SHiP: Search for Hidden Particles

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Outline:

- ✓ Physics case
- ✓ Overview of the detector and simulation
- ✓ Physics performance
- ✓ Detector challenges and project plan
- ✓ Status of collaboration

SHiP history in brief:

- ✓ Letter Of Intent - October 2013
- ✓ Technical Proposal & Physics Paper - April 2015
- ✓ Reviewed by the SPSC and CERN RB by March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2019
  → Input to the European strategy consultation to take a decision about construction of SHiP in 2020

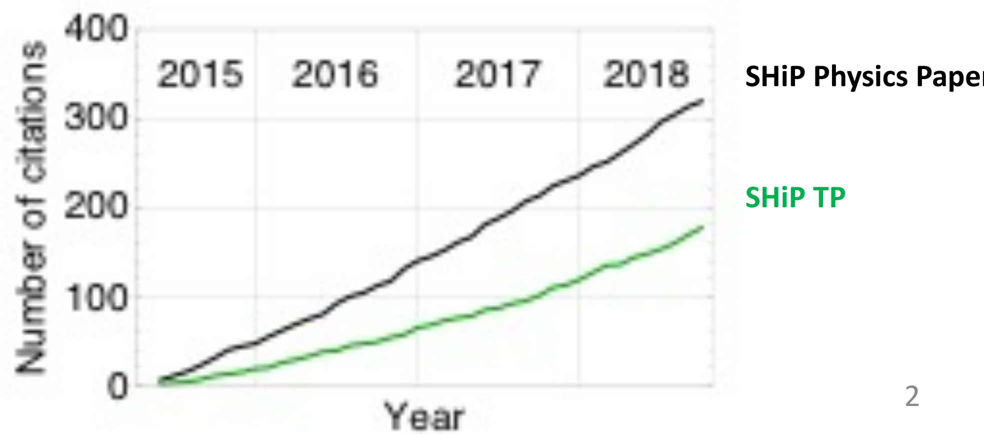
CDS will improve SHiP TP version *respecting cost constraints*

→

Physics landscape today

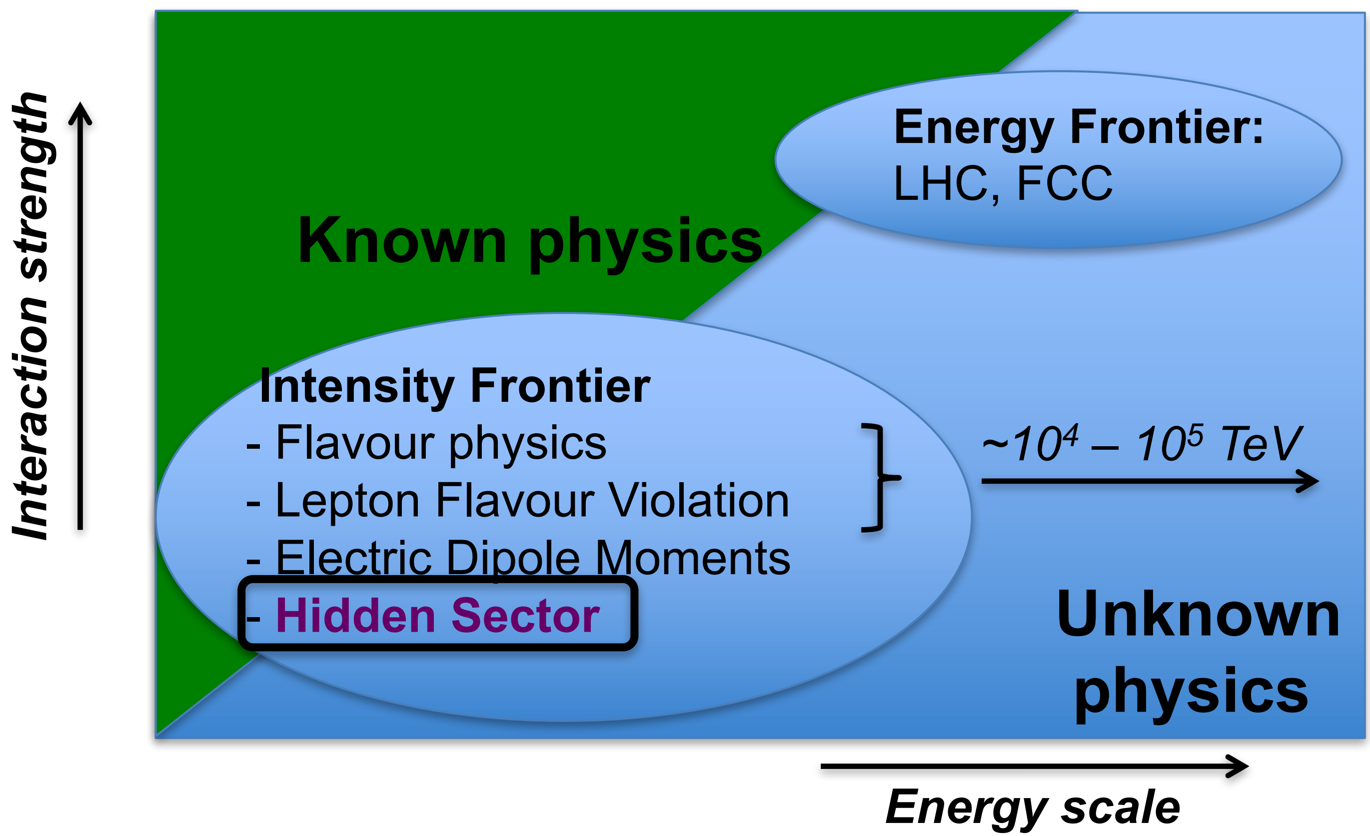
1. Direct searches for NP by ATLAS and CMS have not been successful so far
   → Parameter space for popular BSM models is decreasing rapidly,
   but only 10% of the complete HL-LHC data set has been delivered so far
   → NP discovery still may happen
2. LHCb reported intriguing hints for the violation of Lepton Flavour Universality
   in $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to s e^+e^-$ / $b \to s\mu^+\mu^-$ decays
   → Clear evidence of BSM physics if substantiated with further studies
   But even then it will not be possible to determine NP scale with certainty
   Many models predict enhanced LFV effects (some close to the current experimental limits) in decays of τ lepton (see talk of Guy Wilkinson on TauFV)
3. Significant efforts in neutrino physics did also not ameliorate our knowledge about NP scale. Neutrino masses and oscillations can be accounted in SM extended by two sterile neutrinos of essentially any mass
4. DM: no evidence for WIMP in GeV-TeV mass range neither in direct nor in indirect searches → Light DM?

Growing interest to Hidden Sector models →



Quest for New Physics

- ✓ Higgs discovery made the SM complete
- ✓ SM s a great theory but does not represent the full picture
- ✓ NP should exist but we have no definitive predictions on the masses and coupling constants of NP particles



Hidden Sector

Many theoretical models (portal models) predict new massive light particles which can be tested experimentally

SHiP Physics Paper – Rep.Progr.Phys.79(2016) 124201 (137pp),
SLAC Dark Sector Workshop 2016: Community Report – arXiv: 1608.08632,
Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591
Report by Physics Beyond Collider (PBC) study group – to be published

Hidden Particles:

- ✓ *Light Dark Matter (LDM)*
- ✓ *Portals (mediators) to Hidden Sector (HS):*
  - *- Heavy Neutral Leptons (spin ½, coupling coefficient U^2)*
  - *- Dark photons (spin 1, coupling coefficient ε)*
  - *- Dark scalars (spin 0, coupling coefficient $\sin\theta^2$)*
  - *- Special case (non-renormalizable) Axion Like Particles (ALP)*

Properties of Hidden Particles

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

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*

Portal models	*Final states*
HNL	$l^+\pi^-$, l^+K^-, $l^+\rho^-$
Vector, scalar, axion portals	l^+l^-
HNL	$l^+l^-\nu$
Axion portal	$\gamma\gamma$

Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression

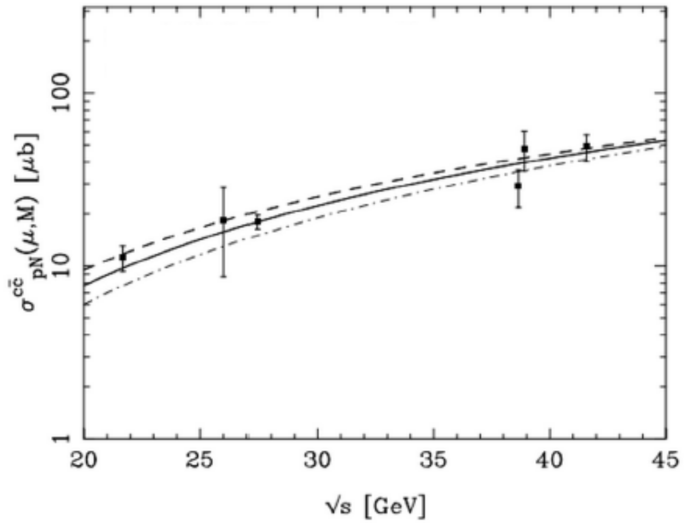
General experimental requirements

to search for decaying Hidden Particles

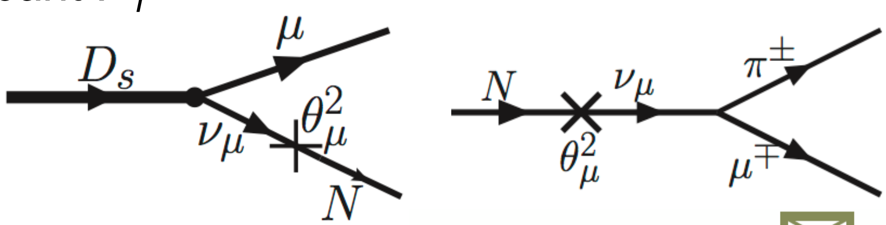
- ✓ *Particle beam with maximal intensity*
- ✓ *Search for HS particles in Heavy Flavour decays*

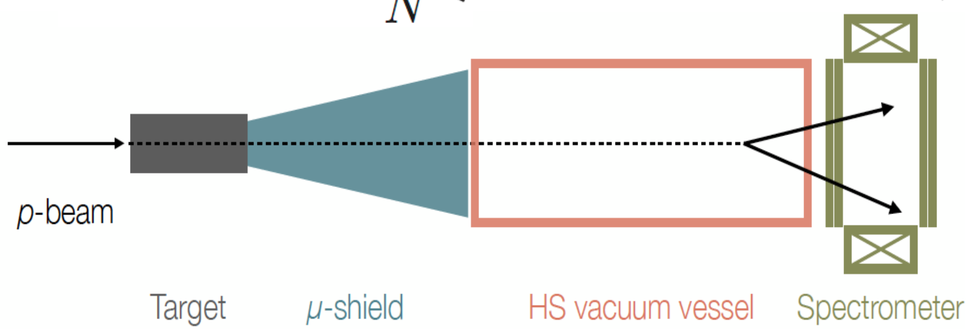
  Charm (and beauty) cross-sections strongly depend on the beam energy.

  At CERN SPS: σ(pp→ssbar X)/σ(pp→ X) ~ 0.15
  σ(pp→ccbar X)/σ(pp→ X) ~ 2 10^{-3}
  σ(pp→bbbar X)/σ(pp→ X) ~ 1.6 10^{-7}



- ✓ *HS produced in charm and beauty decays have significant P_T*





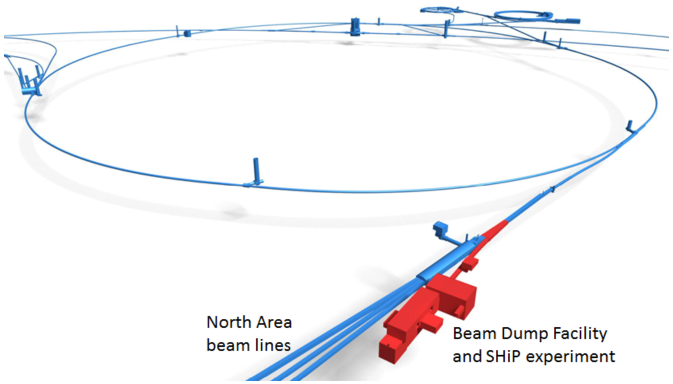
Long decay volume and large geometrical acceptance of the spectrometer are essential to maximize detection efficiency

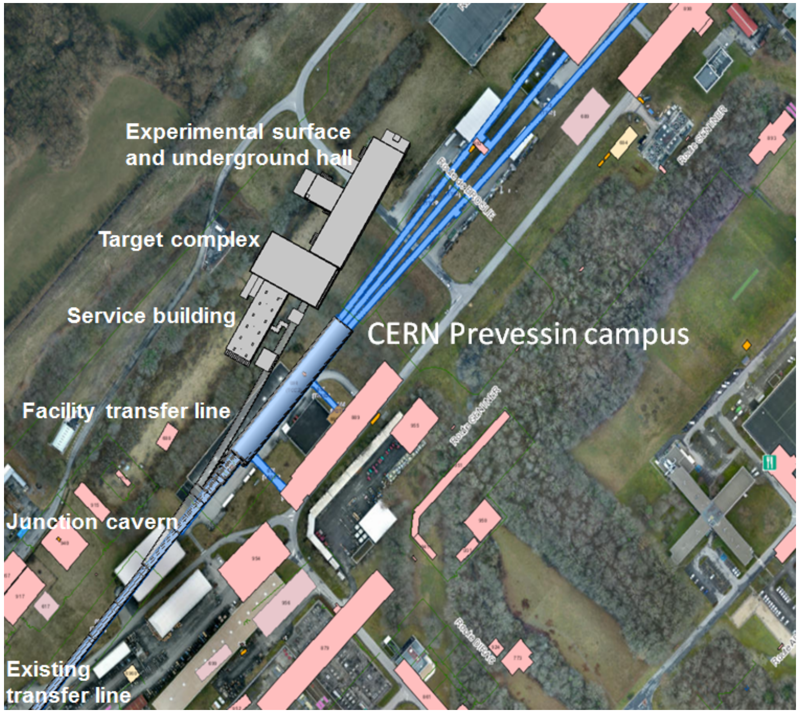
Detector must be placed close to the target to maximize geometrical acceptance.
Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds

Beam Dump Facility (BDF) at CERN (1)

✓ **Location at CERN**

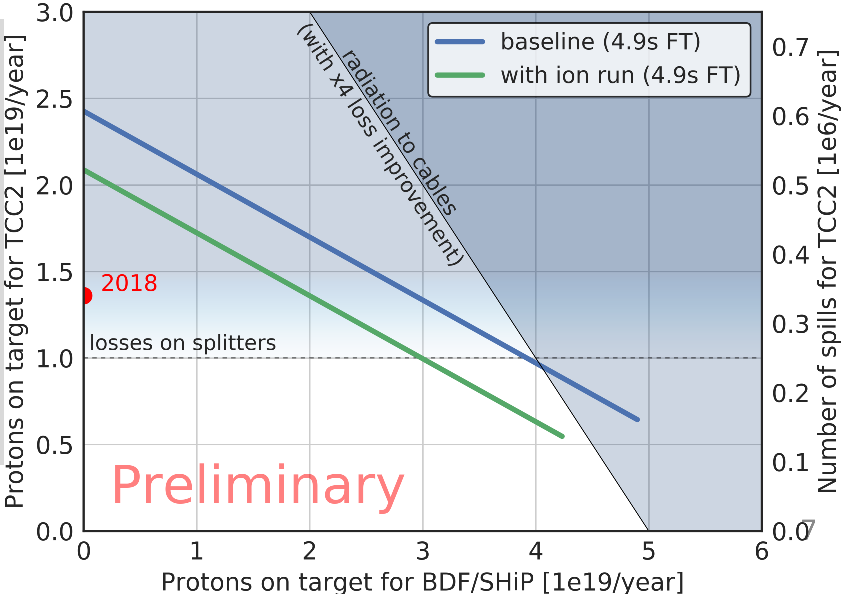
New 400 GeV proton beam line branched off the splitter section of the SPS transfer line to the North Area





✓ **Proton yield and beam delivery**

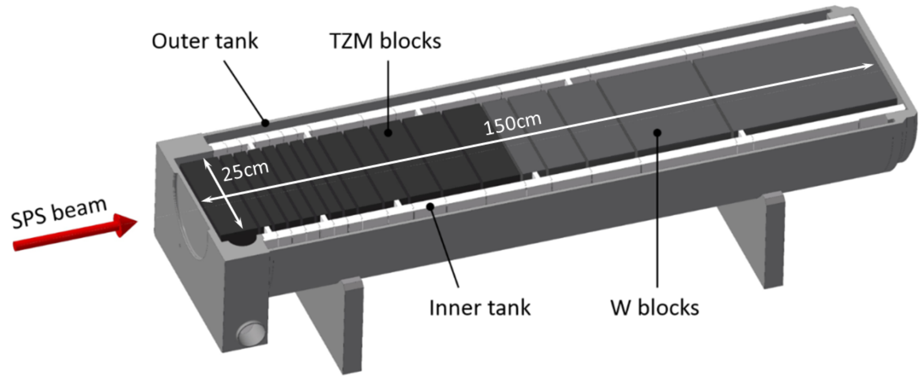
- *Nominal beam intensity 4×10^{13} pot per spill*
- *Baseline scenario: annual yield of 4×10^{19} pot to the BDF, and 10^{19} pot to the other experiments in the North Area, while respecting HL-LHC requirements*
- *SHiP sensitivities assume 5×10^{20} pot in five years of nominal operation*

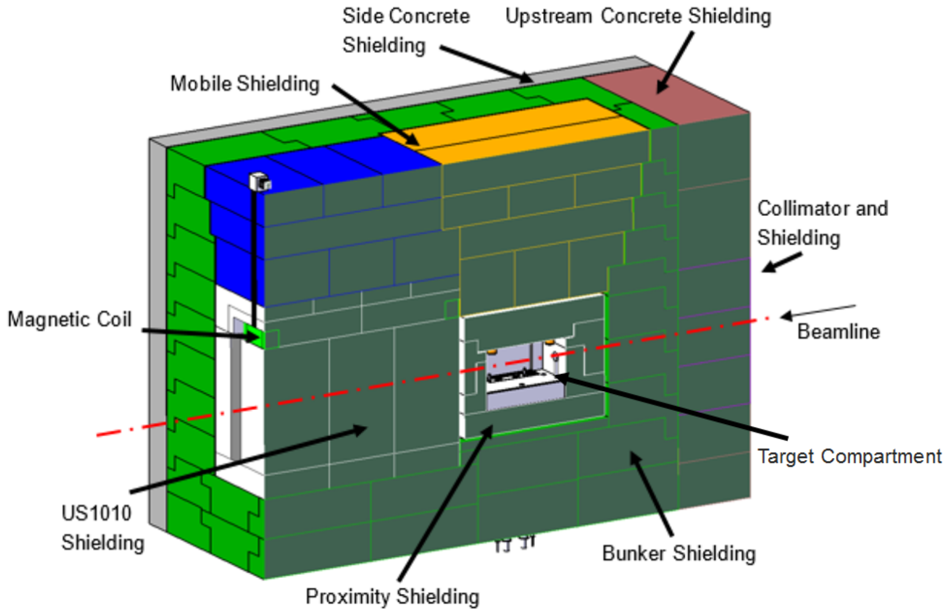


Beam Dump Facility (BDF) at CERN (2)

✓ ***Target***

- *Made of blocks of TZM alloy, in the proton shower core, followed by pure Tungsten*
- *Total depth 12 λ_{int}*
- *Absorbs majority of hadrons before their semileptonic decays*





✓ ***Target complex***

- *Hadron stopper (5 m long) absorbs hadron and em-radiation emerging from the target*
- *Equipped with a coil which magnetises the iron shielding blocks to serve as the first section of the muon shield*

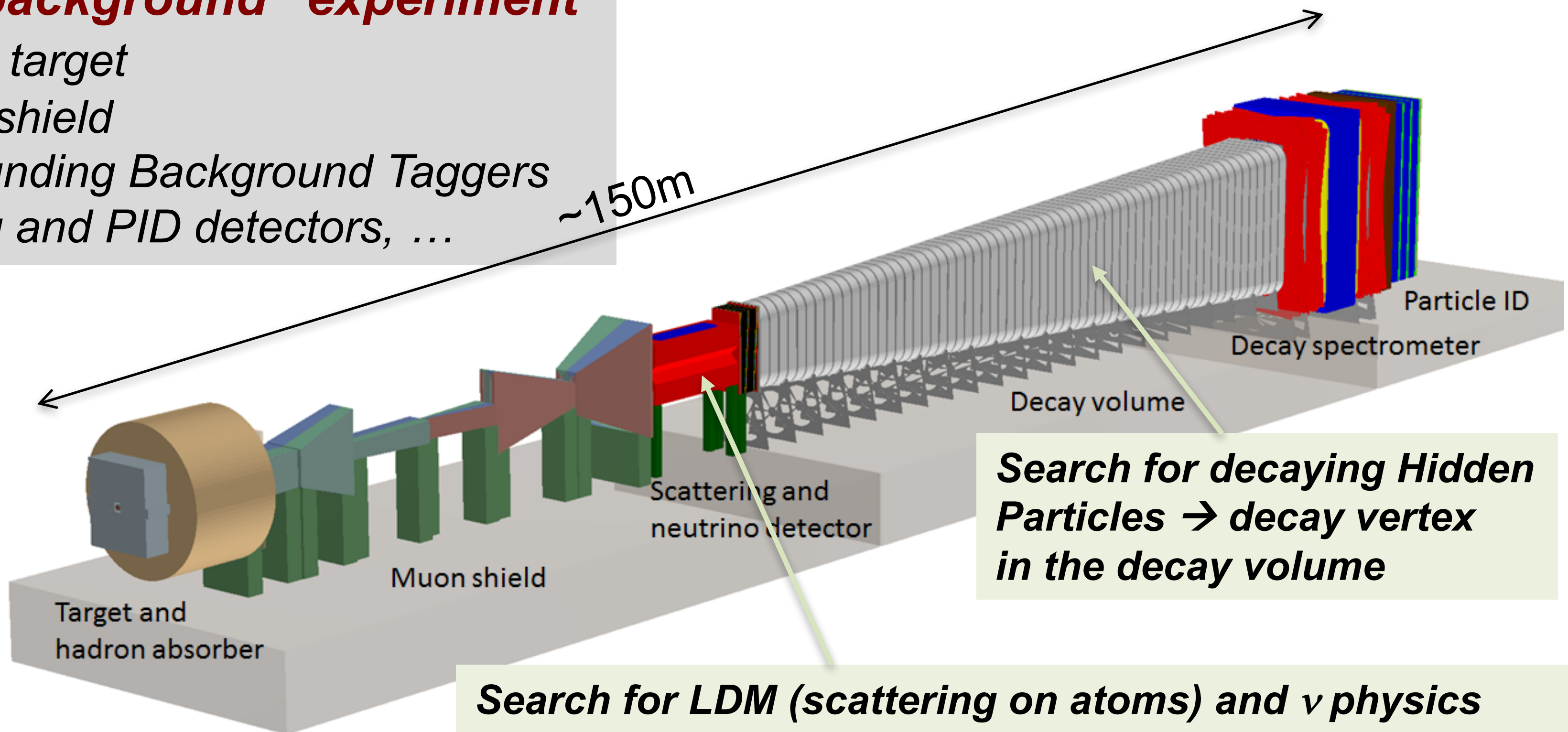
SHiP detector at BDF/CERN

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 Background Taggers*
- *Timing and PID detectors, …*

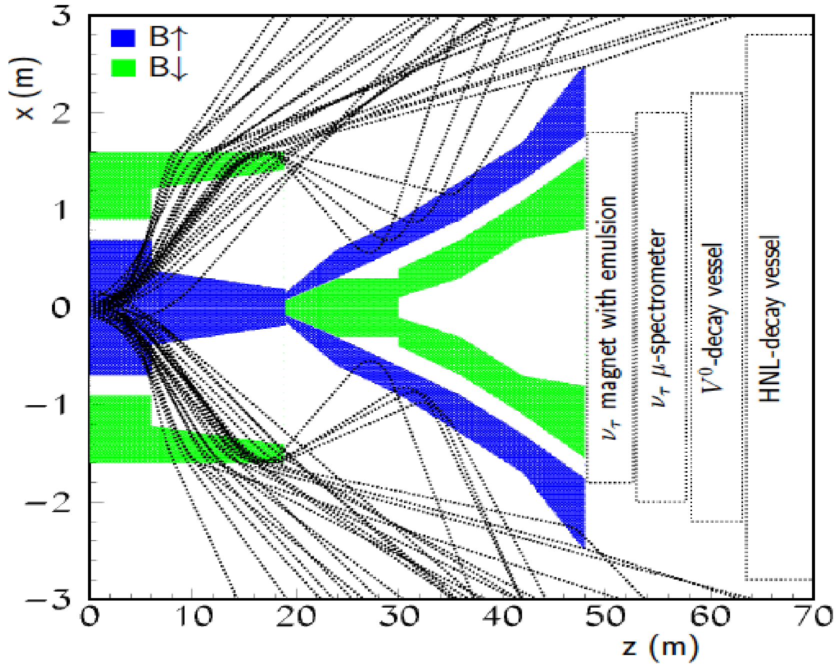


Search for decaying Hidden Particles → decay vertex in the decay volume

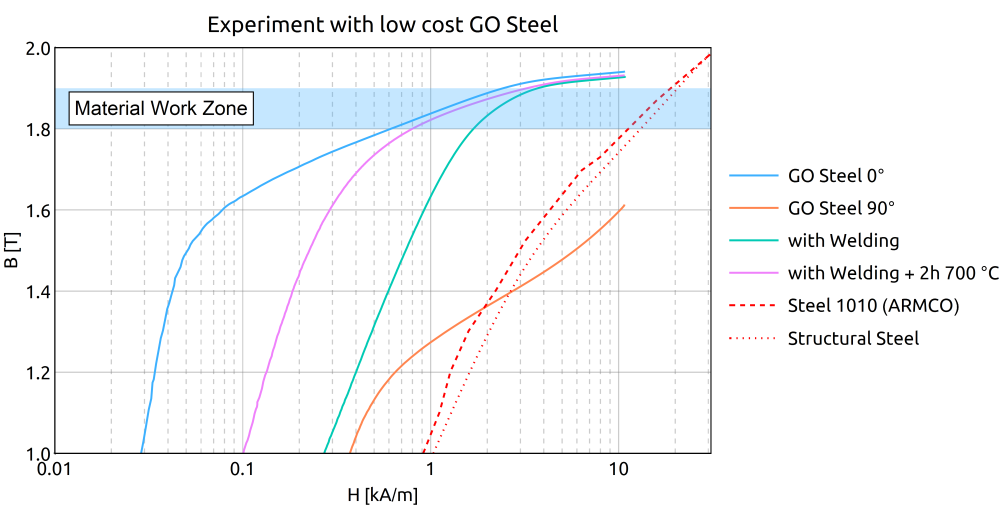
Search for LDM (scattering on atoms) and ν physics
Specific event topology in emulsion. Background from neutrino interaction for vWIMP searches can be reduced to a manageable level

Active Muon Shield

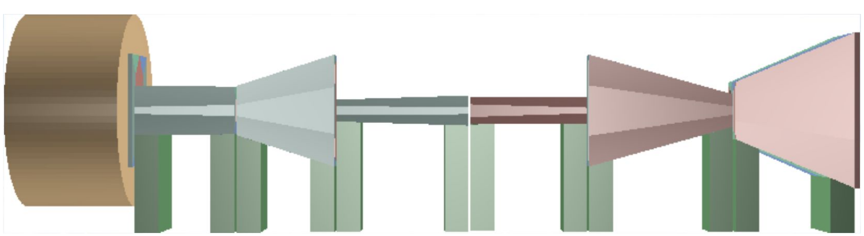
- ✓ *Shield is entirely based on magnetic sweeping*
- ✓ *Initial muon flux ~10^{11} muons / sec*
- ✓ *Residual flux ~50 kHz → negligible occupancy!*



***Huge object:** 5m high, 40m long, Weight ~2000 tons, made of 300 mkm thick sheets of GO steel to achieve 1.8 T field*



Shape optimised using Machine Learning technique



SHiP simulation (FairShip)

✓ ***FairShip*** *incorporates up-to-date versions of*

- GEANT4 to trace particles through the target and detector

Some rare processes producing high momentum muons, such as decays of light vector mesons, γ–conversions and positron annihilation, enabled and boosted by 100

- PYTHIA8 for the primary proton fixed-target interactions

Includes cascade production of charm and beauty from secondary hadrons

- PYTHIA6 for muon DIS

- GENIE for neutrino interactions

✓ ***Production and decays of HS particles are implemented*** *following the recipes of the PBC study group*

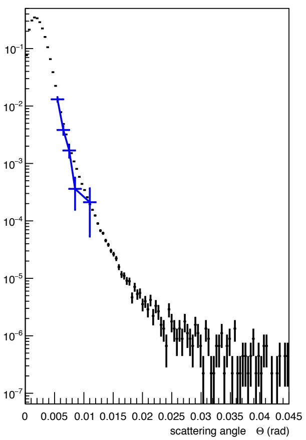
✓ ***Simulated data samples***

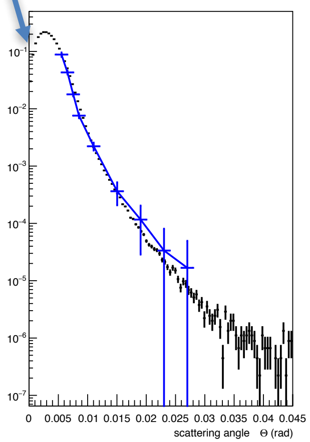
- 65×10^9 protons on target with E > 10 GeV to transport particles after hadron absorber (1.8×10^9 protons on target with E > 1 GeV)

- The samples with charm and beauty hadron correspond to ~10^{11} pot

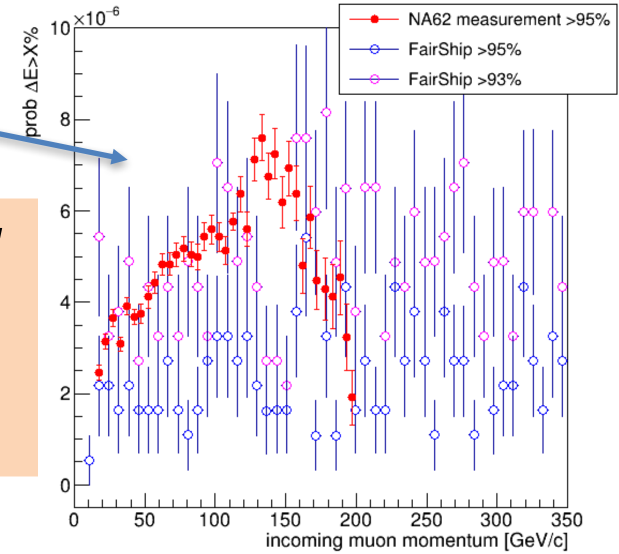
Validation of the SHiP simulation

✓ Multiple scattering and catastrophic energy losses





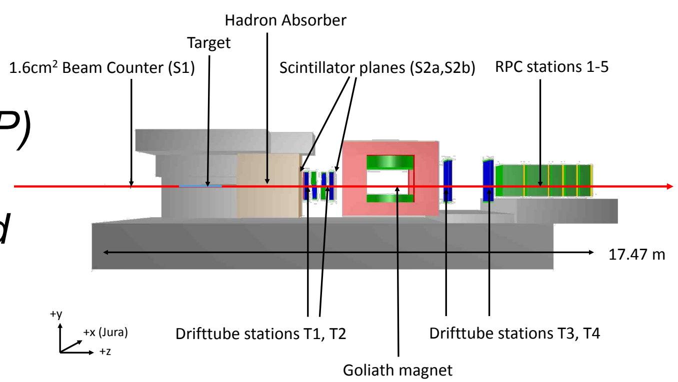
Description of multiple scattering and catastrophic energy loss, which may influence the muon shield performance, tested with existing data



✓ Fluxes and momentum spectra of muons produced in beam dump

- ✓ *Prediction of muon fluxes verified with data from CHARM (see SHiP TP)*
- ✓ *Most realistic cross-check performed in summer 2018*

→ *dedicated measurement of the rate and momentum of 400 GeV protons dumped on a replica of the SHiP target*



Decaying Hidden Particles

- ***Neutrino portal***
  LFV final states → HNL signal can easily be discriminated against other portals

- ***Vector portal***
- ***Scalar portal***
- ***ALP***

Note:
Identical final states with charged particles
(but different BRs of decay channels
and different kinematics of decay products)
→ Need significant statistics to discriminate between portals

ALPs can decay to the 2-photon final state with sizeable BR
→ Electromagnetic calorimeter is essential to distinguish between ALP signal and dark photon, or dark scalar

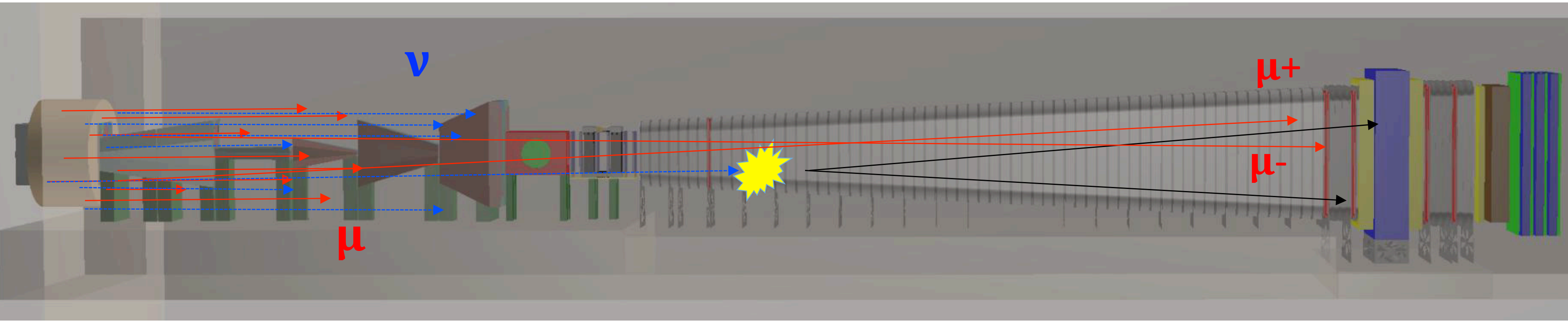
Event selection for decaying Hidden Particles

- ✓ *Event selection is based on very high signal efficiency and redundant background suppression*
- ✓ ***Common selection to ensure model independent search***
- ✓ ***All HS models require an isolated vertex in the decay volume***

Cut	Value
Track momentum	> 1.0 GeV/c
dimuon distace of closes approach	< 1 cm
dimuon vertex	fiducial (> 5 cm from inner wall)
IP w.r.t target (fully reco)	< 10 cm
IP w.r.t target (partially reco)	< 250 cm

- ✓ ***Redundancy cuts:***
  - *Veto criteria from the taggers*
  - *PID cuts*
  - *Time coincidence cut (to reject combinatorial background)*

Backgrounds (1)

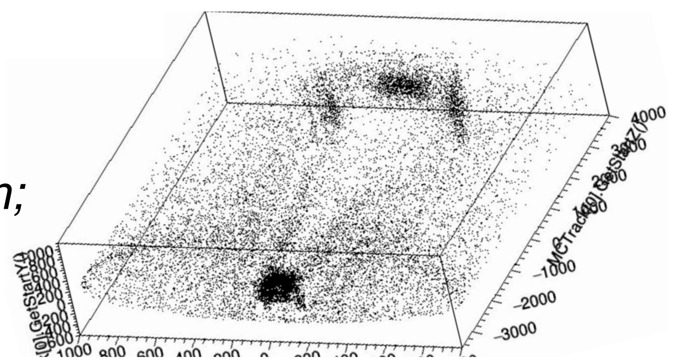


Three main classes of background:

- ***Neutrino induced*** } *interactions in the SND and the walls of decay volume*
- ***Muon inelastic*** } *and surrounding infrastructure*
- ***Combinatorial muon*** *from muons survived the muon shield and entered the decay volume*

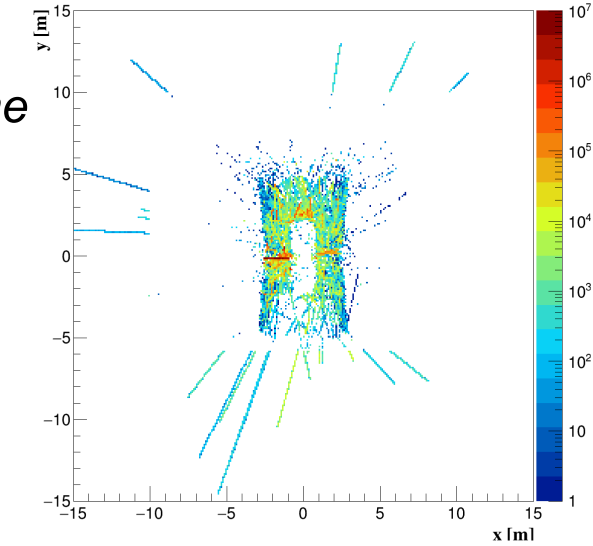
1. Neutrino induced (10 years of SHiP by the FairShip)

- *dominated by interactions in the SND and walls of the decay volume*
- *Only 2 events (from γ-conversions) survived selection; rejected by the cut on the opening angle*
- *Simulation is ongoing to increase the background data sample by an order of magnitude*



Backgrounds (2)

2. **Muon inelastic** *(5 years of SHiP by the FairShip)*
   - *Dominated by interactions in the walls of the decay volume*
   - *Zero background after selection + veto in the taggers*
   - *Assuming no correlation between the veto and selection cuts → < 6×10^{-4} @ 90%CL*



3. **Muon combinatorial** *(1 spill of SHiP by the FairShip)*
   - *Estimated using fully reconstructed muons which pass the muon shield and enter the detector acceptance*
   - *Assume no correlation between selection, veto and timing cuts. Requirement to be in a time window of 3σ time resolution (100 ps) gives large extra suppression factor*
   - *Machine Learning technique is currently being used to generate very large sample of "dangerous" muons*

Background summary

Background source	Expected events
Neutrino background	< 1
Muon DIS (factorization)	< 0.0006
Muon Combinatorial	4.2×10^{-2}

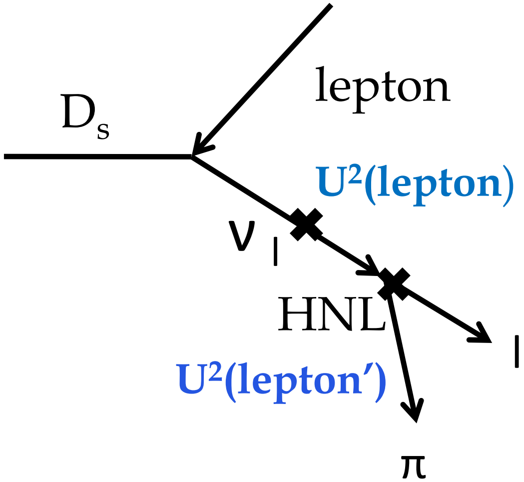
@ 90% CL

Neutrino portal

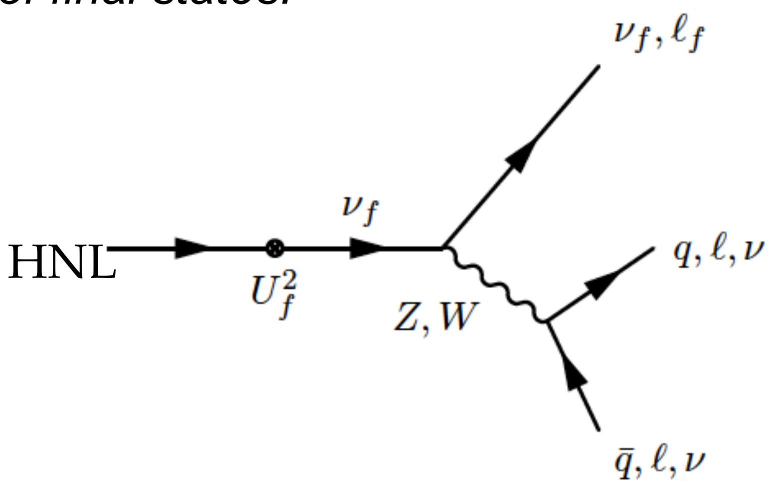
HNLs can be produced in decays of heavy flavours to ordinary neutrinos through kinetic mixing, ~U^2:

Production channels

- $D \to K \ell N$
- $D_s \to \ell N$
- $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
- $B \to \ell N$
- $B \to D \ell N$
- $B_s \to D_s \ell N$
- $B_c \to lN$ *(b-c transition)*



Then HNLs 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:



Decay channels

$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

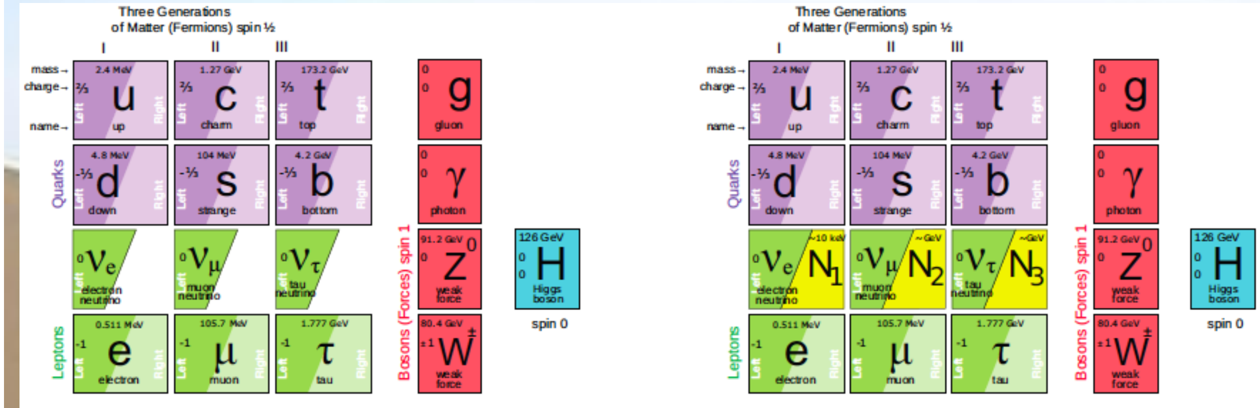
$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$

$N \to 3\nu$

$N \to \ell_i^\pm \ell_j^\mp \nu_j$

$N \to \nu_i \ell_j^\pm \ell_j^\mp$

HNLs in νMSM

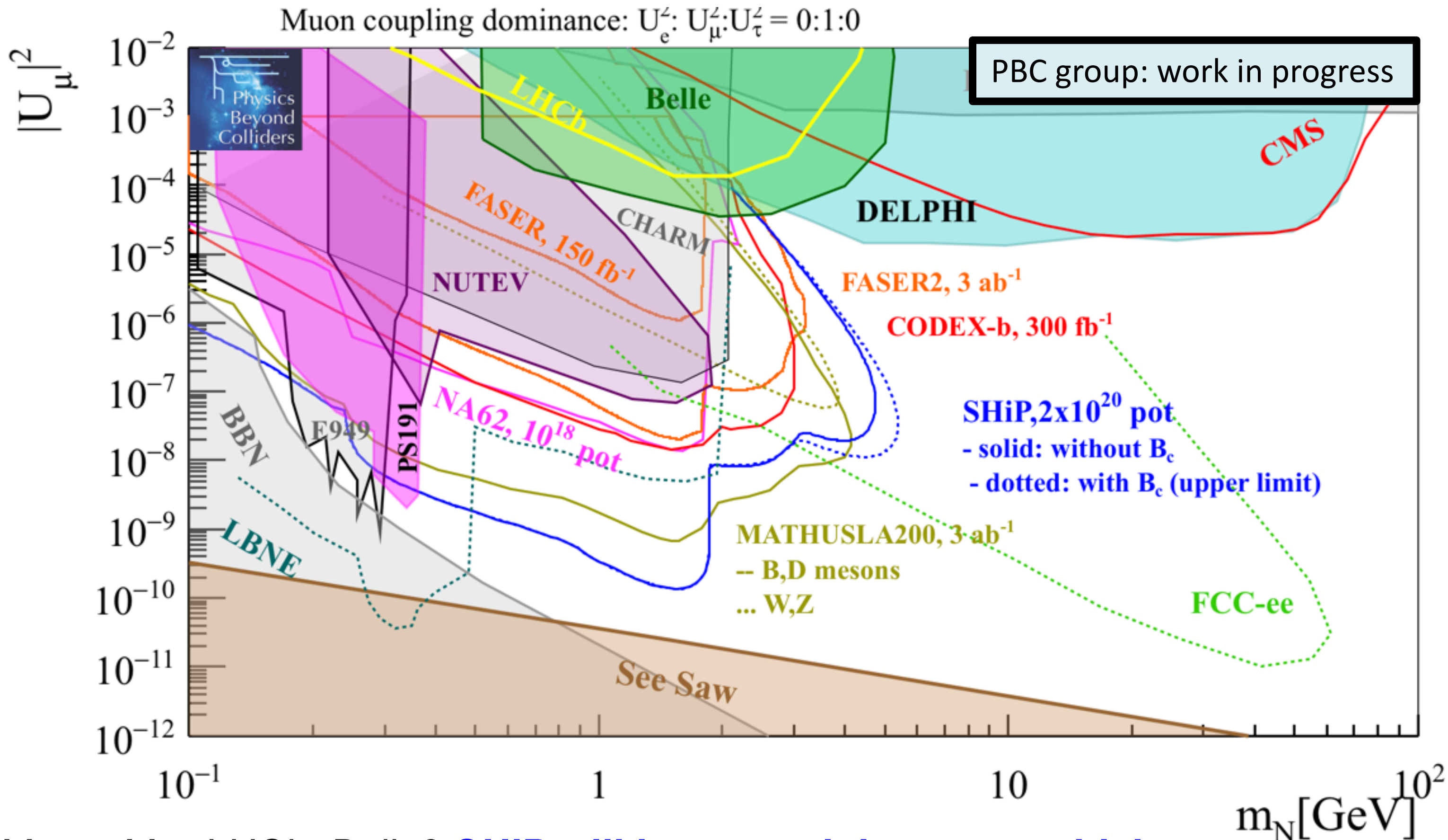


N_1 → Light Dark Matter

$N_{2,3}$ → 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

HNL sensitivities (νMSM)



- ✓ $M_{HNL} < M_b$ 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***

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

Vector portal

Production:

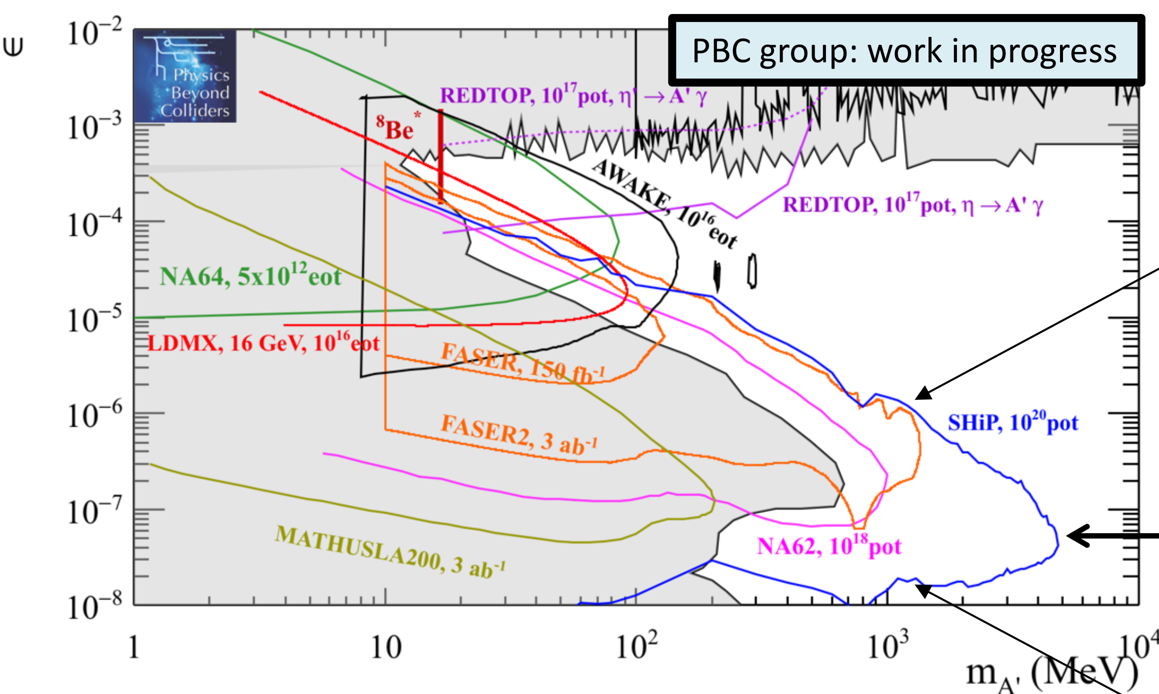
- Meson decays, e.g. $\pi^0 \rightarrow \gamma V (\sim\varepsilon^2)$
- p bremsstrahlung on target nuclei, $pp \rightarrow ppV$
- largest M_V in direct QCD production $qg \rightarrow V$

Decay: into a pair of SM particles: e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^+$, KK, $\eta\eta$, $\tau\tau$, DD, …

A lot of experimental results expected in coming years

EM showers are not taken into account as a source of dark photons

→ Expect significant improvement of sensitivity at low $m_{A'}$



Decay before reaching detector $N \sim \exp(-\epsilon^2 m^2/p)$

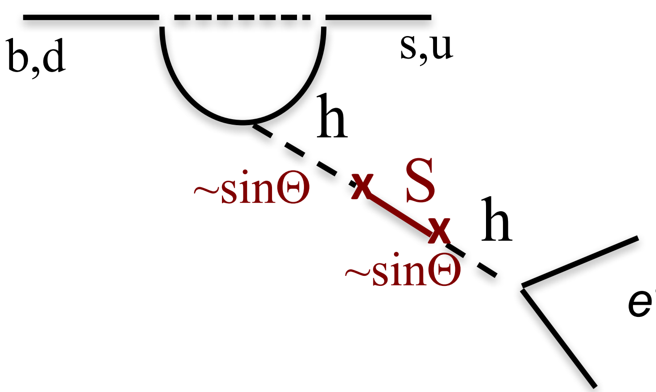
Kinematic limit

Lifetime too large: $N \approx (\epsilon)^4$

SHiP is unique up to O(10GeV) and ε ~10^{-8}

Scalar portal

Dark Scalar particles can couple to the Higgs in FCNC transition in K and B decays:

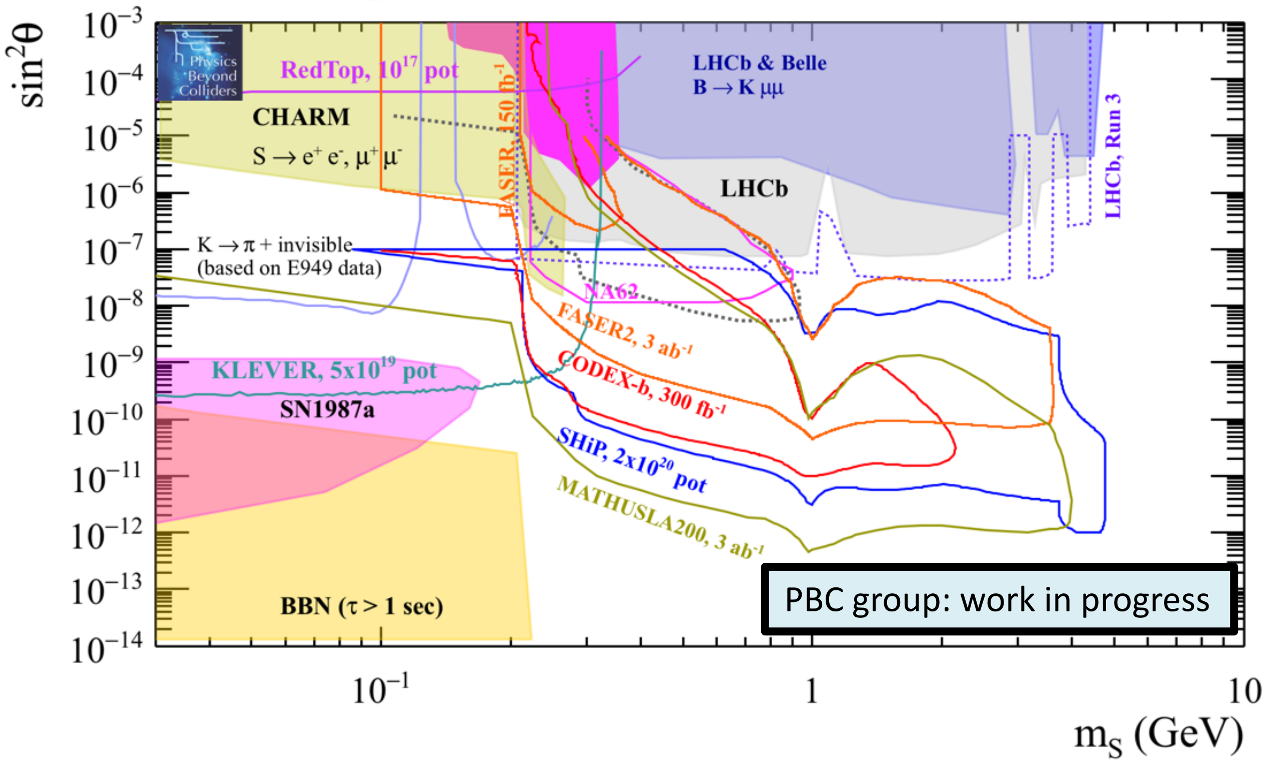


$$\Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

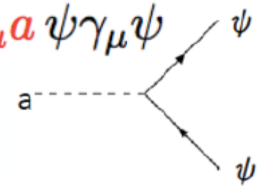
$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

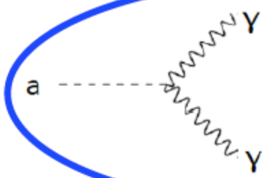
e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^- …



ALPs

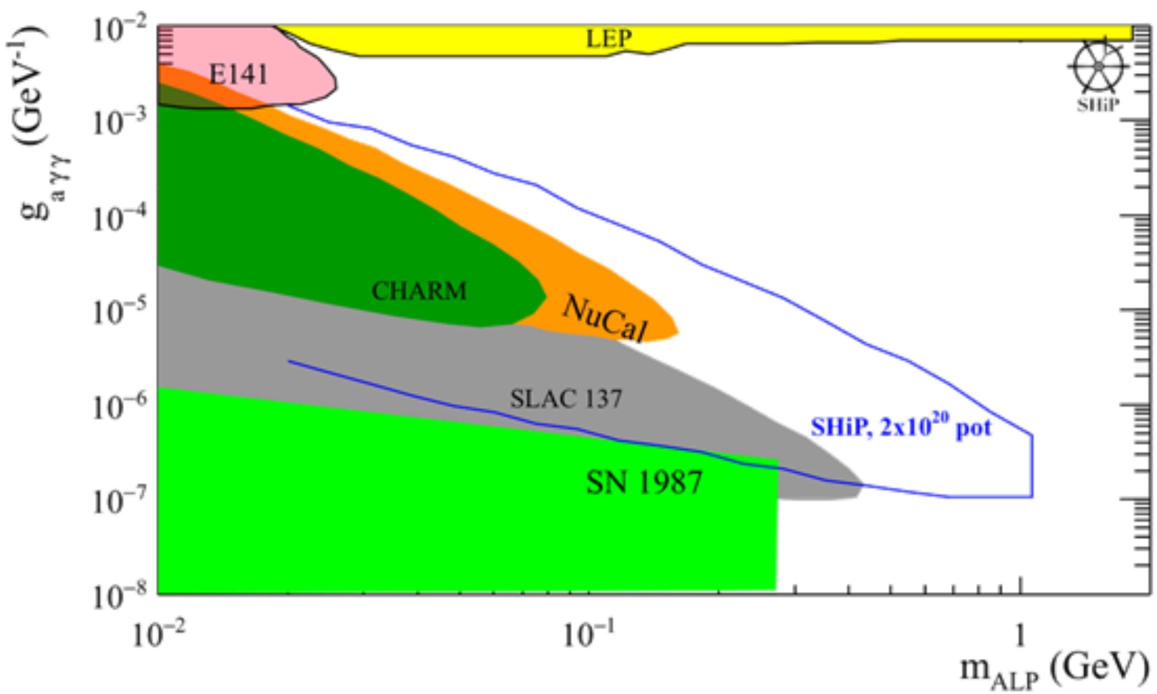
ALPs can couple to fermions $\partial_\mu a\,\bar{\psi}\gamma_\mu\psi$ and to photons $a\,F_{\mu\nu}\tilde{F}^{\mu\nu}$





Two photon final state necessitates electromagnetic calorimeter with a capability to determine directions of the photons in order to reconstruct the decay vertex of ALP → $\gamma\gamma$

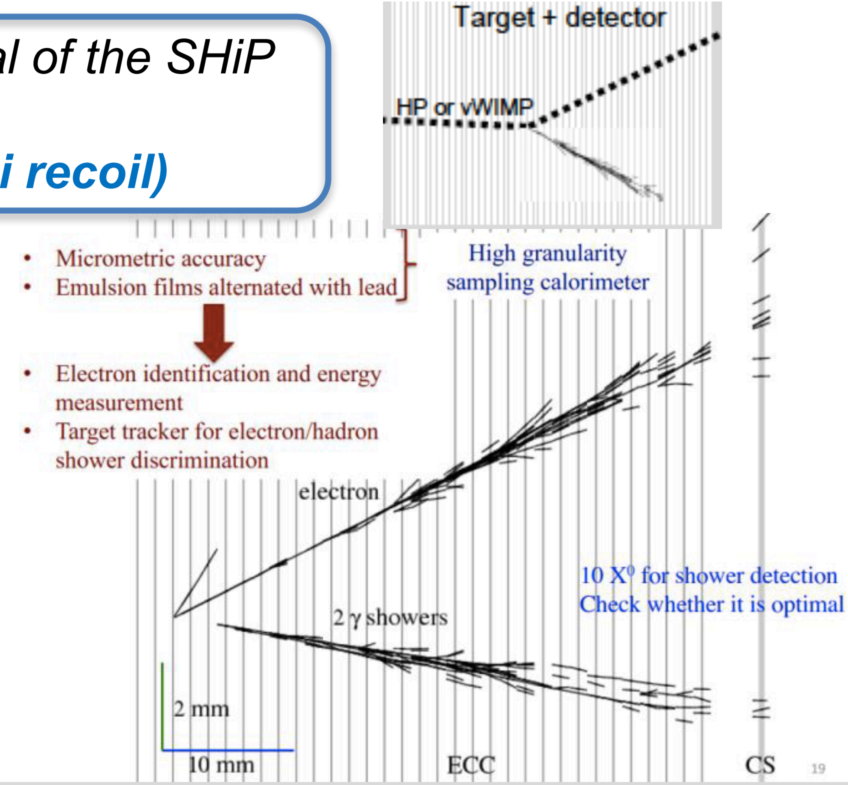
→ **Additional experimental challenge !** (compared to vector and scalar portals)



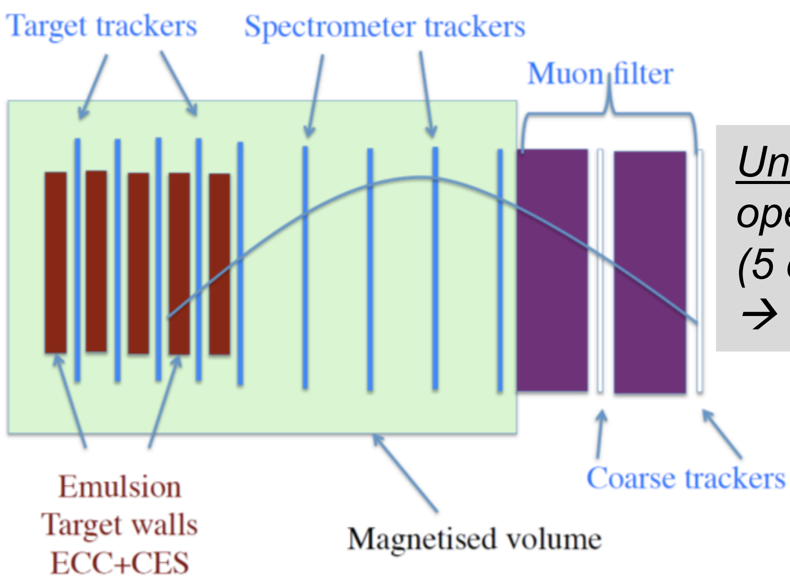
Observation of vWIMP in $\gamma\gamma$–final state is a strong discrimination of the ALP signal against dark vector and dark scalar

Search for Light Dark Matter with iSHiP

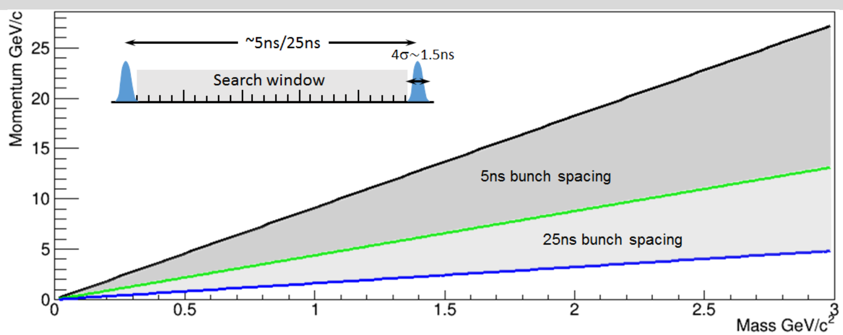
LDM can scatter on atoms of the dense material of the SHiP Scattering and Neutrino Detector (SND)
→ **detection signature: EM shower (or nuclei recoil)**



- Reconstruction of the EM showers in emulsion demonstrated with OPERA data
- Complement emulsion detector with fast electronic Target Tracker to improve electron reconstruction

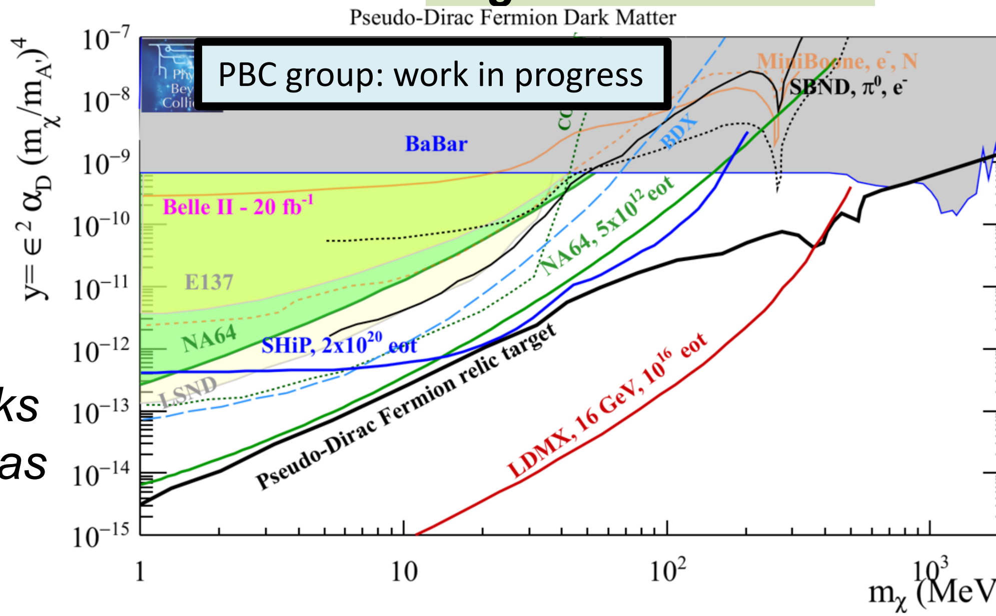


Under study: Elimination of the neutrino background by ToF operating with the SPS bunched beam: 4σ/spacing = 1.5ns / (5 or 25ns) & ~40 m distance from the target
→ ***Requires 0.5 ns time resolution of the Target Tracker***

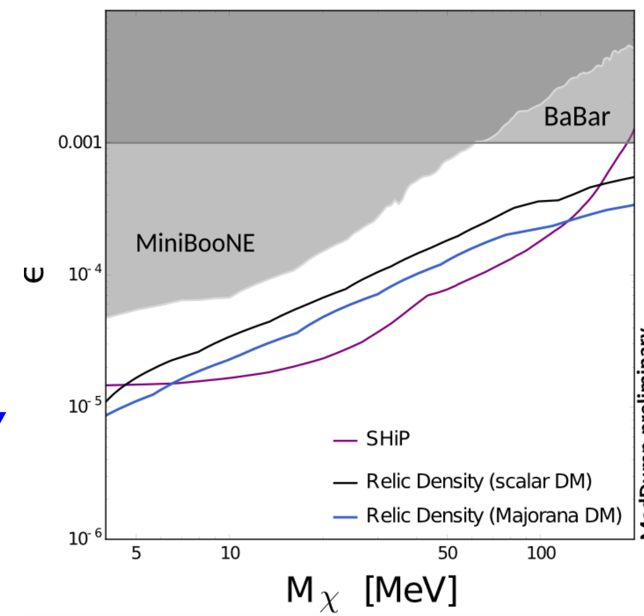


Sensitivities to LDM

Light Dark Matter

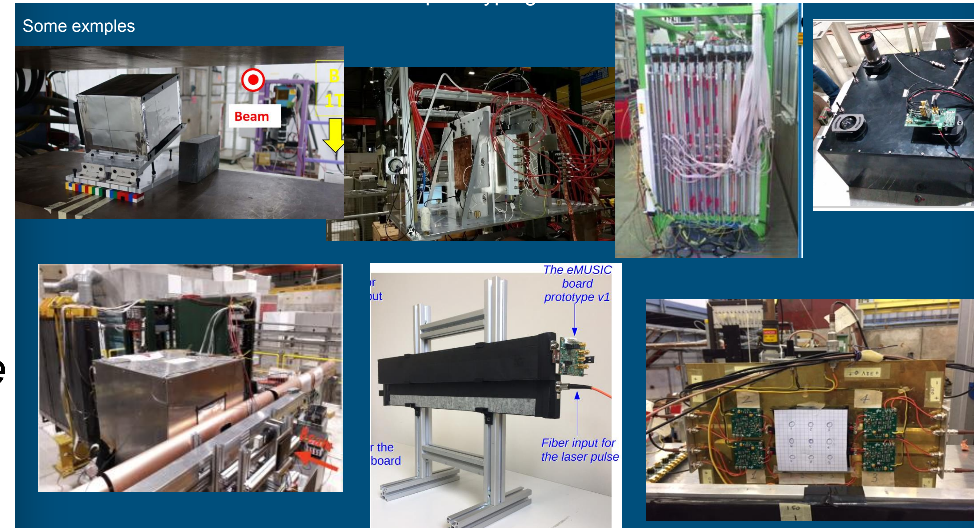


- ✓ ***Missing mass / energy technique***
  (applicable only for the models with dark photon mediator)
  - *Belle II with 50 ab^{-1} provided that low energy mono-photon trigger works*
  - *LDMX (under discussion at SLAC) has the best prospects for $M_\chi < 100$ MeV*



- ✓ ***Detection via scattering at SHiP***
  - *Background is dominated by elastic and quasi-elastic neutrino scattering (~700 events per 2×10^{20} pot)*
  - ***SHiP has the best sensitivity in 20 – 200 MeV***

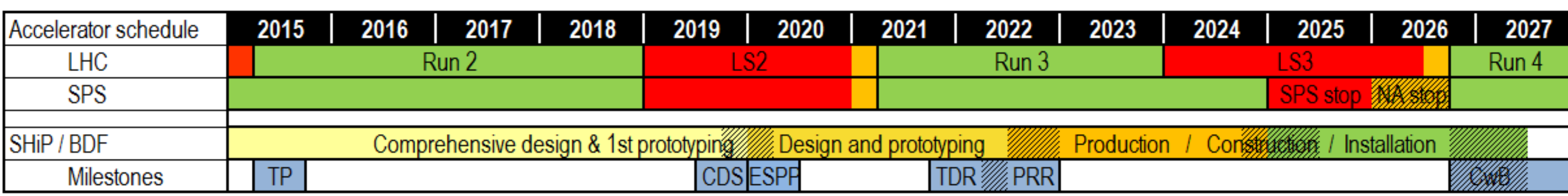
Detector challenges and Project plan



- ✓ ***All SHiP sub-detectors went through active program of prototyping***
  - *Results implemented in FairShip*
  - *Next step - preparation of large scale prototypes to study global performance*

- ✓ ***Particular challenging projects:***
  - *Engineering of the muon shield and straw tracker*
  - *Design of the ECAL with the required energy resolution for ALP→$\gamma\gamma$ (~5 mrad)*

- ✓ ***Project plan***
  - *Both BDF and SHiP schedule is driven by the CERN long-term accelerator schedule*
  - *Most of the facility can be constructed in parallel to operating of other accelerators*
  - *Installation of SHiP is planned for LS3 with start of data taking in RUN 4*



Status of the SHiP collaboration

SHiP is currently a collaboration of 53 institutes and 4 associated institutes, in total representing 18 countries, CERN and JINR. The formal organisation of SHiP, which has been adopted for the Comprehensive Design Study phase, consists of a Country Representative Board (CRB) including the UK (5 groups), Interim Spokesperson, Technical Coordinator and Physics Coordinator, and the Group of Project Conveners (two from the UK) as elected and ratified by the CRB

Conclusion

- ✓ ***Physics case to search for Hidden Particles is very timely !***
  No NP discovered at LHC, *but many theoretical models offer a solution for the BSM experimental facts with light very weakly interacting particles****. Must be tested !***

- ✓ ***CERN is ideal place to search for Hidden Particles at high energy and high intensity SPS beams.*** *Two complementary strategies are being explored at SHiP, direct observation of the decay vertex and indirect detection via scattering on atoms*

- ✓ ***The rich physics programme to search for Hidden Particles at the SPS North Area at CERN nicely complements searches for NP at the energy frontier and in flavour physics at CERN***