Studies for an electro-magnetic calorimeter for the SHiP experiment at CERN with shower direction reconstruction capability

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on behalf of the Collaboration of 250 authors belonging to 49 institutions in 17 countries
- what is SHiP

- the design of the electro-magnetic calorimeter of the Technical Proposal

- potential for a detection of axion-like particles (ALP) decaying to two photons

- ideas for a new design
Where is the new physics?

- EWSB, Hierarchy
- WIMP DM ...

- Energy Frontier - LHC
- RH neutrinos
- Dark Matter
- Hidden sector...

- Intensity Frontier - SHiP

$\frac{g^2}{M^2} \sim G_F$

$\rightarrow$ long lifetimes
What is SHiP?

SHiP is a PROTON BEAM DUMP experiment proposed at CERN with the SPS p beam of 400GeV with $2 \times 10^{20}$pot/5 years.

It would make good use of the full SPS intensity that, apart from the ~2fills/day of the LHC, is not exploited.

Data taking: 2026 (after LS3)
signature: a $\geq 2$ track vertex in the decay vessel

DIRECT EVIDENCE OF NP: DETECTION of long lived particles with masses below few GeV
Sensitivity to HNL

long list of models that we can test in unexplored parameter domains
CERN’s Scientific Strategy

Fabiola Gianotti
CERN scientific strategy (based on ESPP): three pillars

Full exploitation of the LHC:
- successful operation of the nominal LHC (Run 2, LS2, Run 3)
- construction and installation of LHC upgrades: LIU (LHC Injectors Upgrade) and HL-LHC

Scientific diversity programme serving a broad community:
- ongoing experiments and facilities at Booster, PS, SPS and their upgrades (ELENA, HIE-ISOLDE)
- participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

Preparation of CERN’s future:
- vibrant accelerator R&D programme exploiting CERN’s strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- design studies for future accelerators: CLIC, FCC (includes HE-LHC)
- future opportunities of diversity programme (new): “Physics Beyond Colliders” Study Group

Important milestone: update of the European Strategy for Particle Physics (ESPP): ~2019-2020
PHYSICS BEYOND COLLIDERS

Kick-off workshop of the Physics Beyond Colliders study to be held at CERN, Geneva, on 6-7 September 2016.

The aim of the study is to explore the opportunities offered by the non-collider part of the CERN complex to tackle some of the outstanding questions in fundamental physics.

The kick-off workshop is intend to survey the possibilities and stimulate new ideas.

> 500 participants (75% from outside CERN)
The EM calorimeter in the Technical Proposal

Physics: HNL—>\pi \pi^0 l, DP—> \pi \pi \pi^0, e-/\pi separation in HNL—>\pi e

Particle rate —> low

Shashlik (a la LHCb)
Cells of 6×6 cm^2 cross section with 140 alternating layers of 1 mm lead and 2 mm scintillator.
Total depth of ~50 cm = 25 X_0
\sigma(E)/E\approx5.7%/\sqrt{E}
Why evolving compared to TP?

1) reduce possibly cost of Shashlik

2) add the measurement of shower direction for neutral final states (need few mrad resolution for ALP→γγ) and possibly suppress background

3) improve e/π separation

of course it is a 5x10 m² guy (or lady)…
Figure 7: PID efficiency for 2 body events. Most upper row represent the reconstructed events in SHiP experiment and the first column from left shows the Monte Carlo events. The red column stands for the immigration of 2body to 3body events. The upper number in each cell shows the number of reconstructed events over the Monte Carlo events for each channel; the lower number is the efficiency of particle identification for each channel.

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<th>π-π</th>
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</table>

Figure 8: PID efficiency for 3 body events. Most upper row represent the reconstructed events; and the first column from left shows the Monte Carlo events. The red column stands for the immigration of 3body to 2body events. The upper number in each cell shows the number of reconstructed events over the Monte Carlo events for each channel; the lower number is the efficiency of particle identification for each channel.

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Systemical misidentification: The misidentification of particles caused by systematic effects are sorted in 3 items:

- Muon particles identified as pions: this happens when the energy of the muons are very low (around 1-2 GeV), therefore the information giving by muon 8.
Search for ALP → γγ

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Figure 9. Projected sensitivity of SHiP, marked by §, for $2 \cdot 10^{20}$ protons on target overlaid with figure 8. As in figure 8, opaque regions correspond to existing limits, transparent regions correspond to a proposed experimental reach based on assumptions as outlined in the text.

Importantly, we have provided predictions for the angular distribution of the ALP-production cross-section: although transversal momenta of the produced ALPs are typically small, the detector in a beam dump experiment is placed far away from the target and therefore covers only a tiny angle from the production point. A precise determination of the expected spatial distribution for ALP-induced events and an accurate estimate of the geometric acceptance is therefore mandatory in preparing and analysing a real experimental run. Taking all these effects into account, we have shown that even with a rather modest beam-time requirement, the currently operating NA62 experiment would have a sizeable discovery potential for ALPs in the mass range of $\sim (30 - 200)$ MeV. The proposed facility SHiP could extend this reach over the course of its running period up to masses of 1 GeV.

In the present work we have focussed on pseudoscalar ALPs that couple dominantly to photons. It is however straightforward to generalise our results to scalar ALPs as well as ALPs with additional couplings to fermions as follows:

- Writing the coupling between scalar ALPs and photons as $g_{a\gamma}^2 F_{\mu\nu} F^{\mu\nu}$, we obtain identical expressions for the ALP lifetime and the ALP production cross sections as for the case of the pseudoscalar. Our analysis therefore applies to this case as well.

- Even for ALPs with relatively large (derivative) couplings to fermions, the decay into photons will typically give the dominant contribution to the ALP decay length for $100$ MeV $\lesssim m_a \lesssim 2 m_\mu [22]$, which is the region of interest for NA62. For larger ALP masses, as potentially testable at SHiP, decays into muons (and, for scalar ALPs, mesons) can significantly reduce the ALP decay length and hence suppress event rates.
ANGLES

\( \sigma(\theta) = 10 \text{ mrad/}\sqrt{E} \rightarrow \text{black curve} \)
invariant mass reconstruction

Why to care about mass reconstruction? imagine we find 10 two-photon only events. Wouldn’t you like to see an accumulation of a mass peak to claim we have a discovery (and not some background)?

\[ \sigma(\Delta m/m) = 46\% \]
\[ \sigma(\Delta m/m) = 20\% \]
\[ \sigma(\Delta m/m) = 12\% \]

the mass region which is only for us (not for NA62)
The measurement of the shower direction

This is not a completely new subject:

- e.g. ATLAS, though in one direction only ($\eta$)

- $\gamma$-ray experiments (e.g. FERMI) in space can measure it with high precision but very low efficiency (here we need full efficiency)

In SHiP we can take advantage of the fixed target configuration that leaves some room in the longitudinal direction —> increase the lever arm

I show here some new ideas supported by GEANT simulation but work is not finished!
Implemented in GEANT-based simulation with some simplifying assumptions

in blue a sampling ECAL with X-Y plastic scintillator bars readout via WLS fibres from the sides, coarse granularity

in red the high precision layers at $3X_0$, $5X_0$ and $6.5X_0$ ($\mu$-pattern gas detectors with pad readout with digital readout) that could also be staged
20 GeV γ generated in the yz plane with 100mrad angle and z=20m upstream of the ECAL surface
a well-known problem!
satellites
cumulative shower profiles in the three high precision layers
the shower direction reconstructed from linear fit to the reconstructed median distribution in each of the tree high precision layers

angular resolution—$>3.0\text{mrad}$ (about $2.5\text{mm}$ position resolution at shower maximum)
as a comparison: ATLAS ECAL performance TDR: in blue our result at 20GeV; large improvement but cost of high precision layers?

A recent estimate for 140m$^2$ (similar to our requirements) to be used in CMS of $\mu$WELLS was about 1M€ (detector only); readout to be added!

Energy resolution about 15%/√E
Electron/pion separation

20GeV e-

20GeV π-

layer #

# of pads

Profile_ecal

Entries 100
Mean 1835
Std Dev 63.97

Profile_ecal

Entries 4763
Mean 17.04
Std Dev 6.119

Profile_ecal

Entries 2060
Mean 381.2
Std Dev 425

Profile_ecal

Entries 4994
Mean 28.1
Std Dev 17.69
Effective Moliere radius  vs  position of shower max

20GeV e-

20GeV π-

no problem to go below 1% of mis-identification!
Possible layout of scintillator layers

Horizontal layer

[Diagram showing horizontal layer with 504 cm height and 2 x 168 strips]

Vertical layer

[Diagram showing vertical layer with 4 x 84 strips]

1008 cm

504 cm
Still, even for the scintillation section many technical issues to be solved:

Readout with SiPMs:

- fiber bundling within a plane
- (minimum # of SiPM’s 33600)
- longitudinal fiber bundling
- dynamic range

Mechanical assembly:

- huge detector: how to decompose it
- scintillator plane staggering

**R&D**

vertical strips

horizontal strips

vertical strips

WLS fibre

SiPM

scintillator

absorber

absorber
Conclusions

The SHiP project is getting momentum at CERN and the collaboration is preparing a detailed report for the European Strategy meeting in the context of the Beyond Collider Physics WG at CERN

Some new ideas for a calorimeter measuring the shower direction under study

Performance looks great, but on paper!

A lot of work ahead of us!

Ideas and new collaborators welcome!
Journée SHiP/Physique du secteur caché

11 October 2017
LPNHE Univ. Pierre et Marie Curie Paris-6

Welcome

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
10:30 - 11:00
Welcome by the LPNHE director
Gregorio Bernlohr

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
11:00 - 11:05
The GDR-INF, Physics at the Intensity Frontier
Achile Sharoucha

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
11:05 - 11:15
Status of the Physics Beyond Colliders workshop
Claude Veillette

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
11:15 - 11:50
SHiP Overview
Andrea Guimin

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
11:50 - 12:25
BSM Physics with Light Particles (title to be confirmed)
Mikhail Shapiro/Shklov

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
12:26 - 13:00

Leptogenesis, recent progress (title to be confirmed)
Pilar Hernandez

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
14:32 - 15:00
The U boson as a generalised dark photon
Pierre Fayet

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
15:00 - 15:30
SHiP sensitivity (title to be confirmed)
Nickola Siina

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
15:30 - 16:00
Coffee

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
16:00 - 16:30
The SHiP Project
Richard Jacobsen

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
16:30 - 17:00
SHIP Calorimetry and Particle Identification (title to be confirmed)
Dr. Walter Maccio Rossi Bonvento

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
17:00 - 17:30
Prospects in France
Marcel Tell and Jacques Chastel

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
17:30 - 18:00
Discussion

Amphithéâtre Georges Charpak, LPNHE Univ. Pierre et Marie Curie Paris-6
18:00 - 18:30
Closed session

12322 2.39 salle Higgins, LPNHE Univ. Pierre et Marie Curie
18:30 - 19:00