Dark Scalars and Heavy Neutral Leptons at the Fermilab SeaQuest Experiment

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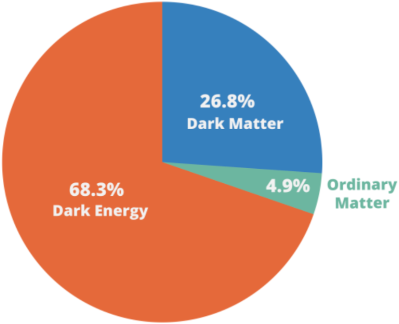
Contents

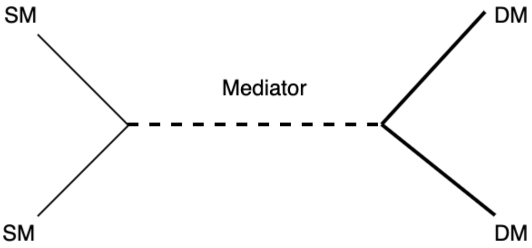
Motivation

- Existence of Dark Matter (DM) has been confirmed by many astrophysical and cosmological observations.
- Hidden sector particles with feeble couplings to Standard Model (SM) are acting as mediators between DM and SM particles providing a viable channel in understanding DM.



Motivation

- Probing these long lived mediators (Decay length $\sim$ few metres) directly is possible at many experiments, even with very small couplings!
- In this study, we focus on HNL and Higgs portals and do a simplistic analysis for detection at SeaQuest.



SeaQuest experiment

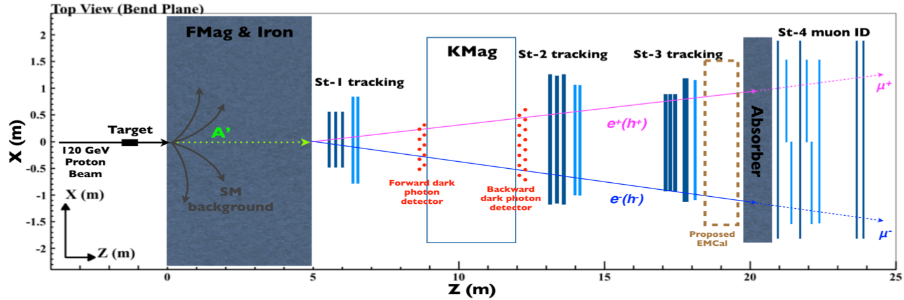


Figure: SeaQuest setup.

Minimal Model for Dark Scalar

- We consider a simple model for the Scalar portal with small mixing to Higgs:

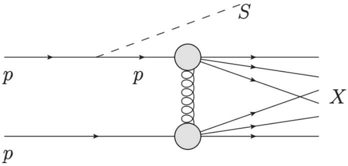
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S + (a_1 S + a_2 S^2)(H^\dagger H) - \frac{m_S^2}{2} S^2.$$

- After EWSB, we transform the Higgs field to get the mass basis via $h \to h + \theta S$, generating interactions of S to SM particles:

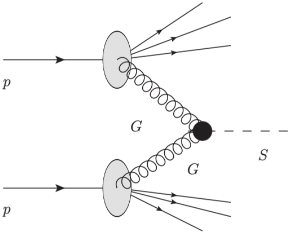
$$\mathcal{L}_{SM}^{S} = -\theta \frac{m_f}{v} S \bar{f} f + 2\theta \frac{m_W^2}{v} S W^+ W^- + \theta \frac{m_Z^2}{v} S Z^2$$

Dark Scalar Production

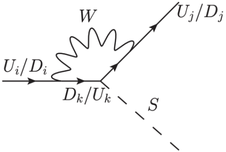
- We consider the following production channels (Boiarska et al., 2019):



(a) Bremstrahlung



(b) Gluon Fusion



(c) B decay

Dark Scalar Production

- Proton Bremsstrahlung can be calculated using the generalized WW method, re-expressing the total cross section in terms of the pp cross section (Boiarska et al., 2019).
- The theoretical uncertainties come from form factor and WW approximation.
- The main contribution for the DIS production comes from $gg \rightarrow S$ which dominates $qq \rightarrow S$. Validity: $m_S > 1$ GeV, via perturbative QCD.
- For meson decay, the main channel is $B \rightarrow X + S$. Although, for $m_\phi < O(100)$ MeV, K decay is more important, it is constrained by previous beam dump experiments.

Dark Scalar Production

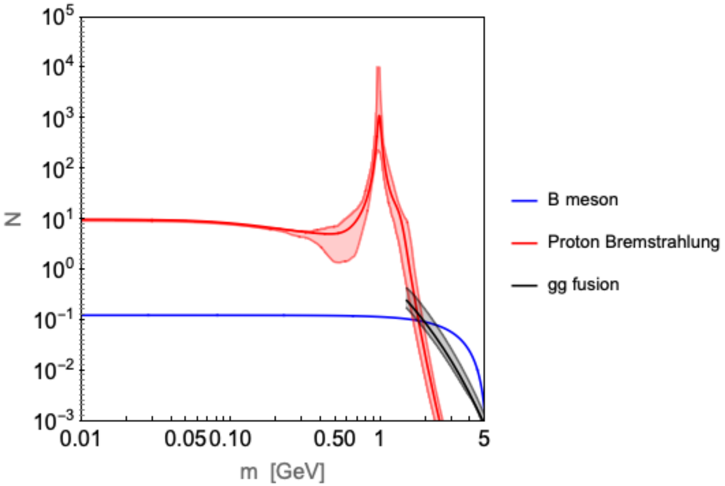


Figure: Production via different channels: $\theta = 10^{-6}$, $E_{beam} = 120$ GeV and POT$= 10^{20}$.

Dark Scalar Decay

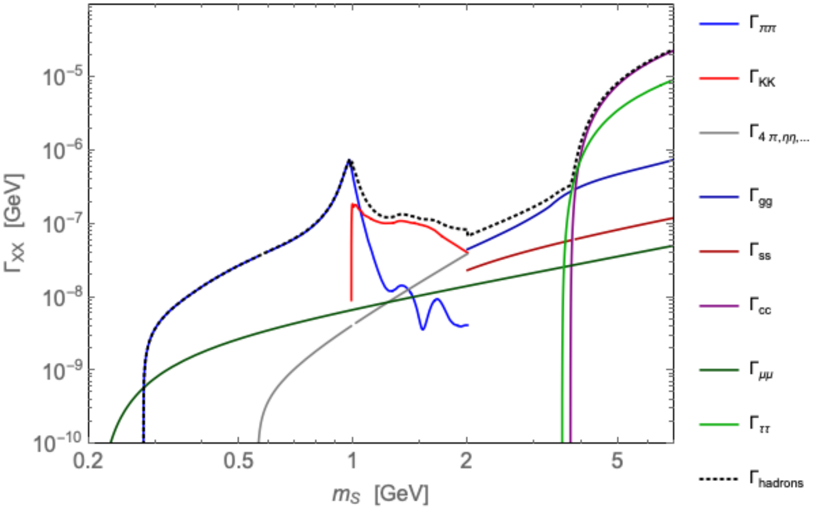


Figure: Decay channels following [Winkler, 2019] with focus on $S \to l^+l^-$ and $S \to \pi^+\pi^-, S \to K^+K^-$.

Detection

- Three stage process :
  1. DS production.
  2. Traverse through some length (metre scale) inside detector.
  3. Decay into SM particles.
- Number of events: $N_{Sig} = N_{prod} \times eff \times BR$
  N: produced DS particles, BR: Branching ratio to $l^{\pm}$, $h^{\pm}$ and efficiency entails the probability for DS particle to decay within the detector.
- Signal Bands in the plots comes from the theoretical uncertainties in production rates as well as decay rates of DS.

Dark Scalar : Signal events at SeaQuest

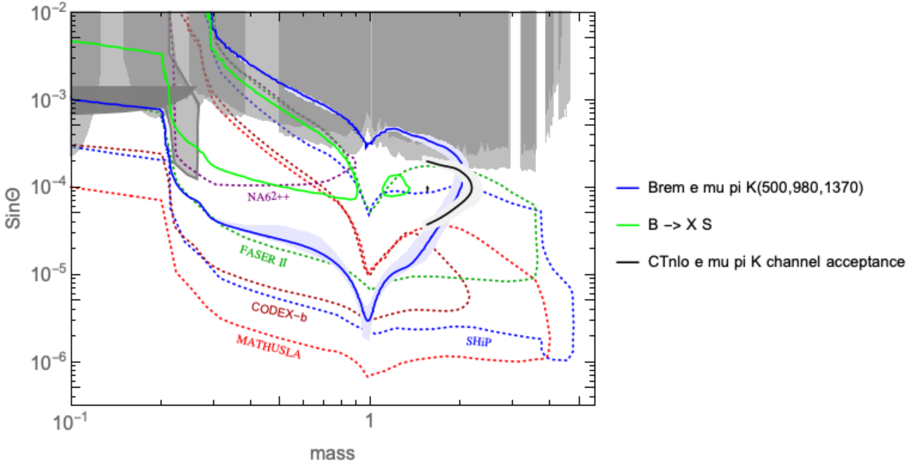


Figure: Signal Events for e, μ, π, K channels. The plot corresponds to 10 Signal events for different m_S and θ values (E_{beam} = 120 GeV, POT= 10^{20}).

Heavy Neutral Leptons : Model

- We consider Heavy Neutrino N, a SM singlet, via:

$$\mathcal{L}_{\mathrm{HNL}} = i\bar{N}\partial\!\!\!/ N + \left(M_\alpha^D \bar{\nu}_\alpha N - \frac{M_N}{2} \bar{N}^c N + h.c. \right)$$

- After mass mixing, N will interact like SM ν, with a small mixing $U_\alpha = M_\alpha^D M_N^{-1}$.

$$\mathcal{L}_{int} = \frac{g}{2\sqrt{2}} W_\mu^+ \overline{N^c} \sum_\alpha U_\alpha^* \gamma^\mu (1-\gamma_5) \ell_\alpha^- + \frac{g}{4\cos\theta_W} Z_\mu \overline{N^c} \sum_\alpha U_\alpha^* \gamma^\mu (1-\gamma_5) \nu_\alpha + \mathrm{h.c.}\ ,$$

Production Channels

- The prominent channels are production via B and D meson (semi)-leptonic decays.
- For B Decay, we consider $B^+ \to l + N$, $B \to l + D + N$, $B \to D^* + l + N$, rest are subdominant.
- For D Decay, we consider $D^+ \to l + N$, $D \to l + K + N$, rest are subdominant.

Production channels

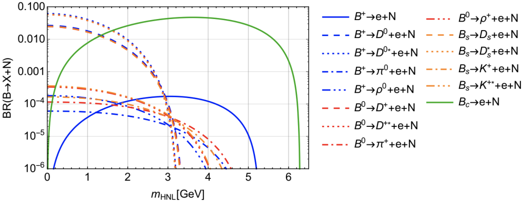


Figure: $B \rightarrow X\ N$ for $U_e = 1$ [Bondarenko et al '18]

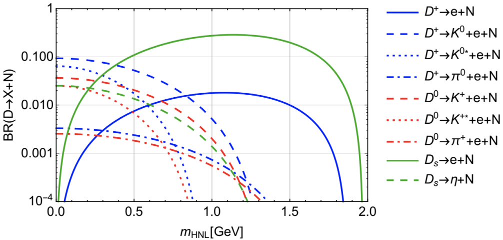


Figure: $D \rightarrow X\ N$ for $U_e = 1$ [Bondarenko et al '18]

Decay Channels

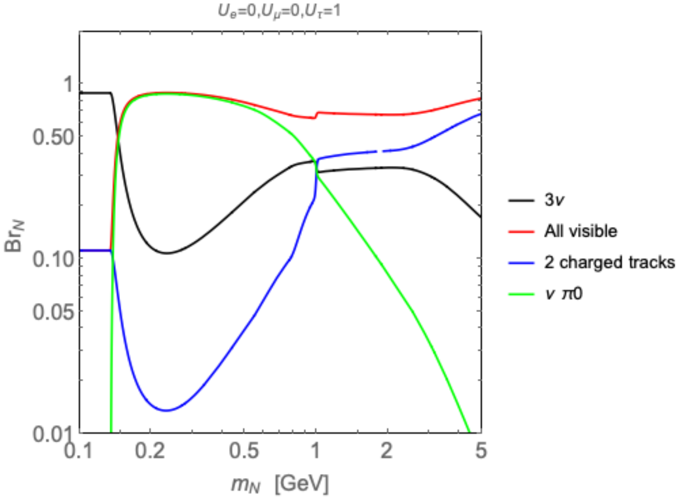


Figure: Decay plot for HNL with $U_e = 0, U_\mu = 0, U_\tau = 1$. For sensitivity, we use the 2 Charged track (blue line).

Sensitivity

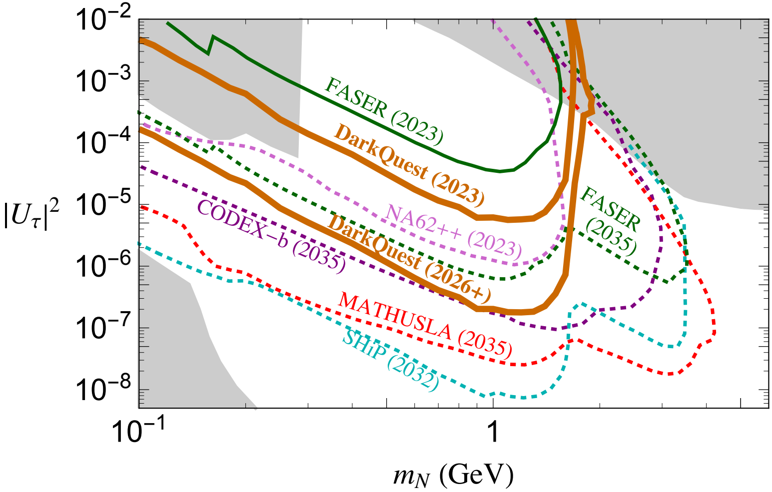


Figure: Sensitivity for HNL with $U_e = 0, U_\mu = 0, U_\tau = 1$.

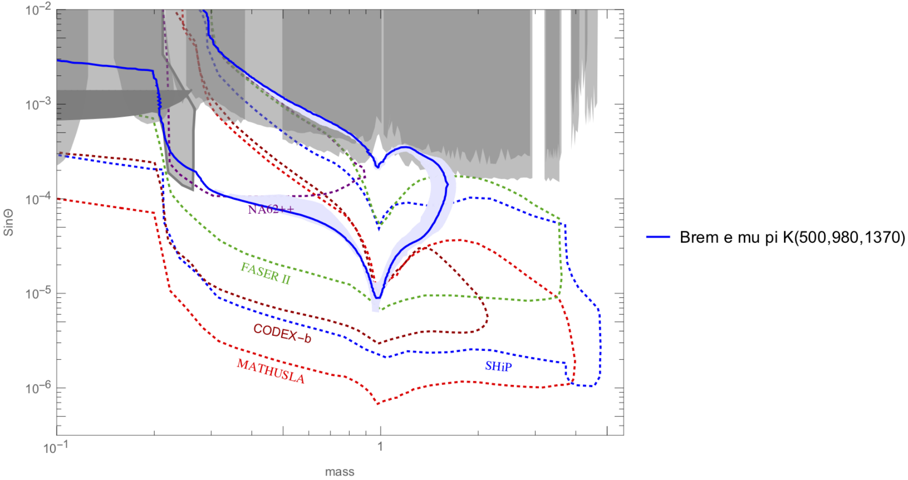
Conclusion

- We analyze the sensitivity of the Fermilab SeaQuest experiment to GeV-scale dark scalars and heavy neutral leptons (HNL).
- We consider a variety of production mechanisms and study a variety of displaced final state signatures for these light exotic new particles.
- SeaQuest has the potential to probe significant new regions of parameter space in these scenarios on a time scale that is competitive with or better than other planned experiments.

Backup Slides - Form Factor for Scalar

- Timelike Form factor $FF(t)$ for S-p-p vertex is parametrized using 3 resonances $f_0(500), f_0(980), f_0(1370)$.
- We parametrize the Form factor as, $ff(t) = \Sigma_j \frac{f_j}{1 - i\frac{\Gamma_j}{m_j} - \frac{t}{m_j^2}}$. The conditions we use to get coefficients f_j are
  1. $\Re[FF(0)] = 1$
  2. $\Im[FF(0)] = 0$
  3. $\lim_{t->\infty} FF(t) \sim 1/t^2$
- Theoretical uncertainties arise from PDG uncertainties in the mass and width for these scalar resonances.

- POT $= 1.44 \times 10^{18}$, PHASE 1



Sensitivity for μ mixing HNL

- Sensitivity for N with $U_e = 0, U_\mu = 1, U_\tau = 0$:

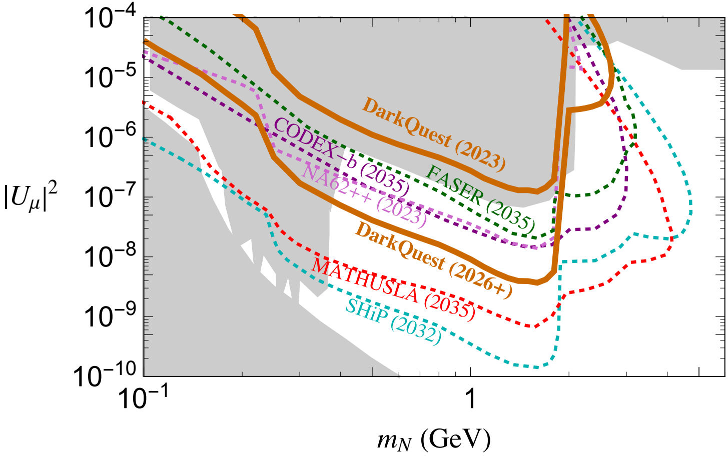


Figure: Sensitivity of HNL