Perspectives of the SHiP experiment at CERN

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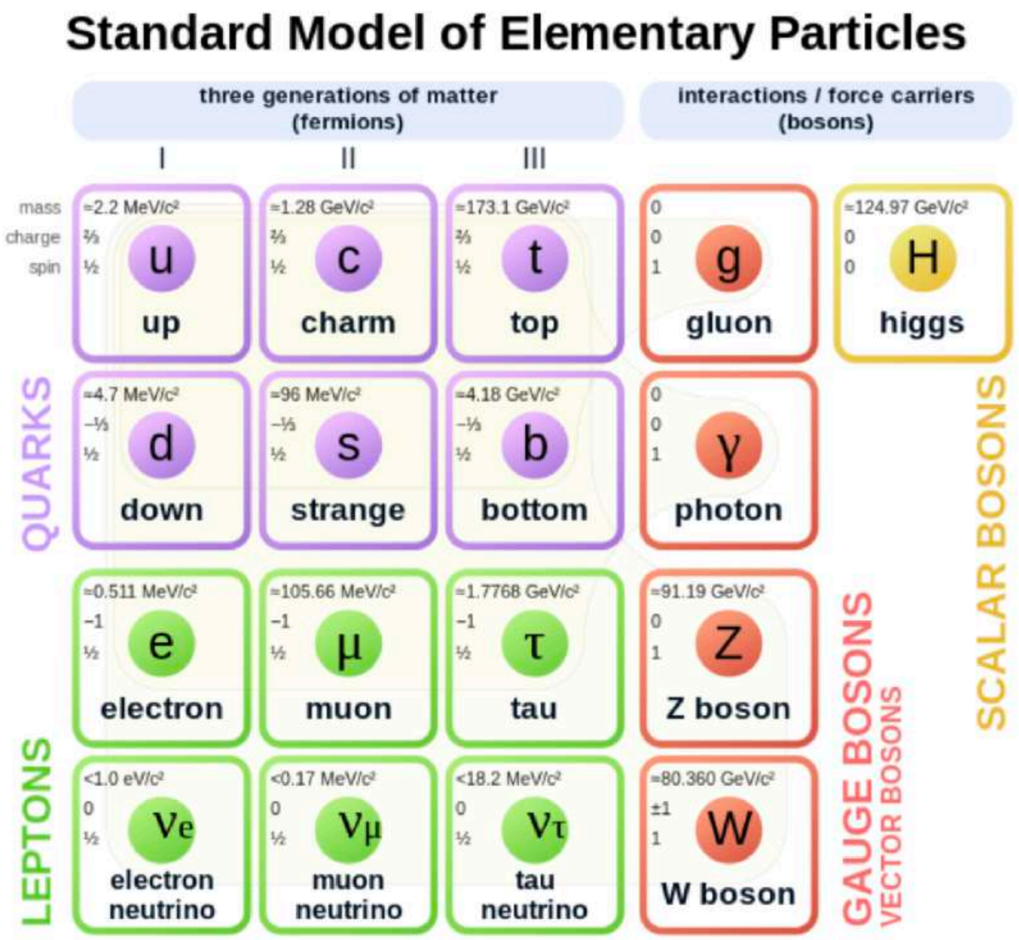
SHiP
Search for Hidden Particles

The need for new physics

- Standard Model (SM) of particle physics consistent with results of almost all experiments

- BUT – three big observational challenges:
  - Neutrinos have non-zero masses
  - The Universe contains Dark Matter
  - There is a matter-antimatter asymmetry

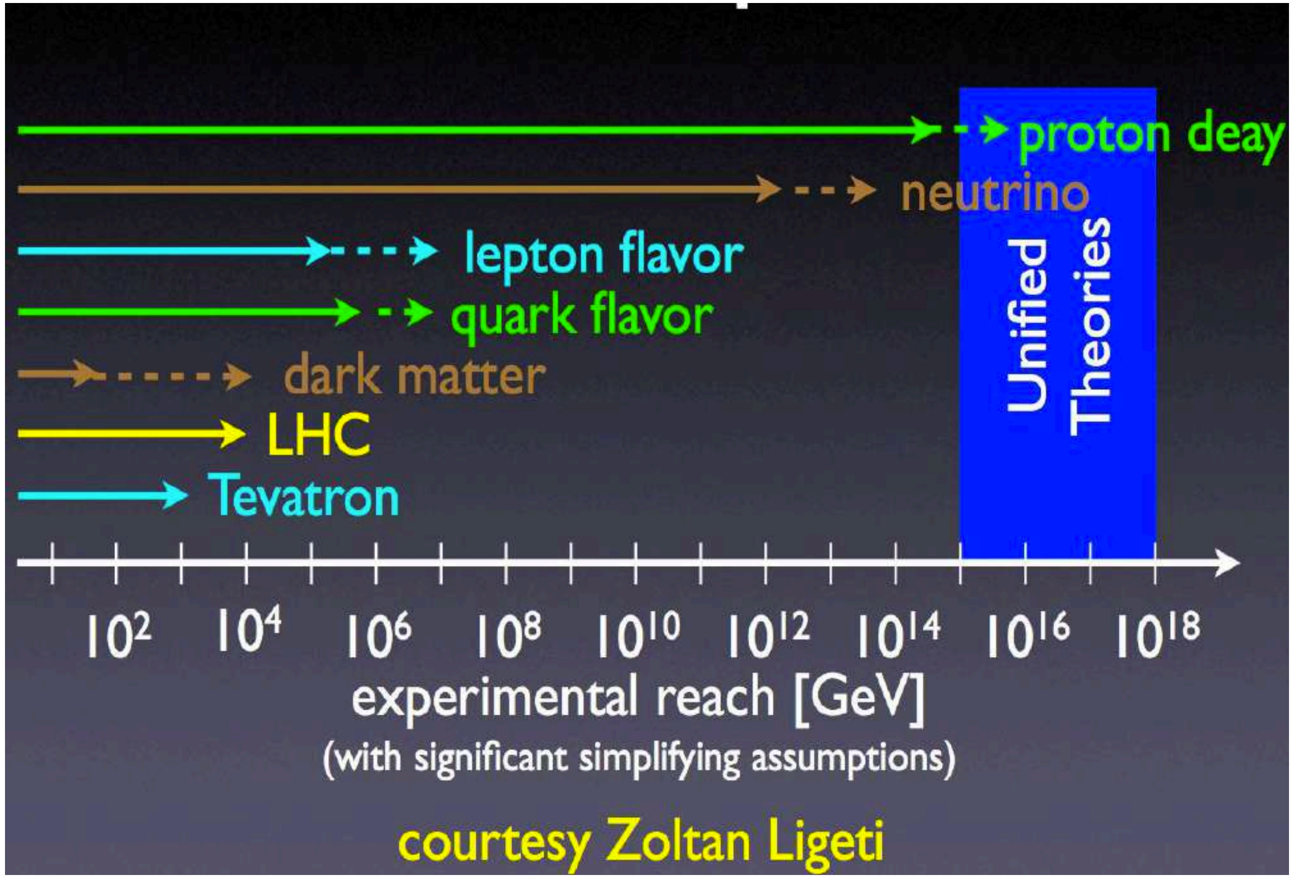


Search for new physics

- No hints for BSM physics neither from direct searches at LHC nor from flavour physics

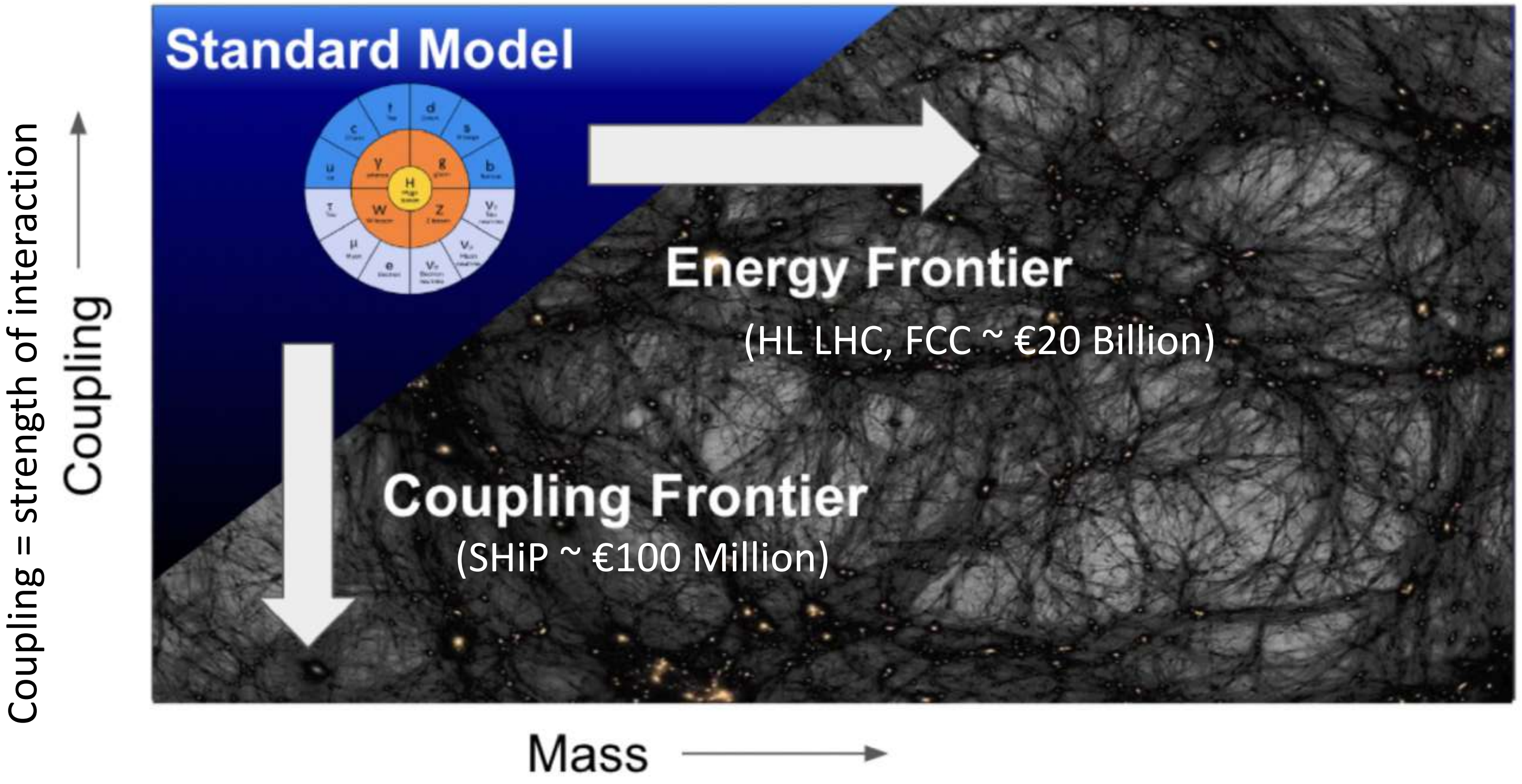
- The scale of strongly coupled NP ($\Lambda > 10^3$ TeV for 10^{-2} coupling) is well above direct reach

- NP is made of Feebly Interacting Particles (FIPs)?



Are we searching in the correct place?

- SHiP will search for FIPs at the coupling frontier



New physics is either too heavy or interacts very feebly, *i.e.* much weaker than neutrino, in order to have escaped detection

Search for **Hi**dden **P**articles of Nature

- Globally unique potential → CERN approval of the SHiP experiment

- Search for a broad range of FIPs:
  - Heavy Neutral Leptons (HNLs)
  - Dark photons
  - Dark Scalar Higgs-like particles
  - Axion-like particles (ALPs)

… and make unprecedented measurements of tau neutrinos

CERNCOURIER | Reporting on international high-energy physics

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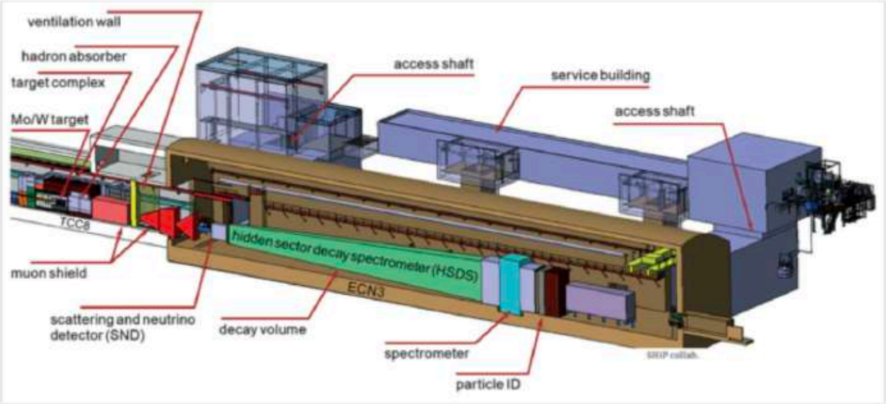
SHiP to chart hidden sector

3 May 2024



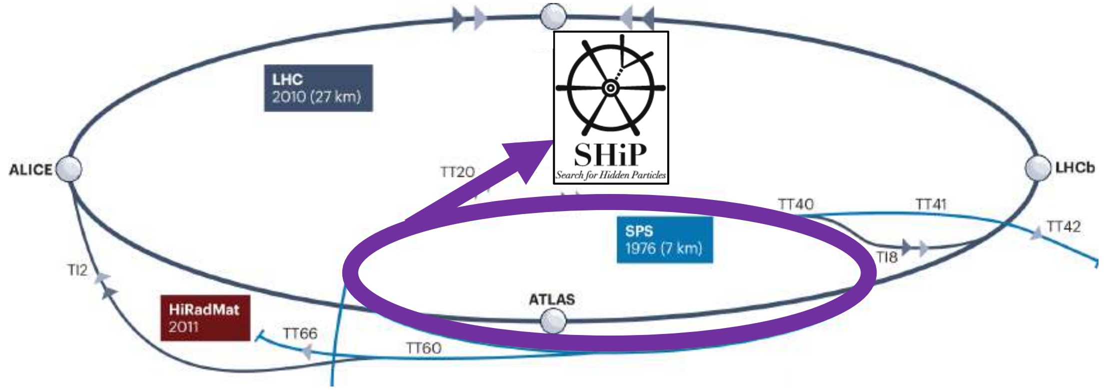
Full speed ahead Layout of the SHiP experiment, with the target on the left and the experiment in the ECN3 hall. Credit: SHiP collab.

In March, CERN selected a new experiment called SHiP to search for hidden particles using high-intensity proton beams from the SPS. First proposed in 2013, SHiP is scheduled to operate in the North Area's ECN3 hall from 2031, where it will enable searches for new physics at the "coupling frontier" complementary to those at high-energy and precision-flavour experiments.

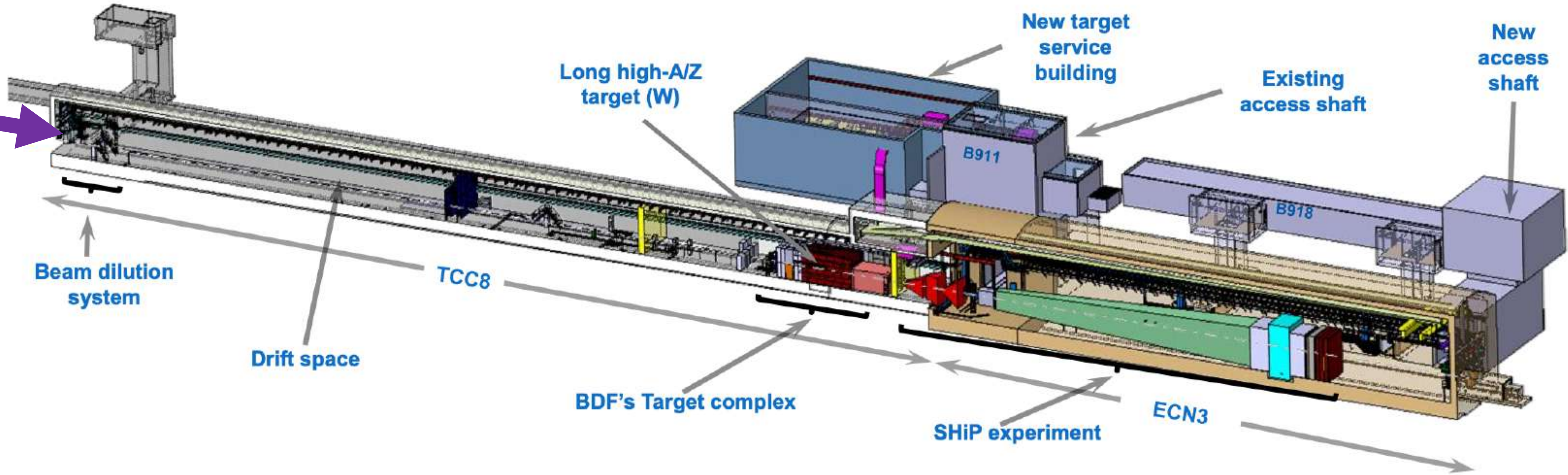
What is the SHiP experiment?

- CERN's **SPS accelerator** will be used to fire protons on to a target (6×10^{20} protons in 15 years)
  - Facility already under construction

CERN accelerator complex



Beam from SPS



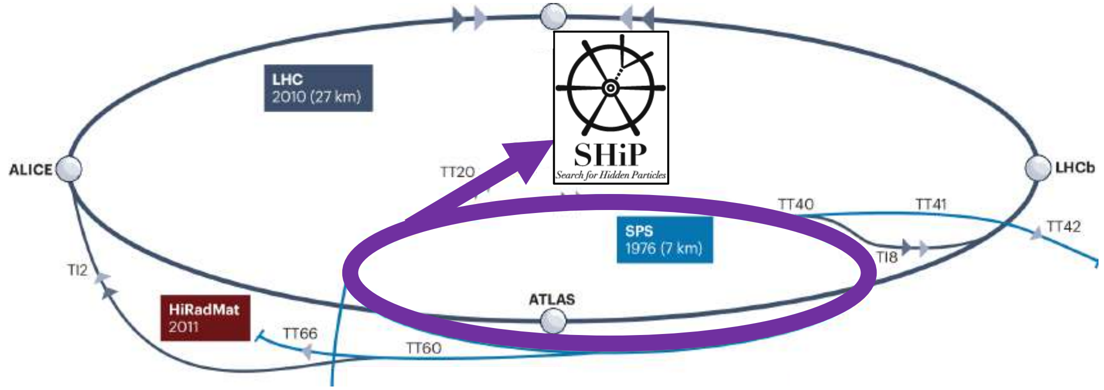
What is the SHiP experiment?

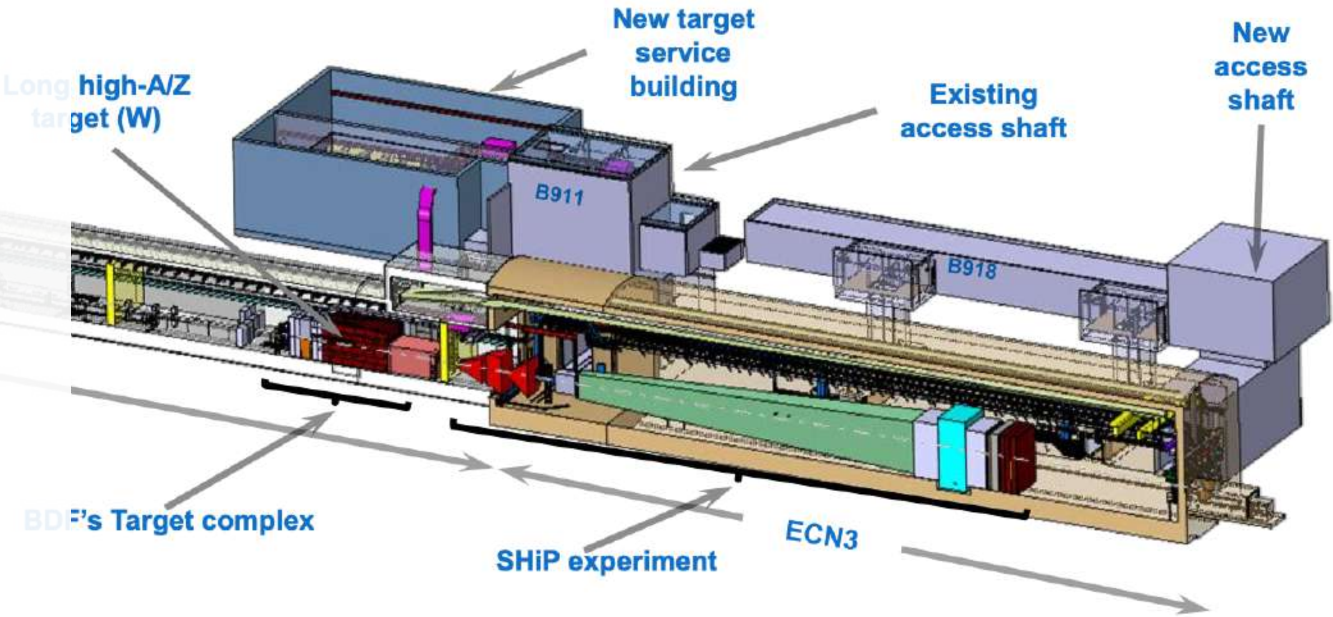
- CERN’s **SPS accelerator** will be used to fire protons on to a target (6×10^{20} protons in 15 years)
    - Facility already under construction

- Collisions could generate new FIPs but will also get:
    - hadrons → hadron absorber
    - muons → muon shield
    - neutrinos → neutrino detector
        - $>10^{17}$ charm and $>10^{15}$ ν_τ
        - So far only a dozen of ν_τ detected

… can exploit collisions only to extent can control backgrounds

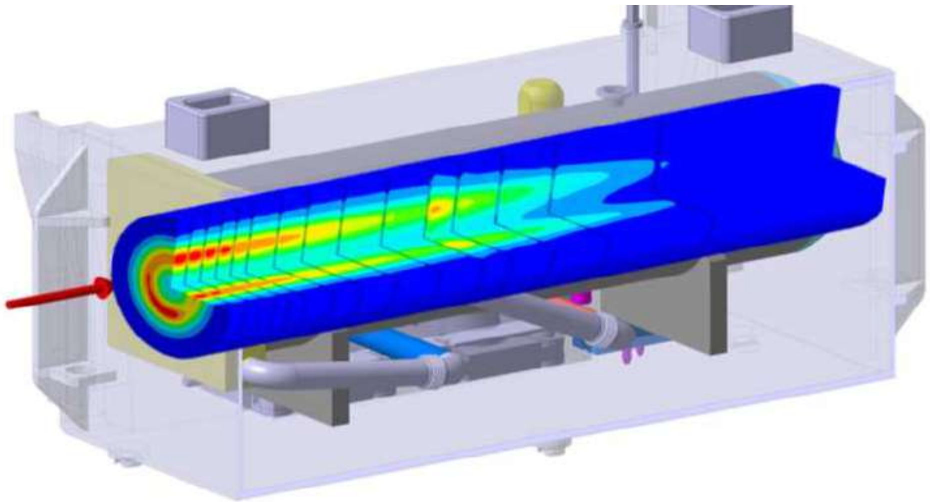
CERN accelerator complex

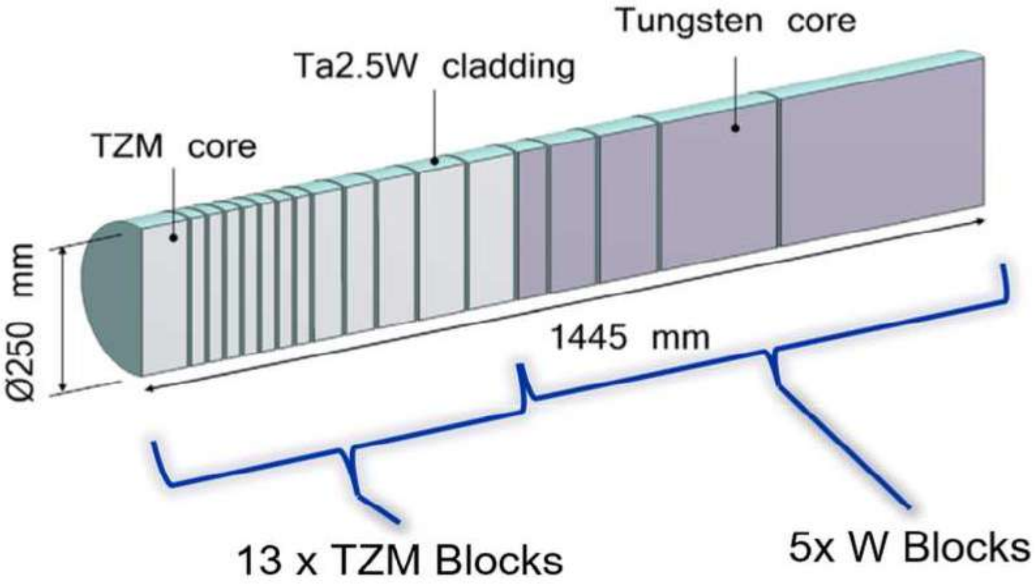




Target

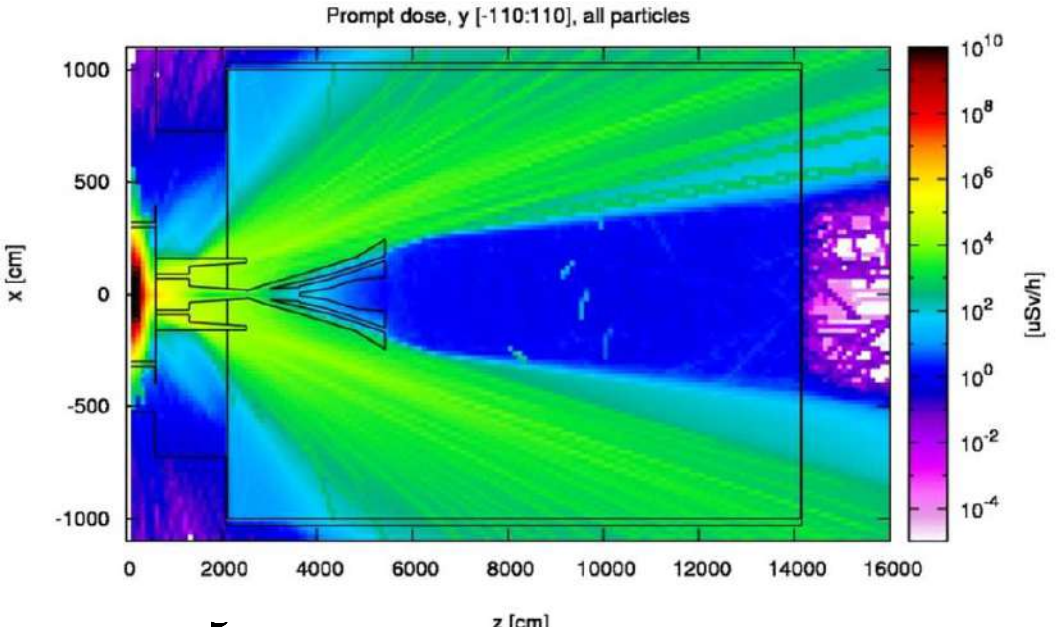
- Very thick (12λ): use full beam intensity including cascade interactions
- High-A & Z: maximize production cross-sections (W)
- Short λ (high density): absorb pions/kaons before decay (to μ & ν)
- 4×10^{19} protons-on-target per year → 6×10^{20} in 15 years
- Beam spot ~1cm

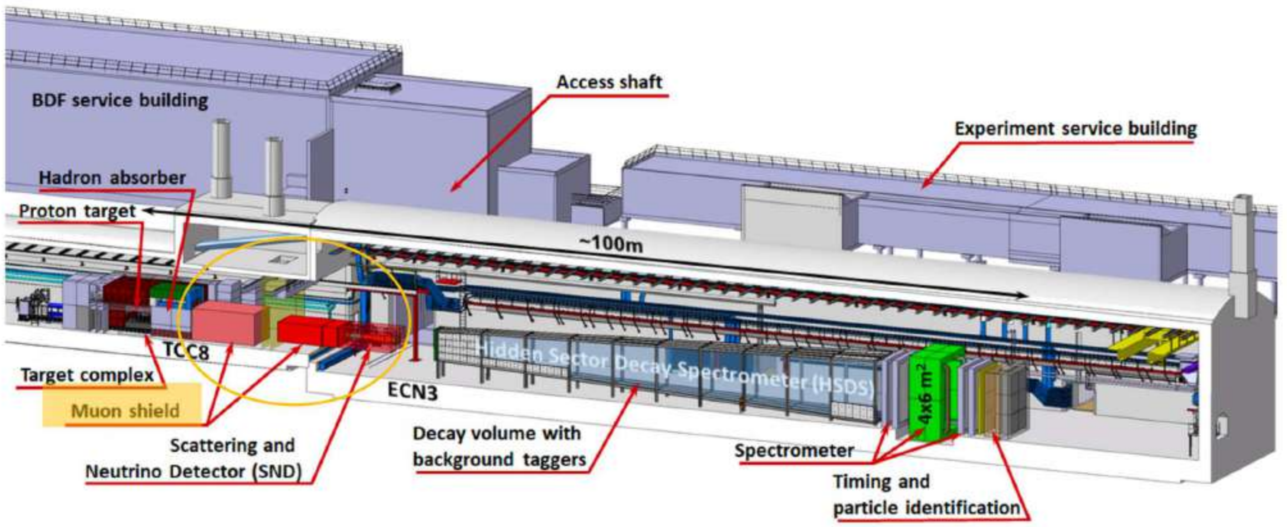


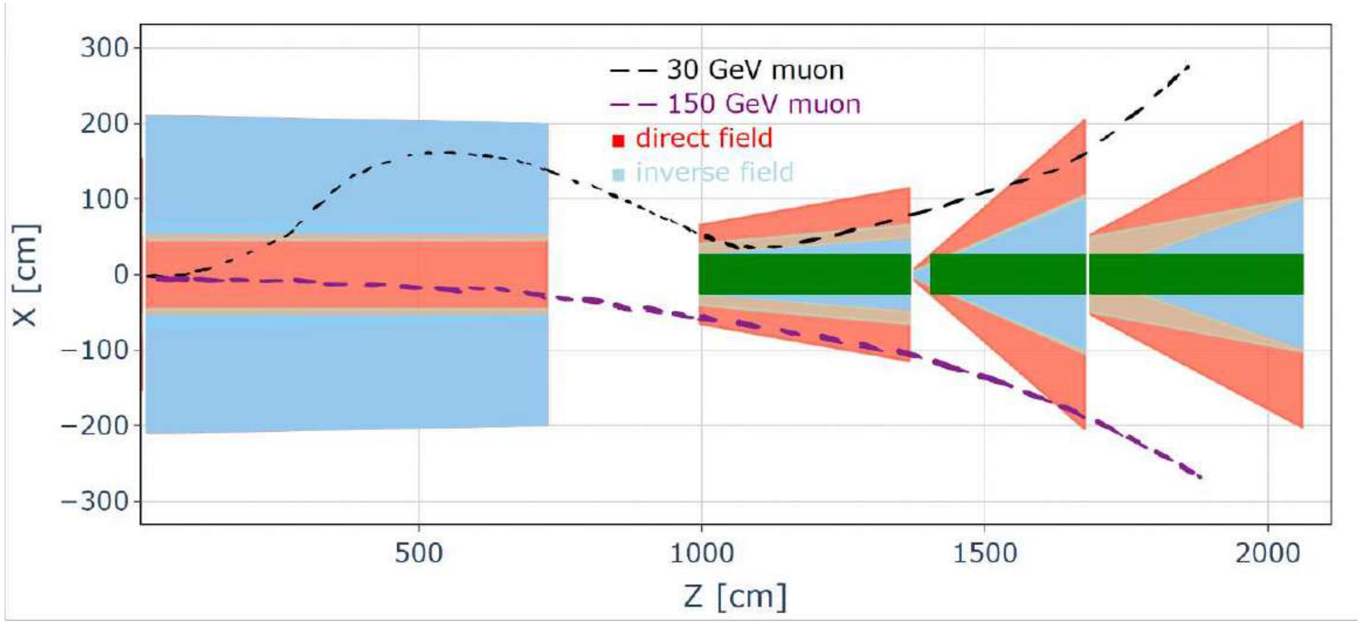


Magnetic muon shield

Reduce muon rate from 10^{10} to 10^5 per spill (1 sec) using active deflection





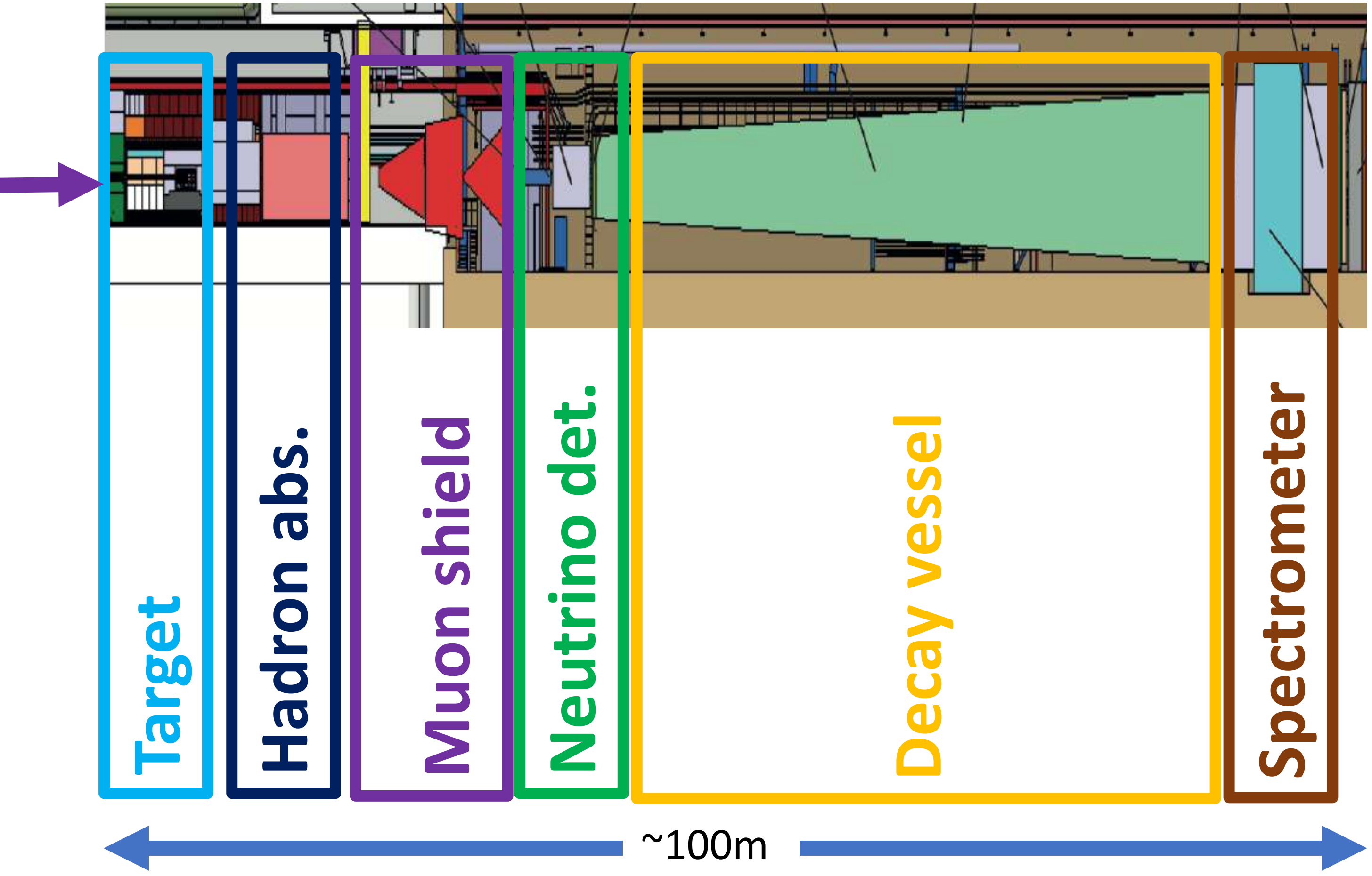


Two options under consideration:

- Fully warm
- Hybrid with 1st section made of SC technology

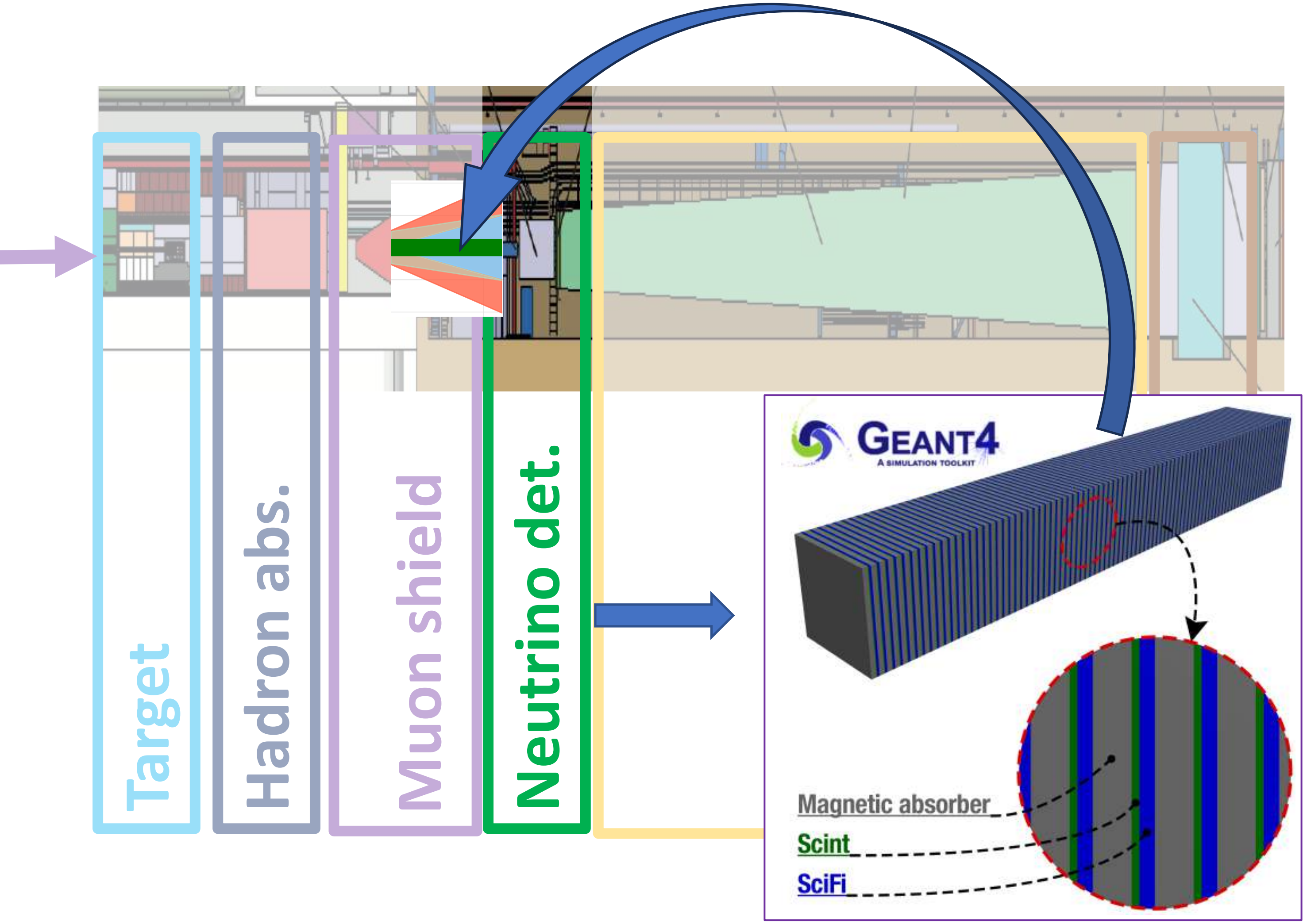
The approved version of SHiP

- SHiP approved with a conservative detector design:



Initial configuration of SHiP

- Transform the detector design to start data taking in 2031/32:

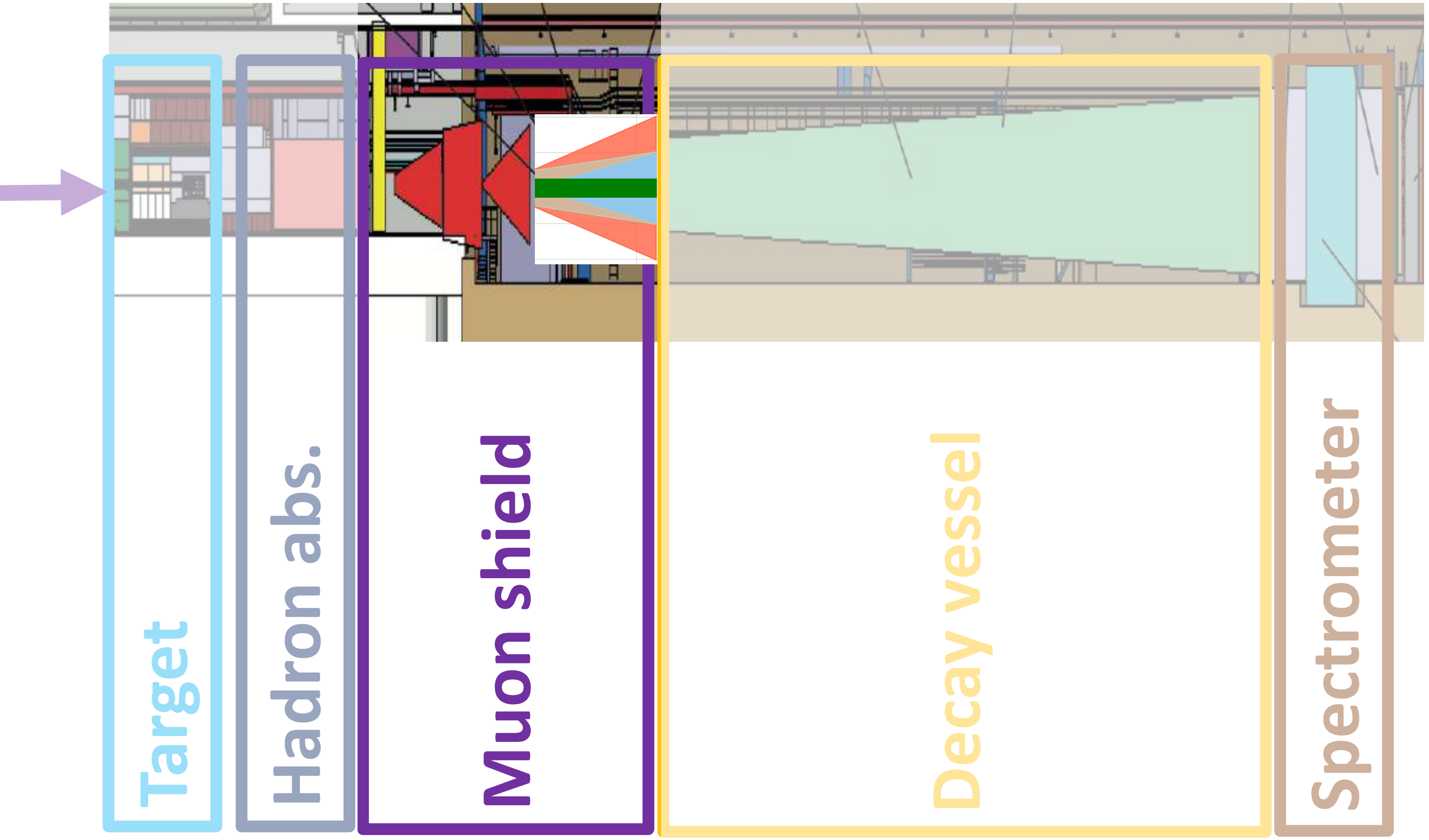


- Replace neutrino detector with a new Magnetised Tracking Calorimeter (MTC)
- Integrate into the muon shield

  → improved neutrino physics

Initial configuration of SHiP

- Transform the detector design to start data taking in 2031/32

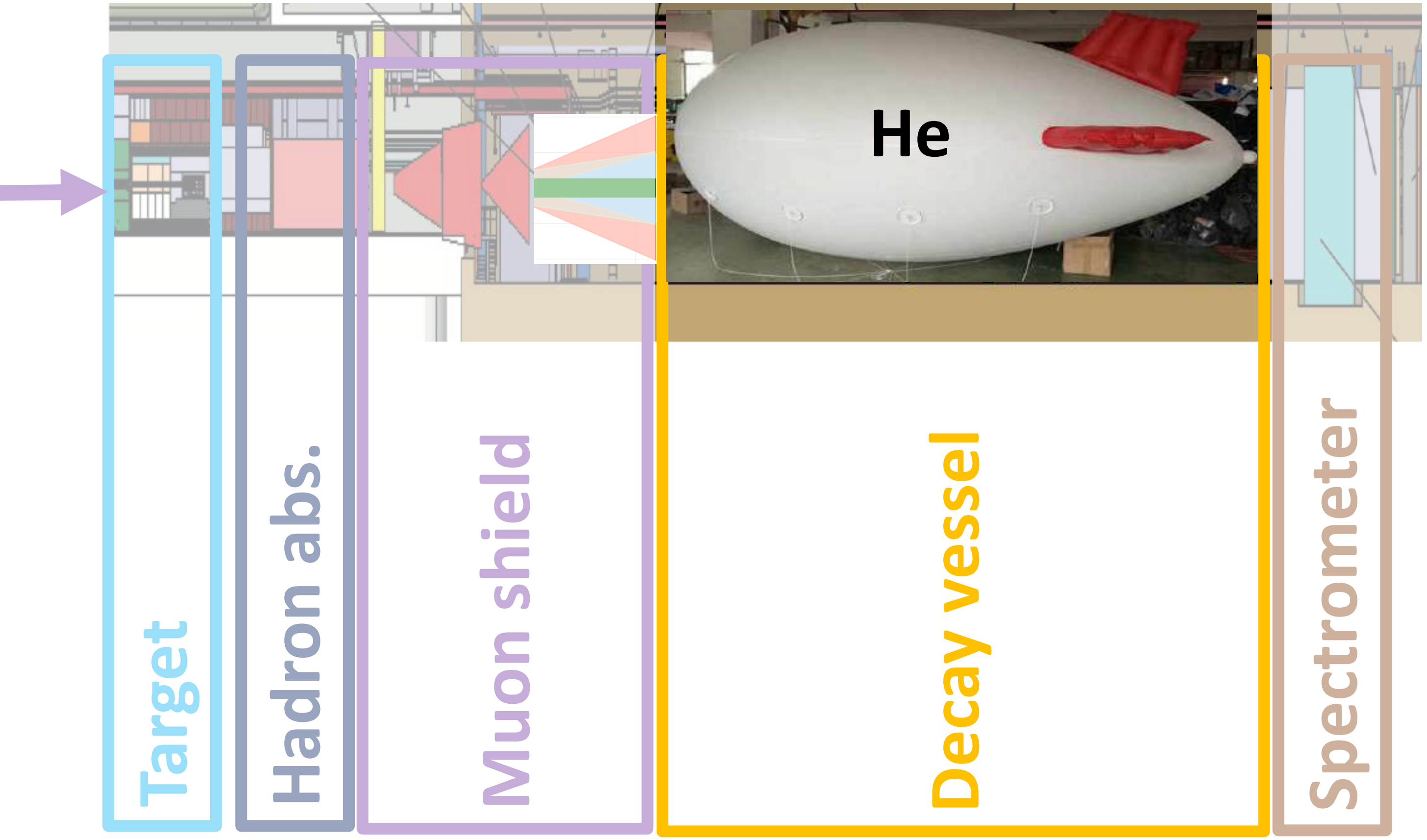


- Expand the muon shield into the space freed-up

  → reduce muon-induced backgrounds

Initial configuration of SHiP

- Transform the detector design to start data taking in 2031/32:



- Replace vacuum vessel with a helium-filled balloon

  ⟶ reduce muon- & neutrino-induced backgrounds

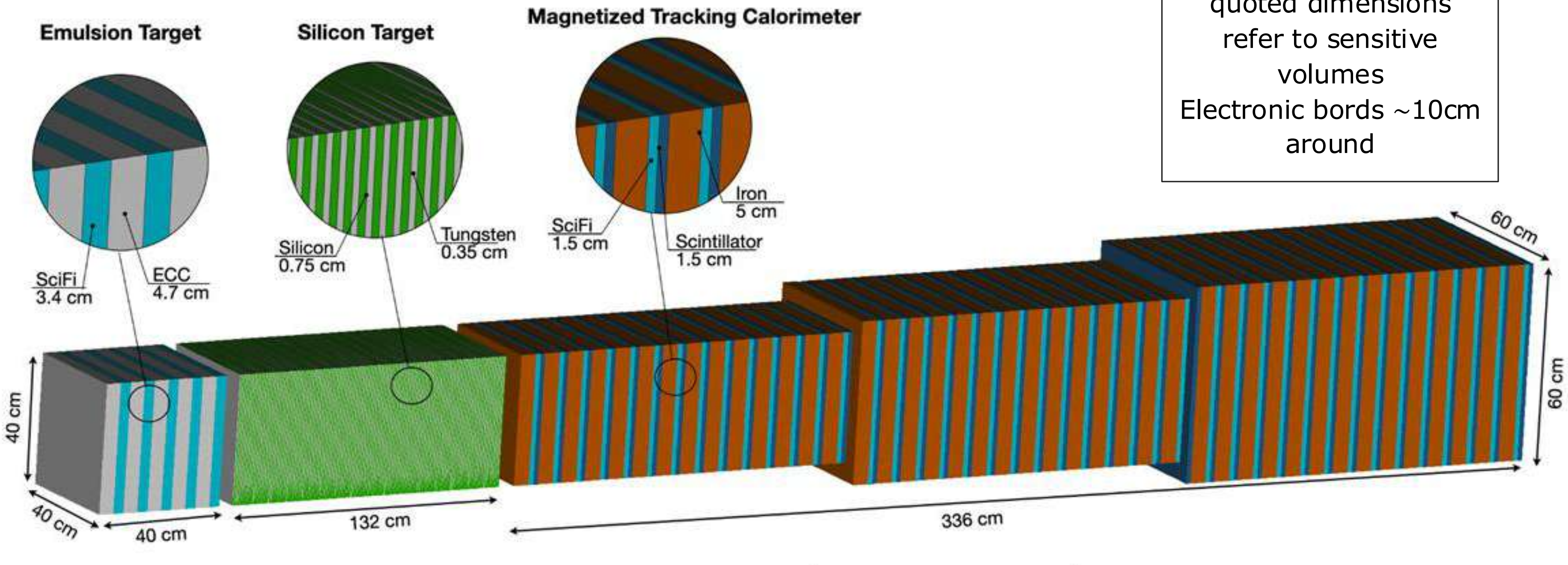
Scattering Neutrino Detector (SND)

- Rich tau-neutrino physics programme
- Light Dark Matter scattering

Si/W → Precision tracking and Ecal, & Vertex detector

Magnetised Tracking Calorimeter (MTC) → Reconstruction of muons, hadronic showers and **missing momentum**

quoted dimensions refer to sensitive volumes
Electronic bords ~10cm around



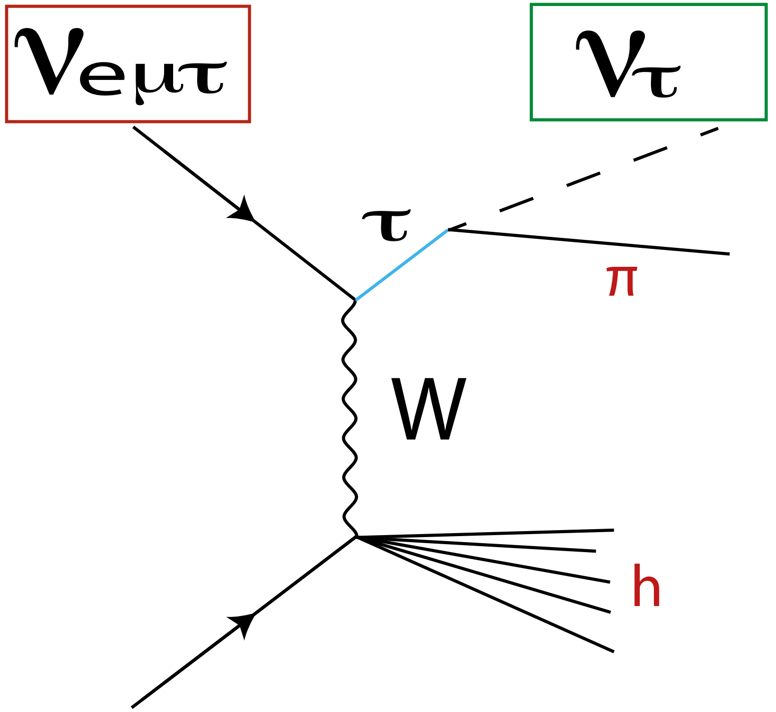
EMULSION TARGET			
ECC	5	Tungsten	180
		Emulsion	180
SciFi	5		
Weight		0.5 ton	

SILICON TARGET	
Tungsten	120
Silicon	120
Weight	1.2 ton

MAGNETIZED TRACKING CAL	
Iron	42
Scintillator	42
SciFi	42
Weight	2.5 ton

Tau-neutrino physics

- Experimental signature of tau neutrino:
  (i) “double-kink” topology
  (from ν_τ-interaction and τ-decay)
  (ii) Missing P_t carried away by
  neutrinos from τ-decay



- Very large sample of tau neutrinos available at BDF/SHIP via $D_s \rightarrow \tau\nu_\tau \rightarrow \sigma_{stat} < 1\%$ for all neutrino flavours
- Accuracy determined by systematic uncertainties ~5% in all neutrino fluxes, dominated by the uncertainty of cascade charm production in the thick SHiP target

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

MTC performance

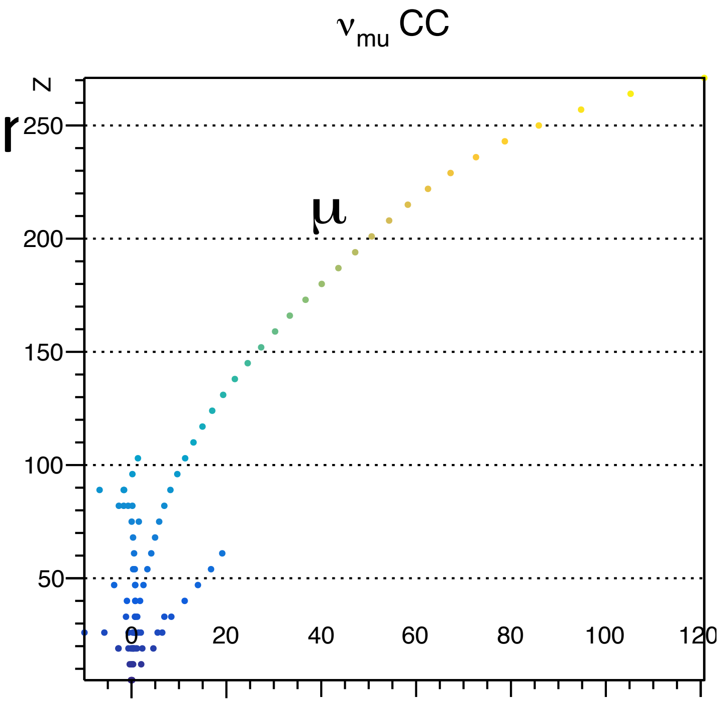
- Muon momentum measurement in magnetised iron (1.7T field) ~15% accuracy
- Hadronic energy measurement

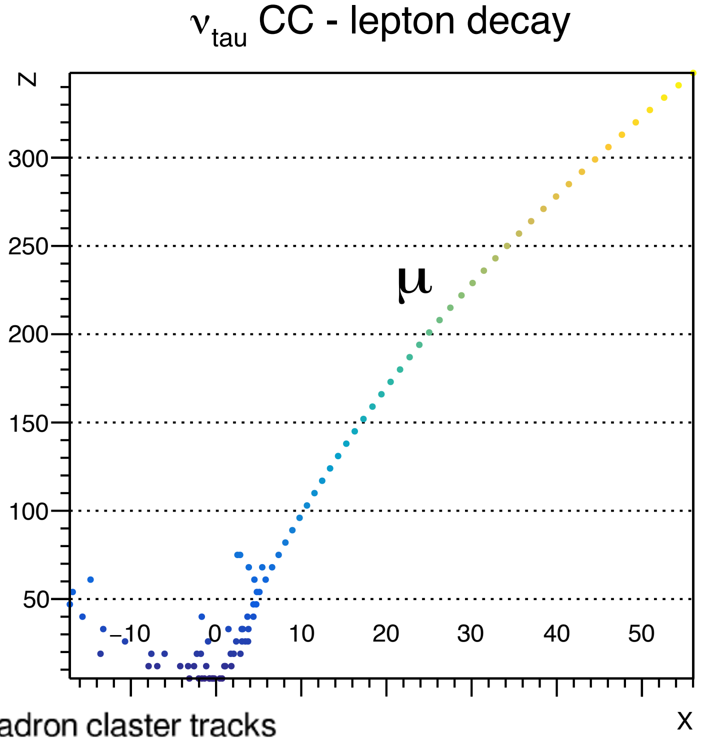
$$\frac{\sigma(E)}{E} \sim \frac{50\%}{\sqrt{E}}$$

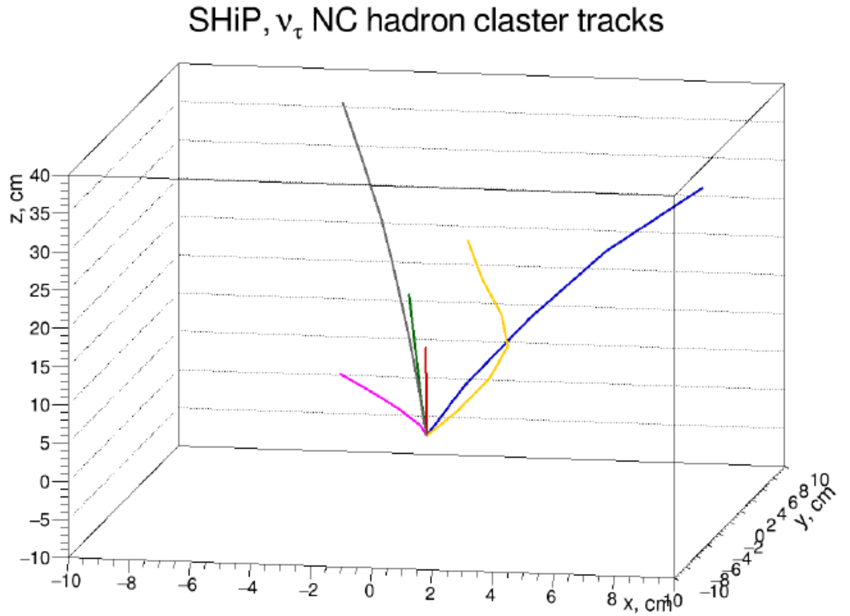
- Neutrino interaction vertex:
  σ ~ 1.5 cm in xy-plane
- Tau neutrino direction ~1%

→ Enable to calculate the missing momentum transverse to the tau neutrino direction

Events are very clean:

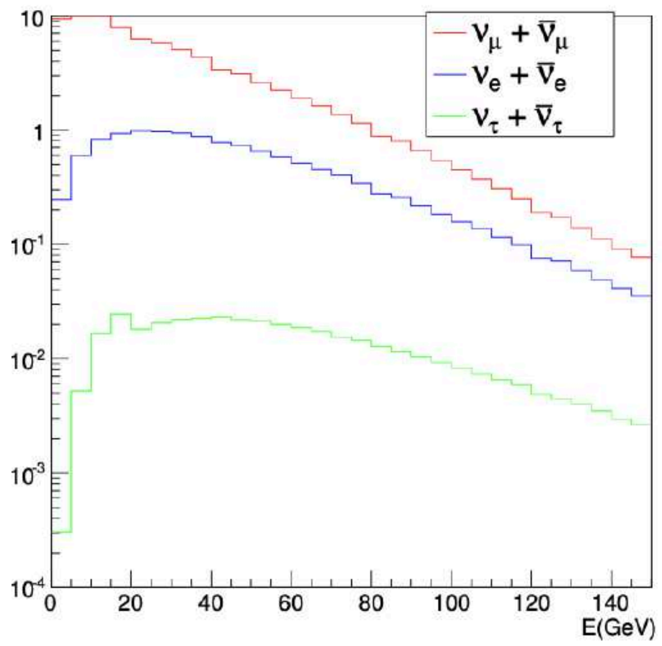


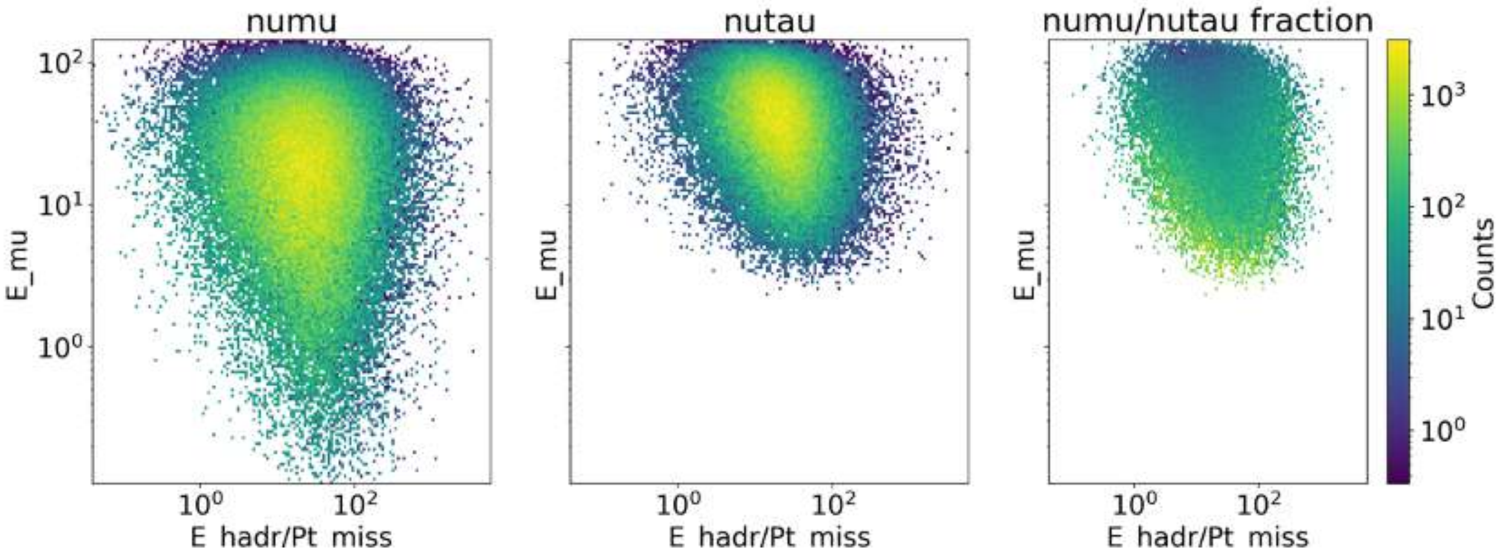


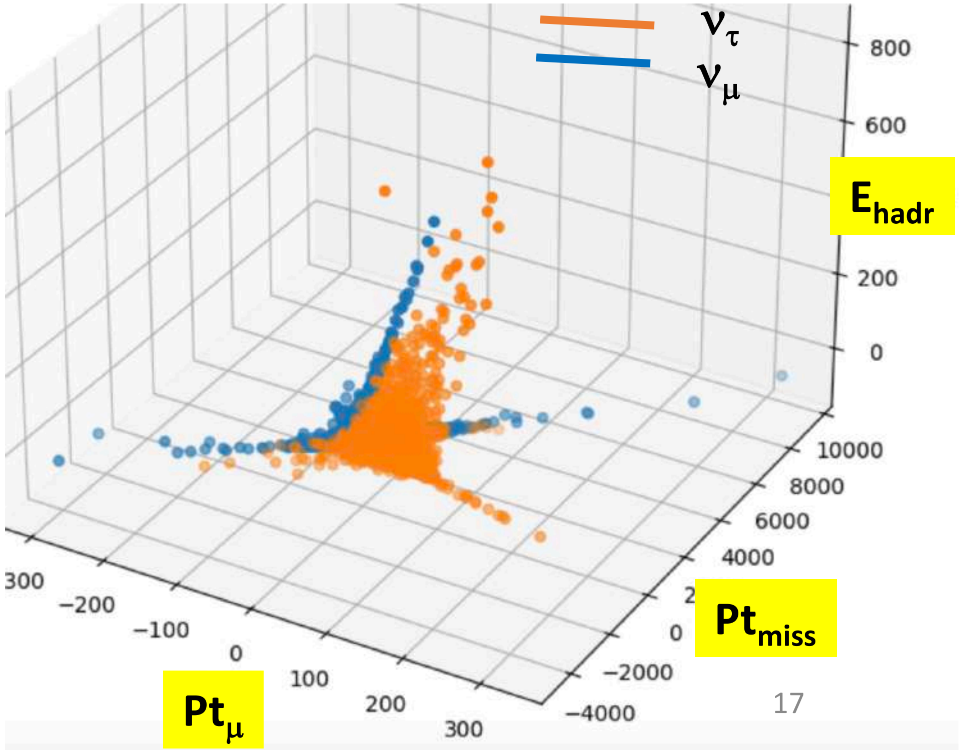


ν_τ reconstruction with MTC

- Main background: muon neutrino interactions (CC for leptonic, NC for hadronic tau decays)
- Kinematical variables used in ML-algorithm
  - missing momentum wrt ν_τ direction-of-flight
  - muon momentum
  - energy of hadrons







- → expect Signal/Background ~10

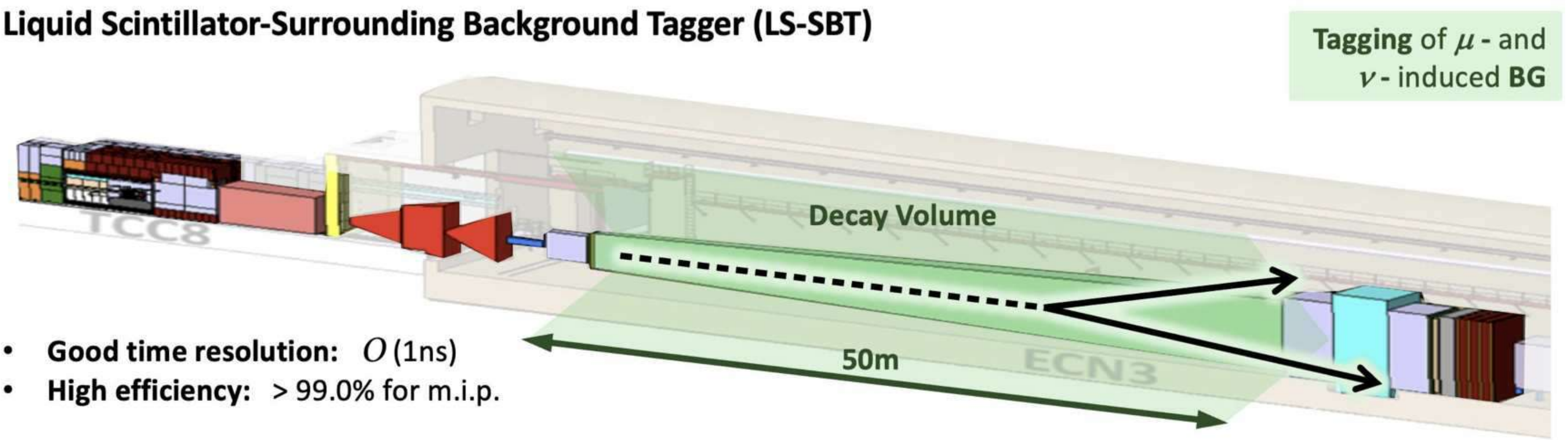
Neutrino interaction physics

- LFU in neutrino interactions
  - $\sigma_{stat+syst}$~3% accuracy in ratios: ν_e/ν_μ , ν_e/ν_τ and ν_μ/ν_τ
- Measurement of neutrino DIS cross-sections up to 100 GeV
  - E_ν< 10 GeV as input to neutrino oscillation programme (DUNE in particular)
  - ν_τ cross-section at higher energies input to cosmic neutrino studies
  - $\sigma_{stat+syst}$< 5%
- Test of F_4 and F_5 ($F_4 \approx 0,\ F_5 = F_2/2x$ with $m_q \to 0$) structure functions in $\sigma_{\nu-\mathrm{CC\ DIS}}$
  - Never measured, only accessible with tau neutrinos [C.Albright and C.Jarlskog, NP B84 (1975)]

Decay volume and background taggers: UBT & SBT

50m long frustum decay volume:

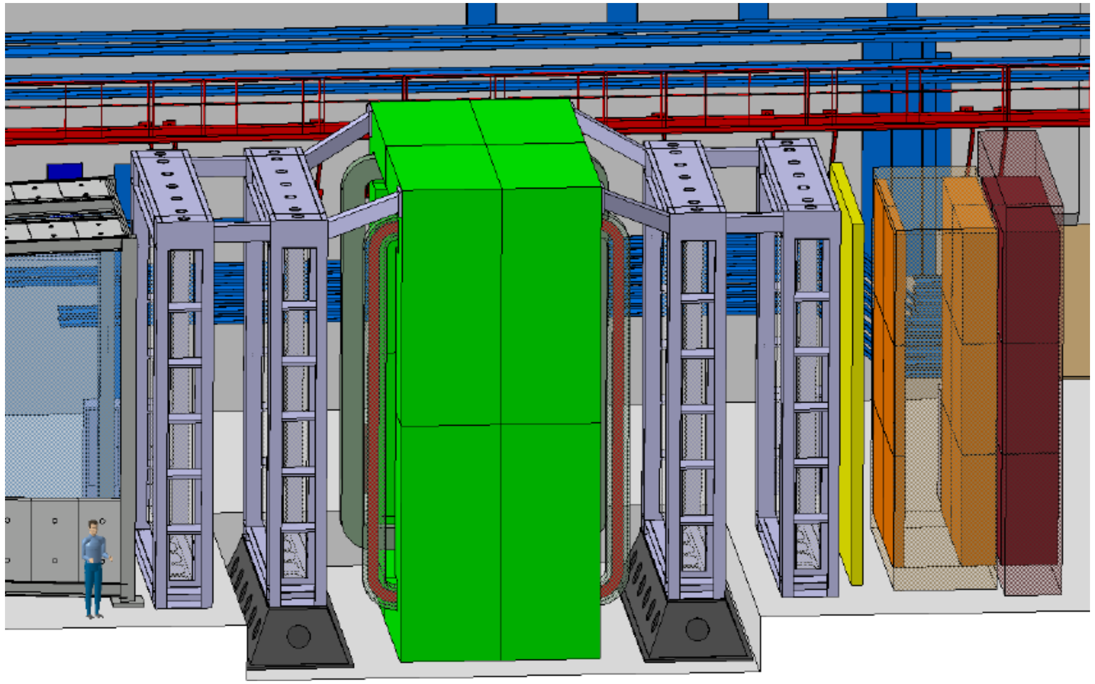
- He at atmospheric pressure
- $1.0 \times 2.7\text{m}^2$ upstream, $4\times 6\text{m}^2$ downstream



- UBT (Multi-gaps RPC or SciFi, or fast straws) to veto muons escaping muon shield
- SBT (Liquid Scint.) to tag muon & neutrino interactions with the surrounding infrastructure

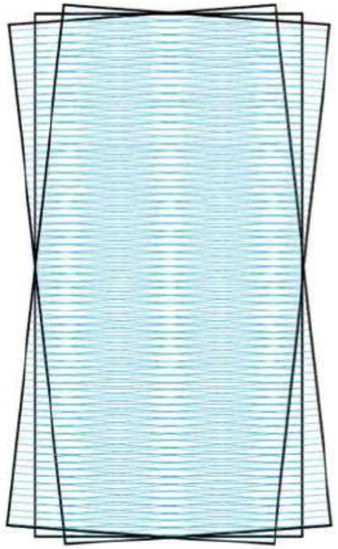
Hidden Sector Decay Spectrometer (HSDS)

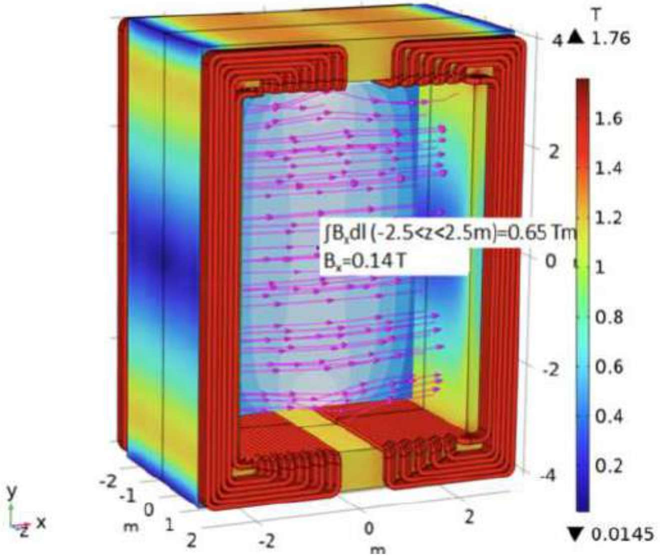
- Large aperture: $4 \times 6\text{m}^2$
- Precise track reconstruction
  - Spatial resolution ~150μ
  - Large 5m-deep SC magnet: $\int Bdl = 0.65\text{Tm}$
- High hit efficiency: >99%
- High rate capability



Baseline option:

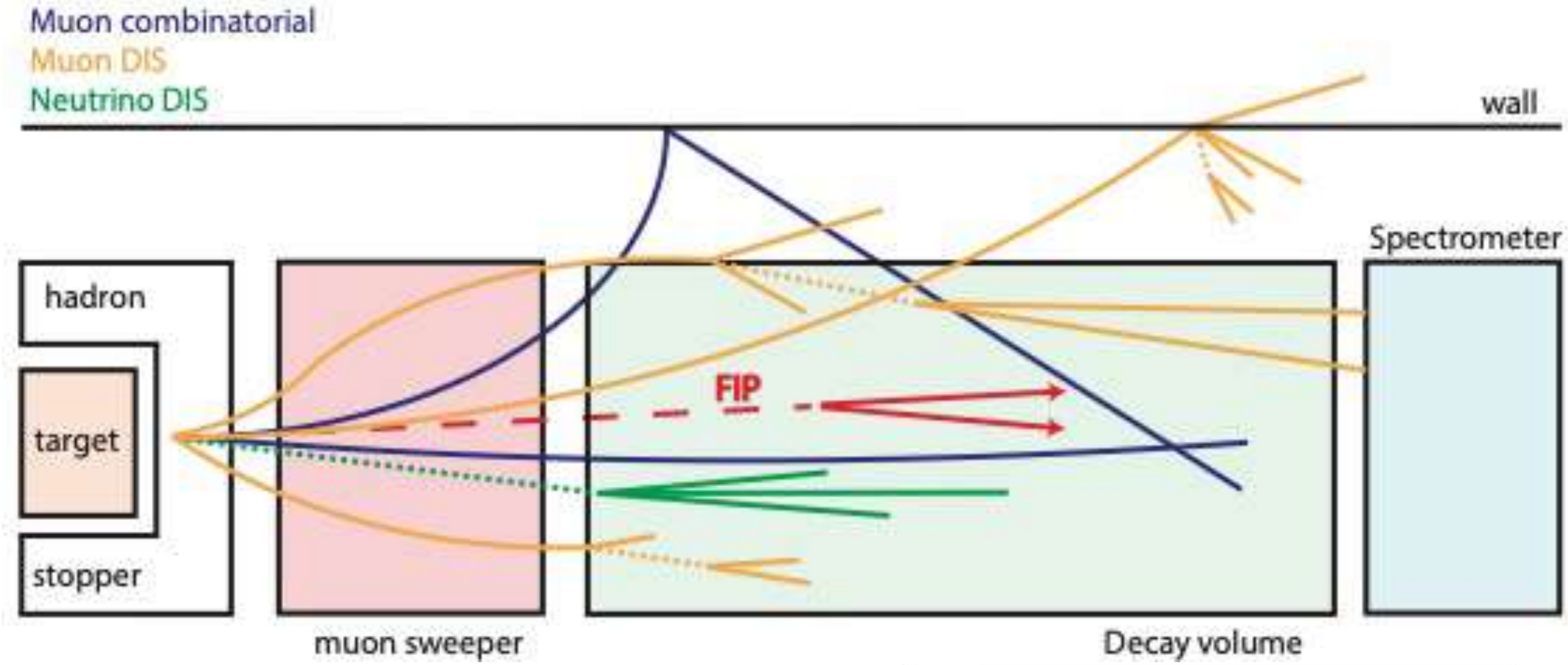
- 20mm Ø Mylar straw tubes ~150μ hit reconstruction
- 2×2 stations of 4 double layers at 5-10° stereo angle, 10k channels

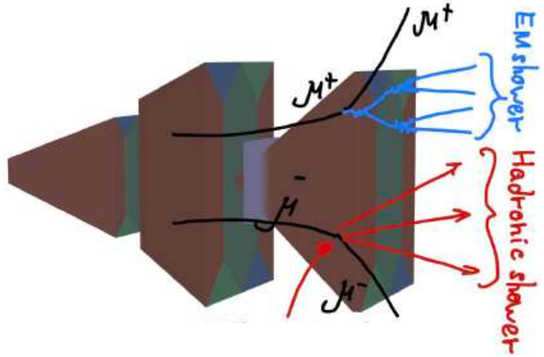




Backgrounds at SHiP

- **Main sources of background:**





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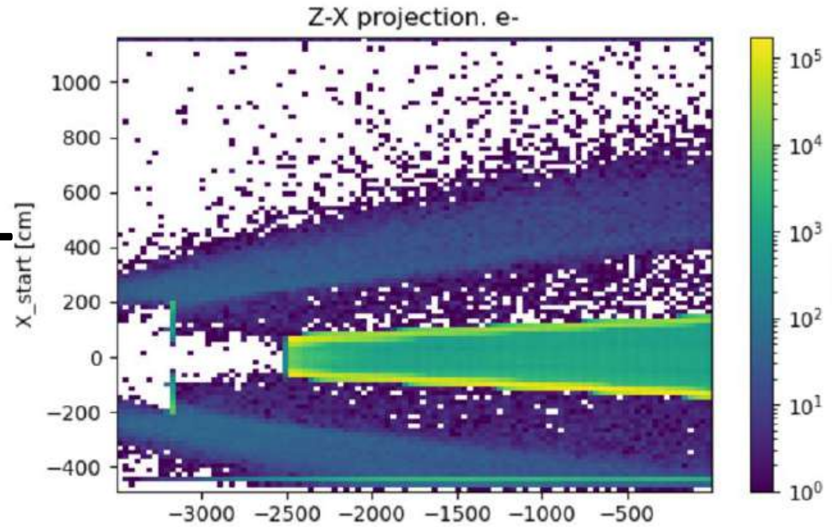
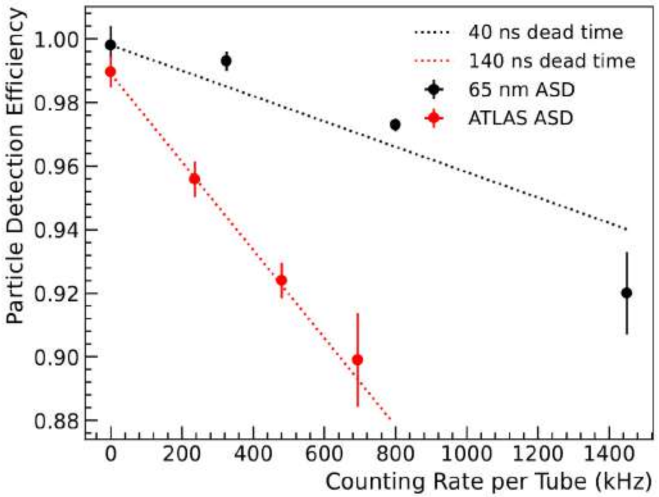
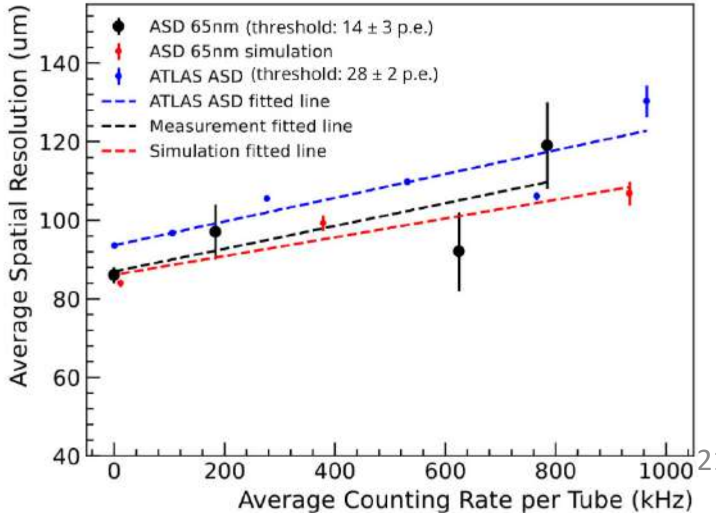


- Need high rate capability (~0.5MHz) straw tracker





Backgrounds at SHiP

- Aims at nearly zero-background to search for FIPs
- Very simple selection for both fully and partially reconstructed events
- Possibility to measure background with data

Selection

Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
	$> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

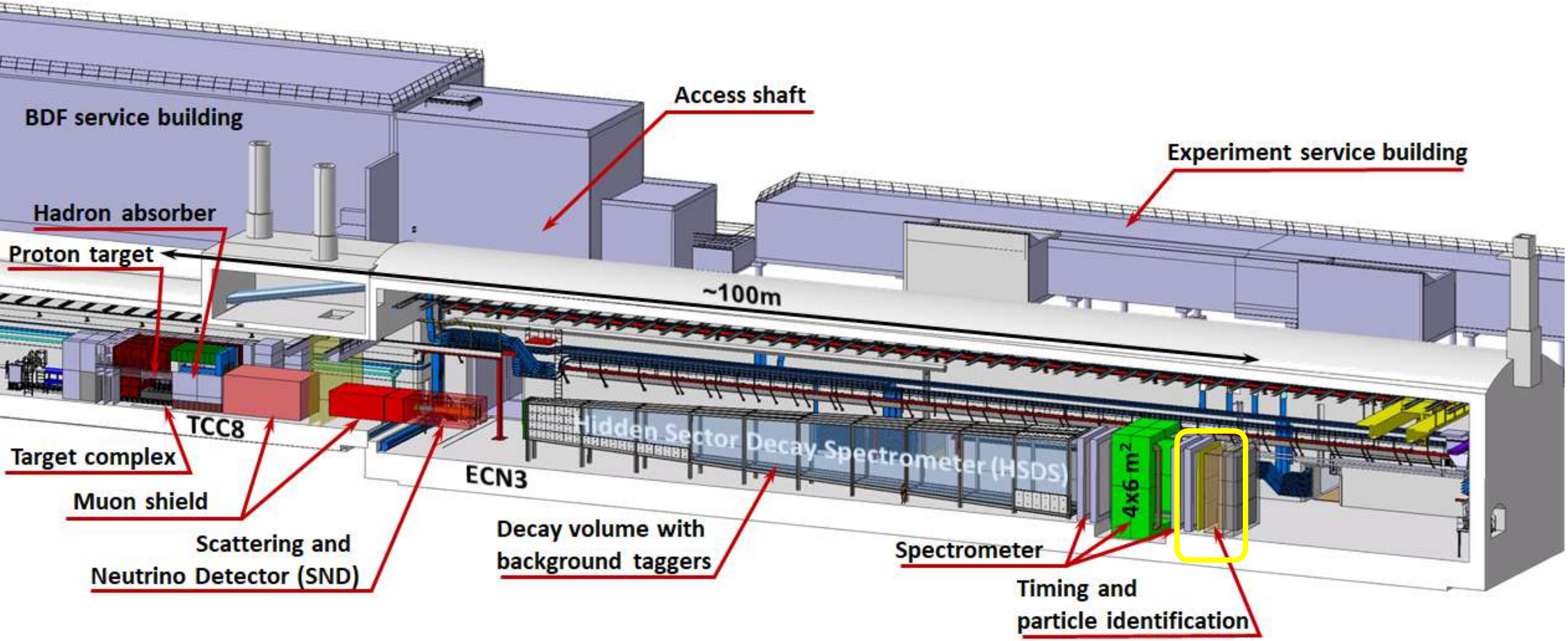
+ **Time coincidence** + **UBT/SBT**

(*) Invariant mass and PID not used

- Expected background in 15 years

Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

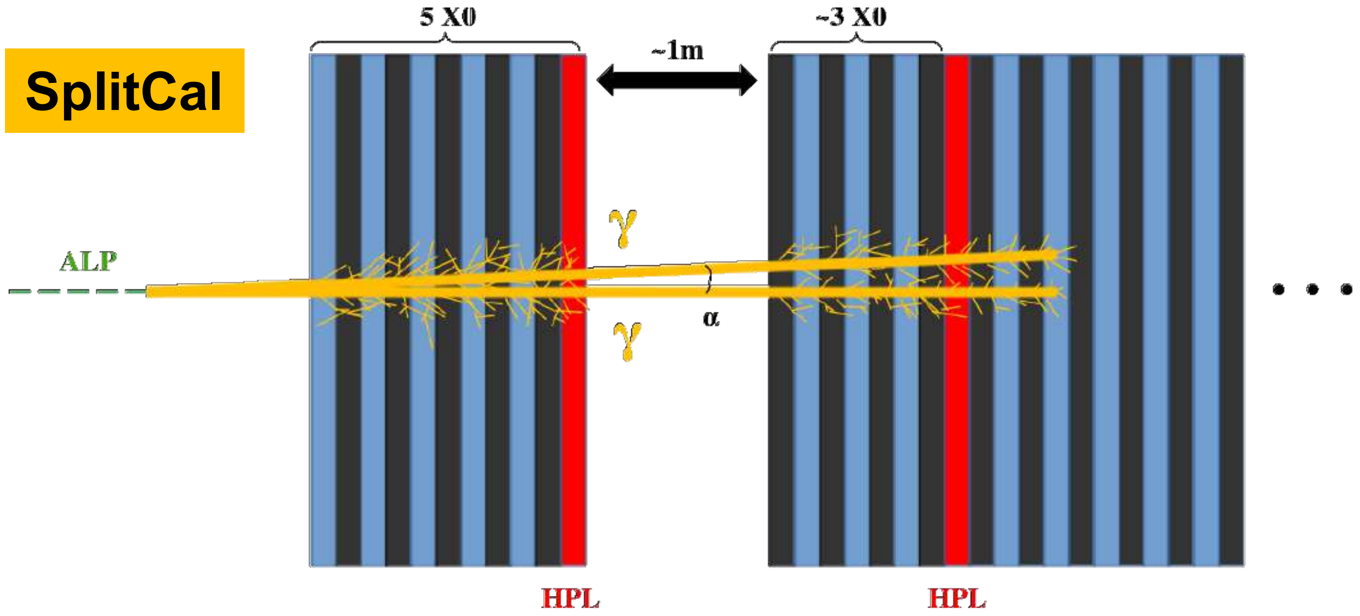
Timing detector, Calorimetry and PID

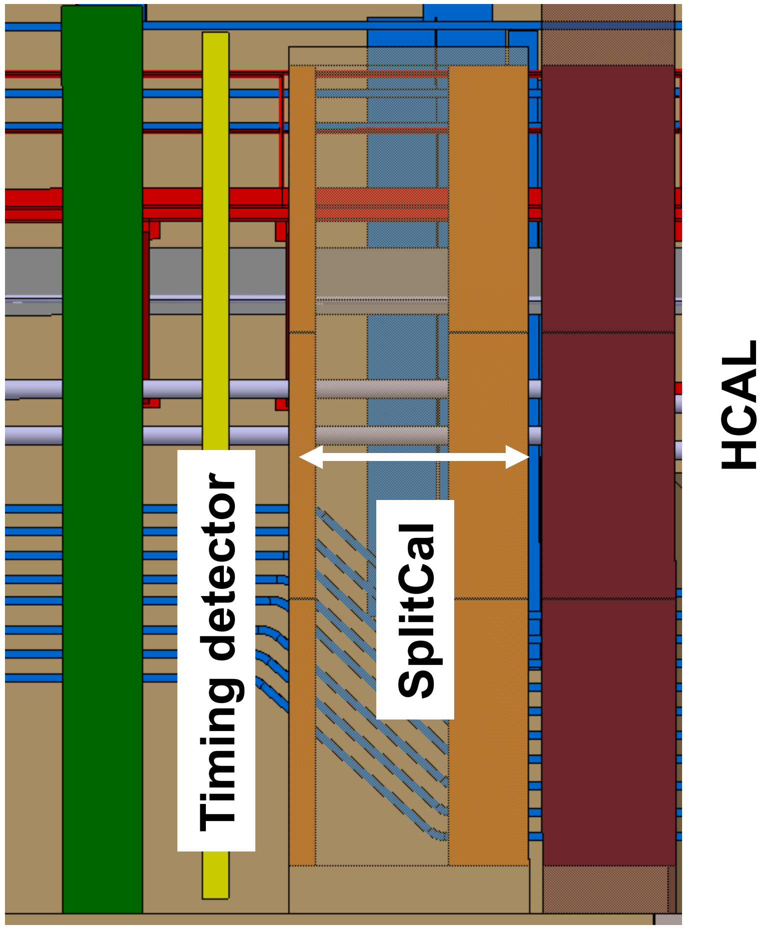


- Located downstream the SHiP spectrometer
- Timing detector: scintillating bars readout by SiPM arrays (<100 ps)
- Calorimetry: sampling ECAL and HCAL
  based on scintillators readout by SiPMs

Calorimetry and PID

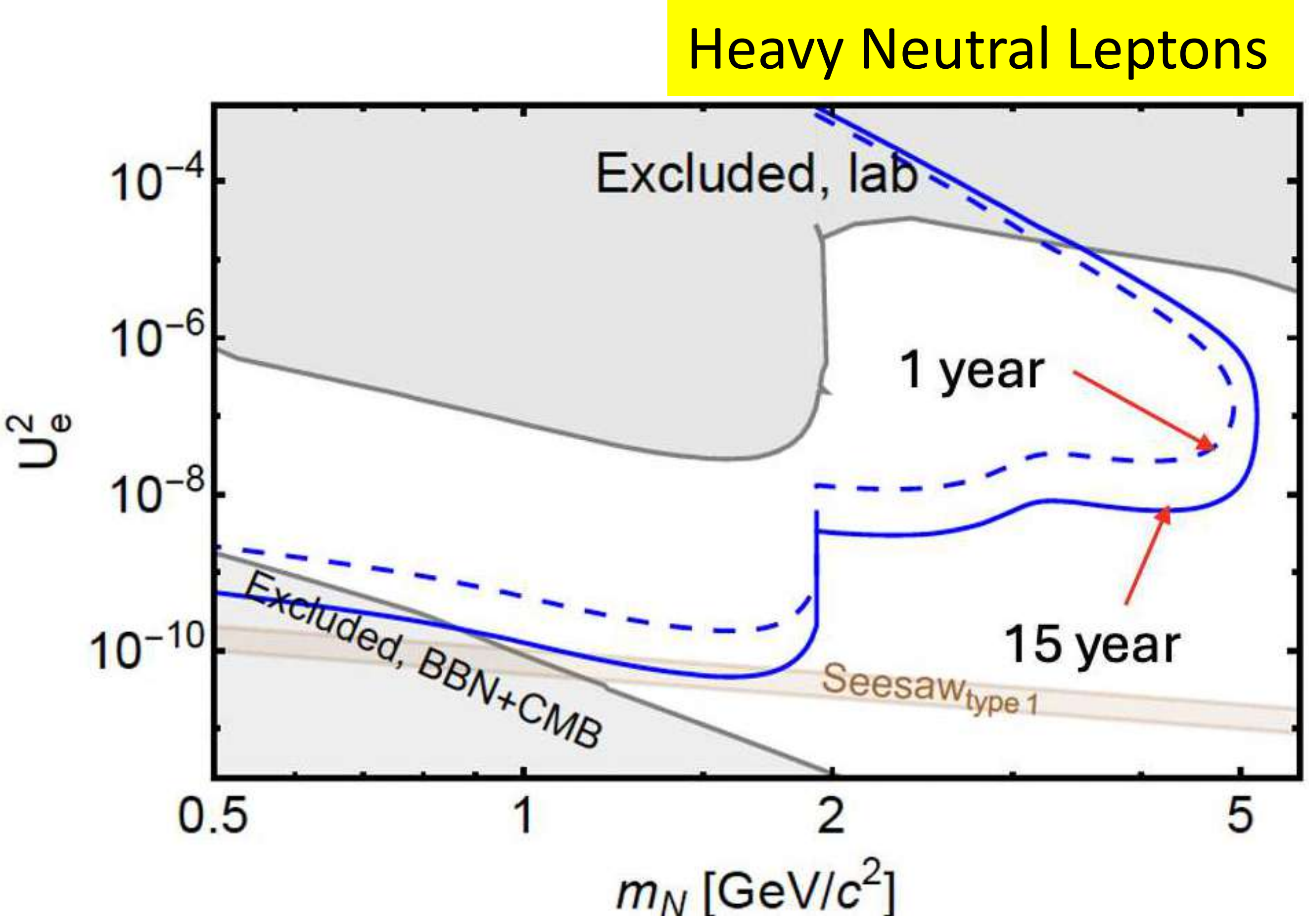
- Located downstream the SHiP spectrometer
- Composed of sampling ECAL and HCAL
  based on scintillators readout by SiPMs
- ECAL (SplitCal concept) with pointing
  - to reconstruct neutral final states
    (e.g. ALP→$\gamma\gamma$ and also π^0 from FIPs decays)
  - Technologies: scintillator bars and GEM or MicroMegas or fast straws for high precision layers

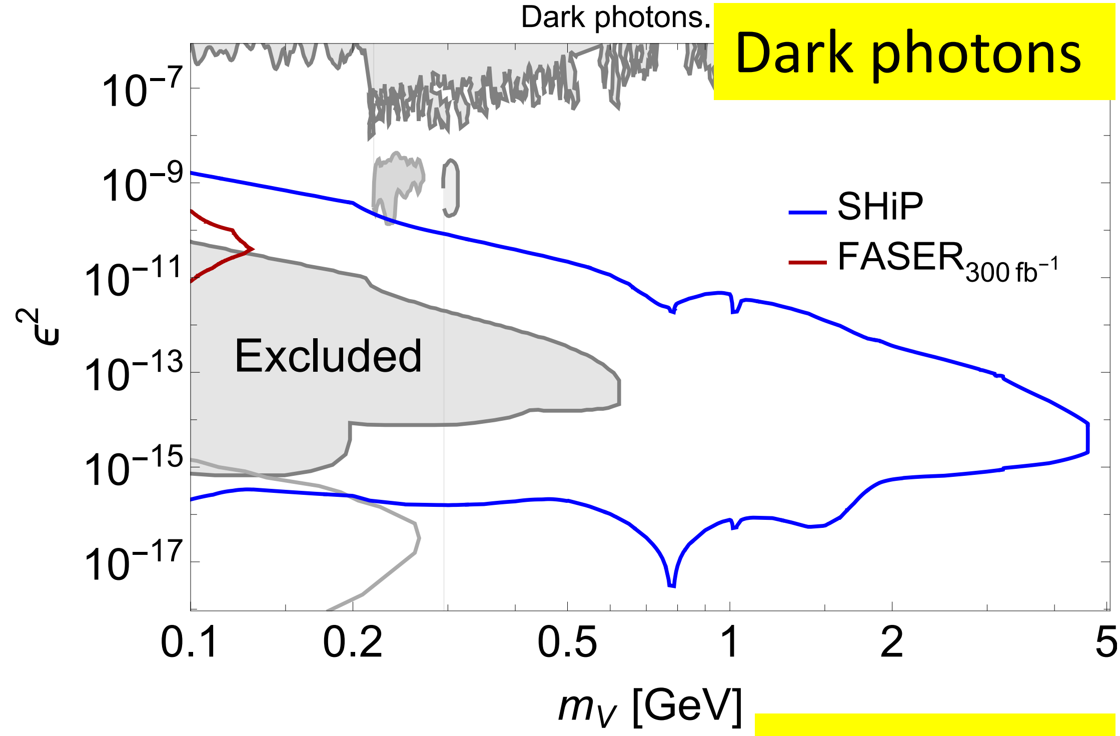


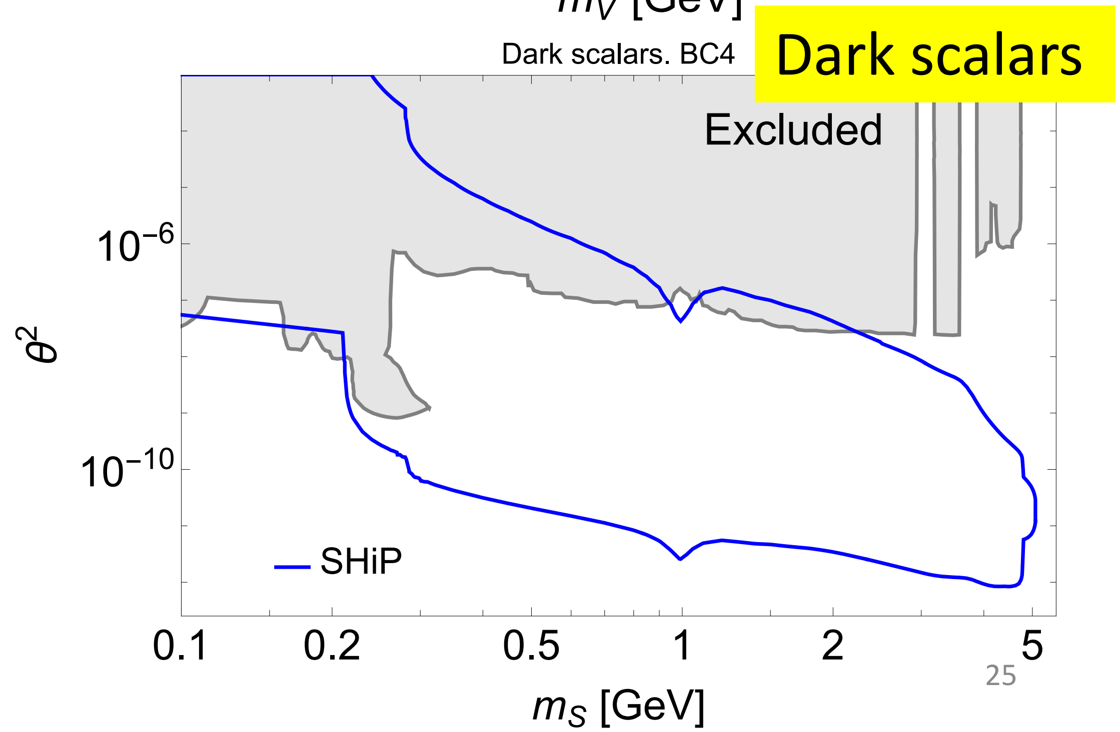


- Compact HCAL (~5λ) for μ/π separation

SHiP sensitivities: HNLs, Dark photons & Higgs-like scalars

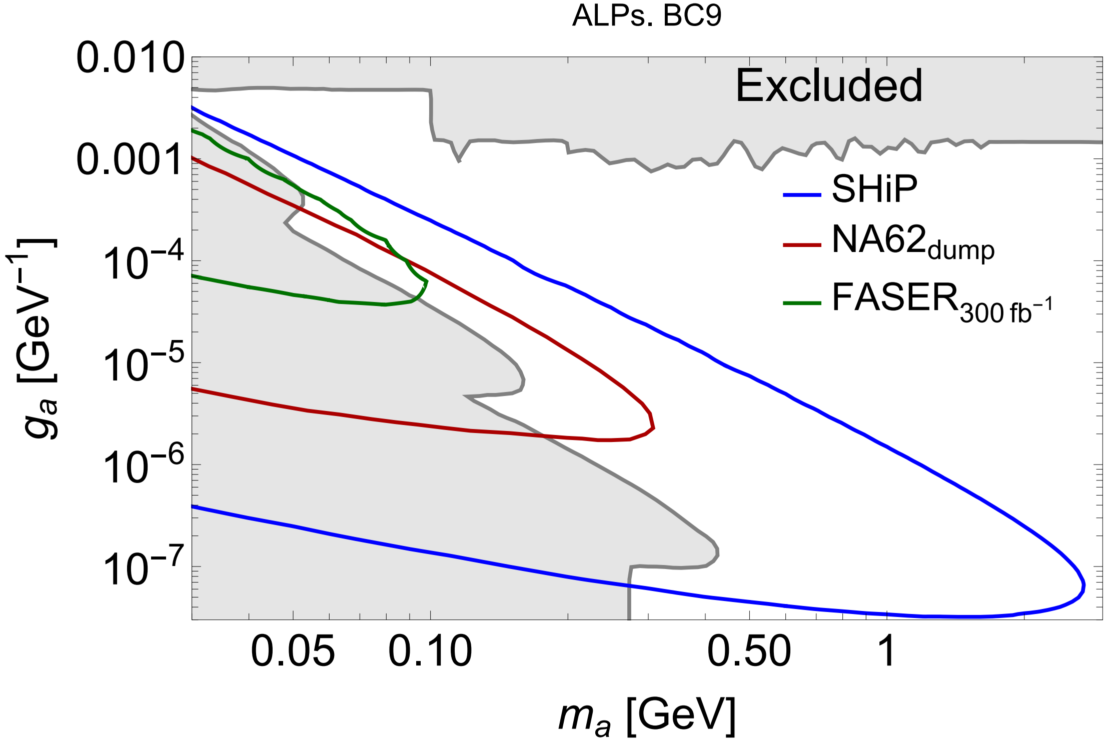




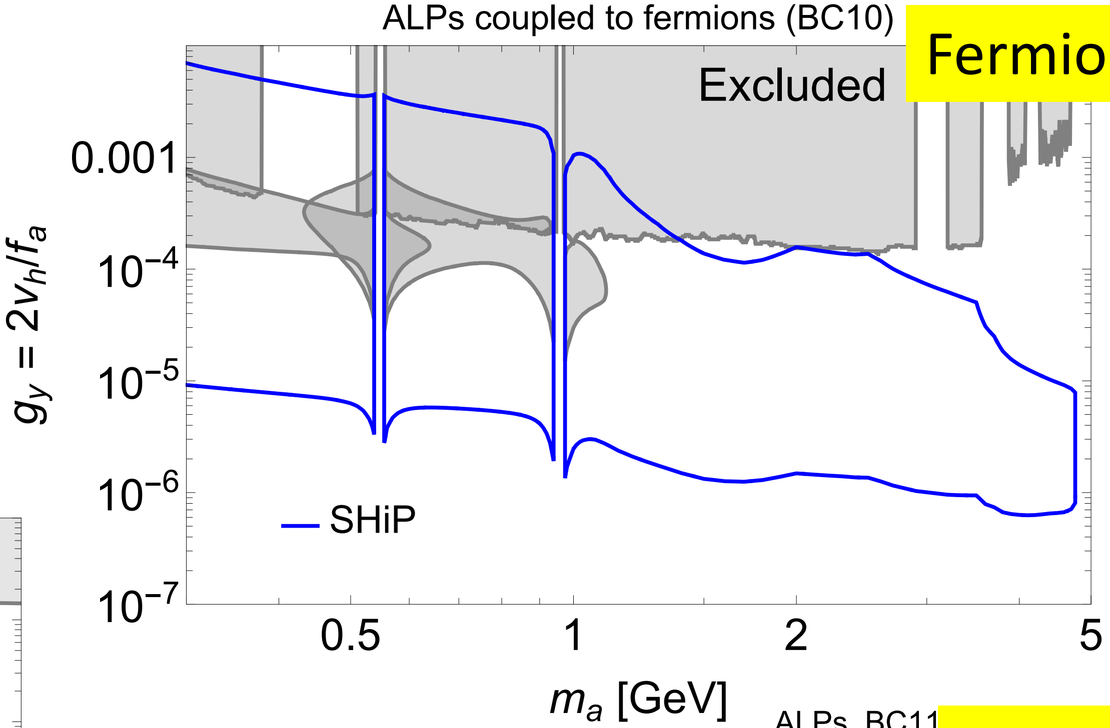


SHiP sensitivities:
Axion Like Particles (ALPs)

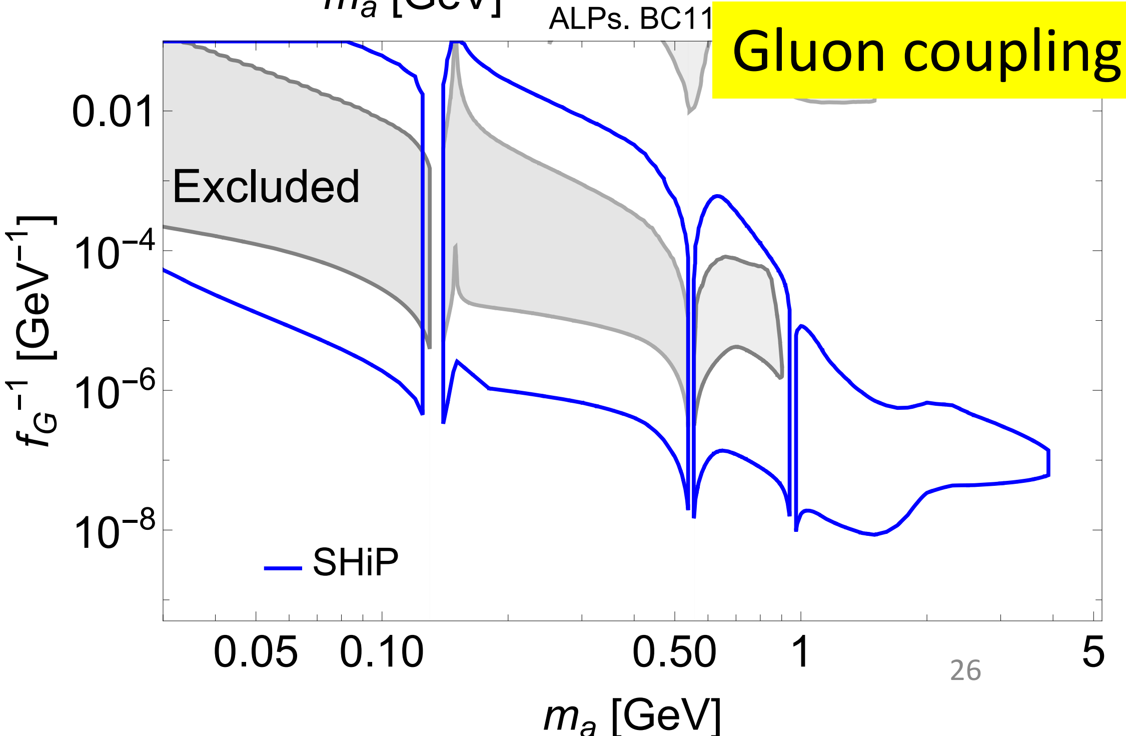
Photon coupling



Fermion coupling

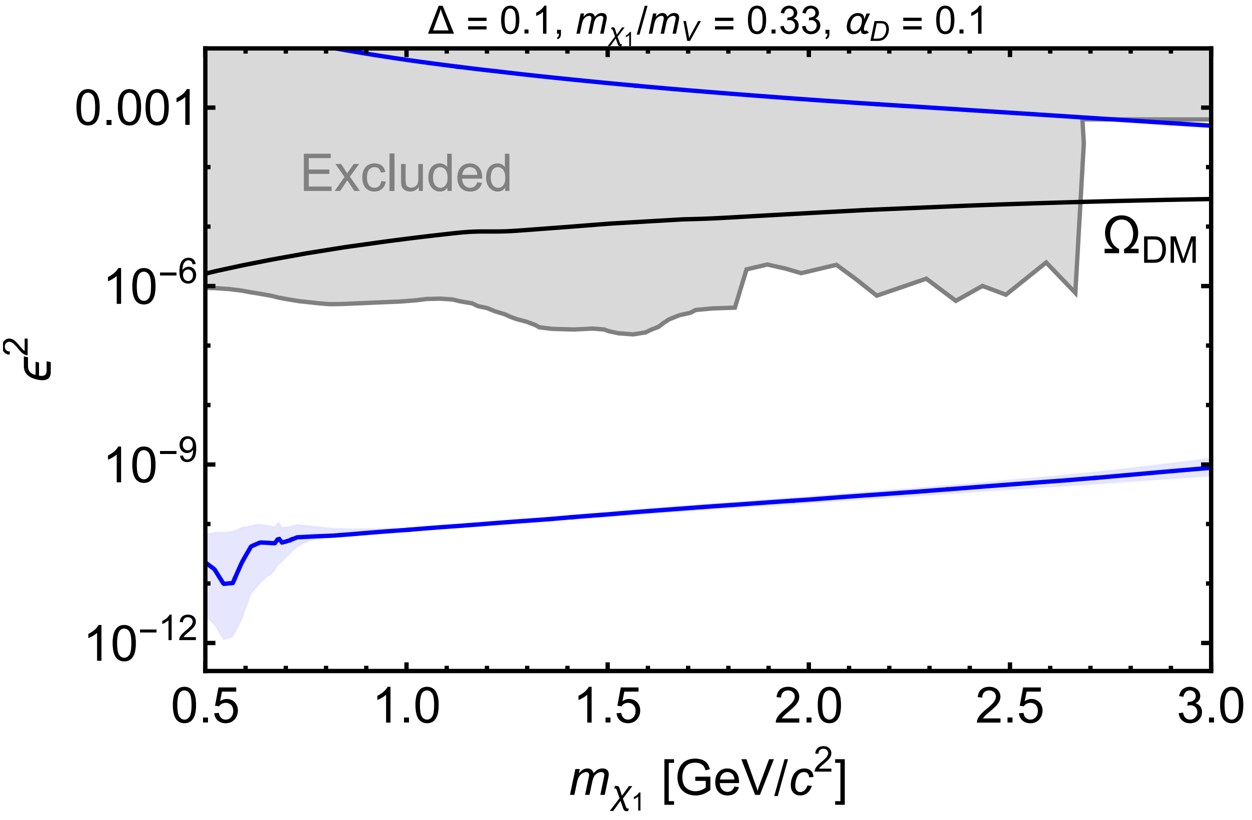


Gluon coupling

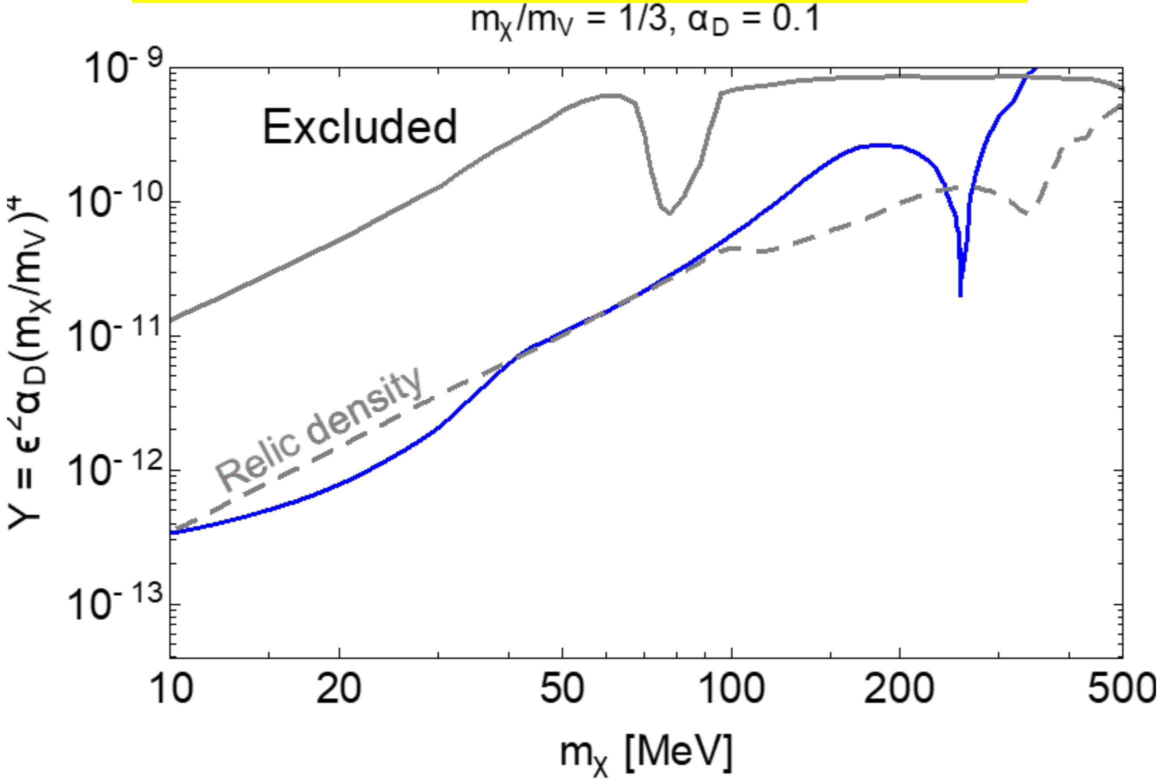


Light Dark Matter: Decaying and Scattering signatures

- Inelastic DM coupled via a mediator interacting with baryon current :
  $\chi_1 + p \rightarrow \chi_1 + X \rightarrow \chi_2 e^+e^- + X$

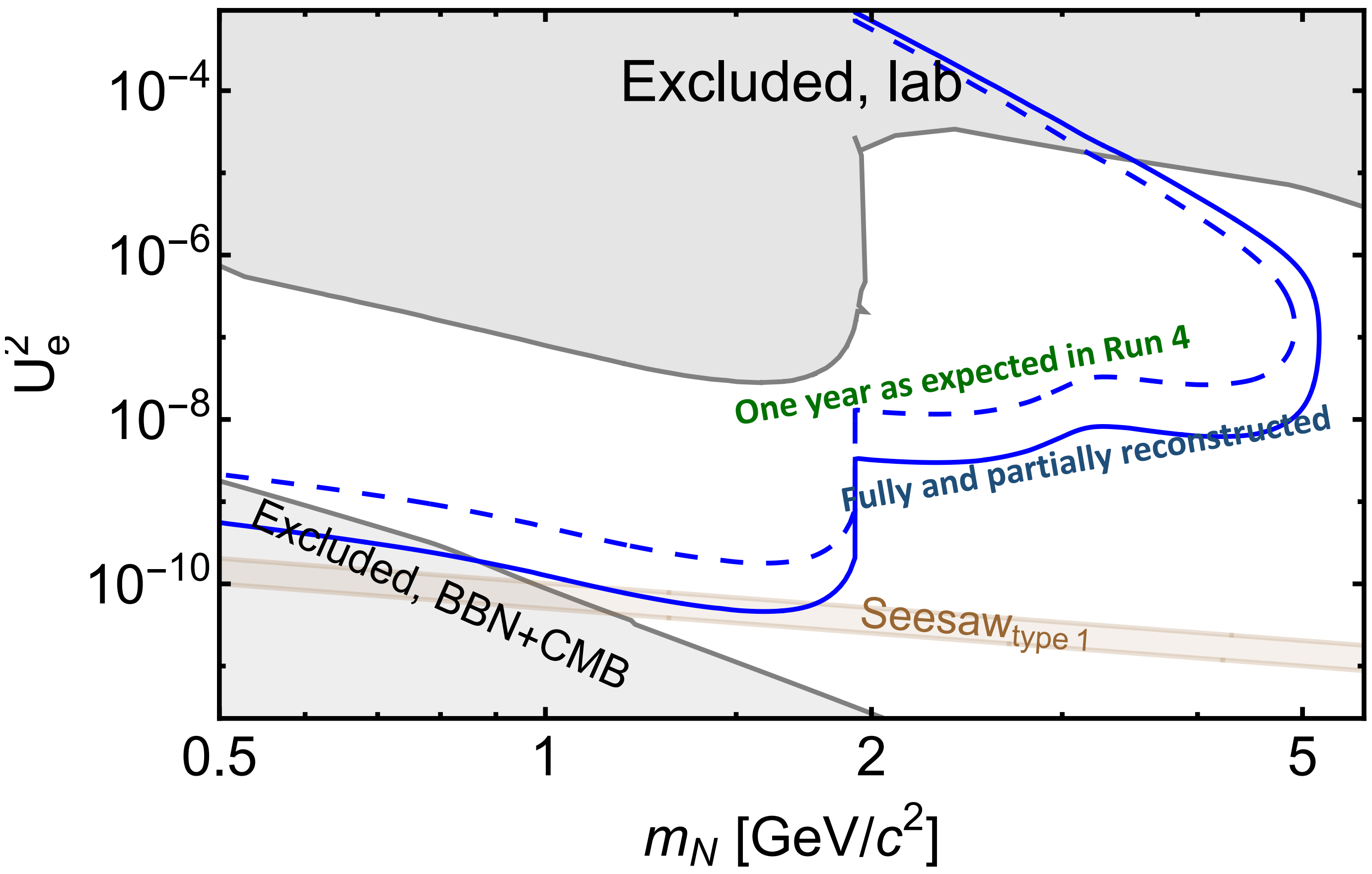


LDM scattering off atomic electrons (and nuclei)



- Background is dominated by neutrino elastic scattering
- Expectation from relic density within reach

Conclusion



- SHiP → Orders of magnitude improvement in FIP searches
  - Discovery would change the direction of the entire field
- Rich and "guarantied" physics of neutrino interactions
- We must see if there are FIPs before committing to a next generation accelerator
  - Could take another decade if SHiP have not started in 2031/32

Accelerator schedule	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC	Run 3		LS3					Run 4			LS4	
SPS (North Area)												