Heavy Neutrinos: Current and Future Colliders

CepC 2018 - IHEP

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Apologies and Disclaimers

Finite time constraints $\implies$ many omissions

- Main focus is on heavy neutrinos (N).
- See Backup Slides for collider tests of Type II and III Seesaws

Source material:

1. Review on Nu Mass Models at Colliders [arXiv:1711.02180], Y. Cai, T. Han, T. Li, **RR**
2. CepC CDR Chapter on Nu Mass Modes
3. Other community documents, both "*public*" and "*in preparation*"

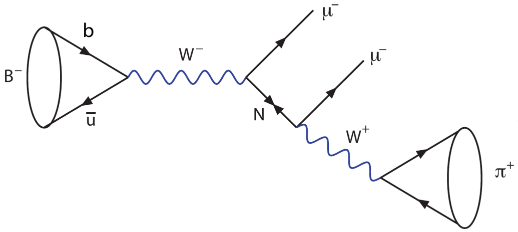
humble reminder: RH neutrinos are **not** the only explanation for tiny ν masses nor are they necessary (e.g., Type II Seesaw)

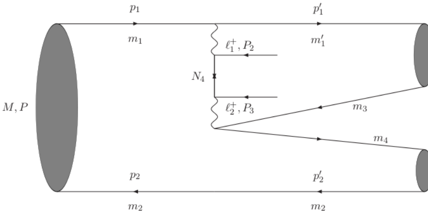
- Lack of guidance from data and theory $\implies$ broad approach needed
- See, e.g., M. Schmidt's talk (Next!) and T. Li's poster

ee Colliders and Low Mass *N*

Searches for Low Mass N

For $m_N \ll M_W$, N can appear in decays[1] of baryons, mesons, and τs!





Production rate of mesons ($\pi^\pm, \mathcal{D}, \mathcal{B}$) at colliders is ***big*** ($\sigma_{bX}^{\rm LHC} \sim 0.1\ mb$)

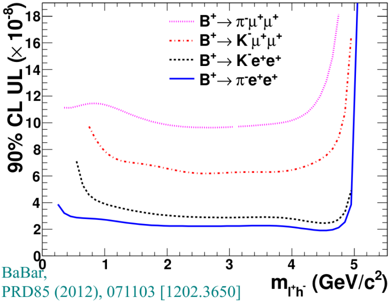
- Sufficient[2] to overcome ***tiny*** mixing for MeV-scale, Majorana N
- Sufficient to probe L-conserving, charged lepton flavor violation

[1] Atre, Han, Pascoli, & Zhang [0901.3589]; Castro & Quintero [1302.1504]; Yuan, Wang×2, Ju, & Zhang [1304.3810]; + lots more. See the review [1711.02180] for details

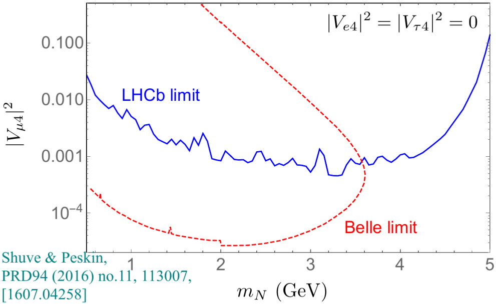
[2] Specifically, Kersten-Smirnov [0705.3221] and Pascoli-Weiland [1712.07611]

Searches for Low Mass Majorana N

(L) BaBar: Limits on BR($\mathcal{B} \to NX$) using 4.7×10^8 $\mathcal{B}\overline{\mathcal{B}}$ [1202.3650]



BaBar,
PRD85 (2012), 071103 [1202.3650]



Shuve & Peskin,
PRD94 (2016) no.11, 113007,
[1607.04258]

(R) LHCb and Belle search for $\mathcal{B} \to N\mu \to \pi\mu\mu$ [1607.04258]

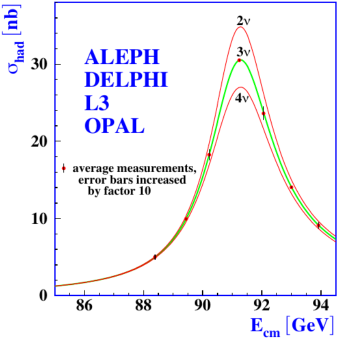
Complementarity between high- (LHC) and low- (Belle) energy colliders!

- LHCb will collect $\gtrsim 100\times$ more data $\implies \gtrsim 10\times$ improvement
- Belle II now operational!
- See also BESIII searches for charged lepton flavor violation

Low Mass N at Z Factories

One of the most important (and neatest!) LEP results:
determination of invisible Z width, $\Gamma^Z_{\text{Inv.}} \implies N_\nu^{\text{Active}}$ with $m_\nu < M_Z/2$

- From line shape,
  $N_\nu^{\text{Active}} = 2.9840 \pm 0.0082$
- From inv. Z decays,
  $N_\nu^{\text{Active}} = 2.92 \pm 0.05$
- 2σ deviations consistent with
  $Z \to N\nu$ decays [Jarlskog, ('91)]



- Helps drive (mild) preference for non-unitarity of 3×3 mixing[3]

Important: A future *ee* collider can resolve this [1411.5230]

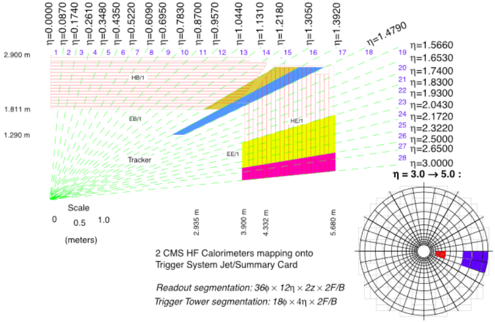
[3] See, e.g., Fernandez-Martinez, et al [1605.08774]

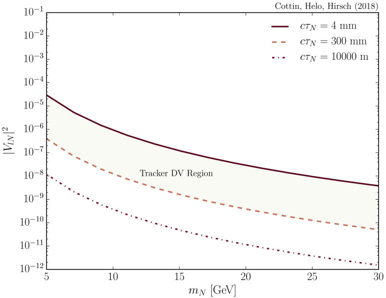
N with Intermediate Masses:

Non-prompt[4] decays / displaced vertices

[4] **Prompt decays postponed since new results overlap with heavier N**

Displaced Vertices





Decays of light N through SM weak currents can be very long-lived:

$$\Gamma_{\rm Tot.} \sim G_F^2 m_N^5 \sum |V|^2 \text{ (small } |V| \implies \text{long lifetime!)}$$

$$\implies d_0 = \beta c\tau = \frac{\beta c\hbar}{\Gamma_{\rm Tot.}} \sim \frac{1.45\ m}{\sum |V|^2}\left(\frac{1\ \mathrm{GeV}}{m_N}\right)$$

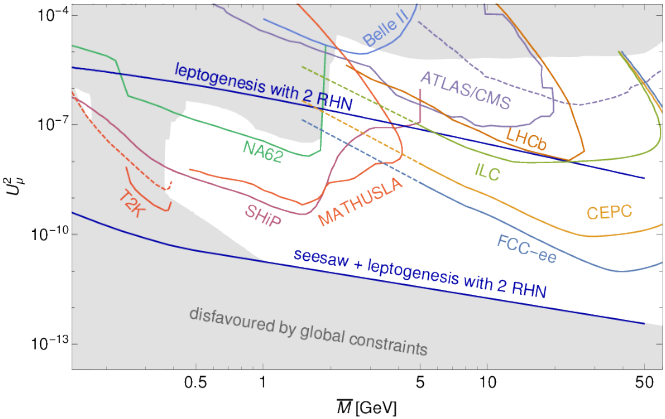
LHC detectors have *finite* detector volume, with radius $< \mathcal{O}(10)$ m

- N may decay in ECAL (1-2m), HCAL (2-3m), μChamber ($\gtrsim$5m)

Intermediate N at Many Machines[5]

Many current and proposed expts sensitive to displaced N decays

- Many, many studies past year with a coherent message forming



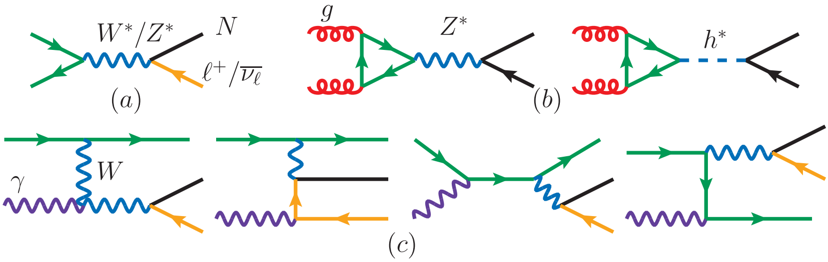
Note: HL-LHC sensitivity updated: $|V|^2 \sim 10^{-9} - 10^{-8}$ [1806.05191]

[5]Many thanks to M. Drewes for updated plot [1609.09069].

High Mass N and the pp Option

Heavy Neutrino Production At Hadron Colliders

Heavy N can be produced through a variety of mechanisms in pp collisions



In fact, a resurgence of calculations in recent years[6]

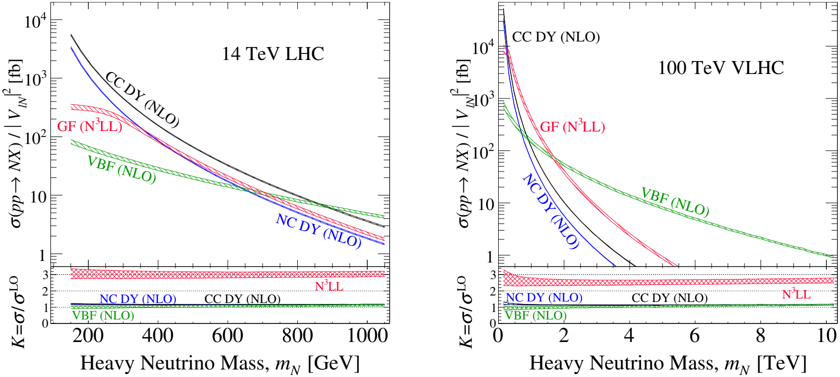
- Driven by need for clarity on $m_N, \sqrt{s}$ dependence

$\Longrightarrow$ more physical/robust collider definitions + public tools[7]

[6]DY@NLO [*1509.06375]; GF [1408.0983, *1602.06957] @NNNLL [*1706.02298]; VBF [1308.2209, *1411.7305, *1602.06957]; DY,VBF Automation@NLO [*1602.06957]; For extensive details, see review: [*1711.02180]; (*) = Pittsburgh and/or IPPP

[7]Fully exclusive up to NLO+PS available with HeavyN libraries + MG5aMC@NLO,

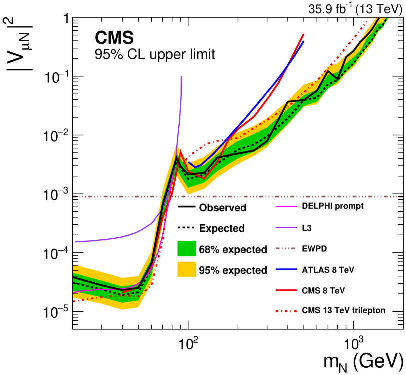
Across different colliders, wild interplay of PDF and matrix elements

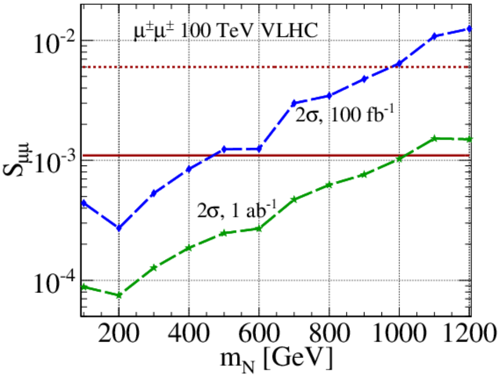


Plotted: Flavor-independent heavy N production rate $(\sigma/|V|^2)$ vs mass

- **GF** and **VBF** dominate at larger $\sqrt{s}$, m_N. 27 TeV similar to 100 TeV
- At $\sqrt{s} = 100$ TeV and $|V_{\ell N}|^2 \sim 10^{-3}$, about one $N(10 \text{ TeV})/\text{ab}^{-1}$
  If roughly BR$\times\varepsilon \times \mathcal{A} \times \mathcal{L} \sim \frac{1}{3} \times 30$ ab^{-1}, then $\sqrt{N_{Obs.}} > 3\sigma$

Unified push by hep-ex and hep-ph/th have broken new ground!





LHC: $|V_{\ell N}|^2 \gtrsim 10^{-3}$ probed for $m_N > M_W$, $\mathcal{L} \approx 36$ fb^{-1} [1806.10905]

- LHC Run III-V: Anticipate $\sim 10 - 150\times$ more data

100 TeV: $|V_{\ell N}|^2 \gtrsim 10^{-5}$ accessible with 1-3 ab^{-1} [1411.7305]

- **Watch this space:** Improved reach due very soon [1805.09335]

Theory Developments:

Clarity on Lepton Number Violation at Colliders

Clarity on Lepton Number Violation vs Colliders

Subtle assumptions in ν mass models have led to overstatements in literature and confusion on feasibility of LNV at colliders

Whether or not N_i decouple from collider experiments has been clarified

- Theorem: In SM + arbitrary number of gauge singlet/sterile fermions, $\tilde{m}_\nu = 0 \implies$ lepton number (L) conservation [1712.07611]

Clarity on Lepton Number Violation vs Colliders

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$\implies$ In pure Type I scenarios, L violation decouples one of two ways:

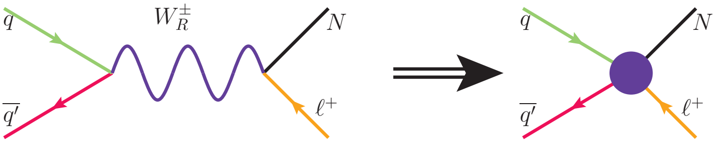
1. **High-scale seesaw**: $\mu_M \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\mu_M}\right), \quad m_N \sim \mu_M$
2. **Low-scale seesaw**: $\mu_M \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \mu_M \left(\frac{m_D}{m_R}\right)^2, \quad m_N \sim m_R$

$\implies$ In Type I scenarios, EW/TeV-scale Dirac-like N_i do not decouple

Collider observation of N_i + L-violation $\implies$ *more new particles!*

- Important since concrete example of a realistic Type II Seesaw mimicking the canonical Type I collider signature

If new gauge mediators are too heavy, light N are still accessible



[8] Han, Lewis, **RR**, Si, [1211.6447]; **RR**, [1703.04669]

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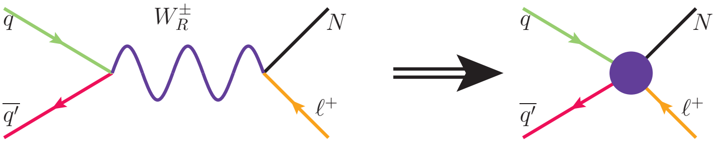
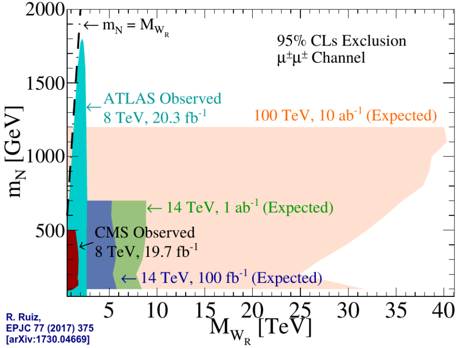


When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ production in the LRSM and minimal Type I Seesaw are not discernible[8]

- **Signature:** $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N)$ + no MET
- At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV probed
- **DO NOT STOP SEARCHING FOR TYPE I LNV**



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Collider LNV from Inaccessible Mediators

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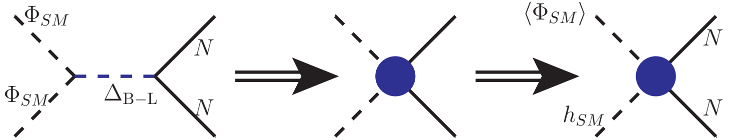

SM-invariant effective field theories with sterile neutrinos exist!

- Heavy Neutrinos EFT (NEFT) [Aparici, 0904.3244]

$$\mathcal{L}_{\mathrm{NEFT}} = \mathcal{L}_{\mathrm{Type\ I}} + \sum_5 \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}, \qquad \mathcal{O}_V^{(6)} = \left(\overline{d}\gamma^\mu P_R u\right)\left(\overline{e}\gamma_\mu P_R N_R\right)$$

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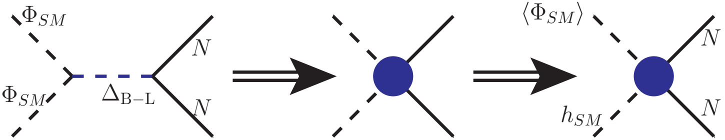

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One subtlety [**RR**, 1703.04669]: N_R here is *chiral/interaction* state

- Must decompose into mass basis: $N_R = \sum X_{\ell m}\nu_m + \sum Y_{\ell m'} N_{m'}$
- After EWSB, maps onto light neutrino NSI operators!
- Can mediate $h_{\rm SM} \to NN$ decays! See, e.g., Caputo, et al [1704.08721]

Summary

Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

1. Future e^+e^- machines explore new levels of mixing for light N
   - Searches for $\mathcal{B} \to N + X$, $Z \to N\nu$, $h \to NN$

2. Future pp machines explore new space for heavy Seesaw particles
   - Searches for N, $H^\pm$, $H^{\pm\pm}$, W_R, Z_{B-L}, $T^\pm T^0$

3. LNV at colliders is well-motivated and feasibility clarified!

4. Colliders offer *incredibly* complementary to oscillation facilities:
   - Direct production of Seesaw particles
   - Test UV realizations of low-scale neutrino NSI

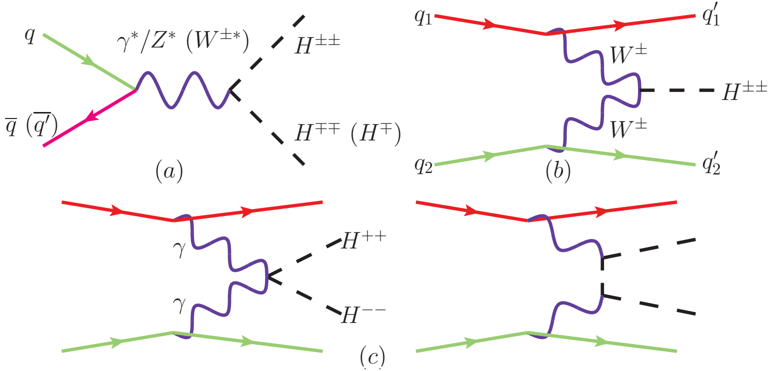
5. Lots not covered today, so see the review [arXiv:1711.02180]

6. Be encouraged! More data soon!

Thank you.

Backup

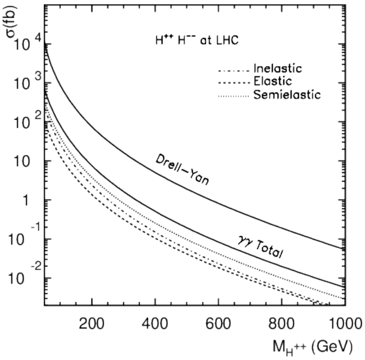
Type II Seesaw[9]

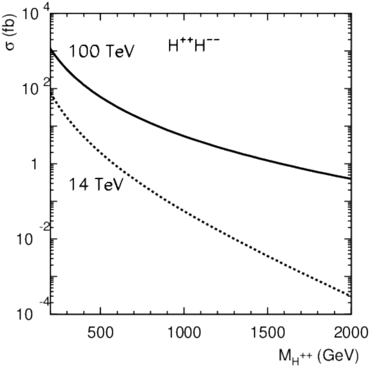


[9] **See Talk by Michael Schmidt**

Type II Seesaw is characterized by existence of scalars that are triplets under $SU(2)_L$: $H^0,\ H^\pm,\ H^{\pm\pm}$

- Couples to W, Z, γ through gauge couplings
- Generates light ν_m masses via vev (NO STERILE N NEEDED!)

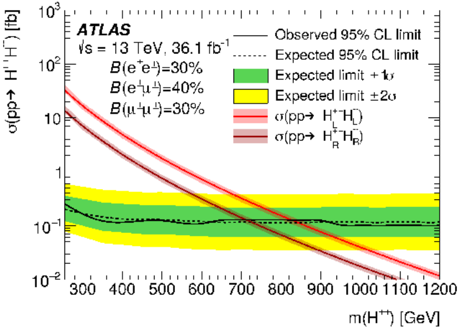


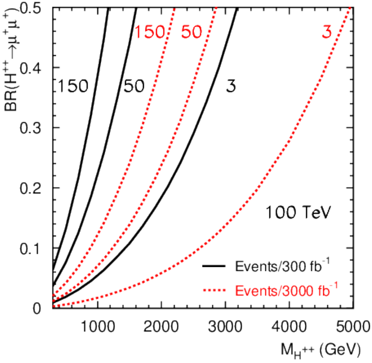


Production at 100 TeV ***HUGE*** compared to LHC!

- Clear that $\sigma_{DY}(H^{\pm\pm}H^{\mp\mp}) \gg \sigma_{\gamma\gamma}(H^{\pm\pm}H^{\mp\mp})$

Discovery Potential of Triplet Scalars



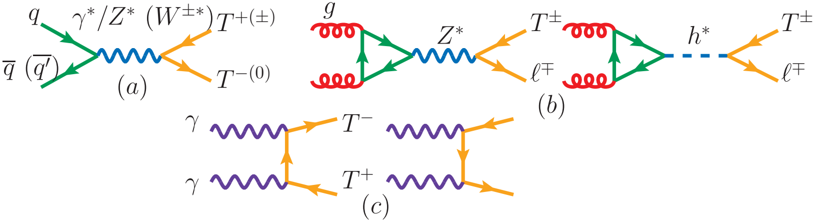


LHC: $m_{H^{\pm\pm}} \lesssim 700 - 900$ GeV excluded with $\mathcal{L} \approx 36$ fb^{-1}

- LHC Run III-V: Anticipate $\sim 10 - 150\times$ more data

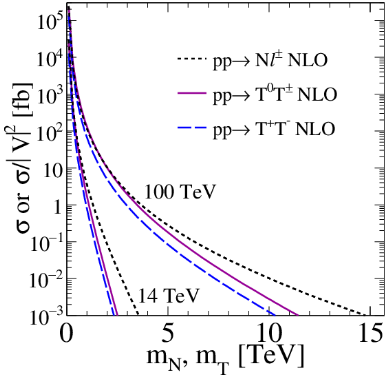
100 TeV: $m_{H^{\pm\pm}} \lesssim 3 - 5$ TeV can be discovered within first 300-3000 fb^{-1}

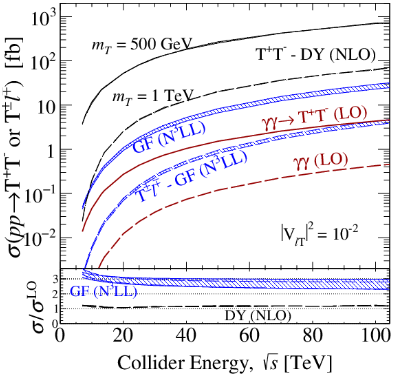
Type III Seesaw



Type III Seesaw is characterized by existence of leptons that are triplets under $SU(2)_L$: T^0, $T^{\pm}$

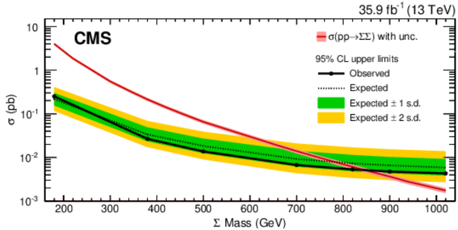
- Couples to W, Z, γ through gauge couplings
- Generates light ν_m masses similar to Type I

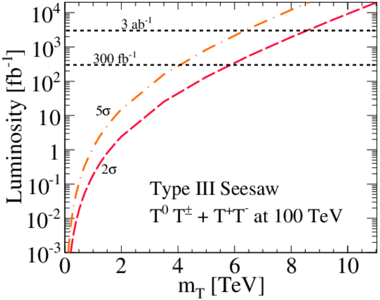




- Production at 100 TeV ***HUGE*** compared to LHC!
- Clear that $\sigma_{DY}(T^+T^-) \gg \sigma_{\gamma\gamma}(T^+T^-)$
  - $\sigma_{GF}(T^{\pm}\ell^{\mp})$ competitive if mixing sizable!

Discovery Potential of Triplet Leptons





LHC: $m_T \lesssim 800$ GeV excluded with $\mathcal{L} \approx 36$ fb^{-1}

- LHC Run III-V: Anticipate $\sim 10 - 150\times$ more data

100 TeV: $m_T \lesssim 4 - 6$ TeV can be discovered within first 300-3000 fb^{-1}

- Sensitivity can be improved with refined analysis and combining channels (See [**RR**, 1509.05416] for details)