SHiP experiment

- status and challenges -

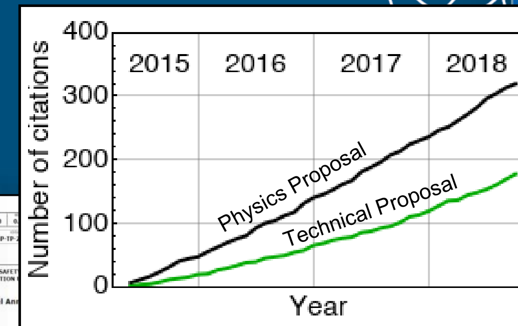
Richard Jacobsson

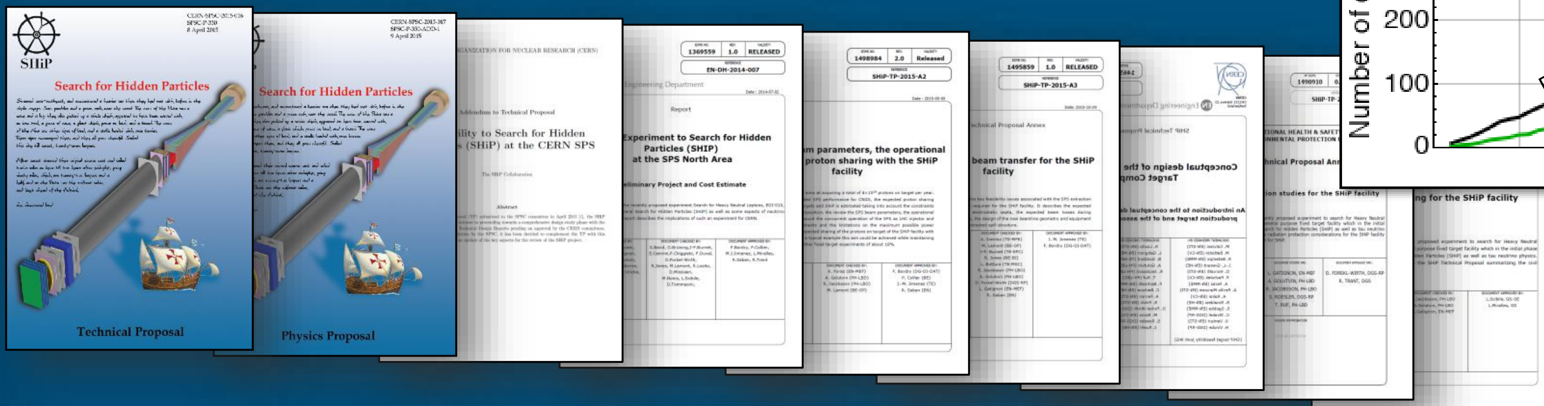
Outline

- SHiP history
- Physics motivation
- Experimental techniques
- Requirements – signals and backgrounds
- Experimental facility and detector setup
- Description of the sub-systems
- Performance
- Conclusions

SHiP history

- 2013 Oct: EOI with SHiP@SPS NA
  ...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF



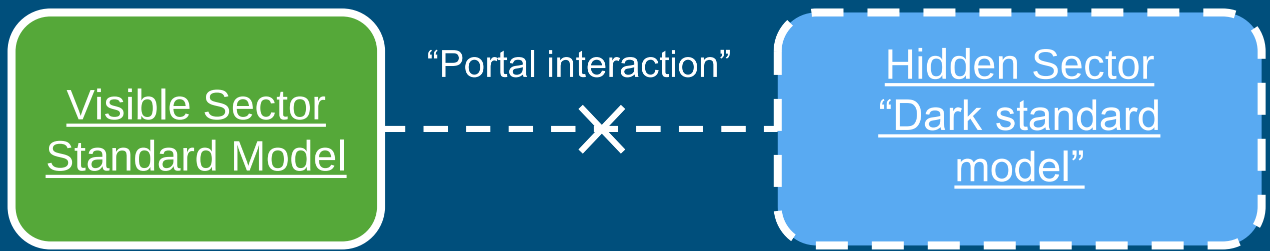


- 2014 Jan: Encouraged to produce TP and inter-departmental task force setup to study feasibility of proposed facility
- 2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments
- 2016 Jan: Recommendation by CERN SPSC to proceed to Comprehensive Design Study
- 2016 Apr: CERN management launch of Beyond Collider Physics study group
  - SHiP experimental facility included under PBC as Beam Dump Facility
- 2018: EPPSU contribution submitted by SHiP and BDF, and submission of SHiP Progress Report
- SHiP Collaboration: ***290 authors, 52 Institutes, 17 countries***

New physics prospects - Hidden Sector

- "New particles" can hide in two ways: Very massive OR very weakly coupled
  - ➔ Natural assumption: DM tells us there could be a "very weakly interacting" scale (cmp ν)
  - ➔ SM not only successful, we discovered everything it predicted, so…
    …why not dark matter self-interaction and a weak "interaction" with the visible sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



➔ Dynamics of Hidden Sector may drive dynamics of Visible Sector!

- Dark Matter (trivial!) – fermionic or scalar
- Neutrino oscillations
- Baryon asymmetry
- Higgs mass
- Dark Energy
- Inflaton
- ……

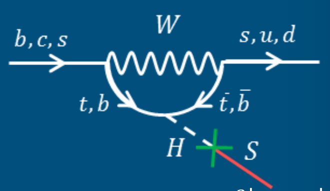
Dark versions can be considered for all (strictly neutral) SM features

Rich variety and phenomenology requires generic and complementary search!

Production and principal sources

- Dark vectors ("Dark Photons")
  - Photons – Bremsstrahlung, light neutral meson decays, quark annihilation
  - Sources: electron fixed target beams, electron colliders, proton fixed heavy target

E.g. Dark scalar



$\Gamma(K \to \pi S) \propto (m_t^2 |V_{ts}^* V_{td}|)^2$

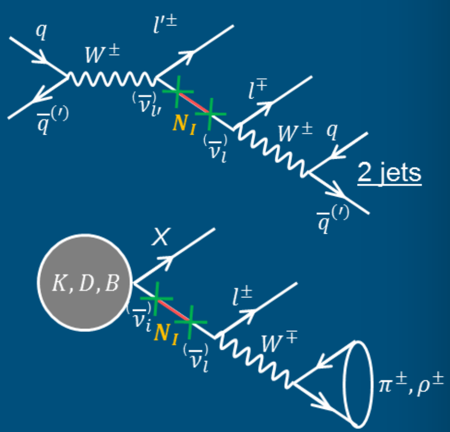
$\Gamma(D \to \pi S) \propto (m_b^2 |V_{cb}^* V_{ub}|)^2$

$\Gamma(B \to \pi S) \propto (m_t^2 |V_{tb}^* V_{ts}|)^2$

- Dark scalars ("Dark Higgses")
  - Higgses (real) or in penguin decays of K, D, B mesons
  - Proton colliders, proton fixed heavy target, electron colliders(H factory)

- Heavy neutral leptons ("sterile neutrinos")
  - Weak semi-leptonic decays of hadrons, W, Z
  - Sources: proton fixed heavy target, proton colliders, electron colliders (W, Z)

E.g. Heavy Neutral Lepton



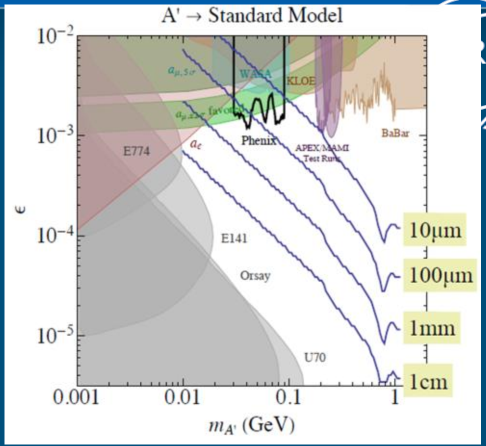
- Axion-like particles ("ALPs")
  - Possible couplings to photons, gluons and fermions
  - Proton colliders, proton heavy fixed target, space

- (Light) Dark Matter direct detection ("vWIMPs")
  - Through one of the portals or Space

We need a general-purpose setup!

Detection

- Weak couplings and light masses make HS particles “long-lived”

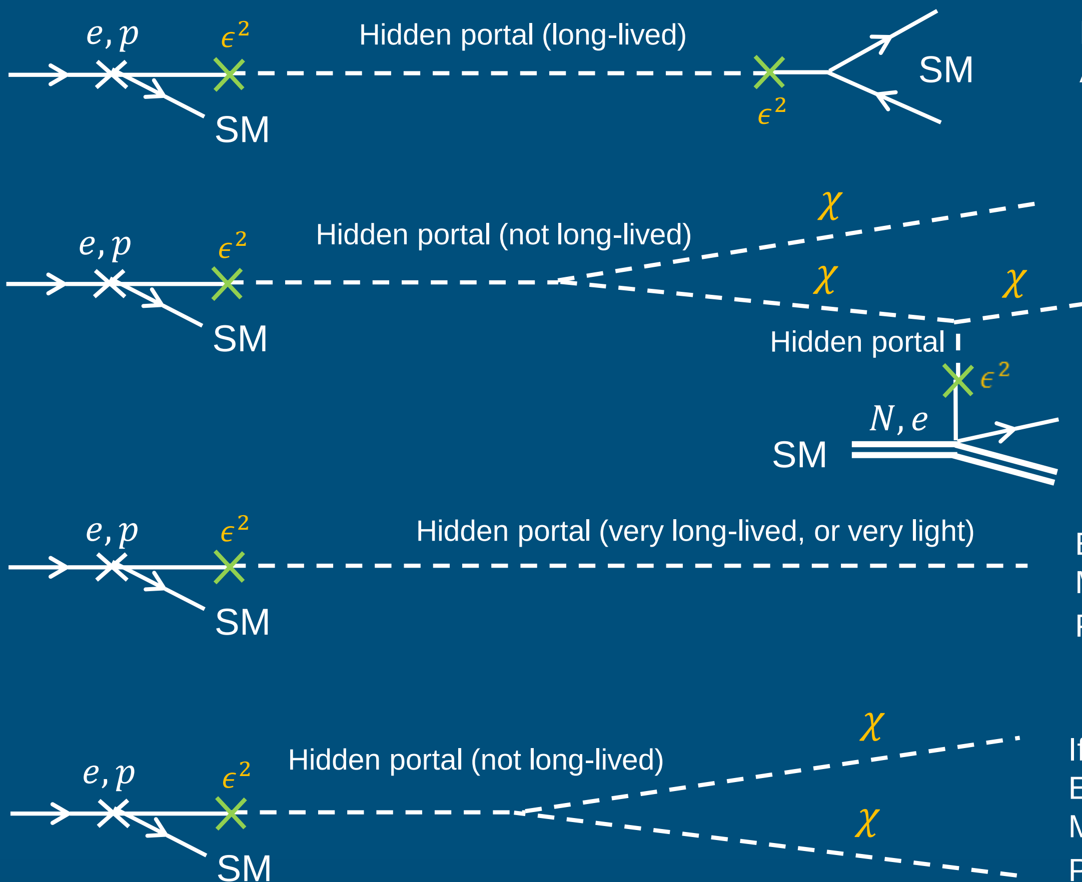


Production

Detection

Direct

Indirect



Decay signature (“displaced vertex)
Allow identification of model
Probability ∝ ϵ^4

Dark matter scattering
Recoil against electron or nuclei
Probability ∝ ϵ^4

Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

Detection

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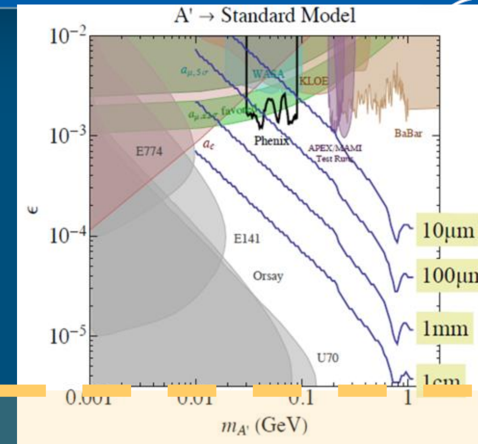
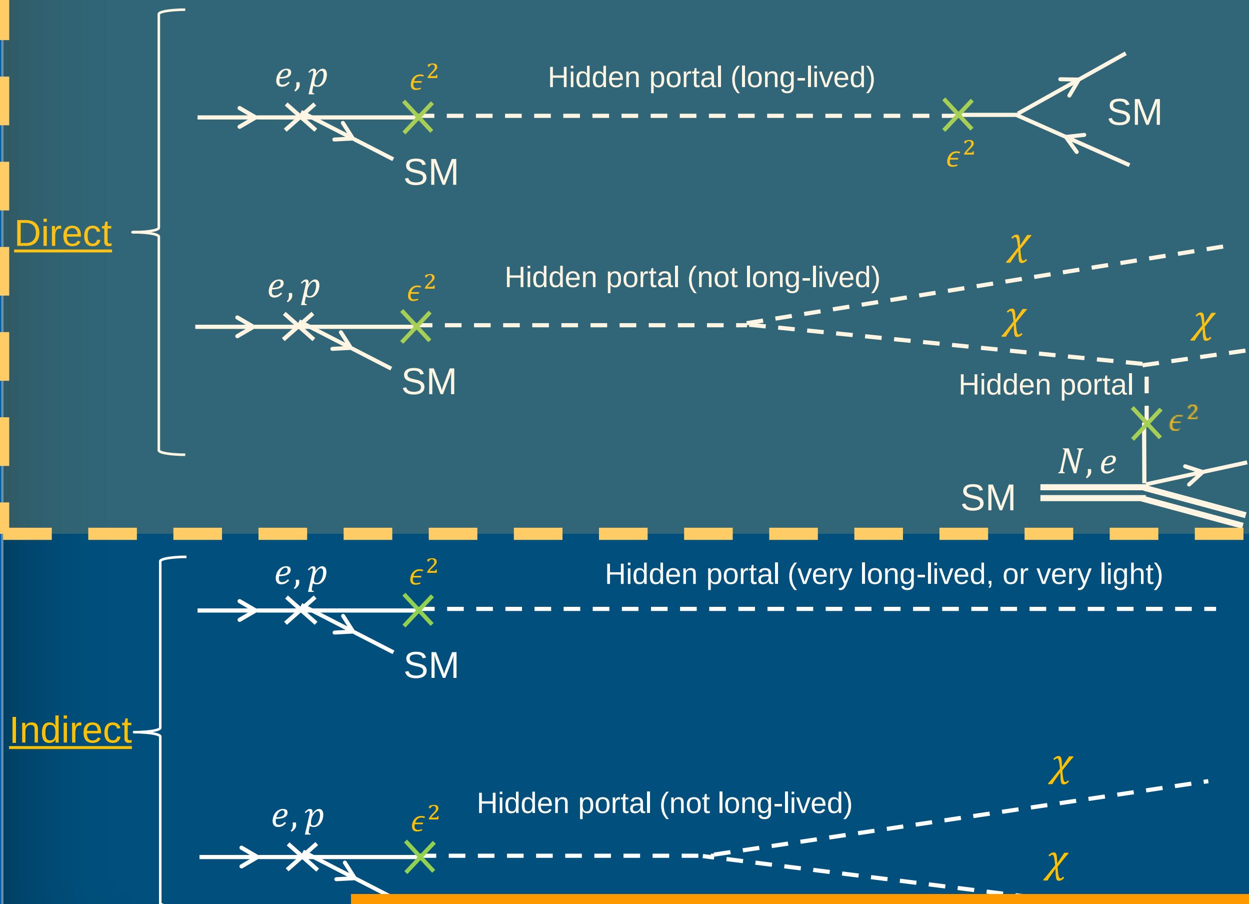


Production

Detection



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SHiP with protons

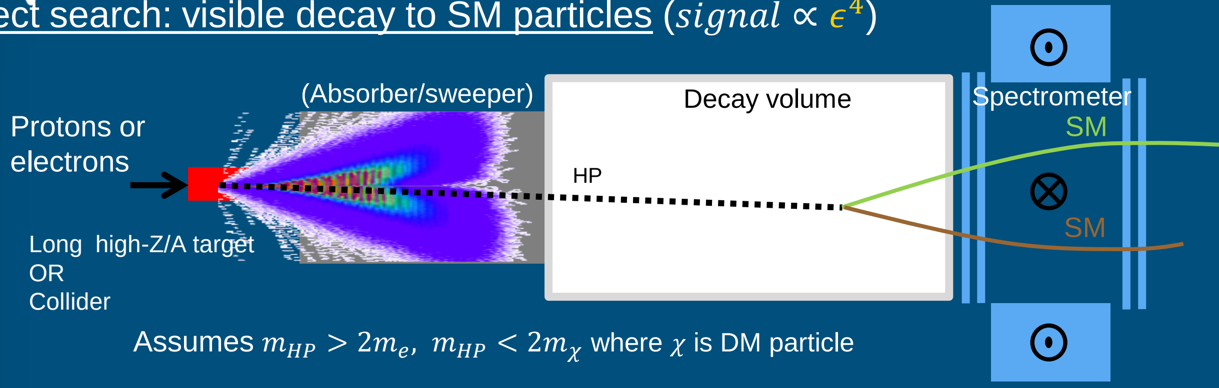
Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass

Experimental challenge → Intensity Frontier

Experimental techniques

Direct search: visible decay to SM particles ($signal \propto \epsilon^4$)



Assumes $m_{HP} > 2m_e$, $m_{HP} < 2m_\chi$ where χ is DM particle

“Fixed target mode setups”:

- NA62++@CERN (p@400, 10^{18})
- HPS, APEX, DarkLight@JLAB (e@1-10)
- SHiP@CERN (p@400, 2×10^{20}),
- SeaQuest@FNAL (p@120, 10^{18}–10^{20})
- (LBNF@FNAL)

“Collider mode setups”:

- ATLAS, CMS, LHCb @LHC (no absorbers)
- BELLE2@sKEKB (no absorber)
- FASER@LHC
- MATHUSLA@LHC (no spectrometer)

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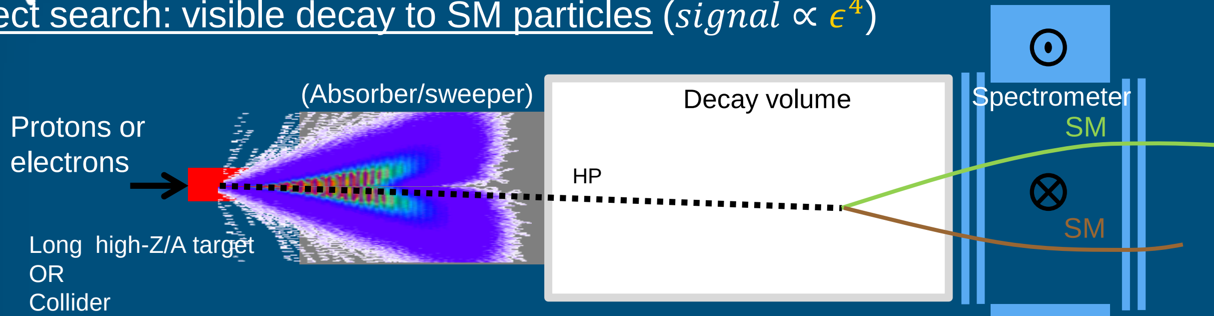

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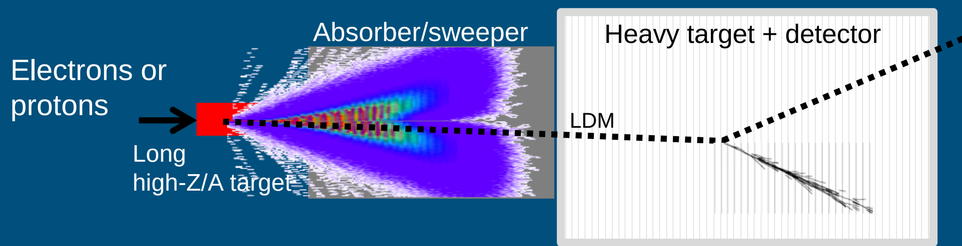
Direct search: Scattering off atomic electrons and nuclei ($signal \propto \epsilon^4$)



"Fixed target mode setups":
BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
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(interest for BDX-like experiments at
LNF, Mainz (MESA),
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Experimental techniques

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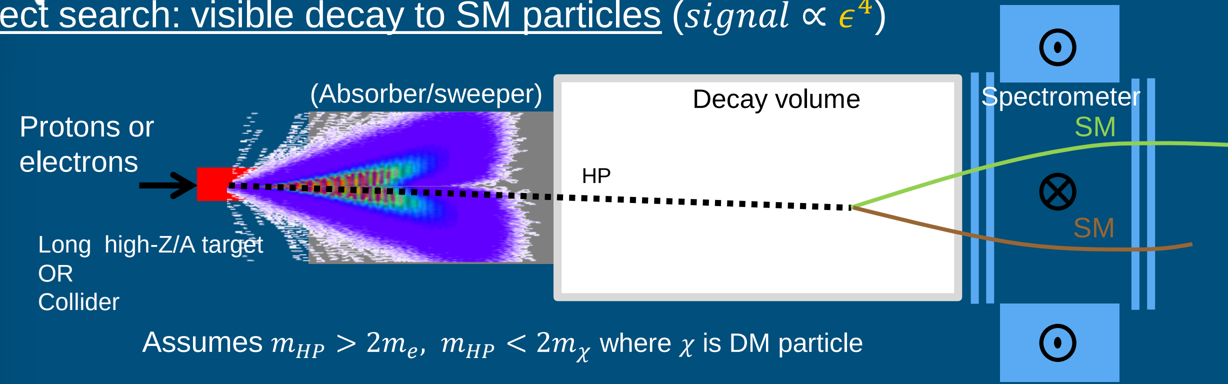

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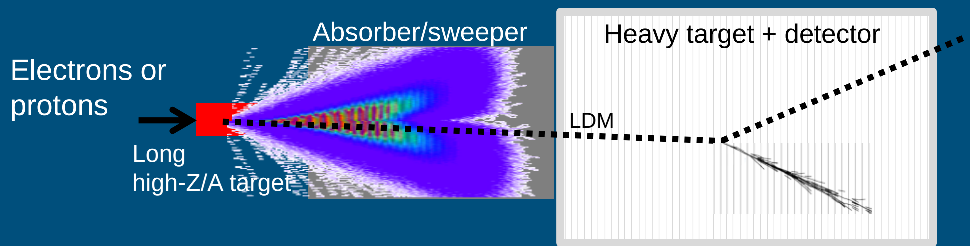

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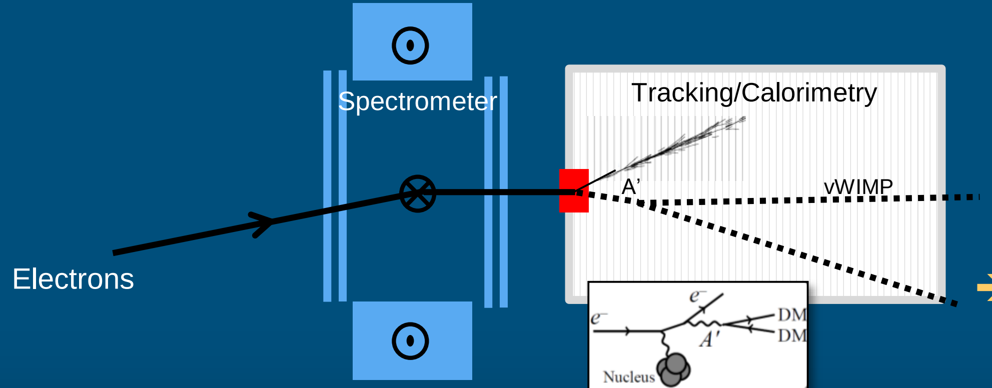
Indirect search: Missing energy/momentum/mass ($signal \propto \epsilon^2$)



- NA64/NA64++@CERN (e@100, 10^{12})
- LDMX@SLAC/CERN (e@8-16, 10^{16})

➔ *Operating with electrons (production/detection) assumes vector portal*

Optimization of a proton beam dump experiment

Hidden Sector phenomenology driven design

- Production branching ratios $\mathcal{O}(10^{-10})$ → Largest possible number of protons

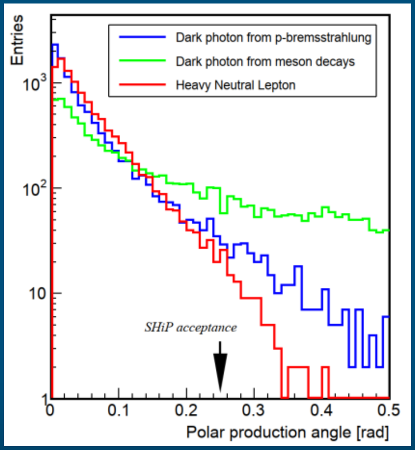
  ➔ "Primary" SPS FT luminosity for a long target (e.g. 1m++ Mo, ρ_N nucleon density)

  SPS $\mathcal{L}_{int}[year^{-1}] = 10^6 s \times \int_0^{"\infty"} \Phi_0 \times \rho_N \times e^{-l/\lambda} dl = \Phi_0 \times \rho_N \times \lambda$ = 3.6 x 10^{45} cm^{-2} (cascade not incl.)

  ➔ HL-LHC $\mathcal{L}_{int}[year^{-1}] = 10^7 s$ $\times 10^{35}$ $s^{-1}cm^{-2}$ = 10^{42} cm^{-2}

- Production in light and heavy hadron decays, photons → High A and Z target
- Large neutrino background → Short λ target
- Travel unperturbed through *ordinary* matter → Filtering out beam induced background
- Significant production angles → Decay volume as close as possible
- Long-lived objects → Long decay volume
- Detection by visible decays → Full reconstruction and identification
- Detection by interaction → Large detector target mass

Decay opening angles (1 GeV/c^2 HNL and DP)



SHiP@BDF : proton yield

- SHiP assumes current capacity of SPS, slowly extracted 1s spills with 4×10^{13} p / 7.2s

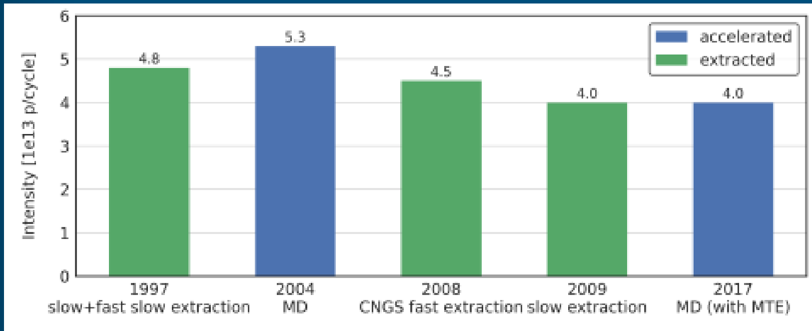
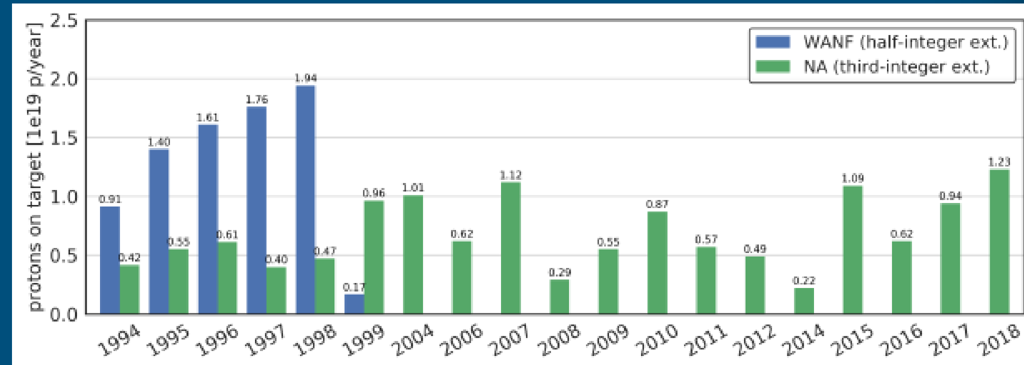
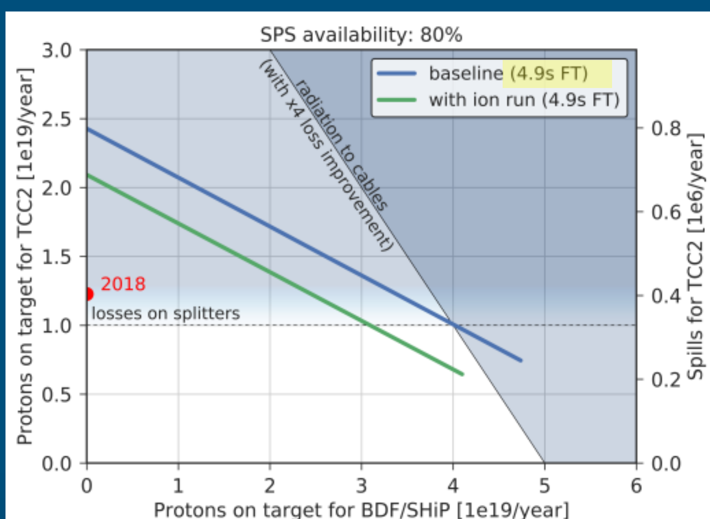


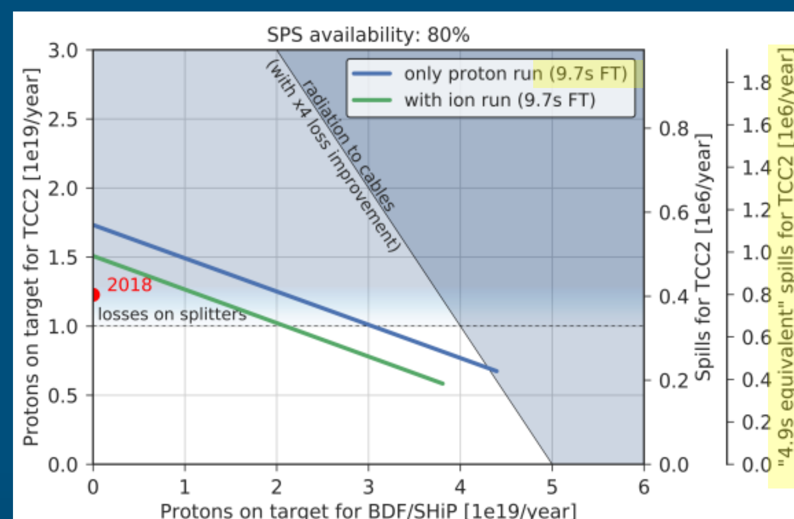
Figure 1: Intensity per cycle achieved in the SPS.



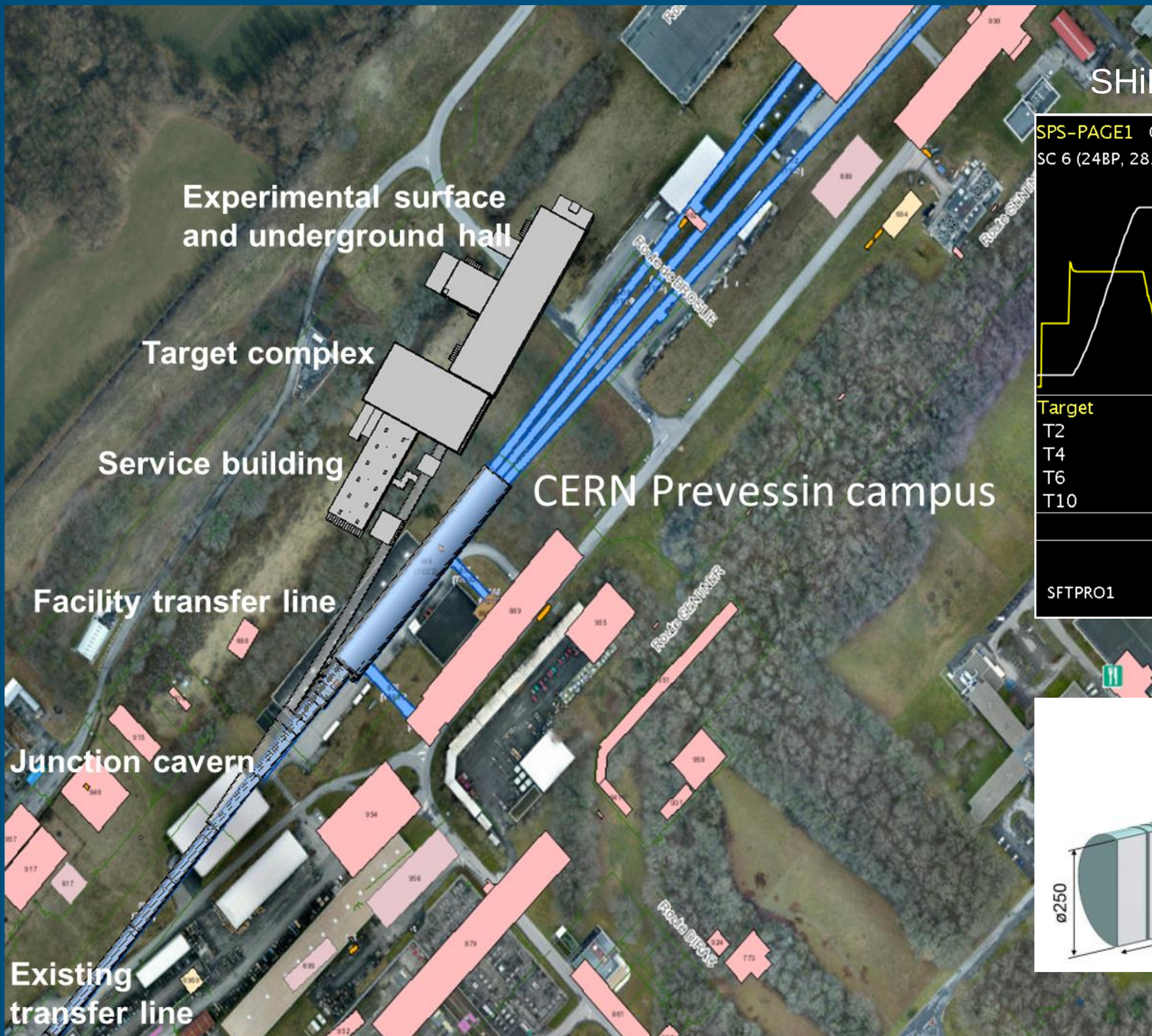
- Slow extraction of (4 + 1) x 10^{19} p/year requires reduction of losses by factor four
  - Factor of three was achieved in MDs in 2018

- Proton sharing scenarios:

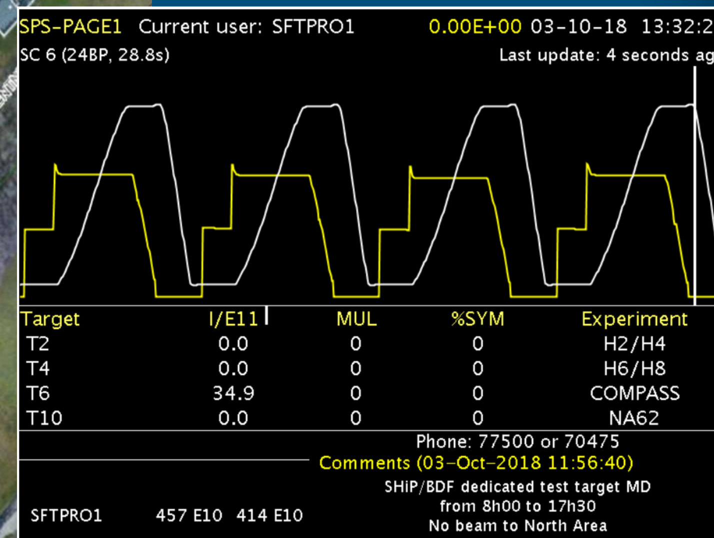




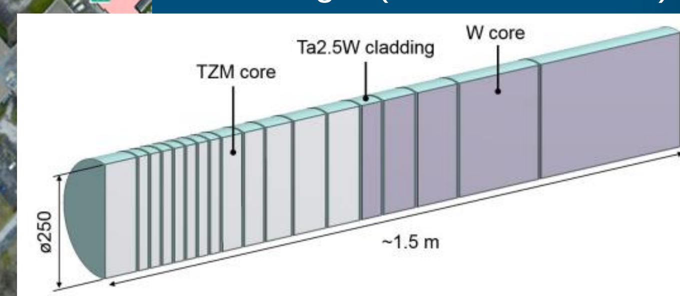
SHiP@BDF



SHiP cycle MD and target test in 2018



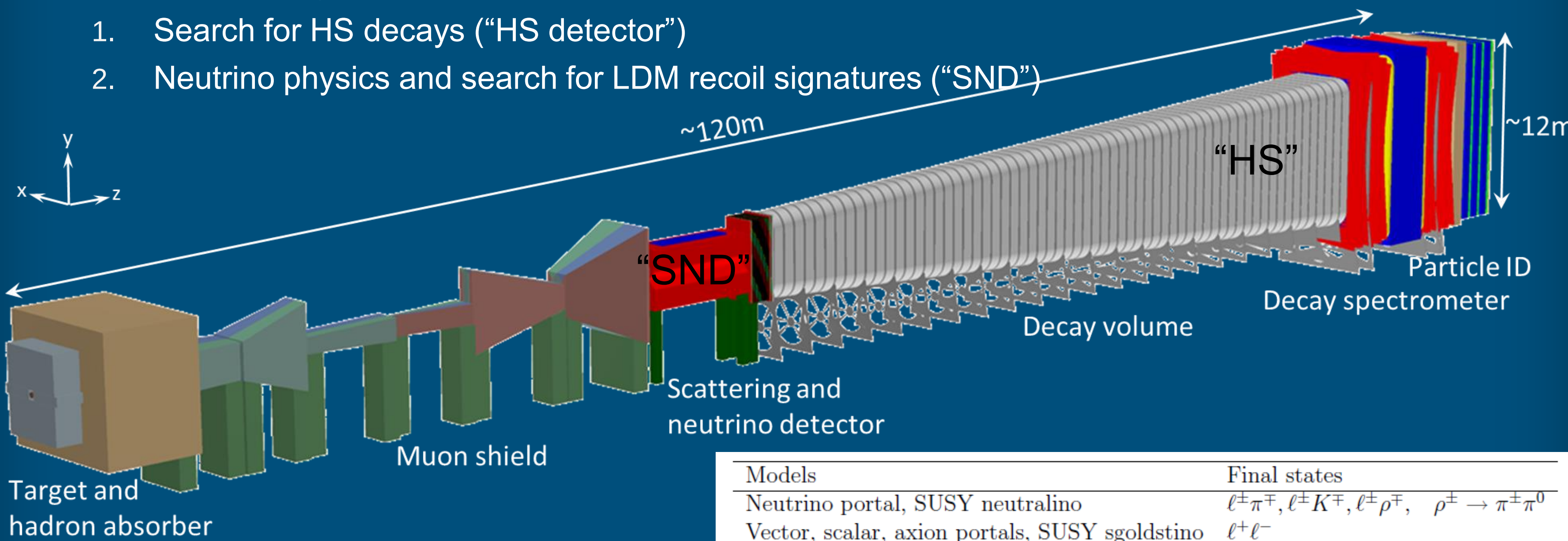
Proton target (2.56 MJ/355 kW)



SHiP experimental setup

- Physics cased based on 2x10^{20} protons on target (5 years of nominal operation)
  - ➔ Signal yields from >10^{18} D mesons, >10^{16} τ, >10^{21} photons (>100 MeV)

- Dual detector system
  1. Search for HS decays (“HS detector”)
  2. Neutrino physics and search for LDM recoil signatures (“SND”)



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	$\pi^0\pi^0$

“Unusual” detector conditions

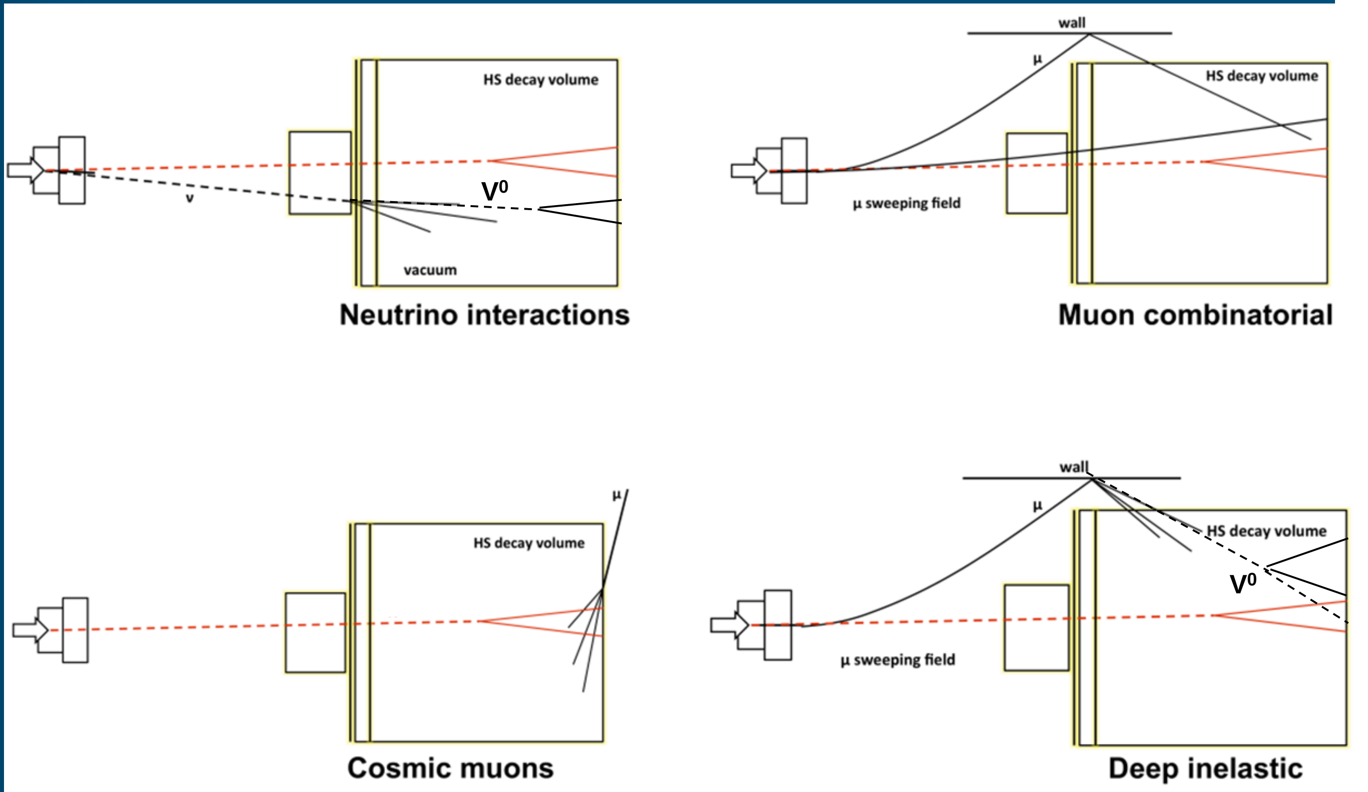
- ➔ No radiation
- ➔ Low data rates
- ➔ Easy cooling and access

Challenge is background suppression

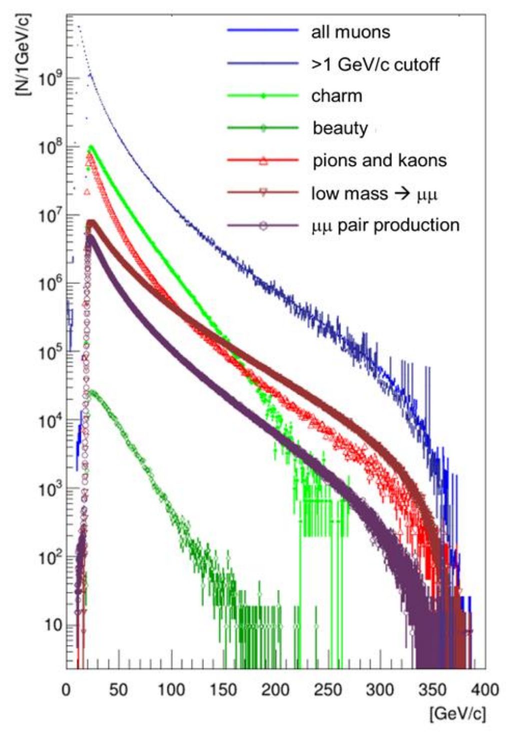
HS beam-induced background

- Beam-induced background flux
  - $\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4\text{x}10^{13}$ protons
  - 4.5×10^{18} neutrinos and $3\text{x}10^{18}$ anti-neutrinos in acceptance in 2×10^{20} proton on target

Hidden sector decay search background types



Muon spectrum for $5\text{x}10^{13}$ protons on target



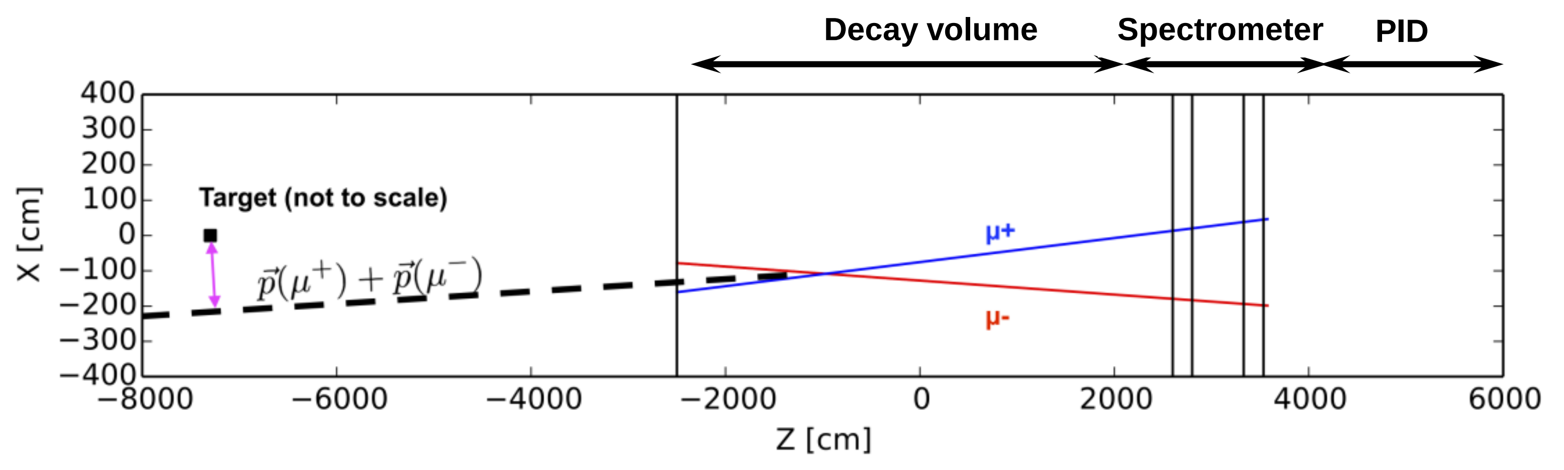
HS Background suppression

- Critical to reduce muon flux and neutrino interactions
  - Active muon shield
  - Decay volume under vacuum

- Redundant rejection of residual background
  - Background taggers
  - Momentum and vertex information
  - Impact parameter at target
  - Coincidence timing
  - Invariant mass
  - Particle identification

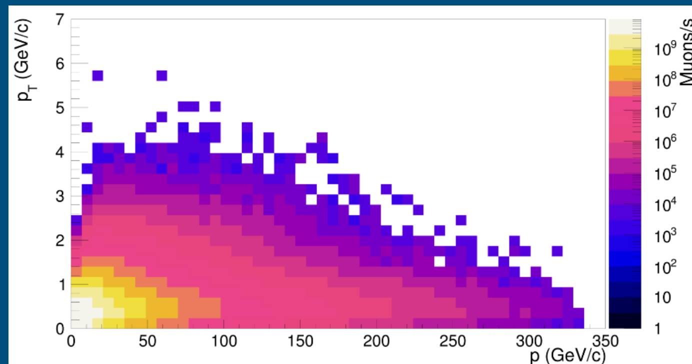
Cut	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Dimuon distance of closest approach	< 1 cm
Dimuon vertex position	(> 5 cm from inner wall)
IP w.r.t. target (fully reconstructed)	< 10 cm
IP w.r.t. target (partially reconstructed)	< 250 cm

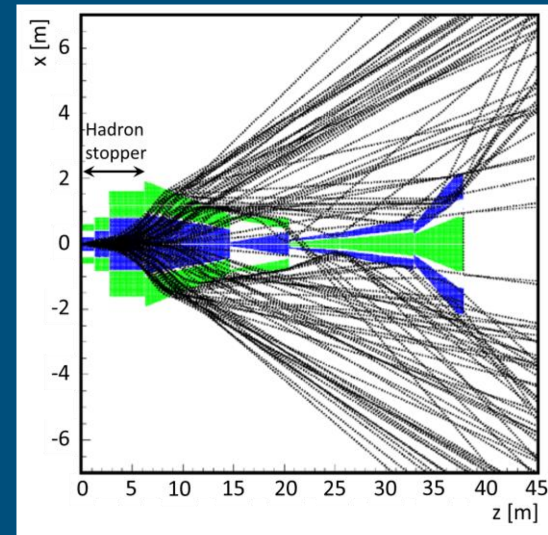
➔ Aim for zero background



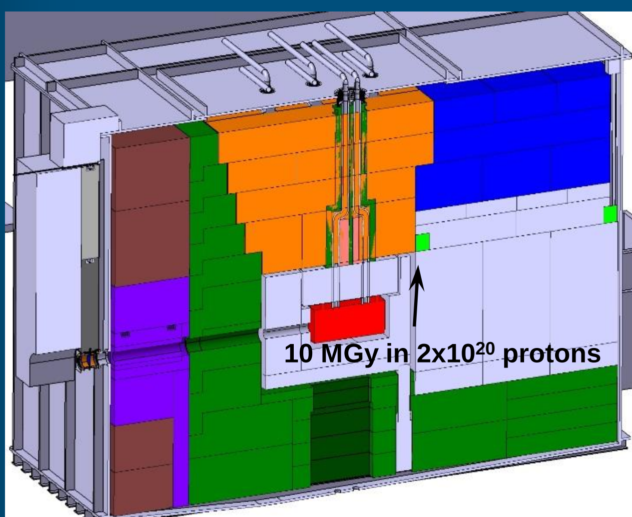
Muon shield

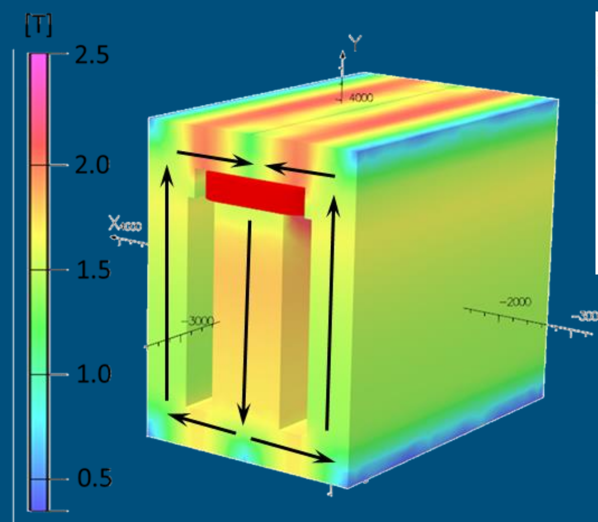
- Based on magnetic deflection of muon flux



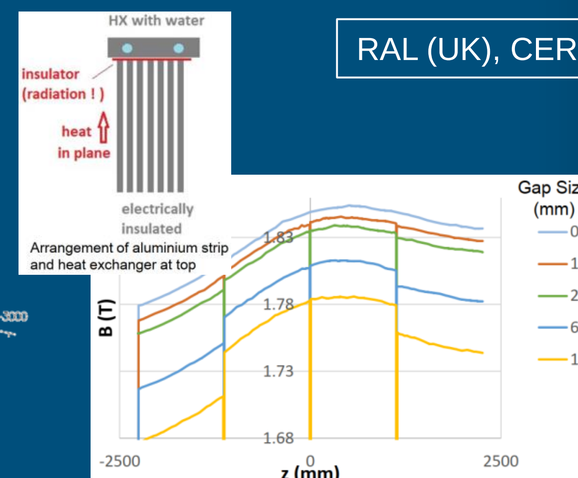


- Muon deflection starts within the target complex: magnetization of hadron stopper





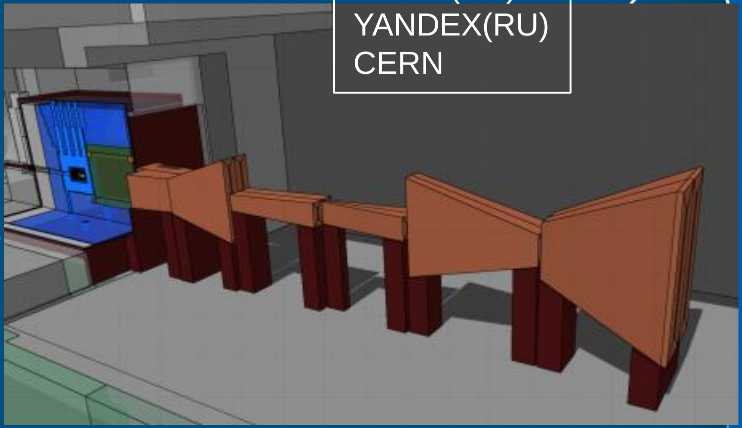
RAL (UK), CERN



- Currently investigating a non-cooled option with a field of <1.6> T

Muon shield (free-standing)

Imperial (UK)
Bristol (UK)
MISIS (RU)
YANDEX(RU)
CERN



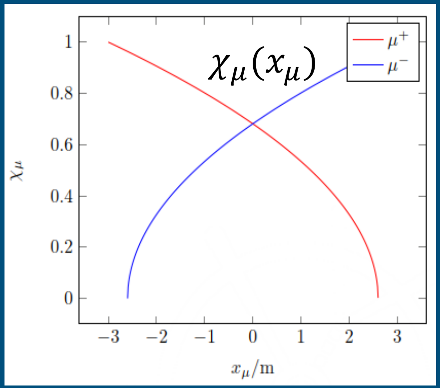
- Rest of muon shield consists of free-standing magnets

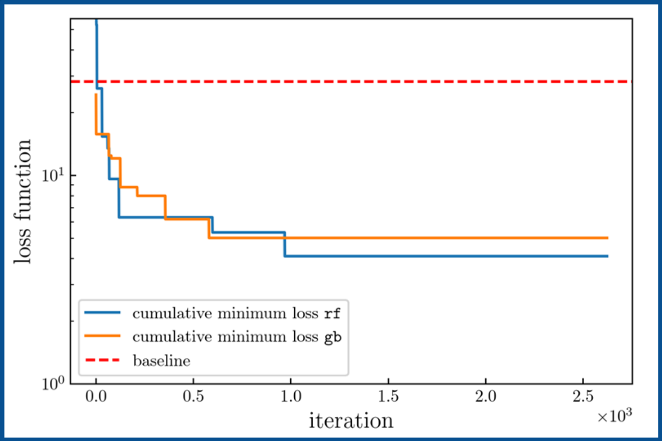
- Optimization of field configuration by Machine Learning with a sample of muons simulated with PYTHIA/GEANT
  - Assumptions: 1.7 T average field in core
    6 magnets of 5m length
    10cm space between magnetic regions
  - Whole setup described by 56 parameters
  - Bayesian optimization procedure

- Current loss function

$$f(W,\chi_\mu) = \begin{cases} 10^8 \; if \; W > 3kt \\ 1 + e^{10\times(W-W_0)/W_0} \times \left[1 + \sum_\mu \chi_\mu(x_\mu)\right] \end{cases}$$

W weight of the muon shield
W_0 weight of the baseline
χ_μ weighted position of muon μ passing sensitive plane at position x_μ



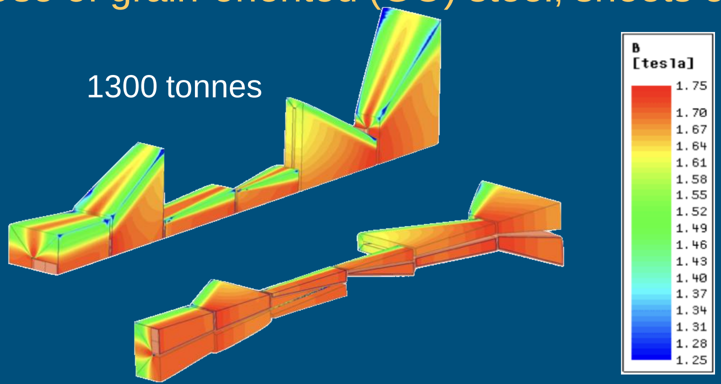


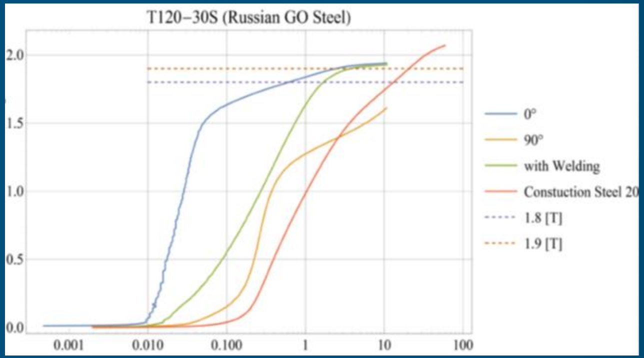
gb = gradient boosted decision trees
rf = random forests

➔ Optimization produces an idealistic field map

Muon shield (free-standing)

- Narrow spaces for coil ➔ limit coil current-turn and power dissipation (air cooling)
  - ➔ Use of grain-oriented (GO) steel, sheets of 0.3-0.5 mm

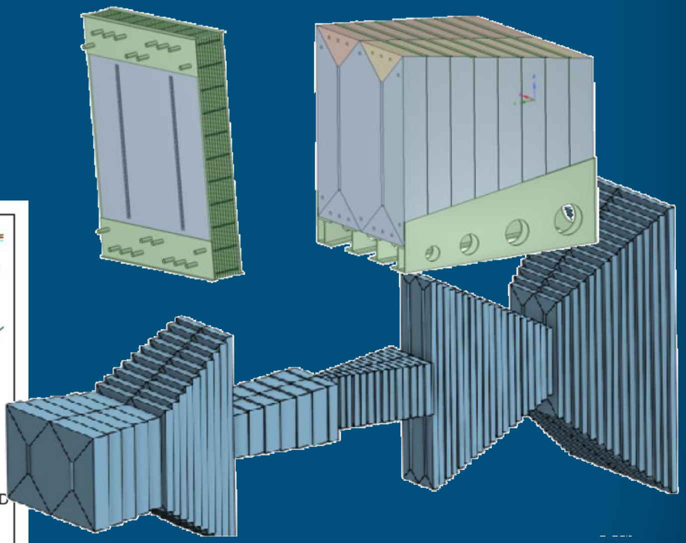




- Technology studies produce realistic field maps for simulation

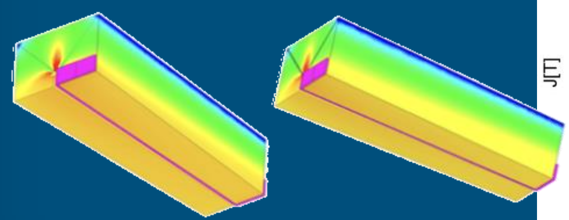
➔ Assembly of GO steel

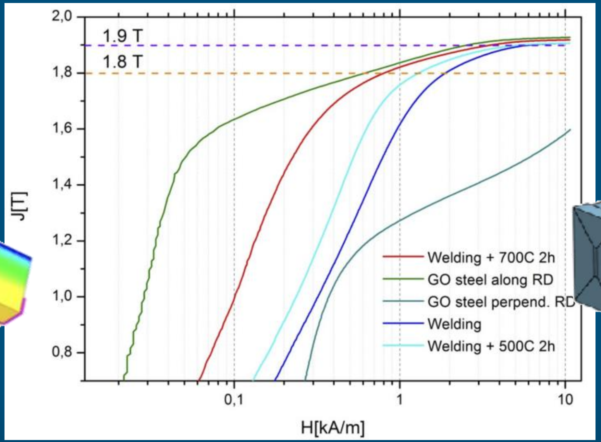
- Investigation of welding followed by annealing
- Welding of 5cm (150 sheets) blocks looks feasible
- Requires large vacuum chamber



Ideal joint

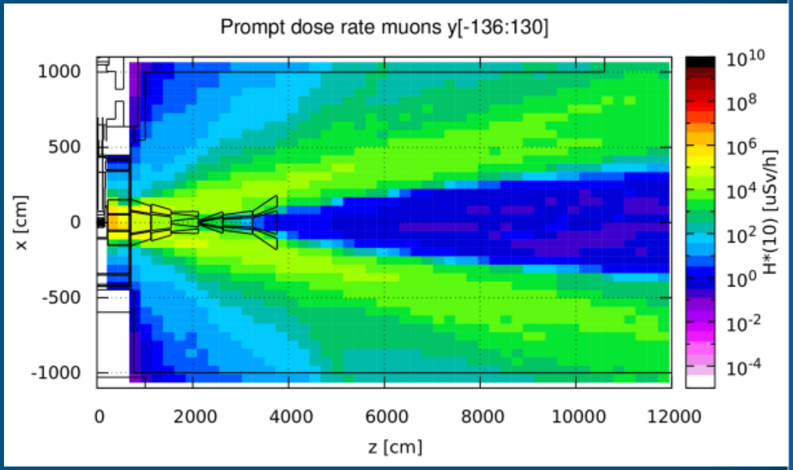
Welded joint

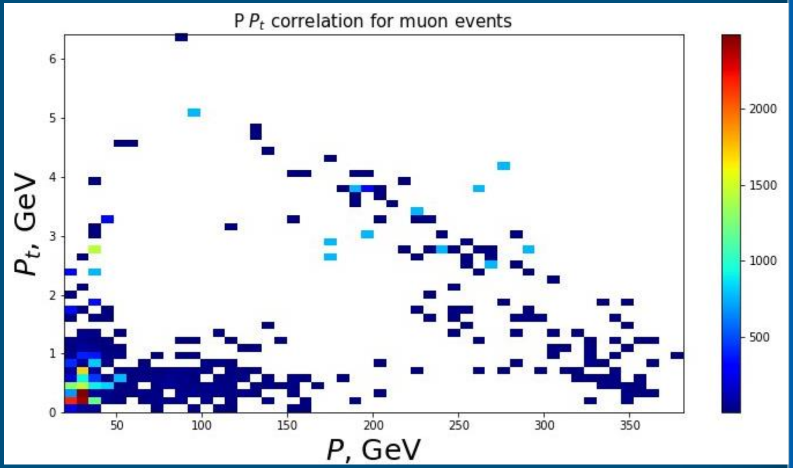




Muon shield (free-standing)

- Performance of muon shield
  - Muons impinging on decay volume: 5.8×10^4 / spill
  - Reconstructed muons in spectrometer 3×10^4 / spill
  - 2.1×10^8 muon DIS interactions in decay volume wall in 2×10^{20} protons on target



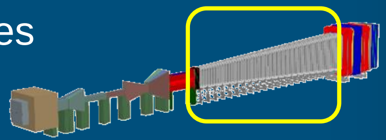


- In depth study of “dangerous” muons
  - Muons on “wrong side”, catastrophic energy loss
  - ➔ Re-optimization

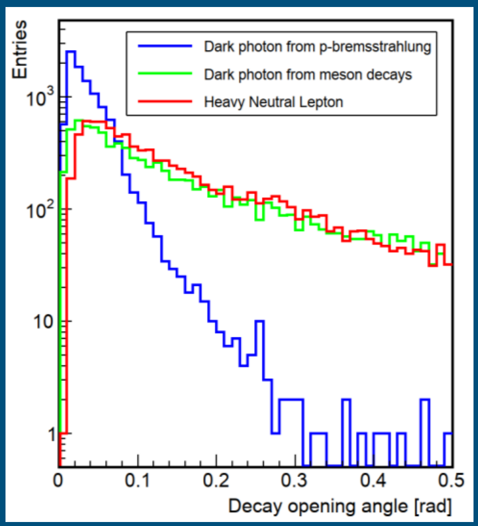
- Final engineering solution requires re-optimization with extra boundary conditions
  - ¼-size prototype in construction
  - Hybrid GO-normal steel solution as backup

HS Decay volume

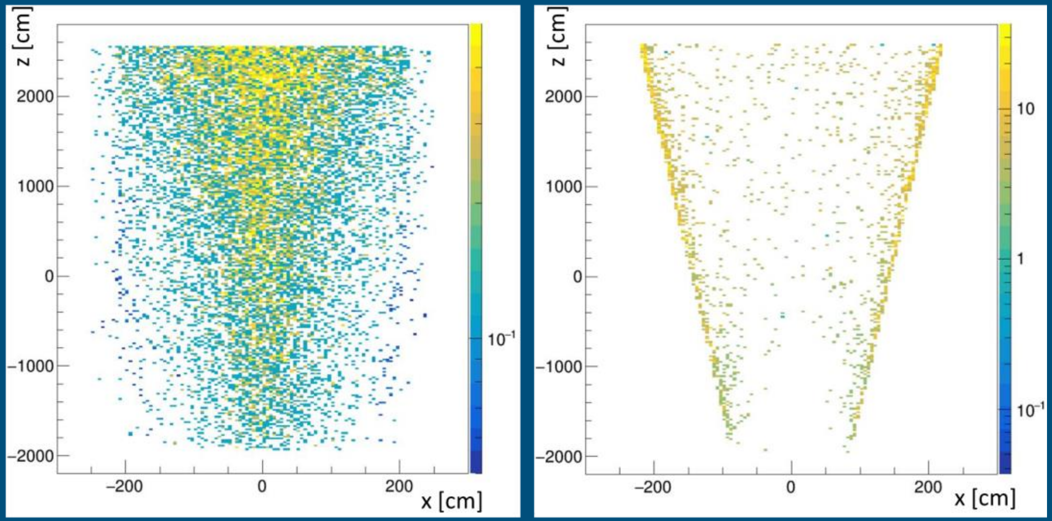
- Optimization of decay volume driven by
  - Muon flux "bow wave" determines ultimate envelope for the fiducial volume
  - Optimization of decay volume geometry (length) with assumption of spectrometer aperture of 5 x 10 m^2 and taking into account decay acceptances for all signal modes
  - ➔ 50m pyramidal frustrum



Decay opening angles (1 GeV/c^2 HNL and DP)



Neutrino interactions in air (left) and in vacuum vessel at 1mbar (right)



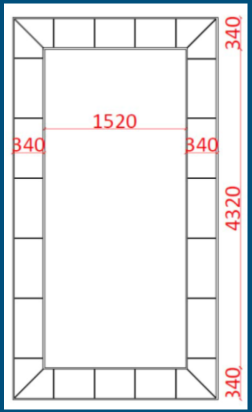
- Neutrino interactions in fiducial volume producing signal candidates (soft selection) in 2x10^{20} protons on target
  - Air: 2.5 x 10^3 candidates with small impact parameter at target ➔ pump down to 10^{-3} bar
  - Vacuum: 1.4 x 10^4 candidates produced in vacuum chamber walls ➔ easily rejected

HS Decay volume

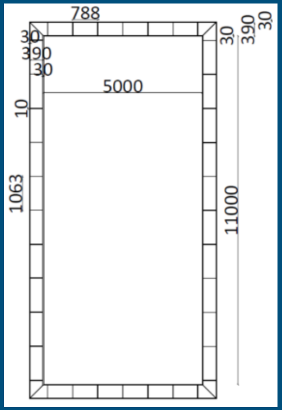
Berlin(DE)
Naples(IT)
NRC KI(RU)
CERN

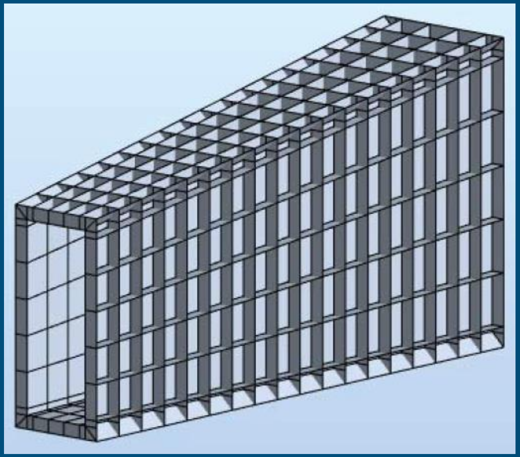
- Requirement:
  - Thin and light wall structure
  - Incorporation of Surrounding Background Tagger
  - ➔ Designed with S355JO(J2/K2)W steel according to EN 13445 Part 3-Section 8 and seismicity

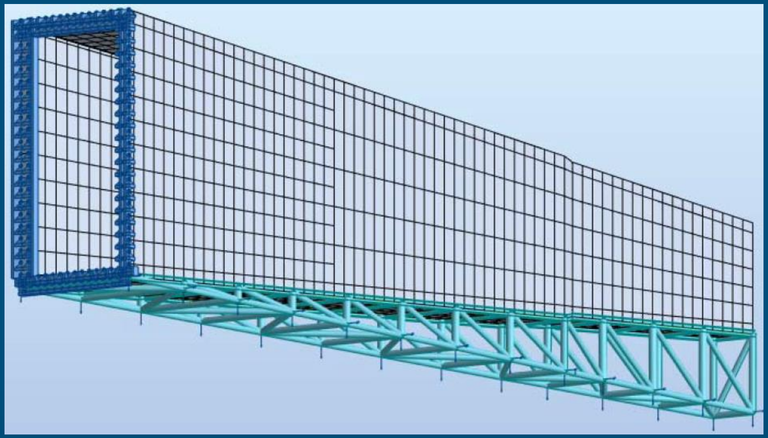
Upstream dimensions

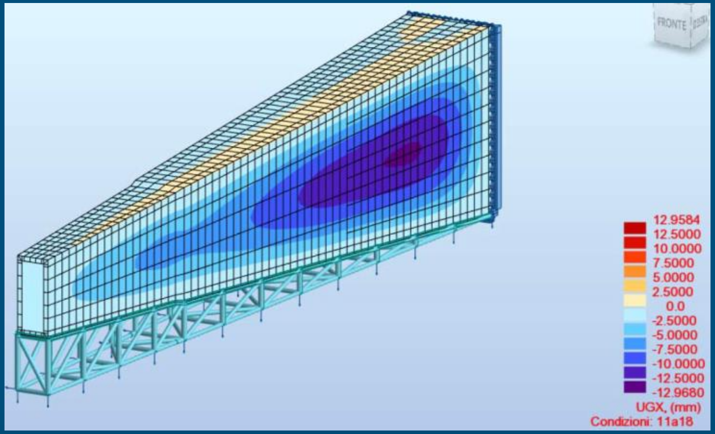


Downstream dimensions







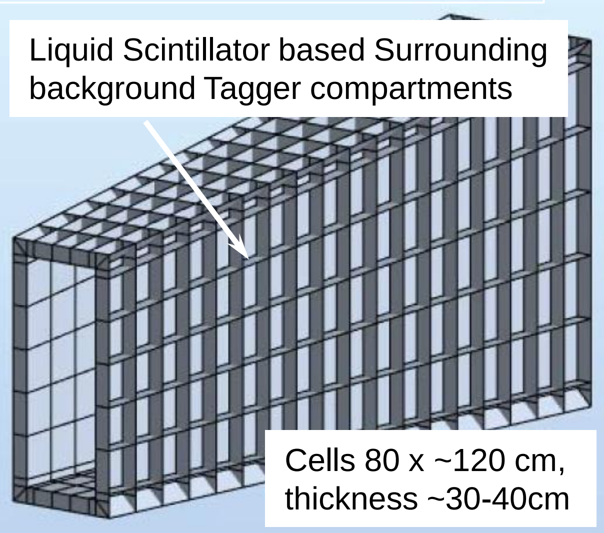


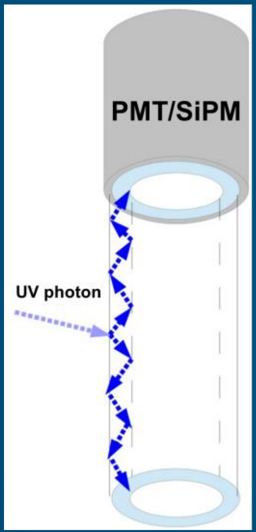
HS Surrounding Background Tagger

Barcelona(ES), Berlin(DE), LAL Orsay(FR), Mainz(DE), Naples(IT), Kyiv(UA)

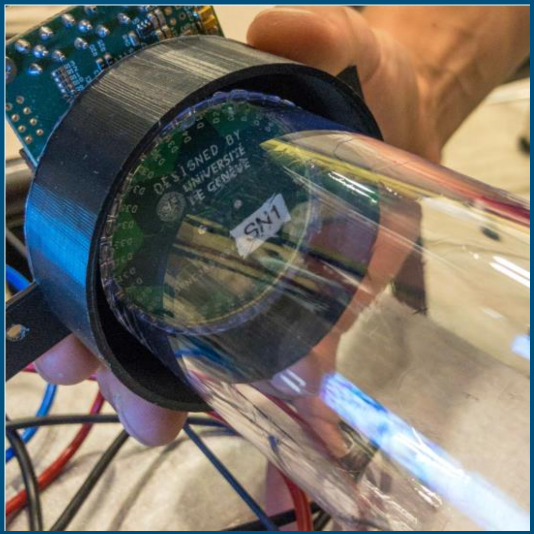
- Purpose: Tagging charged particles entering decay volume and tagging ν and μ interactions in the vacuum chamber walls

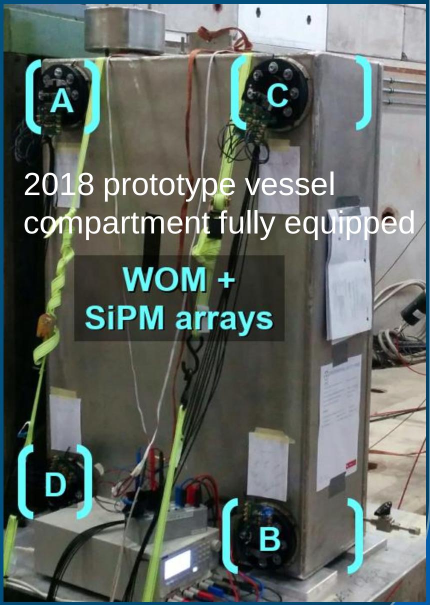
- Characteristics
  - Liquid scintillator based: linear alkylbenzene (LAB) together with 2.0 g/l diphenyl-oxazole (PPO) as the fluorescent
  - Total quantity 250 – 300 m^3
  - Each cell equipped with two wavelength-shifting optical modules (WOM) for 340 nm– 400 nm
  - 32 SiPMs of 3 × 3 mm^2 , O(3500) in total





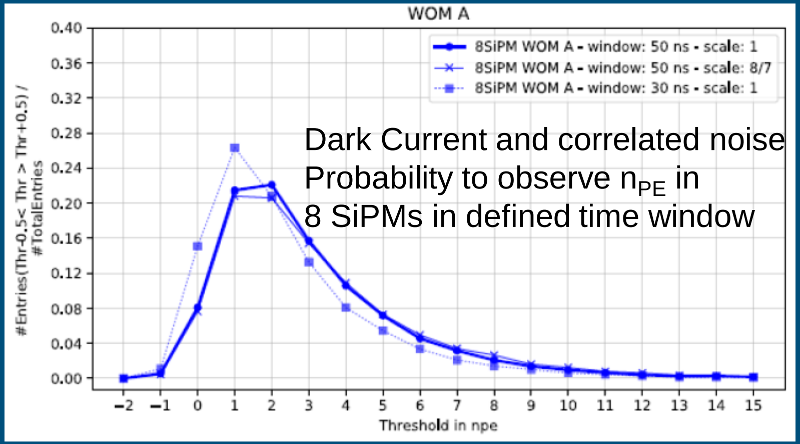
40-SiPMs array built by Geneva

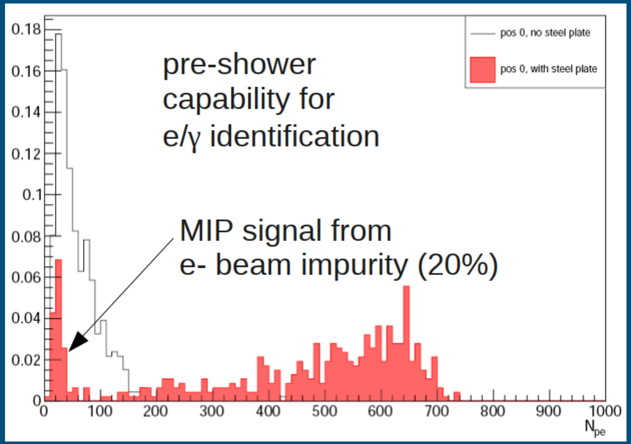


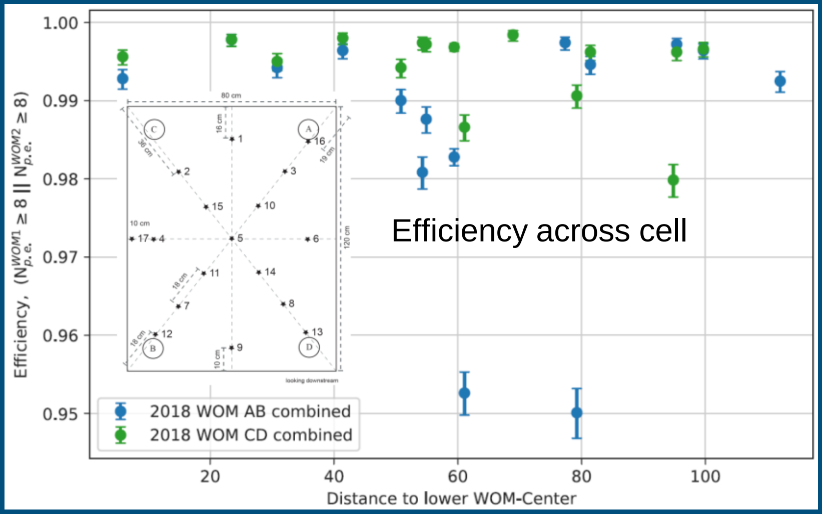


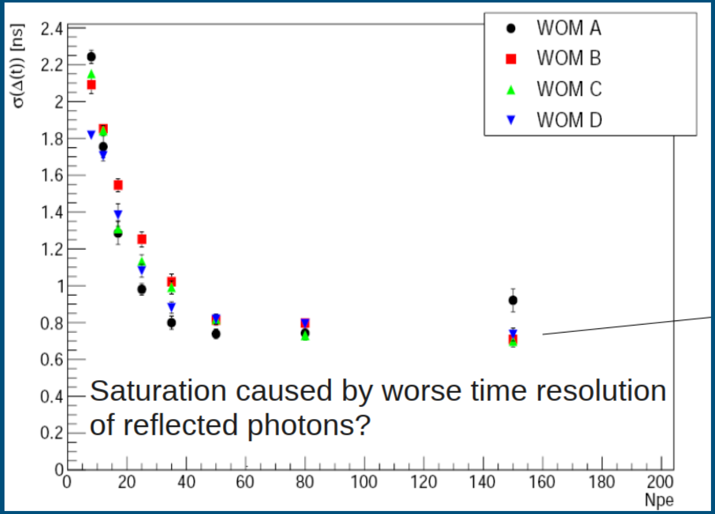
HS Surrounding Background Tagger

2018 test beam results





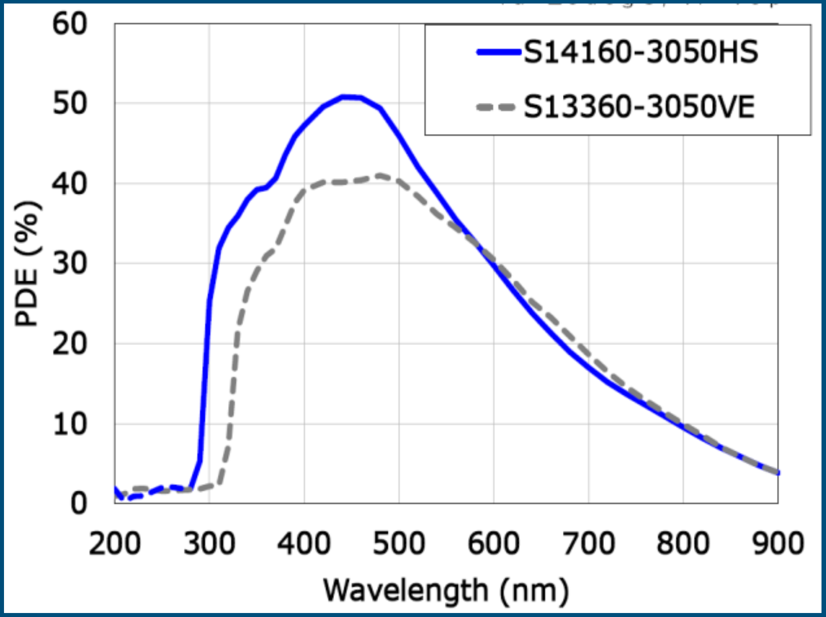


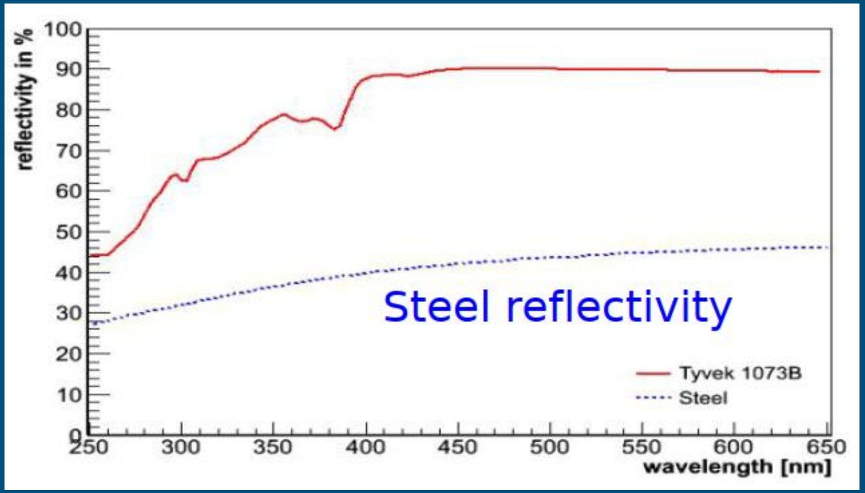


➔ >99% efficiency (>45 MeV deposited), time resolution of 1 ns can be achieved with the threshold for both WOMs set to two photoelectrons

HS Surrounding Background Tagger

- Improving light yields: Optical coupling critical, reflective coating, SiPM

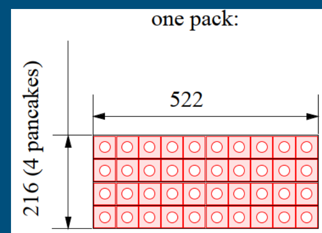


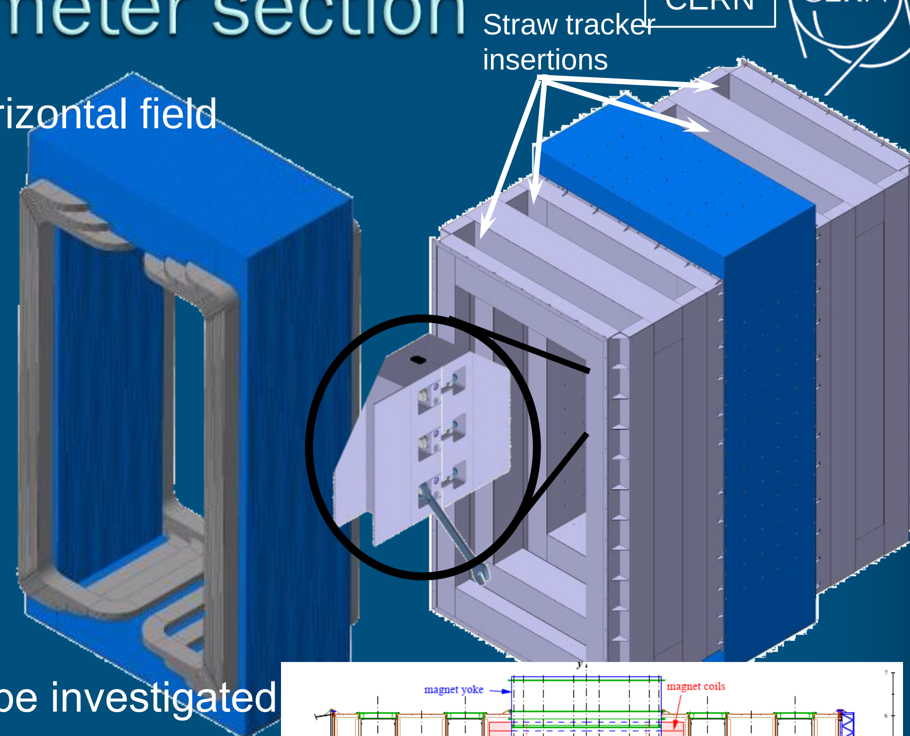


HS Spectrometer section

- Fiducial rectangular aperture 5x10 m² ➔ horizontal field

- Magnetic field of 0.5-1 Tm
  - Magnet yoke mass 1100 tonnes
  - Coil conductor current 3 kA
  - Coil (6 coil packs): 55 tonnes
  - Dissipation: 1.1 MW

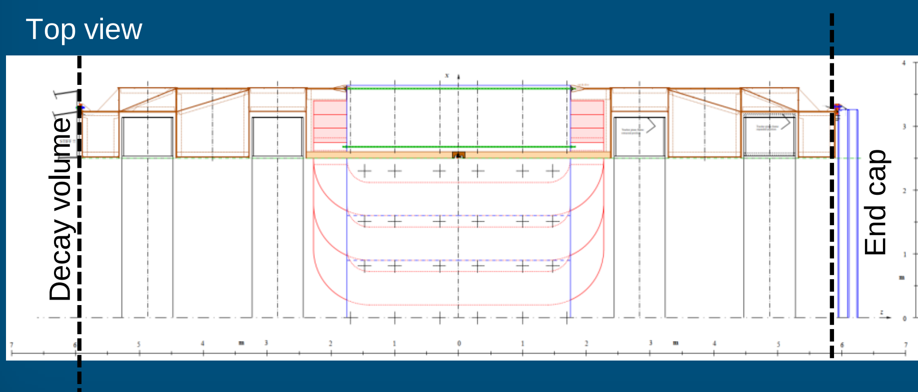




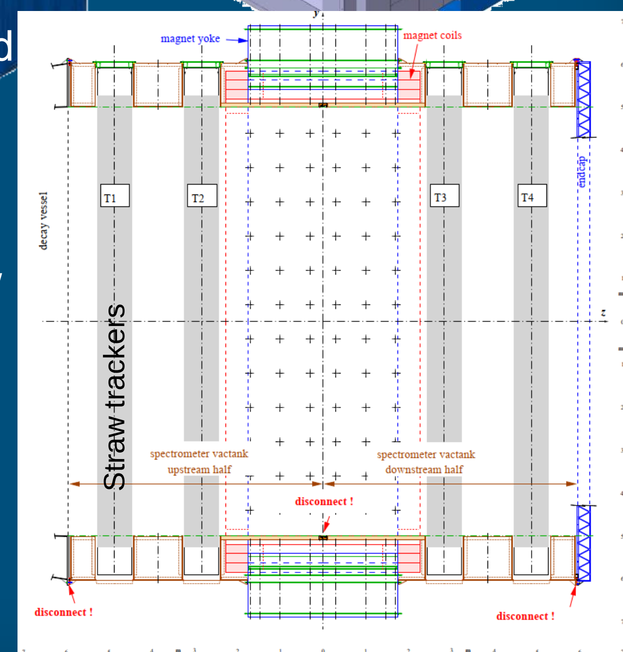
➔ Superconducting ("super-copper") option to be investigated

- Vacuum chamber (two halves) through magnet with no double wall → anchoring in yoke

Top view

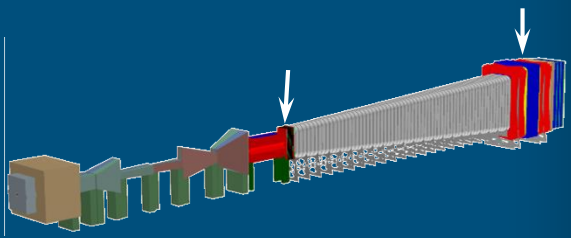


Side view

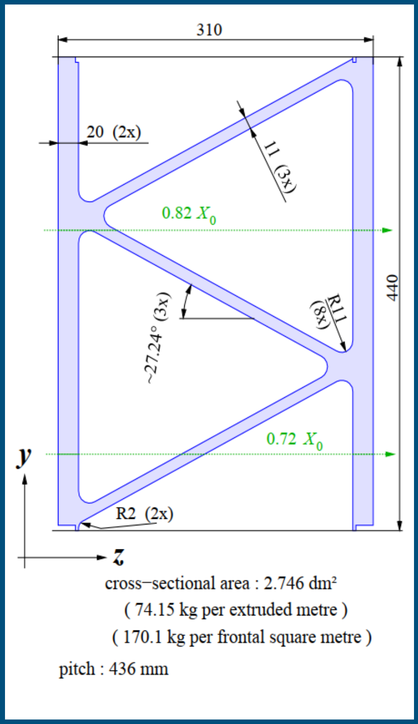


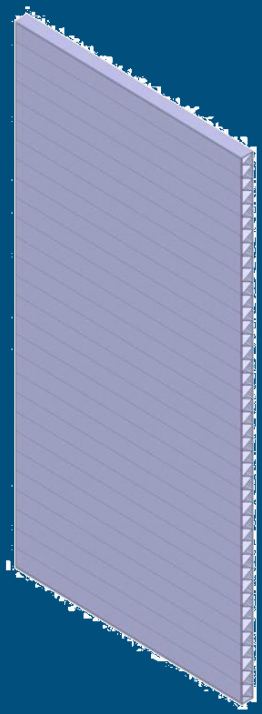
HS Vacuum vessel caps

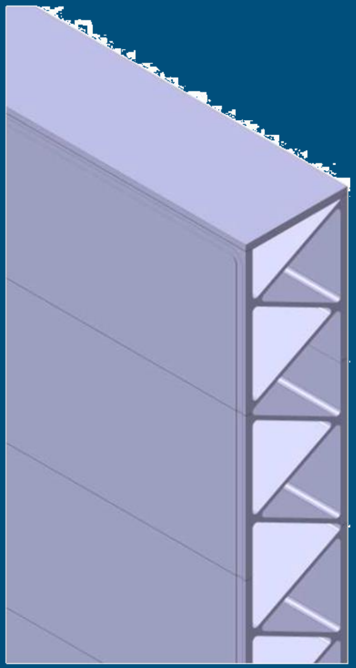
- Front- and end-cap of as low material budget as possible
  - Front: neutrino/muon interactions
  - End: performance of timing detector and calorimeter

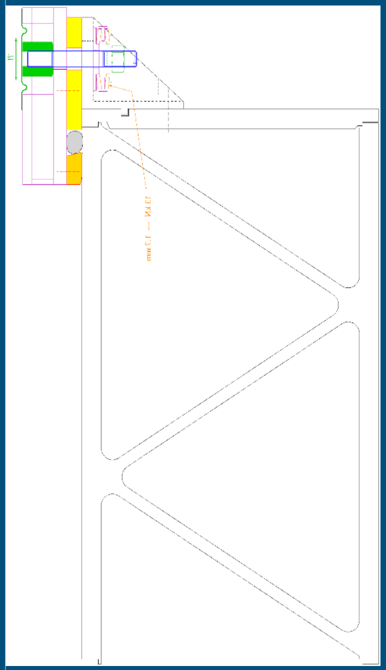


- Current idea: 0.8 X_0 extruded aluminium profiles









- Challenge is welding

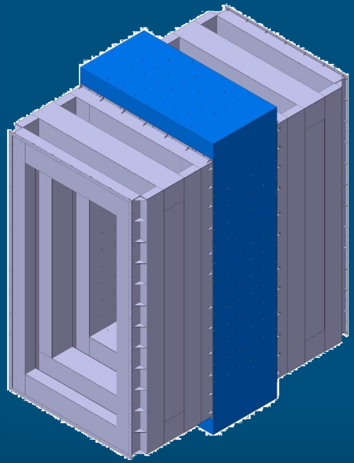
HS Straw Tracker

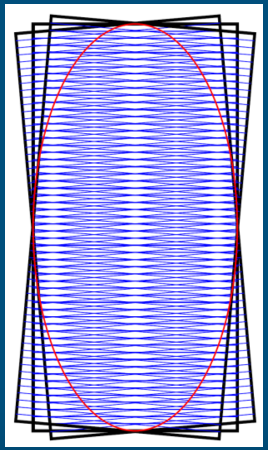
Berlin (DE), Hamburg(DE), JINR(RU), Julich(DE), Kyiv(UA), MEPhi(RU), PNPI(RU), SPPU(RU), Yandex(RU), CERN

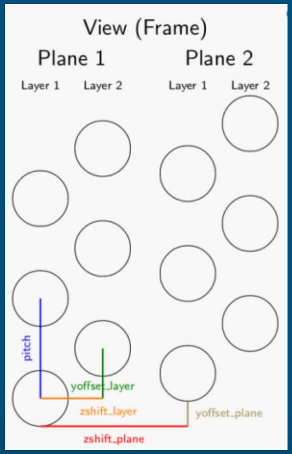
- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector

- Technology developed for the NA62 experiment
  - ➔ SHiP: decoupling supporting frames from vacuum envelope
  - ➔ Horizontal orientation of tubes
  - ➔ Lower rate allows increasing straw diameter (highest rate 7 kHz)

- Characteristics
  - 5 x 10 m^2 sensitive area
  - 5m long 20mm diameter 36µm thick PET film coated with 50nm Cu and 20nm Au operated at 1 bar, produced and tested
  - Four stations, each with four views Y-U-V-Y, ~16 000 straws



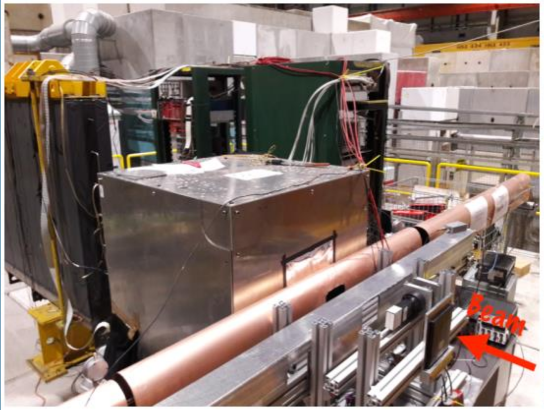


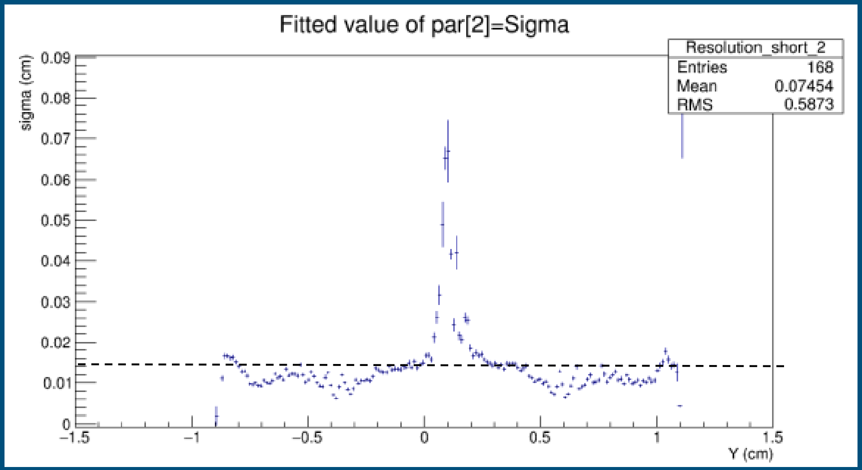


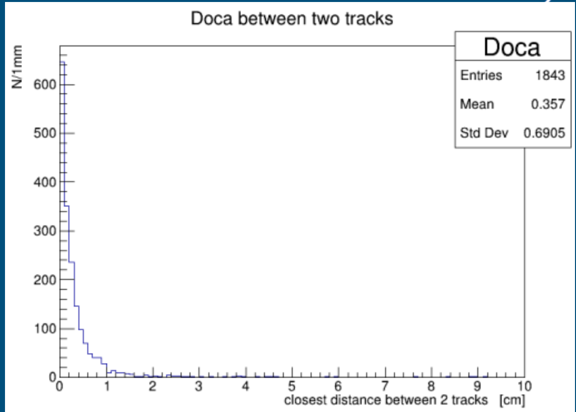
HS Straw Tracker

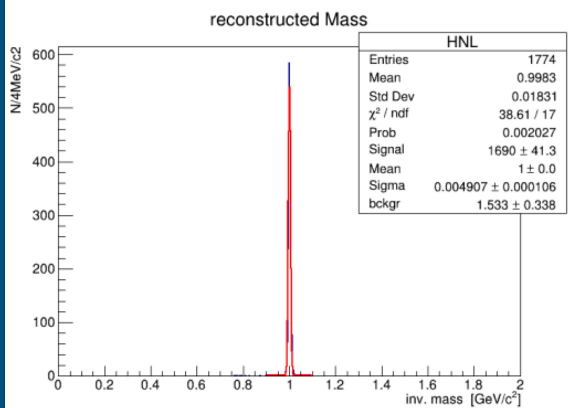
Simulation/reconstruction 1 GeV/c^2 $HNL \rightarrow \mu\pi$

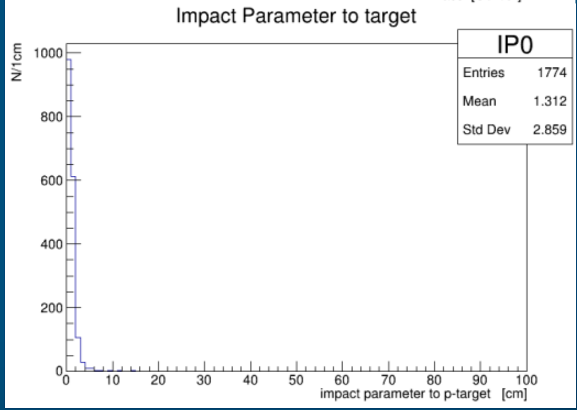
5m long 20mm straw prototype tested at SPS











- Test beams confirm 120µm hit resolution with hit efficiency >99%
- In-situ SHiP space alignment run with muon shield off

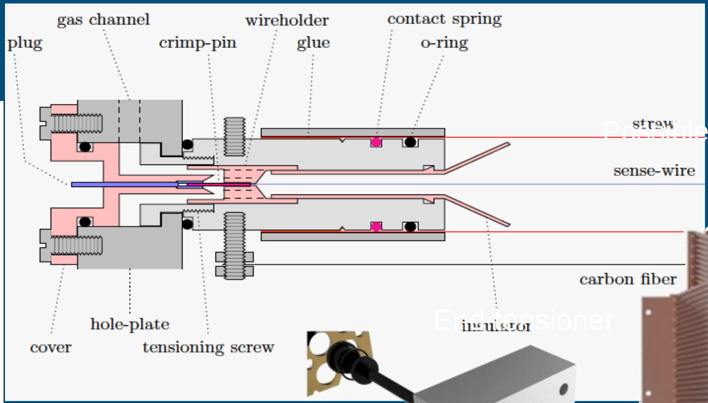
HS Straw Tracker

- Challenge: mechanics
- Sagging and flowing of PET: stretched straw and tungsten wires

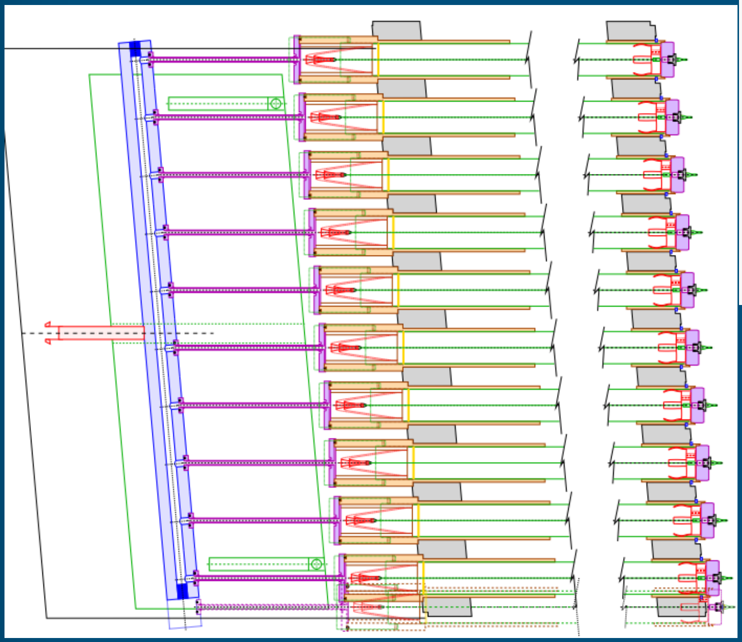
➔ Three option pursued

1. Long-stroke constant-force spring to accommodate elongation of several cm
2. Straw suspension mechanism based on carbon fibre rods
3. Stretching by frame extension

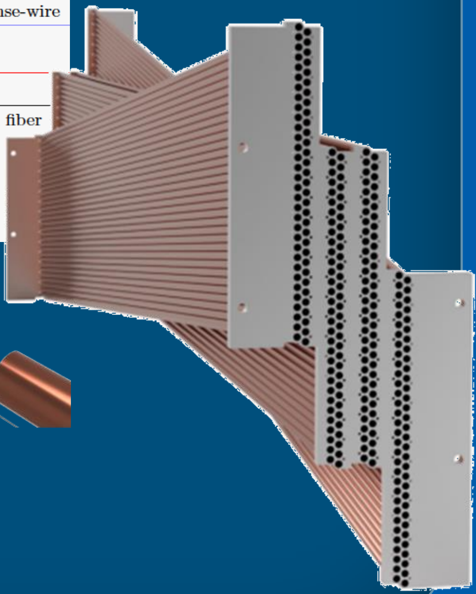
Carbon fibre rod straw suspension



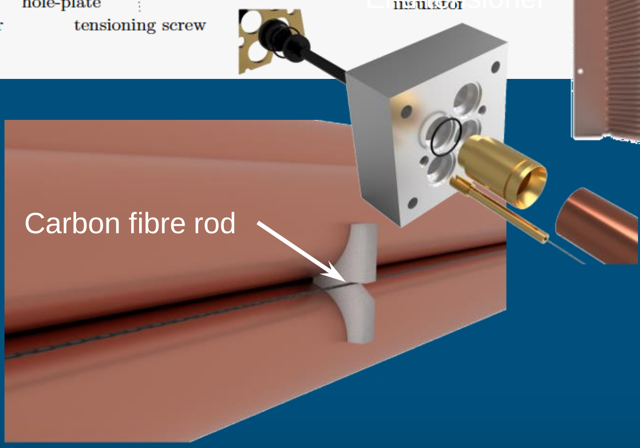
Constant-force spring on stereo-layer



Possible pre-manufacturing of modules



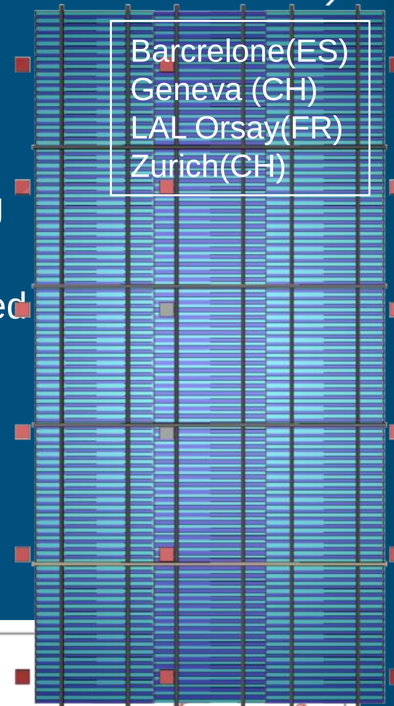
End tensioner

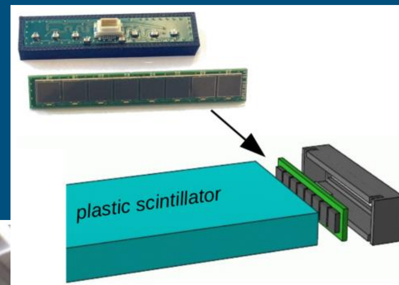


HS Timing Detector (scintillator option)

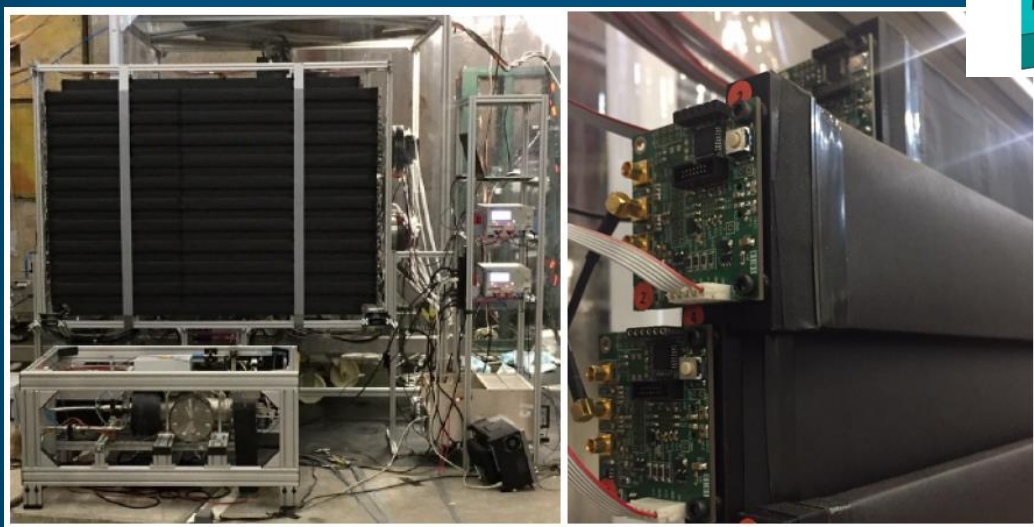
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background

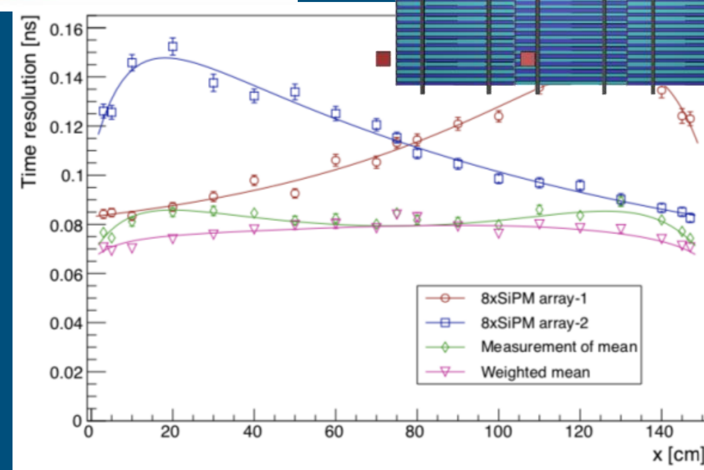
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 168cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed
  - 564 bars and 1128 channels





22x 168cm bar (44 channels) prototype tested at PS

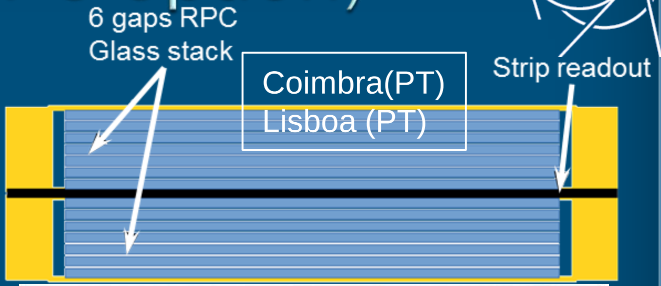


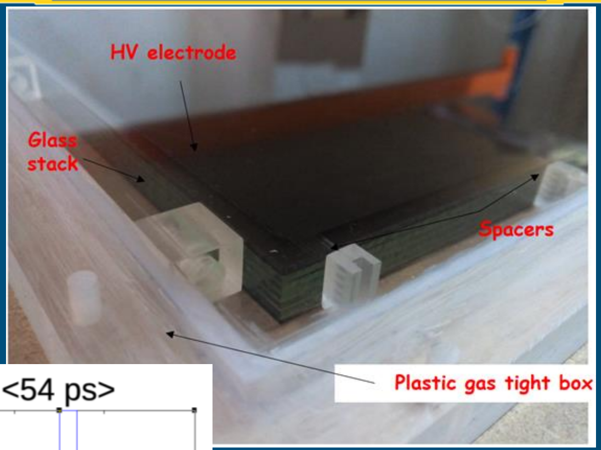


Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

Challenge: In-situ timing alignment

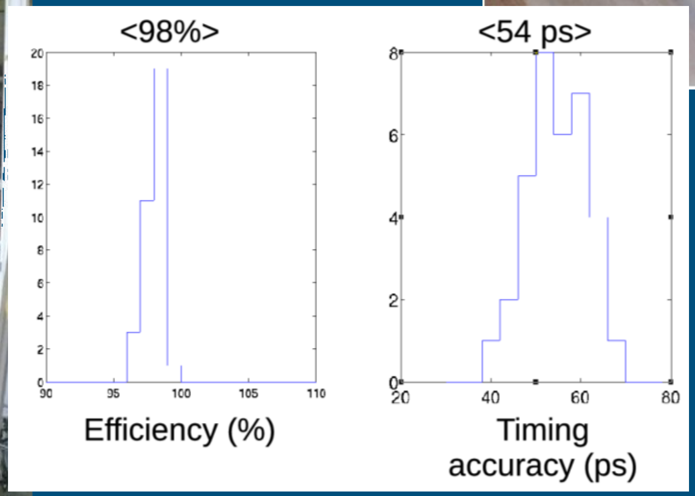
HS Timing detector (MRPC option)





- Characteristics
  - Multi-gap RPC structure: six gas gaps defined by seven 1 mm thick float glass electrodes of about 1550 × 1250 mm^2, separated by 0.3 mm nylon mono-filaments
  - Two identical sensitive modules sandwiched with a plane of pick-up electrodes, consisting of 1600×30 mm^2 Cu strips
  - 2240 FE channels

2m^2 prototype in beam test at PS

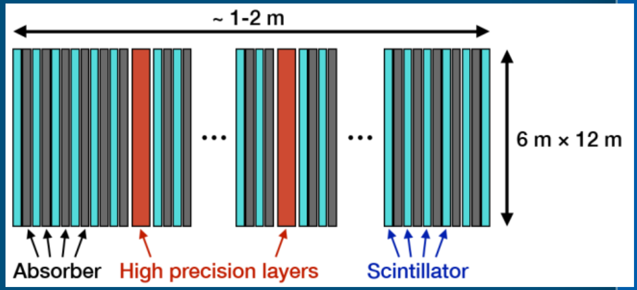


- Efficiency and material budget to be analysed, mechanics and overlap
- Also considered as veto detector in front of decay volume front cap (eq. SBT)

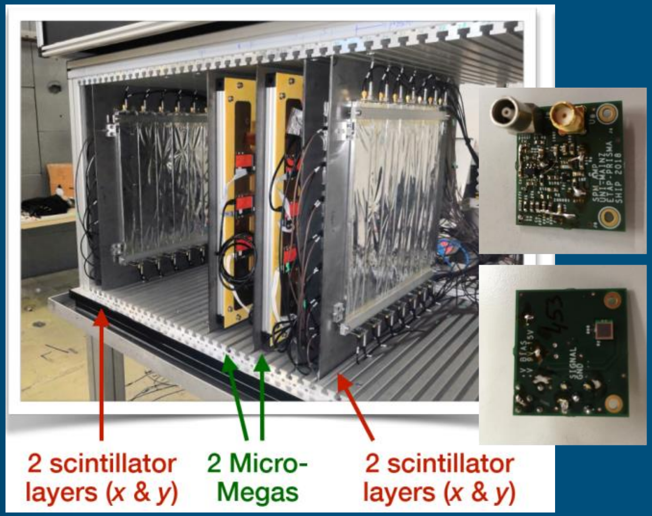
HS ECAL ("SplitCal")

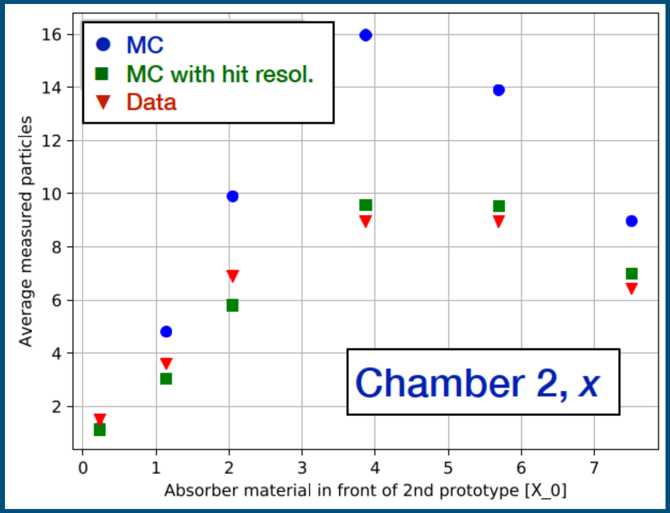
Cagliari(IT)
Mainz (DE)

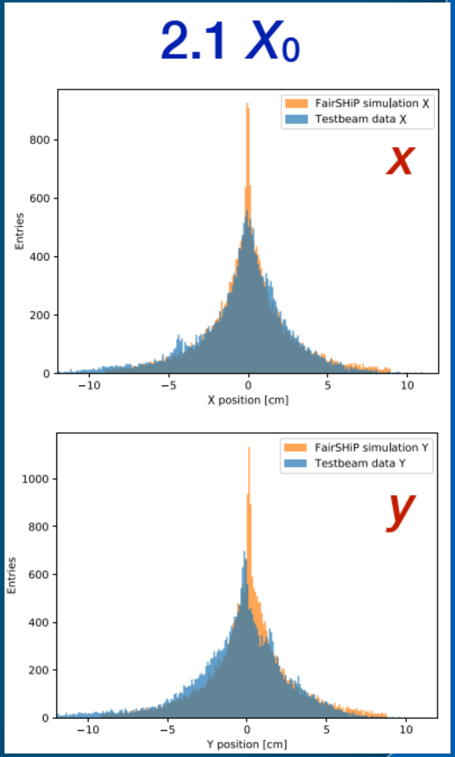
- Purpose: e/γ identification, π^0 reconstruction, photon directionality for ALP→ $\gamma\gamma$
- Characteristics
  - 25 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 40-50 planes of scintillating bar readout by WLS + SiPM (0.28cm/0.5X0 lead + 0.56 plastic)
  - Fine resolution layers: 3 layers (1.12cm thick), first at $3X_0$, and two layers at shower maximum to reconstruct transverse shower barycentre, with resolution of ~200μm micro-pattern or SciFi detectors, to provide photon angular resolution of a few mrad.



Prototype in PS test beam (lead plates removed)





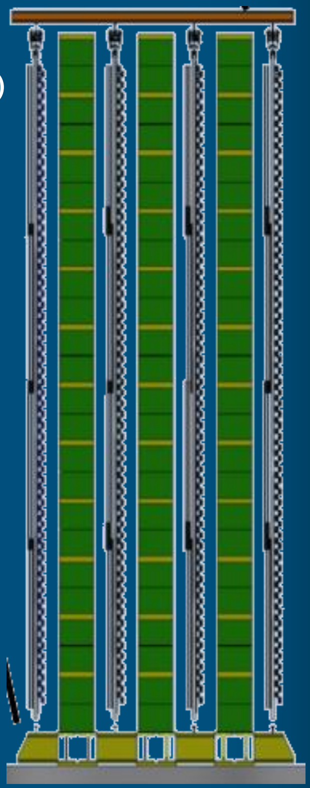


Reconstruction challenge: satellite showers in the long transverse tails

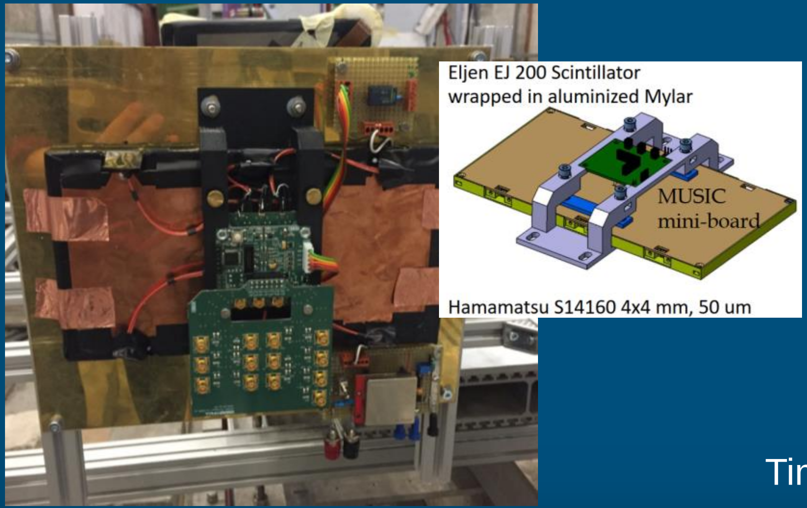
HS Muon system

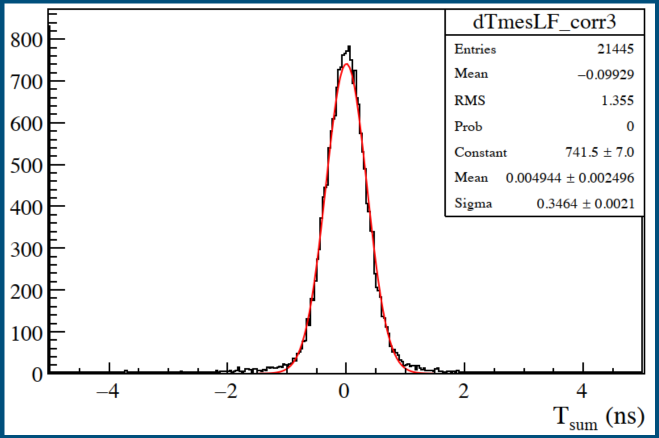
- Purpose: μ/π separation ($\varepsilon_\mu > 95\%,\ p_\mu \in 5-100\ GeV/c$), timing to contribute to reject combinatorial background
- Characteristics
  - Three (four) stations with sensitive area of 6x12m^2
  - Calorimeter equivalent to 6.7λ (p_μ >2.6 GeV/c)
  - Muon filters of 60cm (3.4λ each) + 10cm shielding behind last station (p_μ >5.3 GeV/c)
  - Granularity $\mathcal{O}(10x10)$ cm^2 driven by multiple scattering
  - Hit rates up to 300 kHz along vertical sides
  - Baseline scintillating tiles 10x20cm^2 with direct SiPM (6 SiPM 4x4mm^2) readout
  - 3200 channels/station
  - EJ200 scintillator expensive, test Russian UNIPLAST scintillator

Bologna(IT)
INR(RU)
LAL Orsay(FR)
LNF(IT)
MEPhy(RU)



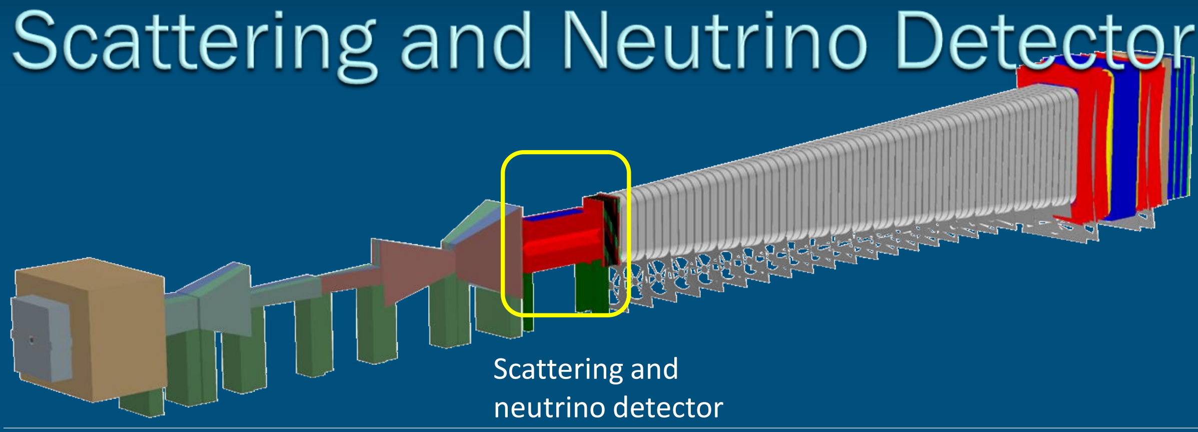
Scintillating tile prototype in PS test beam





Time resolution of ~ 340 ps measured in test beam

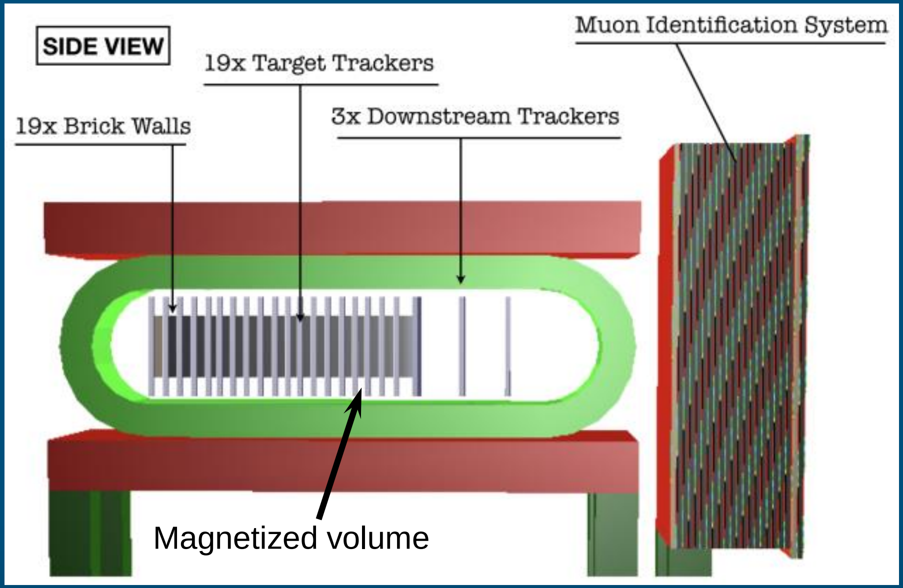
Scattering and Neutrino Detector



- Objective
  1. Studying interactions of ν_τ, charm production induced by neutrinos etc, and normalization of HS yields
  2. Searching for Light Dark Matter through scattering against atomic electrons

  ➔ Detector based on re-development of Opera concepts

  ➔ Magnet allows distinguishing between neutrino and anti-neutrino interactions



Equivalent of 10 tonnes lead target @ 40m is 450 tonnes liqAr @120m

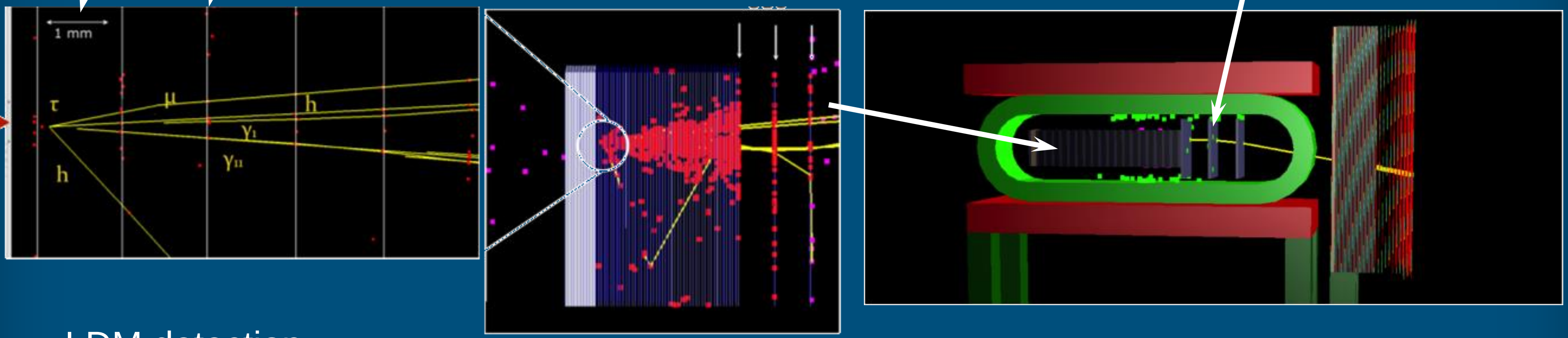
Momentum of hadrons measured by Compact Emulsion Spectrometers in each brick wall

Momentum of muons by Downstream Trackers

Scattering and Neutrino Detector

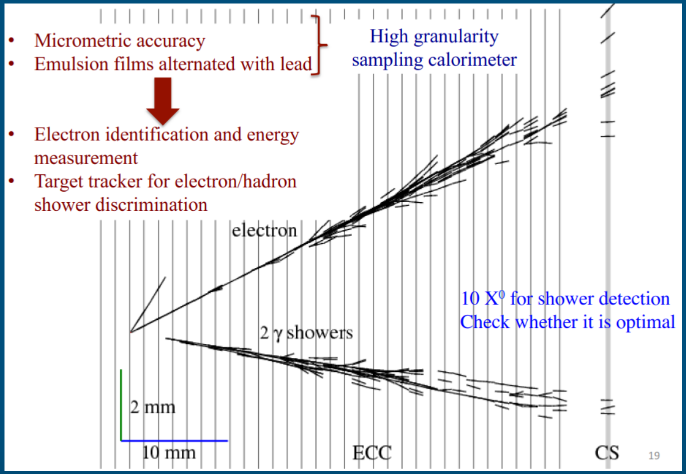
- <u>Neutrino detection</u>

Lead plate   Emulsion film   Muon momentum measurement

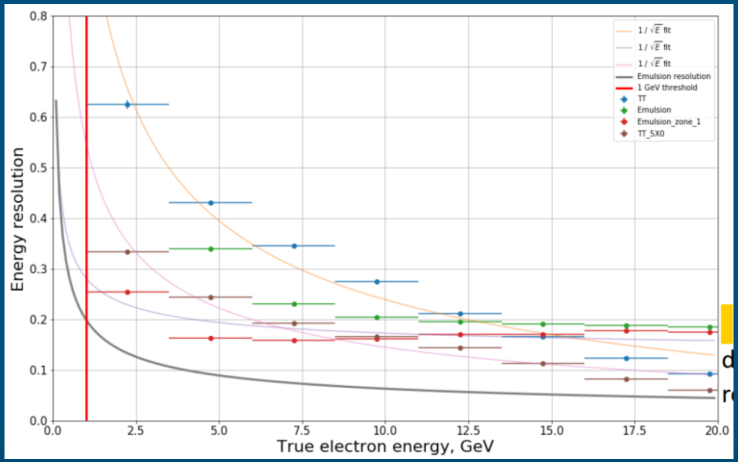


- <u>LDM detection</u>
  - Detection of electromagnetic shower and reconstruction of origin by electronic target tracker

ν_e event in Opera

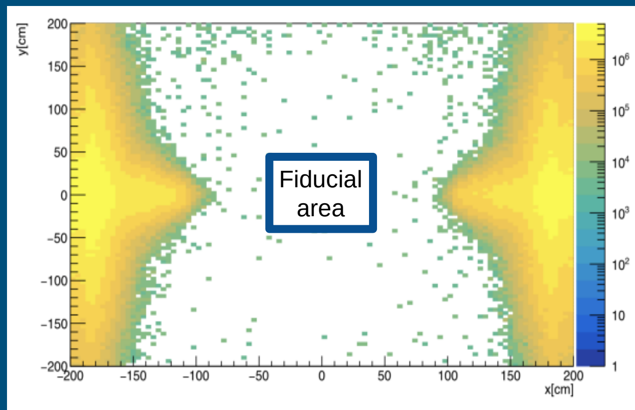


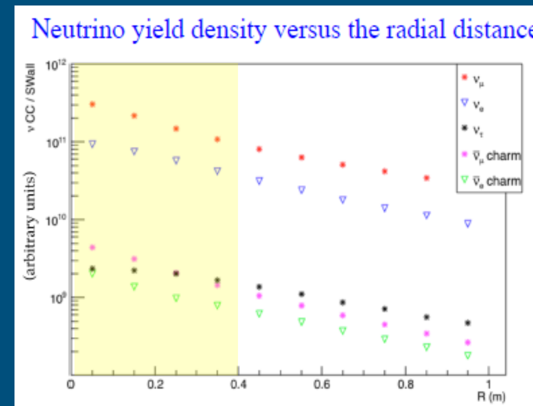
Optimization of emulsion/target tracker configuration: energy resolution

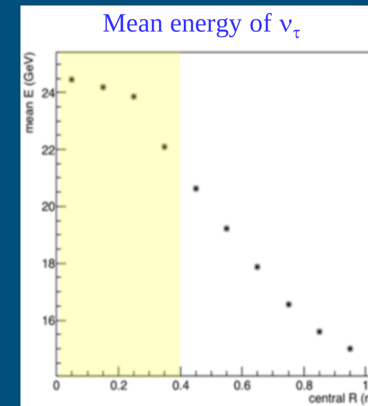


SND optimization

Cross-section of muon flux at start of SND







➔ Target volume 0.8 x 0.8 x 3 m^3 ➔ ~8 tonnes

Number of ν-interactions in ν-target in 2x10^{20} protons on target

	<E>[GeV]	CC DIS interactions
N_{ν_e}	59	1.1×10^6
N_{ν_μ}	42	2.7×10^6
N_{ν_τ}	52	3.2×10^4
$N_{\bar{\nu}_e}$	46	2.6×10^5
$N_{\bar{\nu}_\mu}$	36	6.0×10^5
$N_{\bar{\nu}_\tau}$	70	2.1×10^4

Number of reconstructed ν_τ interactions

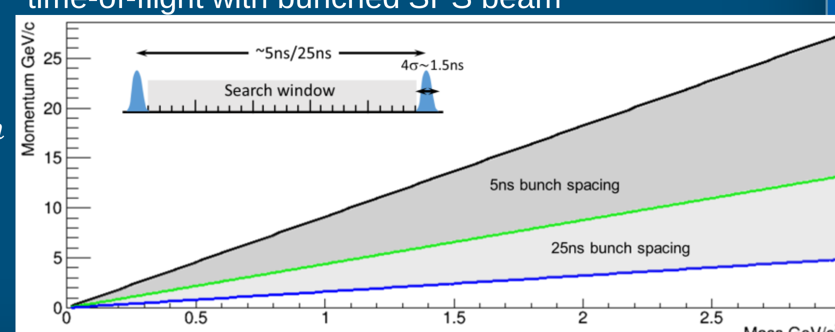
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

Number of background events in LDM search in 2x10^{20} protons on target

Background	ν_e	$\bar{\nu_e}$	ν_μ	$\bar{\nu_\mu}$	all
Elastic Scattering on e^-	81	45	56	35	217
Quasi-elastic Scattering	245	236	-	-	481
Resonant Scattering	8	77	-	-	85
Deep Inelastic Scattering	-	14	-	-	14
Total	334	372	56	35	797

E.g. $\bar{\nu}_e p \to e^+ n$

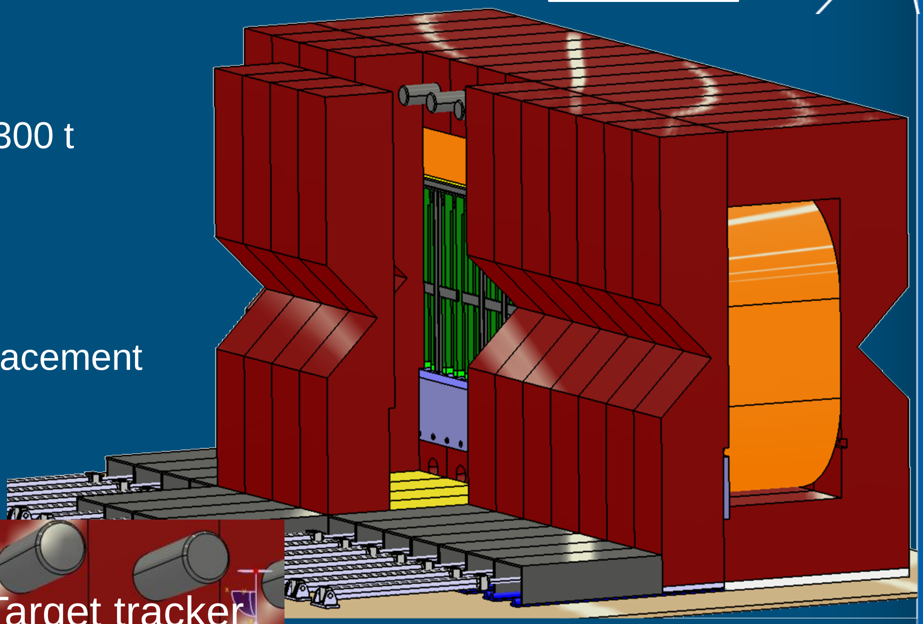
Possibility of discriminating against neutrino by time-of-flight with bunched SPS beam

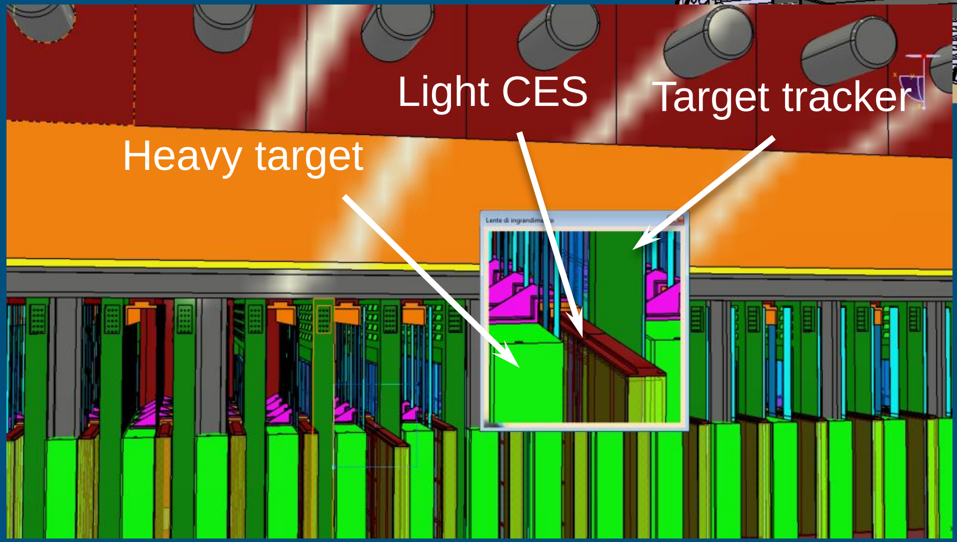


SND magnet

Naples(IT)
CERN

- Characteristics
  - Overall external size 7.2 x 3.6 x 2.2 m^3 , weight 300 t
  - Detector volume 5.6 x 1.6 x 1 m^3
  - Horizontal field ~1.2 T
  - 1.5 – 2 MW
  - To respect emulsion limit of 10^3 tracks/mm^2, replacement every 6 months, CES every few weeks



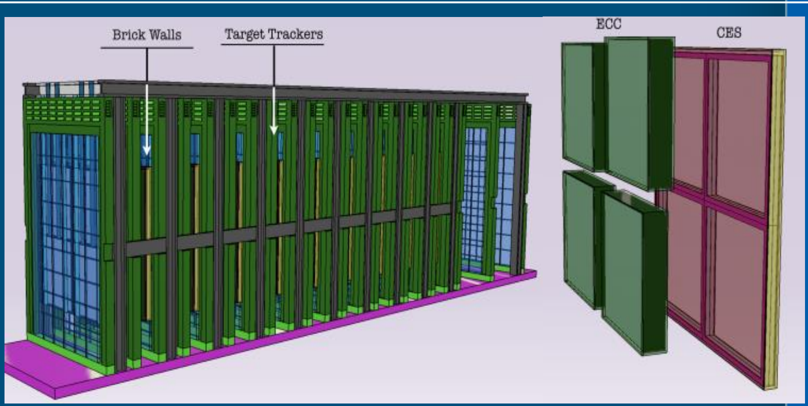


➔ Superconducting option being investigated

SND ECC + Target tracker

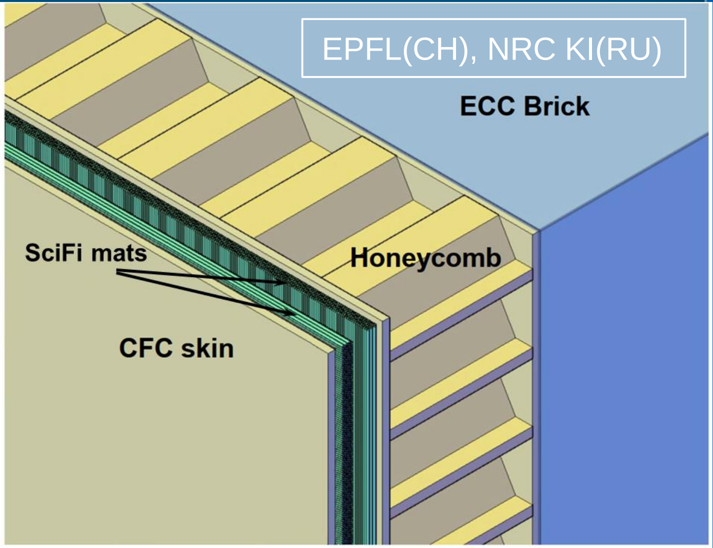
Aichi(JP), Gran Sasso(IT), Gyeongsang (KR), Kobe(JP), LPI(RU), METU(TR), MISiS(RU), SINP MSU(RU), Nagoya(JP), Naples(IT), Nihon(JP), Toho(JP)

- Emulsion Cloud Chamber brick characteristics
  - 4 bricks of 40x40 cm^2
  - Thickness ~8 cm (57 films/lead plates → ~10 X_0)
  - Weight ~100 kg
  - Total 730 m^2 of film x 10 replacements
  - Scanning speed 200 cm^2/h, 10x faster than Opera



- SciFi target tracker characteristics
  - $\sigma_{x,y}$~30-50 μm resolution
  - Six scintillating fibre layers, total 3mm thickness ~ 0.05 X_0
  - Multi-channel SiPM at one end, ESR foils as mirrors on other
  - Time resolution <0.5ns?

EPFL(CH), NRC KI(RU)

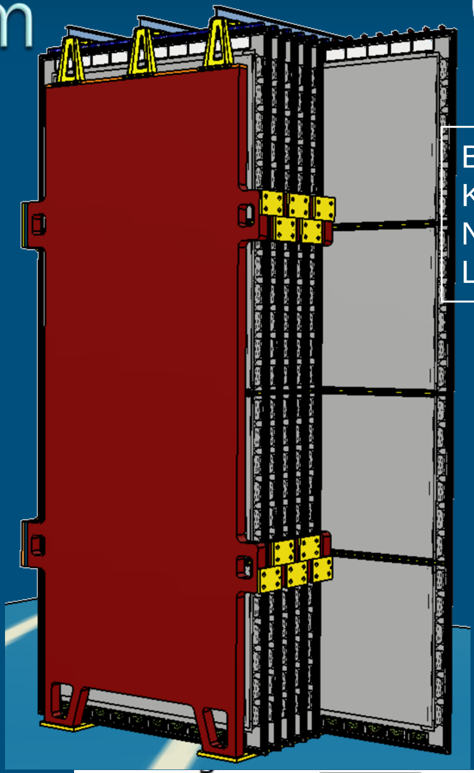


- Detector combination provides a total charge identification efficiency of ~65% for muons produced in ν_μ CC interactions.

- Emulsion + TT beam test at DESY in 2019
  - Emulsion: electron identification and directionality
  - Emulsion + TT: Electron energy and time resolution

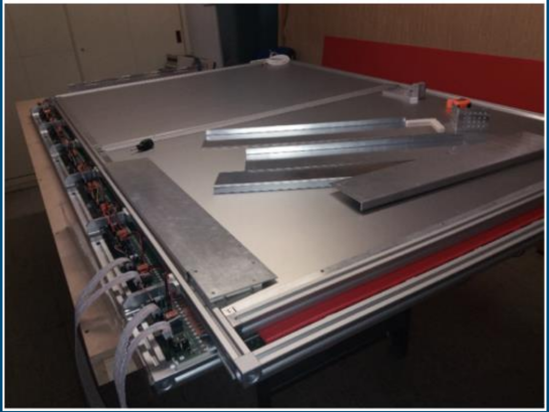
SND Muon system

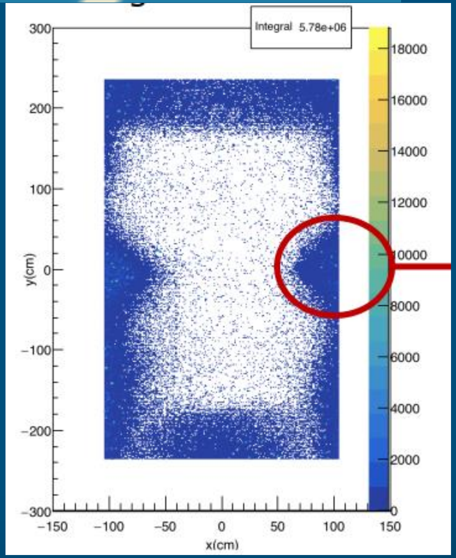
- Purpose: track and identify muons, and tag interactions (ν, μ) in the last layers before entrance window to HS decay volume
- Characteristics
  - 15 iron filters, 10 cm thick
  - 13 RPC, and 3 MRPC layers
  - Sensitive area of ~2×5 m^2
  - RPCs operated in avalanche mode due to high rate of muons
  - Geometrical acceptance ~75% and $\varepsilon_{\mu ID}$ = 96.7% with a mis-identification of hadrons of 1.5%.



Bari(IT)
Kodel(KR)
Naples(IT)
LIP(PT)

RPC prototypes built for muon flux and charm production measurement at SPS in 2018

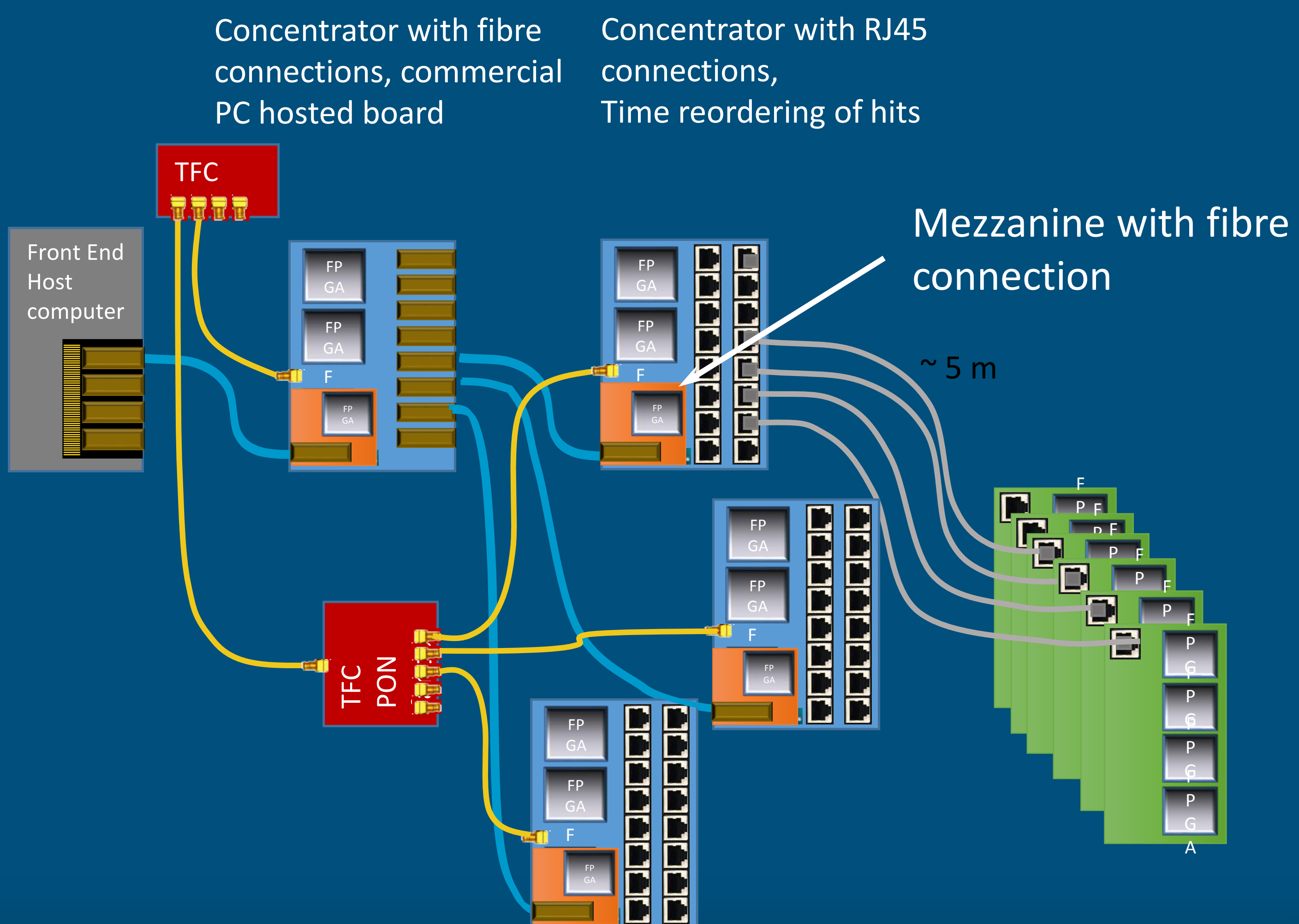




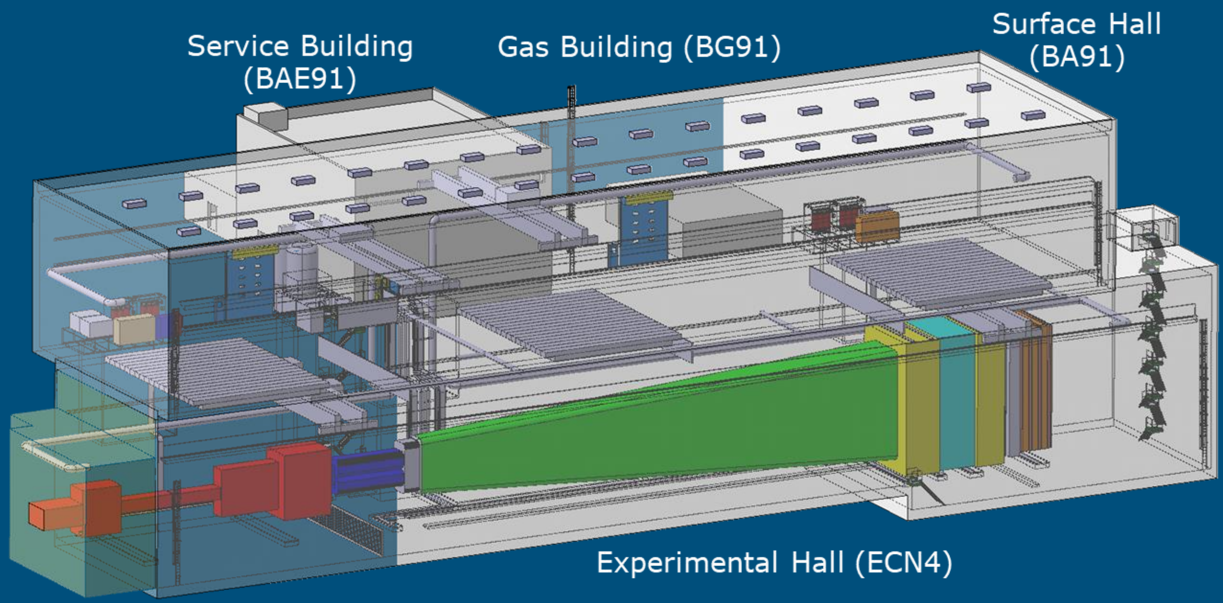
Electronics and readout

- Subsystem architecture – aiming for common electronics
- DAQ system simulation in preparation
- FE available or under development

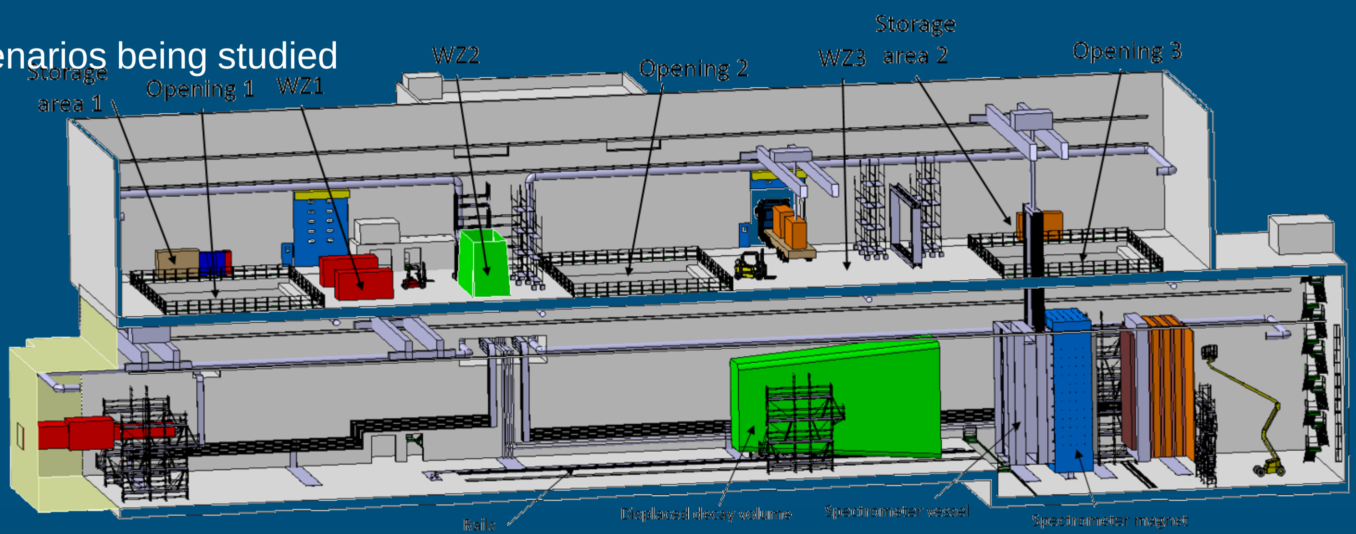
LAL Orsay(FR)
NBI(DK)
Stockholm(SE)
Uppsala(SE)
CERN



Experimental Area



Installation scenarios being studied



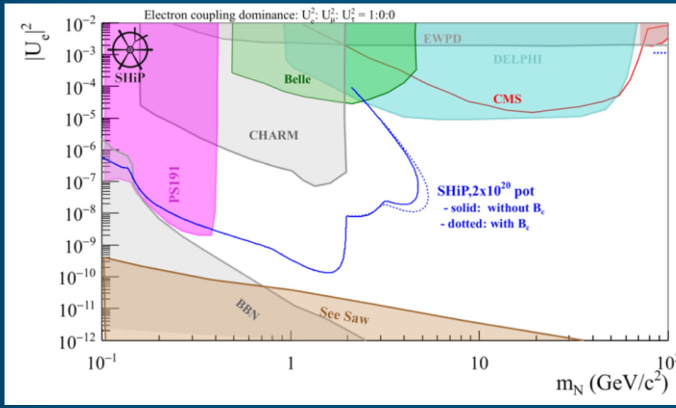

The Beam Dump Facility

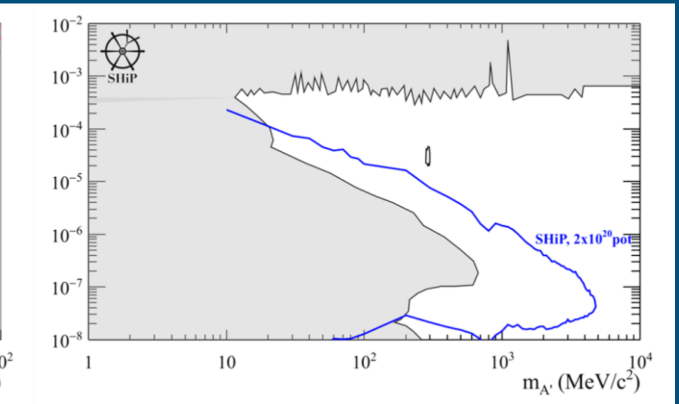
Hidden Sector performance

Hidden Sector decay search background estimates for 2×10^{20} protons on target

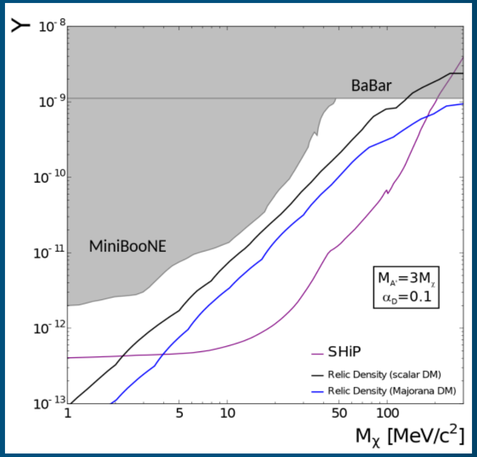
Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}

Sensitivity to HNLs and Dark Photons

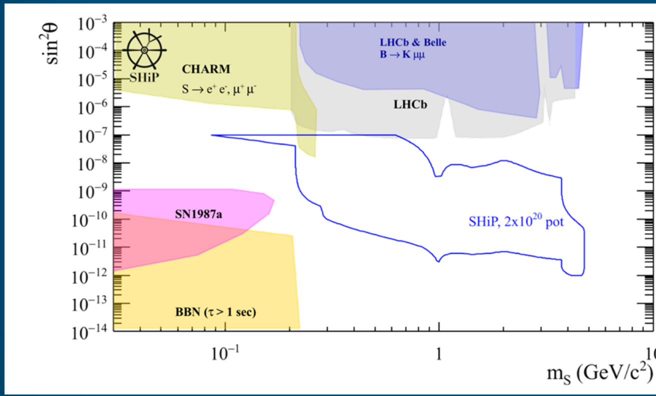


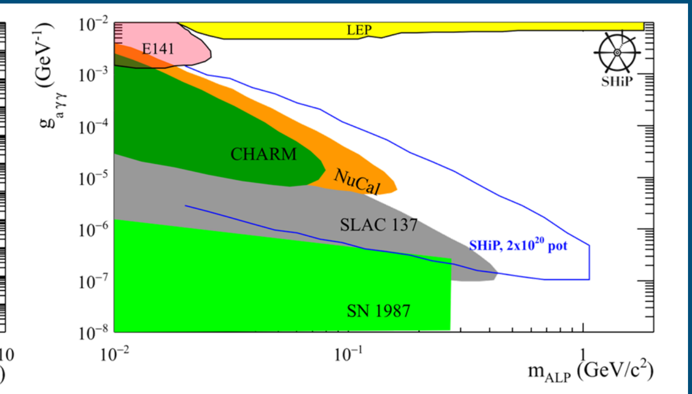


Sensitivity to LDM



Sensitivity to Dark Scalars and ALPs





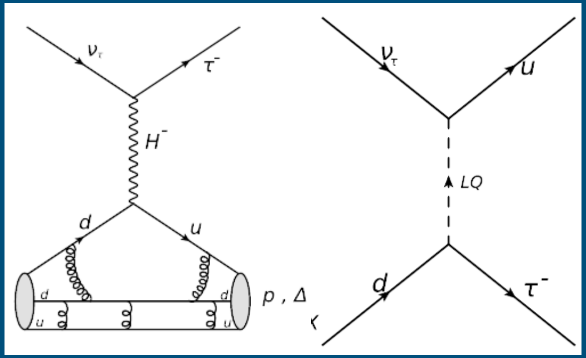
SM Physics: Prospects for ν_τ (ν_e, ν_μ)

1. First observation of $\bar{\nu}_\tau$ interaction
2. Measurement of ν_τ and $\bar{\nu}_\tau$ cross-sections

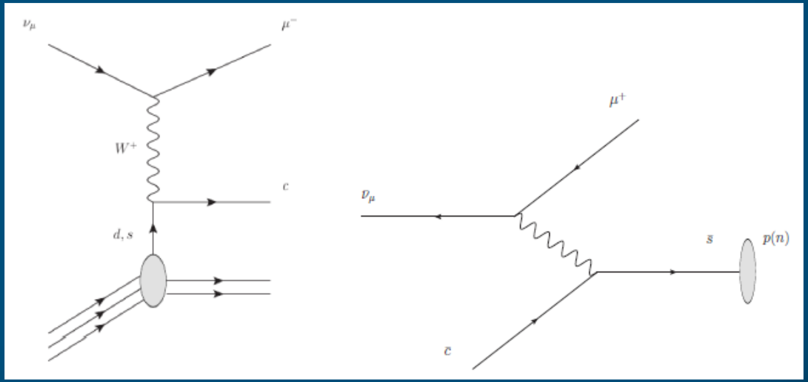
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right] F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2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

➔ Allow extraction of F4 and F5 structure functions from charged current neutrino-nucleon DIS

➔ Beyond SM



3. ν_τ magnetic moment
4. ν_e cross section at high energy
5. Testing strange quark content of nucleon through charm production



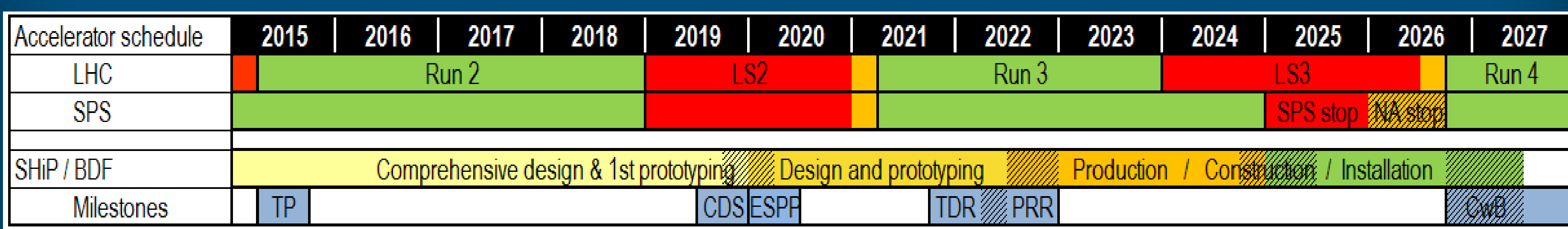
5. Normalization of hidden particle search
6. LNU

Next steps

- BDF CDS report final editing

- SHiP CDS report submission November for review
  - Finalize analyses of updated detector performances (simulation, test beams)
  - Include description of parts that were left out in the progress report, electronics and readout architecture, online system
  - Updated project plan towards TDR and construction
  - Detector costing
  - Preliminary safety file
  - Muon flux and charm results
  - Test beam and measurement requirements in 2021

  ➔ Review muon shield, vacuum vessel, straw tracker



- Latest schedule prepared for BDF is pushing installation of detector into 2027

Conclusion

- *Bright future for Dark Sector*
  - Very much increased interested for Hidden Sector after LHC Run 1

- SHiP@BDF is a mature GP platform for HS exploration
  - Also unique opportunity for ν_τ physics, direct Dark Matter search, LFV τ…

- Facility and physics case based on the current injector complex and SPS

- Detector R&D and design is at an advanced level
  → But many exciting developments still and manpower is more than welcome!

- Ready to produce TDRs by 2021-2022 and data taking in Run 4

Summary

"That was a brilliant idea you had to hire a motivational speaker, Rolf. We must be doing 15 knots."