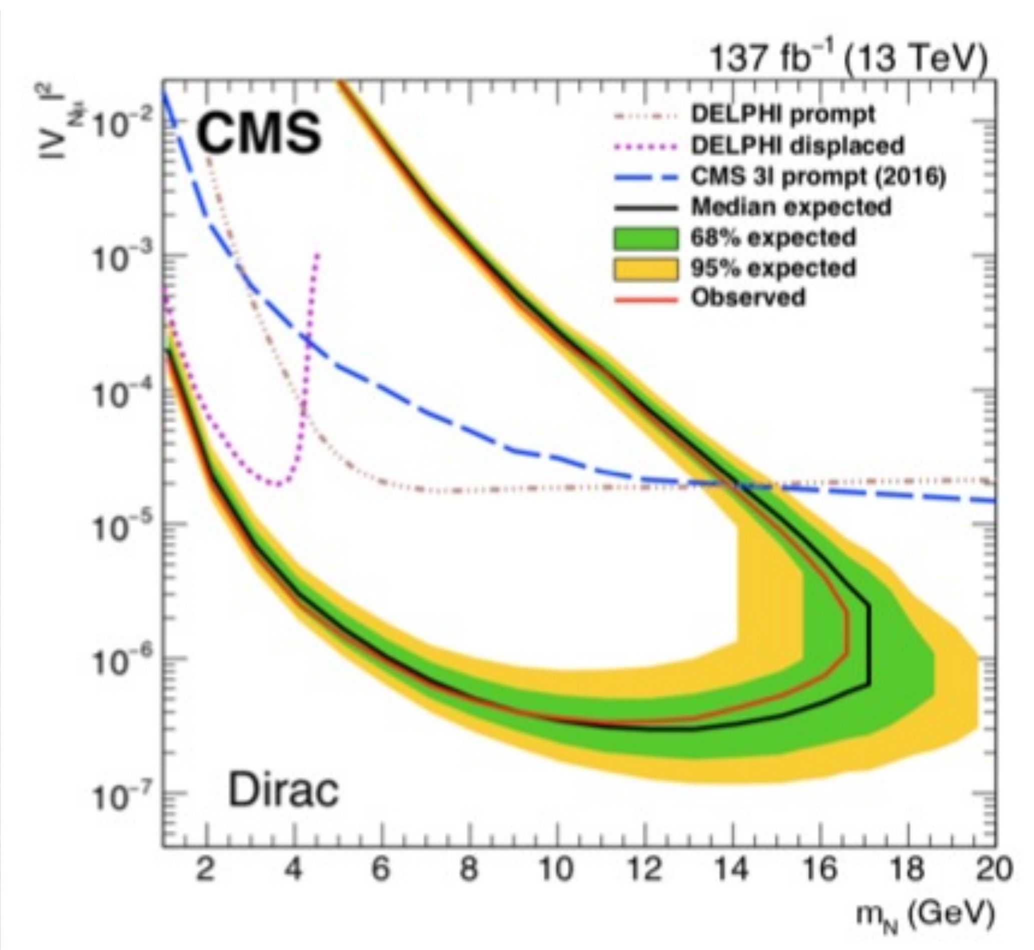
[§] Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

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

Active search @ LHC

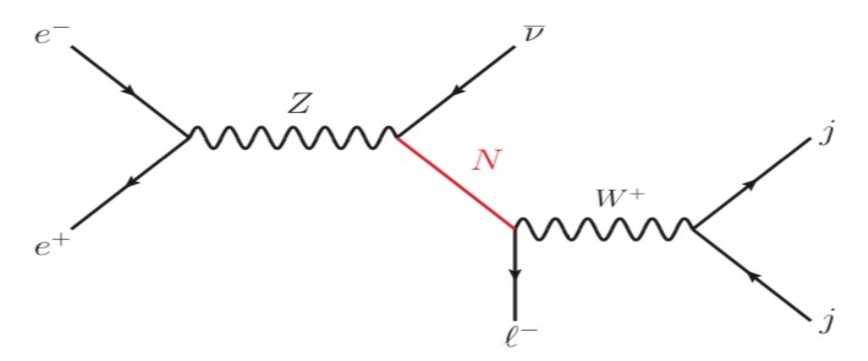


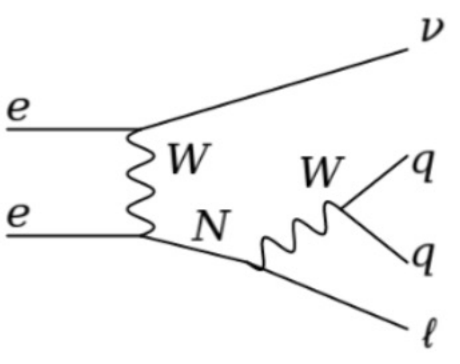




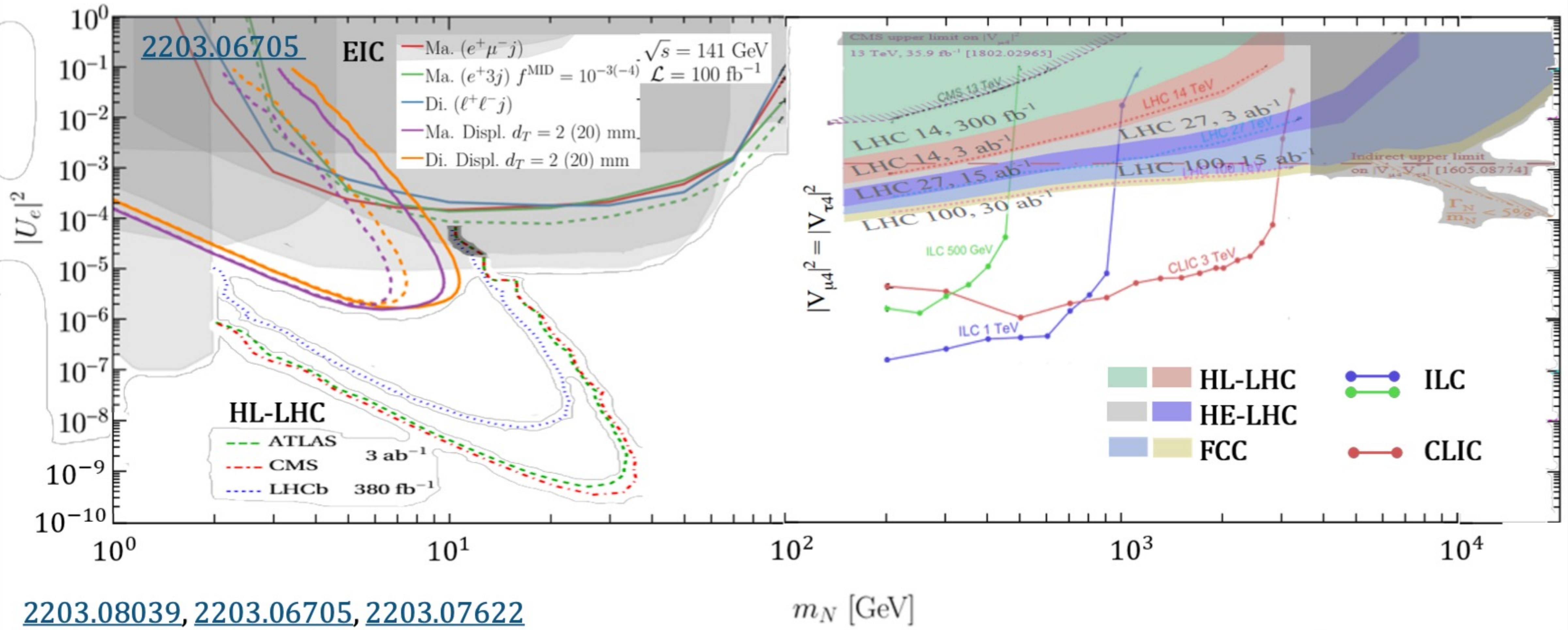
Heavy N Whitepaper: arXiv:2203.08039

Complementarity @ 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

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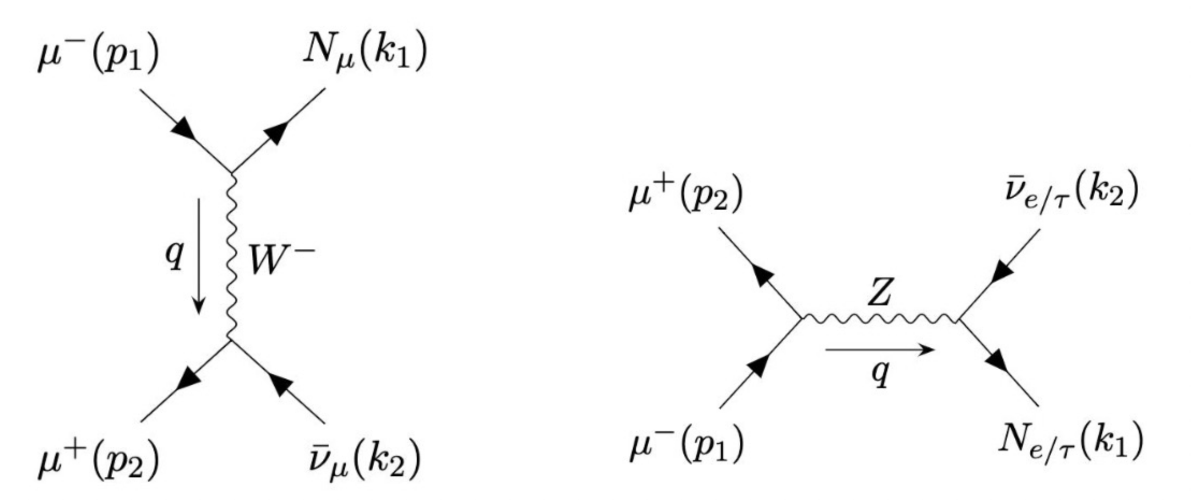
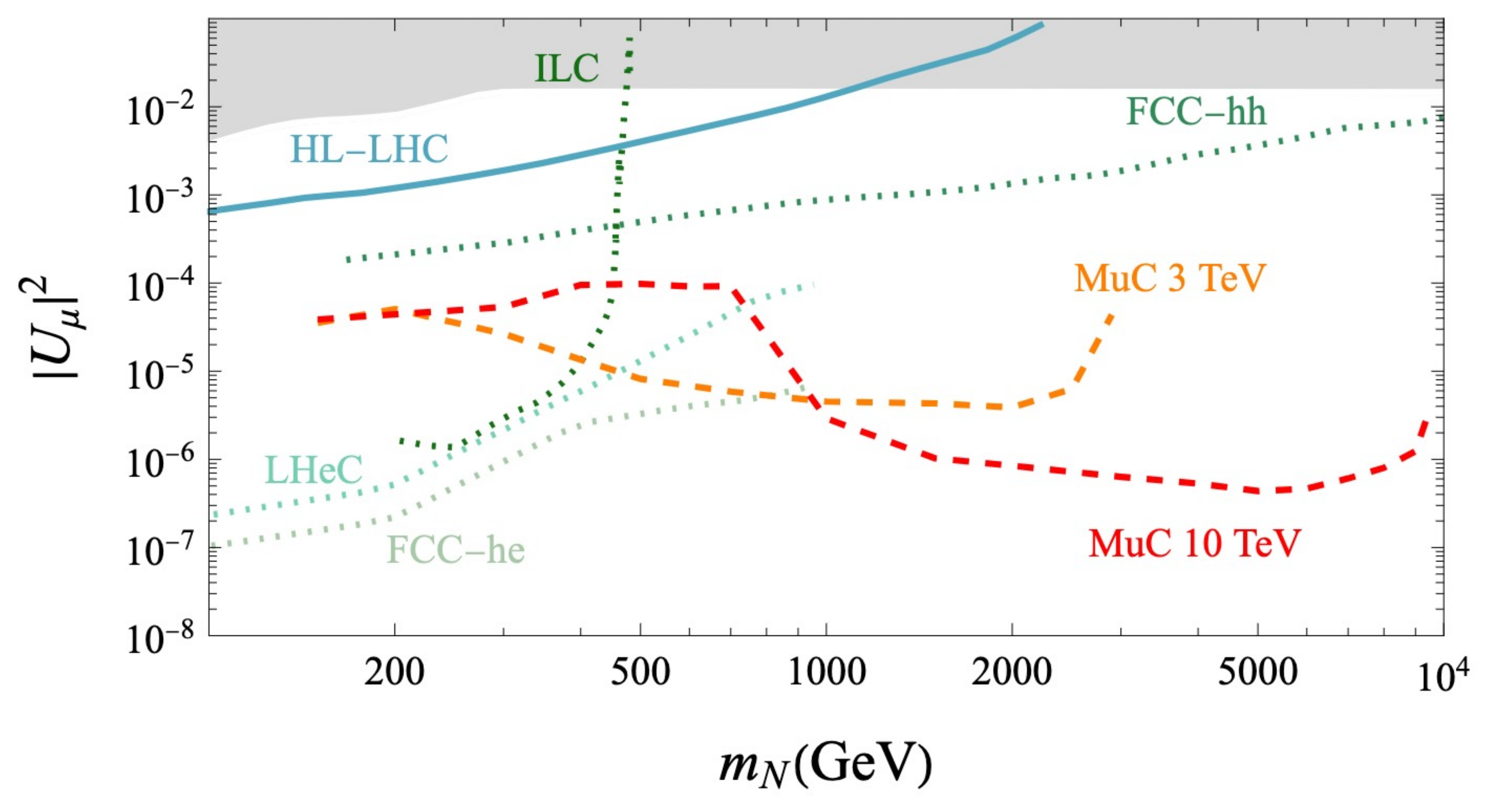
ILC Whitepaper: arXiv:2203.06722

Recent exploration @ muC



P. Li, Z. Liu, K. Lyu, arXiv:2301.07117

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{s-channel}}} \propto \alpha_W^2 \frac{s}{m_Z^2} \log^2 \frac{s}{m_W^2} \log \frac{s}{m_N^2}$$



New Strategy: Long Lived Particles @ Low mass

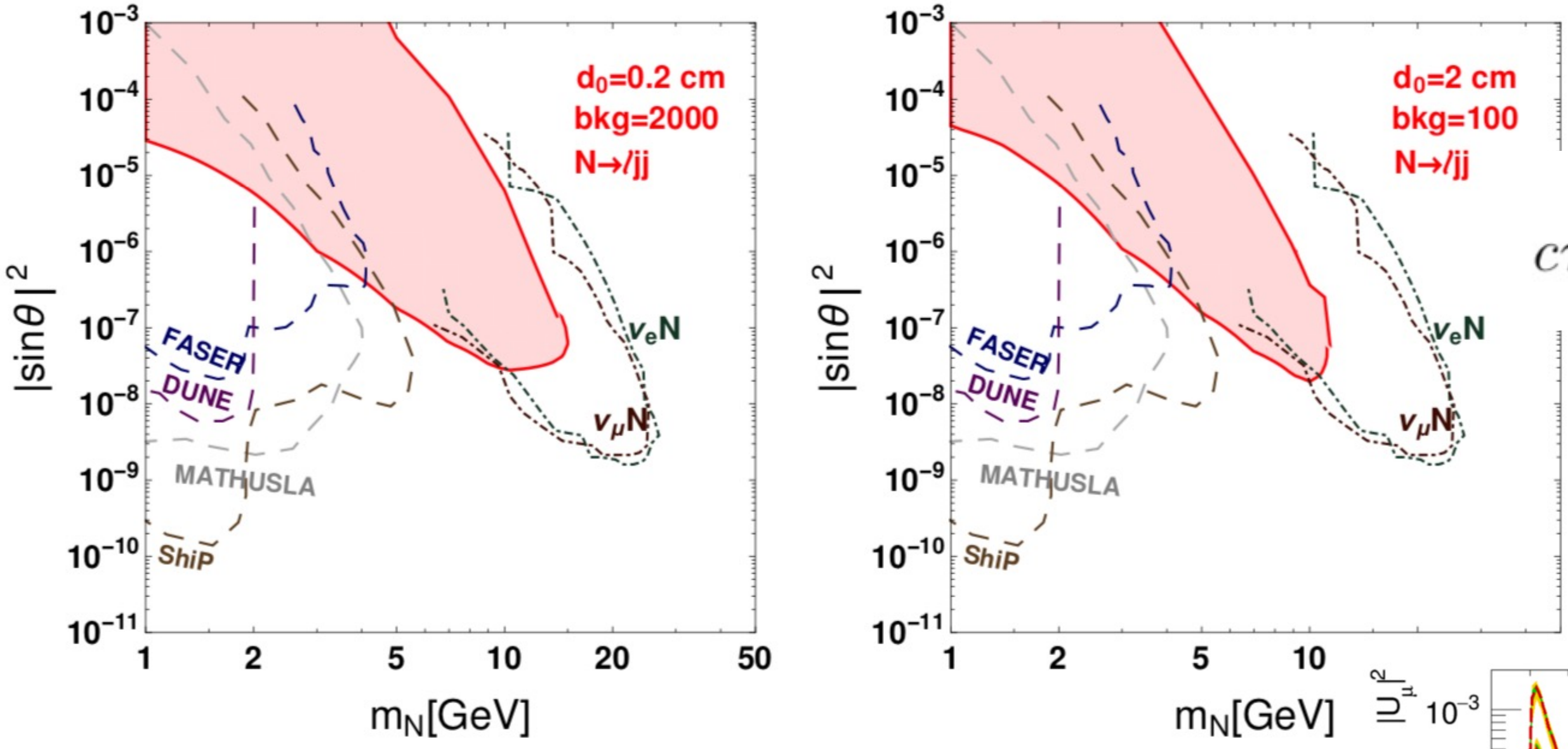
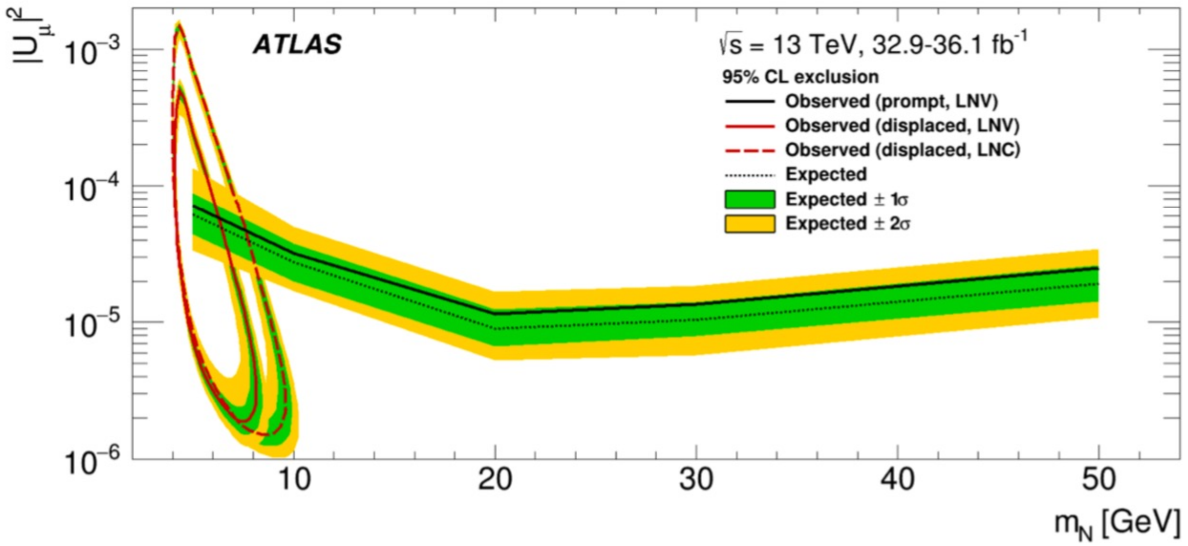
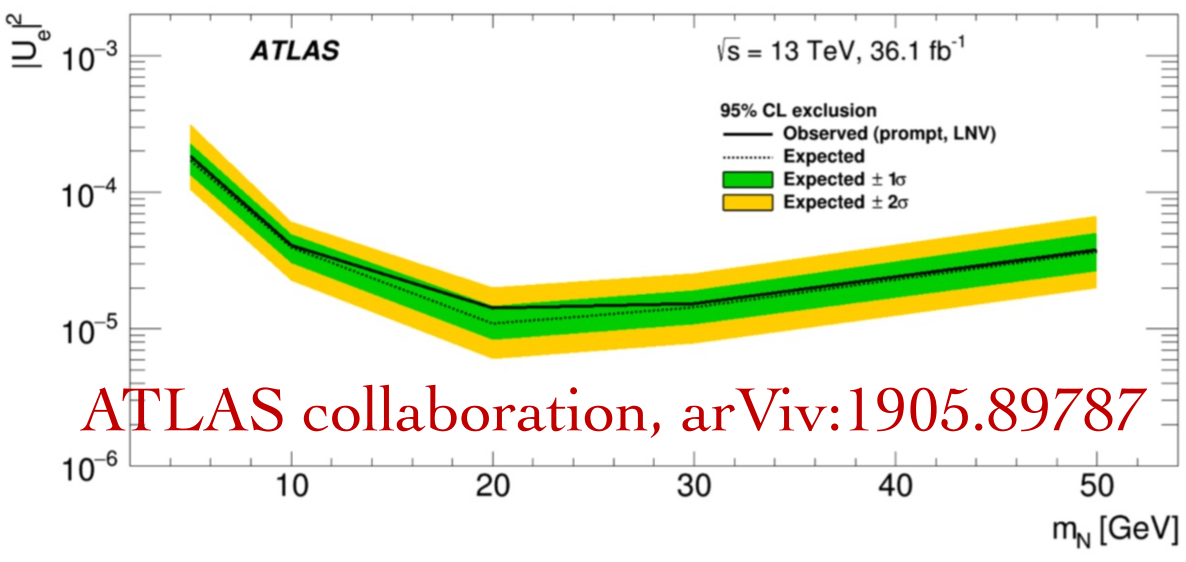


FIG. 6. The 95% C.L. reach for sterile neutrino from W gauge boson decay, plotted plane . The sensitivities for “$\nu_e N$” and “$\nu_\mu N$” come from prompt lepton trigge displaced vertex projection at HL-LHC [70] assuming zero background. The pro reach for MATHUSLA [45], FASER [44], DUNE [29] and SHiP [30, 71] are also s

$$c\tau \simeq 12\ \text{km} \times \left(\frac{10^{-12}}{\sin^2\theta}\right)\left(\frac{10\ \text{GeV}}{m_N}\right)^5$$

M. Drewes and J. Hajer, arXiv:1903.06100;
J. Liu, Z. Liu, L.-T. Wang, X. Wang,
arXiv:1904.01020.

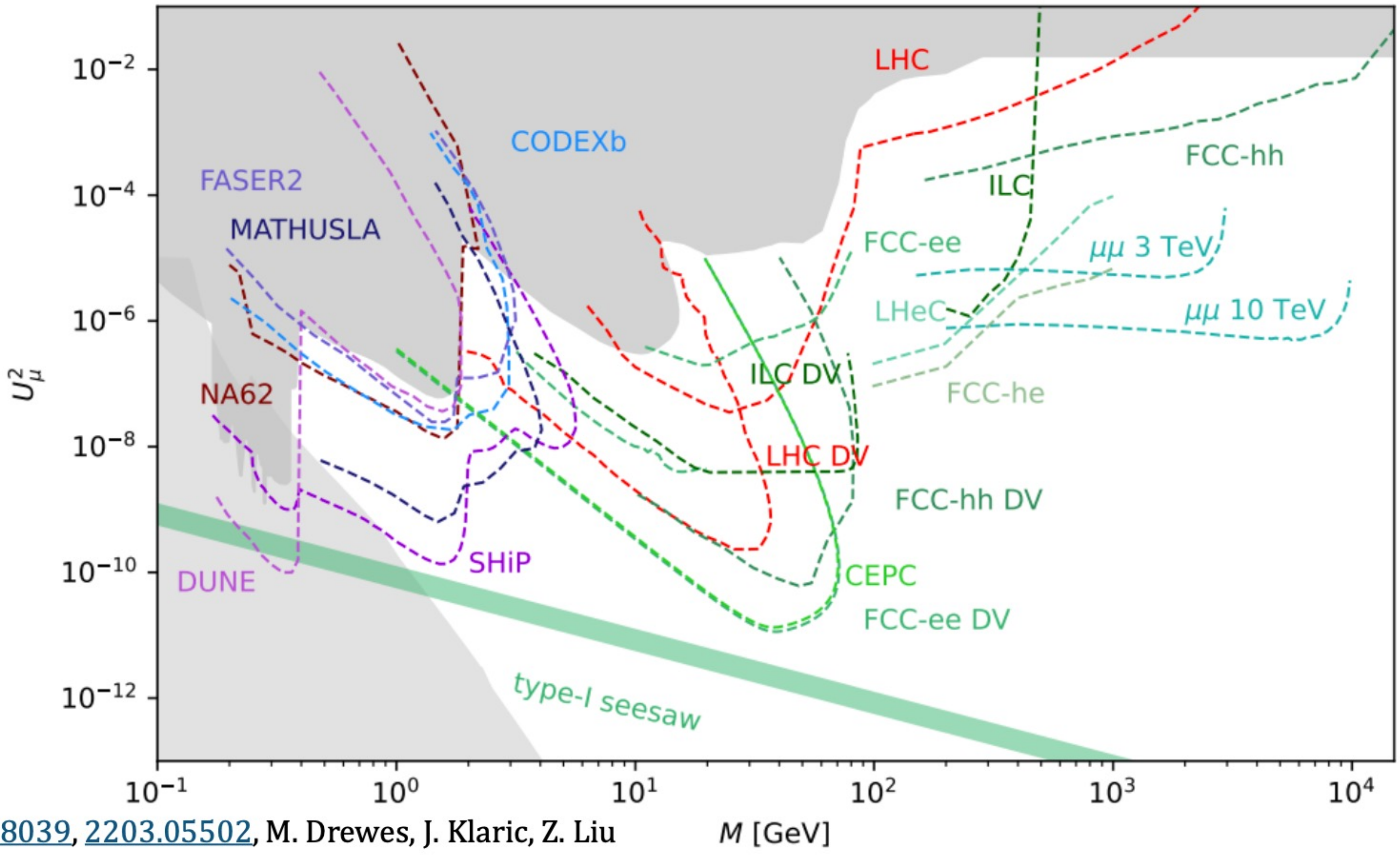




ATLAS collaboration, arViv:1905.89787

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

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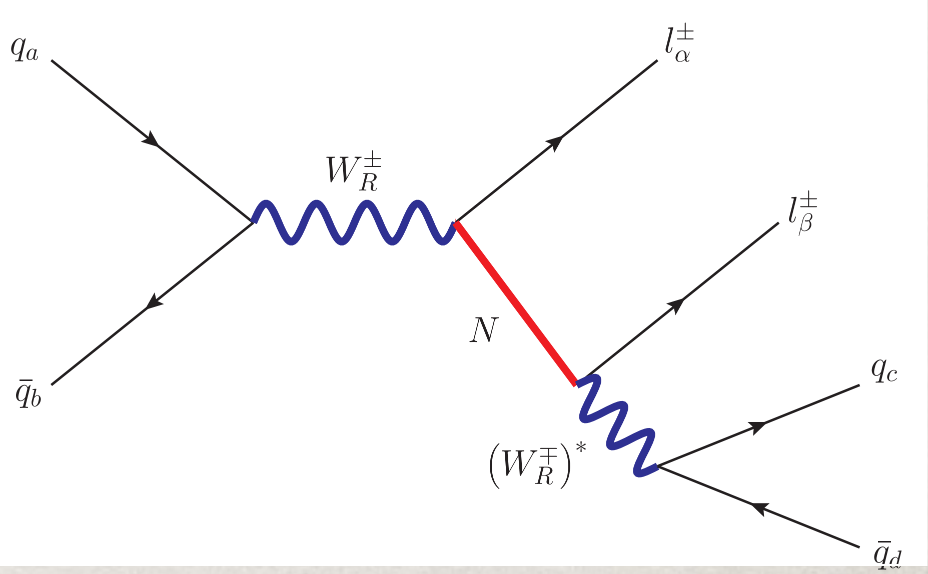
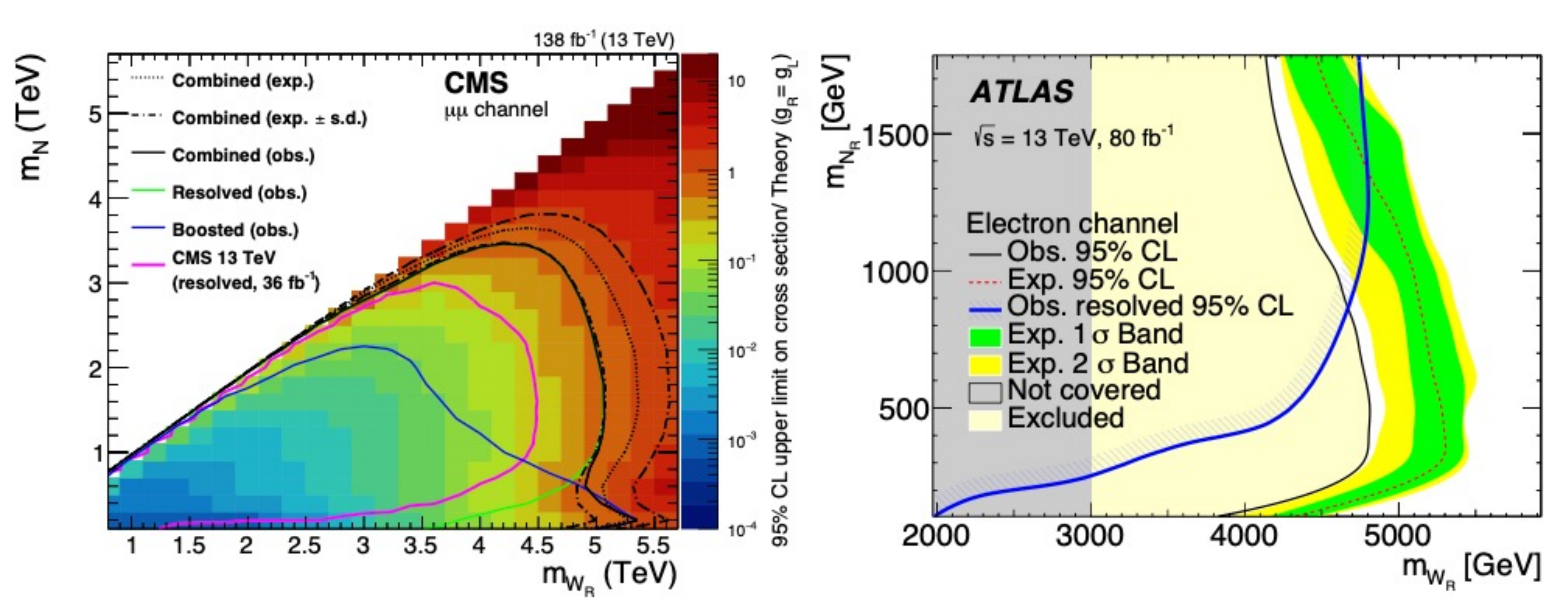
2. N_R & W_R @ Hadron Colliders

In Left-Right symmetric model:

- No mixing suppression
- New unknown mass scale M_R





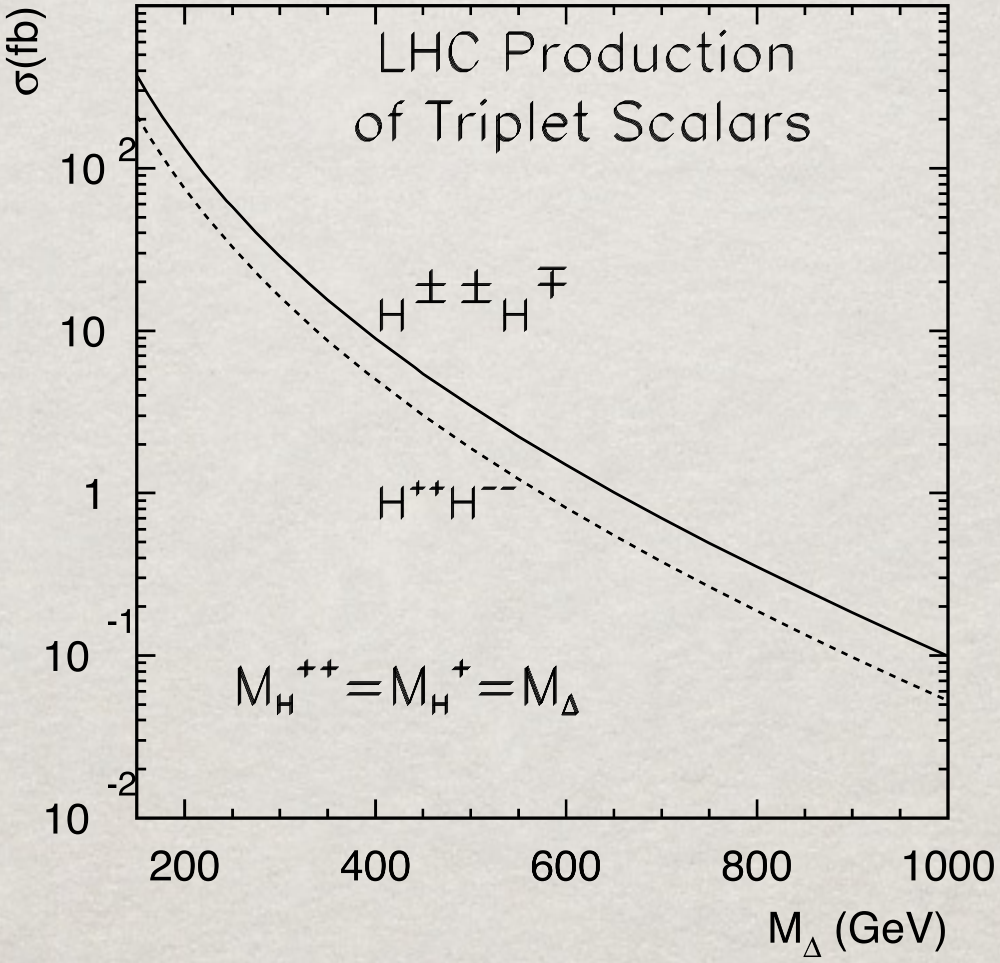
W. Keung & G. Senjanovic, PRL 50 (1983) 1427

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.

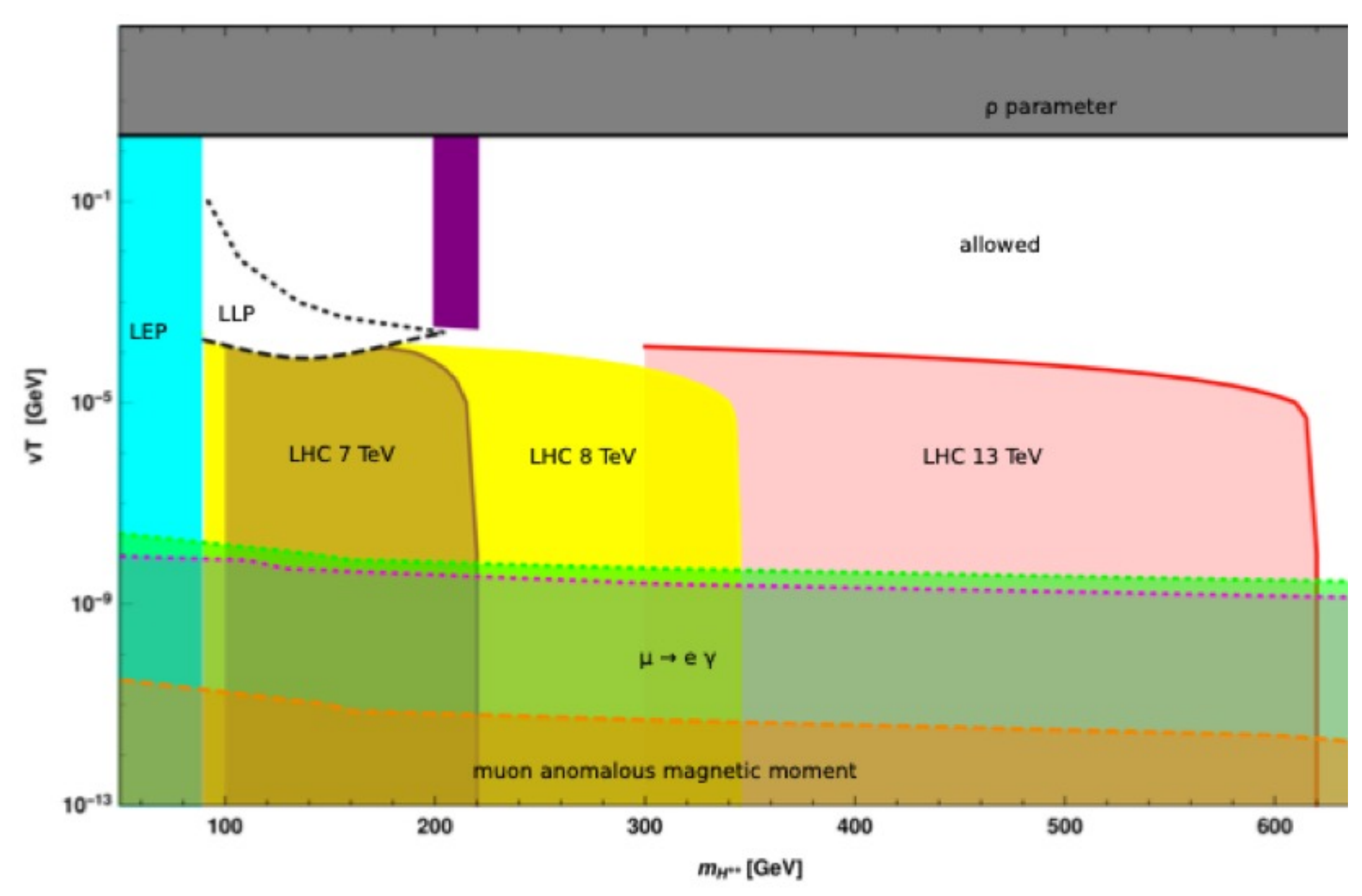
$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY. ~$(2e)^2$

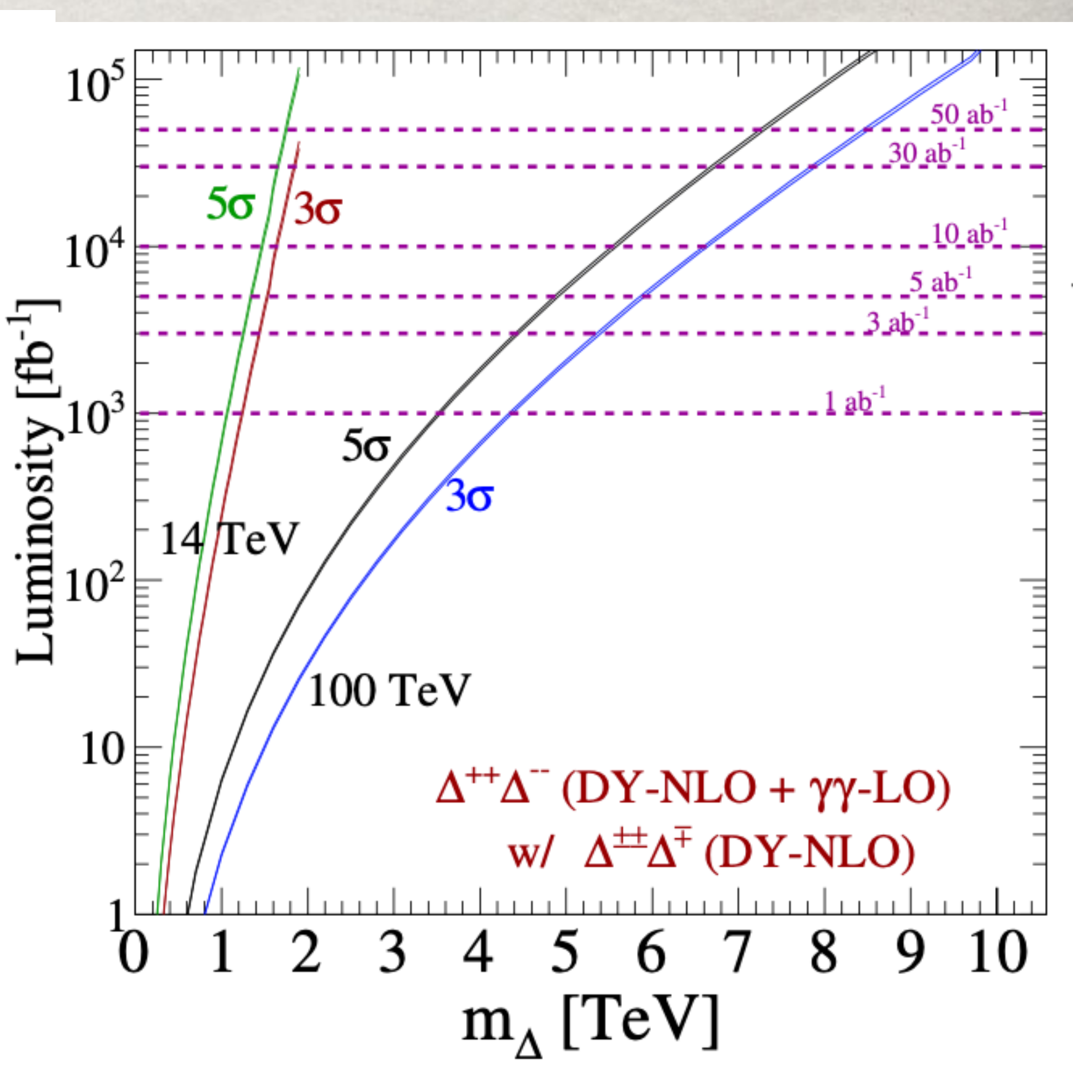
†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

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 continued: $H^{\pm\pm}$ & $H^{\pm}$

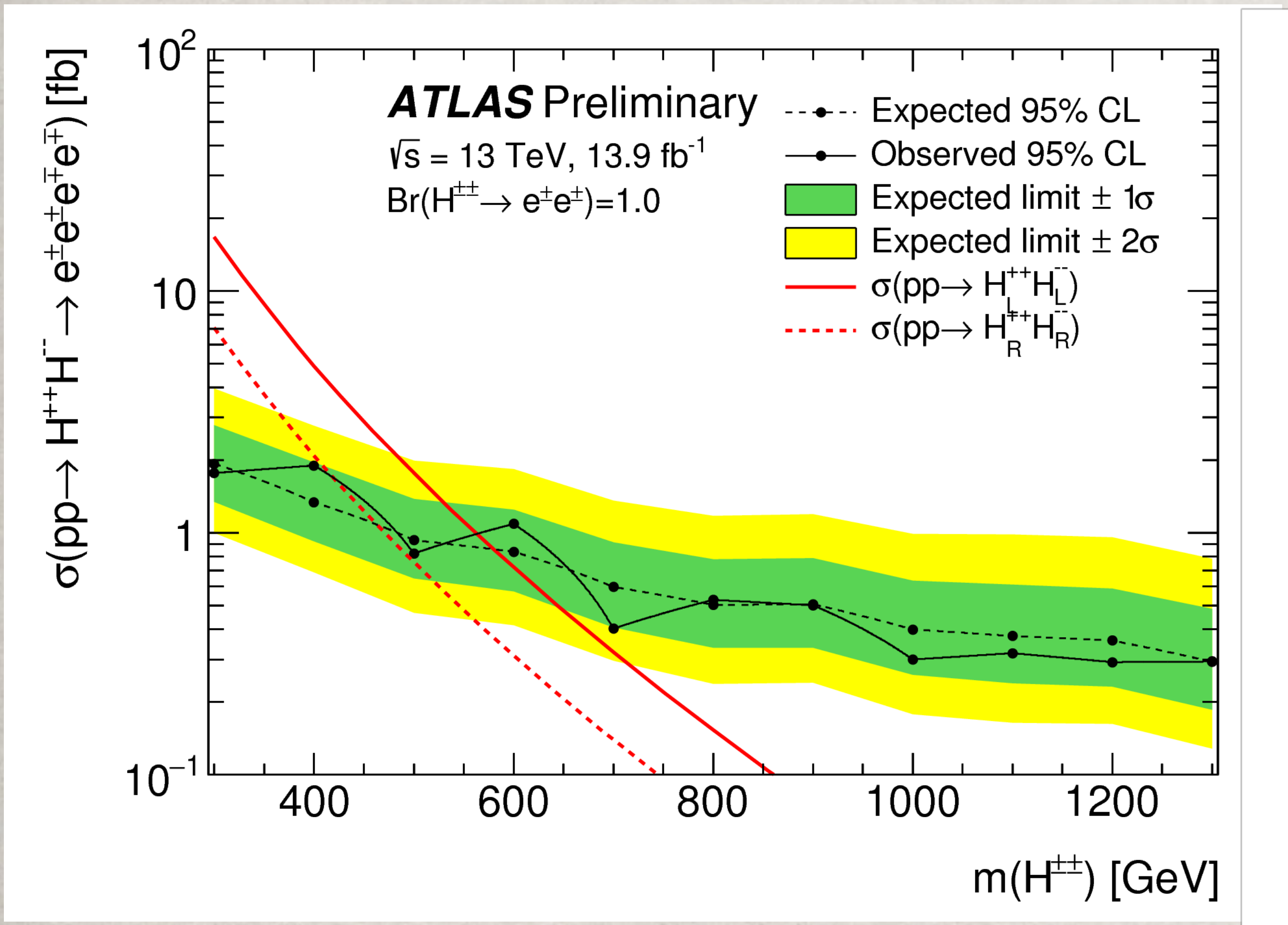




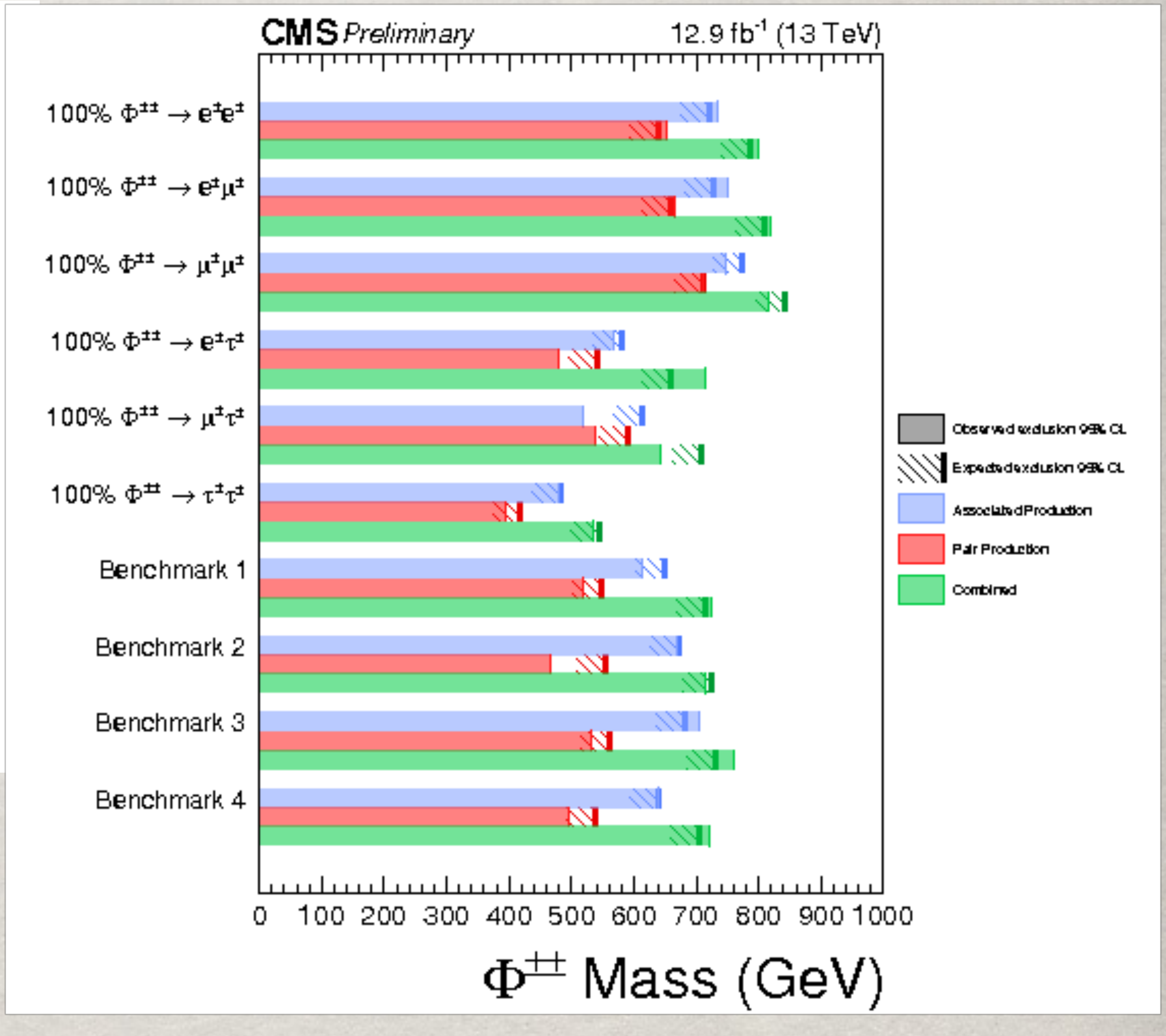
BSM Whitepaper: arXiv:2203.08039

Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode:

ATLAS Bounds:



CMS-PAS-HIG-16-036

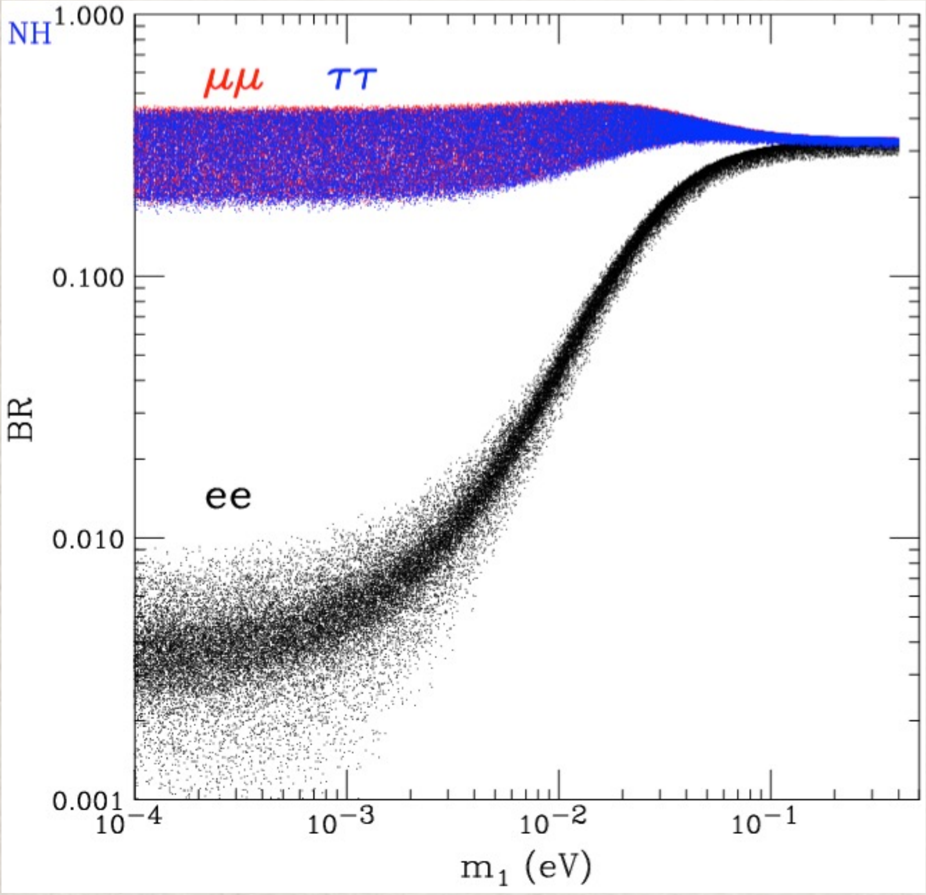


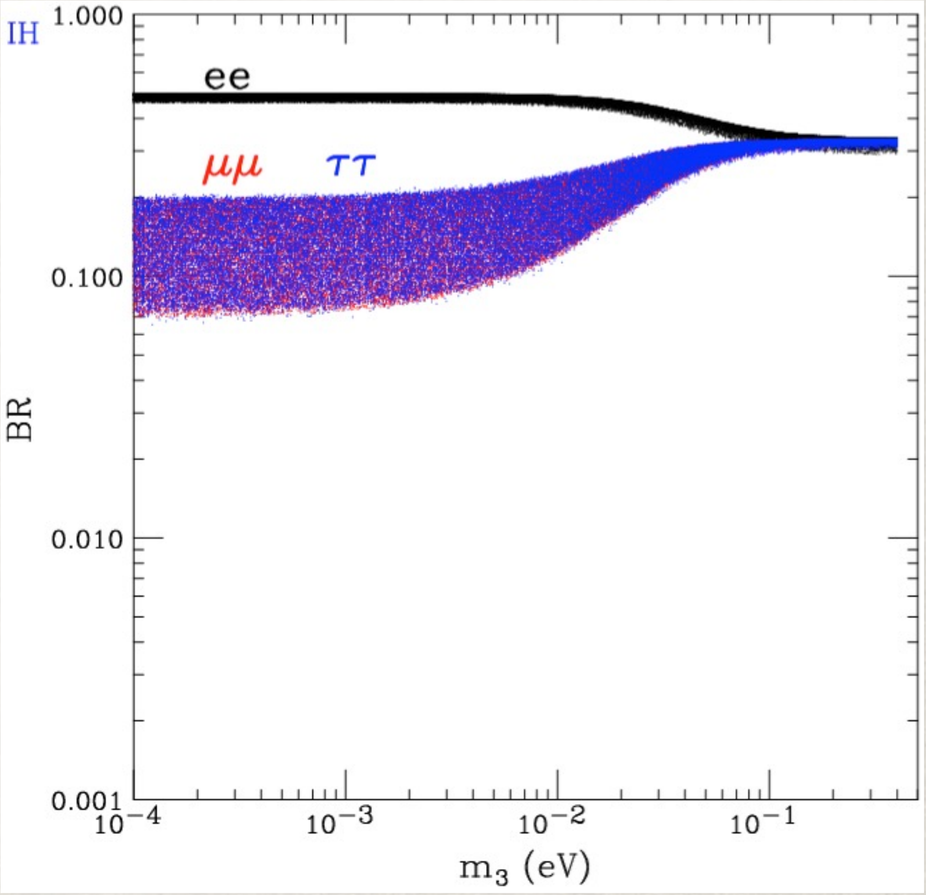
With 300 fb^{-1} integrated luminosity,

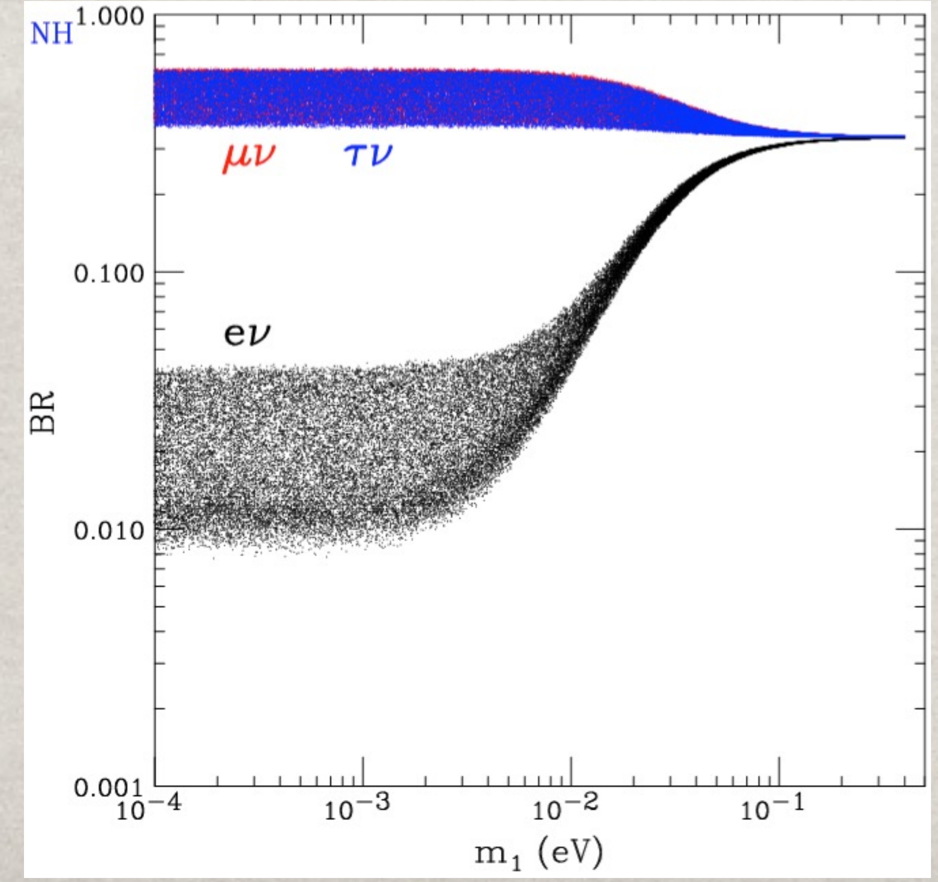
a coverage upto $M_{H^{++}} \sim 1$ TeV even with $BR \sim 40-50\%$.

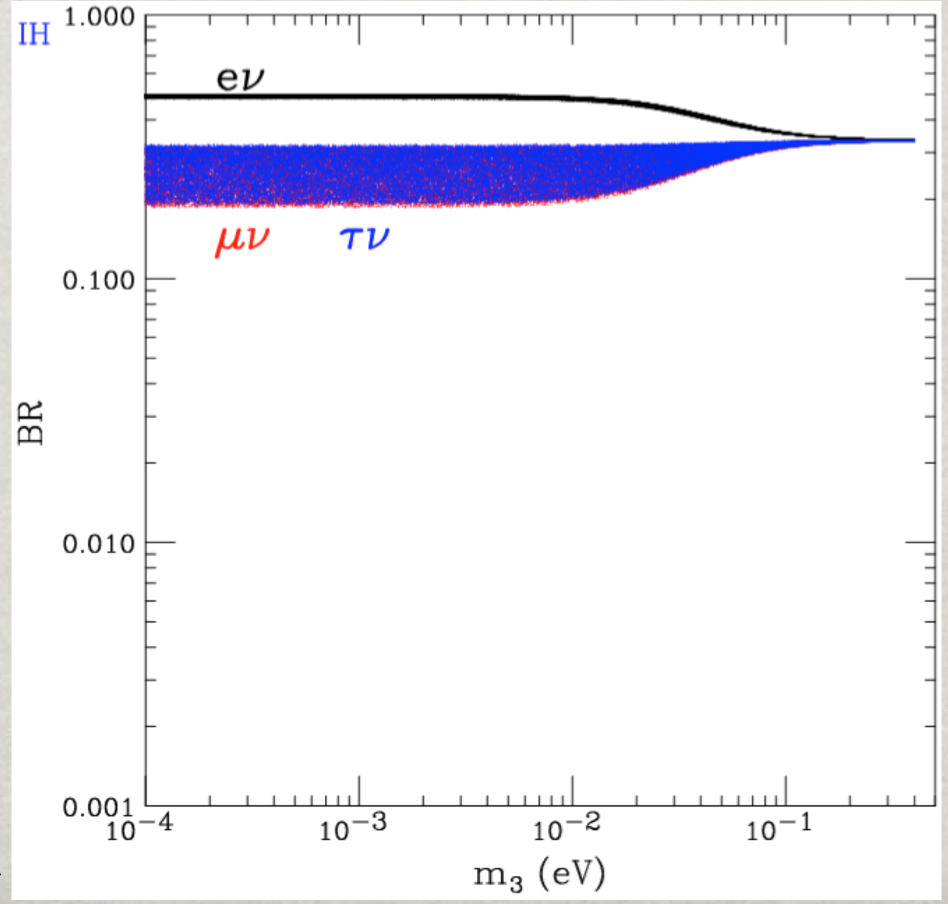
Possible measurements on BR's.

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









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 ($m_1, m_2, m_3 > \lvert\Delta m_{31}\rvert$)	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($H^+ \to \tau^+\bar{\nu}$) $\approx 1/3$

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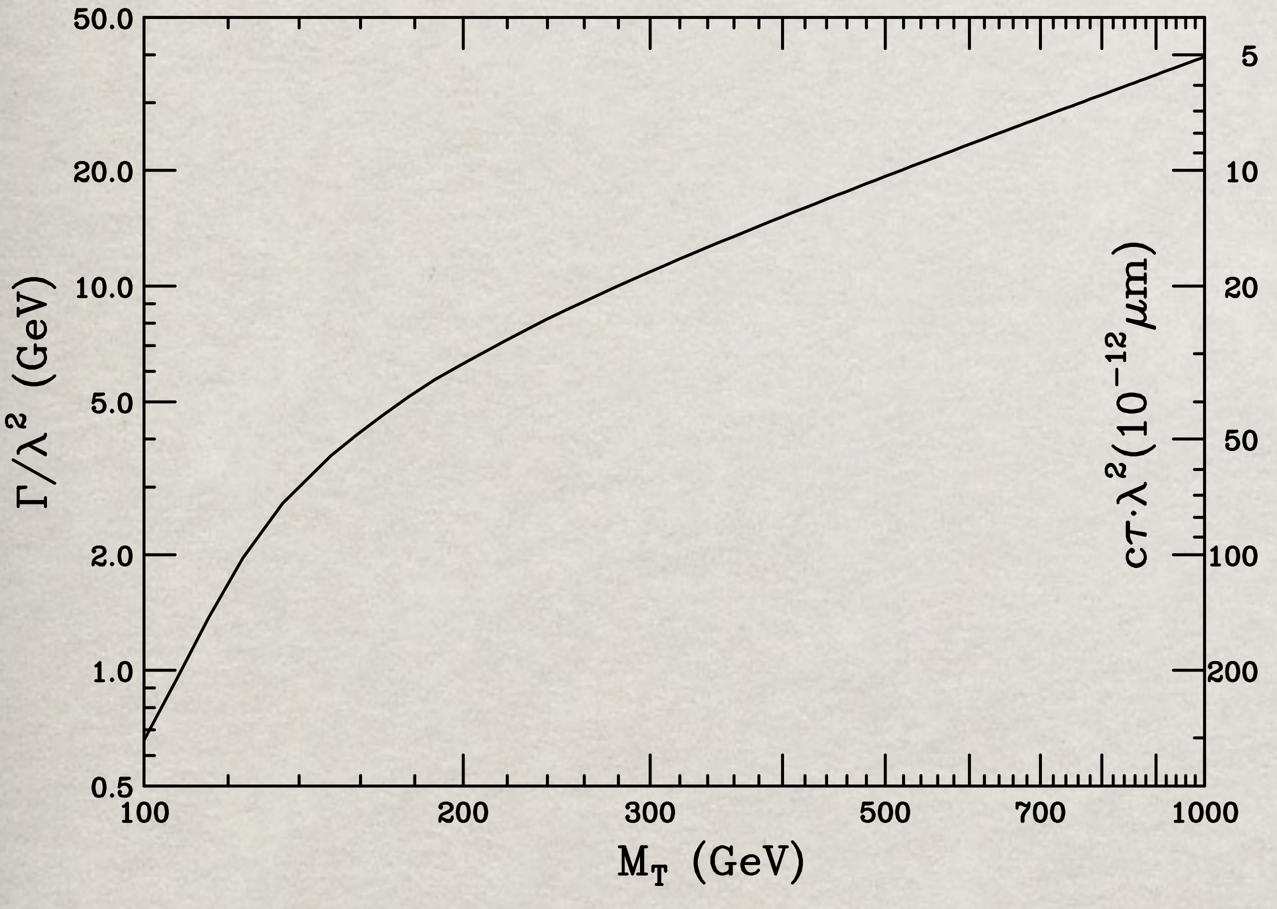
†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

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

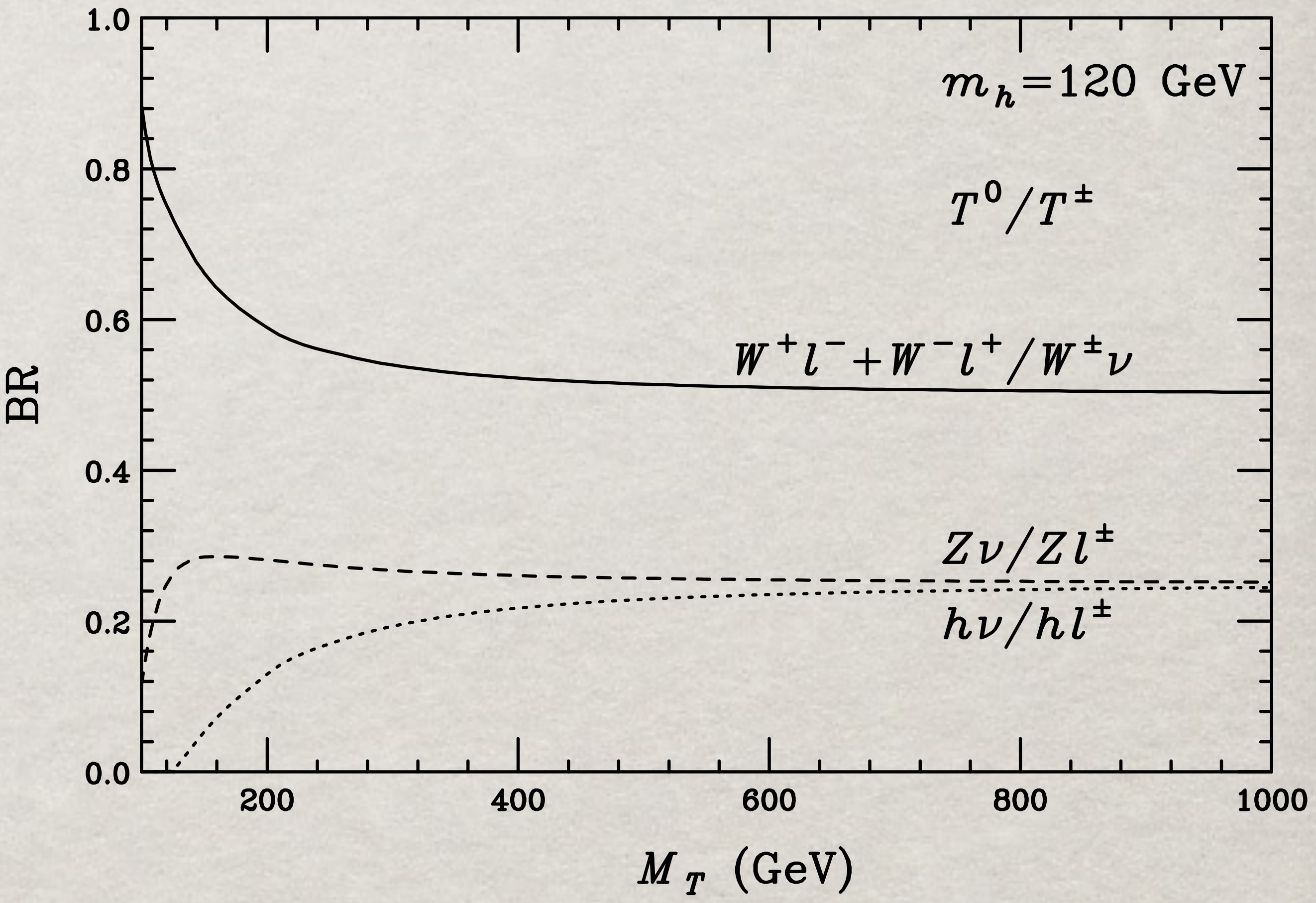
Consider their decay length:

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

Width and Decay Length



Lepton Triplet Branching Fraction

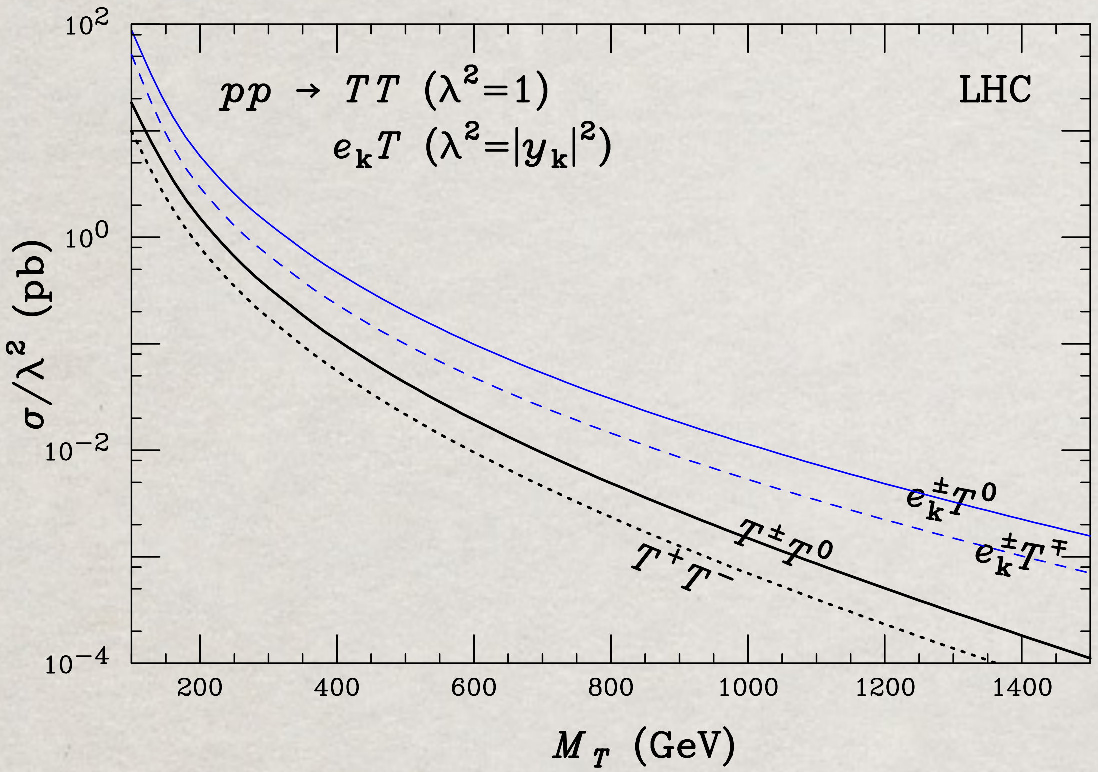


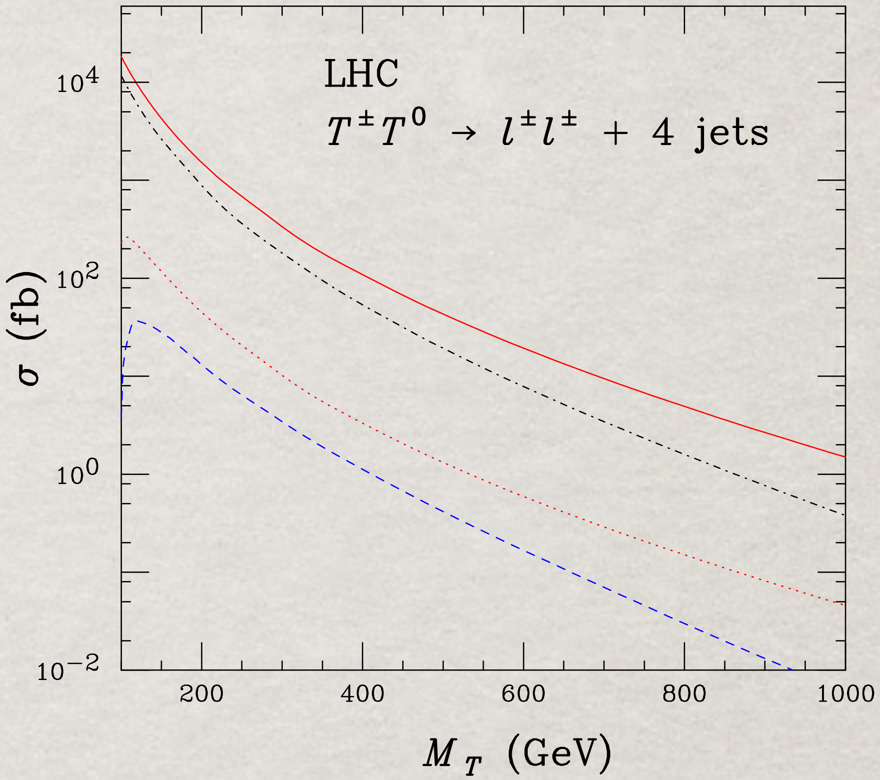
With $\lambda^2 = y_j^2 \sim 10^{-16} - 10^{-12}$, then $c\tau \sim 10^{-2} - 10^{-4}$ m

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

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

Type III Seesaw: T± & T^0





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

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

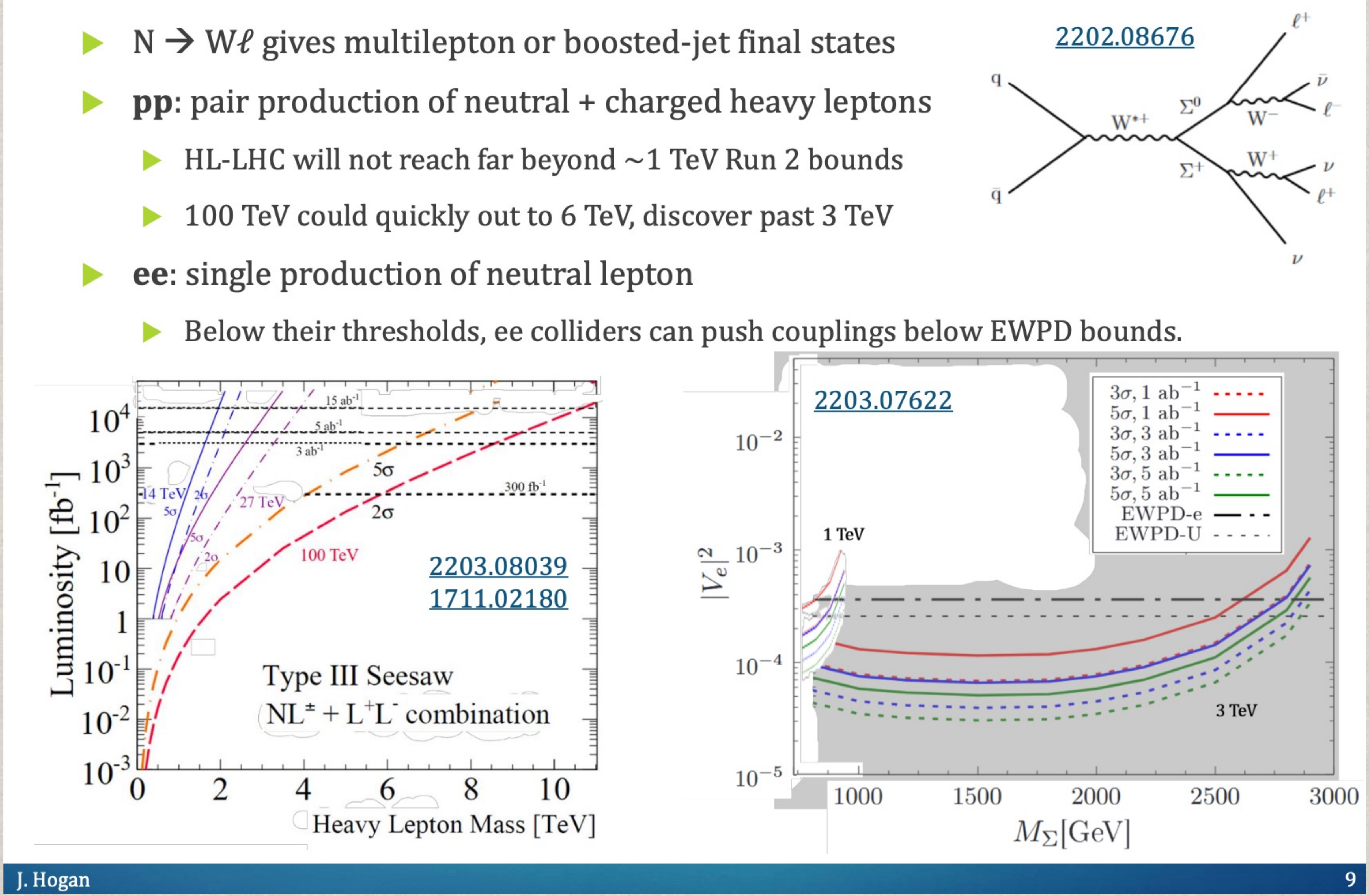
Example: $T^{\pm}+T^0 \to \ell^+Z(h)+\ell^+W^- \to \ell^+jj(b\bar{b})+\ell^+jj$.

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.

J. Hogan

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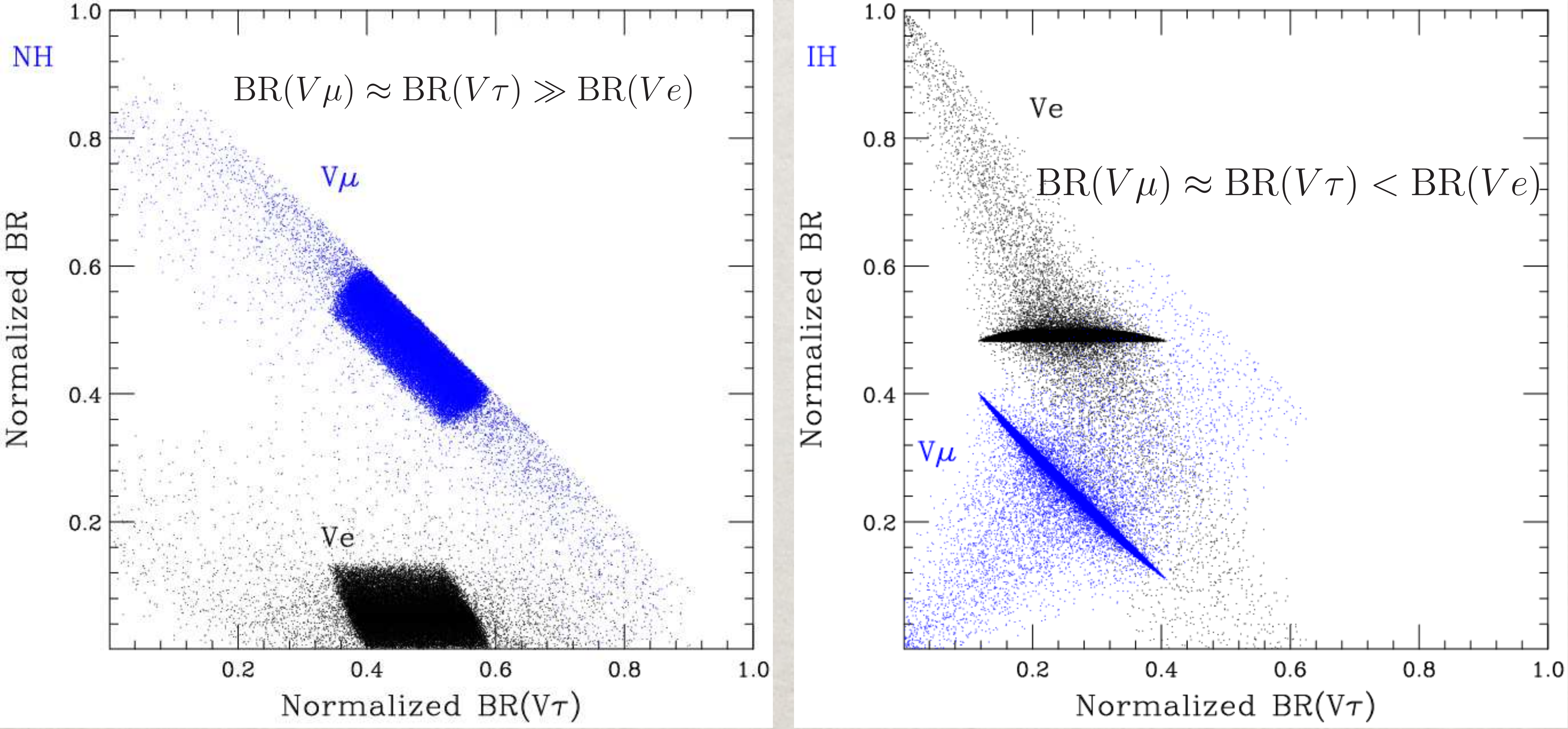
BSM Whitepaper: arXiv:2203.08039

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.

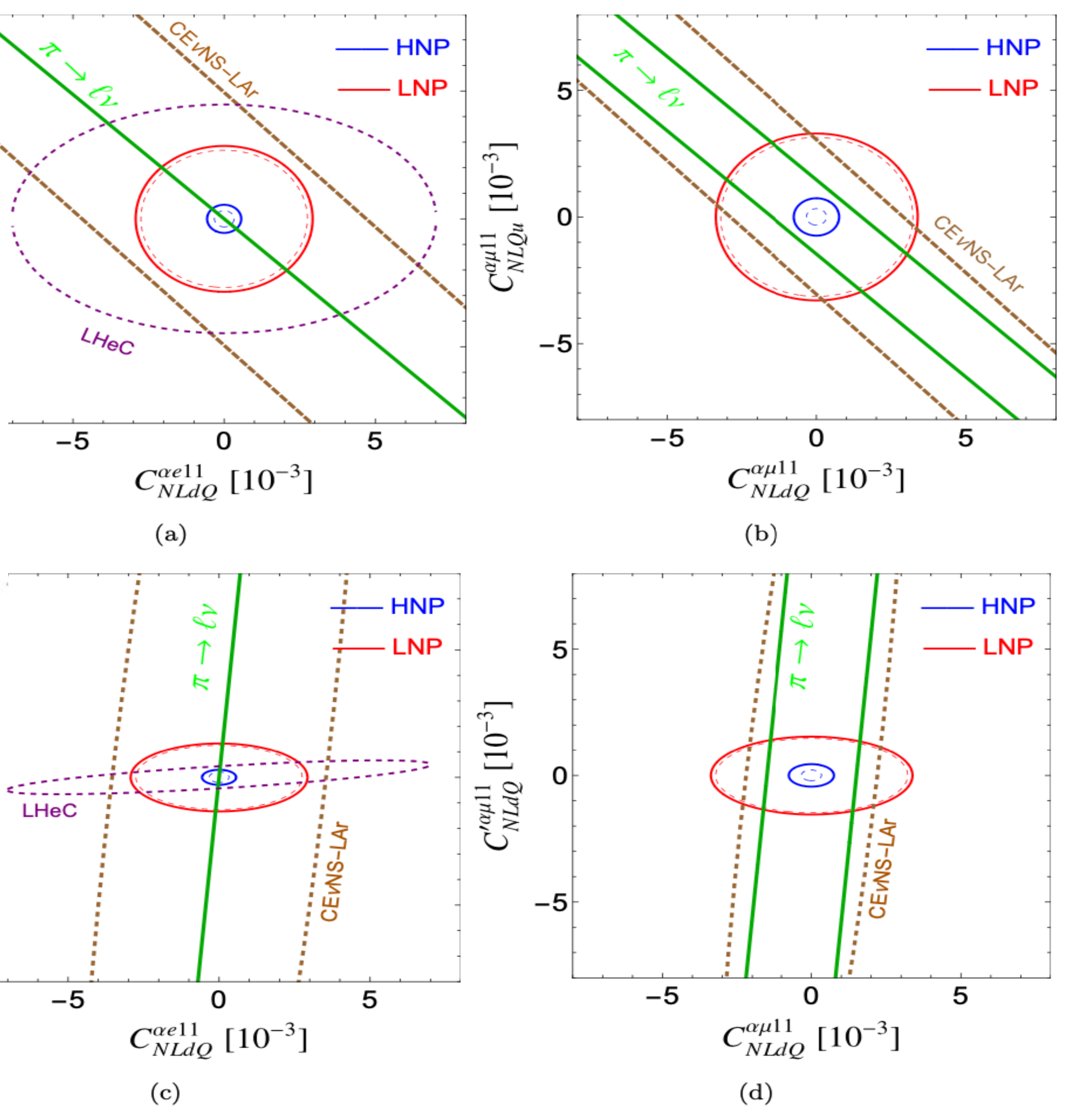
[†] Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, Ivica Puljak, Goran Sejanovic, arXiv:0904.2390.

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 *ν* Whitepaper:
arXiv:2203.06131;
arXiv:1907.00991;
arXiv:2004.13869.

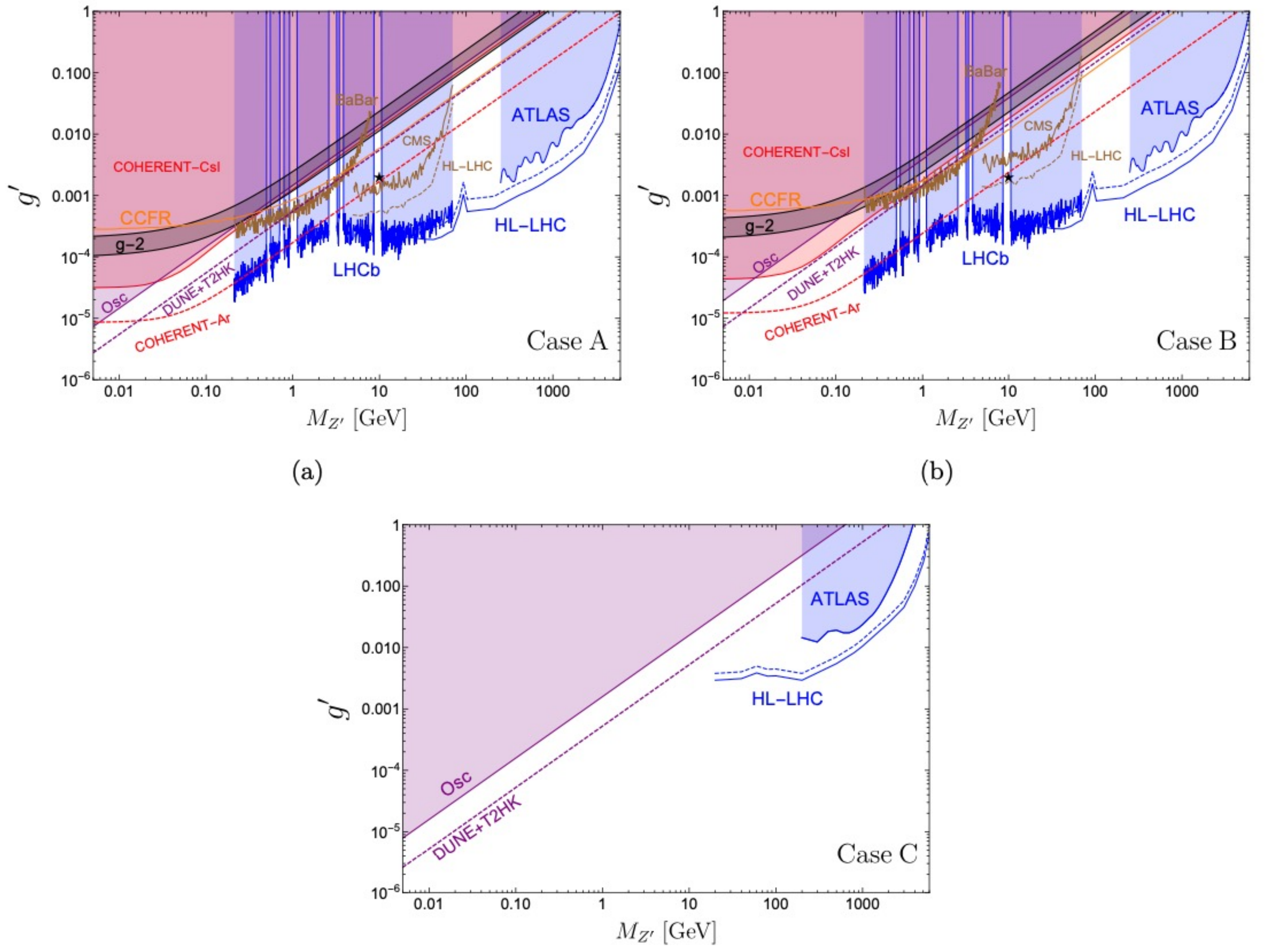


(a) (b)

(c) (d)

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:



(a) (b)

(c)

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 ν 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)!