SHiP Overview

SHiP is currently a collaboration of 49 institutes, 5 associate institutes from 16 countries, CERN and JINR

Outline:

- Brief summary on “Standard” SHiP layout and sensitivities
- Possible extension of SHiP physics programme
- Main goals of the SHiP optimization
- Important measurements towards TDR

More details in the talks of Gaia Lanfranchi and Richard Jacobsson
**Standard Model is great but it is not a complete theory**

Direct searches for NP at ATLAS & CMS have not been successful so far

- Broad program: 23 SUSY searches completed with full 2016 CMS dataset
- Probing different models: inclusive production, strong and **electroweak production**, and 3rd generation sparticles (stops, staus), high ΔM, compressed, ...
- Recent highlight: “EWK combination”

**Parameter space for popular BSM models is being rapidly decreased, but only < 5% of the complete HL-LHC data set has been delivered so far**

→ NP discovery still may happen!
Interesting hints on violation of Lepton Flavour Universality (LFU) 
in two classes of decays:

\[ b \rightarrow clv \]

LHCb combination [FPCP 2017]:
\[ R(D^*) = 0.306 \pm 0.016 \pm 0.022 \]
2.1σ above the SM

\[ b \rightarrow sll \]

World average [HFLAV]:
\[ R(D^*) = 0.304 \pm 0.013 \pm 0.007 \]
(3.4σ from SM)
\[ R(D) \oplus R(D^*) \text{ is } 4.1σ \text{ from SM!} \]

Clear evidence of BSM physics if substantiated with further studies!

Many models predict enhanced LFV effects (some close to the current experimental limits) in the 3rd generation

Journée SHiP/Physique du secteur caché du
11/10/2017
Search for non-LFU tau decays @ BELLE / BELLE II
(extrapolation to BELLE II depends on background)

Main sources of background:

- $e^+e^- \rightarrow \tau^+ \tau^-$
  - 1 prong tau decay (BR~85%)

**Signal**
- Neutrino(s) in tag side
- Particle ID
- (Mass of mesons)

**Two photon process**
- $f =$ leptons, quarks

**Radiative Bhabha process**
- $e^+e^- \rightarrow e^+e^-\gamma$
  - many tracks

**Signal side**
- $\tau^+ \tau^-\nu$ (Neutrino(s) in tag side)

**Tag side**
- 1 prong tau decay (BR~85%)
Current and expected sensitivities

- BELLE reached $O(10^{-8})$ sensitivity using $\sim 10^9 \tau \tau$ events
- BELLE II plans to collect $\sim 5 \times 10^{10} \tau \tau$ events
- Expected sensitivity for UL ($\tau \rightarrow 3\mu$) varies from $10^{-9}$ (BELLE II TDR) to few$\times 10^{-10}$

Sensitivity scales as $1/\sqrt{L}$ or $1/L$ depending on the level of background (beam related background may become an issue)

K. Inami ICHEP 2016
**Mandate**
Explore opportunities offered by the (very rich) CERN accelerator complex to address outstanding questions in particle physics through projects:

- complementary to high-energy colliders (studied at CERN: HE-LHC, CLIC, FCC)
  - we know there is new physics, we don't know where it is → we need to be as broad as possible in our exploratory approach
- exploiting the unique capabilities of CERN accelerator complex and infrastructure and complementary to other efforts in the world:
  - optimise the resources of the discipline globally

**BSM program includes** **Search for Hidden Sector at the CERN SPS proton (SHiP & NA62++) and electron (NA64) beams**

**Many theoretical ideas predict new light particles, which can be tested experimentally**  
(see talk of Misha Shaposhnikov)
Thanks to stable LHC operation and long lifetime of the LHC beams significant fraction of the SPS protons, and its time, are available for physics at the North Area!

Nominal year of the SPS operation → 200 days with typical machine availability ~80%; 20% of the SPS physics time to run LHC and 80% - to run fix target programme
Very intense proton beam with highest in the world energy delivered to fixed target exp. at CERN SPS. The aim is to deliver with $4 \times 10^{13}$ protons / spill (at slow extraction).

The Beam Dump Facility at the SPS at Prevesinin North Area site is being actively studied within the PBC framework.

Proposed implementation is based on minimal modification to the current SPS complex.

Sharing of pot between current fixed target exp. and planned BDF.

Journée SHiP/Physique du secteur caché du 11/10/2017
**Search for Hidden Sector (HS) or very Weakly Interacting Massive Particles (vWIMP)**

\[ L = L_{SM} + L_{mediator} + L_{HS} \]

### Visible Sector

Mediators or portals to the HS: vector, scalar, axial, neutrino

- **Hidden Sector**
  - Naturally accommodates Dark Matter (may have rich structure)

- **HS production and decay rates are strongly suppressed relative to SM**
  - Production branching ratios \( O(10^{-10}) \)
  - Long-lived objects
  - Interact very weakly with matter

### Models

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNL, SUSY neutralino</td>
<td>( l^+\pi^-, l^+K^-, l^+\rho^- \rho^+ \rightarrow \pi^+\pi^0 )</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>( l^+l^- )</td>
</tr>
<tr>
<td>HNL, SUSY neutralino, axino</td>
<td>( \gamma\gamma )</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
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<tr>
<td>SUSY sgoldstino</td>
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- Full reconstruction and PID are essential to minimize model dependence

**Experimental challenge is background suppression**
(see Gaia’s talk)
Evidence for new SM-charged matter at the LHC. Much exceeds the observed cosmological matter density. Much experiments are essentially blind to dark matter of MeV.

New Electron Beam-Dump Experiments to Search for MeV to few-GeV Dark Matter

Injection, positioned roughly 20 meters downstream of the kinetic mix with the photon. Such models readily account for the stability of dark matter and its observed force carrier masses in the MeV.

Various considerations motivate dark matter candidates, extending beyond current sensitivity across a wide range of dark matter and force carriers.

The beam dump approach outlined here is quite common. Taxonomy of Dark Sectors

Long-lived weakly coupled states (see Figure 3). The setup requires a small electron recoil in direct detection [56].

Dramatic further gains can be obtained by shielding from multi-GeV electron beam impinging on a beam dump process. These extend sensitivity to long-lived weakly coupled states (see Figure 3).

Note: Missing mass technique is applicable only if dark photon mediator.

Requirement of displacement: L = (5, 7) m

Produced HS particle
Proton beam

Reconstruction of decay vertex

Indirect detection (SHiP & NA64)

Missing energy technique (NA64)

Scattering technique, electron or nuclei scattered by vWIMP (SHiP)

References [56–58]. If dark matter extends beyond direct detection constraints motivates a study quasi-elastic scattering at momentum transfers or shorter target-detector distances than shown above are typically used for proton beam setups, are negligible for neutrino experiments leave a broad and well-motivated class of dark matter beyond a few GeV.

A high-intensity pulsed beam such as the proposed ILC or simply by using a pulsed beam. The lower red curve corresponds to dark force carriers (for example, a gauge boson that masses in the MeV range and less sensitive than the offending, the incomingelectron and muon [64, 65], neutrino experiment wide open to improving.

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The SHiP experiment at SPS
(to search for HS and vWIMPs with O(10 GeV) masses)

>10^{18} D, >10^{16} \tau, >10^{20} \gamma
for 2\times10^{20} \text{pot (in 5 years)}

“Zero background” experiment
- Heavy target
- Muon shield
- Surrounding Veto detectors
- Timing and PID detectors, …

Search for vWIMP (scattering on atoms) and \nu physics
Specific event topology in emulsion. Background from neutrino interaction for vWIMP searches can be reduced to a manageable level
General experimental requirements to search for HS at beam dump experiment

- Search for HS particles in Heavy Flavour decays
  Charm (and beauty) cross-sections strongly depend on the beam energy

- HS produced in charm and beauty decays have significant $P_T$

Detector must be placed close to the target to maximize geometrical acceptance. Effective (and “short”) muon shield is the key element to reduce muon-induced backgrounds
Brief history and current status of SHiP

- Letter Of Intent - October 2013
- Technical Proposal & Physics Paper - April 2015
- Reviewed by the SPSC and CERN RB by March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2018
  → Input to the European strategy consultation to take a decision about construction of SHiP in 2019/2020

CDS will improve SHiP TP version respecting cost constraints
Main goals of the SHiP optimization for the CDS

- Further optimization of the target
- Configuration of the muon shield, including magnetization of the hadron stopper (MC to be validated with data)
- Shape, dimension and evacuation of the decay volume
- Optimization of physics performance for various sub-detectors
- Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID (see Walter’s talk)
- Optimization of the emulsion detector to search for LDM

Updated background estimates and signal sensitivities, and cost
- Contribution from the secondary interactions in the target improves signal yield by ~50% (to be validated with data)
**Optimization of the emulsion spectrometer**

**TP layout**

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**Brief reminder on the requirements:**

- High spatial resolution to observe the \( \tau \) decay (~1 mm)
  
  ➔ **EMULSION FILMS**

- Electronic detectors to provide the time stamp to the event and match tracks from the emulsion target down to the muon spectrometer
  
  ➔ **TARGET TRACKER PLANES**

- Magnetized target to measure the charge of hadrons from \( \tau \) decays
  
  ➔ **DIPOLAR MAGNET**

- Magnetic spectrometer to perform muon identification and measure its charge and momentum
  
  ➔ **MUON SPECTROMETER**
**TT: Target Trackers** (12 planes, 0.8×1.6 m² each)

Technology is to be chosen!

- Provide time stamp of the neutrino interaction in the brick
- Matching between the electronic detectors and the emulsion tracker in high density environment (long integration time of the emulsion films)
- Matching the muon track with the downstream muon spectrometer

**Requirements:**
- Spatial resolution: 100 um
- Maximum thickness for a plane: 5 cm
- Distance between TT plane and ECC to be small (a few mm) and uniform (constant tracking capabilities)
- Small dead spaces (max 1 mm) to be matched with ECC dead spaces
- High efficiency (>99%)
- Good performances in magnetized region
- Angular information

**Note:** Good spatial resolution needed, e.g. to discriminate between 2-vertices topology ($D^0$-decay) and two neutrino interactions occurring at the same time stamp.
Optimization of the SHiP emulsion spectrometer for vWIMP searches (iSHiP) and $\nu_{\tau}$ physics

Possible improvements:

- Analog readout of TT to provide calorimetric information
- Optimize the distance between consecutive TT planes (currently $\sim 10X_0$)
- Use a combination of TT and ECC to measure electromagnetic and hadronic showers in the event

New layout is under study

- Single long magnet hosting the emulsion and muon spectrometer
- Muon identification using a filter outside the magnet
✓ **Planning very well aligned with**

- Update of European strategy 2019/2020
- Accelerator schedule (to be followed closely)
- TDRs by 2021
- Production Readiness Reviews (PRR) 2021Q2 – 2022Q1
- Construction / production 2021Q2 →
- Data taking (pilot run) 2026 (start of LHC Run 4)

✓ **Main current priority:** *Comprehensive Design Study by 2018*
Future prospects and comparison with other facilities

**HNLs:**

\[ |HNL\text{ coupling to } \mu|^2 \]

- \( M_{\text{HNL}} < M_b \)  LHCb, Belle2  
  **SHiP will have much better sensitivity**

- \( M_b < M_{\text{HNL}} < M_Z \)  FCC in \( e^+e^- \) mode  
  (improvements are also expected from ATLAS / CMS)

- \( M_{\text{HNL}} > M_Z \)  Prerogative of ATLAS/CMS @ HL LHC

**SHiP sensitivity covers large area of parameter space below B mass moving down towards ultimate see-saw limit**

**SHiP will also have the best prospects for HS particles produced in heavy flavour decays, e.g. hidden scalars**  (see Gaia’s talk)
**Detection via scattering**

- **SHiP** has the best sensitivity in 20 – 200 MeV
- Optimization is ongoing
- **COHERENT**, BDX and **SBNe** in US

**Missing mass / energy technique**

- **Belle II** with 50 ab\(^{-1}\) provided that low energy mono-photon trigger works
- **LDMX** (under discussion at SLAC) has the best prospects for **M\(_x\)< 100 MeV**

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**Future prospects and comparison with other facilities**

**Dark photons:**

\[ A' \to \text{visible modes} \]

- **90% UL exclusion**
  - **SHiP**, **Belle II**, **50 ab\(^{-1}\)**, **2024**
  - **LHCb**, **15 fb\(^{-1}\)**, **2023**
  - **HPS**, **2016-2020**
  - **APEX**, **2018+**
  - **SeaQuest**, **2017-2019**
  - **VEPP**, **2016-2020**
  - **SHiP**, **2026+**

- **NA62**, **mesons & brem.**, **2023**
- **APEX**, **2018+**
- **SeaQuest**, **2017-2019**
- **VEPP**, **2016-2020**
- **SHiP**, **2026+**
- **NA62**, **mesons & brem.**, **2023**

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**Light Dark Matter**

- **Dark Photons in visible modes:** past and future sensitivities
- **90% UL exclusion**

**Selected regions**

- **SHiP**
- **LDMX**
- **NA64++** in dump mode (only mesons & brem.)
- **Belle II, 50 ab\(^{-1}\)**, **2023**
- **LHCb, 15 fb\(^{-1}\)**
- **HPS, 2016-2020**
- **APEX, 2018+**
- **SeaQuest, 2017-2019**
- **VEPP, 2016-2020**
- **SHiP, 2026+**
- **NA62, mesons & brem., 2023**

**Future prospects and comparison with other facilities**

**Light Dark Matter**

- **Scalar Elastic DM (Kinetic Mixing)**
- **Community report of US Cosmic visions:** New ideas in Dark Matter 2017

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Search for $\tau \to \mu\mu$ ($\tau$SHiP) at possible extension of SHiP facility
Currently at the pre-EOI stage (see SHiP Physics Paper)

$\tau$SHiP is located upstream SHiP

- Thin (~1mm thick) W target(s) $\rightarrow$ $\tau$-decay vertex in the air
- $\sim 5 \times 10^{13}$ $\tau$ leptons produced in 5 years
- Backgrounds include
  - Combinatorial bckg., mainly from muons produced in em decays of $\eta$, $\rho$, $\omega$, ...
  - Bckg. from various semileptonic $D$ decays, e.g. $D^+ \rightarrow \eta\mu^+\nu$, $\eta \rightarrow \mu^+\mu^-$
- Estimated sensitivity: UL on BR($\tau \rightarrow 3\mu$) better than $10^{-10}$ (SHiP Physics Paper)

BUT: Great improvements in detector technologies are required
Synergy with LHCb tracking and calorimetry for future upgrades

Journée SHiP/Physique du secteur caché du 11/10/2017
Important measurements towards TDR (test beam program and prototypes will be covered by Richard)

- Measurement of muon flux expected at SHiP in 2018
  Replica of the SHiP target followed by a muon spectrometer

- **SHIP target**, 10×10 cm² Mo/W replica
- **Spectrometer** to measure momentum and charge of the muons
- **Muon tagger** to identify muons

10¹¹ pot → 10 times more data than in SHiP MC
Validate simulation in “dangerous” corners of the muon phase space

EoI-016 submitted to the SPSC
**Associated charm production**

**Measurement of inclusive $d^2\sigma/dE_d\theta$ charm cross section in SHiP-like target** (to validate cascade production in the target) in 2018-2021

- **SHIP target**, $10\times10$ cm$^2$ Mo/W blocks (few mm) interleaved with emulsion to identify charm topology
- **Spectrometer** to measure momentum and charge of the charm daughters
- **Muon tagger** to identify muons

Cascade effect $\rightarrow$ a factor $\sim 2$-3

400 GeV protons

5 x $10^7$ pot $\rightarrow$ $\sim$ 10000 charmed hadron pairs

EoI-017 submitted to the SPSC
Physics case to search for Dark Sector is very timely!
No NP finding at LHC, but many theoretical models offer a solution for the BSM experimental facts with light very weakly-interacting particles. Must be tested!

CERN is ideal place to search for Dark Sector at high energy and high intensity SPS beams. Two complementary strategies are being explored, direct observation of the decay vertex and indirect detection via scattering on atoms.

New possibilities to search for LFV in tau decays at the SHiP facility.

SHiP is an ideal experiment to search for new phenomena in $< O(10 \text{ GeV})$ range in “no background” environment.
Complementarity between two detection techniques:
- Reconstruction of the decay vertices in the decay volume
- Detection of interactions with atoms in the emulsion spectrometer

The rich physics programme to search for Dark Sector at the SPS North Area at CERN nicely complements searches for NP at the LHC.