Neutrino background studies with an air sample in SHiP

Ia. Bezshyiko, N. Serra
Outline

- Geometry configuration with air
- Estimation of neutrino interactions in 5 years
- Offline selection appliance for HNL candidates
- Check of other possible impacts of air
- Expectations for He
Neutrino interaction points: expected

A schematic view of air location for these studies
Neutrino interaction points: simulated

**Simulated neutrino interaction points lay down where we expect them to be.**

\[ \frac{x}{220} + \frac{y}{470} \leq 1 \]

\[-1928 < z < 2258\]
Neutrino maximum weight estimation

Density of air $\rightarrow 0.001205 \text{ g/cm}^3$

$Z \rightarrow \text{[from -1928 cm to 2558]}$
Maximum $Y \rightarrow 470 \text{ cm}$
Maximum $X \rightarrow 220 \text{ cm}$

Maximum $L \sim 4510 \text{ cm}$

$\omega_{\text{fairship}} = \rho \cdot L$

Therefore, we should not observe events with higher weight if generation is good.
Weights of simulated neutrino events don't exceed an expected value of 5.43.

Also it's possible to notice that fraction of neutrinos fly along $z$. 
An expected number of interactions inside the vessel

\[ N_{\text{interactions}} = \rho \cdot L \cdot N_A \cdot N_{\nu} \cdot \sigma \]

\( \rho = 0.001205 \frac{g}{cm^3} \) \( \rightarrow \) Air density

\( L = 4486 \text{ cm} \) \( \rightarrow \) Interaction area length

\( N_A = 6.022 \cdot 10^{23} \)

\( N_{\nu} = 8.48 \cdot 10^{11} \cdot \frac{2 \cdot 10^{20}}{5 \cdot 10^{13}} \) \( \rightarrow \) Number of neutrinos in 5 years

\( \sigma/\text{GeV} = 7 \cdot 10^{-39} \frac{\text{cm}^2}{\text{GeV}} \)

\( E_{av} = 1.5 \ \text{GeV} \)

**we checked that our implementation of Genie takes correctly into account the total cross-section → see next slide**
Neutrino energy distribution

- The total neutrino cross section depends linearly on the energy
- We can check that the ratio of neutrino spectrum at production and after interaction is a straight line

Neutrino spectrum after running Genie:

eos/ship/data/GenieEvents/
genie-nu_mumu.root

was used
Neutrino energy distribution

- The total neutrino cross section depends linearly on the energy
- We can check that the ratio of neutrino spectrum at production and after interaction is a straight line

Neutrino spectrum produced after running Pythia:

eos/ship/data/Mbias/pythia8_Geant4-withCharm_onlyNeutrinos.root

was used

Ratio of genie-nu_mu.root to
pythia8_Geant4-withCharm_onlyNeutrinos.root
A number of interactions inside the vessel: expected

\[ N_{\text{interactions}} = \rho \cdot L \cdot N_A \cdot N_{\text{nu}} \cdot \sigma \]

\( \rho = 0.001205 \, \text{g/cm}^3 \)

\( L = 4486 \, \text{cm} \)

\( N_A = 6.022 \cdot 10^{23} \)

\( N_{\text{nu}} = 8.48 \cdot 10^{11} \cdot \frac{2 \cdot 10^{20}}{5 \cdot 10^{13}} \)

\( \sigma/\text{GeV} = 7 \cdot 10^{-39} \, \text{cm}^2/\text{GeV} \)

\( E_{\text{av}} = 1.5 \, \text{GeV} \)

\[ N_{\text{interactions}} = 119,031 \]
A number of interactions inside the vessel: simulated

\[ N^s_{\text{interactions}} = \sum \text{weight}_i \]

\[ \text{weight}_i = \frac{\rho_i \cdot L_i \cdot N_A \cdot N_{\nu} \cdot \sigma_i}{N_{\text{generated}}} \]

\[ w_i = \rho_i \cdot L_i \quad \text{← from FairShip} \]

\[ N^s_{\text{interactions}} = \sum w_i \cdot N_A \cdot N_{\nu} \cdot \frac{\sigma_i}{\text{GeV}} \cdot E_{\text{average}} \]

\[ N_{\text{generated}} = 10^6 \]

\[ N^s_{\text{interactions}} \sim 85299 \]

The value is overestimated. In our assumption we consider that all neutrinos will go straight through all length of the vessel.

\[ N_{\text{expected}} = 119031 \]
Quasi-elastic neutrino interaction points

Fairship events:

If \((\nu_\mu \ n \rightarrow \mu \cdot p)\)

\[
N_{sQE_{\text{interactions}}} = \sum \frac{w_{\text{quasi}} \cdot N_A \cdot N_{nu} \cdot \sigma_i \cdot E_{\text{average}}}{N_{\text{generated}}}
\]

Expected events:

\[
N_{\text{expected}} = \rho \cdot L \cdot N_A \cdot N_{nu} \cdot \sigma_{QE}
\]

\[
\sigma_{QE} = 5 \cdot 10^{-39}
\]

\[
N_{sQE_{\text{interactions}}} \sim 10364
\]

\[
N_{\text{expected}}^{QE} = 55209
\]
Quasi-elastic neutrino interaction points

**Fairship events:**

If \((\nu_\mu \ n \rightarrow \mu \cdot p)\)

\[
N_{sQE_{\text{interactions}}} = \sum \frac{w_{\text{quasi}} \cdot N_A \cdot N_{\nu} \cdot \frac{\sigma_i}{GeV} \cdot E_{\text{average}}}{N_{\text{generated}}}
\]

**Expected events:**

\[
N_{\text{interactions}} = \rho \cdot L \cdot N_A \cdot N_{\nu} \cdot \sigma_{QE}
\]

\[
\sigma_{QE} = 5 \times 10^{-39} \text{ GeV}
\]

\[
N_{sQE_{\text{interactions}}} \sim 10364
\]

\[
N_{\text{expected}^{QE}} = 55209
\]

1. Overestimation for expected value because of path length.
2. Overrated \(\sigma_{QE}\)?
3. Underrated \(\sigma\)?
Total and quasi-elastic cross-sections for neutrino

**Difficult to estimate cross-sections for low energies**

![Graph showing total and quasi-elastic cross-sections for neutrino.](http://pdg.lbl.gov/2014/reviews/rpp2014-rev-nu-cross-sections.pdf)
Reconstructed events (HNL candidates)

$10^6$ interactions were generated:

$$N_{\text{HNL candidates}} = 40,137$$

In 5 years of running:

$$N_{\text{HNL candidates}_5} = 4,704$$

Amount of fake HNL candidates in 5 years which would be produced by neutrino background.
HNL candidates: Selection

- Event reconstructed -> event produces at least one HNL candidate: 100%
- 1 HNL Candidate -> event produce only one HNL candidate: 53%
- Vertex is in the fiducial volume: 95%
- Tracks are in the fiducial volume: 99%
- N.d.f > 25: 67%
- DOCA < 1cm: 55%
- $\chi^2 / \text{N.d.f} < 5$: 99%
- Daughters P > 1 GeV: 81%
- IP < 0.1m: 0.13%
- Event not vetoed -> no hits in the VETO detectors: straw veto and liquid scintillator: 6.7%
- All cuts together: 0.03%

\[ N_{\text{HNL candidates}} = 13 \quad N_{\text{HNL candidates}_{-5}} = 1.56 \]
HNL candidates: Partially reconstructed

- Event reconstructed -> event produces at least one HNL candidate: **100%**
- 1 HNL Candidate -> event produce only one HNL candidate: **53%**
- Vertex is in the fiducial volume: **95%**
- Tracks are in the fiducial volume: **99%**
- N.d.f > 25: **67%**
- DOCA < 10 cm: **85%**
- $\chi^2 / N.d.f < 5$: **99%**
- Daughters P > 1 GeV: **81%**
- IP < 2.5 m: **26%**
- Event not vetoed -> no hits in the VETO detectors: straw veto and liquid scintillator: **6.7%**
- All cuts together: **0.62%**

$N_{\text{HNL candidates}} = 249$  
$N_{\text{HNL candidates}_5} = 29.79$
HNL candidates: Partially reconstructed

- Event reconstructed -> event produces at least one HNL candidate: **100%**
- 1 HNL Candidate -> event produce only one HNL candidate: **53%**
- Vertex is in the fiducial volume: **95%**
- Tracks are in the fiducial volume: **99%**
- N.d.f > 25: **67%**
- DOCA < 10 cm: **85%**
- χ² / N.d.f < 5: **99%**
- Daughters P > 1 GeV: **81%**
- IP < 2.5 m: **26%**
- Event not vetoed -> no hits in the VETO detectors: straw veto and liquid scintillator: **6.7%**
- All cuts together: **6.87%**

\[ N_{\text{HNL candidates}} = 2756 \quad N_{\text{HNL candidates}_5} = 328.49 \]
HNL candidates: Selection

Channel distribution

Applying all cuts with/without Veto

<table>
<thead>
<tr>
<th></th>
<th>IP&lt;10 cm DOCA&lt;1 cm</th>
<th>IP&lt;250 cm DOCA&lt;10 cm</th>
<th>IP&lt;10 cm DOCA&lt;10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetoed</td>
<td>1.56 (0.2)</td>
<td>29.79 (3.72)</td>
<td>1.91 (0.24)</td>
</tr>
<tr>
<td>Not Vetoed</td>
<td>2.27 (0.28)</td>
<td>328.49 (41.06)</td>
<td>2.87 (0.36)</td>
</tr>
</tbody>
</table>

Correlation of channels which survive: QE/π production/others

QE: $\nu_\mu n \rightarrow \mu^- p$

π production: $\nu_\mu p \rightarrow \mu^- p \pi^+$

$\nu_\mu n \rightarrow \mu^- n \pi^+$

$\nu_\mu n \rightarrow \mu^- p \pi^0$

$\nu_\mu A \rightarrow \mu^- A \pi^+$

HNL candidates in 5 years

In 5 years in case of He (expected background was divided by 8)
HNL candidates: Selection

- Assuming PID 100% efficient the partially reconstructed HNL background candidates goes to zero, since we do not have neutrino scattering events with two leptons final state.
- The fully reconstructed HNL signal has ~1 bkg event expected, due to the $\mu\pi\Lambda$ final state. See Bezhad presentation for details on the result applying the real PID.
- Be aware we don't have a safety margin!
Impact of air between straws

Another generation $\rightarrow$ neutrino interaction points:

- $\frac{x}{249} + \frac{y}{499} \leq 1$
- $-1948 < Z < 2578$

- NO specific volume for air in vacuum vessel, instead of that the air was put everywhere in the cave.
HNL candidates: Selection check

Applying all cuts with/without Veto

<table>
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<tr>
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<th>IP&lt;10 cm DOCA&lt;1 cm</th>
<th>IP&lt;250 cm DOCA&lt;10 cm</th>
<th>IP&lt;10 cm DOCA&lt;10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetoed</td>
<td>1.57 (0.2)</td>
<td>31.99 (3.99)</td>
<td>2.17 (0.27)</td>
</tr>
<tr>
<td>Not Vetoed</td>
<td>2.17 (0.27)</td>
<td>316.1 (39.5)</td>
<td>3.38 (0.42)</td>
</tr>
</tbody>
</table>

HNL candidates in 5 years in case of He (expected background was divided by 8)

Impact of air between straws is negligible

Correlation of channels which survive: QE/ π production/ others

<table>
<thead>
<tr>
<th></th>
<th>IP&lt;10 cm DOCA&lt;1 cm</th>
<th>IP&lt;250 cm DOCA&lt;10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetoed</td>
<td>0 / 0.36 / 1.21 (0 / 0.05 / 0.15)</td>
<td>0 / 5.07 / 26.92 (0 /0.63 /3.37)</td>
</tr>
<tr>
<td>Not Vetoed</td>
<td>0 / 0.36 / 1.81 (0 / 0.05 / 0.23)</td>
<td>0.12/5.8/310.2 (0.02/0.73/38.76)</td>
</tr>
</tbody>
</table>

QE: \[ \nu_\mu \, n \rightarrow \mu^- \, p \, \pi^+ \]
production: \[ \nu_\mu \, p \rightarrow \mu^- \, p \, \pi^+ \]
\[ \nu_\mu \, n \rightarrow \mu^- \, n \, \pi^+ \]
\[ \nu_\mu \, A \rightarrow \mu^- \, A \, \pi^+ \]
\[ \nu_\mu \, A \rightarrow \mu^- \, A \, \pi^0 \]
HNL generation: Selection

Part of simulated HNL after reconstruction which would pass selection.

<table>
<thead>
<tr>
<th>Cut name</th>
<th>Vacuum, %</th>
<th>Air, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event reconstructed</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1 HNL Candidate</td>
<td>97.6</td>
<td>95.3</td>
</tr>
<tr>
<td>Vertex is in the fiducial volume</td>
<td>85.1</td>
<td>82.8</td>
</tr>
<tr>
<td>Tracks are in the fiducial volume</td>
<td>98.1</td>
<td>98.8</td>
</tr>
<tr>
<td>N.d.f &gt; 25</td>
<td>87.6</td>
<td>85.2</td>
</tr>
<tr>
<td>DOCA &lt; 1 cm:</td>
<td>87.0</td>
<td>71.0</td>
</tr>
<tr>
<td>$\chi^2$ / N.d.f &lt; 5:</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Daughters P &gt; 1 GeV:</td>
<td>97.5</td>
<td>96.4</td>
</tr>
<tr>
<td>IP &lt; 0.1 m</td>
<td>91.3</td>
<td>87.6</td>
</tr>
<tr>
<td>Event not vetoed</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>All together</td>
<td>71.4</td>
<td>55.6</td>
</tr>
</tbody>
</table>

Cut name | Vacuum,% | Air,% |
---------|----------|------|
DOCA < 1 cm    | 87.0   | 71.0 |
IP < 0.1 m     | 91.3   | 87.6 |
Event not vetoed| ❌  | ❌  |
All together   | 71.4   | 55.6 |

Cut name | Vacuum,% | Air,% |
---------|----------|------|
DOCA < 10 cm   | 96.9   | 95.6 |
IP < 2.5 m     | 95.0   | 94.7 |
Event not vetoed| ❌  | ❌  |
All together   | 70.8   | 68.3 |
Conclusion

- Studied neutrino scattering in the air at atmospheric pressure
- We expect about 5000 HNL candidate for neutrino in the air
- We expect about 30 (4) neutrino background event in the air (He) for partially reconstructed signal, which goes to zero if we consider that we do not have final states that make background for $\mu \mu \nu$ and $ee\nu$
- We have about 2 HNL background events for the fully reconstructed signal
- The effect on the signal resolution have been studied and it does not change these conclusions
- Simulation with He ongoing
- Need to study the Veto carefully (together with the reoptimization)
- Need to study the impact on the sensitivity of the background assuming some safety factors
- It looks like He is a realistic option
Thank you for your attention!
backup slides
MCTrack[0].GetWeight() \{MCTrack[0].GetWeight() < 5.4\}

<table>
<thead>
<tr>
<th>htemp</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>473797</td>
</tr>
<tr>
<td>Mean</td>
<td>2.225</td>
</tr>
<tr>
<td>Std Dev</td>
<td>1.527</td>
</tr>
</tbody>
</table>
### HNL generation: Selection

Part of simulated HNL after reconstruction which would pass selection.

Data from file of the TP time (from Elena)

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<tr>
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<td>100</td>
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</tr>
<tr>
<td>1 HNL Candidate</td>
<td>97,9</td>
<td>97,9</td>
</tr>
<tr>
<td>Vertex is in the fiducial volume</td>
<td>83,4</td>
<td>83,4</td>
</tr>
<tr>
<td>Tracks are in the fiducial volume</td>
<td>92,6</td>
<td>92,6</td>
</tr>
<tr>
<td>N.d.f &gt; 25</td>
<td>87,0</td>
<td>87,0</td>
</tr>
<tr>
<td>DOCA &lt; 1 cm</td>
<td>87,5</td>
<td>87,5</td>
</tr>
<tr>
<td>χ2 / N.d.f &lt; 5:</td>
<td>99,96</td>
<td>99,96</td>
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<tr>
<td>Daughters P &gt; 1 GeV:</td>
<td>97,0</td>
<td>97,0</td>
</tr>
<tr>
<td>IP &lt; 0.1 m</td>
<td>90,2</td>
<td>90,2</td>
</tr>
<tr>
<td>Event not vetoed</td>
<td>77,8</td>
<td></td>
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All together

| Event not vetoed | 77,6 | 76,9 |
| All together     | 70,8 | 68,3 |
**HNL candidates: Selection**

**Channel distribution**

**Applying all cuts with/without Veto**

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<td>29.79 (249)</td>
<td>1.91 (16)</td>
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<td>2.27 (19)</td>
<td>328.49 (2756)</td>
<td>2.87 (24)</td>
</tr>
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**HNL candidates absolute number**

- Vetoed: 0.2
- Not Vetoed: 0.28

**HNL candidates in 5 years**

- Vetoed: 3.72
- Not Vetoed: 41.06

**In case of He we should divide the number by 8**

**Correlation of channels which survive:**

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<tr>
<td>Vetoed</td>
<td>0 / 0.36 / 1.2</td>
<td>0.12 / 4.54 / 25.12</td>
</tr>
<tr>
<td>Not Vetoed</td>
<td>0 / 0.36 / 1.91</td>
<td>0.12 / 5.98 / 322.39</td>
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HNL generation: Selection

**Part of simulated HNL after reconstruction which would pass selection.**

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<td>IP &lt; 0.1 m</td>
<td>91.3</td>
<td>87.6</td>
</tr>
<tr>
<td>Event not vetoed</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>All together</td>
<td>71.4</td>
<td>55.6</td>
</tr>
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</table>

**Cut name** | **Vacuum,%** | **Air,%**

| DOCA < 1 cm                                  | 87.0     | 71.0 |
| IP < 0.1 m                                   | 91.3     | 87.6 |
| Event not vetoed                             | 77.6     | 76.9 |
| All together                                 | 67.1     | 53.8 |

| DOCA < 10 cm                                 | 96.9     | 95.6 |
| IP < 2.5 m                                   | 95.0     | 94.7 |
| Event not vetoed                             | x        | x     |
| All together                                 | 75.2     | 71.6 |

| DOCA < 10 cm                                 | 96.9     | 95.6 |
| IP < 2.5 m                                   | 95.0     | 94.7 |
| Event not vetoed                             | 77.6     | 76.9 |
| All together                                 | 70.8     | 68.3 |

theHNLcouplings = [0.447e-9, 7.15e-9, 1.88e-9]  # ctau=53.3km
theHNLmass = 1.0*u.GeV
N -> pi+ mu- : yes  # Default channel
HNL candidates: Selection
Charged particles distribution

Distribution of number charged daughters for each event

**IP<10 cm**
**DOCA<1 cm**
**Vetoed**

**IP<250 cm**
**DOCA<10 cm**
**Vetoed**

Distribution of number charged daughters for each event

**IP<10 cm**
**DOCA<1 cm**
**Not Vetoed**

**IP<250 cm**
**DOCA<10 cm**
**Not Vetoed**

**HNL candidates: Selection**

**Charged particles distribution**

**Distribution of number charged daughters for each event**

**chargeHist**

Entries: 13
Mean: 2.885
RMS: 0.4865

**Distribution of number charged daughters for each event**

**chargeHist**

Entries: 249
Mean: 4.058
RMS: 2.335

**Distribution of number charged daughters for each event**

**chargeHist**

Entries: 19
Mean: 4.132
RMS: 2.229

**Distribution of number charged daughters for each event**

**chargeHist**

Entries: 2756
Mean: 7.22
RMS: 3.981
**Step 5**

- **ν** background events with GENIE.
  - consider ν-Fe interactions
  - macro/makeGenieEvents.py

- **Preparation of GENIE:**
  - Provide iron-xsec_splines.xml, Fe26 = 1000260560
    - `gmkSpl -p 14,-14,12,-12 -t 1000260560 -n 500 -e 400`
    - `→ eos/ship/data/xsec_splines-iron-nu_e-nu_mu.xml`

- **Making of events, one file for each neutrino NU = [ν_μ, ¯ν_μ, ν_e, ¯ν_e]:**
  - `gevgen -n N -p NU -t 1000260560 -e 0.5,350 --cross-sections xsec_splines-iron-nu_e-nu_mu.xml`
    - N=10^6 events for ν, ¯ν are scaled to the observed abundance

- **Simplified ntuple for later use in FairShip:**
  - `gntpc -i gntpc.0.ghep.root -f gst`
  - Add 2d histograms P/P_T
  - Move to eos/ship/data/GenieEvents:
    -`genie-nu_mu_bar.root genie-nu_mu.root genie-nu_e_bar.root genie-nu_e.root`

- **Simulation of ν background in FairShip:**
  - `run_simScript.py --Genie -f one of the above files`