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

SHiP

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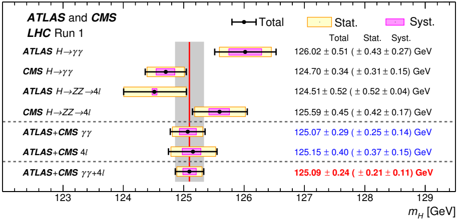
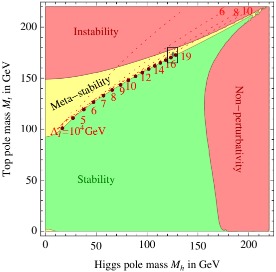
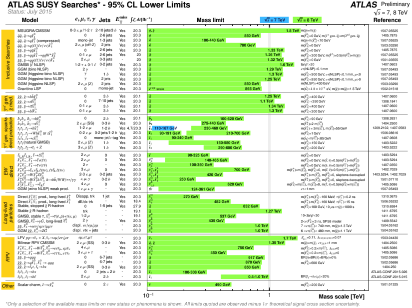
Introduction







- **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...

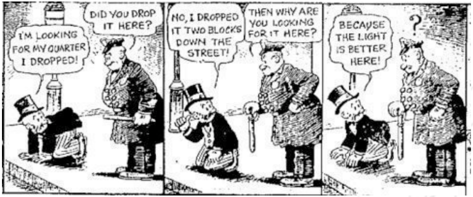
What is the energy scale of new physics?

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

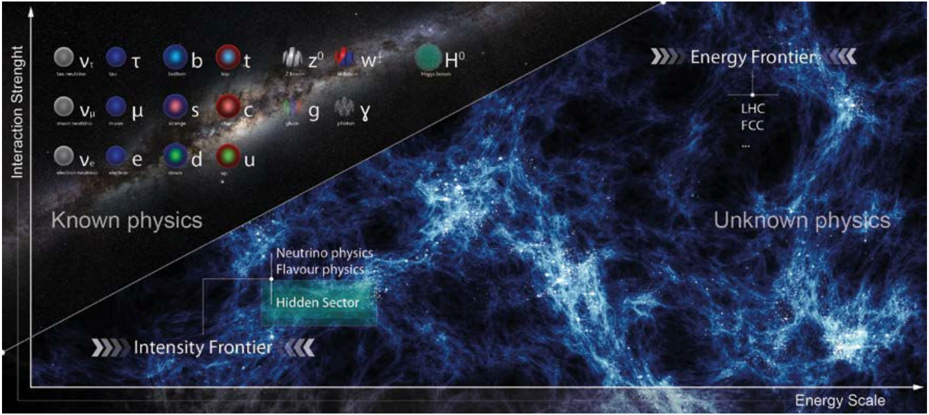
➜ Dark matter:
From 10^{-22} eV (super-light scalars) to 10^{20} GeV (wimpzillas, Q-balls)

➜ Baryogenesis:
Mass of new particle from 10 MeV to 10^{15} 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



Richard Jacobsson and Daniel Dominguez

`http://cerncourier.com/cws/article/cern/63982`

Hidden sector

- Unsolved problems $\Longrightarrow$ new particles
- Why didn't we detect them? Too heavy or too weakly interacting

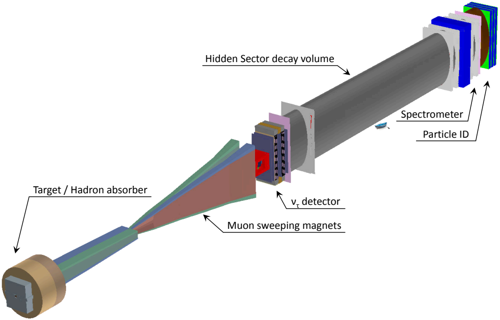
- new particles are light $\Longrightarrow$ they must be singlets with respect to the gauge group of the SM
- they may couple to different singlet operators (**portals**) of the SM
  - dim 2: hypercharge field, $\epsilon F_{\mu\nu} F'^{\mu\nu}$, vector portal
  - dim 2: Higgs field, $\left(\alpha_1 \chi + \alpha \chi^2\right) H^\dagger H$, Higgs/scalar portal
  - dim 2 ½: Higgs-lepton, $Y H^T \bar{N} L$, neutrino portal
  - dim 4: $A G_{\mu\nu} \epsilon^{\mu\nu\rho\eta} G^{\rho\eta}$, $\partial_\mu A \bar{\psi} \gamma^\mu \gamma^5 \psi$, ..., axion portal
  - SUSY models

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 ν_τ and $\bar{\nu}_\tau$ properties and testing lepton flavour universality by comparing interactions of μ and τ 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 ν_τ**
- ➜ **The SHiP experiment**
  - – Detector system
  - – Background strategies
- ➜ **Conclusions**

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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

Majorana mass term

HNL

$$\Delta\mathcal{L} = i\bar{N}_I \not{\partial} N_I - \left(F_{\alpha I}\,\bar{L}_\alpha\, \overset{\uparrow}{\boldsymbol{N_I}}\, \tilde{\Phi} + \frac{M_I}{2}\bar{N}_I^c N_I \right)$$

dimensionless Yukawa couplings

left lepton doublet

Higgs doublet

Heavy Neutral leptons

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

$\Longrightarrow$ **change flavour** of SM neutrino $\nu_\alpha \equiv \tilde{\Phi} L_\alpha$

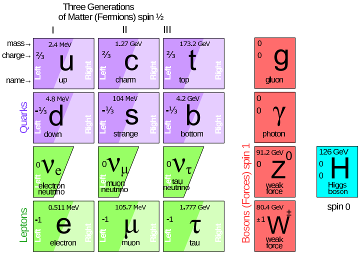
Seesaw mechanism

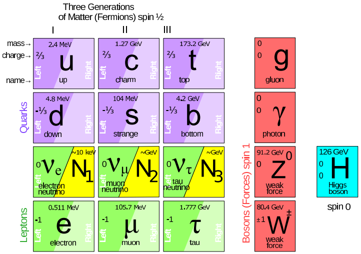
$m_D =$ Dirac mass term, $(m_D)_{\alpha I} = F_{\alpha I} < \Phi >$

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

GeV scale seesaw can generate BAU through HNL oscillations. Because of $\nu - N$ mixing, HNLs take part in all ν processes with strength reduced by $U^2_{\alpha I}$ and kinematics reflecting m_N.

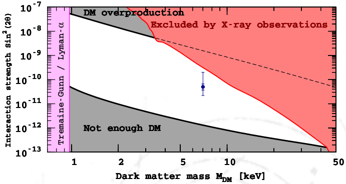
The νMSM Asaka, Blanchet, Shaposhnikov, Phys.Lett. B631 (2005) 151-156





Suitable values of m_N and U_f^2 allow to simultaneously explain:

- ν oscillations induced by massive states N_2, N_3
- dark matter: N_1 with mass ~keV
- BAU: leptogenesis due to Majorana mass term

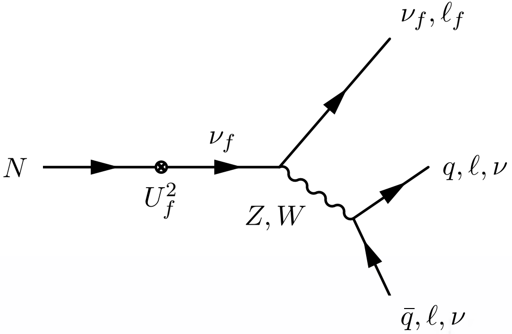


Astrophys. J. 789(2014)13

Phys.Rev.Lett. 113(2014)251301

HNL phenomenology

HNLs can be produced in decays where a ν is replaced by a N (kinetic mixing, low $\mathcal{BR}$). 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:

$$\Phi(p.o.t) \times \sigma(pp \to NX) \times \mathcal{P}_{vtx} \times \mathcal{BR}(N \to visible) \times \mathcal{A}$$

with

$$\sigma(pp \to NX) \propto \chi_{cc}, \chi_{bb}, U_f^2$$
$$\mathcal{BR}(N \to visible) \propto U_f^2$$

- HNL production:
  - χ_{cc}, χ_{bb} obtained from simulations (Pythia8)
  - $\mathcal{BR}(m_N, U_f^2)$ parametrised according to theory *JHEP 0710 (2007) 015*
- Daughters acceptance ($\mathcal{A}$):
  - HNLs kinematics obtained from simulation
  - every decay channel with detectable daughters is simulated

HNL production in SHiP

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 $\tau \to \pi N$
  - $B \to \ell N$
  - $B \to D \ell N$
  - $B_s \to D_s \ell N$
- ➜ $\mathcal{BR}(pp \to N X)$ computed as sum of the BRs of the kinematically-allowed channels

HNL lifetime and decay channels

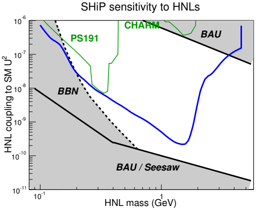
For a given N mass, its lifetime was computed on the basis of the widths of its kinematically allowed decay channels:

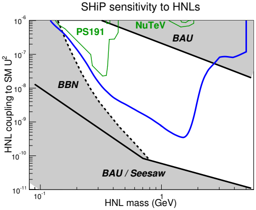
- $N \to H^0\nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
- $N \to H^\pm \ell^\mp$, with $H = \pi, \rho$
- $N \to 3\nu$
- $N \to \ell_i^\pm \ell_j^\mp \nu_j$
- $N \to \nu_i \ell_j^\pm \ell_j^\mp$

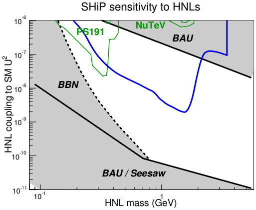
All decay channels into ≥ 2 charged particles were taken to be **visible**.

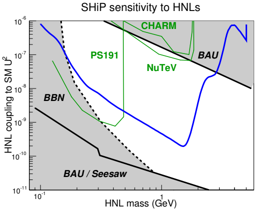
SHiP sensitivity to HNLs

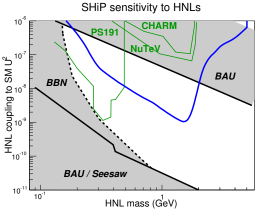
- scenarios I-III: benchmarks with U_e^2, U_μ^2, U_τ^2 dominating (JHEP 0710 ...)
- scenarios IV-V: baryogenesis numerically proven (JCAP 1009(2010)001)











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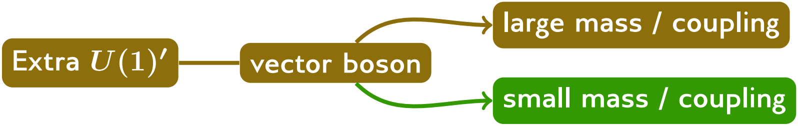
The vector portal

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

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



Extra $U(1)'$

vector boson

large mass / coupling

small mass / coupling

Interesting at SHiP

- kinetically mixing $\mathcal{O}$(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

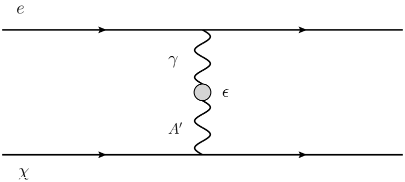
$$\mathcal{L} = \overbrace{\mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'}}^{\text{QED-like}} - \frac{\epsilon}{2} F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2$$

QED fields **$U(1)'$ fields** **mass term**

field strength tensors

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

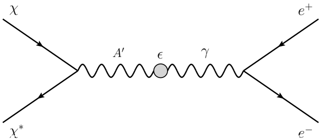
$\Longrightarrow$ coupling to EM current reduced by $\boldsymbol{\epsilon}$.

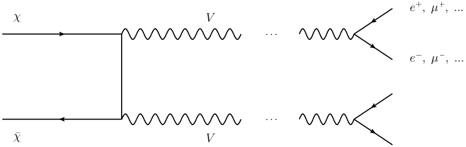


$m_{A'} \to 0 \Longrightarrow$
e.m. charge of $\chi \to e\epsilon$.

Okun, Sov. Phys. JETP 56 (1982) 502 – Holdom, Phys. Lett. B 166 (1986) 196

Motivations for light vector particles





➜ Dark matter ($\Omega_{DM} \sim 0.25$):

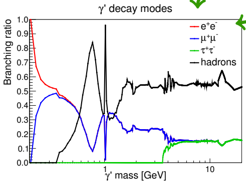
- light scalar dark matter $m_\chi \sim$ MeV can solve the positron excess
- WIMP interacting with SM through light mediator ($\chi\bar{\chi} \to VV \to$ SM) (hides DM from direct searches)
- non thermal DM (sterile neutrinos)
- DM self-interaction in structure formation ($m_V \sim$ MeV–GeV)

➜ 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:** $$\Gamma_{tot} = \Gamma(\ell^+\ell^-) + \Gamma(\text{hadrons}) + \Gamma(\chi\bar{\chi})$$



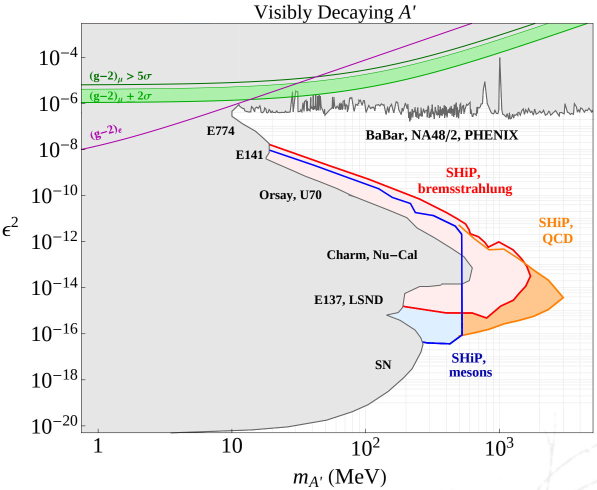
$$\frac{\ell\ell}{\chi\chi} \sim \frac{\alpha\epsilon^2}{\alpha_D},$$ α_D = dark fine structure constant

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

- **Light dark matter at SHiP:**

  if $\chi\bar{\chi}$ decays dominant $\Rightarrow \chi$ can scatter on electrons $\sim \alpha\alpha_D\epsilon^2$: dense detector to look for light DM.

SHiP sensitivity: vector portal



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

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The scalar portal

Most general renormalizable $\mathcal{L}$:

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

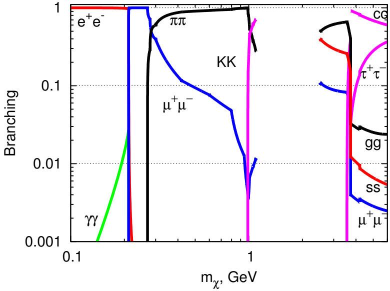
portal couplings to SM H

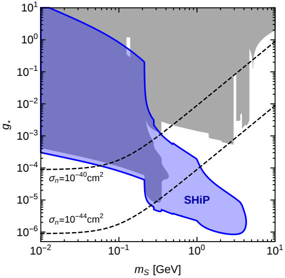
lowest-dim gauge and Lorentz singlet from SM fields

scalar self-couplings

- $\boldsymbol{\alpha_1 \neq 0}$: S mixes with Higgs after EW symmetry breaking
  $\Rightarrow$ coupling between S and all SM particles
- $\boldsymbol{\alpha_1 = 0}$ (forbidden by exact $\mathcal{Z}_2$ symmetry): S does not mix with H
  $\Rightarrow$new particles must be pair-produced

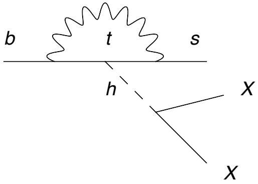
Linear scalar portal

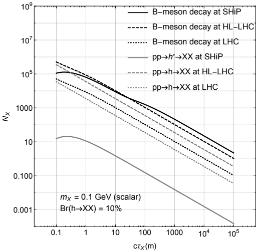




- ➜ Existing limits from searches for rare meson decays e.g. $B \to KS$
- ➜ Production: K decays (SHiP efficiency $\approx 0.2\%$) and B decays
- ➜ Decay: $S \to \gamma\gamma, ee, \mu\mu, \pi\pi, KK$

$\mathcal{Z}_2$ scalar portal

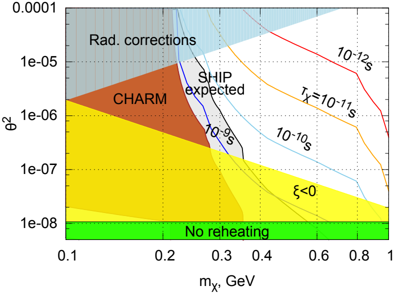




- ➜ Higher dimension portals: $\frac{1}{\Lambda}|H|^2\bar{\psi}\psi$ (dark fermions), $\frac{1}{\Lambda^2}m^2_{Z_D}|H|^2 Z_{D\mu}Z_D{}^{\mu}$ (dark gauge boson)
- ➜ decays of the SM Higgs into hidden states
- ➜ at SHiP $E_{CM} \simeq 28$ GeV $< m_H$
  Production channels at SHiP:
  - heavy meson decays (dominant is $B \to K^{(*)}XX$)
  - gluon fusion $pp \to h^* \to XX$
- ➜ X decays back to SM with different coupling

Inflaton

- ➜ 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. $10^{-11} < \alpha < 10^{-7}$
  - $\alpha < 10^{-11} \longrightarrow$ inefficient reheating
  - $\alpha > 10^{-7} \longrightarrow$ quantum correction would imply large, scale-dependent density perturbations ($\neq$ observations)
- ➜ **Sensitivity at SHiP** is dominated by the lifetime exponential.



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Axion-like particles

strong CP problem

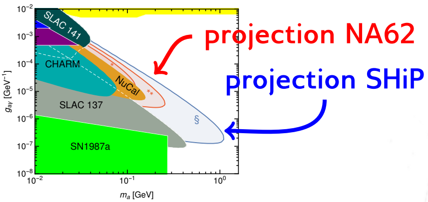
Dark matter

AXION

PNGBs arising from the Peccei-Quinn symmetry

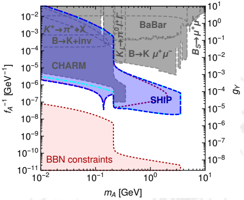
- The axion mass m_A is very constrained due to the axial QCD anomaly breaking the PQ symmetry. Other ALPs are not so constrained.
- SHiP can probe ALPs coupled to gauge bosons and to SM fermions:
  - $pp \to AX,\ A \to \gamma\gamma$: all neutral, more challenging (left plot)
  - $pp \to BX,\ B \to AK,\ A \to \mu^+\mu^-$ (right plot)

JHEP 1602(2016)018



projection NA62

projection SHiP



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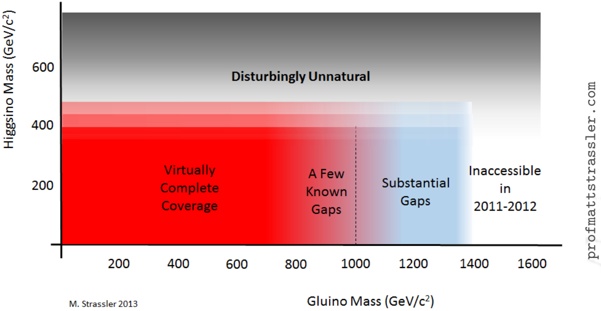
SUSY: where do we stand?

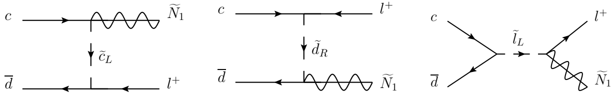
- ➜ SUSY is one of the most popular options to solve naturalness, grand unification and dark matter (WIMP)
- ➜ $\mathbf{W}_{\mathbf{RPC}} = (Y_e)_{ij} L_i H_1 \bar{E}_j + (Y_d)_{ij} Q_i H_1 \bar{D}_j + (Y_u)_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2$

  SUSY particles produced in pairs. Accelerator searches significantly constrain "natural" scenarios (e.g. MSSM, fine tuning at $\sim 1\%$).



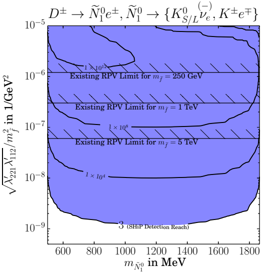
SUSY at SHiP: RPV neutralino

- $\mathbf{W_{RPV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2$
  - The lightest SUSY particle is not anymore stable (no DM)
  - Can be searched for at SHiP in D meson decays:

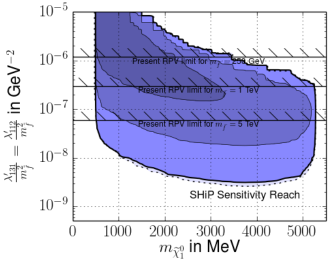


  - SHiP sensitivity studied with channels $\tilde{N}_1^0 \to K^0 \overset{(-)}{\nu}$ and $\tilde{N}_1^0 \to K^\pm \ell^\mp$

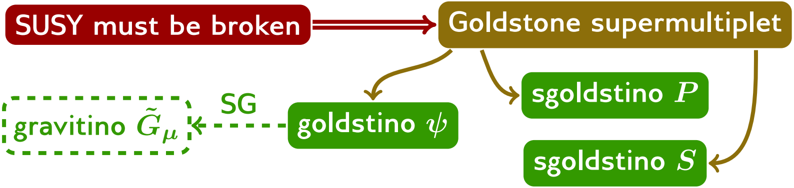
SHiP Physics Proposal



arXiv:1511.07436



SUSY at SHiP: sgoldstino



SUSY must be broken ⟹ **Goldstone supermultiplet**

gravitino $\tilde{G}_\mu$ ← SG – **goldstino ψ**

sgoldstino P

sgoldstino S

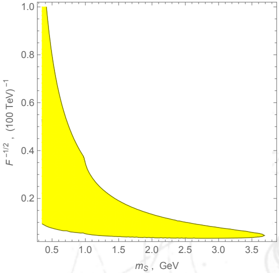
- $\tilde{G}_\mu$ (ψ) is R-odd
- P, S are R-even $\Longrightarrow$ can be singly produced and may decay back to pairs of SM particles
- **at SHiP**:

$$pp \xrightarrow{\text{gluon fusion}} S$$

$$D \to SX$$

$$S \to \ell\ell, \pi\pi$$

SUSY breaking



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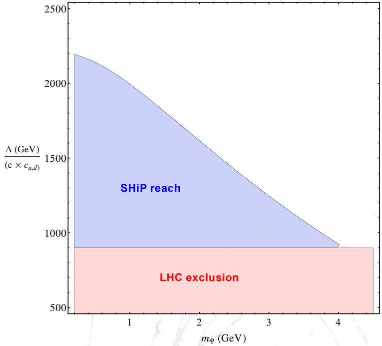
SUSY at SHiP: pseudo-Dirac gauginos

- ➜ Dirac fermion (Ψ) split in two Majorana components (χ_1, χ_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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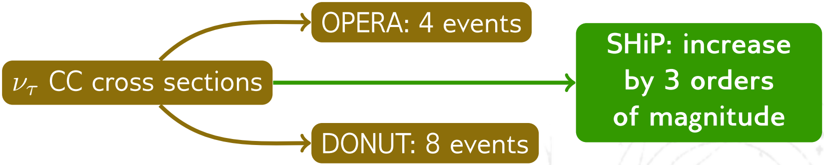
A unique opportunity

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

Neutrino detector (mostly lead) allows to:

- identify flavour
- measure charge of emerging μ and τ
- measure kinematic variables of DIS processes
  - for both NC and CC interactions



ν_τ CC cross sections

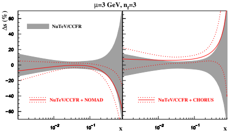
OPERA: 4 events

DONUT: 8 events

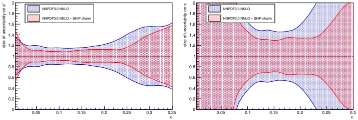
SHiP: increase by 3 orders of magnitude

Tests of perturbative QCD and lepton universality

- ➜ PDF improvements with ν-nucleon DIS: strange sea quark content currently relies on $\mathcal{O}(5000)$ charm di-μ events:

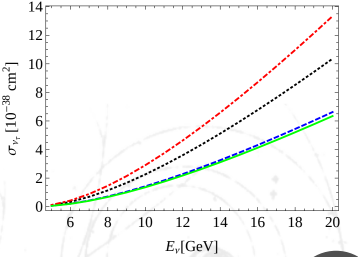


SHiP $> 10^5$ evts



LHC and SHiP will probe different ranges of x.

- ➜ Lepton universality tests:
  - hints from LHCb, B factories, ...
  - DIS σ including BSM: *Liu, Rashed, Datta PRD92(2015)7, 073016*, to compare to σ_{SM}
  - results depend on our knowledge of the ν_τ flux!



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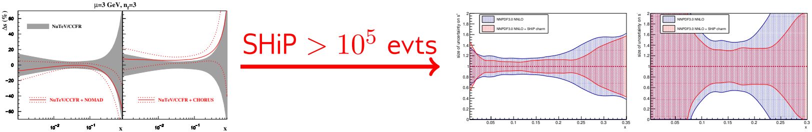

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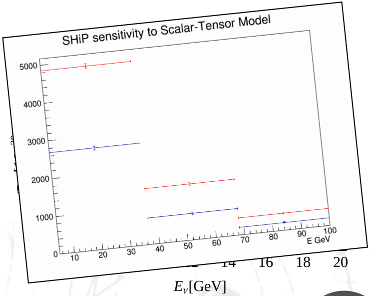
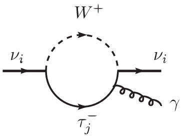
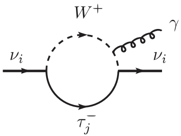
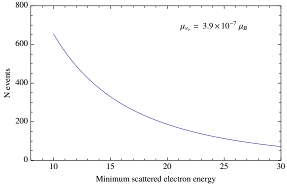


Neutrino magnetic moment







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

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} \simeq \left(3.2\times10^{-19}\right)\frac{m_\nu}{1\text{ eV}}\,\mu_B$$

BSM can enhance μ_ν. (E.g.: *Shrock, Nucl.Phys. B206 (1982) 359*)

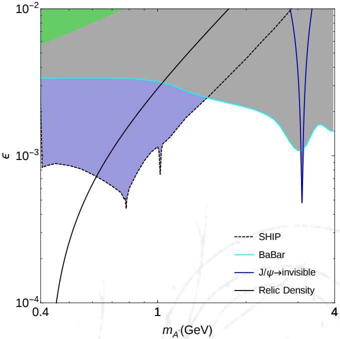
$$e\nu \to e\nu \Longrightarrow \left.\frac{dN}{dE_e}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{E_e}-\frac{1}{E_\nu}\right)$$

Remove BG from νN scattering: $\theta_{\nu e}^2 < 2m_e/E_e \Longrightarrow$ sensitivity: $N_{evt} \sim 4.3\times10^{15}\mu_\nu^2/\mu_B^2$. Prev. limits from 10^{-7} (ν_τ) to 10^{-11} (ν_e).

Dark matter search

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

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



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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:

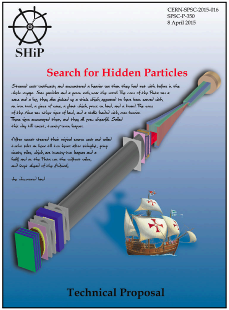
- submission of TP (April, 233 authors)
  → *arXiv:1504.04956*
- submission of PP (April, 85 authors)
  → *arXiv:1504.04855*
- discussion with SPSC referees

2016:

- endorsement by the SPSC (February)

2014–today:

- 7 collaboration meetings



CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

SHiP

Search for Hidden Particles

Technical Proposal

Experimental requirements

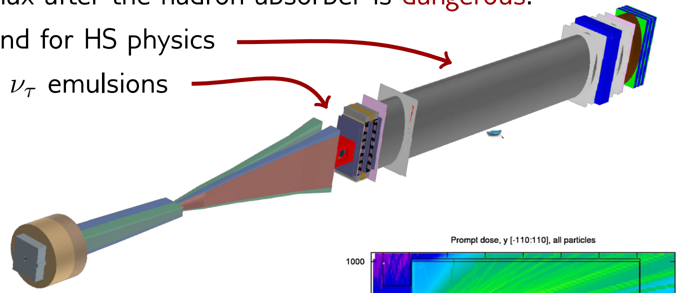
- HNL production in **charm decays**
  - LHC: $\int \mathcal{L} dt \sim 10^3$ fb^{-1}, $\sigma_{c\bar{c}} = 11$ mb
  - SPS 400 GeV + Mo target: $\mathcal{L} \sim 10^{38}$ cm^{-2} s^{-1}, $\sigma_{c\bar{c}} = 18$ µb/nucleon
  - 10× more charm at SPS, forward boost, BG shielding
  - slow beam extraction to minimize occupancy
- decay of hidden particles:

  - large decay volume followed by spectrometer, calorimeter, PID
  - shielding from SM particles: hadron absorber + VETO detectors
- τ neutrinos:
  - $N_{\overset{(-)}{\nu}_\tau} = 4N_p \left(\sigma_{c\bar{c}}/\sigma_{pN}\right) f_{D_s} \times \mathrm{Br}(D_s \to \tau) \simeq 6 \times 10^{15}$
  - distinguish ν_τ / $\bar{\nu}_\tau$: magnetized emulsion target + high-res tracker

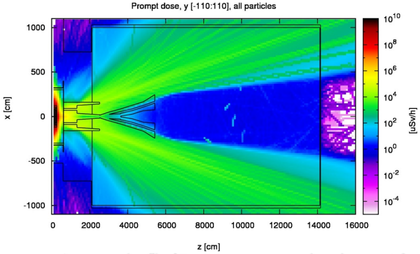
...and the muons?

Residual μ flux after the hadron absorber is dangerous:

- background for HS physics
- ageing of ν_τ emulsions



- active muon shield based on sweeping magnets
- option for a conical vessel



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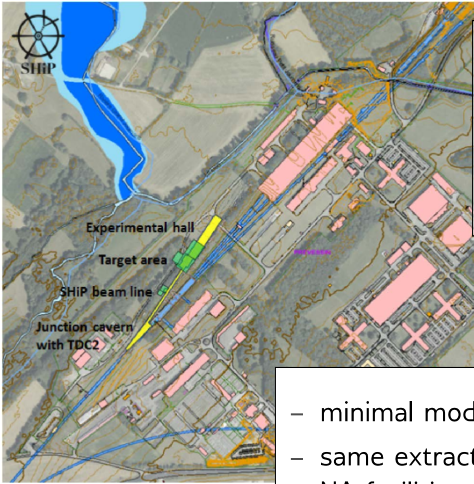
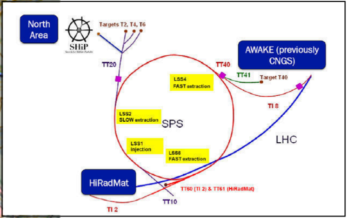
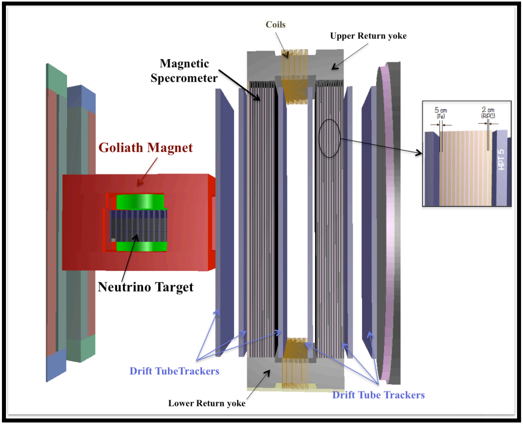
The facility at the SPS





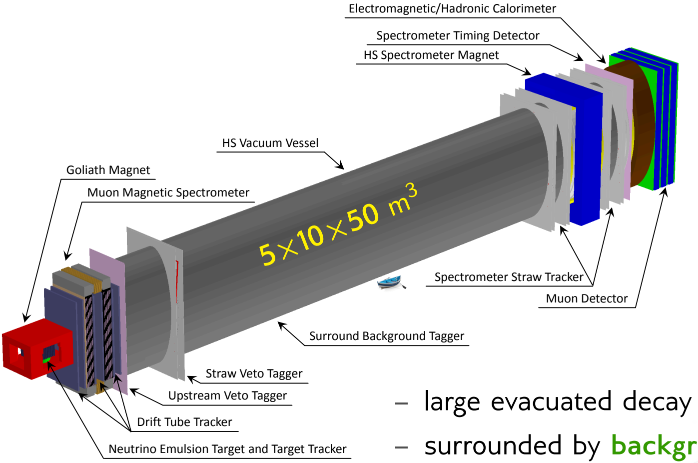
- minimal modification to the SPS complex
- same extraction and transfer line as other NA facilities
- 190 m long, 20 m wide hall

The ν_τ detector



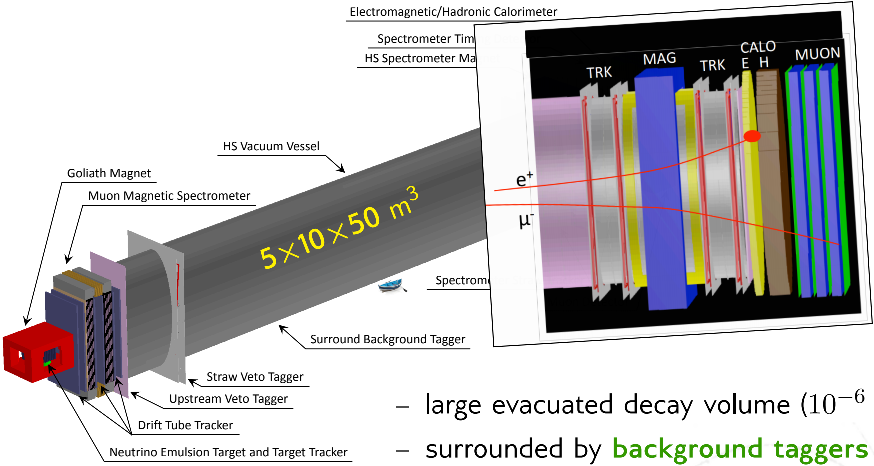
Target made of interlaced layers of emulsion bricks and scintillating fibres, resolution of 1 µm $\Longrightarrow$ charge of τ daughters.
Muon tracker: RPCs and drift tubes. Also tags BG for HS physics.

The Hidden Sector detector



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

The Hidden Sector detector



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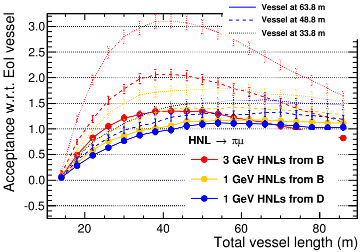
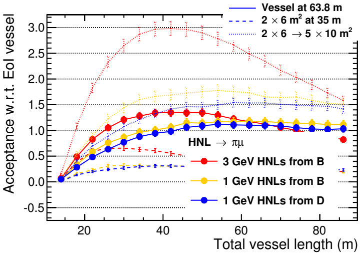
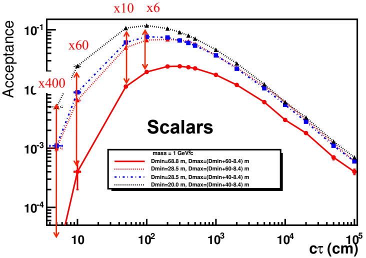
Optimization of the decay volume







- ➜ 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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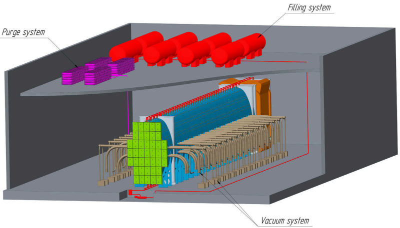
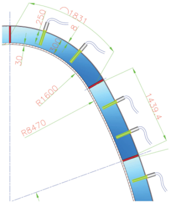
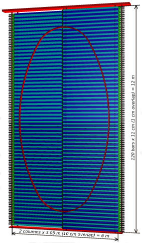
Shields and background taggers

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

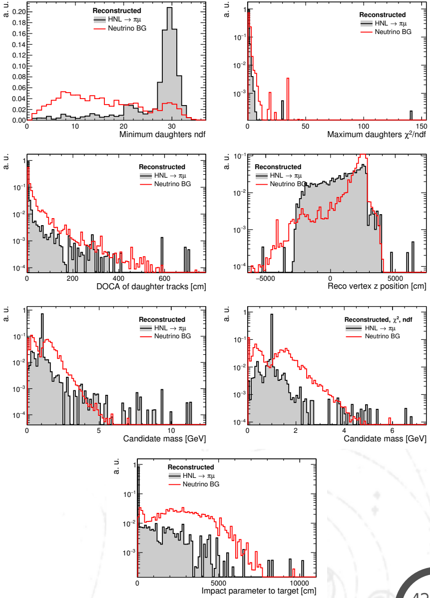






Background sources

- ➜ **cosmic μ** can scatter on the cavern/vessel walls
- ➜ **combinatorial combinations** of tracks from different events/vertices
- ➜ **μ DIS** on the cavern walls can produce charged tracks
- ➜ **ν 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
$HNL \to \pi\mu$	97.5 %	76.1 %	87.0 %	94.2 %
$\gamma' \to \mu\mu$	99.6 %	85.2 %	94.4 %	94.0 %
ν **background**	79.1 %	21.0 %	6.5 %	0.0 %

Overall $\lesssim 0.1$ background events / 5 years is attainable!

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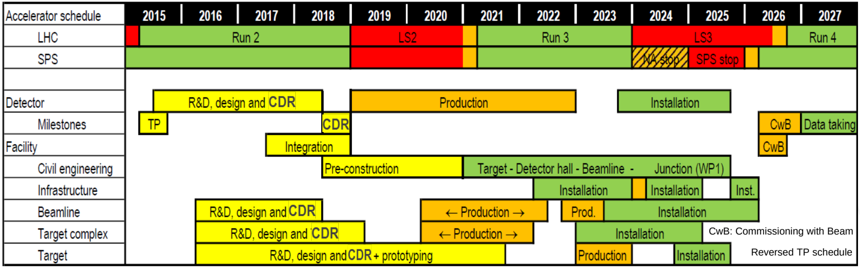
What's next

- ➜ **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



CwB: Commissioning with Beam

Reversed TP schedule

Conclusions

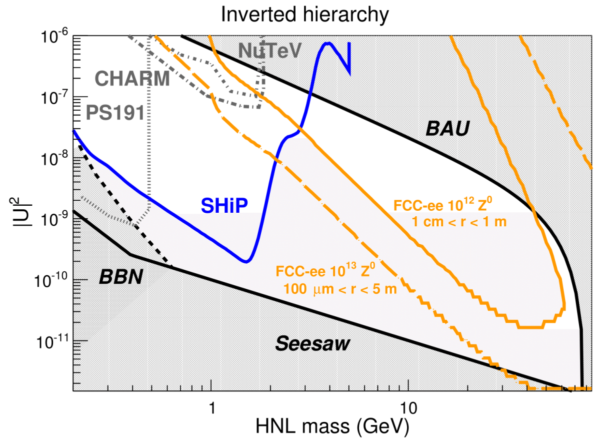
- **General purpose** experiment to look for weakly interacting long lived particles
  - covers previously unexplored regions of the Hidden Sector in several theories
  - covers cosmologically interesting regions
- **Unique** opportunity for **ν_τ physics** allowing for
  - $\bar{\nu}_\tau$ discovery
  - σ and form factors measurements
  - also dark matter search
- **Complements** LEP/LHC and boosts past experiments sensitivities
  - $\times 10^5$ for HS, $\times 200$ for ν_τ
  - makes best use of existing SPS complex
- **Next phase:** comprehensive design report 2018

SHiP

Questions?

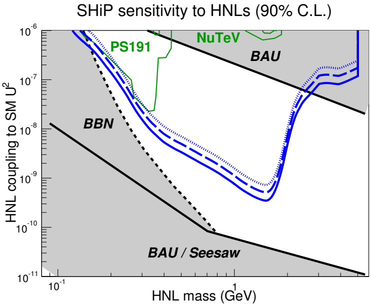
– spare slides –

HNLs at future colliders



http://arxiv.org/abs/1411.5230
http://arxiv.org/abs/1503.08624

Sensitivity with non-zero background



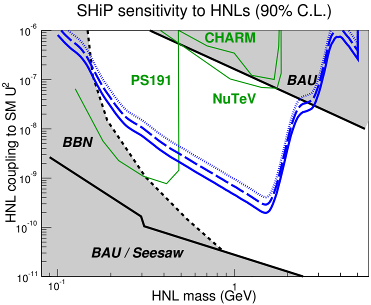
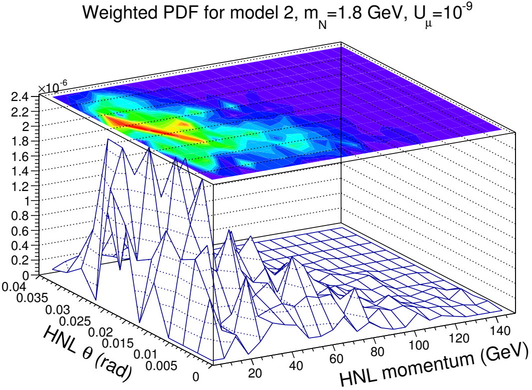


Figure: Variation of the sensitivity contours for scenarios II (left) and IV (right) as a function of the background estimates. The solid blue curve represents the 90% C.L. upper limit assuming 0.1 background events in 2×10^{20} proton-target collisions. The dashed blue curve assumes 10 background events.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

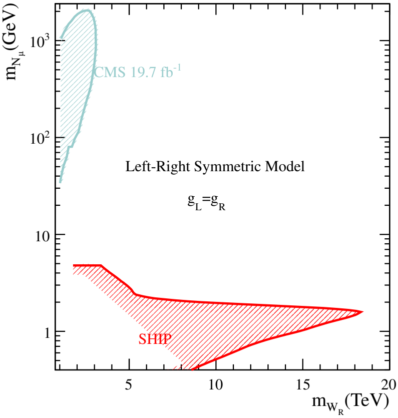
Estimating SHiP's physics reach

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

- HNL's momentum and angle are stored in a binned PDF
- HNL spectra are re-weighted by the probability $\mathcal{P}_{vtx}(p, \theta \,|\, m_N, U_f^2) \sim \int_V e^{-l/\gamma c\tau} dl$
- 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 GeV, U_μ=10^{-9}

Sensitivity in the Left-Right symmetric model



- SHiP limits on m_{W_R} can be extracted from the HNL limits by $|U_{\mu I}|^2 \to (m_{W_L}/m_{W_R})^4$
- 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*

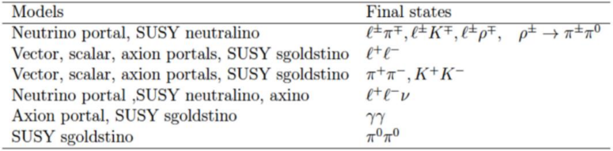
LFV processes

- ➜ **ν oscillations** provide evidence of LFV in the neutral sector
- ➜ **LFV** in charged sector foreseen with $\mathcal{BR} \sim \mathcal{O}(10^{-40})$!
- ➜ **New physics** models can enhance these $\mathcal{BR}$s
  - in seesaw models charged LFV can happen in tree or loop diagrams
  - $\ell \to 3\ell'$ generally favoured with respect to $\ell \to \ell'\gamma$ (type 2 and 3 seesaw)
- ➜ $\boldsymbol{\ell \to 3\ell'}$ related by unitarity to $Z^0, h, V \to \ell^+\ell'^-$ and $\ell \to \ell'$ conversion in nuclei (most stringent limits so far by SINDRUM II)
  - $\tau \to 3\mu$ and $\mu \to 3e$ can provide better limits than direct searches e.g. for $\phi \to e\mu$, $J/\Psi \to e\mu$
  - $\mathcal{BR}(\tau \to 3\mu) < 1.2 \times 10^{-8}$ (BaBar,Belle,LHCb) *HFAG, arXiv:1412.7515*
- ➜ **SHiP** will collect 3×10^{15} τ in the forward region
  - requires changes to conceptual design (upgrade):
  - 1 mm W target: 100× less τ, but decaying outside target
  - LHCb VELO + Si tracker + hadron absorber + μ spectrometer
  - sensitivity $\sim 10^{-10}/\sqrt{N_{\text{targets}}}$

The Hidden Sector

$$L_{world} = L_{SM} + L_{mediation} + L_{HS}$$

- **Neutrino portal**: new Heavy Neutral Leptons coupling with Yukawa coupling, $L_{NP} = F_{\alpha I}\left(\bar{L}_{\alpha}\tilde{\Phi}\right)N_I$
- **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 $L_{SP} = \left(\lambda_i S_i^2 + g_i S_i\right)\bar{\Phi}\Phi$
- **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…

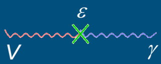


Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, 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:

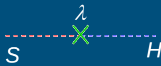
- **D = 2: Vector portal**



  - Kinetic mixing with massive dark/secluded/paraphoton *V* : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu}F^{\mu\nu}_{HS}$

  ➔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 $q\bar{q} \to V, qg \to Vq$, meson decays ($\pi^0, \eta,\ \omega,\ \eta', \ldots$)

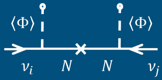
- **D = 2: Scalar portal**



  - Mass mixing with dark singlet scalar χ : $(gS +\ \lambda S^2)H^\dagger H$

  ➔ Mass to Higgs boson and right-handed neutrino, inflaton, dark phase transitions BAU, dark matter, "dark naturalness",..
  - Production: Direct $p + target \to X + S,$ meson decays e.g. $B \to KS,\ K \to \pi S$

- **D = 5/2: Neutrino portal**



  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell}H^\dagger \bar{N}_I L_\ell$

  ➔ 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* : $\frac{a}{F}G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

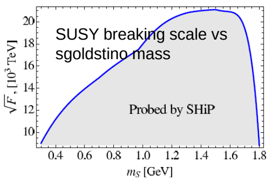
  ➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

  ➔ 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)

New Physics prospects in Hidden Sector

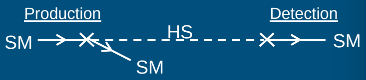
- **SUper-SYmmetric “portals”**
  - Some of SUSY low-energy parameter space open to complementary searches
  - Sgoldstino S(P) : $\frac{M_{\gamma\gamma}}{F} S F^{\mu\nu} F_{\mu\nu}$
  - Neutralino in R-Parity Violating SUSY
  - Hidden Photinos, axinos and saxions….



➔ 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


Production

Detection

SM

HS

SM

SM

➔ *SHiP has significant sensitivity to all of these!*

Assumption invisible decay width $\chi\bar{\chi}$ is absent or sub-dominant, $m_\chi > \frac{1}{2} m_{portal}$, where χ hidden sector particle

Sterile Neutrinos

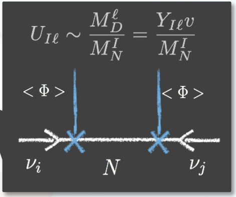
Fermions get mass via the Yukawa couplings:

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi} U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.}$$

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

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$

Kinetic term | Majorana mass term | Yukawa coupling



Seesaw mechanism:

$$\mathcal{V} = (\nu_{Li}, N_j)$$

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

$$-\mathcal{L}_{M_\nu} = \frac{1}{2}\overline{\mathcal{V}}M_\nu\mathcal{V} + h.c.$$

$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

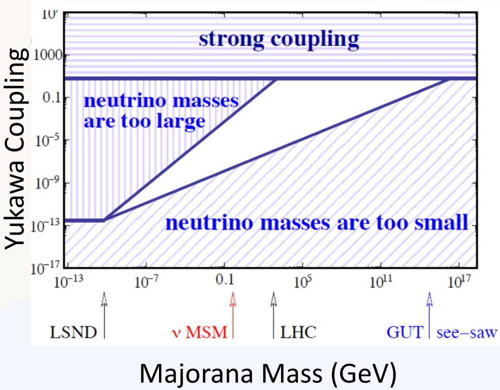
if $M_N \gg M_D$:

$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

Sterile neutrino masses

Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ 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 $Y_\nu \sim 10^{-7}$

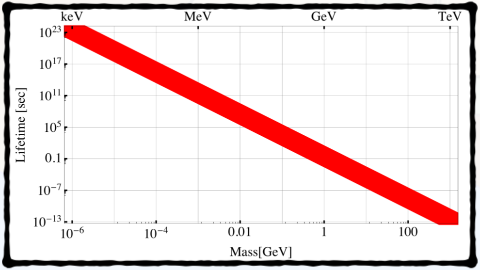
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

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

Constraints on N_1

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

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

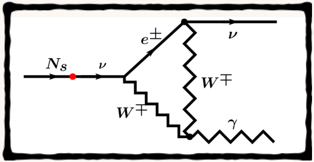


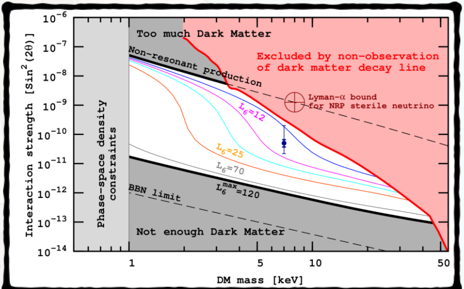
This gives an upper bound for the mass of the mass of the sterile neutrino Dark Matter

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

Constraints on N_1

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





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

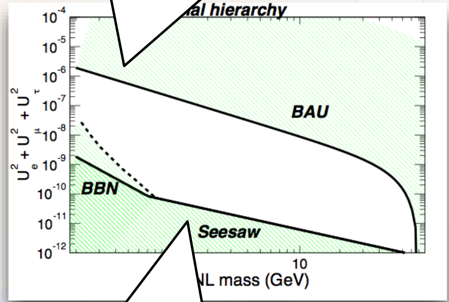
Bulbul et al. 2014 (arXiv:1402.2301)

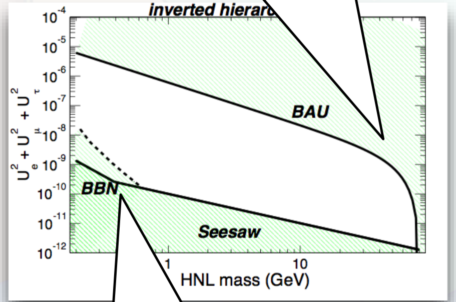
Boyarsky et al. 2014 (arXiv:1402.4119)

Constraints on N_2, N_3

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

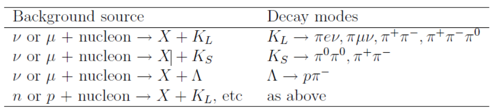




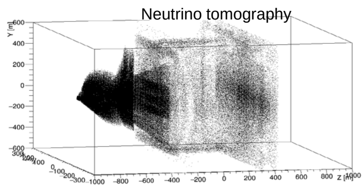
The **seesaw** limit defines the region where $N_{2,3}$ can explain the observed active neutrino Δm^2

If $\tau(N_2, N_3) < 0.1\ s$, they cannot affect the **Big Bang nucleosynthesis**

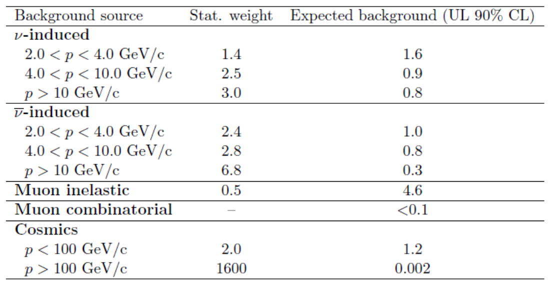
Backgrounds with TP detector



Background source	Decay modes
ν or μ + nucleon $\to X + K_L$	$K_L \to \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\to X + K_S$	$K_S \to \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\to X + \Lambda$	$\Lambda \to p\pi^-$
n or p + nucleon $\to X + K_L$, etc	as above

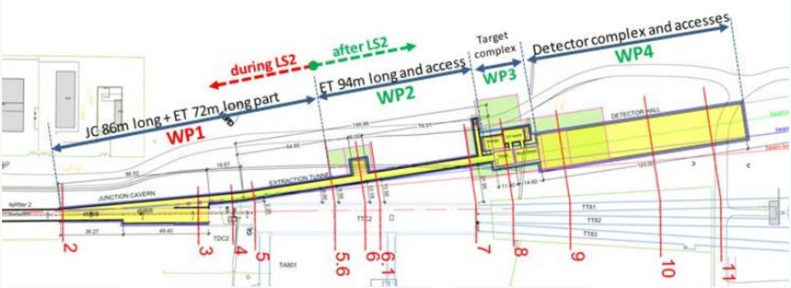


- **Background summary: no evidence for any irreducible background**
  - No events selected in MC ➔ Expected background UL @ 90% CL



Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.4	1.6
$4.0 < p < 10.0$ GeV/c	2.5	0.9
$p > 10$ GeV/c	3.0	0.8
$\overline{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	2.4	1.0
$4.0 < p < 10.0$ GeV/c	2.8	0.8
$p > 10$ GeV/c	6.8	0.3
Muon inelastic	0.5	4.6
Muon combinatorial	–	<0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

NA work packages



- 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

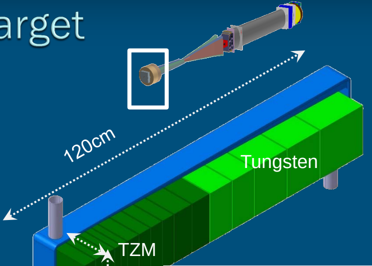
SHiP target

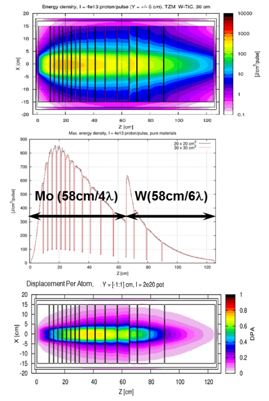
Design considerations with $4x10^{13}$ p / 7s

➔ 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…)

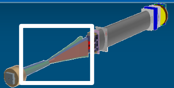
➔ Hybrid solution: Mo allow TZM (4λ) + W(6λ)





	DONUT ¹⁾	CHARM ²⁾	SHiP
Target material	W-alloy	Cu (variable ρ)	TZM + pure W
Momentum (GeV/c)	800	400	400
Intensity	$0.8*10^{13}$	$1.3*10^{13}$	**$4*10^{13}$**
Pulse length (s)	20	$23*10^{-6}$	1
Rep. rate (s)	60	~10	7.2
Beam energy (kJ)	1020	830	2560
Avg. beam power (spill) (kW)	51	$3.4*10^{7}$ (fast)	2560
Avg. beam power (SC) (kW)	17	69	355
POT	Few 10^{17}	Few 10^{18}	**$2*10^{20}$**

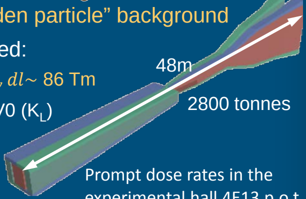
Active muon shield

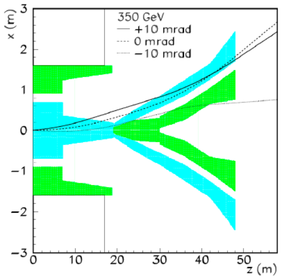


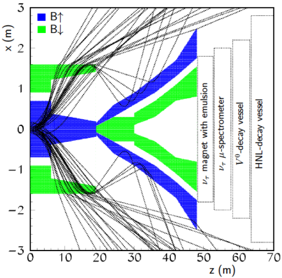
- Muon flux limit driven by emulsion based ν-detector and "hidden particle" background
- Passive and magnet sweeper/passive absorber options studied:
  - Conclusion: Shield based entirely on magnetic sweeping with $\int B_y\, dl \sim$ 86 Tm

➔ <7x10^3 muons / spill (E_μ > 3 GeV) which can potentially produce V0 (K_L)

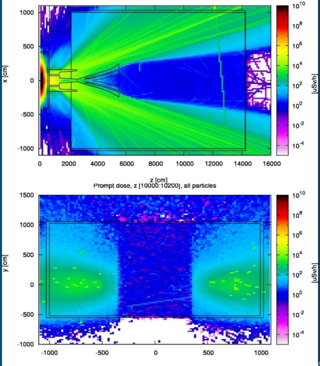
➔ Negligible occupancy





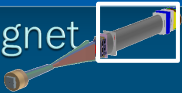


Prompt dose rates in the experimental hall 4E13 p.o.t. / 7s

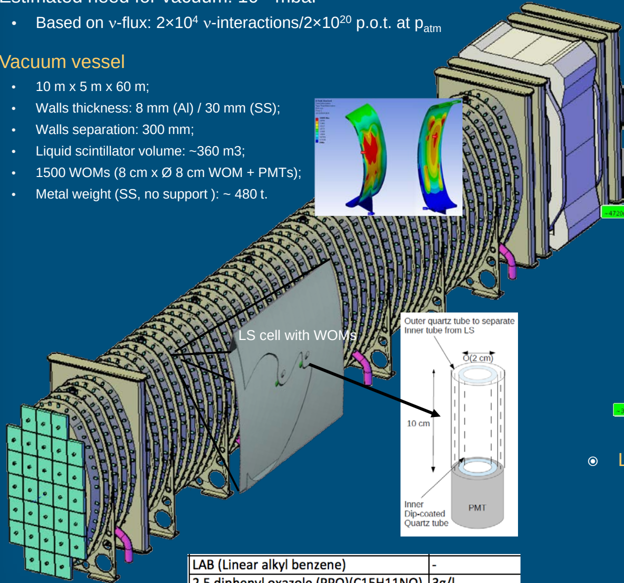


➔ Challenges: flux leakage, constant field profile, modelling magnet shape

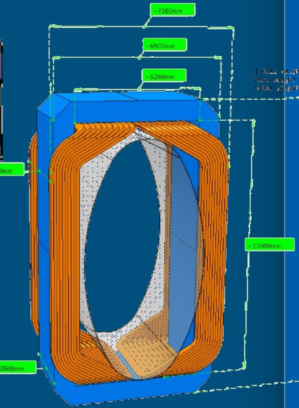
TP: Vessel and spectrometer magnet



- Estimated need for vacuum: 10^{-3} mbar
  - Based on ν-flux: 2×10^{4} ν-interactions/2×10^{20} p.o.t. at p_{atm}
- Vacuum vessel
  - 10 m x 5 m x 60 m;
  - Walls thickness: 8 mm (Al) / 30 mm (SS);
  - Walls separation: 300 mm;
  - Liquid scintillator volume: ~360 m3;
  - 1500 WOMs (8 cm x Ø 8 cm WOM + PMTs);
  - Metal weight (SS, no support): ~ 480 t.

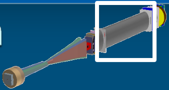


LAB (Linear alkyl benzene)	-
2.5 diphenyl oxazole (PPO)(C15H11NO)	3g/l

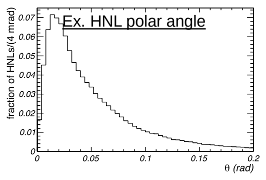


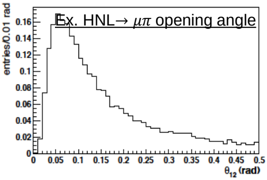
- Low power magnet designed
  - Field integral: 0.65Tm over 5m
  - Current 2500 A (1.7 A/mm2
  - Power consumption < 1 MW
  - Weight ~800 tonnes

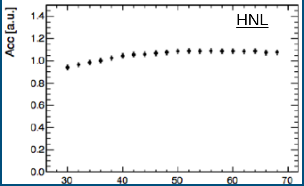
HS detector optimization

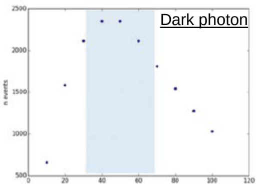


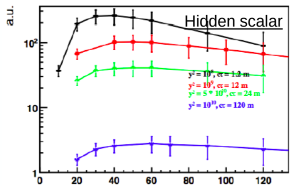
- Optimization of geometrical acceptance for a given E_{beam} and Φ_{beam}
  - Hidden particle lifetime (~flat for longlived)
  - Hidden particle production angles (~distance and transversal size)
  - Hidden particle decay opening angle (~length and transversal size)
  - Muon flux (~distance and acceptable occupancy)
  - Background (~detector time and spatial resolution)
  - Evacuation in decay volume / technically feasible size ~ W:5m x H:10m





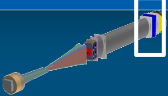




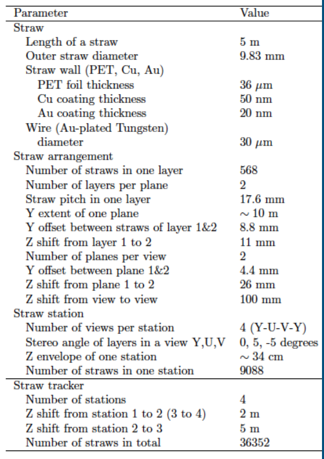


➔ Acceptance saturates ~40m – 50m

HS tracking system

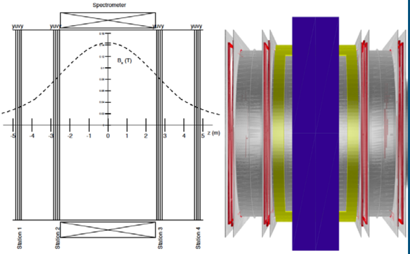


- NA62-like straw detector

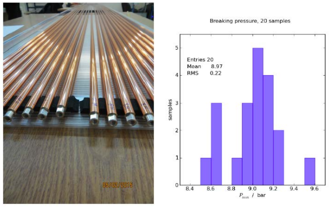


Parameter	Value
Straw	
Length of a straw	5 m
Outer straw diameter	9.83 mm
Straw wall (PET, Cu, Au)	
PET foil thickness	36 μm
Cu coating thickness	50 nm
Au coating thickness	20 nm
Wire (Au-plated Tungsten)	
diameter	30 μm
Straw arrangement	
Number of straws in one layer	568
Number of layers per plane	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
Straw station	
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
Straw tracker	
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

Horizontal orientation of 5m straws



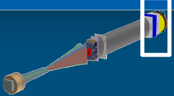
First production of 5m straws at JINR

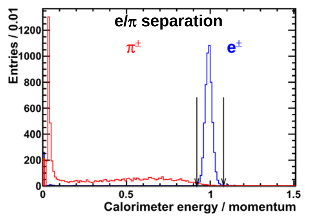


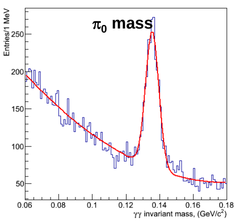
- Straws in test beam 2016
    - Study sagging effects and compensation
    - Read out of signal, attenuation / two-sided readout
- Upstream straw veto may be based on same technology

JINR Dubna (NA62, SHiP): Straws
St Petersburg (CMS, SHiP): Infra

PID performance





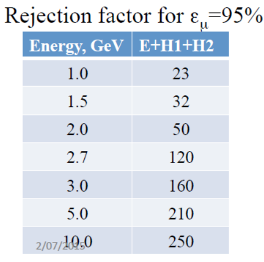


Electron efficiency >98%

Pion contamination:<2%

Neutral pion mass resolution: 5 MeV

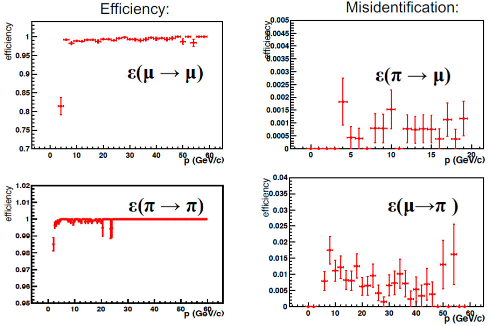
Muon misid with ECAL+HCAL



Rejection factor for ε_{μ}=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

2/07/2015



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