Heavy Neutrinos: From Beam Dumps to Colliders

ESPP Neutrino Town Hall Meeting - CERN

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24 October 2018

Disclaimers and Source Material

Finite time constraints $\implies$ many omissions

1. Review on Nu Mass Models at Colliders [arXiv:1711.02180], Y. Cai, T. Han, T. Li, **RR**
2. HL/HE-LHC Yellow Book Chapter on Nu Mass Modes, T. Han, T. Li, X. Marcano, S. Pascoli, **RR**, C. Weiland
3. Other community documents, both "*public*" and "*in preparation*"

Language / Breakdown of Talk

- Beam dumps and colliders cover overlapping range of $\sqrt{s}$ and Q^2. (Physics-wise, Energy vs Intensity Frontiers not well-defined.)
  Solution: Talk divided into low-, intermediate-, and high-mass N

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

- Lack of guidance from data and theory $\implies$ broad approach needed
- See, e.g., Lindner's talk (Monday)

Keeping an Open Mind on Origin of Neutrinos Masses

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

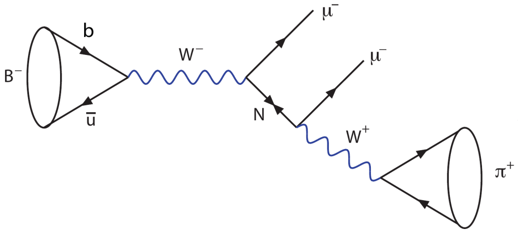
$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

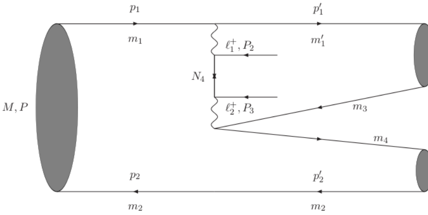
- New particles might be charged under new or old gauge symm., e.g., (N_R, e_R) form $\text{SU}(2)_R$ doublet and Δ_L is scalar $\text{SU}(2)_L$ triplet
- *Exciting* since long to "do list" in case of discovery!

Experiment Perspective on Low Mass N

Searches for Low Mass N

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





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

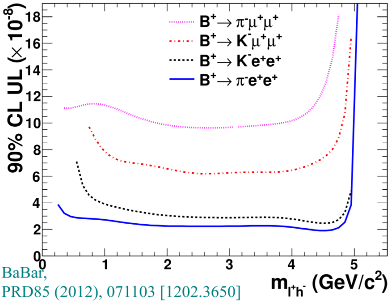
- Sufficient[2] to overcome ***tiny*** mixing for MeV-scale, Majorana N
- Sufficient to probe L-conserving, charged lepton flavor violation

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

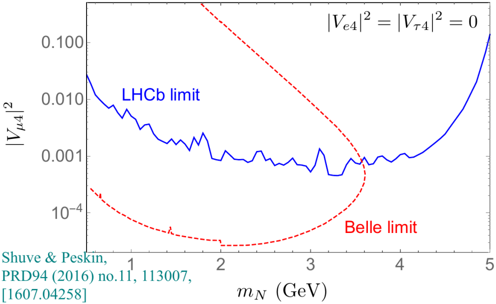
[2] Specifically, Kersten-Smirnov [0705.3221] and Pascoli-Weiland [1712.07611]

Searches for Low Mass Majorana N

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



BaBar,
PRD85 (2012), 071103 [1202.3650]



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

(R) LHCb and Belle search for $\mathcal{B} \to N\mu \to \pi\mu\mu$ [1607.04258]
Complementarity between high- (LHC) and low- (Belle) energy colliders!

- LHCb will collect $\gtrsim 100\times$ more data $\implies \gtrsim 10 - 50\times$ improvement
- Searches for N via LNC-cLFV interactions more difficult[3] (larger bkg)

[3] We will come back to this point!

Searches[4] for Low-Mass N at NA-62

Limits on BR($K \to N\ell$) using 1-2% of nominal data set [1712.00297]

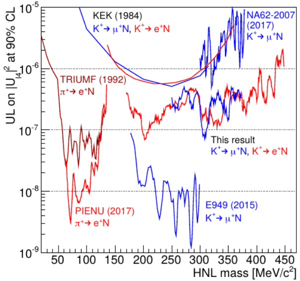
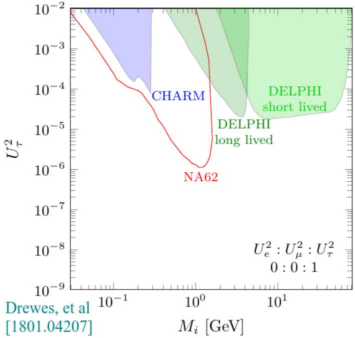


Figure 6: Upper limits at 90% CL on $|U_{\ell 4}|^2$ obtained for each assumed HNL mass compared to the limits established by earlier HNL production searches in π^+ decays: TRIUMF (1992) [5], PIENU (2017) [6] and K^+ decays: KEK (1984) [7], E949 (2015) [8], NA62-2007 (2017) [9].



Drewes, et al [1801.04207]

Active-sterile mixing of $|V_{\ell N}|^2 \sim 10^{-7} - 10^{-6}$ for $m_N \sim 0.1 - 0.5$ GeV

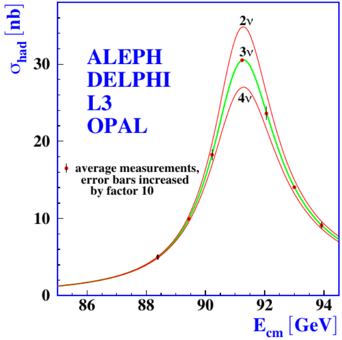
- **Goal:** Discovery! Otherwise, surpass BNL's E949 over larger range
- Beam dump mode can exceptionally probe $|V_{\tau N}|^2 < 10^{-6}$

[4] See also recent results of of BESIII and

Low-Mass N at ee Machines

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

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



- Helps drive (mild) preference for non-unitarity of 3×3 mixing[5]

Future ee collider can resolve this, see FCC-ee Study Team [1411.5230]

[5] See E. Fernandez-Martinez's talk (Monday) and, e.g., [1605.08774]

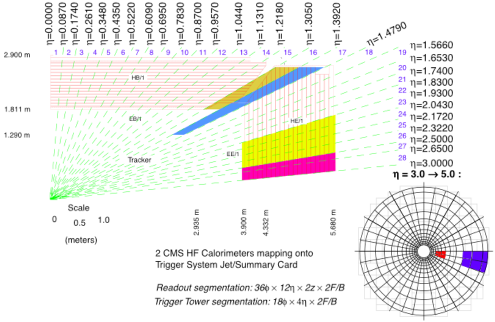
Experiment Perspective on N with Intermediate Masses I:

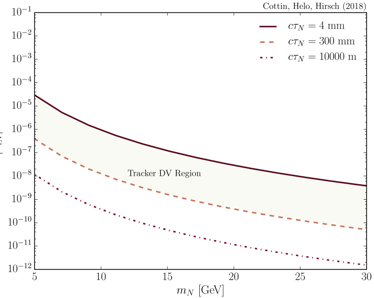
Prompt decays[6]

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

Experiment Perspective on N with Intermediate Masses II:

Non-prompt decays / 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)

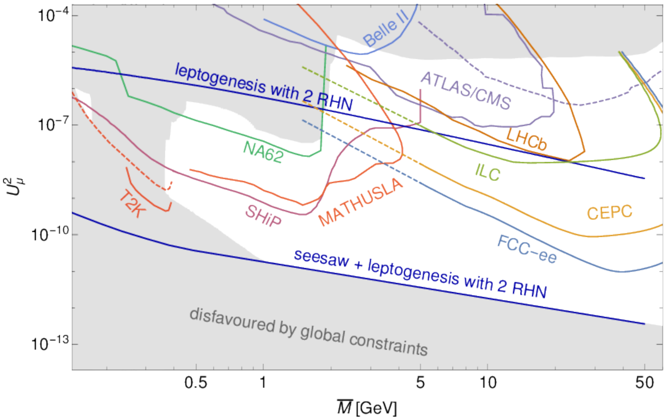
Intermediate N at Many Machines

List of current and proposed experiments sensitive to displaced N decays

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

Intermediate N at Many Machines[8]



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

- Driven by lepton [1504.02470] and neutrino [1607.03504] jets[7]

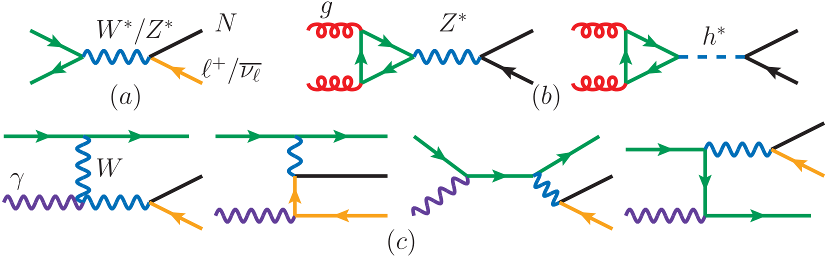
[7]Non-Expert: $W \to N\ell \implies \Delta R_N \sim 2m_N/M_W \ll 1 \implies$ merged topologies

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

Perspective on High Mass N

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[9]

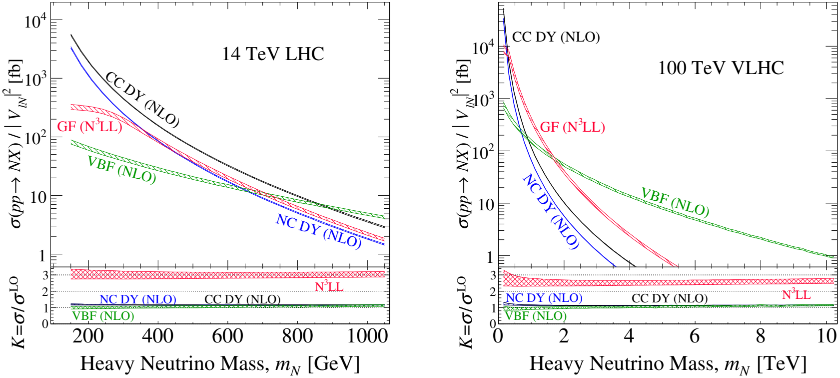
- Driven by need for clarity on $m_N, \sqrt{s}$ dependence

$\Longrightarrow$ more physical/robust collider definitions + public tools[10]

[9] 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

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

Across different colliders, wild interplay of PDF and matrix elements

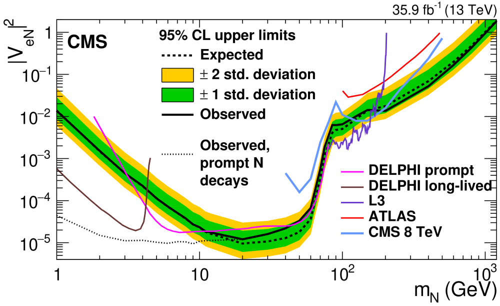


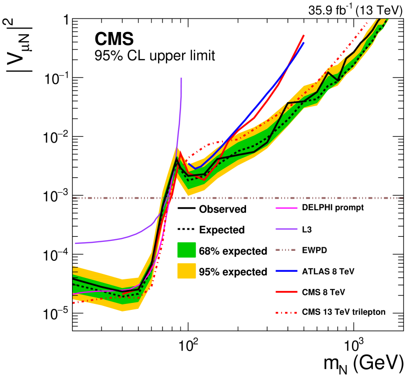
Plotted: Model-independent heavy N production rate $(\sigma/|V|^2)$ vs mass

- **GF** and **VBF** dominate at larger $\sqrt{s}$, m_N. 27 TeV similar to 100 TeV

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

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





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]

Prospects on High Mass N at pp Machines

New developments still ongoing:

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

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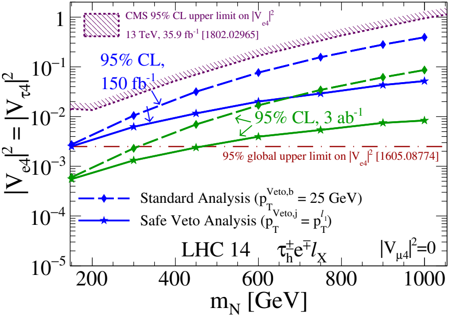
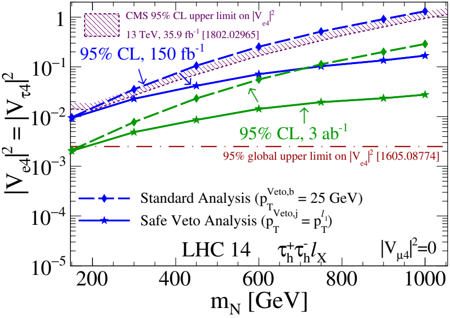
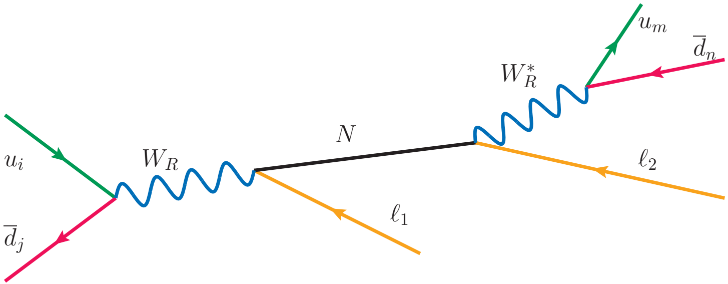




New sensitivity: $|V_{N\ell}|^2 < 0.01$ for $m_N < 1$ TeV at LHC [1805.09335]

- Pushing boundary of MC modeling and jet physics (jet vetoes) $\Longrightarrow$ Improved sensitivity up to $10 - 11\times$ with $\mathcal{L} = 3$ ab^{-1} at LHC 14
- **Watch this space:** Reach at future pp colliders due very soon

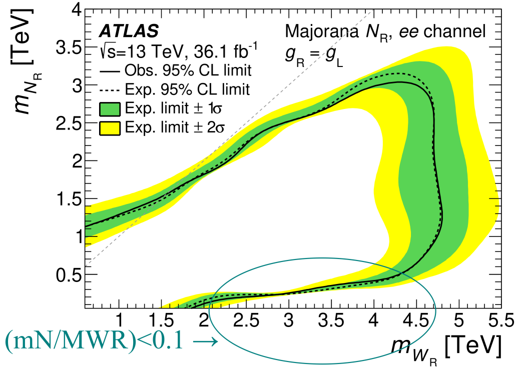
Heavy N with New Gauge Fields



Left-Right Symmetric Model and $SM \otimes U(1)_{B-L}$

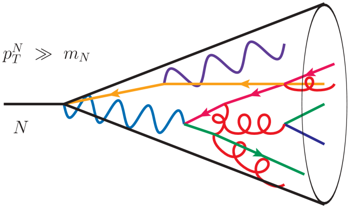
Heavier N can be produced if associated with new gauge boson W_R, Z_{B-L}

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



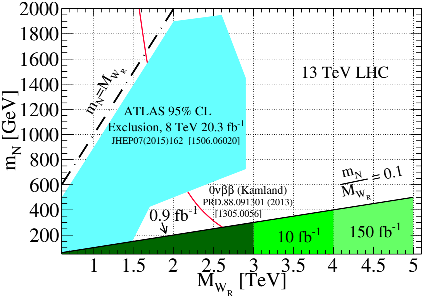
For $(m_N/M_{W_R}) \ll 1$, i.e., boosted N, searches are losing sensitivity!

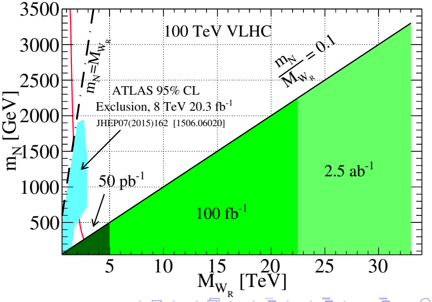
Like boosted t, treat decays of boosted N as a single ***neutrino jet*** (j_N)



j_N sensitivity (green) is precisely where current $\ell\ell jj$ searches exclusion (blue) stop [1607.03504; 1610.08985]

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

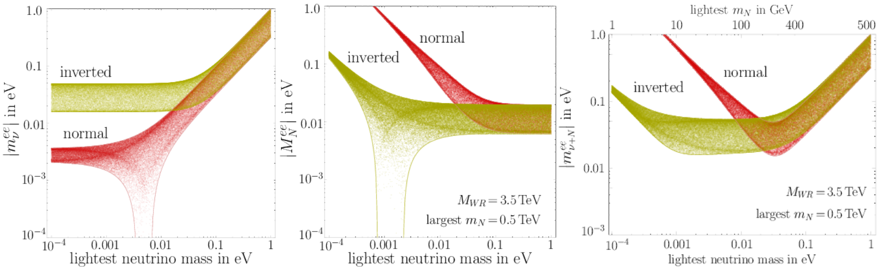




Complementarity to Low Energy Expts

TeV-scale neutrino mass partners extremely far reaching in impact:

- Eg. flavor-changing neutral transitions via Higgs mediation[11]
- Breakdown of naive "Weinberg operator" picture for $0\nu\beta\beta$ spectrum[12]



(L) Canonical description, (C) RH currents, (R) LH+RH currents

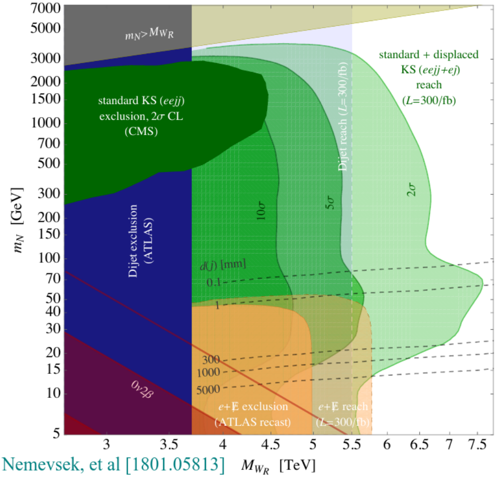
[11] Chakrabortty, et al [1204.0736]; Bertolini, et al [1403.7112]; + others

[12] E.g., Tello, Nemevsek , Nesti, Senjanovic, Vissani [1011.3522]

Left-Right Symmetric Model and $SM \otimes U(1)_{B-L}$

Taken together, a picture is emerging on sensitivity

to heavy N with new gauge fields at current and future facilities



Nemevsek, et al [1801.05813]

Summary

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

Community response to the challenge is incredible:

1. Europe has taken a leadership role in tests of neutrino mass models
   - Leadership should not be ceded but be expanded (Type II, loop, etc.)
   - Requires **support** / resources for theory

2. Experiments are *incredibly* complementary:
   - Lowest masses: short baseline and beam dump
   - Intermediate masses: beam dump and ee/pp-collider
   - High masses and/or additional particles: collider

3. Lots not covered today; see referenced documents.

4. Be encouraged! More data soon! Be prepared for a discovery.
   - E.g., What sets value of M_R? Multiple sources of LNV? What can precision measurement of $V_{\ell N}$ tell us?

Thank you.