The SHiP experiment at CERN

A. Murat GÜLER
METU Ankara
On behalf of the SHiP Collaboration
Physics Motivation

- Standard Model provided consistent description of Nature’s constituents and their interactions.
  - No significant deviation from SM.
- But the Standard Model can not explain
  - Neutrino masses and oscillations
  - Dark matter
  - Baryon asymmetry

CMB: $\frac{n_b}{\gamma} = (6.3 \pm 0.3) \times 10^{-10}$
$\text{CPV (SM)} \sim 10^{-20}$

Universe content
- Visible matter 5%
- Dark matter 27%
- Dark energy 68%
Physics Motivation

- If the *hidden* particles have very feeble interaction with standard model particles. The only way to observe these interactions is to go high intensity.
- The SHiP is proposed to explore the domain of hidden particles in intensity frontier.
Physics Goals

- Hidden particles are coupled to the Standard Model sector via renormalizable “portals”.

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

- Large number of models investigated.
- Tau Neutrino Physics.

- HP production and decay rates are strongly suppressed relative to SM
  - Production branching ratios $O(10^{-10})$
  - Long-lived objects
Physics Goals

- Production through hadron decays (π, K, D, B, proton bremsstrahlung, …)

<table>
<thead>
<tr>
<th>Models tested</th>
<th>Final states</th>
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<td>Neutrino portal, SUSY neutralino</td>
<td>lπ, lK, lp (l=e,μ,ν) (ρ⁺→π⁺π⁰)</td>
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<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>e⁺e⁻, μ⁺μ⁻</td>
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<td>SUSY sgoldstino</td>
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- Full reconstruction and PID are essential to minimize model dependence
- Experimental challenge is background suppression
  - It requires O(0.01)
The neutrino Minimal Standard Model (νMSM) aims to explain.

- Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter.
- Adds three right-handed, Majorana, Heavy Neutral Leptons (HNL), N1, N2 and N3.

- N1 is a dark matter candidate (m≈ O(1) keV).
- N2, N3 give masses to neutrinos and produce baryon asymmetry of the Universe m≈ O(100 MeV-GeV)
HNL Sensitivity

- Production in charm and beauty meson decays
- Decay into $hl$ and $ll\nu$
- $\nu$MSM parameter space almost totally explored for $m_N \leq 2$ GeV

- SHiP sensitivity covers large area of parameter space below the B mass & moving down towards the ultimate see-saw limit
 Scalar Portal : Hidden scalar can mix with the SM Higgs. Mostly produced in penguin-type decays of B and K decays
- Decay into a pair of SM particles: $S \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, KK, \eta\eta, \tau\tau, DD$

 Vector portal : dark photon ($A'$) produced in QCD processes or in decays of $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma\pi^0$ and $\eta' \rightarrow \gamma'\gamma$
- Decay into SM particles through a virtual photon: $\gamma' \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}$
A facility to search for hidden particles (SHiP) at the SPS: the physics case

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85 theorists
arXiv: 1504.0855
The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode.

- 400 GeV protons from SPS
- $4 \times 10^{19}$ pot/year (~200 days of running)
- Spill = $4 \times 10^{13}$ pot per cycle of 7.2 s with slow beam extraction (1s)

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

- **Initial reduction of beam induced backgrounds**
  - Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in $\pi/K \rightarrow \mu\nu$ decays (short $\lambda_{int}$)
  - Hadron absorber
  - Effective muon shield (without shield: muon rate $\sim 10^{10}$ per spill of $4 \times 10^{13}$ pot)
  - Slow (and uniform) beam extraction $\sim 1$ s to reduce occupancy in the detector
The SHiP Detector

- $N_{\text{pot}} = 2 \times 10^{20}$ in 5 years of data taking
  - $> 10^{17} D$
  - $> 10^{15} \tau$
  - Zero background

- All heavy infrastructure is at distance to reduce neutrino/muon interactions.

- Long decay volume protected by various Veto Taggers,

$\sim 150 \text{m}$
Active Muon Shield

- Active muon shield based entirely on magnet sweeper with a total field integral $B_y = 86.4 \text{ Tm}$
- Realistic design of sweeper magnets in progress
- $< 7k$ muons / spill ($E_\mu > 3 \text{ GeV}$), from $10^{10}$
- Negligible flux in terms of detector occupancy
Background rejection:
• $\mu$ or $\nu$ interactions in decay volume: evacuated vacuum vessel: (10 µbar)
• $K/\Lambda$-decays produced in surrounding material in $\mu$, $\nu$-interaction:
  – Taggers: liquid scintillator in double walled vessel to veto candidates with accompanying particles.
  – Veto: veto short lived $K_S$, $\Lambda$, or candidate with accompanying particles.

Spectrometer to reconstruct signal:
• Ecal and muon filter/chambers at the end.
• Tracking straw chambers and magnet for reconstruction.
Particle Identification

ECAL: $e/\gamma$, $\pi^0$ and $\eta$ reconstruction (Shashlik technique)

HCAL: $\pi/\mu$ separation
Emulsion Target

- **Dimensions:** 0.8 x 2 x 1.6 m³
- **Number of ECC bricks:** ~900
- **Modular structure made of a sandwich of passive material plates interleaved with emulsion films.**
- **Total mass:** ~7 tons
The Neutrino Target

Target Trackers
- Provide time stamp
- Link track information in emulsion to signal in TT.

Dipolar Magnet & Compact Emulsion Spectrometer
- To measure the charge of the decay products.
- $\nu_\tau$/anti-$\nu_\tau$ separation, charge measurement.

ECC
- Primary and secondary vertex reconstruction with $\mu$m resolution
- Momentum measurement by multiple Coulomb Scattering
- Electron/pion identification.

Muon Spectrometer
- Perform the muon identification and measure its charge and momentum.

~230 events/brick
SHiP Neutrino Program

- SHiP setup ideally suited to study neutrino and anti-neutrino physics for all three active flavours.
- High charmed hadrons production rates ⇒ high neutrino fluxes from their decays, including remnant pion and kaon decays.

- Energy spectrum of different neutrino flavors at target
- Anti-$\nu_\tau$ is not detected!

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5/25/17

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**ν_τ/anti-ν_τ yield**

- Number of ν_τ and anti-ν_τ produced in the beam dump.

\[
N_{ν_τ+ν̅_τ} = 4N_p \frac{σ_{c\bar{c}}}{σ_{pN}} f_{D_s} Br(D_s → τ) = 3.26 \times 10^{-5} N_p = 6.5 \times 10^{15}
\]

- Main background in ν_τ and anti-ν_τ searches is the charm production in ν_μCC (anti-ν_μCC ) and ν_eCC (anti-ν_eCC ) interactions, when the primary lepton is not identified.

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**R = S/B Ratio**
F₄ and F₅ Structure Functions

- Through νₜ and anti-νₜ identification: unique capability of being sensitive to F₄ and F₅

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

\[\pm \left[ xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3 + \frac{m_\tau^2(m_\tau^2 + Q^2)}{4E_\nu^2 M^2 x} \left( F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right),\]

- SM prediction:
  \[F_4 = F_5 = 0\]

- At LO F₄ = 0, 2xF₅=F₂
- At NLO F₄ ~ 1% at 10 GeV

- E(\bar{\nu}_t) < 38 GeV
  r>1.6 evidence for non-zero values of F₄ and F₅
Expected charm exceeds the statistics available in previous experiments by more than one order of magnitude.

In NuTeV: \( \sim 5100 \nu_\mu, \sim 1460 \text{anti-} \nu_\mu \)

In CHORUS: \( \sim 2000 \nu_\mu, 32 \text{anti-} \nu_\mu \)

- **No charm candidate from \( \nu_e \) and \( \nu_\tau \) interactions ever reported!**
### Project Schedule

**Form SHiP Collaboration December 2014**
- Technical Proposal April 2015
- Positive SPSC recommendation for CDS September 2016
- **Comprehensive Design Study 2018**
- **Construction and Installation 2021-2025**
- Commissioning and data taking 2026

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SHiP: Search for Hidden Particles

- SHiP is a new proposed fixed-target experiment at the CERN SPS accelerator to search for hidden, very weakly interacting new particles.
- At the same time, also ideal for $\nu_\tau$ physics.

Collaboration
- 49 institutes from 16 Countries, plus CERN
SHiP is a fixed target experiment proposal at CERN SPS.
SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with mass $O(10)\text{ GeV}$.
SHiP will perform a complement searches for new searches at energy frontier at CERN.
SHiP is also unique detector for neutrino/charm physics.
Positive recommendation from the SPSC in January 2016.
## Costs

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</tr>
<tr>
<td><strong>Grand total</strong></td>
<td>194.5</td>
</tr>
</tbody>
</table>
Vacuum Vessel
- 10 m x 5 m x 60 m
- Walls thickness: 8 mm (Al) / 30 mm (SS)
- Walls separation: 300 mm
- Liquid scintillator (LS) volume (~36 m³) readout by WLS optical modules (WOM) and PMTs
- Vessel weight ~ 480 t

Magnet designed with an emphasis on low power
- Power consumption < 1 MW
- Field integral: 0.65 Tm over 5m
- Weight ~800 t
- Aperture ~50 m²

Estimated need for vacuum: ~10⁻³ mbar
• Tracking
  – TT, Straw tracker (polyethylene terephthalate tubes), Emulsion

• Particle ID
  – ECAL, HCAL, Muon spectrometer, Emulsion

• Reconstruction
  – Decay vtx, IP, mass

• Momentum
  – ECC, CES with magnet, Muon spectrometer

• Charge
  – CES with magnet, Muon spectrometer

• Timing detector
  – Plastic scintillator or MRPC (multigap RPC), TT
Calorimeters

ECAL
- Almost elliptical shape (5 m x 10 m)
- 2876 Shashlik modules
- 2x2 cells/modules, width=6 cm
- 11504 independent readout channels

HCAL
- Matched with ECAL acceptance
- 2 stations
- 5 m x 10 m
- 1512 modules
- 24x24 cm² dimensions
- Stratigraphy: N x (1.5 cm steel+0.5 cm scint)
- 1512 independent readout channels

Dimensions 60x60 mm²
Radiation length 17 mm
Moliere radius 36 mm
Radiation thickness 25 X₀
Scintillator thickness 1.5 mm
Lead thickness 0.8 mm
Energy resolution 1%
Muon System

- Based on scintillating bars, with WLS fibers and SiPM readout

Requirements:
1) High-efficiency identification of muons in the final state
2) Separation between muons and hadrons/electrons
3) Complement timing detector to reject combinatorial muon background
Timing Detector

Challenges:
- Large area
- Required resolution < 100 ps
- Spatial resolution under study

Two options considered:
- Scintillator bars (NA61/SHINE, COMPASS)
  - NA61/SHINE ToF
  - 100 ps resolution
  - Long scintillator bars
- Multi-gap resistive plate chambers (MRPC)
  - 61 chambers x 120 cm strips, 3 cm pitch
    - Used in ALICE TOF
    - 50 ps resolution achievable
Muon Identification

Muon come from
- $\tau \rightarrow \mu$ decays
- $\nu_\mu$ CC interactions
- $\mu$ identification at primary vertex for background rejection

12 iron layers
11 RPC layers
6 Drift Tube Trackers Planes
** Tau/anti-tau Separation **

** TASK **
- Electric charge and momentum measurement of $\tau$ lepton decay products
- Key role for the $\tau \rightarrow h$ decay channel
- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field

** PERFORMANCES **
- Electric charge determined up to 10 GeV/c.
- Momentum estimated from the sagitta.
- $\Delta p/p < 20\%$ up to 12 GeV/c
LHM Search

- Generated in the beam-dump, e.g. via light dark photon mediators (V)
- Main production modes
  1) direct production
  2) decay in flight
  3) resonant vector meson mixing

LDM elastic scattering on atomic electrons of the target

High energy beam dump:
- LDM-electron scattering is highly peaked in the forward direction
Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon.

Strangeness important for precision SM tests and for BSM searches.

W boson production at 14 TeV: 80% via $ud$ and 20% via $cs$. 