Heavy Neutrino search at FCC-*ee*

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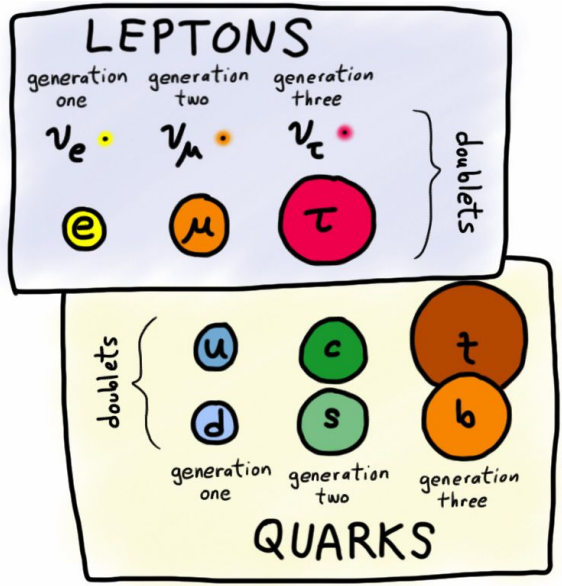
Standard Model

- Successful theory:
  - Higgs boson $\rightarrow$ observed
  - complete theory
  - consistent with high precision measurements

- Problems!
  - neutrinos oscillations: neutrinos have mass
  - gravitational effects of extra (dark) matter observed
  - small degree of $\not{CP}_{SM}$ cannot explain large matter/antimatter asymmetry

"New Physics" out there



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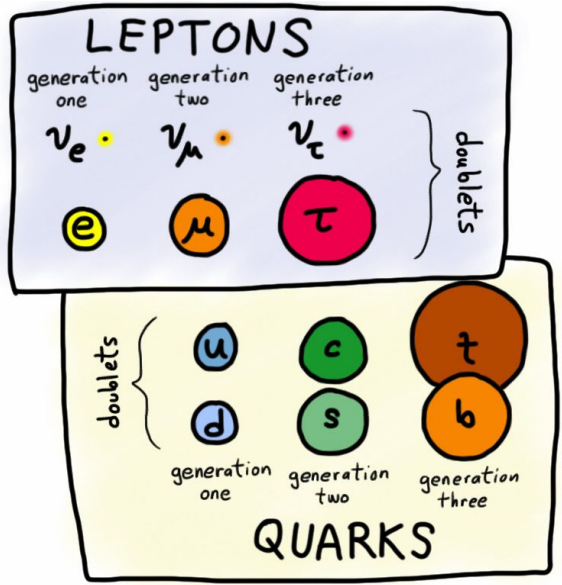
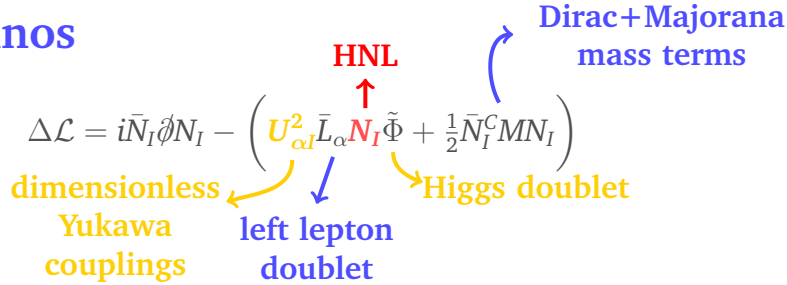


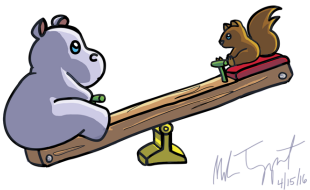
Sterile neutrinos



- SM has only LH ν (and RH $\bar{\nu}$)
- Simple extension: enter neutrinos with RH chirality
  - Zero EW and color charge: "sterile"
  - Only couples to Higgs and SM neutrinos
  - Can be massive: "heavy neutral leptons", HNLs
- They appear in a number of BSM theories with wide number and mass range
- Dirac + Majorana mass terms (needed to explain smallness of ν masses)

Seesaw mechanism

$$\mathcal{L}^{D+M} = \frac{1}{2}\bar{N}_I^C M N_I \text{ with } M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \text{ and } N_I = \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix}$$



- mass-flavour mixing angles θ_f
- n HNLs: m_D, m_M become $n \times n$ matrices, $\theta_f \to \theta_{fI}$
- "Seesaw" mechanism: $|m_D| \ll m_M$
- mass eigenstates (for small θ):

$$m_1 \approx \frac{m_D^2}{m_M} \qquad m_2 \approx m_M$$

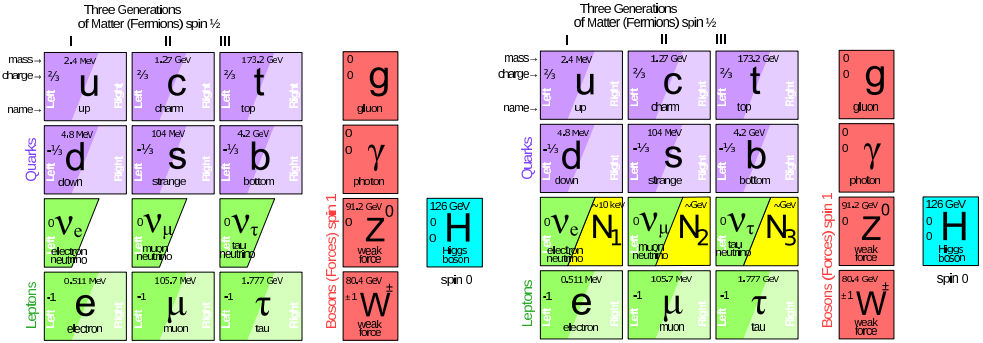
m_1: **SM neutrino**

m_2: **sterile neutrino**

$\sim$ **Dirac mass of same generation fermions**

The νMSM

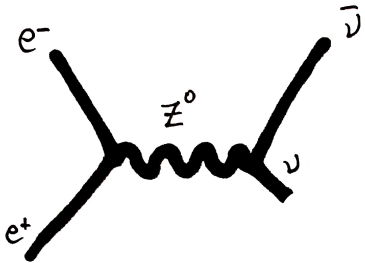
[Asaka, Blanchet, Shaposhnikov, Phys.Lett. B631 (2005) 151-156]



3 HNLs. Suitable values of mass and coupling allow to simultaneously explain:

- ν oscillations induced by massive states N_2, N_3
- dark matter: N_1 with mass $\sim$keV
- disappearance of antimatter: leptogenesis due to Majorana term

HNL phenomenology



- Mixes with SM neutrino ν_α via U_α^2
- Can occur in any process involving SM neutrinos...

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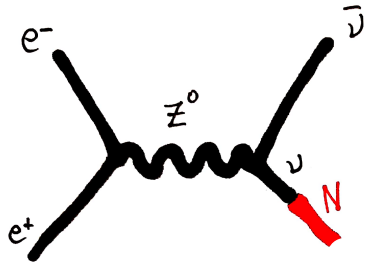

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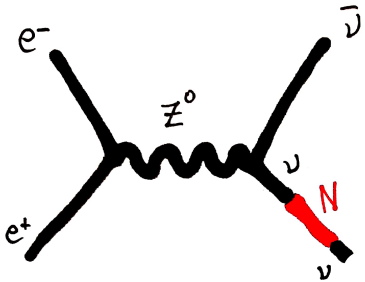

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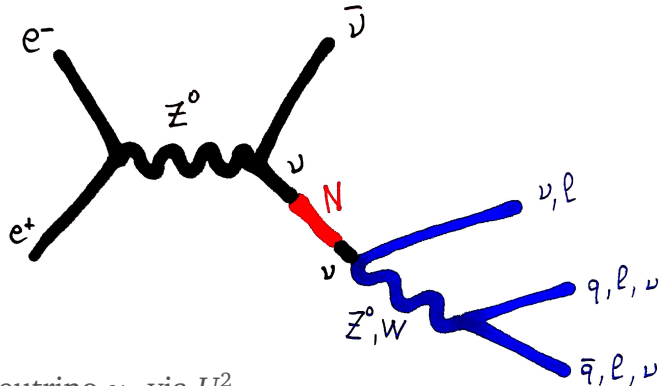

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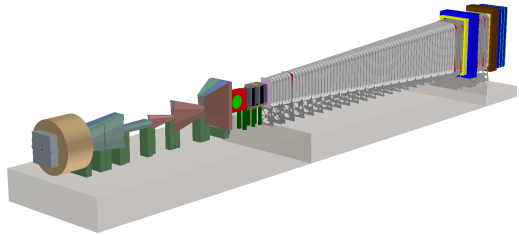
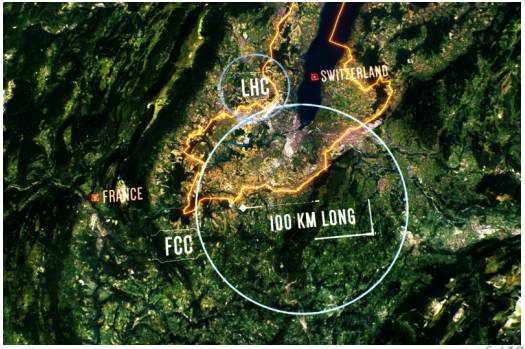
- Decays through emission of a Z^0 or $W^\pm$ boson

How to look for HNLs?

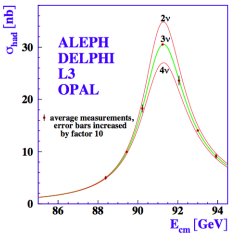
- Dedicated hidden particle experiments
  - SHiP (beam dump, 0-BG)
  - from meson decays
  - Mathusla, CODEX-b, FASER, *etc.*
- Collider searches
  - from Z^0, $W^{\pm}$ bosons
  - from precise EWP measurements
  - *ee*: clear signature, easy analysis
  - *hh*: large background, difficult triggering/analysis



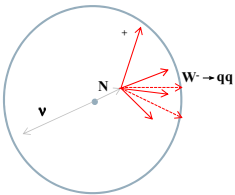


HNLs at FCC-*ee*

- **Neutrino counting from Z line shape**
  - LEP: $N_\nu = 2.984 \pm 0.008$, uncertainty from theory and σ_{had}
  - FCC-*ee*: improve by factor 10–20 with $\mathcal{B}(\gamma Z_{inv}) / \mathcal{B}(\gamma Z_{\ell\ell})$
  - sensitivity $U^2 \sim 10^{-4}$ for sterile neutrino search

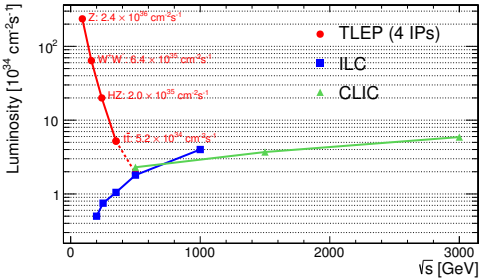


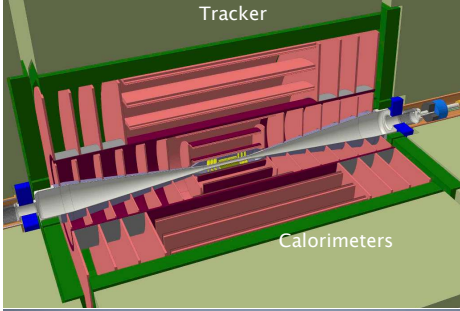
- **Direct search in Z decays**
  - production in $Z^0 \to \nu N$ mixing
  - decay: 2 jets + lepton/E_{miss} (CC), or 2 leptons + E_{miss} (NC)
  - clean events, background killed by SV displacement
  - displaced vertex search: focus of this talk

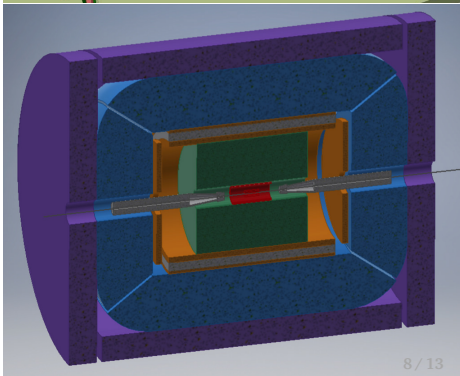


Experimental conditions

- $1.5 \times 10^{12}\, Z^0\ \mathrm{yr}^{-1} \times 6\ \mathrm{yr}$ [P.Janot, FCCw2017]
  - Assuming $5 \times 10^{12}\ Z^0$ bosons
- 2 detector concepts: CLD/IDEA
  - tracker half-size $S \simeq 2$ m
  - few μm vtx resolution, but SV can be outside the vertex detector
  - min. displacement $\Delta \equiv 100\ \mu$m





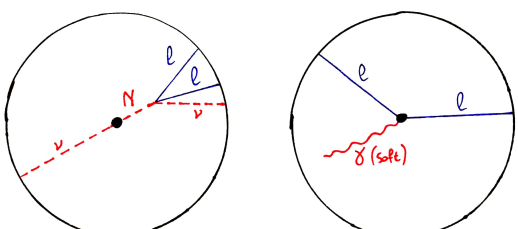


Signature & backgrounds

Considering only di-lepton final states.

- W^*W^*, Z^*Z^*, $Z^*\gamma^*$ with $2\ell + 2\nu$ final state: min. SV displacement
- $Z \to \ell\ell$ with E_{miss} from ISR/FSR: min. SV displacement
- $Z \to \tau\tau \to 2\ell + 4\nu$: the two ℓ are almost back-to-back
- atmospheric ν interactions: candidate direction/topology

More background sources for $N \to W\ell \to qq\ell$, but fully reconstructed final state!



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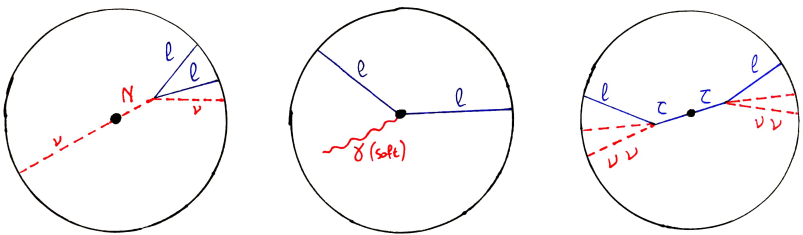

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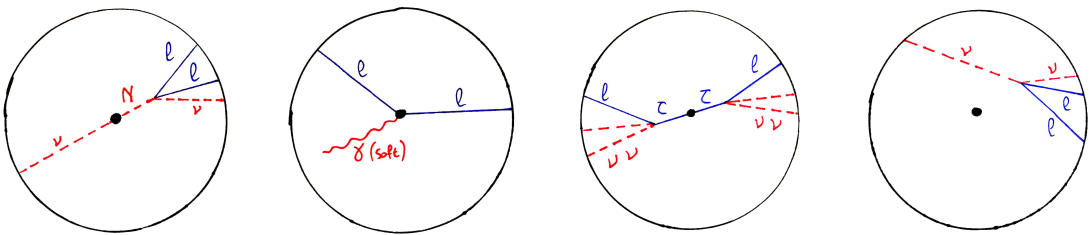
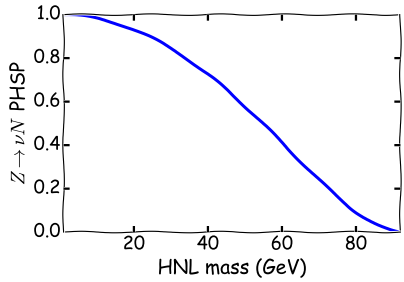
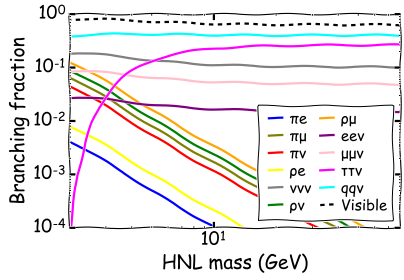


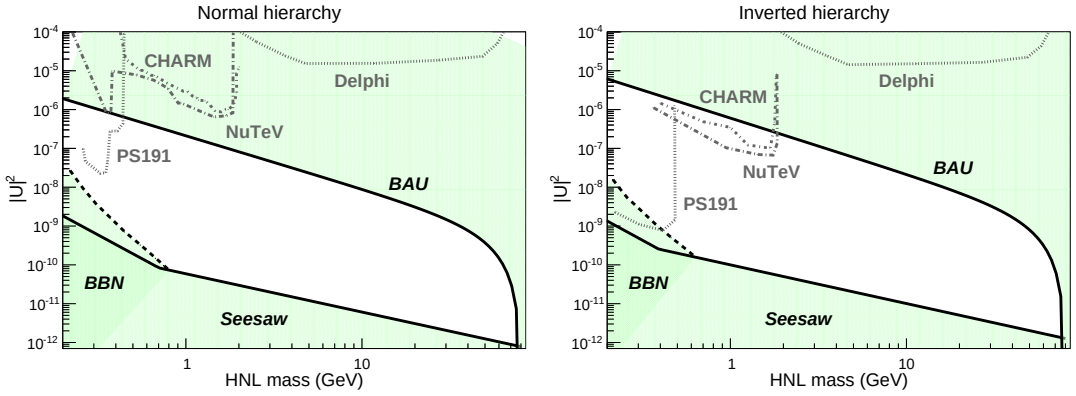
Estimating FCC-*ee*'s sensitivity

- Exploring the νMSM phase space in $\left(U_f^2, m_N\right)$
  - fixed U_f^2 ratios, of cosmological interest
- $\left[m_N\right]$ HNL boost from $e^+e^- \to Z^0 \to \nu N$
- $\left[U_f^2, m_N\right]$ lifetime based on the kinematically allowed decay channels:
  $h^0\nu,\ h^\pm\ell^\mp,\ 3\nu,\ \ell_i^\pm\ell_j^\mp\nu_j,\ \ell_j^\pm\ell_j^\mp\nu_i,\ q\bar{q}\nu,\ q\bar{q}\ell$
- $\left[U_f^2, m_N\right]$ experimental acceptance:
  $\mathcal{P}_{vtx} \sim \int_\Delta^S e^{-l/\gamma c\tau} dl$
- $\left[U_f^2, m_N\right]$ final state efficiency:
  - all di-lepton final states taken visible
- $n_{HNL} \equiv n_{Z^0} \times \mathcal{B}\left(Z^0 \to \nu N\right) \times SES$





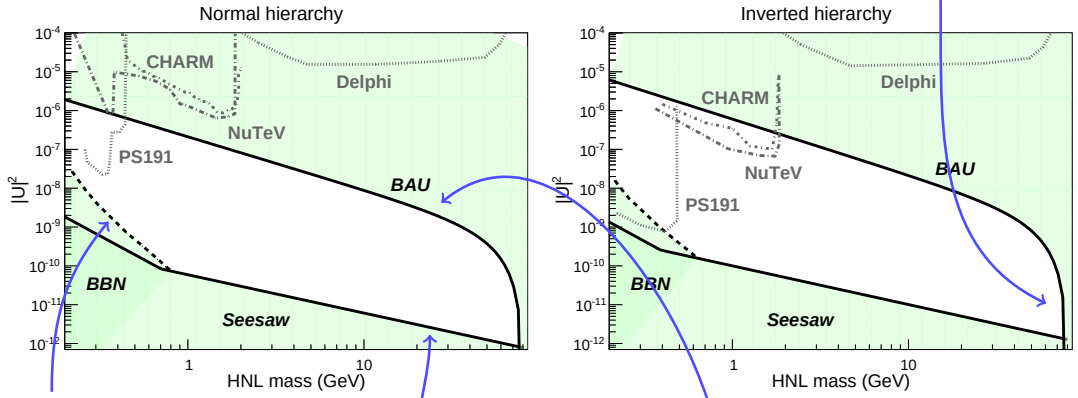
νMSM parameter space



[Blondel, EG, Serra, Shaposhnikov, hep-ex/1411.5230]

νMSM parameter space

rate enhanced: on-shell $N \to W\ell$



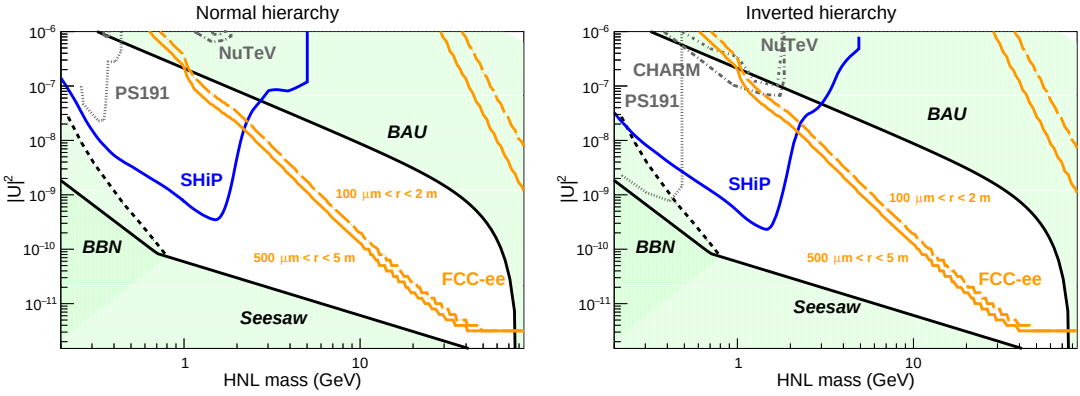
[Blondel, EG, Serra, Shaposhnikov, hep-ex/1411.5230]

would affect BBN

cannot explain observed Δm_{ν_i}

in thermal equilibrium during Universe expansion
(no baryogenesis due to HNL oscillation)

FCC-*ee*'s sensitivity to HNLs



[UPDATE] [Blondel, EG, Serra, Shaposhnikov, hep-ex/1411.5230]

- **Best sensitivity** above the charm mass + complementarity with BDF
- Higher vertexing resolution $\longrightarrow$ larger couplings
- Larger sensitive area $\longrightarrow$ smaller couplings

Conclusions

- Sterile neutrinos can solve several SM shortcomings
- Sensitivity studied in νMSM context, but general validity
- FCC-*ee* at the Z^0 pole: down to $U^2 < 10^{-11}$ for large m_N
  - complementary to beam dump facility

[physics.ins-det/1504.04956]

How to improve

- minimum Δ based on outer tracker resolution: it can be set much smaller for decays in the vertex detector!
- large external tracking volume (4-10 m)? [M.Dam, FCCw2017]
- $q\bar{q}\ell$ and $q\bar{q}\nu$ final states

Backup slides

Independent analyses

- sensitivity confirmed by independent analyses
- long + short lifetime search
- sensitivity of individual subdetectors

[S. B. Nielsen, MSc thesis]

[hep-ph/1604.02420]