Signatures from type-I,-II,-III seesaw at LHCb

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Implications of LHCb measurements and future prospects
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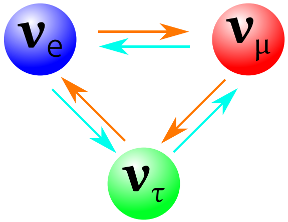
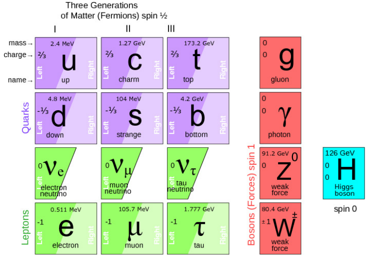
The slide on motivation





courtsy M. Shaposhnikov

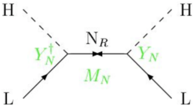
- Observation of neutrino oscillations $\Rightarrow$ light neutrinos massive.
- No neutrino mass mechanism in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.

$\Rightarrow$ Evidence for physics beyond the SM.

The 3 basic seesaw models

i.e. tree level ways to generate the dim 5 operator

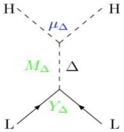
Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

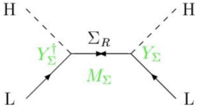
Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Slide from T. Hambye.

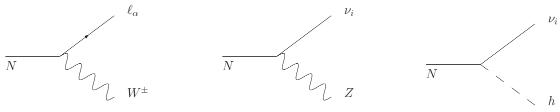
Type-I seesaw for light neutrino masses

Lagrangian:

$$\mathcal{L}_N = i\,\overline{N}_I \partial\!\!\!/ N_I - y_{\nu_{\alpha I}} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_{IJ}}}{2} \overline{N}_I^c N_J + \text{h.c.}\,,$$

- Sterile neutrinos N_I, indices $I, J = 1, 2, \ldots, n$.
- Parameters: Mass matrix M_N, Yukawa matrix y_ν.
- Neutrino oscillations observe $\Delta m^2_{\rm atm}$, $\Delta m^2_{\rm sol}$ $\Rightarrow n \geq 2$

charged current	neutral current	Higgs



θ_α	$\sum_\alpha \theta_\alpha$	$\sum_\alpha \theta_\alpha$

Light neutrino masses

- Neutrino mass matrix:

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$$ Majorana mass matrix M. Dirac mass matrix $m_D = y_\nu v_{\mathrm{EW}}$

- Seesaw $\Leftrightarrow m_D \ll M$.
- Naïve seesaw relation:

$$m_\nu = \frac{1}{2}\frac{m_D^2}{M_N} \Rightarrow |y_\nu|_{1,2} \simeq \sqrt{\frac{2\Delta m_{\mathrm{sol,atm}} M_{N_{1,2}}}{v_{\mathrm{EW}}^2}}$$

- In inverse seesaw $m_\nu = 0 \Leftrightarrow$ associated symmetry exact.
  $\Rightarrow$ Heavy neutrinos form degenerate "pseudo Dirac" pairs.
  $\Rightarrow$ Neutrino Yukawa couplings are not constrained by m_ν.

The meaning of neutrino masses for collider pheno

- Production rates at LHCb for $M_N < m_W \simeq 7$ nb $\times |V_{\ell N}|^2$
- Naïve type I seesaw relation: $|V_{\ell N}|^2 = \mathcal{O}(10^{-11})$
  $\Rightarrow$ **no events even in HL phase!**
  $\Rightarrow$ Possibly visible at the Z pole run of the FCC-ee

A. Blondel *et al.* [FCC-ee study Team], Nucl. Part. Phys. Proc. **273-275** (2016) 1883

- Symmetry protected type I seesaw with $|V_{\ell N}|^2 < 10^{-5}$.
  $\Rightarrow$ Sizable event numbers, **LNV suppressed** by m_ν.

Kersten, Smirnov; Phys. Rev. D **76** (2007) 073005

- LNV reintroduced via propagation effects:
  $\Leftrightarrow$ mass splitting between HNL pairs $>$ decay width.

Anamiati, Hirsch, Nardi; JHEP **1610** (2016) 010

- This effect can be experimentally resolvable.

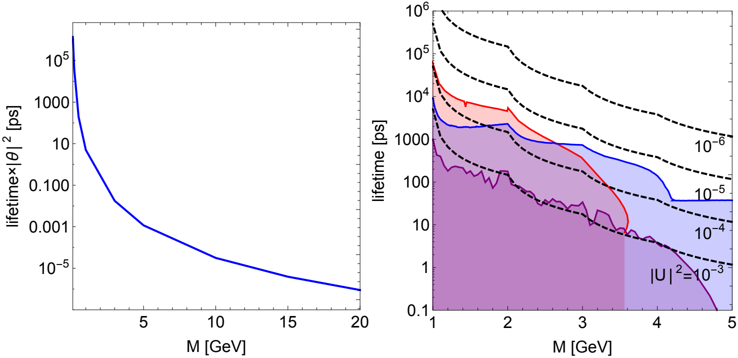
Antusch, Cazzato, OF; arXiv:1709.03797 [hep-ph].

Comment:

for $M > m_W$ LHC cross sections small and backgrounds huge.

Heavy neutrinos with symmetry protection and $M < m_W$

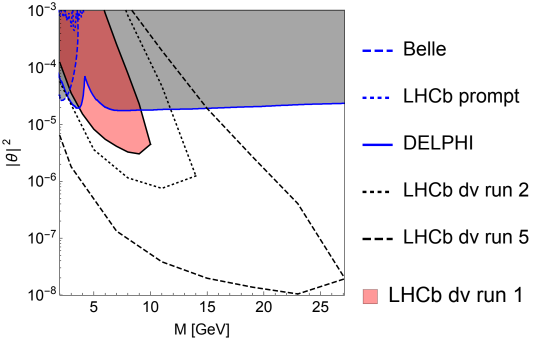
For $M \sim 1$ GeV hadronic final states.



- Fixing mass and mixing angle also fixes lifetime.
- Displaced vertex signatures, even for masses $M = \mathcal{O}(10)$ GeV.
- Blue: DELPHI, looking for *singly* produced HNL.

P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **74** (1997) 57

Forecasts, assuming dedicated analyses

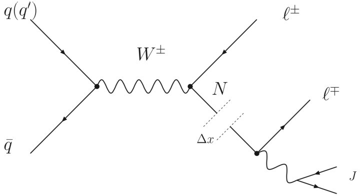


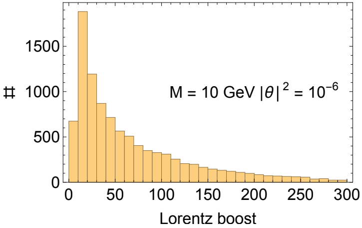
Antusch, Cazzato, OF; Phys. Lett. B **774** (2017) 114

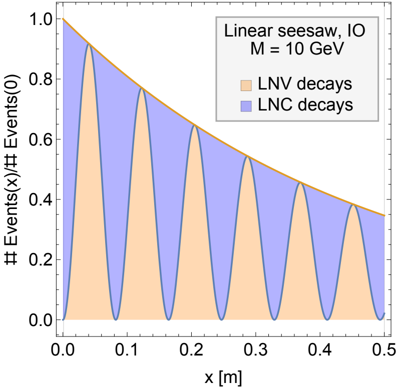
- Displaced muons plus jets at 13 TeV
- black dotted: exclusion power for 5 fb^{-1} from run 2...
- black dashed: 380 fb^{-1} for the high-luminosity run.
- All limits for $|\theta|^2 = |\theta_\mu|^2$ (i.e. $|\theta_e| = |\theta_\tau| = 0$).

Assume we would discover displaced decays from HNL.

Heavy neutrino oscillations in a nutshell







- Propagation effect: LNV as function of displacement Δx.
- Emergent pattern of SS vs OS dileptons in the proper frame.
- Proper oscillation length: $\lambda_{\rm osc}^{\rm lin,IO} = 3.29 \cdot 10^{-3}\sqrt{\gamma^2 - 1}$ m
- In this example, proper lifetime: $c\tau = 0.0094$ m

Dropping some 'standard assumptions' for type-I HNL

Assumption 1: $|\theta_\mu| \gg |\theta_e|, |\theta_\tau|$

Instead: theoretically motivated choice: $|\theta_\tau| \gg |\theta_e|, |\theta_\mu|$

Consequences:

- Precision constraints on $|\theta_\tau|$ weaker compared to others. (They are $|\theta_\tau|^2$ a few times 10^{-2} for $M \sim 1$ GeV.)
- Associated leptons (production) are tau leptons.
- Associated leptons (decay) are tau leptons if $M > m_\tau$.
  $\Rightarrow$ Signatures with two tau leptons important.
  $\Rightarrow$ Example: $p\,p \to \tau^\pm N \to \tau^\pm(\tau^\mp X)_{\mathrm{displaced}}$
- Semi leptonic decays suppressed if $M < m_\tau$!
  $\Rightarrow$ One prompt tau lepton and displaced vertex.
  $\Rightarrow$ Lepton non-universality from charged current decays.
  $\Rightarrow$ Example: $B^\pm \to \tau^\pm N \to \tau^\pm(X)_{\mathrm{displaced}}$, $X \supset e^+e^-, \mu^+\mu^-$

Assumption 2: single production

Notice: many experimental constraints are based on this assumption, e.g. DELPHI search P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **74** (1997) 57.

HNL pair production via scalars:

- Scalar mixing between SM Higgs doublet and scalar singlet
- Production via $h(125)$ or heavy scalar $\propto \sin^2\alpha$ (scalar mixing).
  $\Rightarrow$ Naïve type-I seesaw relation for θ predicts $h \to 2\, X_{\rm displaced}$

Deppisch, Liu, Mitra; JHEP **1808** (2018) 181

HNL pair production via Z' bosons:

- Production via resonant Z' possible if $\mathrm{Br}(Z' \to NN) \sim 1$.
- Production via γ, Z with gauge mixing angle $< 10^{-2}$.
- Production $\propto g_{Z'}^4/m_{Z'}^4$ for $m_{Z'} > \sqrt{s}$

E. Accomando et al.; JHEP **1802** (2018) 109

Type-III seesaw: neutrino masses from Fermion triplets

Type-III seesaw for light neutrino masses

Lagrangian:

- Σ: fermion field, isospin triplet, hypercharge 0.
- $\mathcal{L}_{\rm kinetic} = {\rm Tr}[\overline{\Sigma} i \not{D} \Sigma]$ Gauge interactions
- $\mathcal{L}_{\rm Majorana} = -\frac{1}{2}{\rm Tr}[\overline{\Sigma} M_\Sigma \Sigma^c + \overline{\Sigma^c} M_\Sigma^* \Sigma]$ Majorana mass
- $\mathcal{L}_{\rm Yukawa} = \sqrt{2}\tilde{\Phi}^\dagger \overline{\Sigma} L$ Yukawa interactions

Neutrino masses:

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma \, v_{\rm EW}^2 \,,$$

- Mass matrix identical to type-I seesaw.
- The same conclusions apply.

Some type -III phenomenology

Leptonic mixing:

- Neutral component Σ^0 mixes with ν_L
- Charged components $\Sigma^\pm$ mix with charged leptons
- Mass eigenstates: $\nu_1, ..., N^0$ and $e, \mu, \tau, N^\pm \Rightarrow$ Precision measurements of leptons imply mixing $< 10^{-1.5}$.
- Usually naïve seesaw relation applied: mixing $\sim 10^{-6}$

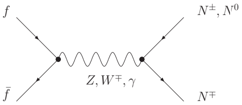
Interactions:

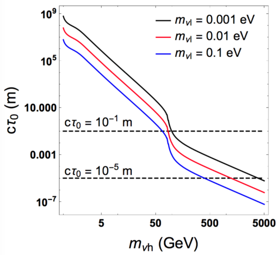
- Isospin fixes coupling strength to the gauge bosons.
- Measurement of Γ_Z at LEP requires $m_{N^\pm} > m_Z/2$.

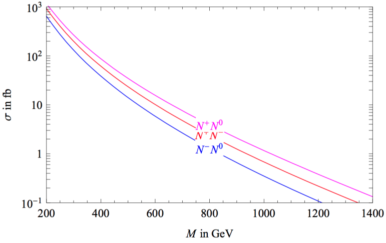
Lifetime:

- N^0 decays via leptonic mixing $\Rightarrow$ large $c\tau$ possible.
- Radiative corrections: $m_{N^\pm} = m_{N^0} + 166$ MeV
  $\Rightarrow N^\pm \to N^0(W^\pm)^*$, very short lifetime

Type-III signatures at the LHC







Franceschini, Hambye, Strumia; Phys. Rev. D **78** (2008) 033002

- N^0, $N^{\pm}$ can be pair produced via Drell Yan.
- $N^{\pm}$ decay promptly into N^0 plus soft pion or lepton
- ATLAS/CMS analyses include N^0 decays

The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2018-020.

A. M. Sirunyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **119** (2017) no.22, 221802

- Displacements due to long lifetimes not considered
  $\Rightarrow$ Long lived N^0 gives neither MET nor prompt tracks!

Type-II seesaw: neutrino masses from scalar triplets

Neutrino masses via type-II seesaw

Lagrangian:

- Δ scalar field, isospin triplet, hypercharge 2.
- $\mathrm{Tr}\left[(D_\mu\Delta)^\dagger(D^\mu\Delta)\right]$ Gauge interactions
- $\lambda_1\Phi^2\Delta^2 - \lambda_2\Delta^4 - \kappa\Delta^0\Phi^2$ Scalar interactions
- $Y_\Delta\bar{\ell}^c\Delta\ell + \mathrm{h.c}$ Yukawa interactions

Neutrino masses:

$$m_\nu = Y_\Delta \frac{v_\Delta}{M_\Delta^2} v_{\mathrm{EW}}^2$$

- Neutral component Δ^0 with non-zero VEV v_Δ
- Small $m_\nu \Leftrightarrow$ small $Y_\Delta, v_\Delta, M_\Delta^{-1}$

Phenomenology

"Standard" components of the triplet:

- Neutral mass eigenstate mixes with the SM Higgs doublet $\Rightarrow$ two neutral CP even Higgs-like bosons.
- Singly charged $\Delta^{\pm}$, difficult to search for at LHC.

Focus on the doubly charged $\Delta^{\pm\pm}$:

- Decay into SS dilepton $\propto Y_\Delta$
- Decay into SS W boson $\propto v_\Delta$
- Searches for prompt SS dileptons: $m_{\Delta^{\pm\pm}} > 620$ GeV

M. Aaboud *et al.* [ATLAS Collaboration], Eur. Phys. J. C **78**, no. 3, 199 (2018)

- Can be long lived for $m_\Delta < 2m_W$, not stable!
- Searches exist for charged massive stable particles (CMSP)

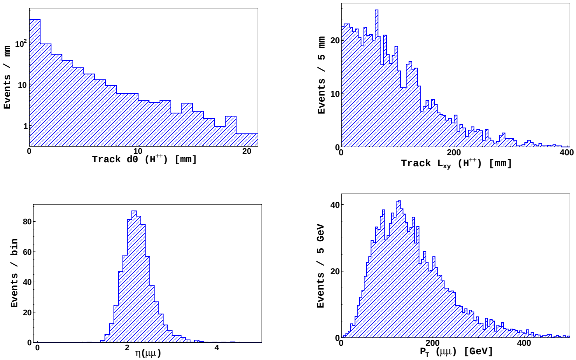
R. Aaij *et al.* [LHCb Collaboration], Eur. Phys. J. C **75** (2015) no.12, 595

- Intermediate lifetimes are subject of study.

Dev, Zhang; arXiv:1808.00943 [hep-ph].

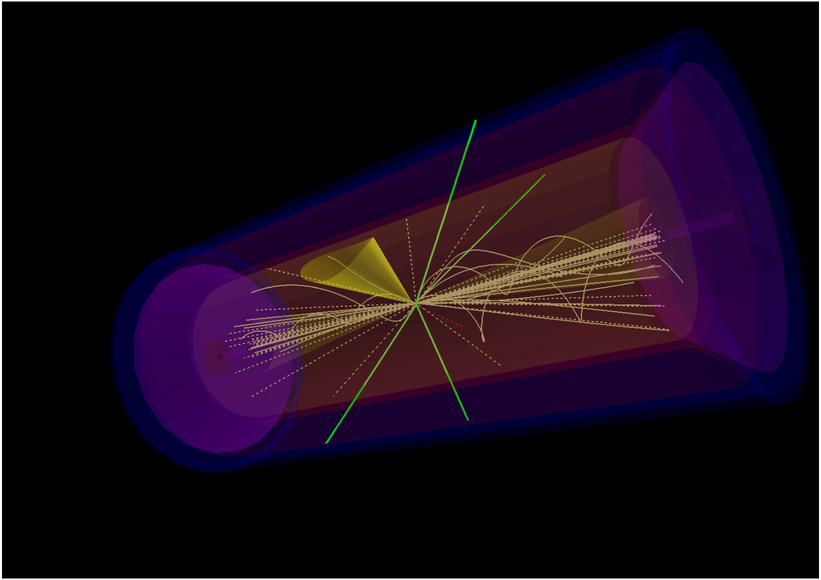
One example benchmark point

- $\sqrt{s}$ =14 TeV, luminosity = 3/ab, $\eta > 2$,
- m_Δ=130 GeV, $v_\Delta = 5 \times 10^{-4}$ GeV
- $c\tau_{\rm proper} > 1$ mm, invalidates ATLAS/CMS prompt searches!
- Compatible with all current constraints.



⇒ Signal: non-prompt dileptons; this is certainly visible?

A Delphes event display



Conclusions

Neutrino masses via seesaw:

- Type-I: right-handed (or sterile) neutrinos $\Rightarrow$ HNL.
- Type-II: scalar isotriplets with hypercharge
  $\Rightarrow$ neutral scalar mixing, singly/doubly charged scalars, LNV.
- Type-III: fermion isotriplets, no hypercharge
  $\Rightarrow$ Gauge interactions fixed, pair production, decay chains, neutral component is HNL

Signatures related to seesaw:

- Displaced vertices everywhere in the detector!
- Drell-Yan produced final states with prompt and displaced $\tau^{\pm}$.
- Meson decays with prompt $\tau^{\pm}$ and displaced dileptons.
- Pairs of displaced vertices w/ & w/o soft pions/leptons.
- Displaced same sign dimuons.

Can LHCb detect e^+e^- or a single photon with $E < GeV$ that appear anywhere in the detector?