Light Dark Matter 2017

24-28 May 2017 **La Biodola** - Isola d'Elba

SHiP Dark Sector searches

Laura Fabbri
on behalf of the SHiP Collaboration

SHiP
Search for Hidden Particles

Outline

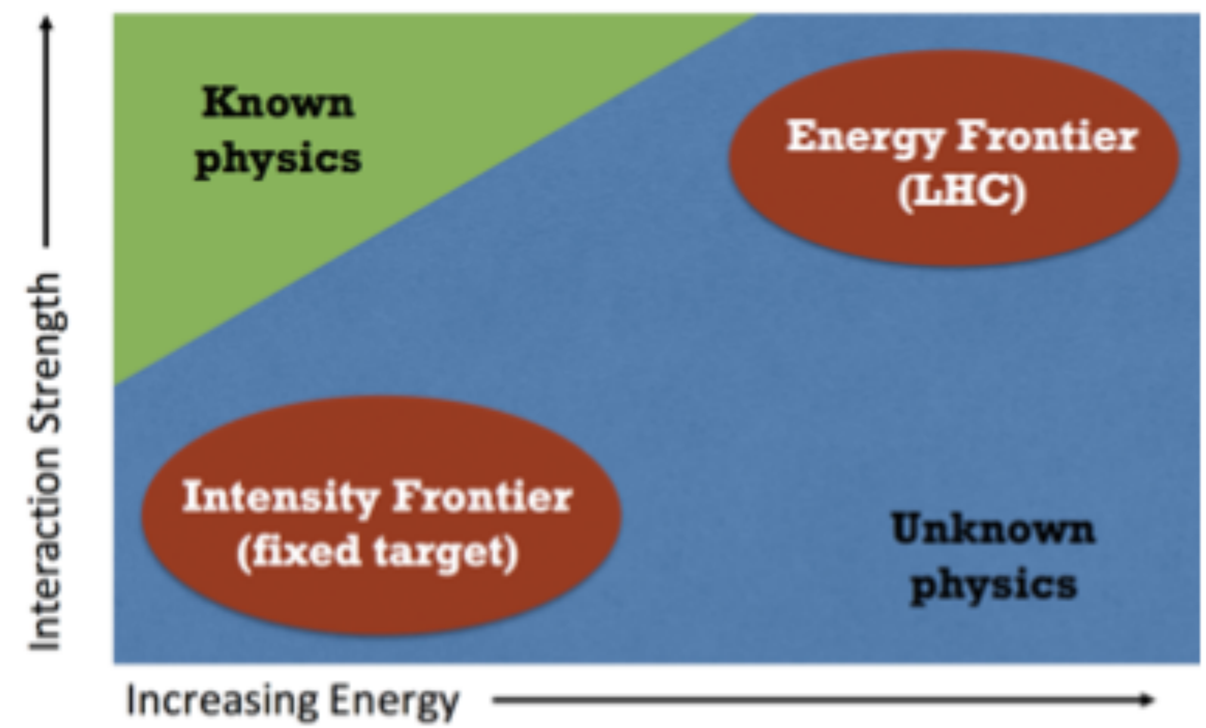
- Physics Motivation
- Overview of the experiment
- Physics performances

Physics Motivation

- The Standard Model provides an explanation for many subatomic processes, but it fails to explain many observed phenomena:
  - Higgs mass:
    - lifetime of SM vacuum exceed the age of the Universe
    - the theory become strongly coupled well above the Planck scale
  - Neutrino oscillation and masses
  - Dark Matter
  - Baryon asymmetry of the Universe (BAU)
  - Cosmic Inflation

INCOMPLETE THEORY

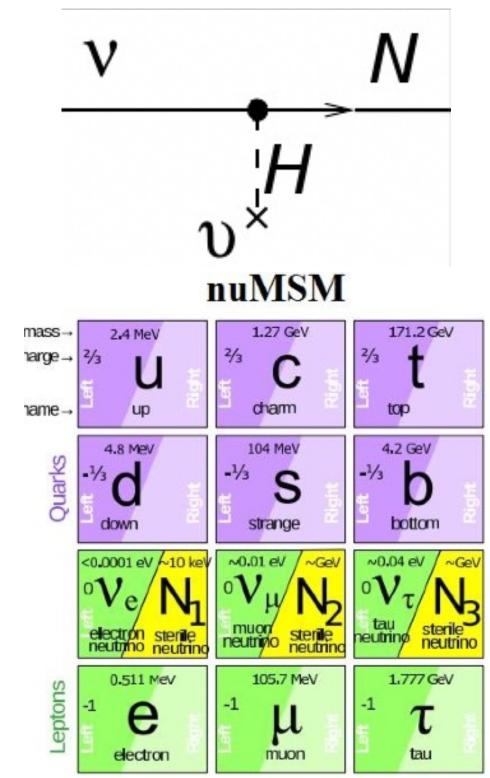
lack of theoretical guidance —> experimental searches at both energy and intensity frontiers



Physics Motivation

- TWO scenarios for BSM theories:

1. No new physics between the Fermi and the Planck scales:
    - νMSM introduces 3 right-handed Majorana HNLs: N1, N2 and N3
        - N_1 light, O(1 keV) : Dark Matter candidate
        - $N_{2,3}$ degenerate, O(100 MeV - few GeV) : neutrino masses via see-saw
        - $N_{2,3}$ leptogenesis → baryogenesis by increased CP violation (BAU)



2. New energy scale which may also incorporate light particles
    - SUSY: partners with masses comparable to the Higgs mass needed to protect against quartic radiative corrections w/o fine-tuning
    - Models with a Dark Sector: interact with SM particles through “portal” particles (vectors, Higghs, neutrinos, axions) -> DM

Light new particles may have remained undetected by previous experiments because of the **very small couplings** involved

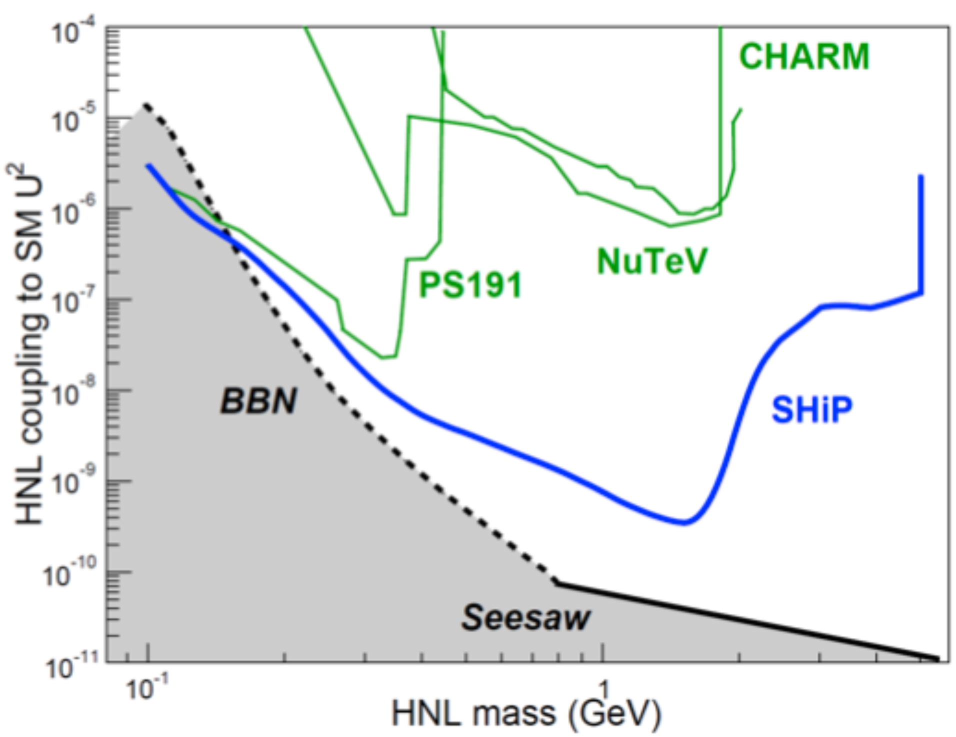
INTENSITY FRONTIER

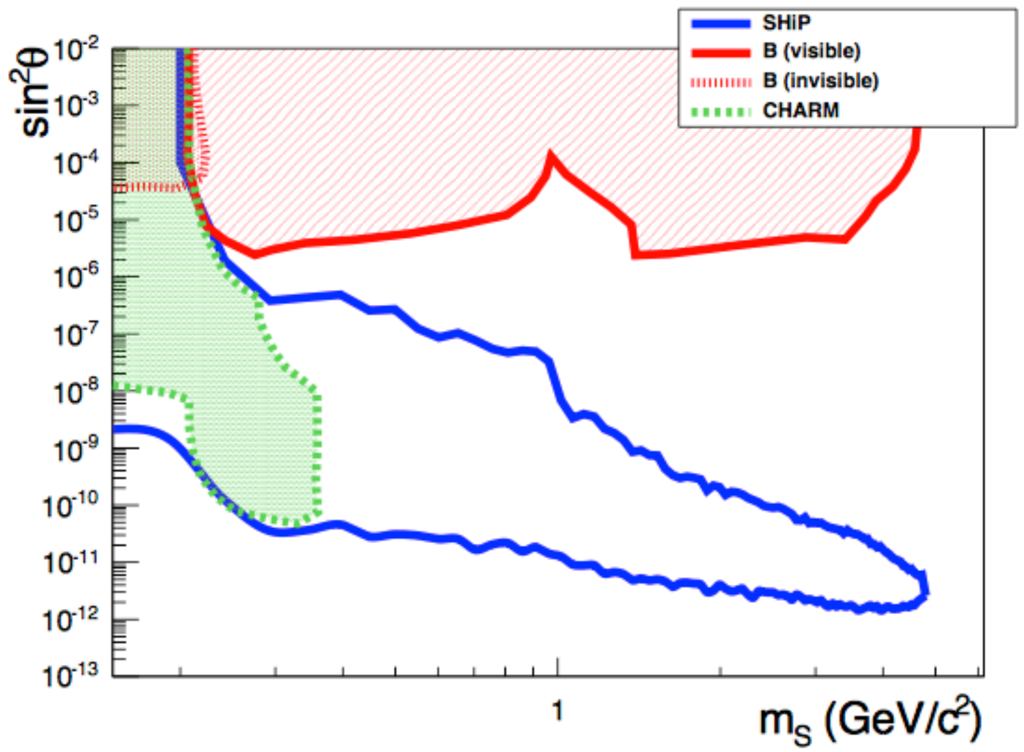
SHiP Experimental prospects

- **Primary Physics goals**

  1. Exploring hidden portals and extensions of the SM:
     - searches for Dark Matter, Sterile Neutrinos and Dark Photons => <u>long-lived</u> and <u>very weakly interacting particles</u> through their decays to SM particles

Technical Proposal CERN-SPSC-2015-016

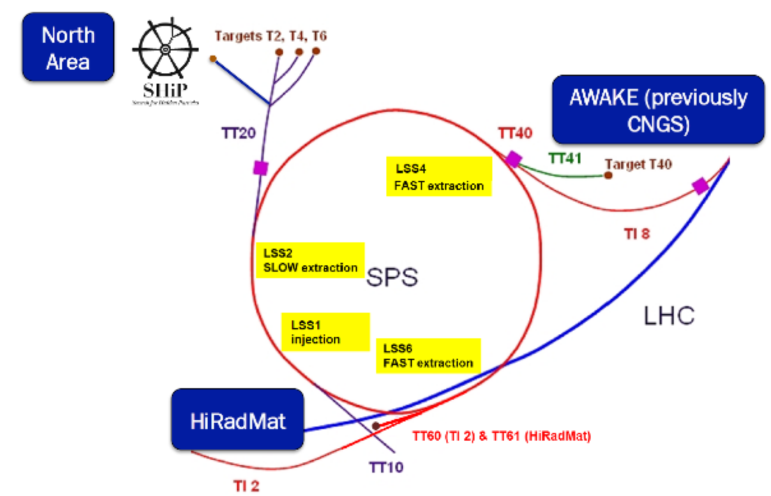




  2. Explore the physics of τ-neutrino:
     - first observation of $\bar{\nu}_\tau$
     - independent measurement of σ_{ν_τ} and $\sigma_{\bar{\nu}_\tau}$

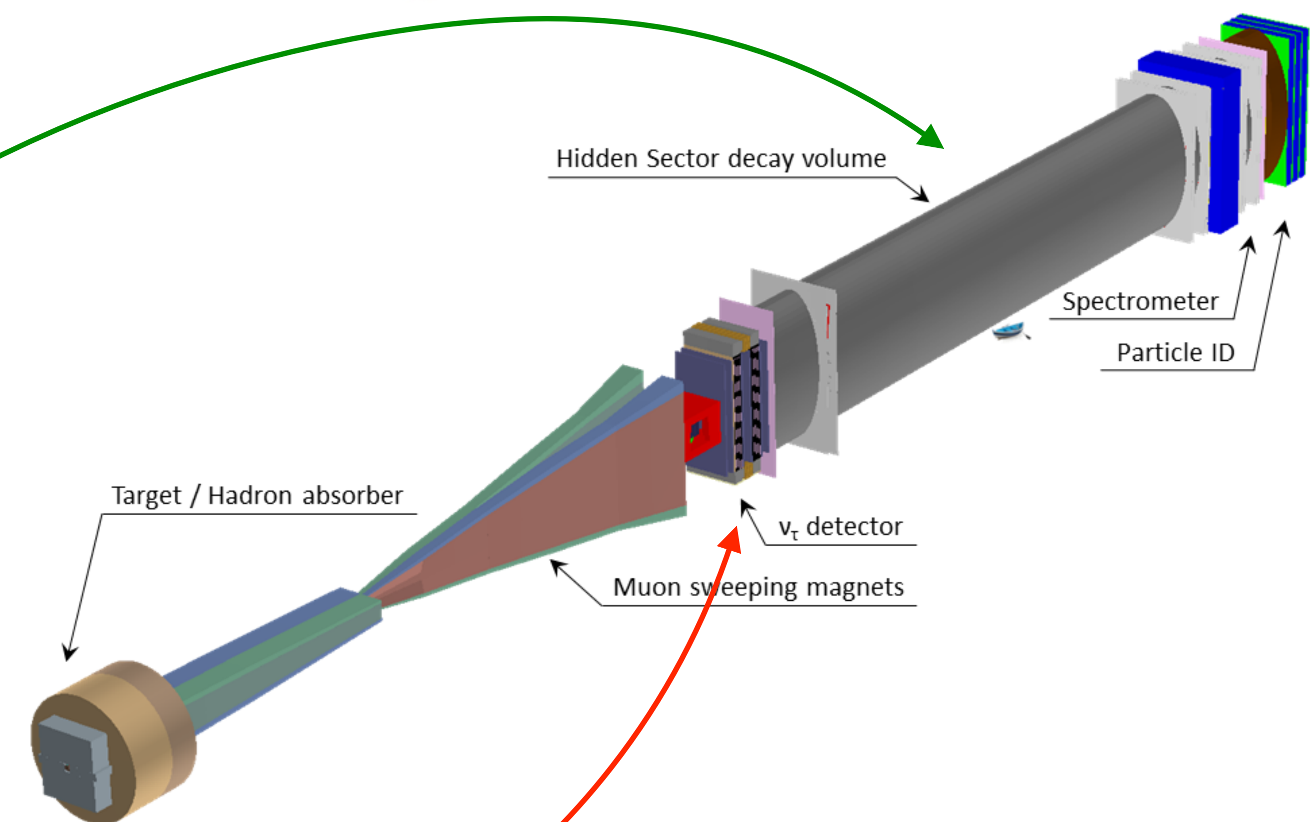
The SHiP Experiment

- The SHiP (**S**earch for **Hi**dden **P**articles) experiment is a proposed fixed target experiment at the CERN SPS



5×10^{13} protons per spill @ 400 GeV → 2×10^{20} collisions in 5 years

- **Hidden particle detector** will consist of a long evacuated decay volume with a magnetic spectrometer, calorimeters, and a muon detector located on the far end



- **Neutrino detector** consists emulsion target with tracking in a magnetic field followed by a muon spectrometer $N\nu_\tau \sim 10^4$

Hidden Sector Detection

- **REQUIREMENTS:**
  - Particles predominantly produced in decays of hadrons (charmed and beauty)
    - small coupling => long-lived particles => long detector
    - heavy hadron decays => small boost => relatively large polar angles
  - Model independency
    - detector sensitive to as many model as possible

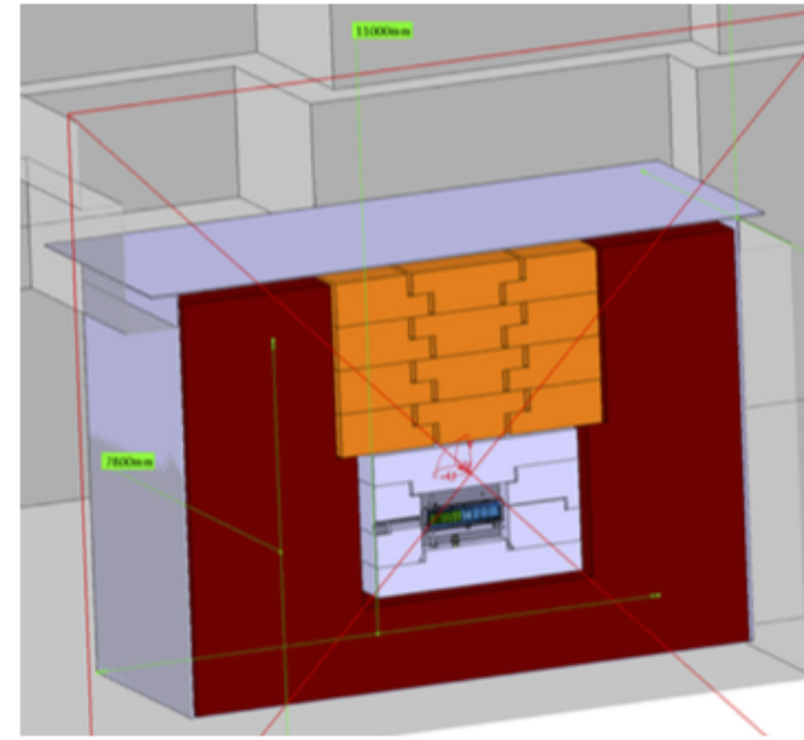
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

identify e, μ, π, ρ final states

  - Minimise background sources: **0.1 expected bkg events** / whole data taking (2 10^{20} pot)
    - pion and kaon stopper =>target with the shorter interaction length, long enough to contain the hadronic shower
    - muon flux => magnetic deflector + veto taggers
    - neutrino flux => veto taggers + decay volume under vacuum

The Target and Muon Shield

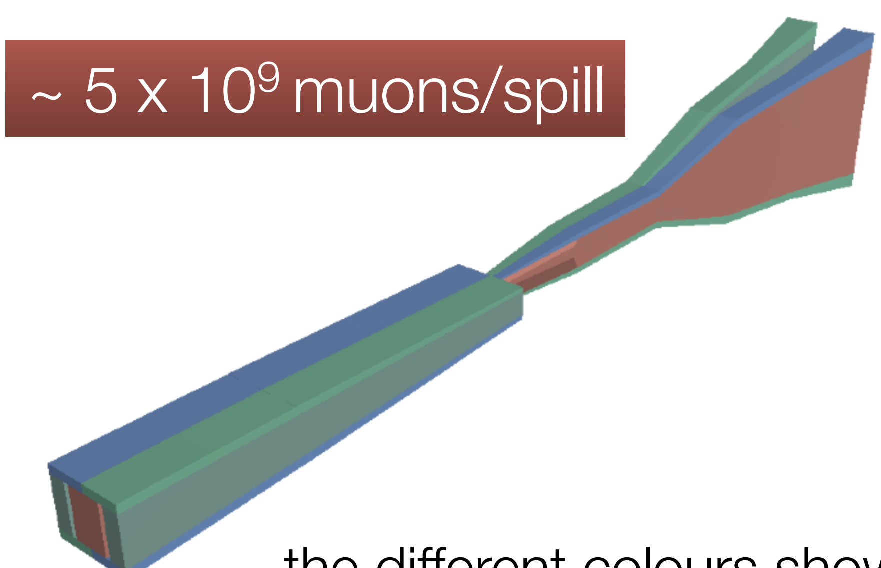
- Longitudinally segmented hybrid target
  - Core of shower: four interaction lengths of titanium-zirconium doped molybdenum alloy
  - Followed by six interaction lengths of pure tungsten
  - Water cooling
- Neutral particle absorber protects upstream beam-line from neutrons and other neutral radiation
- Target embedded in cast Iron bunker



high average beam power: 2.56 MW per 1 sec. spill

- Muon shield needs to be as compact as possible along beam-line
  - **Active shield** needs B_y = 40 Tm to bend 350 GeV muons away from the 5 m aperture of vacuum vessel
    - Need to separate μ^+ from μ^-
    - Bend muons further outward

~ 5 x 10^9 muons/spill



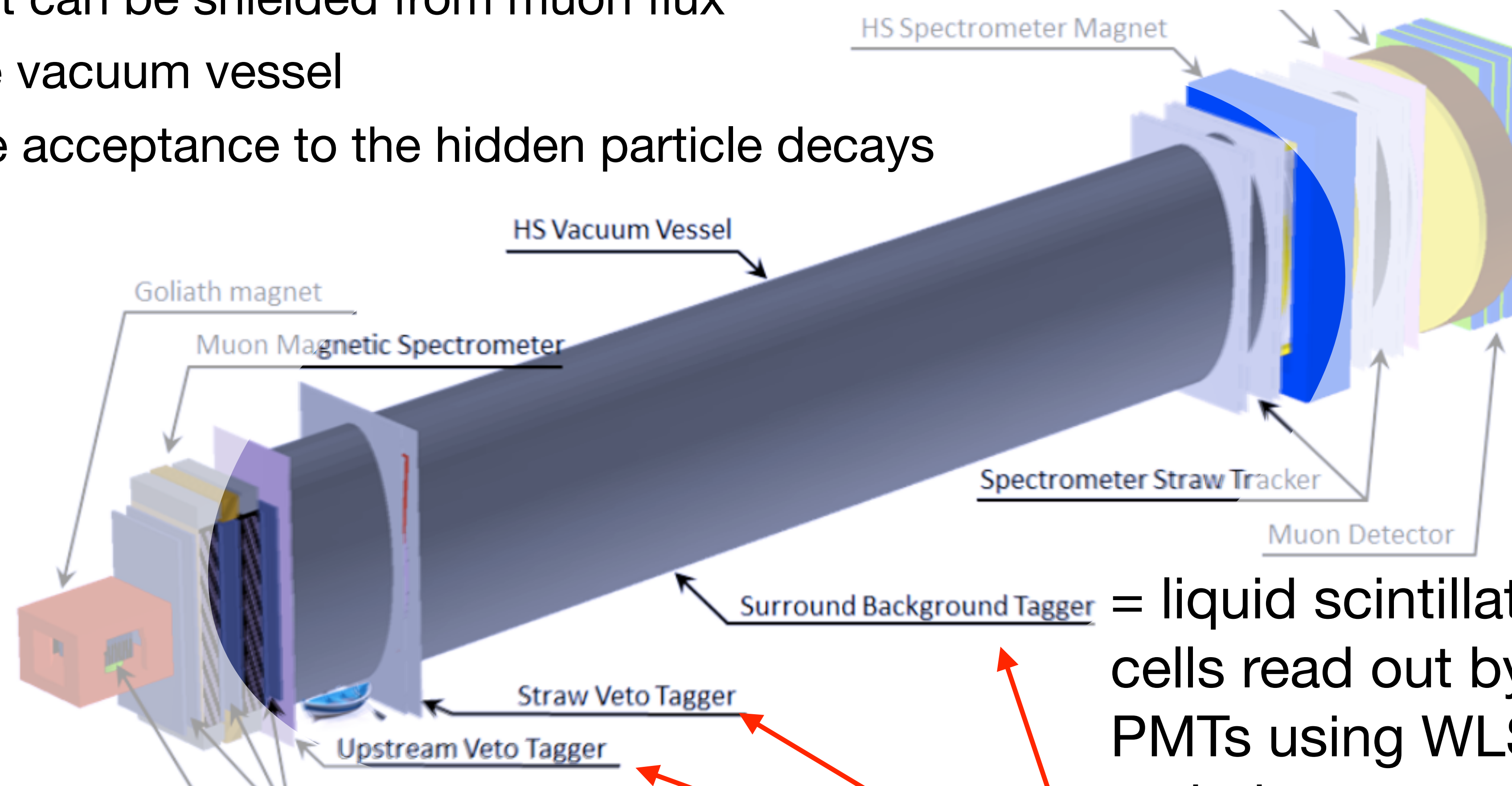
the different colours show the field orientation

The Decay Volume

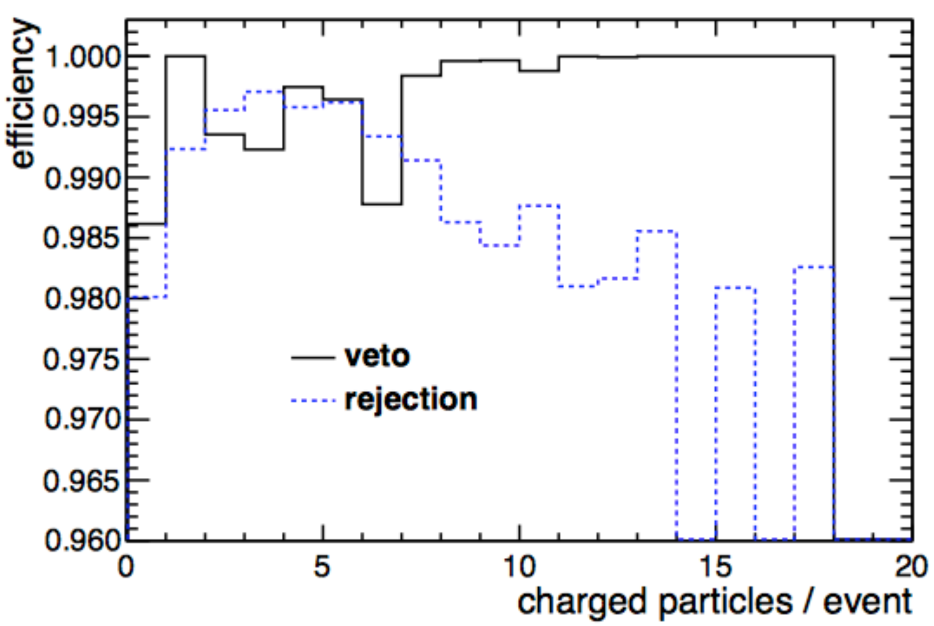
- **width:** defined by the region that can be shielded from muon flux
- **height**: driven by the cost of the vacuum vessel
- **length:** obtained maximising the acceptance to the hidden particle decays

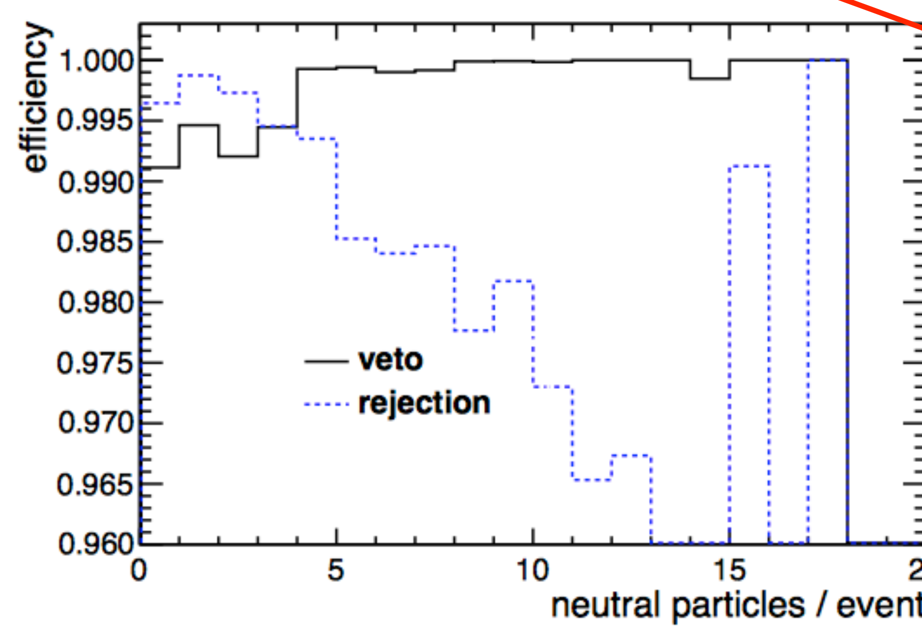
elliptical shape:
5 m width x **10 m** height x **50 m** length
pressure: ~mbar

to prevent neutrino interaction inside vacuum vessel



= liquid scintillator cells read out by PMTs using WLS technique

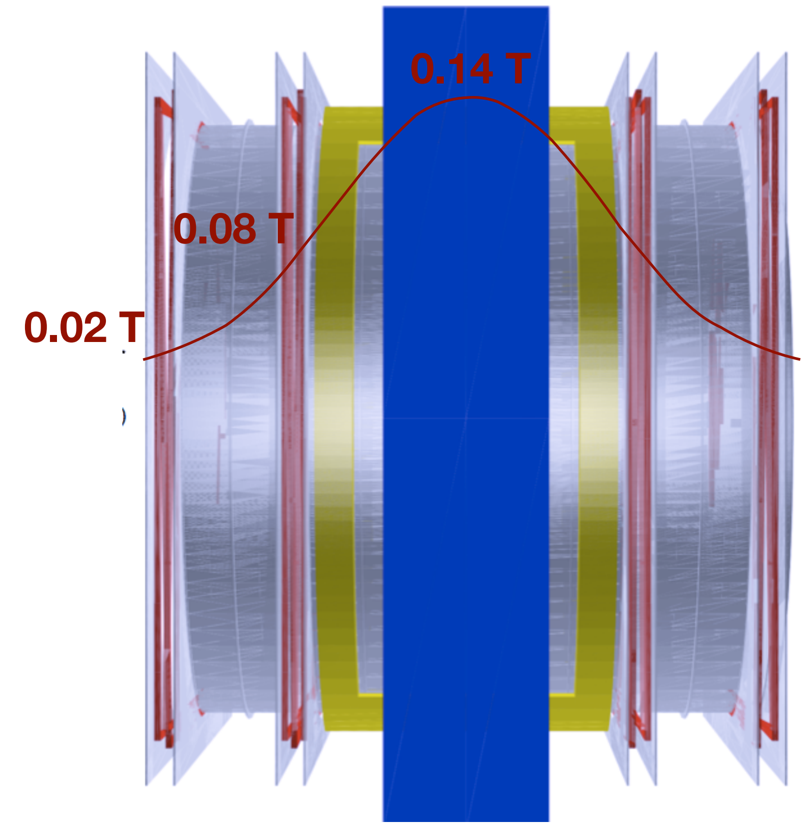




- **Taggers**: to detect muons sent back by scattering and hadronic showers from inelastic interactions by neutrinos and muons and ensure **background ~ 0**

The Spectrometer Tracker

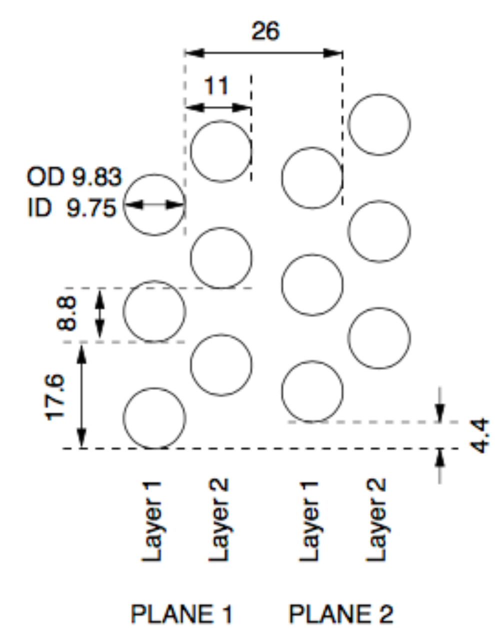
- Provides discrimination against background with:
  - high reconstruction **efficiency**
  - good **tracking** and **mass resolution**
  - precise determination of the **position of the decay vertex** and particle **impact parameter**
- Detector layout:
  - a large dipole magnet and two tracking telescopes on each side
  - Straw tracker made up of thin polyethylene terephthalate (PET) tubes used for each station.
  - 4 views (Y, U, V, Y) for each station
- Expected 10^7 hits/station in 1 s ==> **2kHz/straw** (NA62 500 kHz/straw)

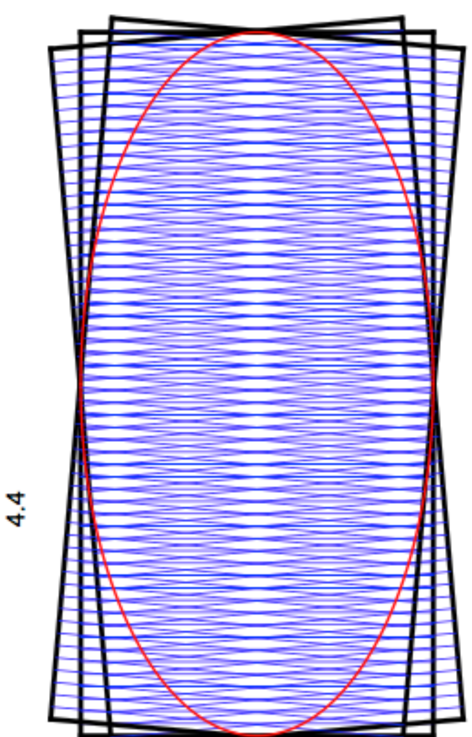


$$\left(\frac{\sigma_p}{p}\right)^2 \approx [0.49\%]^2 + [0.022\%/(\text{GeV}/c)]^2 \cdot p^2$$

multiple scattering

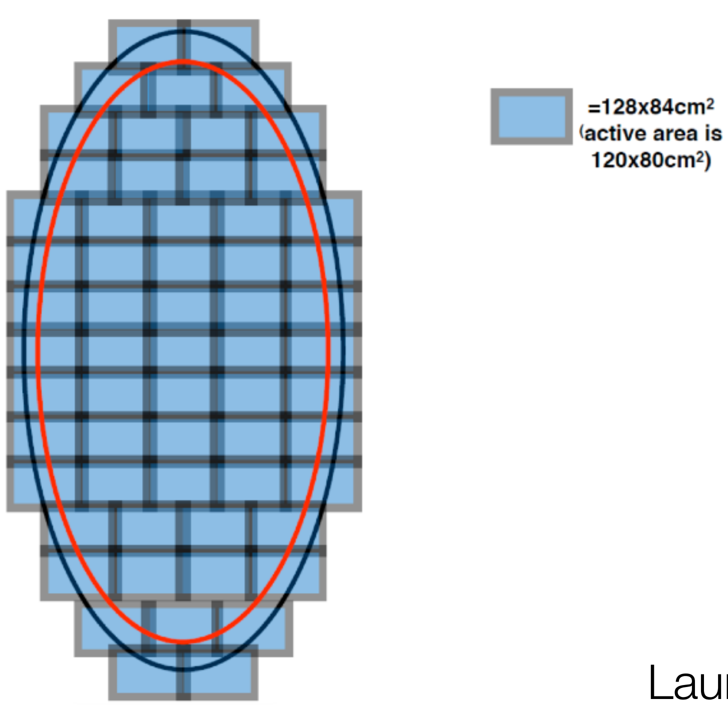
detector resolution

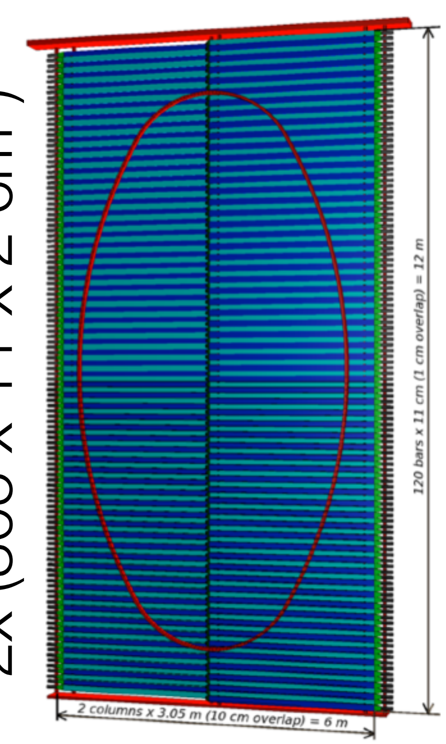


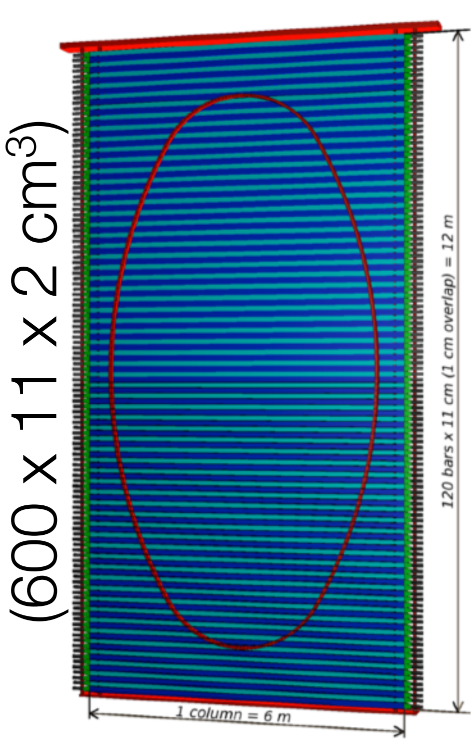


The Spectrometer Timing Detector

- A dedicated **timing** detector can be used to reduce random crossing in the detector
- Combinatorial di-muon background can be reduced to an acceptable level by requiring a timing resolution of **100 ps or less**
  - Requires dedicated timing detector located after spectrometer and before calorimeters
- Two options have been proposed for the timing detector
  1. plastic scintillators read-out by PMTs or SiPMs
     - efficiently cover large areas, low cost, robustness, low maintenance and reliability
  2. multigap resistive plate chambers (MRPCs)
     - used in ALICE-TOF, EEE and other experiments







Calorimetry

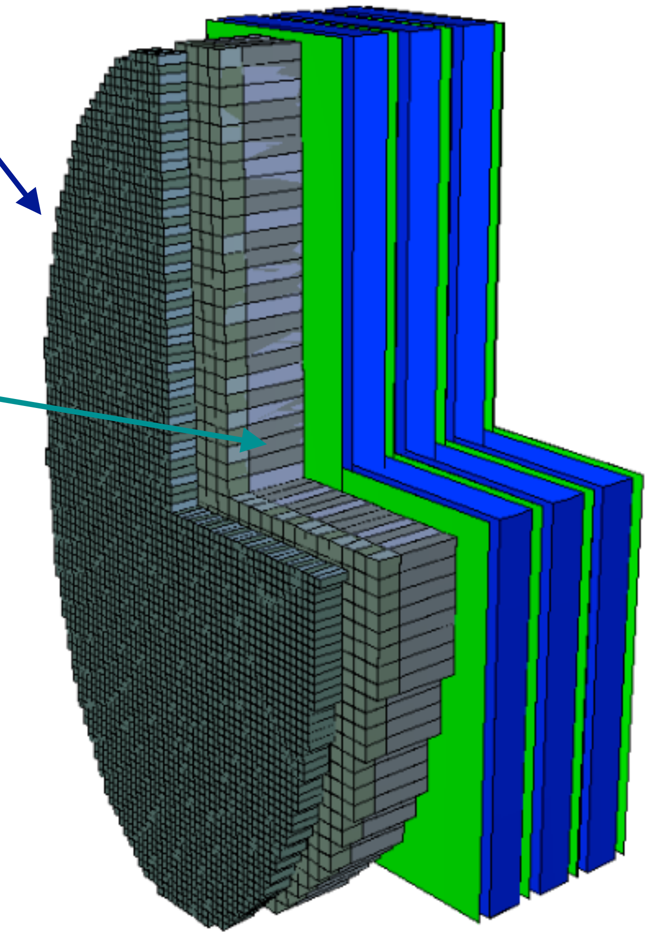
- **Calorimeters** are needed to identify **γ**, **e**, **μ** and π^0 and measure their energy
  - **Electromagnetic Calorimeter** for e/γ identification
    - granularity and energy resolution sufficient to reconstruct π^0's (0.6 -100 GeV)
    - σ_E (e, γ) < 10% from 0.3 to 70 GeV
    - timing information on signal at ns level to reject background
  - **Hadronic Calorimeter** in combination with a muon detector for π/μ separation (especially for p < 5 GeV/c)
    - Tag neutral particles (K_L, n) for background rejection
    - timing information on signal at ns level to reject background

$$HNL \rightarrow l^{\pm}\pi^{\mp}$$

$$K_S^0 \rightarrow \pi^+\pi^-$$

$$HNL \rightarrow l^{\pm}\rho^{\mp} \rightarrow l^{\pm}\pi^{\mp}\pi^0$$

$$K_L^0 \rightarrow \pi^+\pi^-\pi^0$$



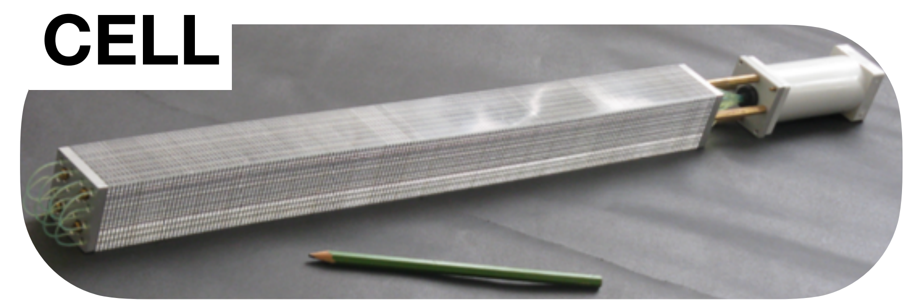
ECAL

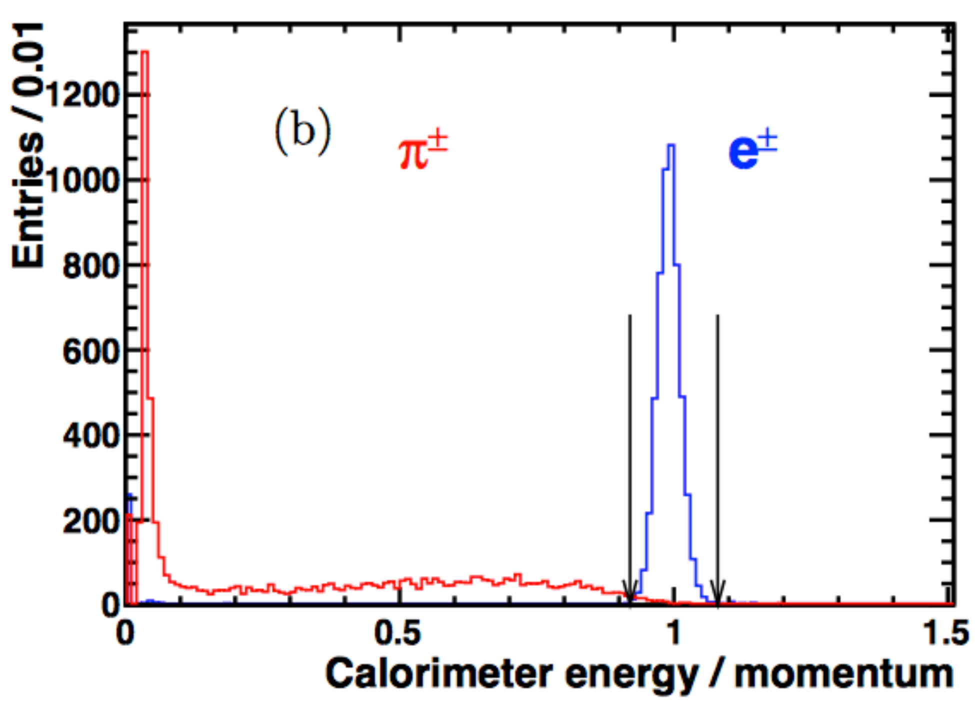
- **Electromagnetic Calorimeter** (ECAL)
  - Located right after timing detector
  - Almost elliptical shape 5m x 10m to maximise acceptance and minimise costs
  - Shaslik modules made of scintillator-lead structure read out by plastic WLS fibres

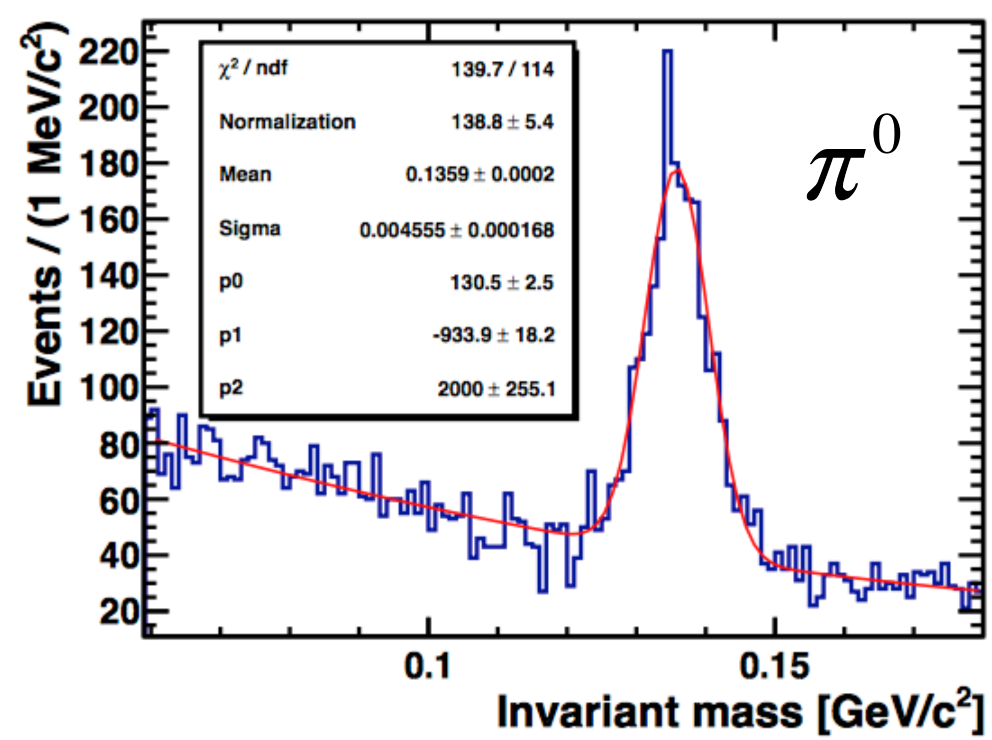
2876 modules

2x2 cells/ module

6x6 cm^2 each cell

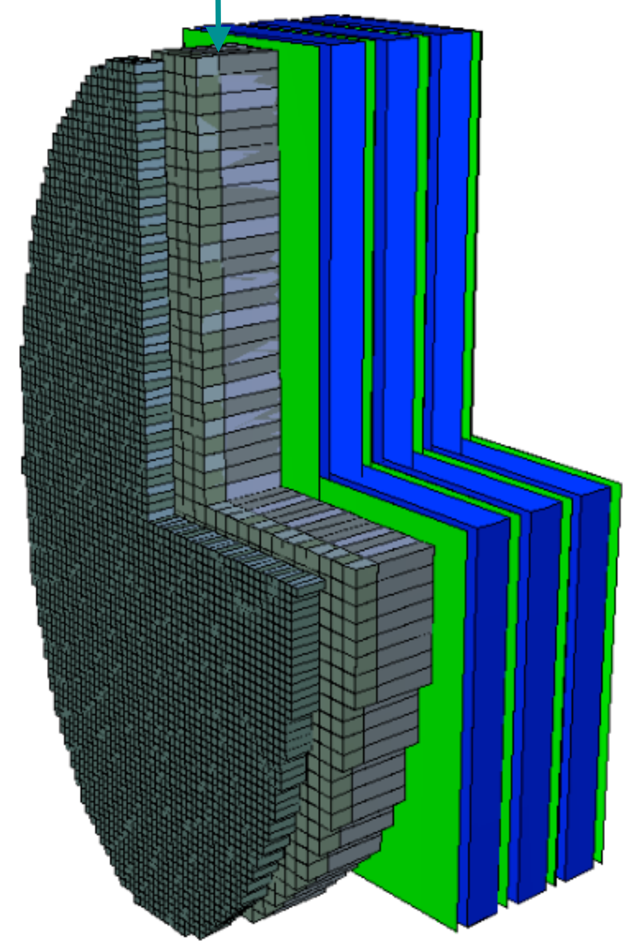






HCAL

- **Hadronic Calorimeter** (HCAL)
  - Right after ECAL with the same acceptance
  - Shaslik technology as for ECAL
    - converting layer = 15 mm iron
    - active layer = 5 mm polystyrene-based scintillator
  - module size to be optimised to minimise the total number of independent channels
  - longitudinal segmentation under study to maximise the π/μ separation keeping the overall material at minimum



Preliminary solution:

2 HCAL stations: H1 followed by H2

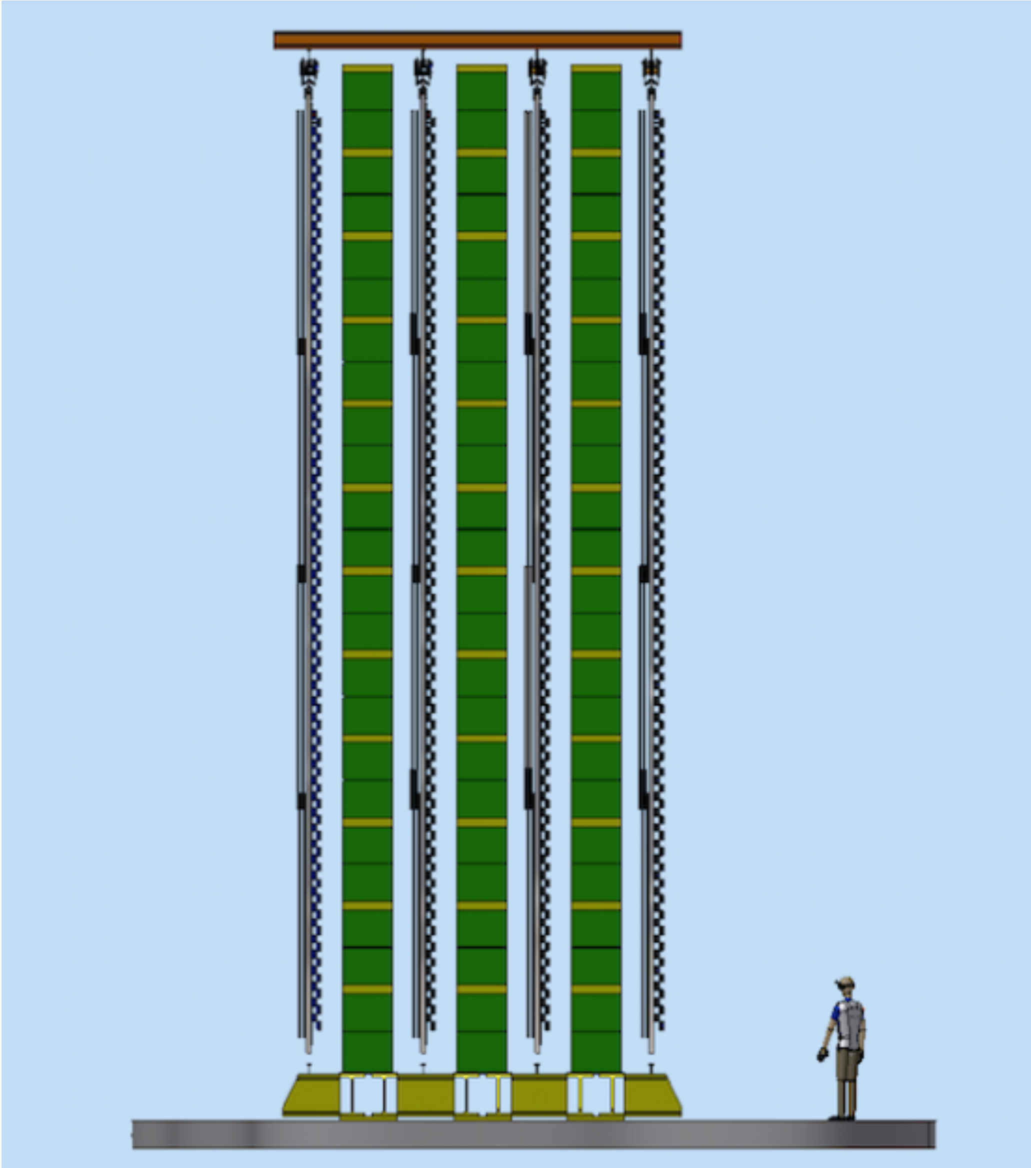
- H1= 18 sampling layers
- H2 = 48 layers

The Muon Detector

- Need to identify muons with high efficiency in signal channels:

$$N \to \mu^+\pi^-, \mu^+\mu^-\nu_\mu$$
$$V \to \mu^+\mu^-$$
$$S \to \mu^+\mu^-$$

- Separate signal from ν^- and μ^- induced backgrounds



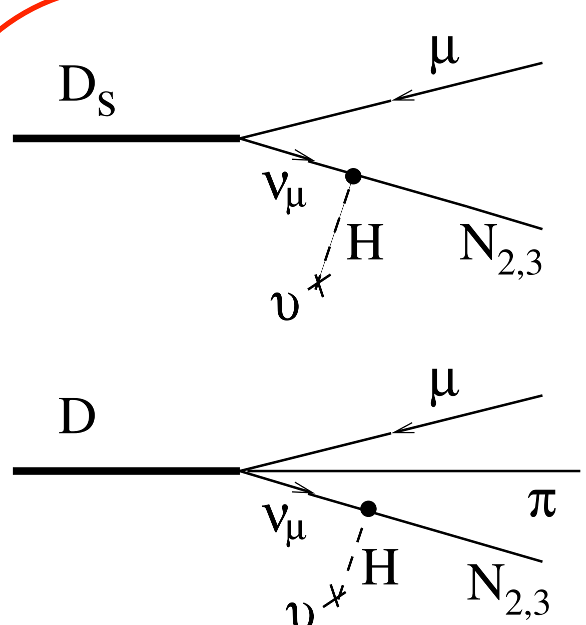
- **Detector layout:**
  - Downstream of the calorimeter systems
  - Four stations of active layers separated by three muon filters
  - Granularity dictated by muon filters and multiple scattering in calorimeters (5-10 cm in the transverse direction)
  - Active layers - extruded plastic scintillator strips with WLS fibers and opto-electronic readout

HNL Production and Decay

- Benchmark assumptions:
  - Normal hierarchy of active neutrino masses: $U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:16:3.8$
  - Total coupling $U^2 = 9.3\ 10^{-9}$ and $m_{HNL} = 1\ GeV/c^2$

2 × 10^{20} collisions in 5 years

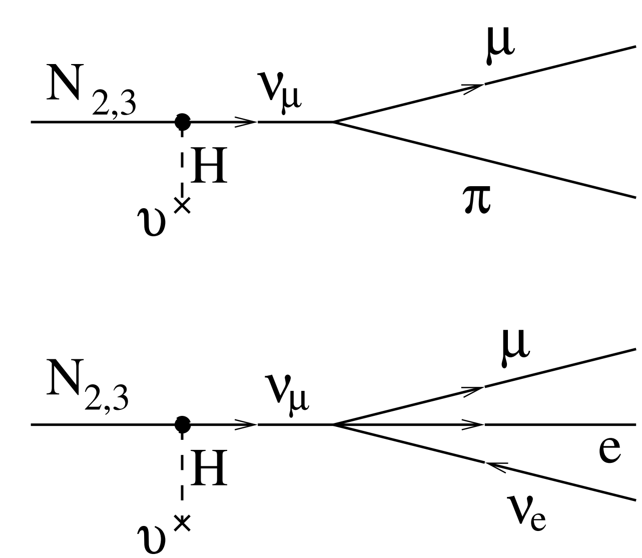
$$n(HNL) = N(\text{p.o.t}) \times \chi(pp \to HNL) \times \mathcal{P}_{\text{vtx}} \times \mathcal{A}_{\text{tot}}(HNL \to \text{visible})$$



TOTAL PRODUCTION RATE

Probability that the decay vertex is located within the fiducial volume

DETECTOR ACCEPTANCE



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

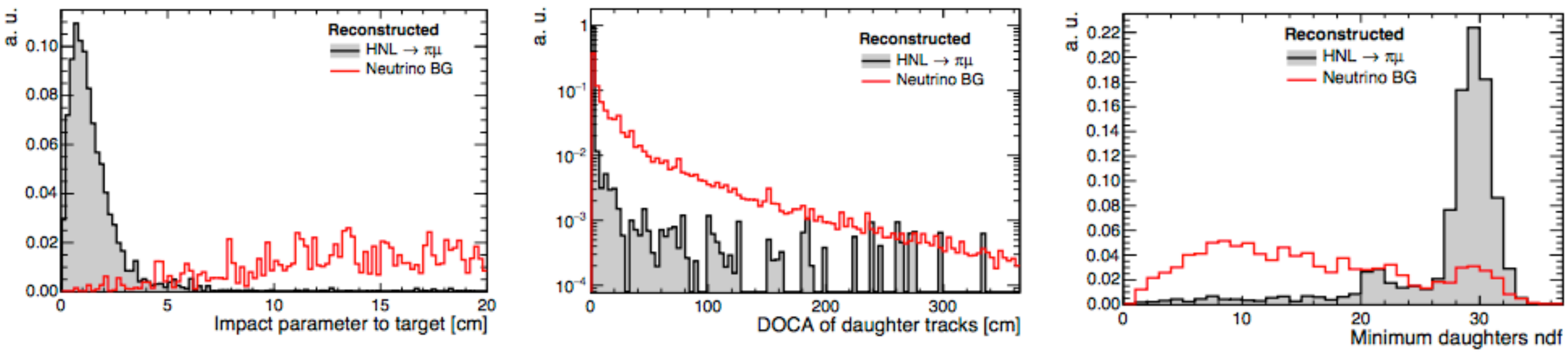
$$Br(D \to HNL\ X) \sim 10^{-8} - 10^{-12}$$
$$Br(B \to HNL\ X) \sim 10^{-12} - 10^{-16}$$

$$Br(HNL \to \mu(e)\pi) \sim 0.1 - 50\%$$
$$Br(HNL \to \mu(e)\rho) \sim 0.5 - 20\%$$
$$Br(HNL \to \mu e \nu_e) \sim 1 - 10\%$$

Reconstruction and Selection

$HNL \rightarrow \mu\pi$

BENCHMARK SCENARIO



SIGNAL

Table 5.10: Effect of the offline selection on $HNL \rightarrow \pi\mu$

Selection	Entries	Acceptance	Selection efficiency
Event reconstructed	4471	$6.43 \cdot 10^{-6}$	-
Event not vetoed	3540	$4.87 \cdot 10^{-6}$	75.8 %
χ^2/N.d.f. < 5	3540	$4.87 \cdot 10^{-6}$	100.0 %
N.d.f. > 25	3249	$4.37 \cdot 10^{-6}$	89.7 %
Vtx in fiducial vol.	3224	$4.34 \cdot 10^{-6}$	99.3 %
Tracks ∈ fiducial vol.	3223	$4.34 \cdot 10^{-6}$	100.0 %
150 MeV in Ecal	3223	$4.34 \cdot 10^{-6}$	100.0 %
1 muon in 1^{st} muon station	3201	$4.3 \cdot 10^{-6}$	99.1 %
1 muon in 2^{nd} muon station	3156	$4.22 \cdot 10^{-6}$	98.2 %
DOCA < 30 cm	3155	$4.22 \cdot 10^{-6}$	100.0 %
IP < 2.5 m	3155	$4.22 \cdot 10^{-6}$	100.0 %

BACKGROUND

Table 5.12: Effect of the offline selection on neutrino-induced background

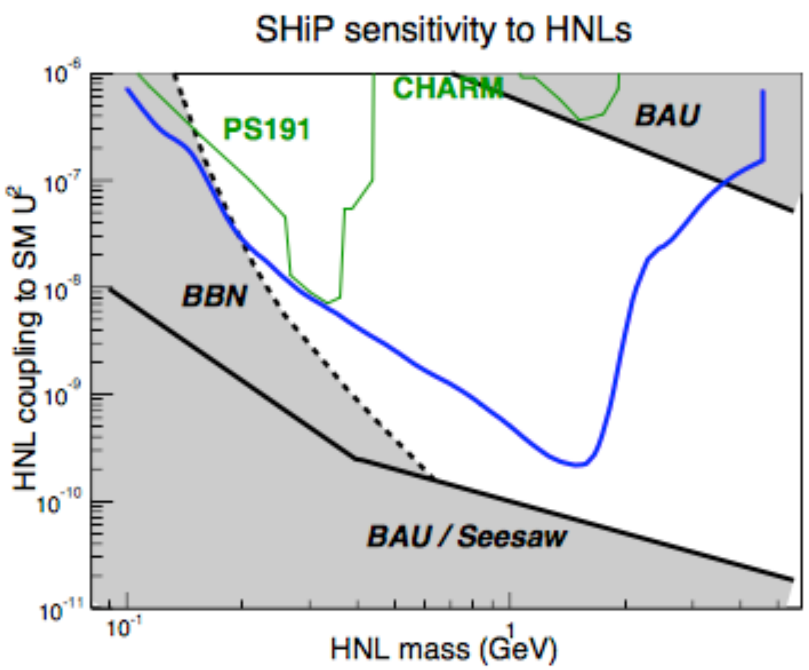
Selection	Entries	Events / 5 years	Selection efficiency
Event reconstructed	107828	$1 \cdot 10^4$	-
Event not vetoed	254	51.8	0.5 %
χ^2/N.d.f. < 5	253	51.7	99.9 %
N.d.f. > 25	74	8.98	17.4 %
Vtx in fiducial vol.	10	3.94	43.8 %
Tracks ∈ fiducial vol.	10	3.94	100.0 %
150 MeV in Ecal	9	2.01	51.1 %
1 muon in 1^{st} muon station	8	2.01	99.7 %
1 muon in 2^{nd} muon station	8	2.01	100.0 %
DOCA < 30 cm	7	1.72	85.5 %
IP < 2.5 m	0	0	0.0 %

Total Acceptance: $A = (5.6 \pm 0.6) \cdot 10^{-6}$

*Distance Of Closest Approach

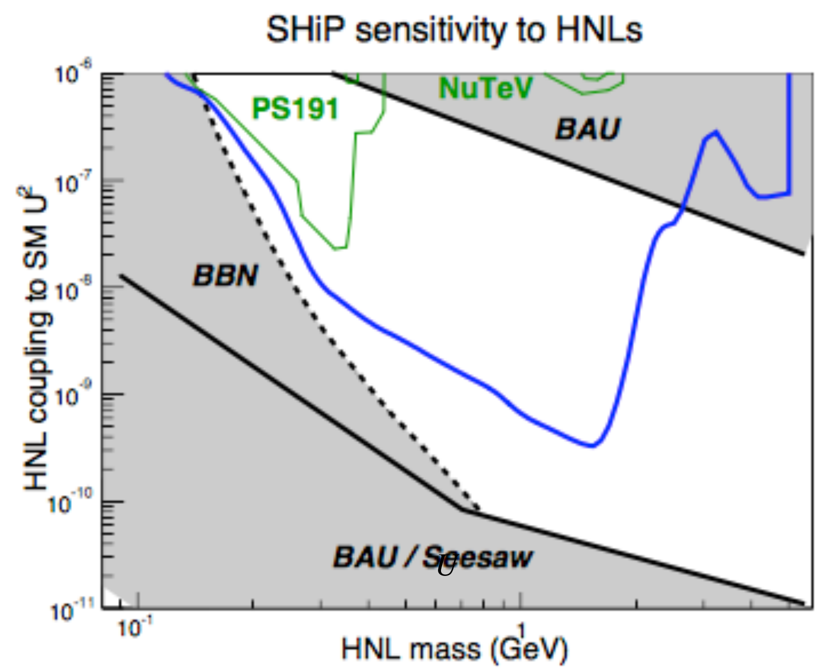
Sensitivity to Hidden Sector

INVERTED HIERARCHY SCENARIO



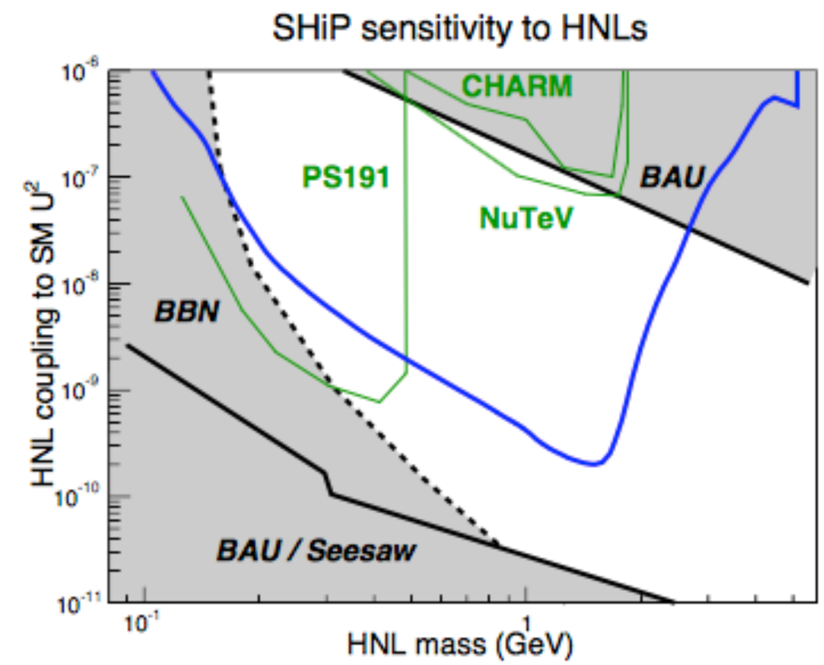
$$U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$$

BENCHMARK SCENARIO

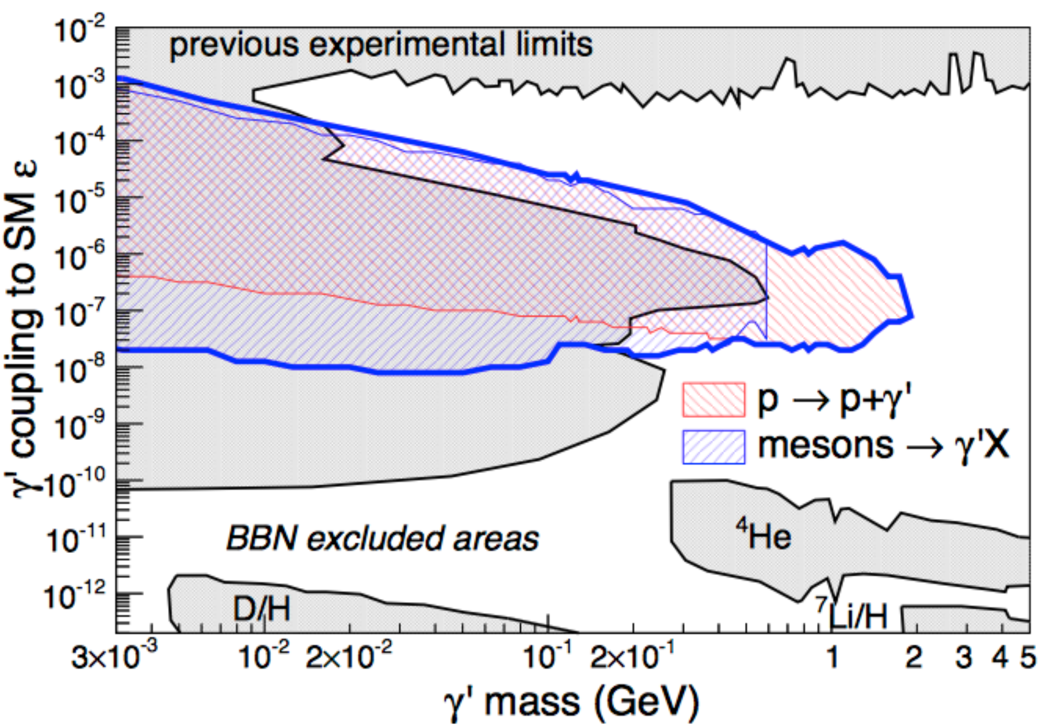


$$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$$

SCENARIO SENSITIVE TO BARYOGENESIS



$$U_e^2 : U_\mu^2 : U_\tau^2 = 48 : 1 : 1$$



Sensitivity to dark photon as a function of the mixing with the SM photon and the dark photon mass

Technical Proposal CERN-SPSC-2015-016

CONCLUSIONS

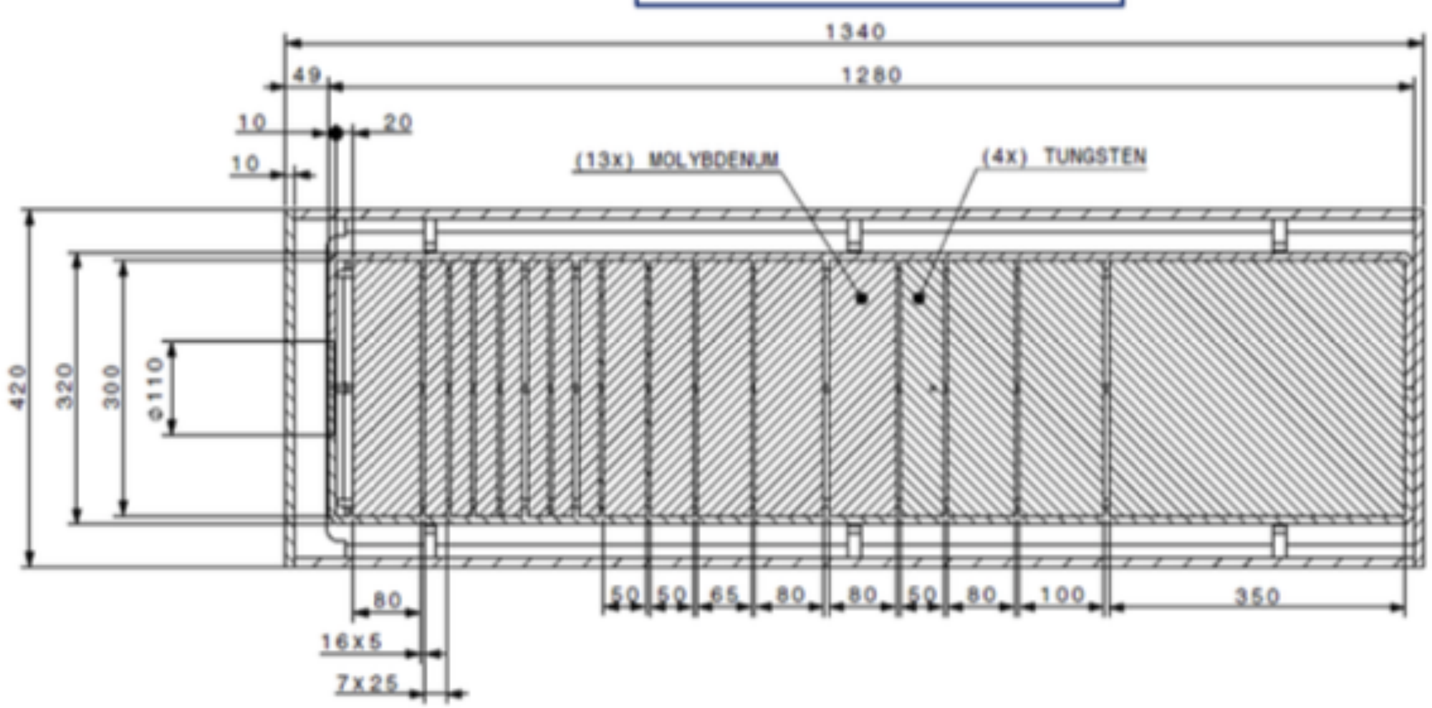
- A new general purpose fixed facility is proposed at the CERN SPS
- SHiP wide interesting physics case extends the exploration at the intensity frontier
- The proposed detector design is presented with particular attention to
  - requirement for hidden section particles detection
  - background suppression (<0.1 event/whole data tacking)
- Sensitivity to Hidden Sector is presented for
  - HNL produced in three different scenarios that differ for the relative strength of the coupling to the SM flavours
  - Dark Photon as a function of the mixing with the SM photon and the dark photon mass

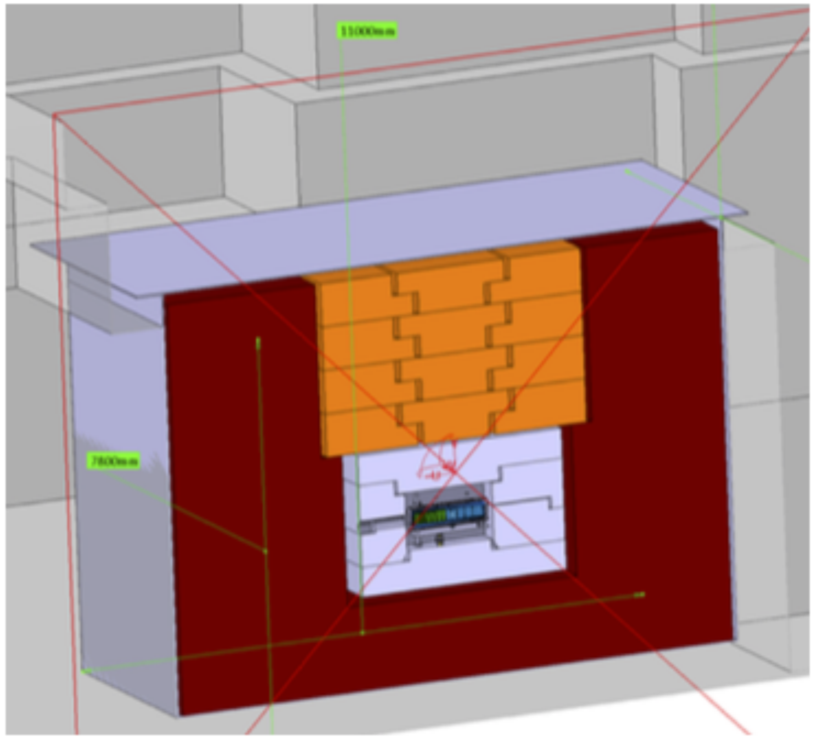
BACKUP

The Target

- Longitudinally segmented hybrid target
  - Core of shower: four interaction lengths of titanium-zirconium doped molybdenum alloy
  - Followed by six interaction lengths of pure tungsten
  - Water cooling
- Neutral particle absorber protects upstream beam-line from neutrons and other neutral radiation
- Target embedded in cast Iron bunker

Longitudinal cross-cut

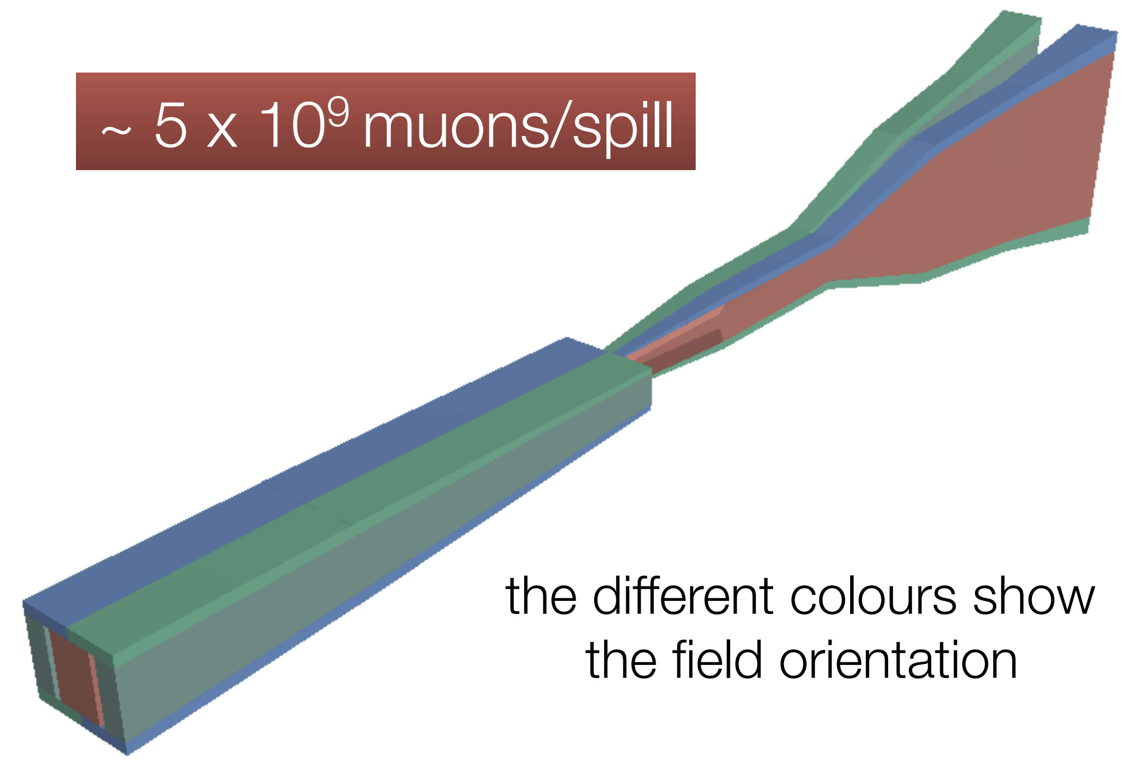


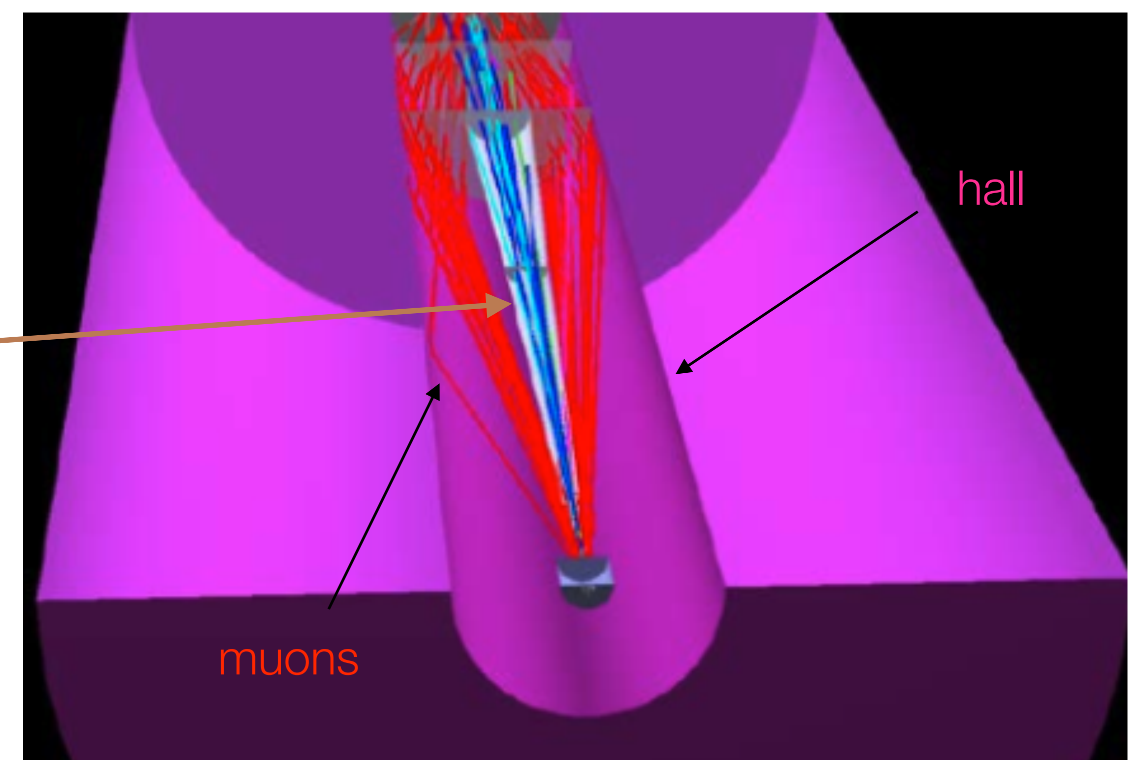


high average beam power: 2.56 MW per 1 sec. spill

The Muon Shield

- Muon shield needs to be as compact as possible along beam-line
- Both active and passive shields being investigated
  - **Active shield** needs B_y = 40 Tm to bend 350 GeV muons away from the 5 m aperture of vacuum vessel
    - Need to separate μ^+ from μ^-
    - Bend muons further outward
  - **Passive shield** uses dense material to slow down muons ~40 m of tungsten (110 tonnes) + 2500 ton Pb
    - Backscatter from wall of experimental hall still lead to <u>an unacceptably large flux of muons</u>





Straw Tracker Parameters

Parameter	Value	Note
Straw		
Length of a straw	5 m	
Outer straw diameter	9.83 mm	
Straw wall (PET, Cu, Au)		
PET foil thickness	36 μm	40 μm PET in simulation
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	$\sim$ 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	$\sim$ 34 cm	
Number of straws in one station	9088	
Straw tracker		
Number of stations	4	2 before, 2 after the magnet
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	

Background Sources

GOAL: 0.1 expected background events / whole data tacking (210^{20} pot)

Background source	Statistical factor	Expected background
ν ($p > 10.0$ GeV/c)	35.	< 0.07
ν (4.0 GeV/c$< p <$ 10.0 GeV/c)	~ 1	0 (MC)
ν (2.0 GeV/c$< p <$ 4.0 GeV/c)	0.07	0 (MC)
μ DIS HS	~ 1	0 (MC)
μ DIS wall	0.001	0 (MC)
μ Combinatorial	10^4	< 0.1
μ Cosmics ($p < 100$ GeV/c)	0.2	0 (MC)
μ Cosmics ($p > 100$ GeV/c)	800.	< 0.1
μ Cosmics DIS ($p > 100$ GeV/c)	10^3	< 0.1
μ Cosmics DIS (10 GeV/c$< p <$ 100 GeV/c)	~ 1	0 (MC)

- neutrino induced bkg:
  - interaction mostly take place in the vacuum vessel entrance and walls => **taggers veto** (90%) + **topological rejection** (99.4%)
- muon inelastic scattering:
  - thanks to the **muon shield** most of them hit the caver wall with a small angle downstream and stop in concrete walls. **Topological rejection** reduces muon background at the required level

Background Sources

GOAL: 0.1 expected background events / whole data tacking (210^{20} pot)

Background source	Statistical factor	Expected background
ν ($p > 10.0$ GeV/c)	35.	< 0.07
ν (4.0 GeV/c$< p < 10.0$ GeV/c)	~ 1	0 (MC)
ν (2.0 GeV/c$< p < 4.0$ GeV/c)	0.07	0 (MC)
μ DIS HS	~ 1	0 (MC)
μ DIS wall	0.001	0 (MC)
μ Combinatorial	10^4	< 0.1
μ Cosmics ($p < 100$ GeV/c)	0.2	0 (MC)
μ Cosmics ($p > 100$ GeV/c)	800.	< 0.1
μ Cosmics DIS ($p > 100$ GeV/c)	10^3	< 0.1
μ Cosmics DIS (10 GeV/c$< p < 100$ GeV/c)	~ 1	0 (MC)

- muon combinatorial background
  - $O(10^{12})$ random combinations of muons enter the vacuum vessel in five years of data taking. **Timing veto** (window of 340 ps) + **upstream veto detectors**
- cosmic muons
  - Particularly important are DIS with experimental hall concrete walls and detector material. Rejected by DOCA* and vertex location, + veto tagger

*Distance Of Closest Approach

Background Sources

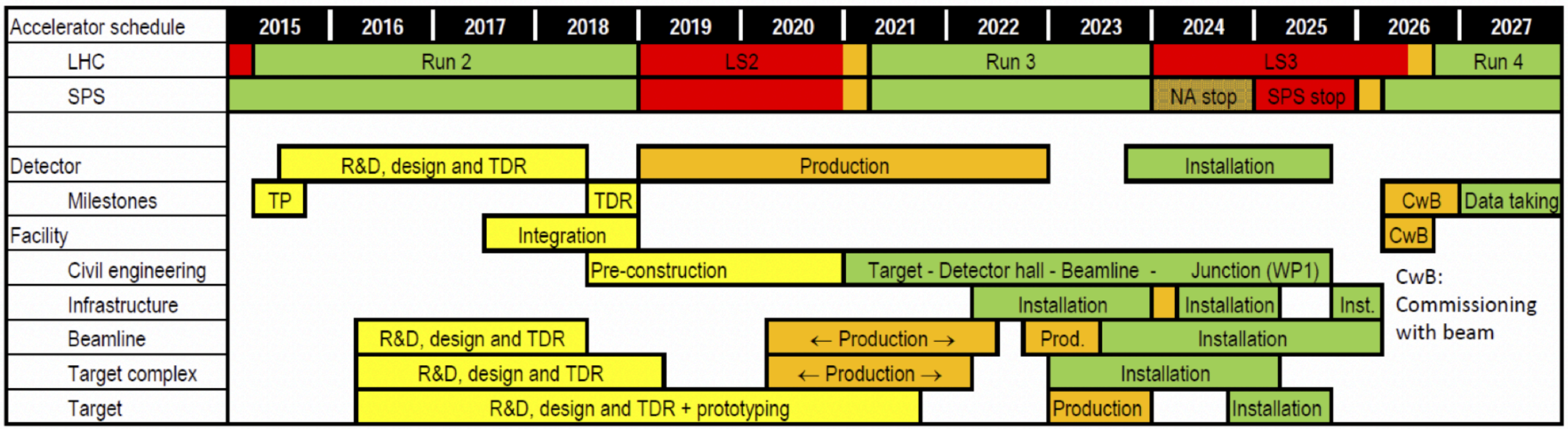
GOAL: 0.1 expected background events / whole data tacking (210^{20} pot)

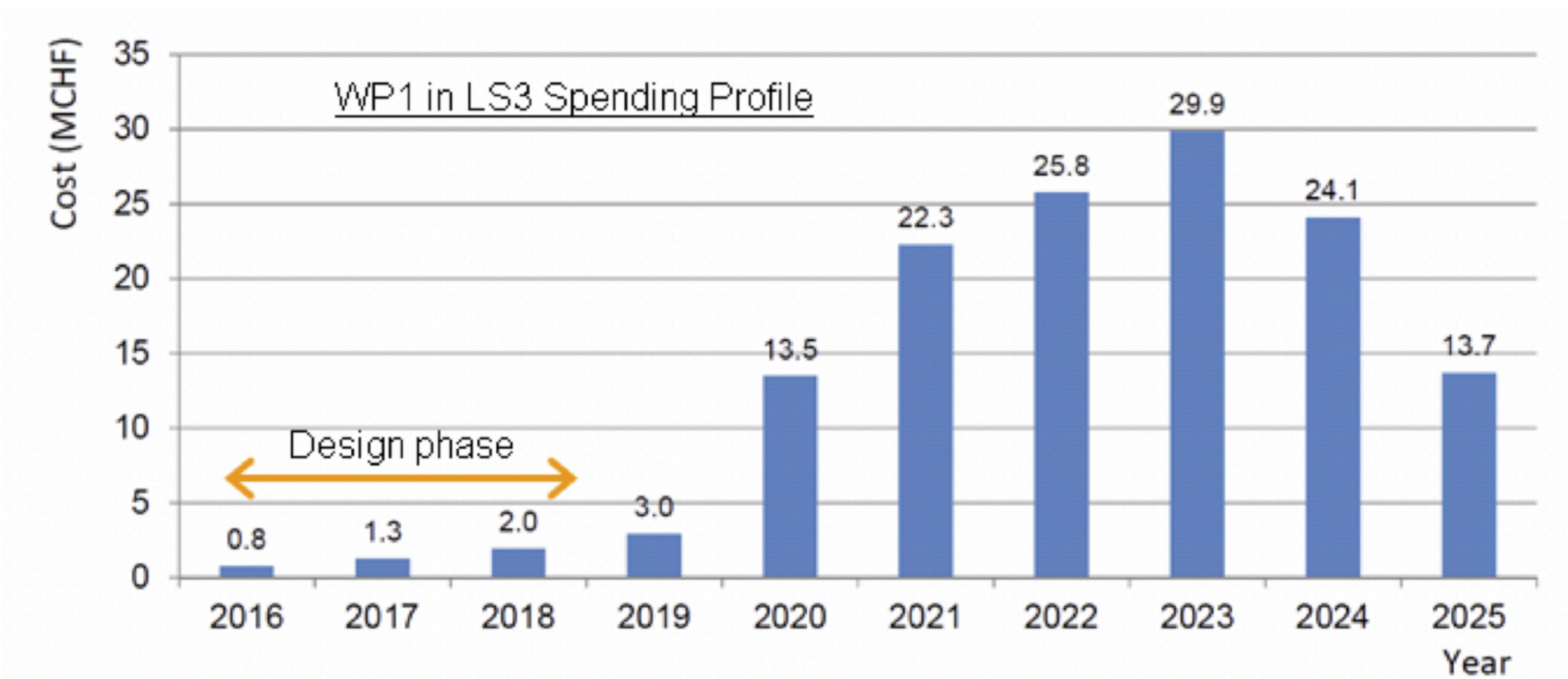
- Main background sources:
  - neutrino induced bkg:
    - Nν ~4x10^{17} and Nanti-ν ~3x10^{17} in 5 years with 2 GeV< p < 100 GeV and within 100 mrad. Products dominated by pions and kaons decays
    - interaction mostly take place in the muon magnetic spectrometer of the tau neutrino detector, the entrance window of the vacuum vessel and the surrounding walls of the vacuum vessel => vetoed by taggers (90%)
    - topology of the interaction easy to reject with loose selection cuts: 2 high quality reconstructed tracks of opposite charge, coming from a vertex inside the decay volume that points to the target (99.4% rejection efficiency)
  - muon inelastic scattering:
    - most of the muons hit the caver wall with a small angle downstream of the decay volume. The products of muon inelastic scattering with nucleons stop in concrete without other bkg activity in the SHiP spectrometer
    - muons which are not sufficiently deflected and which hit material close the entry of the decay volume => similar neutrino induced bkg Nmu = 3x10^{3} /spill safely tolerated
    - simulation shows Distance of closest approach (DOCA) of two tracks, impact parameter Veto tagger reduce muon background at the required level

Background Sources

- muon combinatorial background
  - random combinations of muons which enter the vacuum vessel, either by backscattering in the surrounding caver walls or due to the imperfection of the muon shield may mimic signal events.
  - Expected 7kHz during spill => O(10) enter the decay volume in five years of data taking 0(10^{12})
  - rejected with timing veto with a timing window of 340 ps (3 times the resolution of the timing detector) + upstream veto detectors
- cosmic muons
  - muon from cosmic rays, particularly DIS with experimental hall concrete walls and detector material
  - interaction in lower concrete wall do not see any reconstructed two track event
  - most of the event produced by interaction in the upper concrete wall are rejected by DOCA and vertex location, the rest are vetoed by tagger
  - inside vessel material we expect 0.07 events with reconstructed two-track. Applying DOCA cut and vertex location it is further reduced

Timescale and Costs





Main decay modes and backgrounds

Main decay modes of hidden particles

Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}$, $\rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}, \pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

Background sources with V^{0} particles

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 $\to X + K_S$	$K_L \to \pi^{0}\pi^{0}, \pi^{+}, \pi^{-}$
ν or μ + nucleon $\to X + K_\Lambda$	$\Lambda \to p\pi^{-}$
n or μ + nucleon $\to X + K_L$, etc	as above