New physics search with SHiP at CERN

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ICNFP 2019
Present status of HEP

**Triumph** of the Standard Model: Higgs boson, flavour physics, rare decays and **nothing beyond**..
At the same time we are sure (not from LHC) that there is physics beyond the SM:

• Neutrino masses and oscillations
• Dark matter
• Baryon asymmetry of the Universe
• ...

Besides that, there are many «why» and «how» in the SM:

• How is EW scale so smaller than UV scale?
• Why hierarchy between SM scales?
• Why are lefts doublets and rights singlets?
• Why 3 generations? Why CKM hierarchy & CP?
• ...

3/25
Observable Higgs mass corresponds to metastability of the SM vacuum

(from arXiv:1307.3536)


Strong hint to NO New Physics up to the Planck scale.
Standard Model Criticality Prediction:
Top mass $173 \pm 5$ GeV and
Higgs mass $135 \pm 9$ GeV.

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Abstract

Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima ( vacua), one of which should be - order of magnitudewise - at the Planck scale, leads to the top mass being $173 \pm 5$ GeV and the Higgs mass $135 \pm 9$ GeV. This requirement of the degeneracy of different phases is a special case of what we call the multiple point criticality principle. In the present work we use the Standard Model all the way to the Planck scale, and do not introduce supersymmetry or any extension of the Standard Model gauge group. A possible model to explain the multiple point criticality principle is lack of locality fundamentally.
Revival of interest to NP searches on Intensity Frontier

- Proton decay, $n\rightarrow\bar{n}$ oscillations
- Neutrino physics (not covered in this talk)
- Flavour physics
- Lepton Flavour Violation
- Electric Dipole Moments
- Hidden Sector

Energy Frontier:
- LHC, FCC

known physics

unknown physics

Interaction strength

Energy scale
Search for Hidden Particles (SHiP) experiment

Fixed target beam dump type experiment @SPS CERN

- $4 \times 10^{13}$ protons @ 400 GeV, $2 \times 10^{20}$ pot in 5 years
  - $10^{18}$ charm mesons
  - $10^{14}$ beauty mesons
  - $10^{16}$ tau leptons

- Large vacuum detector volume
  To reduce neutrino interactions and to give hidden particles space to fly

- Active muon shield
  To deflect muons at short distances in order to put detector close to the target (HS particles may have large $p_T$)

2013: Expression of Interest submitted
2015: Technical and Physics proposals
2016: Recommendation by CERN SPSC to proceed to CDR
2018: CDR by the Beam Dump Facility group published
2019: CDR to be submitted

~290 authors, 54 institutes, 18 countries
The lowest dimensional renormalizable portals in the SM are:

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Photon, $A_{\mu}$</td>
<td>$-\frac{\epsilon}{2\cos\theta_W} F_{\mu\nu}^I B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^+ H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}<em>{i}^{\mu\nu}$, $\frac{\partial</em>{\mu} a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>

where $L = L_{SM} + L_{HS} + L_{portal}$

$\mathcal{L}_{portal} = \sum O_{SM} \times O_{DS}$
What HS particle is SHiP looking for?

• **Heavy neutral leptons**
  - Could explain SM neutrino masses (via seesaw), Dark Matter, Baryon Asymmetry.
  - Seen in weak semi-leptonic decays of hadrons, W, Z.

• **«Dark Photons»**
  - Addition of $U(1)$ gauge group to SM, kinetic mixing with $\gamma$ and $Z$.
  - Seen in bremsstrahlung, light neutral meson decays, quark annihilation.

• **(Light) Dark Matter**
  - Stable or very long-lived particles.

• **«Dark Higgses»**
  - Neutral singlet scalars that couple to the SM Higgs field.

• **Axion-like particles**
Most interest has been attracted so far to the neutrino portal (heavy neutral leptons). General renormalizable type I see-saw Lagrangian with 3 HNLs:

\[ L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \Phi \bar{N}_I L_\alpha - \frac{M_I}{2} \bar{N}_I^c N_I + h.c. \]

\[ N_1 \] with mass \( \mathcal{O}(\text{keV}) \) – dark matter

\[ N_2, N_3 \] with mass \( \mathcal{O}(\text{GeV}) \) – neutrino masses via see-saw and baryon asymmetry

(T.Asaka, M.Shaposhnikov, ‘05; D.Gorbunov, M.Shaposhnikov, ‘07; etc)
Difference (and complementarity) between direct and indirect searches

Direct:
- Clean decay signature ("displaced vertex")
- Allow identification of the model (portal type)
- But: probability $\propto \epsilon^4$

Indirect:
- Hidden particles escape detector
- Missing energy/momentum/mass
- Probability $\propto \epsilon^2$

Case of SHiP

Highest possible intensity on target vs zero background in the detector
Target and active muon shield

- $4 \times 10^{13} \, p / 7 \, \text{sec} \rightarrow 355 \, \text{kW average, 2.6 MW during 1 sec spill} - \text{water cooled to dissipate}$
- **Target** – to maximize production of charm. $\sim 12 \lambda_{\text{int}}$-long segmented; high-Z hybrid solution composed of Mo alloy (TZM) & pure W
- **Shield** – designed to reduce muon flux as $10^{11} \rightarrow 2.5 \times 10^4$; assembled of 0.3 mm grain-oriented (GO) steel sheets; magnetic field 1.7 T
SM Physics
- physics of $\tau$-(anti)neutrino physics, $N \sim 10^4$
- first observation of $\tau$-antineutrino
- structure functions $F_4(x, Q^2)$ and $F_5(x, Q^2)$
- $\nu$-$N$ DIS physics
- $\nu_{\tau}$ magnetic moment

Hidden sector physics
- Light dark matter search via electron scattering

(see Antonia Di Crescenzo’s talk on ICNFP 2019)

Scattering and neutrino detector
- emulsion detector with 12 SciFi tracker planes for time stamp
- muon identification
- magnetic field 1.25 T – info on particles’ electric charge
Vacuum decay vessel

Length: 50 m
Downstream size: 6×11 m

Liquid scintillator based surrounding background tagger, tagging charged particles entering decay volume and tagging \( \nu \) and \( \mu \) interactions in the vacuum chamber walls.
Hidden sector spectrometer

- precise reconstruction of decay vertices produced by charged particles
- precise timing (< 0.1 ns) to reject background
- magnetic field 0.5-1.0 Tm
- particle identification

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino portal, SUSY neutralino</td>
<td>$\ell^+\pi^\pm, \ell^+K^\pm, \ell^+\rho^\pm, \rho^\pm \rightarrow \pi^\pm\pi^0$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\ell^+\ell^-$</td>
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<td>$\pi^\pm\pi^-, K^+K^-$</td>
</tr>
<tr>
<td>Neutrino portal, SUSY neutralino, axino</td>
<td>$\ell^+\ell^-\nu$</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
<td>$\gamma\gamma$, $\pi^0\pi^0$</td>
</tr>
<tr>
<td>SUSY sgoldstino</td>
<td></td>
</tr>
</tbody>
</table>
Simulation status and background studies

Mature software framework using **Pythia6, Pythia8, Genie, Geant4**
- Cascade production of heavy flavours
- Validation on data from **NA62** and Hyperon
- Validation using two dedicated experiments in summer 2018 at SPS:
  - muon flux measurement with target replica accumulated $10^{11}$ pot;
  - charm cross-section measurement with a target prototype

Background summary:

<table>
<thead>
<tr>
<th>Background source</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino background</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Muon DIS (factorisation)</td>
<td>$&lt; 6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Muon Combinatorial</td>
<td>$4.2 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Backgrounds redundantly shown to be $< 1$, even for partially reconstructed signal
Various prototypes have been produced and tested (and more are in progress) in order to check and prove experiment’s sub-detectors concept.

(see SHiP Experiment progress report, CERN-SPSC-2019-010 / SPSC-SR-248; 25/01/2019)
SHiP sensitivity – HNL

*(sensitivity plots from CERN-PBC-REPORT-2018-007)*

\[ M_{\text{HNL}} < M_B : \]
SHiP will have much better sensitivity than LHCb & Belle-II

\[ M_B < M_{\text{HNL}} < M_Z : \]
FCC in ee-mode

\[ M_{\text{HNL}} < M_Z : \]
HL-HE LHC

SHiP covers most of parameter space below B-mass. Moving down towards the ultimate see-saw limit.
SHiP sensitivity – scalars
SHiP sensitivity – vectors and axions

Axion portal:

Vector portal:
Conclusion

- Search for Hidden Particles (SHiP) experiment – exploration of the Intensity Frontier
- Beam Dump Facility (BDF) – new infrastructure in the North Area of CERN SPS: extraction tunnel, target complex, experimental area
- Physics case – direct search for feebly interacting particles: Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector
- SHiP CDS report submission November 2019 finalize analyses of updated detector performances (simulation, test beams); include description of parts that were left out in the progress report; include results of the DESY test beam 2019 and measurement etc
- Preparation of the Technical Design Report (TDR) by the end of 2022

7 years between approval and the first run
The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being. But the big questions of our field remain wide open (hierarchy problem, flavour, neutrinos, DM, BAU, etc.). This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias(es).

We need a clue where New Physics is

The word «clue» derives from «clew», an Old English word for a ball of string. It came to mean ‘a hint that aids a solution’ through allusion to the Greek legend of Theseus.

The same story is with the Russian word «клубок», which means a ball of thread.

Notice that Ariadne’s string could not help Theseus to find the Minotaur in the Labyrinth, but was extremely helpful to follow the right way out.

«Post-conclusion»

M. Mangano