Neutrino physics with the SHiP experiment at CERN

Alessandra Pastore (INFN Bari) on behalf of the SHiP Collaboration
Beyond Standard Model ...

Experimental hints of BSM physics
- $\nu$ masses and oscillations
- Baryon Asymmetry of the Universe
- Dark Matter

New Physics can be hidden due to

- very heavy masses
- very weak couplings

Energy Frontier, high energy collisions
Intensity Frontier, beam dump
Search for Hidden Particles (SHiP) @ CERN-based Beam Dump Facility (BDF)

- Slow extraction (1 sec)
- High intensity proton beam
  \[4 \times 10^{13} \text{ p/spill}, 4 \times 10^{19} \text{ pot/year}\]
  \[2 \times 10^{20} \text{ pot/5 years}\]
- \(O(400 \text{ GeV/c})\) optimal beam momentum

SHiP/BDF cycle test target MD in 2018

existing tunnels
existing buildings
new installations

EPS-HEP2019
The SHiP experiment

Dual detector system
- Hidden Sector detector (HS)
  \(\rightarrow\) search for new, weakly coupled, long lived particles from the Hidden Sector

- Scattering and Neutrino Detector (SND)
  \(\rightarrow\) neutrino physics and Light Dark Matter searches
The SHiP experiment

Dual detector system

- **Hidden Sector detector (HS)**
  - search for new, weakly coupled, long lived particles from the Hidden Sector

- **Scattering and Neutrino Detector (SND)**
  - neutrino physics and Light Dark Matter searches

see A. Korzenev’s talk, EPS-HEP2019
The SHiP experiment: general requirements

driven by Hidden Sector phenomenology

5 years of BDF@SPS ($2 \times 10^{20}$pot):

- $10^{18}$ charm mesons
- $10^{14}$ beauty mesons
- $10^{16}$ tau leptons
The SHiP experiment: general requirements

Driven by Hidden Sector phenomenology

Target and hadron absorber

High A and Z, and short $\lambda$ target

Hadron absorber
Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay
The SHiP experiment: general requirements

Driven by Hidden Sector phenomenology

Target and hadron absorber

High $A$ and $Z$, and short $\lambda$ target

Hadron absorber
Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay

Magnetised muon shield

$\mu$ rate reduced to $\approx 25$ kHz

$\mu$ spectrum validated with dedicated experiment in 2018
The Scattering and Neutrino Detector concept

High $\nu$ flux expected@BDF

$\rightarrow$ Unique opportunity to perform studies on $\nu_\tau$, $\nu_\mu$, $\nu_e$ (+ cc) @SHiP SND

\[ p + N \rightarrow X + \pi^\pm, K^\pm \quad \pi^\pm, K^\pm \rightarrow \nu_\mu \mu^\pm \]

Proton Beam  Target  Charged Mesons  Neutrino Beam

$\pi^\pm, K^\pm$

$\nu$ Physics potential:
- first ever observation of anti- $\nu_\tau$
- $\nu_\tau$ and anti- $\nu_\tau$ physics with high statistics wrt the state of the art
- $\nu$ induced charm production studies
- $\nu_f$ cross sections measurements

Experimental requirements:
- reconstruct $\nu$ interactions $\rightarrow$ Emulsion Cloud Chamber technique + TT
- tag $\nu$ flavour $\rightarrow$ ECC technique + $\mu$ ID system
- tag $\nu$ and anti-$\nu$ $\rightarrow$ Magnetised target

# of $\nu$ CC DIS int. in SND target in $2\times10^{20}$ pot

<table>
<thead>
<tr>
<th>$\bar{\nu}$ [GeV]</th>
<th>CC DIS int.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$2.7 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
<td>$3.2 \times 10^4$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$2.6 \times 10^5$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$6.0 \times 10^5$</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
<td>$2.1 \times 10^4$</td>
</tr>
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</table>
The Scattering and Neutrino Detector

Experimental requirements:

- reconstruct $\nu$ interactions $\rightarrow$ **Emulsion Cloud Chamber (ECC) technique + Target Tracker (TT)**
- tag $\nu$ flavour $\rightarrow$ **ECC technique + $\mu$ ID system**
- tag $\nu$ and anti-$\nu$ $\rightarrow$ **Magnetised target**
The SND magnetized target (I)

B field (H dir) 
\(\approx 1.2 \, \text{T}\)

Target mass 
\(\approx 8 \, \text{ton}\)

\(\approx 230\) events in 1 ECC exp.

\(\text{vtx definition @ } \mu\text{m resolution}\)

ECC thickness \(\approx 10 \, X_0\) (shower ID)

Techniques successfully exploited in the OPERA experiment
The SND magnetized target (II)

B field (H dir) \( \approx 1.2 \) T

SciFi target tracker characteristics provide time stamp and link muon track information from the target to the magnetic spectrometer with:

- \( \sigma_{x,y} \sim 30-50 \) \( \mu \)m resolution
- Six scintillating fibre layers, total 3mm thickness \( \sim 0.05 X_0 \)
- Multi channel SiPM at one end, ESR foils as mirrors on other

ECC+TT combination provides a total chargeID efficiency of \( \sim 65\% \) for \( \mu \) produced in \( \nu_\mu \) CC interactions
The SND muon identification system

track and identify muons, and tag interactions ($\nu, \mu$) in the last layers before entrance window to HS decay volume

RPCs sensitive area of $\sim 2 \times 4 \, m^2$

geometrical acceptance $\sim 60\%$

$\varepsilon_{\mu ID} = 96.7\%$

Hadrons’ mis-identification 1.5%.

RPC prototypes built and successfully operated for muon flux and charm production measurement at SPS in 2018
Light dark matter searches with SND

Ideal laboratory also for Light Dark Matter scattering signatures

Look for LDM elastic scattering on atomic electrons of the target

\[ \chi e^- \rightarrow \chi e^- \]

signal: single EM shower w/o associated tracks

background: neutrinos can mimic LDM scattering in case of only one visible track at primary vertex, \textit{f.e.}


Neutrino physics prospects

- First observation of anti-$\nu_\tau$

- Measurement of $\nu_\tau$ and anti-$\nu_\tau$ cross-sections

- First evaluation of $F_4$ and $F_5$ not accessible with other $\nu$

\[
\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_\nu^2)^2} \left( y^2 x + \frac{m_\tau^2 y}{2 E_\nu M} \right) F_1 + \left[ 1 - \frac{m_\tau^2}{4 E_\nu^2} \right] F_2 \\
\pm \left[ x y \left( 1 - \frac{y}{2} \right) - \frac{m_\tau^2 y}{4 E_\nu M} \right] F_3 + \frac{m_\tau^2 Q^2}{4 E_\nu^2 M^2 x} \left( F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right),
\]

$F_4 = F_5 = 0$

\begin{align*}
\text{anti-$\nu_\tau$ CC DIS cross section} & \quad E(\text{anti-$\nu_\tau$}) < 38 \text{ GeV}, \approx 300 \text{ events exp.}
\end{align*}
Neutrino physics prospects (II)

- $\nu_e$ cross sections at high energies
- strange quark nucleon content through charm production

Expected anti-$\nu_\mu$ induced charm yield in SHIP $\sim 2.7 \times 10^4$
Observed in CHORUS $\sim 32$, in NuTeV $\sim 1400$

Significant gain in $s^+/s^-$ vs $x$, with SHIP data (factor 2) obtained in the $x$ range between 0.03 and 0.35

- normalization of hidden particle search
Conclusion

- The SHiP SND detector offers a unique opportunity for neutrino physics/scattering programme

- The detector R&D and its design are under optimisation, already in good shape

- The Collaboration is moving forward to submit the CDS by 2019 to the SPSC and produce TDRs in 2021-2022
backup
SHiP history

- **2013 Oct**: EOI with SHiP@SPS NA
  ...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF

- **2014 Jan**: Encouraged to produce TP and inter-departmental task force setup to study feasibility of proposed facility

- **2015 Apr**: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments

- **2016 Jan**: Recommendation by CERN SPSC to proceed to Comprehensive Design Study

- **2016 Apr**: CERN management launch of Beyond Collider Physics study group
  - SHiP experimental facility included under PBC as Beam Dump Facility

- **2018**: EPPSU contribution submitted by SHiP and BDF, and submission of SHiP Progress Report

- SHiP Collaboration: **290 authors, 52 Institutes, 17 countries**

R. Jacobsson - *Detector Seminar, CERN, 22 March 2019*
## Costs and project plan

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (MCHF)</th>
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<tbody>
<tr>
<td><strong>Muon Shield</strong></td>
<td>11.4</td>
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<tr>
<td><strong>Scattering and Neutrino Detector</strong></td>
<td>11.6</td>
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<tr>
<td>Emulsion Target (no magnet)</td>
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<tr>
<td>Target Tracker</td>
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<tr>
<td>Muon Magnetic Spectrometer</td>
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<td><strong>Decay Spectrometer</strong></td>
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<tr>
<td>Decay Volume</td>
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<td>Surround Background Tagger</td>
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<tr>
<td>Upstream Veto Tagger</td>
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<tr>
<td>Straw Veto Tagger</td>
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<td>Spectrometer Straw Tracker</td>
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<td>Spectrometer Magnet</td>
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<td><strong>Total</strong></td>
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### Accelerator schedule

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<td>CwB</td>
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**ντ/ANTI-ντ SEPARATION**

**REQUIREMENTS**
- Electric charge measurement of τ lepton decay products
- Key role for ντ/ντ separation in the τ→h decay channel
- Momentum measurement

**LAYOUT**
- 3 OPERA-like emulsion films
- 2 Air gaps
- 1.2 Tesla magnetic field

Charge measured from the curvature of the track with the **sagitta** method

**PERFORMANCES**
- Sign of the **electric charge** can be determined with better than 3 standard deviation level up to 12 GeV
- The **momentum** of the track can be estimated from the sagitta
- Δp/p < 20% up to 12 GeV/c

A. DiCrescenzo, *Vacuum Fluctuations at Nanoscale and Gravitation: theory and experiments*, 1 May 2019
Charm/$\mu$ flux measurements (July 2018, Cern H4)

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

- Measure of charm production essential for HS and $\nu$ study studies
- Lead target + emulsions. $1.6 \times 10^6$ pot + 10x run after LS2