Introduction to Neutrino BSM

MadGraph School 2019
Institute of Mathematical Sciences, Chennai

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Good Morning!

Thank you for the invitation and thank you for being here

Most important rule: This is an informal lecture, so ask questions!

You are encouraged to interrupt and ask questions

Apologies, Disclaimers, Words of Warning

Lectures are "Summer School" style: fast and intense

- There is more material here than time permits (aiming for 3/4 of slides)
- Not everything will be covered (slides kept for completeness)
- Not an historical talk

Lectures include modern topics and research

- While known by the community, much material is not yet in textbooks

Central goal is to fill in gaps between coursework and research

- I never saw some of the following ever in any lecture

(informal survey of lecturers shows the same)

- Again, questions are welcomed! :)

(and sorry for the typos!)

Lecture Plan

Lecture I (Thursday): Intro to Neutrino BSM

- Neutrino Oscillations
- Neutrino Masses and Possible Origins

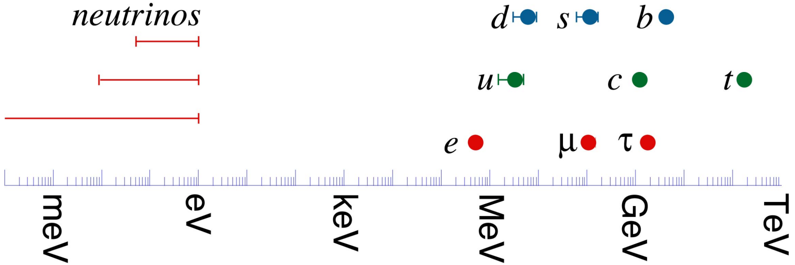
Lecture II (Friday): Neutrino Physics at the LHC

- Building a Collider Analysis: Left-Right Symmetric Model Case Study
- Monte Carlo Tool Chain

Lunch break at 1:00ish

Big Picture (1 slide)

Big Picture



Unambiguous expt evidence that neutrino have nonzero masses

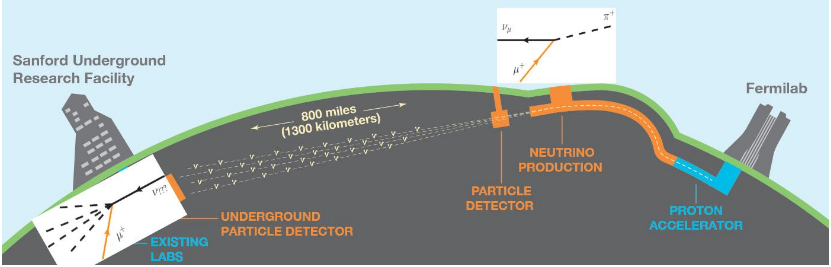
- This is contrary to the Standard Model (SM) of particle physics
- Under general arguments, implies new particles exist (more later)

Investigating $m_\nu \neq 0$ is a very active research topic

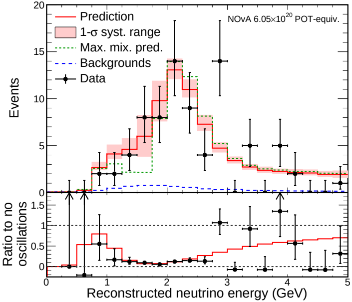
- InSpires: `find hep-ph (hep-ex) and ti neutrino and date > 2014` $\sim$ 2.6k (1.1k) hits

Collider and oscillation facilities provide complementary probes of ν physics

ν **Oscillations**



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



Deficit/disappearance of expected ν_μ (+apperance of ν_e/ν_τ) now interpreted as $\nu_{\ell_1} \to \nu_{\text{mass}} \to \nu_{\ell_2}$ neutrino flavor **transitions/oscillations**

[E.g. NOνA ν_μ disapp., 1701.05891]

Question: How does one describe the data?

The Massive ν Hypothesis

Consider left-handed (LH), $SU(2)_L$ lepton doublets (**gauge eigenbasis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The SM $W^{\pm}$ boson coupling to **leptons** in the **flavor eigenbasis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{s}} W_\mu^+ \sum_{l=1}^{3} \left[\overline{\nu_{lL}} \gamma^\mu P_L l^-\right] + \text{H.c.}$$

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Supposing $m_{\nu} \neq 0$, we can rotate ν_l and l into the **mass eigenbasis**:

$$\nu_l = \sum_{m=1}^{3} \Omega_{lm} \nu_m \quad \text{and} \quad l = \sum_{\ell=3}^{\tau} \Omega_{l\ell} \ell$$

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This allows us to describe SM $W^\pm$ boson coupling to *massive neutrinos*:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{s}} W_\mu^+ \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} \overline{\nu_m} \underbrace{U_{m\ell}^*}_{U_{m\ell}^* \equiv \sum_l \Omega_{ml}^* \Omega_{l\ell}} \gamma^\mu P_L \ell^- + \text{H.c.}$$

Like the CKM, SM Feynman rules are modified by **PMNS** mixing factor:

$$\Gamma^\mu = \frac{-ig}{\sqrt{2}} \gamma^\mu P_L \rightarrow \tilde{\Gamma}^\mu = \frac{-ig}{\sqrt{2}} U_{m\ell}^* \gamma^\mu P_L$$

2-State Neutrino Mixing

Generically, mixing between **flavor eigenstates** and **mass eigenstates** is given by unitary transformation/rotation

$$\underbrace{\begin{pmatrix}\nu_e \\ \nu_e\end{pmatrix}}_{\text{flavor basis}} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2}\end{pmatrix}}_{\text{mixing}} \underbrace{\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}}_{\text{mass basis}} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix} \begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

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For a **two-state system**, the state vector for ν_ℓ ($\ell = e, \mu$) is simply

$$\underbrace{|\nu_e\rangle}_{\text{flavor basis}} = U_{e1} \underbrace{|\nu_1\rangle}_{\textit{light}} + U_{e2} \underbrace{|\nu_2\rangle}_{\textit{heavy}} = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

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If we treat the spacetime propagation of ν_m ($m = 1, 2$) as a plane wave, then the evolution from $x^\mu = x_a^\mu$ to $x^\mu = x_b^\mu$ is

$$|\nu_\ell(x_b, x_a)\rangle = U_\ell(x_b, x_a)|\nu_\ell\rangle = U_{\ell 1}U_1(x_b, x_a)|\nu_1\rangle + U_{\ell 2}U_2(x_b, x_a)|\nu_2\rangle$$

Evolution through space and time

Assuming $\hat{p}_\nu = \Delta\hat{x}$, the plane wave evolution over $L = |\vec{x}_b - \vec{x}_a]|$ is

$$U_m(x_b, x_a) = e^{-ip_m\cdot(x_b - x_a)} = e^{-i(E_m\Delta t_m - \vec{p}_m\cdot(\vec{x}_b - \vec{x}_a))} \approx e^{-i(E_m\Delta t_m - |\vec{p}_m|L_m)}$$

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Now, working in the ultra relativistic limit, where $E_m + |\vec{p}_m| \approx 2E_m$,

$$(E_m\Delta t_m - |\vec{p}_m|L) \approx (E_m - |\vec{p}_m|)\,L = \left(\frac{E_m^2 - |\vec{p}_m|^2}{E_m + |\vec{p}_m|}\right) L \approx \left(\frac{m_m^2}{2E_m}\right) L$$

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Since $m_2, m_1 \ll E_1, E_2$, the E_m can be approximated as the same:

$$|\nu_e(E, L)\rangle = U_{e1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{e2} e^{-im_2^2 L/2E} |\nu_2\rangle$$

$$|\nu_\mu(E, L)\rangle = U_{\mu 1} e^{-im_1^2 L/2E} |\nu_1\rangle + U_{\mu 2} e^{-im_2^2 L/2E} |\nu_2\rangle$$

We are now ready to compute oscillation transtions!

Neutrino Oscillation Transitions

To reproduce the ν_μ deficit, consider the $\nu_\mu \to \nu_\mu$ *transition amplitude*:

$$\mathcal{M}(\nu_\mu \to \nu_\mu) \equiv \langle \nu_\mu | \nu_\mu(E, L) \rangle$$

$$= \underbrace{\left[\langle \nu_1 | U^*_{\mu 1} + \langle \nu_2 | U^*_{\mu 2}\right]}_{=\langle \nu_\mu |} \times \underbrace{\left[U_{\mu 1} e^{-i m_1^2 L/2E} |\nu_1\rangle + U_{\mu 2} e^{-i m_2^2 L/2E} |\nu_2\rangle\right]}_{=|\nu_\mu(E,L)\rangle}$$

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Since $|\nu_m\rangle$ are mass **eigenstates**, $\langle \nu_{m'} | \nu_m \rangle = \delta_{m'm}$. This implies

$$\mathcal{M}(\nu_\mu \to \nu_\mu) = e^{-i m_1^2 L/2E} |U_{\mu 1}|^2 \langle \nu_1 | \nu_1 \rangle + e^{-i m_2^2 L/2E} |U_{\mu 2}|^2 \langle \nu_2 | \nu_2 \rangle$$

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The $\nu_\mu \to \nu_\mu$ *transition probability* is

$$\Pr(\nu_\mu \to \nu_\mu) = |\mathcal{M}(\nu_\mu \to \nu_\mu)|^2 = |U_{\mu 1}|^4 + |U_{\mu 2}|^4$$

$$+ e^{-i \Delta m_{21}^2 L/2E} |U_{\mu 1}|^2 |U_{\mu 2}|^2 + e^{+i \Delta m_{21}^2 L/2E} |U_{\mu 1}|^2 |U_{\mu 2}|^2$$

where we defined $\Delta m_{21}^2 \equiv (m_2^2 - m_1^2)$

Some Quick Algebra

Recalling that $U_{e1} = U_{\mu 2} = \cos\theta$ and $U_{e2} = -U_{\mu 1} = \sin\theta$,

$$\Pr(\nu_\mu \to \nu_\mu) = \sin^4\theta + \cos^4\theta + 2\sin^2\theta\cos^2\theta\cos\left[\frac{\Delta m_{21}^2 L}{2E}\right]$$

$$= 1 - \sin^2(2\theta)\sin^2\left[\frac{\Delta m_{21}^2 L}{4E}\right] \quad \overset{\theta\ll 1}{\approx} \quad = 1 - 4\theta^2\left[\frac{\Delta m_{21}^2 L}{4E}\right]^2$$

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Lots to unpack:

$$\Pr(\nu_\mu \to \nu_\mu) = \underbrace{1}_{\text{unitarity}} - \underbrace{\sin^2(2\theta)}_{\text{minimum of dip}} \quad \underbrace{\sin^2\left[\frac{\Delta m^2_{21} L}{4E}\right]}_{\text{spacing between beats}}$$

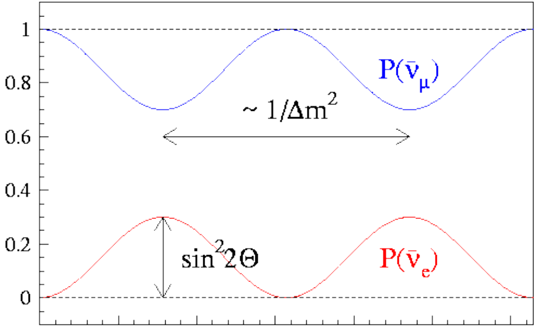
By conservation of probability $1 = \Pr(\nu_\mu \to \nu_\mu) + \Pr(\nu_\mu \to \nu_e)$, so the $\nu_\mu \to \nu_e$ *appearance probability* is

$$\Pr(\nu_\mu \to \nu_e) = 1 \text{ - } \Pr(\nu_\mu \to \nu_\mu) = \sin^2(2\theta)\sin^2\left[\frac{\Delta m^2_{21} L}{4E}\right]$$

Understanding Neutrino Oscillation Plots

$$\Pr(\nu_\mu \to \nu_\mu) = \underbrace{1}_{\text{unitarity}} - \underbrace{\sin^2(2\theta)}_{\text{minimum of dip}} \underbrace{\sin^2\left[\frac{\Delta m^2_{21} L}{4E}\right]}_{\text{spacing between beats}}$$

$$\Pr(\nu_\mu \to \nu_e) = \underbrace{\sin^2(2\theta)}_{\text{maximum of peak}}$$



The succss and the maturity of the ν oscillation paradigm provides us with a new probe of new physics:

- Are there additional neutrinos N? Would manifest as non-unitarity of 3×3 $U_{\ell m}$

- How much CP violation is in the lepton sector?

- What drives the CKM matrix "diagonal" but the PMNS matrix "non-diagonal"?

- Are neutrinos Majorana?

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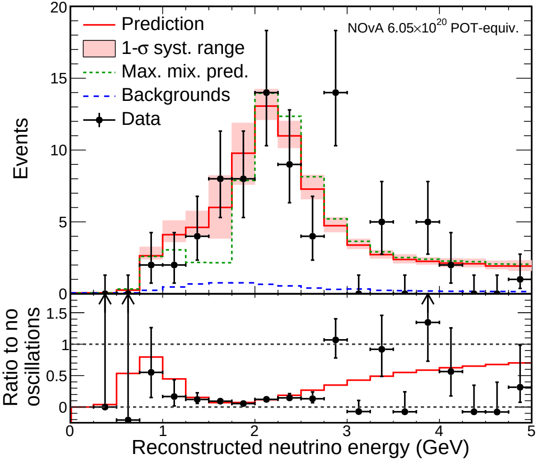
- What is the origin of m_ν?

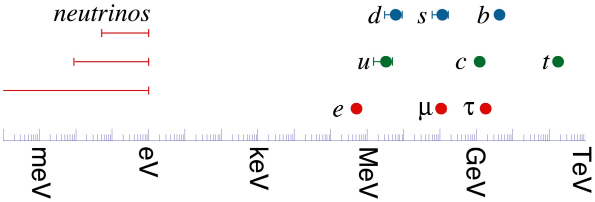


The Massive ν Problem

Okay, so neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV

Is this a problem?

Yes.



Neutrinos Masses and New Physics

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

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right) \begin{pmatrix} \langle\Phi\rangle + h \\ 0 \end{pmatrix} N_R + H.c.$$

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

However, N_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, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu\ \text{masses}}}_{BSM\ physics!} + \ldots$

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]:

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

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

$m_\nu^L = y\langle\Delta\rangle$ or strong dynamics

$m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$

$m_\nu \neq 0$ **+ 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 an $SU(2)_L$ triplet
- Particles must couple to h or L, often inducing LNV/cLFV!

Pathways to Nautrally Small m_ν

Seesaw Mechanisms: Pathways to Naturally Small m_ν

Spinor/gauge algebra + renormalizability restrict ways to build m_ν [Ma'98]

"Type 0": Add SM-singlet N_R with $y_\nu \sim 10^{-12}$ and forbid Majorana mass

- Possible, but tiny y_ν is theoretically unsatisfying

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Type I: Add N_R and keep the Majorana mass term

- $\mathcal{L} \ni -y_\nu \overline{L}\tilde{\Phi} N_R - \frac{m_R}{2}\overline{N_R{}^c} N_R \implies m_\nu \propto m_D^2/m_R, \quad m_D = y_\nu \langle \Phi \rangle$

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Type II: Add scalar $SU(2)_L$ triplet ($\Delta^{0,\pm,\pm\pm}$) - **No N_R required**

- $\mathcal{L} \ni y_\Delta \overline{L}(i\sigma_2)\Delta L^c \implies m_\nu \propto y_\Delta \langle \Delta \rangle \overline{\nu^c}\nu, \quad \langle \Delta \rangle <$ few GeV

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Type III: Add fermion $SU(2)_L$ triplet ($T^{0,\pm}$)

- $\mathcal{L} \ni y_T \overline{L} T^a \sigma^a (i\sigma^2)\Phi + \frac{m_T}{2}\overline{T^{0c}} T^0 \implies m_\nu \propto m_D^2/m_T$

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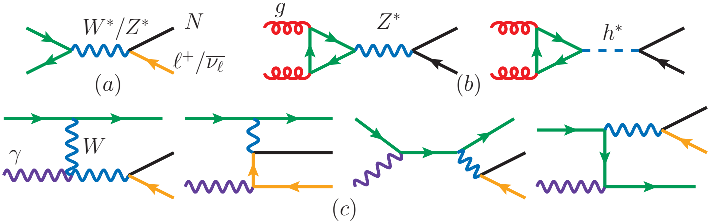
Less Minimal Models: Hybrid, Inverse, Radiative, ..., all with rich pheno

Type I Seesaw



Canonical Type I Seesaw Mechanism

... extends the Standard Model (**SM**) field content with N_R, and supposes the existence of Dirac and RH Majorana masses:

$$\mathcal{L}_{\text{Type I}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{N\ Kin.} - \underbrace{y_\nu \overline{L}\tilde{\Phi} N_R + H.c.}_{\text{Dirac mass}} - \underbrace{\mu_R \overline{N_R^c} N_R}_{\text{Majorana mass}}$$

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Combining the mass terms makes manifest neutrino mass-mixing

$$\mathcal{L}_{D+M} = -\frac{1}{2}\overline{\tilde{N}}\tilde{M}\tilde{N} = \begin{pmatrix} \overline{\nu_L} & \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

Canonical Type I Seesaw Mechanism

... extends the Standard Model (**SM**) field content with N_R, and supposes the existence of Dirac and RH Majorana masses:

$$\mathcal{L}_{\text{Type I}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{N\ Kin.} - \underbrace{y_\nu \overline{L}\tilde{\Phi} N_R + H.c.}_{\text{Dirac mass}} - \underbrace{\mu_R \overline{N_R^c} N_R}_{\text{Majorana mass}}$$

Combining the mass terms makes manifest neutrino mass-mixing

$$\mathcal{L}_{D+M} = -\frac{1}{2}\overline{\tilde{N}}\tilde{M}\tilde{N} = \begin{pmatrix} \overline{\nu_L} & \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

This gives the following mass eigenvalues when $\mu_R \gg m_D$:

$$m_1 \approx -m_D |V|^2 = -m_D \frac{m_D}{\mu_R}, \quad m_2 \approx \mu_R$$

Realistic ***models*** have large and messy mass matrix $\tilde{M}$, where

$$\tilde{m}_\nu = -\tilde{M}_D \tilde{M}_R^{-1} \tilde{M}_D^T \text{ with active-sterile mixing } \tilde{V} = \tilde{M}_D \tilde{M}_R^{-1}$$

Seesaw Mechanisms at Work

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

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

However, Seesaws are more frameworks than models. Their strength and weakness are their ability to be readily embedded in specific models.

- Going beyond fermionic $SU(3)_c \otimes U(1)_{EM}$ singlets makes physics and life more entertaining due to additional mixing

E.g., Type II, III Seesaws, (N)MSSM, Randall-Sundrum, GUTs

Agnostic Approach to Heavy N Mixing

In pure Type I scenarios, tiny m_ν obtained in two ways:

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

   Leads to generic decoupling of N and LNV from colliders

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

   Known also in literature as Inverse Seesaw, Linear Seesaw, Protective Symmetries, etc.

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Apriori, no preference for either without additional theory prejudice:

- **LNC Option**: Low-scale Type I + if ν approx. massless on expt scale, i.e., $\tilde{m}_\nu^2/Q^2 \approx 0 \implies$ approximate L conservation w/ Pascoli, et al, [1812.08750]

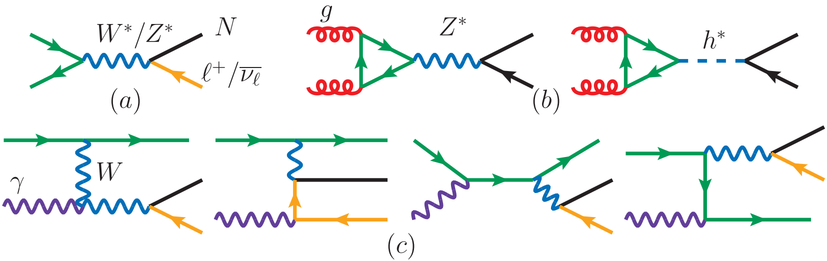
  See also, Pilaftsis [hep-ph/9901206], Kersten and Smirnov [0705.3221], Pascoli, et al, [1712.07611]

- **LNV Options**: Collider LNV via $N_i \implies$ *more new particles!*

  RR [1703.04669]

Heavy Neutrino Production At Hadron Colliders

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



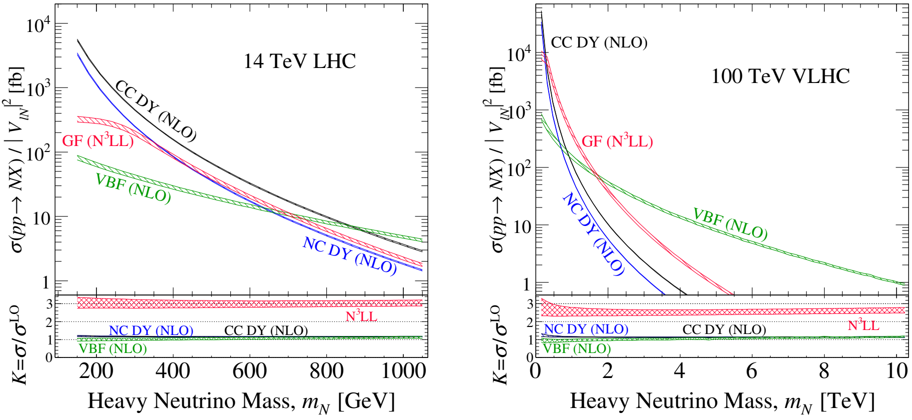
In fact, a resurgence of calculations in recent years[1]

- Clarity needed on understanding $m_N, \sqrt{s}$ dependence

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

[1] 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]

Across different colliders, wild interplay of PDF and matrix elements



w/ Pascoli, RR, et al, [1812.08750]

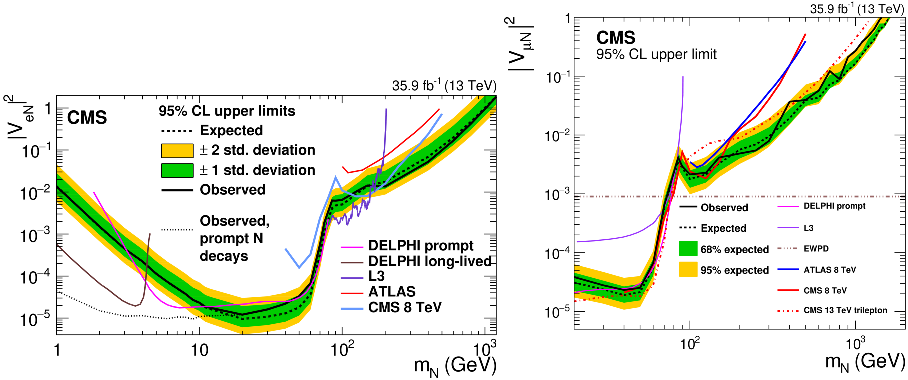
Plotted: Flavor-independent heavy N production rate $(\sigma/|V|^2)$ vs mass

- **GF** and **VBF** dominate at larger $\sqrt{s}$, m_N
- 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 $\sqrt{N_{Obs.}} > 3\sigma$

Experimental Tests on Intermediate- and High-Mass N

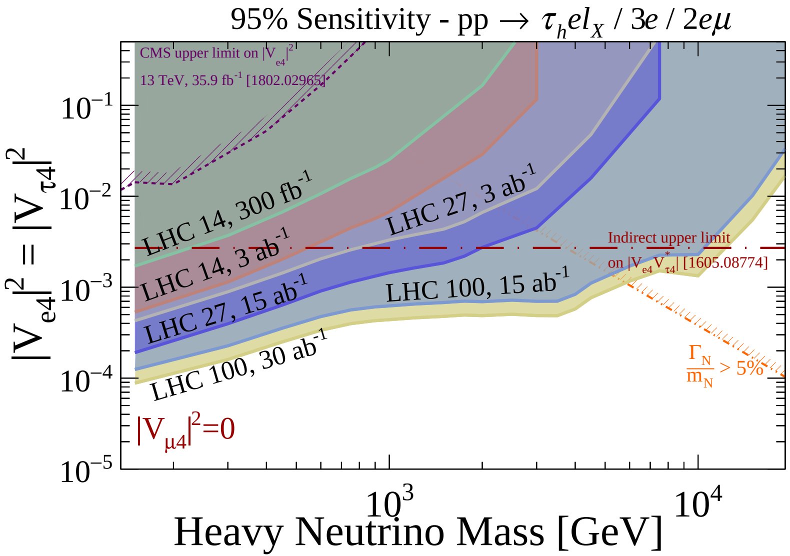
Joint push by hep-ex and hep-ph/th have broken new ground!

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)

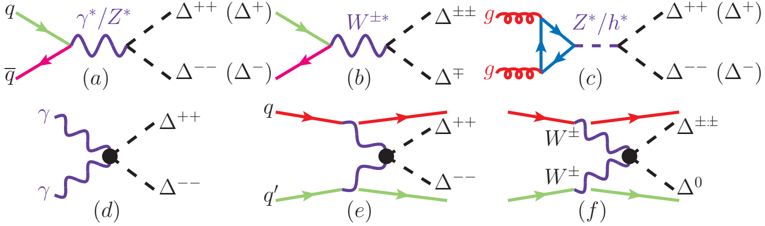
- (L) Search for $pp \to N\ell \to 3\ell + X$ [1802.02965]
- (R) Search for $pp \to N\ell \to \ell^\pm\ell^\pm + nj + X$ [1806.10905]



With $\mathcal{L} = 300 - 3000$ fb^{-1} of data, LHC can compete with dedicated experiments testing charged lepton flavor violation

Pascoli, RR, et al [1812.08750]

Type II Seesaw



Type II Seesaw Mechanism

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

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

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

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

This includes a left-handed Majorana mass of neutrinos!

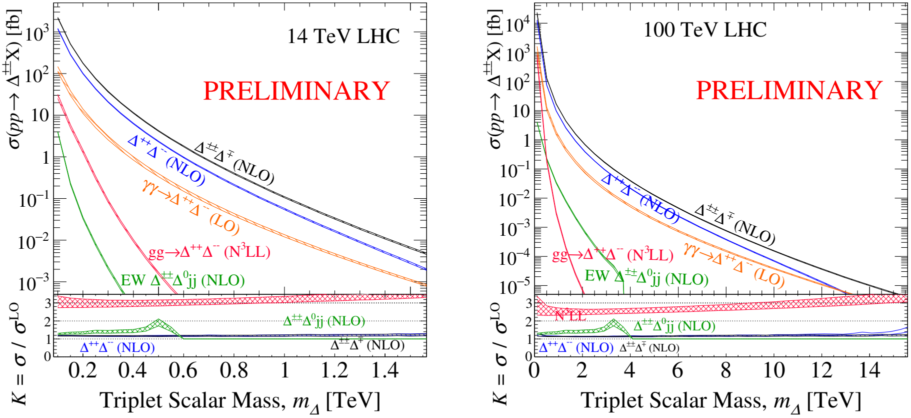
$$\mathcal{L} = \frac{y_{\Delta}^{ij}}{\sqrt{2}}\overline{L^{c}}\hat{\Delta}L = \frac{y_{\Delta}^{ij}}{\sqrt{2}}\begin{pmatrix}\overline{\nu^{jc}} & \overline{\ell^{jc}}\end{pmatrix}\begin{pmatrix}0 & 0\\ v_{\Delta} & 0\end{pmatrix}\begin{pmatrix}\nu^{i}\\ \ell^{i}\end{pmatrix}$$

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

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

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

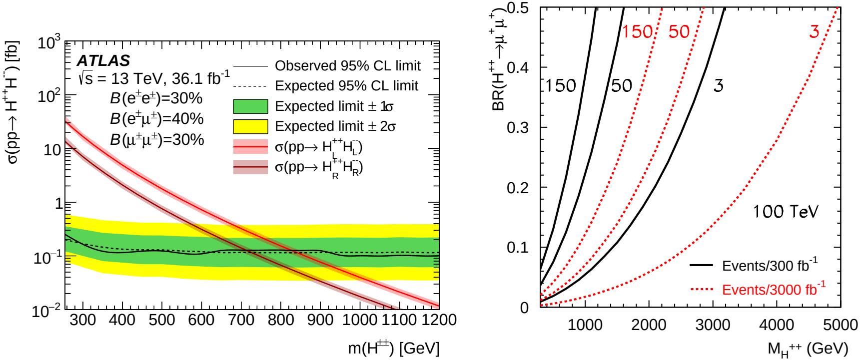
- Couples to W, Z, γ through gauge couplings



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

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

Discovery Potential of Triplet Scalars

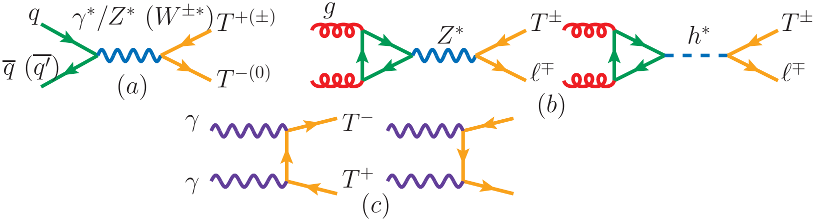


LHC: $m_{\Delta^{\pm\pm}} \lesssim 700 - 900$ GeV excluded with $\mathcal{L} \approx 36$ fb^{-1}

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

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

Type III Seesaw



Type III Seesaw Mechanism

Introduce SU(2)$_L$ **fermion** triplet (zero hypercharge) with mass m_T

$$\Sigma = \begin{pmatrix} \Sigma_L^3 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma^3 \end{pmatrix},$$

$$\mathcal{L}_T = \frac{1}{2}\mathrm{Tr}\left[\overline{\Sigma_L} i \not{D} \Sigma_L\right] - \left(\frac{m_T}{2}\overline{\Sigma_L^3}\Sigma_R^{3c} + m_T \overline{\Sigma_L^-}\Sigma_R^{+c} + \mathrm{H.c.}\right)$$

and couple to SM leptons via Higgs Yukawa couplings

$$\mathcal{L}_Y = y_T \overline{L^c}\ \Sigma_L (i\sigma^2)\Phi \to \frac{y_T}{\sqrt{2}}(v+h)\overline{\nu_R^c}\Sigma_L^3 + y_T(v+h)\overline{e_R}\Sigma_L^-$$

The resulting mass matrix for neutral fermions is

$$\mathcal{L} \ni \frac{1}{2}\overline{\mathcal{N}^c}\mathcal{M}\mathcal{N} = \frac{1}{2}\begin{pmatrix} \overline{\nu_L^c} & \overline{\Sigma_L^{3c}} \end{pmatrix} \begin{pmatrix} 0 & y_\Sigma v/\sqrt{2} \\ y_\Sigma v/\sqrt{2} & m_T \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_L^3 \end{pmatrix}$$

Type III Interaction Theory

Assuming that m_T (**Majorana** mass) $\gg y_T \langle \Phi \rangle$ (**Dirac** mass)

$$m_{\text{light}} \approx \frac{y_\Sigma^2 v^2}{2m_T}, \quad m_{\text{heavy}} \approx -m_T$$

For $m_{\text{light}} = 0.1$ eV, if $y_T \sim \mathcal{O}(y_e) \sim 1 \cdot 10^{-6}$, $m_{\text{heavy}} \approx 300$ GeV!
For today, denote mixing between gauge and mass states by Y and ϵ:

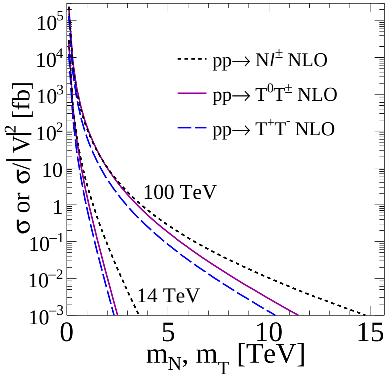
$$\tilde{T}^\pm = Y \ T^\pm + \epsilon \ \ell^\pm, \quad \tilde{T}^0 = Y \ T^0 + \epsilon \ \nu_m, \quad |Y| \sim \mathcal{O}(1), \quad |\epsilon| \ll 1.$$

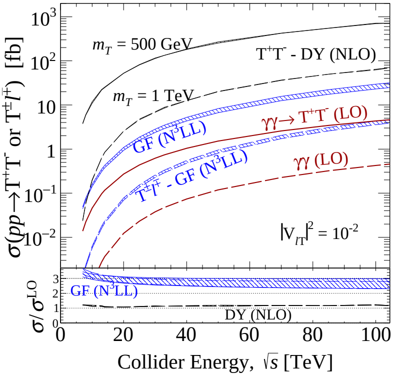
In the mass basis (after mixing)

$$\mathcal{L}_T^{\text{Mass Basis}} \ni -\overline{T^-} \left(eY\gamma^\mu A_\mu + g\cos\theta_W Y\gamma^\mu Z_\mu \right) T^- \\ - gY\overline{T^-}\gamma^\mu W_\mu^- T^0 - gY\overline{T^0}\gamma^\mu W_\mu^+ T^-$$

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

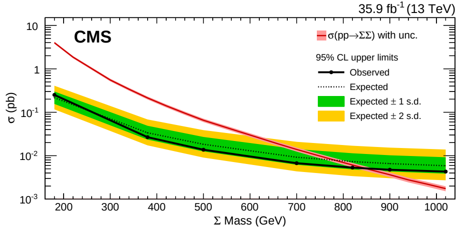
- Couples to W, Z, γ through gauge couplings
- Generates light ν_m masses similar to Type I

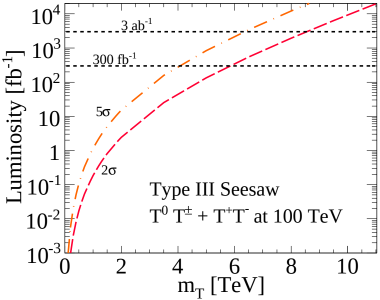




- Production at 100 TeV ***HUGE*** compared to LHC!
- Clear that $\sigma_{DY}(T^+T^-) \gg \sigma_{\gamma\gamma}(T^+T^-)$
  - $\sigma_{GF}(T^{\pm}\ell^{\mp})$ competitive if mixing sizable!

Discovery Potential of Triplet Leptons





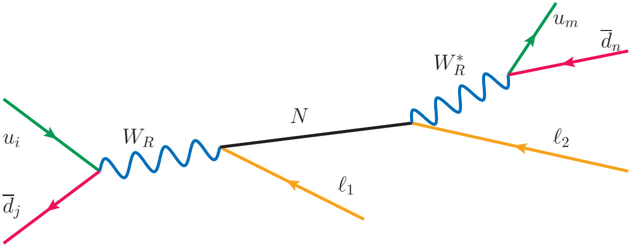
LHC: $m_T \lesssim 800$ GeV excluded with $\mathcal{L} \approx 36$ fb^{-1}

- 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)

Lecture II: Left-Right Symmetric Model



Thank you for your time.