Dark Sector searches with proton beams

E. Graverini for the SHiP collaboration

European Strategy for Particle Physics Update, Granada, May 2019
New Physics hunt in beam dump

➤ LHC runs I+II heritage: need to probe much weaker couplings
➤ giving existing facilities and reliable technologies a new challenge: **intensity**
➤ long tradition of beam dump searches with far (CHARM, NuTeV) and near detectors (PS191)

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

[**CERN-PBC-REPORT-2018-001**, see M. Lamont’s talk]

5 years of BDF @ SPS ($2 \times 10^{20}$ **pot**):
- $10^{18}$ charm mesons
- $10^{14}$ beauty mesons
- $10^{16}$ $\tau$ leptons

North Area beam lines

Beam Dump Facility and SHiP experiment
a discovery machine for weakly coupled LLPs, with a complementary detector for $\nu$ physics and LDM scattering signatures

- large geometrical acceptance: long volume close to dump
- zero background with spectrometry, PID and VETO taggers
Target and shielding

- heavy target to absorb πs before decay
- magnetized hadron stopper: immediately separate $\mu^{\pm}$
- ideal muon shield configuration optimised with machine learning ➞ $\mu$ rate reduced to $\sim 25$ kHz

- $\mu$ spectrum validated with dedicated experiment in 2018
Decay Spectrometer

- surround tagger (liquid scintillator)
- straw spectrometer: $2\% X_0$, $(\frac{\sigma p}{p})^2 \approx (0.5\%)^2 + (0.02 \times p)^2$
- 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)

- 0 background $\implies$ 2 candidates are a discovery
- mass, charge, flavour information available at observation $\implies$ narrow down physics models
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

<table>
<thead>
<tr>
<th>$\bar{E}$ [GeV]</th>
<th>CC DIS int.</th>
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<tbody>
<tr>
<td>$\nu_e$</td>
<td>59</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>42</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>52</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>46</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>36</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
<td>70</td>
</tr>
</tbody>
</table>

- ideal laboratory also for Light Dark Matter scattering signatures!
Detector and infrastructure development

▶ beam facility is being developed by the CERN BDF team (see M. Lamont’s talk)

▶ all detector subsystems have undergone:
  – simulation studies, requirements definition, R&D
  – phase 1 prototyping (small scale, single modules)
  – off and on-beam testing (2017–2018)

▶ phase 2 prototyping ongoing, beam tests planned for 2019-2021
Simulation and validation

- Simulation tuned on data (Pythia8 + Genie + Geant4)
- $\mu$ spectrum validated using data from Hyperon and NA62
- two dedicated measurements in July 2018:
  - $\mu$ flux, critical for dark sector searches: $\sim 6 \times 10^{11} \text{ pot}$
  - charm production cross-section, for dark sector and $\nu$ physics

- repeat $\chi_{cc}$ measurement after LS2, collecting $> 10^{7} \text{ pot}$
SHiP is a 0 background LLP experiment

- **Muon combinatorial:**
  - $10^{16}$ selection $\rightarrow$ $10^9$ timing $\rightarrow$ $10^{-2}$ 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: $5 \times 10^5$
    - $\frac{\text{cuts (fully reco)}}{\text{cuts (part. reco)}}$ $\rightarrow$ 0, opening angle $\rightarrow$ 0 @ 90% CL
Physics performance: 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 $\Rightarrow$ 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
Physics performance: visible decays

- from top left: HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD), scalar (K and B decays), ALPs coupled to fermions, ALPs coupled to photons
- event selection: high signal efficiency + redundant BG suppression
Physics performance: visible decays

▶ in case of discovery $\Rightarrow$ full reconstruction and PID allows identifying models and measuring parameters
Conclusions

- scale of NP after LHC run II = ? ⇒ diversifying is key
- high intensity SPS beam allows probing couplings $\mathcal{O}(10^{-10})$
  - with minimal modifications to existing facilities
- BDF can fit other experiments after SHiP or at the same time
  - tauFV can run in parallel and could give a spin to flavour anomalies
- SHiP enters the game as a discovery experiment
  - with large acceptance, spectrometry, PID
  - with reliable zero-background expectations
  - and with a complementary neutrino physics / scattering programme
- Physics performance guaranteed by redundant VETO system and event selection
- project in very good shape, moving fast towards TDR
Spare slides
Cost and schedule

- all sub-detector’s phase 1 prototypes constructed and tested with beam, with nice results
  - schedule driven by SPS/LHC schedule: installation LS3
  - phase 2 prototyping ongoing
  - 3 years for TDRs
  - construction of BDF $\sim 5$ years (see M. Lamont’s talk)
  - detector production, installation, commissioning $\sim 6-7$ years (in parallel to BDF construction)
  - aiming for operation in Run 4 (as early as possible)
  - project mature and no showstoppers

- $+10-30\%$ cost estimate produced for the Technical Proposal

- $-10-20\%$

- major design changes since TP, but cost stable
  - revised costing together with updated project plan is being prepared for the detector Comprehensive Design Study (November 2019)
Comparison with previous beam dump experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>PS191</th>
<th>NuTeV</th>
<th>CHARM</th>
<th>SHiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton energy (GeV)</td>
<td>19.2</td>
<td>800</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Protons on target ($\times 10^{19}$)</td>
<td>0.86</td>
<td>0.25</td>
<td>0.24</td>
<td>20</td>
</tr>
<tr>
<td>Decay volume (m$^3$)</td>
<td>360</td>
<td>1100</td>
<td>315</td>
<td>1780</td>
</tr>
<tr>
<td>Decay volume pressure (bar)</td>
<td>1 (He)</td>
<td>1 (He)</td>
<td>1 (air)</td>
<td>$10^{-6}$ (air)</td>
</tr>
<tr>
<td>Distance to target (m)</td>
<td>128</td>
<td>1400</td>
<td>480</td>
<td>80-90</td>
</tr>
<tr>
<td>Off beam axis (mrad)</td>
<td>40</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Table: Comparison of the experimental conditions for HNL search experiments [SHiP Tech. Prop. 1504.04956].
HNL production and decay $B$’s revised

cascade production of charm and beauty

flavour-independent sensitivity matrix including $B_c$ contribution

HNL identification and discovery reach close to seesaw limit

great sensitivity also in $U^2_{\tau}$-enhanced scenario
Physics performance: HNL

- HNL production and decay $B$’s revised [JHEP11(2018)032]
- cascade production of charm and beauty [SHiP-NOTE-2015-009]
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Benchmark models for visible decays

- Dark photon:
  - meson decays, proton bremsstrahlung, $qq \to \gamma'$
  - expect improvements at low mass from:
    - cascade production
    - EM showers

- Dark scalar:
  - couple to Higgs in FCNC $K$ and $B$ decays

- Axion-like particles:
  - couple to fermions and to photons
  - SplitCal developed for $ALP \to \gamma\gamma$
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Scattering Spectrometer: status

- CES tested at CERN PS in 2017
- $\mu$-RWELL or SciFi for tracking, both tested on beam (2018)
- $\mu$ ID system: RPC tested in CERN H4 in summer 2018
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**SBT** Several improvements *w.r.t.* TP. Tested on beam Oct. 2018

**SST** Straw $\varnothing$ increased to 20mm. Tested on beam: $\sigma_{\text{hit}} \approx 120\mu$m

**TD** Plastic scint + large-area SiPMs feasible, large-scale prototype yields $\sigma_t \approx 80$ps. RPC alternative tested Oct. 2018 with $\sigma_t \approx 54$ps

**ECAL** SplitCal with 3 high-res layers for $ALP \rightarrow \gamma\gamma$ ($\sigma_\theta \sim$ few mrad)
- measure barycentre at 3 depths with MPGDs; $> 1$ m lever arm

**MUON** move to scintillating tiles with SiPM readout. Beam test Oct. 2018, aim at $\sigma_t < 200$ps
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Hidden sector: physics performance

- setup ideally suited for *any* weakly interacting LLP

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track momentum</td>
<td>$&gt; 1.0\text{GeV/c}$</td>
</tr>
<tr>
<td>Children distance of closest approach</td>
<td>$&lt; 1 \text{ cm}$</td>
</tr>
<tr>
<td>Decay vertex position</td>
<td>($&gt; 5 \text{ cm from inner wall}$)</td>
</tr>
<tr>
<td>IP w.r.t. target (fully reconstructed)</td>
<td>$&lt; 10 \text{ cm}$</td>
</tr>
<tr>
<td>IP w.r.t. target (partially reconstructed)</td>
<td>$&lt; 250 \text{ cm}$</td>
</tr>
</tbody>
</table>

- event selection: high signal efficiency + redundant BG suppression
- common selection (model independent search)
- redundancy cuts:
  - associated activity in VETO systems
  - PID cuts
  - time coincidence (suppress combinatorial background)
  - opening angle (reject events from $\gamma$ conversions in the material)
Hidden sector: backgrounds

▸ **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^9 \xrightarrow{\Delta t < 340 \text{ps}} 10^{-2}$ candidates in 5 years @ 90%CL
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▸ **Muon inelastic:**
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    \[
    \begin{align*}
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    @ 90\% CL
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SHiP simulation / validation

- based on FairRoot, uses:
  - Pythia8 for $p$-on-target collisions, tuned to include production of $c$, $b$ mesons from secondaries
  - Geant4 for propagation through the target and detector material. $V^0 \rightarrow \mu\mu$, $\gamma \rightarrow \mu\mu$, $ee \rightarrow \mu\mu$ activated and boosted
  - Genie for neutrino interactions

- several HS models added/extended (HNL, $\gamma'$, $S$, RPV $\tilde{\chi}^0$...)
- $1.8 \times 10^9 / 6.5 \times 10^{10}$ pot simulated with $E_{th} = 1 / 10$ GeV
- $\mu$ MS and catastrophic energy loss validated with existing data

**Data from HYPERON**

**NA62 LKr**
Charm / $\mu$ flux measurements (July 2018)

- replica of BDF target + drift tube spectrometer + RPC $\mu$ tagger
- $\sim 6 \times 10^{11}$ pot recorded, analysis ongoing

- measure of charm production essential for HS and $\nu_\tau$ studies
- lead target + emulsions. $1.6 \times 10^6$ pot + 10× run after LS2