Neutrino Physics with the SHiP experiment at CERN

C. S. Yoon (GNU)
On behalf of the SHiP Collaboration
Where is new physics?

Why couldn't we detect them?
→ Too heavy or too weakly interacting

Energy frontier
High mass scale, strong coupling
(LHC, HL-LHC, FCC, ILC etc.)

Intensity frontier
Low mass scale, very weak coupling
Long lifetime (fixed target, beam dump ...)

The intensity frontier aimed at exploring the Hidden sector region: Main target of PBC (Physics Beyond Colliders) activity at CERN → SHiP (Search for Hidden Particles)
Many hidden sector models often include low mass particles around GeV scale (LDM candidates).
**Neutrino portal**

**νMSM**

Extends SM by RH partners of neutrinos

T. Asaka, M. Shaposhnikov

PLB 620 (2005) 17

\[ N_1 \, (\sim 10 \text{ keV}) \]

Dark matter candidate

\[ N_{2,3} \, (100 \text{ MeV} \sim \text{GeV}) \]

Matter–Antimatter asymmetry

Neutrino mass (oscillation)

\[ N = \text{Heavy Neutral Lepton (HNL)} \]

Heavy RH neutrinos
The cosmologically interesting region is at low couplings

Assuming $U^2 = 10^{-7}$
and $\tau_N = 1.8 \times 10^{-5}$ s
$\sim 12k$ fully reconstructed
$N_{2,3} \rightarrow \mu^- \pi^+$ events are expected for $M_N = 1$ GeV.

$\sim 330$ events for cosmologically favored region:
$U^2 = 10^{-8}$ & $\text{BR}(N \rightarrow \mu \pi) = 20%$

early estimations

#HNL will be increased if other decay products ($e\pi, \mu\rho, e\rho$ etc.) can be identified.

BAU, Seesaw and BBN constraints indicate that previous exp did not prove the interesting region of HNL masses above the Kaon mass.
A new experiment proposed at CERN in order to search for *Hidden particles* which is feebly interacting long-lived particles (LLPs) including *Light dark matter (LDM)* and to study *Neutrino physics*.

**Using High-intensity**

**400 GeV proton beam**

**2 x 10^{20}** *pot*, **5 years run**
The SHiP facility is located on the North Area (Prénessin site), and shares the TT20 transfer line.

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

The SHiP facility is located on the North Area (Prénessin site), and shares the TT20 transfer line.
Hidden Sector proposals in CERN North Area

**NA62**++ , KLEVER @ K12
400 GeV p beam
up to $3 \times 10^{18}$ pot/year (now)
up to $10^{19}$ pot/year (upgrade)

**NA64**++ (e) @ H4
(100 GeV e- beam
up to $5 \times 10^{12}$ eot/year)

**SHiP, TauFV** @ BDF
400 GeV p
up to $4 \times 10^{19}$ pot/year

**NA64**++ ($\mu$) @ M2
100-160 GeV muons, up to $10^{13}$ $\mu$/year

CERN can provide the highest energy proton, electron and muon beams for fixed target experiments in the world.

The “Hidden Sector Campus” (HSC)

Gaia Lanfranchi
The SHiP detector

A discovery machine for **feebly coupled LLPs**, with a complementary detector for **Neutrino physics** and **LDM scattering**

**HS Decay Spectrometer**
- ECAL, Muon detector
- Straw trackers
- Timing detector
- Surround bg tagger

→ large geometrical acceptance:
  - long decay volume close to dump

**Scattering and Neutrino Detector (SND)**
- Emulsion target (ECC+CES) - high spatial resolution tracker (sub-μm)
- Target Tracker (TT)
- Muon filter (RPC) - muon identification
Active muon shield
deflect $\mu$ from 2ry meson decay
~ 35m long, 1.7 T magnet

Hadron absorber
eliminate 2ry mesons ($\pi, K$) ~ 5m Fe

Scattering and Neutrino Detector
LDM & Tau neutrino
ECC + CES
(Nuclear emulsion)
TT, RPC

Vacuum vessel
~50 m long evacuated decay vessel
surrounded by liquid scintillator veto system

The SHiP detector
**Active muon shield**  

1400 tons magnet  
μ rate reduced to ~ 25 kHz

Blocks of TZM (Titanium-Zirconium) doped Molibdenum alloy (10.22 g/cm³) followed by blocks of pure Tungsten

SHiP replica target used for beam test at SPS H4 beamline in July 2018

JINST 12 (2017) no.5, P05011
Decay of Hidden Particles

**Models tested**
- Neutrino portal, SUSY neutralino
- Vector, scalar, axion portals, SUSY sgoldstino
- Neutrino portal, SUSY neutralino, axino
- Axion portal, SUSY sgoldstino
- SUSY sgoldstino

Final states
- $\ell^\pm \pi^\pm$, $\ell^\pm K^\pm$, $\ell^\pm \rho^\pm$
- $e^+ e^-$, $\mu^+ \mu^-$
- $\pi^+ \pi^-$, $K^+ K^-$
- $\ell^+ \ell^-$, $\nu$
- $\gamma \gamma$
- $\pi^0 \pi^0$

$\ell = (e, \mu, \nu)$, $\rho^\pm \rightarrow \pi^\pm \pi^0$

Many Vee decay modes

→ **Particle ID and Full reconstruction are essential to minimize model dependence.**
$10^{18}$ charm mesons
$10^{14}$ beauty mesons
$10^{16}$ $\tau$ leptons
for $2 \times 10^{20}$ pot (in 5 yrs)
Neutrino Physics with SHiP

- About 10,000 Tau neutrino & Anti-tau Neutrino CC events can be observed in ECC target.
  - First observation of the Anti-tau neutrino
- Tau neutrino physics
  - Cross section, Magnetic moment measurements
  - First evaluation of F4 and F5 structure functions
  - Study of Strange quark content of nucleon
- LDM search in SND
**Tau Neutrinos so far**

**DONuT** 9 events
- First direct observation
- Proton beam dump exp.
- Cross section, mag mom

\[ \sigma_{const}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1} \]

could not distinguish \( \nu_\tau \) and \( \bar{\nu}_\tau \)

**OPERA** 10 events from oscillation
- Long-baseline CNGS beam
- Discovery of \( \nu_\tau \) appearance
- event by event basis (6.1\( \sigma \))
- not statistical basis

Using Emulsion-Counter hybrid system & High speed auto-scanning system

→ Same technique will be used in SHiP
**Scattering and Neutrino Detector**

- **ECC (Emulsion Cloud Chamber)**: High spatial resolution (~μm) to observe the τ decay
- **CES (Compact Emulsion Spectrometer)**: measure muon charge & momentum
- **TT (Target tracker)**: Electronic detector to predict ν interaction contained in ECC brick and provide the time stamp
- **Magnet**: to measure the charge of τ products (1.25 T)
- **Muon filter (RPC)**: Muon identification and tracking (area 2 x 5 m² x 12 planes)
Scattering and Neutrino Detector

Copper Coil

Iron yoke/shield

Heavy target ECC

Light CES
**ECC brick**

*1 brick* - 57 Emulsion film (40 x 40 cm²) interleaved with 1 mm thick lead plates, ~100 kg

**Total 19 walls**

76 (=2x2x19) large bricks (~700 m²), ~10 tons to be replaced 10 times (~7000 m² total)

---

**CES**

made of 3 emulsion films interleaved by 2 layers of low density materials to be replaced every ~2 weeks

each CES ~ 10kg
**Anti-tau Neutrino identification by CES**

- Electric charge can be determined with better than 3σ level up to 12 GeV/c
- Momentum estimated from the sagitta $\Delta p/p < 20\%$ up to 12 GeV/c
Identification of Neutrino flavors

\[ \nu_\mu \text{ CC interaction} \]

\[ \nu_e \text{ CC interaction} \]

Emulsion film as high precision tracker

→ identification of \( \nu_e, \nu_\mu, \nu_\tau \) is possible by distinguishing \( e, \mu, \tau \) particles
Tau Neutrino

Topological selection & Kinematical cuts

$P_T, \phi, \theta_{kink} \ldots$

at interaction vtx & decay vtx

Charm & Single-prong interaction of 2ry hadrons (white kink)
Track reconstruction in ECC brick

Scan 10 films around vertex plate and reconstruct tracks

Reject passing-through tracks & low energy tracks

Neutrino interaction vertex

Tau neutrino event (OPERA)
Infrastructure at CERN

Emulsion handling room

Laboratory used for past emulsion experiments
(CHORUS, OPERA preparatory phase)

Brick
Assembling machine

Dark room

Emulsion development

Flash box used in CHORUS

CES
SPS Test beam experiment (July 2018) using Prototype RPC, DT, pixel detector ...
Expected yield of Neutrino CC DIS interactions in the SND (5 yrs)

<table>
<thead>
<tr>
<th>$E$ [GeV]</th>
<th>CC DIS int.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$2.7 \times 10^6$</td>
</tr>
<tr>
<td>$\nu_\tau$</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>
</tbody>
</table>

Expected Neutrino CC DIS interactions with Charm production

<table>
<thead>
<tr>
<th>$&lt;E&gt;$ (GeV)</th>
<th>CC DIS with charm prod</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\nu_\mu}$</td>
<td>$1.3 \times 10^5$</td>
</tr>
<tr>
<td>$N_{\nu_e}$</td>
<td>$6.0 \times 10^4$</td>
</tr>
<tr>
<td>$N_{\nu_\tau}$</td>
<td>$2.5 \times 10^4$</td>
</tr>
<tr>
<td>$N_{\bar{\nu}_e}$</td>
<td>$1.3 \times 10^4$</td>
</tr>
<tr>
<td>total</td>
<td>$2.3 \times 10^5$</td>
</tr>
</tbody>
</table>

No charm candidates from electron neutrino was ever reported so far.
Significant reduction of uncertainty on s-quark distribution (factor two) in nucleon with SHiP data in the x range between 0.03 and 0.35.

**Uncertainty band**

LHC and SHiP will probe the strangeness distribution in different ranges of x.

Neutrino induced Charm production is sensitive to s-quark content of nucleon.

Anti-charm production in Anti-neutrino CC interaction selects the anti s-quark content of nucleon.

**Charm from anti-ν_μ**

32 events in CHORUS
(2013 events from ν_μ)

Expected in SHiP ~ 25,000
Structure functions $F_4$, $F_5$

First evaluation of $F_4$ and $F_5$ only accessible by Tau neutrino

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

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

+ neutrino
- anti-neutrino

$F_4 = F_5 = 0$
Dark photon can decay into pair of Light Dark matter.
Production of dark photon $A'$

Meson decay \[ \pi^0 (\eta, \eta', \omega) \to \gamma A' \]

Proton bremsstrahlung \[ pp \to pp A' \]

QCD production \[ q + q \to A', q + g \to q + A' \]

Decay of dark photon

\[ A' \to e^+ e^-, \mu^+ \mu^- \]
\[ A' \to \text{hadrons} \]
\[ A' \to \chi \bar{\chi} \quad (\chi: \text{Dark matter}) \]

$\chi$ scatter on $e$ or $n, p \to \text{DM search}$
LDM ($\chi$) can produce via dark photon ($A'$) decay:

$$ pp \rightarrow \pi^0 \chi \hspace{1cm} \pi^0 \rightarrow A' \gamma \hspace{1cm} A' \rightarrow \chi \bar{\chi} \hspace{1cm} \chi: \text{LDM} $$

Scatter on e:

$$ \chi \, e \rightarrow \chi \, e $$

Electron recoil high energy

~ GeV electron sample in emulsion

Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected background.
LDM search in emulsion

LDM $\chi$ produced in a dark photon decay interact with electron.

$$\chi e^- \rightarrow \chi e^-$$

**SIGNAL SELECTION**

\[
\begin{align*}
0.01 < \theta < 0.02 \text{ rad} \\
E < 20 \text{ GeV}
\end{align*}
\]

**SHiP sensitivity to LDM** produced in dark photon decays. The coupling is given as

$$Y = \varepsilon^2 \alpha'_D \left( m_\chi / m_{A'} \right)^4.$$
**Number of background events** in the LDM search after the selection for $2 \times 10^{20}$ protons on target.

<table>
<thead>
<tr>
<th>Background</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Scattering on $e^-$</td>
<td>81</td>
<td>45</td>
<td>56</td>
<td>35</td>
<td>217</td>
</tr>
<tr>
<td>Quasi-elastic Scattering</td>
<td>245</td>
<td>236</td>
<td>-</td>
<td>-</td>
<td>481</td>
</tr>
<tr>
<td>Resonant Scattering</td>
<td>8</td>
<td>77</td>
<td>-</td>
<td>-</td>
<td>85</td>
</tr>
<tr>
<td>Deep Inelastic Scattering</td>
<td>-</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>334</td>
<td>372</td>
<td>56</td>
<td>35</td>
<td>797</td>
</tr>
</tbody>
</table>

**BG rejection**
1) Energy–angle correlation
2) Presence of **proton** rejects  
   Quasi-elastic scattering (QE)
3) Presence of **hadron jets** rejects  
   Deep inelastic scattering (DIS)
Sensitivities of the SHiP to HS particles

HNL

Dark photon

Dark scalars

ALP

see K.Y. Lee’s talk
Member countries of the SHiP

~250 scientific authors
16 member countries: Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Korea, Portugal, Russia, Sweden, Switzerland, Turkey, United Kingdom, Ukraine, United States of America + CERN, DUBNA
48 member institutes: Sofia, Valparaiso, Niels Bohr Institute Copenhagen, LAL Orsay, LPNHE Paris, Berlin, Humboldt University Hamburg, Mainz, Bari, Bologna, Cagliari, Ferrara, Lab. Naz. Gran Sasso, Frascati, Naples, Rome, Aichi, Kobe, Nagoya, Nihon, Toho, Gyeongsang, LIP Coimbra, Dubna, ITEP Moscow, INR Moscow, P.N. Lebedev Physical Institute Moscow, Kurchatov Institute Moscow, IHEP Protvino, Petersburg Nuclear Physics Institute St. Petersburg, Moscow Engineering Physics Institute, Skobeltsyn Institute of Nuclear Physics Moscow, Yandex School of Data Analysis, Stockholm, Uppsala, CERN, Geneva, EPFL Lausanne, Zurich, Middle East Technical University Ankara, Ankara University, Imperial College London, University College London, Rutherford Appleton Laboratory, Bristol, Warwick, Taras Shevchenko National University Kyiv, Florida
5 associated institutes: Jeju, Gwangju, Chonnam, National University of Science and Technology "MISIS" Moscow, St. Petersburg Polytechnic University

54 institutes from 18 countries
295 members
SHiP Detector & Institutions

Decay volume
- Germany, Russia, Ukraine, JINR, CERN
- Italy, Germany, Russia, CERN

Surround Background Tagger
- Germany, Russia, Switzerland, Ukraine

Upstream Muon Detector
- Italy, Korea, Russia

Emulsion Spectrometer Tracker
- Italy, Japan, Russia, Switzerland

Emulsion spectrometer
- Italy, Japan, Korea, Turkey, Russia

Muon shield
- Russia, UK, CERN

Target/hadron absorber

Electronics
- France, CERN

Online system
- Denmark, Sweden, UK, CERN

Computing and Software
- Russia, UK, CERN
• Document submitted to ESPP on Dec. 2018 together with CERN Beam Dump Facility (BDF)

• **CDR (Comprehensive Design Report)** is in preparation for submission to SPSC in fall 2019

• Continue phase 2 module-level prototyping for **test beams**
  - at DESY (2019-2010), at CERN (2021)

• Detector engineering design and preparation of **TDR** after **Approval**
Summary

• The SHiP is a multi-purpose and very timely experiment for **Hidden particles**, LDM and **Tau neutrino physics**.

• About 10,000 $\nu_\tau$ & Anti-$\nu_\tau$ CC events can be observed with ECC target.

• First observation of the Anti-$\nu_\tau$

• $\nu_\tau$ & Anti-$\nu_\tau$ Cross-section and Mag moment measurements

• First evaluation of the F4 and F5 structure functions

• Study of Strange quark content of nucleon

• **LDM** search in the SND

...
Backup
CERN Courier
March 2016

SHiP sets a new course in intensity-frontier exploration

Why is the SHiP physics programme so timely and attractive?

A Golovkin, Imperial College, London/CERN, and R. Jacobsson, CERN, on behalf of SHiP.

SHiP (Search for Hidden Particles) is a newly proposed experiment for CERN’s Super Proton Synchrotron accelerator. It is designed to be installed downstream of a new beam dump facility at the Super Proton Synchrotron (SPS). The CERN SPS and PS experiments Committee (SPSC) has recently completed a review of the SHiP Technical and Physics Proposal, and it recommended that the SHiP collaboration proceed towards preparing a Comprehensive Design Report, which will provide input into the next update of the European Strategy for Particle Physics, in 2018/2019.

While these phenomena are well-established observationally, they give no indication about the energy scale of the new physics. The analysis of new LHC data collected at \(\sqrt{s} = 13\) TeV will soon have directly probed the TeV scale for new particles with couplings at 0(\%\) level. The experimental effort in flavour physics, and searches for charged lepton flavour violation and electric dipole moments, will continue the quest for specific flavour symmetries to complement direct exploration of the TeV scale.

However, it is possible that we have not observed some of the particles responsible for the BSM problems due to their extremely feeble interactions, rather than due to their heavy masses. Even in the scenarios in which BSM physics is related to high-mass scales, many models contain degrees of freedom with suppressed couplings that stay relevant at much lower energies.

Given the small couplings and mixings, and hence typically long lifetimes, these hidden particles have not been significantly...
CERN launches Physics Beyond Colliders study group

CERN invites abstract applications for the workshop, which will investigate how CERN's accelerators can help solve questions of particle physics

24 MAY, 2016
SHiP-like LLP projects at LHC

MilliQan, MATHUSLA, FASER, CODEX-b @ LHC IPs

MilliQan: 1607.04669

AL3X @ALICE: 1810.03636
Light dark matter detection in Neutrino detector

Protons 400 GeV

Electron recoil
Cascade shower in Emulsion

\[ A' \rightarrow \chi \bar{\chi} \]
\[ \chi e^- \rightarrow \chi e^- \]

Top: Light Dark Matter simulation process in FairShip.
Bottom: Event display of a LDM scattering process simulated inside the Scattering Spectrometer.
**HS background rejection**

*Muon induced background (inelastic interaction)*

- 6 \cdot 10^4 \mu/\text{spill impinging on the decay volume}
- 2.1 \cdot 10^8 \text{ inelastic interaction in 5 years}
- BG after cuts (full reco) = 2.7 \cdot 10^{-5}
- BG after cuts (partial reco) = 6 \cdot 10^{-4}

<table>
<thead>
<tr>
<th>Selection cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track momentum</td>
<td>&gt; 1 GeV/c</td>
</tr>
<tr>
<td>Distance of closest approach</td>
<td>&lt; 1 cm</td>
</tr>
<tr>
<td>Vertex position</td>
<td>&gt; 5 cm from vessel wall</td>
</tr>
<tr>
<td>Imp. Param. w.r.t. target (full reco)</td>
<td>&lt; 10 cm</td>
</tr>
<tr>
<td>Imp. Param. w.r.t. target (partial reco)</td>
<td>&lt; 250 cm</td>
</tr>
</tbody>
</table>

8.5 \cdot 10^{15} \text{ fake vertices without time info. Reduced to } 4.2 \cdot 10^{-2} \text{ with time info (TD)}

*Neutrino induced background (inelastic interaction)*

- 2 \cdot 10^{18} \nu \text{ from target in 5 years}
- 3.5 \cdot 10^{7} \text{ inelastic interaction in 5 years}
- BG after cuts (full reco) = 10^{-2}
- BG after cuts (partial reco) < 0.1 (\gamma conversion cut)
### Signal & Background channels for HS


<table>
<thead>
<tr>
<th>Signature</th>
<th>Physics</th>
<th>Backgrounds</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-\mu^+,K^-\mu^+$</td>
<td>HNL, NEU</td>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$</td>
<td>IP, TI, PID($\mu\pi$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P, IP, NT</td>
</tr>
<tr>
<td>$\pi^-\pi^0\mu^+$</td>
<td>HNL($\rightarrow \rho^-\mu^+$)</td>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu(+\pi^0)$</td>
<td>P, IP, NT, TI,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P, IP, NT, PID($\pi\mu$)</td>
</tr>
<tr>
<td>$\pi^-e^+,K^-e^+$</td>
<td>HNL, NEU</td>
<td>$K_L^0 \rightarrow \pi^-e^+\nu_e$</td>
<td>P, IP, NT</td>
</tr>
<tr>
<td>$\pi^-\pi^0e^+$</td>
<td>HNL($\rightarrow \rho^-e^+$)</td>
<td>$K_L^0 \rightarrow \pi^-e^+\nu_e,+\pi^0$</td>
<td>P, IP, NT, TI, PID($\pi\mu$)</td>
</tr>
<tr>
<td>$\mu^-e^++p^{\text{miss}}$</td>
<td>HNL, HP($\rightarrow \tau\tau$)</td>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$, $\pi^0$</td>
<td>IP, NT, PID($\pi\mu$, $\pi\tau$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TI, IP, PID($\pi\mu$)</td>
</tr>
<tr>
<td>$\mu^-\mu^++p^{\text{miss}}$</td>
<td>HNL, HP($\rightarrow \tau\tau$)</td>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$</td>
<td>P, NT, PID($\pi\mu$)</td>
</tr>
<tr>
<td>$\mu^-\mu^+$</td>
<td>DP, PNGB, HP</td>
<td>$K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$</td>
<td>TI, IP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P, NT, IP, PID($\pi\mu$)</td>
</tr>
<tr>
<td>$\mu^-\mu^+\gamma$</td>
<td>CS</td>
<td>$K_L^0 \rightarrow \pi^-\pi^0,+\pi^0$</td>
<td>P, IP, NT, PID($\pi\mu$), TI, VP</td>
</tr>
<tr>
<td>$e^-e^++p^{\text{miss}}$</td>
<td>HNL, HP</td>
<td>$K_L^0 \rightarrow \pi^-e^+\nu_e$</td>
<td>P, NT, PID($\pi\mu$, $\pi\tau$)</td>
</tr>
<tr>
<td>Process</td>
<td>Decays</td>
<td>Annotations</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>$e^- e^+$</td>
<td>$K_L^0 \rightarrow \pi^- e^+ \nu_e$</td>
<td>P,IP,NT, PID($\pi e$)</td>
<td></td>
</tr>
<tr>
<td>$\pi^- \pi^+$</td>
<td>$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$</td>
<td>P,NT, PID($e\pi$), IP, POA, IP</td>
<td></td>
</tr>
<tr>
<td>$\pi^- \pi^+ + p^{\text{miss}}$</td>
<td>$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+, K_S^0 \rightarrow \pi^- \pi^+, \Lambda \rightarrow p\pi$</td>
<td>P,NT, PID($e\pi$), POA</td>
<td></td>
</tr>
<tr>
<td>$K^+ K^-$</td>
<td>$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+, K_S^0 \rightarrow \pi^- \pi^+, \Lambda \rightarrow p\pi$</td>
<td>P,NT, PID($\pi\mu, \pi e$), IP</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$</td>
<td>P,IP,NT</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \pi^0$</td>
<td>$K_L^0 \rightarrow \pi^- \pi^+ \pi^0 (+\pi^0)$</td>
<td>P,IP,NT, TI</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \pi^0 \pi^0$</td>
<td>$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$</td>
<td>P, IP, NT, M($\gamma\gamma$)</td>
<td></td>
</tr>
<tr>
<td>(\pi^+\pi^-\pi^+\pi^-)</td>
<td>DP, PNGB, HP</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\pi^+\pi^-\mu^+\mu^-)</td>
<td>HSU</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\pi^+\pi^-\mu^+\mu^-)</td>
<td>HSU</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\mu^+\mu^-\mu^+\mu^-)</td>
<td>HSU</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\mu^+\mu^-e^+e^-)</td>
<td>HSU</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 5.3: Signal and background channels for the Hidden Sector detector. The last column lists the cuts which can be used to suppress the backgrounds. The abbreviations for the physics channels correspond to: HNL=Heavy Neutral Lepton, NEU=neutralino, DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson, HP=Higgs Portal, CS=Chern-Simons, HSU=Hidden SUSY, RDM=random di-muons from the target. The abbreviations used for techniques to reject the backgrounds correspond to: IP=impact parameter at the target, CPV=charged particle veto, NT=neutrino interaction tagger, VP=photon veto (i.e. if there is a photon around), TI=timing cuts with timing detector, P=total momentum cuts of the daughters, POA=1 particle outside acceptance, PID(\(\mu\pi\))=probability that a \(\mu\) is misidentified as \(\pi\) or kaon.
Selection criteria for Tau Neutrino event

At primary vertex

- there are no tracks compatible with that of a muon or an electron;
- the missing transverse momentum ($P_T^{\text{miss}}$) is smaller than 1 GeV/c;
- the angle $\Phi$ in the transverse plane between the $\tau$ candidate track and the hadronic shower direction is larger than $\pi/2$.

At decay vertex

- the kink angle $\theta_{\text{kink}}$ is larger than 20 mrad;
- the secondary vertex is within the two lead plates downstream of the primary vertex;
- the momentum of the charged secondary particles is larger than 2 GeV/c;
- the total transverse momentum ($P_T$) of the decay products is larger than 0.6 GeV/c if there are no photons emitted at the decay vertex, and 0.3 GeV/c otherwise.