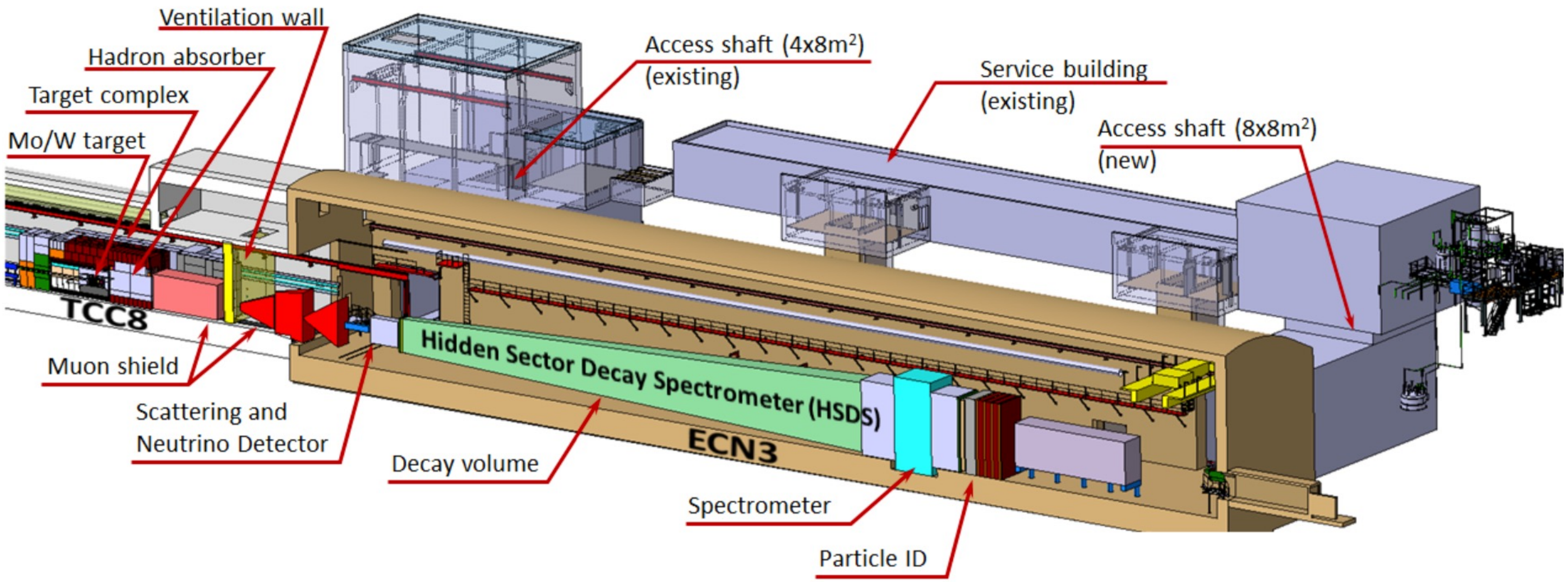
Status Report from the Search for Hidden Particles (SHiP) experiment



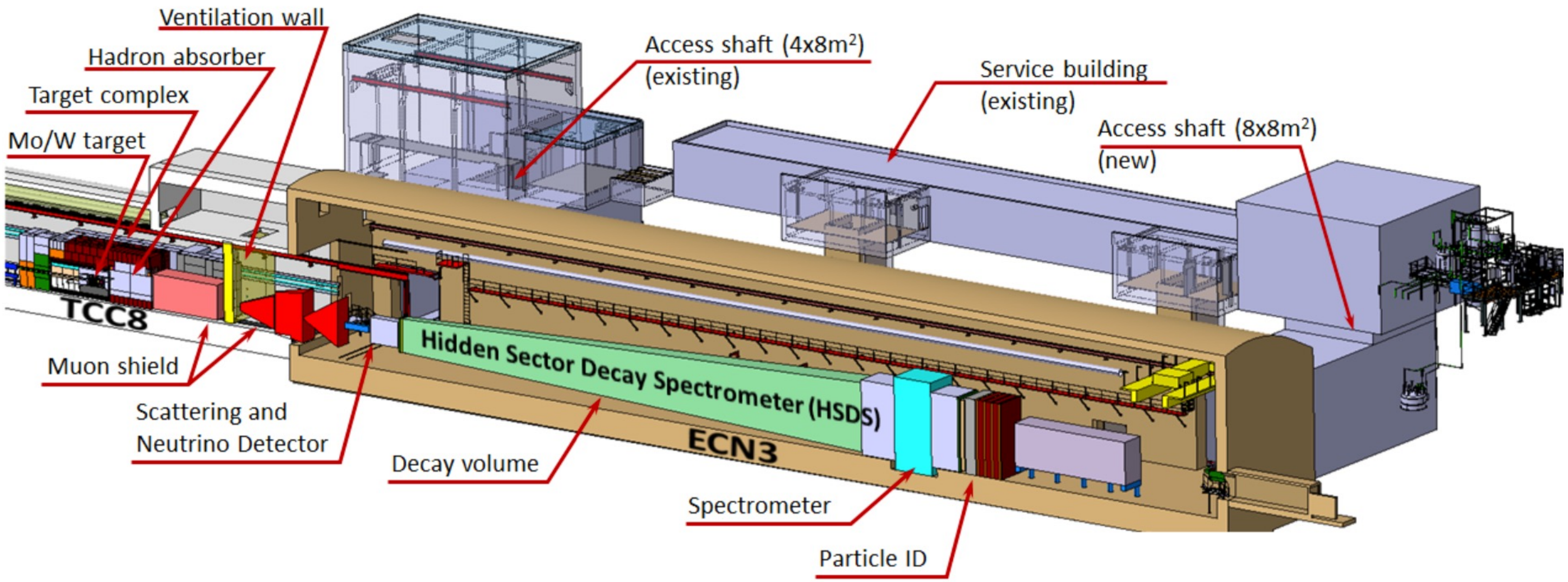
Mitesh Patel (Imperial College London)

SPSC Meeting Nov 2024

Imperial College London

SHiP
Search for Hidden Particles

Reminder of the experimental concept/aims



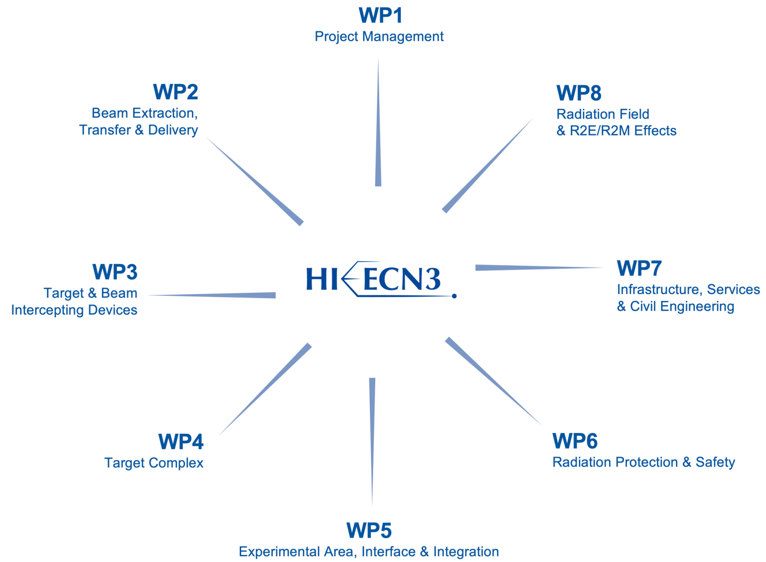
Outline

- News from the beam dump facility

- Presentation of SHiP collaboration's progress since our last meeting with SPSC in Sept 2024 :
  - plans to replace the SHiP vacuum vessel with a helium-filled gas bag
  - development of the muon shield
  - plans to integrate the neutrino detector within the muon shield
  - optimisation of the spectrometer
  - expansion of the collaboration
  - test beam requests

- Collaboration will provide a (detailed) annual report in Sept 2025

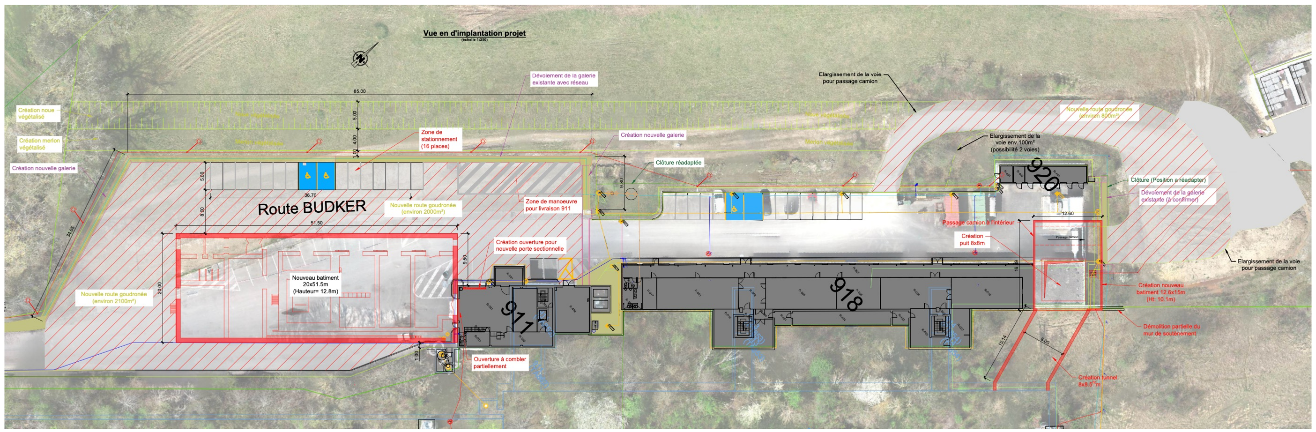
HI-ECN3 project news



TDR phase moving fast and team almost complete:

- Team ~ 20 graduates/fellows supporting 8 work packages
- Priority is on finalising scope and envelope of the civil engineering for IRP Design Study Authorisation Q3-2025 to allow the long procurement process to start
- NA-CONS concept agreed for T4 target bypass in TCC2 for installation in LS3: detailed design work now ongoing
- LS3 shift: BDF commissioning now from 2031
- Facility TDR to be published Q2-2026

- **New service building:** B754 / BB85
- **New access shaft (PA855), connecting tunnel to ECN3 and access building:** B758 / BA85
- **Underground excavations**: in TCC8 / ECN3



HI-ECN3 project news (ii)

Target R&D to investigate a He-cooled pure W target option:

- Optimised physics performance and improved operation and maintenance (vs. water-cooled option)
- Prototype target tests planned during SPS Machine Development time on T6 (existing test skid) foreseen in 2025 and 2026: **requesting MD time 3x 10h in both 2025 and 2026**, aiming to install a new He cooling skid during the short YETS25/26

Shielding Recovery from PS Neutrino Facility (end of TT7 tunnel)

- Excavations to start next year to recover ~ 3 MCHF of iron shielding blocks for use at BDF and across CERN

Proton sharing across CERN's facilities during the BDF/SHiP era is underway by IEFC (pSAC)

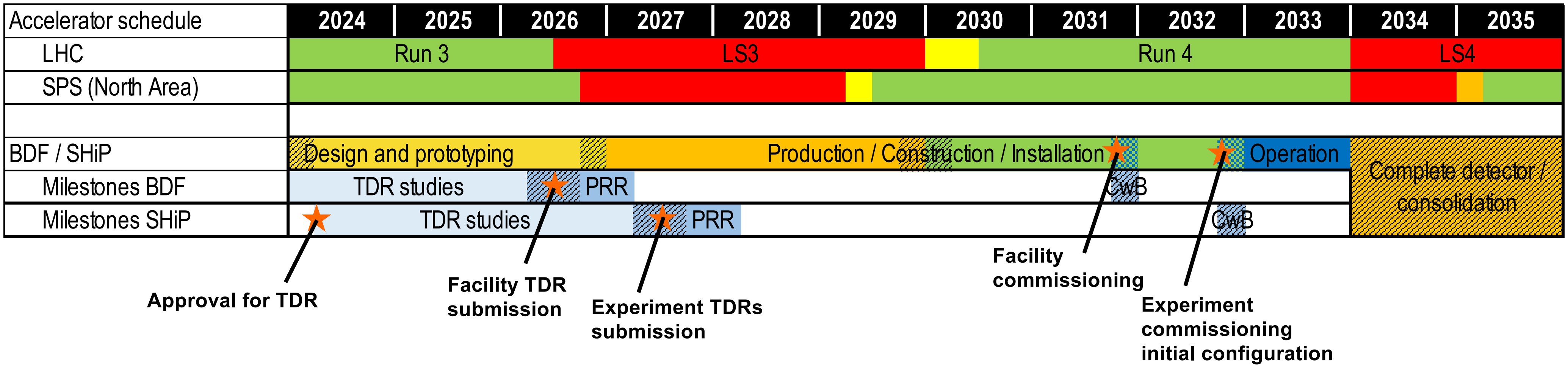
- Different ideas investigated to supply CERN's wide-array of future users with protons whilst giving SHiP $\geq 4\times10^{19}$ POT/year: strong interest to push the BDF/SHiP spill intensity by 25% to ~ 5×10^{13} ppp

Fire-Induced Radiological Integrated Assessment of TCC8/ECN3 launched in September

- HSE are supporting us to assess risks associated to fire and incorporate mitigation measures into our facility TDR (and for the SHiP experiment from January 2025)

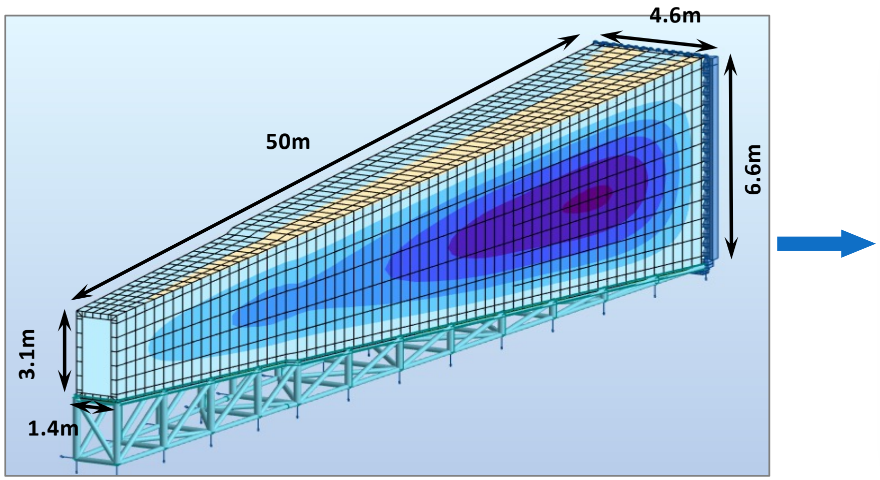
Impact of LS4 shift on SHiP's schedule

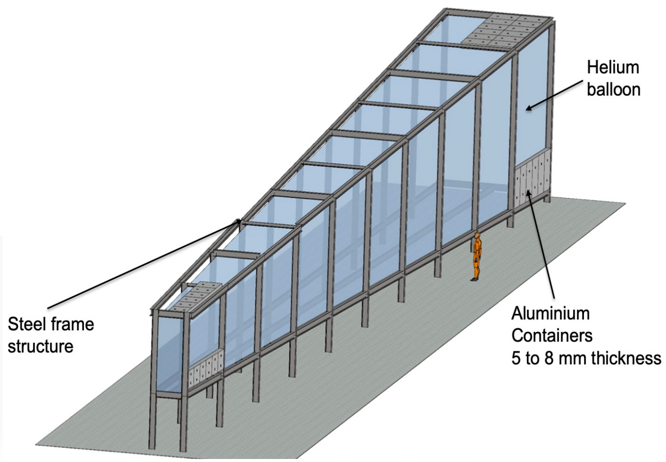
- Aim to commission and operate BDF and experiment before LS4
  - Then have LS4 to complete detector or make any consolidation required
- Confirmation of delayed LS4 → SHiP now targeting taking commissioning data 2033
  - (Expt) TDRs – have ~3 years to submit ~2027
  - Construction needs to start 2029 – compressed schedule, funding impl.



Replacing the vacuum vessel with a He-filled gas bag

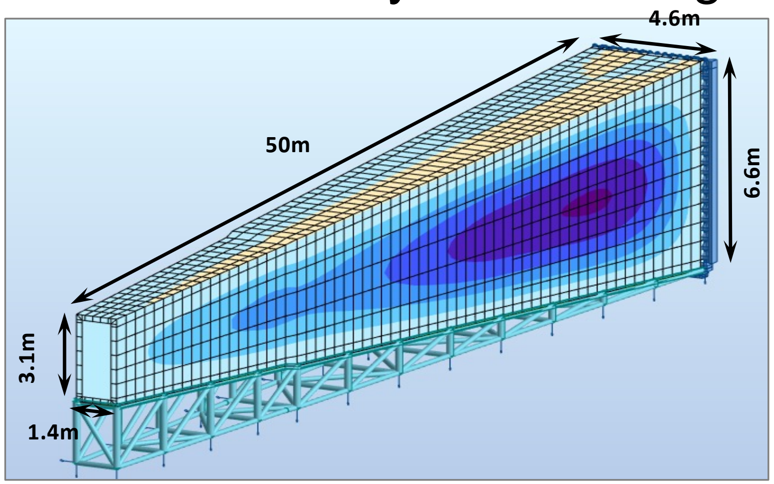
- Per spill of 4×10^{13} protons: 1.5×10^{12} $\nu/\bar{\nu}$ through fiducial vol.
  - Suppress to <10 interactions in ~550 m^3 decay volume (~700 m^2 membrane)
  - Reject interactions in decay volume structure by surrounding scintillator veto system

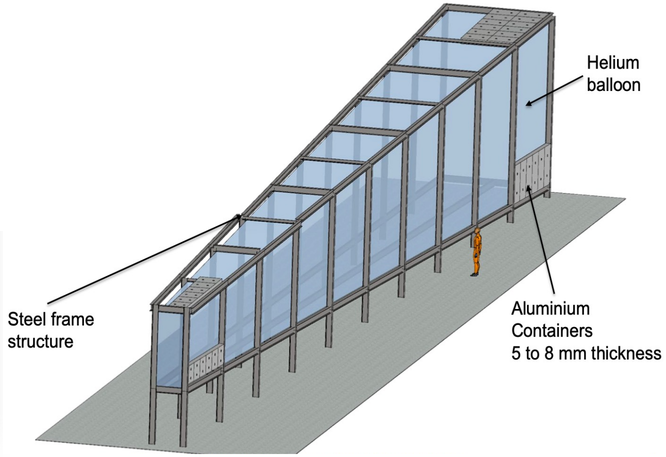




Replacing the vacuum vessel with a He-filled gas bag

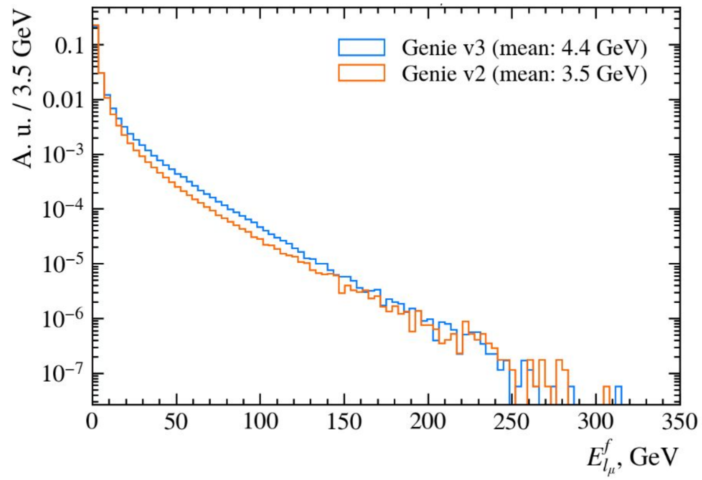
- Helium at 1atm sufficient instead of vacuum at 1mbar
- Steel vacuum vessel replaced by gas bag held in place by Al frame
  - Reduces material/cost, easier to construct, greater flexibility in the shape (…)
  - Need large-volume helium circulation and purification system
  - Study how to integrate suitable veto system

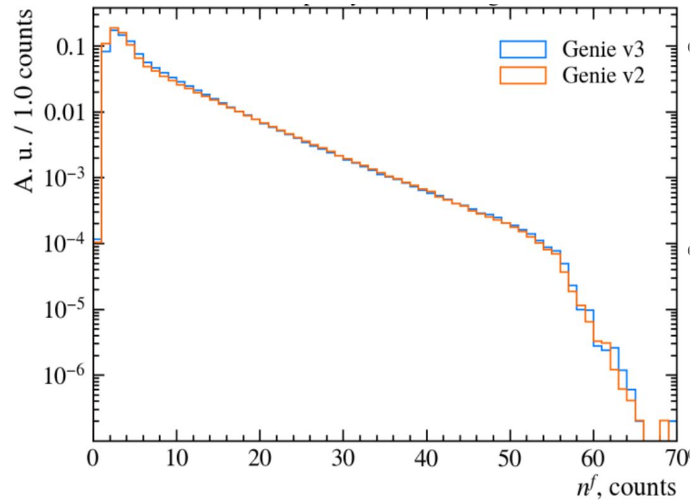




Replacing the vacuum vessel with a He-filled gas bag

- Background estimated from a simulation sample with neutrinos forced to interact in the Helium – can then generate a very large equivalent sample
  - Genie used to generate neutrino interactions with material
  - Now with Genie v3, final state lepton energy spectrum similar but small shift to higher energies
  - Final state hadron multiplicity unchanged



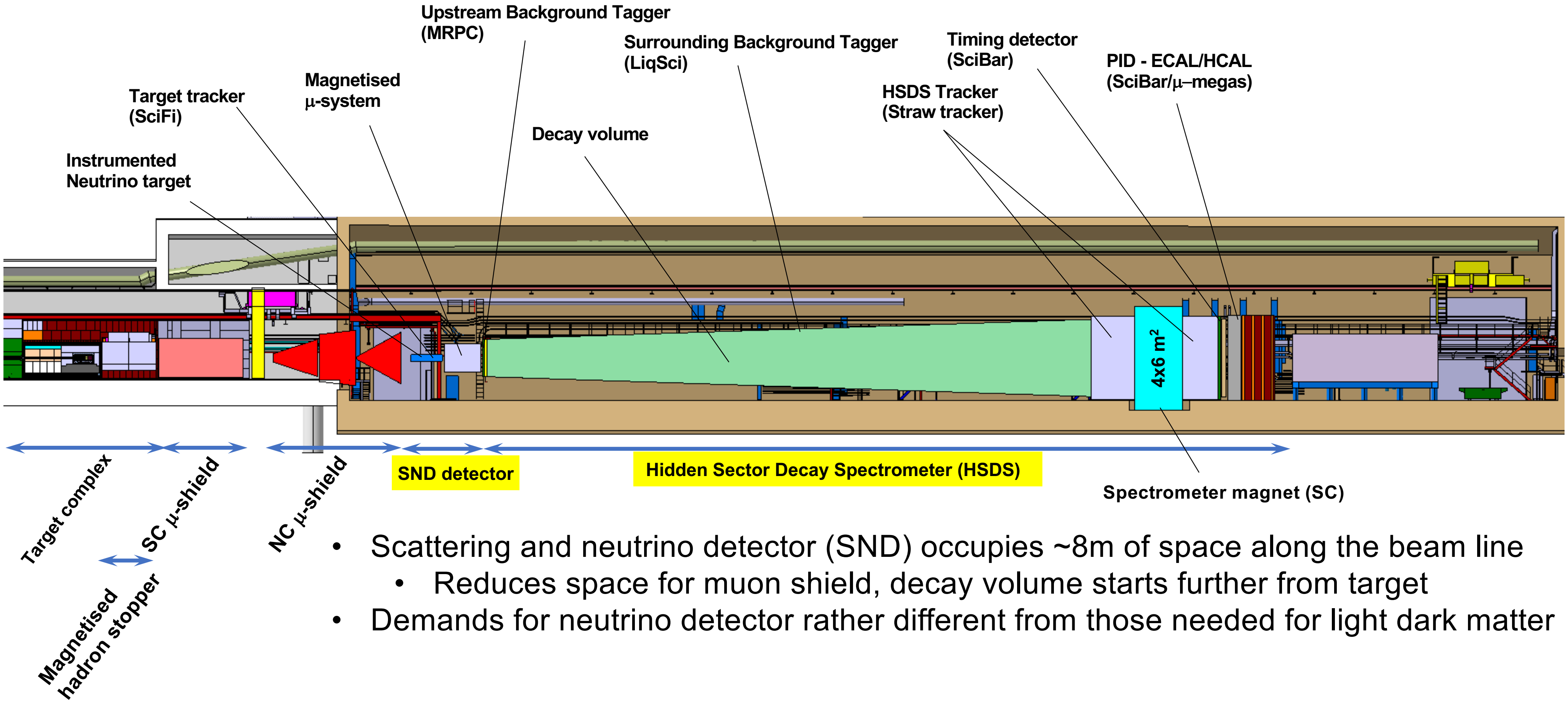


Replacing the vacuum vessel with a He-filled gas bag

- For *discovery* of any new hidden sector particle, fully-reconstructed final states are the most powerful
  - With He still expect zero background for such final states
- To *set the best limits* will also use partially-reconstructed states
  - With He find expect a few residual background events – non-trivial selection requirements under study to reduce these

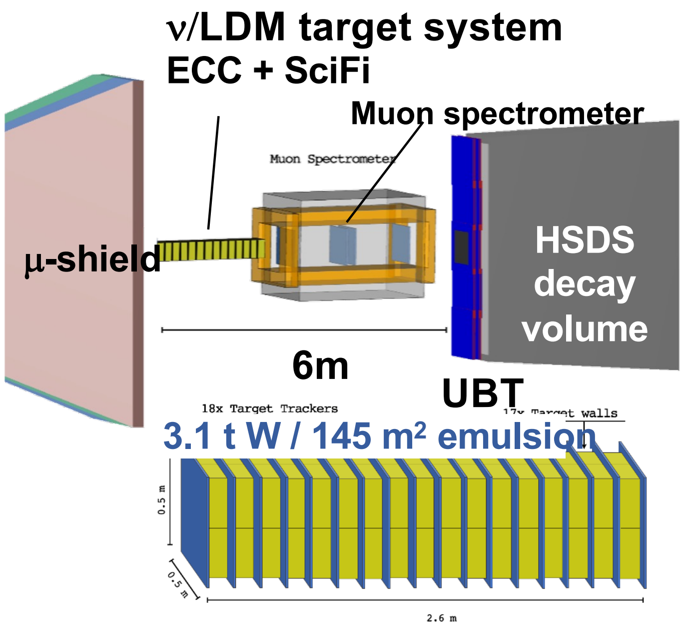
Final state	Selection	Vacuum	Helium
Fully reconstructed final state	Basic Selection	0.11	0.56
	Basic Selection+SBT	0.07	0.35
Partially reconstructed final state	Basic Selection	0.32	2.97
	Basic Selection+SBT	0.01	0.72

Integrating the neutrino detector within the muon shield

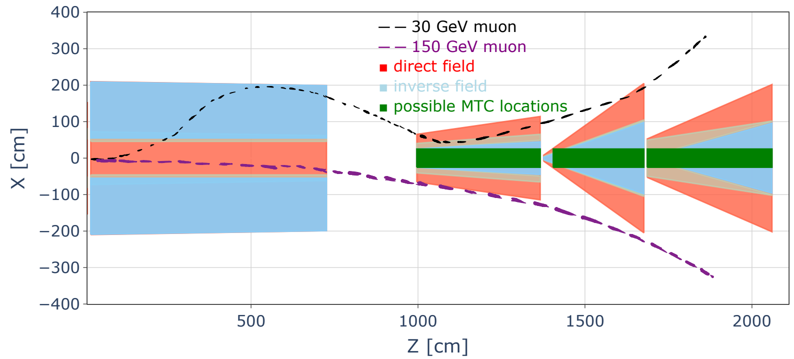


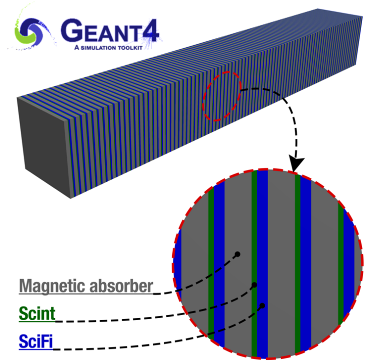
- Scattering and neutrino detector (SND) occupies ~8m of space along the beam line
  - Reduces space for muon shield, decay volume starts further from target
- Demands for neutrino detector rather different from those needed for light dark matter

Integrating the neutrino detector within the muon shield



Replace emulsion films with electronic detectors



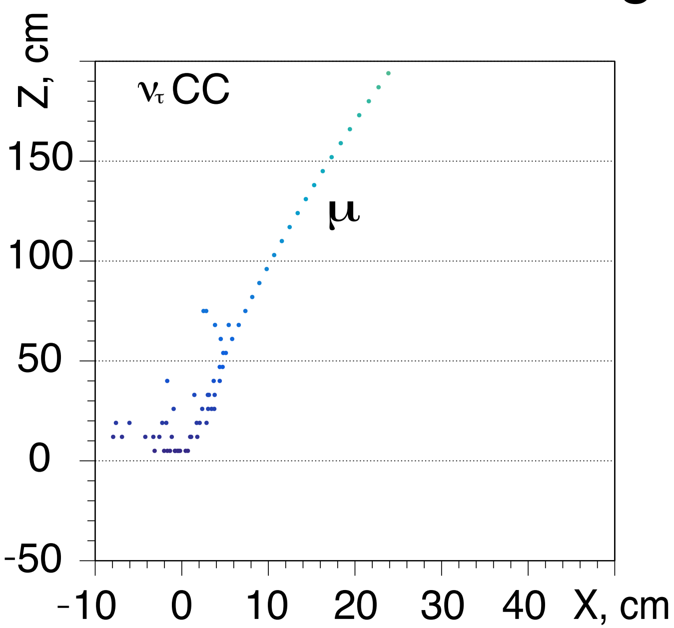


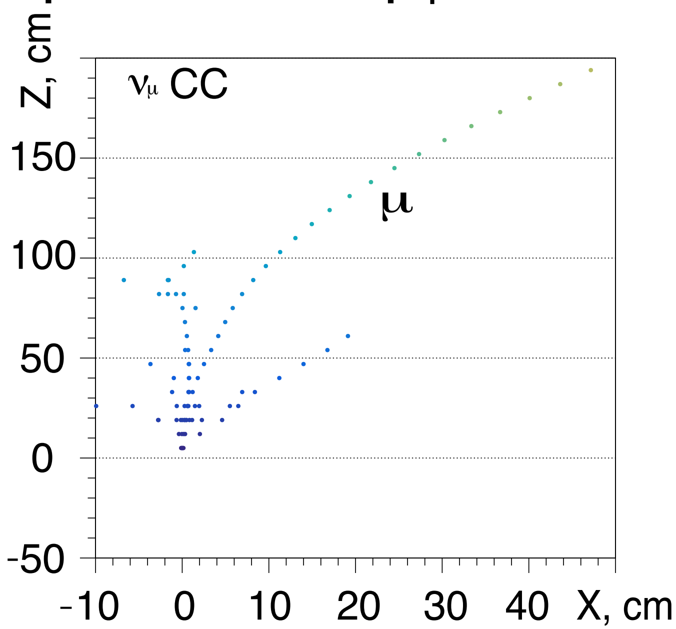
- Neutrino W-target instrumented with layers of emulsion films, allowing topological analysis
- Dedicated muon spectrometer measures charge and momentum (10% accuracy in 1T field)

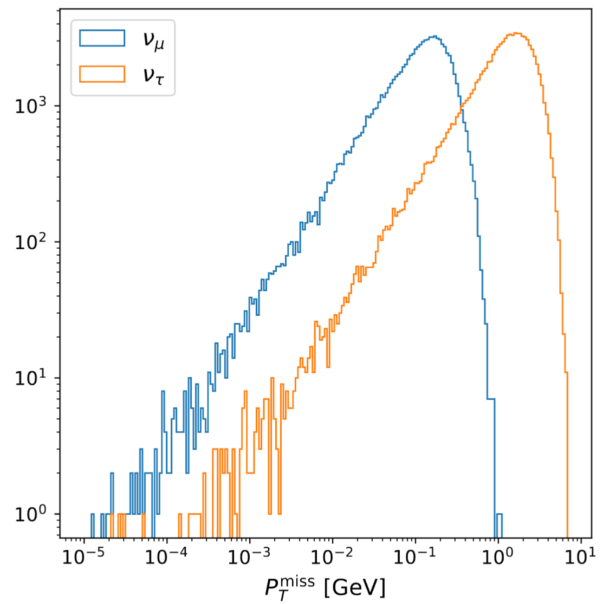
- Use iron absorber within muon shield, where there is already a magnetic field (and in region no muons left)
- Reconstruction strategy based on the missing-energy carried away by neutrinos from tau decays and the impact parameter of the leptons produced

Integrating the neutrino detector within the muon shield

- Can identify tau neutrino interactions without using vertex reconstruction e.g. lepton IP and p_T^{miss}



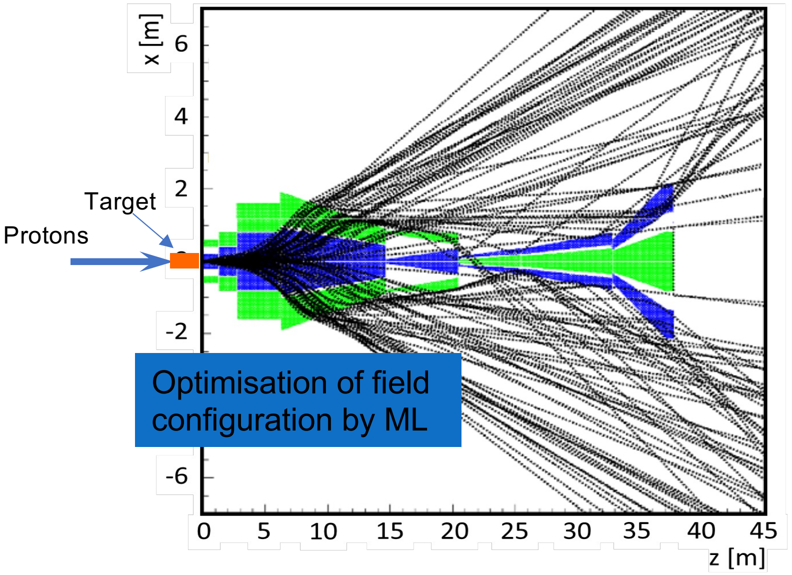


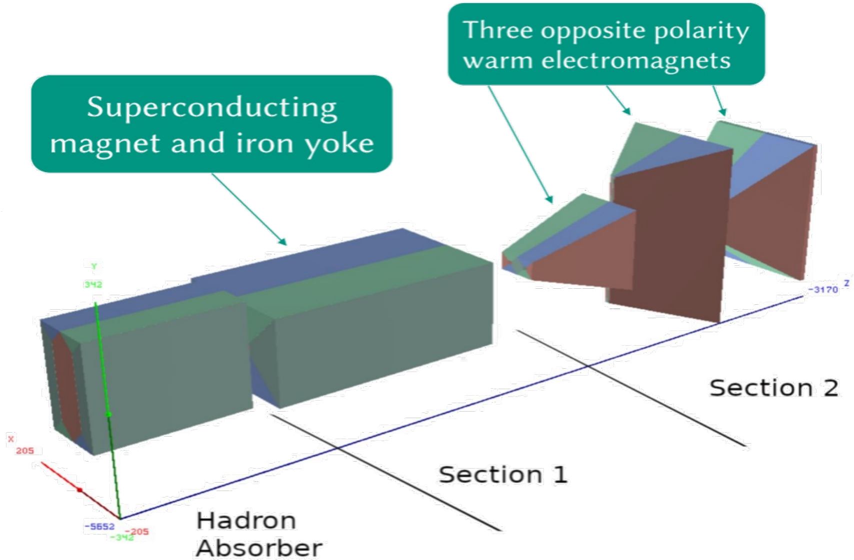


- Note expect ν_τ measurements systematically limited – flux from cascade production

Development of the muon shield

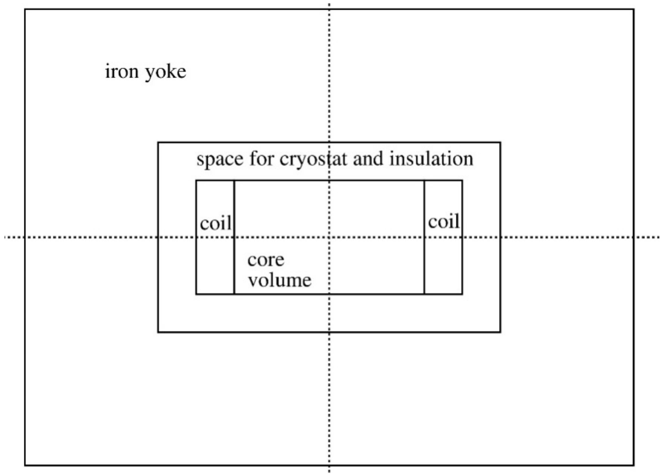
- Every spill of $4x10^{13}$ protons → 10^{10} muons
- Sweep out of the active volume of the experiment with a system of magnets: “muon shield”
- Fully warm magnet configuration developed for CDS - now exploring (shorter) hybrid configuration with SC magnet in first section

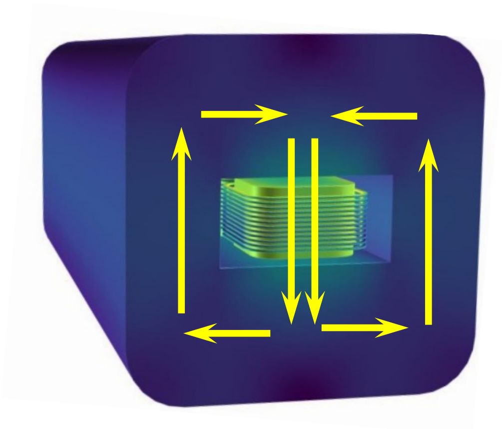




Development of the muon shield – HTS

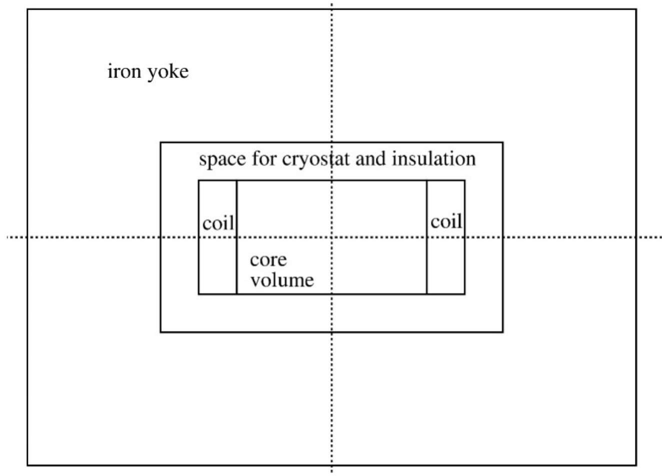
- Aim for 5T HTS magnet along first ~7m (field homogeneity non-critical)
- Core cross section: ~1m×0.5m, may be filled with iron
- Gap space: 0.2m surround for cryostat and insulation
- Surround iron yoke thickness: 0.7m–1.2m

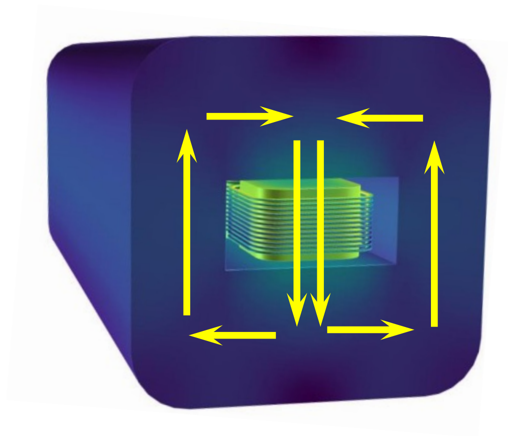




Development of the muon shield – HTS

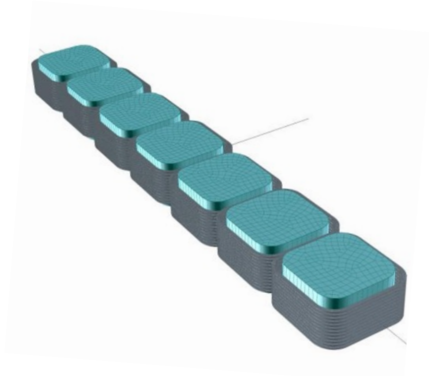
- Single-wound ReBCO tape
  - Width: 12 mm
  - Total thickness: 0.1 mm
- No-insulation winding technique
- Epoxy impregnated
- Operating temperature of 30 K
- Closed-cycle neon-refrigeration system
- Cooling tubes run throughout the magnet system

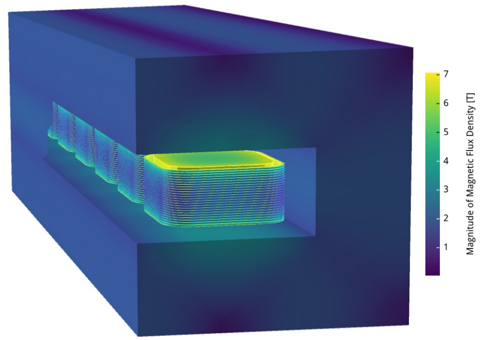


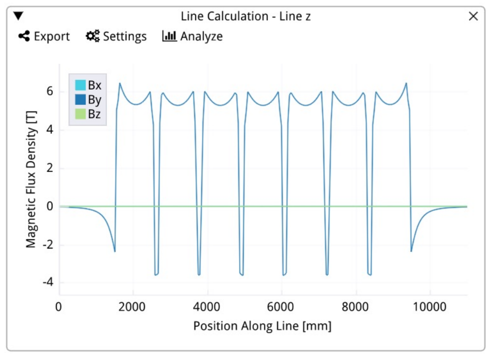


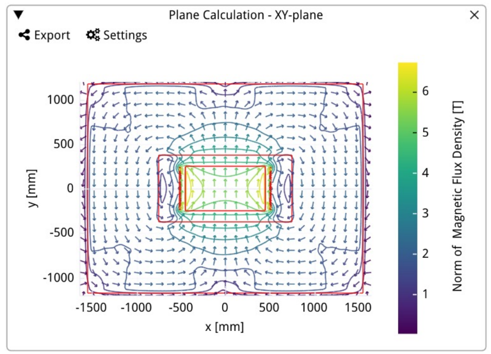
Development of the muon shield – HTS

- Propose an array of square coils with inner and outer iron yoke
  - Coil inner dimensions: 1m x 1m
  - Radial coil thickness: 20 mm
  - Winding turns per pancake coil: 200
    Coil bending radius: 200 mm
  - Operating current: ~650 A
  - Total tape length: ~125 km
  - Magnetic energy: 68.6 MJ
  - Estimated mass ~450 tonnes
- Programme of feasibility defined, initially focussing on winding process and coil characterisation



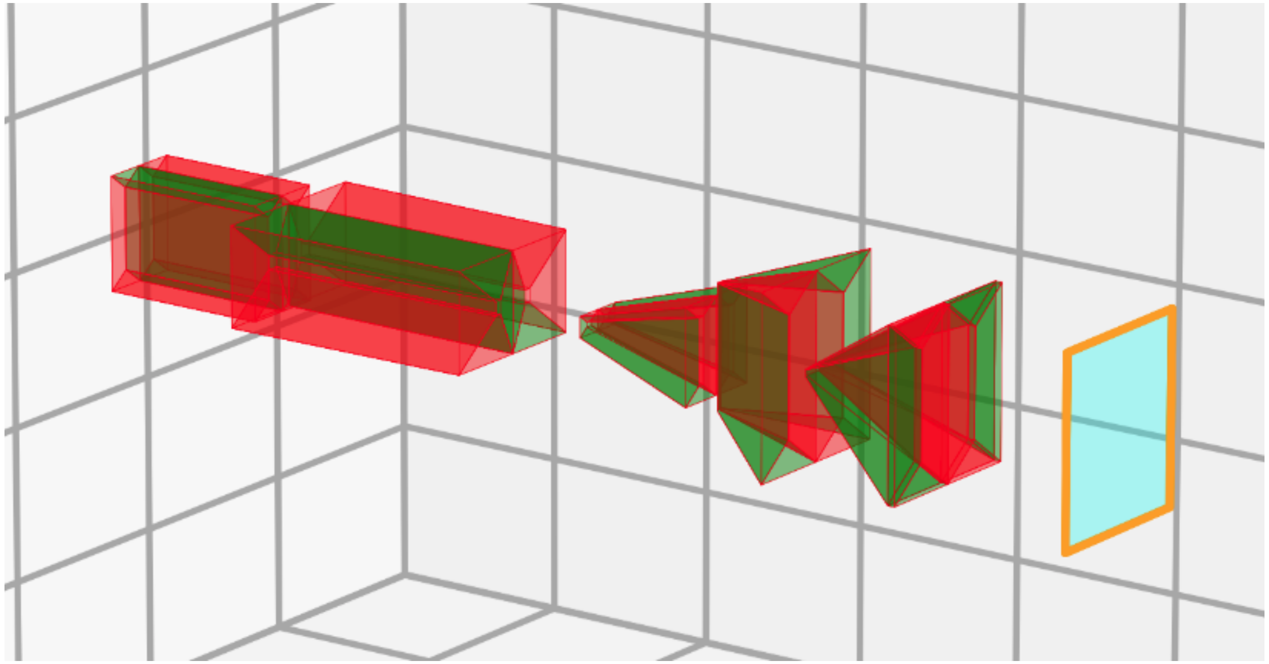


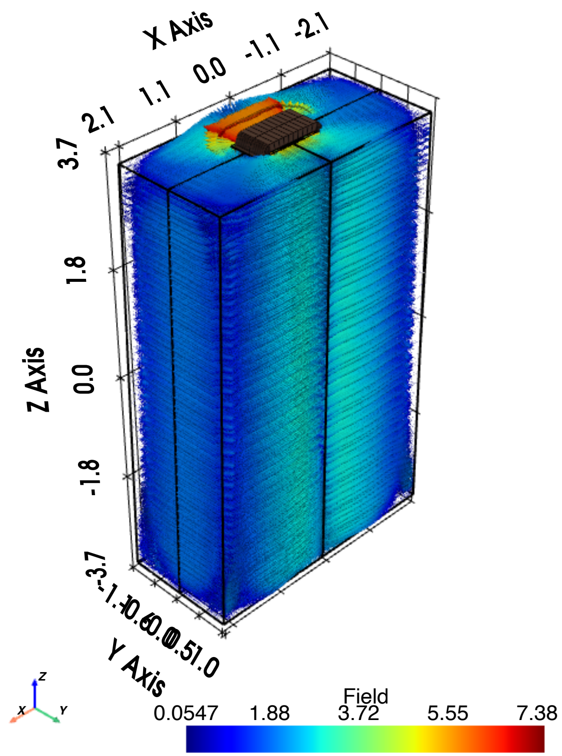




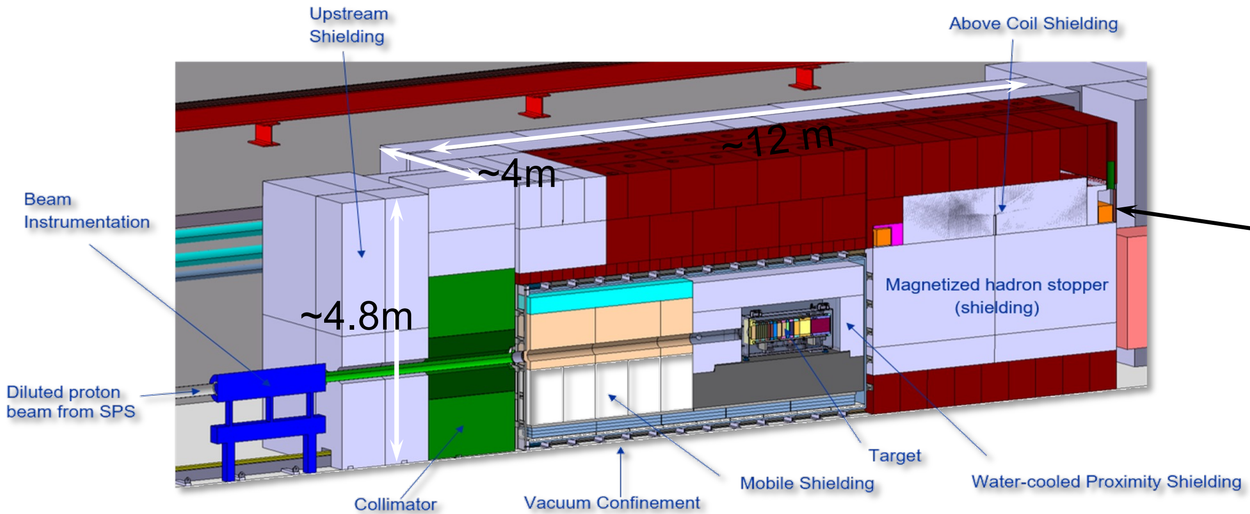
Development of the muon shield – warm

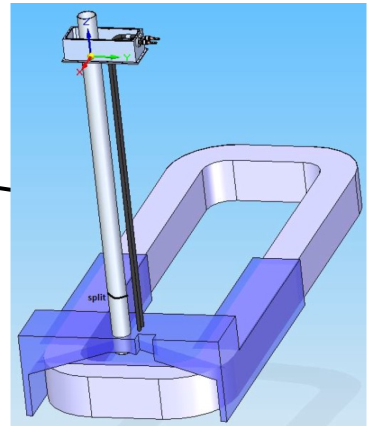
- Studying non-uniformity with Roxie – idea to integrate more sophisticated understanding of field into machine-learning optimisation of field configuration



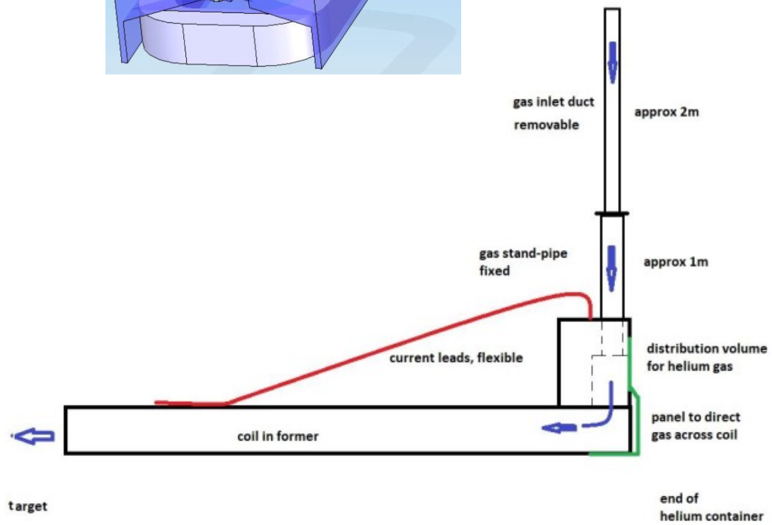


Magnetisation of the hadron stopper





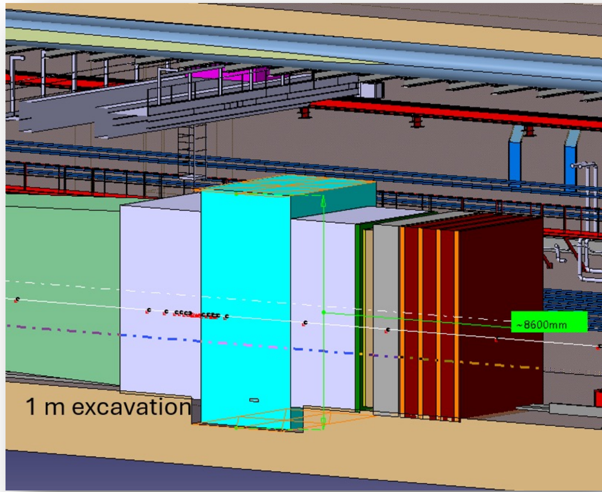
- Reoptimise magnetisation of absorber
- For CDS: single, gas cooled, coil provide 1.5T along the 5m length
- Challenge: providing services/handing in region with 200kGy/yr – careful integration with target complex required

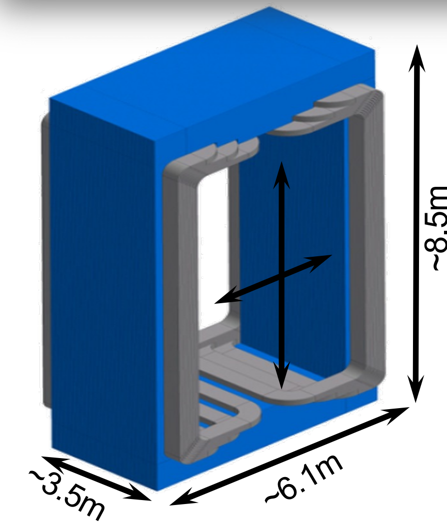


Optimisation of the spectrometer

- Spectrometer magnet requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field ~0.6-0.8 Tm , nominal on axis ~0.15T
  - Integrated field more important than field uniformity (~5-10%)
  - Field mapping in-situ important

- Initial conceptual studies
  - CERN-SHiP-INT-2019-008 → Resistive version ~1 MW
  - EDMS 2440157 → Exploratory study of NbTi / Nb_3Sn / MgB_2 / ReBCO

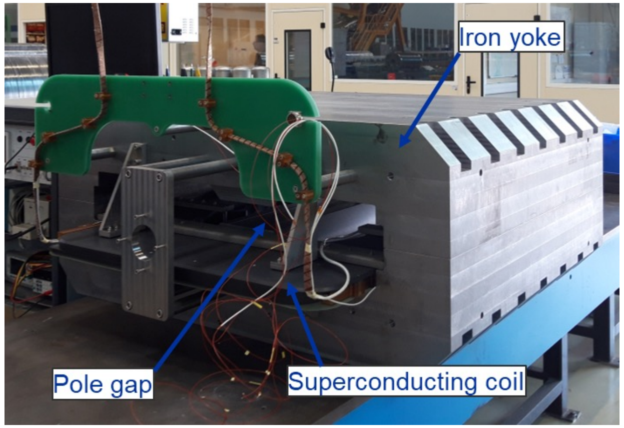




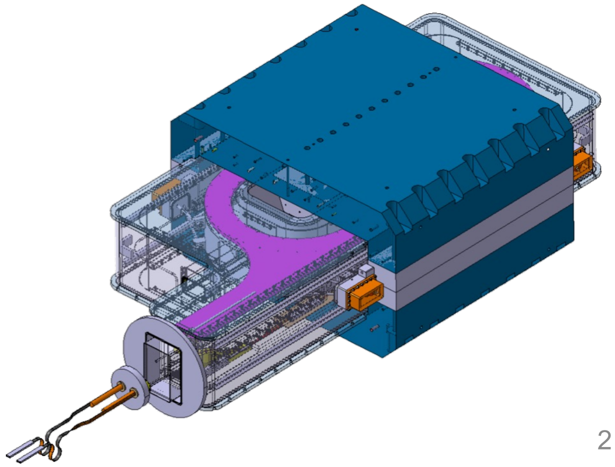
Optimisation of the spectrometer

- Proposal from TE-MSC
  - Design with MgB_2 sub-cables, operate with gaseous helium at 20K with cryocoolers
- Under investigation with demonstrator
  - Prototype phase 1 (lHe@4.5K) and 2 (gHe@20-30K) : thermal cycling, no training, no performance change after quench test
  - Phase 3 (preparation ongoing): Test with warm yoke and coil at 20 K integrated in a dedicated cryostat with indirect cooling
- Next steps: optimisation of cooling configuration and current leads, and study of final coil configuration and support

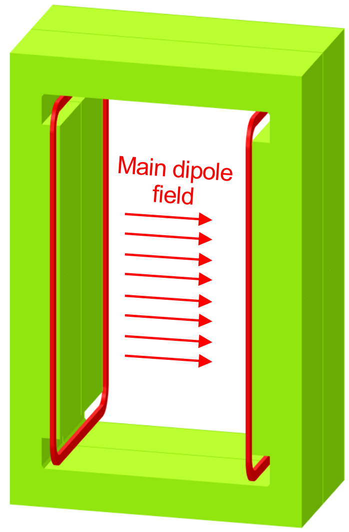
Prototype for phase 1 and 2 (2023-24)



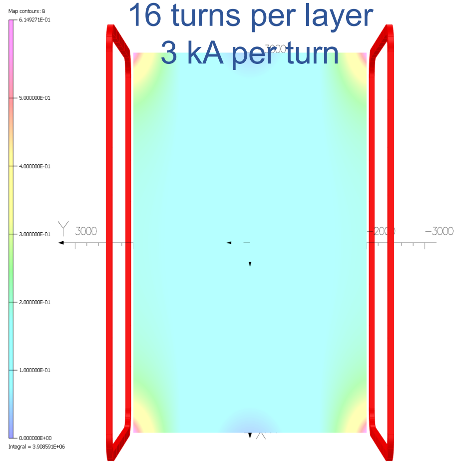
Prototype for phase 3 (2025)



Optimisation of the spectrometer



- Conceptual design study of full-scale magnet also in progress
  - H-type iron yoke
  - 2 symmetric coils
  - Double-pancake, racetrack-type coils = flat coils
  - Pole gap: 6000 x 4000 mm
  - Target central field: 0.15 T at 3 kA and 20 K
- First field map provided and implemented in SHiP simulation
  - Evaluate field parameters and detector performance in new set-up with decay volume under helium and spectrometer in air



Int *B.dl* [-2.5 m; 2.5m] = 0.630 T.m
Stored energy: ~ 2.75 MJ

Expansion of the SHiP collaboration

- Institute of Nuclear Physics, Kazakhstan joined SHiP in October
- Collaboration Board will consider application for the university of Ghent, Belgium at next meeting
- Membership committee in discussion with seven groups from Austria, Italy, the Netherlands and the UK
- Preliminary discussions have been initiated with new groups in Finland, France and Sweden
- Collaboration now stands at 40 institutes from 18 countries + CERN

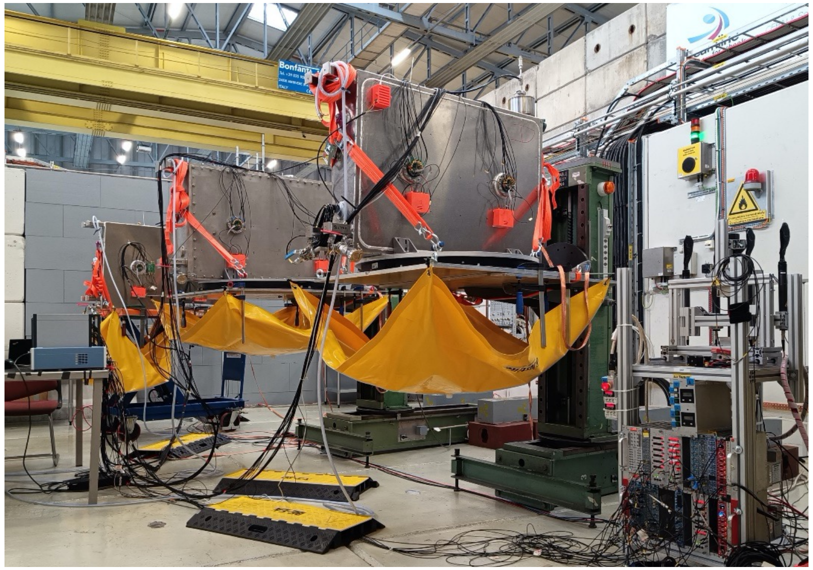
Test beam requests

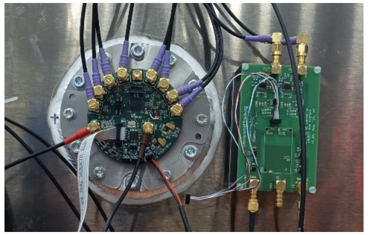
Surrounding background tagger test beam 2024

Studies of different configurations adapted to decay volume under helium

1 week @CERN PS EA T10: μ at 5GeV

- **3 identical full-size** SBT prototypes with **different inner surface reflectivity**

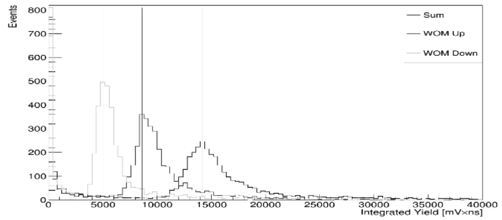


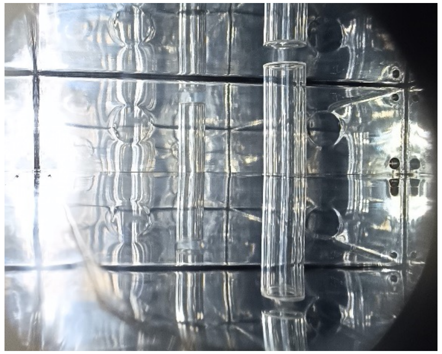


First test of new readout electronics using **SiPM sum signal**

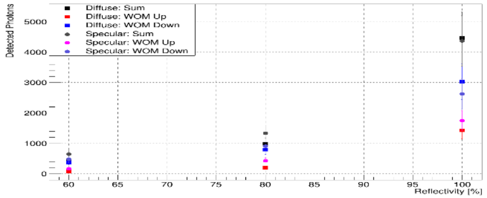
Direct comparison of **total light yield** and **WOM light sharing:**

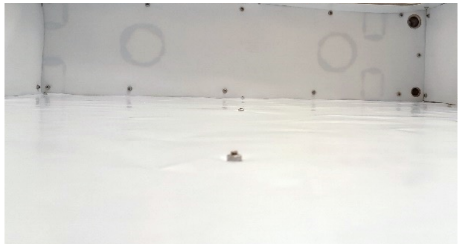
- **Polished AlMg4,5**
  ► best **light sharing**





- **CRES with PTFE liner**
  ► highest **light yield**



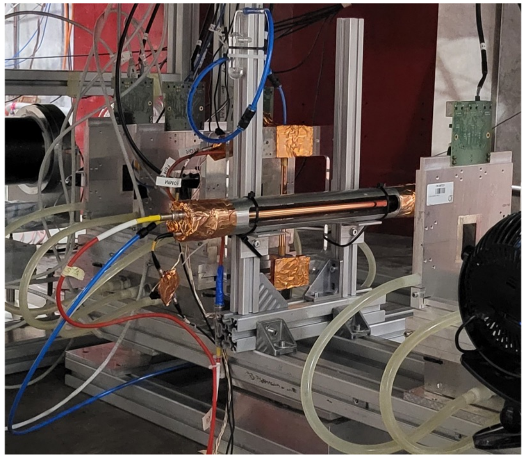


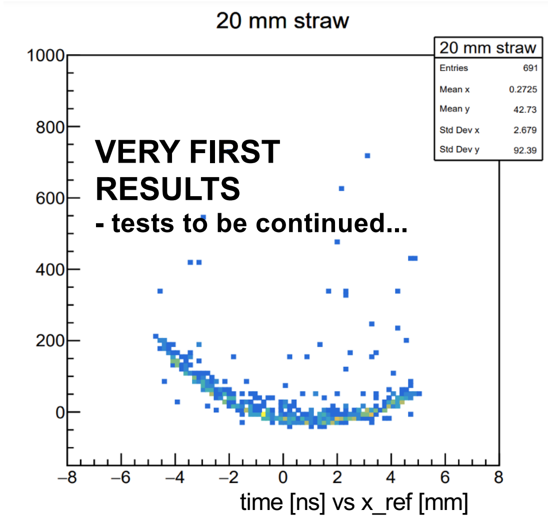
- **Raw AlMg4,5**
  ► easiest manufacture

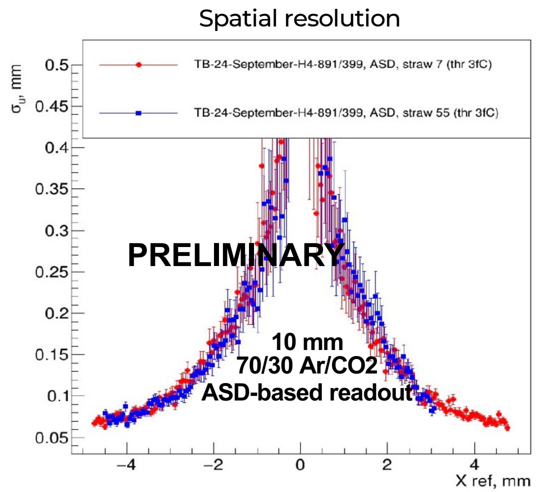
Straw tracker test beam 2024

- In context of DRD1/WP3, tests of straw-readout interface and electronics for straw tracker with small prototypes
  - ➔ Important input for SHiP straw tracker:
  - Prototypes of Ø10 mm straws with stereo-angle, combined with Ø5, 10 and 20 mm
  - Straw readout with different ASICs: VMM3a (excluded)/VMM3, Tiger (together with INFN Torino), ASD (together with Uni Michigan)

- Evaluation of SAMPIC as a potential solution for digital part of the SHiP straw tracker readout
  - Precise small acceptance setup with AZALEA telescope

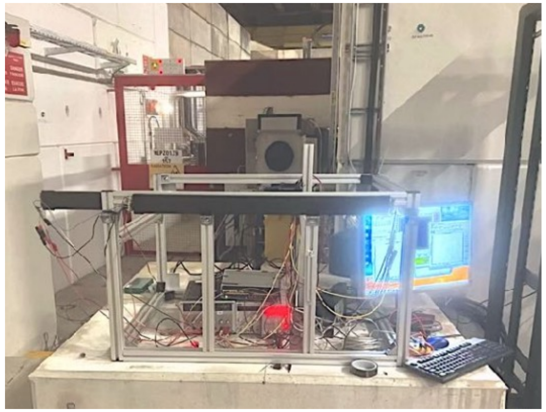




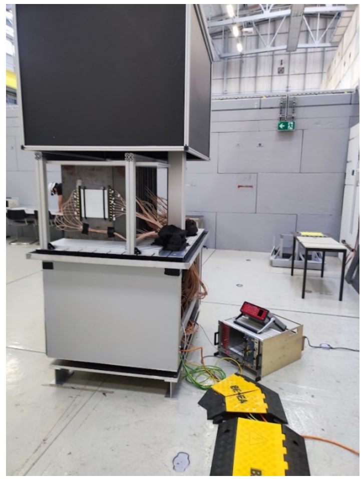


Timing and calorimeter detector test beams 2024

Timing detectors
- Test of readout baseline option eMUSIC (pre-amp.) + SAMPIC (digitisation): electronics configuration optimisation
- Study of efficiency of overlapping bars, horizontal with e- and pions@[1,3,5] GeV, to understand edge effects.
- Setup with 2xEJ-200 Scintillating bars; S14 Hamamatsu Series SiPMs and 4 eMUSIC boards



Calorimeters
- 3 Test beams in 2024: two at DESY and one at CERN PS
  - DESY (March 2024): Evaluation with calorimeter prototype with scalable readout electronics based on the KLauS and the CITIROC-1A chips
  - CERN PS and second DESY: Evaluated prototype - angular and energy resolution with O(GeV) electron beams
  - CERN PS test beam also looked at PID performance evaluation



Test beams in 2025-2026

Surround Background Tagger

- Spring 2025:
  - Repeat test beam measurement from Oct 2024 (Aging)
  - Study steel cell with highly-reflective aluminium foil (99% specular reflector)
  - Study first version of new readout concept with high/low sum signal
- Autumn 2025:
  - Test refined WOM mechanics, WOMs glued to SiPM array
  - First step towards the final readout concept
- Early Autumn 2026: test multi-cell box
  - Complete WOM-PMMA vessel system
  - Prototype for the readout concept
- Combined with tests of plastic scintillator concept
  - Experience from timing detector

Straw Tracker

- 2025 (SPS):
  - Small stereo-prototype of Ø20 mm straws
  - First large prototype of 32 full-length (4 m) straws
  - Studies with the small stereo-prototype of Ø20 mm straws (performance, tracking, readout and HV interfaces, different readout options)
  - First tests with the full-length prototype at DESY
- 2026 (SPS)
  - Measurements with the full-length prototype, final electronics and readout
  - Efficiency and resolution measurements and evaluation of rate capabilities

Test beams in 2025-2026

Timing Detector

- Spring 2025:
  - Test the readout option for the timing detector with SiPMs placed on top of a bar
  - Test the FastIC+ readout option for the front-end (as opposed to eMUSIC + SAMPIC)
- Autumn 2025:
  - Measure the time resolution for overlapping bars for the baseline design (both vertical and horizontal overlap), and optimize the horizontal overlap distance
  - Measure the efficiency of the detector
  - Compare readout schemes (eMUSIC vs. FastIC vs. Discrete circuit board)
  - Test the timing calibration procedure
- 2026: Validate the DAQ implementation

Calorimeters

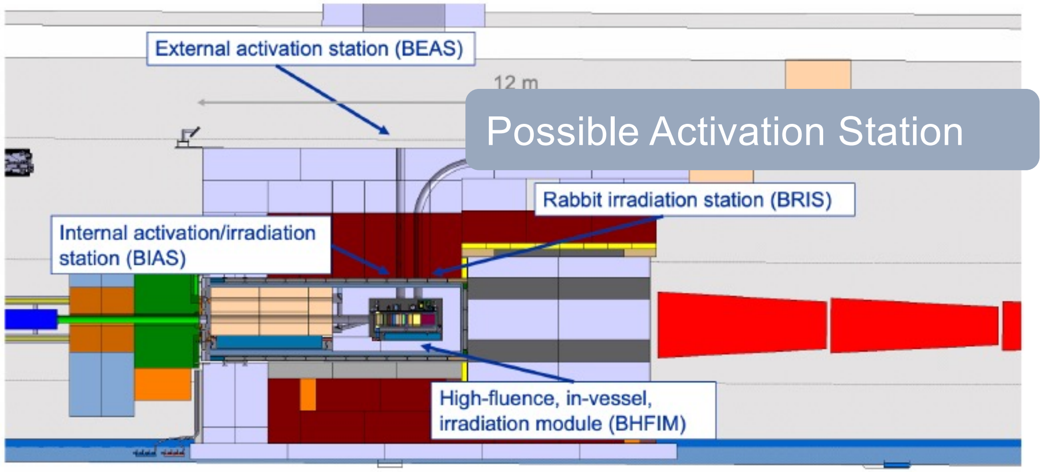
- 2025 (SPS)
  - Evaluate angular and energy resolution at SHiP using scintillator strips and maybe iRPCs/GEMs, upgrade of the existing prototype in progress
  - Test of the HCAL section prototype (up to $3\lambda_a$) to tune PID simulation
- 2026, as late as possible (SPS)
  - Evaluate technological prototype, final integration of high precision layers, electronics, readout chain and gas detector integration in the detector

Upstream Background Tagger and new configuration of SND

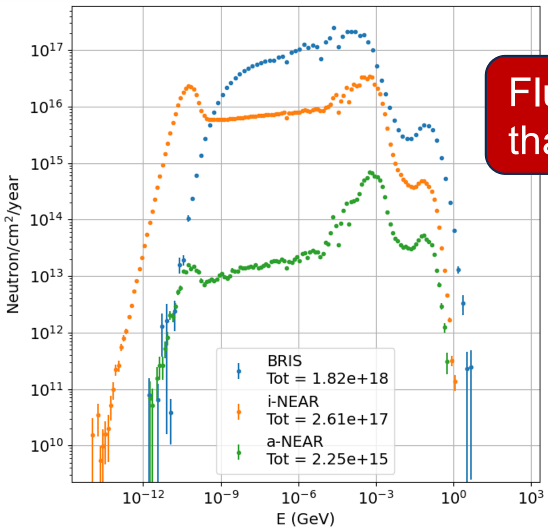
- Test beam needs still under discussion

Neutron activation station at BDF

CERN-SPSC-2024-027 / SPSC-EOI-023

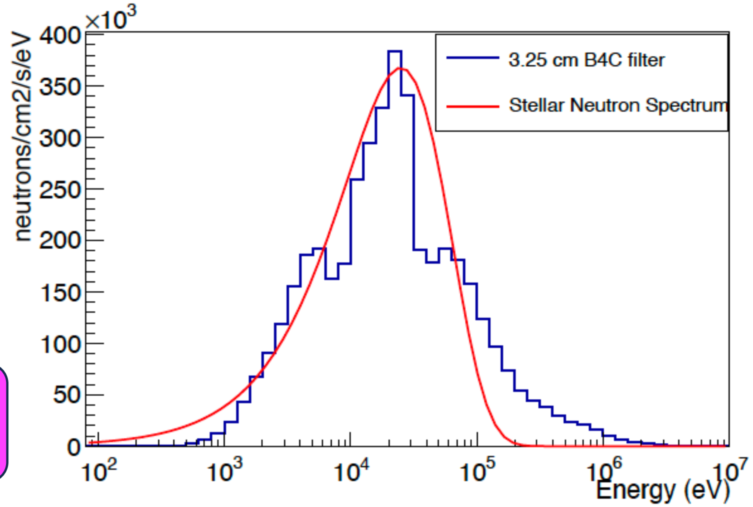


- Parasitic **neutron cross section measurements**
- **Unique** installation providing **ultra high neutron fluxes** over a wide energy range for activation measurements – complementary to n_TOF capabilities
- Proximity to ISOLDE – measurements on **radioactive** nuclei
- **World-first measurements** of key reactions for nuclear astrophysics and nuclear applications



Flux 3-4 orders of magnitudes higher than at present n_TOF NEAR

Filters create quasi-stellar neutron spectra

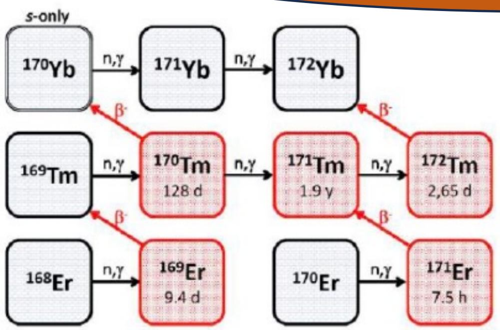


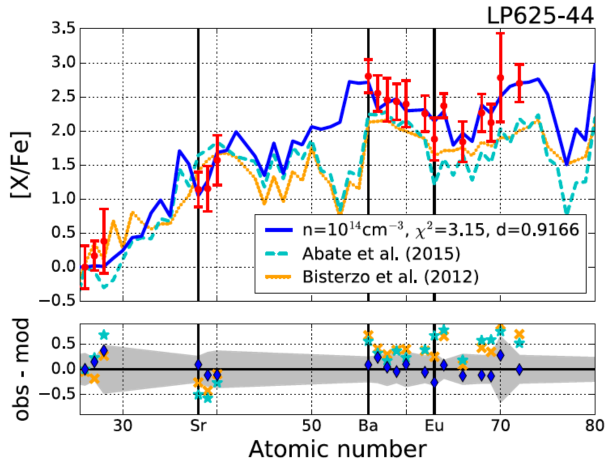
Neutron activation station at BDF

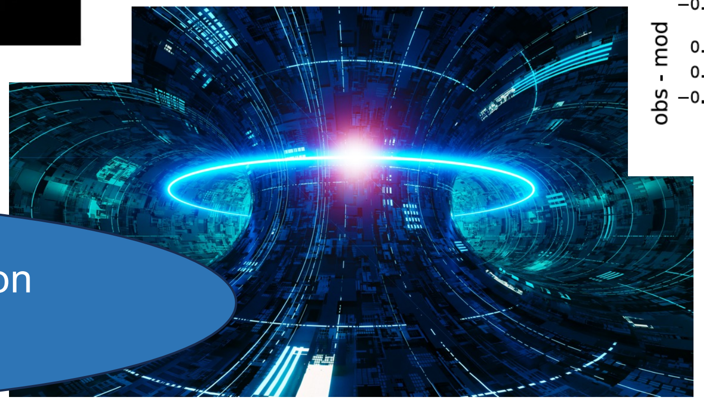
Science Examples:

Measurements to determine neutron densities and temperature in stellar interiors e.g. (n,γ) on ^{94}Nb, ^{147}Pm, ^{163}Ho and ^{171}Tm

Measurements to explain peculiar abundances in old stars e.g. (n,γ) on ^{125}Sb, ^{137}Cs, ^{144}Ce







Measurements for next generation fission and fusion reactors e.g. (n,2n) on ^{109}Ag, ^{151,153}Eu

Neutron activation station at BDF

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- Separate initiative that the SHiP collaboration support, but priorities are such that it can only be pursued if additional dedicated resources are given to the HIECN3 project

Summary

- Preparation of BDF and SHiP experiment advancing on many fronts
- The collaboration warmly thank CERN ATS and, in particular, the HIECN3 project team
- Look forward to providing SPSC with a detailed progress report in Sept 2025