Heavy Neutrinos: Prospects at Colliders for Experiment and Theory

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[1] IPPP → CP3, Universite Catholique de Louvain, Belgium (October '18)

Disclaimers

Finite time constraints $\implies$ will not cover all neutrino mass models

- Many omissions :(
- For a comprehensive look at collider tests of neutrino mass models, see the review! Y. Cai, T. Han, T. Li, **RR**, [arXiv:1711.02180]

Language: "prospects for ***heavy neutrinos***" (mass eigenstate)

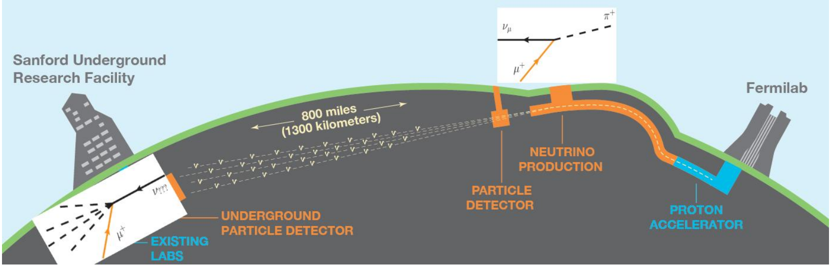
- Not "prospects for right-handed neutrinos" (chiral eigenstate).

  2015 : ν mass eigenstates $\neq$ ν chiral eigenstates
- Less often "sterile" since N_R may be charged under new gauge group

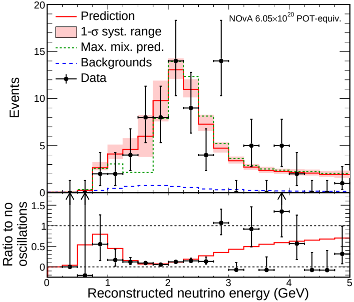
Humble request: remember that RH neutrinos are not the only explanation for tiny ν masses nor are they necessary (e.g., Type II Seesaw)

- Realistic models with only singlet fermions (Type I-like) introduce ***many*** parameters and/or hierarchies

Motivation for new physics from ν physics



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)



Deficit/disappearance of expected ν_μ (+apperance of ν_e/ν_τ) interpreted as $\nu_{\ell_1} \to \nu_{\text{mass}} \to \nu_{\ell_2}$ transitions/oscillations [E.g. NOνA ν_μ disapp., 1701.05891]

$\Longrightarrow$ ν have mass!

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*** elementary fermions, need N_R

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

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

However, ${N_R}^i$ do not exist in the SM, implying $m_D = 0$

Significance of Neutrino Oscillations:

1. Neutrino masses $\implies \mathcal{L}_{\text{Universe}} \neq \mathcal{L}_{\text{SM}} \quad (+\mathcal{L}_{\text{gravity}})$
2. Instead, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu\ \text{masses}}}_{BSM\ physics!} + \dots$

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]:

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

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

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

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

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

- No guarantee that new particles are N_R, e.g. Type II Seesaw
- New particles might be charged under new gauge symmetries, e.g., (N_R, e_R) form $SU(2)_R$ doublet or Δ_L is scalar $SU(2)_L$ triplet

Collider Connection to Neutrino Mass Models

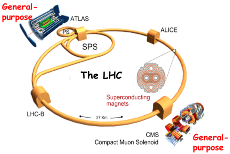
Neutrino mass models (aka Seesaw models) hypothesize new particles of all shapes, spins, charges, and color:

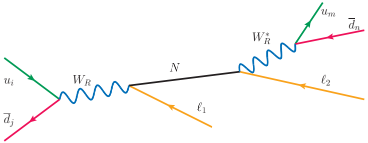
$$N \text{ (Type I)}, \; T^{0,\pm} \text{ (Type III)}, \; Z_{B-L}, \; H_R^{\pm,\pm\pm} \text{ (Type I+II)}, \; \dots$$

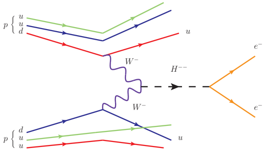
Produced in *ee*/*ep*/*pp* collisions through gauge couplings and mixing:

$$\textbf{DY} : q\overline{q} \rightarrow \gamma^*/Z^* \rightarrow T^+T^- \quad \text{and} \quad q\overline{q'} \rightarrow W_R^\pm \rightarrow N\ell^\pm$$

$$\textbf{VBF} : W^\pm W^\pm \rightarrow H^{\pm\pm} \qquad \textbf{GF} : gg \rightarrow h^*/Z^* \rightarrow N\nu_\ell$$







Identification of Seesaw particles through decays to SM particles

Theory Perspective on

Heavy Neutrinos and Lepton Number Violation at Colliders

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

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

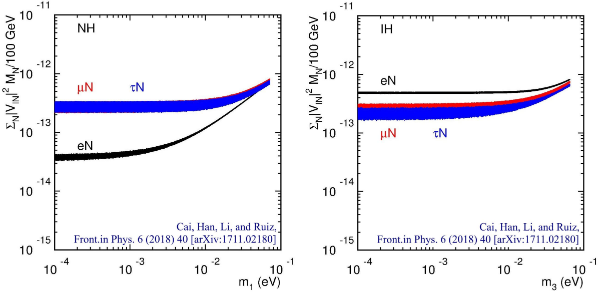
which gives in the following mass eigenvalues when $\mu_R \gg m_D$:

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

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

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

Plugging in measured ν mass splittings and solving for mixing reveals very small $|V_{\ell N}|$ for *three* EW/TeV-scale N



This suggests that N *might decouple from colliders experiments*[2]

- For MeV N, rate okay if can be produced from meson decays
- Many attempts to invoke flavor symmetries to obtain sizable mixing
- Exception[3] when (lots) more N added with ***small*** Majorana mass $\mu_X \ll m_D, \mu_R$, leading to $\tilde{m}_\nu = -\tilde{M}_D^T \tilde{M}_R^{T\,-1} \mu_X \tilde{M}_R^{-1} \tilde{M}_D$

[2] Pilaftsis [hep-ph/9901206] and Kersten & Smirnov [0705.3221]

[3] Known as Inverse and Linear Seesaw Mechanisms, and N is Dirac-like/pseudo-Dirac

Clarity on Lepton Number Violation vs Colliders

Whether or not N_i decouple from collider experiments has been clarified

- Theorem[4]: In SM + arbitrary number of gauge singlet/sterile fermions, $\tilde{m}_\nu = 0 \Leftrightarrow$ lepton number (L) conservation

$\implies$ 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

Hence, observation of N_i+ L violation $\implies$ *even more new particles!*

- Important since there is a concrete example[5] of a realistic Type II Seesaw mimicking the classical Type I collider signature

[4] Moffat, Pascoli, and Weiland [1712.07611]
[5] **RR**, [1703.04669]

Agnostic Approach

In light of this, an EW/TeV-scale heavy neutrino N_i will likely have a complicated mass matrix

$$\underbrace{\begin{pmatrix} \nu_L \\ \dots \\ N_R^c \\ \dots \end{pmatrix}}_{\text{chiral basis}} = \underbrace{\begin{pmatrix} U & V \\ X & Y \end{pmatrix}}_{\text{mass matrix}} \underbrace{\begin{pmatrix} \nu_{m=1} \\ \dots \\ N_{m'=4} \\ \dots \end{pmatrix}}_{\text{mass basis}}$$

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

- This requires modifying SM interactions with the following[6]:

$$\nu_{\ell L} \approx \sum_{m=1}^{3} U_{\ell m} \nu_m + V_{\ell m'=4} N_{m'=4}$$

Note: $U_{\ell m}$ is measured by oscillation experiments; $V_{\ell m'}$ by $0\nu\beta\beta$.

[6] Atre, Han, Pascoli, Zhang [0901.3589]; Han, Lewis, **RR**, Si [1211.6447]

Coupling N_R to SM Particles

Example: **SM** W chiral coupling to **leptons** in **flavor basis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\overline{\nu_{\ell L}} \gamma^\mu P_L \ell^-\right] \quad + \quad H.c.$$

In the **mass basis,** it is

$$\implies \mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\sum_{m=1}^{3} \overline{\nu_m} U_{m\ell}^* + \overline{N^c} V_{N\ell}^*\right] \gamma^\mu P_L \ell^- \quad + \quad H.c.$$

One can also decompose $N_R \approx \sum_m X_{\ell m} \nu_m^c + Y_{\ell m'} N_{m'}$ and consistently expand heavy **Neutrino Effective Field Theory** operators[7], e.g.,

$$\mathcal{O}_V^{(6)} = (\overline{d}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_R N_R)$$

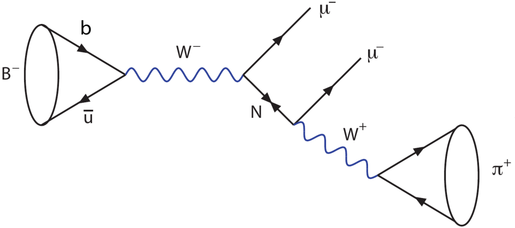
$$= \sum_{m=1}^{3} (\overline{d}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_R X_{em} \nu_m^c) + (\overline{d}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_R Y_{em'} N_{m'})$$

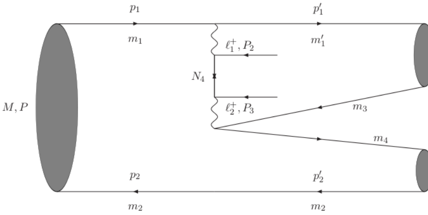
[7]NEFT: Gauge invariant way to parameterize anomalous heavy N couplings to SM. del Aguilar, et al [0806.0876]; + neutrino mixing, **RR** [1703.04669]

Experiment Perspective on Low Mass N

Searches for Low Mass N

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





Production rate of mesons $(\pi^{\pm}, \mathcal{D}, \mathcal{B})$ at colliders is ***big***

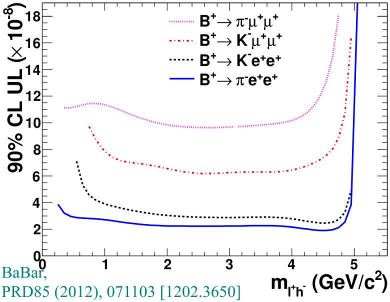
- Sufficient[8] to overcome ***tiny*** mixing for MeV-scale, Majorana N
- Sufficient[9] to probe L-conserving, charged lepton flavor violation

[8] 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

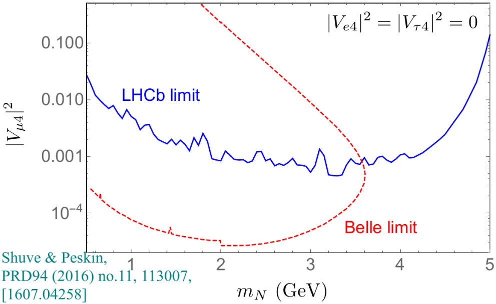
[9] Dedicated LNC+cLFV theses: Weiland [1311.5860] and Marcano [1710.08032]

Searches[11] 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) Equivalent 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!

- Searches for N via LNC-cLFV interactions less sensitive / more difficult[10] due to larger backgrounds

[10] We will come back to this point!

[11] See also talk by Wang Dayong on behalf of BESIII, and NA62 results [1712.00297]

Experiment Perspective on N with Intermediate Masses I:

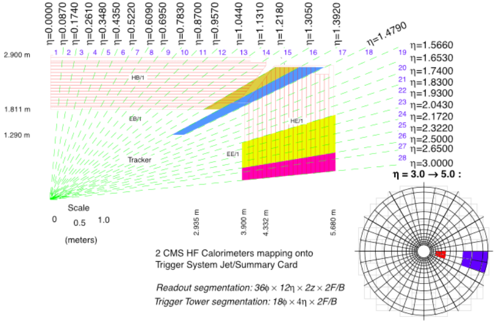
Prompt decays[12]

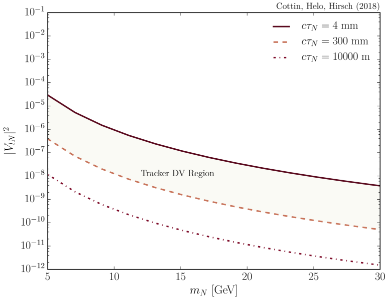
[12] Postponed since new results overlap with high-mass searches

Experiment Perspective on N with Intermediate Masses II:

Non-prompt decays / displaced vertices

Displaced Vertices





Decays of low-mass *N* through SM weak currents can be very suppressed:

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

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

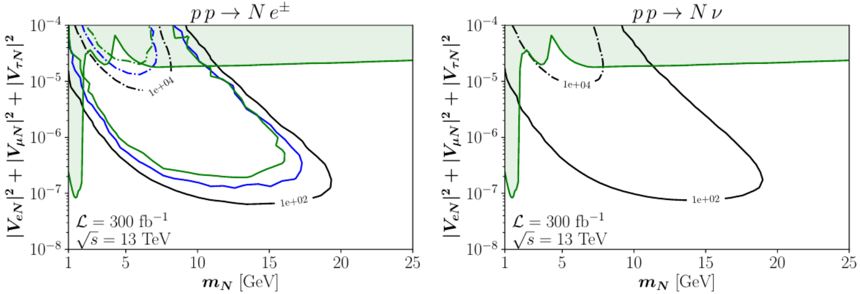
LHC detectors have *finite* detector volume, with radius $< \mathcal{O}(10)$ m

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

Heavy N from Displaced Vertices

Many, studies in the past year (very popular topic)

- Higgs: A. Gago, et al [1505.05880]; W: G. Cottin, et al [1806.05191]; Z: A. Abada, et al [1807.10024]; many others
- Including via non-resonant[13] W_R gauge currents: M. Nemevsek, et al [1801.05813]



Note: Many studies assume zero background; unclear if this is reliable.

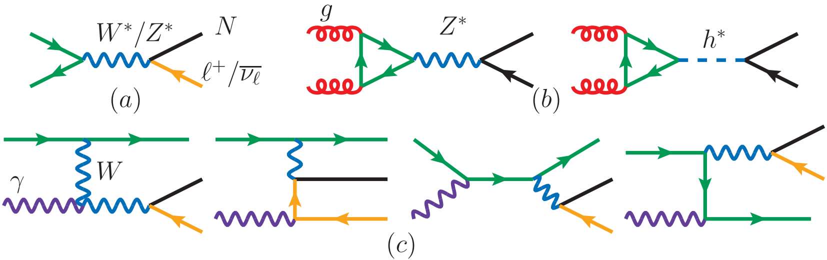
[13] **RR**, [1703.04669]

Experiment Perspective on High Mass N

Brief Theoretical Interlude

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[14]

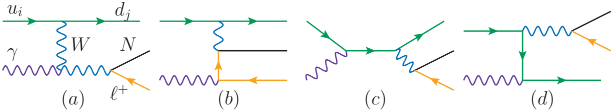
- Clarity needed on (i) $m_N, \sqrt{s}$ dependence and (ii) conflicting claims

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

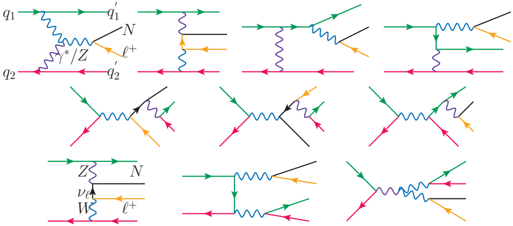
[14] DY@NLO [*1509.06375]; GF [1408.0983, *1602.06957] @NNNLL [*1706.02298]; VBF [1308.2209, *1411.7305, *1602.06957]; DY,VBF Automation@NLO [*1602.06957]; For extensive details, see review: [*1711.02180]; (*) = Pittsburgh and/or IPPP

Missing Piece in N from $W\gamma$ Fusion[15]

Elastic and inelastic (on-shell) initial-state γ (one resolved jet)



as well as DIS (far off-shell) γ (two resolved jets)

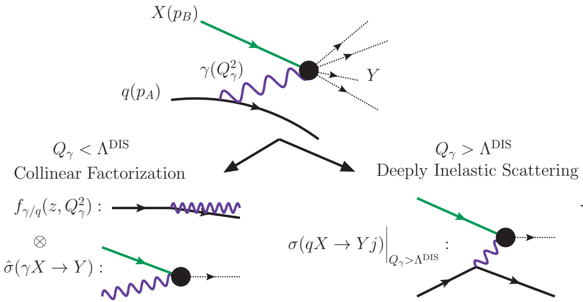


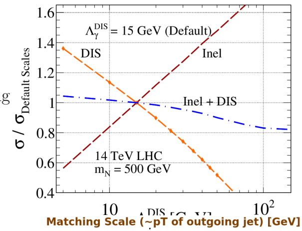
Care needed to avoid double counting phase space.

[15]DIS: Datta, et al [hep-ph/9311257]; Elastic: Dev, et al [1308.2209]; Inelastic+Matching Scheme: **PITT** [1411.7305]; resummation **IPPP** [1602.06957]

Matching[16] t-Channel Photons in $W\gamma \to N\ell^{\pm}$

(a) collinear photon radiation and (b) finite-angle photon radiation





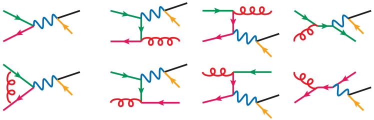
Recognize that the logs appearing in each expression are the same!

$$f_{\gamma/p}(Q_\gamma^2) \sim \log \frac{Q_\gamma^2}{\Lambda^{\rm El\ 2}} \longleftarrow \text{same log} \longrightarrow \frac{d\sigma(qX)}{dQ_\gamma^2} \propto \frac{1}{Q_\gamma^2}$$

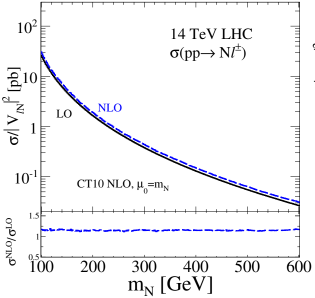
Evolve $f_{\gamma/p}(Q_\gamma)$ in **up to** and integrate (b) **from** same scale Λ^{DIS}

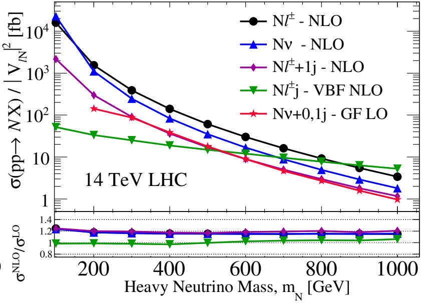
[16] **NEW**: γ PDF normalization+resummation using LUXqed+DGLAP

Motivation for more precise predictions also due to strange (but well-cited) claims of large "quark-gluon fusion enhancement"



So we did the first NLO(+PS) calculations (and published our libraries[17]!)





[17] http://feynrules.irmp.ucl.ac.be/wiki/HeavyN

[18] **RR** [1509.06375]; Degrande, Mattelaer, **RR**, Turner [1602.06957]

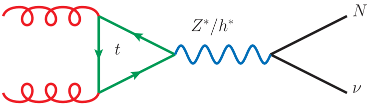
Heavy N Production from Loops[19]

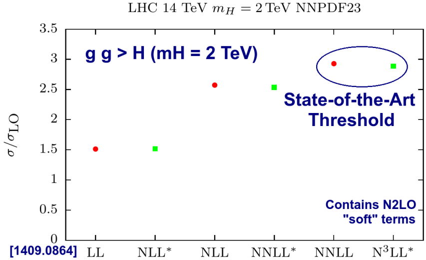
Motivation also because we were curious!

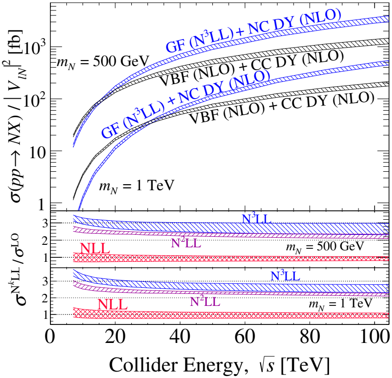
- $gg \to H^0,\ A^0$: QCD corrections are *large*

Are they as large as for $gg \to N\nu$?

- *YES!* For $\sqrt{s} \gtrsim 20 - 30$ TeV, GF > DY

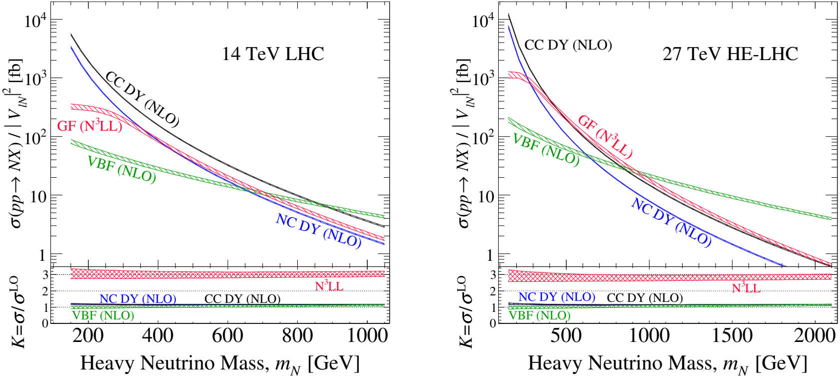






[19] Willenbrock, Dicus ('85); Dicus, Roy ('91); Hessler, et al [1408.0983]; Degrande, Mattelaer, **RR**, Turner [1602.06957]; **RR**, Spannowsky, Waite [1706.02298]

Across different colliders, wild interplay of PDF and matrix elements[20]



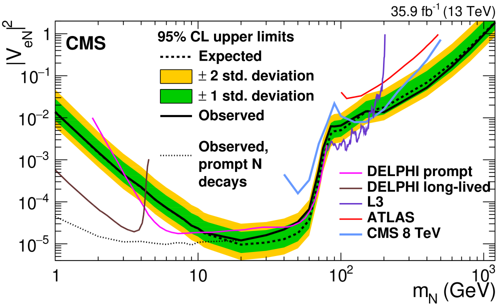
Plotted: Model-independent heavy N production rate $(\sigma/|V|^2)$ vs mass

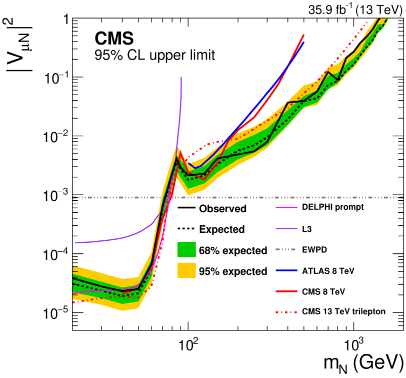
- For $\sqrt{s} \gtrsim 25-27$ TeV **GF** greater than **DY** due to *gg* luminosity
- For $m_N \gtrsim 1-2$ TeV, **VBF** dominant due to large Yukawa couplings

[20] Fully exclusive up to NLO+PS available with `HeavyN` libraries + MG5aMC@NLO, [1602.06957, http://feynrules.irmp.ucl.ac.be/wiki/HeavyN]

Experiment Perspective on High Mass N[21]

All this is now standard for LHC experiments :)





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

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

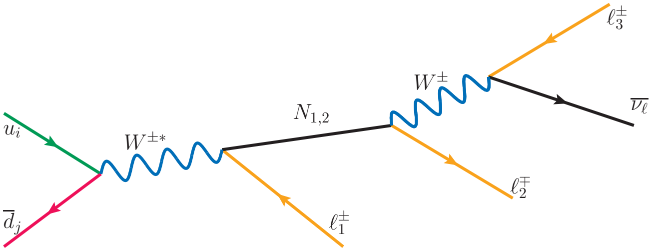
[21] CMS: Trilepton [1802.02965] and Dilepton [1806.10905]

Anything Else?

Anything Else?

:)

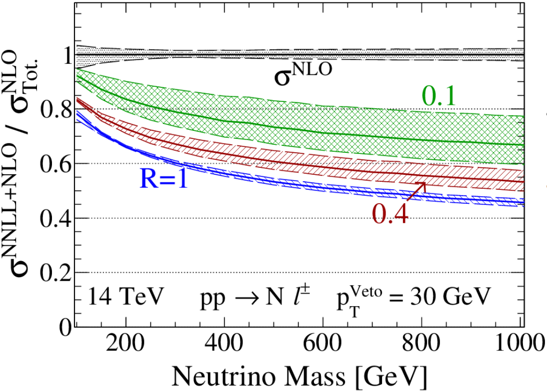
Heavy Neutrinos and Jet Vetoes[22]



[22] Pascoli, RR, Weiland, PLB (just accepted!) [1805.09335]

For BSM Signal Efficiencies and Uncertainties are Poor [23]

For Drell-Yan and other color-singlet processes,
more/harder QCD radiation (jets!) for systems with larger masses



Prob. for signal to survive veto:

$$\varepsilon = \frac{\sigma^{\rm NLO+NNLL}(p_T^j < p_T^{\rm Veto})}{\sigma^{\rm NLO}_{\rm Tot.}}$$

$\varepsilon \to 0$ as $(p_T^{\rm Veto}/m_N) \to 0$

Large uncertainty despite high (NLO+NNLL!) precision
(R = jet radius parameter)

Paradox: Want to relax $p_T^{\rm Veto}$ for increasing m_N but background jumps!

[23] Eg., Sleptons: F. Tackmann, et al [1603.03052]; W': B. Fuks, **RR** [1701.05263]

Heavy Neutrinos and *Dynamical* Jet Vetoes

A Thought:[24] charged leptons in a signal event are typically more energetic than in a QCD background event

- For $pp \to N\ell \to 3\ell X$ event, $p_T^\ell \propto m_N \implies$ increases for larger m_N

How about setting $p_T^{\rm Veto}$ on an event-by-event basis to the p_T of the leading charged lepton in each event?

[24] Disclosure: discovered basis of idea in an unrelated CMS paper on $WW + 0j$

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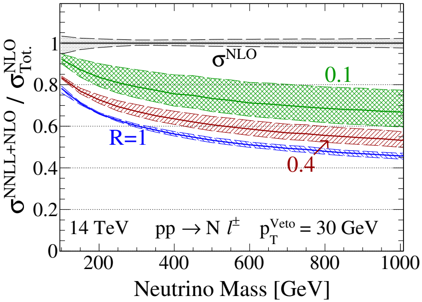

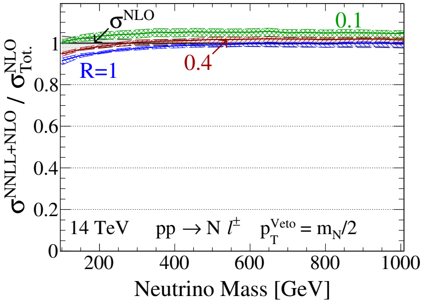

QCD uncertainties ***shrink*** since 2-scale problem converted into 1-scale

- less precise predictions, e.g., LL/parton shower, now more reliable

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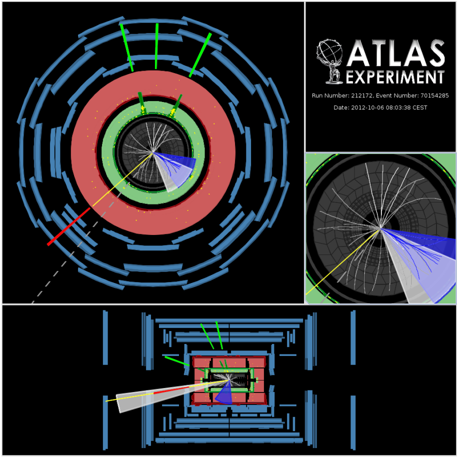
Top Quark Background vs Dynamical Jet Vetoes



$pp \to t\bar{t}Z \to 1\mu + 3e + 2j_b + \not{E}_T$ candidate event [1509.05276]

Classic kinematics:

- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

Typically,

- $p_T^{e_1} \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ GeV
- $p_T^{b_1} \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 60$ GeV

$p_T^{b_1} > p_T^{\rm Veto} = p_T^{\ell_1} \implies$ evt rejected!

Setting $p_T^{\rm Veto}$ on event-by-event basis to $p_T^{\ell_1}$ can eliminate top quark and "fake lepton" background ***without*** flavor-tagging jets!

Results[25]

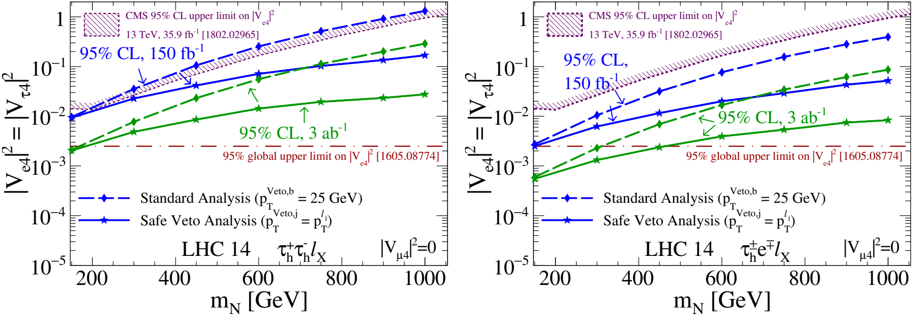
[25] with Silvia Pascoli and Cedric Weiland [1805.09335]

Benchmark flavor mixing scenario:

$$|V_{e4}| = |V_{\tau 4}| \neq 0 \quad \text{and} \quad |V_{\mu 4}| = 0$$

Two complementary signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \tau^+\tau^-\ell_X$+MET and **Signal II:** $pp \to \tau^\pm e^\mp \ell_X$+MET



- Dash = standard search with b-jet veto (13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

Improved sensitivity up to $10 - 11\times$ with $\mathcal{L} = 3$ ab^{-1}

Summary

Heavy neutrinos remain one of the best (but not the only!) explanations for tiny neutrino masses

- Theory advances, e.g., clarity on conditions for L violation at colliders
- Pheno advances, e.g., new public software / qualitatively new analyses
- Expt advances, e.g., more people and more data!
- Lots not covered today; see the review: [1711.02180]

Remember: "*The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work*" [press.cern]

- High-Luminosity LHC and Belle II goals: 3-5 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

Thank you.