Beyond colliders: dark sector searches at beam dumps

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Fundamental questions of particle physics:

▶ what is dark matter?
▶ where has antimatter gone?
▶ how do neutrinos acquire a mass?

found no answers at the LHC nor elsewhere.

No theory guidance on the mass of new particles.
Fundamental questions of particle physics:

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What is the energy scale of New Physics?

- **Dark matter:**
  \[10^{-22} \text{ eV (superlight scalars)} \text{ to } \geq 10^{20} \text{ GeV (wimpzillas & co.)}\]

- **Neutrino masses/oscillations:**
  right-handed seesaw neutrinos up to \(10^{15}\) GeV

- **\(\text{CP} \rightarrow \text{baryogenesis:}\)**
  new particle(s) from 10 MeV to \(10^{15}\) GeV
Dark matter, dark mediators... a dark sector?

- Dark matter mediated by EW, $H$ interactions heavily constrained
- Lee-Weinberg bound: $m_{DM} > 2$ GeV
  - can be lifted by introducing new light boson mediators
  - DM-SM coupling reduced, DM annihilation cross-section increased

$$\mathcal{L}_{\text{world}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{DS}}$$

- “mediators” as “portals” to a “Dark Sector”
  - feebly interacting (“FIPs”) and low mass

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
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</thead>
<tbody>
<tr>
<td>Dark Photon, $A_\mu$</td>
<td>$-\frac{e}{2\cos\theta_W} F^\mu_{\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F^\mu_{\nu} f^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}^{\mu\nu}_{i}$, $\frac{\partial}{\partial f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
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</table>
Discovery strategies

- Hidden particle decaying into visible particles
- Hidden particle scattering
- Missing energy or momentum
- Displaced vertex and/or peculiar final state

Requirements:
- Sensitivity to extremely small couplings $U^2$
- Small or no background
- $E_{\text{miss}}/p_{\text{miss}}$ techniques sensitive to $U^2$, others $U^4$
Proton beam dumps

- long tradition of beam dump searches with far (CHARM, NuTeV) and near detectors (PS191)
- decays of charm and beauty: reach $m \lesssim 5$ GeV
  - dump proton beam to remove light mesons before they decay

The SPS provides a unique high-intensity beam of 400 GeV protons: ideal setting for a CERN-based Beam Dump Facility (BDF)

5 years of BDF @ SPS ($2 \times 10^{20}$ pot):
- $10^{18}$ charm mesons
- $10^{14}$ beauty mesons
- $10^{16}$ $\tau$ leptons
- **discovery experiment for weakly coupled LLPs**, with a complementary detector for $\nu$ physics and LDM scattering
- **large geometrical acceptance**: long volume close to dump
- **zero background** with spectrometry, PID and VETO taggers
Target and shielding

- heavy target to absorb pions
- magnetized hadron stopper: immediately separate $\mu^\pm$
- muon shield config optimised with ML $\Rightarrow \mu$ rate reduced to $\sim 25$ kHz

- $\mu$ simulation validated with existing data from Hyperon and NA62
- and with dedicated exp. in 2018 using replica of BDF target, $10^{11}$ pot
SHiP Decay Spectrometer

- surround tagger (liquid scintillator)
- straw spectrometer: $2% X_0, \left(\frac{\sigma_p}{p}\right)^2 \approx (0.5\%)^2 + (0.02 \times p)^2$
- timing detector (scint. bars + large SiPMs, $\sigma_t \lesssim 80$ps)
- ECAL with tracking capability (SplitCal, $\sigma_\theta \approx$ few mrad)
- muon detector (scintillating tiles + SiPMs)

▶ mass, charge, flavour information available at observation
⇒ narrow down physics models
Background for decay signatures @ SHiP

- Muon combinatorial
- Muon inelastic
- $\nu$ interactions:
  - 10 years of SHiP simulated, increasing to 100
  - $\nu$-air: keep pressure $\sim 1$ mbar
  - $\nu$-material: some $K_L$, combination of tracks from primary and secondary interactions
  - vetoed by topology & signal selection

0 background $\implies$ 2 candidates are a discovery
SHiP Scattering and Neutrino Detector

- distinguish $\nu_e$, $\nu_\mu$, $\nu_\tau$ and hadrons
  - measure charge
- $\nu_f$ cross sections measurements relevant for flavour anomalies
- first $\bar{\nu}_\tau$ observation
- Target (emulsion chambers + target tracker) + Downstream spectrometer + Muon filter

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- ideal laboratory also for Light Dark Matter scattering signatures!
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<td>$\nu_\mu$</td>
<td>42, $2.7 \times 10^6$</td>
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<td>46, $2.6 \times 10^5$</td>
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SHiP SND: invisible decays

- benchmark: $\gamma' \rightarrow \chi \chi$, $\chi e \rightarrow \chi e$ scattering in the emulsion target
- expect single EM shower w/o associated tracks
  - $\bar{\nu}_e N \rightarrow eX$ background reduced by tagging extra activity at the vertex
  - $\nu e \rightarrow \nu e$ slightly kinematically different
  - if excess is observed $\implies$ can switch to bunched beam and use TOF
  - excess observed in real time using target tracker (R&D ongoing)

- $\chi_2 \rightarrow \chi_1 \gamma' (\rightarrow \ell \ell)$ can be searched with the Decay Spectrometer

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**Relic Density**

- Scalar DM
- Majorana DM
- Pseudo-Dirac DM

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<th>$M_\chi$ [MeV/c$^2$]</th>
<th>$Y=\alpha D \epsilon^2 (M_{\chi}/M_\chi)^4$</th>
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<tr>
<td>$10^{-13}$</td>
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<tr>
<td>$10^{-12}$</td>
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**SHiP**

- $\mathrm{BaBar}$
- $\mathrm{MiniBooNE}$

- $M_{\chi}' = 3M_\chi$
- $\alpha_0 = 0.1$
built to measure $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$

can quickly switch between beam and dump (collimators)

studies on $\mu-$ and $\nu-$halo BG in dump mode ongoing

in beam mode: $K^+ \rightarrow \mu^+ N$ with $N$ decaying visibly or invisibly,
$K^+ \rightarrow \pi^+ (\pi^0 \rightarrow \gamma\gamma')$

[PLB 791 (2019) 156]
- built to measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$
- can quickly switch between beam and dump (collimators)
- studies on $\mu^-$ and $\nu^-$-halo BG in dump mode ongoing
- in beam mode: $K^+ \to \mu^+ N$ with $N$ decaying visibly or invisibly, $K^+ \to \pi^+ \left(\pi^0 \to \gamma\gamma'\right)$
NA64 approved in 2016 to search for NP in missing energy
- ruled out $\gamma'$ explanation for $\mu(g - 2)$ with $10^{11}$ eot

NA64++: $5 \times 10^{12}$ eot after LS2
- extend $\gamma'$ search to muon beams
- configurable to look for visible signatures too

Studied as possible application for the AWAKE plasma wakefield acceleration scheme
• small scale experiment to measure up to $10^{16}$ eot
• missing energy & missing momentum techniques
• potential beam lines: JLab CEBAF, SLAC S30XL, CERN eSPS

[hep-ex/1808.05219]
Performance: visible decays

- **HNL** (heavy meson decays), **dark photon** (decays + bremsstrahlung + QCD)
- **Time scale:**
  - NA62 (10^{18} \text{ pot}): 5 years.
  - SHiP (2 \times 10^{20} \text{ pot}): 6 + 5 years.
- See F. Redi’s next talk for collider-based experiments!

[1504.04956, 1504.04855, 1811.00930, 1901.09966]
Performance: invisible decays / missing energy

Physics reach of PBC projects on 5 and 10-15 years timescales

PBC projects able to put bounds on the $y$ versus $m_{\chi}$ plane are NA64$^{++}(e)$ on a 5-year timescale and LDMX and SHiP on a 10-15 year timescale, as shown in Figure 24. NA64$^{++}(e)$ and LDMX will use the missing energy/missing momentum techniques, respectively. SHiP, instead, will exploit the elastic scattering of DM candidates with the electrons in the medium of the emulsion-based neutrino detector. As such, SHiP is fully complementary to the other two.

Figure 24: Dark Photon decaying to DM Elastic Scalar (top) or Pseudo-Dirac fermion (bottom) particle. Prospects for PBC projects on a timescale of 5 years (NA64$^{++}$, green line) and 10-15 years (LDMX, red line and SHiP, blue line) are compared to the current bounds (solid areas) and future experimental landscape (other solid and dashed lines). In the limit computation we assume a dark coupling constant value $\alpha_D = 0.1$ and a ratio between the dark photon $A'$ and LDM $\chi$ masses $m_{A'}/m_{\chi} = 3$.

▶ scattering vs. missing $E$ approaches offer complementary insights

▶ Time scale:

- NA64 ($5 \times 10^{12}$ eot): 5 years.
- SHiP ($2 \times 10^{20}$ pot): 6 + 5 years.
- LDMX ($10^{16}$ pot): beam selection + 5 years.

[1901.09966 and refs. therein]
Conclusions

- current data leave open a **wide window on the unknown**
- Dark Sector exploration very well justified
  - active theory community, formulating benchmark models
  - ...that can be thoroughly tested **within 15 years**!
- CERN’s new “Physics Beyond Colliders” WG largely devoted to DS

**short term:**
- existing experiments such as NA62 and NA64 will have results soon, while serving as training grounds towards dedicated beam dump explorations with e.g. BDF/SHiP and AWAKE++

**medium/long term:**
- future facilities like BDF/SHiP and eSPS/LDMX will grant significant progress towards the exploration of the dark sector
- nice **complementarity** with dark sector programme at the LHC
  - and at the FCC-ee!
Spare slides
Visible decays

- **scalar** ($K$ and $B$ decays)
- **Time scale:**
  - NA62 ($10^{18}$ pot): 5 years.
  - SHiP ($2 \times 10^{20}$ pot): $6 + 5$ years.
- See F. Redi’s next talk for collider-based experiments!
Visible decays

from left: ALPs coupled to fermions, ALPs coupled to photons

Time scale:
- NA62 (10^{18} pot): 5 years.
- SHiP (2 \times 10^{20} pot): 6 + 5 years.

See F. Redi’s next talk for collider-based experiments!
Background for decay signatures @ SHiP

▶ Muon combinatorial:
- \(10^{16} \xrightarrow{\text{selection}} 10^9 \xrightarrow{\text{timing}} 10^{-2}\) candidates in 5 years @ 90%CL
- ML used to generate large sample of dangerous \(\mu\)

▶ Muon inelastic:
- 5 years of SHiP simulated
- correlation between VETO and selection: \(< 6 \times 10^{-4}\) @ 90%CL

▶ \(\nu\) interactions:
- 10 years of SHiP simulated, increasing to 100
- \(\nu\)-air: \(< 10^{-2}\) with pressure \(\sim 1\) mbar
- \(\nu\)-material: \(5 \times 10^5\) \(\left\{\frac{\text{cuts (fully reco)}}{\text{cuts (part. reco)}} \rightarrow 0, \frac{\text{opening angle}}{2} \rightarrow 0\right\}\) @ 90%CL