Fixed Target Probes of Light Dark Scalars

Based on 2004.14515 [SF & A. Ritz '20] CAP 2021

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Overview

1. Motivations to new physics BSM
2. Hidden sector portals
3. Probing Higgs portal at fixed target experiments
4. Existing constraints & future projection on dark scalars
5. Light scalars production & sensitivity reach at LSND

Empirical Evidence for Physics BSM

Dark Matter

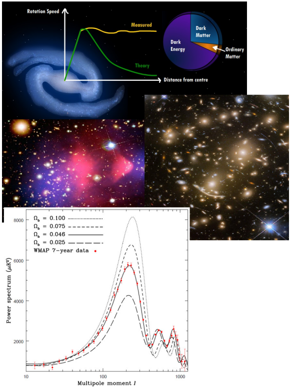
CMB power spectrum
Cluster and galactic rotation curves
Gravitational lensing

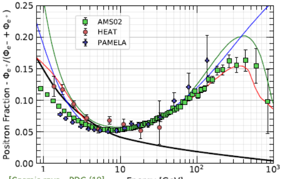
Neutrino Oscillations & Mixing

mixing between the flavor and mass eigenstates of neutrinos
Sterile neutrinos

Anomalies, e.g. the cosmic ray excess

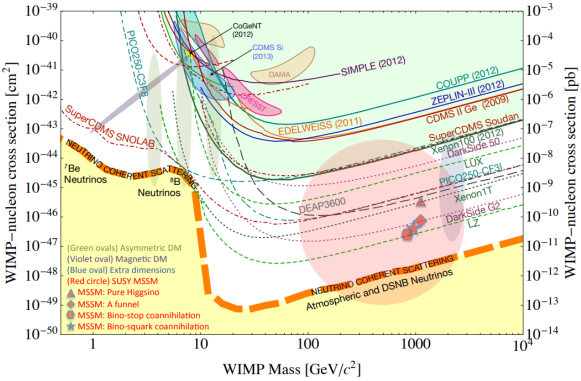
Observations of the e^+ excess by PAMELA & AMS II $\Rightarrow$ Potential hint of enhanced DM annihilation mediated by light force carriers





WIMP-like (thermal relic) DM

For sub-GeV DM:
$m_e < m_{\rm DM} < m_{\rm had}$
a high intensity relativistic beam is advantageous, as direct detection sensitivity drops due to recoil thresholds

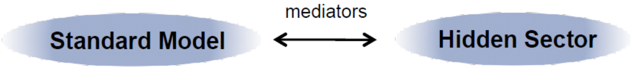


[Snowmass Summary; Cushman et al. '13]

$$\Omega_\chi h^2 \propto \frac{1}{<\sigma v>}\ ,\ \sigma_{\rm ann} \propto \frac{m_{\rm DM}^2}{M_{\rm mediator}^4}$$

Viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states as part of a hidden sector [Pospelov et al '07]

EFT for a (neutral) hidden sector

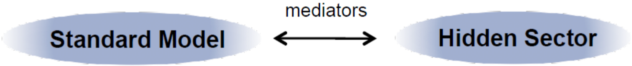


$$\mathcal{L}_{mediation} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(\mathrm{SM})}\mathcal{O}_l^{(\mathrm{med})}}{\Lambda^n} \sim \mathcal{O}_{\mathrm{portals}} + \mathcal{O}(\frac{1}{\Lambda})$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal "portals" to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\epsilon}{2\cos\theta_w} B^{\mu\nu} F'_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H(AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = y_N \bar{L} H\, N$

(Minimal) Higgs portal and light scalars



$$\mathcal{L} \supset -ASH^\dagger H$$

- A potential extension of the Higgs sector
- Consider the DM scenario $m_S < 2m_{DM}$
  The light scalar S acts as a force mediator between fermionic DM and SM
- Interested in sub-GeV mass range:

Induced couplings after EWSB

$$\mathcal{L} \supset -\theta S \left(\frac{m_f}{v} \bar{f} f + g_{S\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + g_{SNN} \bar{N} N + \cdots \right)$$

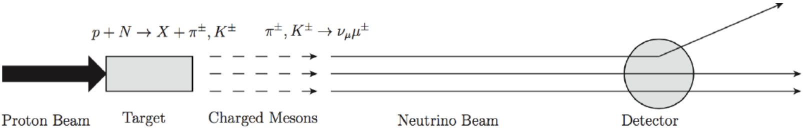
$\theta \simeq Av/m_h^2 \ll 1$

$g_{S\gamma\gamma} = \frac{\alpha}{8\pi v} F_\gamma(m_S)$

$g_{SNN} \sim 1.2 \times 10^{-3}$

Fixed target probes - Neutrino Beams

- Ability to probe the hidden sector experimentally?
- Advantage of fixed targets compare to colliders [Batell, pospelov, Ritz '09]
- Long-Baseline Neutrino Experiments: ν beams generated by high-intensity proton sources directed on fixed targets reach the (near) detector set up.



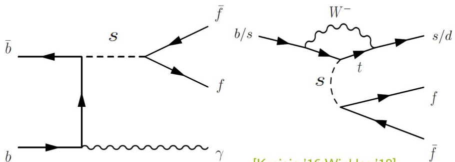
- Consequence of a HS: production of a high intensity "new weakly coupled light mediator beam" followed by the decay (or recoil) in the detector [Batell et al '09, '14]

  $\Rightarrow$ an additional contribution to events

Fixed target probes - Scalar production and signature

Production modes

- Direct production
  $p+A \to S+X$ e.g. bremsstrahlung
- Secondary hadronic decays
  $p+A \to H+X \Rightarrow H \to S+X$
- The most relevant processes: flavor changing rare B and K meson decays + radiative Υ decays.
  $B \to K + S$ for $m_S < m_B - m_K$
  $K \to \pi + S$ for $m_S < m_K - m_\pi$



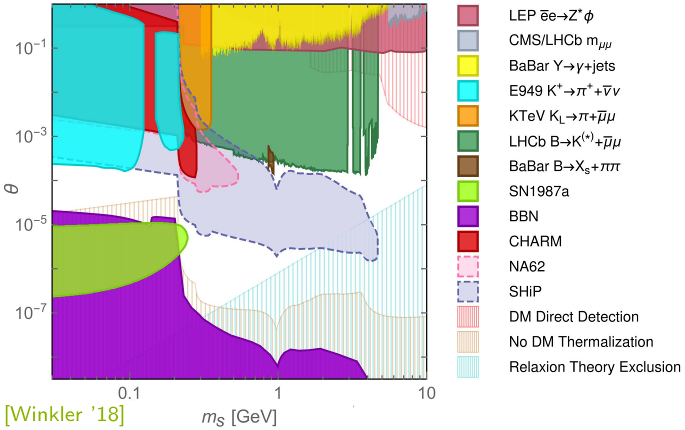
[Krnjaic '16;Winkler '18]

Analysis

- Number of S produced under the Higgs portal scenario?
- Probability that a produced S mediator will reach the detector?
  $$P_{\rm decay} = e^{-L_i/\gamma\beta\tau} - e^{-L_f/\gamma\beta\tau}$$
- How likely is that the decay $S \to l^+l^-, \pi\pi, KK, \ldots$ produce an event?

  Number of events: $N_S \times P_{\rm det}$
  $$P_{\rm det} \sim \left(\frac{\gamma^2\Omega_{lab}}{4\pi}\right) \times P_{\rm decay} \times \epsilon_{\rm eff}$$

Constraints on dark scalars through Higgs Portal



[Winkler '18]

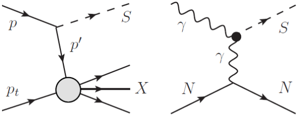
@ E949 & NA62 (kaon-mode): Rare decay measurement of $K^+ \to \pi^+ \nu\bar{\nu}$, interpret as $K^+ \to \pi^+ S$.

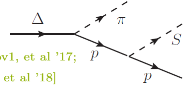
@ CHARM: Bounds on ALP ($S \to l^+ l^-$)

@ LHCb & Belle: Visibly decaying of S contributes to $B \to K l^+ l^-$ (bump hunt)

Light scalar production at LSND

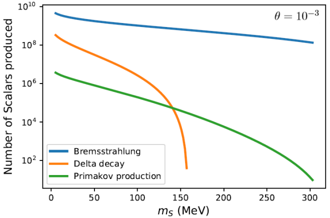
- The largest proton on target data sets of any fixed target experiment: over 10^{23} POT
- Important constraint on low mass A': pseudoscalar meson decay, e.g. large $\text{Br}(\pi \to A'\gamma) \sim \epsilon^2$ leads to $N_{A'}^{(\pi)} \sim \epsilon^2 N_\pi$.

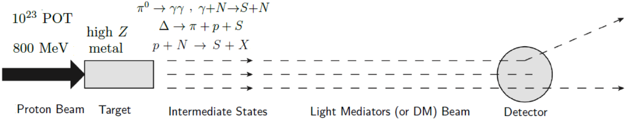




[Pospelov1, et al '17; Döbrich et al '18]

- At LSND: π and Δ are the relevant hadronic dof. K and B mesons are not kinematically accessible.
- Normalized production rate [SF, Ritz '20]



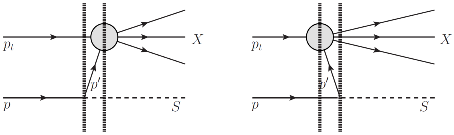


Proton bremsstrahlung - splitting function

OFPT

Approximate the rate in terms of the pp cross-section and a calculable sub-process [Altarelli, Parisi] [Boiarska '19]

Two possible time orderings exchanging the intermediate state p':



emit absorb

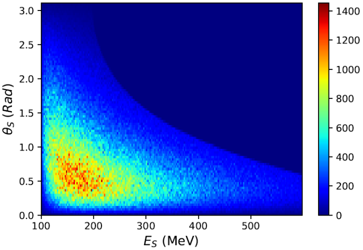
$$\mathcal{M}^{\text{emit}} = \frac{\mathcal{M}_{p\to p'S}\mathcal{M}_{pp'\to X}}{2E_{p'}(E_p - E_S - E_{p'})}$$

$$\mathcal{M}^{\text{absorb}} = \frac{\mathcal{M}_{p\to p'X}\mathcal{M}_{pp'\to S}}{2E_{p'}(E_S - E_p - E_{p'})}$$

$$\mathcal{M}^{emit} \gg \mathcal{M}^{absorb}$$

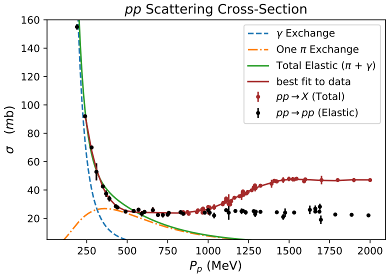
$$\frac{d\sigma_{pp_t\to SX}}{dz\,dp_T^2} \approx P_S^{\text{split}}(z, p_T)\sigma_{pp}(s')$$

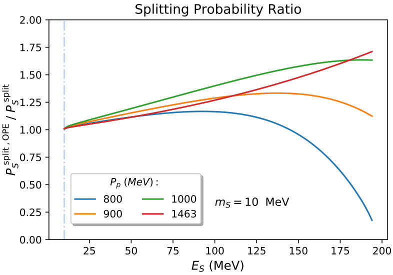
Verified that this condition is satisfied to a few percent for LSND kinematics if $z \in [0, 0.5]$ and $p_T < 300$ MeV



$pp \to ppS$ via OPE - complementary approach

- Modelling of pp scattering at sub-relativistic beam energies via One Pion-Exchange. Additional processes (e.g. two pion exchange) become important for $P_p \gtrsim 600\text{-}700$ MeV.
- Inelastic contribution to σ_{pp} via Δ-resonance important at moderately relativistic beam proton. [PDG '06]
- At low P_p: the rate calculation agrees with the splitting probability of the proton to emit S via OPE at the $\mathcal{O}(1)$ level. [SF, A. Ritz '20]



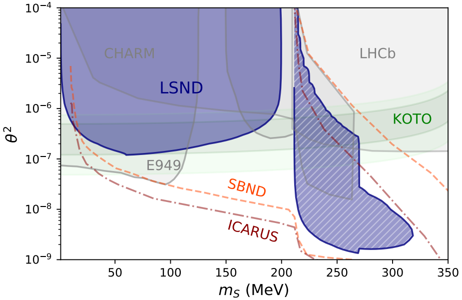


Sensitivity at LSND

Neutrino backgrounds

- LSND Collab. analysis:
  $\nu_e + {}^{12}C \to e^- + X$
  $\nu_\mu + {}^{12}C \to \mu^- + p + X$
- Assumption: $e^+e^-(\mu^+\mu^-)$ pairs produced are indistinguishable from single electrons (muons)
- Kinematic cuts:
  $60 < E_S < 200$ MeV for e^-
  $160 < E_S < 600$ MeV for μ^-
  efficiency ~ 0.1
- Number of beam-excess events < 20
- Br$(S \to l^+l^-) \simeq 1$

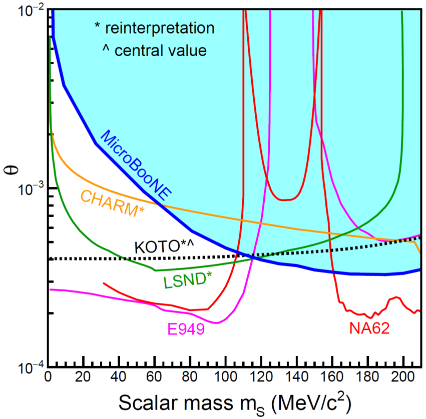
The leading constraint in a small window in scalar mass from 120 to 180 MeV & from $2m_\mu$ up to 320 MeV. [SF, A. Ritz '20]



- KOTO provides sensitivity through the neutral decay channel $K_L \to \pi^0 \nu\bar{\nu}$

Search for a Higgs Portal scalar in MicroBooNE

Search for mono-energetic scalars from the NuMI hadron absorber and decaying to electron-positron pairs. [MicroBooNE Collab. '21] n



Upper limit on the scalar–Higgs mixing angle θ for masses in the range 100-200 MeV.

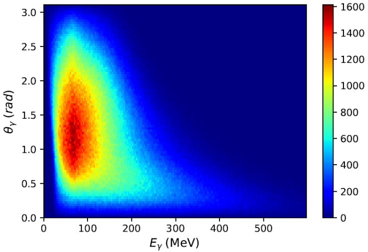
Conclusion

- Light sub-GeV thermal relics are difficult to probe using conventional direct detection experiments.
- High-luminosity fixed target experiments provide impressive sensitivity to new light weakly coupled degrees of freedom.
- Revisited: the minimal model of scalar singlet coupled to the SM through the Higgs portal, decaying visibly to leptons for masses below 350 MeV.
- Proton bremsstrahlung is found to be the dominant S production mechanism at LSND beam energies.
- LSND experiment imposes the leading constraints within two mass windows between $m_S \sim 150$ and 350 MeV.
- Among the possible future analyses is the NA62 at CERN which provides greater sensitivity to $K^+ \to \pi^+ + invisible$ at low S mass.
- (SBN) program at Fermilab could also provide new sensitivity to the Higgs portal. [Batell et al '20]

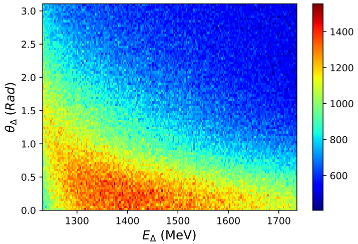
Thanks for your attention!

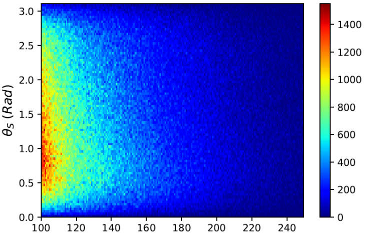
Backup Slides

photon distribution from π_0 decay



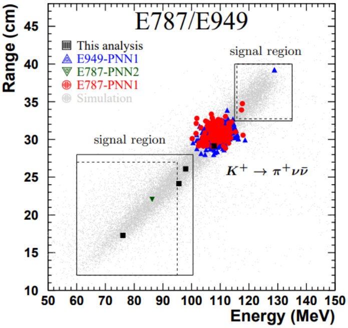
Δ distribution in lab frame





$K^+ \to \pi^+ \nu\bar{\nu}$ at E949 experiment

Kinetic energy vs. range of all events $K^+ \to \pi^+ \nu\bar{\nu}$



Upper limit on Br($K^+ \to \pi^+ X$) assuming X is stable

S can escape the detector before decaying