SHiP: a new facility to search for long lived neutral particles and investigate the $\nu_T$ properties

Seminar at the Université Libre de Bruxelles, Service de Physique Théorique

February 26, 2016
**Higgs found!** SM complete and consistent up to Plank scale. But...

- Higgs mass fine tuned?
- matter-antimatter asymmetry
- neutrino masses/mixing
- dark matter

- flavour anomalies, excesses... NP?
- theory problems: hierarchy, strong CP...

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What is the energy scale of new physics?

- **Neutrino masses and oscillations:**
  Right Handed see-saw neutrino masses from 1 eV to $10^{15} \text{ GeV}$

- **Dark matter:**
  From $10^{-22} \text{ eV}$ (super-light scalars) to $10^{20} \text{ GeV}$ (wimpzillas, Q-balls)

- **Baryogenesis:**
  Mass of new particle from 10 MeV to $10^{15} \text{ GeV}$

- **Higgs mass hierarchy:**
  SUSY, GUT, composite Higgs, large extra dimensions theories require the presence of new particles above the Fermi scale. Scale invariance models predict no new physics up to Planck scale.
Where is new physics? Experimental approach

http://cerncourier.com/cws/article/cern/63982
Hidden sector

- Unsolved problems $\implies$ new particles
- Why didn’t we detect them? Too heavy or too weakly interacting
- new particles are light $\implies$ they must be singlets with respect to the gauge group of the SM
- they may couple to different singlet operators (portals) of the SM
  - dim 2: hypercharge field, $\epsilon F_{\mu\nu} F'_{\mu\nu}$, vector portal
  - dim 2: Higgs field, $(\alpha_1 \chi + \alpha \chi^2) H^\dagger H$, Higgs/scalar portal
  - dim 2 ½: Higgs-lepton, $Y H^T N L$, neutrino portal
  - dim 4: $AG_{\mu\nu} \epsilon^{\mu\nu\rho\eta} G_{\rho\eta}$, $\partial_\mu A \bar{\psi} \gamma^\mu \gamma^5 \psi$, ..., axion portal
  - SUSY models

[Diagram of SM and hidden sector with dark photon $\gamma'$ and "vector portal"]

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SHiP: Search for Hidden Particles
SHiP: Search for Hidden Particles

SHiP is a new proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to $\mathcal{O}(10)$ GeV and extremely weak couplings, down to $10^{-10}$.

SHiP aims to be a zero background experiment.

The facility is also ideally suited for studying $\nu_\tau$ and $\bar{\nu}_\tau$ properties and testing lepton flavour universality by comparing interactions of $\mu$ and $\tau$ neutrinos.
Outline

- The search for Heavy Neutral Leptons
  - Evaluating SHiP sensitivity

- Probing the Hidden Sector
  - Vector portal
  - Scalar portal
  - Axion-like particles
  - Supersymmetry

- Physics with $\nu_\tau$

- The SHiP experiment
  - Detector system
  - Background strategies

- Conclusions
The search for Heavy Neutral Leptons
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Heavy neutral leptons

- dark matter
- neutrino masses/oscillations
- short-baseline neutrino anomalies
- matter-antimatter asymmetry

Could be explained with additional, sterile neutrinos

$$\Delta \mathcal{L} = i \tilde{N}_I \phi N_I - \left( F_{\alpha I} \bar{L}_{\alpha} N_I \tilde{\phi} + \frac{M_I}{2} \bar{N}_I^c N_I \right)$$

- dimensionless Yukawa couplings
- left lepton doublet
- Higgs doublet
- Majorana mass term
Heavy Neutral leptons

The Majorana mass term induces
\[ \mathcal{L}_{osc} = c_{\alpha\beta} \left( \bar{L}^c_\alpha \tilde{\Phi} \right) \left( \tilde{\Phi} L_\beta \right) / \Lambda \]

\[ \implies \text{change flavour} \text{ of SM neutrino } \nu_\alpha \equiv \tilde{\Phi} L_\alpha \]

Seesaw mechanism

\[ m_D = \text{Dirac mass term}, \quad (m_D)_{\alpha I} = F_{\alpha I} < \Phi > \]

\[ (\mathcal{M}_\nu)_{\alpha\beta} = - \sum_I (m_D)_{\alpha I} \frac{1}{M_I} (m_D)_{\beta I} \]

GeV scale seesaw can generate BAU through HNL oscillations. Because of \( \nu - N \) mixing, HNLs take part in all \( \nu \) processes with strength reduced by \( U_{\alpha I}^2 \) and kinematics reflecting \( m_N \).
Suitable values of $m_N$ and $U^2_f$ allow to simultaneously explain:

- $\nu$ oscillations induced by massive states $N_2, N_3$
- dark matter: $N_1$ with mass $\sim$keV
- BAU: leptogenesis due to Majorana mass term

**Astrophys. J. 789(2014)13**

**Phys.Rev.Lett. 113(2014)251301**
HNLs can be produced in decays where a $\nu$ is replaced by a $N$ (kinetic mixing, low $BR$). Main neutrino sources in SHiP: $c$ and $b$ mesons.

They can then decay again to SM particles through mixing ($U^2$) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a $Z^0$ or $W^\pm$ boson.
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Estimating SHiP’s sensitivity to HNLs

- **Number** of detected HNL events:

\[ \Phi(p.o.t) \times \sigma(pp \rightarrow NX) \times P_{\text{vtx}} \times BR(N \rightarrow \text{visible}) \times A \]

with

\[ \sigma(pp \rightarrow NX) \propto \chi_{cc}, \chi_{bb}, U_{f}^{2} \]

\[ BR(N \rightarrow \text{visible}) \propto U_{f}^{2} \]

- **HNL production:**
  - \( \chi_{cc}, \chi_{bb} \) obtained from simulations (Pythia8)
  - \( BR(m_{N}, U_{f}^{2}) \) parametrised according to theory [JHEP 0710 (2007) 015]

- **Daughters acceptance (A):**
  - HNLs kinematics obtained from simulation
  - every decay channel with detectable daughters is simulated
Charm mesons are the main source of HNLs in SHiP. Contribution of \( b \) mesons for \( m_N > 2 \) GeV.

- **Pythia8** used to retrieve the spectrum of \( c \) and \( b \) mesons in 400 GeV/c proton-on-target collisions

- HNL production simulated in kinematically-allowed decay chains:
  - \( D \to K \ell N \)
  - \( D_s \to \ell N \)
  - \( D_s \to \tau \nu_\tau \) followed by \( \tau \to \mu \nu N \) or \( \tau \to \pi N \)
  - \( B \to \ell N \)
  - \( B \to D \ell N \)
  - \( B_s \to D_s \ell N \)

- \( BR(pp \to NX) \) computed as sum of the BRs of the kinematically-allowed channels
HNL lifetime and decay channels

For a given $N$ mass, its lifetime was computed on the basis of the widths of its kinematically allowed decay channels:

- $N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
- $N \to H^{\pm} \ell^\mp$, with $H = \pi, \rho$
- $N \to 3\nu$
- $N \to \ell_i^{\pm} \ell_j^{\mp} \nu_j$
- $N \to \nu_i \ell_j^{\pm} \ell_j^{\mp}$

All decay channels into $\geq 2$ charged particles were taken to be visible.
SHiP sensitivity to HNLs

- scenarios I-III: benchmarks with $U^2_{e}$, $U^2_{\mu}$, $U^2_{\tau}$ dominating (JHEP 0710 ...)
- scenarios IV-V: baryogenesis numerically proven (JCAP 1009(2010)001)
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The vector portal

SM group $SU(3) \times SU(2) \times U(1)$ may descend from a larger group:

$$SU(3) \times SU(2) \times [U(1)]^n$$

Interesting at SHiP

- kinetically mixing $O(\text{GeV})$ dark photons
- $V^{(B-L)}$: 3 RH neutrinos with mass $\sim m_V$
- bosons coupled to baryons $V^{(B)}$
- Chern-Simons (dim. 4/6 operators)
Dark photons and kinetic mixing

\[ \mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 \]

Eq. of motion: \[ \partial_\mu F^{\mu\nu} = e J^{(EM)}_\nu \implies -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} = e \epsilon A'_\mu J^{(EM)}_\mu \]

\( m_{A'} \to 0 \implies \text{e.m. charge of } \chi \to e \epsilon. \)

Okun, Sov. Phys. JETP 56 (1982) 502 – Holdom, Phys. Lett. B 166 (1986) 196
Motivations for light vector particles

→ Dark matter ($\Omega_{DM} \sim 0.25$):
  - light scalar dark matter $m_\chi \sim$ MeV can solve the positron excess
  - WIMP interacting with SM through light mediator ($\chi\bar{\chi} \rightarrowVV \rightarrow SM$) (hides DM from direct searches)
  - non thermal DM (sterile neutrinos)
  - DM self-interaction in structure formation ($m_V \sim$ MeV–GeV)

→ Muon $g - 2$:
  Light vector particle coupled to muons provides upward correction through one-loop diagram (exchange of $A'$). Not minimal model.
Vector portal phenomenology

→ Decay:
\[ \Gamma_{tot} = \Gamma(\ell^+\ell^-) + \Gamma(\text{hadrons}) + \Gamma(\chi\bar{\chi}) \]

→ Production at SHiP:
- meson decays e.g. \( \pi^0 \rightarrow \gamma V \) \( (\sim \epsilon^2) \) \( \text{Phys.Rev. D80(2009)095024} \)
- \( p \) bremsstrahlung on target nuclei \( pp \rightarrow ppV \) \( \text{Phys.Lett. B731(2014)320-326} \)
- large \( m_V \) ⇒ direct QCD production through underlying \( q\bar{q} \rightarrow V \), \( qg \rightarrow V \) (need some more theory work!) \( \text{Phys.Rev. D86(2012)035022} \)

→ Light dark matter at SHiP:
if \( \chi\bar{\chi} \) decays dominant ⇒ \( \chi \) can scatter on electrons \( \sim \alpha\alpha_D\epsilon^2 \):
dense detector to look for light DM.
SHiP sensitivity: vector portal

Visibly Decaying $A'$

Sensitivity studied considering $\Gamma_{tot} = \Gamma(\ell^+\ell^-) + \Gamma(\text{hadrons})$. 

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The scalar portal

Most general renormalizable $\mathcal{L}$:

$$\Delta \mathcal{L} = \frac{1}{2} \partial_\mu S \partial^\mu S + \left( \alpha_1 S + \alpha S^2 \right) \left( H^\dagger H \right) + \lambda_2 S^2 + \lambda_3 S^3 + \lambda_4 S^4$$

- $\alpha_1 \neq 0$: $S$ mixes with Higgs after EW symmetry breaking
  $\Rightarrow$ coupling between $S$ and all SM particles
- $\alpha_1 = 0$ (forbidden by exact $\mathbb{Z}_2$ symmetry): $S$ does not mix with $H$
  $\Rightarrow$ new particles must be pair-produced
→ **Existing limits** from searches for rare meson decays e.g. $B \to KS$

→ **Production**: $K$ decays (SHiP efficiency $\approx 0.2\%$) and $B$ decays

→ **Decay**: $S \to \gamma\gamma, ee, \mu\mu, \pi\pi, KK$
Higher dimension portals: \( \frac{1}{\Lambda} |H|^2 \bar{\psi} \psi \) (dark fermions), 
\( \frac{1}{\Lambda^2} m_{Z_D}^2 |H|^2 Z_{D \mu} Z_{D \mu} \) (dark gauge boson)

decays of the SM Higgs into hidden states

at SHiP \( E_{CM} \simeq 28 \text{ GeV} < m_H \)

Production channels at SHiP:
- heavy meson decays (dominant is \( B \to K^{(*)} X X \))
- gluon fusion \( pp \to h^* \to X X \)

\( X \) decays back to SM with different coupling
In particle physics, the inflaton is a **scalar field** that couples to SM fields to ensure **re-heating** of the post-inflation Universe (production of particles that thermalize) and transfer of inflaton fluctuations into **adiabatic matter perturbations**.

\[ \mathcal{L}_{int} = \alpha S^2 H^\dagger H, \]  
with approx. \(10^{-11} < \alpha < 10^{-7}\)
- \(\alpha < 10^{-11}\) \(\rightarrow\) inefficient reheating
- \(\alpha > 10^{-7}\) \(\rightarrow\) quantum correction would imply large, scale-dependent density perturbations (\(\neq\) observations)

**Sensitivity at SHiP** is dominated by the lifetime exponential.

\[ \theta^2 = \frac{1}{m_{\chi} \tau_{\chi}}, \text{ GeV}^{10^{-12}} \text{s}^{-1} \]
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Axion-like particles

- The axion mass $m_A$ is very constrained due to the axial QCD anomaly breaking the PQ symmetry. Other ALPs are not so constrained.
- SHiP can probe ALPs coupled to gauge bosons and to SM fermions:
  - $pp \rightarrow AX, A \rightarrow \gamma\gamma$: all neutral, more challenging (left plot)
  - $pp \rightarrow BX, B \rightarrow AK, A \rightarrow \mu^+\mu^-$ (right plot)
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→ **SUSY** is one of the most popular options to solve naturalness, grand unification and dark matter (WIMP)

→ $W_{RPC} = (Y_e)_{ij} L_i H_1 \tilde{E}_j + (Y_d)_{ij} Q_i H_1 \tilde{D}_j + (Y_u)_{ij} Q_i H_2 \tilde{U}_j + \mu H_1 H_2$

SUSY particles produced in pairs. Accelerator searches significantly constrain “natural” scenarios (e.g. MSSM, fine tuning at $\sim 1\%$).
SUSY at SHiP: RPV neutralino

\[ W_{\text{RPV}} = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2 \]

- The lightest SUSY particle is not anymore stable (no DM)
- Can be searched for at SHiP in \( D \) meson decays:

\[
\begin{align*}
    c & \rightarrow \tilde{N}_1 \tilde{c}_L \\
    d & \rightarrow \tilde{N}_1 \tilde{d}_R \\
    c & \rightarrow l^+ \tilde{l}_L \\
    d & \rightarrow l^+ \tilde{N}_1
\end{align*}
\]

- SHiP sensitivity studied with channels \( \tilde{N}_1^0 \rightarrow K^0(\bar{\nu}) \) and \( \tilde{N}_1^0 \rightarrow K^\pm \ell_\mp \)
SUSY must be broken \( \rightarrow \) Goldstone supermultiplet

- \( \tilde{G}_\mu (\psi) \) is \( R \)-odd
- \( P, S \) are \( R \)-even \( \rightarrow \) can be singly produced and may decay back to pairs of SM particles
- at SHiP:
  - \( pp \xrightarrow{\text{gluon fusion}} S \)
  - \( D \rightarrow SX \)
  - \( S \rightarrow \ell\ell, \pi\pi \)

\[ F^{-1/2} = (100 \text{ TeV})^{-1} \]

\( m_S, \text{GeV} \)

\( \text{Phys. Rev. D93 (2016) 3} \)
SUSY at SHiP: pseudo-Dirac gauginos

- Dirac fermion ($\Psi$) split in two Majorana components ($\chi_1$, $\chi_2$)
- interesting dark matter candidate: allows annihilation but appears as Majorana particle for direct and indirect detection purposes
- Production at SHiP: $pp \rightarrow \Psi \bar{\Psi}$
- Decay: $\chi_2 \rightarrow \ell^+ \ell^- \chi_1$
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A unique opportunity

High intensity beam dump $\implies$ high flux of neutrinos (all species).

Neutrino detector (mostly lead) allows to:

- identify flavour
- measure charge of emerging $\mu$ and $\tau$
- measure kinematic variables of DIS processes
  - for both NC and CC interactions

$\nu_\tau$ CC cross sections

- OPERA: 4 events
- DONUT: 8 events

SHiP: increase by 3 orders of magnitude
Tests of perturbative QCD and lepton universality

→ PDF improvements with $\nu$-nucleon DIS: strange sea quark content currently relies on $O(5000)$ charm di-$\mu$ events:

\[ \text{SHiP} > 10^5 \text{ evts} \]

LHC and SHiP will probe different ranges of $x$.

→ Lepton universality tests:

- hints from LHCb, $B$ factories, ...
- DIS $\sigma$ including BSM: Liu, Rashed, Datta
  \[ \text{PRD92(2015)7, 073016}, \text{ to compare to } \sigma_{SM} \]
- results depend on our knowledge of the $\nu_\tau$ flux!
Tests of perturbative QCD and lepton universality

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  - hints from LHCb, $B$ factories, ...
  
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  - results depend on our knowledge of the $\nu_\tau$ flux!
Neutrino magnetic moment

If neutrinos are Dirac particles they can get a magnetic moment:

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2 \sqrt{2}} \simeq \left(3.2 \times 10^{-19}\right) \frac{m_\nu}{1\text{ eV}} \mu_B$$

BSM can enhance $\mu_\nu$. (E.g.: Shrock, Nucl.Phys. B206 (1982) 359)

$$e\nu \rightarrow e\nu \Rightarrow \frac{dN}{dE_e}\bigg|_{\mu_\nu} = \frac{\pi \alpha^2 \mu_\nu^2}{m_e^2} \left( \frac{1}{E_e} - \frac{1}{E_\nu} \right)$$

Remove BG from $\nu N$ scattering: $\theta_{\nu e}^2 < 2m_e/E_e \rightarrow$ sensitivity:

$$N_{\text{evt}} \sim 4.3 \times 10^{15} \frac{\mu_\nu^2}{\mu_B^2}.$$  Prev. limits from $10^{-7} (\nu_\tau)$ to $10^{-11} (\nu_e)$. 
Dark matter search

Detect dark matter from dark photon decay through elastic scattering on electrons: $\chi e^- \rightarrow \chi e^-$. Signature in the emulsion target: a vertex with only $e^-$ coming out. Simulation $\rightarrow$ background from neutrino scattering can be reduced with kinematical selections to 284 events / 5 y.

Dark photon parameter space for $\gamma' \rightarrow$ invisible decays excluded by SHiP at 90% C.L., with such expected background and for $m_\chi = 200$ MeV and $\chi \gamma'$ coupling $\alpha' = 0.1$:  

![Graph showing dark matter parameter space](image)
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The SHiP collaboration

2013:
- submission of the EOI (October, 16 authors)

2014:
- SPSC discusses EOI (January)
- 1st workshop (June, 100 participants)

2015:
- submission of TP (April, 233 authors)
  → arXiv:1504.04956
- submission of PP (April, 85 authors)
  → arXiv:1504.04855
- discussion with SPSC referees

2016:
- endorsement by the SPSC (February)

2014–today:
- 7 collaboration meetings
Experimental requirements

- HNL production in charm decays
  - LHC: \( \int \mathcal{L} dt \sim 10^3 \text{ fb}^{-1} \), \( \sigma_{c\bar{c}} = 11 \text{ mb} \)
  - SPS 400 GeV + Mo target: \( \mathcal{L} \sim 10^{38} \text{ cm}^{-2} \text{ s}^{-1} \), \( \sigma_{c\bar{c}} = 18 \mu \text{b/nucleon} \)
  - 10\( \times \) more charm at SPS, forward boost, BG shielding
  - slow beam extraction to minimize occupancy

- decay of hidden particles:
  - large decay volume followed by spectrometer, calorimeter, PID
  - shielding from SM particles: hadron absorber + VETO detectors

- \( \tau \) neutrinos:
  - \( N_{\nu_{\tau}} = 4N_p \left( \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} \right) f_{D_s} \times Br(D_s \to \tau) \approx 6 \times 10^{15} \)
  - distinguish \( \nu_{\tau} / \bar{\nu}_{\tau} \): magnetized emulsion target + high-res tracker
...and the muons?

Residual $\mu$ flux after the hadron absorber is dangerous:

- background for HS physics
- ageing of $\nu_\tau$ emulsions
- active muon shield based on sweeping magnets
- option for a conical vessel
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The facility at the SPS

- minimal modification to the SPS complex
- same extraction and transfer line as other NA facilities
- 190 m long, 20 m wide hall
The $\nu_\tau$ detector

Target made of interlaced layers of emulsion bricks and scintillating fibres, resolution of $1 \, \mu m \implies$ charge of $\tau$ daughters.

Muon tracker: RPCs and drift tubes. Also tags BG for HS physics.
The Hidden Sector detector

- large evacuated decay volume \((10^{-6} \text{ bar})\)
- surrounded by **background taggers**
- as close as possible to target
- in a \(\mu\)-free area thanks to active shield
The Hidden Sector detector

- large evacuated decay volume \( (10^{-6} \text{ bar}) \)
- surrounded by **background taggers**
- as close as possible to target
- in a \( \mu \)-free area thanks to active shield
Optimization of the decay volume

- Studying cylindrical, conical solutions in vacuum or He
- Surrounded by liquid scintillator to tag BG
- Acceptance depends on the hidden particle’s lifetime
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Physics with $\nu$\tau

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Shields and background taggers

- **Hadron stopper** after the target
- **Magnetic $\mu$ sweeper** creates a 5 m wide fiducial area
- **$\nu$ detector** precedes HS detector and tags upstream particles
- **Upstream VETO** complements its acceptance
- **Straw VETO** tags decays of $K_L$ produced in the $\nu$ detector
- **Liquid scintillator** tags interactions crossing the vessel walls
- **Timing detector** reduces combinatorial background
Background sources

- cosmic $\mu$ can scatter on the cavern/vessel walls
- combinatorial combinations of tracks from different events/vertices
- $\mu$ DIS on the cavern walls can produce charged tracks
- $\nu$ interactions in the material of the HS detector and upstream closely mimick HP decay topology
Offline selection

- discard events with activity in the VETO detectors
- select candidates based on the reconstructed direction (must point back to the target)
- require good quality tracks & reconstructed vertex
- event must be fully contained in the fiducial volume, with margins
- we expect < 1 candidate per event

**Selection efficiency**

| Sample       | Multiplicity | Fiducial vol | Track q. | BG cuts/VETO |
|--------------|--------------|--------------|----------|--------------|
| $HNL \rightarrow \pi \mu$ | 97.5 %       | 76.1 %       | 87.0 %   | 94.2 %       |
| $\gamma' \rightarrow \mu \mu$ | 99.6 %       | 85.2 %       | 94.4 %   | 94.0 %       |
| $\nu$ background | 79.1 %       | 21.0 %       | 6.5 %    | 0.0 %        |

Overall $\lesssim 0.1$ background events / 5 years is attainable!
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What's next

- **Technical and Physics proposals** prepared in 2014-2015
  - feasibility studies, facility design, engineering, test beams, sensitivities

- **Green lights** from the SPSC, recommendation to produce CDR (Comprehensive Design Report) for European HEP strategy 2019

- **10 years** from Technical Proposal to data taking
  - schedule optimized for **minimal interference** with SPS operation

![Accelerator schedule chart](image)

- LHC
  - 2015: Run 2
  - 2017: LS2
  - 2020: Run 3
  - 2024: LS3
  - 2026: Run 4

- SPS
  - 2019: Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)
  - Use of Long Shutdown 3 for junction cavern and first short section of SHiP beam line

- Comprehensive Design Study 2016–2018: Starting now!
- Construction/production 2021–
- Data taking 2026 (start of LHC Run 4)

Reversed TP schedule

CwB: Commissioning with Beam
Conclusions

- **General purpose** experiment to look for weakly interacting long lived particles
  - covers previously unexplored regions of the Hidden Sector in several theories
  - covers cosmologically interesting regions

- **Unique** opportunity for $\nu_\tau$ physics allowing for
  - $\bar{\nu}_\tau$ discovery
  - $\sigma$ and form factors measurements
  - also dark matter search

- **Complements** LEP/LHC and boosts past experiments sensitivities
  - $\times 10^5$ for HS, $\times 200$ for $\nu_\tau$
  - makes best use of existing SPS complex

- **Next phase:** comprehensive design report 2018
Questions?

- spare slides -
HNLs at future colliders

http://arxiv.org/abs/1411.5230
http://arxiv.org/abs/1503.08624
Sensitivity with non-zero background

Figure: Variation of the sensitivity contours for scenarios II (left) and IV (right) as a function of the background estimates. The solid blue curve represents the 90% C.L. upper limit assuming 0.1 background events in $2 \times 10^{20}$ proton-target collisions. The dashed blue curve assumes 10 background events. The dotted blue curve assumes a systematic uncertainty of 60% on the level of background, i.e. $10 \pm 6$ background events.
Estimating SHiP’s physics reach

\[ \Phi(p.o.t) \times BR(pp \rightarrow NX) \times \mathcal{P}_{vtx} \times BR(N \rightarrow visible) \times A \]

- HNL’s momentum and angle are stored in a binned PDF
- HNL spectra are re-weighted by the probability
  \[ \mathcal{P}_{vtx}(p, \theta | m_N, U_f^2) \sim \int_V e^{-l/\gamma c t} dl \]
- Integral of the weighted PDF gives the total probability
  \[ \mathcal{P}_{vtx}(m_N, U_f^2) \]
  that HNLs leave a vertex in SHiP’s fiducial volume

Weighted PDF for model 2, \( m_N = 1.8 \text{ GeV}, U_\mu = 10^{-9} \)
Sensitivity in the Left-Right symmetric model

\[ D_s \rightarrow S \rightarrow \mu \]

\[ W_R \rightarrow c \rightarrow N \]

\[ W_\mu \rightarrow u \rightarrow \pi \]

\[ m_{W_R} \text{ (GeV)} \]

\[ m_{N_{\mu}} \text{ (GeV)} \]

- SHiP limits on \( m_{W_R} \) can be extracted from the HNL limits by \( |U_{\mu I}|^2 \rightarrow (m_{W_L}/m_{W_R})^4 \)
- LHC can perform direct searches on both \( W_R \) and \( N_R \)
- SHiP can only look for \( N_R \), but in a domain inaccessible to LHC
- based on CMS, *Eur. Phys. J. C* 74 (2014) 3149, and Helo, Hirsch, Kovalenko, *Phys.Rev. D89* (2014) 073005

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SHiP: Search for Hidden Particles
LFV processes

- **ν oscillations** provide evidence of LFV in the neutral sector
- **LFV** in charged sector foreseen with \( BR \sim O(10^{-40})! \)
- **New physics** models can enhance these \( BRs \)
  - in seesaw models charged LFV can happen in tree or loop diagrams
  - \( \ell \rightarrow 3\ell' \) generally favoured with respect to \( \ell \rightarrow \ell'\gamma \) (type 2 and 3 seesaw)
- \( \ell \rightarrow 3\ell' \) related by unitarity to \( Z^0, h, V \rightarrow \ell^+\ell'^- \) and \( \ell \rightarrow \ell' \)
  - conversion in nuclei (most stringent limits so far by SINDRUM II)
  - \( \tau \rightarrow 3\mu \) and \( \mu \rightarrow 3e \) can provide better limits than direct searches e.g. for \( \phi \rightarrow e\mu, J/\Psi \rightarrow e\mu \)
  - \( BR(\tau \rightarrow 3\mu) < 1.2 \times 10^{-8} \) (BaBar,Belle,LHCb)
- **SHiP** will collect \( 3 \times 10^{15} \, \tau \) in the forward region
  - requires **changes to conceptual design** (upgrade):
    - 1 mm W target: 100× less \( \tau \), but decaying outside target
    - LHCb VELO + Si tracker + hadron absorber + \( \mu \) spectrometer
  - sensitivity \( \sim 10^{-10} / \sqrt{N_{\text{targets}}} \)
\[ L_{world} = L_{SM} + L_{mediation} + L_{HS} \]

- **Neutrino portal**: new Heavy Neutral Leptons coupling with Yukawa coupling, \( L_{NP} = F_{\alpha I}(L_\alpha \Phi)N_I \)
- **Vector portal**: massive dark photon coupling through loops of particles charged both under \( U(1) \) and \( U'(1) \): \( L_{VP} = \epsilon F'_{\mu\nu}F^{\mu\nu} \)
- **Scalar portal**: light scalar mixing with the Higgs \( L_{SP} = (\lambda_i S_i^2 + g_i S_i)\Phi \)
- **Axion portal**: axion-like particles, \( L_{AP} = \frac{A}{4f_A}\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu}F_{\lambda\rho} \)
- **SUSY**: neutralino, sgoldstino, gaugino...

| Models                                      | Final states                                  |
|----------------------------------------------|-----------------------------------------------|
| Neutrino portal, SUSY neutralino             | \( \ell^\pm, K^\pm, \ell^\pm \pi^\pm, \rho^\pm \rightarrow \pi^\pm \pi^0 \) |
| Vector, scalar, axion portals, SUSY sgoldstino| \( \ell^+\ell^- \)                             |
| Vector, scalar, axion portals, SUSY sgoldstino| \( \pi^+\pi^-, K^+K^- \)                        |
| Neutrino portal, SUSY neutralino, axino      | \( \ell^+\ell^- \nu \)                         |
| Axion portal, SUSY sgoldstino                | \( \gamma\gamma \)                             |
| SUSY sgoldstino                              | \( \pi^0\pi^0 \)                              |
New Physics prospects in Hidden Sector

Standard Model portals:

- **D = 2: Vector portal**
  - Kinetic mixing with massive dark/secluded/paraphoton $V : \frac{1}{2} \varepsilon F_{\mu \nu}^{SM} F_{HS}^{\mu \nu}$
  - Motivated in part by idea of “mirror world” restoring left and right symmetry, constituting dark matter, g-2 anomaly, …
  - Production: proton bremsstrahlung, direct QCD production $q\bar{q} \rightarrow V, qg \rightarrow Vq$, meson decays ($\pi^0, \eta, \omega, \eta', ...$)

- **D = 2: Scalar portal**
  - Mass mixing with dark singlet scalar $\chi : (gS + \lambda S^2)H^\dagger H$
  - Mass to Higgs boson and right-handed neutrino, inflaton, dark phase transitions BAU, dark matter, “dark naturalness”,…
  - Production: Direct $p + target \rightarrow X + S$, meson decays e.g. $B \rightarrow KS, K \rightarrow \pi S$

- **D = 5/2: Neutrino portal**
  - Mixing with right-handed neutrino $N$ (Heavy Neutral Lepton): $Y_{i\ell} H^\dagger N_{1} L_{\ell}$
  - Neutrino oscillation, baryon asymmetry, dark matter
  - Production: Leptonic, semi-leptonic decays of heavy hadrons

- **D = 4: Axion portal**
  - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors $a : \alpha F G_{\mu \nu} \tilde{G}^{\mu \nu}, \frac{\partial \mu a}{F} \bar{\psi} Y_{\mu} \gamma_5 \psi$, etc
  - Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale $F$
  - Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…
  - Production: Primakoff production, mixing with pions and heavy meson decays

- **And higher dimensional operator portals**
  - Chern-Simons portal (vector portal)
• **SUper-SYmmetric “portals”**
  - Some of SUSY low-energy parameter space open to complementary searches
  - Sgoldstino S(P): \( \frac{M_{YY}}{F} S \mu \nu F_{\mu \nu} \)
  - Neutralino in R-Parity Violating SUSY
  - Hidden Photinos, axinos and saxions….

\[ \Rightarrow \text{A very large variety of models based on these or mixtures thereof} \]

- **Two search methods:**
  1. “Indirect detection” through portals in (missing mass)
  2. “Direct detection” through both portals in and out

\[ \Rightarrow \text{SHiP has significant sensitivity to all of these!} \]

Assumption invisible decay width \( \chi^\pm \chi^- \) is absent or sub-dominant, \( m_\chi > \frac{1}{2} m_{\text{portal}} \), where \( \chi \) hidden sector particle
Fermions get mass via the Yukawa couplings:

\[
-L_{\text{Yukawa}} = Y_{ij}^d Q_i \phi D_R + Y_{ij}^u Q_i \phi U_R + Y_{ij}^\ell L_i \phi E_R + \text{h.c.}
\]

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos... the most generic Lagrangian is

\[
L_N = i \overline{N_i} \partial_\mu \gamma^\mu N_i - \frac{1}{2} M_{ij} \overline{N}^c_i N_j - Y_{ij}^\nu \overline{L_i} \phi N_j
\]

Kinetic term  Majorana mass term  Yukawa coupling

Seesaw mechanism:

\[
\mathcal{V} = (\nu_L, N_j)
\]

\[
M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}
\]

\[
-L_{\mathcal{M}_\nu} = \frac{1}{2} \overline{\nu} M_\nu \nu + \text{h.c.}
\]

if \(M_N \gg M_D\):

\[
\lambda_- \sim \frac{M_D^2}{M_N}
\]

\[
\lambda_+ \sim M_N
\]
Sterile neutrino masses

Seesaw formula $m_D \sim Y_{I\alpha} \langle \phi \rangle$ and $m_\nu = \frac{m_D^2}{M}$

- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1$. and $Y_e \sim 10^{-6}$

If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

Majorana Mass (GeV)
Constraints on $N_1$

The decay mode $N \rightarrow \nu \nu \nu$ is always present

$$LT = \left( \frac{U^2 G_F M_N^5}{86 \pi^3} \right)^{-1} \simeq 0.3 \left( \frac{1\text{GeV}}{M_N} \right)^4 \text{sec}$$

This gives an upper bound for the mass of the sterile neutrino Dark Matter:

- $M_N \sim 1\text{KeV} \implies \tau_N \sim 10^{24}\text{sec}$
- $\frac{\text{Age of the Universe}}{\tau_N} \sim 10^{-6}$
Constraints on $N_1$

DM sterile neutrinos decay subdominantly as $N_1 \rightarrow \nu \gamma$ with a branching ration $\mathcal{B}(N_1 \rightarrow \gamma \nu) \sim \frac{1}{123}$.

Discussion in the community, not yet clear if this is a “good” signal, needs confirmation.

Bulbul et al. 2014 (arXiv:1402.2301)
Boyarsky et al. 2014 (arXiv:1402.4119)
If $U^2$ is too large, $N_{2,3}$ are in **thermal equilibrium** during the expansion of the Universe.

At $M_N \geq M_W$ the rate is enhanced by $N \rightarrow Wl$ leading to stronger constraints on $U^2$.

The **seesaw** limit defines the region where $N_{2,3}$ can explain the observed active neutrino $\Delta m^2$.

If $\tau(N_2, N_3) < 0.1 \text{ s}$, they cannot affect the **Big Bang nucleosynthesis**.
Background summary: no evidence for any irreducible background

- No events selected in MC ➔ Expected background UL @ 90% CL

| Background source | Decay modes | Stat. weight | Expected background (UL 90% CL) |
|-------------------|-------------|--------------|----------------------------------|
| ν or μ + nucleon → X + Kl | Kl → πνν, πμν, π^+π^-, π^+π^-π^0 | 1.4 | 1.6 |
| ν or μ + nucleon → X + Ks | Ks → π^0π^0, π^+π^- | 2.5 | 0.9 |
| ν or μ + nucleon → X + Λ | Λ → pπ^- | 3.0 | 0.8 |
| n or p + nucleon → X + Kl, etc | as above | | |

Neutrino tomography
Preparation of facility in four well-defined quasi-independent work packages

- WP1: Junction cavern + 70m beam line for clearance during operation (21 months)
- WP2: Rest of beam line (12 months)
- WP3: Target complex (12 months)
- WP4: Experiment facility (18 months)

- Only WP1 has to be done during a stop of the North Area only
- WP1 associated with cool down, removal and re-installation of services and beam line (24-27 months)
- Construction of facility has no interference with operation of SPS and LHC at any time
Design considerations with $4 \times 10^{13}$ p / 7s

- 355 kW average, 2.56 MW during 1s spill
  - High temperature
  - Compressive stresses
  - Atomic displacement
  - Erosion/corrosion
  - Material properties as a function of irradiation
  - Remote handling (Initial dose rate of 50 Sv/h…)

Hybrid solution: Mo allow TZM ($4\lambda$) + W ($6\lambda$)

|                | DONUT 1$|$ | CHARM 2$|$ | SHiP       |
|----------------|-----------|-----------|------------|
| Target material| W-alloy   | Cu (variable $\rho$) | TZM + pure W |
| Momentum (GeV/c)| 800      | 400       | 400        |
| Intensity      | $0.8 \times 10^{13}$ | $1.3 \times 10^{13}$ | $4 \times 10^{13}$ |
| Pulse length (s) | 20      | $23 \times 10^{-6}$ | 1          |
| Rep. rate (s)  | 60       | $\sim 10$  | 7.2        |
| Beam energy (kJ)| 1020   | 830       | 2560       |
| Avg. beam power (spill) (kW) | 51      | $3.4 \times 10^{7}$ (fast) | 2560 |
| Avg. beam power (SC) (kW) | 17      | 69        | 355        |
| POT           | Few $10^{17}$ | Few $10^{18}$ | $2 \times 10^{20}$ |
Muon flux limit driven by emulsion based $\nu$-detector and “hidden particle” background

Passive and magnet sweeper/passive absorber options studied:
- Conclusion: Shield based entirely on magnetic sweeping with $\int B_y \, dl \sim 86 \text{Tm}$
  - $<7 \times 10^3$ muons / spill ($E_\mu > 3 \text{ GeV}$) which can potentially produce $V_0 (K_L)$
  - Negligible occupancy

- Challenges: flux leakage, constant field profile, modelling magnet shape
Estimated need for vacuum: \(10^{-3}\) mbar

- Based on \(\nu\)-flux: \(2 \times 10^4\ \nu\)-interactions/\(2 \times 10^{20}\) p.o.t. at \(p_{atm}\)

Vacuum vessel

- \(10\ m \times 5\ m \times 60\ m\);
- Walls thickness: \(8\ mm\) (Al) / \(30\ mm\) (SS);
- Walls separation: \(300\ mm\);
- Liquid scintillator volume: \(\sim 360\ m^3\);
- 1500 WOMs (8 cm x \(8\ cm\) WOM + PMTs);
- Metal weight (SS, no support): \(~ 480\ t\).

Low power magnet designed

- Field integral: \(0.65 Tm\) over 5m
- Current 2500 A (1.7 A/mm²)
- Power consumption < 1 MW
- Weight \(~ 800\ tonnes\)
Optimization of geometrical acceptance for a given $E_{\text{beam}}$ and $\Phi_{\text{beam}}$

- Hidden particle lifetime (~flat for longlived)
- Hidden particle production angles (~distance and transversal size)
- Hidden particle decay opening angle (~length and transversal size)
- Muon flux (~distance and acceptable occupancy)
- Background (~detector time and spatial resolution)
- Evacuation in decay volume / technically feasible size ~ W:5m x H:10m

Acceptance saturates ~40m – 50m
HS tracking system

- NA62-like straw detector

| Parameter                        | Value     |
|----------------------------------|-----------|
| Length of a straw                | 5 m       |
| Outer straw diameter             | 9.83 mm   |
| Straw wall (PET, Cu, Au)          |           |
| PET foil thickness               | 36 μm     |
| Cu coating thickness             | 50 mm     |
| Au coating thickness             | 20 nm     |
| Wire (Au-plated Tungsten) diameter | 30 μm    |
| Number of straws in one layer    | 568       |
| Number of layers per plane       | 2         |
| Straw pitch in one layer         | 17.6 mm   |
| Y extent of one plane            | ~10 m     |
| Y offset between straws of layer 1&2 | 8.8 mm   |
| Z shift from layer 1 to 2         | 11 mm     |
| Number of planes per view        | 2         |
| Y offset between plane 1&2        | 4.4 mm    |
| Z shift from plane 1 to 2         | 26 mm     |
| Z shift from view to view         | 100 mm    |
| Number of views per station      | 4 (Y-U-V-Y) |
| Stereo angle of layers in a view Y,U,V | 0, 5, -5 degrees |
| Z envelope of one station         | ~34 cm    |
| Number of straws in one station  | 9088      |
| Number of stations               | 4         |
| Z shift from station 1 to 2 (3 to 4) | 2 m     |
| Z shift from station 2 to 3       | 5 m       |
| Number of straws in total        | 36352     |

- Straws in test beam 2016
  - Study sagging effects and compensation
  - Read out of signal, attenuation / two-sided readout
- Upstream straw veto may be based on same technology

JINR Dubna (NA62, SHiP): Straws
St Petersburg (CMS, SHiP): Infra
Electron efficiency >98%

Pion contamination: <2%

Neutral pion mass resolution: 5 MeV

Muon misid with ECAL+HCAL

Rejection factor for $\varepsilon_\mu = 95\%$

| Energy, GeV | $E+H1+H2$ |
|------------|-----------|
| 1.0        | 23        |
| 1.5        | 32        |
| 2.0        | 50        |
| 2.7        | 120       |
| 3.0        | 160       |
| 5.0        | 210       |
| 10.0       | 250       |

ECAL (July), HCAL (September), MUON (October) in test beam 2015 on PS and SPS