Search for Hidden Particles

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The picture of new physics

- Large number of direct searches resulting in no new physics at scales up to $\sim 5\text{TeV}$

- Even more stringent constraints through indirect flavour measurements

- No smoking gun at high energy scales
A Hidden Sector

- New particles are light and interact very weakly with SM particles through portals
  → Provide DM candidate, explain BAU and neutrino masses
  \[ \mathcal{L}_{\text{World}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{HS}} \]

- Such particles found in very wide range of theories
  → SUSY, Axion Like Particles, Heavy Neutral Leptons etc
  → Interactions sufficiently weak, evading precision flavour and electroweak constraints
  → Can search through decays to visible SM particles

- Physics proposal including > 80 theorists

- Can also search using decays to invisible particles (DM candidates)
  → Reoptimise \( \nu_{\tau} \) detector

[arXiv:1504.04855]

SHiP will make world-beating and model independent searches in of all of these areas.
Searches for Light Dark Matter

- DM experiments have in general low sensitivity for masses below a few GeV
- Many models predicting DM candidate in this mass range
  - Important to complement with our physics programme

- Light DM models predict a Hidden sector containing a DM candidate
 Searches for Light Dark Matter cont’d

- If the Dark Photons (or other mediators) couple to DM it will not reach the SHiP detector
- However we can detect the DM scattering with electrons in the emulsion detector
- Preliminary study for the TP, we are now optimising the emulsion detector to take into account this physics case

- Mediator of HS decays to DM candidate
  → Invisible to downstream SHiP detector
  → Detect DM through electron scattering in emulsion detector initially designed for $\nu_\tau$ physics

- Optimising emulsion detector to take into account this physics case

- SHiP has the unique ability to simultaneously search for HS particles including the DM candidate!
Technical Proposal and beyond

- TP reviewed by SPSC and CERN RB and recommended to prepare a Comprehensive Design Study (CDS) by 2018
  → Input to the European strategy consultation in 2019/2020 as a basis for an approval of SHiP

For the CDS: **New phase of optimisation**

- Improve sensitivity to hidden sector searches
  - Re-optimise detector design
- Investigate additional hidden sector models and expand physics case
  - e.g. Dark Photon, SUSY, models with multihadron final states, LDM
Evolution of the design

- Improve sensitivity to variety of HS signals
  - While ensuring still a zero background experiment

Left: TP SHiP, Right: Star-SHiP
Evolution of the design

- Improve sensitivity to variety of HS signals
  - While ensuring still a zero background experiment
  - Respect cost constraints of the TP

Left: TP SHiP, Right: New SHiP

- Magnetise the hadron stopper → shield shorter and lighter
- Lower muon flux entering shield → Decay volume closer to target
  → Increased signal acceptance and reduced muon background
- Simulate support structures and cavern floor and walls

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Evolution of the design cont’d

- Decay vessel now pyramidal frustum shaped
- Vacuum vessel as baseline option

Other design decisions (CDS and beyond):
- Upstream and Surrounding Background Tagger: liquid or plastic scintillator
- Timing detector: Plastic scintillator or MRPC
- Calorimetry and PID: study $e, \gamma, \pi, \mu$ separation
  - Crucial to suppress neutrino bkg in $N \rightarrow \ell^+ \ell^- \nu$
  - Study some options with test beam in 2017
- Implementing additional HS models in simulation with variety of final states: e.g multihadrons and diphotons
- Detail study of backgrounds with new design
- Prototyping of all subsystems in place many of which close to “module 0” level
Understanding muon flux and charm production

- Muon shield design depends on the muon spectrum
  - Validate simulation based estimates of muon spectrum after the hadron absorber induced backgrounds

- Understanding the charm production cross section
  - Important in normalising the signal yield and for validating background estimates from high $p_T$ neutrinos
Measuring muon flux

- Expect $6 \times 10^5 \mu/s$ with $p > 100\text{GeV}$, $p_T > 3\text{GeV}$
- PYTHIA simulations result in limited events in above phase space
  - Simulation validated using measurement of flux from CHARM expt.
  - Restricted to low $p_T$ muons and does not cover dangerous part of phase space
- Use beam-tests to improve statistical uncertainty, allowing to test our simulation and use in optimising muon shield

- Find appropriate test beam area for measurement (Collaborate with NA61/SHINE?)
  - Study using simulations
Measuring muon flux cont’d

- Sent EOI to SPSC with proposal based on a NA61/SHINE like detector
  → Install replica SHiP target
  → In order to validate bulk of phase space to $\leq 30\%$ precision need $\sim 10^{11}$ POT
  → 2-3 weeks

- The BDF target WG is re-evaluating the target design which could result to changes to SHiP target
  → Wait for updated design expected summer 2017
  → Aim to collect data by mid 2018 (before CDS report)
Measuring the charm cross section

- Need to know the charm production cross-section in proton interactions, including the contribution from hadronic cascades in the SHiP target
  - Normalisation of HS signals and $\nu_\tau$ cross-section measurements
  - Validating background estimates from high $p_T$ neutrinos

- Current knowledge of inclusive associated charm cross-section measurement is scarce
  → Missing information:
    - Contribution from charm production through hadron cascades
    - Kinematic distributions of charmed hadrons

![Graph showing charm cross-sections](image)
Measuring the charm cross section II

- Propose to measure double-differential cross-section $d^2\sigma_{cc}/dEd\theta$
- Proton collisions with smaller (10 $\times$ 10 cm$^2$) replica Mo/W target instrumented with nuclear emulsions
- No water cooling required
- Use emulsion as tracking detector to identify hadronic and leptonic charm decay modes

Part of instrumented target ($\sim 1\lambda_I$)

- Each ECC is made by a sequence of 3mm-thick TZM planes interleaved with 290 $\mu$m-thick nuclear emulsion films, with a total thickness of $\sim 1\lambda_I$
- ECC1: study charm production in first $\lambda_I$
- ECC2: study charm production in second $\lambda_I$

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Measuring the charm cross section III

- Position distribution along beam axis of charm production vertices in the target TZM.

- Ratio between different production modes:
  - \( r(1^{\text{st}}\lambda_I) = \frac{\#\text{Primary}}{\#\text{Secondary}} = 2.7 \)
  - \( r(2^{\text{nd}}\lambda_I) = \frac{\#\text{Primary}}{\#\text{Secondary}} = 0.8 \)

- Fraction of interactions within \( 2\lambda_I \):
  - Primary 92%
  - Secondary 66%

- Instrumentation of first and second \( \lambda_I \) allows the study of a large fraction of charmed hadrons.

- Detector design implemented in SHiP’s simulation framework:
  - Study exposure needed to observe 10000 charmed pairs
  - Require \( 8 \times 10^7 \) pot and a total of \( 250 m^2 \) of emulsion surface

- Possible location H4 where the Goliath magnet could be used

- Wait for updated target design expected summer 2017
Summary

A lot of progress since TP. In the next two years:

- Moving onto CDS and TDR stages
- New detector design which significantly increases HS particle acceptance relative to TP design, while satisfying zero background requirement constraints
  → Reoptimisation under way
  → Extend physics case to DM searches exploiting SHiPs unique design
- Technology decisions to be made with the help of planned test beams
- Detailed plan of measurements to better understand muon flux and charm production

### Milestone chart for CDS

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<thead>
<tr>
<th>Milestone</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td>Iteration 1: Global re-optimization with &quot;current detectors&quot;</td>
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<td>Iteration 2: Optimization with refined detectors</td>
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<td>Design and prototyping</td>
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<td>Testing and updated performance</td>
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<td>Test beam to measure muon spectra, $\sigma_{\text{charm}}$, etc</td>
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<td>Design, performance, cost review</td>
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<td>Write-up</td>
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Internal | External
Backup
First phase reoptimisation

- Decay Volume
  - Pyramidal frustum shape
  - Vacuum baseline, helium balloon as backup
- Detector options
  - Configurations of the LDM/$\nu_\tau$ emulsion detector
  - Straw tube technology considered for the upstream muon spectrometer
  - Technologies for Upstream and Surround Background Tagger: Liquid and Plastic scintillator + SiPM
  - Technologies for Timing Detector: Plastic Scintillator/MRPC
  - Revisit completely calorimetry and PID
- First iterations and optimisation implemented in our full simulation
  → Launching complete background simulation
Test beam activities

- **2016**
  - Beam time exploited by straw tracker and BDT plastic scintillator option

- **2017**
  - Joint test beam for Straw Tracker, SBT, CALO on SPS (≈ 2.5 weeks)
  - Emulsion test beam on PS (≈ 2 weeks)
  - Muon system test beam on PS (≈ 2 weeks)

- **2018 and beyond**
  - Likely to have several sub-detector requests as in 2017
  - Tuning of muon spectra
  - Measurement of inclusive charm production