# Search for new physics with the SHiP experiment at CERN

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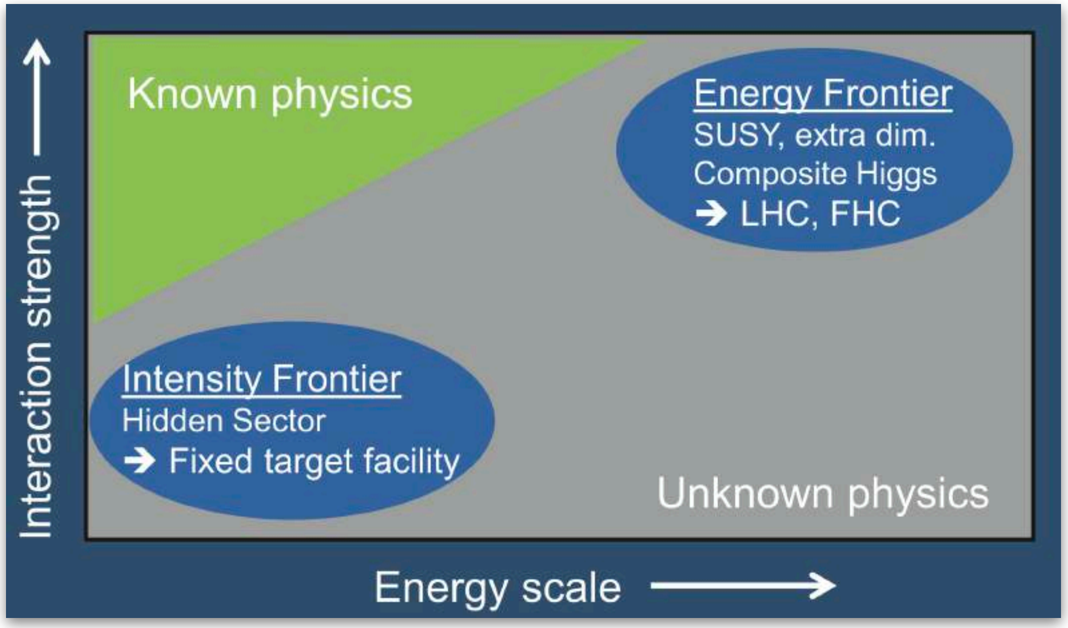
*on behalf of the SHiP collaboration*

Session: Search for New Physics
EPS-HEP2019 in Ghent
*12/07/2019*

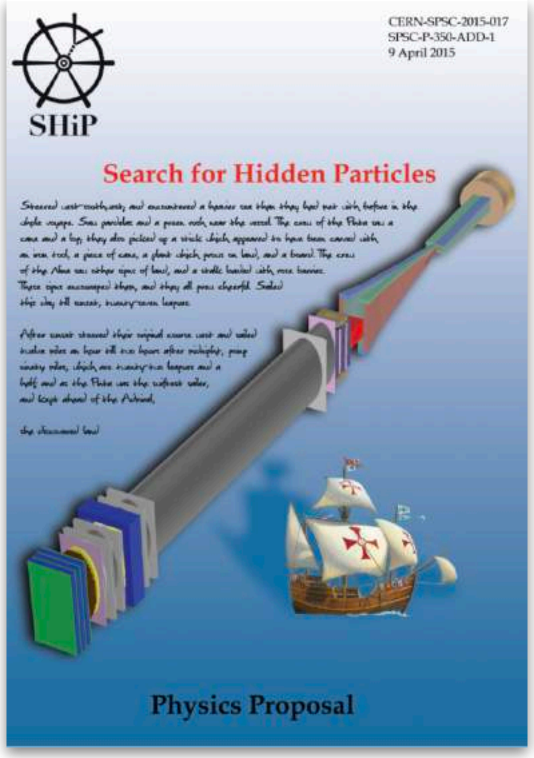
# Search for Hidden Particles (SHiP) experiment



- Fixed target facility at the CERN SPS (400 GeV)
- Designed to find a solution for BSM physics by searching for very weakly interacting particles
- Hidden Sector (HS) production and decay rates are strongly suppressed relative to SM: production branching ratios *O*($10^{-10}$)
- Detection of long-lived particles in the "zero background" experiment

- ***2013*** *Expression of Interest* for a new CERN SPS experiment submitted
- ***2015*** *Technical proposal* and description of physics case submitted
- ***2016*** *Recommendation* by CERN SPSC to proceed to Comprehensive Design Study
- ***2018*** Comprehensive design study by the *Beam Dump Facility* group published
- **2019** *Comprehensive Design Report* to be submitted

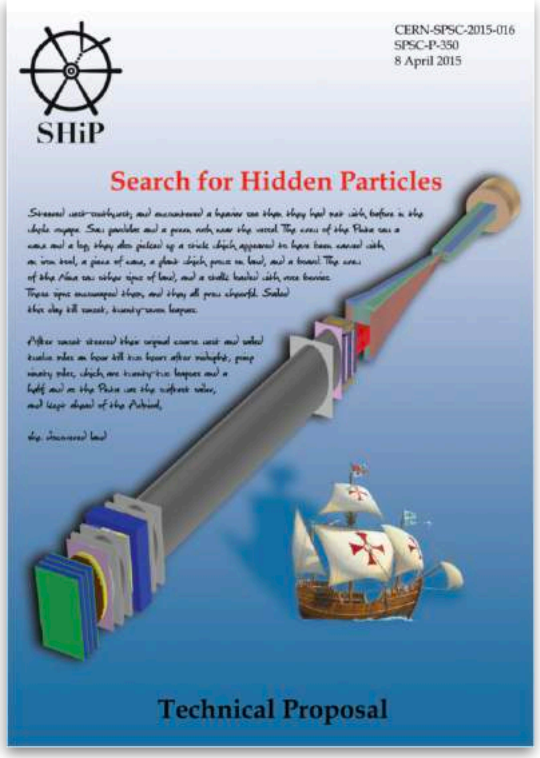
***290 authors, 52 institutes, 17 countries***


CERN-SPSC-2015-017
SPSC-P-350-ADD-1
9 April 2015

SHiP

Search for Hidden Particles

Physics Proposal


CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

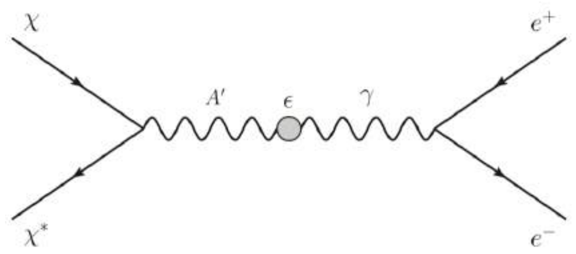
SHiP

Search for Hidden Particles

Technical Proposal

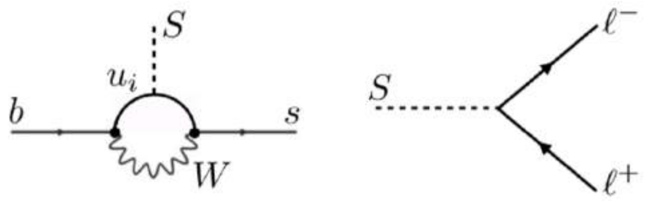
# Hidden Sector (HS) under study

- Dark vectors ("Dark Photons")
  - Addition of U(1) gauge group to SM, kinetic mixing with $\gamma$ and Z
  - Bremsstrahlung, light neutral meson decays, quark annihilation

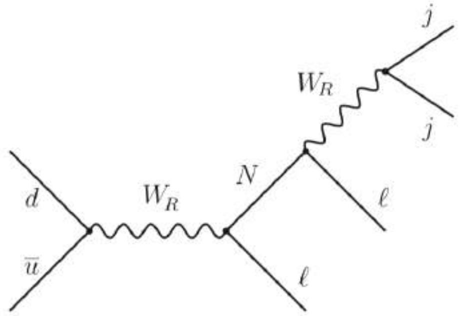


- (Light) Dark Matter direct detection ("WIMPs")
  - Stable or long-lived DM that couple to EM current via *A'*

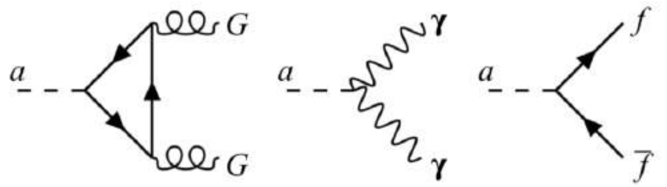
- Dark scalars ("Dark Higgses")
  - Neutral singlet scalers that couple to the SM Higgs field
  - Produced in penguin decays of K, D, B mesons



- Heavy neutral leptons ("sterile neutrinos")
  - Explains SM neutrino masses (seesaw), Dark Matter, Baryon Asymmetry
  - Weak semi-leptonic decays of hadrons, W, Z



- Axion-like particles ("ALPs")
  - Non-renormalizable coupling to SM, solution of the strong CP problem
  - Generalisation of the axion model in MeV-GeV mass range



| Portal | Coupling to SM |
|---|---|
| Dark Photon, $\mathcal{A}'_\mu$ | $\epsilon/(2\cos\theta_W)\ \mathcal{F}'_{\mu\nu}\ \mathcal{B}_{\mu\nu}$ |
| Dark Higgs, $S$ | $(\mu S + \lambda S^2)\ \mathcal{H}^\dagger\mathcal{H}$ |
| Axion or ALP, $a$ | $a/f_\gamma \cdot \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}_{\mu\nu}\ ,\ a/f_\gamma \cdot \mathcal{G}_{i,\mu\nu}\tilde{\mathcal{G}}_i^{\mu\nu}\ ,\ \partial a/f_a \cdot \bar{\psi}\gamma^\mu\gamma^5\psi$ |
| Sterile Neutrino, $N$ | $\Sigma\ F_{\alpha I}(\bar{L}_\alpha H)N_I$ |

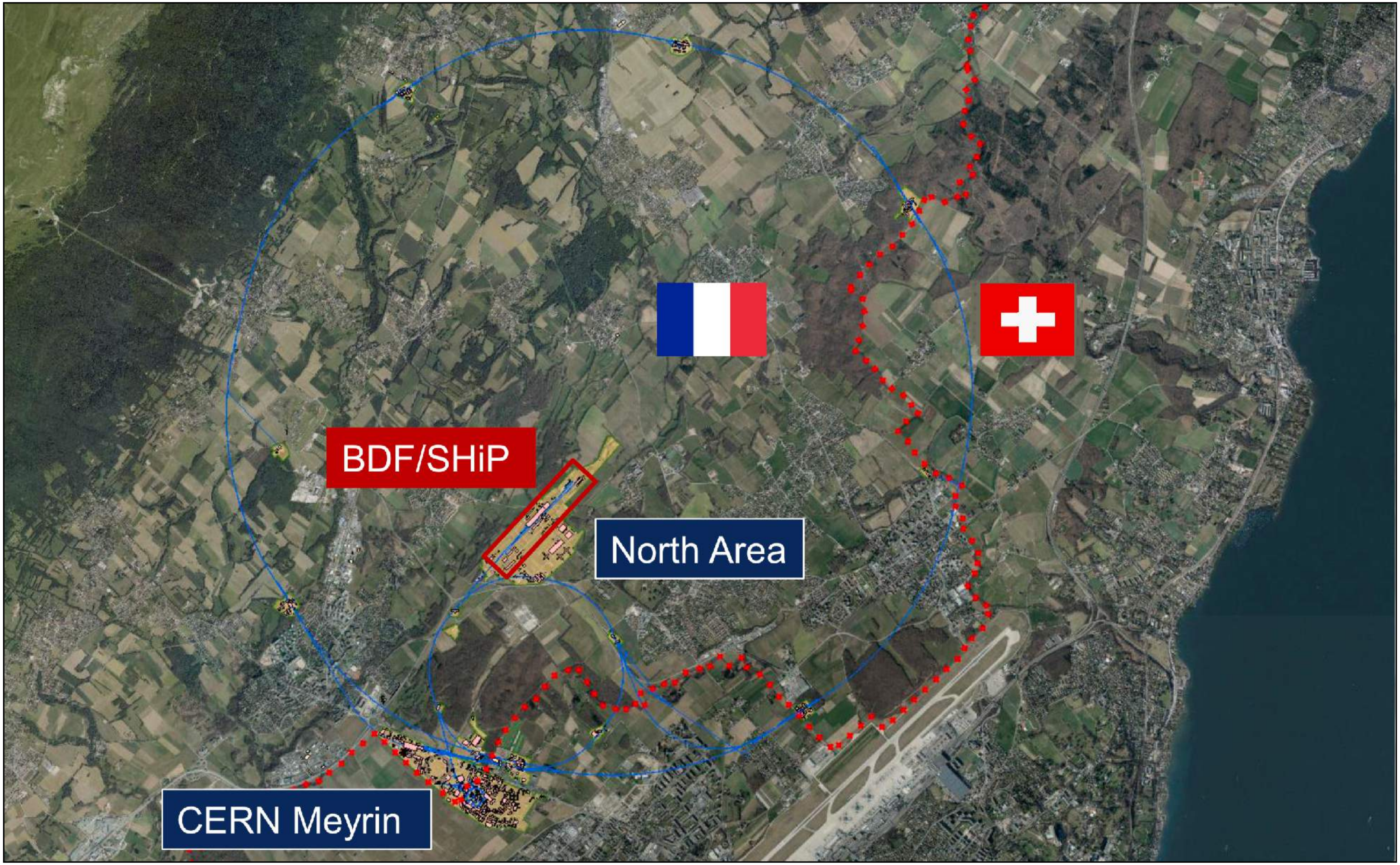
*CERN-PBC-REPORT-2018-007*

Main **decay modes** of hidden particles in various models ($l = e, \mu$)

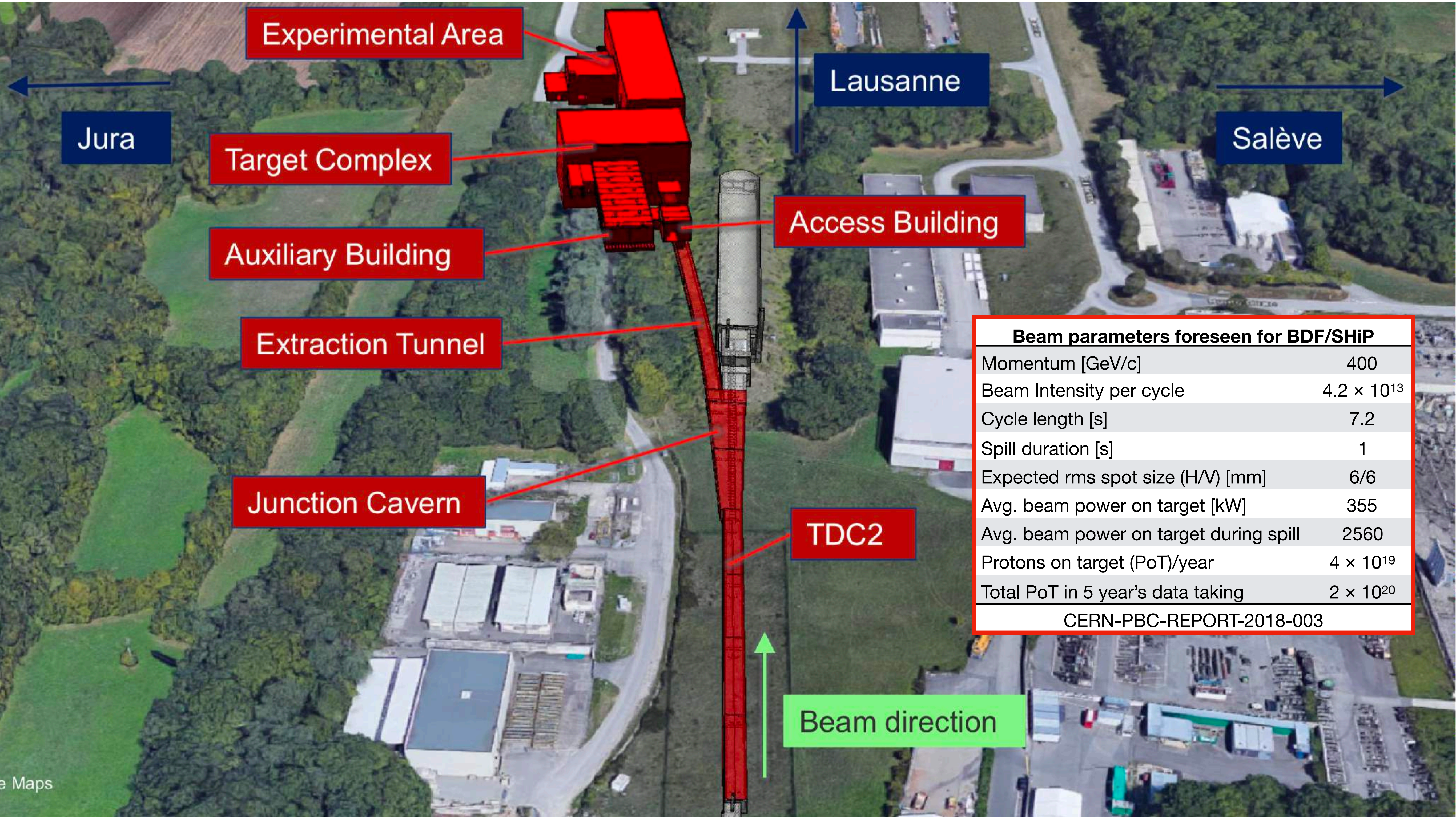
| Model | Final state |
|---|---|
| Neutrino portal, SUSY neutralino | $l^\pm\pi^\mp$, $l^\pm K^\mp$, $l^\pm\rho^\mp$, $\rho^\pm \longrightarrow \pi^\pm\pi^0$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $l^+l^-$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\pi^+\pi^-$, $K^+K^-$ |
| Neutrino portal ,SUSY neutralino, axino | $l^+l^-\nu$ |
| Axion portal, SUSY sgoldstino | $\gamma\gamma$ |
| SUSY sgoldstino | $\pi^0\pi^0$ |

*CERN-SPSC-2015-016*

# Beam Dump Facility (BDF) in the North Area of CERN SPS



# New extraction tunnel for BDF (SHiP & TauFV) in the North Area

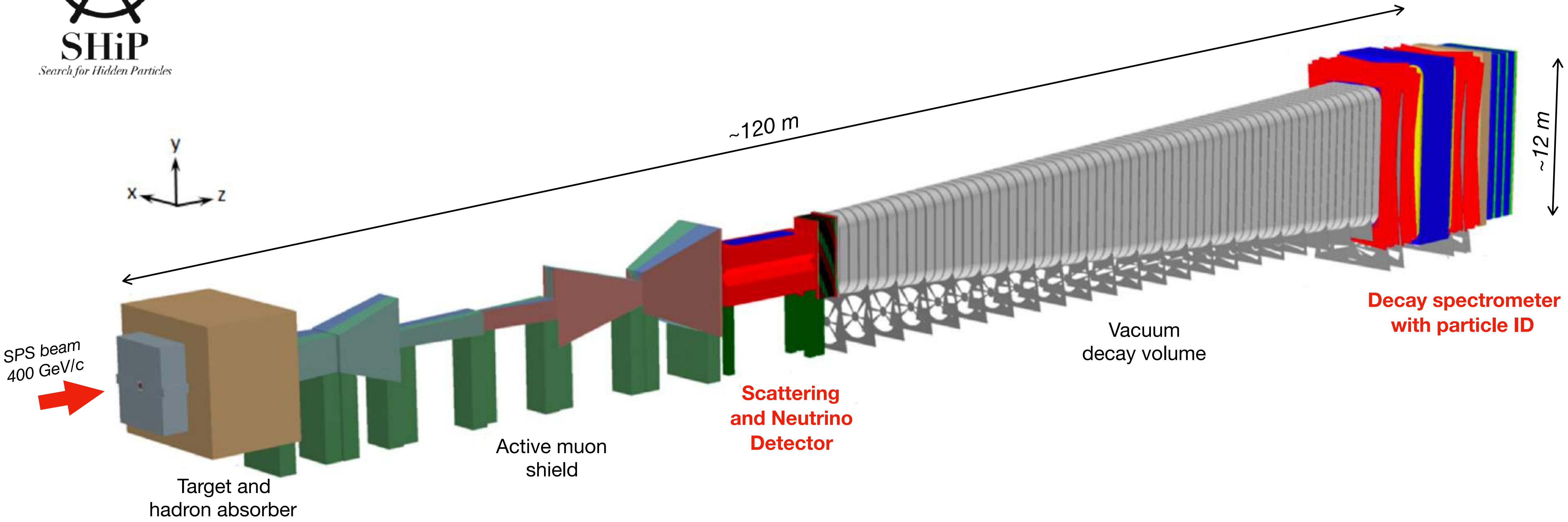


| Beam parameters foreseen for BDF/SHiP | |
|---|---|
| Momentum [GeV/c] | 400 |
| Beam Intensity per cycle | $4.2 \times 10^{13}$ |
| Cycle length [s] | 7.2 |
| Spill duration [s] | 1 |
| Expected rms spot size (H/V) [mm] | 6/6 |
| Avg. beam power on target [kW] | 355 |
| Avg. beam power on target during spill | 2560 |
| Protons on target (PoT)/year | $4 \times 10^{19}$ |
| Total PoT in 5 year's data taking | $2 \times 10^{20}$ |

CERN-PBC-REPORT-2018-003

EDMS 2044415 L. Dougherty - 07 November 2018

# Experimental setup of SHiP

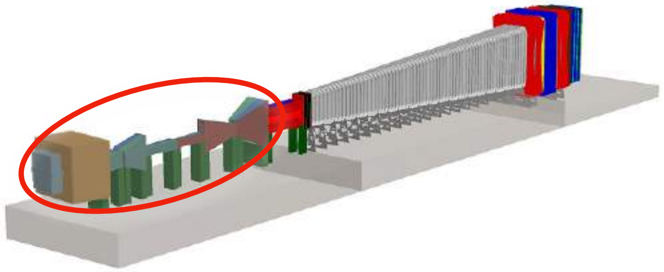


## *Scattering and Neutrino Detector (SND)*

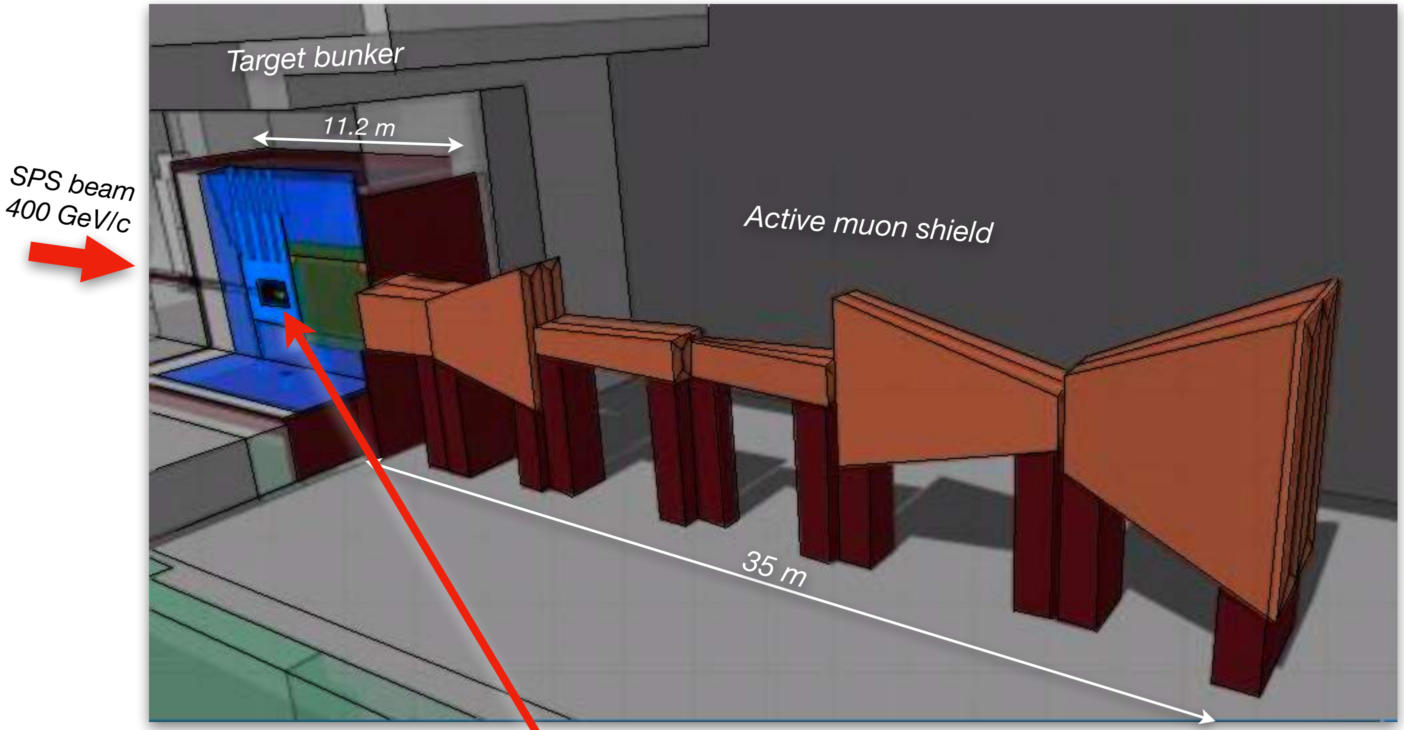
- Emulsion spectrometer located inside of a long dipole magnet B=1.2T
- Muon identification system downstream
- **Physics goals**:
  - SM physics: $\boldsymbol{\nu_\tau}$ cross section and magnetic moment, DIS structure functions $F_4$ and $F_5$, neutrino-induced charm production and strangeness, nuclear effects
  - Search for LDM scattering

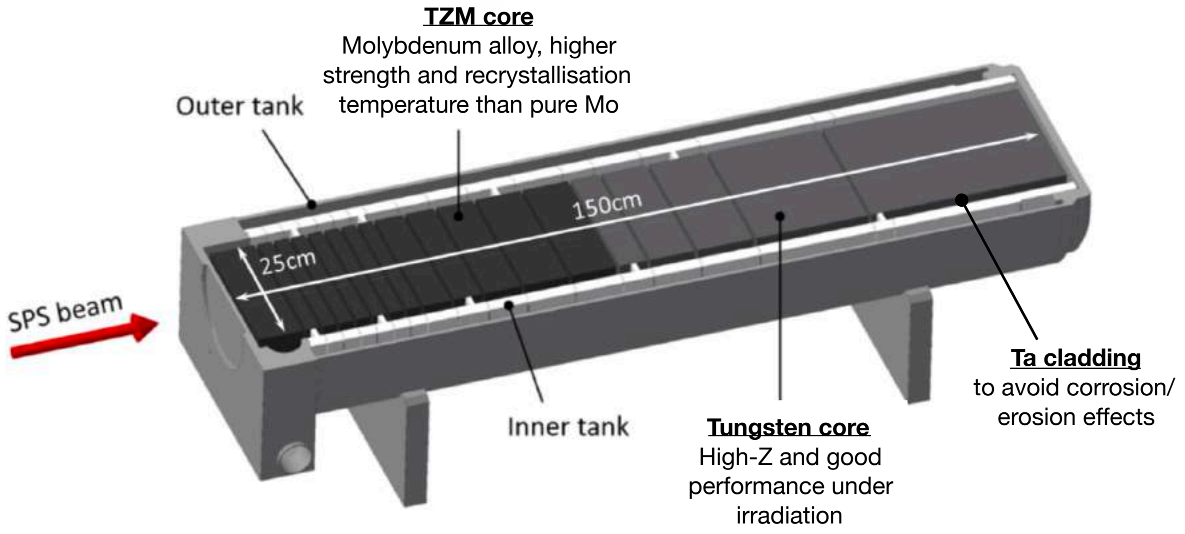
## *Hidden Sector (HS) Spectrometer*

- Distance from the target is a compromise between
  - HS life time and angular acceptance
  - muon induced background
- Decay volume 50m long, 1 mbar pressure
- Magnetic spectrometer downstream
- **Physics goal**: search for very weakly interacting long lived particles including Heavy Neutral Leptons - right-handed partners of the active neutrinos, vector, scalar, axion portals to the Hidden Sector, and light supersymmetric particles



# BDF target bunker and magnetic shield





**TZM core**
Molybdenum alloy, higher strength and recrystallisation temperature than pure Mo

**Tungsten core**
High-Z and good performance under irradiation

**Ta cladding**
to avoid corrosion/ erosion effects

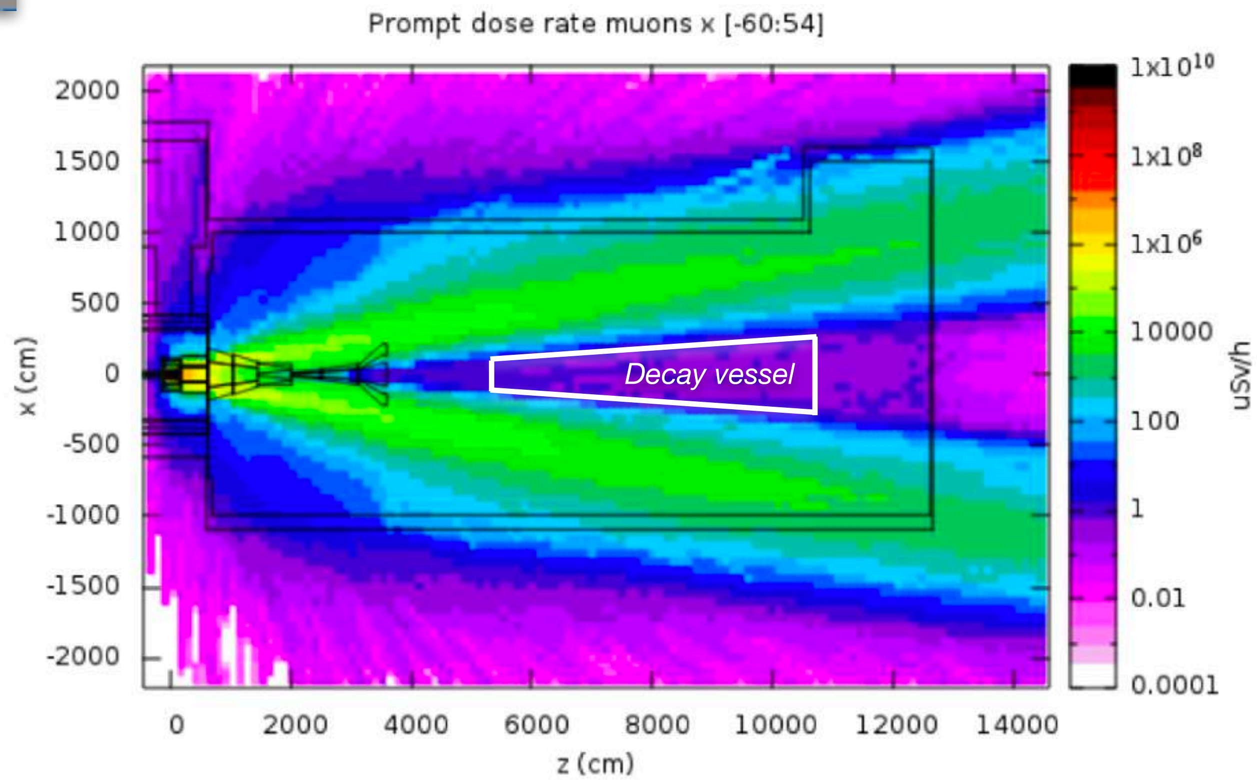
*JINST 13 (2018) no.10, P10011*

### *Target*

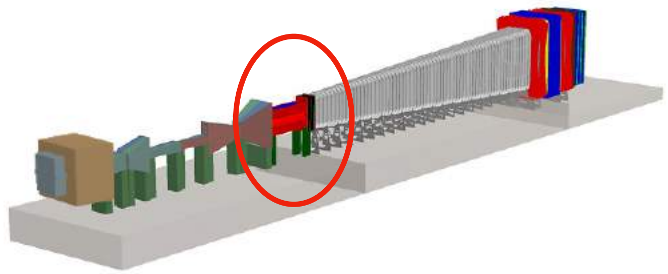
- Maximise production of charmed mesons
- Increase reabsorption of pions and kaons; 12 $\lambda_I$ to reduce the shower leakage
- High-Z material: $_{42}$Mo and $_{74}$W

### *Magnetic shield*

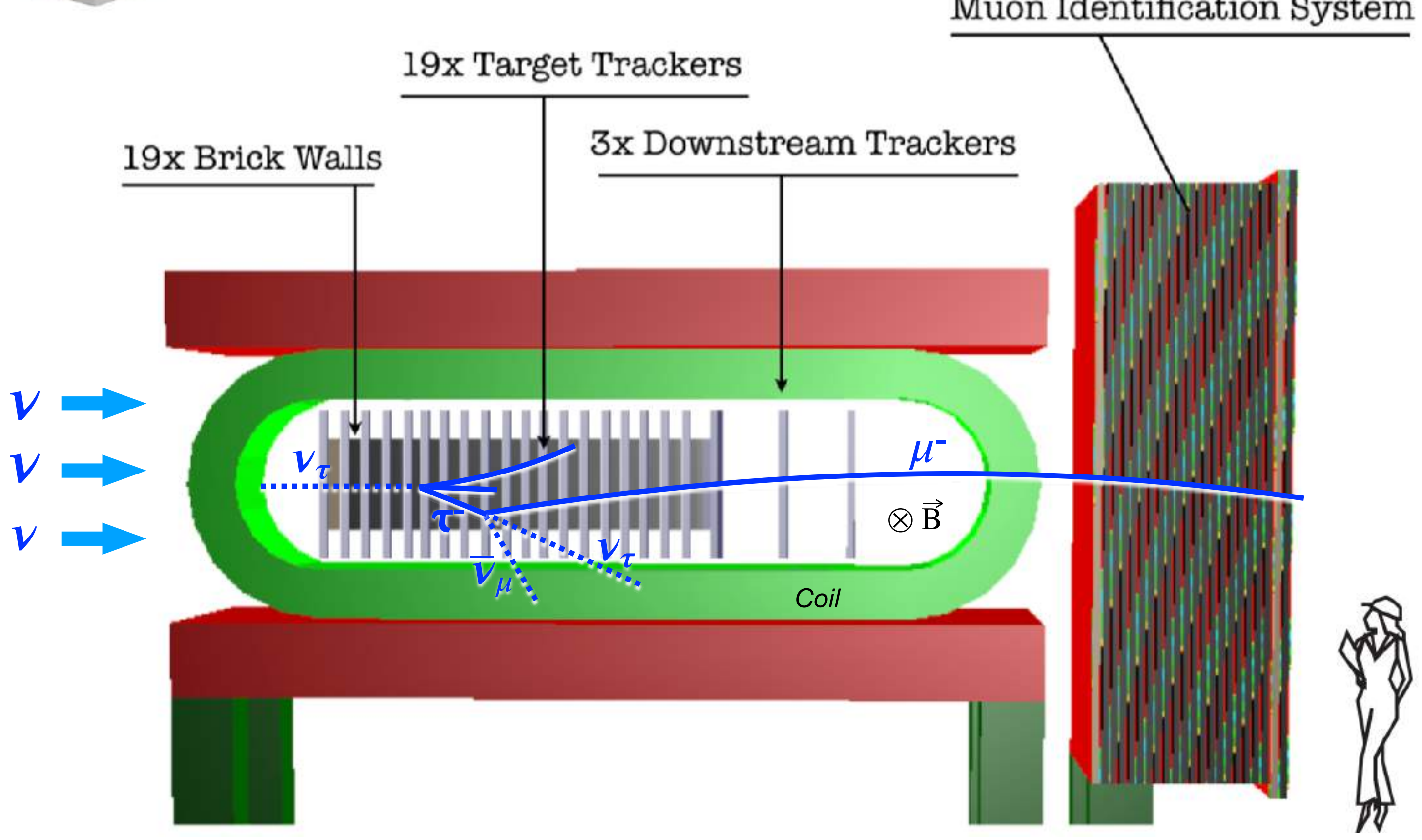
- Designed to reduce the $\mu$ flux by 6 orders of magnitude
- Assembled of Grain-Oriented (GO) steel sheets (0.3 mm thick) in sections of 5 cm thick
- Magnetic field of 1.7 T in critical magnet areas
- ~$10^5$ muons/spill pass to the vacuum vessel



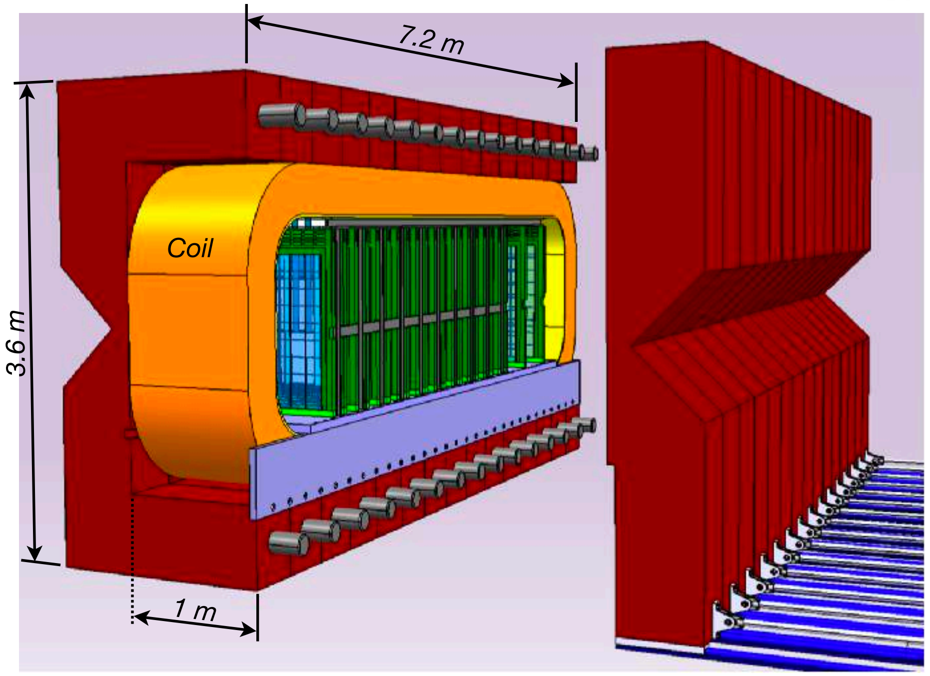
*JINST 12 (2017) no.5, P05011*



# Scattering and Neutrino Detector



***See talk of Alessandra Pastore in Neutrino Session***



### *Target detector*

- Emulsion detector with trackers & time stamp
- 19 x (SciFi x ECC x CES)

### *Muon identification system*

- 13 iron filters (10 cm thick)
- 12 RPC planes for tracking (area 2x5 m$^2$)
- For muon momenta > 10 GeV/c

### *Magnet*

- Warm magnet, can be open for access
- Horizontal magnetic field B=1.25 T
- Active cooling system for coil + thermal shield

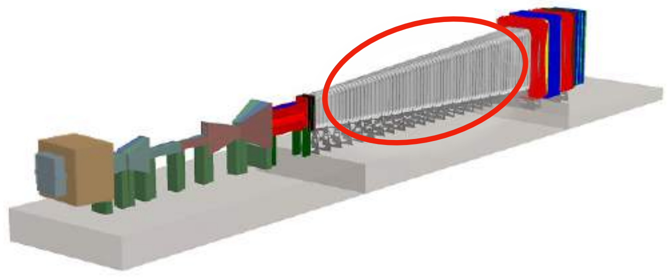
### *SM Physics*

- 3 flavours $\nu_e$, $\nu_\mu$, $\nu_\tau$ and distinguish $\nu$ and $\bar{\nu}$
- $\tau$ (anti)neutrino physics, N≈10$^4$
- Structure functions $F_4(x,Q^2)$ and $F_5(x,Q^2)$
- Neutrino-induced charm production, strangeness
- Nuclear effects in $\nu$N DIS: shadowing, anti-shadowing, EMC region, Fermi motion region
- $\nu_\tau$ magnetic moment ($m_\nu \neq 0$)

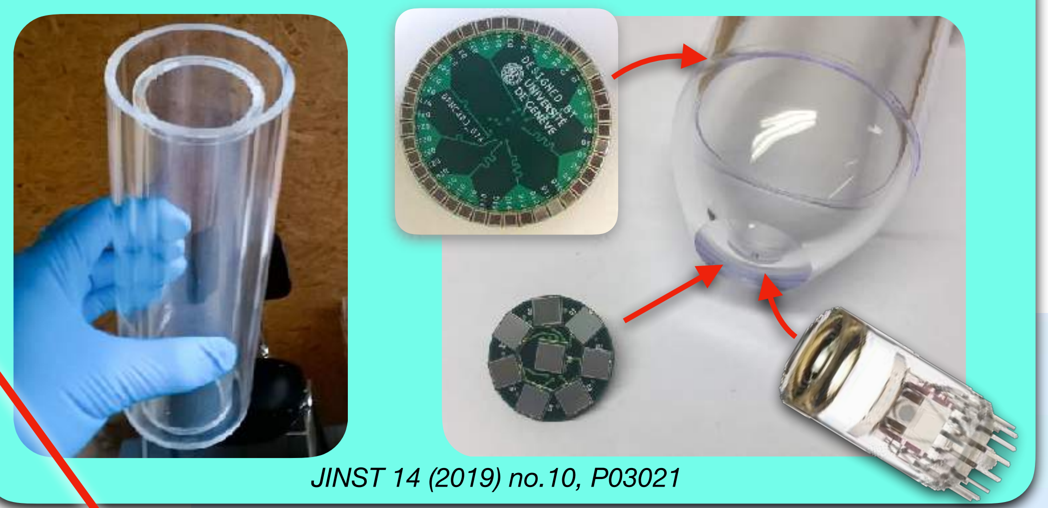
### *HS Physics*

- LDM detection via scattering off electrons

# Vacuum vessel and Surrounding Background Tagger

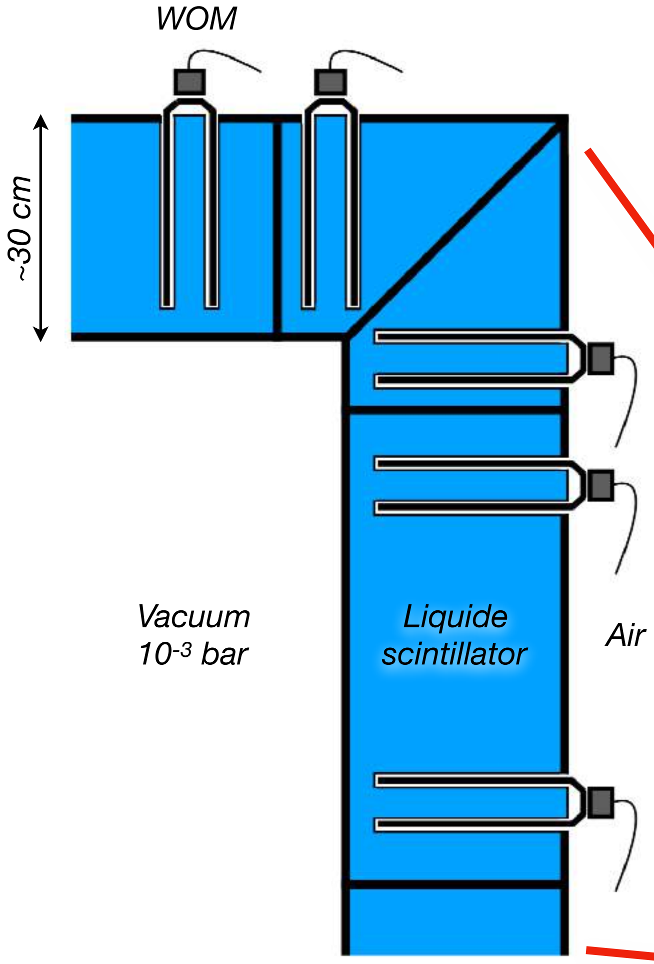


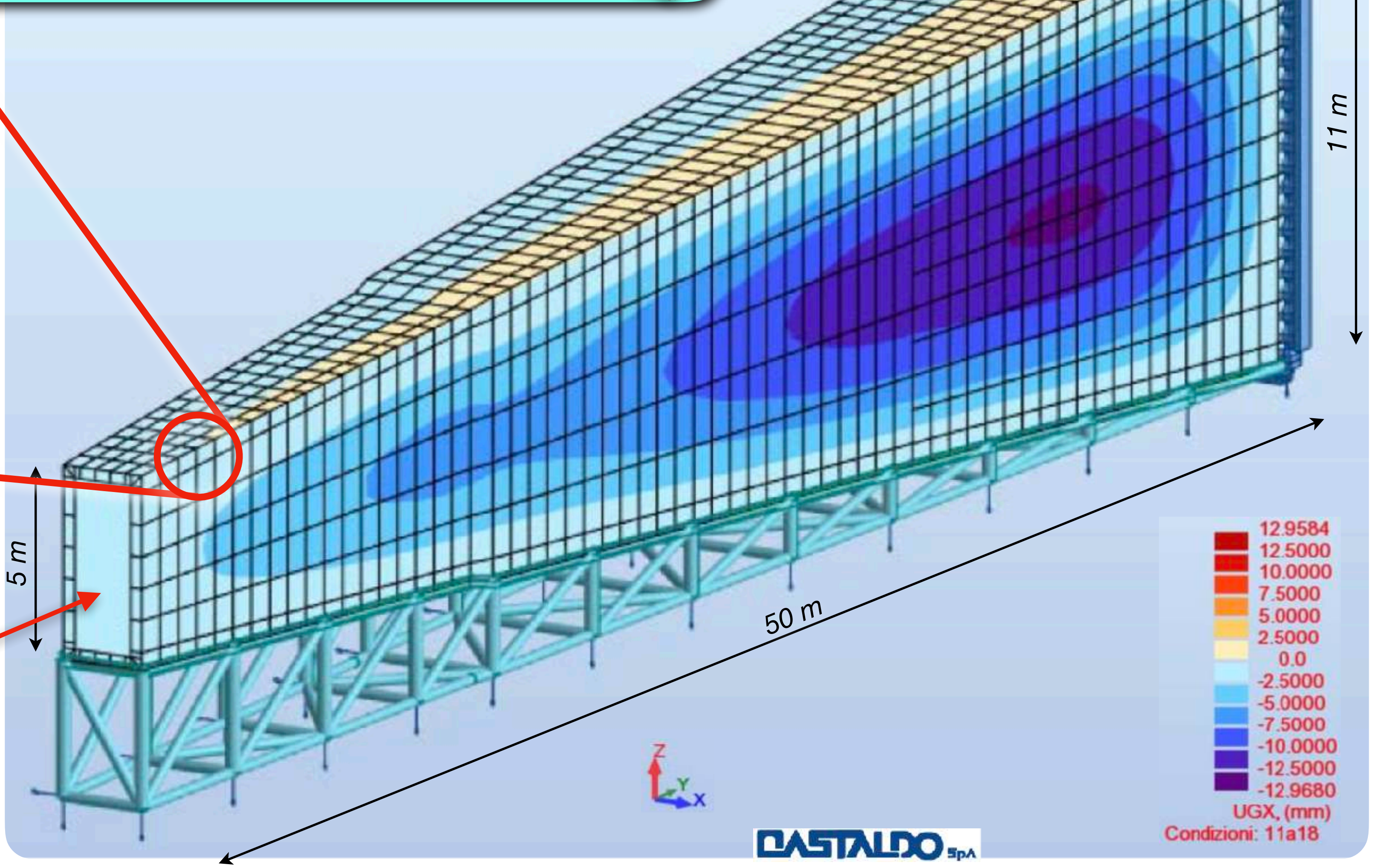
## *Wavelength-shifting Optical Module (**WOM**)*



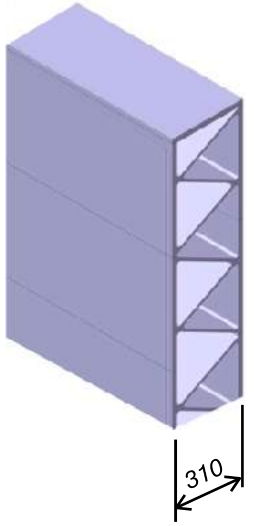
*JINST 14 (2019) no.10, P03021*

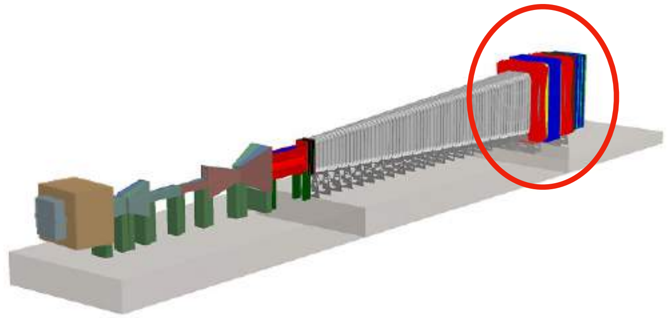
- Production of $V_0$ ($K_L$,$K_S$,$\Lambda$) produced in DIS interactions mimics decays of HS particles
- Pressure of **1 mbar** inside
- 2-3 cm thick continuous steel sheets
- Compartments for the liquid scintillator which will act as a veto
- Total scintillator volume 243 m$^3$



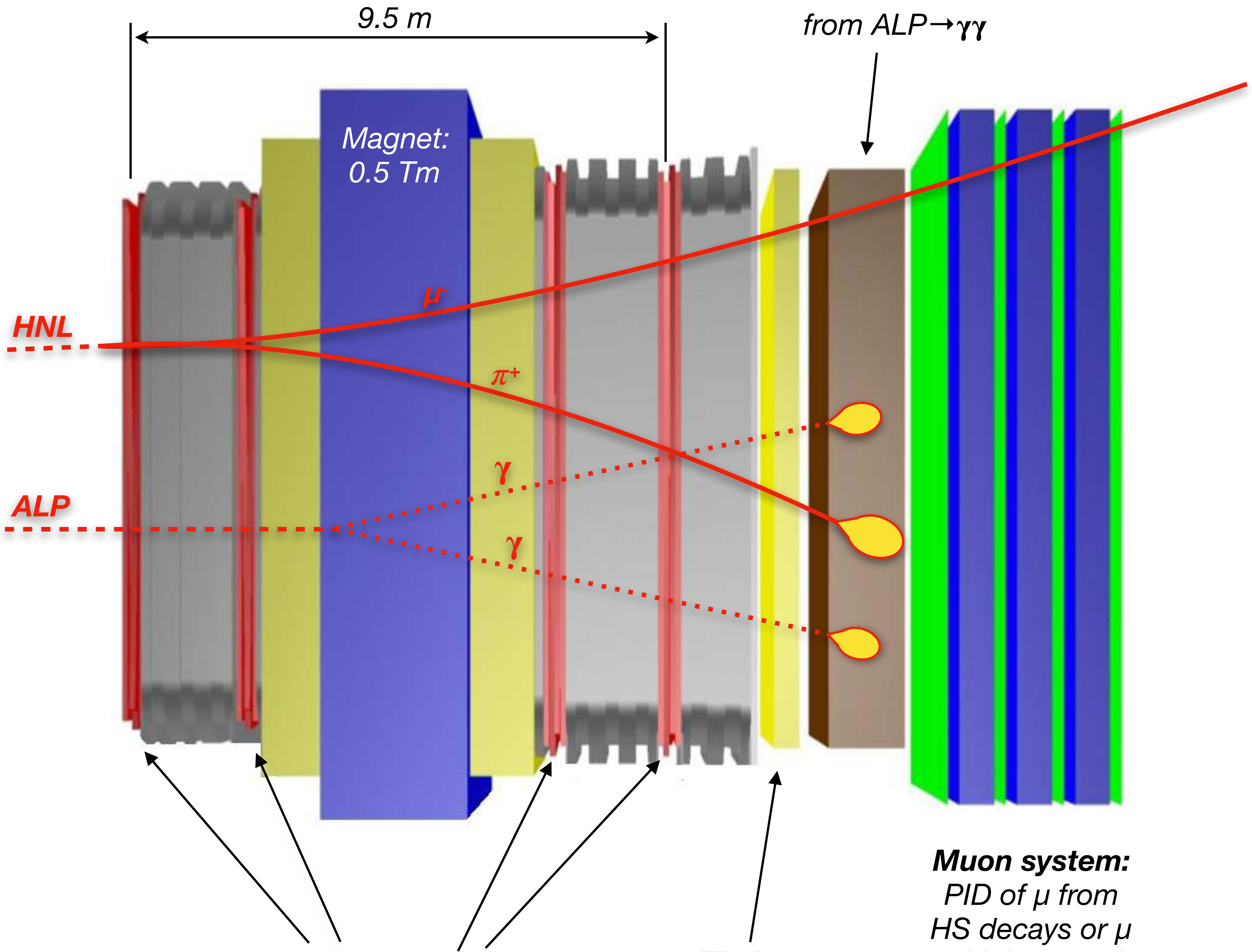


- Extruded Al profile for the entrance and exit caps
- Goal: minimise number of interactions





# Magnetic spectrometer with particle identification



***ECAL (SplitCAL):*** *reconstruction of trajectories of photons from ALP→γγ*

***Straw trackers:*** *reconstruction of charged particle tracks*

***Timing Detector:*** *tags particles belonging to a single event*

***Muon system:*** *PID of μ from HS decays or μ which passed the filter*

- Purpose:
  - Precise reconstruction of decay vertices produced by charged particles
  - Partical Identification (PID)
  - Background suppression using timing and spacial information
- Universal spectrometer to reduce the model dependence

- Vacuum volume is a continuation but not a part of the decay vessel. Other material (non-magnetic)
- Slits for the top-load tracker station installation
- Very stiff box concept to minimise deformations

Main **decay modes** of hidden particles in various models ($l = e, \mu$)

| Model | Final state |
|---|---|
| Neutrino portal, SUSY neutralino | $l^\pm\pi^\mp$, $l^\pm K^\mp$, $l^\pm\rho^\mp$, $\rho^\pm \to \pi^\pm\pi^0$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $l^+l^-$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $\pi^+\pi^-$, $K^+K^-$ |
| Neutrino portal ,SUSY neutralino, axino | $l^+l^-\nu$ |
| Axion portal, SUSY sgoldstino | $\gamma\gamma$ |
| SUSY sgoldstino | $\pi^0\pi^0$ |

*CERN-SPSC-2015-016*

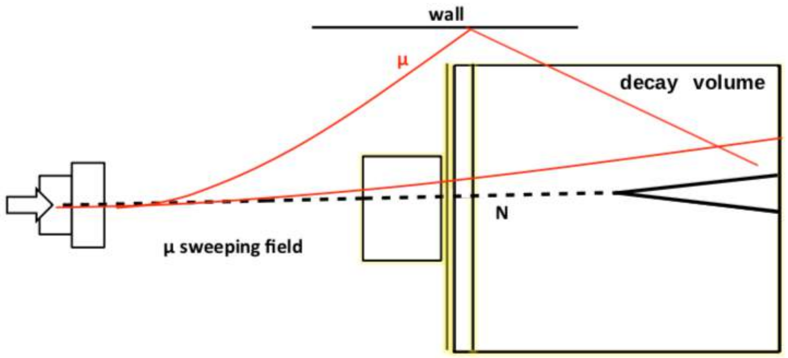
# HS background rejection

- Efficient and *redundant* background suppression
- Sensitivity to many decay modes
  - Model independent search
- Signature with an insulated vertex in the decay volume of the HS spectrometer
- Contribution from the comics is negligible
- Sample of MC events assuming 100% interaction
  - interaction distributed along trajectory with weight according to the material density
  - 5 years of operation: 2 x $10^{20}$ p.o.t.

| Selection cut | Value |
|---|---|
| Track momentum | > 1 GeV/c |
| Distance of closest approach | < 1 cm |
| Vertex position | > 5 cm from vessel wall |
| Imp. Param. w.r.t. target (full reco) | < 10 cm |
| Imp. Param. w.r.t. target (partial reco) | < 250 cm |

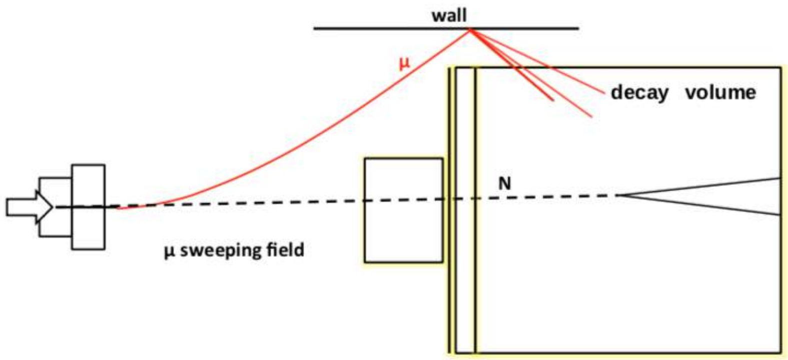
*CERN-SPSC-2019-010*

***Muon combinatorial background (mimic vertex)***



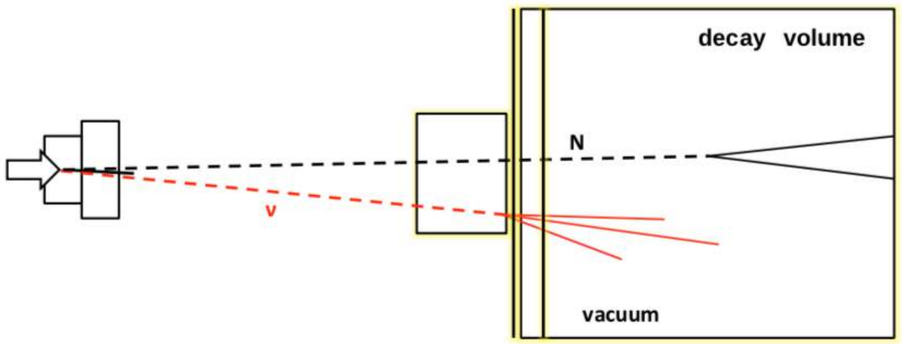
*$8.5\cdot10^{15}$ fake vertices without time info. Reduced to $4.2\cdot10^{-2}$ with time info (TD)*

***Muon induced background (inelastic interaction)***



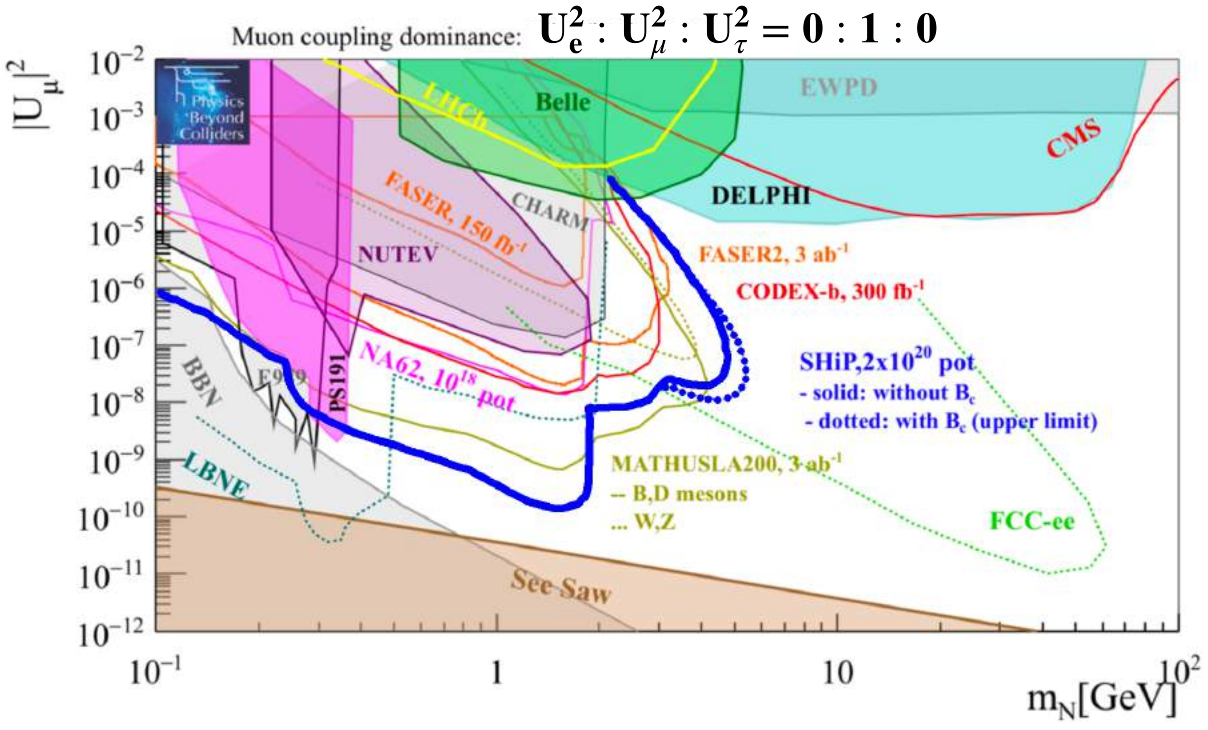
*$6\cdot10^{4}$ μ/spill impinging on the decay volume.*
*$2.1\cdot10^{8}$ inelastic interaction in 5 years.*
*BG after cuts (full reco) = $2.7\cdot10^{-5}$*
*BG after cuts (partial reco) = $6\cdot10^{-4}$*

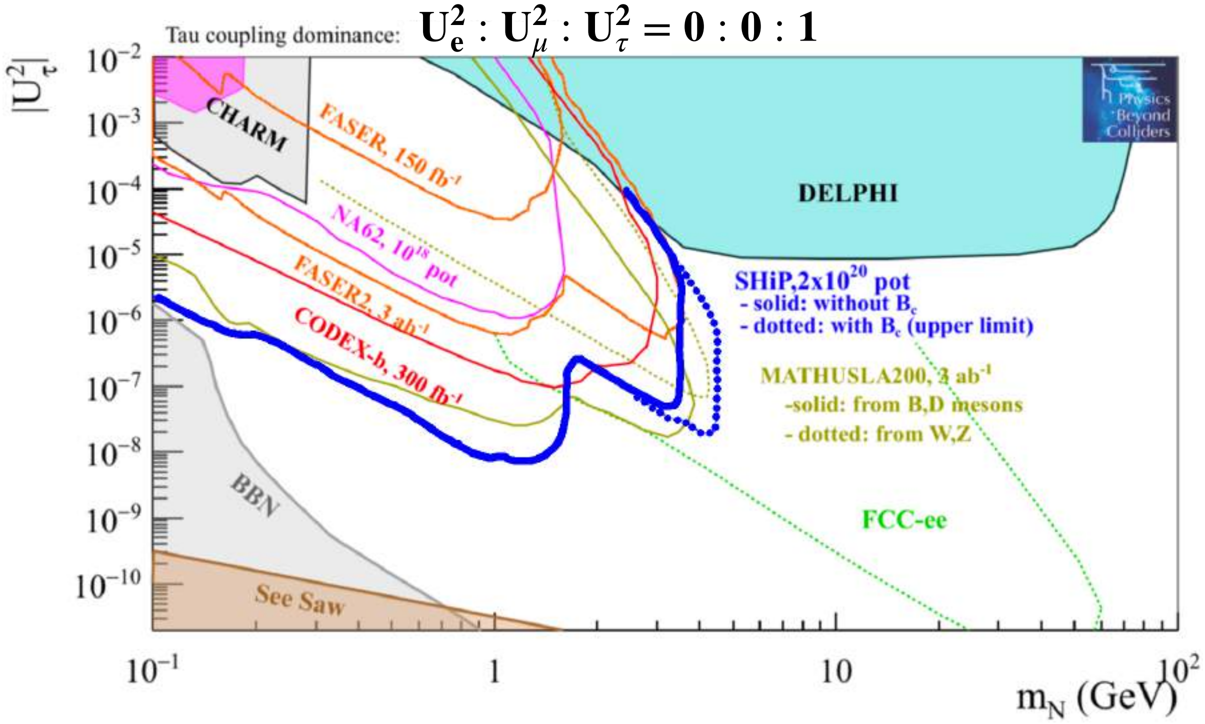
***Neutrino induced background (inelastic interaction)***

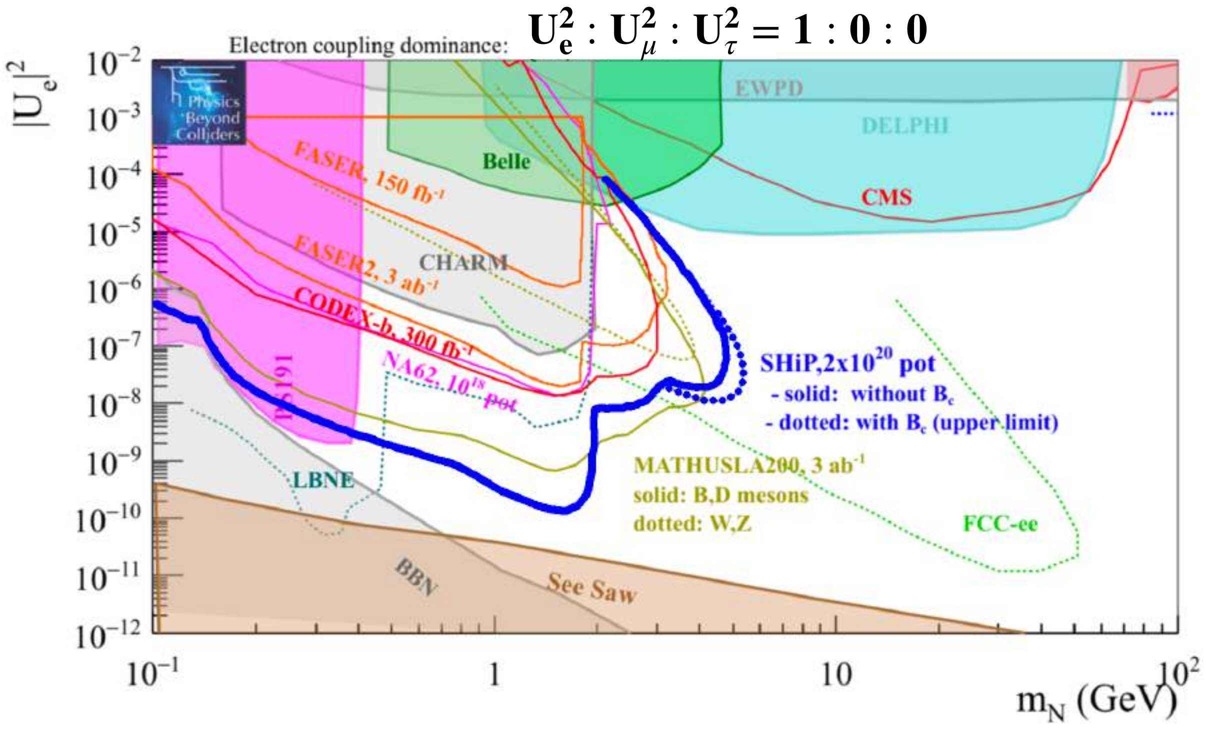


*$2\cdot10^{18}$ ν from target in 5 years.*
*$3.5\cdot10^{7}$ inelastic interaction in 5 years.*
*BG after cuts (full reco) = $10^{-2}$*
*BG after cuts (partial reco) < 0.1 (γ conversion cut)*

# Heavy Neutral Leptons (HNL) below the EW scale







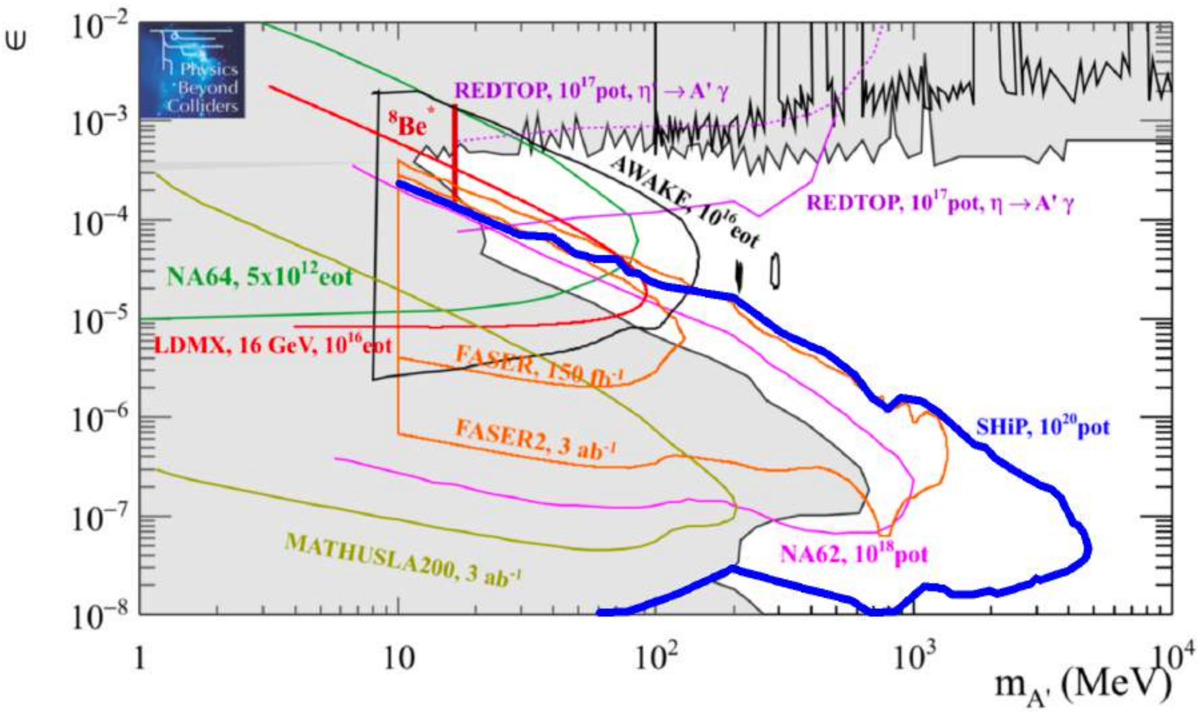
## *HNL → $l^\pm\pi^\mp$, $l^\pm K^\mp$, $l^\pm\rho^\mp$*

$$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \Sigma\, F_{\alpha I}(\bar{L}_\alpha H)N_I$$

- Neutrino portal extension of the SM (**ν**MSM)
    - motivated by the fact that it can be tightly related with the neutrino mass generation mechanism (see-saw), provide dark mater candidate and explain the baryon asymmetry
    - $N_1$(dark matter, ~10 keV), $N_{2,3}$ (see-saw, baryon asymmetry, few GeV)
- Shown in figures: single-flavour dominance was assumed, e.g. HNLs couple only with one flavour of the active neutrinos at the time.

*JHEP 1904 (2019) 077, [1811.00930]*

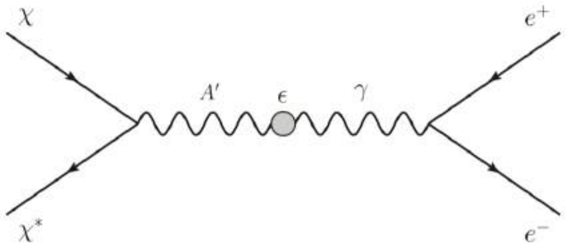
# Dark Photon couple to SM particles



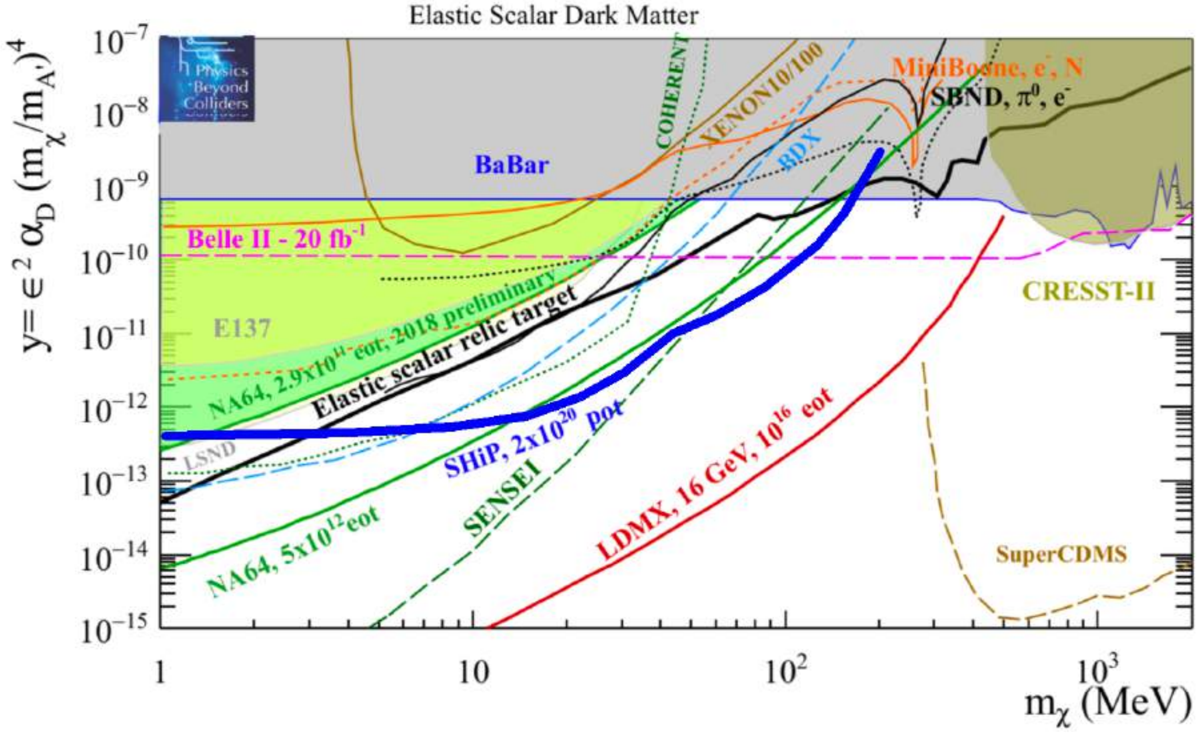
$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - \epsilon/(2\cos\theta_W)\, \mathcal{F}'_{\mu\nu}\, \mathcal{B}_{\mu\nu}$

- The SM is augmented by a single new state $\mathcal{A}'$
- DM is assumed to be either heavy or contained in a different sector



# Dark Photon couple to Light DM

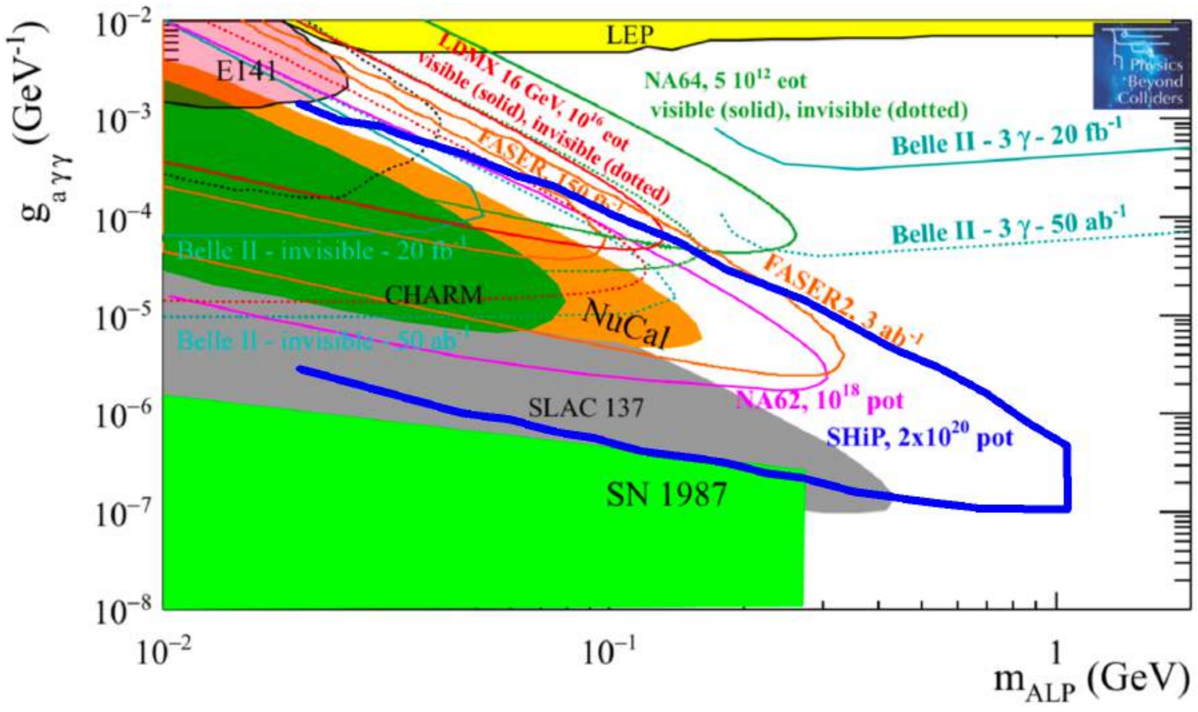


$A' \to \chi\chi$

$\mathcal{L}_{DS} = -1/4\, (\mathcal{F}'_{\mu\nu})^2 + 1/2\, m_{\mathcal{A}'}^2 (\mathcal{A}'_\mu)^2 + |(\partial_\mu + i g_{\mathcal{D}} \mathcal{A}'_\mu)\chi|^2 + \ldots$

- Model where minimally coupled viable WIMP dark matter model can be constructed
- The parameter space for this model is: $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$
  - $m(\mathcal{A}') = 3m(\chi)$, $\alpha(\mathcal{D}) = 0.1$

## Axions and ALPs with photon coupling in the MeV-GeV mass range

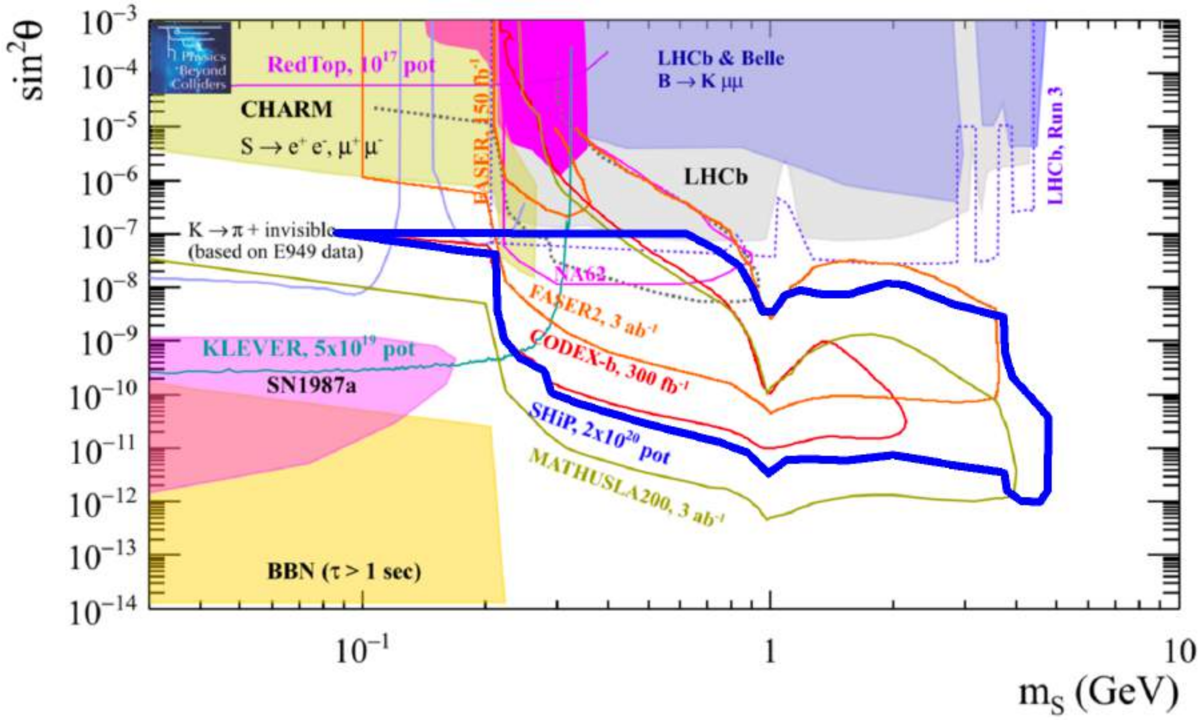


$ALP \rightarrow \gamma\gamma$

$$\mathcal{L}_{axion} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - a/(4f_{\gamma})\, F_{\mu\nu}\, \tilde{F}_{\mu\nu} + \ldots$$

- Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global U(1), introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.
- Axion-Like Particle (ALP): a generalised version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.
- Interest to explore the MeV-GeV region at accelerator-based experiments

## Dark Scalar coupled to the Higgs



$S \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$

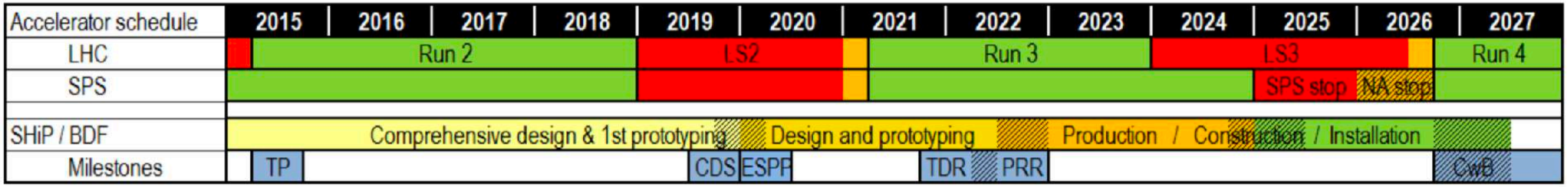
$$\mathcal{L}_{scalar} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - (\mu S + \lambda S^2)\, \mathcal{H}^{\dagger}\mathcal{H}$$

- The minimal scalar portal model operates with one extra singlet field $S$ and two types of couplings, $\mu$ and $\lambda$
- Benchmark 4: assume $\lambda$=0

# Conclusions and outlook

- Explore the intensity frontier in the framework of study of new physics PBC-BSM
- New infrastructure in the North Area of CERN SPS: extraction tunnel, target complex, experimental area
- Detector concept:
  - Beam Dump Facility: average beam power 355 kW, 2.6 MW during the spill
  - Active muon shield: muon flux reduction by $10^6$
  - Scattering and Neutrino Detector: emulsions + magnetic spectrometer
    - LDM scattering; SM neutrino physics: $\nu_\tau$ study, magnetic moment, induced charm production, nuclear effects, strangeness
  - Hidden Sector spectrometer: 50 m decay volume + magnetic spectrometer
    - Direct search for very weakly interacting long lived particles: Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector, and light SUSY particles
- Comprehensive Design Report (CDR) at the end of 2019
- Preparation of the Technical Design Report (TDR) by the end of 2022
  - Final detector cost and schedule of the experiment
- 3 years to complete detector R&D, prototyping and validation
- ~6 years for the construction of BDF, detector production, installation, commissioning
- Data-taking for the LHC Run 4 and Run 5

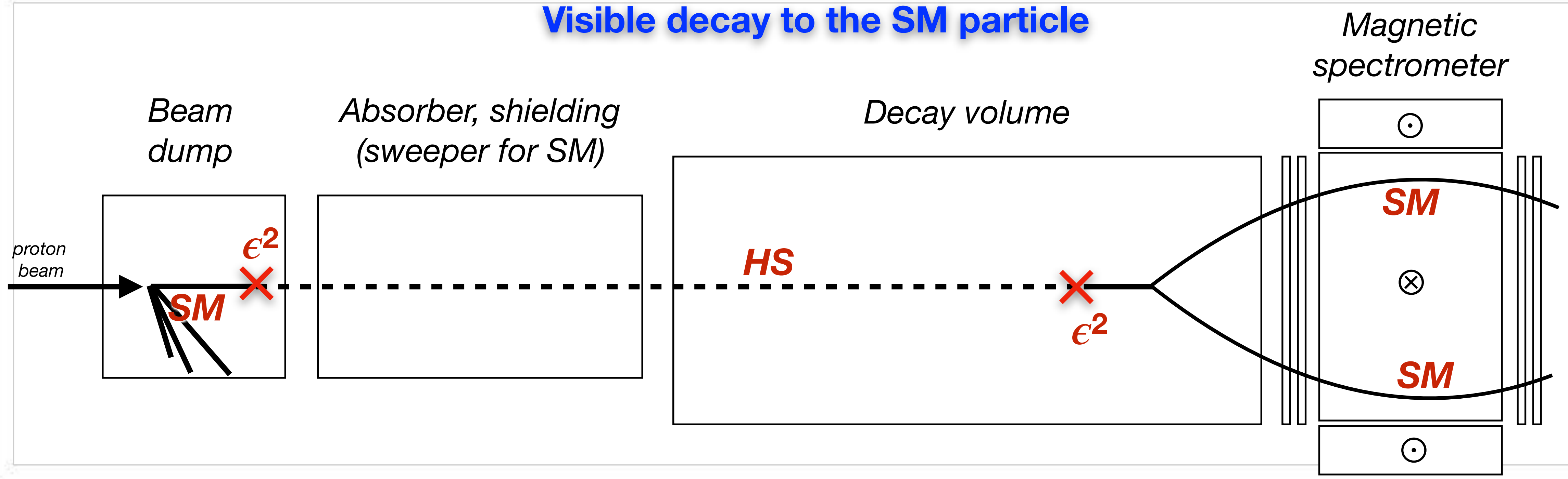
Global project schedule for the Beam Dump Facility and the SHiP detector (CERN-SPSC-2019-010)



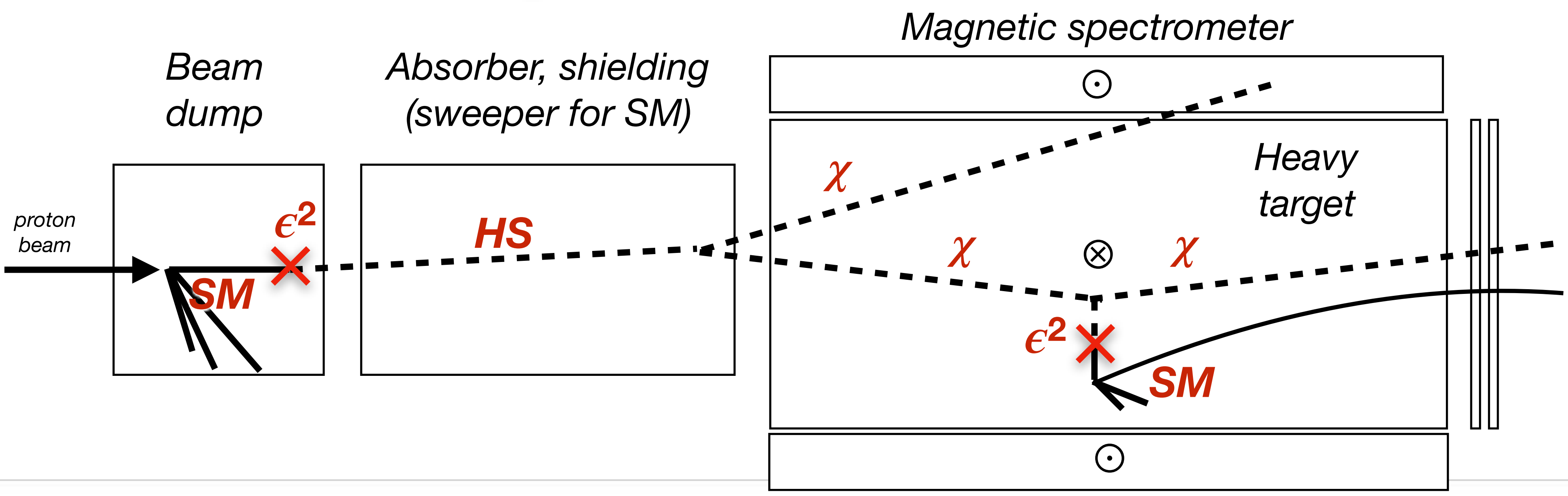
# backup

# Experimental technique for the HS direct search (*signal* $\propto \epsilon^4$)

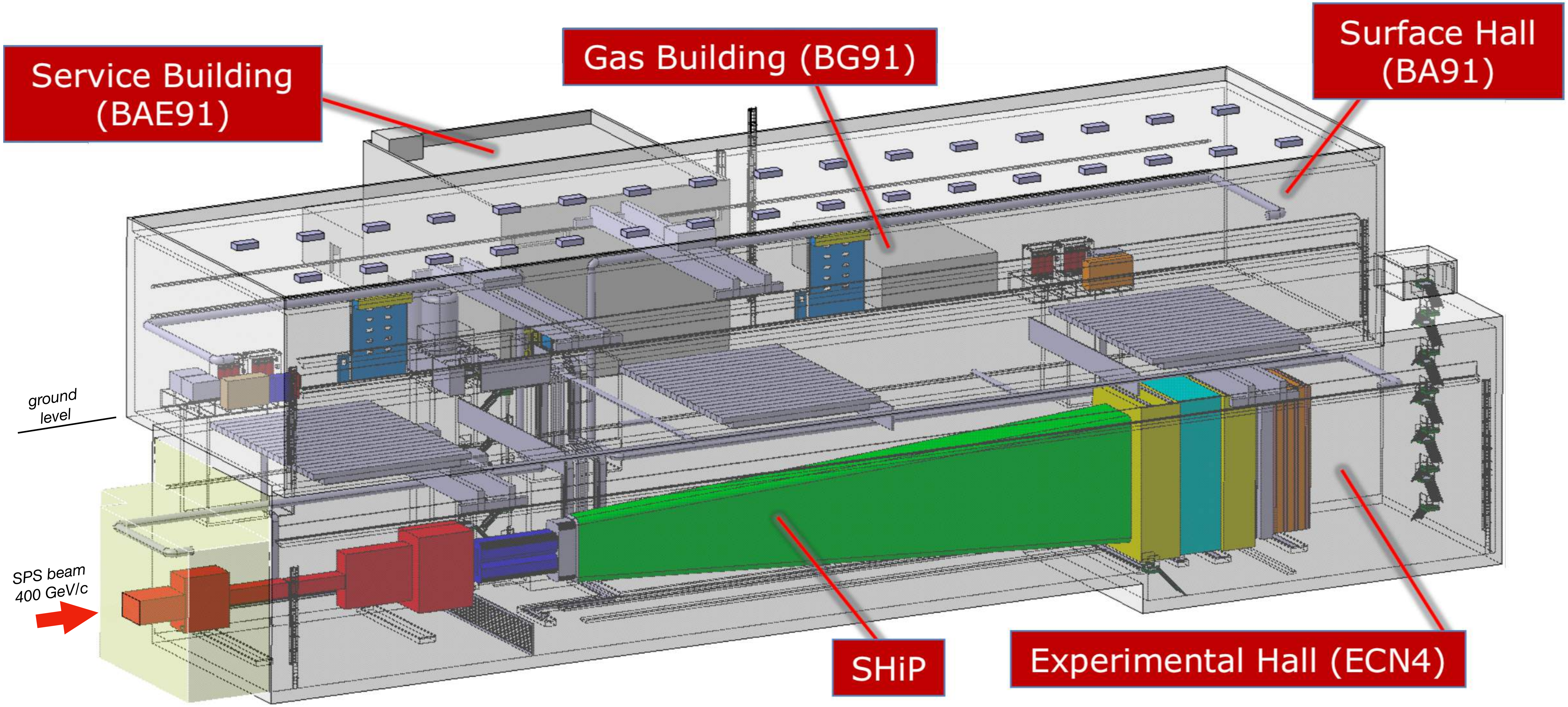
## Visible decay to the SM particle



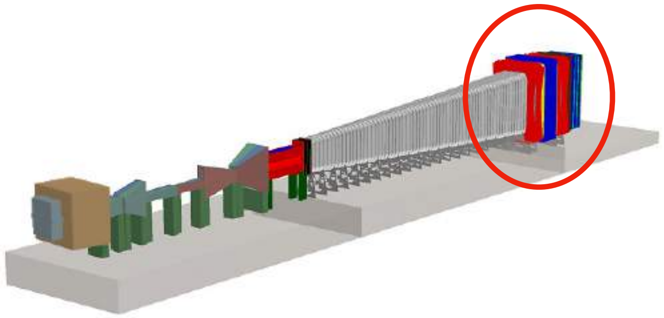
## Scattering off atomic electrons and nuclei



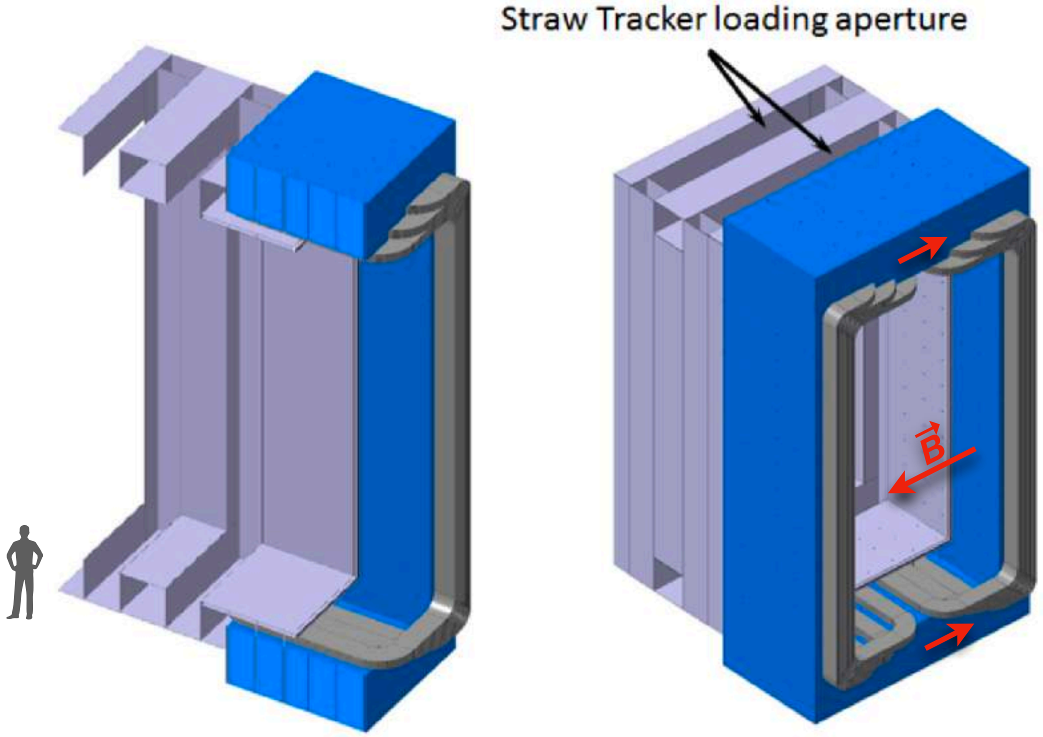
# Experimental area of SHiP in the North Area of CERN



- 120 m long and 20 m wide underground experimental hall at a depth of ~15 m
- Minimising the background induced by muon and neutrino interactions with material
  - no infrastructure systems on the sides of the detector along the entire length



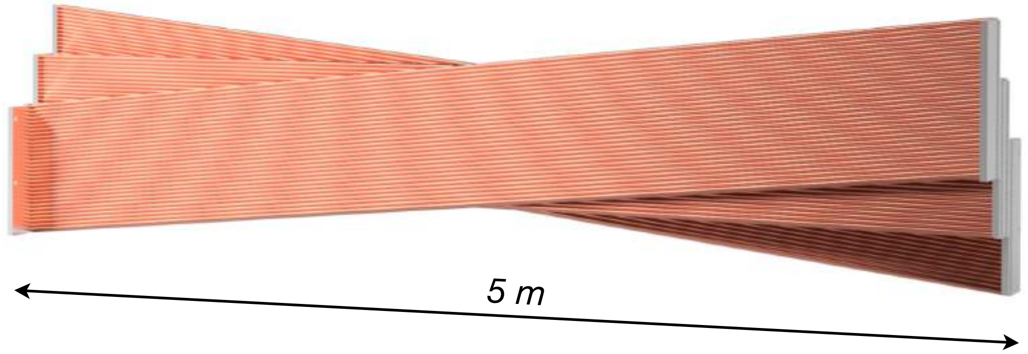
# Magnetic spectrometer: tracking system



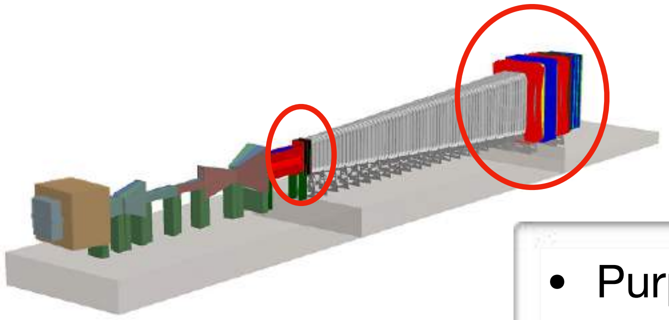
### *Dipole magnet*

- Rectangular aperture 5 x 10 $m^2$
- Warm Al coils is a baseline option
- Field integral along the central axis 0.5 Tm
- Superconducting option is under consideration
- Particle bending plane is *vertical*
- Yoke provides stiffening support for the vacuum tank
- Total mass (yoke+6 coil packs) 1155 tones
- Power dissipation 1.1 MW

### *Straw trackers*



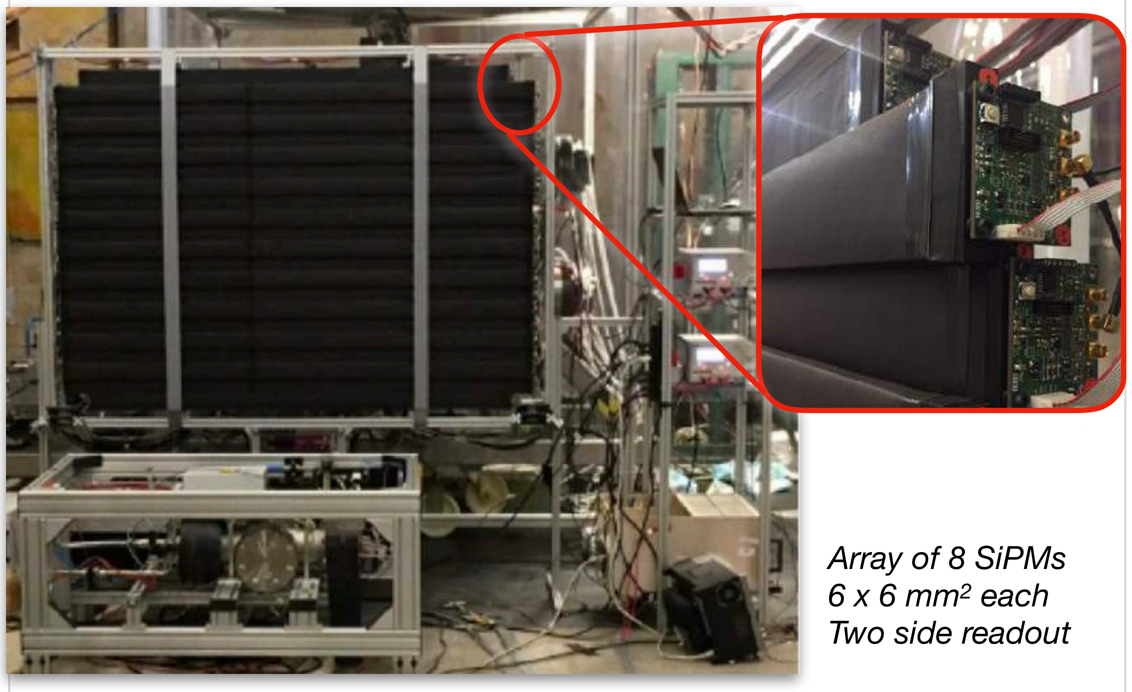
- 4 identical stations:
  - Oriented horizontally
  - Each station has U-Y-Y-V projections
- Each station assembled outside, to be loaded from top
- Diameter 20 mm
- 36 µm thick PET film coated with 50 nm Cu and 20 nm Au
- Procedure is established during mass production in JINR/Dubna for NA62
- Pressure=1bar, 70% Ar / 30% $CO_2$
- Start time is taken from the Timing Detector (downstream)
- Spacial resolution 120 µm
- Sagging effect will be reduced by
  - long-stock constant force spring for wire
  - suspension mechanism based on carbon fibres
- Front-end electronics located inside the vacuum and will require active cooling



# Magnetic spectrometer: Timing Detector(s)

- Purpose: reduction of *combinatorial background* by tagging particle belonging to a single event
- Active surface: 5 x 10 m². Required time resolution <100 ps

## *Cast Plastic Scintillator*

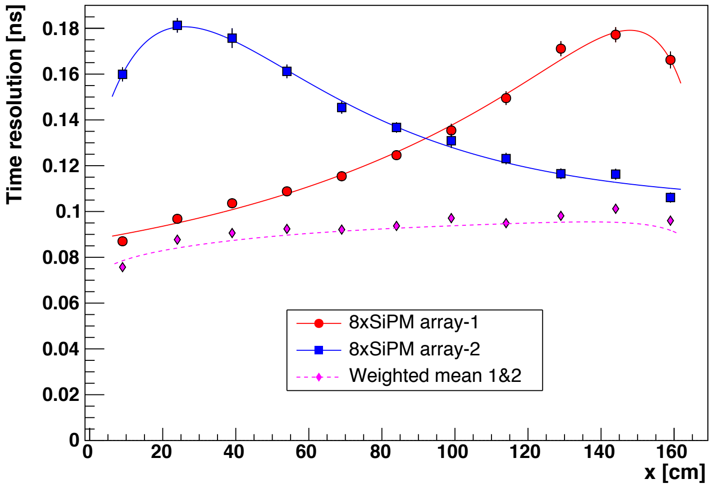


*Array of 8 SiPMs*
*6 x 6 mm² each*
*Two side readout*

*Plastic EJ-200*
*Attenuation ~4 m*
*Bar dimensions:*
*168 x 6 x 1 cm³*

*Time resolut. ~85 ps*
*$Eff_{plastic}$=100%*
*Deadtime defined by electronics*

*Full detector:*
*182 row x 3 column*
*564 bars*

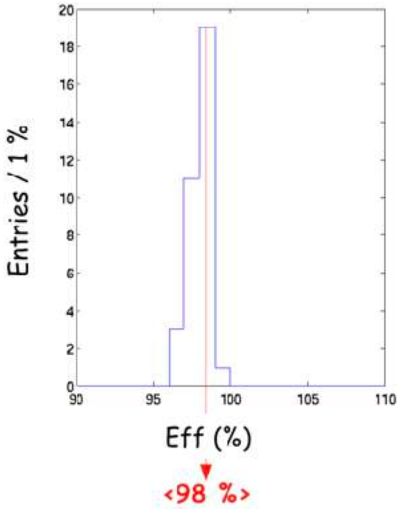


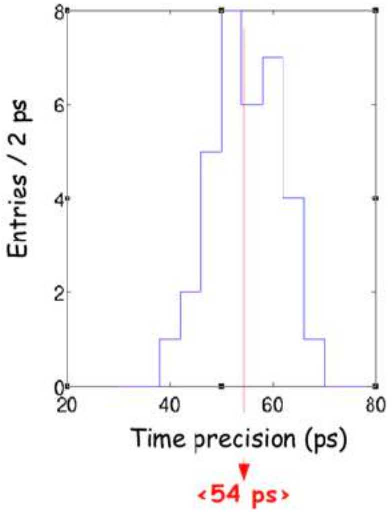
*JINST 12 (2017) no.11, P11023*

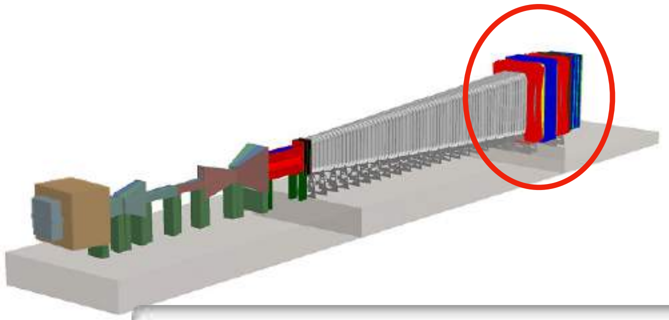
## *Timing Resistive Plate Chamber*

*0.3 mm gas gap*
*12 gas gaps*
*Strips in the middle*
*Strip 3 cm wide*
*Two-end readout*
*Area 1.6 x 1.2 m²*

*Full detector:*
*7 row x 5 column*
*35 modules*

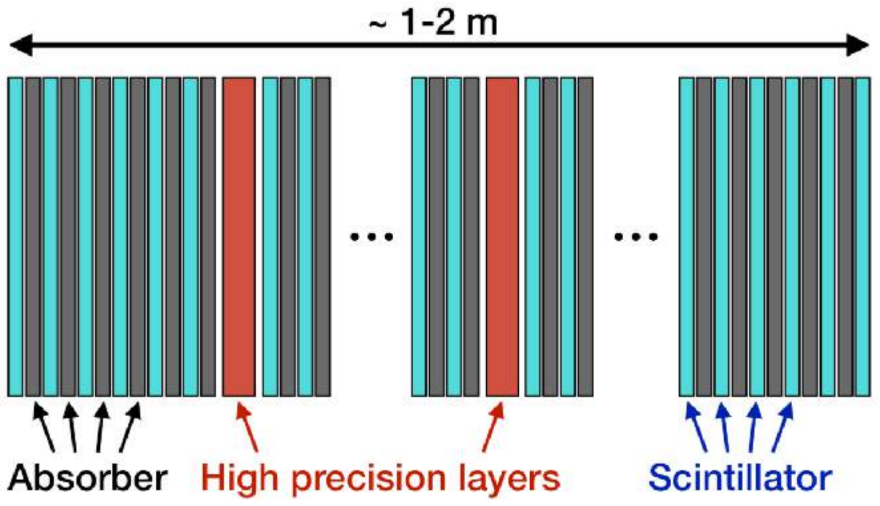






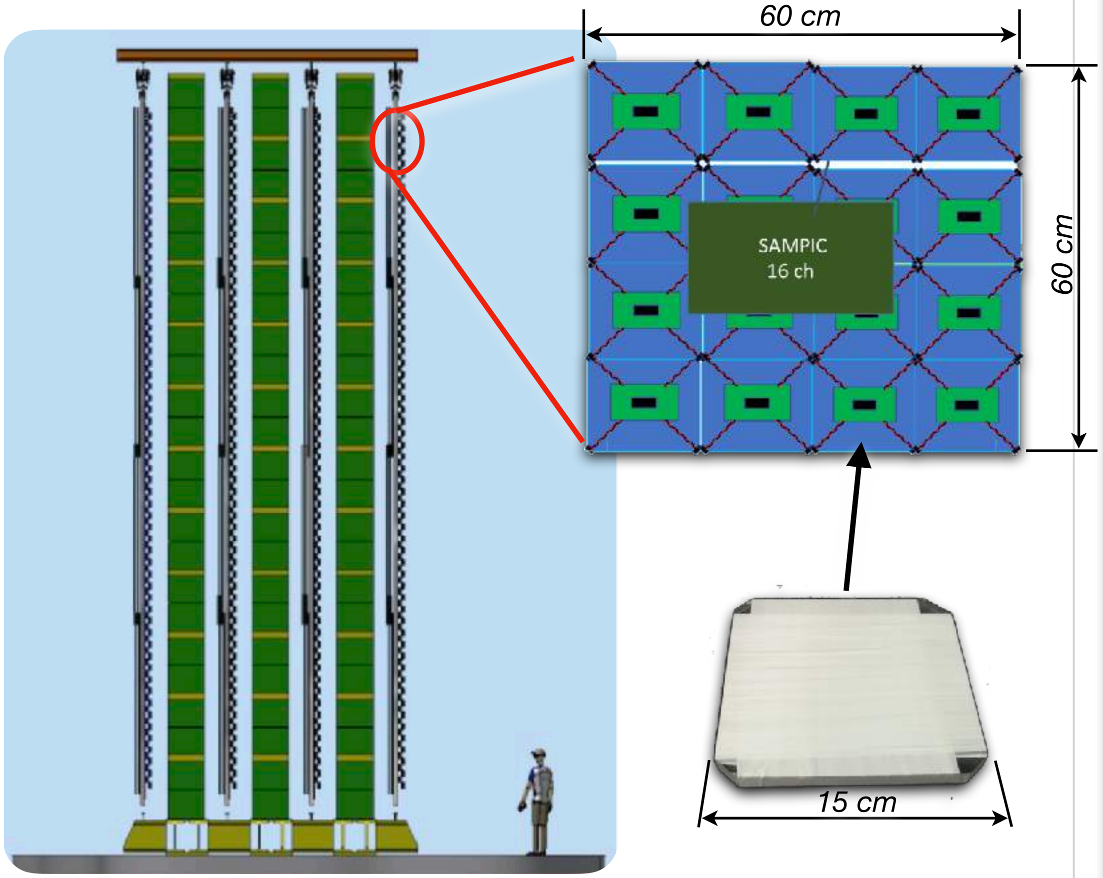
# Magnetic spectrometer: particle identification

## ECAL (SplitCAL)

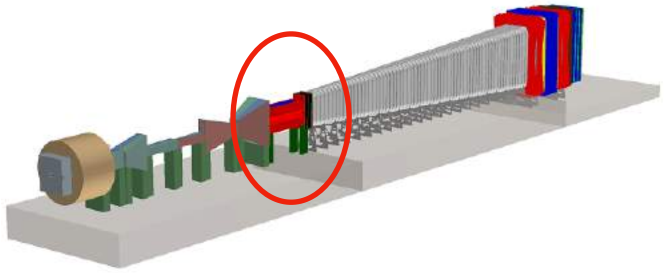


- Purpose:
  - trajectories of photons from ALP$\to\gamma\gamma$
  - electron/hadron separation
- Total thickness ~$25X_0$
  - sheets of absorber
  - 2-3 high precision layers (XY)
  - ~40 scintillator planes for timing & calorimetry
- Photon trajectory is calculated by reconstructing transverse shower barycentre at different depths
- High precision layer
  - Spacial resolution required ~200 μm
  - Two technology:
    - micro-pattern (MicroMegas)
    - scintillating fibres detectors
- Scintillator plane: plastic scintillator strips with WLS fibre + SiPM readout, $\delta t$ ~1 ns

## Muon system

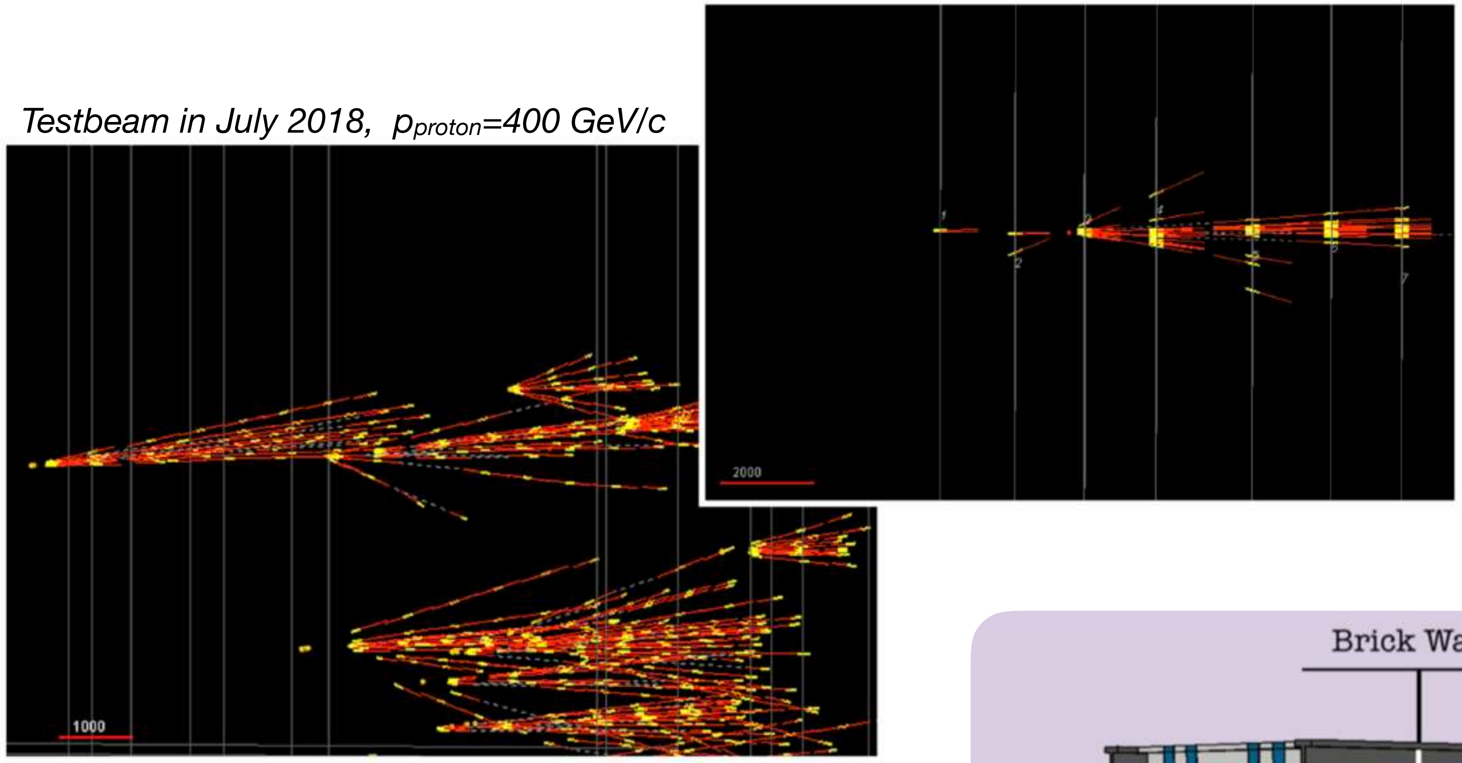


- Active area 6 x 12 m$^2$
- 4 identical active layers
- 3 iron walls with thickness of 60 cm ($3.4\lambda_I$)
- Two technologies:
  - Extruded plastic scintillator *bars* with WLS fibre and SiPM readout, $\delta t$~800 ps
  - Cast plastic scintillator *tiles* with direct SiPM readout, $\delta t$~300 ps
- Scintillator weight 11.5 ton
- Iron weight 1000 ton



# Scattering and Neutrino Detector (2)

*Testbeam in July 2018, $p_{proton}$=400 GeV/c*

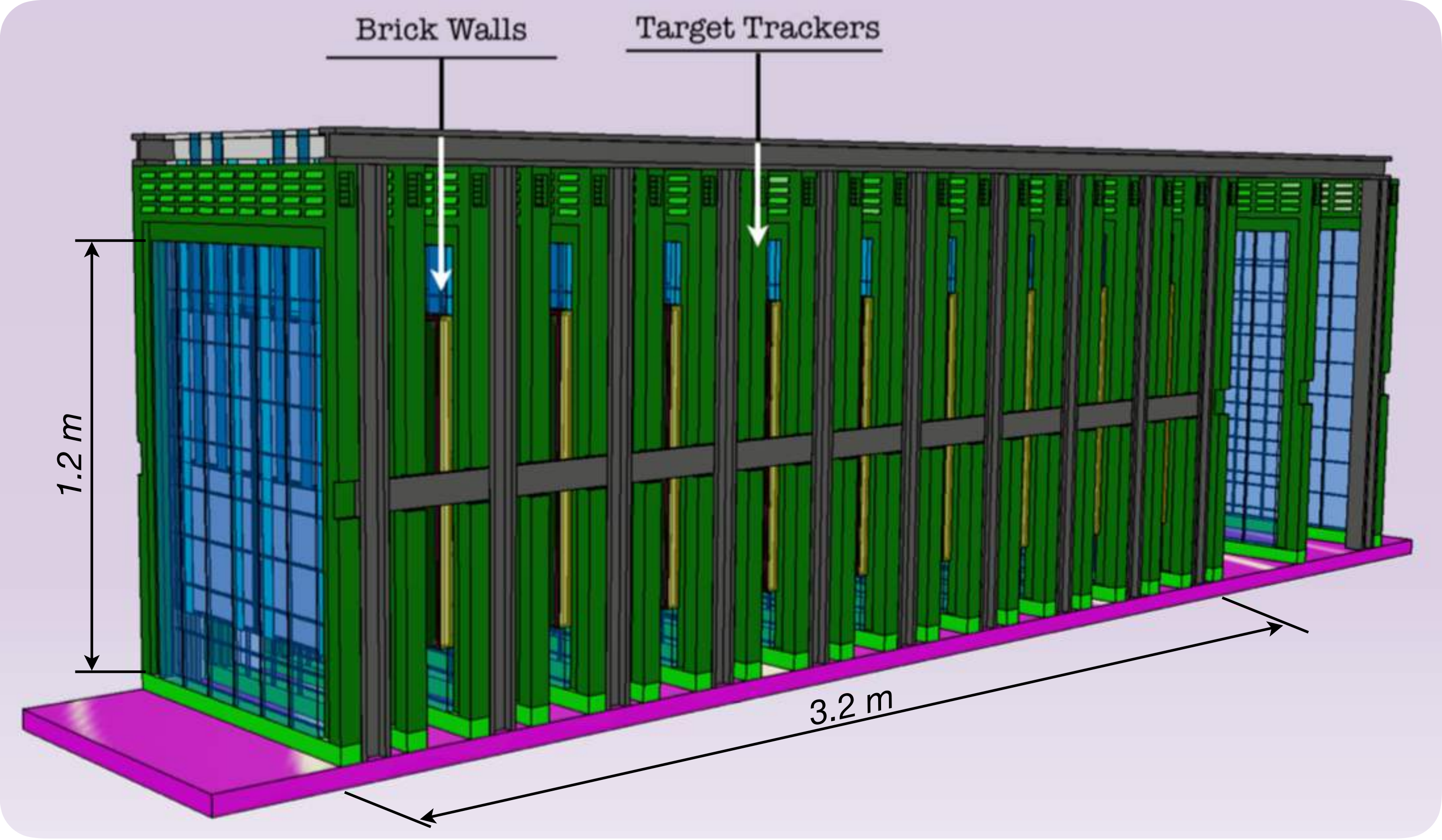


***Two types of emulsion technology***

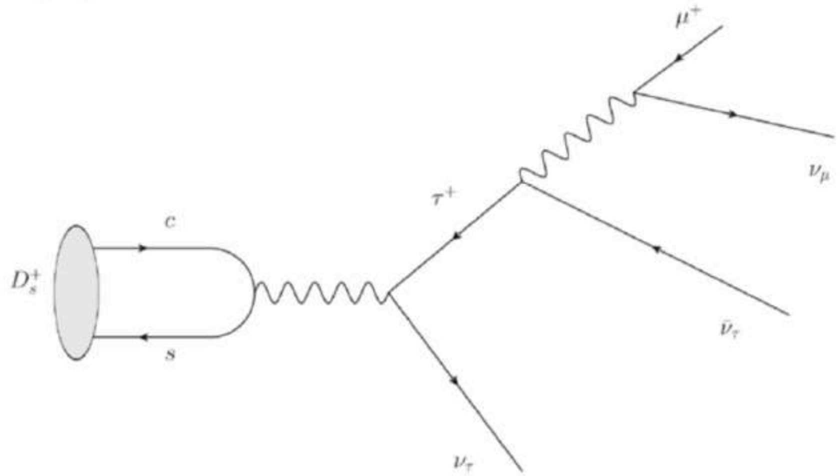
- Emulsion Cloud Chamber (ECC)
  - 57 films interleaved with 1 mm Pb
  - thickness 8 cm, $10X_0$ , 100 kg
  - replaced twice a year
- Compact Emulsion Spectrometer (CES)
  - 3 films interleaved with 2 layers of low density material
  - 10 kg
  - replaced every 2 weeks
- Transverse dimensions
  - 80x80 $cm^2$ assembled of 2x2 cells

***Target & Downstream Trackers***

- Time stamp for tracks reconstructed in emulsion => connection to downstream trackers
- Time resolution requited <10 ns
- Transverse size: 80x120 $cm^2$
- Two technologies developed in LHCb:
  - $\mu$-RWELL (Micro-Patern Gaseous Detector)
  - Scintillating Fiber (SciFi) Tracker
- Spacial resolution ~40 μm
- Projections XY(UV)



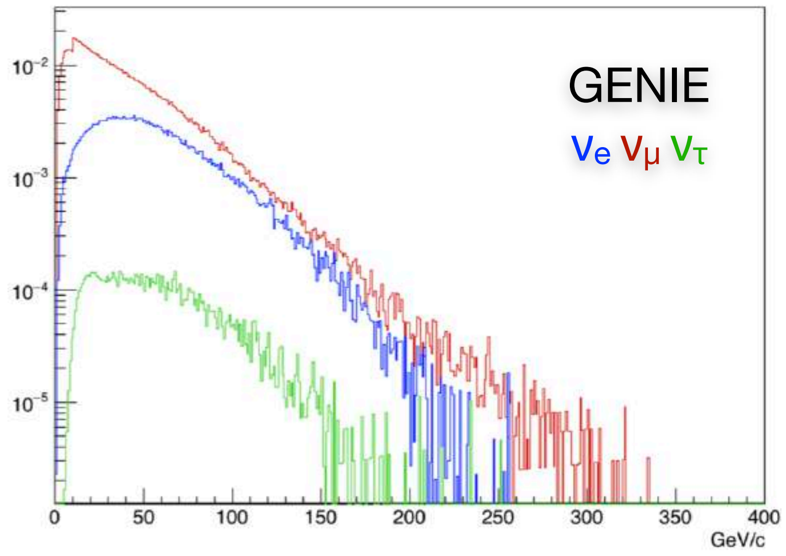
# SM neutrino physics in SND (1)



- $\nu_\tau$ and $\bar{\nu}_\tau$ produced in the leptonic decay $D^\pm_s$ mesons
- Number of $\nu_\tau$ and $\bar{\nu}_\tau$ produced in the beam dump

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \cdot 10^{-5}\, N_p$$

- $\nu_\tau$ in previous experiments: DONUT (9), OPERA (4)
- Unique capability in SHiP to detect all 3 flavours $\nu_e$, $\nu_\mu$, $\nu_\tau$ and distinguish $\nu$ and $\bar{\nu}$
  - CC channel to identify the flavour via lepton
  - Electrons shower in emulsion before their charge can be measured
  - Momentum either via bending in magnetic field or via Multiple Coulomb Scattering (used in OPERA)
  - Impact parameter to reconstruct the $\nu_\tau$ vertex (resolution ~μm)


$\nu$ interacting in SND

Expected number of CC DIS interactions in SND

| | <E>[GeV] | N interactions |
|---|---|---|
| $N_{\nu_e}$ | 59 | $1.1\cdot10^6$ |
| $N_{\nu_\mu}$ | 42 | $2.7\cdot10^6$ |
| $N_{\nu_\tau}$ | 52 | $3.2\cdot10^4$ |
| $N_{\bar{\nu}_e}$ | 46 | $2.6\cdot10^5$ |
| $N_{\bar{\nu}_\mu}$ | 36 | $6.0\cdot10^5$ |
| $N_{\bar{\nu}_\tau}$ | 70 | $2.1\cdot10^4$ |

Expected number of observed $\nu_\tau$ and $\bar{\nu}_\tau$

| channel | $\nu_\tau$ | $\bar{\nu}_\tau$ |
|---|---|---|
| $\tau\to\mu$ | $1.2\cdot10^3$ | $1\cdot10^3$ |
| $\tau\to h$ | $4\cdot10^3$ | $3\cdot10^3$ |
| $\tau\to 3h$ | $1\cdot10^3$ | $0.7\cdot10^3$ |

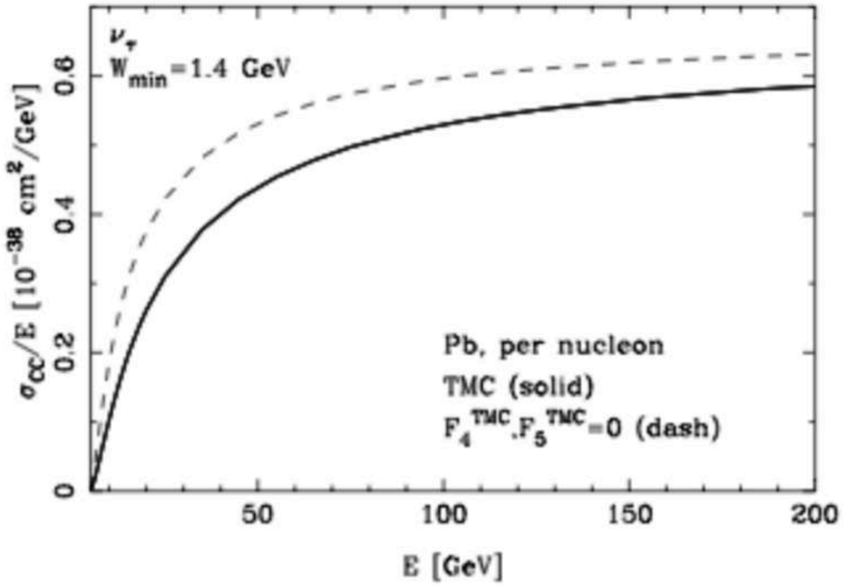
- efficiencies were taken into account

# SM neutrino physics in SND (2)

- Access to structure functions $F_4(x,Q^2)$ and $F_5(x,Q^2)$ in DIS CC interactions
- Suppressed by the lepton mass squared $m_l^2$
- Albright-Jarlskog relations: $F_4=0$, $F_5=F_2/(2x)$

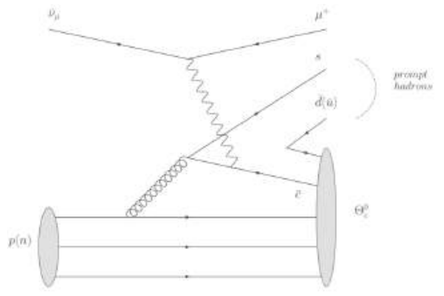
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \right.$$
$$\left. \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right)$$

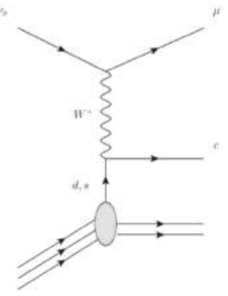
*SM prediction for $\nu_\tau$*

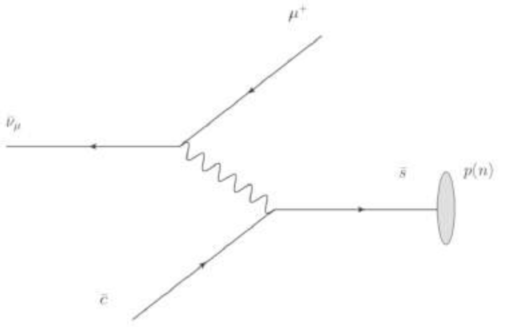


- Neutrino induced charm production
- Expected charm yield exceeds the statistics available in previous experiments by more than one order of magnitude
    - 2013 charm $\nu_\mu$ and 32 charm $\bar{\nu}_\mu$ events in CHORUS
- Search for pentaquark $\Theta_c^0$ with charm quark content

| Expected number of CC DIS interaction with charm production | | | |
|---|---|---|---|
| | <E>[GeV] | # interactions | fraction [%] |
| $N_{\nu_\mu}$ | 55 | $1.3\cdot10^5$ | 4.7 |
| $N_{\nu_e}$ | 66 | $6.0\cdot10^4$ | 5.7 |
| $N_{\bar{\nu}_\mu}$ | 49 | $2.5\cdot10^4$ | 4.2 |
| $N_{\bar{\nu}_e}$ | 57 | $1.3\cdot10^4$ | 5.1 |
| total | | $2.3\cdot10^5$ | |

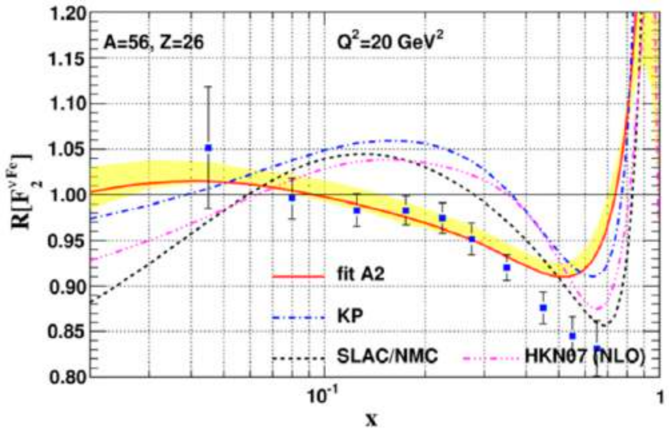




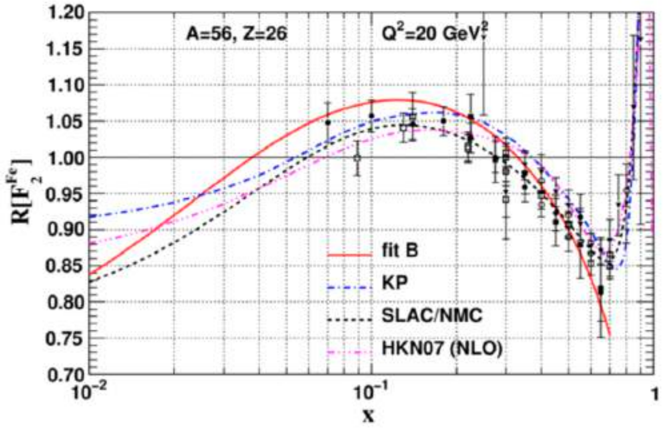


# SM neutrino physics in SND (3)

- Nuclear effects in $\nu$N DIS: shadowing, anti-shadowing, EMC region, Fermi motion region
- Different from charged lepton interaction: slight tension in global fit between $F_2^{\nu N}$ and $F_2^{l\pm N}$

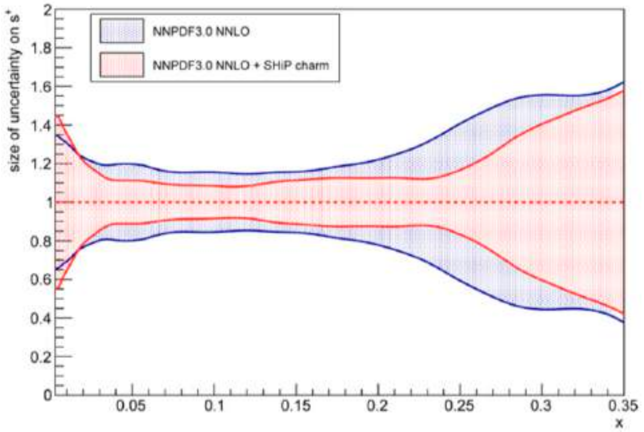


$F_2^{\nu N}/F_2^{\nu D}$

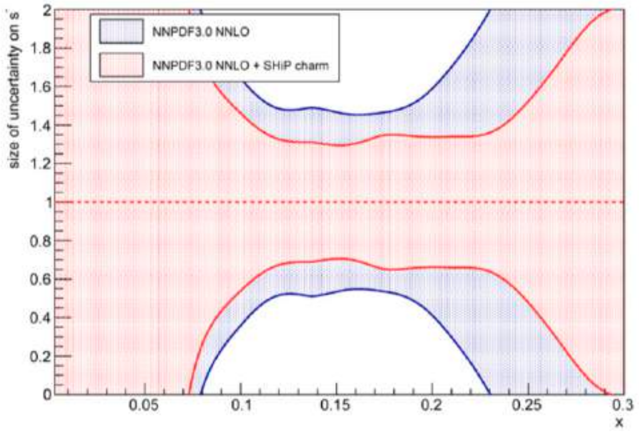


$F_2^{lN}/F_2^{lD}$

- Flavour decomposition: unique way to access strange quark PDFs
- Statistics of expected of $\nu_\mu$ events is comparable to NuTeV/CCFR
  - lower cut on $\mu$ momentum in SHiP (5 GeV/c in NuTeV/CCFR)



$\sigma_{s+\bar{s}}$



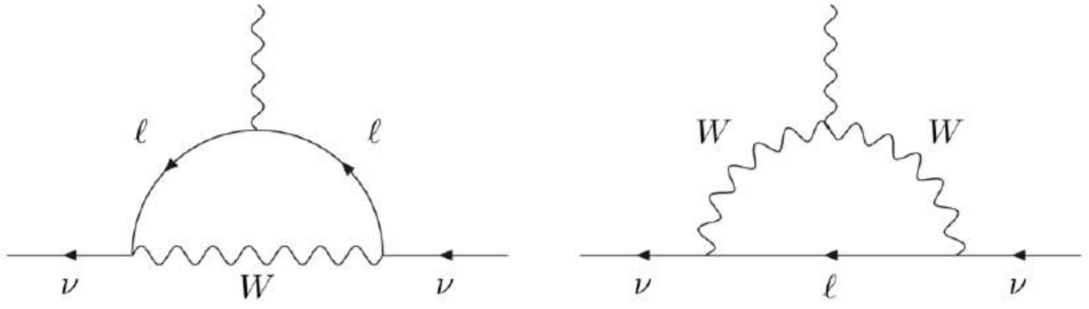
$\sigma_{s-\bar{s}}$

- $\nu_\tau$ magnetic moment ($m_\nu \neq 0$)
  - Extra components to the $\nu_\tau$ cross section
  - Measured so far: $\mu_{\nu e} < 1.9\cdot10^{-11}\mu_B$ and $\mu_{\nu_\mu} < 6.9\cdot10^{-10}\mu_B$

$$\mu_\nu = \frac{3eG_F m_\nu}{8\sqrt{2}\pi^2} = 3.2\cdot10^{-19}\left(\frac{m_\nu}{1\,eV}\right)\mu_B$$

- Larger magnetic moment will be a sign of new physics
- The region down to $\mu_{\nu_\tau}$=1.3·10$^{-7}\mu_B$ can be explored

SM diagrams

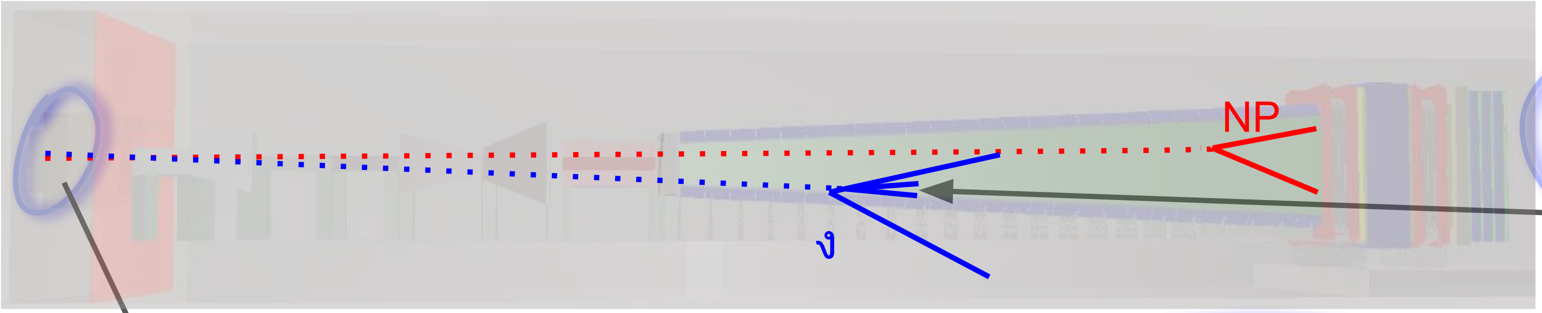


# Neutrino Background in SHiP

*How do we simulate the Neutrino Background in SHiP?*

A precise estimation of neutrino background is crucial for us →

We use a specific neutrino event generator GENIE as a mediator between Pythia8 and GEANT4 to simulate neutrino interactions.



1. We simulate POT interactions with Pythia8 and extract a momentum distribution of outcoming neutrinos.
2. We give obtained spectrum of neutrinos to GENIE to generate neutrino interactions with material
3. As output of GENIE we have a set of particles produced in interactions which we pass GEANT4.
4. Using a P/Pt distribution we position our event in the geometry based on its weight, where weight = $\sum \rho \ell$

# Number of signal candidates

We generated the new huge neutrino MC interaction sample

Number of signal candidates in 5 years before the selection

$N_{\text{candidates}} \sim 65\,612$

Number of signal candidates in 5 years after the basic selection

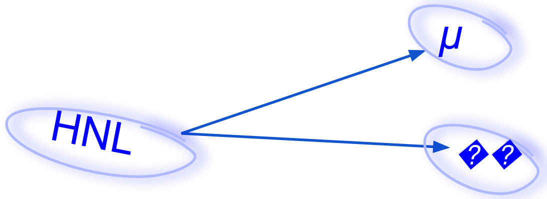
(Just one candidate, vertex is in the fiducial volume,tracks are reconstructed, number of degrees of freedom > 25, daughters track momentum > 1.5 GeV, $\chi^2$ /ndf < 5,RPC veto, DOCA < 1.0 cm, IP < 10 cm(fully reco), 250 cm (partially reco)), PID, safety distance to walls

$N_{\text{partially}} \sim 8$

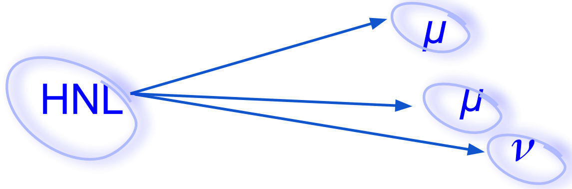
$N_{\text{fully}} \sim 0$

Signal signature:

fully reconstructed

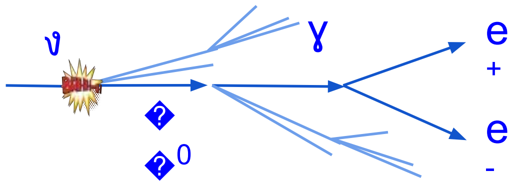


partially reconstructed



Decay opening angle

$N_{\text{partially}} \sim 0.25$



SBT signal around the vertex

$N_{\text{partially}} \sim 0.05$