ν Physics at Colliders

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Good afternoon and thank you for being here!

Most important rule: ask questions!

You are welcomed and encouraged to interrupt me.

Plan

Lecture I: MC event simulation ✓

- leading order cross sections and event simulation
- next-to-leading order event simulation

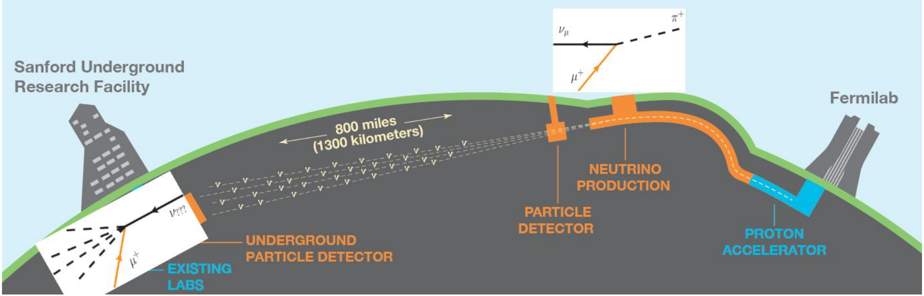
Lecture II: Jets ✓

- particle reconstruction and ID
- jets as tools for discovery

Lecture III (today!): neutrino physics at colliders

- possible explanations for $m_\nu \neq 0$
- collider tests of these ideas

the big picture

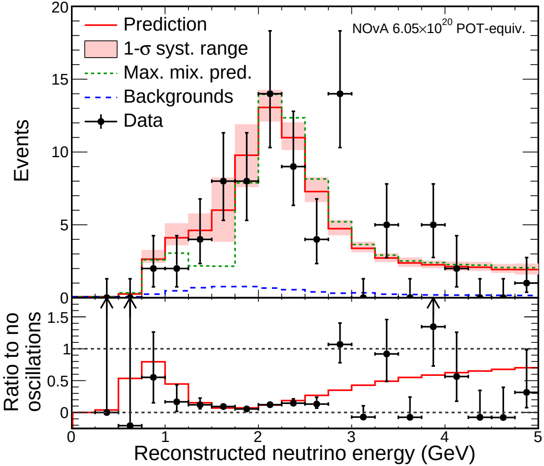


In neutrino fixed-target expts, ν_μ beams from collimated $\pi^\pm$, then studied at near and far detectors (reminiscent of early SLAC DIS expts)

Count ν_ℓ at far detector (FD) and **compare** to # at near detector (ND)

ν_μ deficit + ν_e/ν_τ apperance at FD best described by $\nu_{\ell_1} \to \nu_{\text{mass}} \to \nu_{\ell_2}$ transitions/oscillations

([E.g. NOνA ν_μ disapp., 1701.05891])



$\Longrightarrow$ **evidence for ν masses!**

So, neutrinos have masses, with $m_\nu \lesssim \mathcal{O}(0.1)$ eV

Is this a problem?

Yes.

Neutrinos Masses and New Physics

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. = -y_\nu \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \langle \Phi \rangle + h \\ 0 \end{pmatrix} \nu_R + H.c.$$

$$= \underbrace{-y_\nu \langle \Phi \rangle}_{=m_D} \overline{\nu_L}\nu_R + H.c. + \ldots$$

However, ν_R^i do not exist in the SM, implying $m_D = 0$

Significance of Neutrino Oscillations:

- Neutrino masses $\implies \mathcal{L}_{\text{Universe}} \neq \mathcal{L}_{\text{SM}} \quad (+\mathcal{L}_{\text{gravity}})$
- Instead, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu \text{ masses}}}_{\textit{BSM physics!}} + \ldots$

Neutrino masses $\implies$ existence of physics beyond the SM!

Neutrinos Masses and New Particles

Nonzero neutrino masses $\implies$ new degrees of freedom exist ([Ma'98]):

$$m_\nu \neq 0 + \text{LH currents}$$

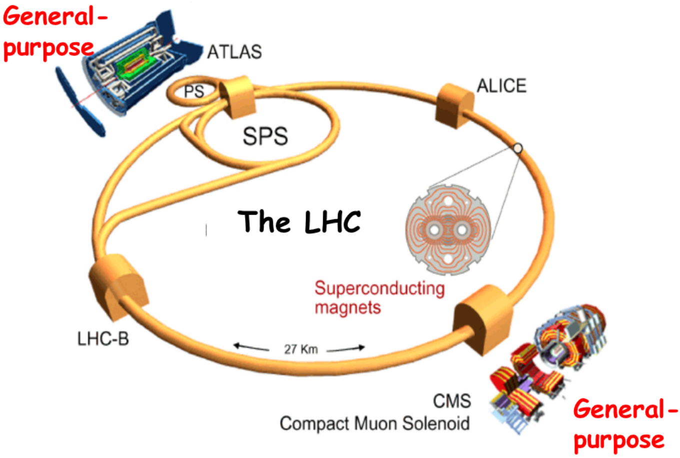
$$\text{LH Majorana Mass}: m_\nu^L \overline{\nu_L} \nu_L^c \quad \text{and/or} \quad \text{Dirac Mass}: m_\nu^D \overline{\nu_L} N_R$$

$$m_\nu^L = y\langle\Delta\rangle \text{ or strong dynamics} \qquad m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

- New particles might be charged under new or old gauge symm. E.g., N_R may have $U(1)_{B-L}$ charge and Δ_L is scalar $SU(2)_L$ triplet
- *Exciting* since long "to do/check" list in case of particle discovery!

The Collider Connection?



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N (Type I), $H^{\pm,\pm\pm}$ (Type II), $T^{0,\pm}$ (Type III), Z_{B-L}, W_R, ...

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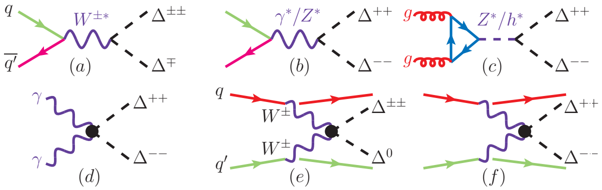

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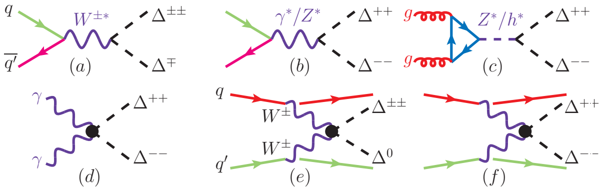
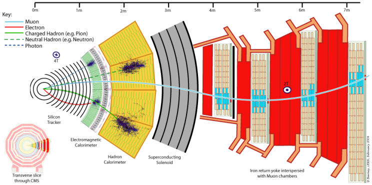
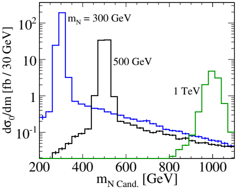


and **identification** through their **decays** to SM particles





Today's Plans

finite time constraints $\Longrightarrow$ many omissions

- introduce Types I, II, III Seesaws, LRSM $m_\nu \neq 0$
- collider tests of these ideas

source material:

1. Review on Nu Mass Models at Colliders Y. Cai, T. Han, T. Li, RR [1711.02180]
2. European Strategy Update 2019 Chapter on Nu Mass Models
   T. Han, T. Li, X. Marcano, S. Pascoli, RR, C. Weiland [1812.07831]
3. Other community documents, and some newer publications

humble reminder: RH neutrinos ν_R 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 $\Longrightarrow$ broad approach needed
- E.g., Models without N, UV completions of NSI, other Seesaws, ...

Type I Seesaw:

mechanisms vs model[1][2]

[1] high-scale Type I: Minkowski (1977); Yanagita (1979); Gell-Mann, Ramond, Slansky (1979); Weinberg (1979); S.L. Glashow (1980); Mohapatra, Senjanovic (1980) 2x Mohapatra, et al (1986); Foot, et al. (1989); Ma. (1989); etc

[2] low-scale Type I (Inverse): Mohapatra (PRL'86); Mohapatra, Valle (PRD'86); Bernabeu, et al ('87); (Linear Seesaw): Akhmedov, et al (PLB'96, PRD'96)

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Gauge singlet nature of ν_R allows a RH Majorana mass term

- A Majorana mass term requires $N = N^c$ (← mass basis!)

(okay as no fundamental symmetry of the SM is violated)

- *"Any process which is not forbidden by a conservation law actually does take place with appreciable probability"* Gell-Man

Thus, the most general,gauge invariant, renormalizable theory is

$$\mathcal{L}_{\text{Type I}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Kin. } \nu_\text{R}} + \mathcal{L}_{\nu \text{ Yuk.}} + \mathcal{L}_{\text{Maj. Mass}}$$

High-Scale Type I Seesaw Mechanism

Suppose ν_R exists and y_ν is nonzero. The Dirac mass follows from

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. \implies -m_D\overline{\nu_L}\nu_R + H.c.$$

In chiral basis, $\psi^c = \mathcal{C}\overline{\psi}^T$ and $\psi^c_L \equiv (\psi^c)_L = (\psi_R)^c$, so we write

$$\mathcal{L}_{\text{Maj. Mass}} = -\frac{1}{2}\mu_R\overline{\nu^c_R}\nu_R$$

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Assuming $\mu_R \gg m_D$ **(high-scale assumption!)**, the mass eigenvalues are

$$m_1 \approx m_D \times V,\ V = \frac{m_D}{\mu_R}\ \text{(active-sterile mixing!)}, \quad m_2 \approx \mu_R$$

For $m_D \sim 100$ KeV (GeV), $m_{\text{light}} \sim 0.1$ eV, then $\mu_{heavy} \sim 10^{8(14)}$ GeV

Realistic **models have complicated $\tilde{M}$ but lower μ_R**

Low-Scale Type I Seesaw Mechanism

Now suppose also a fermion S with no $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ charge

If our universe were described at the EW-scale by $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\nu$,

$$\mathcal{L}_\nu = \mathcal{L}_{Kin.} - y_\nu \overline{L}\tilde{\Phi}\nu_R - \frac{1}{2}\mu_R \overline{\nu_R^c}\nu_R - \frac{1}{2}\mu_{RX}\overline{\nu_R^c}S - \frac{1}{2}\mu_X \overline{S_R^c}S_R + \text{H.c.}$$

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Assuming $\mu_R \ll m_D,\ \mu_{RX}$ **(low-scale assumption!)**, masses are:

$$m_1 \approx \mu_X \times V,\ V = \frac{m_D^2}{m_D^2 + \mu_{RX}^2}, \quad m_{2,3} \approx \pm\sqrt{\mu_{RX}^2 + m_D^2} + \mu_X \frac{m_{RX}^2}{2(m_D^2 + \mu_{RX}^2)} + \frac{1}{2}\mu_R$$

$m_{\text{light}} \sim 0.1$ eV possible at scales within LHC's reach:

$(m_D, \mu_{RX}, \mu_X) \sim (1\text{ MeV}, 1\text{ GeV}, 100\text{ KeV})$ or $\sim (1\text{ GeV}, 100\text{ GeV}, 1\text{ KeV})$

Theory Developments:

Clarity on Lepton Number Violation at Colliders

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

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1. **High-scale seesaw**: $\mu_M \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\mu_M}\right), \quad m_N \sim \mu_M$
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Corollary 1: Low-scale Type I + if ν are approx. massless on exp't scale, i.e., $\tilde{m}_\nu^2/Q^2 \approx 0, \implies$ approximate L conservation   w/ Pascoli, RR, et al, [1812.08750]
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Corollary 2: Collider LNV via $N_i \implies$ *more new particles!* E.g., RR [1703.04669]

but in practice?

For ***discovery purposes***, no need to complicate life. Take agnostic/pheno. approach with generic $V_{\ell N}$ parametrization and one N mass eigenstate

(Atre, Han, Pascoli, Zhang [0901.3589])

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

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$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

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$\implies$ SM W coupling to N and charged **leptons** in the **mass basis is**

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\implies$ N is **accessible through** SM currents

Searches for Low Mass N

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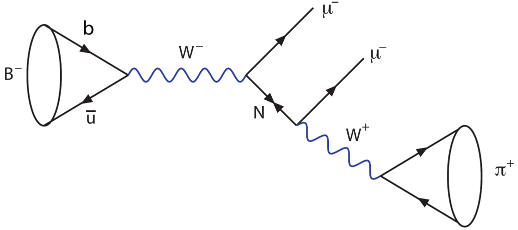
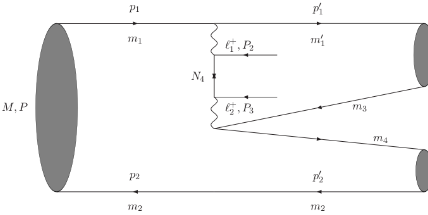
For $m_N \ll M_W$, N can appear in decays of baryons, mesons, and τs!

Atre, Han, Pascoli, & Zhang [0901.3589]; Castro & Quintero [1302.1504]; Yuan, Wang $\times 2$, Ju, & Zhang [1304.3810]; + others





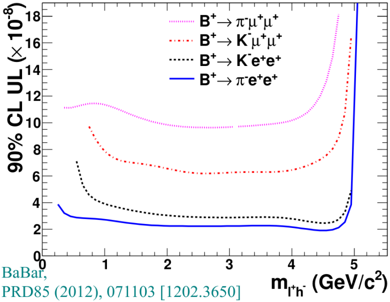
Production rate of mesons ($\pi^{\pm}, \mathcal{D}, \mathcal{B}$) at colliders is ***big*** ($\sigma^{\rm LHC}_{bX} \sim 0.1\ mb$)

- Sufficient[3] to overcome ***tiny*** mixing for MeV-scale, Majorana N
- Sufficient to probe L-conserving, charged lepton flavor violation

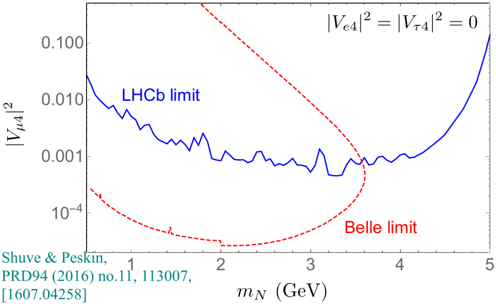
[3] Specifically, Kersten-Smirnov [0705.3221] and Pascoli, et al [1712.07611]

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]

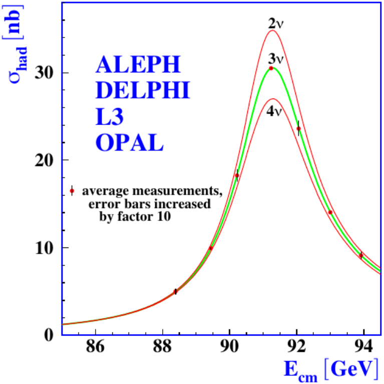
Complementarity between high- (LHC) and low- (Belle) energy colliders!

- 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, $\Gamma^Z_{\text{Inv.}} \implies N_\nu^{\text{Active}}$ for $m_\nu < M_Z/2$

- 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

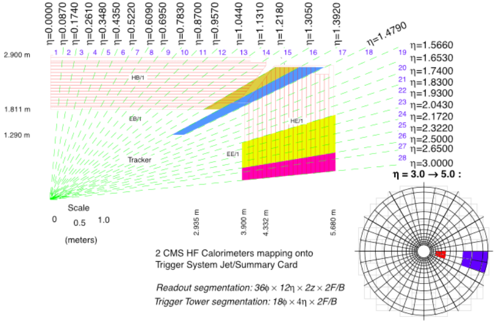
See, e.g., Fernandez-Martinez, et al [1605.08774]

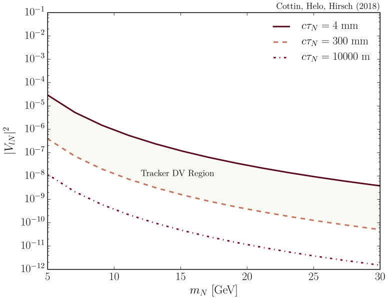
Important: Proposed *ee* colliders can comment on this   Blondel, et al [1411.5230]

N with Intermediate Masses:

Non-prompt decays / displaced vertices

Displaced Vertices





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

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

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

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

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

Light/Intermediate N at Current and Future Machines

List of current and proposed experiments sensitive to displaced N decays

- **Ongoing:** ATLAS, CMS, LHCb, Belle2: sensitivity to μ, τ flavors

  ATLAS[1905.09787], CMS[1802.02965]

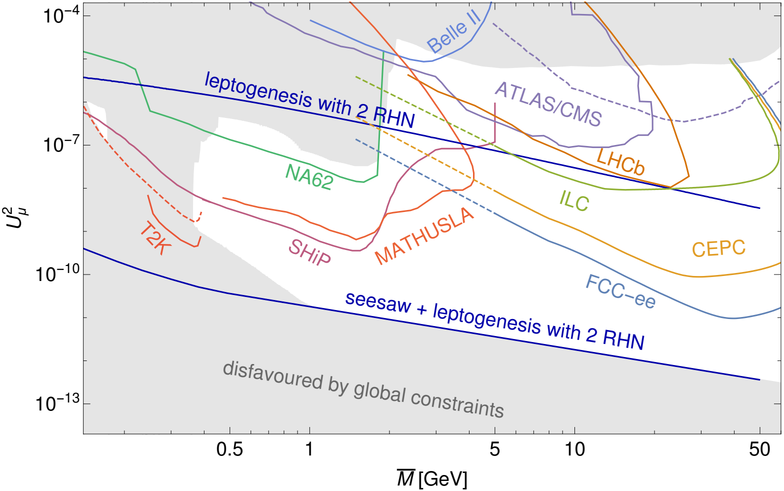
- **Ongoing:** T2K: $N \to \pi\ell, 2\ell\nu$ at ND280 [Lamoureux, Neutrino2018]

- **Proposed:** FCC-ee, CepC(5YP-2021): $ee \to N\nu$

- **Proposed:** SHiP [1805.08567] and MATHUSLA [1803.02212]

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

Community Message: Next-gen. facilities will be able to directly test *simplest* resonant leptogenesis scenarios with high-scale Type I Seesaw

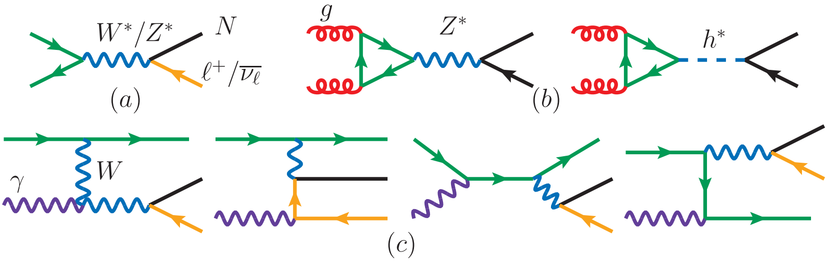


Update of Drewes, et al [1609.09069]

Searches for High Mass N

Heavy Neutrino Production At Hadron Colliders

... can occur through a variety of mechanisms:



In fact, a resurgence of calculations in recent years[4]

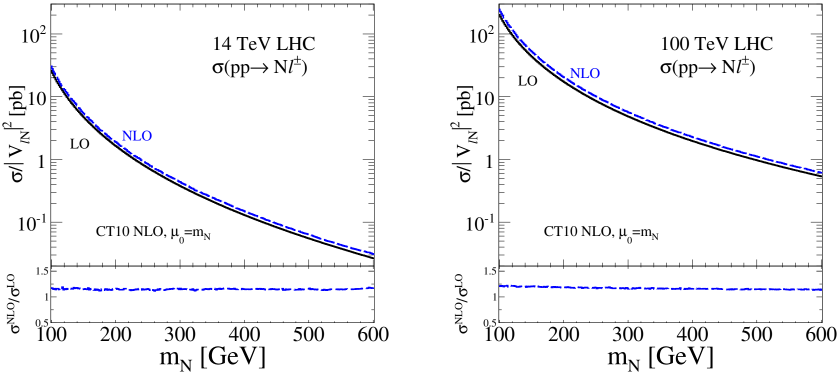
- Clarity needed on (i) $m_N, \sqrt{s}$ dependence and (ii) conflicting claims

$\Longrightarrow$ more physical collider definitions + public tools HeavyN UFOs [1602.06957]

[4] 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]; (*) = Pitt or IPPP

$N\ell^\pm$ Production @ NLO in QCD

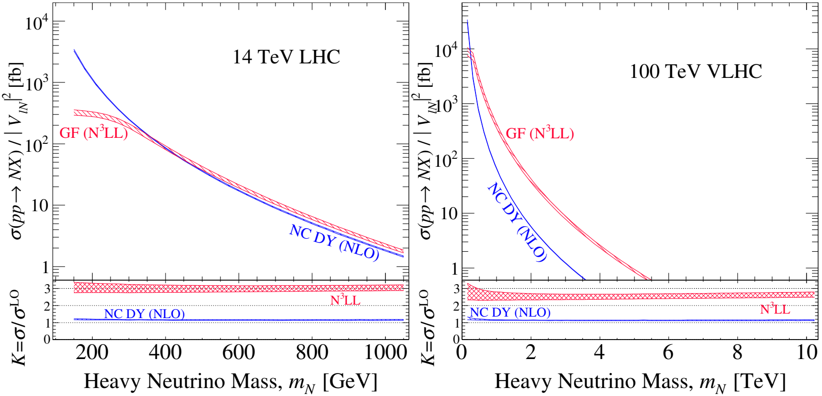
Plotted: Normalized production rate ($\sigma/|V|^2$) vs heavy N mass (m_N)



RR [1509.05416, 1509.06375]

- Well-cited claims of large ($> 100\%$) QCD corrections **unfounded**
  - Issue due to double counting $\mathcal{O}(\alpha_s)$ contributions, i.e., QCD ISR
- **Inspired new guidelines** for modeling N @LHC (w/ Degrande, Mattelaer, Turner)

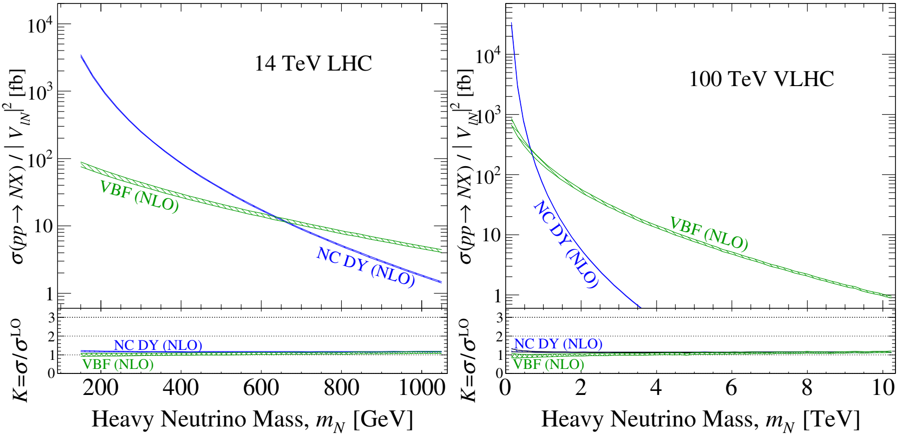
$N\nu$ Production @ NLO and N^{3}LL



Maturity of modern QCD formalism $\Longrightarrow$ readily applied to BSM

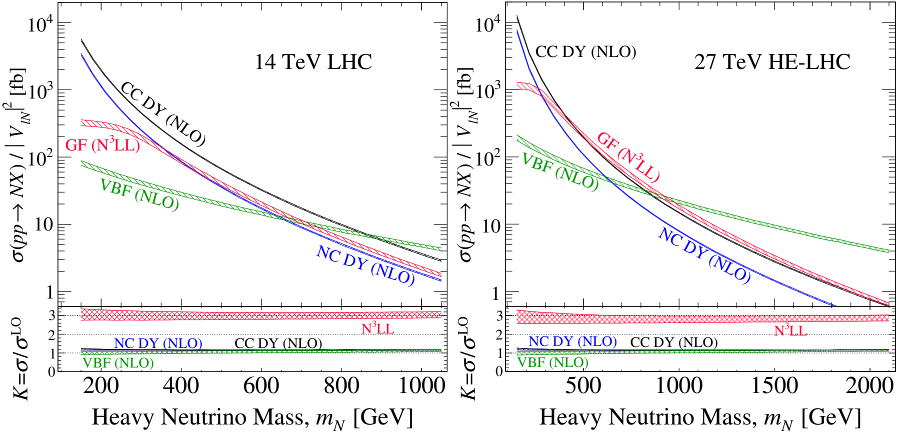
- $pp \to W^* \to \ell N$ @ NLO $\Longrightarrow$ $pp \to Z^* \to \nu N$ @ NLO done!
- $gg \to h^*/Z^* \to \nu N$ at N^{3}LL ($\approx$ N^{2}LO) w/ Spannowsky, Waite [1509.05416]
  $\mathcal{O}(+200\%)$ corrections consistent with $gg \to H/A$ in 2HDM

$W\gamma$ Fusion @ NLO in QCD



- $W\gamma \to N\ell^{\pm}$ fusion is interesting but subtle due to QED singularities and matching to γ PDF — w/ Alva, Han [1411.7305]
- Once addressed, beyond LO is clear — w/ Degrande, Mattelaer, Turner [1602.06957]

Across different colliders, wild interplay of PDF and matrix elements



w/ Pascoli, et al, [1812.08750]

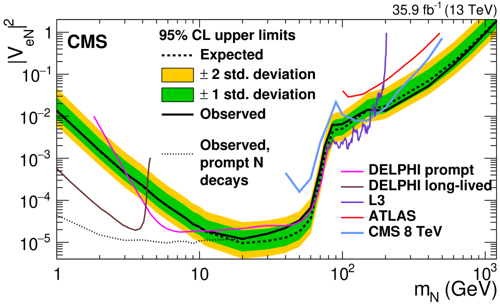
Plotted: Normalized production rate $(\sigma/|V|^2)$ vs heavy N mass (m_N)

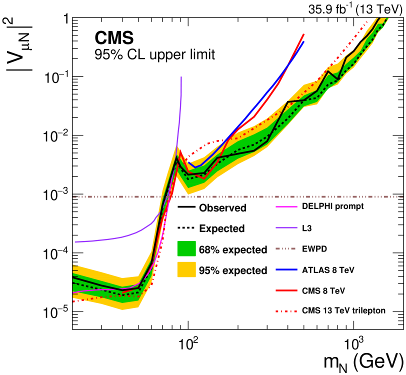
- For $\sqrt{s} \gtrsim 25-27$ TeV, **GF** greater than **DY** due to gg luminosity
- For $m_N \gtrsim 1-2$ TeV, **VBF** dominant due to milder Q^2-suppression
- Trend more exaggerated at $\sqrt{s} = 100$ TeV

Experimental Tests on Intermediate- and High-Mass *N*

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

Plotted: LHC 14 sensitivity to (coupling)^2 vs heavy neutrino mass



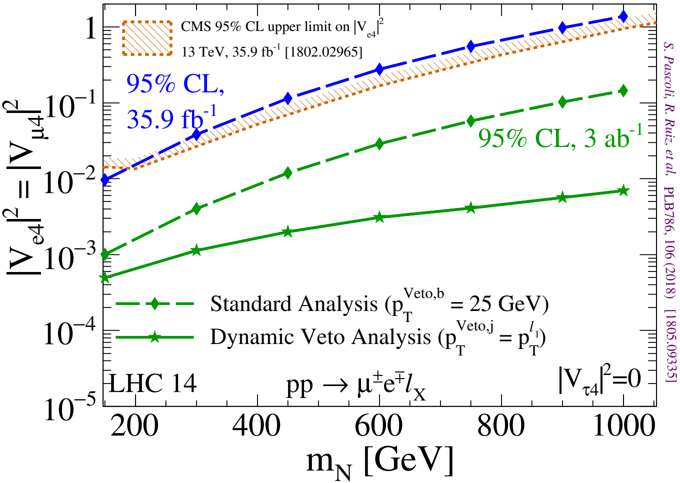


Plotted: Exclusion on mixing $|V_{\ell N}|^2$ vs heavy *N* mass (m_N)

- (L) Search for $pp \to N\ell \to 3\ell + X$ [1802.02965]
- (R) Search for $pp \to N\ell \to \ell^\pm\ell^\pm + nj + X$ [1806.10905]

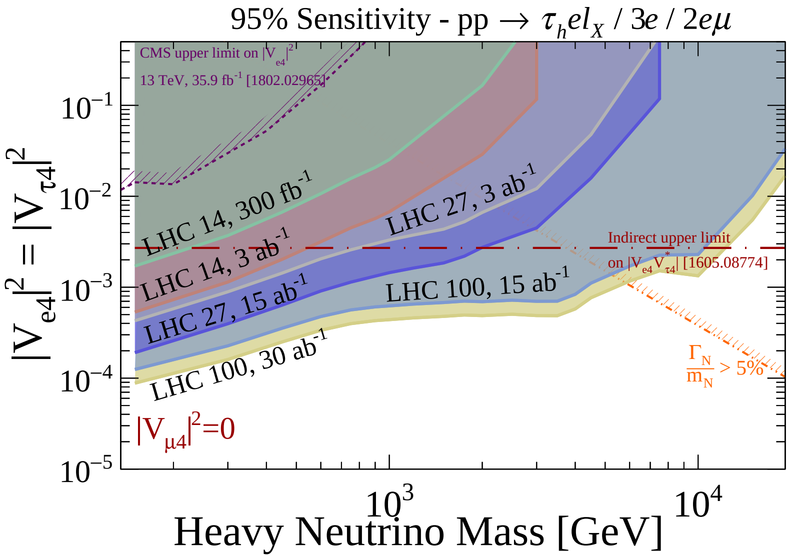
New: improved handle on QCD/jets now allows jet observables to be used as discriminats, e.g., *dynamic* jet vetoes

Signal: $pp \to \mu^{\pm} e^{\mp} \ell_X$+MET



[1805.09335]

Improved sensitivity up to $10 - 11\times$ with $\mathcal{L} = 300 - 3000$ fb^{-1}

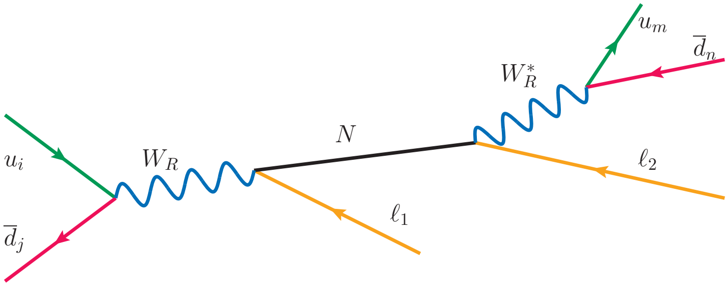


After 3 yrs, *total* rewrite of $pp \to 3\ell X$ search for Dirac (and Majorana!) N!

$10 - 11\times$ improved sensitivity to cLFV at LHC

Pascoli, RR, et al [1805.09335,1812.08750]

Heavy N with New Gauge Fields



Left-Right Symmetric Model postulates that nature was once left-right parity symmetric but spontenously broken by a new Higgs sector

[Pati, Salam, Mohapatra, Senjanovic, etc., ('74-'79)]

Postulate new RH weak interaction:

- LR-breakdown responsible for SM

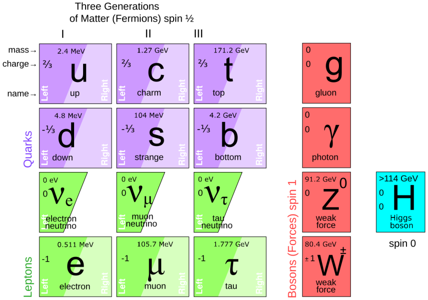
$$\mathcal{G} = SU(3)_c \otimes U(1)_{\rm EM}$$

$$\Uparrow$$

$$\mathcal{G} = SU(3)_c \otimes {\rm SU}(2)_L \otimes {\rm U}(1)_{\rm Y}$$

$$\Uparrow$$

$$\mathcal{G} = SU(3)_c \otimes {\rm SU}(2)_L \otimes SU(2)_R \otimes {\rm U}(1)_{\rm B-L}$$



To do this:

- mediated by new W_R, Z_R bosons

- assign RH particles RH weak charge

- no ν_R?? Let's add them!!!

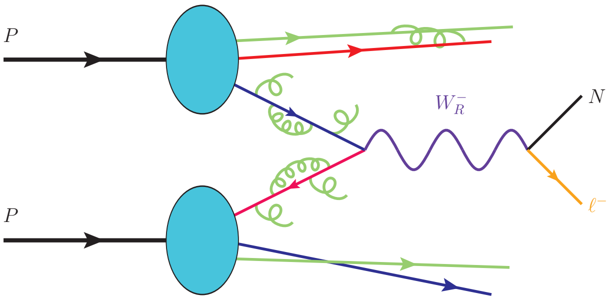
Pre-/postdiction:

- 3 light ν_m : ν_1, ν_2, ν_3 ☺

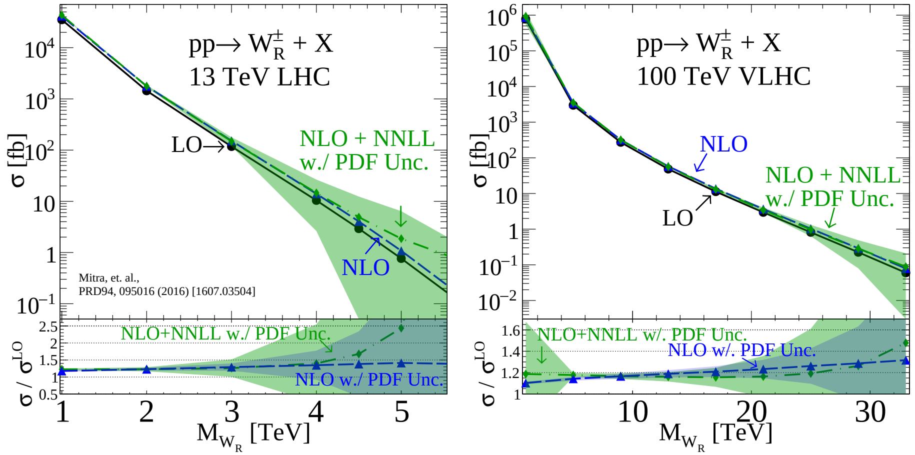
- 3 heavy $N_{m'}$: N_1, N_2, N_3 ☺

- new W_R, Z_R interactions ☺

production



Plotted: W_R production rate (σ) vs W_R mass (M_{W_R})



Mitra, RR, Scott*, Spannowsky [1607.03504];

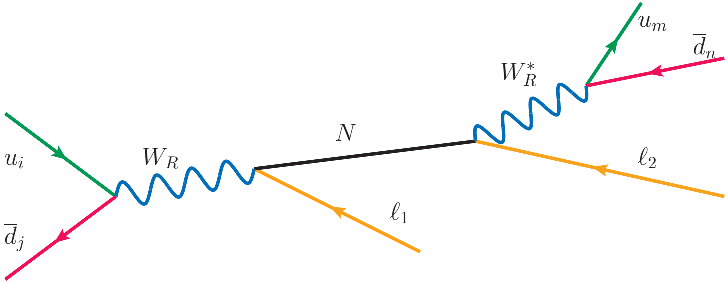
At the LHC, $N \sim \mathcal{O}(100) - \mathcal{O}(10^6)$ W_R/year for $M_{W_R} = 1 - 5$ TeV

- For $M_{W_R} \sim 5 - 6$ TeV $\implies N \sim 500 - 3000$ W_R over LHC lifetime
- Assuming $\mathrm{BR} \times \varepsilon \times \mathcal{A} = 2\% \implies N \approx 10 - 60$ events ($\sim 3 - 8\sigma$)

Hallmark LRSM collider signature is the spectacular same-sign lepton pairs:

(Keung & Senjanovic [PRL ('83)])

$$q\overline{q'} \to W_R^\pm \to N\ell_1^\pm \to \ell_1^\pm \ell_2^\pm q'\overline{q}$$



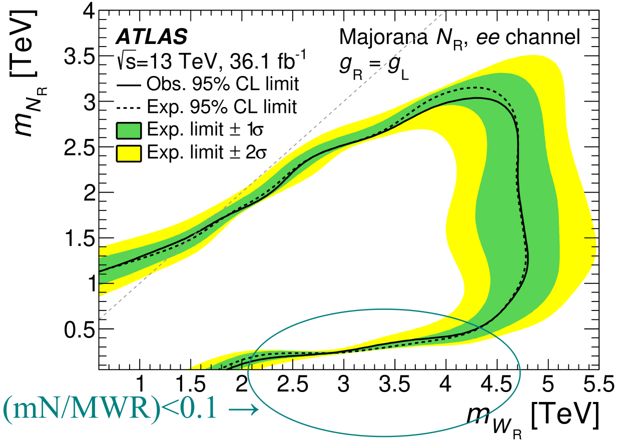
Proposed in ('83) and remains basis for most tests of ν mass models:

- If kinematically accessible, $q\overline{q'} \to W_R^\pm$ production rate is largest
- L violating ($\Delta L = \pm 2$) $\implies$ tests Majorana nature of ν
- $W_R^* \to q'\overline{q}$ allows for full reconstruction of kinematics $\Rightarrow$ **properties**
- High background rejection rate

Left-Right Symmetric Model at the LHC

Heavier N can be produced if associated with new gauge boson W_R, Z_{B-L}

- Canonical channels, e.g., $pp \to \ell_i^\pm \ell_j^\pm + nj$, very sensitive but limited



For $(m_N/M_{W_R}) \ll 1$, i.e., boosted N, searches are losing sensitivity!

For a $1 \to 2$ decay, $m_{ij}^2 = (p_i + p_j)^2 \approx 2E_iE_j(1 - \cos\theta_{ij}) \approx E_iE_j\theta_{ij}^2$

$$\Rightarrow \text{Angle between } e \text{ and } (q\overline{q'})\text{-system} = \theta_{e(q\overline{q'})} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}}$$

As (m_N/M_{W_R}) shrinks, N is more boosted, and its decay *more collimated:*

$$\text{For } \left(\frac{m_N}{M_{W_R}}\right) < 0.1, \theta_{e(q\overline{q'})} \text{ is below } \theta_{\ell X}^{\text{min}} = 0.4, \text{ isolation threshold}$$

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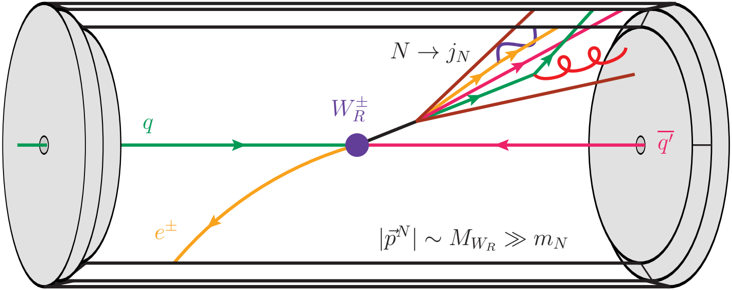
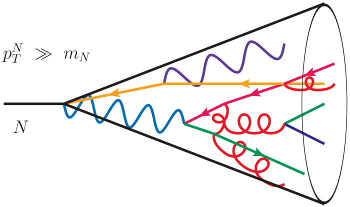


Fun Idea: Why not treat second $e^{\pm}$ like any other poorly isolated particle bathed in QCD radiation and label it as constituent of a jet?

Neutrino Jets at the LHC

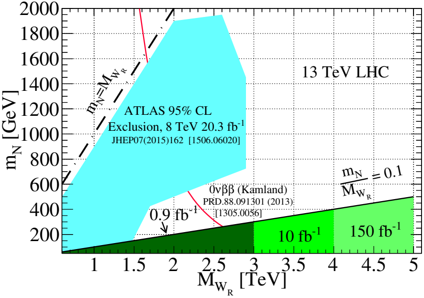
Like boosted t, treat decays of boosted N as a single ***neutrino jet*** (j_N)

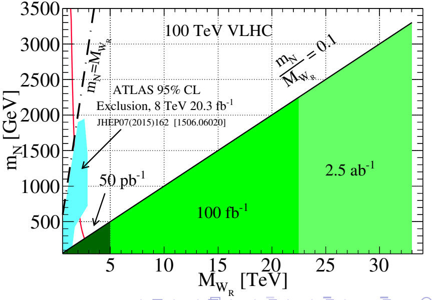


j_N sensitivity (green) is precisely where current $\ell\ell jj$ searches exclusion (blue) stop

Mitra, RR, Scott, Spannowsky + w/ Mattelaer [1607.03504; 1610.08985]

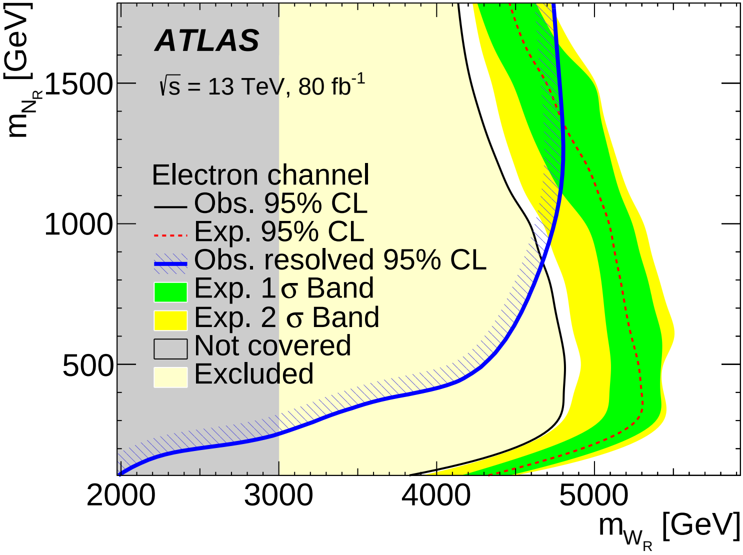
W_R sensitivity recovered and can reach $5-6$ $(35-45)$ TeV at $\sqrt{s} = 14$ (100) TeV





Neutrino Jets at ATLAS

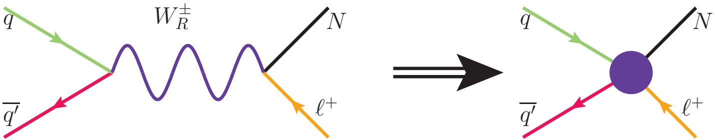
New: search for $pp \to \ell^\pm j_N + X$ at ATLAS [1904.12679]



Neutrino “Nonstandard Interactions”

Neutrino Effective Field Theories

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



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

(Han, Lewis, RR, Si, [1211.6447]; RR, [1703.04669])

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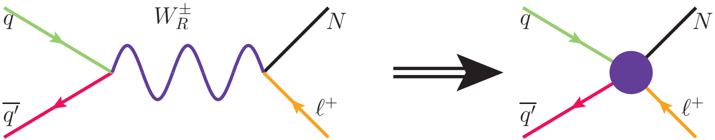

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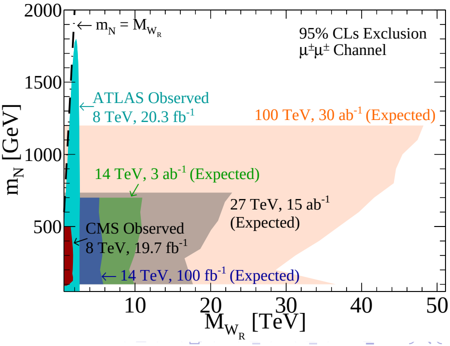
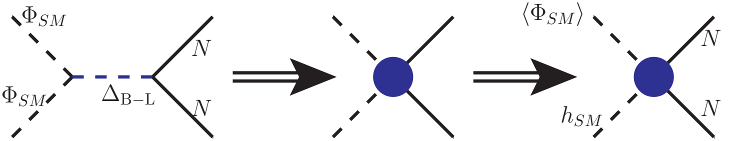
(Han, Lewis, RR, Si, [1211.6447]; RR, [1703.04669])

- **Signature:** $pp \rightarrow \ell^\pm\ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) +$ 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**



LNV at e^-e^+ Machines

If Higgs that breaks $\mathrm{U}(1)_{B-L}$ is too heavy, light N are still accessible



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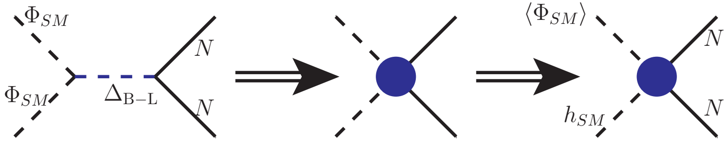

SM-invariant effective field theories with sterile neutrinos exist!

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

$$\mathcal{L}_{\mathrm{NEFT}} = \mathcal{L}_{\mathrm{Type\ I}} + \sum_5 \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}, \qquad \mathcal{O}_S^{(5)} = \left(\Phi^\dagger_{\mathrm{SM}} \Phi_{\mathrm{SM}}\right) \left(\overline{\nu_R^c} \nu_R\right)$$

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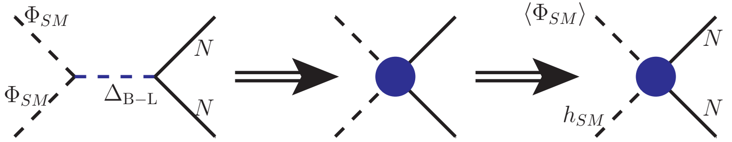

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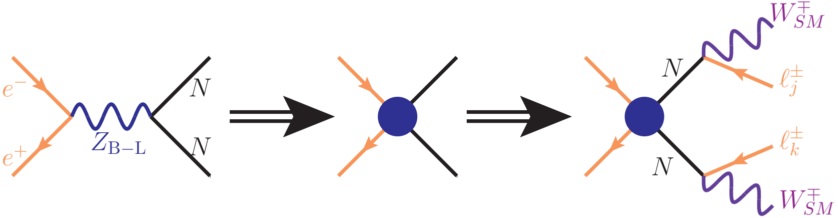
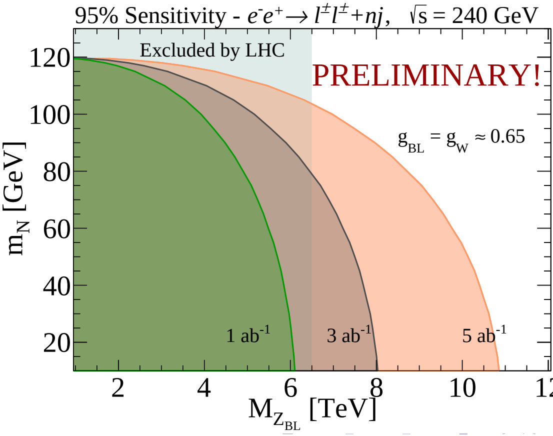
One subtlety ν_R here is *chiral/interaction* state (RR [1703.04669])

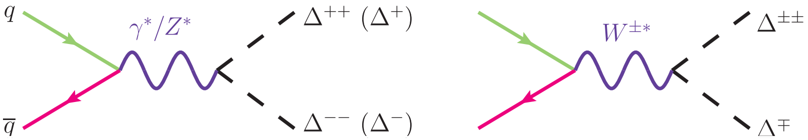
- Must decompose into mass basis: $\nu_R = \sum X_{\ell m}\nu_m + \sum Y_{\ell m'} N_{m'}$
- After EWSB, NEFT operators map onto light neutrino NSI operators!
- Can mediate $h_{\rm SM} \to NN$ decays! (See, e.g., Caputo, et al[1704.08721])



- If ν are Majorana, is (B-L) broken spontaneously?
- If Z_{BL} gauge boson of $U(1)_{B-L}$ is too heavy, LNV is still accessible
- For $g_{BL} = g_W \approx 0.65$, LNV territory beyond LHC reach accessible at Higgs factory!



Type II Seesaw[5]



[5] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

Type II Seesaw Mechanism

Hypothesize an $SU(2)_L$ **scalar** triplet with lepton number $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \text{H.c.}\right)$$

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The mass scale $\mu_{h\Delta}$ explicitly breaks lepton number, and induces $\langle \Delta \rangle$:

$$\langle \hat{\Delta} \rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\rm EW}}{\sqrt{2} m_\Delta^2}$$

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$$\langle\hat{\Delta}\rangle = v_{\Delta} \approx \frac{\mu_{h\Delta} v_{\mathrm{EW}}}{\sqrt{2}m_{\Delta}^{2}}$$

This induces a left-handed Majorana mass for neutrinos

$$\Delta\mathcal{L} = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\overline{L^{c}}\hat{\Delta}L = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\begin{pmatrix}\overline{\nu^{jc}} & \overline{\ell^{jc}}\end{pmatrix}\begin{pmatrix} 0 & 0 \\ v_{\Delta} & 0 \end{pmatrix}\begin{pmatrix}\nu^{i} \\ \ell^{i}\end{pmatrix}$$

$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2}y_{\Delta}^{ij}v_{\Delta}\right)}_{=m_{\nu}^{ij}}\overline{\nu^{jc}}\nu^{i}$$

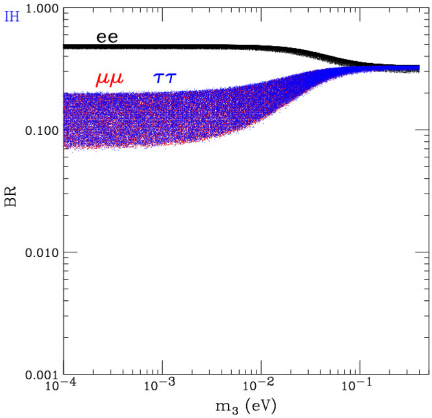
Generates light ν_m masses via vev **WITHOUT** invoking a sterile N!

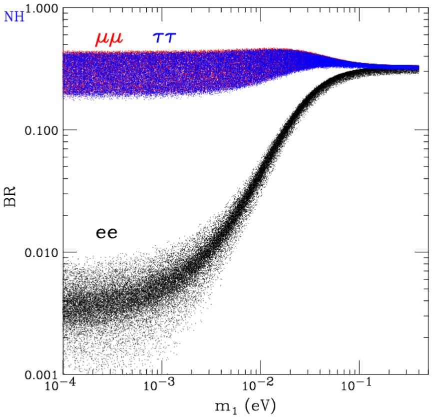
Limited number of parameters $\Longrightarrow$ rich experimental predictions

Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224] + others

- E.g., Higgs branching rates that encode inverse (L) vs normal (R) ordering of light neutrino masses

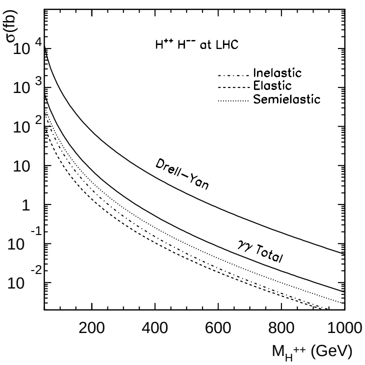
$$\mathrm{BR}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim (U^*_{\mathrm{PMNS}}\tilde{m}_\nu^{\mathrm{diag}}U^\dagger_{\mathrm{PMNS}})_{ij}$$

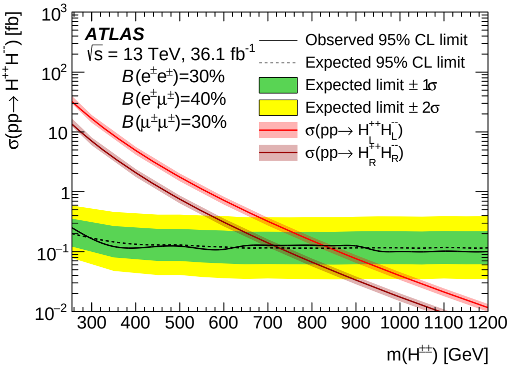




Type II Seesaw is characterized by new scalars $\Delta^0,\ \Delta^{\pm},\ \Delta^{\pm\pm}, \chi^0$

- Couples directly to W, Z, γ (unambiguous σ prediction)





LHC searches for $\Delta^{\pm},\ \Delta^{\pm\pm}$ are on going **but...**

Room For Improvements

Searches for Δ are classic LHC exotica, but room for improvement exists[6]

Monte Carlo generation:

- `Pythia 8.2` for Drell-Yan production@LO of $pp \to \Delta^{++}\Delta^{--}$ but in context of Left-Right Symmetric Model
- `CalcHEP` for Drell-Yan production of $pp \to \Delta^{\pm\pm}\Delta^{\mp}$
- NLO normalizations / K-factor only known with CTEQ6

$(K^{NLO} = \sigma^{NLO}/\sigma^{LO})$

[6] Rizzo ('82); Huitu, et al ('96); Muhlleitner and Spira ('03); Akeroyd and Aoki ('05); Perez, Han, et al ('08); etc

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Modeling Woes:

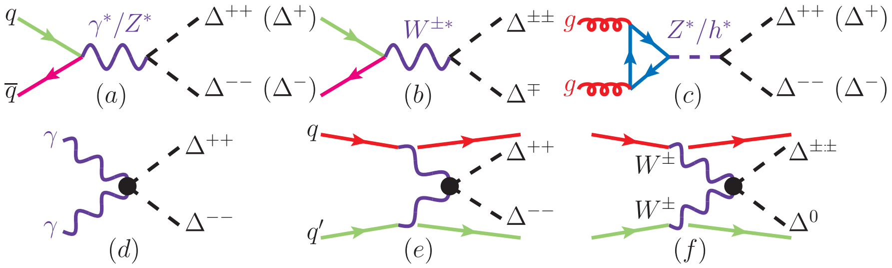
- VBS production $\Delta^{++}\Delta^{--}$ biased by LRSM Higgs sector

(not same as Type II!)

- CalcHEP event generation and CTEQ6 normalization do not describe associated soft hadronic and jet activity
- Uncertainty propagation and control over evt gen. limited, etc.

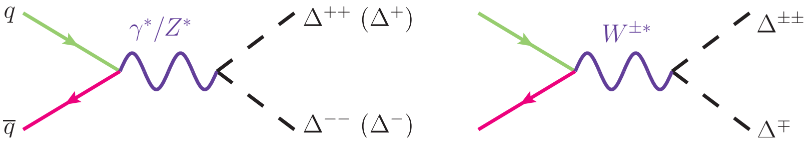
[6] Rizzo ('82); Huitu, et al ('96); Muhlleitner and Spira ('03); Akeroyd and Aoki ('05); Perez, Han, et al ('08); etc

TypeIISeesaw@NLO[7]



[7] with B. Fuks, and M. Nemevšek [1912.08975], feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

Charged Current and Neutral Current Drell-Yan



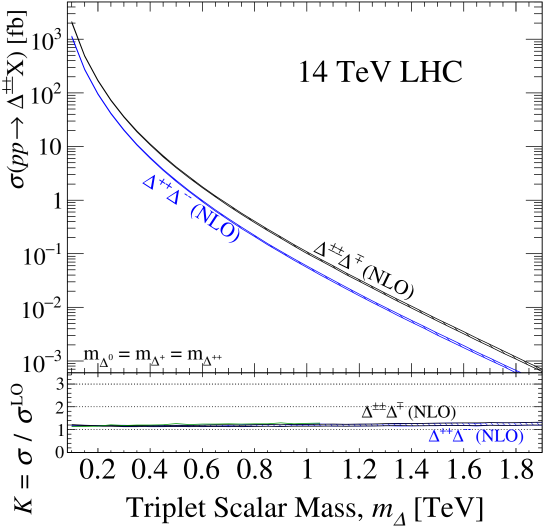
Charged Current and Neutral Current Drell-Yan

Drell-Yan production at NLO in QCD is sanity check[8]

- With one event generator, all the following can be computed: $pp \to \Delta^{++}\Delta^{--}$, $\Delta^{\pm\pm}\Delta^{\mp}, \Delta^{+}\Delta^{-}, \Delta^{\pm}\Delta^{0}$, $\Delta^{\pm}\chi^{0}, \Delta^{0}\chi^{0}$ ($\leftarrow$ *unexplored*)

- Other channels necessary to determine gauge quantum numbers and discriminate against Georgi-Machacek

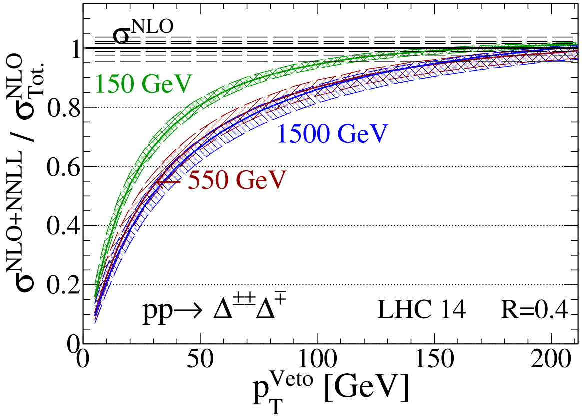
- At NLO, jet vetoes can be modeled / implemented (yay!)



[8] Only other group to compute this is Muhlleitner and Spira ('03)

Unfortunately, for high-mass BSM, jet vetoes $\Longrightarrow$ poor signal efficiency :

Plotted:[9] jet veto efficiency $\varepsilon = \sigma^{\rm NLO+NNLL}(p_T^j < p_T^{\rm Veto}) \ / \ \sigma^{\rm NLO}_{\rm Tot.}$



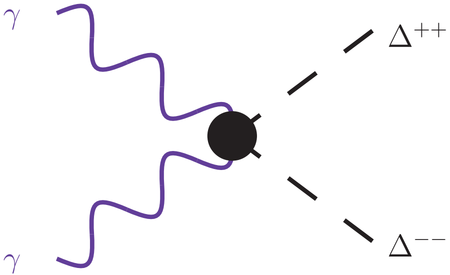
Signal veto efficiency is pretty terrible for $p_T^{\rm Veto} = 20 - 50$ GeV

- Clear that dynamic / safe jet veto schemes[10] are meritted

[9] Using MG5aMC@NLO+SCET. See Becher, et al [1412.8408]

[10] See with Pascoli and Weiland [1805.09335, 1812.08750], as well as with Fuks, Nordstrom, and Williamson [1901.09937]

Photon Fusion

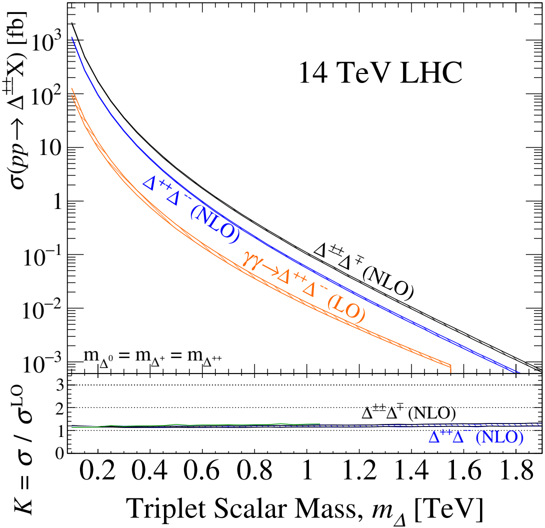


$\gamma\gamma \to \Delta^{++}\Delta^{--}$ is wickedly cool!

- Modern γ PDFs match LUXqed (elastic PDF) and perturbative QCD (inelastic PDF) formalisms

- LO+Pythia8* can match γ to $q \to \gamma q$ splitting, i.e., match to forward jets

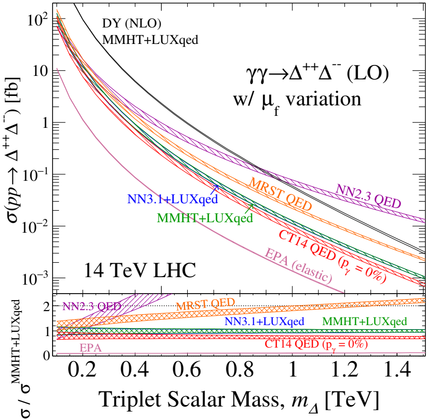
- How do different γ PDFs compare?

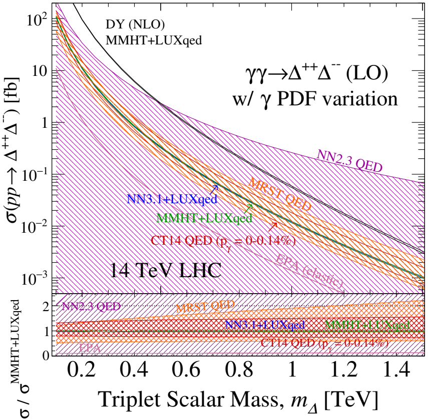


*For details, see home.thep.lu.se/ torbjorn/pythia81html/SpacelikeShowers.html

Historically, back-and-forth about importance of $\gamma\gamma \to \Delta^{++}\Delta^{--}$

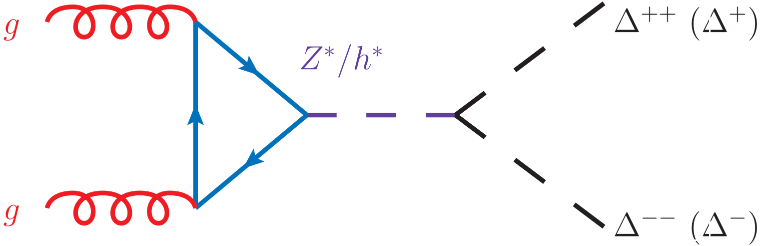
- How do different γ PDFs compare?





With LUXqed, discrepancies have disappeared (again)

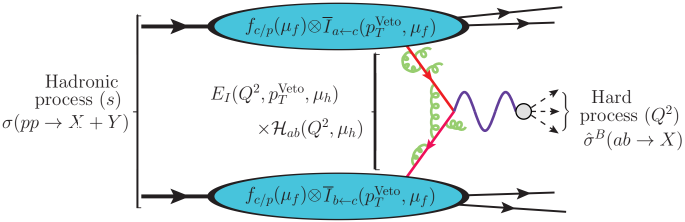
Gluon Fusion



Threshold Resummation in SCET

Each component of the **Factorization Theorem** obeys[11]: $\mathcal{D}X = \Gamma X$

$$d\sigma(pp \to \mathcal{B} + X) = f(\mu_f) \times f(\mu_f) \times \Delta(\mu_s) \times \underbrace{U(\mu_f, \mu_s, \mu_h)}_{Messy,\ but\ universal} \times d\hat{\sigma}(\mu_h)$$



This expression is known as "RG-improved" factorization theorem (SCET)

- Sudakov-like factors act as "dressing" functions, in QFT sense

[11] (Contopanagos, et al; Becher, Neubert etc; Bauer, Stewart, Tackmann etc)

Threshold resummation at (approximately) N^3LL captures leading normalization at N^2LO in QCD (Bonvini, et al, [1409.0864])

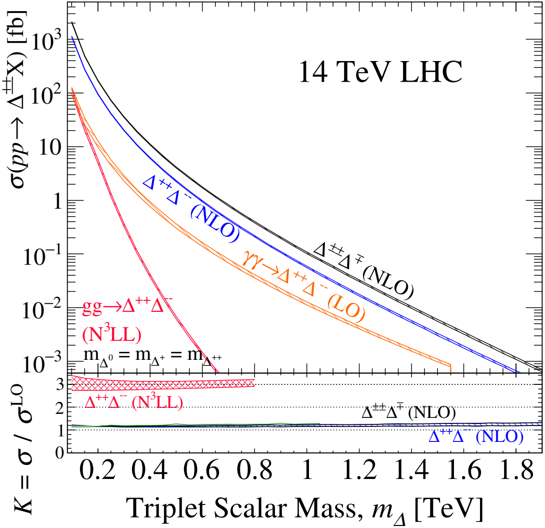
Loop-induced $gg \to \Delta\Delta$ is possible at LO with new UFO - N^3LL a bit more work

For lower masses, gg and $\gamma\gamma$ are competitive, but $\gamma\gamma$ becomes more relevant

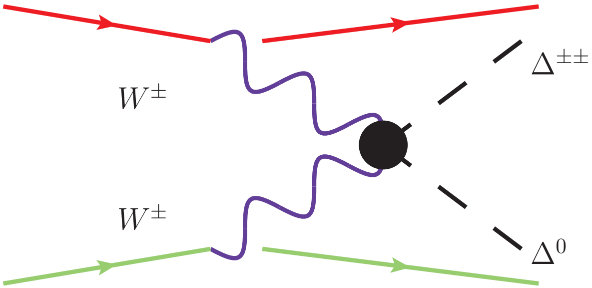
(again, cool)

Caveat: we assume all Δ masses degenerate

$\implies$ scalar-scalar couplings are small (probably not justified)



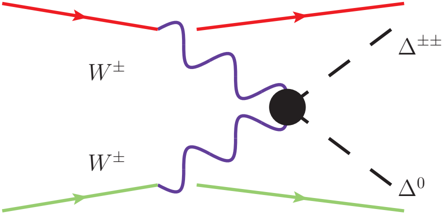
Weak Boson Fusion



$\Delta^{\pm\pm}$ from Vector Boson Scattering

Weak boson fusion is a useful production mechanism of $\Delta^{\pm\pm}$ (See R. Santo's talk)

- Except $W^{\pm}W^{\pm} \to \Delta^{\pm\pm}$ is vev/coupling-suppressed
- Except $VV \to \Delta^{++}\Delta^{--}$ is mass-suppressed



$W^{\pm}W^{\pm} \to \Delta^{\pm\pm}\Delta^{0}$ for $m_{\Delta^0} \ll m_{\Delta^{++}}$ keeps important features

- LNV/LFV dilepton signature with resonant invariant mass
- Difficulty is modeling beyond NLO in QCD (needed for jet veto modeling)

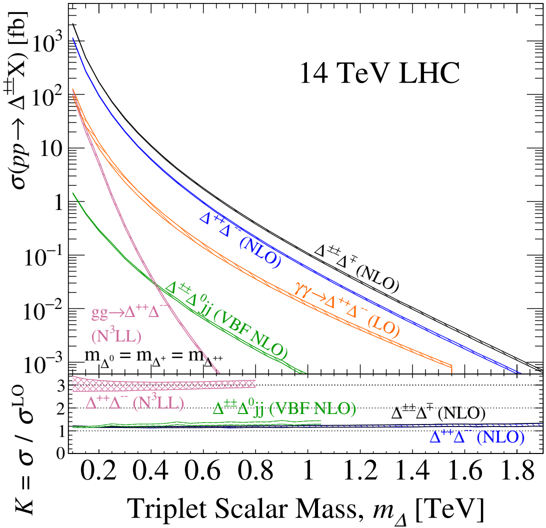
$pp \to \Delta^{\pm\pm}\Delta^0 jj$ + VBS Cuts at NLO is under control!

$\sigma_{\rm DY}/\sigma_{\rm VBF} \sim 10^3$difference hides three things:

- VBF cuts already applied at generator-level

- Scalar-scalar couplings are small since mass degenerate

- Larger mass splittings
$\Longrightarrow$ higher mass reach



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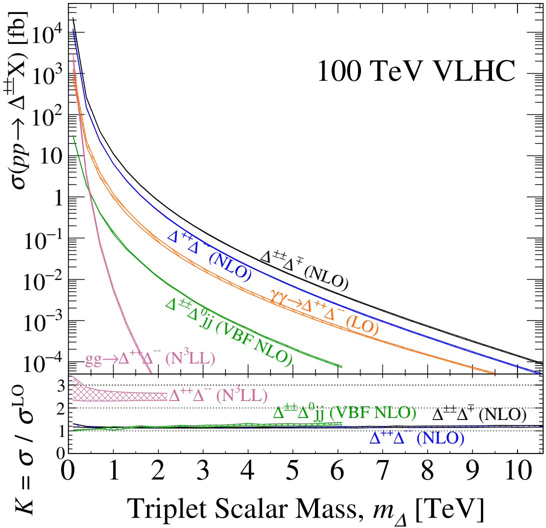
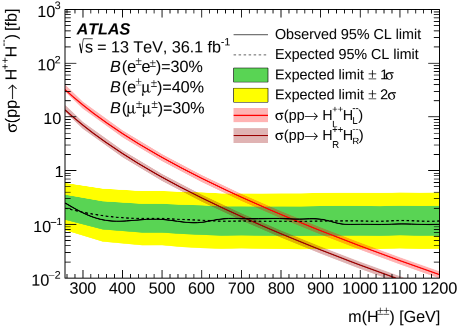
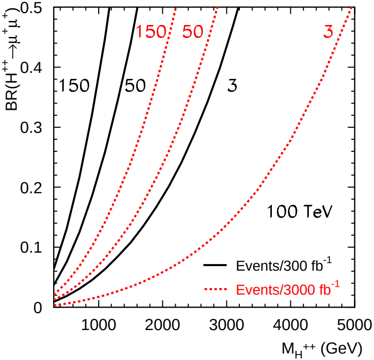


Discovery Potential of Triplet Scalars





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

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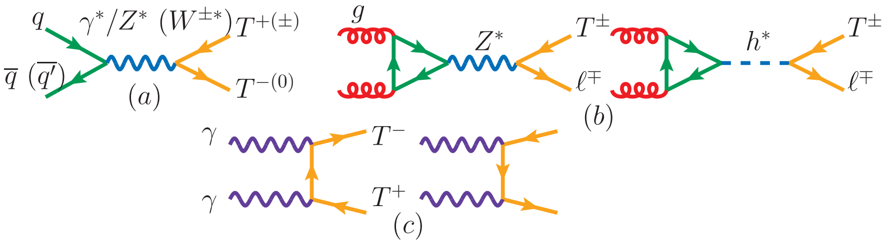
Type III Seesaw



Type III Seesaw combines main features of Types I and II Seesaws:

- **Idea:** add $SU(2)_L$ fermion triplet ($Y = 0$) with mass m_Σ
- Key to reconciling GUTs with proton decay E.g., Bajc, Senjanovic [hep-ph/0612029], ...

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\Sigma \overline{L}\Sigma\Phi_{\text{SM}} = -y_\Sigma \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix} \begin{pmatrix}\Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0\end{pmatrix} \begin{pmatrix}\langle\Phi_{\text{SM}}\rangle + h \\ 0\end{pmatrix}$$

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$$= \underbrace{-y_\Sigma \langle \Phi_{\mathrm{SM}} \rangle}_{=m_D} \overline{\nu_L \Sigma^0} + \ \dots$$

Assuming that m_Σ (Majorana mass) $\gg y_\Sigma \langle \Phi \rangle$ (Dirac mass)

$$m_{\mathrm{light}} \approx y_\Sigma^2 v^2 / 2m_\Sigma, \quad m_{\mathrm{heavy}} \approx -m_\Sigma$$

For $m_{\mathrm{light}} = 0.1$ eV, if $y_\Sigma \sim \mathcal{O}(y_e) \sim 1 \cdot 10^{-6}$, $m_{\mathrm{heavy}} \approx 300$ GeV!

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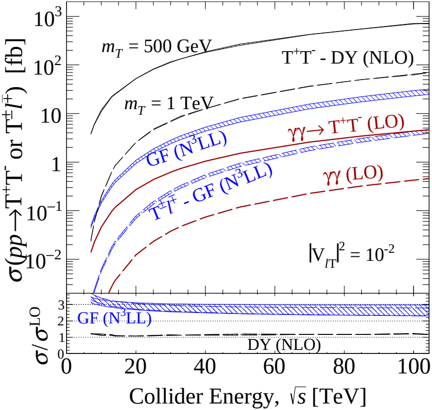
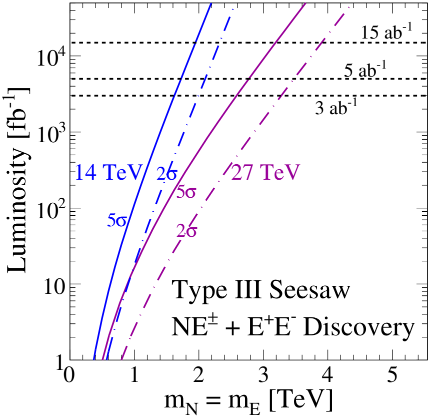
After rotating into the mass basis, mixing-induced cLFV:

$$|T^0\rangle = \cos\theta\ |\Sigma^0\rangle + \sin\theta\ |\nu_\ell\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^0\rangle + \epsilon\ |\nu_\ell\rangle$$
$$|T^\pm\rangle = \cos\phi\ |\Sigma^\pm\rangle + \sin\phi\ |\ell^\pm\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^\pm\rangle + \epsilon\ |\ell^\pm\rangle$$

Collider prediction: heavy charged ($T^{\pm}$) and neutral (T^{0}) leptons:

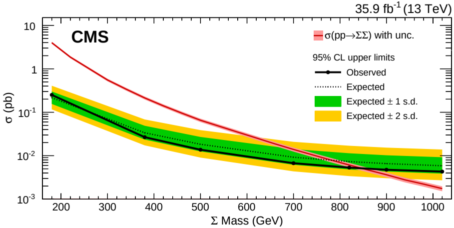
- Production through gauge couplings to W, Z, γ
- Decays to SM leptons through mixing, e.g., $T^{\pm} \to \ell^{\pm}\nu$

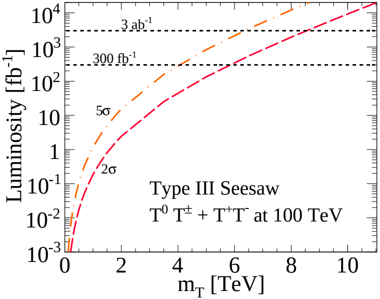




TeV-scale heavy charged and neutral leptons discoverable at LHC

Discovery Potential of Triplet Leptons





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- 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)

Monte Carlo Support for Neutrino Mass Models

MC 4 ν Masses

Improved outlook for LHC tests of LNV and cLFV stems from:

- New channels, e.g., VBF, GF, $W/Z/h/\gamma$ associated production
- New kinematic limits, e.g., off-shell currents, boosted topologies
- Predictions for **both** Dirac and Majorana particles w/ LNV and cLFV
- Qualitatively and quantitatively reliable descriptions of jets

In other words, improved outlook stems from improved MC support!

Now available: robust FeynRules UFOs (inputs to event generators, etc)

- `HeavyN`: Dirac and Majorana N_k feynrules.irmp.ucl.ac.be/wiki/HeavyN
- Simplified LRSM: W_R, Z_R, N_k feynrules.irmp.ucl.ac.be/wiki/EffLRSM
- $W'/Z'/\gamma_D/Z_D$ with arbitrary coup: feynrules.irmp.ucl.ac.be/wiki/WZPrimeAtNLO
- **NEW**Type II Seesaw: $\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0} feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

Summary

Seesaw Mechanisms at Work

By introducing new fermions and writing the most general, gauge-invariant Lagrangian allowed, we simultaneously:

- **Established neutrino masses through Yukawa couplings**
- **Suppressed the effective neutrino masses through mixing**

Seesaws are more frameworks than realistic models

- important to distinguish mechanism (in a model) vs model
- strength and weakness are their ability to be embedded in models

Main Idea of Seesaws is to make $m_\nu \sim \mu$ or $m_\nu \sim \mu_1^2/\mu_2^2$

- does not require sterile fermions, just new scales
- E.g., Type III seesaw, (N)MSSM, Randall-Sundrum, etc.

nonzero neutrino masses are clear evidence of physics beyond the SM

- Lack of guidance from $0\nu\beta\beta$, oscillation data, flavor factories, etc
  $\Longrightarrow$ broad hep-ex/ph/th approaches are needed

1. Colliders are *incredibly complementary* to oscillation facilities:
   - Direct production of Seesaw particles
   - Direct test of LNV/cLFV
   - Test UV realizations of low-scale neutrino EFTs / NSIs
2. e^+e^- and DIS machines explore new depths for light N
   - $\mathcal{L} = 1 - 3$ ab^{-1} at $\sqrt{s} = 240$ GeV sufficient to go beyond LHC
3. pp machines offers many opportunites:
   - New analysis techniques $\Longrightarrow$ new territory for cLFV and LNV at LHC

Lots not covered today, so see the review [1711.02180]

- Be encouraged! More data soon, so be prepared for a discovery!

thank you for your attention! :)