HNL searches with the FCC-hh

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Viable HNL Parameter Space for Testable Leptogenesis

Get needed matter-antimatter asymmetry + light neutrino oscillation data w/o fine-tuning

SHiP: to be or not to be?

Even if there is FCC, SHiP is the only one closing fully allowed gap below 5 GeV (?)
HNL production sources

• FCC-ee: Z-mediated production, no advantage to go to b decays
• FCC-hh:
  • $\times 30 \, b \ (1.5 \times 10^{17})$ and $\times 120 \, W$ compared to HL-LHC
  • plenty of time to think how to best exploit these sources
• estimates:
  • use distributions and predictions from PYTHIA8 and FONLL for heavy flavor and W bosons production
  • take 100% signal efficiency in visible decay channels
  • compute only signal rate (no background estimate)
Brute force solution

FIP decay volume and detector

space/cost permitting
FCC-hh “toy” design

• Tracking stations composed of two layers of tracking detectors separated by 1 m, and providing spatial resolution of 1 mm

• Mid-\(\eta_1\):
  • over full detector length
  • \(|z|<33\, m\)
  • \(10\, m < r < 15\, m\)
  • \(|\eta| < 1.5\)
  • more expensive

• Mid-\(\eta_2\):
  • two disjoint pieces
  • \(12\, m < |z| < 33\, m\)
  • \(5\, m < r < 15\, m\)
  • \(1.5 < |\eta| < 2.6\)
  • less expensive

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FCC-hh 3-event contours

\( \mu \) (or \( e \))-dominated scenario

\( \tau \)-dominated scenario

\[ m_N [\text{GeV}] \]

\[ U^2 \]

\[ 10^{-12} \quad 10^{-9} \quad 10^{-6} \]

\( U^2 \]

\[ m_N [\text{GeV}] \]

\[ 10^{-12} \quad 10^{-9} \quad 10^{-6} \]

\[ U^2 \]

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\[ m_N [\text{GeV}] \]

\[ 10^{-12} \quad 10^{-9} \quad 10^{-6} \]

\[ U^2 \]

\[ m_N [\text{GeV}] \]
Less brute force?

Muon system design optimized for both muons and FIPs?

FIP decay volume and detector
Now: subdetector usage for HNLs @ LHC

- Intermediate lifetime:
  - displaced vertices in tracker

- Large lifetime:
  - standalone muons in muon system
    (*decay volume*: all before MS)
  - showers in muon system
    (*decay volume*: entire MS)
  - missing momentum signatures
    (*decay volume*: everything outside the detector)

- low HNL masses: not usable due to insufficient energy resolution
- high HNL masses: not relevant due to prompt decays

Tracker:
displaced vertices

Muon system: huge decay volume and little bkg after shielding
Decay volume for HNLs @ LHC

Decay volume of
• displaced vertices
• standalone muons
• muon detector showers

\[ \gamma = 30 \]
\[ c \tau = 0.01 \text{ m} \]
\[ c \tau = 0.1 \text{ m} \]
\[ c \tau = 10 \text{ m} \]

\[ p_T^\text{miss} \text{ signatures} \]

FASER/SND/FACET...
Displaced vertices in the tracker vs with standalone muons @ LHC

Sensitivity of
- displaced vertices (DV$_S$)
- standalone muons (DV$_L$)
- muon detector showers

Lower masses
Lower couplings

Phys.Rev.D 100 (2019) 075015
Muon detector showers (MDS) @ CMS

Example event display of a LLP signal event

- FIP traverses the detector and decays in the muon system
  - signal is proportional to the FIP energy rather than its mass
- muon detector acts as a sampling calorimeter
- low SM background as only muons typically survive there
- muons have much lower hit multiplicity than FIP-induced hadronic/EM shower – clear signature for a trigger
Muon detector showers (MDS): ATLAS/CMS

- signature sensitive to all visible non-muonic decays (no final state suppression)
- efficiency depends on the decay vertex and FIP energy:
  - if decay happens at the beginning of steel layer, the shower can be absorbed before reaching the sensitive layer
- → in future detectors, can optimize absorber thickness to be also sensitive to a typical spectrum of FIPs (e.g. at the FCC-ee/-hh)

*Phys.Rev.Lett.* 127 (2021) 261804
*Phys.Rev.D* 106 (2022) 032005
If triggering on MDS is accessible at (HL-)LHC

- Back-of-an-envelope estimate for HNLs in $\tau$-dominant scenario:
  - HNLs produced in W, Z, B, D decays
  - coupling only to tau
  - visible decays within muon system (endcaps for CMS)
  - assume 70% detection eff-cy

- Sensitivity of $10^{-8}$ with Run 3 data!
- 2-3 orders of magnitude better than existing results
If triggering on MDS is accessible at (HL-)LHC

At low masses $\times 10^{2-3}$ better than projections with more conventional techniques

$U_r^2$ vs $m_N$ [GeV]

Displaced vertex search projection

$2$ GeV

$2$ GeV

$0.5$ $1$ $2$ $5$ $10$

$10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$ $10^{-9}$ $10^{-10}$

Solid: Run 3. Dashed: HL

$U_r^2$ $m_N$ [GeV]

$10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$ $10^{-9}$ $10^{-10}$

$U_r^2$ $M_r$ [GeV]

$10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$ $10^{-9}$

$2$ GeV

$3$ ab$^{-1}$

$380$ fb$^{-1}$
Another subdetector usage for HNLs @ LHC?

Decay volume of
• displaced vertices
• standalone muons
• muon detector showers
• missing particle?

\[
\text{probability/m} \quad \gamma = 30 \\
\text{p}_{\text{T}}^{\text{miss}} \text{ signatures} \\
\text{FASER/SND/FACET}...
\]

- \( \text{ct} = 0.01 \text{ m} \)
- \( \text{ct} = 0.1 \text{ m} \)
- \( \text{ct} = 10 \text{ m} \)
HNLs escaping detector

Can smth be done?

HNLs decay promptly

HNLs decay outside detector

too few HNLs produced

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“Stable” low-mass particles: $P_T^{\text{miss}}$ @ LHCb

Proposal to use fully reconstructed decay vertices to infer missing particles:

- non-hermetic detector but excellent vertex resolution
- look for missing momentum in hadron decays!
- get access to much lower masses: 1-5 GeV

Systematic uncertainty is a challenge!

$\Sigma_b^{(*)\pm} \to \Lambda_b^{0}\pi^{\pm}$

$p_T^{\text{miss}}$ in hadron decays

$50 \text{ fb}^{-1}$

Science fiction idea: $M_{\text{miss}}$?

- missing mass used in the LHCb search for LFV decays with $\tau$:
  - $B^+$ momentum computed from its flight direction and known $m(B^{+}K^-)$
  - missing $\tau$ 4-momentum is computed as $P(B^+)-B(K^+\mu^-)$
- can be applied for HNLs at FCC?
  - fully inclusive for HNL decays
  - suppressed by $B_{s2}$ cross section
  - can consider $B\rightarrow D\rightarrow$HNL chains
  - needs hadron identification...

Looking for $B^+ \rightarrow K^+ \mu^+ \tau^+$

Tagging by $B_{s2}^{*0} \rightarrow B^+ K^-$

$LHCb$ simulation

- $B_{s2}^{*0}$ signal
- non-$B_{s2}^{*0}$ signal

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Summary

• FCC-hh is a powerful source of neutrinos from b and W decays
• have quite some time to take into account the lessons from the LHC and optimize the FCC main detectors

• main strategy – shield as much as possible from the interaction point:
  • target a combined muon/FIP detector from the start (dimensions, absorber thickness)
  • envision a possibility for simple additional detectors on the walls or in the tunnel
  • sensitivity competes with SHiP and is complementary to FCC-ee

• strategy to consider: check options for hadron identification and precise secondary vertex measurement for missing mass signatures
  • sensitivity to be checked