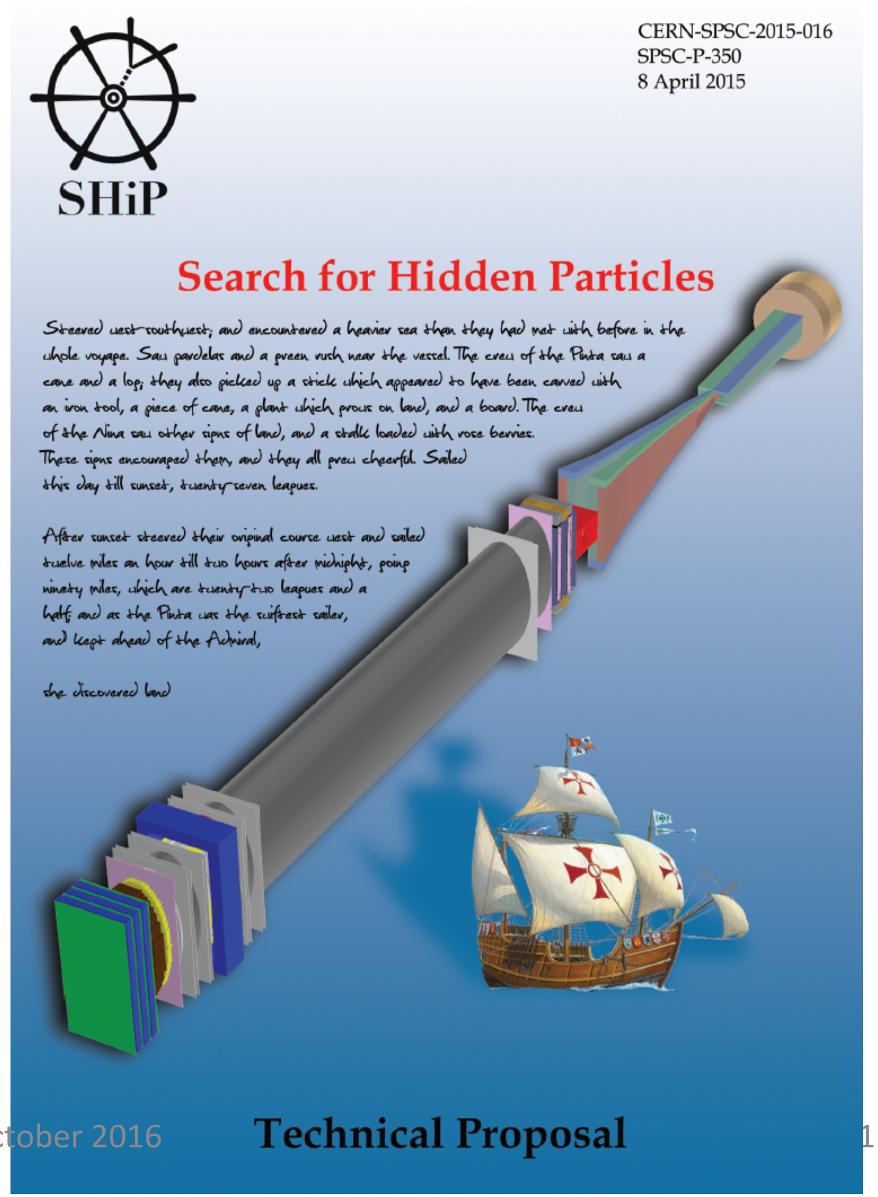
Andrey Golutvin
Imperial College / CERN

The SHiP experiment at CERN SPS

(on behalf of the SHiP collaboration)



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

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

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Zu…

Abs… …s paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (…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
§Convener of the Chapter

Technical Proposal

SHiP
Search for Hidden Particl…

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

250 physicists, 46 Institutes, 16 countries

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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Standard Model is great but it is not a complete theory

Experimental facts of BSM physics

- Neutrino masses & oscillations
- Baryon Asymmetry of the Universe (BAU)
- The nature of non-baryonic Dark Matter (DM)

Many theoretical ideas, including those which predict new light particles, and which can be tested experimentally

SHiP Physics Paper: 1504.04855

SHiP is designed to find a solution for BSM physics by searching for very weakly interacting particles of <10 GeV mass

Brief history of SHiP:

✓ *Letter Of Intent - October 2013*
✓ *Technical Proposal & Physics Paper - April 2015*

Reviewed by the SPSC in March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2018
→ Input to the European strategy consultation to take a decision about approval of SHiP in 2019/2020

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 rich structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*
- *Production branching ratios O(10^{-10})*
- *Long-lived objects*
- *Interact very weakly with matter*

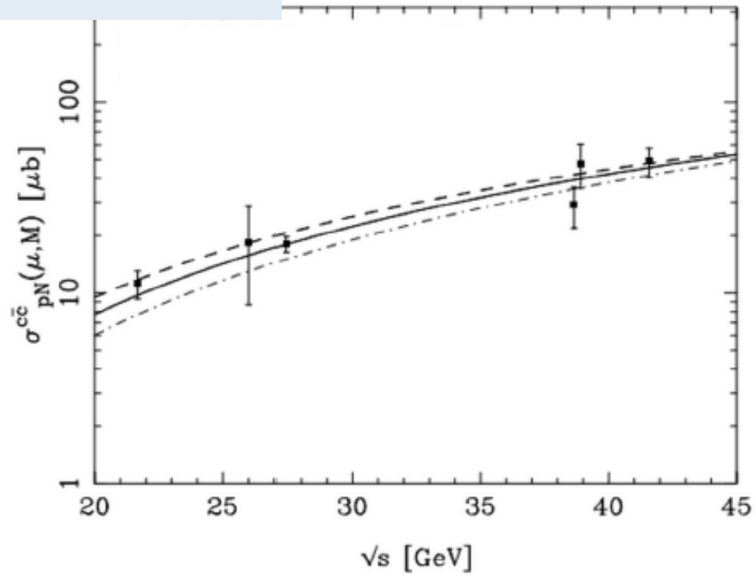
Models	Final states
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\rightarrow\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

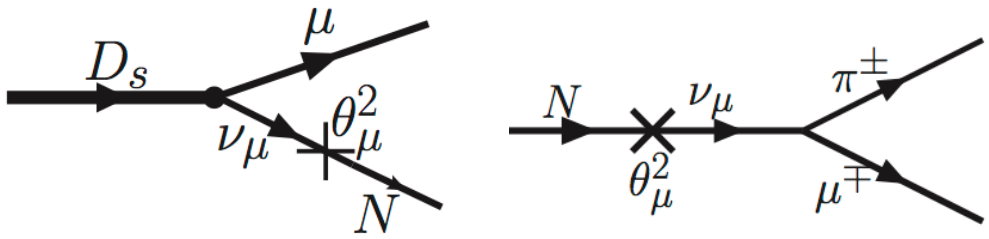
Experimental challenge is background suppression

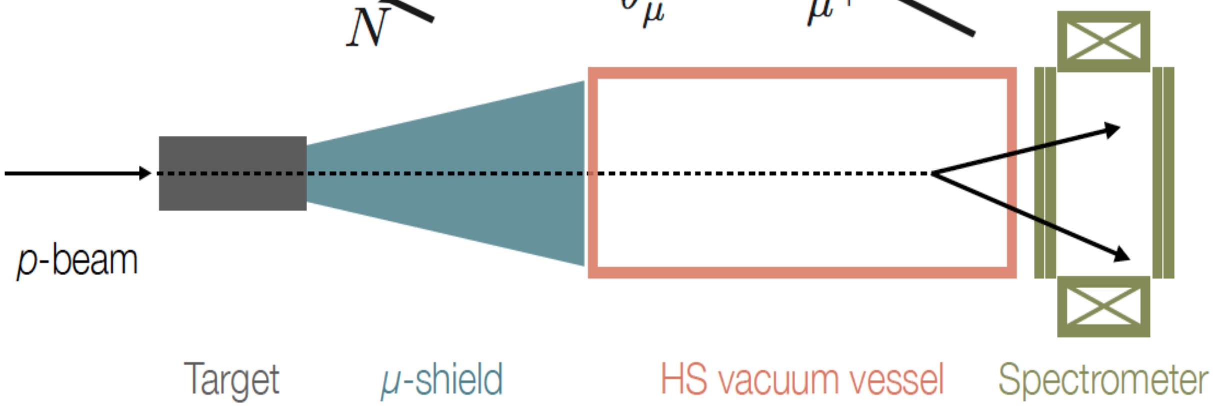
General experimental requirements

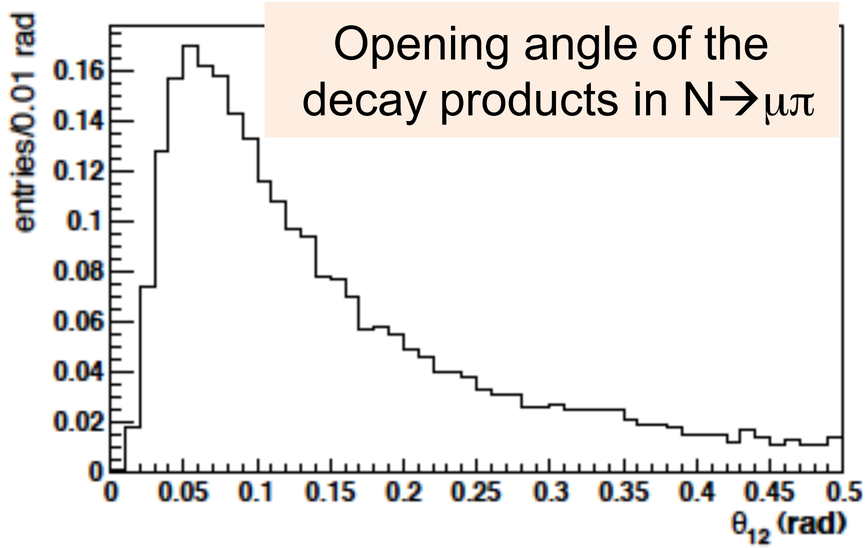
- ✓ Search for HS particles in Heavy Flavour decays
  Charm (and beauty) cross-sections strongly depend on the beam energy



- ✓ 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

The SHiP experiment at SPS

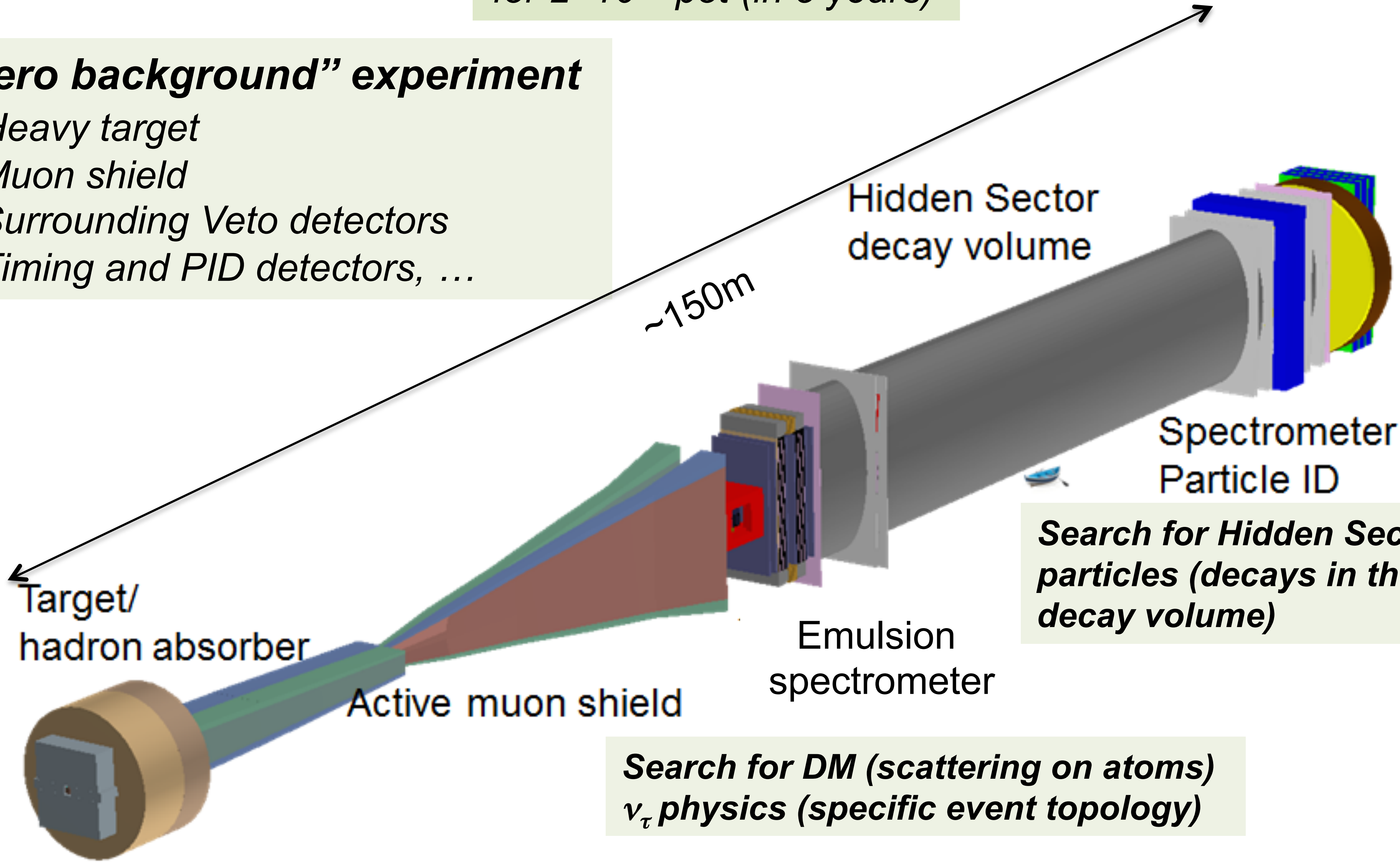
(as implemented in Geant4 for TP)

SHiP Technical Proposal: 1504.04956

>10^{18} D, >10^{16} τ, >10^{20} γ for 2×10^{20} pot (in 5 years)

"Zero background" experiment

- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*

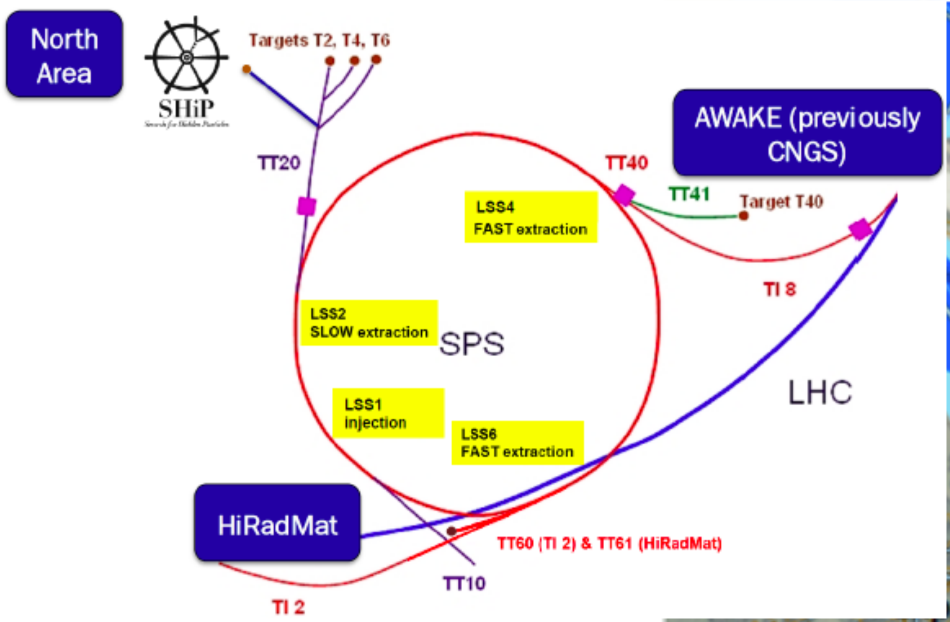


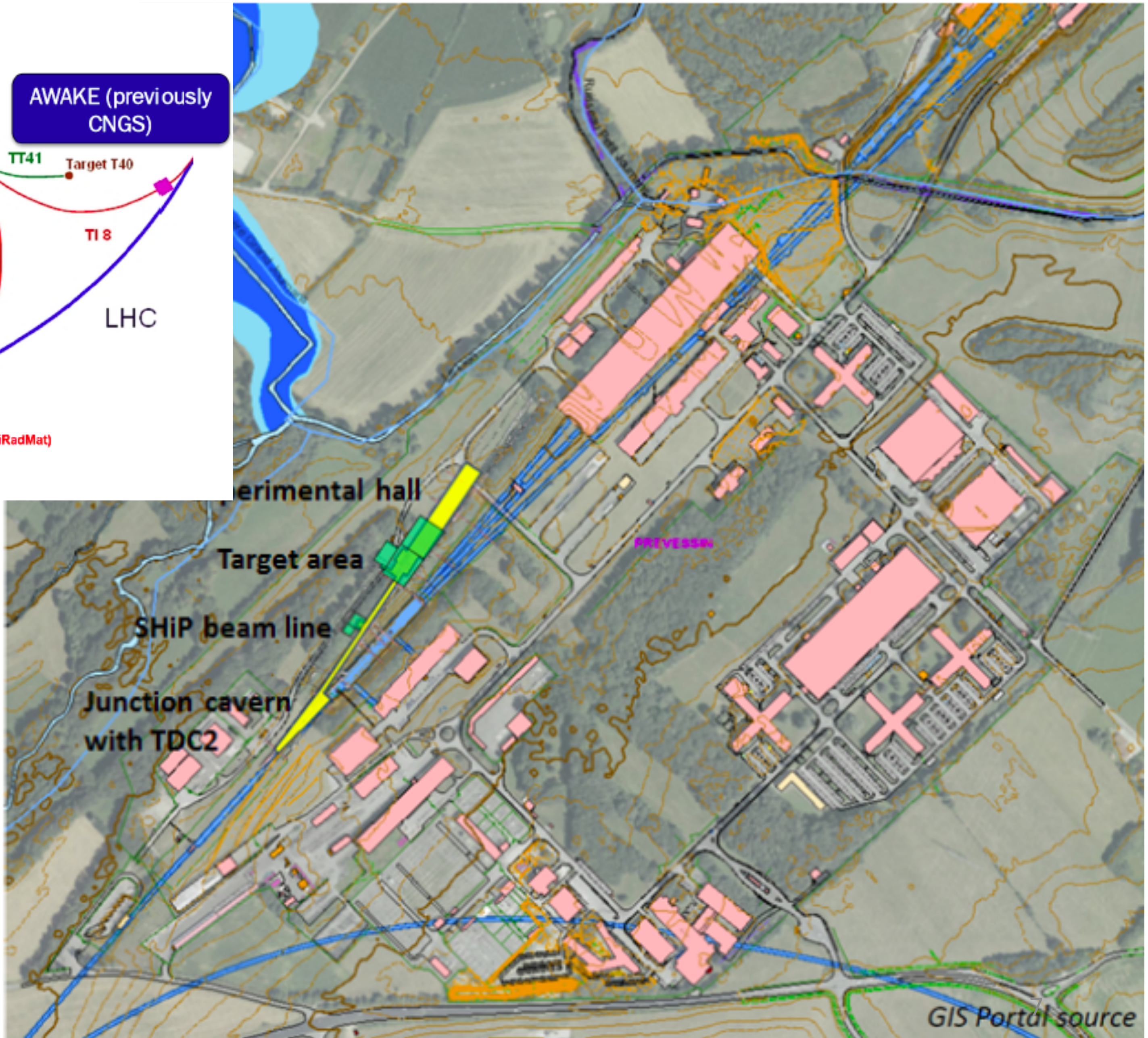
Search for Hidden Sector particles (decays in the decay volume)

Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

The Beam Dump Facility at the SPS
(Prevessin North Area site)

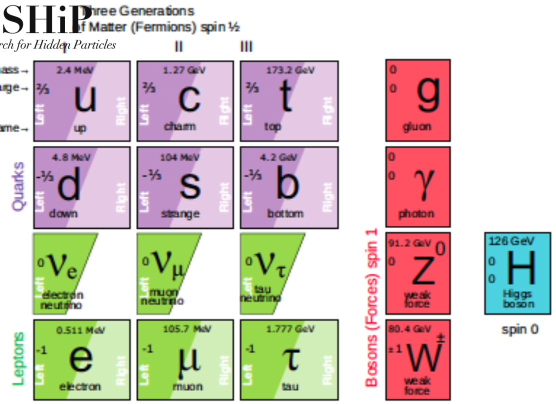
Proposed implementation is based on minimal modification to the SPS complex

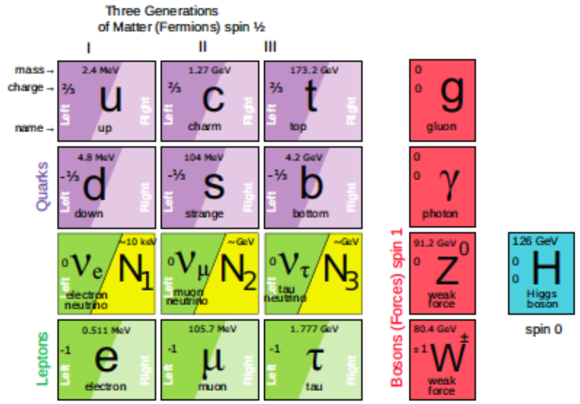




The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes

Neutrino masses & BAU *can be solved with Heavy Neutral Leptons (HNL)*



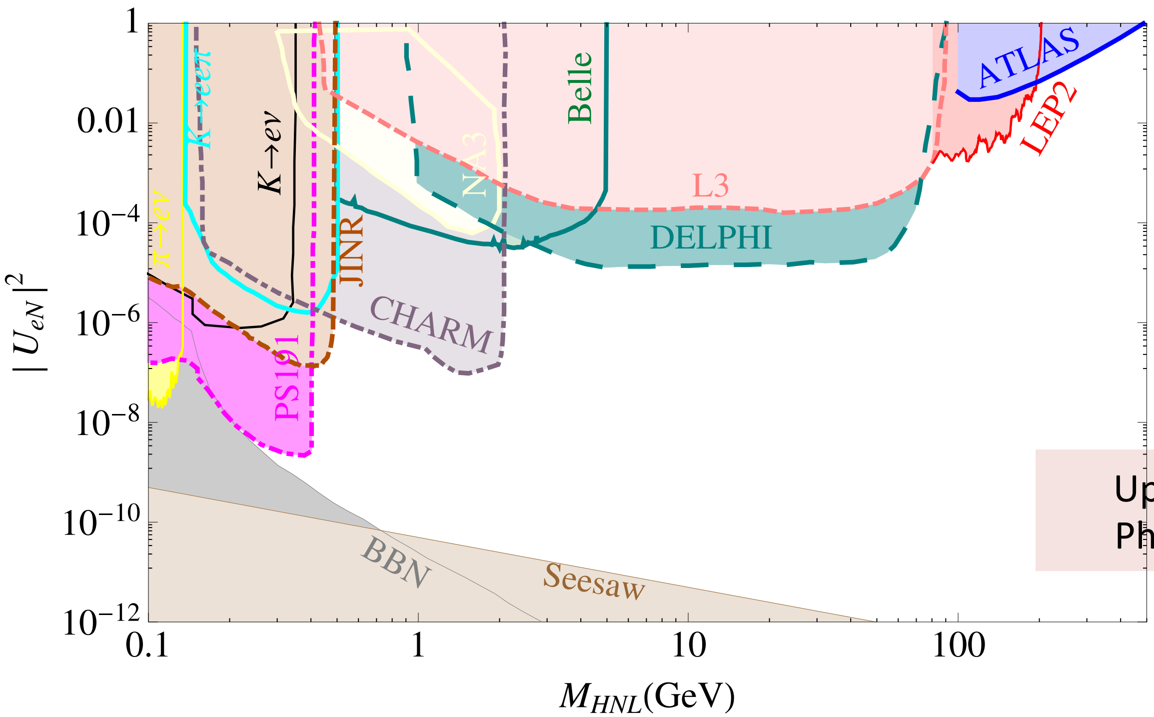


νMSM: T.Asaka, M.Shaposhnikov
PL B620 (2005) 17

N_1 (O(keV) mass) → Dark Matter

$N_{2,3}$ (O(GeV mass) → Neutrino masses and BAU

Existing constraints



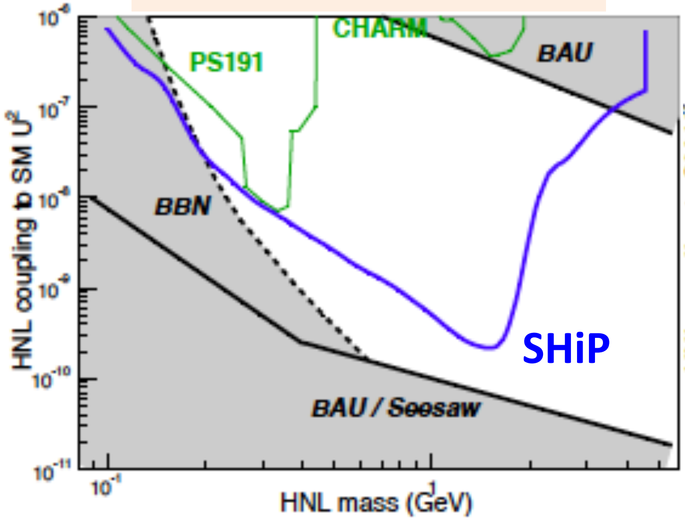
Updated SHiP Physics Paper

Previous experiments did not probe cosmologically interesting region for HNL masses above the kaon mass

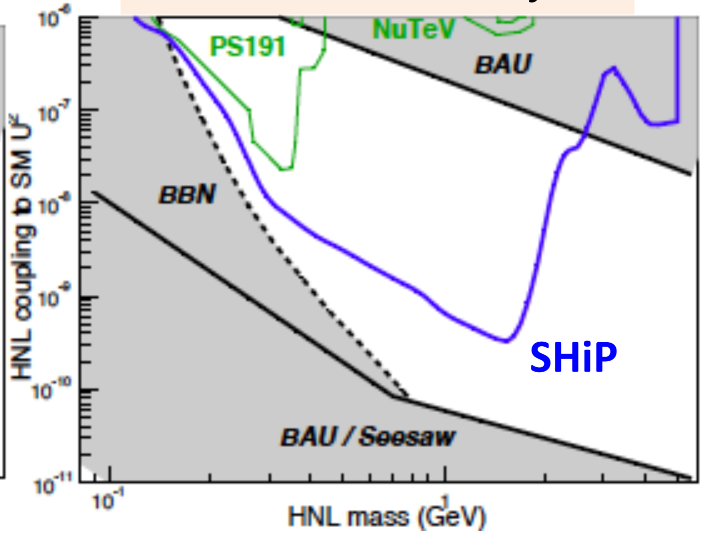
HNL prospects @ SHiP

BAU constraint is model-dependent (shown below for νMSM)

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



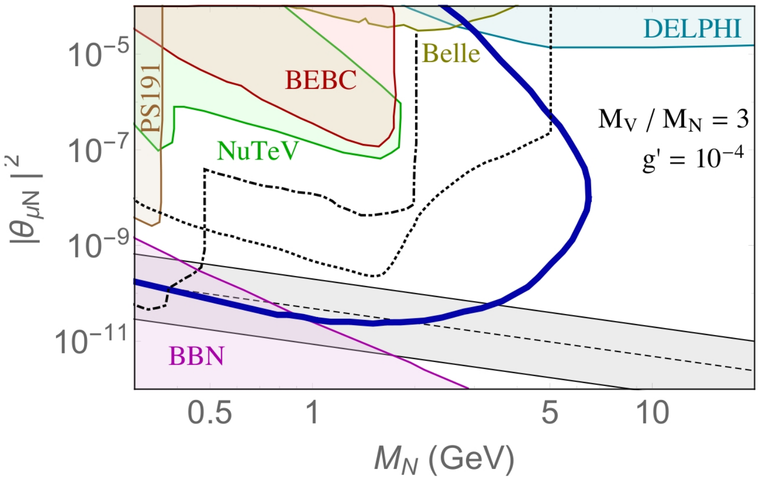
$U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$
Normal hierarchy



Further studies:
Drewes et al. (2016)
Hernandez et al. (2016)
Hernández (2015)
Drewes & Garbrecht (2012)
Abada et al. (2015)

Enhanced HNL production
(B-L gauge symmetry)

Batell, Pospelov, Shuve 1604.06099



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

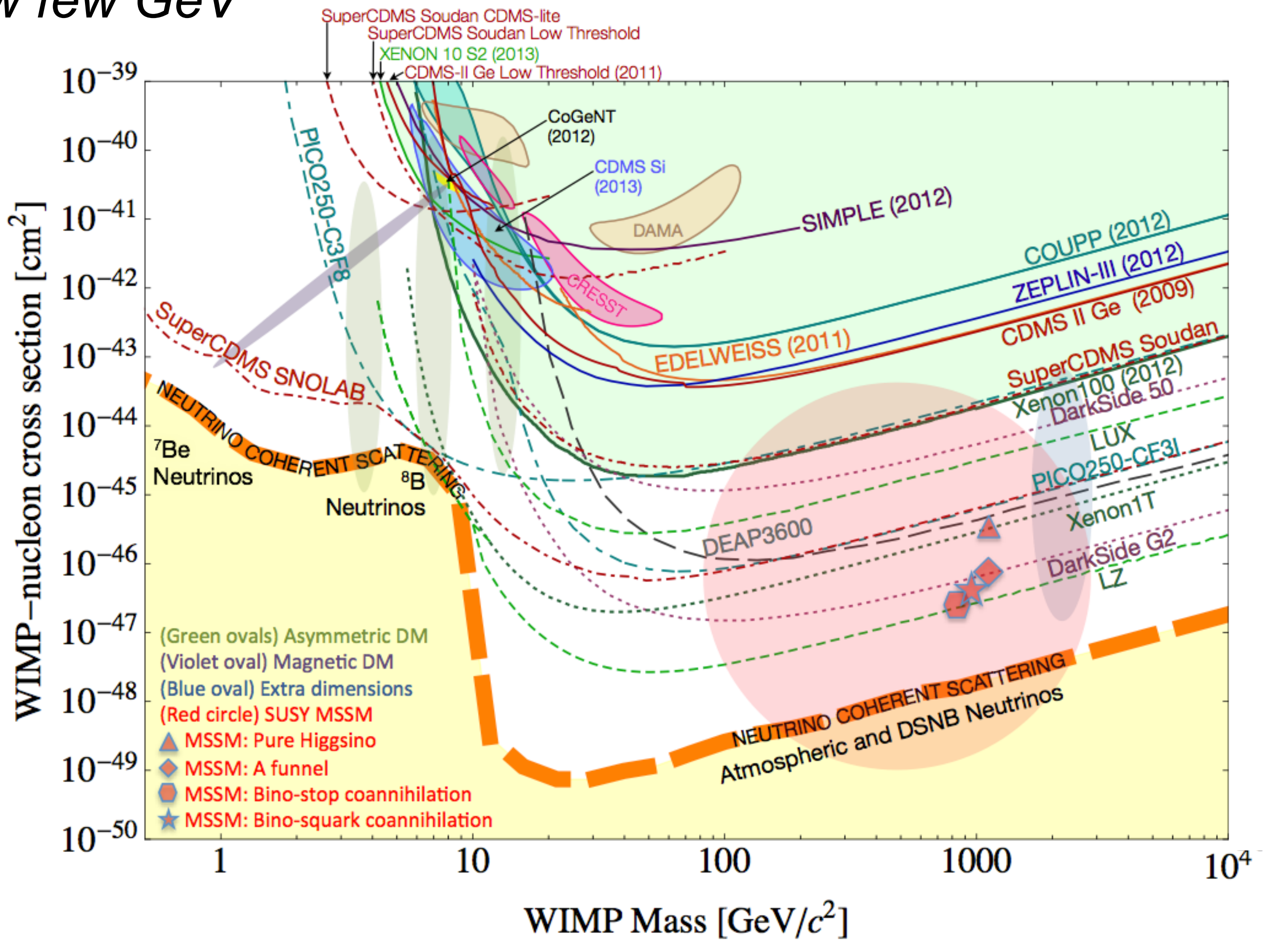
Light Dark Matter (LDM)

The prediction for the mass scale of DM spans from 10^{-22} eV to 10^{20} GeV

- ✓ *WIMP DM is a popular theoretical paradigm ("WIMP miracle")*
- ✓ *Extensive exp. search for WIMPs with masses 10 GeV – 1 TeV*
  Sensitivity is very limited below few GeV

Large classes of theor. models can make the observed relic density with sub-GeV DM:

- Hidden-sector models
- Supersymmetry
- Strongly Interacting DM (SIMP)
- Extra dimensions



Essential to explore the sub-GeV mass range for DM

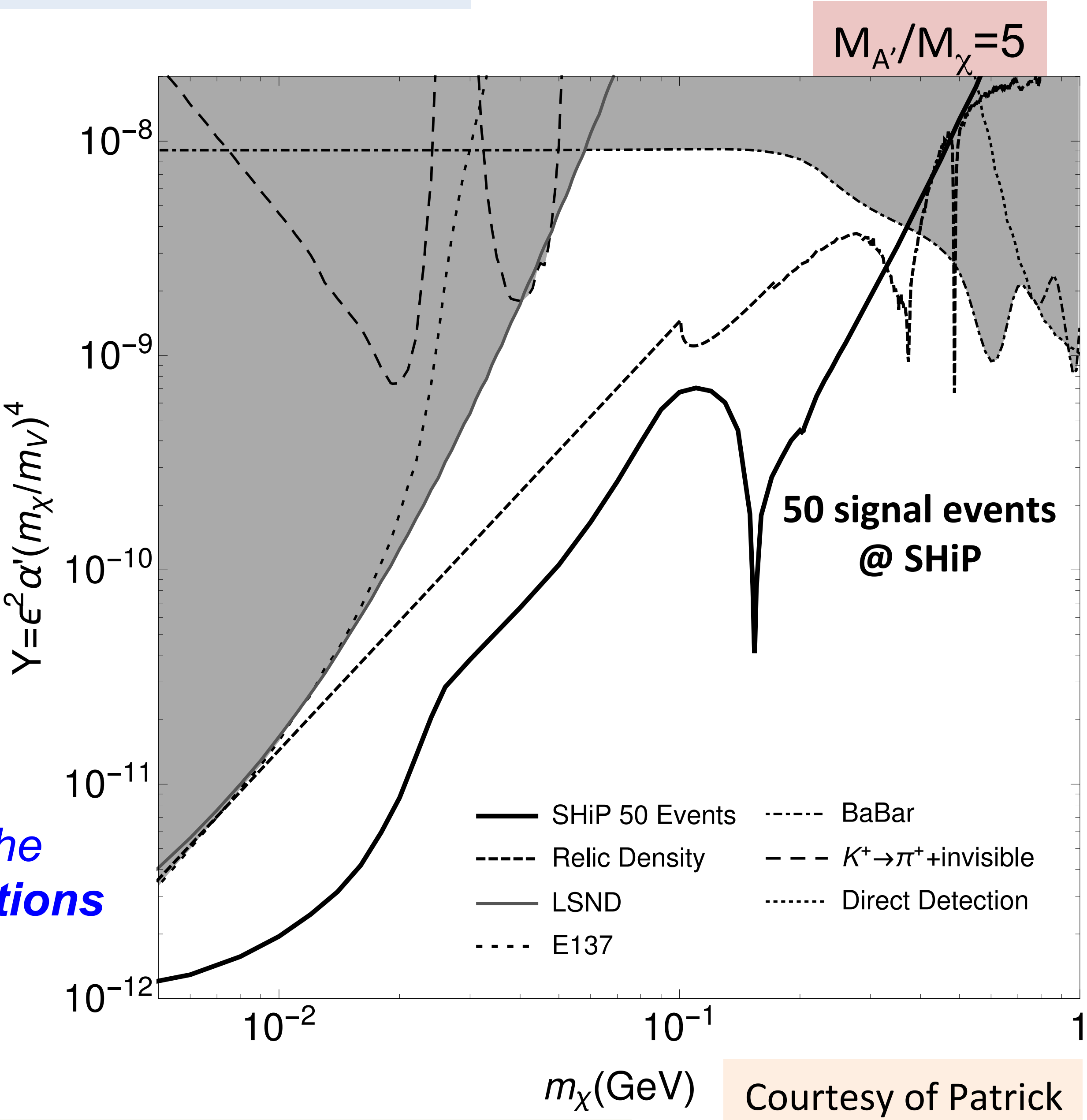
LDM prospects @ SHiP

LDM (χ) can be generated in a beam-dump, *for example in* ***decays of HS mediators****,*
e.g. dark photons A' → χχ

>10²⁰ photons expected in SHiP can be used as ***a LDM beam***

Detect LDM via its scattering on atoms of emulsion spectrometer

SHiP would be able to probe even beyond relic density in minimal hidden-photon model provided that the ***background from neutrino interactions Is kept under control***



Courtesy of Patrick deNiverville

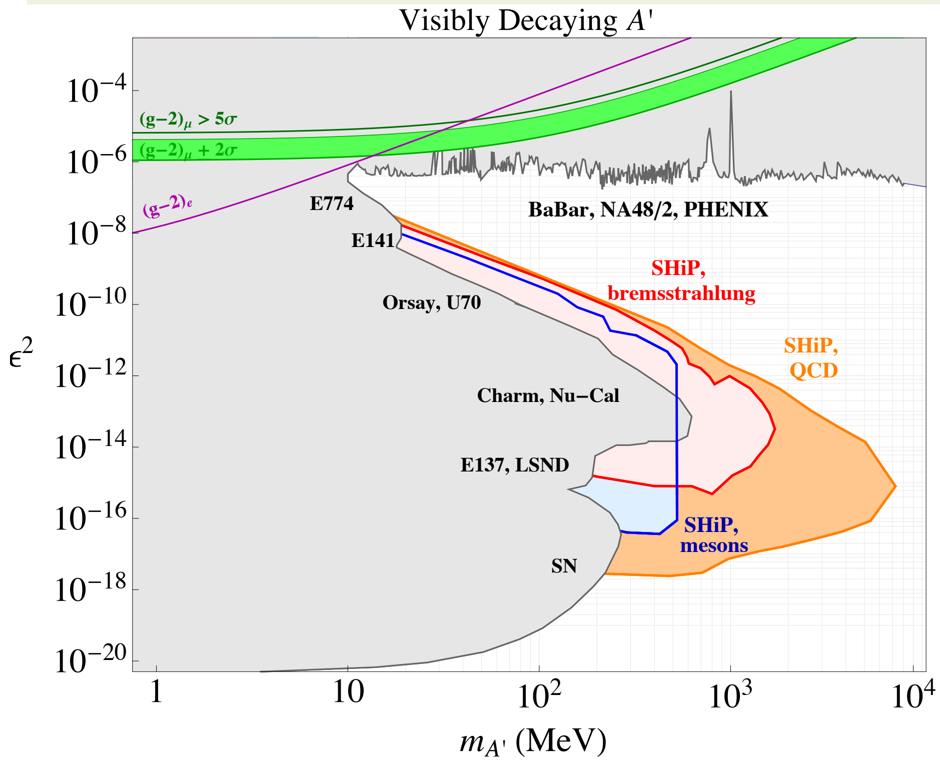
Requires dedicated study/beam test for CDS !

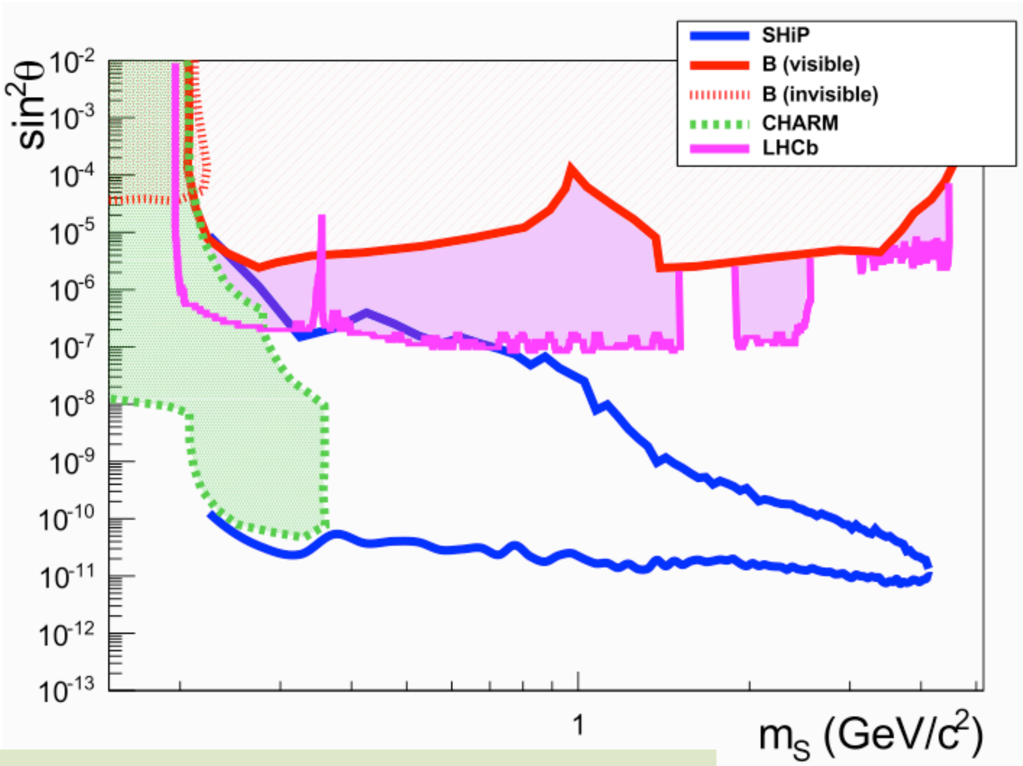
SHiP sensitivity to hidden-sector mediators

- ✓ ***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 bremsstrahlung and 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 $\sin^2\Theta$*
  Mostly produced in penguin-type B and K decays

*Search for **the decay vertex** into a pair of SM particles into <u>e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^+$, KK,</u> $\eta\eta$, $\tau\tau$, DD, …*



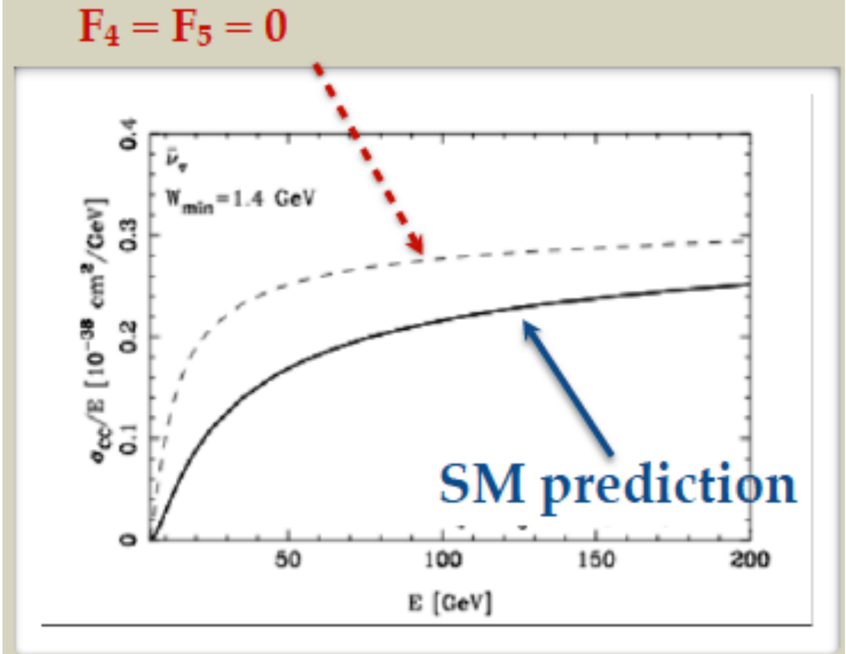


SHiP probes unique range of couplings and masses
(complimentary to existing experiments)

Neutrino physics @ SHiP

✓ ***Copious neutrino production,***
including ν_τ from $D_s \to \tau\nu_\tau$

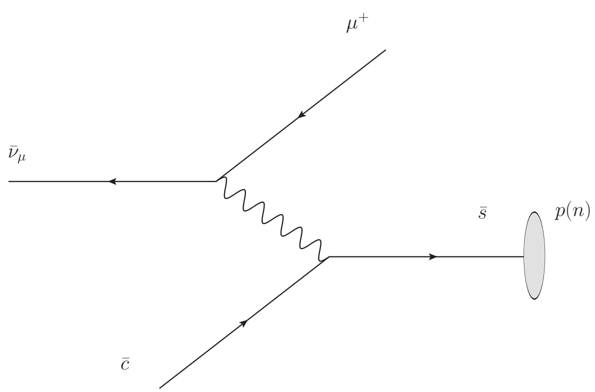
	CC DIS
$N_{\nu_\mu} + N_{\overline{\nu}_\mu}$	2.4×10^6
$N_{\nu_e} + N_{\overline{\nu}_e}$	3.4×10^5
$N_{\nu_\tau} + N_{\overline{\nu}_\tau}$	1.1×10^4

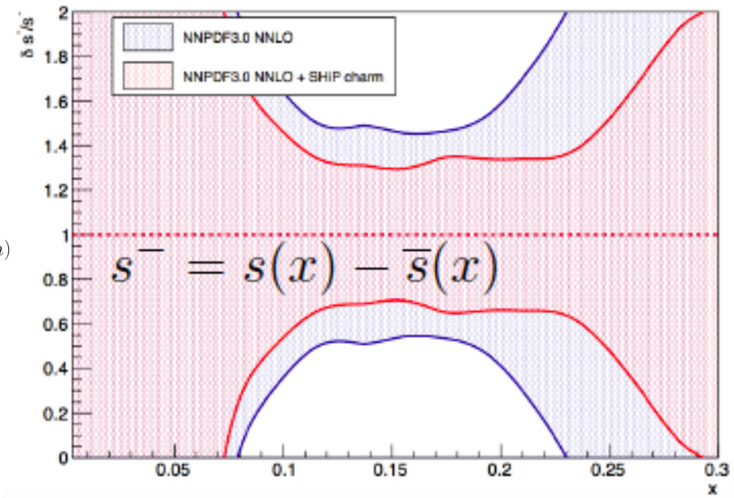


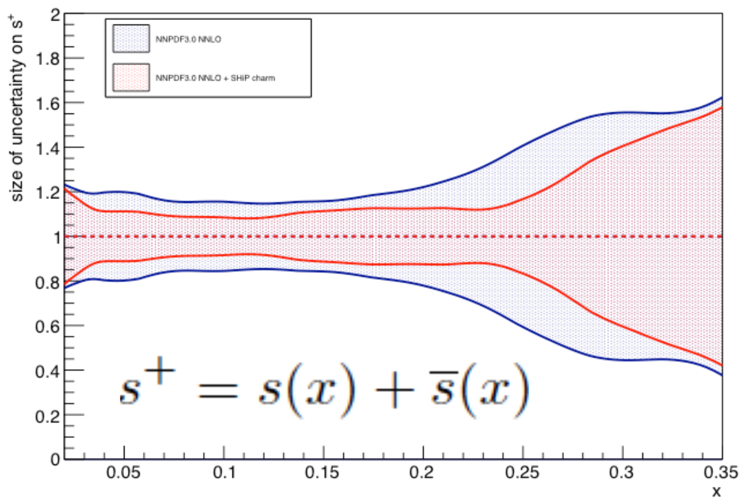
$\overline{\nu}_\tau$ CC DIS cross-section

✓ *First observation of the anti-ν_τ interactions*
Measurement of F4, F5 structure functions

✓ ***Charm physics with neutrinos and anti-neutrinos***
Charm yield in ν int. @ SHiP is >10 the sample from previous experiments
(~10^5 expected events)
Strange quark content of the nucleon for precision tests of SM







SHiP is a "background-free experiment"

SPSC –P350-ADD-2

Accurate control of backgrounds is critical for SHiP physics performance
Bkg. estimation is based on FairSHiP → data samples comparable to the expected ones simulated with Pythia, Genie and run through full GEANT4

Neutrino induced

>

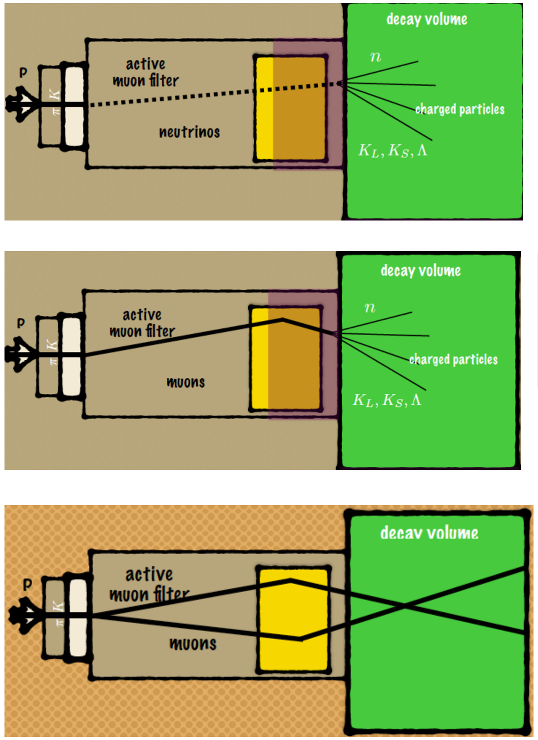
Muon inelastic

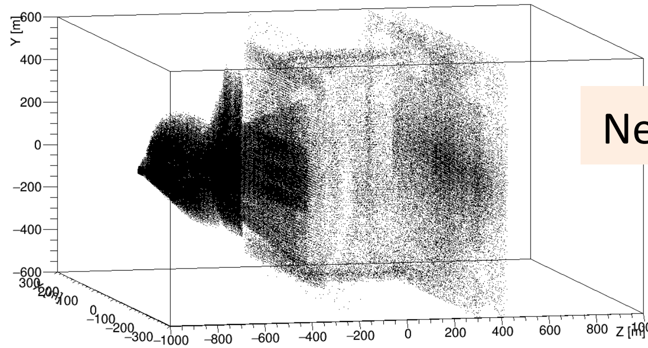
>

Muon Comb.

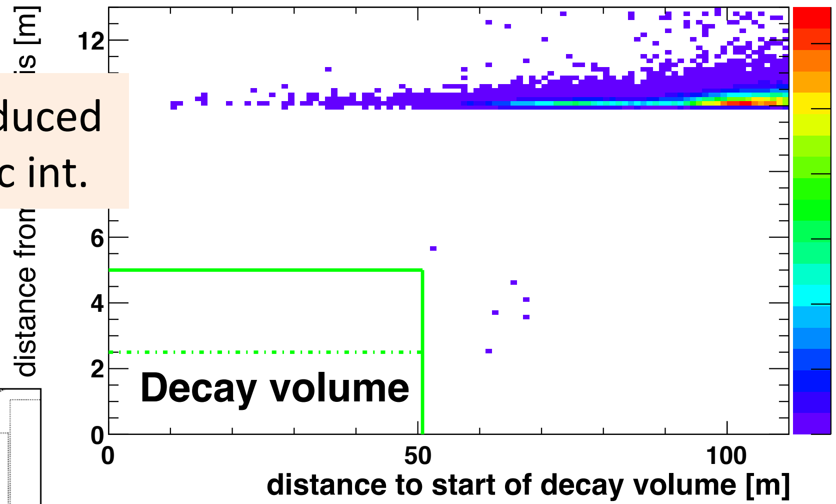
>

Cosmics

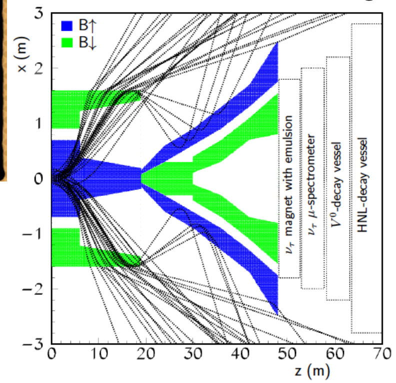




Neutrino tomography



Origin of V_0 produced in muon inelastic int.



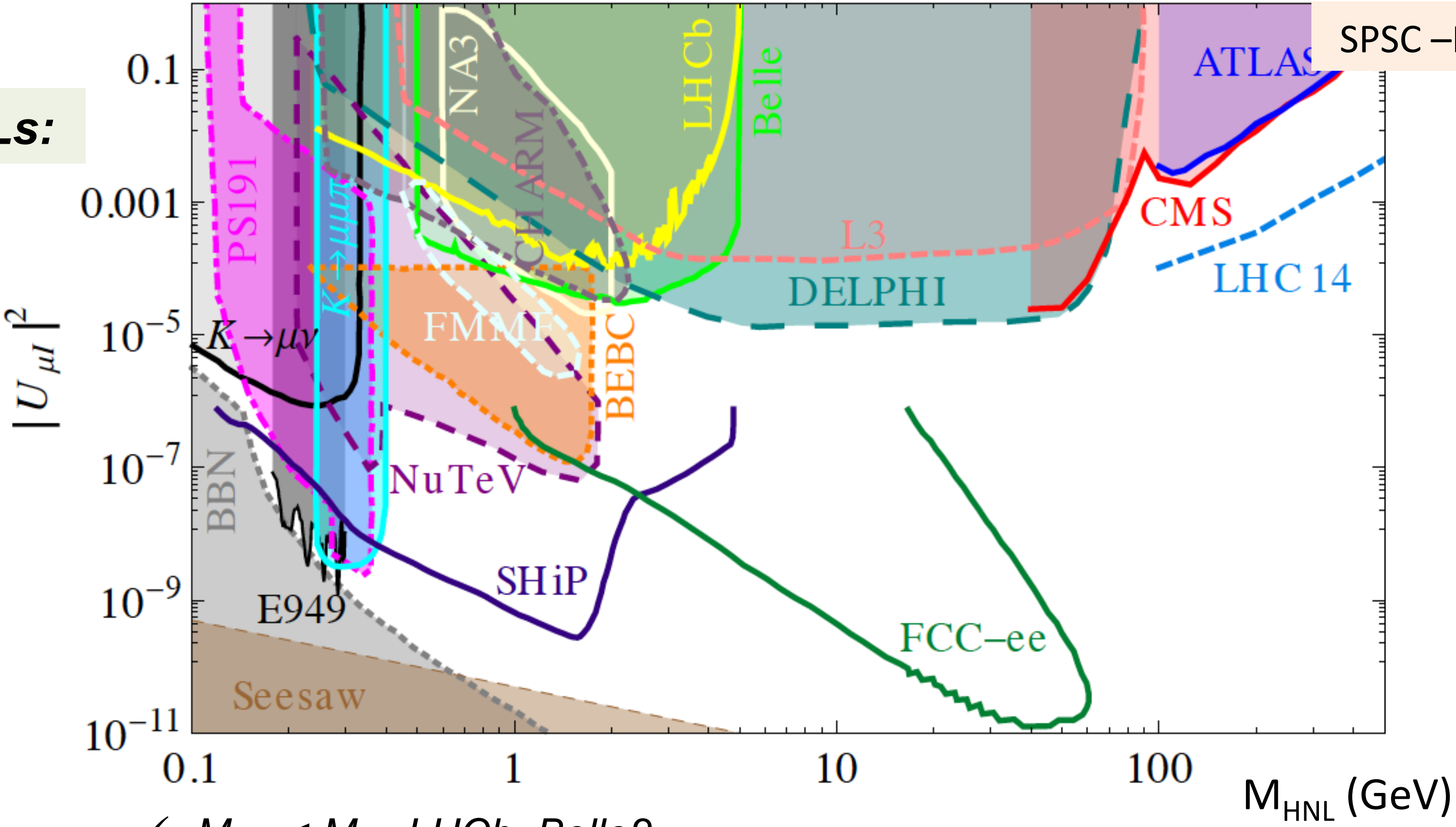
Muon trajectories

No evidence for any irreducible background !

Comparison with future facilities

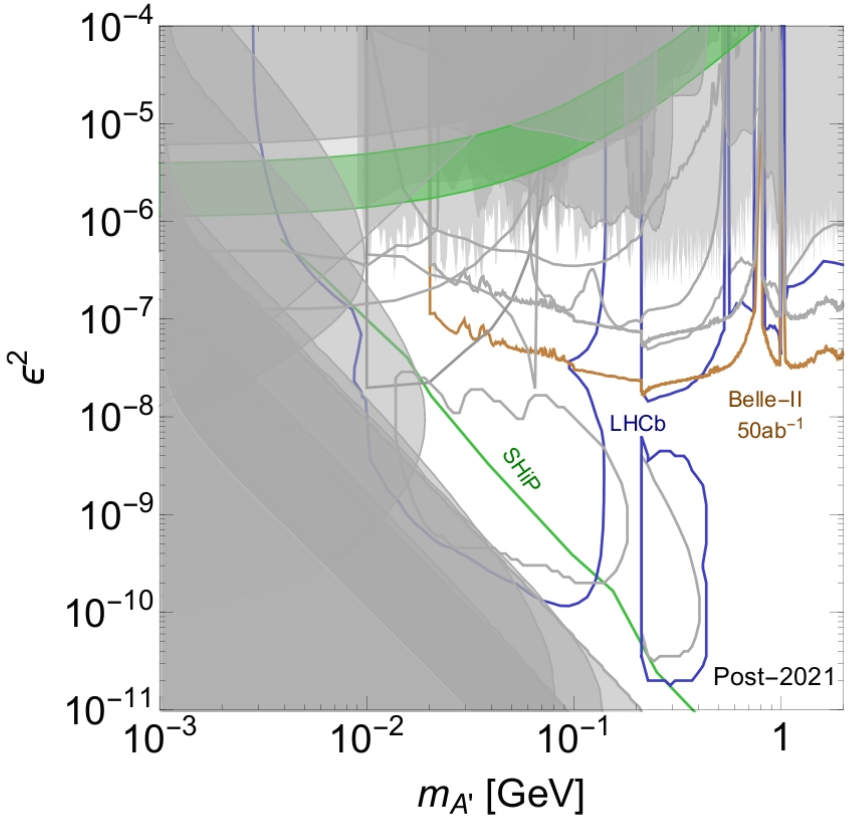
SPSC –P350-ADD-2

HNLs:



- ✓ *$M_{HNL} < M_b$ LHCb, Belle2*
  SHiP will have much better sensitivity
- ✓ *$M_b < M_{HNL} < M_Z$* ***FCC in e^+e^- mode*** *(improvements are also expected from ATLAS / CMS)*
- ✓ *$M_{HNL} > M_Z$* ***Prerogative of ATLAS/CMS @ HL LHC***

Also the best prospects for HS particles produced in heavy flavour decays (e.g. hidden scalars) and ν_τ physics



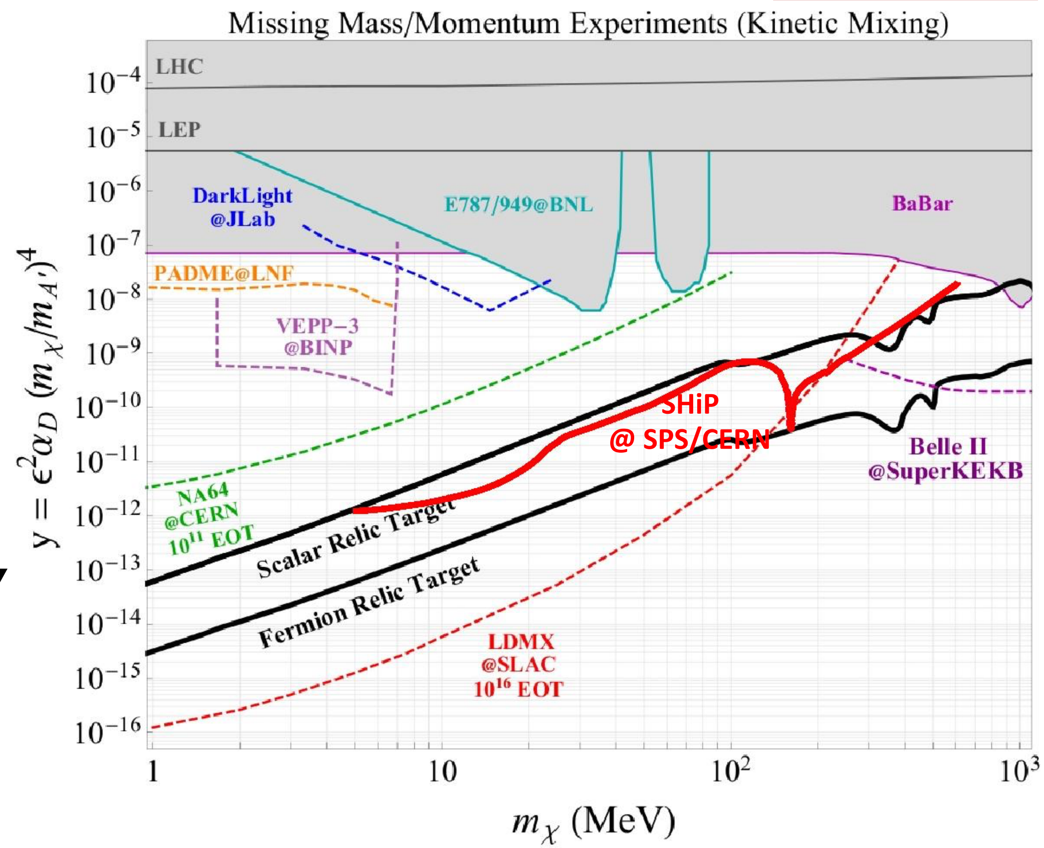
Comparison with future facilities

SHiP
Search for Hidden Particles

Dark photons:

SHiP is unique up to O(10GeV) and ε^2 < 10^{-11}
(see slide 12)

$M_{A'}/M_\chi=3$



Light Dark Matter

Direct Detection exp.

- ***SHiP has unique potential for M_χ <1GeV***
- *BDX in JLab may have a competitive sensitivity for M_χ <10 MeV with 10^{22}eot.*

Missing mass / momentum exp.

- *Belle II – comparable to SHiP for M_χ>0.5 GeV with 50 ab^{-1} provided that low energy mono-photon is implemented*
- *LDMX (under discussion at SLAC) has the best prospects for M_χ< 100 MeV with 3×10^{21} eot. Time scale is unclear.*

Dark sectors 2016: 1608.08632

Next steps towards Comprehensive Design Study (CDS)

(for European Strategy Panel)

Global optimization of the SHiP performance:

- ✓ *Configuration of the muon shield*
- ✓ *Shape, dimension and evacuation of the decay volume*
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID*

Updated background estimates and signal sensitivities, and cost

- ✓ *Contribution from the secondary interactions in the target improves signal yield by ~50%*
  Will be validated with data

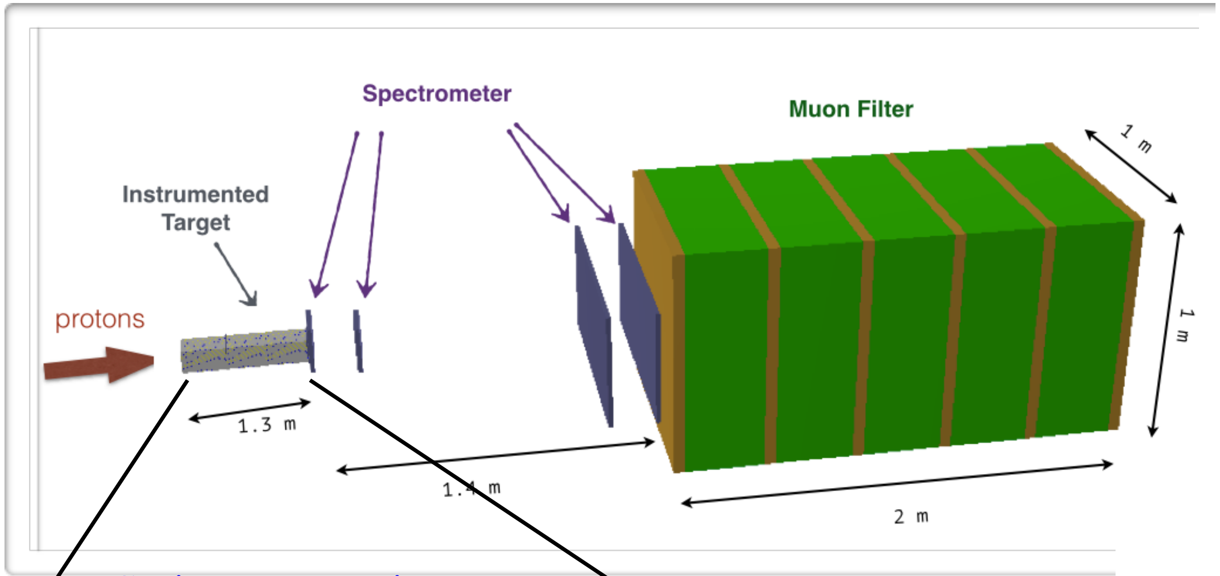
New groups are welcome to join SHiP at the CDS stage !

Active test beam programme in 2016-2018

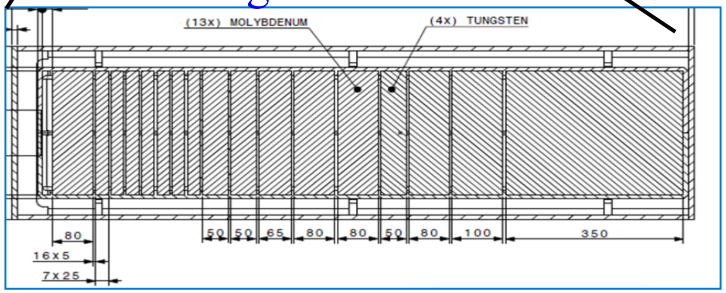
✓ ***Construct and test prototypes of various sub-detectors***

✓ ***Measurement of muon flux expected at SHiP***
Replica of the SHiP target in front of the NA-61/SHINE spectrometer

✓ ***Measurement of inclusive $d^2\sigma / dEd\theta$ charm cross section in SHiP-like target*** *(to validate cascade production in the target)*



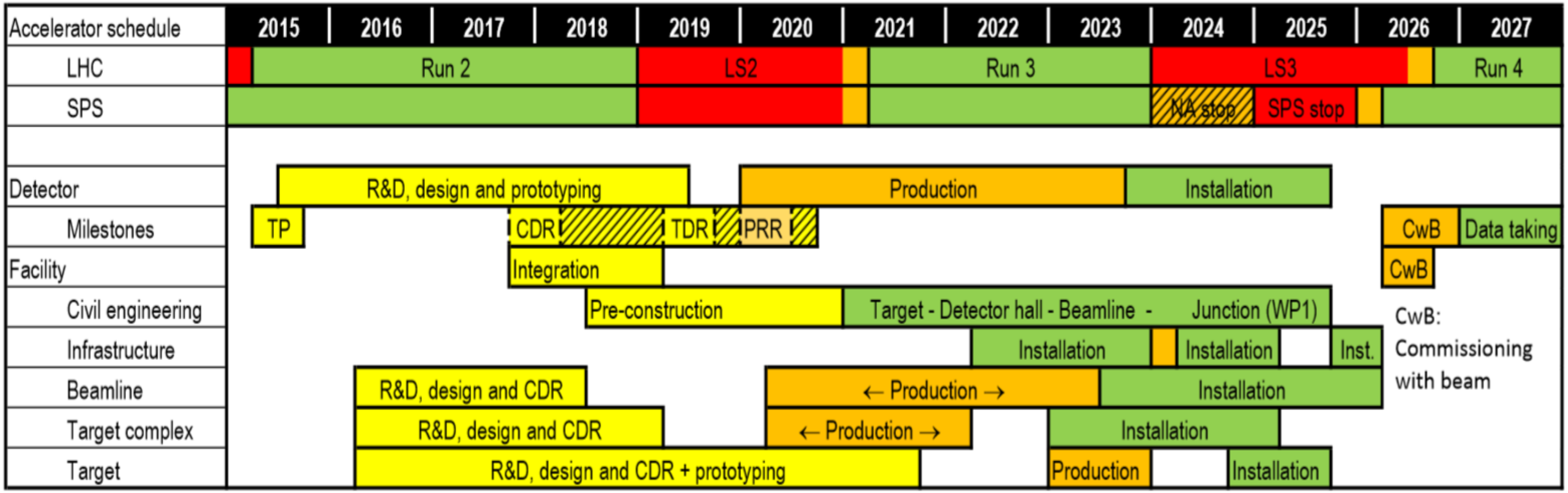
SHiP target as in TP



✓ ***SHIP target***, *10×10 cm² Mo/W blocks (few mm) interleaved with emulsion to identify charm topology*
✓ ***Spectrometer*** *to measure momentum and charge of the charm daughters*
✓ ***Muon detector*** *to measure muon flux*

Measurement strategy:
✓ *Low density beam exposure*
✓ *Instrumentation of ~1 int. length per run → 10 runs needed*

Global SHiP schedule



- ✓ ***Planning very well aligned with***
  - *Update of European strategy 2019/2020*
  - *Accelerator schedule (to be followed closely)*
  - *Production Readiness Reviews (PRR) 2020Q1 –*
  - *Construction / production 2020 –*
  - *Data taking 2026 (start of LHC Run 4)*

- ✓ ***Main current priority: Comprehensive Design Study by 2018***

Conclusions

- ✓ ***SHiP is an ideal experiment to search for new phenomena in < O(10 GeV) range in "no background" environment***
  Complementarity between two detection techniques:
  - *Reconstruction of the decay vertices in the decay volume*
  - *Interactions with atoms in the emulsion spectrometer*

- ✓ ***Physics case is very timely !***
  Many theoretical models offer a solution for the BSM experimental facts with light very weakly-interacting Particles ***. Must be tested !***

- ✓ *SHiP is based on existing technologies and can be built in time to start data-taking in 2026 (in line with the LHC schedule)*
  This requires approval in ~2020!

- ✓ ***No existing, or near future facility could make the proposed physics programme****, which nicely complements searches for NP at the LHC*