Revising sensitivities for HNLs

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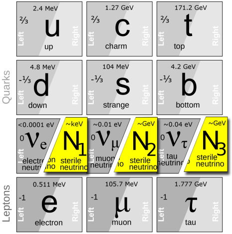
Heavy Neutral Leptons

HNL can explain each of the major BSM phenomena:

- Neutrino masses and oscillations
- Matter-antimatter asymmetry of the Universe
- Dark matter

- Neutrino Minimal Standard Model (ν**MSM**) – resolves **all** above BSM phenomena with **3** HNLs
- More generally: HNL is a part of **neutrino portal**

$$\mathcal{L}_{\text{Neutrino portal}} = F_{\alpha I}(\bar{L}_{\alpha} \cdot \tilde{\Phi}) N_I \ .$$



- HNL was the first model implemented in FairSHiP
- Sensitivity studis presented in TP

Goal of this work

- Review (and check in cases of discrepancies) theoretical predictions and details of implementation in FairSHiP of HNL production and decay
- Improve treatment of HNL decays in the region $M_N > 1$ GeV
- Improved estimates of the production via heavy meson decays
- Some results have been reported at 10^{th} SHiP collaboration meeting as well as at SHiP Physics Meeting

- Theoretical analysis is finished
- Decay channels are organized according to their relevance
- Commits in FairSHiP for all these changes are prepared
- Draft is being prepared

Leptonic channels. Summary

- HNL decay channels into leptons are correctly implemented in FairSHiP (modulo few bugs)

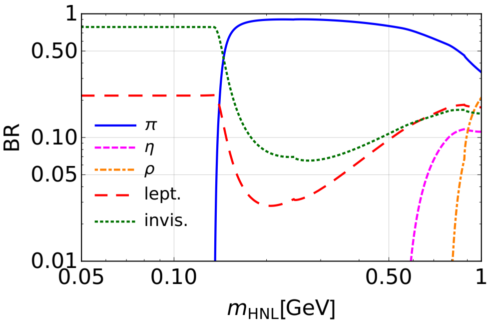
Channel	FairSHiP?	Comments
$N \to 3\nu$		Invisible. Contributes to total width
$N \to \nu\bar{\ell}\ell$		
$N \to \ell'\bar{\ell}\nu$		Some mass corrections were missing. Commits to FairSHiP will be submitted
Total leptonic width		Channels with $N \to \bar{\ell}\ell'\nu$ were counted twice. Commits to FairSHiP will be submitted

Semi-leptonic two-body decays

HNL $\to$ meson $+ \ell/\nu$

- For $150\,\mathrm{MeV} \lesssim M_{HNL} \lesssim 1$ GeV semi-leptonic two-body decay channels dominate the total width

- The first such channels to open are $N \to \pi^{\pm}\ell^{\mp}$ or $N \to \pi^0\nu$
- there was a **factor 2** disagreement in the literature for $N \to \pi^0\nu$ decay width (between **Gorbunov & Shaposhnikov (2007)** and **Atre et al. (2009)**)



- The formula used in FairSHiP implementation is **correct**

Decay to ρ-meson

- Above $770\,\mathrm{MeV}$ decays to ρ-meson become important and dominant
- There was a disagreement in the literature regarding $N \to \rho^0 \nu$ decays width **(Gorbunov & Shaposhnikov 2007; Atre et al. 2009; Helo et al. 2010)**
- We found that **none of them** are correct
- The correct expression has an extra factor $(1 - 2\sin^2\theta_W)^2$ as compared to FairSHiP implementation

$$\Gamma(N \to \nu_\alpha \rho^0) = \frac{G_F^2 g_\rho^2 \,(1 - 2\sin^2\theta_W)^2\, |U_\alpha|^2 M_N^3}{16\pi m_\rho^2} \left(1 + 2x_\rho^2\right)\left(1 - x_\rho^2\right)^2$$

(and factor 2 larger for Majorana case). $x_\rho = \frac{m_\rho}{M_N}$

- Constant g_ρ should be determined from the τ-lepton decay $\mathrm{BR}(\tau \to \nu\rho)$
- We get $g_{\rho,\tau} = 0.115\,\mathrm{GeV}^2$ (FairSHiP uses $g_\rho = 0.102\,\mathrm{GeV}^2$ which gives 26% difference in the decay width)

Two-body decays. Summary

Channel	FairSHiP?	Comments
$N \to \pi(\nu/\ell)$		
$N \to \rho^{\pm}\ell$		Wrong value of the ρ-meson decay constant, about 25% error. Commits to FairSHiP will be submitted
$N \to \rho^0\nu$		Disagreement in the literature regarding the decay width to ρ^0. The formula used in FairSHiP is **not correct**. Commits to FairSHiP will be submitted
$N \to (\eta/\eta')\nu$		Discrepancies in the values of decay constants in the literature
$N \to \phi\nu$		Not in FairSHiP. Can be used to include $2K$ final states
$N \to D_s^{(*)}\ell$		Not in FairSHiP. Adds between 50% and 110% to one-meson decay widths for $M_N = 3 \div 5$ GeV

Multimeson final states

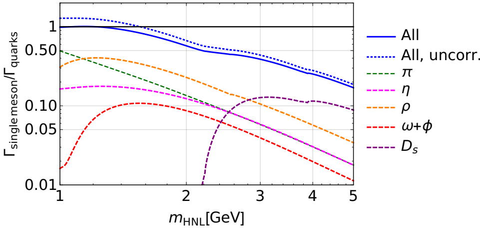
To estimate relative importance of multi-meson final states we need to know the full **hadronic decay width**

Full hadronic width of HNL

Currently in FairSHiP **hadronic decay width** is estimated

- as sum of single-meson channels below $1\,\mathrm{GeV}$
- as a tree-level decay to quarks above $2\,\mathrm{GeV}$
- **Linear** interpolation in-between

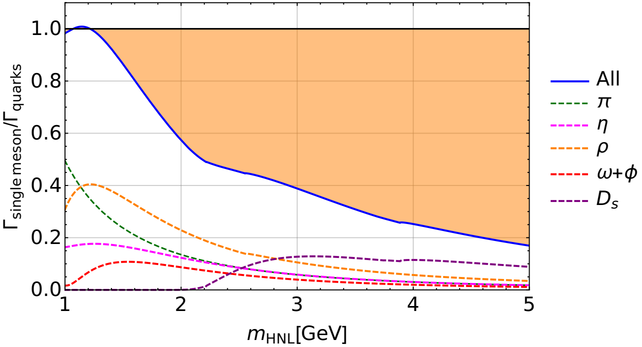
- To estimate the total hadronic decay width we have computed decays to quarks
- We included QCD corrections (known for hadronic decays of τ) by scaling $\alpha_s(m_\tau) \to \alpha_s(M_N)$ (For τ-lepton this gives the full hadronic width within few %)



Full hadronic width. Summary

Channel	FairSHiP?	Comments
$N \to \bar{q}q'\nu$		Only tree-level corrections were included in the estimate of Γ_{hadronic}. Incorrect numerical factors for CC and NC decays
Full hadronic decay width		Propose to match sum of single-meson channels and decay into quarks (with QCD corrections) at $\sim 1.2\,\mathrm{GeV}$

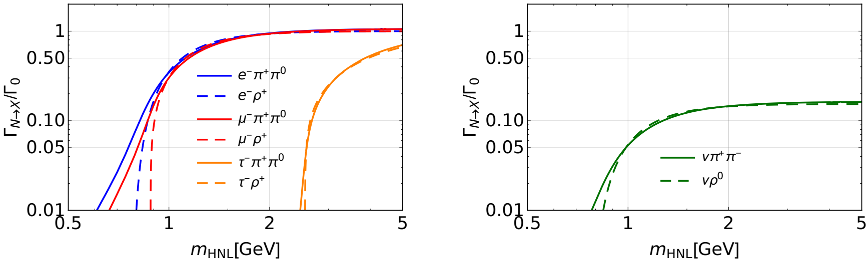
Multi-meson states



- From comparison between total hadronic width and sum of single-meson channels we see that above $\sim 1.2\,\mathrm{GeV}$ multi-meson states are important
- They can constitute up to 80% of all hadronic decays

Two pion decay channel vs. decay to ρ-meson

- The first kinematically allowed **multi-meson** state is
  - $N \to \pi^+\pi^0\ell^-$ (CC mediated)
  - $N \to \pi^+\pi^-\nu$ (NC mediated)
- Two-body decay $\boxed{N \to \rho X}$ **saturates** $N \to \pi\pi\ell$ and $N \to \pi\pi\nu$



Decay to 3 pions

- The most relevant decay channel among those that are not implemented in FairSHiP are 3π decays:
  - $N \to \nu_\alpha (3\pi)^0$
  - $N \to \ell_\alpha^- (3\pi)^+$
- For NHL with $M_N > m_\tau$ we expect even larger branching than 18.2% (as in case of τ)

Branching ratios $\tau^- \to \nu_\tau + X^-$	[%]
$\tau \to \nu_\tau + \pi^-$	10.8
$\tau \to \nu_\tau + \pi^- \pi^0$	25.5
$\tau \to \nu_\tau + 3\pi$	18.2
$\tau \to \nu_\tau + 4\pi$	6
$\tau \to \nu_\tau + 5\pi$	$\mathcal{O}(1)$
$\tau \to \nu_\tau + K^-$ or $K^- \pi^0$	$\mathcal{O}(1)$
$\tau \to \nu_\tau + K^- K^0$	$\mathcal{O}(0.1)$
$\tau \to \nu_\tau + K^- K^0 \pi^0$	$\mathcal{O}(0.1)$

- Decays are (mostly) mediated via a_1 meson and can be computed in analogy with ρ-meson

Multimeson channels. Summary

Channel	FairSHiP?	Comments
$N \to 2\pi(\ell/\nu)$		Equivalent to decay into ρ
$N \to n\pi(\ell/\nu)$, for $n > 2$ and $N \to 2K\nu$		To increase sensitivity for $M_N > 1\,\mathrm{GeV}$ we should include 3π and 4π channels. We will implement these channels in FairSHiP
$N \to n\pi K\ell$, $N \to K^+K^0\ell^-$		These channel are suppressed

HNL decay channels are listed in the draft in the order of relevance

Channel	Open, MeV	Rel. from, MeV	Rel. to, MeV	Max BR, %	Formula
$N \to \mu^- \nu_e e^+$	106	315	—	5.15	(3.1)
$N \to \nu_\alpha \mu^+ \mu^-$	211	441	—	4.21	(3.5)
$N \to \nu_\alpha \eta$	548	590	4160	11.1	(3.8)
$N \to e^- \pi^+ \pi^0$	275	666	4550	10.4	(3.16)
$N \to \nu_\alpha \pi^+ \pi^-$	279	750	3300	4.81	(3.17)

Production of HNLs

- HNLs are produced in leptonic and semi-leptonic decays of charmed and beauty hadrons
- Leptonic and main semi-leptonic 3-body decay channels have been implemented in FairSHiP (modulo some bugs)

- Leptonic decays: $B^{\pm} \to \ell^{\pm} N$
- Decays to D-mesons: $B \to D \ell N$
- Decays to D^*-mesons: $B \to D^* \ell N$

Reminder from the 10th SHiP meeting

Is it enough to consider only several main channels of production or should we aim at **inclusive** HNL production cross-section?

Our conclusions

- Current FairSHiP implementation captures $\mathcal{O}(70\%)$ of all HNL produced via B-meson
- Trying to modify inclusive cross-section of semi-leptonic B-dcays (with ν in the final state) to account for different kinematic of HNL introduces errors of comparable level (that are not easy to control)
- Implementation of $b \to u$ transitions (e.g. $B \to \pi \ell N$) roughly doubles HNL production cross-section at $M_N \sim 3\,\mathrm{GeV}$

Some of these results were presented at Thursday Physics Meeting in March

What are the leading channels in decays $B \to X \ell \nu_\ell$?

Semileptonic decays of B mesons to massless neutrino

PDG (2017)

Decay $B^+ \to \ell^+ \nu_\ell X$		BR [%]
Inclusive branching:		11.0 ± 0.3
Dominant one-meson channels:	$\overline{D}^0 \ell^+ \nu_\ell$	2.27 ± 0.11
	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	5.7 ± 0.19
Two above channels together:		8.0 ± 0.2
Channels with 2 meson:	$D^- \pi^+ \ell^+ \nu_\ell$	0.42 ± 0.05
	$D^{*-} \pi^+ \ell^+ \nu_\ell$	0.61 ± 0.06
Sum of other multimeson channels, $n > 1$:	$\overline{D}^{(*)} n\pi \ell^+ \nu_\ell$	1.26 ± 0.27

Decay $B^0 \to \ell^+ \nu_\ell X$		BR [%]
Inclusive branching:		10.33 ± 0.28
Dominant one-meson channels:	$D^- \ell^+ \nu_\ell$	2.19 ± 0.12
	$D^*(2010)^- \ell^+ \nu_\ell$	4.93 ± 0.11
Two above channels together:		7.12 ± 0.16
Channels with 2 meson:	$\overline{D}^0 \pi^- \ell^+ \nu_\ell$	0.43 ± 0.06
	$\overline{D}^{*0} \pi^- \ell^+ \nu_\ell$	0.49 ± 0.08
Sum of other multimeson channels, $n > 1$:	$\overline{D}^{(*)} n\pi \ell^+ \nu_\ell$	1.8 ± 0.5

Semileptonic B-meson decay channels with a single vector or pseudoscalar meson in the final state saturate 70% of the total semi-leptonic width

All this is relevant for HNL $m_D < M_N < (m_B - m_D)$

Inclusive production?

- At 10th SHiP collaboration meeting (**Talk by Patrick Owen**) it was suggested that one can use "reverse engineering" of the JETSET and extract needed data about hadronic matrix elements
- To this end differential decay width $\frac{d\Gamma(B\to\nu_\alpha\ell_\alpha X)}{dq^2}$ was extracted (q^2 – invariant mass of lepton pair)
- The idea was that to substitute neutrino with **massive HNL** it is enough to rescale the differential decay width:

$$\frac{d\Gamma(B\to N\ell X)}{d\Gamma(B\to\nu\ell X)}\sim\left(1-\frac{M_N^2}{q^2}\right)^2\left(1+\frac{M_N^2}{2q^2}\right),\quad\text{with}\quad q^2>M_N^2 \tag{1}$$

Neutrino vs. HNL in semileptopic decays I

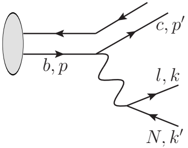
- Matrix element for the process $b \to u + \ell + \nu$ **factorizes**:

$$|\mathcal{M}|^2 = \frac{G_F^2}{2} |V_{ckm}|^2 L^{\mu\nu} H_\mu H_\nu^\dagger \tag{2}$$

- When changing $\nu \to N$ the **lepton matrix element $L^{\mu\nu}$** changes

- **Hadronic matrix element $H_\mu H_\nu^\dagger$** does not change **but** the integration limits change

- The matrix element of depends on 2 invariant variables, say q^2 and $\tilde{q}^2 = (k + p')^2$, where $\tilde{q}$ depends on c quark 4-momentum and decay width



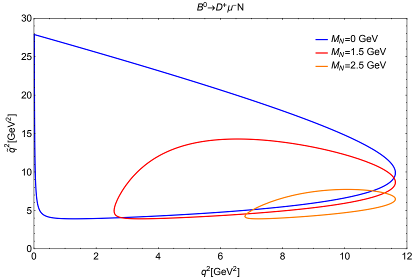
$$\Gamma \propto \int_{(M_N+m_l)^2}^{(M_B-M_D)^2} dq^2 \int_{q_1^2}^{q_2^2} d\tilde{q}^2 \left|\mathcal{M}(q^2, \tilde{q}^2)\right|^2 \tag{3}$$

Inclusive vs. exclusive production

- The width is given by

$$\Gamma \propto \int_{(M_N+m_l)^2}^{(M_B-M_D)^2} dq^2 \int_{q_1^2}^{q_2^2} d\tilde{q}^2 \left|\mathcal{M}(q^2,\tilde{q}^2)\right|^2 \quad (4)$$

- The dependence of the matrix element on $\tilde{q}^2$ and q^2 is non-trivial
- The above method extracts only q^2 dependence, $\tilde{q}^2$ dependence is integrated out in uncontrollable way



Exclusive $b \to u$ transitions

- Decay $B \to \pi \ell N$ is suppressed w.r.t. $B \to D \ell N$ by 10^2
  CKM elements $V_{ub}/V_{cb} \approx 0.1$
- Decays $B \to \pi \ell N$ (or any other X_u) **not implemented in FairSHiP**
- Above $m_B - m_D$ threshold HNLs are produced via $B \to \ell N$ **or** $B \to X_u \ell N$