SHIP BSM Signals

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SHiP

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Introduction

- We know the SM can't be complete but no significant hints of NP at the GPD experiments
  - Could have a low coupling → feebly interacting particles (FIPs)
  - Low coupling tends to lead to long lifetimes → long-lived particles (LLPs)

- Efficiently exploring these needs a dedicated experiments
  - Transverse or forward of colliders (e.g. FASER, Mathusala)
  - At proton beam dumps (e.g. SHIP)

- SHIP is designed to search for low-mass ($m < 5$ GeV) FIPs
  - Slamming protons into targets produces copious number of D, and large number of B, mesons
  - These could decay immediately into FIPs in narrow solid angle
  - Look for subsequent decays of FIPS while vetoing backgrounds to near 0 level

- Can also search for neutrinos using dedicated scattering neutrino detector (SND)
  - Large statistics and allows study of tau neutrino, but will not cover this here
  - SND can also serve as scatterer for light dark matter → additional BSM search avenue

Target Physics Models

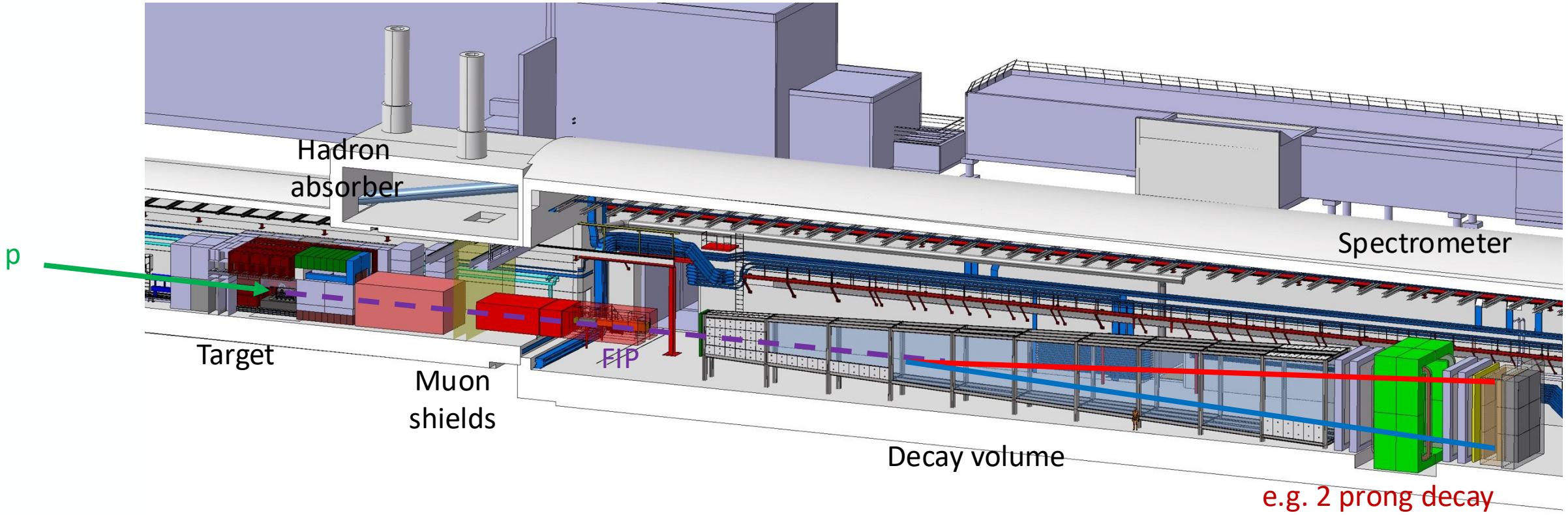
- Strong sensitivity to large variety of hidden sector models (assuming can reach zero background)
  - With various decay signatures to neutral or charge particles; 2- or multi-prong

	Physics model	Final state
HSDS	SUSY neutralino	$\ell^{\pm}\pi^{\mp},\ \ell^{\pm}K^{\mp},\ \ell^{\pm}\rho^{\mp}, \ell^{+}\ell^{-}\nu$
	Dark photons	$\ell^{+}\ell^{-}, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^{+}\ell^{-}, 3\pi, \eta\pi\pi, q\bar{q}$
	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^{+}\ell'^{-}\nu, \pi l, \rho l, \pi^{0}\nu, q\bar{q}'l$
	Axino	$\ell^{+}\ell^{-}\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^{+}\ell^{-}, 2\pi, 2K$
SND	LDM	electron, proton, hadronic shower
	ν_{τ}, $\bar{\nu}_{\tau}$ measurements	$\tau^{\pm}$
	Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^{\pm}$, $D^{\pm}$, D^{0}, $\overline{D^{0}}$, Λ_c^{+}, $\overline{\Lambda_c}^{-}$

Table 1: Examples of the physics models and final states that the SHiP's scattering and neutrino detector (SND) and the hidden sector decay spectrometer (HSDS) are sensitive to. Here, $\ell = e, \mu, \tau$, and the abbreviates are HNL=heavy neutral lepton, ALP=axion-like particle, LDM=light dark matter.

- FIPs can act as mediators to dark sector of matter
  - Probes of Dark Matter

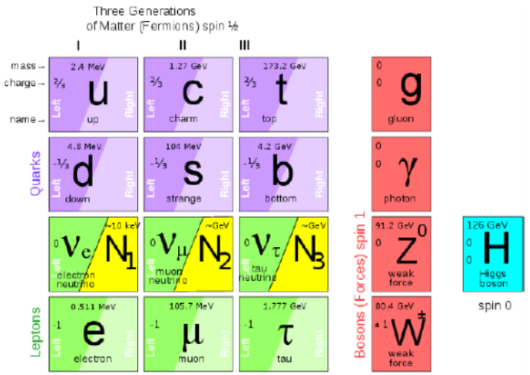
Typical Signature



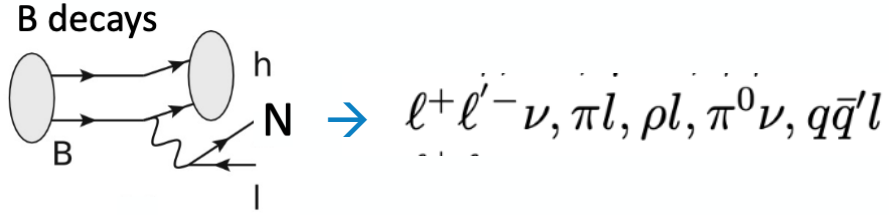
- Sensitivity depends on
  - POT (projections assume full 6×10^{20})
  - Acceptance, lifetime & coverage
  - Background levels (projections assume B=0)
- Signal reconstruction
  - Tracking to reconstruct decay vertex for charged
  - Calorimeters to measure neutrals and inv. mass
  - PID to distinguish between models

Heavy Neutral Leptons (HNLs)

- Heavy right-handed neutrinos
  - The original motivation for SHIP
  - Can explain ν masses and could also form ν portal to dark sector

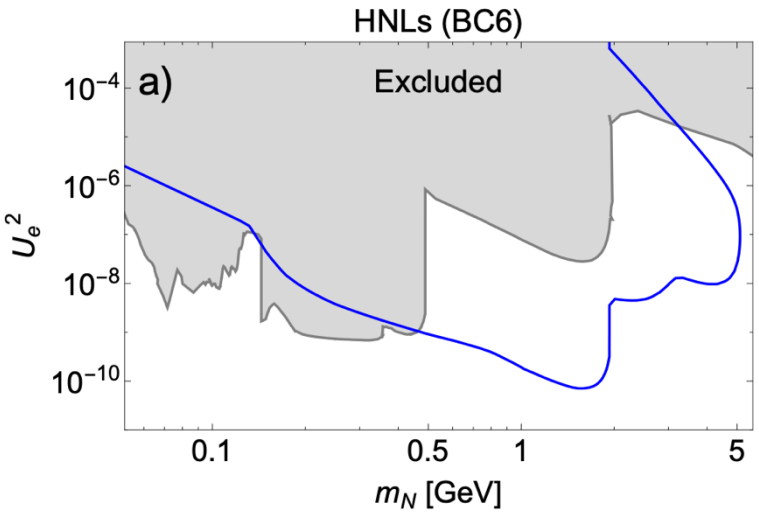


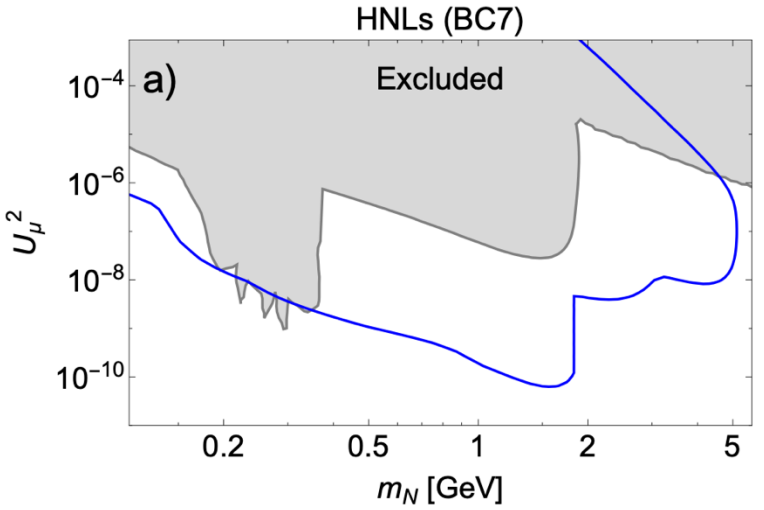
- Produced via semilieptionic meson decays; various decay modes depending on m_N

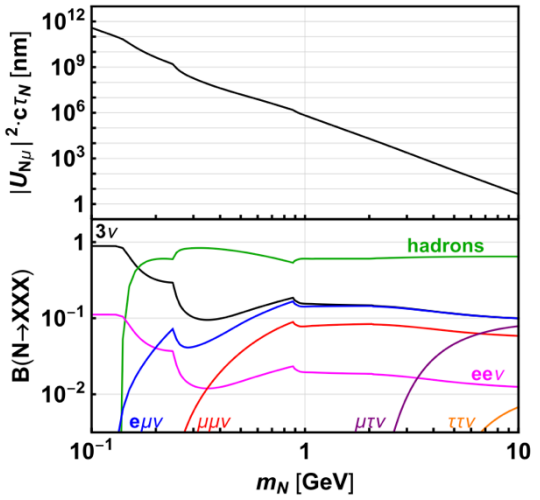


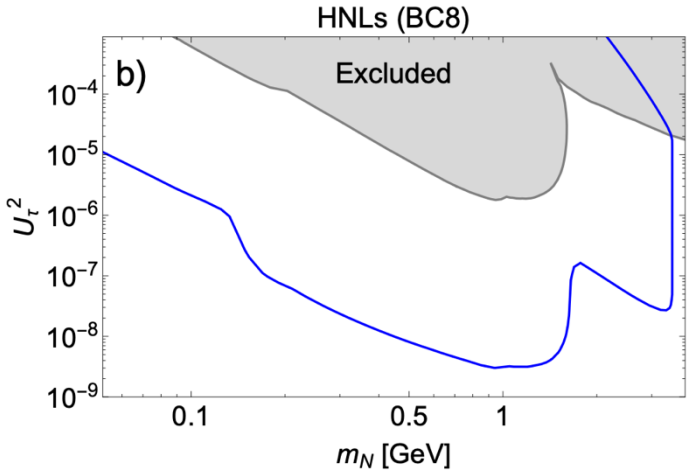
$$\rightarrow \quad \ell^+\ell'^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$$

- Results for 100% coupling to ν_e , ν_μ , ν_τ
  - Personally find tau particularly interesting





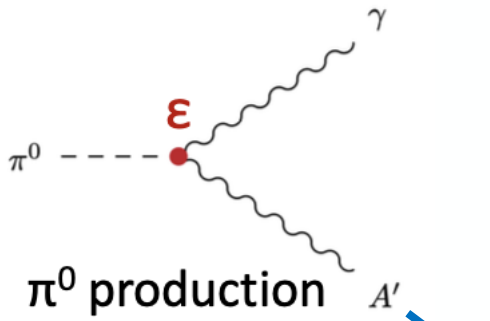




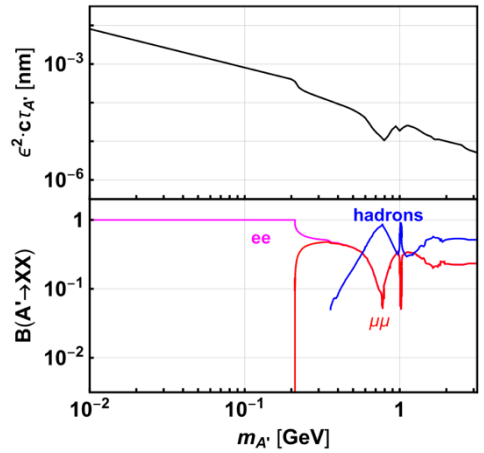
Dark Vector

- Dark sector may have a dark photon
  - Kinetic mixing (ε) with SM photon
  - Acts as mediator between sectors

- Produced via decay of mesons into photons; various decay modes depending on m_A

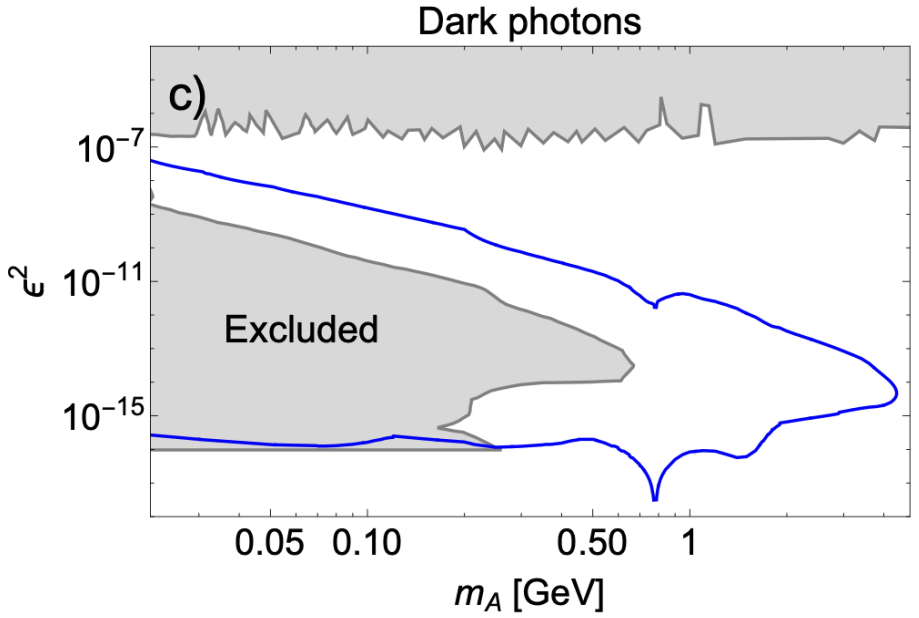


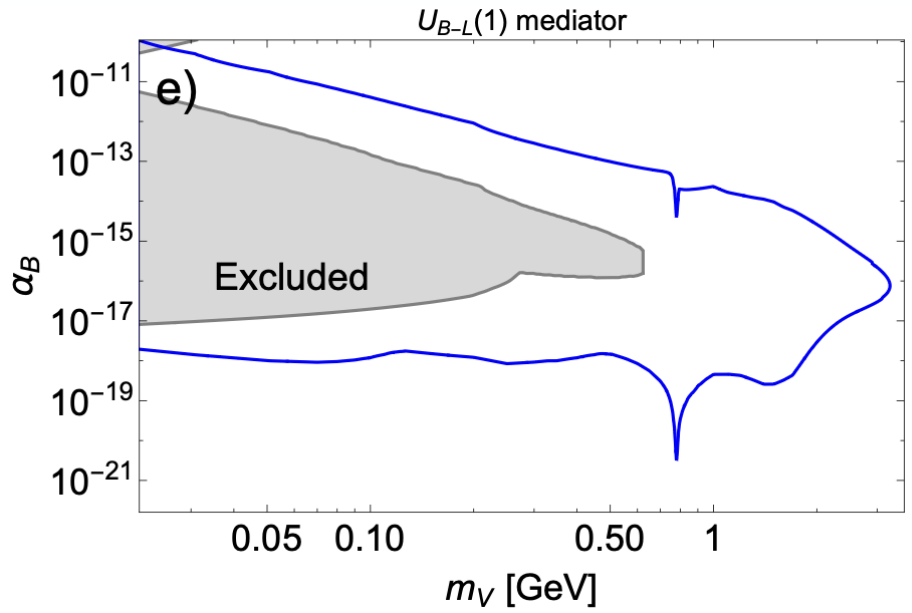
π⁰ production



$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, K\bar{K}, q\bar{q}, D\bar{D}$

- Other dark vectors can couple to B-L charge
  - One of few anomaly free SM global symmetries



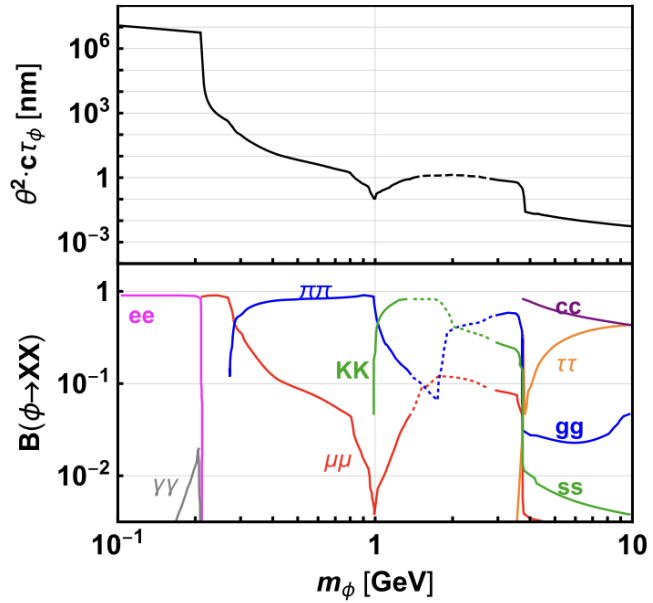


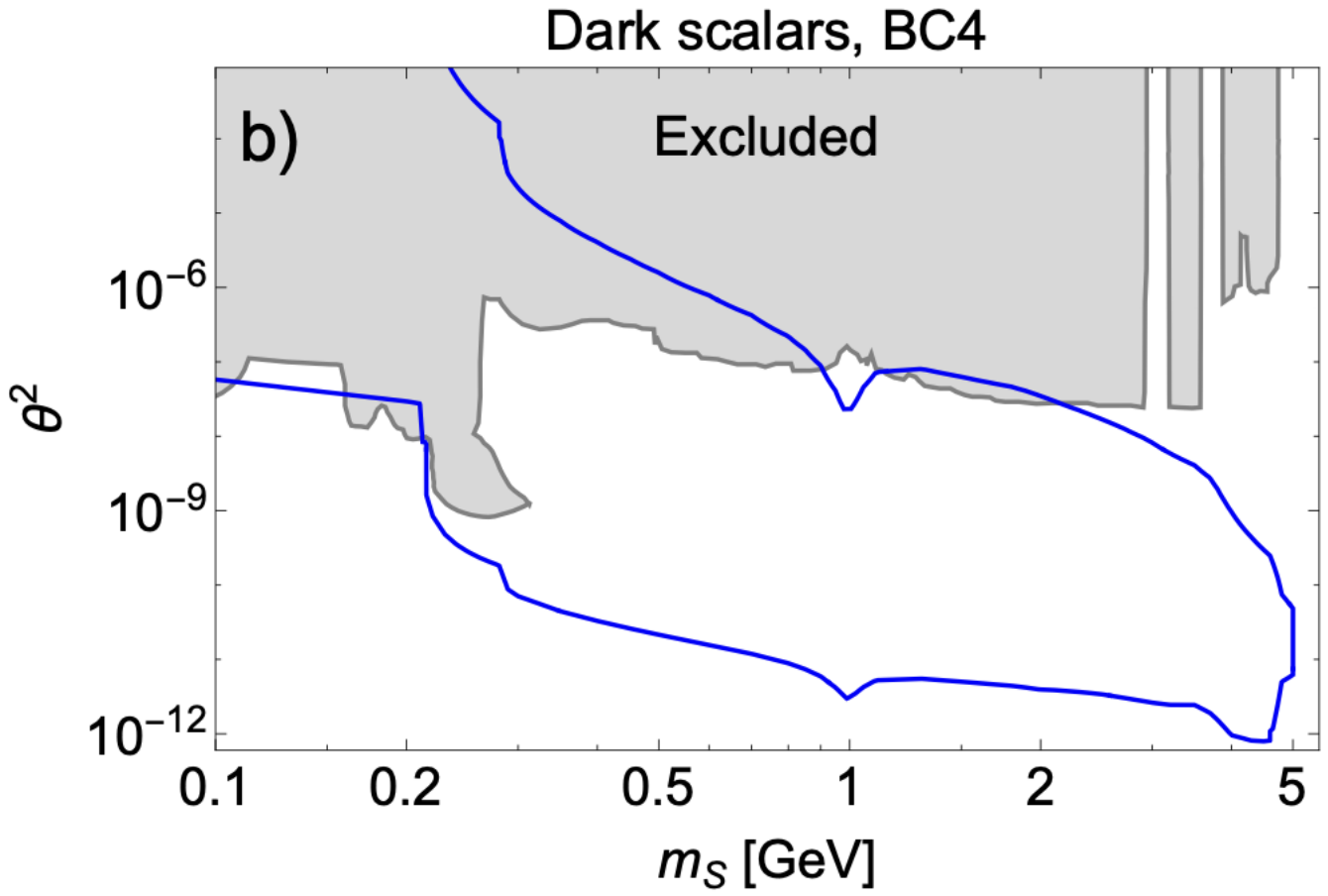
Dark Scalar

- Dark Sector may have a dark Higgs
  - Mixes (θ) with the SM Higgs
  - Acts as mediator between sectors

- Various decay modes depending on m_S

$$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$$

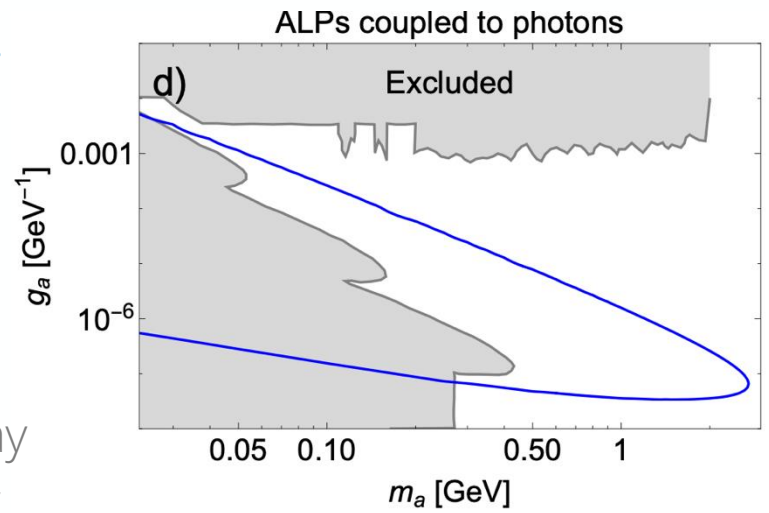


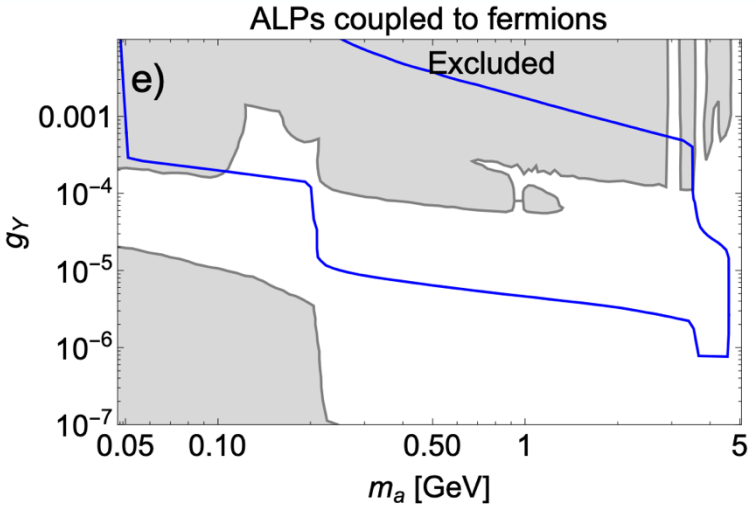


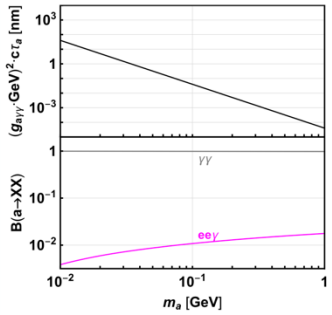
ALPs

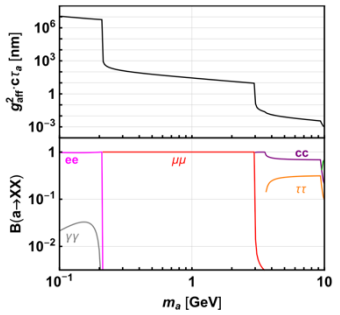
- Axion-like particles are extensions of QCD axion (no m-ε relation)
  - Can act as pseudoscalar mediator to dark sector
- Various coupling scenarios
  - Photon: produced in meson decay
  - Gluon: produced in meson decay
  - Fermion: produced via Primakoff
  - SU(2): produced in meson decay
- Decay modes depend on coupling scenario and m_a

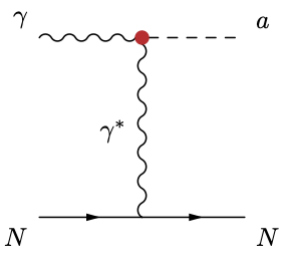
ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
ALP (photon coupling)	$\gamma\gamma$

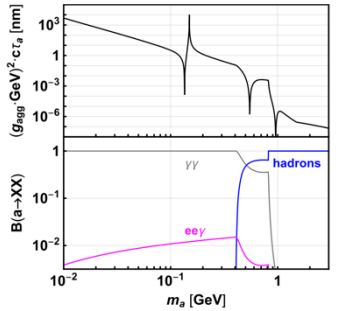


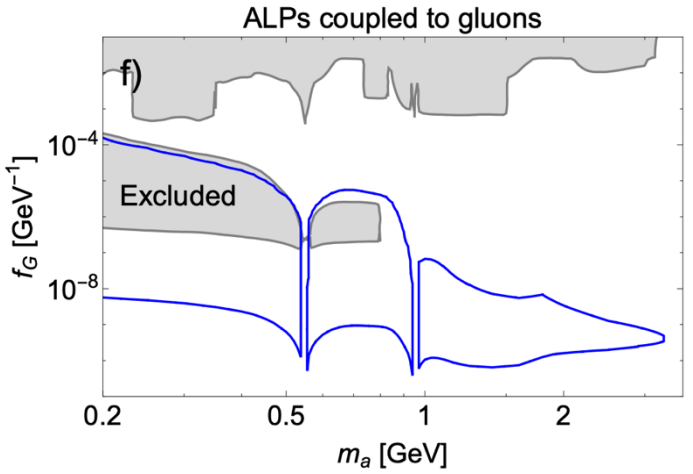








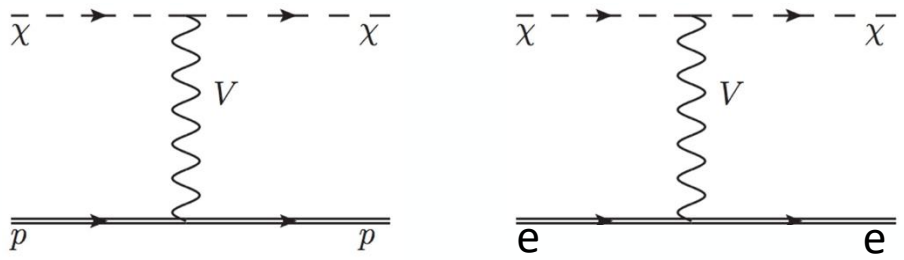


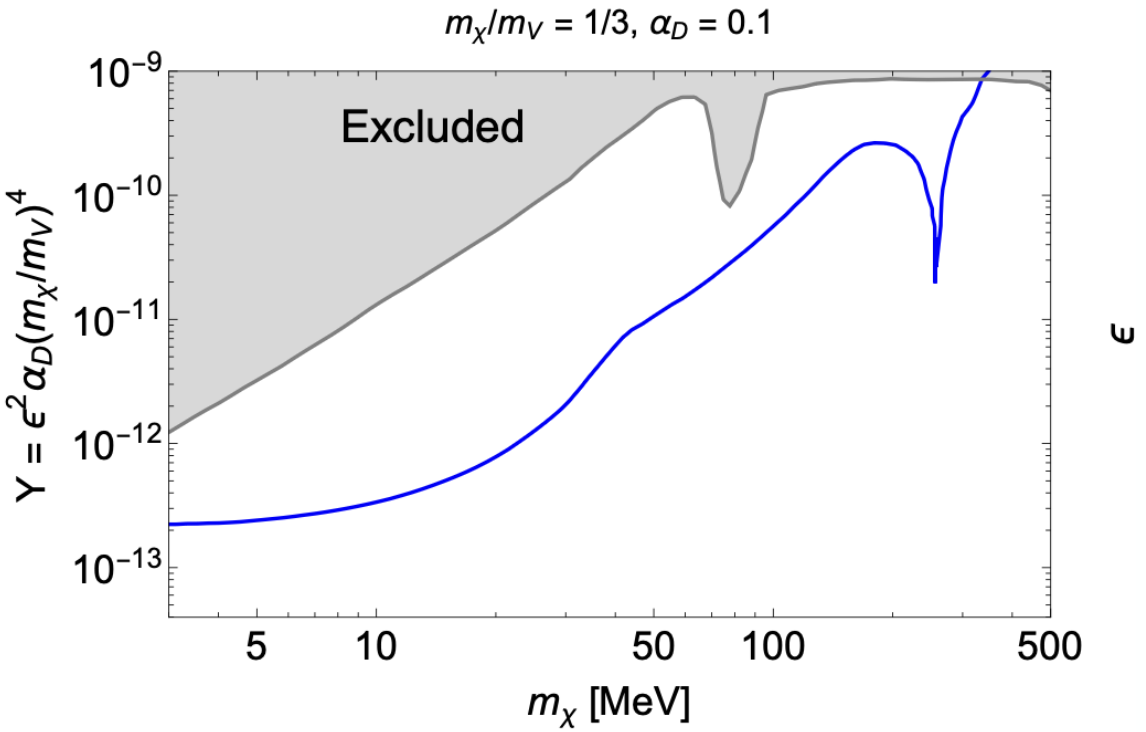


LDM

- Ship can detect scattering of light (sub-GeV) dark matter (LDM) from variety of dark sector models

- Scatters in SND via mediator particle
  - Can scatter off nucleus or electron





- Variety final states depending on what scatters off, which are detected in SND

electron, proton, hadronic shower

- Example shows LDM scattering off electron via A' which is then detected via EM shower

Summary

- Large variety of BSM searches
  - Mainly FIPs decays, allowing access to dark sectors
  - But also light dark matter, millicharged particles, …
- Projected sensitivity to a large range of unexplored phase space
  - But critically all these assume 0 background
  - Somewhat sceptical that can reach this
    - FASER has ~0 for A′ → ee, and ~1 for ALP → γγ
    - But likely more for other final states e.g. pions
- On FASER Liverpool have looked at several of these
  - Major role in A′ → ee and ALP → γγ
  - Now looking at S → μμ, ππ, ee
- Also interested in HNL, particularly in tau final state
  - But need to understand sensitivity with early data to see what to target first

References

- BDF/SHiP at the ECN3 high-intensity beam facility
  - https://cds.cern.ch/record/2878604?ln=en
- The SHiP Experiment: Search for hidden particles (LLP2025)
  - https://indico.cern.ch/event/1441321/contributions/6542403/attachments/3078461/5451176/deroeck_LLP2025_SHIP_v2-2.pdf
- FASER's Physics Reach for Long-Lived Particles
  - https://arxiv.org/abs/1811.12522