SHiP project
- status and challenges -

Richard Jacobsson

Experimental context

Limited theoretical guidance on the Higgs boson initially…

Nucl. Phys. B106 (1976)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

334 *J. Ellis et al. / Higgs boson*

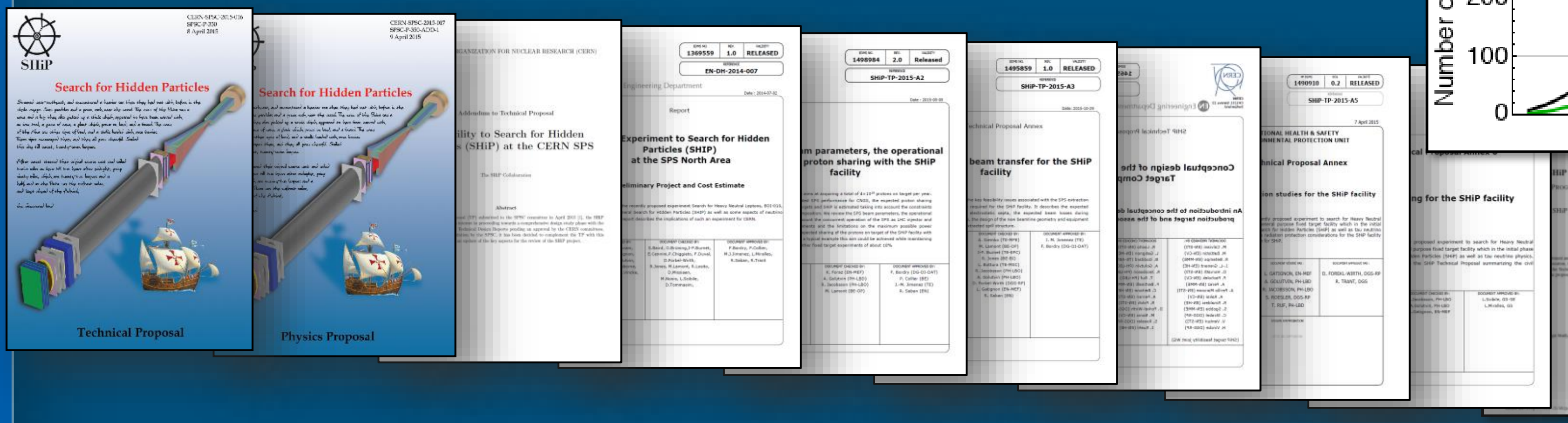
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

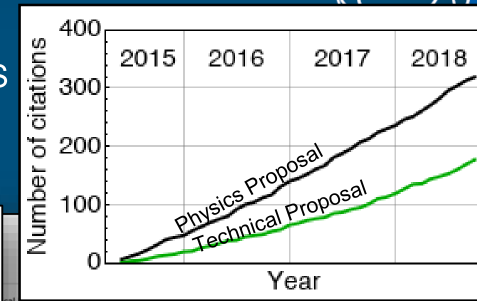
Compare J. Jaeckel….

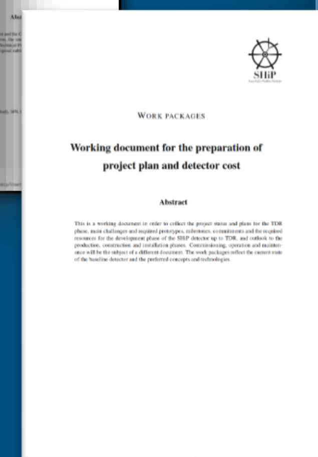
➔ Hidden Sector: Room for progress in theory and expect guidance from the cosmic frontier

SHiP history

- 2013 Oct: EOI with SHiP@SPS North Area, right E and 4×10^{19} p/year 'free' after CNGS
  ...following brainstorming SHiP@IP8, SHiP@LBD, SHiP@CNGS, SHiP@WANF







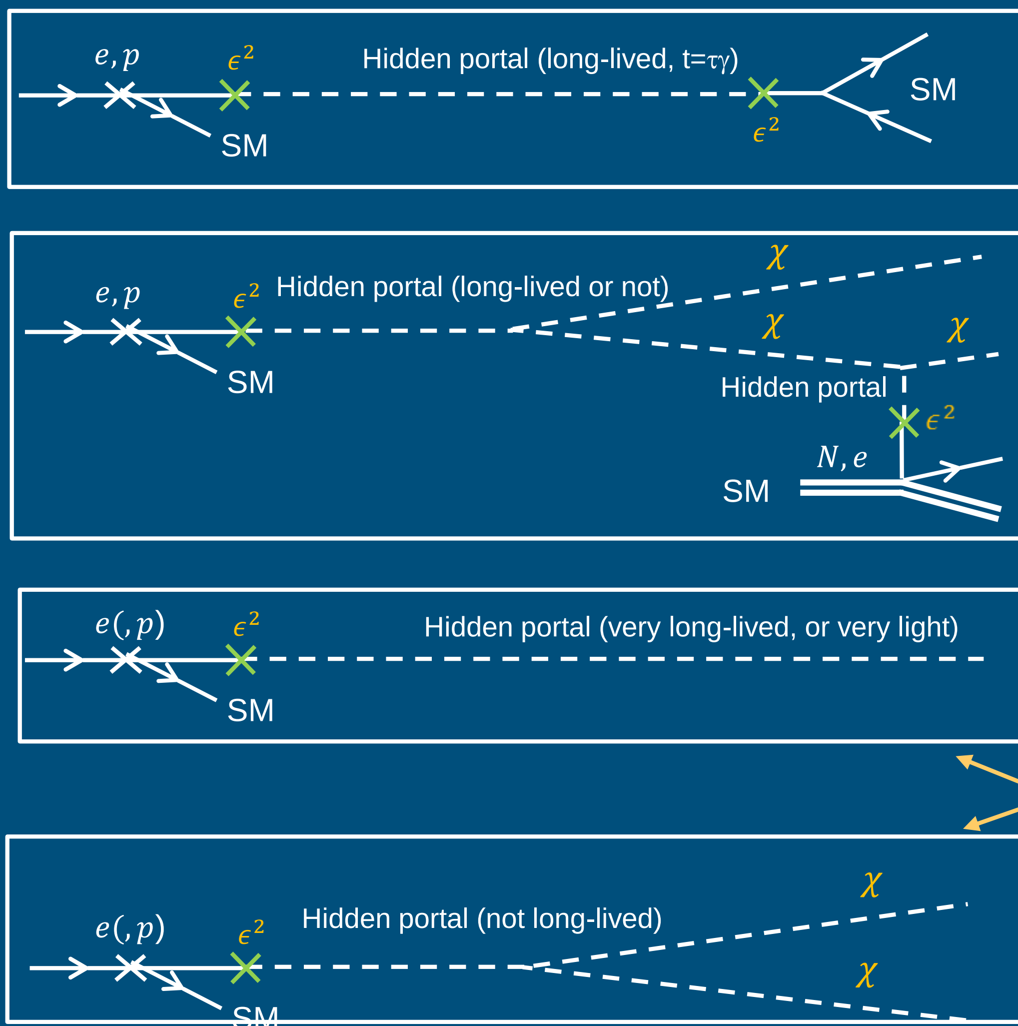
- 2014 Jan: Encouraged to form collaboration and produce TP and inter-departmental task force setup to study feasibility of proposed facility
- 2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments
- 2016 Jan: Recommendation by CERN SPSC to proceed to Comprehensive Design Study (CDS)
- 2016 Apr: CERN management launch of Beyond Collider Physics study group
  - SHiP experimental facility included under PBC as Beam Dump Facility
- 2018 Dec: EPPSU contribution submitted by SHiP and BDF, and submission of SHiP Progress Report
- 2019 Dec: CDS report submitted by SHiP and BDF
- SHiP Collaboration: ***330 authors, 53 + 4 Institutes, 18 countries, CERN, JINR***

SHiP experimental technique

Production — Detection

Direct

Indirect



Decay signature ("displaced vertex")
Probability $\propto \epsilon^4$
Model independent
+
Reconstruction of decay: mass, PID
→ Distinguish models
→ Measurement of properties

MATHUSLA
ANUBIS
CODEX-b

NA62
NA64
FASER
SHiP

Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP
SND@LHC

Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation

If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

NA64
LDMX

Use of electrons limits search to Dark Photon mediator (&ALPs)

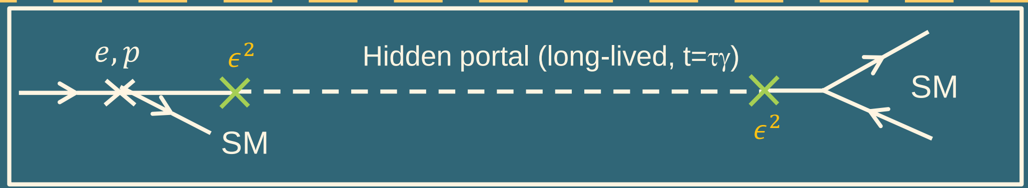
→ Background situation very different in the different techniques!!

SHiP experimental technique

Production

Detection

Direct



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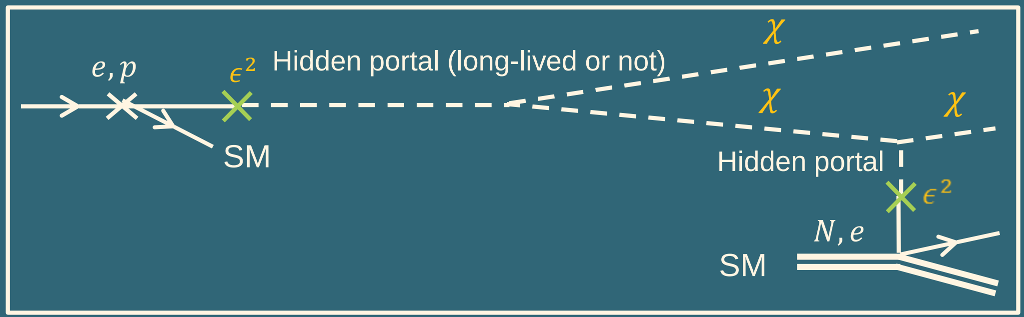
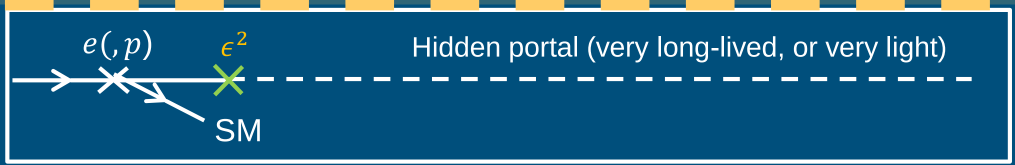


Dark matter scattering
Model-dependent interpretation
Recoil against electron or nuclei
Probability $\propto \epsilon^4$

SHiP
SND@LHC

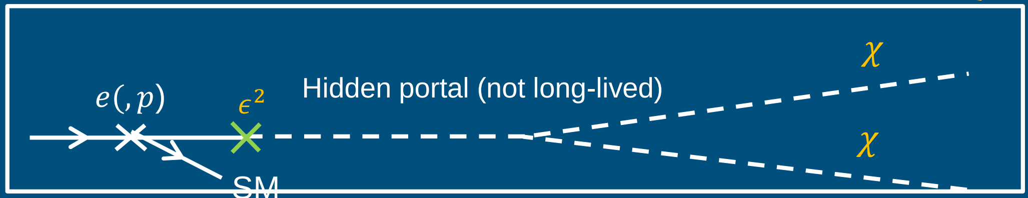
SHiP with protons

Indirect



Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Cannot be directly distinguished
→ Model-dependent interpretation



If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

NA64
LDMX

→ Background situation very different in the different techniques!!

Use of electrons limits search to Dark Photon mediator (&ALPs)

Optimisation of a proton beam dump experiment

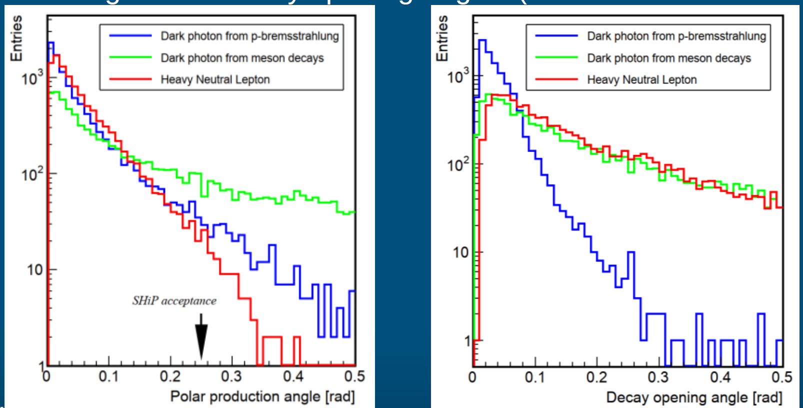
- Hidden Sector phenomenology driven design
  - Production branching ratios $\mathcal{O}(10^{-10})$ → Largest possible number of protons

    ➔ "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
  - Large muon flux → Slow extraction (unique at SPS)
  - Hidden particles 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 scattering → Large detector target mass

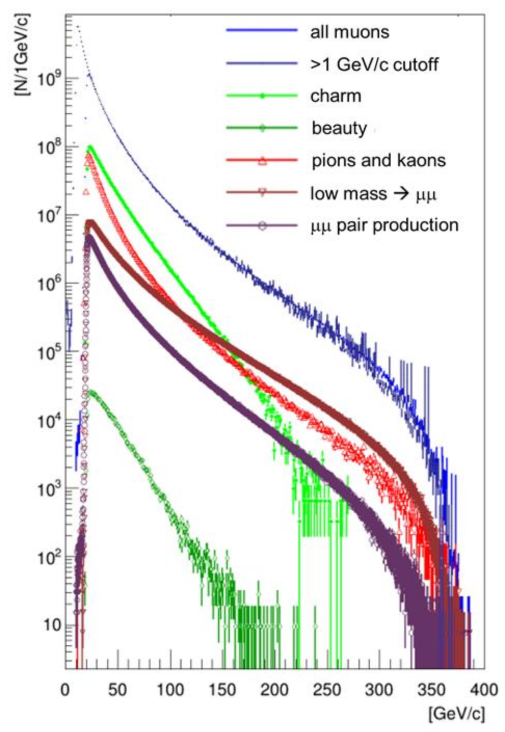
Production angles and decay opening angles (1 GeV/c^2 HNL and DP)



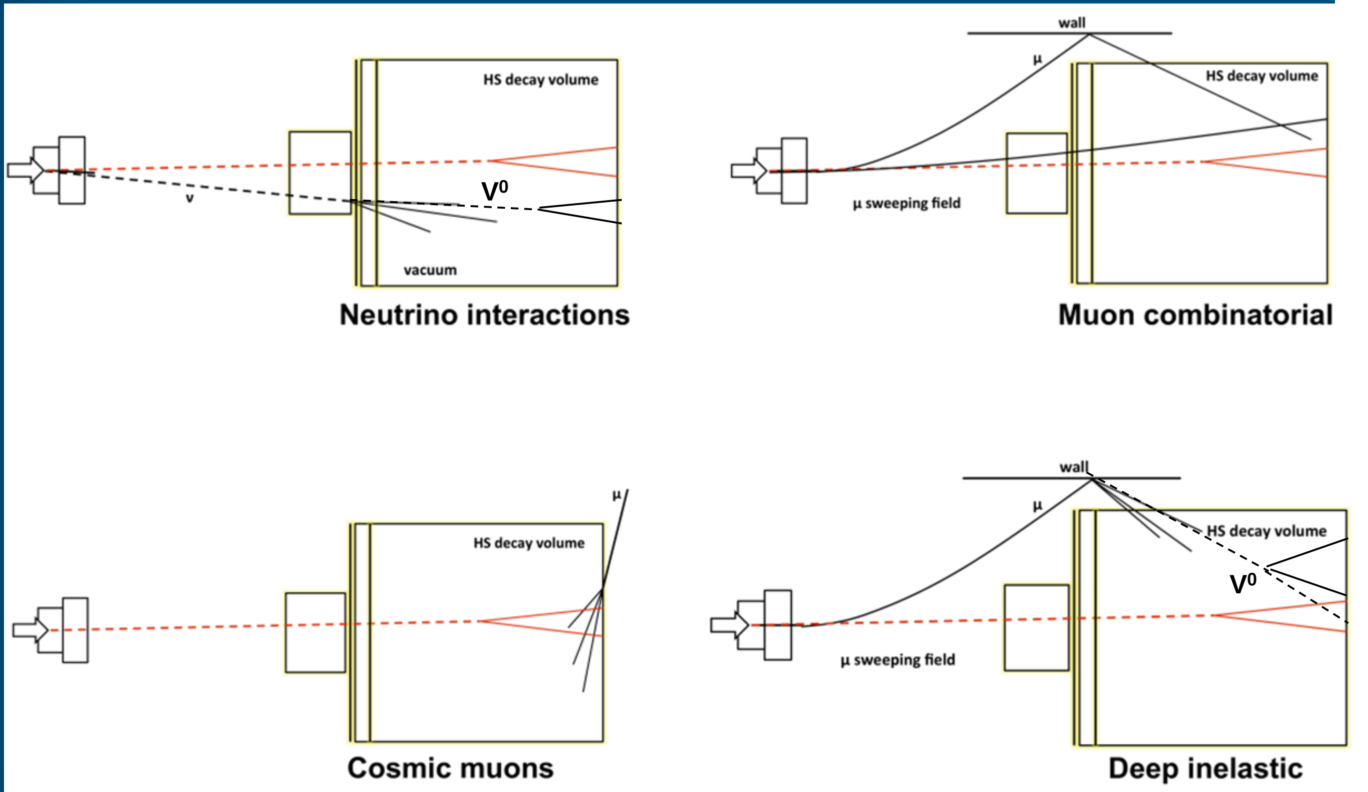
HS beam-induced background

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

Muon spectrum for 5×10^{13} protons on target



Hidden sector decay search background types



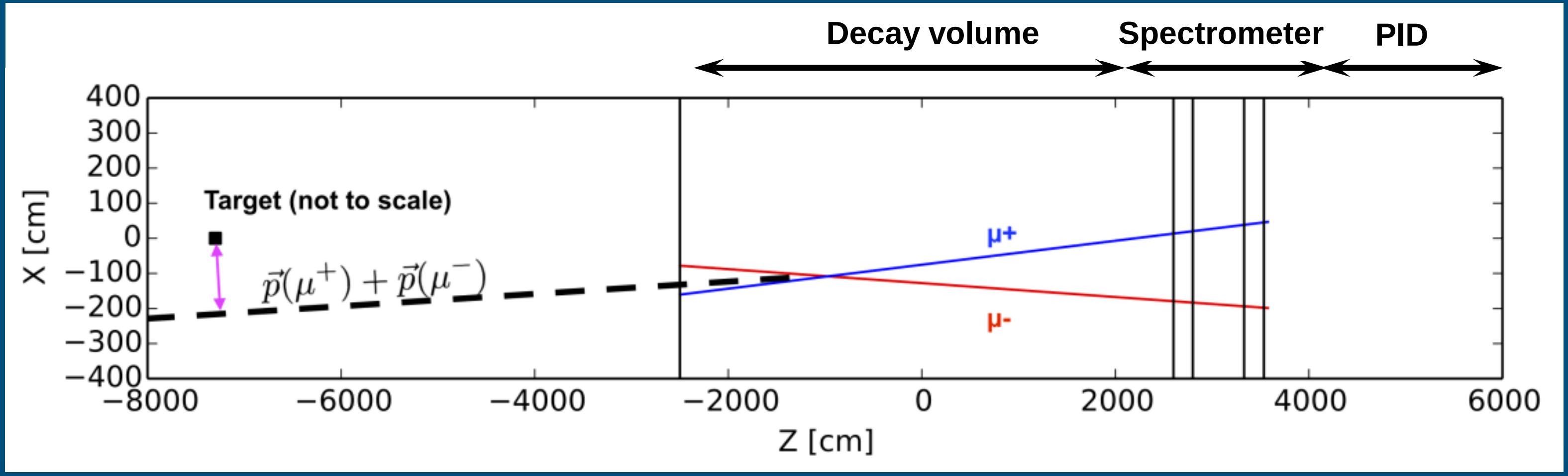
HS Background suppression

- 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	$> 1.0\,\text{GeV}/c$
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

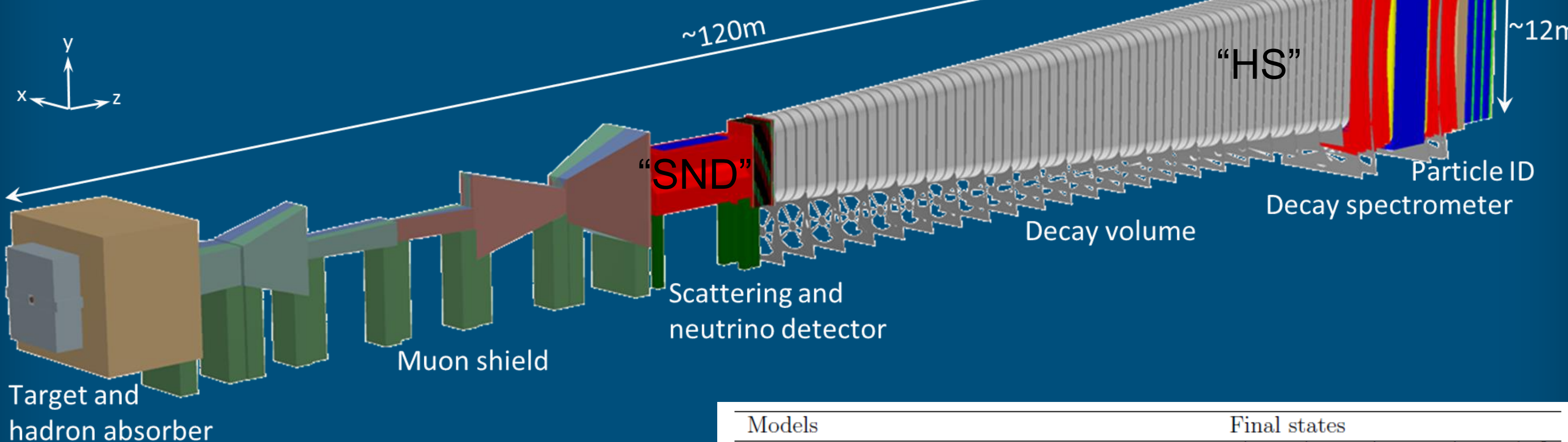
➔ Aim for zero background



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”)



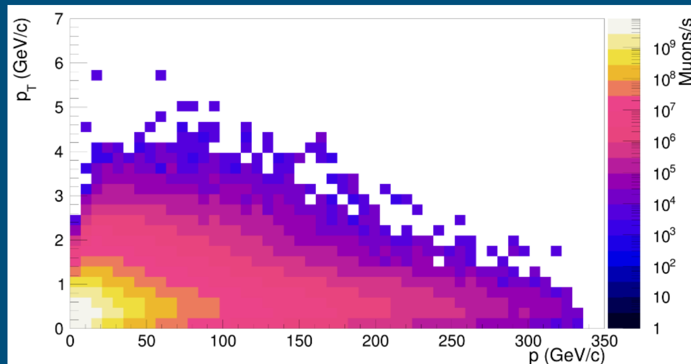
“Unusual” detector conditions
- No radiation
- Low data rates
- Easy cooling and access

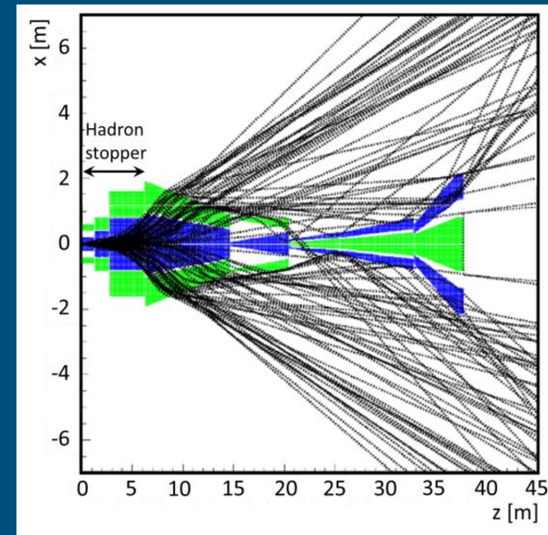
➔ Large-scale engineering of a precision instrument requiring accurate knowledge about background and detector efficiencies

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	$\pi^{0}\pi^{0}$

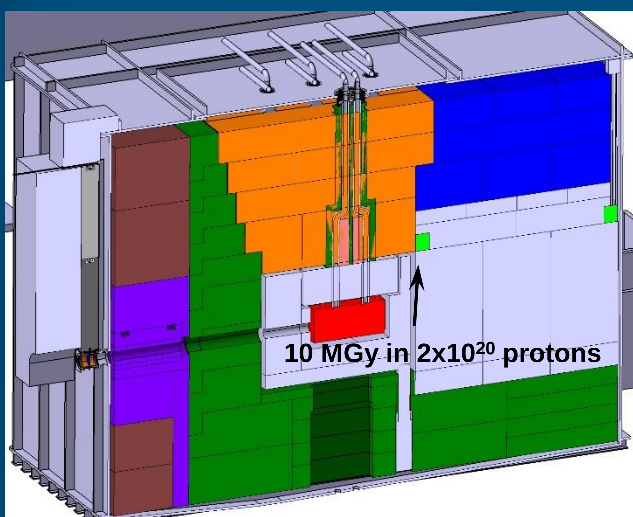
Muon shield

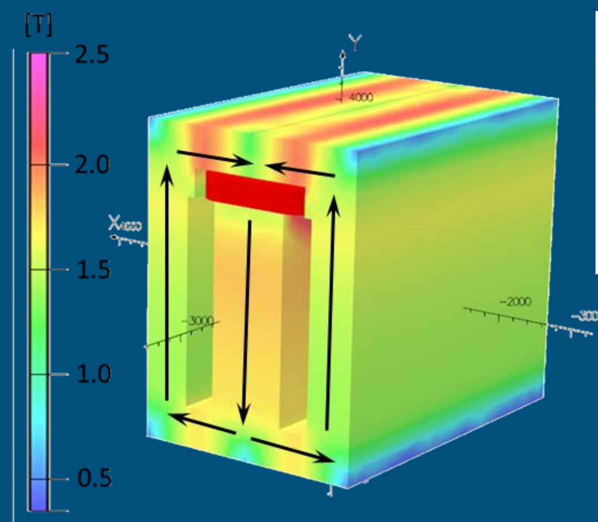
- Based on magnetic deflection of muon flux

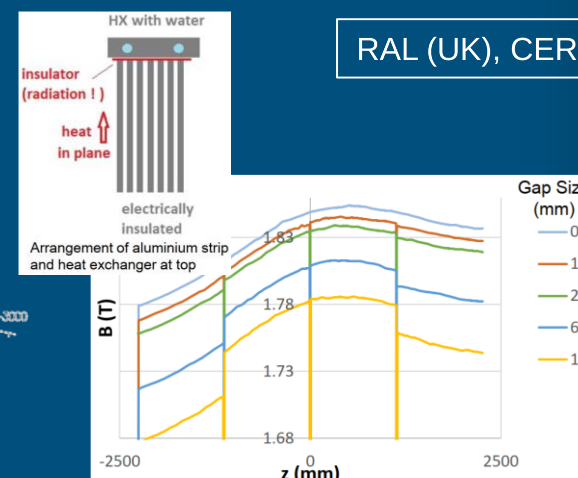




- Muon deflection starts within the target complex: magnetization of hadron stopper







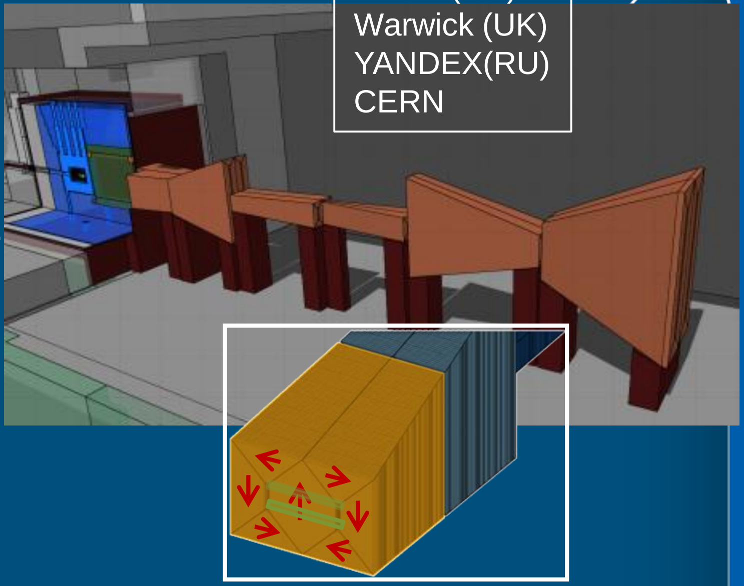
RAL (UK), CERN

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

Muon shield (free-standing)

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

- Rest of muon shield consists of free-standing magnets

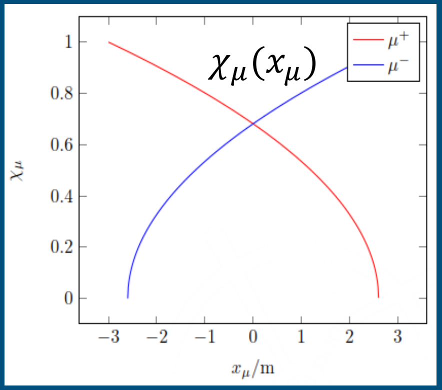


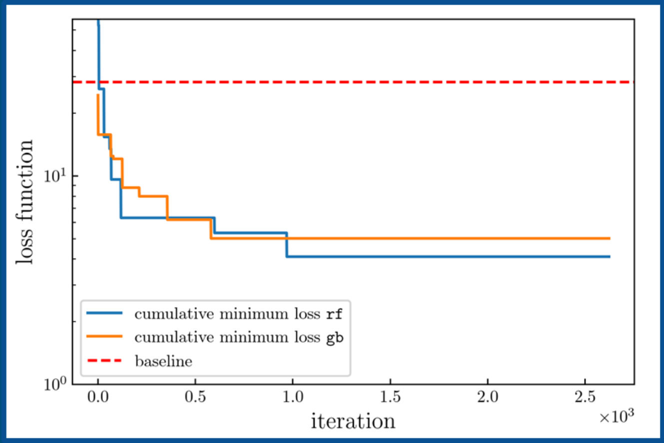
- Optimization of field configuration by Machine Learning with a sample of muons simulated with PYTHIA/GEANT
  - Assumptions: 1.7 T average field in core
    6 magnets of 5m length
    10cm space between magnetic regions
  - Whole setup described by 56 parameters
  - Bayesian optimization→ gradient descent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



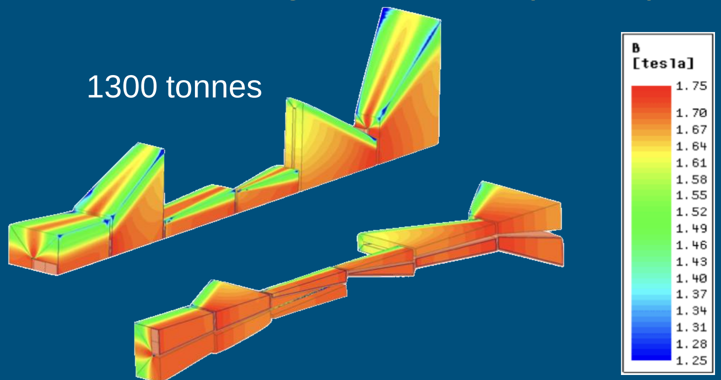


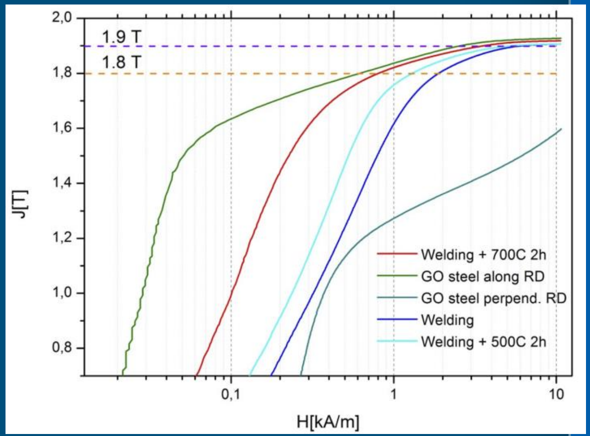
gb = gradient boosted decision trees
rf = random forests

➔ 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 cold-rolled grain-oriented (CRGO) steel, sheets of 0.3-2 mm

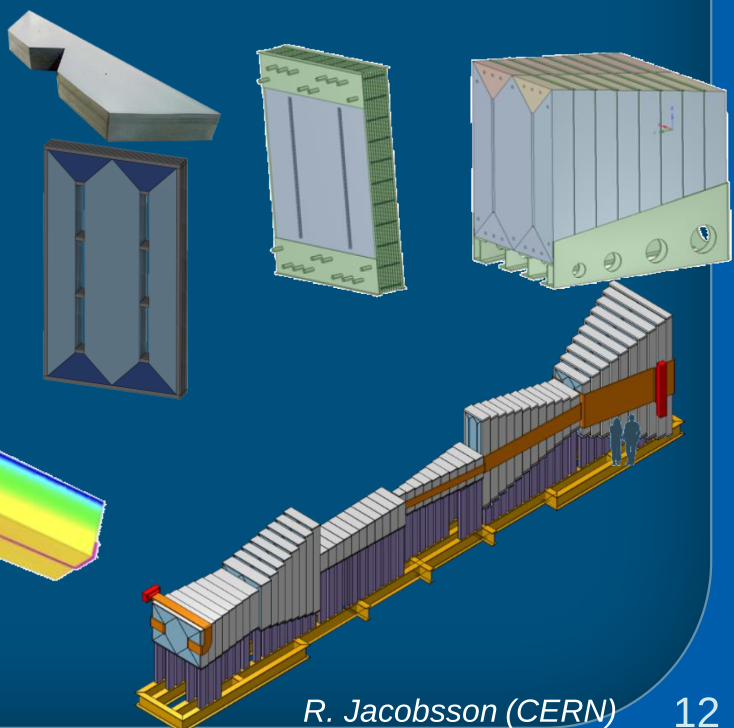


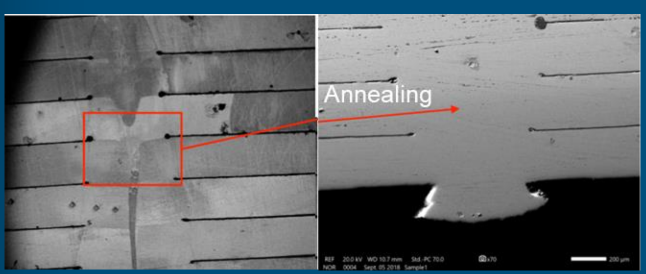


- Technology studies produce realistic field maps for simulation

➔ Assembly of GO steel
- Stacking factor critical
- Investigation of welding of blocks followed by annealing
- Requires large vacuum chamber
- Alternatives? Hydrostatic pressing?

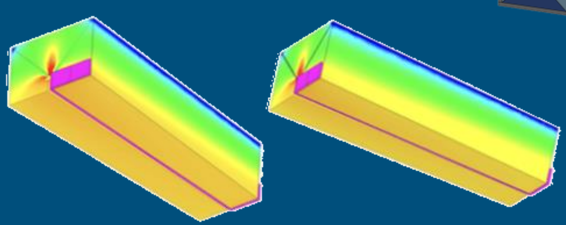
Packs of 50 mm thickness with 150-160 sheets





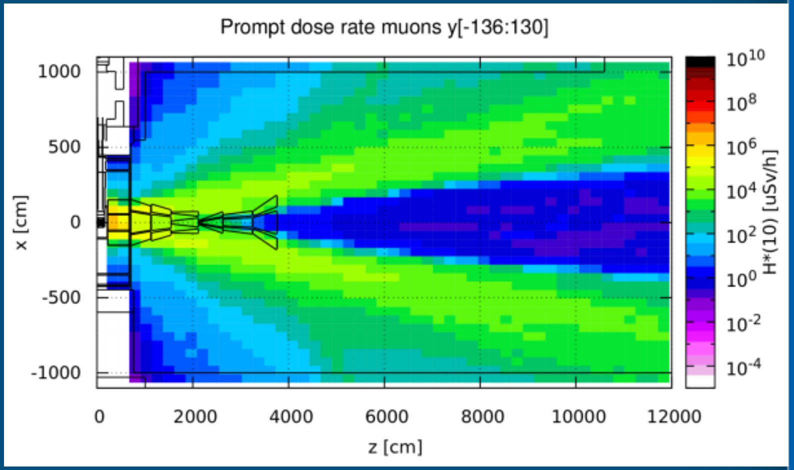
Ideal joint

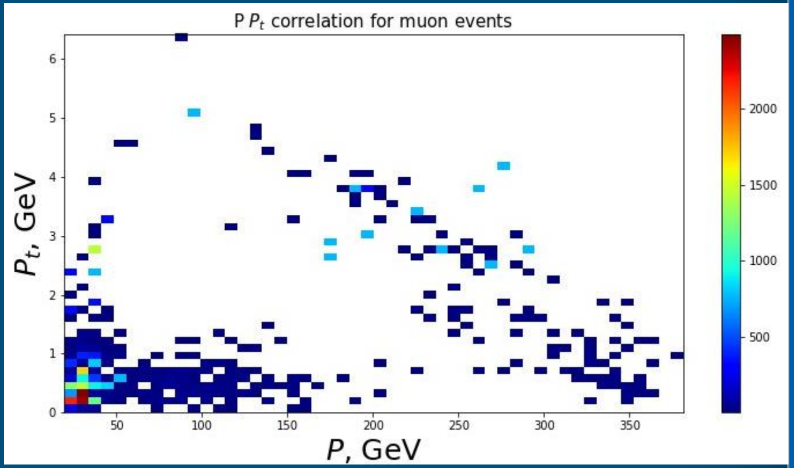
Welded joint



Muon shield (free-standing)

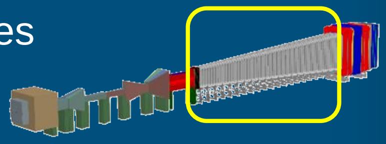
- Performance of muon shield
  - Muons impinging on decay volume: ~5.8x10^4 / spill
  - Reconstructed muons in spectrometer ~3x10^4 / spill
  - 2.1x10^8 muon DIS interactions in decay volume wall in 2x10^{20} protons on target
  - More work is needed on flux in SND detector
- In depth study of “dangerous” muons
  - Muon flux measurement at SPS in 2018
  - Study of catastrophic energy loss
  - Study of ‘electromagnetic debris’
  - ➔ Validation of MC
- Final engineering solution requires re-optimization with extra boundary conditions
  - Prototyping!



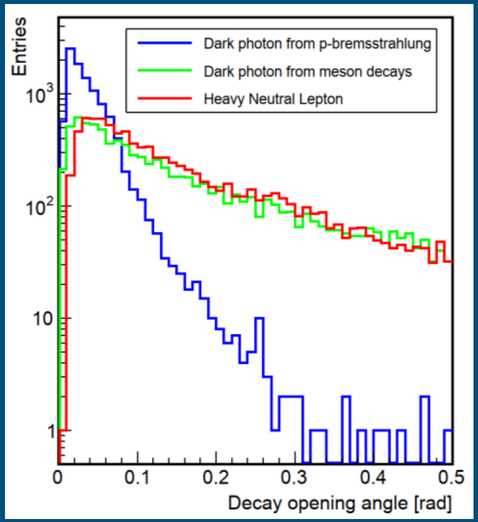


HS Decay volume

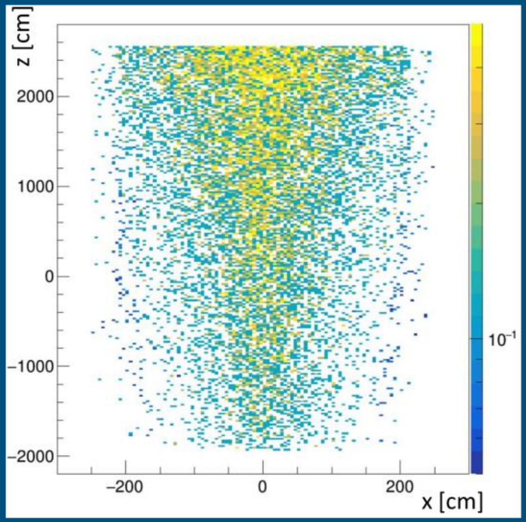
- Optimization of decay volume driven by
  - Muon flux "bow wave" determines ultimate envelope for the fiducial volume
  - Optimization of decay volume geometry (length) with assumption of spectrometer aperture of 5 x 10 m^2 and taking into account decay acceptances for all signal modes
  - ➔ 50m pyramidal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

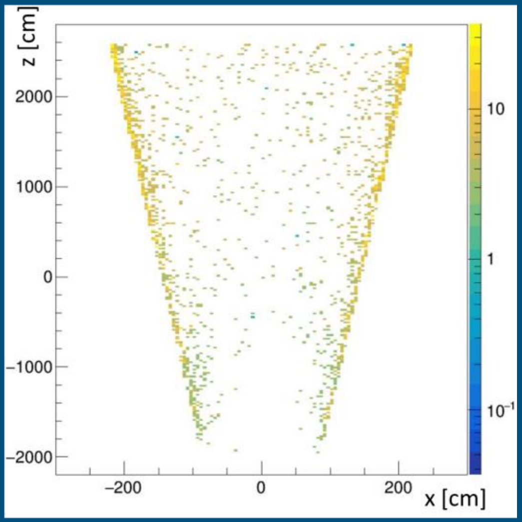


Decay opening angles (1 GeV/c^2 HNL and DP)



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





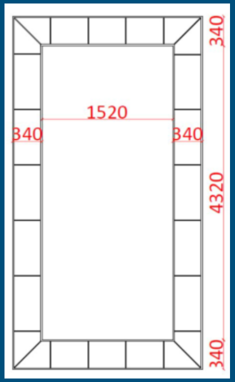
- Neutrino interactions in fiducial volume producing signal candidates (soft selection) in 2x10^{20} protons on target
  - Air: 2.5 x 10^3 candidates with small impact parameter at target ➔ pump down to 10^{-3} bar
  - Vacuum: 1.4 x 10^4 candidates produced in vacuum chamber walls ➔ easily rejected

HS Decay volume

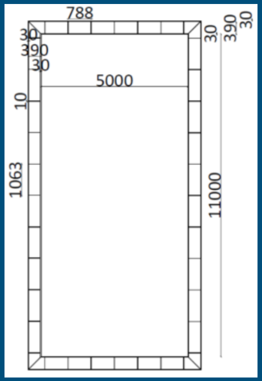
Berlin(DE)
Naples(IT)
NRC KI(RU)
CERN

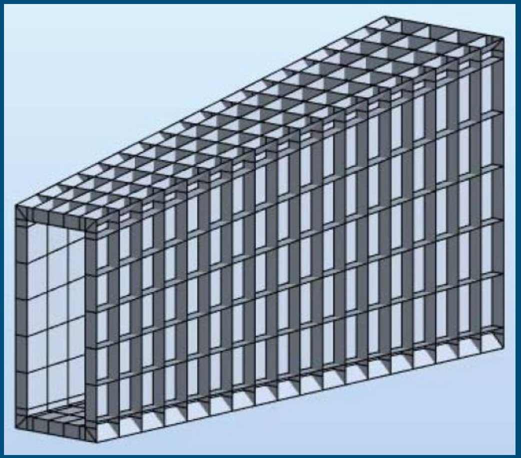
- Requirement:
  - Thin and light wall structure
  - Incorporation of Surrounding Background Tagger
  - ➔ Designed with S355JO(J2/K2)W steel according to EN 13445 Part 3-Section 8 and seismicity
  - ➔ Main challenge is the SBT-LS driven design and integration

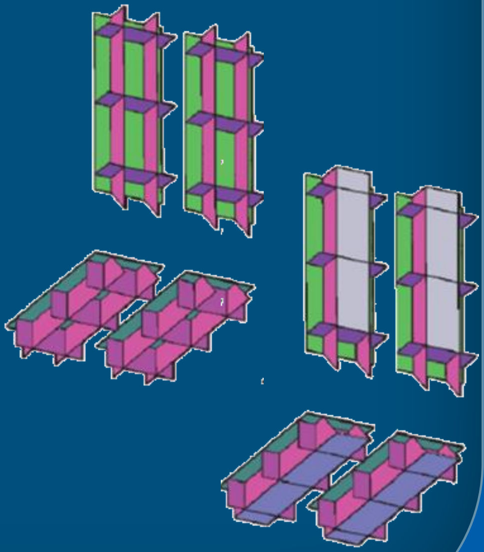
Upstream dimensions

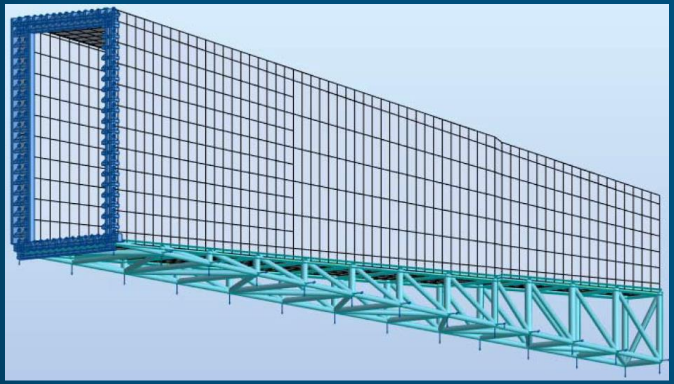


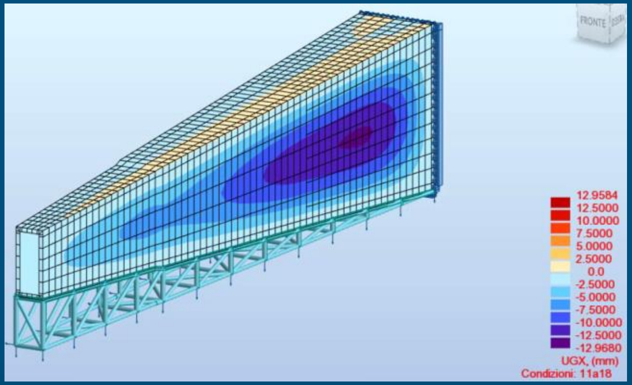
Downstream dimensions









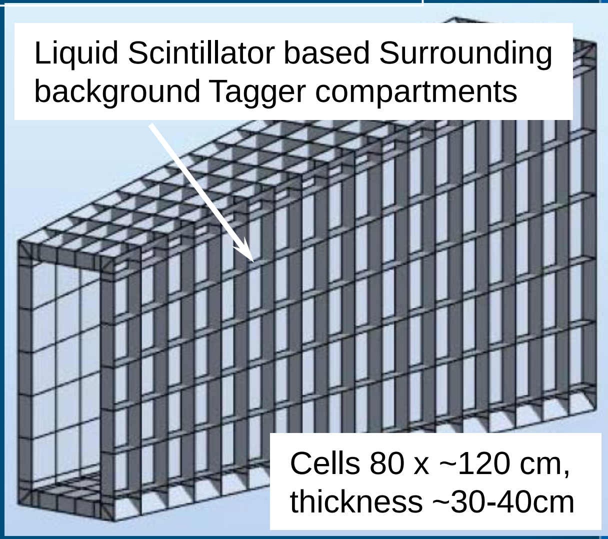


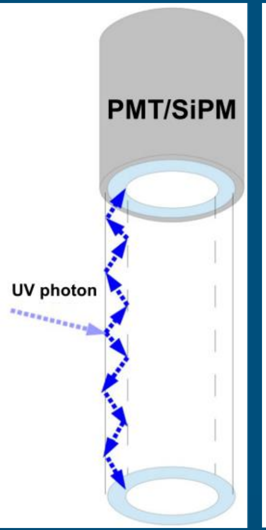
HS Surrounding Background Tagger

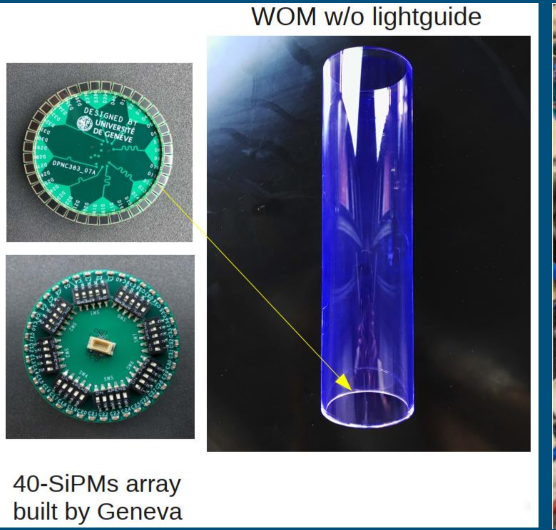
Berlin(DE), Julich(DE), Orsay(FR), Mainz(DE), Naples(IT), Kyiv(UA)

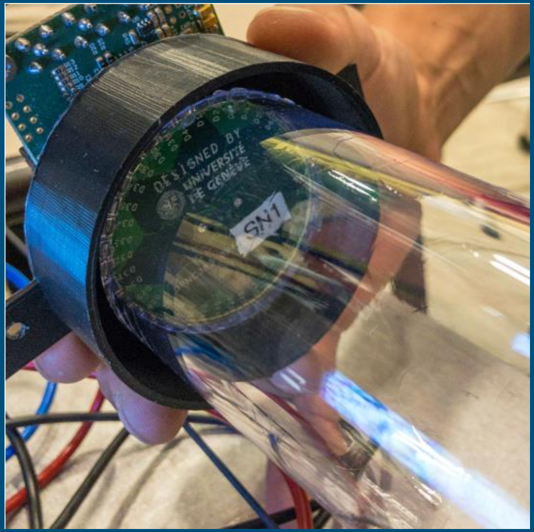
- Purpose: Tagging charged particles entering decay volume and tagging ν and μ interactions in the vacuum chamber walls

- 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



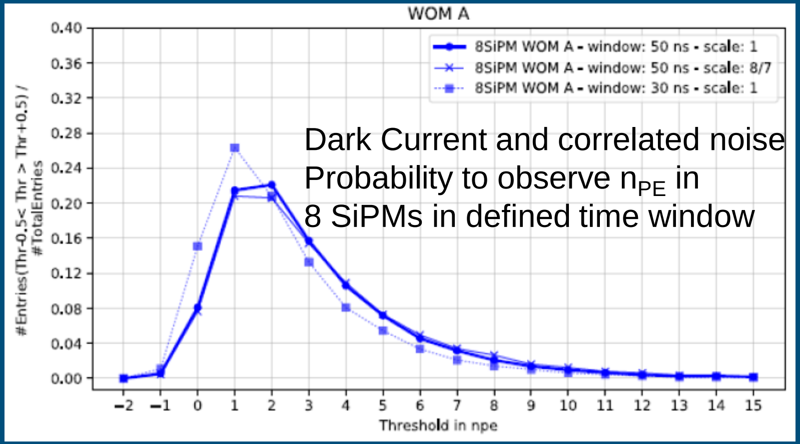


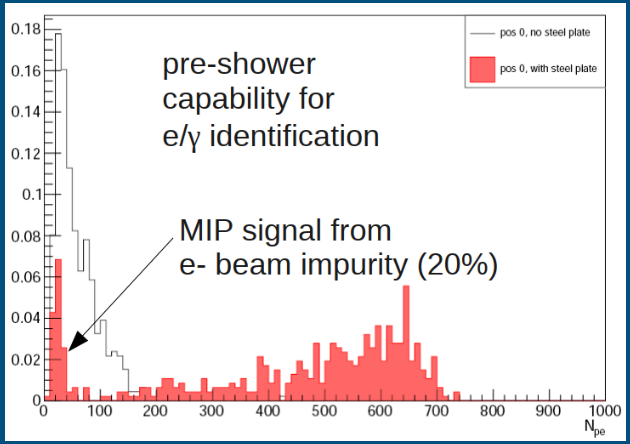


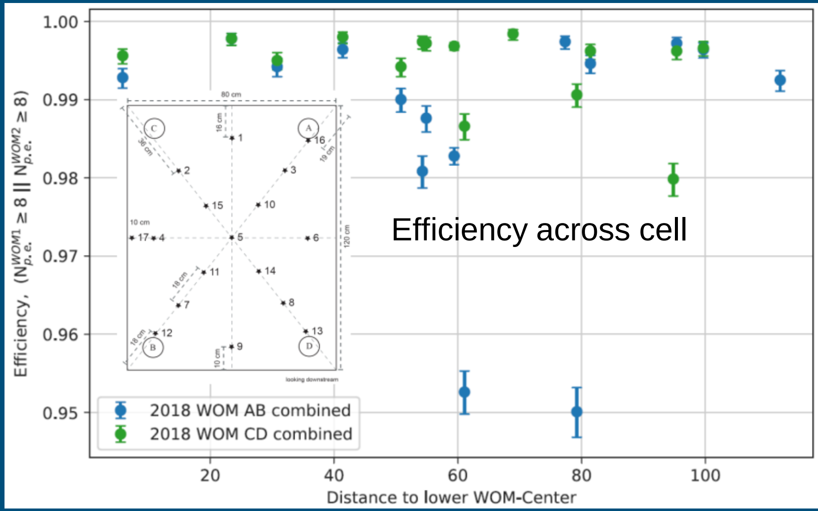


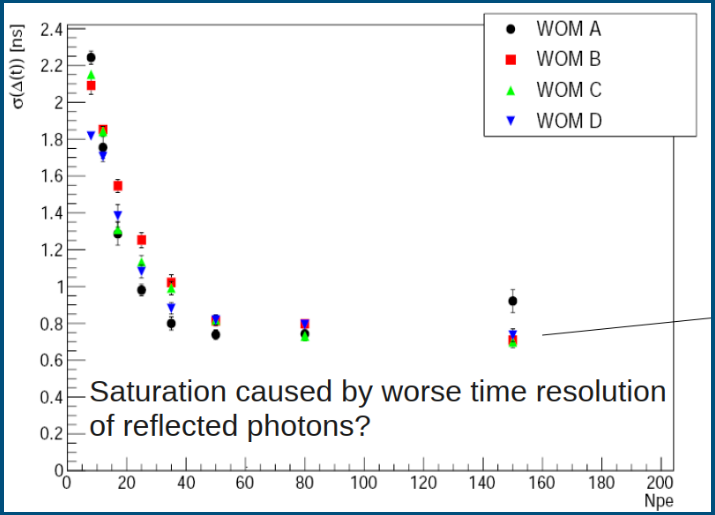
HS Surrounding Background Tagger

2018 test beam results





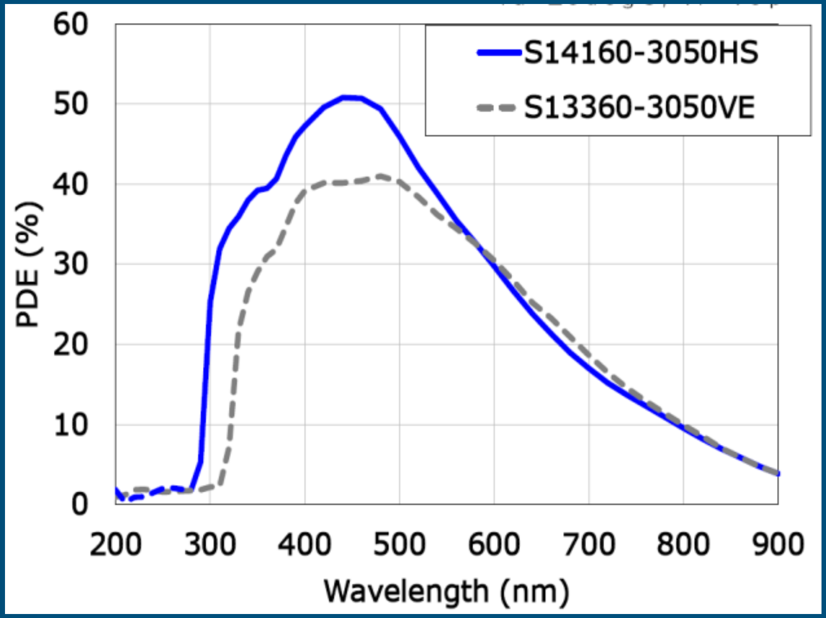


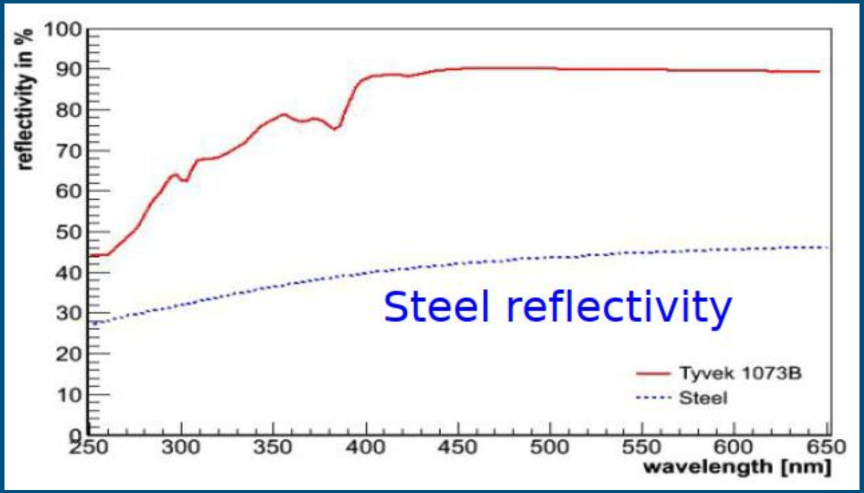


➔ >99% efficiency (>45 MeV deposited), time resolution of 1 ns can be achieved with the threshold for both WOMs set to two photoelectrons

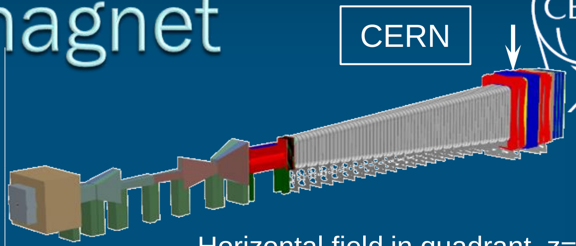
HS Surrounding Background Tagger

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



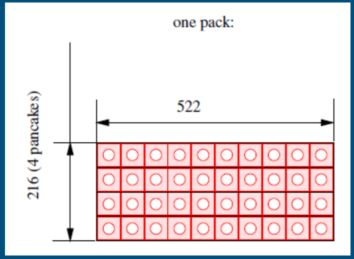


HS Spectrometer magnet



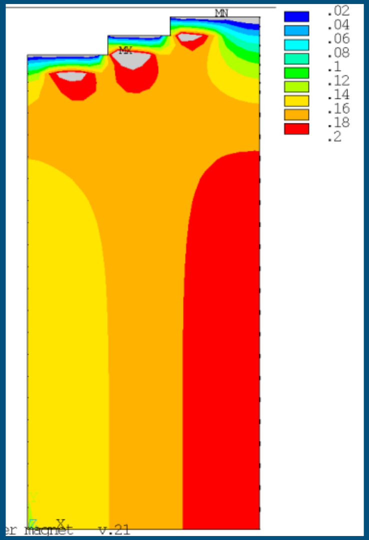
- Fiducial rectangular aperture 5x10 m^2 ➔ horizontal field
  - Magnetic field of 0.5-1 Tm
  - Coil conductor current 3 kA

sheet type	horizontal	vertical	grand total
surfacial area [m^2]	7.632	13.26	
unit mass [kg]	3015.	5236.	
quantity	140	140	
total mass [t]	422.1	733.1	1155.1

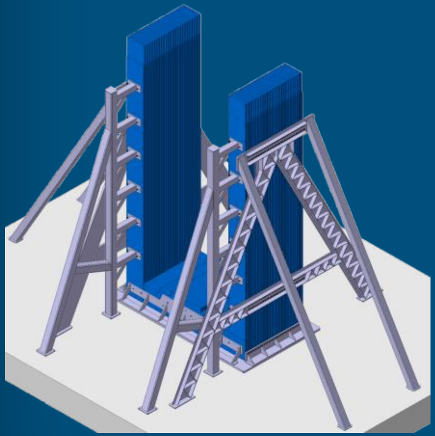


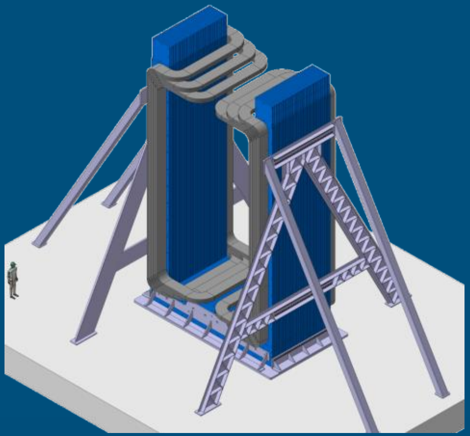
coil pack	A	B	C
length [m]	37.03	35.96	34.89
mass [kg]	8617.	8368.	8118.
dissipation [kW]	185.8	180.4	175.0

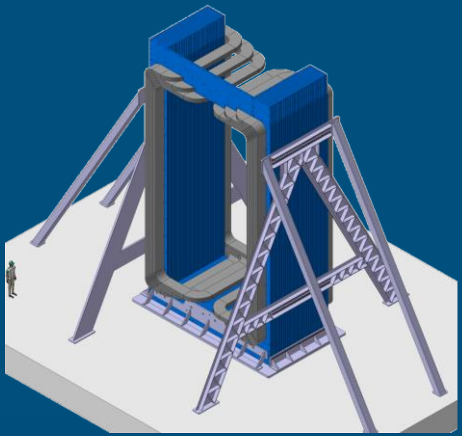
Horizontal field in quadrant, z=0

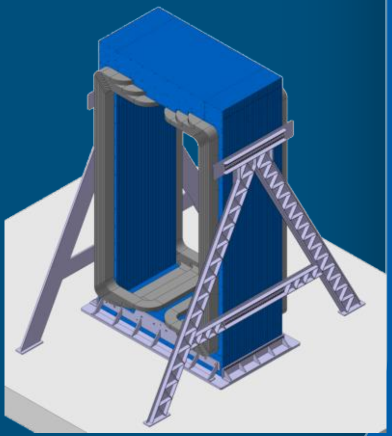


➔ Superconducting (“super-copper”) option being investigated







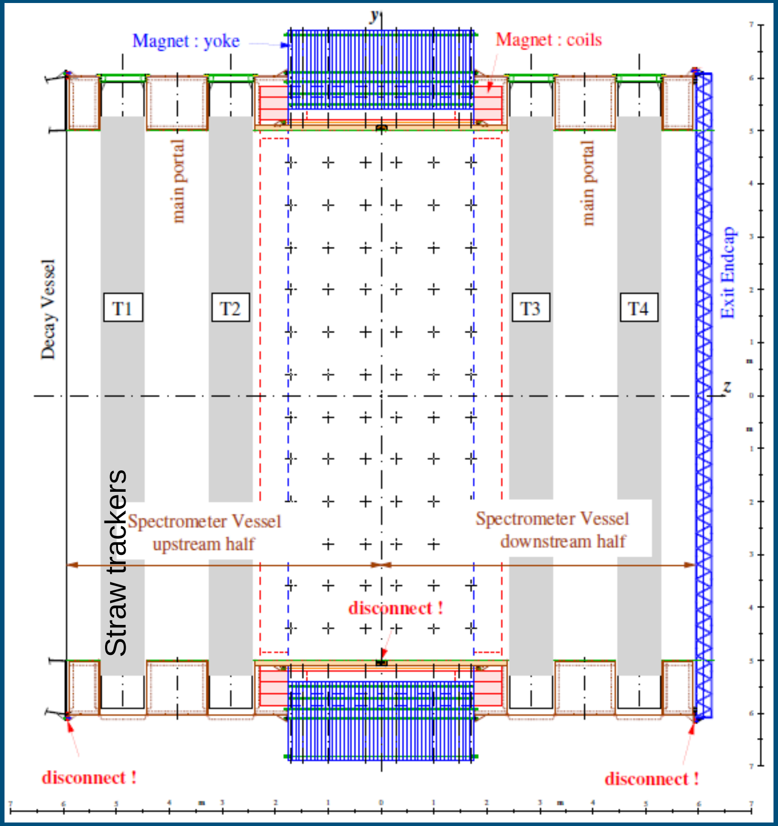


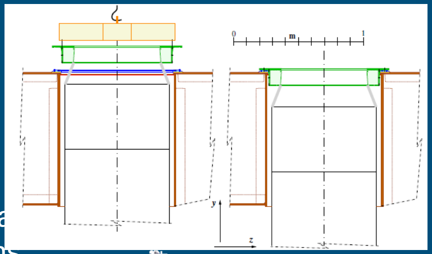
HS Spectrometer vacuum tank

- Vacuum chamber (two halves) through magnet
  with no structural reinforcement → anchoring in yoke

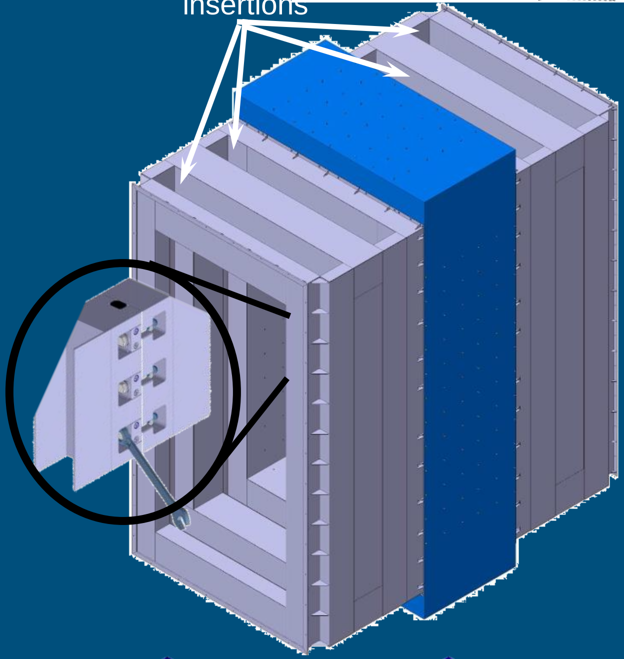
- Challenging integration of Straw Tracker

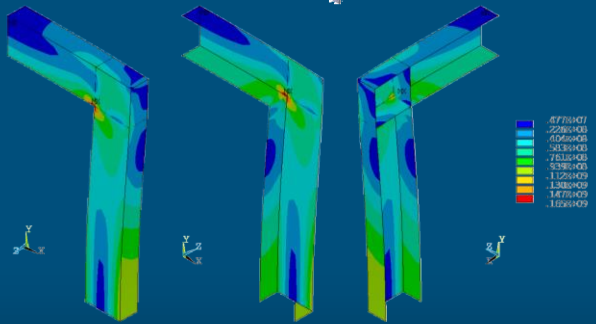
Side view





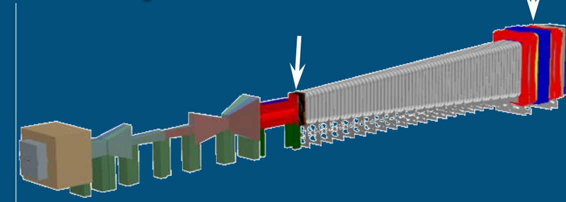
Straw tracker insertions



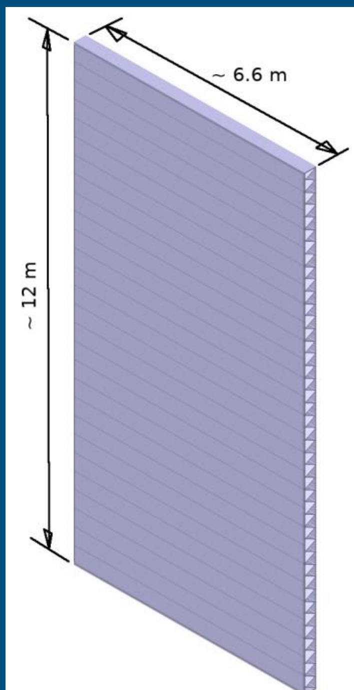


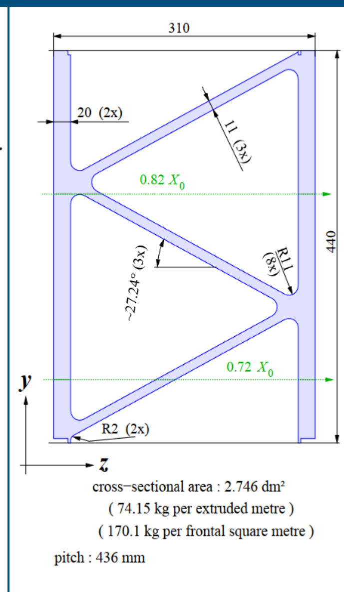
HS Vacuum vessel caps

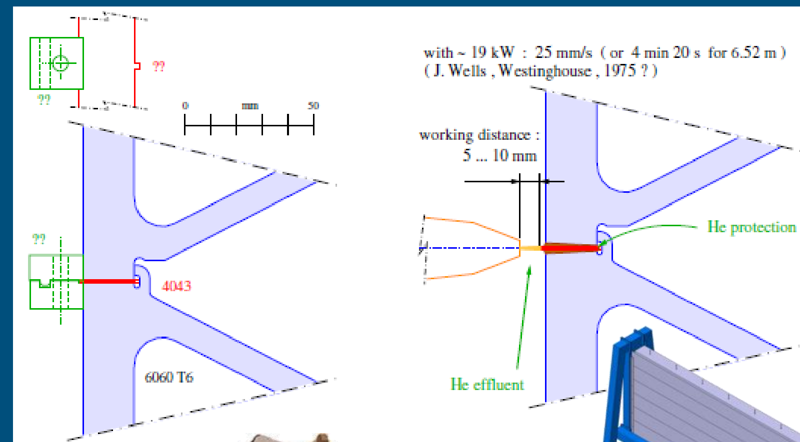
CERN

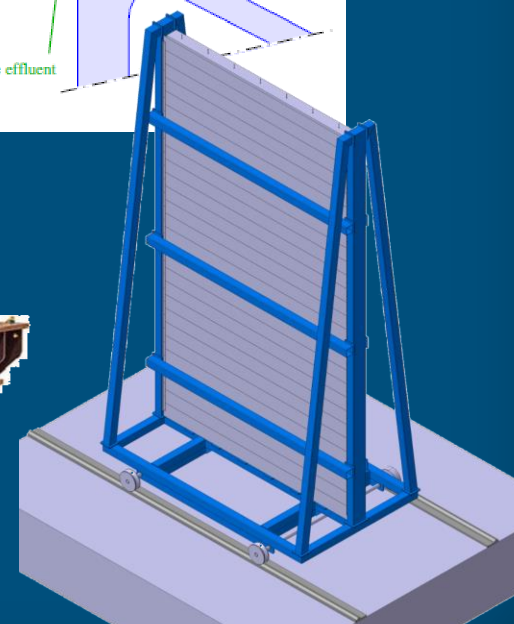


- Front- and end-cap of as low material budget as possible
  - Front: neutrino/muon interactions
  - End: performance of timing detector and calorimeter
- Current idea: 0.8 X_0 extruded Al-6060/T6 aluminium profiles









- Challenging manufacturing – in situ
  - Several techniques investigated
  - Non-vacuum electron beam welding (EBW) most obvious
  - ➔ Contact with Steigerwald Strahltechnik GmbH
  - ➔ Gun available at Hannover (contacted) and Achen universities

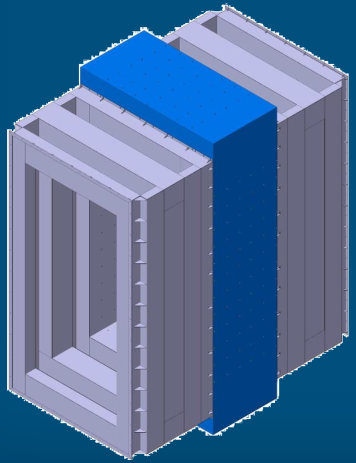
HS Straw Tracker

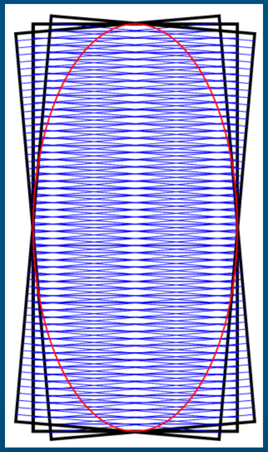
Berlin (DE), Hamburg(DE), JINR(RU), Julich(DE), Kyiv(UA), MEPhi(RU), PNPI(RU), SPPU(RU), Yandex(RU), CERN

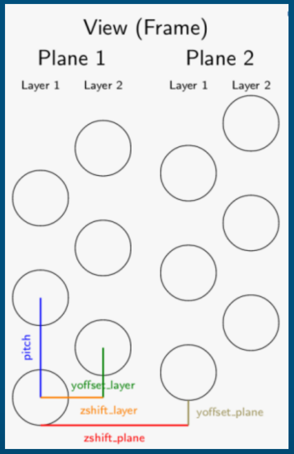
- Purpose: Track reconstruction and momentum, reconstruction of origin of neutral particle candidate. Match hits in timing detector

- 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

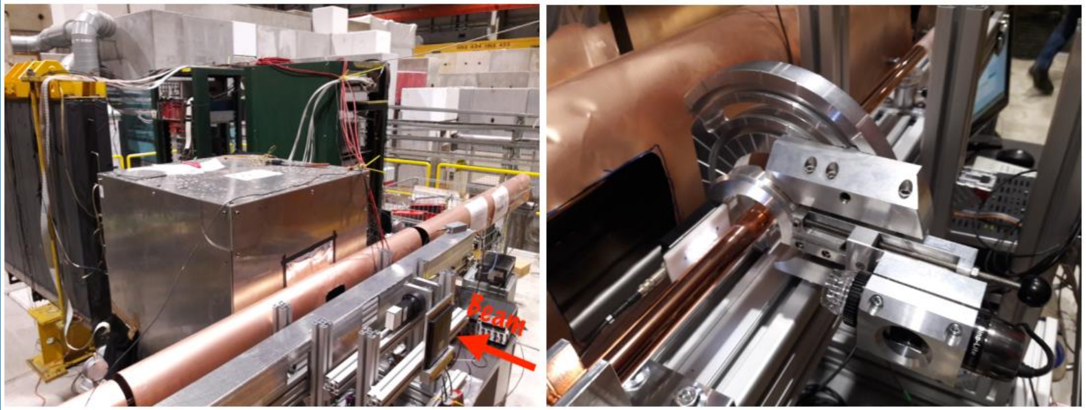


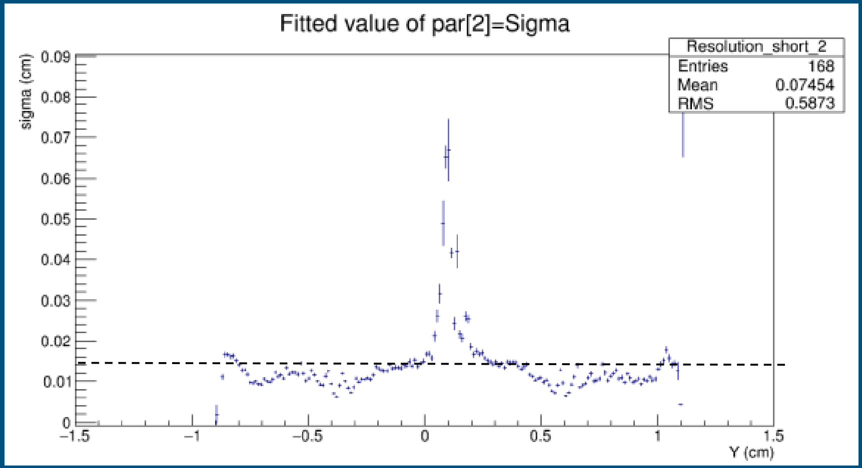




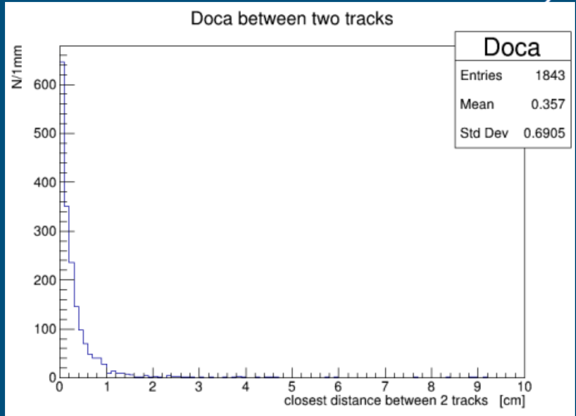
HS Straw Tracker

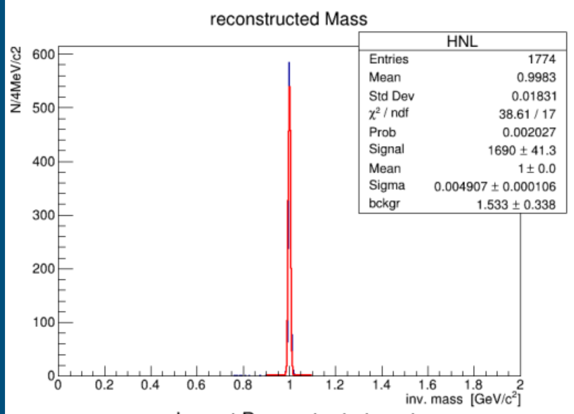
5m long 20mm straw prototype tested at SPS

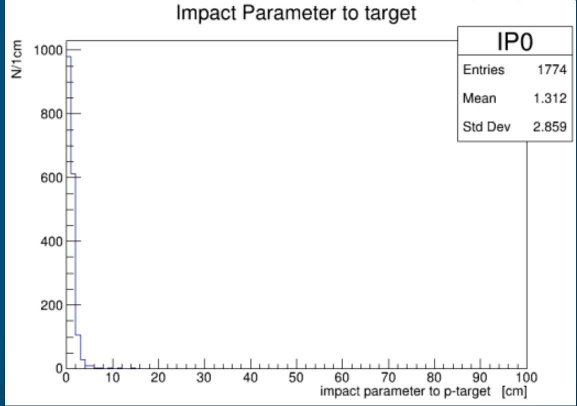




Simulation/reconstruction 1 GeV/c^2 $HNL \rightarrow \mu\pi$







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

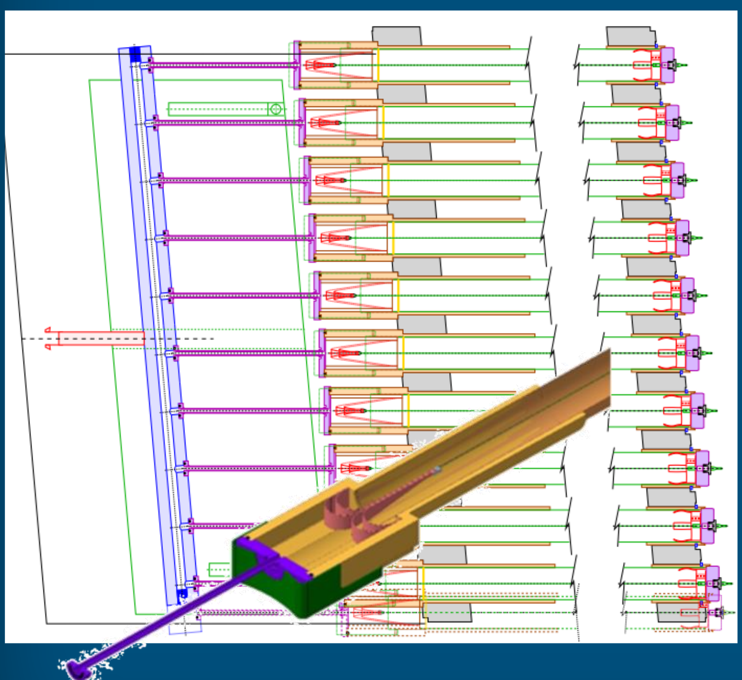
HS Straw Tracker

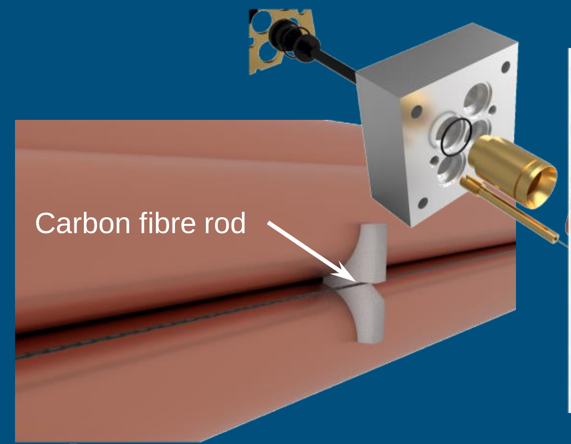
- Challenge: mechanics
- Sagging and flowing of PET: stretched straw and tungsten wires

→ Three option pursued for straw support

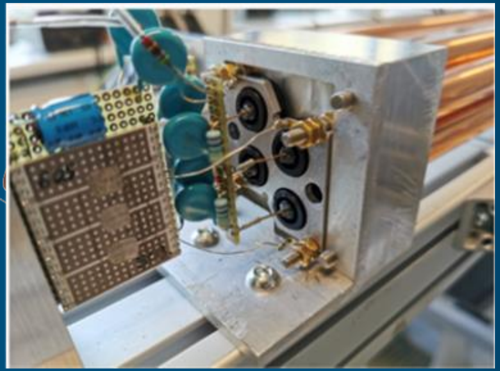
1. Long-stroke constant-force spring
2. Straw suspension mechanism based on carbon fibre rods
3. Stretching by frame extension
4. Cemented pack

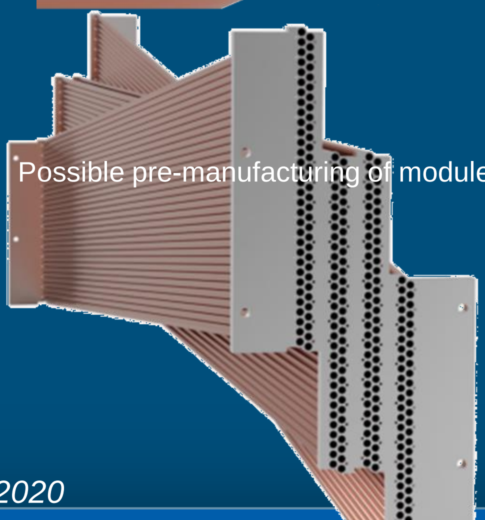
Constant-force spring on stereo-layer





End tensioner

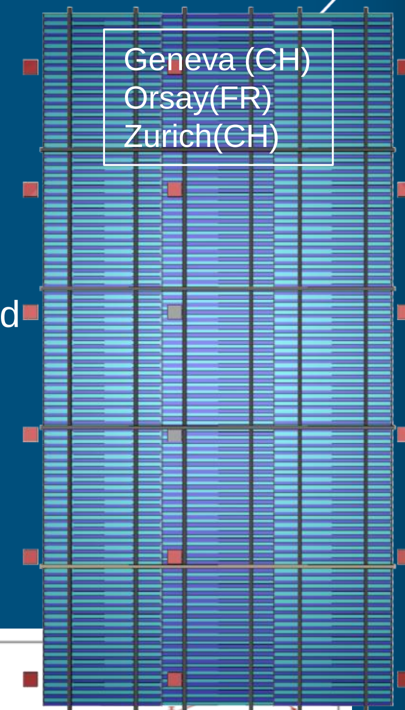


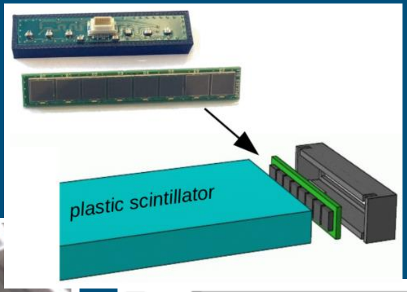


Cemented packs

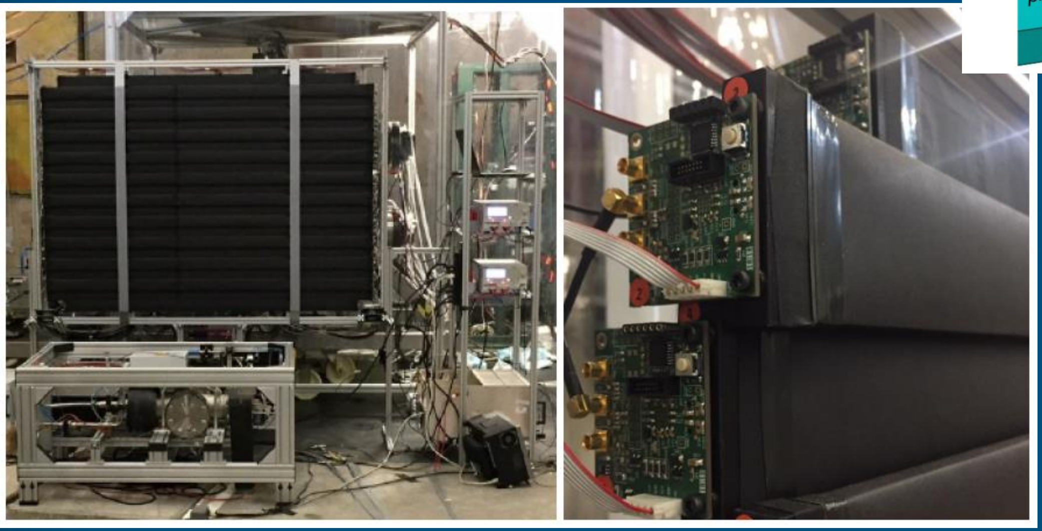
HS Timing Detector (scintillator option)

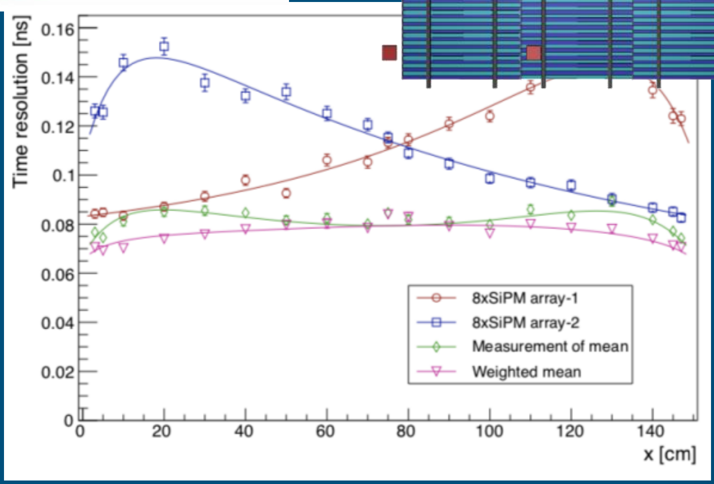
- Purpose: Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 168cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals are summed
  - 564 bars and 1128 channels





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



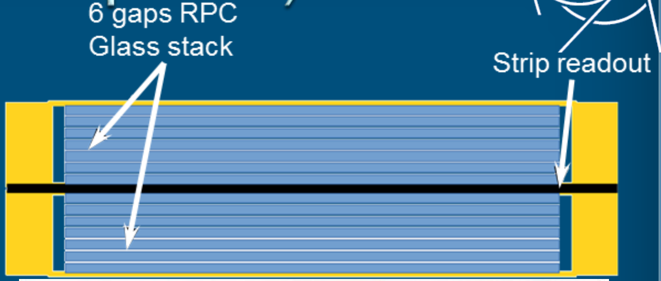


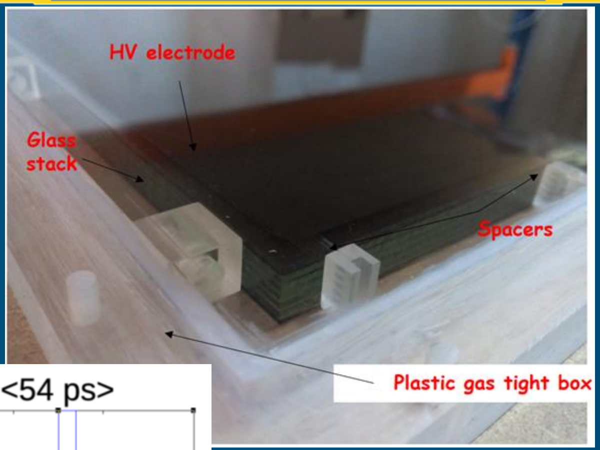
Resolution demonstrated to be ~80 ps along the whole length of the bar and over 2m^2 prototype

Challenge: In-situ timing alignment

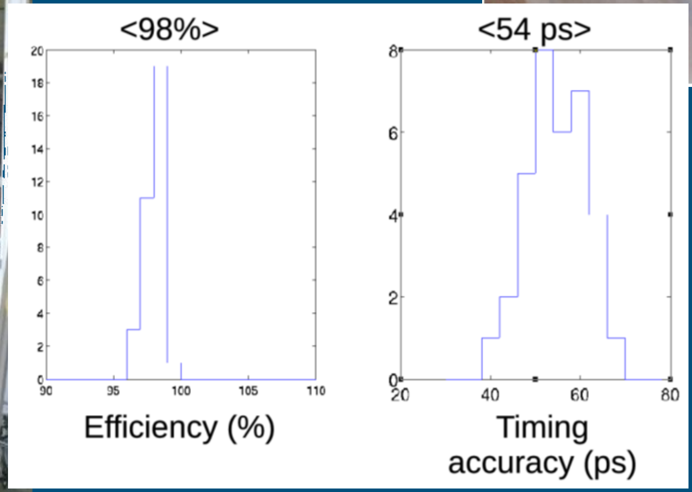
HS Timing detector (MRPC option) LIP (PT)

- 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

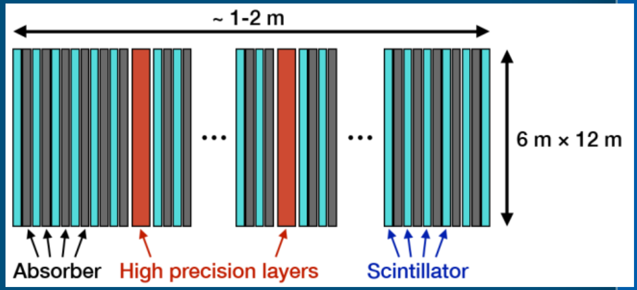


- Efficiency (double-hit) and material budget to be analysed, mechanics and overlap
- Also considered as veto detector in front of decay volume front cap (eq. SBT)

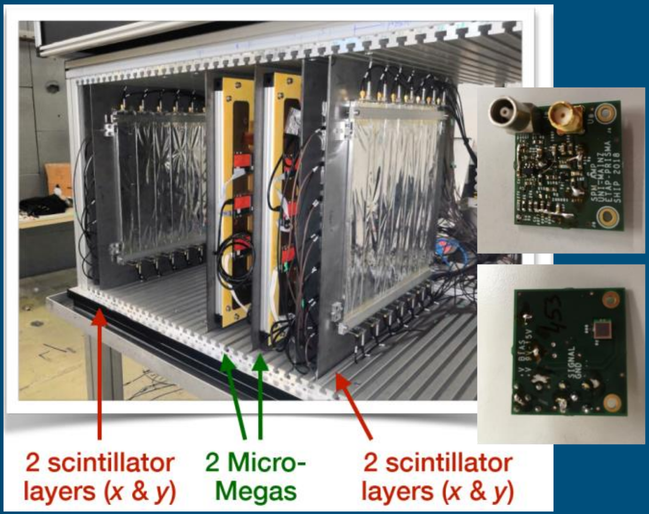
HS ECAL ("SplitCal")

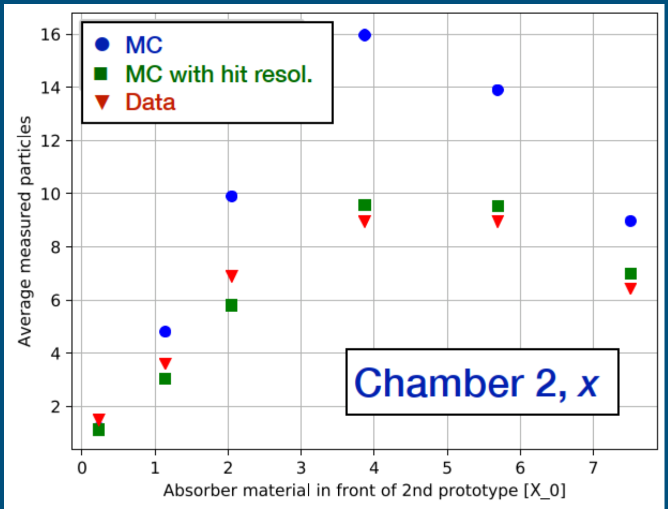
Cagliari(IT)
Mainz (DE)

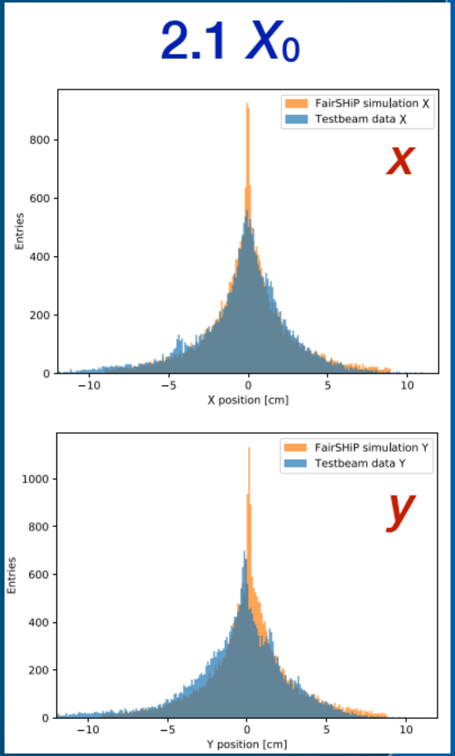
- Purpose: e/γ identification, π^0 reconstruction, photon directionality for ALP→ $\gamma\gamma$
- Characteristics
  - 25 X_0 longitudinally segmented calorimeter with coarse and fine space resolution active layers
  - Coarse layers: 40-50 planes of scintillating bar readout by WLS + SiPM (0.28cm/0.5X0 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)







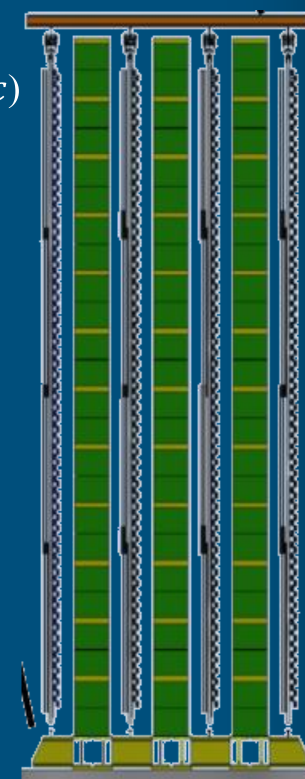
Reconstruction challenge: satellite showers in the long transverse tails

HS Muon system

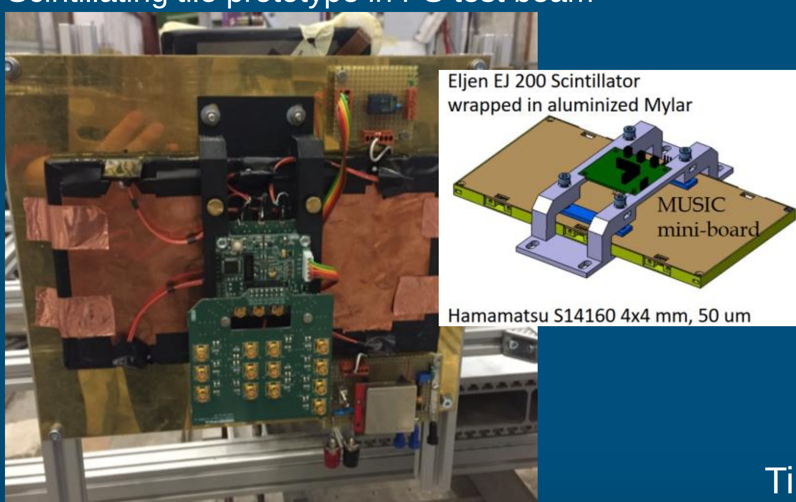
- Purpose: μ/π separation ($\varepsilon_\mu > 95\%,\ p_\mu \in 5-100\ GeV/c$), timing to contribute to reject combinatorial background

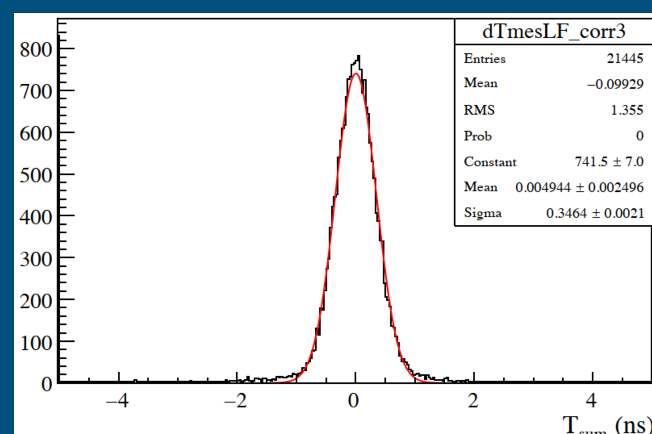
- Characteristics
  - Three (four) stations with sensitive area of 6x12m^2
  - Calorimeter equivalent to 6.7λ (p_μ >2.6 GeV/c)
  - Muon filters of 60cm (3.4λ each) + 10cm shielding behind last station (p_μ >5.3 GeV/c)
  - Granularity $\mathcal{O}(10x10)$ cm^2 driven by multiple scattering
  - Hit rates 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)
Orsay(FR)
LNF(IT)
MEPhI(RU)



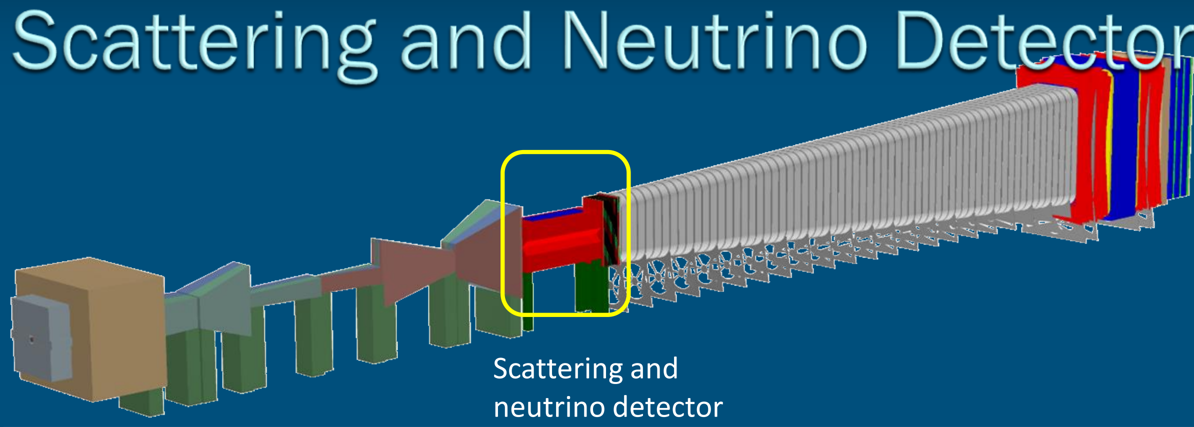
Scintillating tile prototype in PS test beam





Time resolution of ~ 340 ps measured in test beam

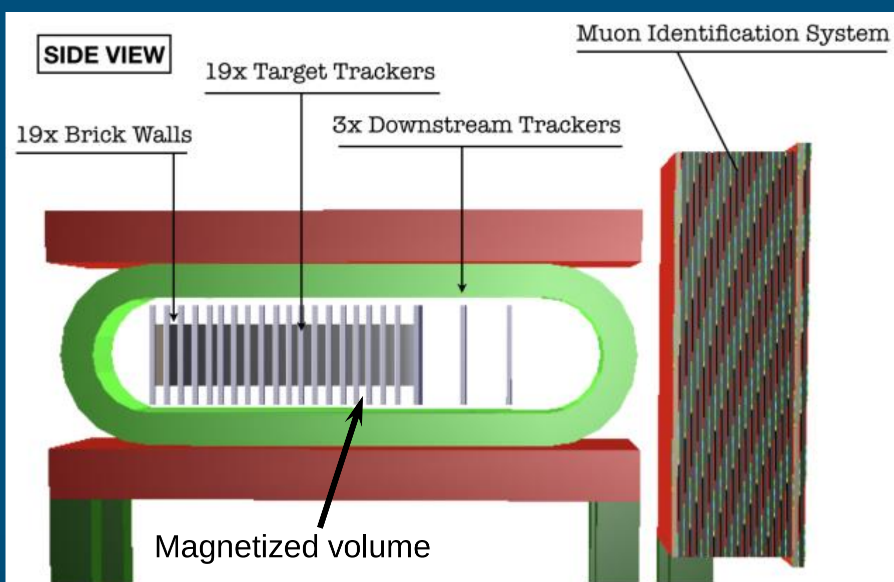
Scattering and Neutrino Detector



- 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

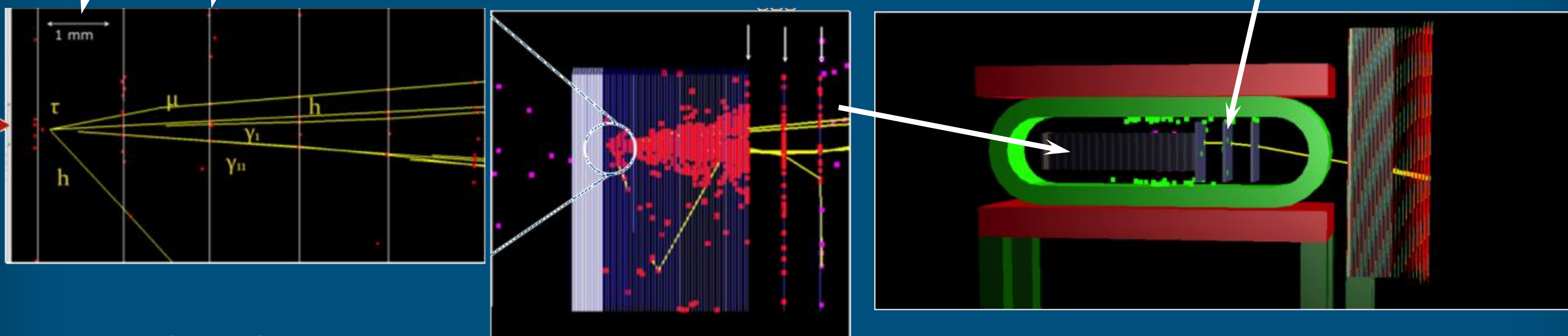
Momentum of hadrons measured by Compact Emulsion Spectrometers in each brick wall

Momentum of muons by Downstream Trackers

Scattering and Neutrino Detector

Neutrino detection

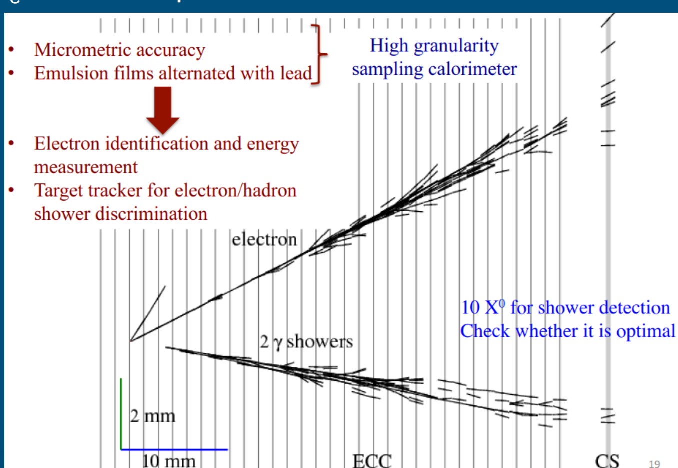
Lead plate Emulsion film Muon momentum measurement



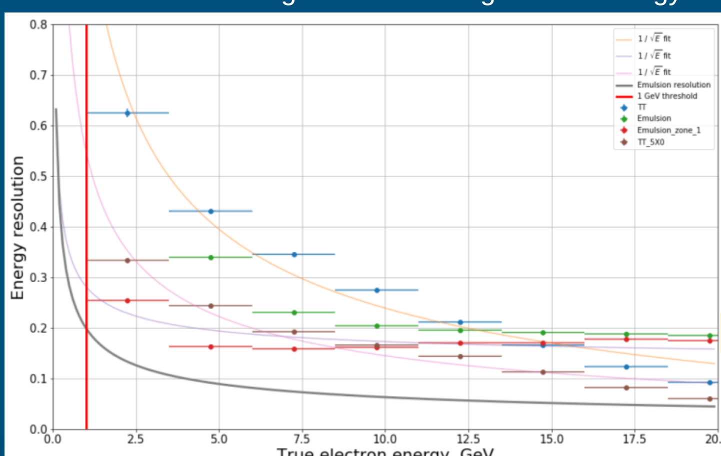
LDM detection

- Detection of electromagnetic shower and reconstruction of origin by electronic target tracker

ν_e event in Opera

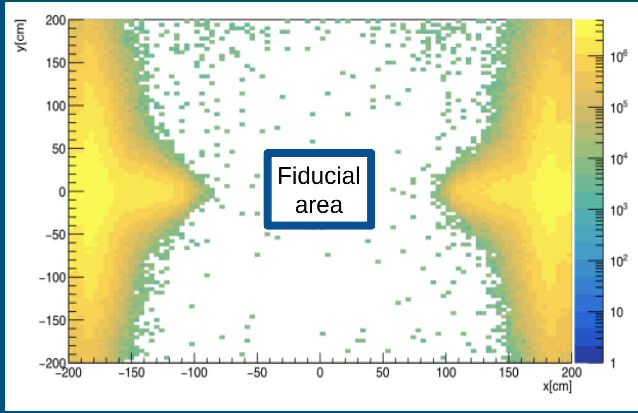


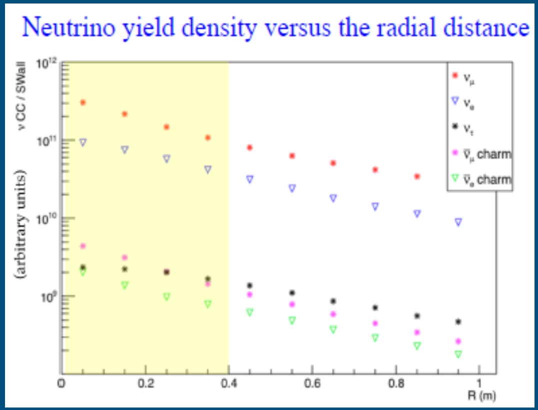
Optimization of emulsion/target tracker configuration: energy resolution

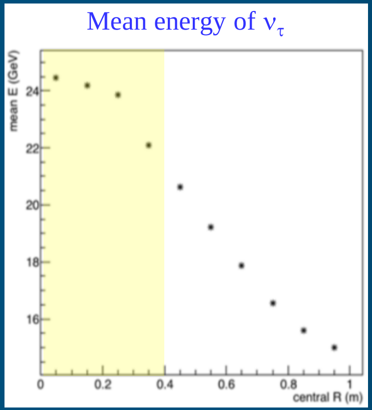


SND optimization

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 2×10^{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

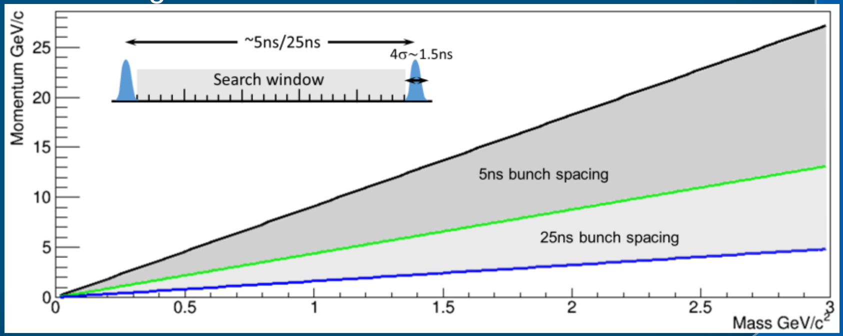
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

Number of background events in LDM search in 2×10^{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

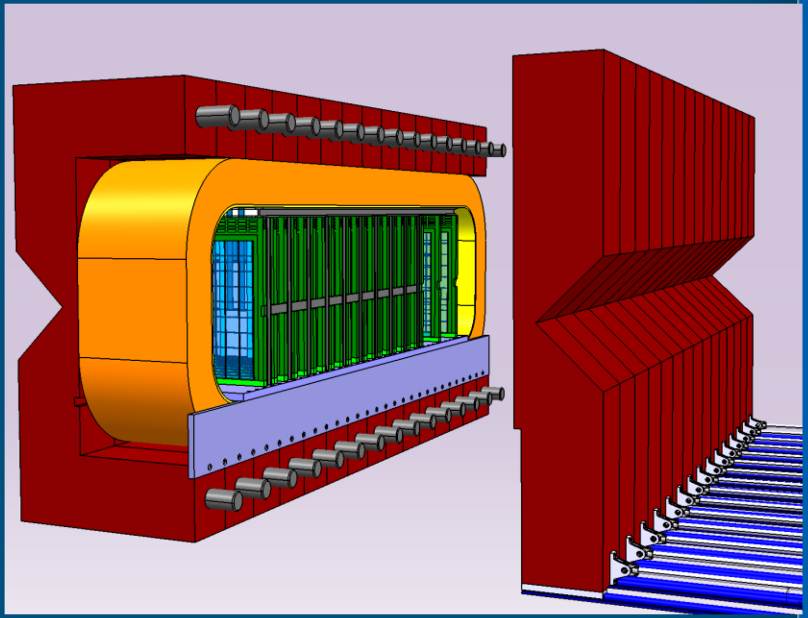


SND magnet

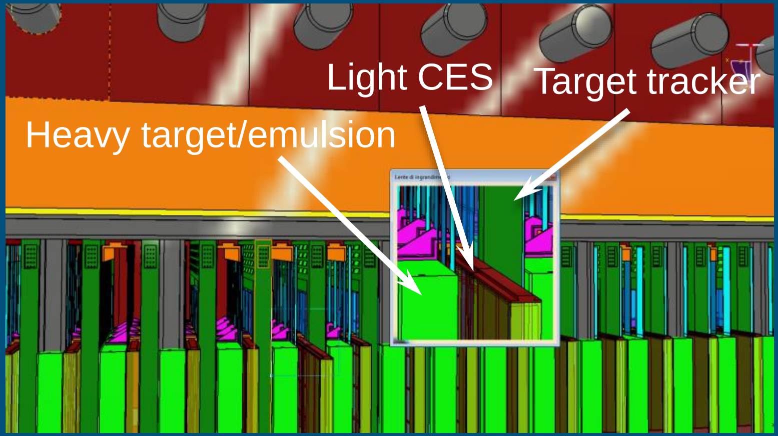
Naples(IT)
CERN

- Characteristics
  - Overall external size ~2.4 x 4.0 x 7.2 m^3
  - Detector volume ~1 x 1.6 x 6.4 m^3

	Cu	Al
Reference B field	1.25	1.25
Overall ampere turns (MA)	1.05	1.05
Net coil volume (m^3)	4.3	4.6
Iron yoke volume (m^3)	36.0	36.0
Total magnet mass (tonnes)	300	275
Reference electrical power (MW)	1.32	1.90



- To respect emulsion limit of 10^3 tracks/mm^2, replacement every 6 months, CES every few weeks

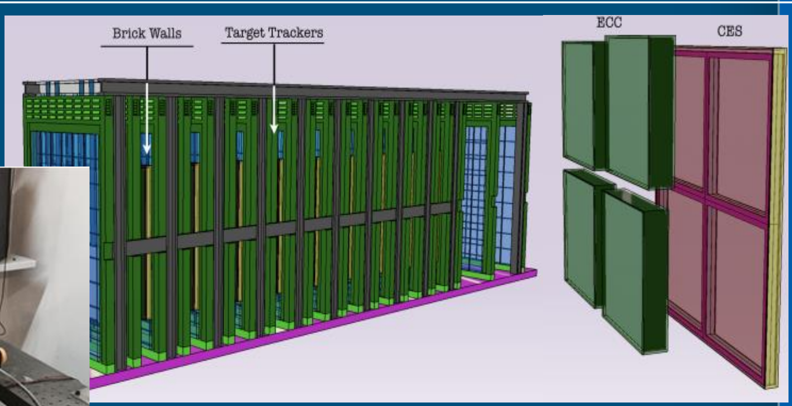


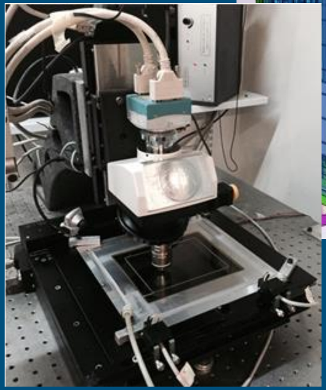
➔ Superconducting ("super-copper") option being investigated

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)

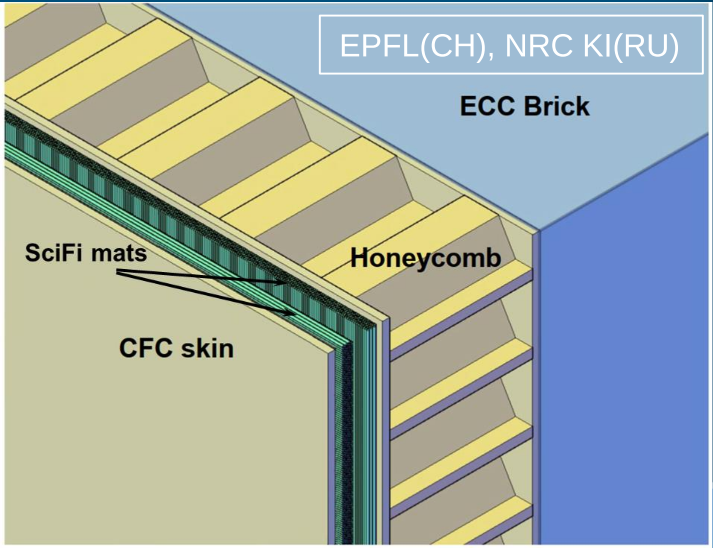
- Emulsion Cloud Chamber brick characteristics
  - 4 bricks of 40x40 cm^2
  - Thickness ~8 cm (57 films/lead plates → ~10 X_0)
  - Weight ~100 kg
  - Total 730 m^2 of film x 10 replacements
  - Scanning speed 200 cm^2/h, 10x faster than Opera





- 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.

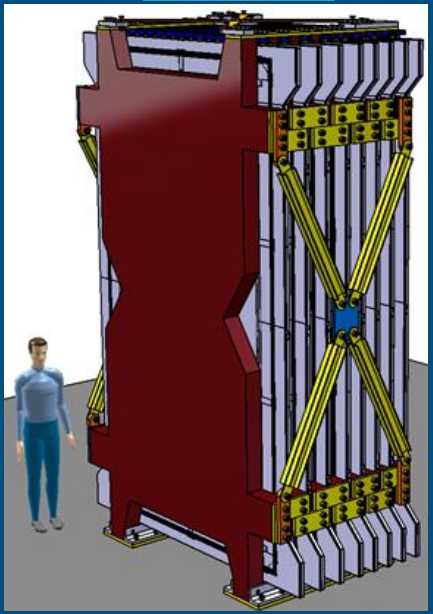
- Emulsion + TT beam test at DESY in 2019
  - Emulsion: electron identification and directionality
  - Emulsion + TT: Electron energy and time resolution

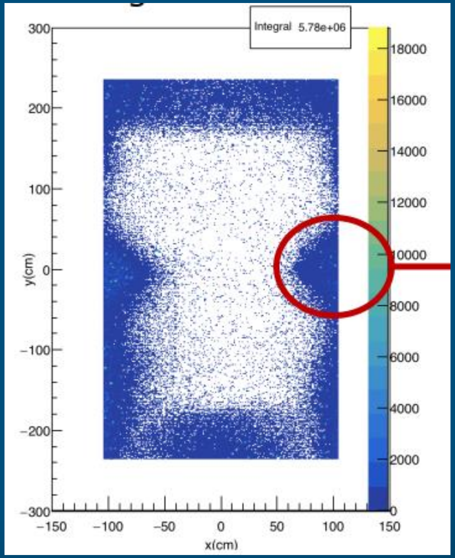
SND Muon system

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

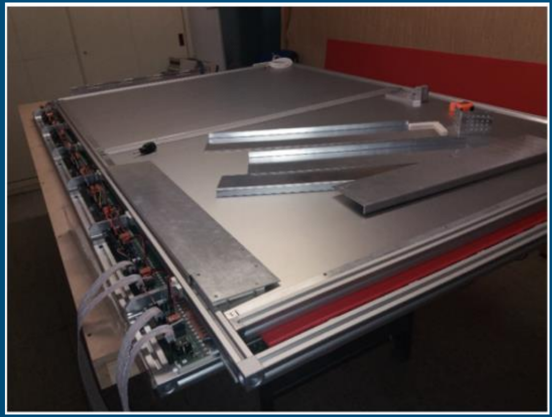
- Purpose: track and identify muons, and tag interactions (ν, μ) in the last layers before entrance window to HS decay volume

- Characteristics
  - 8 iron filters, 15/10 cm thick
  - 8 RPC, and 2 MRPC layers
  - Sensitive area of ~2.8×4.3 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%.





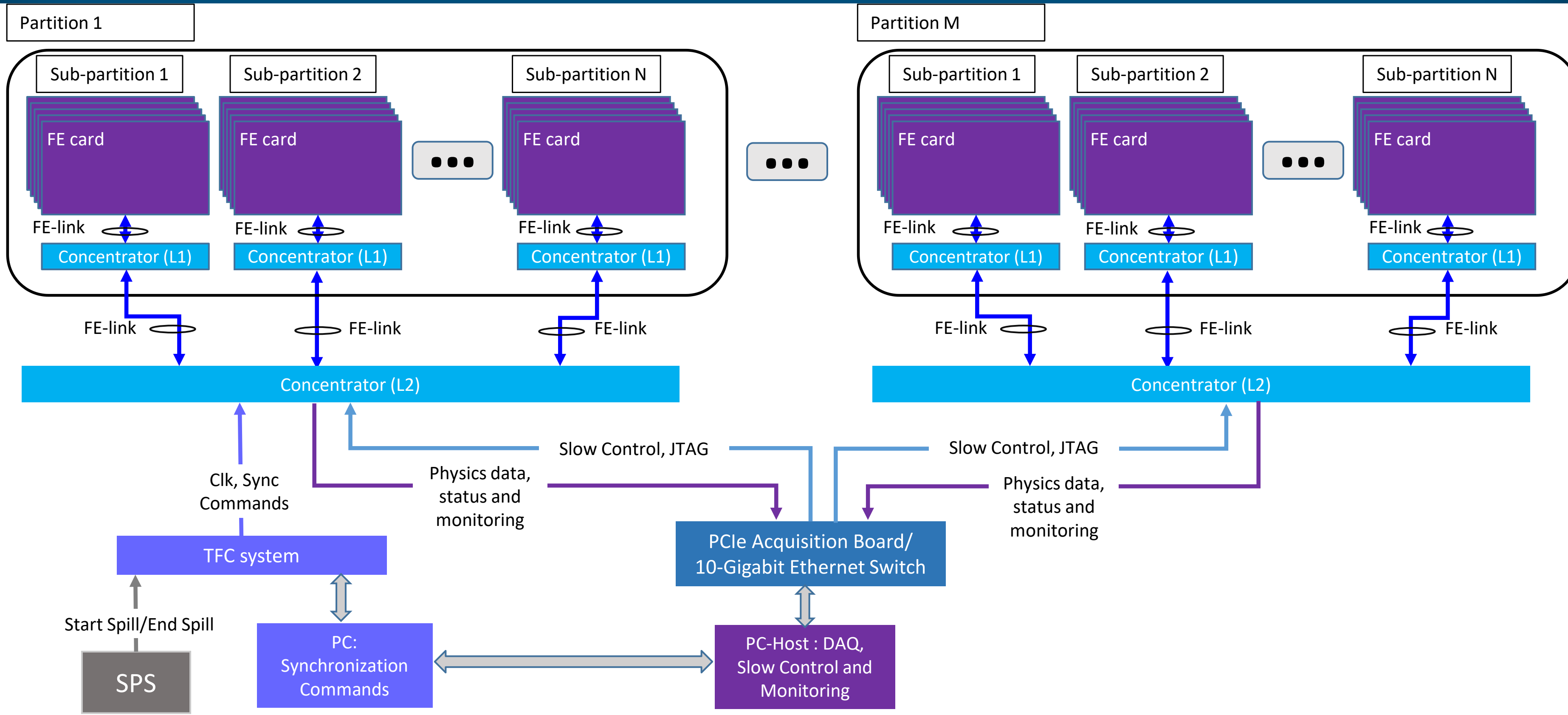
RPC prototypes built for muon flux and charm production measurement at SPS in 2018



Electronics and readout

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

- **Triggerless** continuous readout
- System architecture – aiming for common electronics
- DAQ system simulation under study



FE-link : 4 LVDS copper pairs
- Physics data : high speed up to 400 Mbits/s
- Clock : 40 MHz
- Fast Commands/Slow control/JTAG: 40 Mbits/s
- Status/Monitoring : :40 Mbits/s

Electronics and readout

- A series of electronics workshop over the two last years in order to share the competence of the different groups and converge on the definition of common requirements

- General architecture of the electronics system has been specified
  - Tailored to the needs and specific characteristics of the detector
  - Optimized in terms of cost and complexity
  - Takes advantage of already developed ASICs and favors commercial components as much as possible
  - Hardware and protocol specification document prepared

  ➔ Physics measurements at SPS was already a “culture forming exercise”!

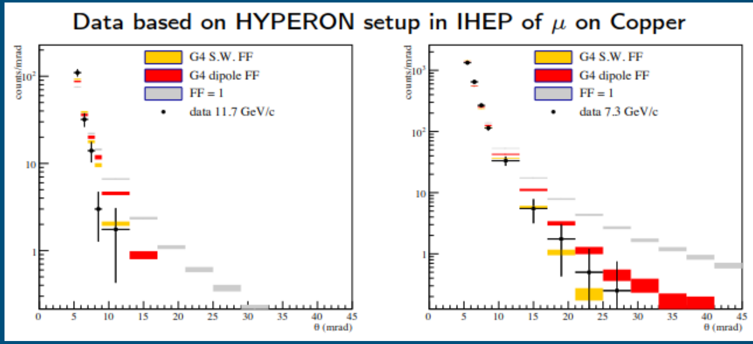
- Plans for initial phase of TDR 2020-2021
  - FE designs starting
  - Development of a prototype of the data concentrator starting.
  - Developing the firmware for detector control and data concentration and transfer
  - Developing the interfaces on the front-end of sub-detectors
  - Building prototype systems for lab and beam tests

Work package	Timeline
Prototype of the FE Concentrator	2020
Firmware for the FE Concentrator	2020
Software for test and stand-alone mode	2020
Test of FE link	2020
Pre-series for FE Concentrator	2021
TFC system specification	2021
TFC Emulator	2021
Specification of DAQ interface on FEH	2021
Prototype of DAQ interface on FEH	2022
Tests of DAQ link	2022
Prototype of TFC system (generation and distribution)	2023
TDR for common electronics and online system	end 2023

Computing

Yandex (RU)
CERN

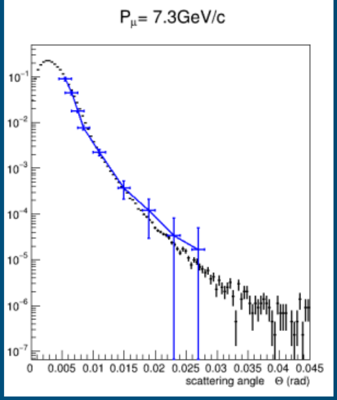
- SHiP's complete suite of simulation, reconstruction and analysis framework based on FairRoot
  - ➔ "FairSHiP" including GEANT4, GENIE, PYTHIA8, and EVTGEN
  - Generators and cascade production
  - Detailed geometry and detector descriptions of the "CDS detector"
  - MC validation



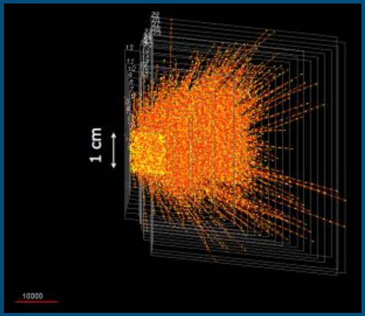
arXiv:1506.08759

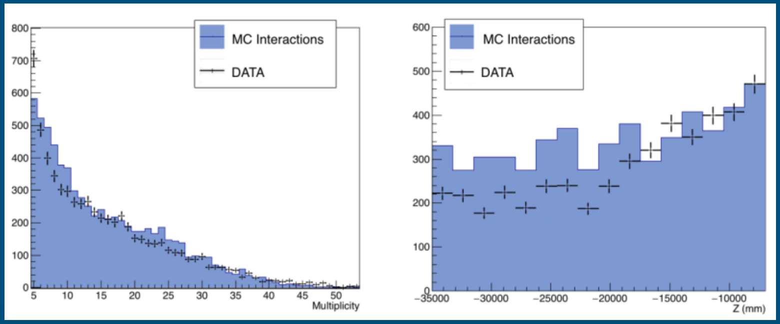
- Subsidiary measurements and test beams
  - Muon flux at SPS (see M. Cristinziani)
  - Inclusive charm production at SPS (see M. Cristinziani)
  - ➔ Prototyping and MC tuning
  - Towards module-0 test beams 2021 – 2023
  - Continued measurement of charm production

GEANT4 used by SHiP

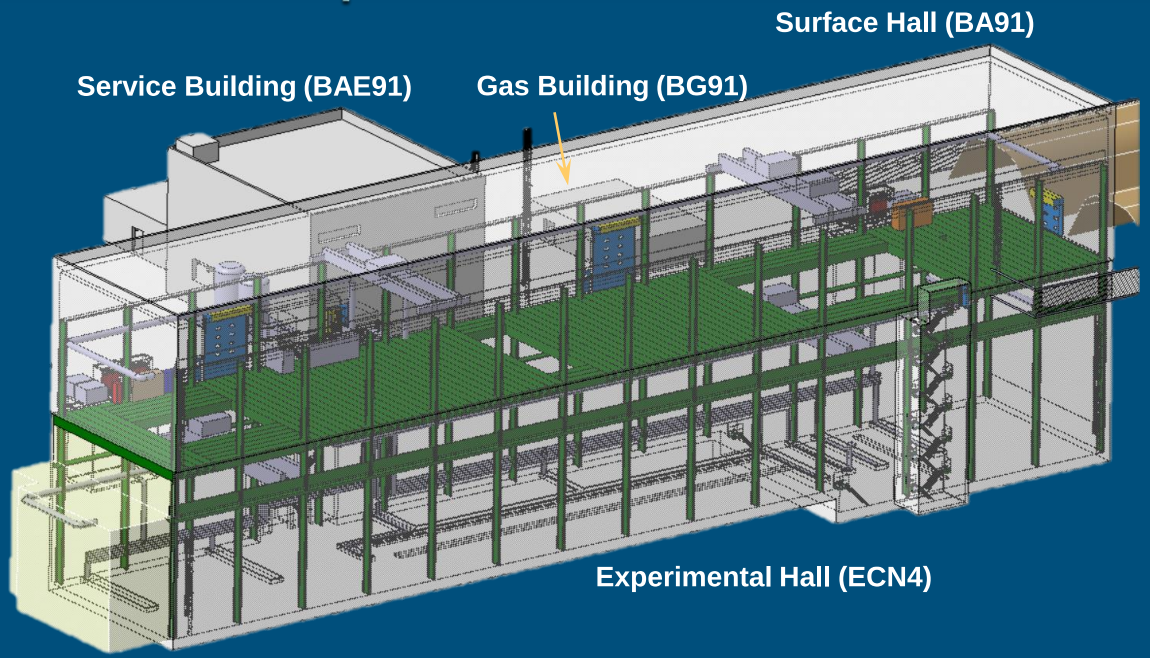


SHiP charm: 5x10^{5} reconstructed vertices in brick

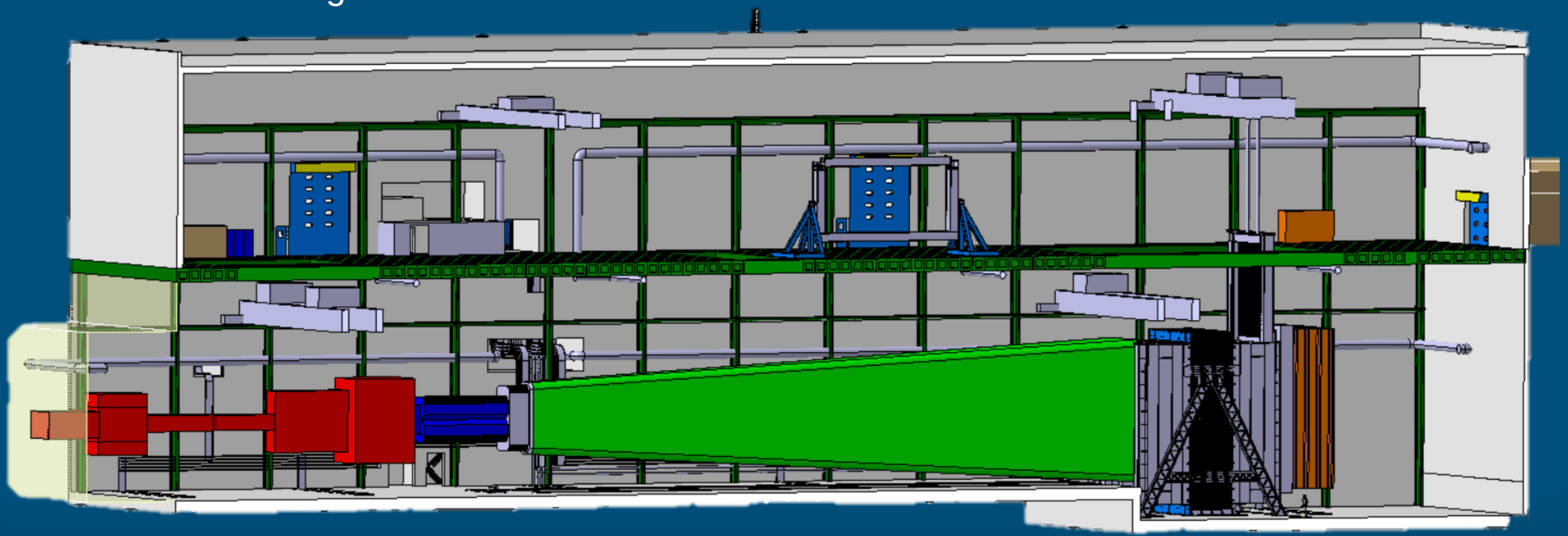




Experimental Area

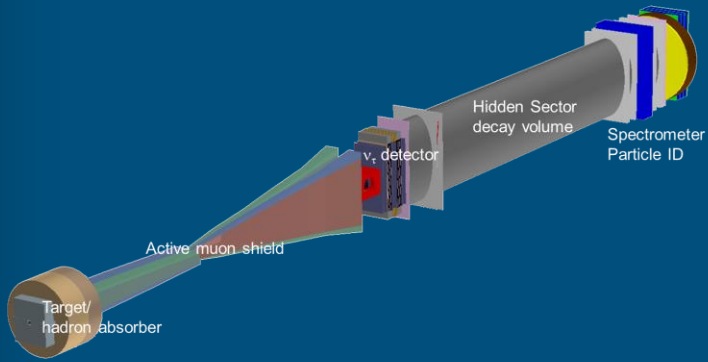


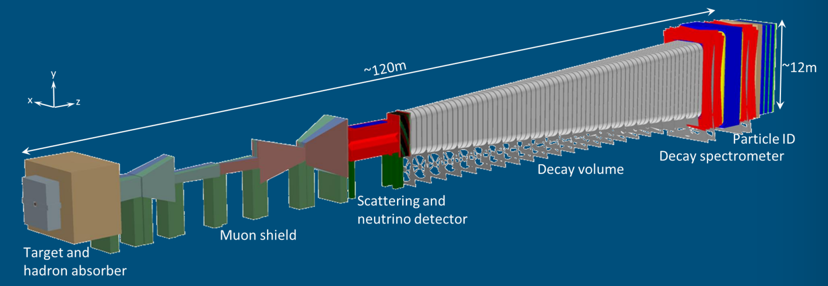
Installation scenarios being studied



Summary of CDS high-lights

- Complete re-optimization of the experiment starting from physics, in particular background studies with increased statistics, “figuratively”:





- Choice/consolidation of detector technologies, still to be continued during TDR phase
- All detectors have undergone first level prototyping and beam tests, and have or are about to prepare next level
- Progress on detector engineering studies
- Full physics simulations with detector described in increasing detail
- Muon flux measurements / inclusive charm production measurement at SPS in long target

➔ First leg on Technical Design reports

CDS reviews and documents

Review objectives

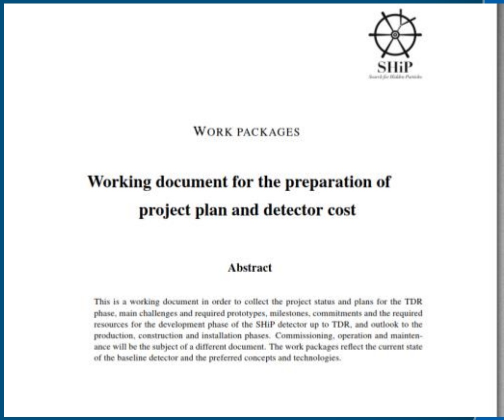
- Choice of solution to the physics requirements and design strategy
- Current status of development, modelling, prototyping
- Identification of difficulties and challenges → mitigations
- Safety aspects and implications → mitigations
- Project plan for Technical Design Reports, including prototyping, tests and validation
- Ideas for production and installation
- Costing (development and production)
- Inform relevant CERN groups and identify resources from CERN

External reviewers

Marco Andreini (safety engineering, CERN)
Vincent Baglin (vacuum, CERN)
Jeremie Bauche (magnets, CERN)
Hans Danielsson (NA62 straw tracker, CERN)
Corrado Gargiulo (structural engineering, CERN)
Marco Garlasche (mechanical engineering, CERN)
Jean-Christophe Gayde (survey, CERN)
Jean-Louid Grenard (transport&handling, CERN)
Dirk Mergelkuhl (survey, CERN)
Antonio Pellegrino (LHCb outer tracker, NIKEH)
Diego Perini (mechanical engineering, CERN)
Pablo Santos Diaz (Integration, CERN)
Davide Tommasini (magnets, CERN)

- All subsystem reviewed (with exception of common electronics, online and computing)
  - External reviews of magnetization of hadron stopper, muon shield, vacuum chamber, spectrometer magnets, straw tracker
  - No showstoppers identified but many recommendations and identification of challenges and alternatives!

- Documented in "internal SHiP Project Plan"
  - Source document for TDR plan, resource needs (including personnel, missing expertise and new groups) and funding requests
  - T0 for TDR phase is end of 2020



SHiP

WORK PACKAGES

Working document for the preparation of project plan and detector cost

Abstract

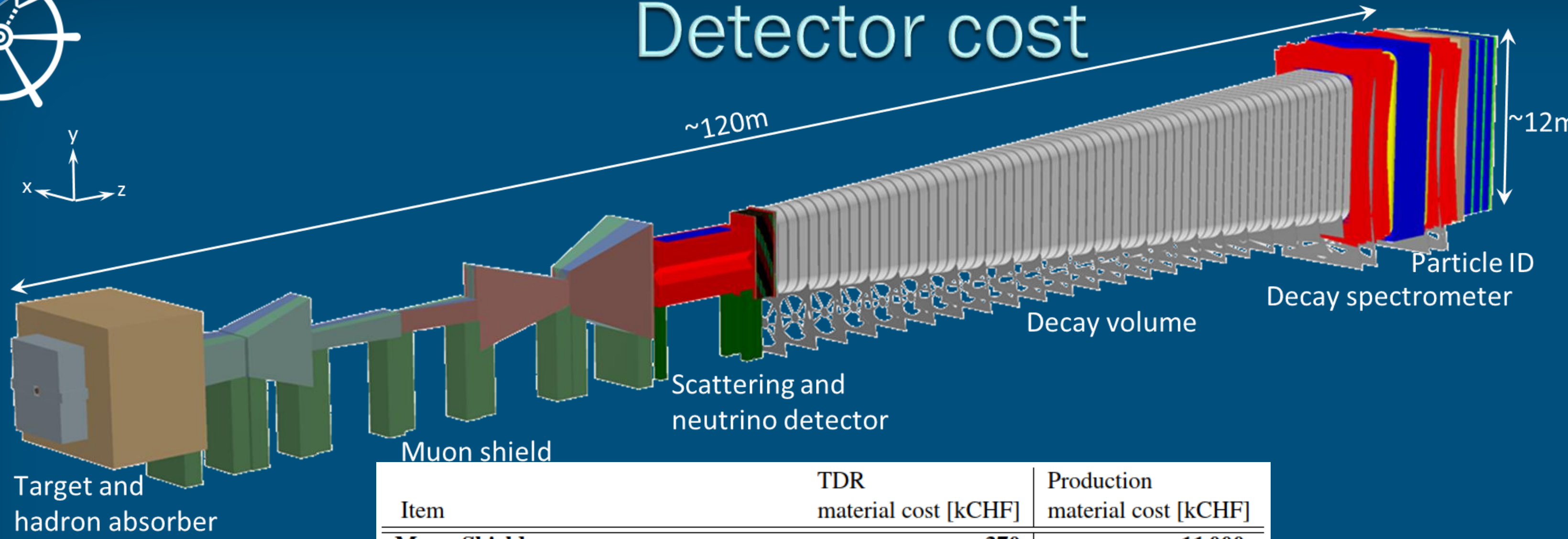
This is a working document in order to collect the project status and plans for the TDR phase, main challenges and required prototypes, milestones, commitments and the required resources for the development phase of the SHiP detector up to TDR, and outlook to the production, construction and installation phases. Commissioning, operation and maintenance will be the subject of a different document. The work packages reflect the current state of the baseline detector and the preferred concepts and technologies.

- CDS report is a concise report on status and TDR work plan
  - http://cds.cern.ch/record/2704147
  - Supported by supplementary reports, notes and publications

Detector cost

- Based on detailed breakdowns per subsystem (no contingency included)
- Arranged in categories of
  - Apparatus, Mechanics, Electronics, Support system and infrastructure, Calibration and instrumentation, Tooling, (Personnel&Services), Transport
- Uncertainty/contingency associated with each category of each system (to both R&D and production)
  - ~~Real 0%~~
  - (Quote 10%)
  - Scaling from quote/existing 20%
  - Estimate with company 25%
  - Estimate in-house 30%
  - "Guesstimate" 40%
- Transport: far end of Europe, normal 170 CHF/tonne, special 220 CHF/tonne (J-L Grenard)
- Tooling incomplete
- No personnel (and no storage and installation costs)

Detector cost



Item	TDR material cost [kCHF]		Production material cost [kCHF]	
Muon Shield		**370**		**11 000**
Magnetisation of hadron stopper	120		1 300	
Free-standing muon shield	250		9 700	
Scattering and Neutrino Detector		**1 230**		**21 330**
Spectrometer magnet	240		3 540	
Emulsion target	430		11 430	
Target tracker	360		4 940	
Muon system (RPCs and iron filters)	150		1 200	
Upstream background tagger	50		220	
Hidden Sector Detector		**2 380**		**37 010**
Decay volume vacuum vessel	350		3 750	
Spectrometer vacuum vessel	N/A		4 540	
Vacuum vessel front- and end cap	30		310	
Spectrometer magnet	100		6 300	
Surround background tagger	490		3 850	
Spectrometer straw tracker	1 070		6 190	
Spectrometer timing detector	50		700	
Option: Scintillating bars			*(600)*	
Option: MRPC			*(700)*	
Calorimeter	200		7 470	
Hadron absorber	N/A		300	
Muon system	90		3 600	
Common electronics and online system	150	**150**	1 190	**1 190**
Total	**4 130**			**70 530**

Combined uncertainty 25%

Critical items for TDR phase

- Muon shield
  - Magnetised hadron stopper: Prototyping of non-cooled coil, services and remote handling
  - Another round of freestanding magnet field optimization with engineering knowledge
  - Free-standing part: mid-size 1.3x2.0 m^2 prototypes to investigate assembly technique, mechanical stability and packing factor, and magnetic performance
- Scattering and Neutrino Detector (SND)
  - Large-scale prototypes of ECC, CES, target tracker (SciFi) and SND muon detector
  - Prototypes of the emulsion facility tools and microscopy to demonstrate emulsion brick production and required scanning speed
- Decay volume and Surround Background Tagger (SBT)
  - Investigation of decay volume construction and SBT-LS integration
  - Sub-assembly consisting of 2x2 SBT cells of 80x1.20 m^2 to test the integration, hydraulics and LS purification system, and SBT performance
  - Full size double ring vessel fitted with flanges and upstream and downstream end-caps, structural and vacuum tests and full integration tests
- Spectrometer magnets
  - Engineering and “super-copper” coils R&D
- Spectrometer vacuum tank
  - Engineering and construction challenges
- HS Spectrometer Straw Tracker (SST)
  - Large-scale prototype of realistic size to demonstrate the mechanical performance, operated in vacuum

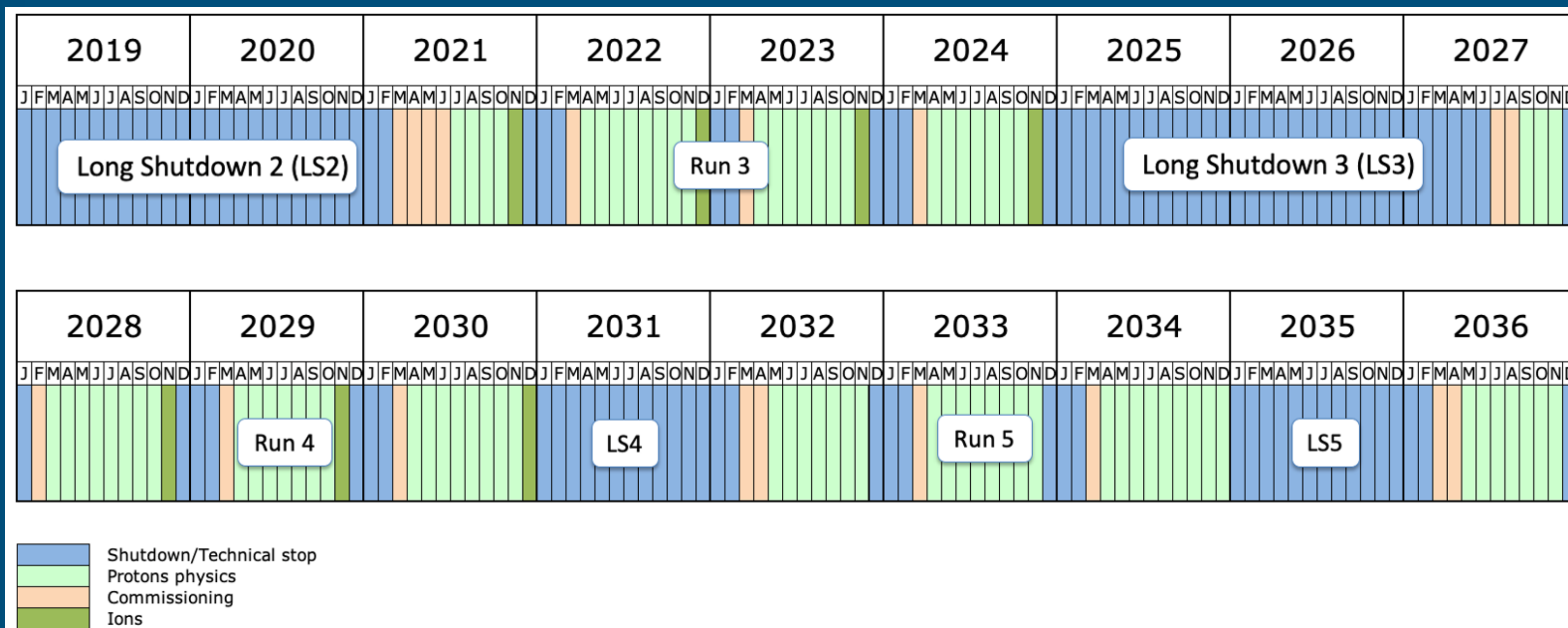
Critical items for TDR phase

- HS timing detector
  - Engineering and time alignment
- HS split calorimeter (ECAL) and HS muon system
  - Optimisation of particle ID
  - Large-scale technological prototypes
- Engineering and development of integration model
  - 3D, component properties, production+assembly, timeline, cost, operational procedures, safety
- Electronics and DAQ
  - Implement full-slice system for test beam measurements with module-0 prototypes
- Computing plans during TDR phase
  - Update versions review software framework
  - Detector and channel conventions
  - Configuration and condition databases
  - Online framework
  - TDR phase will include an overall optimisation of the detector and updates of detectors
  - ➔ Very limited manpower currently

Timeline	Milestone
2020	Continued design studies and beam tests at DESY Preparation of next level prototypes and funding applications
End 2020	Approval to proceed with TDRs
2021	Construction of next level prototypes and beam tests Further R&D and engineering design
2022	Design and construction of module-0 prototypes Detailed integration studies
End 2022	Design reviews of critical SHiP components *Delivery of the BDF TDR*
2023	*Seek approval for construction of BDF* Final beam tests Executive designs Specification towards production Engineering Design Reviews (where foreseen)
End 2023	TDR delivery
2024	Production Readiness Reviews
2024+	Tender, component production

Beyond TDR...

- Timeline beyond TDR driven mainly by BDF construction and SHiP installation
  - ➔ Expect detector production to be in the shadow of BDF construction
  - ➔ Challenging detector installation
  - ➔ Data taking as early as possible in Run 4



Project organisation

Project structure (http://ship.web.cern.ch/ship/Constitution/Project_structure.html)

- Spokesperson: A. Golutvin
- Country Representative Board: E. van Herwijnen
- Project leader/Technical Coordinator: R. Jacobsson
- Physics Coordinator: N. Serra
- Conference and publication: W. Bonivento
- GLIMOS: R. Jacobsson
- Experiment safety supervision: L. di Giulio
- Physics Planning Group
  - HS signal
  - HS background
  - ν physics
  - LDM
  - Theory
- Detector electronics/services: J. Maalmi, D. Breton
- Offline computing: T. Ruf
- Subsystem: 2 conveners per subsystem

Component	Institutes
Hadron stopper magnetisation	RAL(UK)[51], CERN[44]
Free-standing muon shield	MISiS(RU)[34], YSDA(RU)[40], ICL(UK)[52], UCL(UK)[53], UOB(UK)[50], UWAR(UK)[54], CERN[44]
SND spectrometer magnet	INFN-UNINA(IT)[14,d], CERN[44]
SND emulsion target	INFN-LNGS(IT)[16], INFN-UNINA(IT)[14,d], AIC(JP)[17], KOBE(JP)[18], NAG(JP)[19], NIH(JP)[20], TOHO(JP)[21], GNU(KR)[22], LPI RAS(RU)[32], MISiS(RU)[34], SINP MSU(RU)[39], METU(TR)[48], ICL(UK)[52]
SND target tracker	EPFL(CH)[46], UNIBON(DE)[7], MISiS(RU)[34], NRC KI(RU)[33],
SND muon system	INFN-UNIBA(IT)[11,a], INFN-UNINA(IT)[14,d], KODEL(KR)[25]
SND upstream background tagger	LIP(PT)[28]
HS decay volume vacuum section	INFN-UNINA(IT)[14,d], NRC KI(RU)[33], CERN[44]
HS spectrometer vacuum vessel	NRC KI(RU)[33], CERN[44]
HS vacuum vessel front/end cap	NRC KI(RU)[33], CERN[44]
HS spectrometer magnet	CERN[44]
HS surround background tagger	HUB(DE)[6], FZJ(DE)[9], JGU(DE)[10], INFN-UNINA(IT)[14,d], TSNU(UA)[55]
HS spectrometer straw tracker	FZJ(DE)[9], UHH(DE)[8], MEPhI(RU)[38], PNPI(RU)[36], SPPU(RU)[37], YSDA(RU)[40], TSNU(UA)[55], JINR[29], CERN[44]
HS timing detector (Sci)	UNIGE(CH)[45], UZH(CH)[47], LAL(FR)[4],
HS timing detector (MRPC)	LIP(PT)[28]
HS SplitCal	JGU(DE)[10], INFN-UNICA(IT)[13,c], IHEP(RU)[35], ITEP(RU)[30]
HS muon system	INFN-UNIBO(IT)[12,b], INFN-LNF(IT)[15], INR RAS(RU)[31], MEPhI(RU)[38]
Common electronics	LAL(FR)[4]
Online system	NBI(DK)[3], LAL(FR)[4], SU(SE)[42], UU(SE)[43], CERN[44]
Offline computing	YSDA(RU)[40], CERN[44]

All systems have 'some' level of coverage but far from all expertise and manpower to fully develop and construct detector

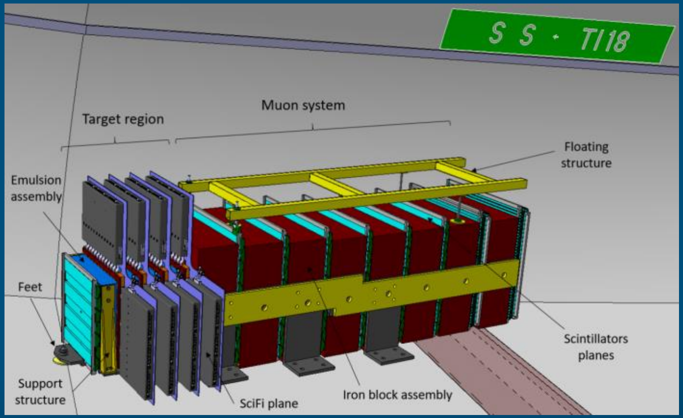
Transition to TDR phase

- TDR phase
  - Seeking provisional approval to continue with a dedicated and sustained activity to perform the R&D required to submit TDRs in 2023 in conjunction with BDF
  - ➔ Compatible with jointly seeking approval for construction of BDF/SHiP in 2023

- CDS review of SHiP/BDF by SPSC (pending ESPPU)
  - Specify TDR phase resource needs

- 2020 year to organise activity
  - Strengthen collaboration
  - Funding applications

- Planning of test beams in 2021 – 2023
  - Several module-0 prototype will require space for assembly at CERN
  - Large scale cosmic test setup at CERN?
  - Charm inclusive production measurement at SPS
  - SND@LHC in 2022?



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 many openings for new groups

- Aiming to produce TDRs by end 2023 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."