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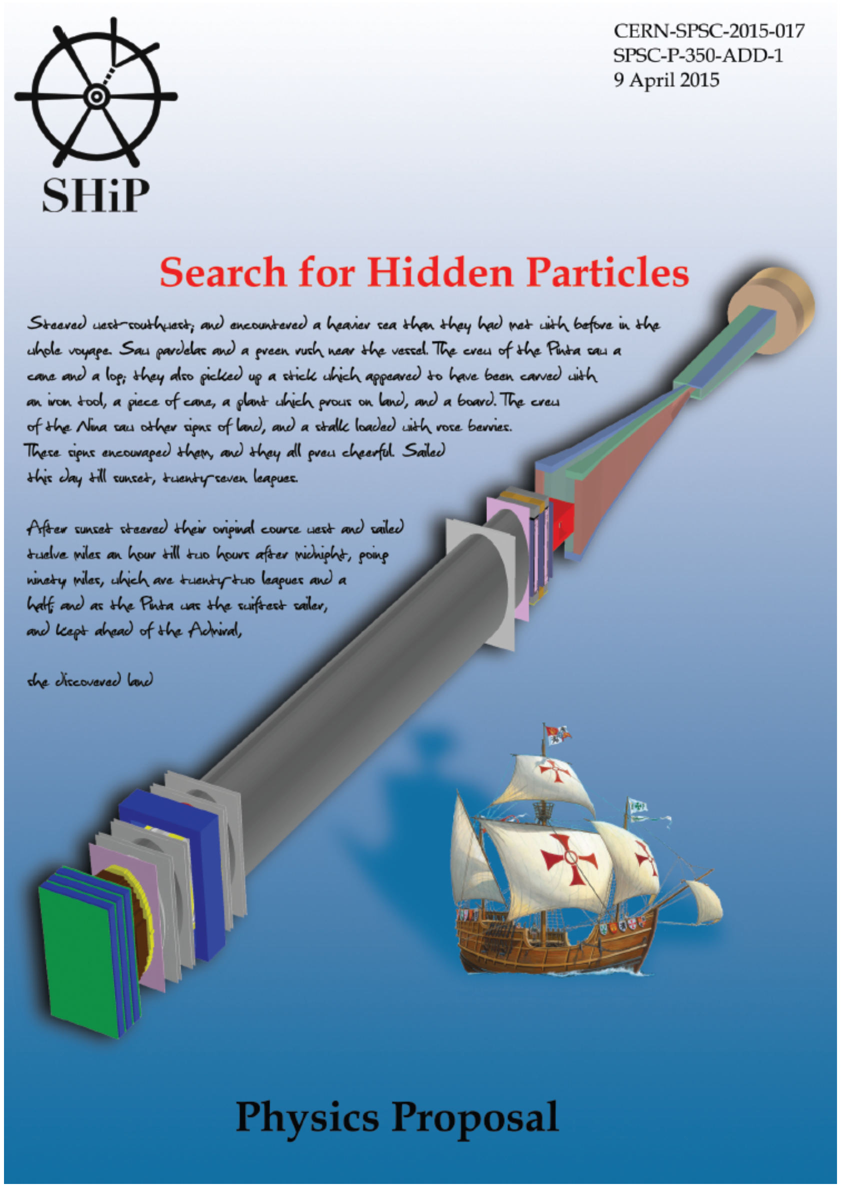

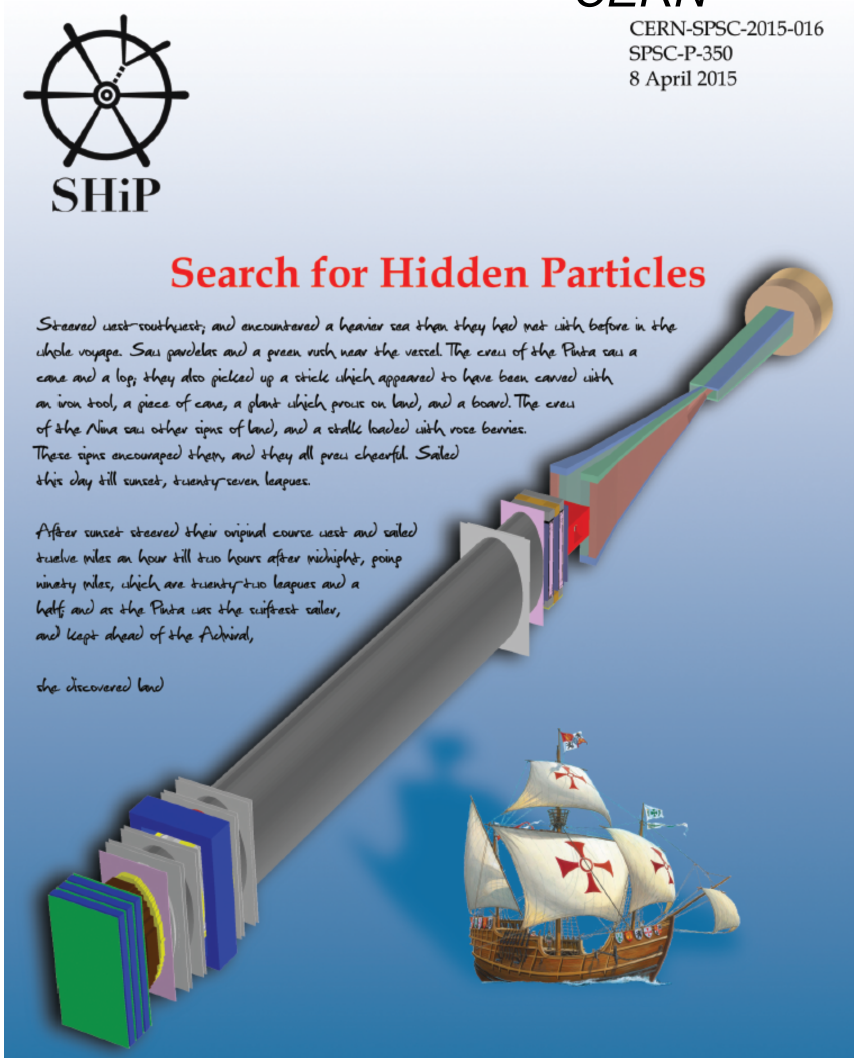

SHiP Technical Proposal: arXiv 1504.04956
SHiP Physics Paper: arXiv 1504.04855

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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85 theorists, 65 Institutes, submitted to Reviews on Progress in Physics (RPOP)

Abs… …s paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (S…ch for *Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

*Editor of the paper
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SHiP

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

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250 physicists, 46 Institutes, 15 countries

Standard Model is great but it is not a complete theory

Experimental facts of BSM physics

- Neutrino masses & oscillations
- The nature of non-baryonic Dark Matter
- Excess of matter over antimatter in the Universe
- Inflation of the Universe

Theoretical shortcomings

Gap between Fermi and Planck scales, Dark Energy, connection to gravity, resolution of the strong CP problem, the naturalness of the Higgs mass, the pattern of masses and mixings in the quark and lepton sectors, …

No clear guidance at the scale of New Physics and on its coupling strength to the SM particles !

Scale of NP: See-saw generation of neutrino masses

Most elegant way to incorporate non-zero neutrino mass to the SM Lagrangian is given by the see-saw formula:

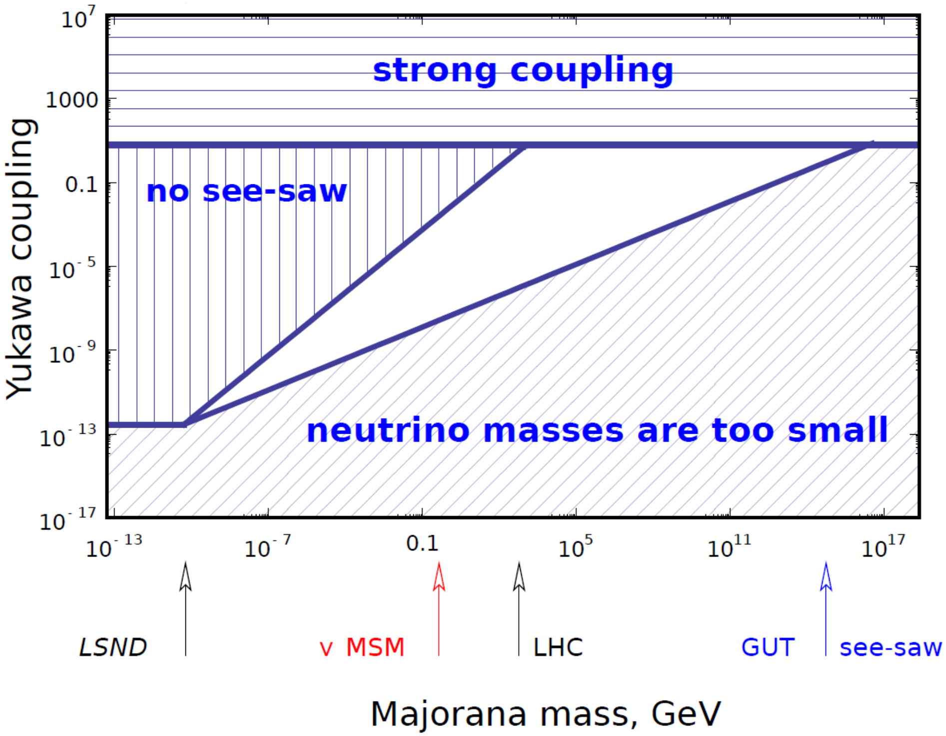
$$m_\nu = \frac{m_D^2}{M}$$

where $m_D \sim Y_{I\alpha} < \phi >$ *- typical value of the Dirac mass term*

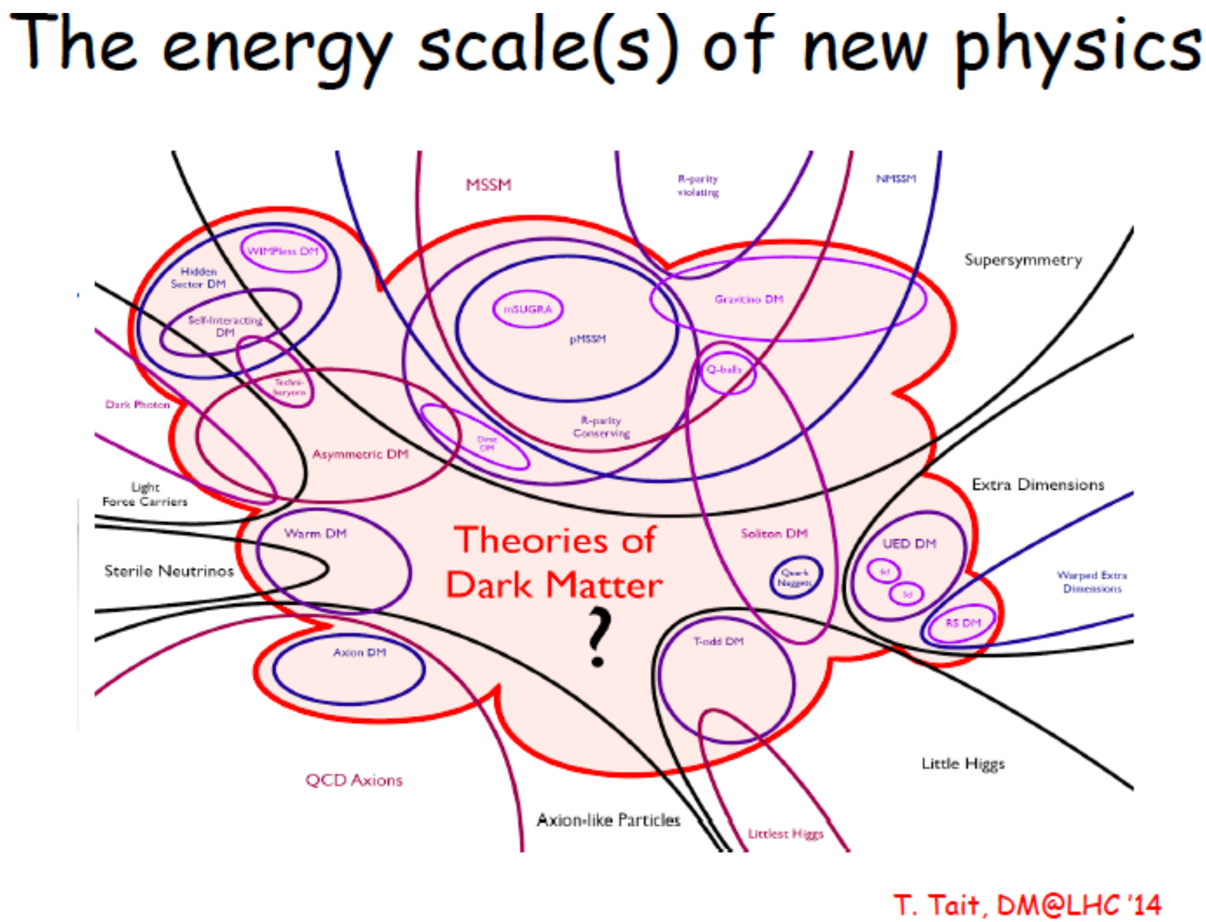
Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}

Smallness of the neutrino mass hints either on very large M or very small $Y_{I\alpha}$

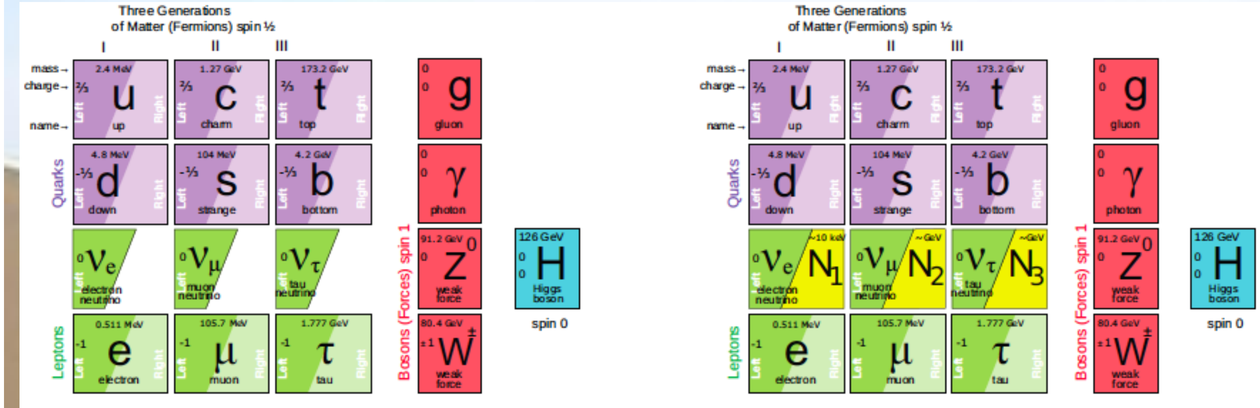


Scale of NP: Dark Matter



The prediction for the mass scale of Dark Matter spans from 10^{-22} eV (ALPs) to 10^{20} GeV (Wimpzillas, Q-balls)

BSM theories with no NP between Fermi and Planck scales

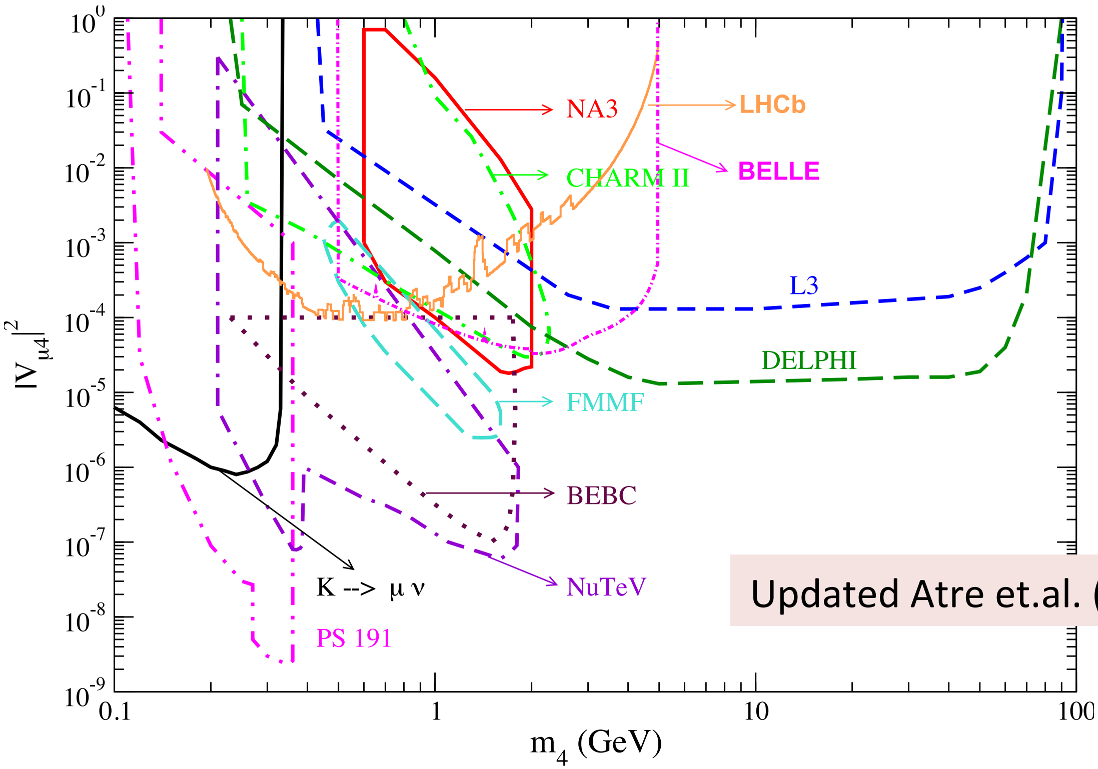


N_1 → Dark Matter

$N_{2,3}$ → Neutrino masses and BAU

νMSM (T.Asaka, M.Shaposhnikov PL B620 (2005) 17) explains all experimental evidences of the BSM physics at once by adding 3 Heavy Neutral Leptons (HNL): N_1, N_2 and N_3

Experimental and cosmological constraints on HNLs

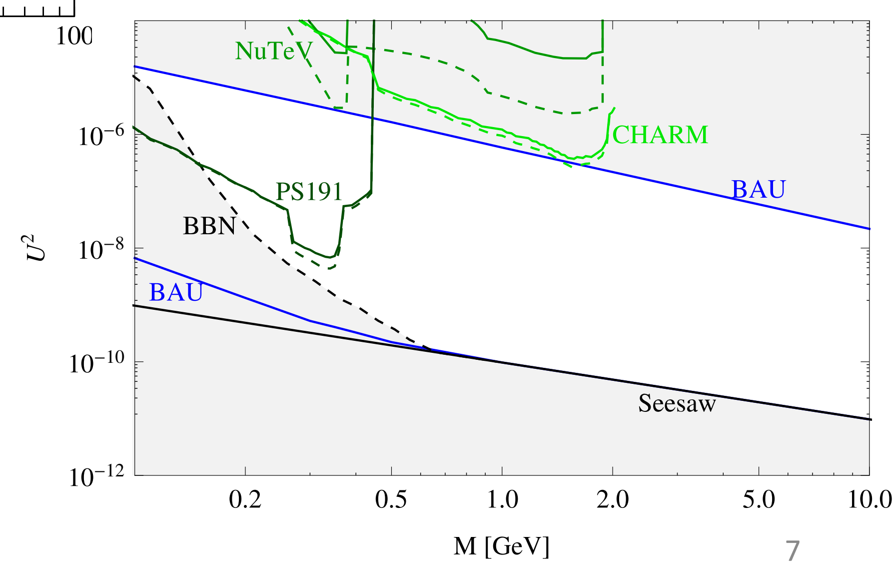


Updated Atre et.al. (0901.3589)

- ✓ *Coupling to active neutrinos* $U^2 = U_e^2+U_\mu^2+U_\tau^2$ $(V_{\mu 4}^2 = U_\mu^2)$
- ✓ *Stringent constraints on light HNLs below kaon mass*
- ✓ *The mass range above charm is relatively poor explored*

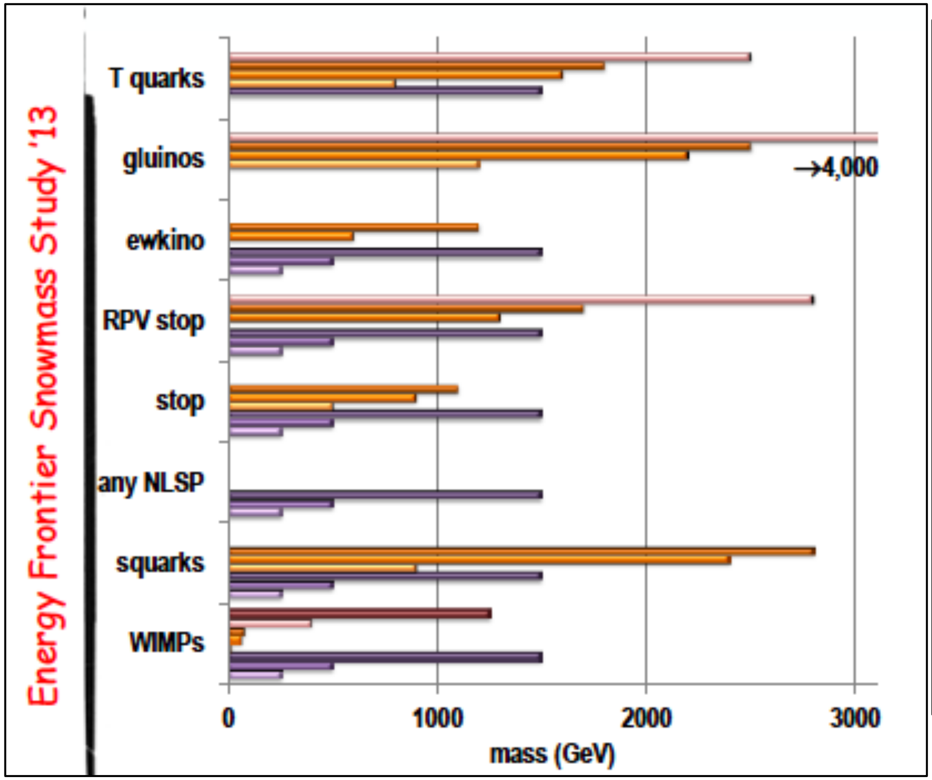
- ✓ ***Recent progress in cosmology***

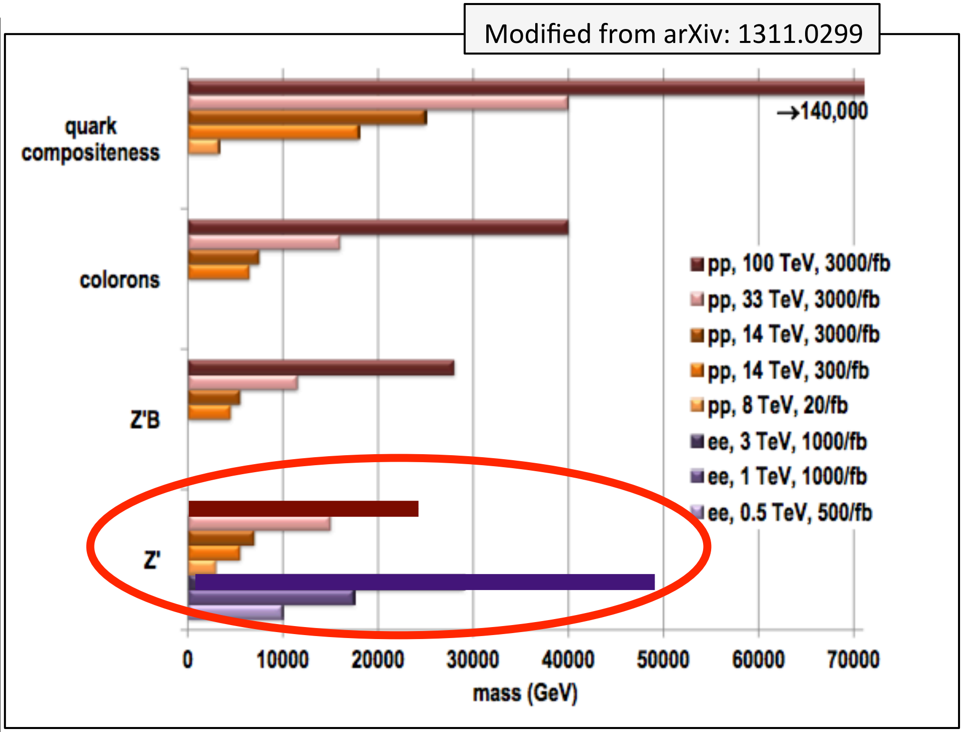
- ✓ *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*



Reach at the Energy Frontier

No sign of New Physics yet





Wait for new LHC data at $\sqrt{s}$ = 13 TeV

Search for Hidden Sector (HS)

or very weakly interacting NP

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter
(may have very complicated structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*
- *Production branching ratios $O(10^{-10})$*
- *Long-lived objects*
- *Travel unperturbed through ordinary matter*

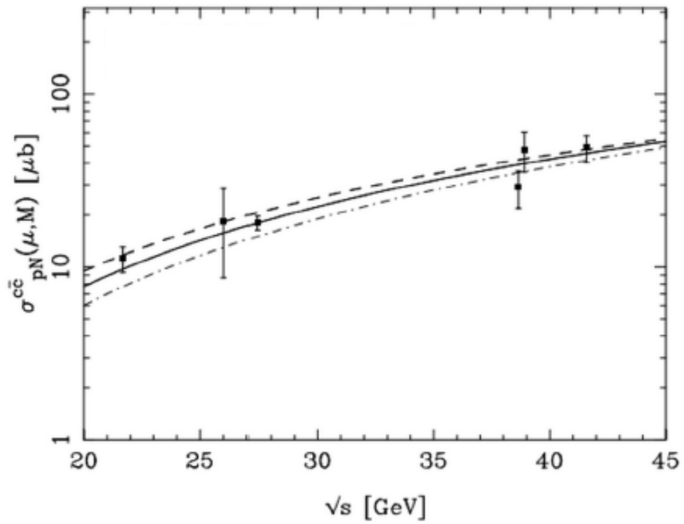
Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\to\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

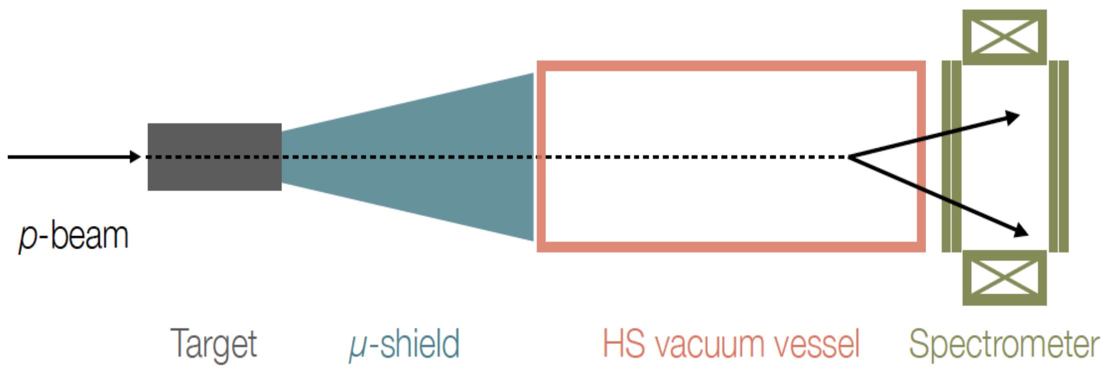
Experimental challenge is background suppression
→ requires O(0.01) carefully estimated

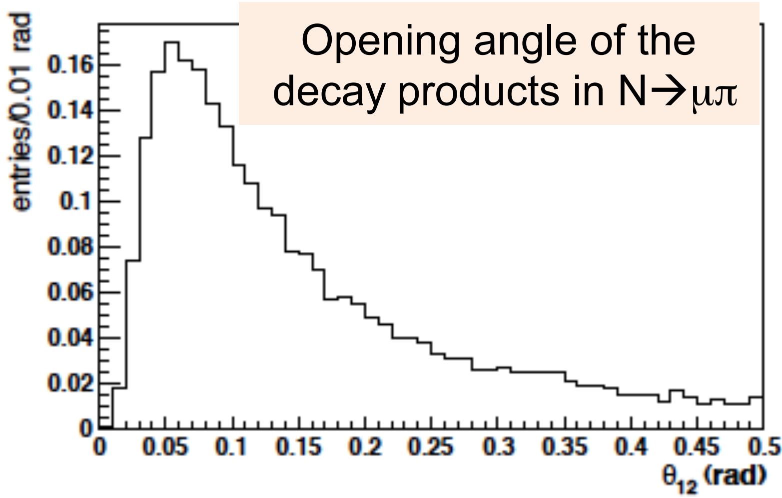
General experimental requirements

✓ Search for HS particles in Heavy Flavour decays
Charm (and beauty) cross-sections strongly depend on the beam energy



✓ HS produced in charm and beauty decays have significant P_T



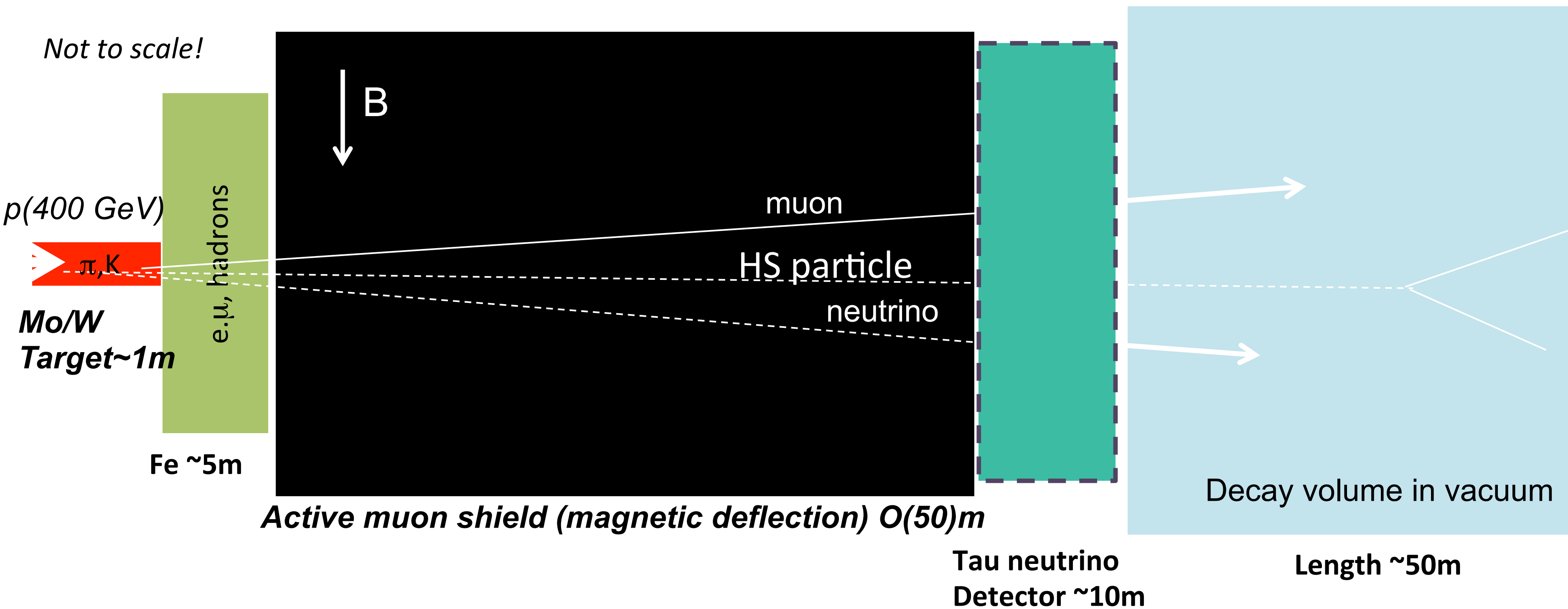


Detector must be placed close to the target to maximize geometrical acceptance
Effective (and "short") muon shield is essential to reduce muon-induced backgrounds

SHiP beam-line
(incompatible with conventional neutrino facility)

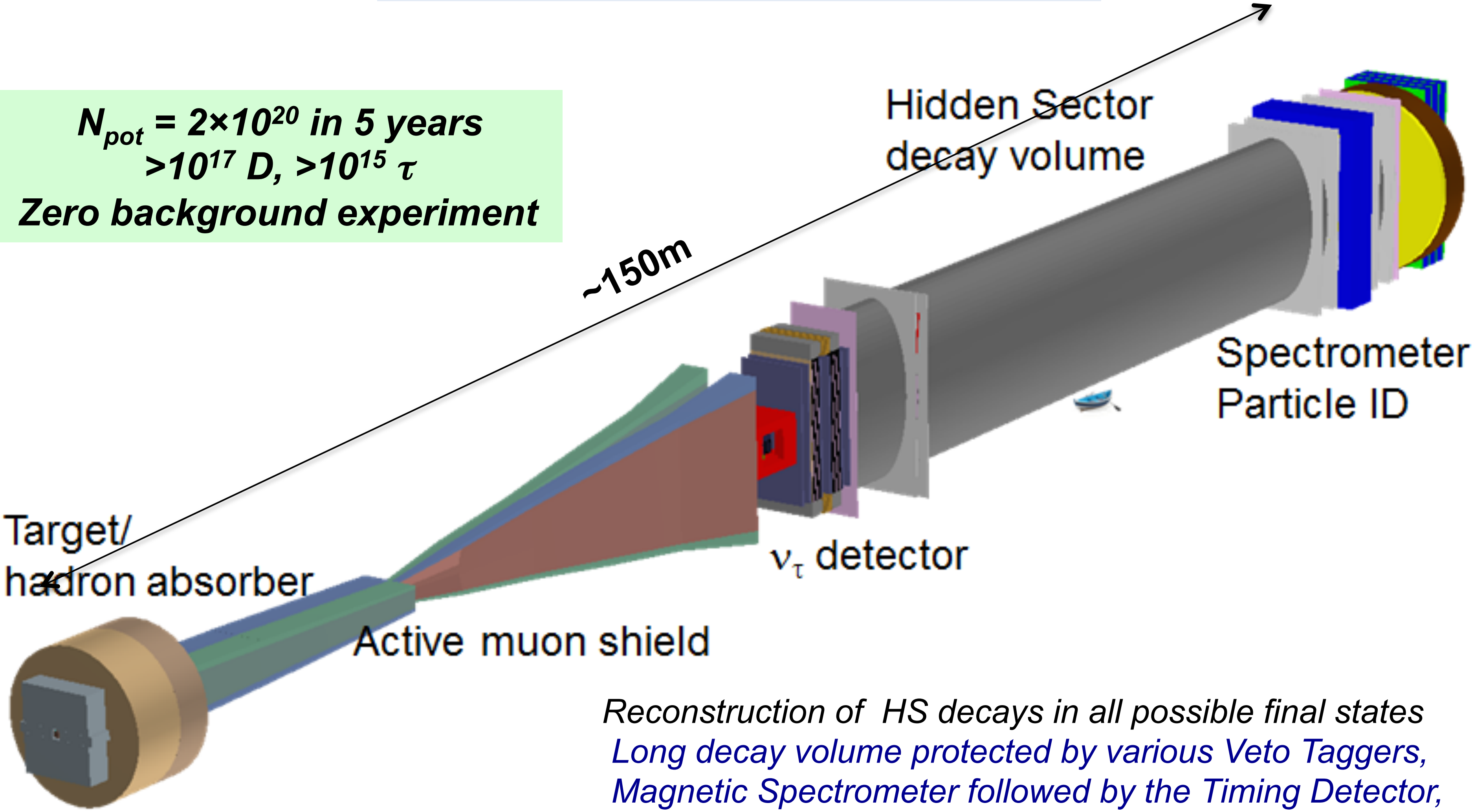
Initial reduction of beam induced backgrounds

- *Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in $\pi/K \rightarrow \mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{10} per spill of 5×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*



The SHiP experiment at SPS
(as implemented in Geant4)

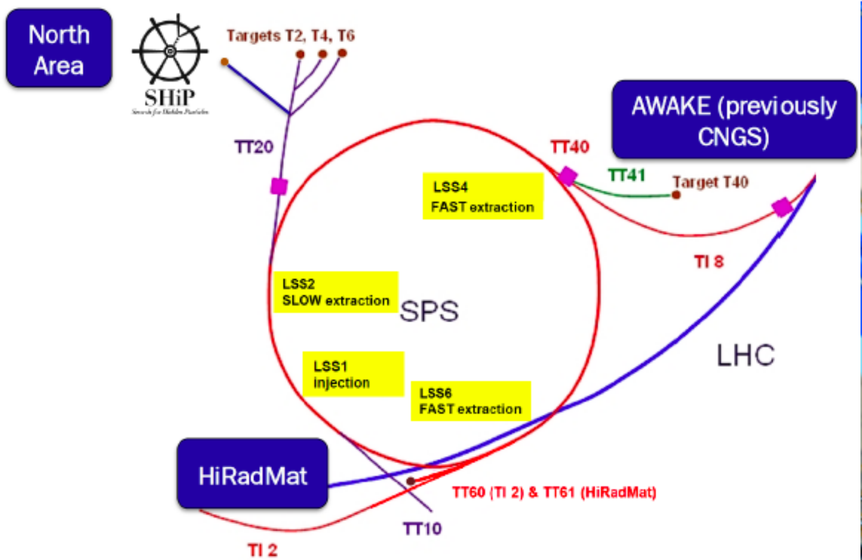
N_{pot} = 2×10^{20} in 5 years
>10^{17} D, >10^{15} τ
Zero background experiment

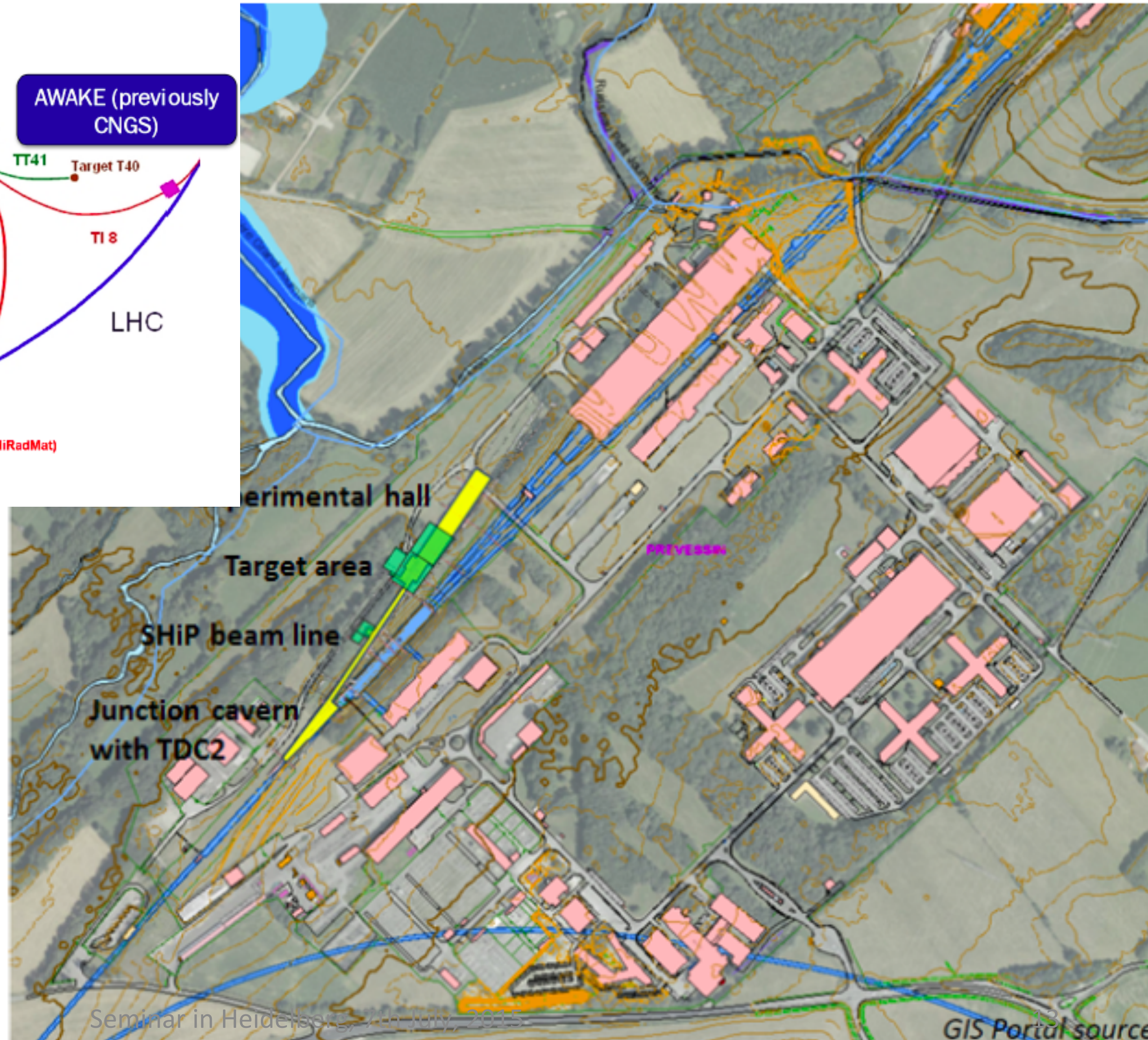


Reconstruction of HS decays in all possible final states
Long decay volume protected by various Veto Taggers,
Magnetic Spectrometer followed by the Timing Detector,
and Calorimeters and Muon systems.
All heavy infrastructure is at distance to reduce neutrino / muon interactions in proximity of the detector

The Fixed-target facility at the SPS: Prevessin North Area site

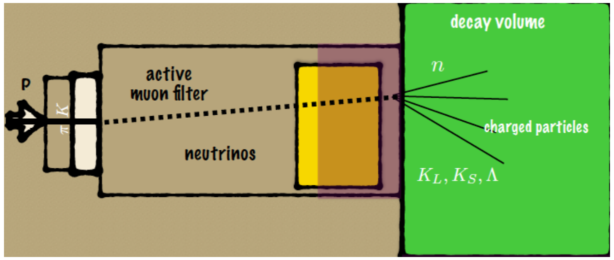
Proposed implementation is based on minimal modification to the SPS complex





The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

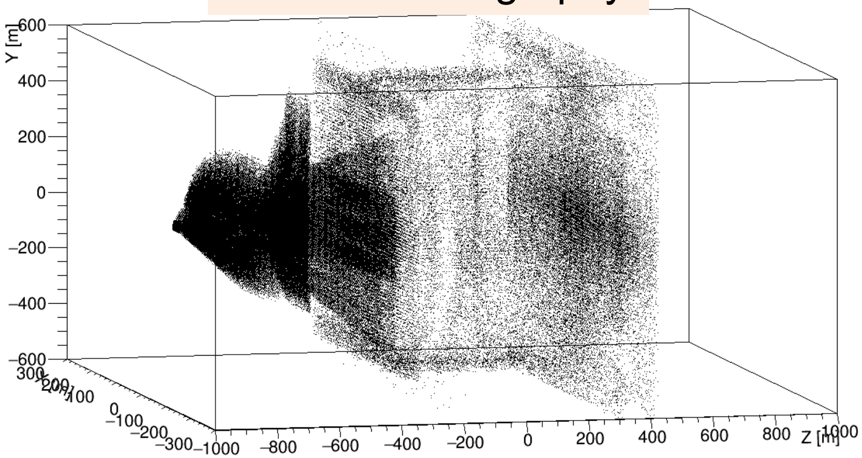
HS Backgrounds (1)



Main sources of background

✓ ***Neutrino DIS interactions with material in the vicinity of the HS decay volume***
(interactions of ν with air in the decay volume are negligible at 10^{-3} mbar)

Neutrino tomography

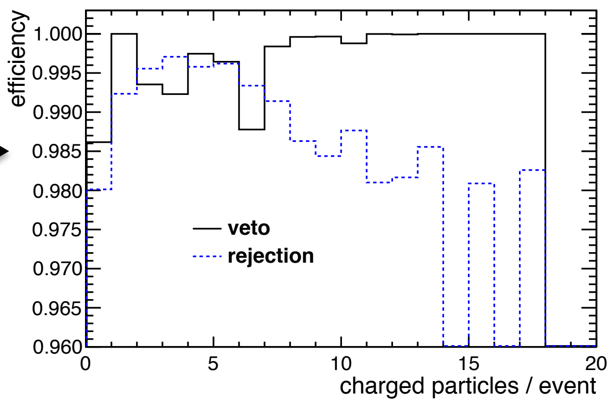


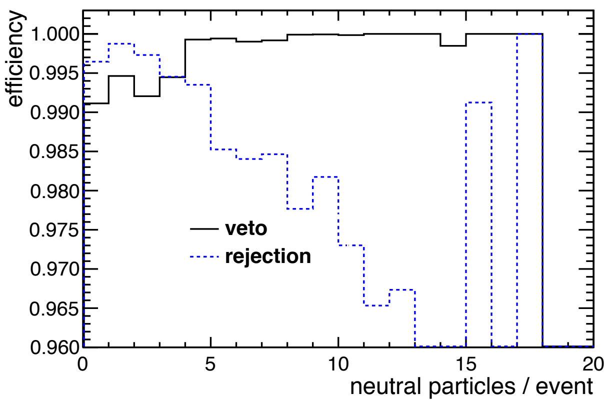
Origin of neutrino interactions

- *Walls of the decay volume (>80%)*
- *Tau neutrino detector*
- *HS tracking system*

Combination of veto and selection cuts reduces the ν-induced background to zero

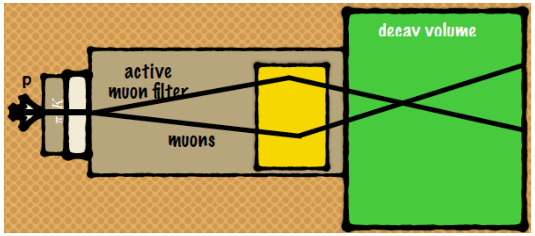
Veto efficiency increases with event multiplicity →





HS Backgrounds (2)

✓ ***Muon combinatorial background***



Simulation predicts O(10^{12}) muon pairs in the decay volume in 5 years of data taking

Suppressed by:

- Basic kinematic and topological cuts ~10^4

- Timing veto detectors ~10^7

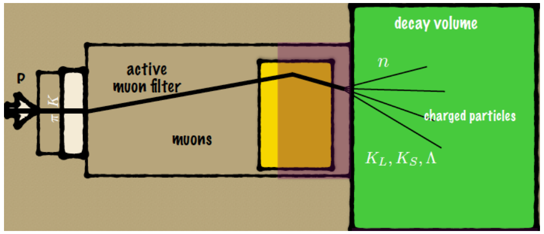
- Upstream veto and surrounding veto taggers ~10^4

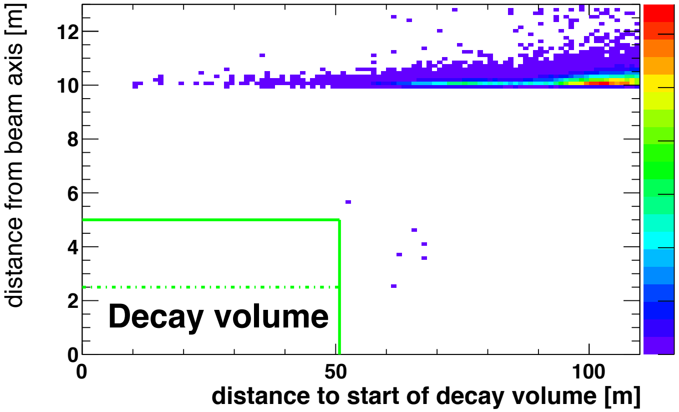
✓ ***Muon DIS interactions***

- V^0s produced in the walls of the cavern

- DIS close to the entry of the decay volume

→ smaller than neutrino induced background





✓ ***Cosmics***

Background summary: no evidence for any irreducible background

HS Signal yield

The same procedure applied to all physics signals, outlined here for HNLs:

$$n(HNL) = N(\text{p.o.t}) \times \chi(pp \to HNL) \times \mathcal{P}_{\text{vtx}} \times \mathcal{A}_{\text{tot}}(HNL \to \text{visible})$$

- ✓ *N(p.o.t.) = 2×10^{20}*
- ✓ $$\chi(pp \to HNL) = 2 \times [\chi(pp \to c\bar{c}) \times \mathcal{BR}(c \to HNL) + \chi(pp \to b\bar{b}) \times \mathcal{BR}(b \to HNL)] \times U^2$$
  - *χ(pp → cc) = 1.7×10^{-3}, χ(pp → bb) = 1.6×10^{-7} are production fractions for 400 GeV proton colliding on a Mo target*
  - *$U^2 = U^2_e+U^2_\mu+U^2_\tau$ (ratio between different LF is model dependent)*
- ✓ *$\mathcal{P}_{vtx}$ - probability that HNL (of a given mass and couplings) decays in the SHiP fiducial volume*
- ✓ *$\mathcal{A}_{tot}$ (HNL→visible) – detector acceptance for all HNL final states, HNL → 3ν, $\pi^0\nu$, π^+l^-, $\rho^0\nu$, ρ^+l^-, $l^+l^-\nu$*

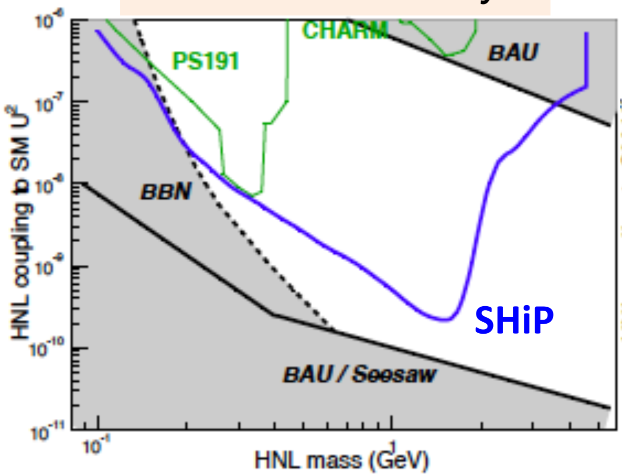
$$\mathcal{A}_{\text{tot}}(HNL \to \text{visible}) = \sum_{i=\text{visible channel}} \mathcal{BR}(HNL \to i) \times \mathcal{A}(i)$$

Typical $\mathcal{P}_{vtx} \times \mathcal{A} \times$ Selection ~ 10^{-6}

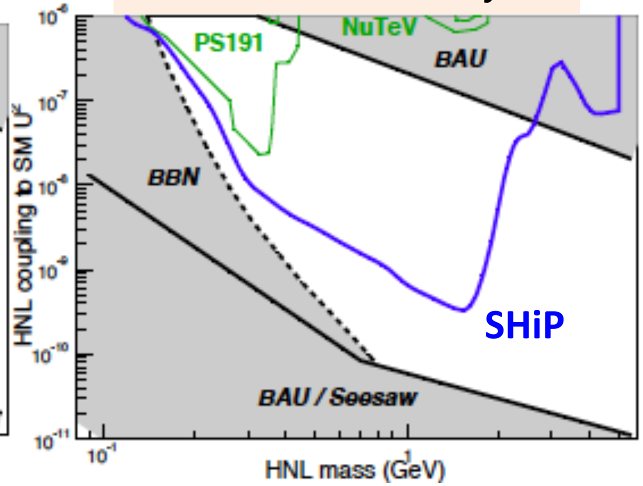
SHiP sensitivity to HNLs for representative scenarios

- ✓ *BAU constraint is model-dependent (shown below for νMSM)*
- ✓ *Seesaw limit is not*

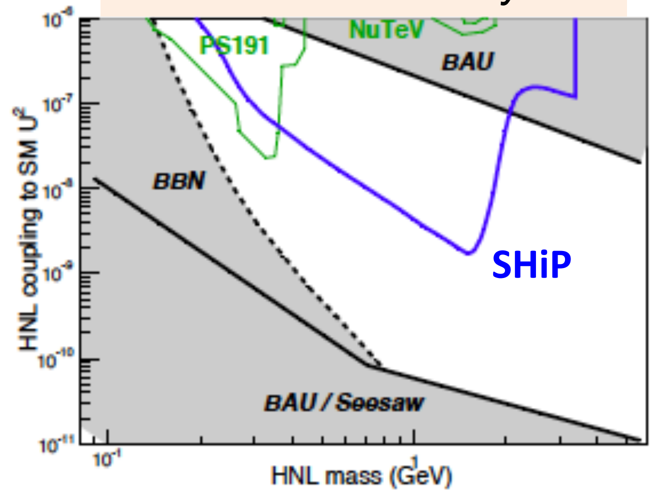
$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$
Inverted hierarchy



$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
Normal hierarchy



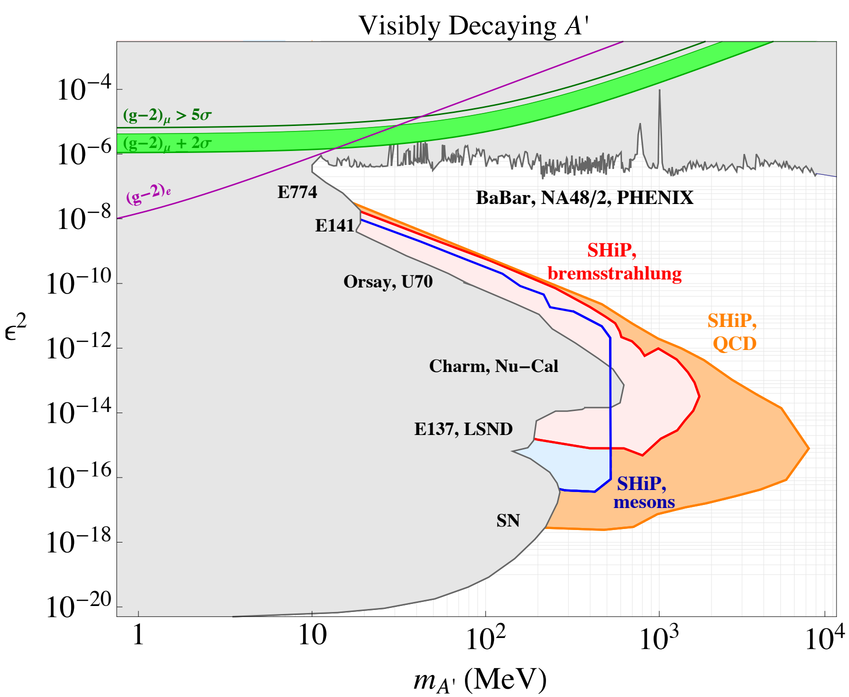
$U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$
Normal hierarchy

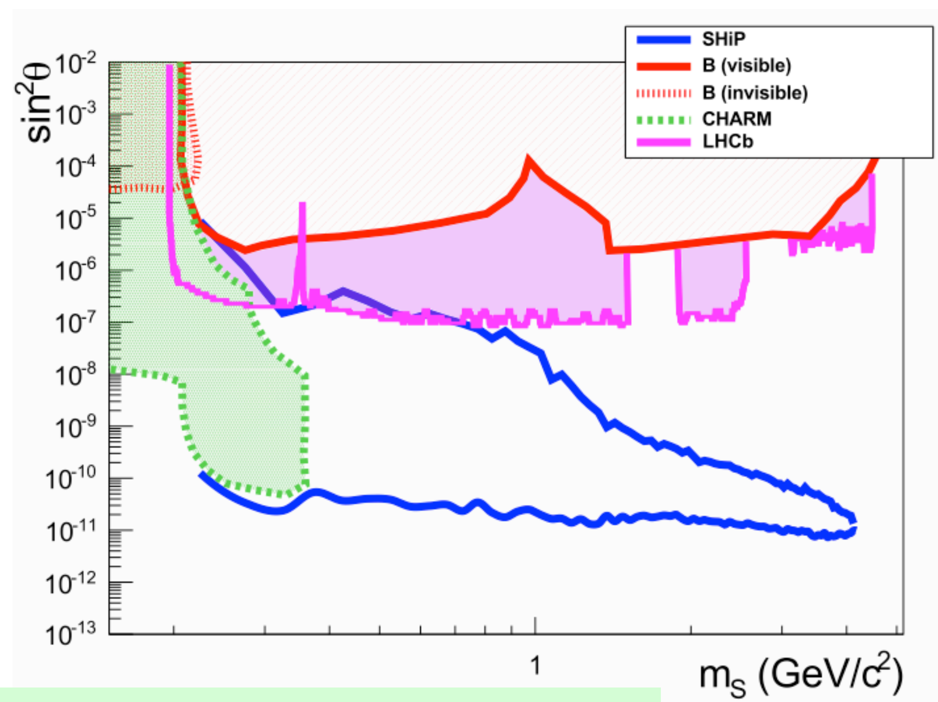


SHiP sensitivity covers large area of parameter space below the B mass
Moving down towards the ultimate see-saw limit

SHiP sensitivity to dark photons and hidden scalars

- ✓ **Dark photons** → *U(1) associated particle* ***A' (γ')*** *in HS that can have non-zero mass and mix with the SM photon with* ε
  Produced in QCD processes or in decays of $\pi^0 \to \gamma'\gamma$, $\eta \to \gamma'\gamma$, $\omega \to \gamma'\pi^0$ *and* $\eta' \to \gamma'\gamma$
- ✓ ***Hidden scalars, S,*** *can mix with the SM Higgs with with* $\sin^2\Theta$
  Mostly produced in penguin-type decays of B and K decays
- ✓ ***Decay*** *into a pair of SM particles into* $\underline{e^+e^-, \mu^+\mu^-, \pi^+\pi^+, KK,}$ $\eta\eta$, $\tau\tau$, *DD, …*

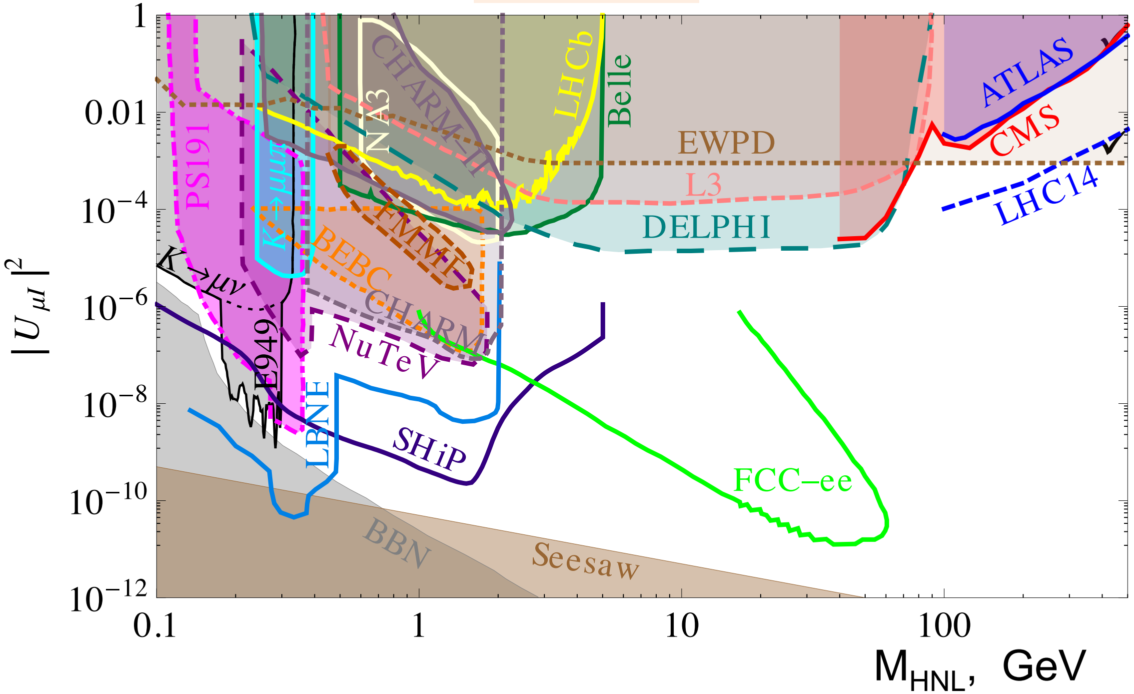




SHiP probes unique range of couplings and masses

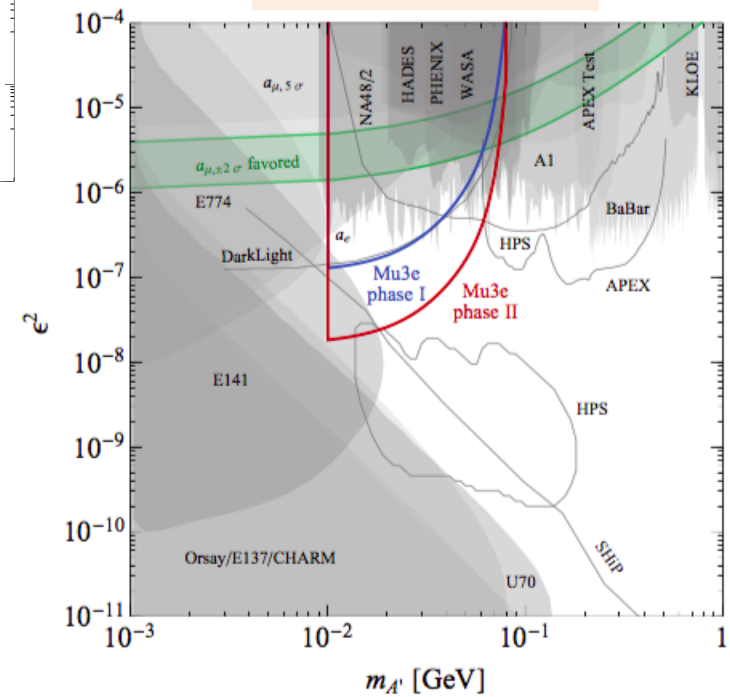
Hidden Sector experimental constraints in future

HNL



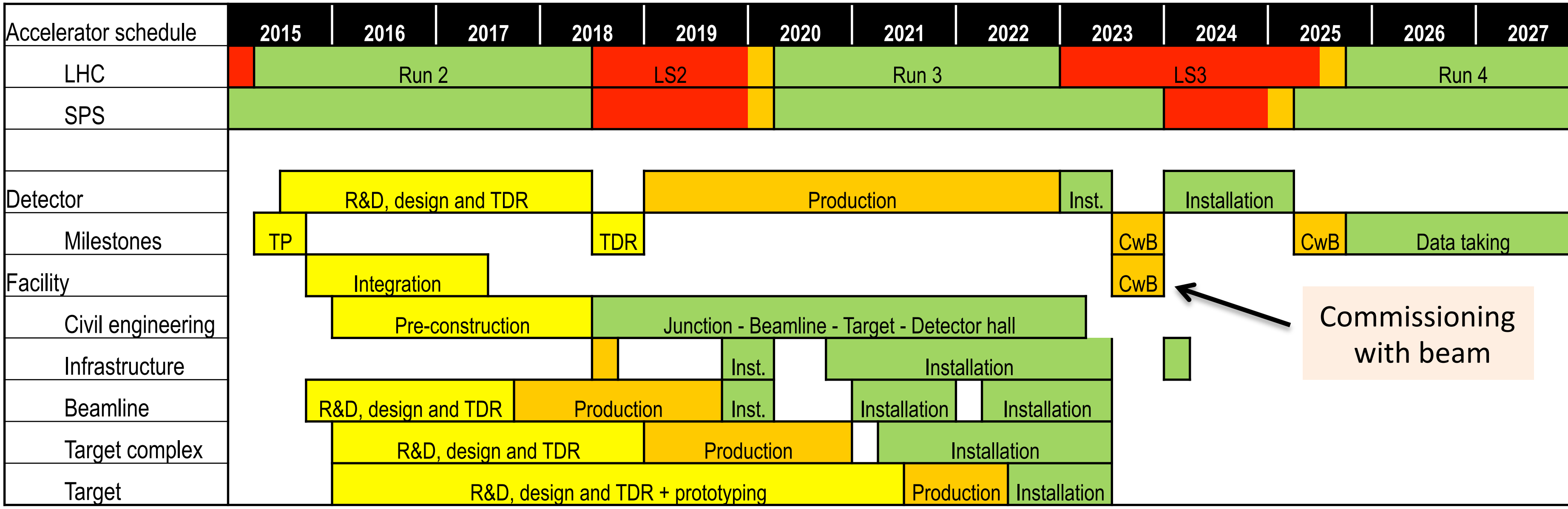
- ✓ *M_{HNL}< M_b LHCb, BelleII SHiP will have much better sensitivity*
- *M_b<M_{HNL}<M_Z FCC in ee mode*
- *M_{HNL}>M_Z Prerogative of ATLAS/CMS @ HL LHC*

Dark photon



- ✓ *SHiP will have unique sensitivity for “heavy” dark photons*
- ✓ *HPS is expected to cover new range of ε^2 in a couple of years*

Project schedule



10 years from TP to data taking

- ✓ *Schedule optimized for almost no interference with operation of North Area*
  - ➔ *Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)*
  - ➔ *Maximum use of LS2 for junction cavern and first short section of SHiP beam line*
- ✓ *All TDRs by end of 2018*
- ✓ *Commissioning run at the end of 2023 for beam line, target, muon shield and background*
- ✓ *Four years for detector construction, plus two years for installation*
- ✓ *Updated schedule with new accelerator schedule (Run 2 up to end 2018, 2 years LS2) relaxes current schedule*
  - ➔ ***Data taking 2026***

Summary

- ✓ *SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with masses O(10) GeV*
- ✓ *Also unique opportunity for ν_τ physics*
- ✓ *Sensitivity improves previous experiments by O(10000) for Hidden Sector and by O(200) for ν_τ physics*
- ✓ ***The technical feasibility of the SHiP facility has been demonstrated by the CERN Task Force.***
- ✓ ***The impact of the discovery of a new light hidden particle is hard to overestimate !***
- ✓ ***SHiP will greatly complement searches for New Physics at CERN***

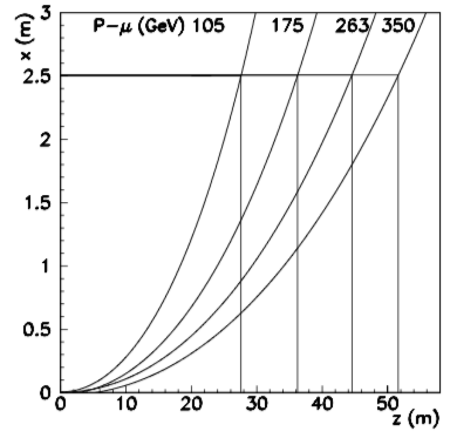
SHiP at CERN @ 400 GeV vs XXX at Fermilab @ 120 GeV

Assume:

- Hypothetical detector XXX has similar size to the SHiP detector
- Slow beam extraction (*)
- The target with the same material (*)
- Full background suppression
- Dedicated to XXX operation (in conflict with neutrino programme)
(*) – technical feasibility to be demonstrated for XXX

	SHiP	XXX 40 m long and at 37 m from the target
N_{pot} / year delivered at ~1s extraction	4×10^{19}	$\sim5.3\times10^{20}$
σ_{cc} (E_{beam}), au	1	1/7
Detector acceptance (E), au	1	0.6

Trajectory of m in Fe(1.8T)



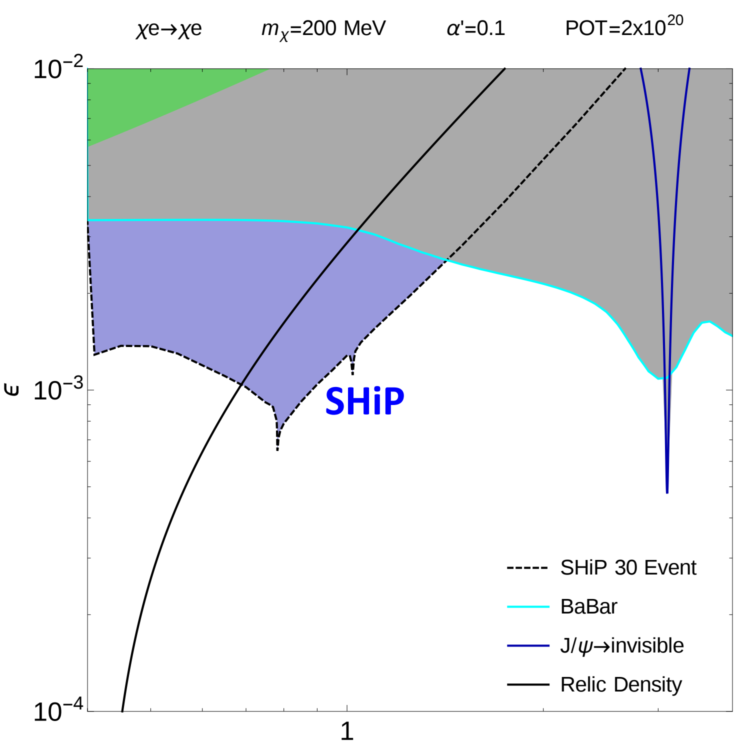
✓ ***Similar performance for HS produced in charm decays***
Sensitivity for HS produced in B decay is severely compromised, σ_{bb} (120/400) = 625

✓ ***Really poor prospects for tau neutrino physics at 120 GeV beam energy***

✓ ***SPS @ 400 GeV is ideal to perform the physics programme of SHiP***

Direct DM detection

Dark photon can decay to DM, χ
- detect its NC interactions on atomic electrons



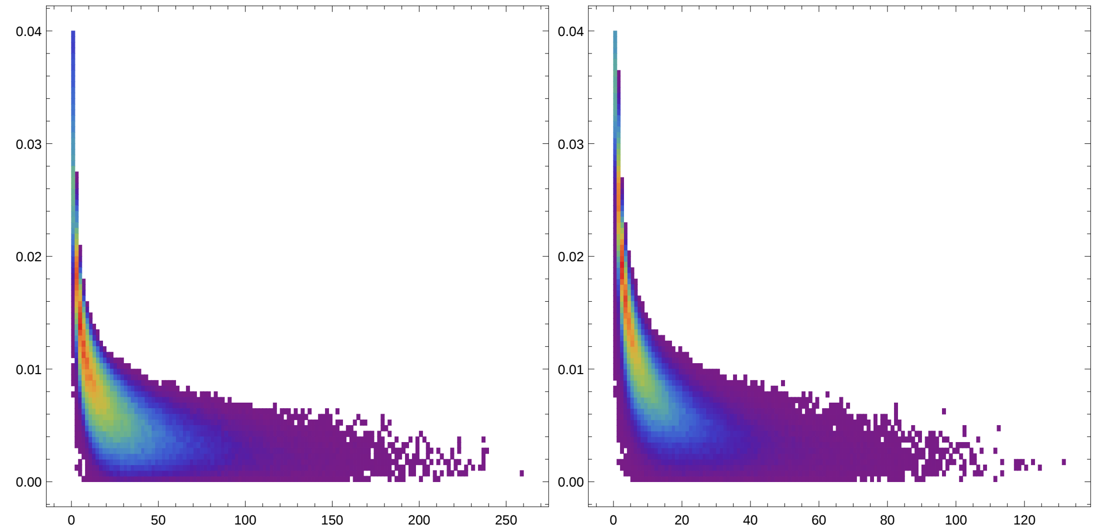


Figure 5.36: Electron scattering angle (mrad) versus the electron energy (GeV) for signal candidates, (a) in a model with m_A = 800 MeV/c^2 and m_χ = 200 MeV/c^2 and (b) with m_A = 405 MeV/c^2 and m_χ = 200 MeV/c^2.

Not a background free search
Backgrounds survived selection (OPERA based cuts: angle 10-20 mrad, E<20 GeV)

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	16	2	20	18	56
Quasi - elastic scattering	105	73			178
Resonant scattering	13	27			40
Deep inelastic scattering	3	7			10
Total	137	109	20	18	284

SHiP may have an interesting sensitivity in the leptophobic scenario
Dedicated experiment at the CERN beam-dump facility ???

Extract from the CERN RB minutes

2.1 F. Gianotti presented the draft mandate for a new "**Physics Beyond Colliders**" study group [2]. The CERN management wishes to launch an exploratory study aimed at exploiting the full scientific potential of its accelerator complex through projects complementary to the LHC, HL-LHC and possible future colliders (such as HE-LHC, CLIC, or FCC). These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments. The study should provide input for the future of CERN's scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS. Complementarity with similar initiatives elsewhere in the world should be sought, so as to optimize the resources of the discipline globally, create synergies with other laboratories and institutions, and attract the international community. Examples of physics objectives include searches for rare processes and very-weakly interacting particles, measurements of electric dipole moments, etc. The group will be led by three coordinators representing the scientific communities of theory, accelerators and experimental particle physics. Following consultation with the relevant communities, they will define the structure and the main activities of the group and appoint convenors of thematic working groups as needed. They will call a kick-off meeting in the first half of 2016, organize regular plenary meetings, and monitor the overall scientific activity. The scientific findings will be collected in a report to be delivered by the end of 2018, and will serve as input to the next update of the European Strategy for Particle Physics. In discussion it was clarified that the focus of this study will be accelerator-based particle physics rather than atomic, nuclear or medical physics; axion searches may be included if they require features that are uniquely available at CERN, as would future plans for antiproton and muon facilities. **The Research Board took note.**

Extract from the CERN RB minutes

4.12 The SPSC has reviewed the proposal for "A Facility to Search for Hidden Particles (**SHiP**) at the CERN SPS" submitted in April 2015. The review included questions from the referees that were all answered, including submission of an addendum in October 2015 [6]. Significant progress has been made during the review, including optimisation of the proton beam-dump design, broadening of the physics case and adaptation of the schedule to external constraints. The SPSC supports the motivation for the search for hidden particles, which will explore a domain of interest for many open questions in particle physics and cosmology, and acknowledges the interest of the measurements foreseen in the neutrino sector. The committee encourages the proponents to further explore the potential benefit of inputs from NA62 to strengthen the experimental evaluation of backgrounds and systematic uncertainties. **The Research Board endorsed the recommendation from the SPSC that the collaboration should perform a comprehensive design study, focussed on the SHiP detector, including detailed simulations of the response to the signal and background signatures and comparisons with alternative search programmes; it should be performed in close collaboration with the Physics Beyond Colliders study group (discussed in item 2), which will consider physics motivations and technical optimisation of a beam-dump facility at CERN and other possible experiments that might use it. The study should be completed in time for the next update of the European Strategy for Particle Physics, on the timescale of three years, and the decision on approval will be taken following the conclusion of that update.**

Impact of the background uncertainty on the SHiP sensitivity