*Andrey Golutvin*
*Imperial College / CERN*

# *Search for Hidden Particles with the SHiP experiment*

*(on behalf of the SHiP collaboration)*

SHiP
*Search for Hidden Particles*

*See also other presentations at this workshop:*

- *Theoretical motivation: M. Shaposhnikov and A. Ringwald*
- *Beam-dump facility: G. Rumolo, L. Gatignon, M. Calviani and M. Fraser*

# 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 2019*
*→ 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***

# *The SHiP experiment at SPS*

*( as implemented in Geant4 for TP )*

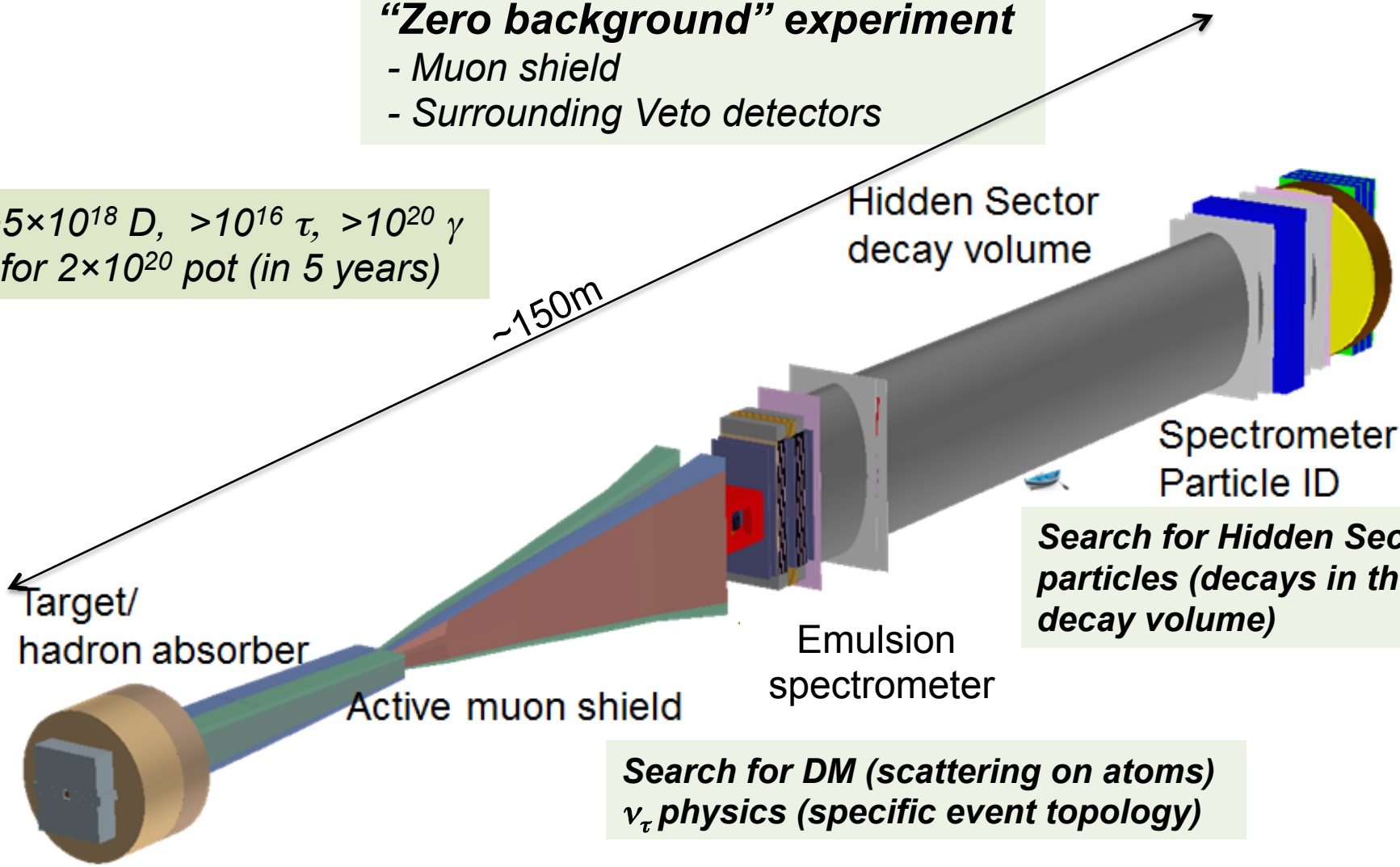
SHiP Technical Proposal: 1504.04956

***"Zero background" experiment***

*- Muon shield*

*- Surrounding Veto detectors*

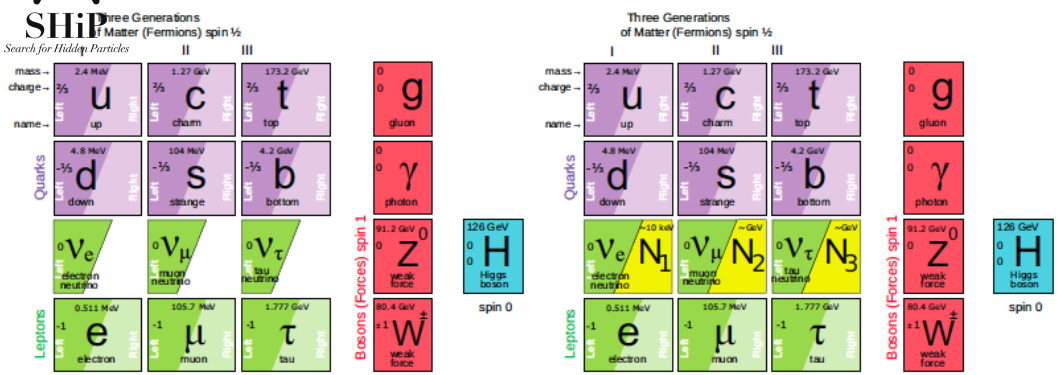
*>5×10$^{18}$ D, >10$^{16}$ $\tau$, >10$^{20}$ $\gamma$ for 2×10$^{20}$ pot (in 5 years)*




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

***Search for DM (scattering on atoms)***
***$\nu_\tau$ physics (specific event topology)***

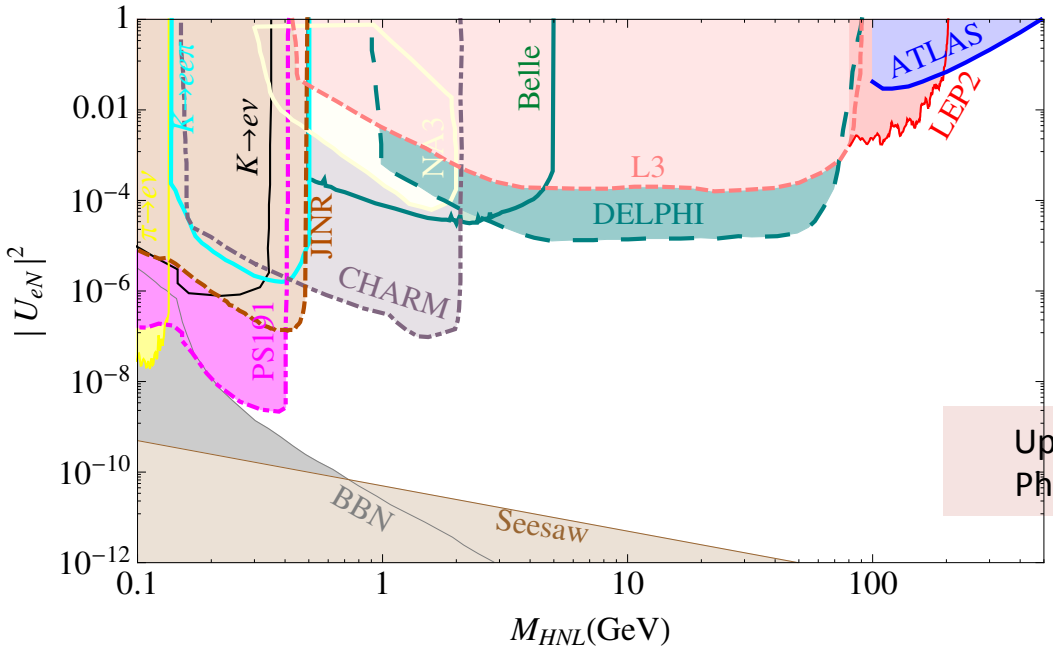
# ***Neutrino masses & BAU*** *can be solved with Heavy Neutral Leptons (HNL)*




***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***



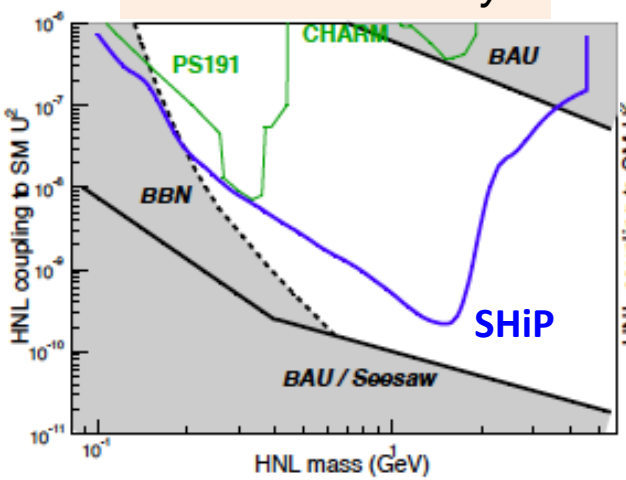

Updated SHiP Physics Paper

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

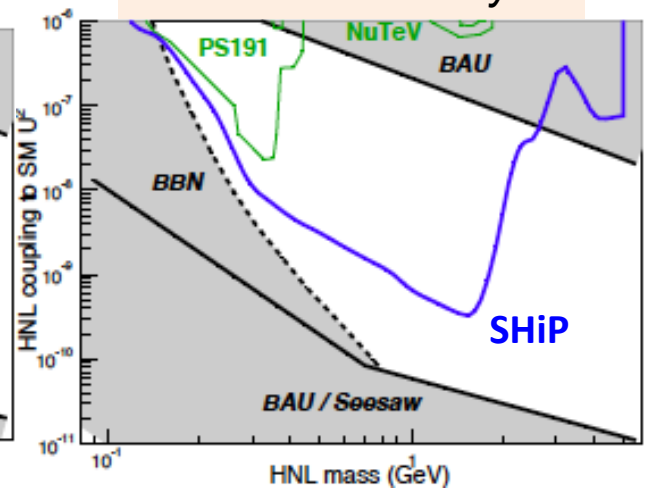
# HNL prospects @ SHiP

*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*

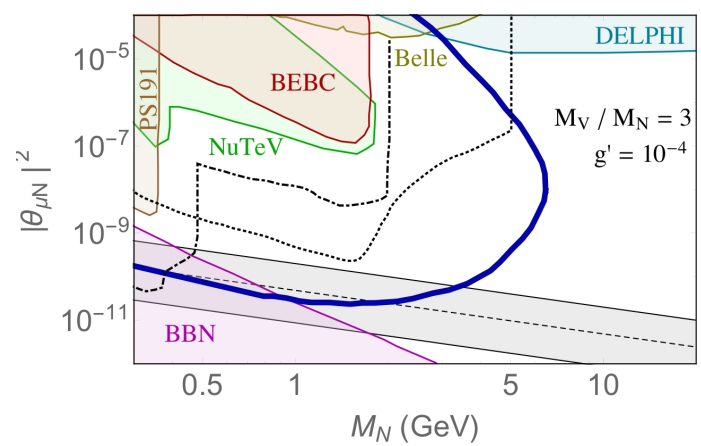



***Further studies:***

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***

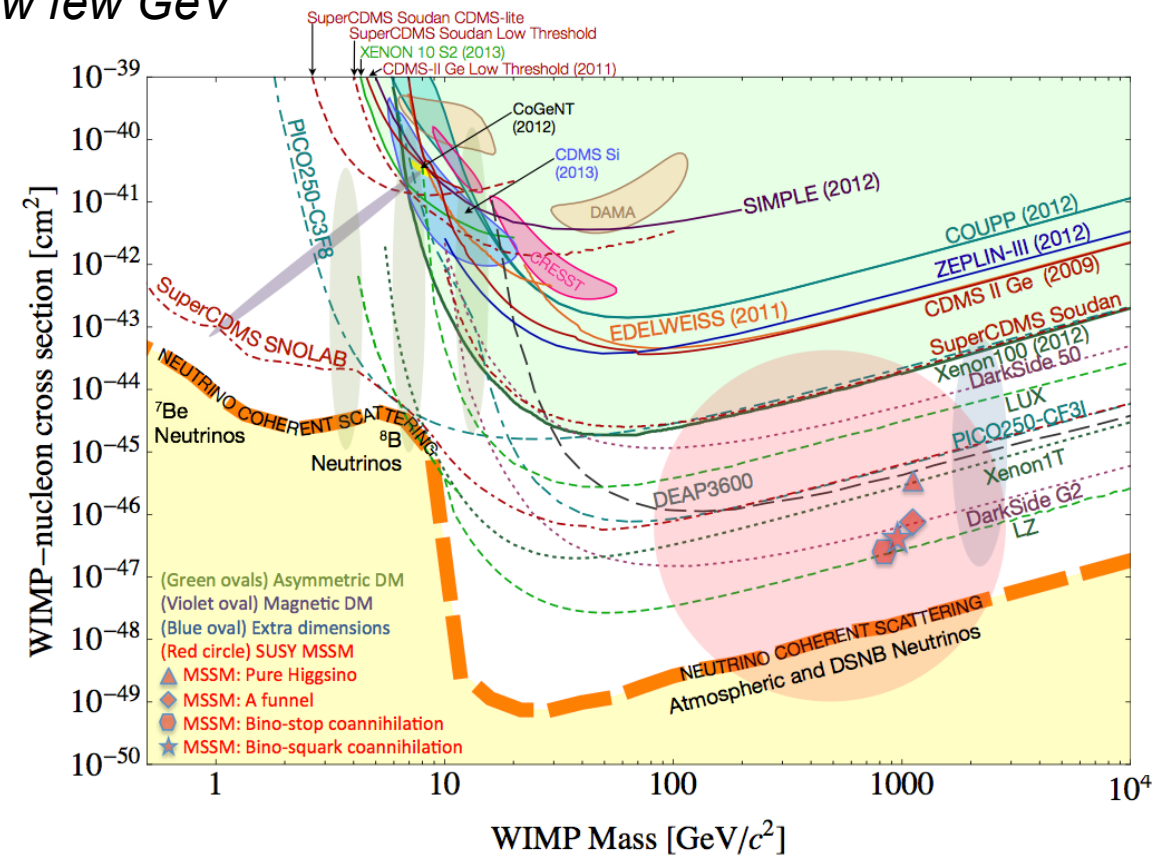
# Light Dark Matter (LDM)

**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**

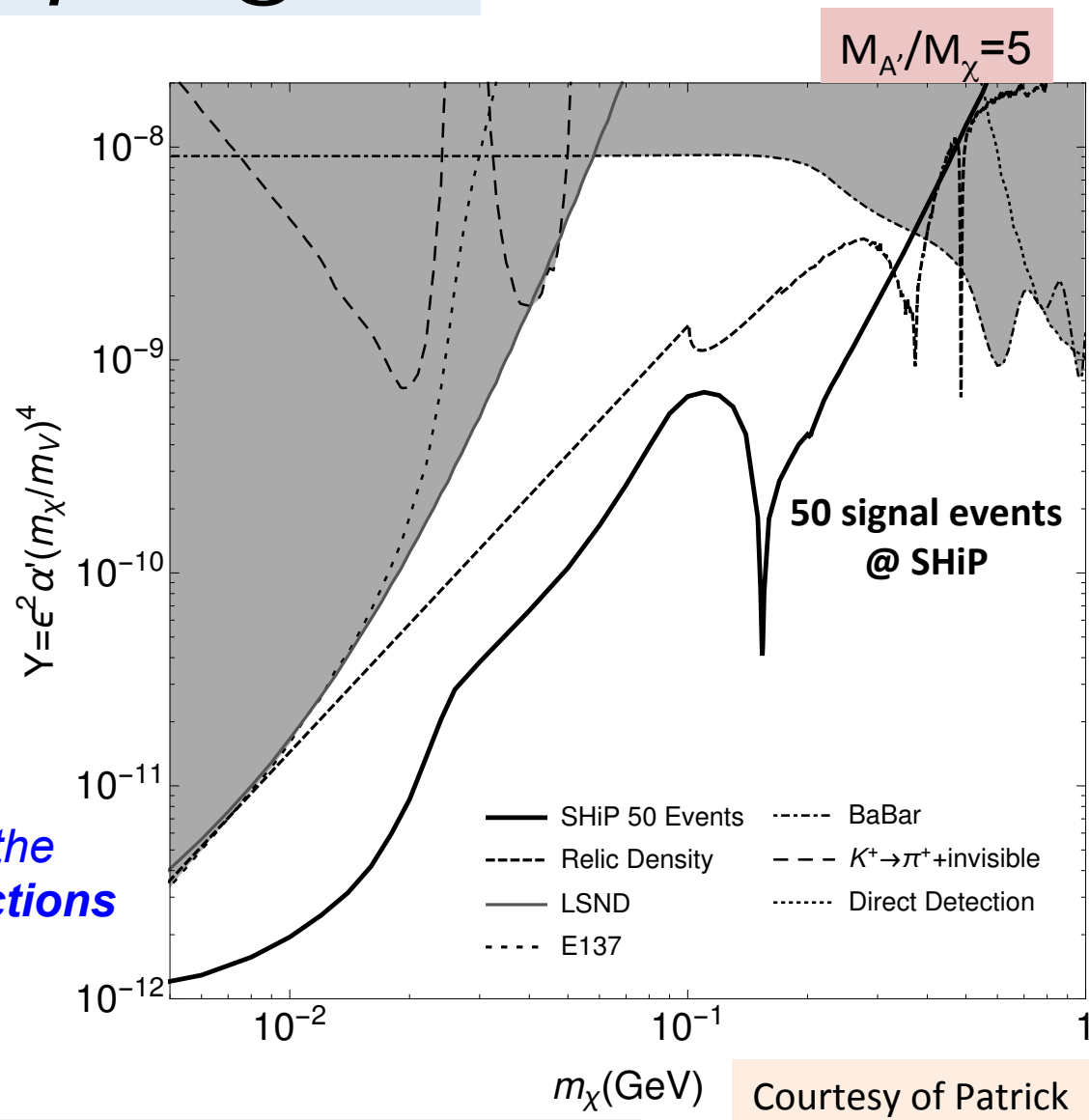
# LDM prospects @ SHiP

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

*>$10^{20}$ 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

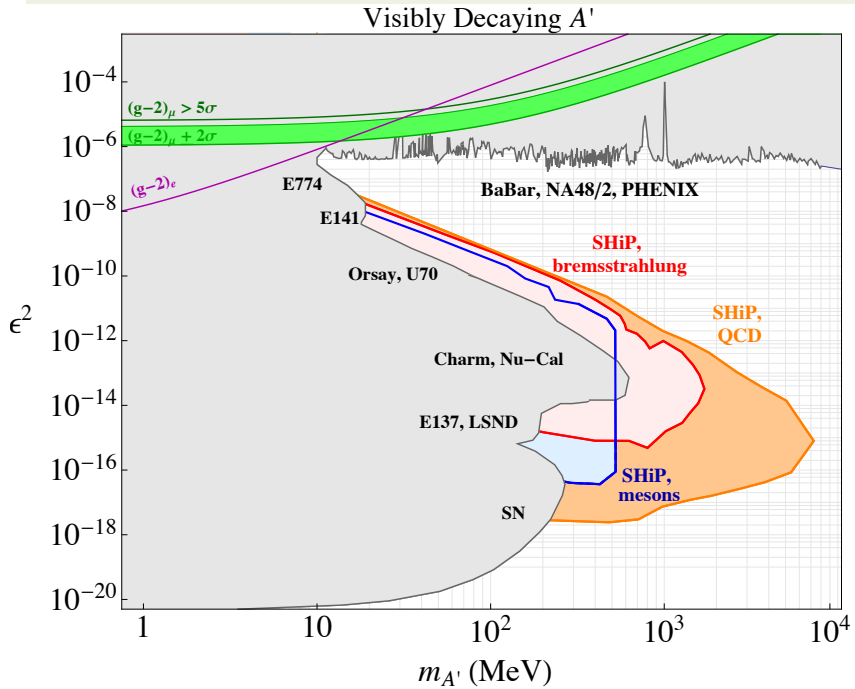
***Requires dedicated study/beam test for CDS !***

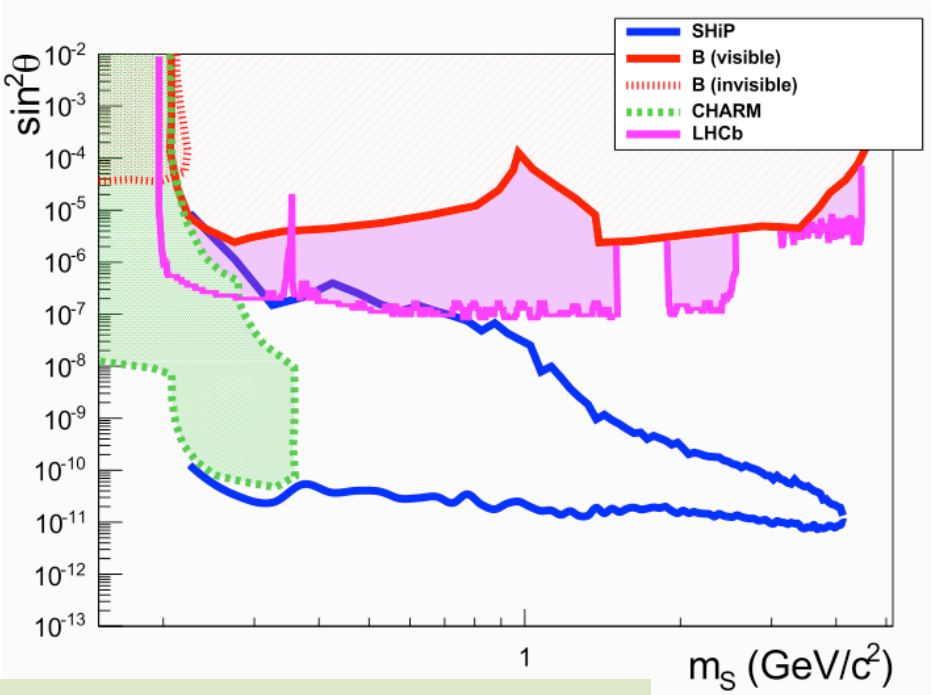
# SHiP sensitivity to hidden-sector mediators

- ✓ ***Dark photons*** → *U(1) associated particle* ***A' (γ')*** *in HS that can have non-zero mass and mix with the SM photon with* $\varepsilon$
  *Produced in QCD processes or in decays of* $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma'\pi^0$ *and* $\eta' \rightarrow \gamma'\gamma$

- ✓ ***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* $e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^+$, *KK*, $\eta\eta$, $\tau\tau$, *DD, …*



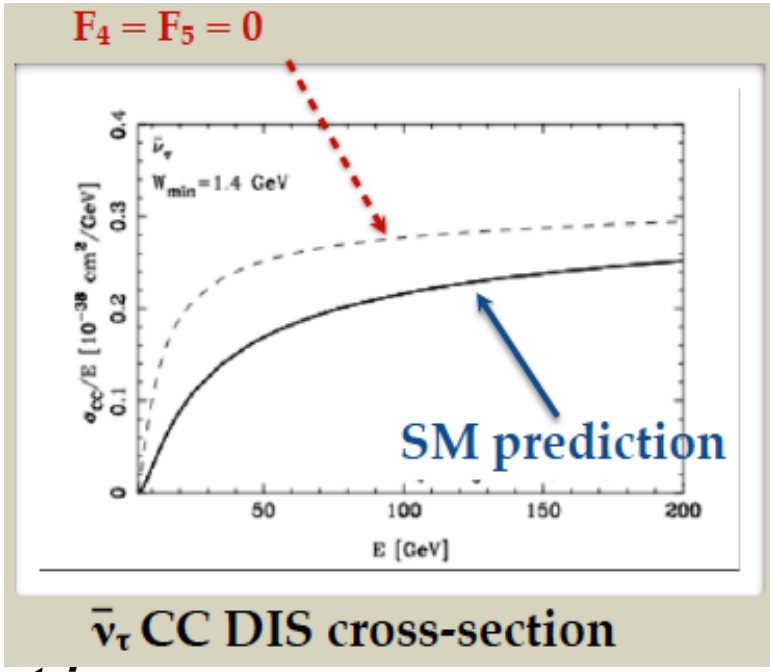

***SHiP probes unique range of couplings and masses***

# Neutrino physics @ SHiP

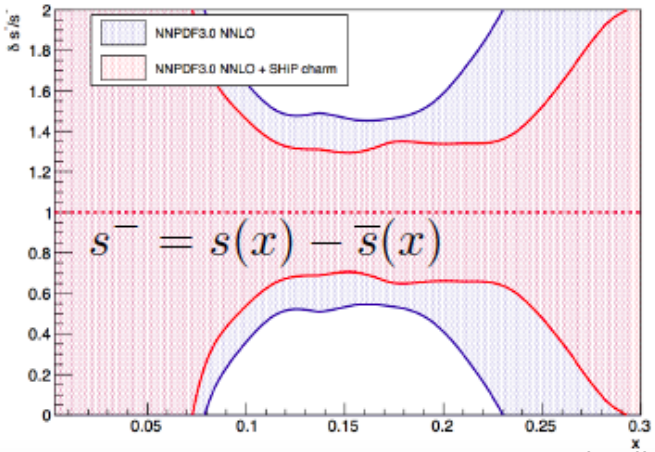
- ✓ ***Copious neutrino production,***
  *including $\nu_\tau$ from $D_s \rightarrow \tau\nu_\tau$*

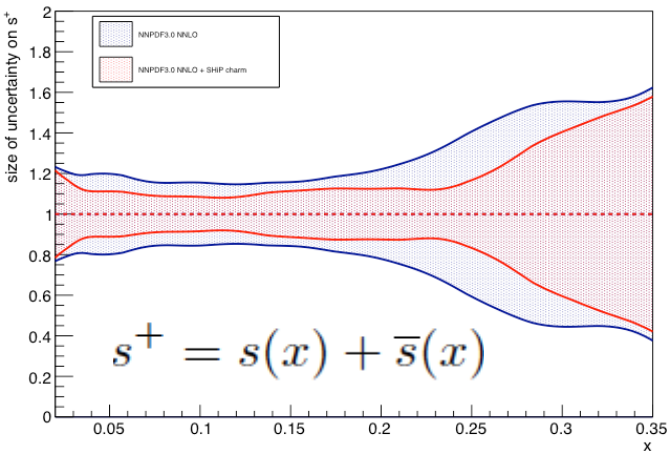
| | CC DIS |
|---|---|
| $N_{\nu_\mu} + N_{\overline{\nu}_\mu}$ | $2.4 \times 10^6$ |
| $N_{\nu_e} + N_{\overline{\nu}_e}$ | $3.4 \times 10^5$ |
| $N_{\nu_\tau} + N_{\overline{\nu}_\tau}$ | $1.1 \times 10^4$ |

- ✓ *First observation of the anti-$\nu_\tau$ interactions*
  *Measurement of F4, F5 structure functions*




- ✓ ***Charm physics with neutrinos and anti-neutrinos***
  *Charm yield in $\nu$ 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***

**>**

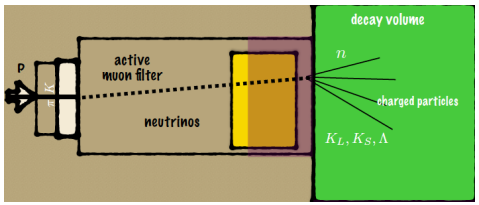
***Muon inelastic***

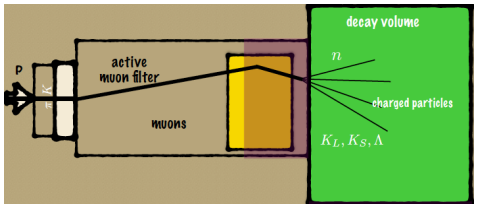
**>**

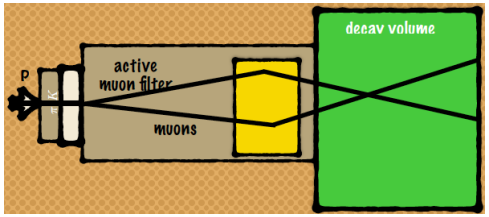
***Muon Comb.***

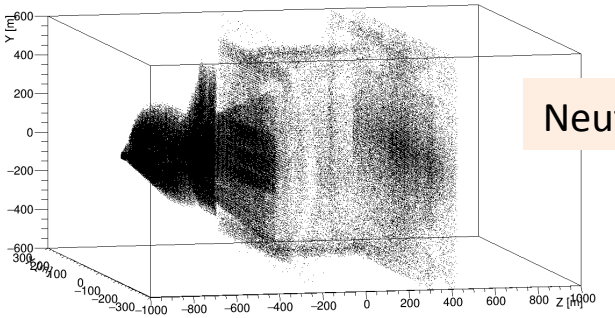
**>**

***Cosmics***



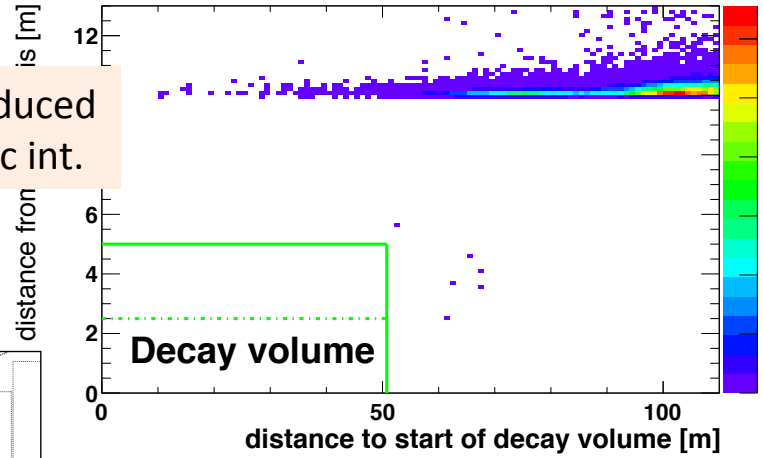



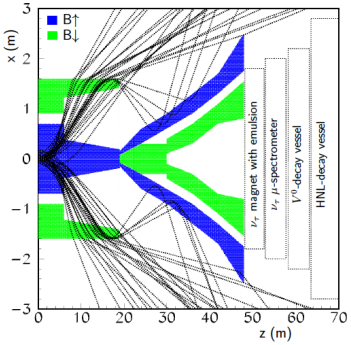




Neutrino tomography

Origin of $V_0$ produced in muon inelastic int.



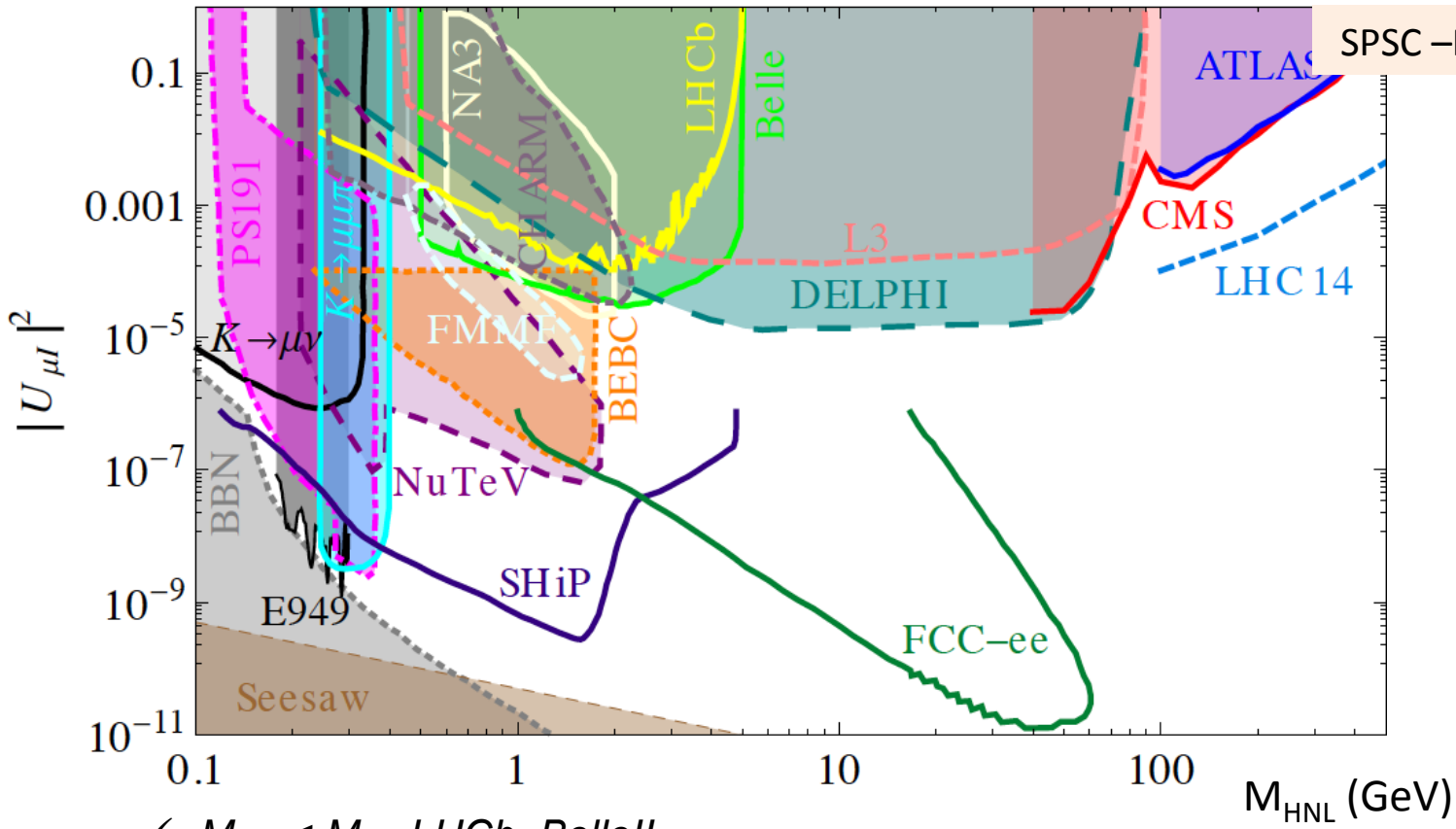




Muon trajectories

***No evidence for any irreducible background !***

# Comparison with future facilities

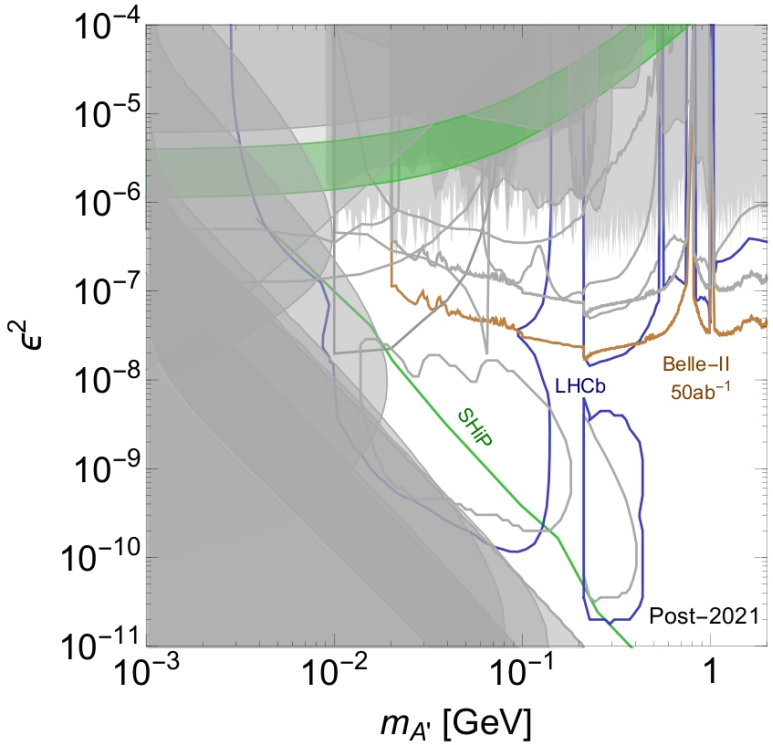
SPSC –P350-ADD-2




- ✓ $M_{HNL} < M_b$ LHCb, BelleII
  ***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 $\nu_\tau$ physics***

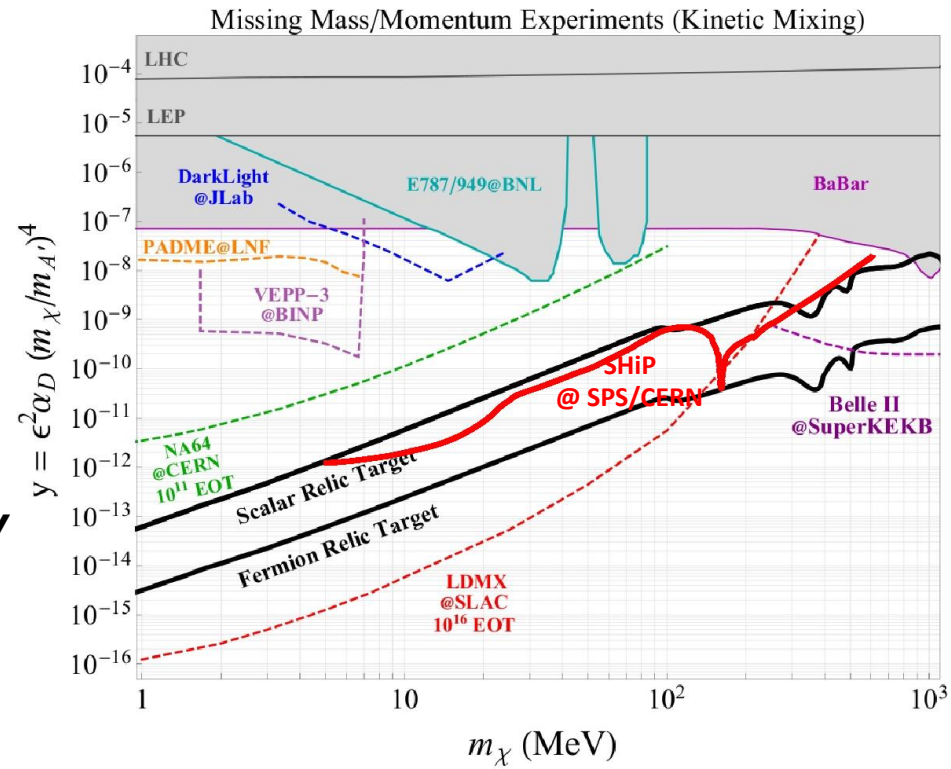
# Comparison with future facilities




## Dark photons:

***SHiP is unique up to O(10GeV) and $\varepsilon^2 < 10^{-11}$***
*(see slide 9)*

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




## Light Dark Matter

***Direct Detection exp.***

- ***SHiP has unique potential for $M_\chi$ <1GeV***
- *BDX in Jlab may have a competitive sensitivity for $M_\chi$ <10 MeV with $10^{22}$eot.*

***Missing mass / momentum exp.***

- *Belle II – comparable to SHiP for $M_\chi$>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 $M_\chi$< 100 MeV with 3×$10^{21}$ eot. Time scale is unclear.*

Dark sectors 2016: 1608.08632

# *Next steps towards Comprehensive Design Study*

*(for European Strategy Panel)*

***Global optimization of the SHiP performance:***

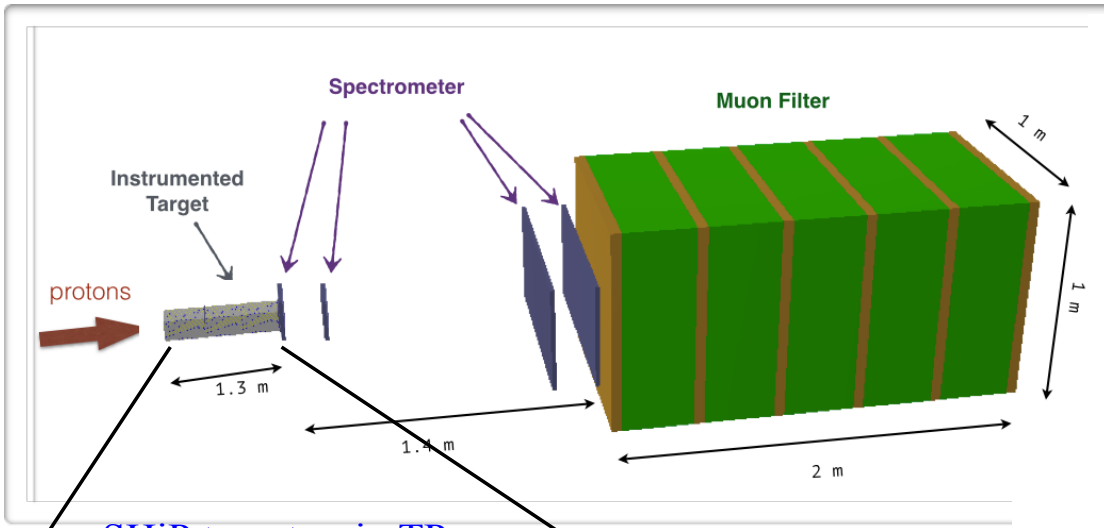
- ✓ *Configuration of the muon shield*
- ✓ *Shape, dimension and evacuation of the decay volume*
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID*

***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***

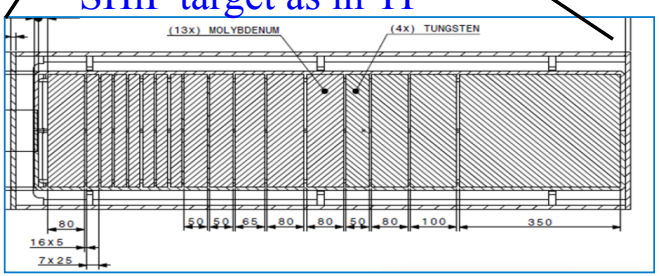
# Active test beam programme

- ✓ ***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***, *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*

SHiP target as in TP




***Measurement strategy:***

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

***Note also a proposal from DsTau coll. to measure $D_s$ yield (via $D_s \rightarrow \tau\nu_\tau$). See back-up slide.***

# 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!***

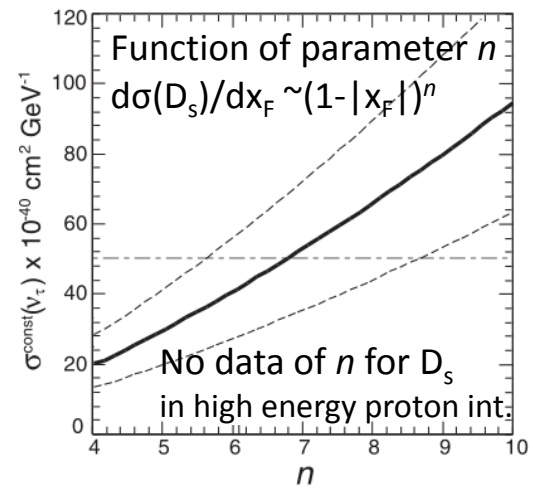
- ✓ ***No existing, or near future facility could make the proposed physics programme****, which nicely complements searches for NP at the LHC*

# *BACKUP*

# The DsTau project: Tau-neutrino production study at CERN SPS

- Aim: Improve knowledge of tau-neutrino production
  - Re-evaluate existing $\nu_\tau$ cross section (DONUT result): systematic uncertainty >50% → ~10%
  - Provide useful data for future $\nu_\tau$ experiments, e.g. SHIP
- Method: Direct measurement of tau-neutrino production in 400 GeV proton interactions
  - Dominant source (>95%): $D_s \to \tau\, \nu_\tau \to X\, \nu_\tau\, \nu_\tau$
  - Detect the double-kink topology in a few mm by emulsion detector
  - Measure $x_F$ distribution ($D_s$ momentum estimation using topological variables)
  - About 1000 $D_s \to \tau \to X$ events will be collected in $2\times10^8$ proton interactions
- Status
  - LOI submitted to the CERN-SPSC
  - Prototype test experiment in Nov. 2016 (with 20 $m^2$ emulsion surface)
- Collaboration
  - Japan, Romania, Russia, Switzerland and Turkey

DONUT result




Proton target in this project: tungsten foil + emulsion tracker

Double-kink topology