Neutrinos and hidden particle searches at CERN

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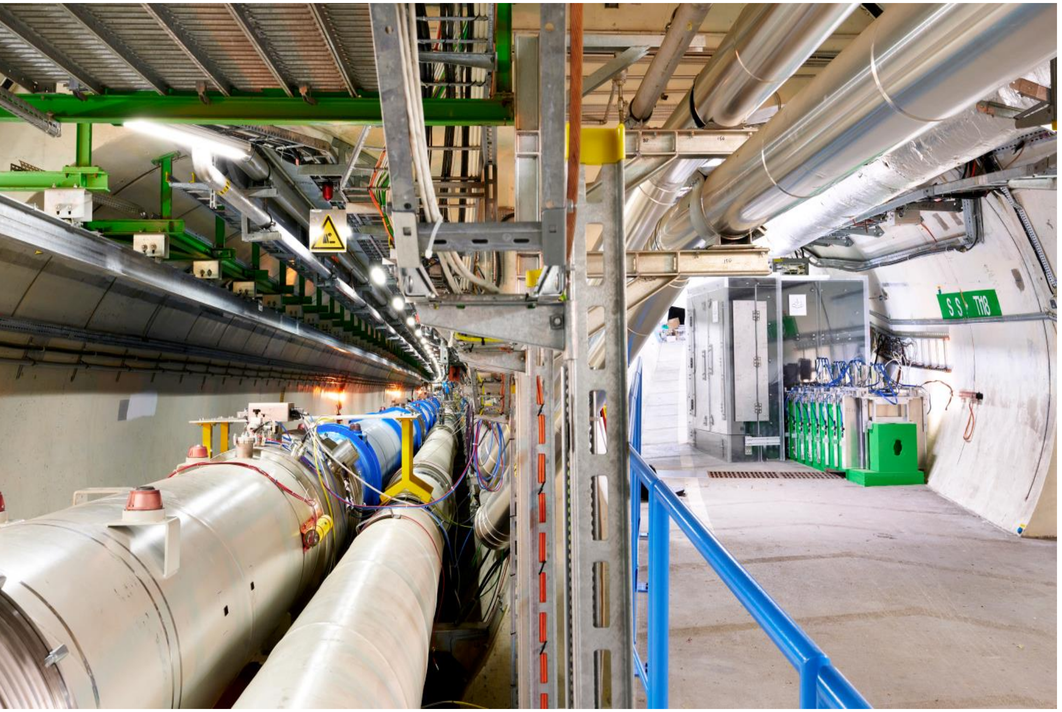
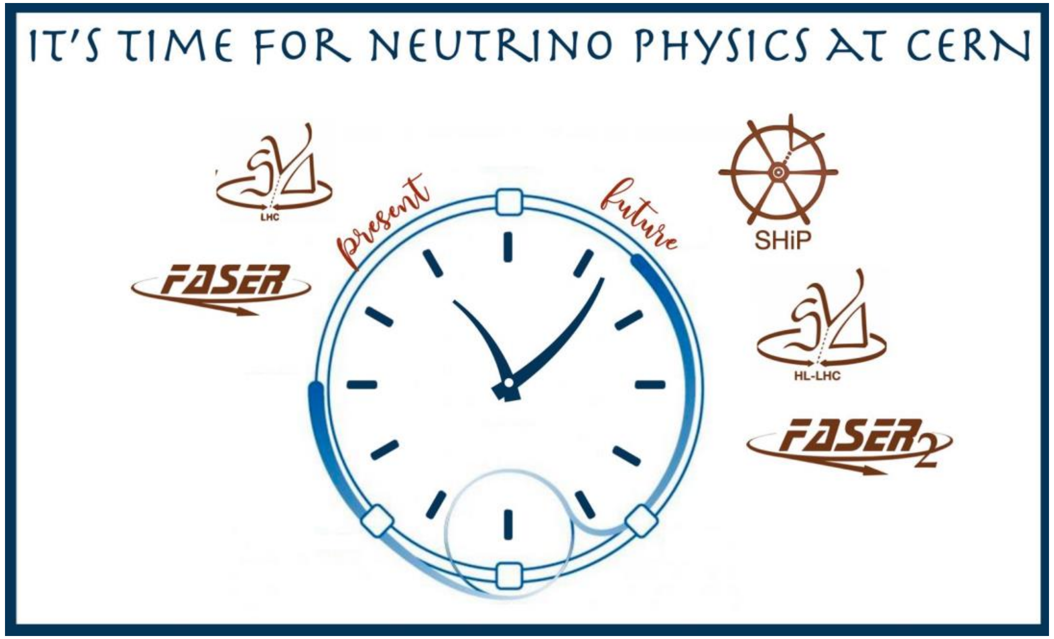
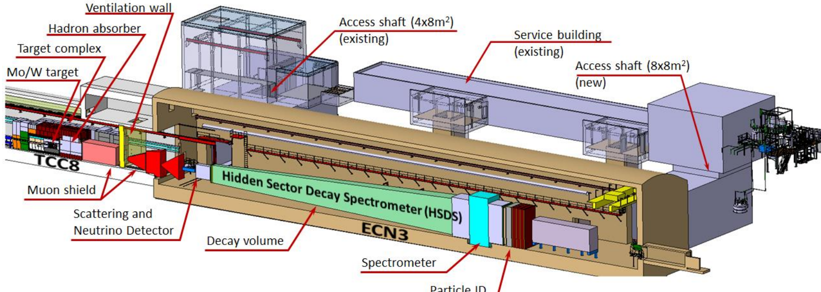
University "Federico II" and INFN, Naples, Italy
CERN, Geneva, Switzerland





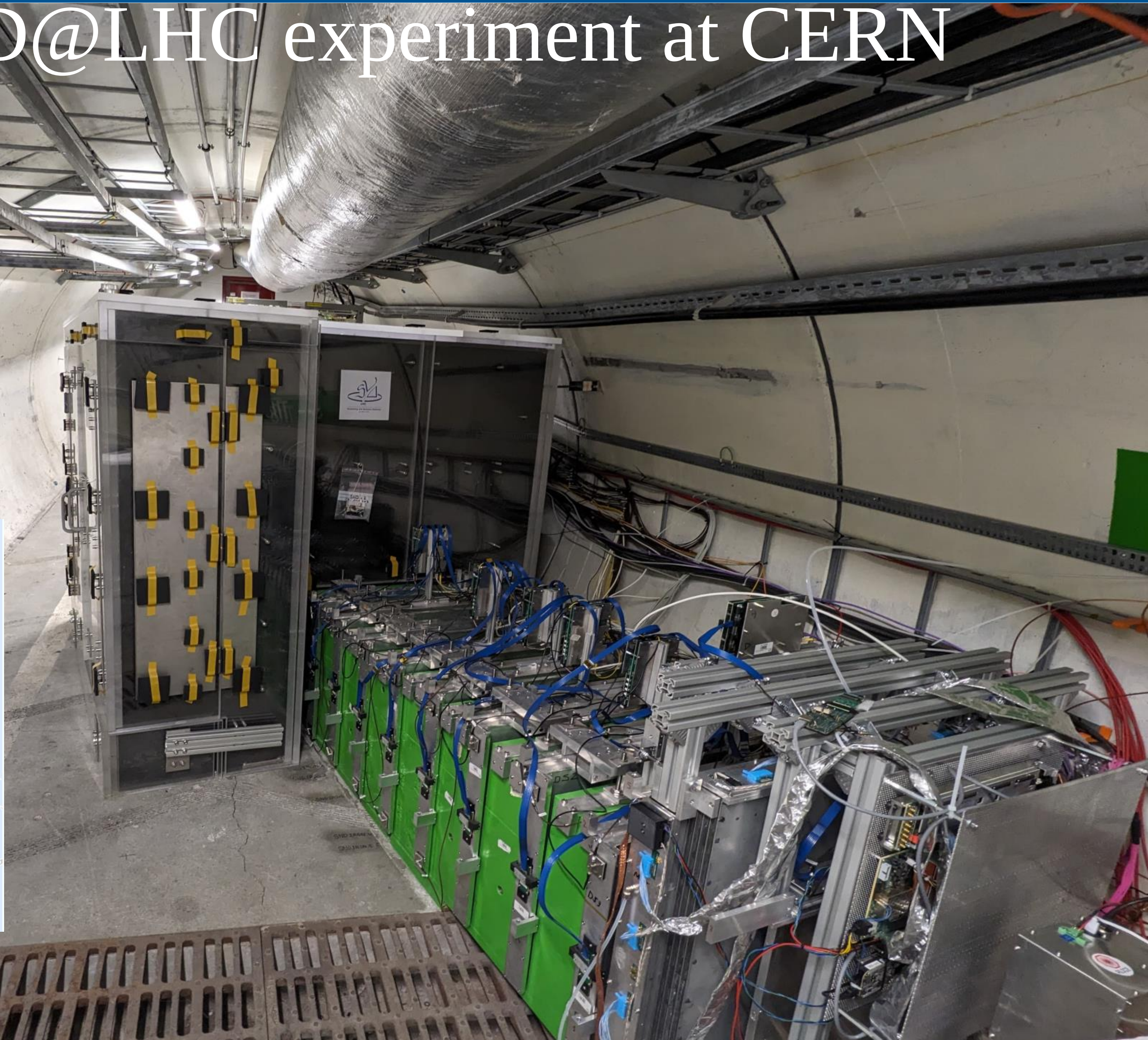
- *The SND@LHC experiment at the LHC: status and plans for the High Luminosity run*
- *The Beam Dump Facility and the SHiP experiment at the SPS*



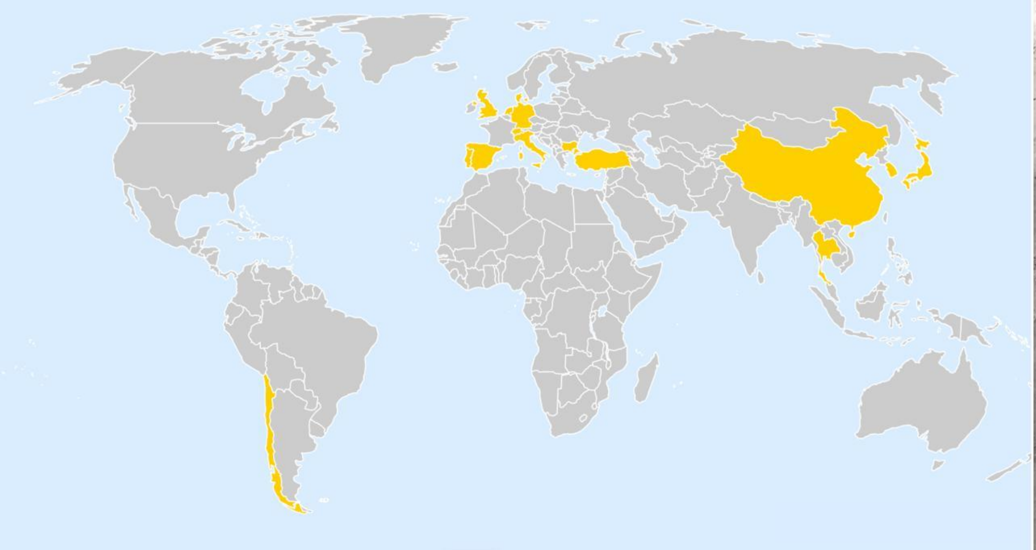
CIEMAT, Madrid, January 22nd 2026

The SND@LHC experiment at CERN

LHC
Scattering and Neutrino Detector
at the LHC



Collaboration: 160 members
24 Institutes in 14 Countries and CERN

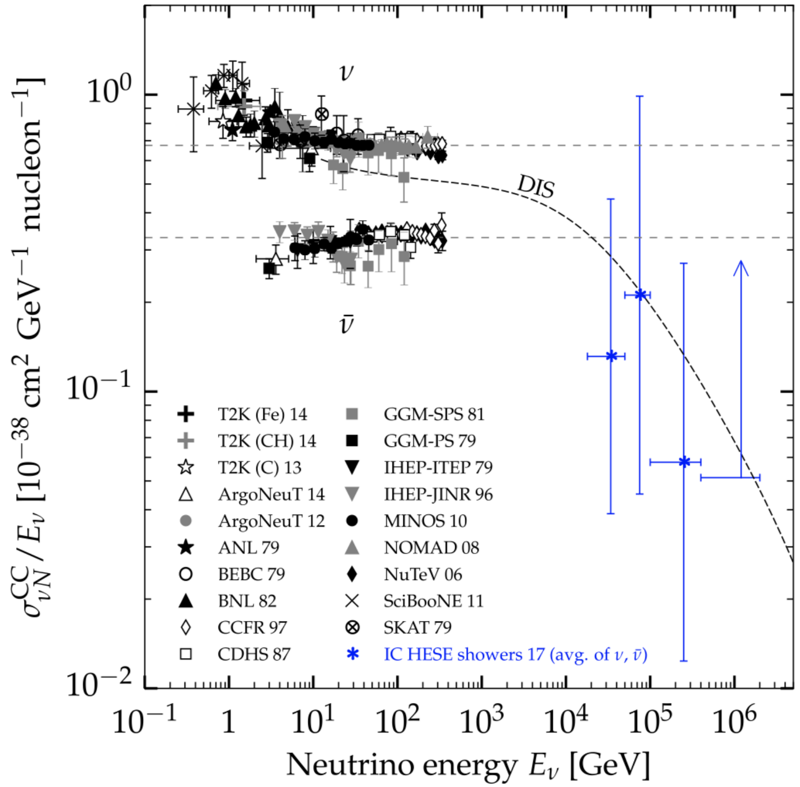


The current era of neutrino physics at the LHC

LHC
Scattering and Neutrino Detector
at the LHC

- A. De Rujula and R. Ruckl, Neutrino and muon physics in the collider mode of future accelerators, CERN-TH-3892/84
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- F. Vannucci, 1993, neutrino physics at the LHC
- [http://arxiv.org/abs/1804.04413 April 12th 2018](http://arxiv.org/abs/1804.04413), First paper on feasibility of studying neutrinos at LHC

PRL 122 (2019) 041101



OPEN ACCESS
IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **46** (2019) 115008 (19pp) https://doi.org/10.1088/1361-6471/ab3f7c

Physics potential of an experiment using LHC neutrinos

N Beni[1], M Brucoli[2], S Buontempo[5], V Cafaro[4], G M Dallavalle[4,8], S Danzeca[2], G De Lellis[2,3,5], A Di Crescenzo[3,5], V Giordano[4], C Guandalini[4], D Lazic[6], S Lo Meo[7], F L Navarria[4] and Z Szillasi[1,2]

Eur. Phys. J. C (2020) 80:61
https://doi.org/10.1140/epjc/s10052-020-7631-5
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Regular Article - Experimental Physics

Detecting and studying high-energy collider neutrinos with FASER at the LHC

FASER Collaboration

CERN is unique in providing energetic **ν** (from LHC) and measure pp → **ν**X in an unexplored domain

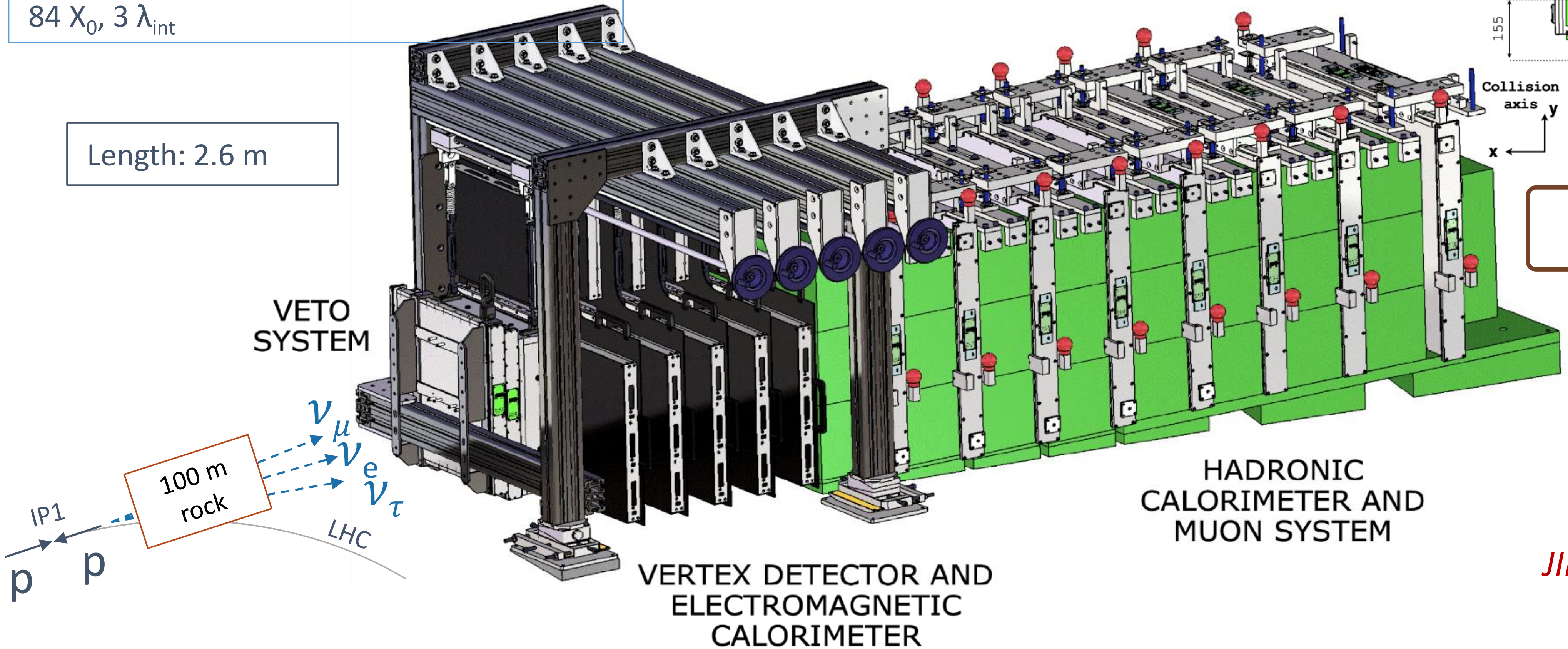
SND@LHC detector

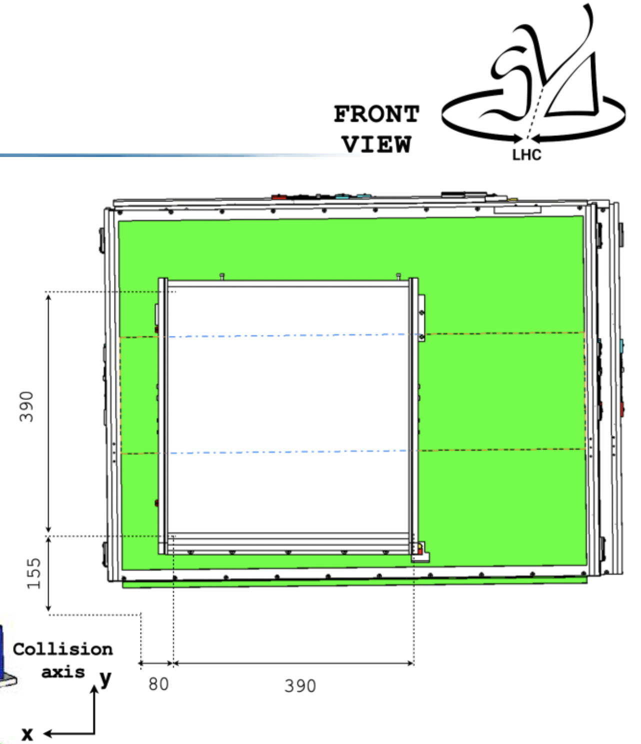
Veto system
Two 1 cm thick scintillator planes.

Target, vertex detector and ECal
830 kg tungsten target.
Five walls x 59 emulsion layers
+ five scintillating fibre stations.
84 X_0, 3 λ_{int}

HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer
granularity to track muons.
9.5 λ_{int}

Length: 2.6 m





Off axis location

$7.2 < \eta < 8.4$

JINST 19 (2024) 05, P05067

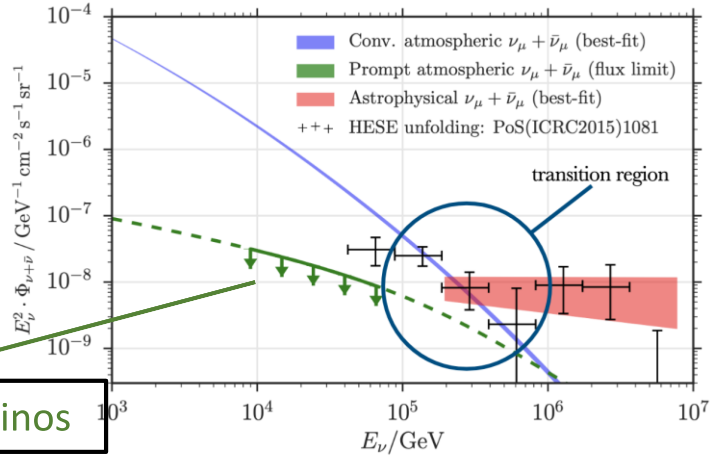
Physics goals

LHC
Scattering and Neutrino Detector at the LHC

- Study ν interactions of all 3 types (cross-section, LFU, ..) in a new energy domain
- Systematic uncertainty on the cross-section measurement dominated by the uncertainty on the neutrino flux
- Studying the neutrino source, i.e. using neutrinos as probes → measuring charm production in pp collisions in the forward region using ν_e
- Manyfold interest for the charm measurement in pp collision at high η
- Charm production within the acceptance of FCC detectors
- Prediction of very high-energy neutrinos produced in cosmic-ray interactions → experiments also acting as a bridge between accelerator and astroparticle physics

IceCube Collaboration, six years data, Astrophysics J. 833 (2016) 3, https://iopscience.iop.org/article/10.3847/0004-637X/833/1/3/pdf

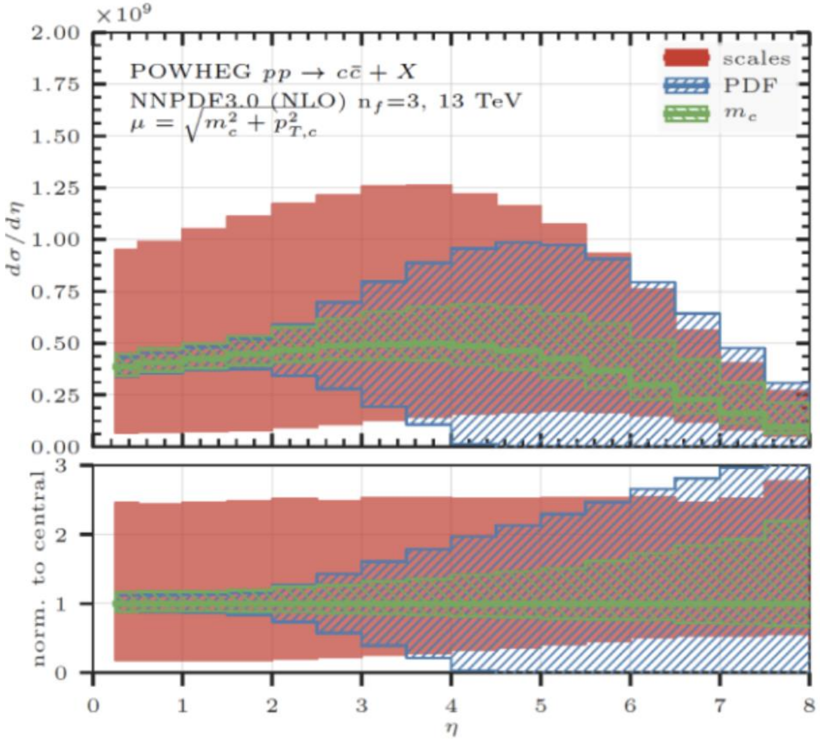
7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

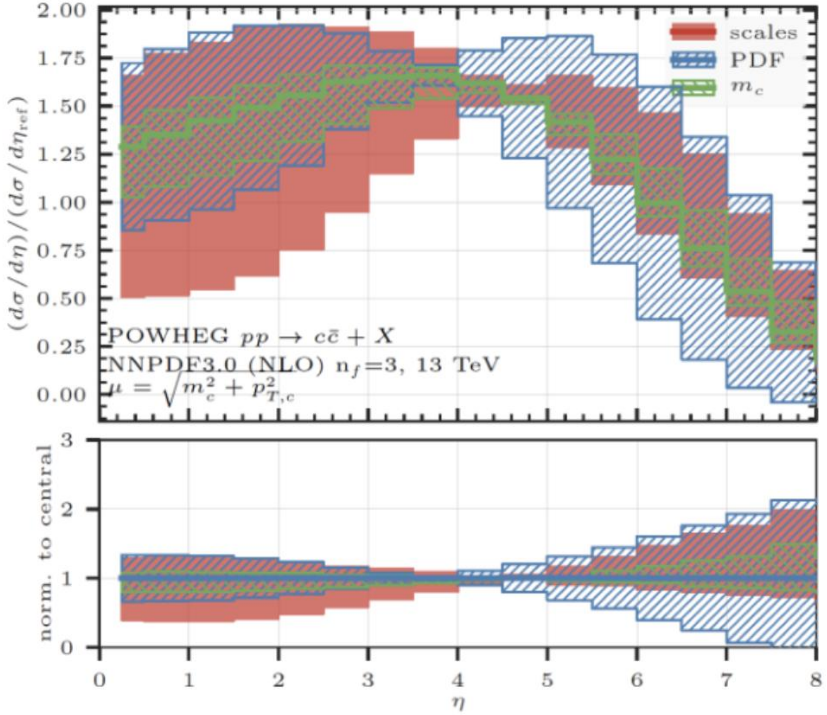


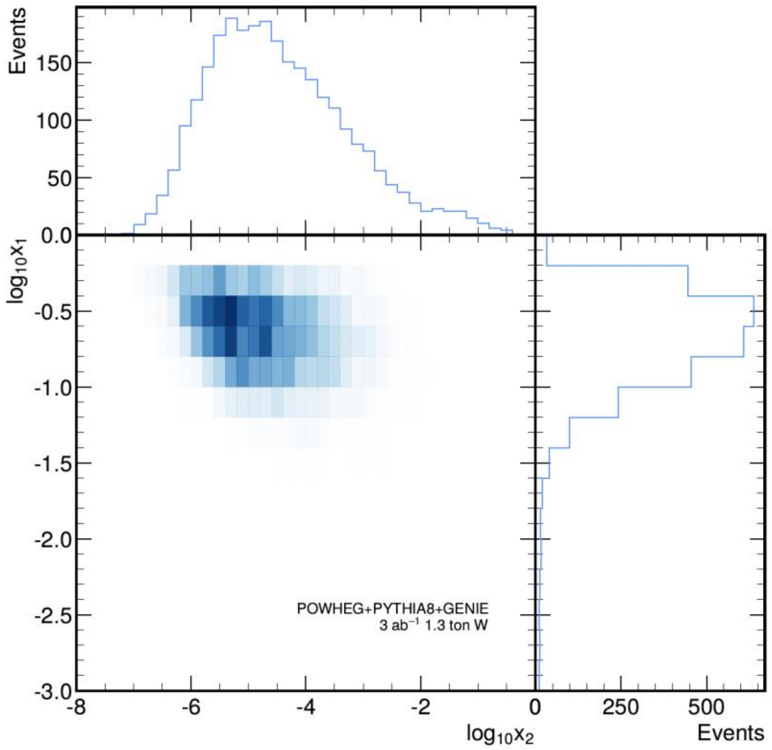
prompt atmospheric neutrinos

Extraction of the gluon PDF from ν_e

- Dominant partonic process: gluon-gluon scattering
- SND@LHC data to constraint the gluon PDF in the very-small x region







$d\sigma/d\eta$ at 13 TeV

$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

η_{ref} = [4,4.5]

Detector improvements during the YETS

Scattering and Neutrino Detector at the LHC

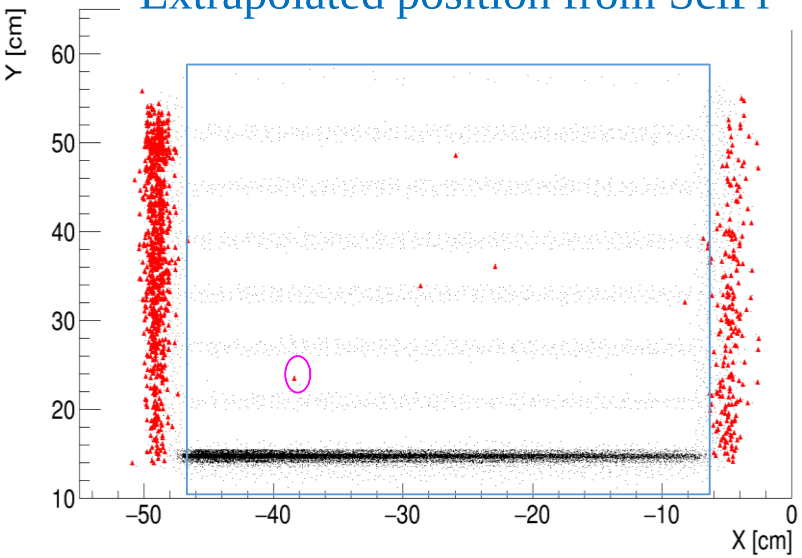
- Test beam for energy calibration: inter-calibration of SciFi (target) and scintillating bars (HCAL)
- Dug a small trench to lower the veto system and install a third veto station in YETS 2023-24
- Add 2 drift tube stations downstream to improve the muon identification system

Acceptance and efficiency with the new configuration

Upgraded layout in the 2023-24 YETS: third plane with vertical bars

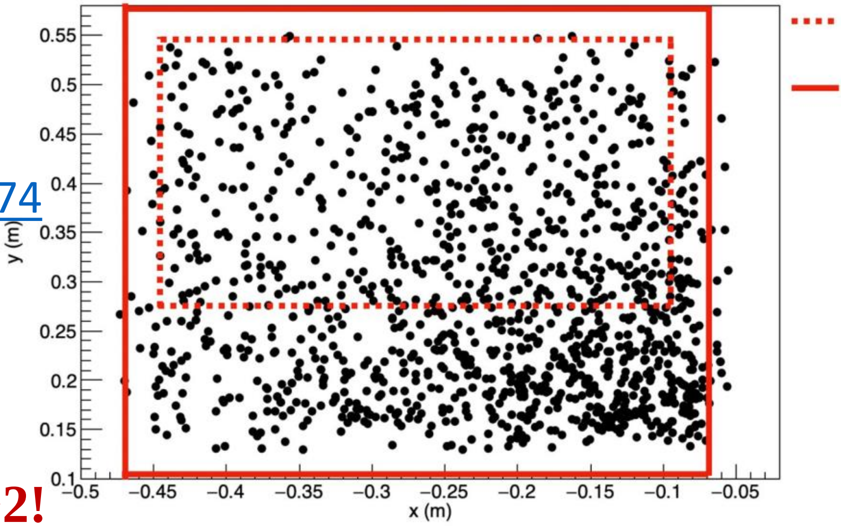
- Using all 2024 data, i.e. **1.6e+9 tagged events**
- Veto system **inefficiency: 4.9E-9**
- Cyan rectangle = fiducial region used for the estimate
- Red triangles = inefficient events where muons didn't produce a hit in any Veto plane
- Black dots = muons hitting a specific Veto plane but not producing a hit there
- 8 inefficient events in total: 3 close to the borders, 3 in the dead region of 2 planes, 1 in the dead region of one plane, only 1 event (magenta circle) well within the acceptance.

Extrapolated position from SciFi



JINST **20** (2025) P07011
https://iopscience.iop.org/article/10.1088/1748-0221/20/07/P07011

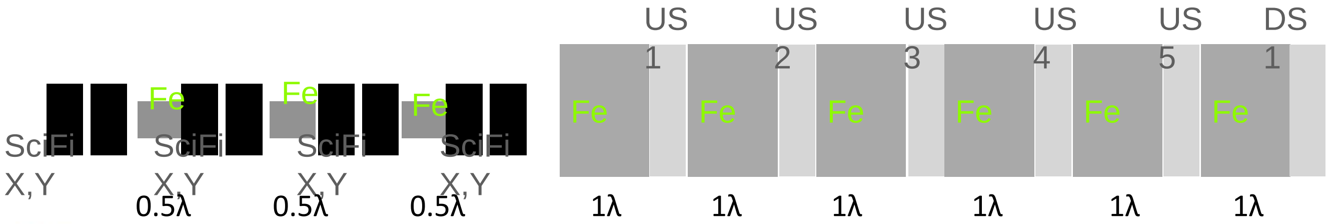
XY position of ν interactions

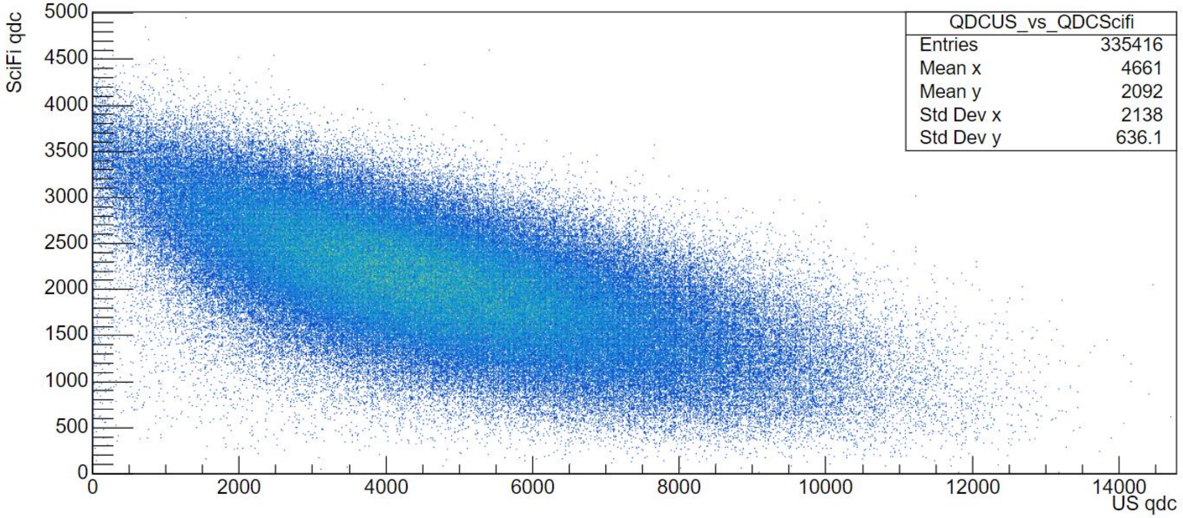


Neutrino yield increased by **a factor of ~2!**

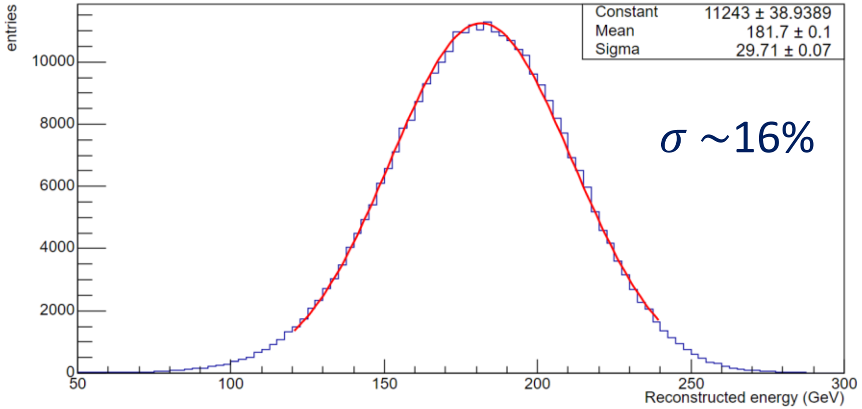
Calibration studies and energy resolution

Reconstruction of the total energy requires the estimate of the fraction lost in the target region





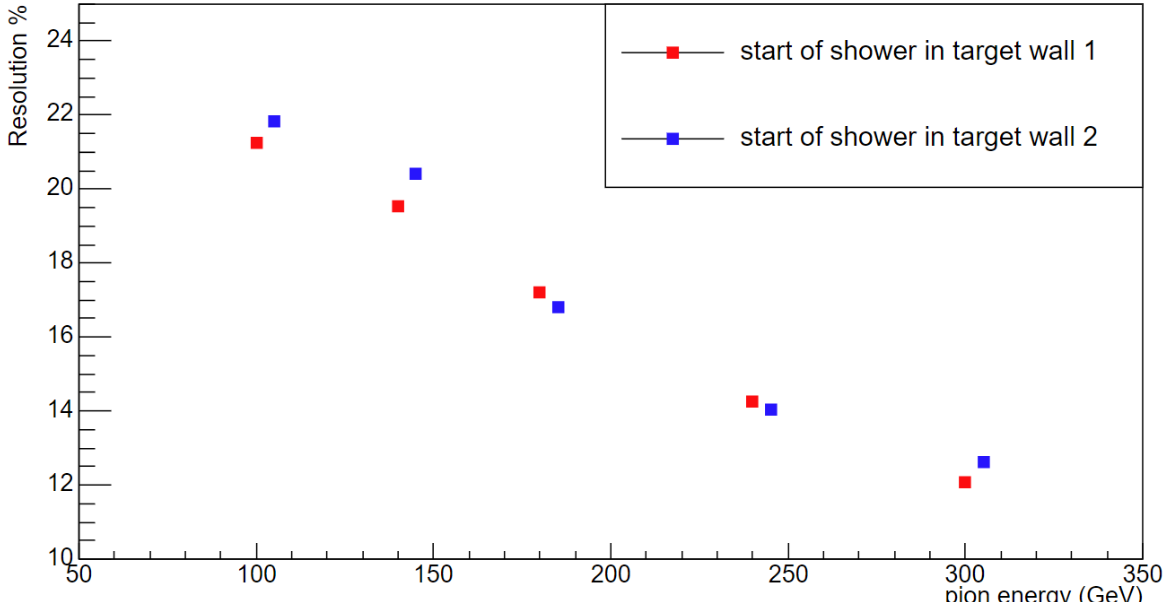
Reconstructed energy for 180 GeV π



JINST **20** (2025) P10039

https://iopscience.iop.org/article/10.1088/1748-0221/20/10/P10039

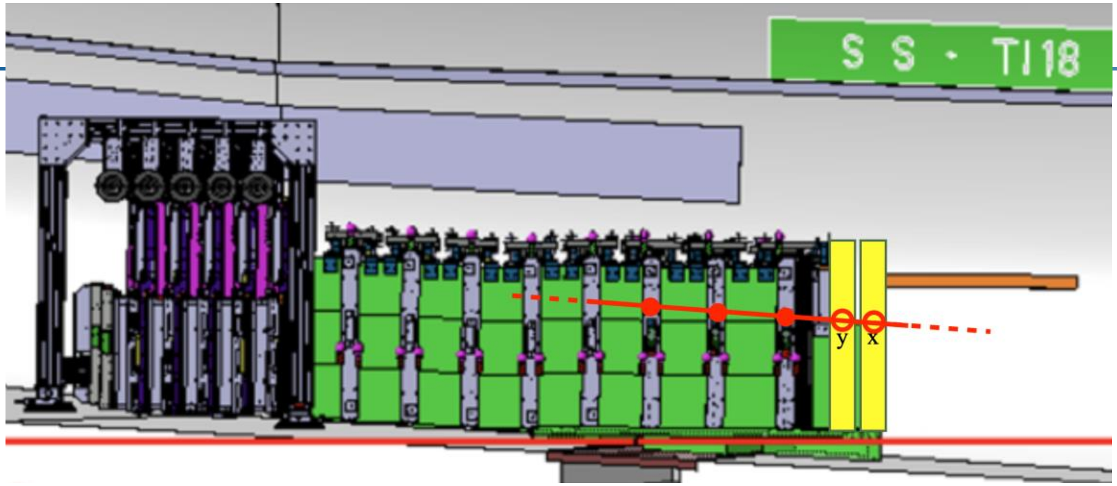
Test beam setup in H8



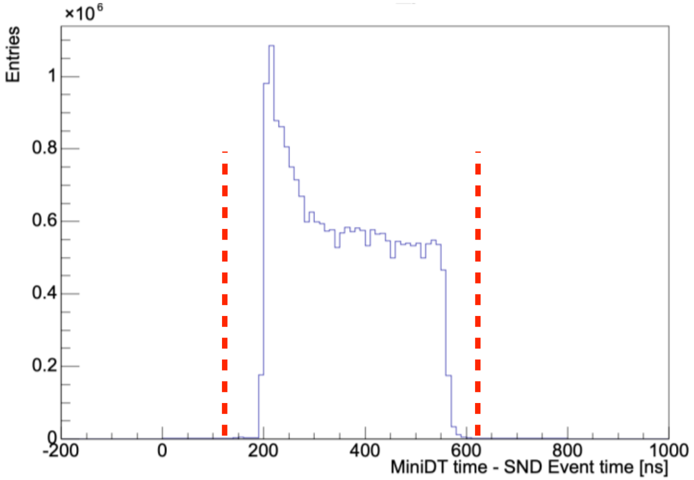
Drift tube chambers installed to improve the muon system

after

Installation **Mar 3-6 2025**

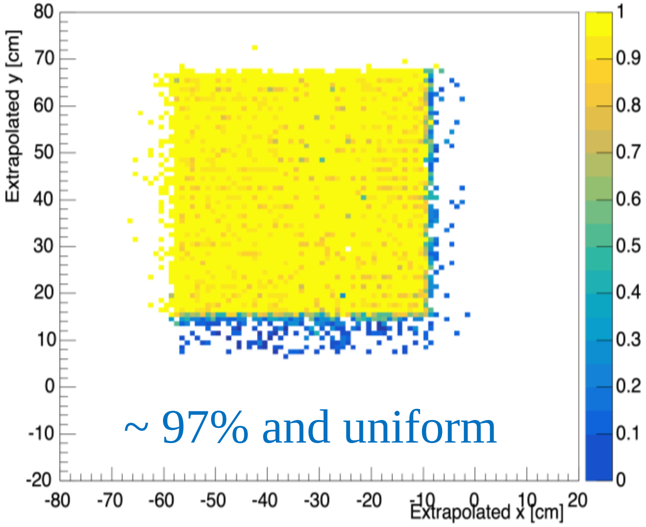


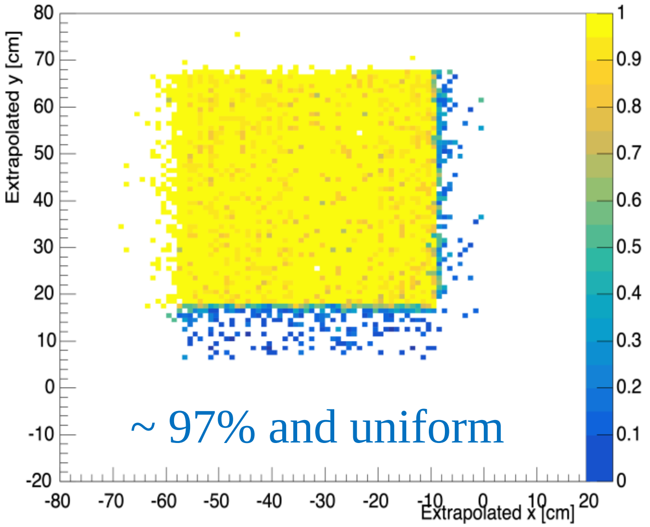
Efficiency study: events with μ track reconstructed by Downstream stations, extrapolate to (x,y) position in DT layers (≥ 3 hits)



Coherent with the drift speed of 54 μm/ns and 2 cm distance

MiniDT efficiency





With the contribution from CIEMAT!

Data taking with emulsion detector

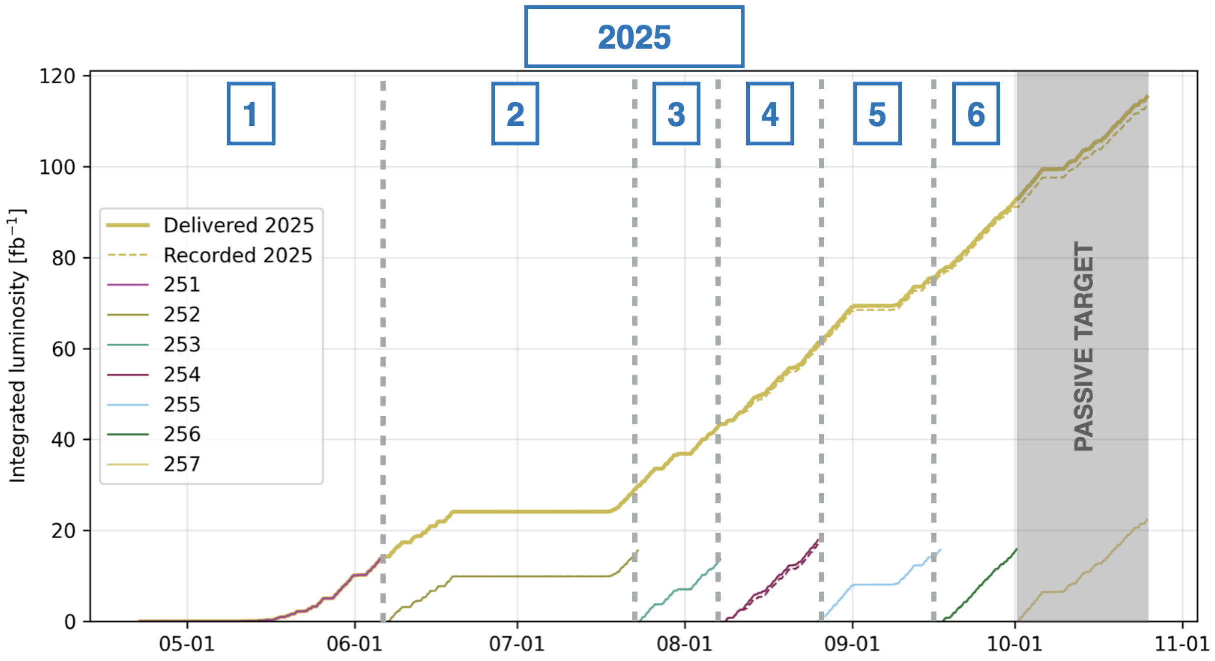
EMULSION DATA TAKING IN 2025

Delivered 2025

- 124 fb^{-1}

Recorded 2025

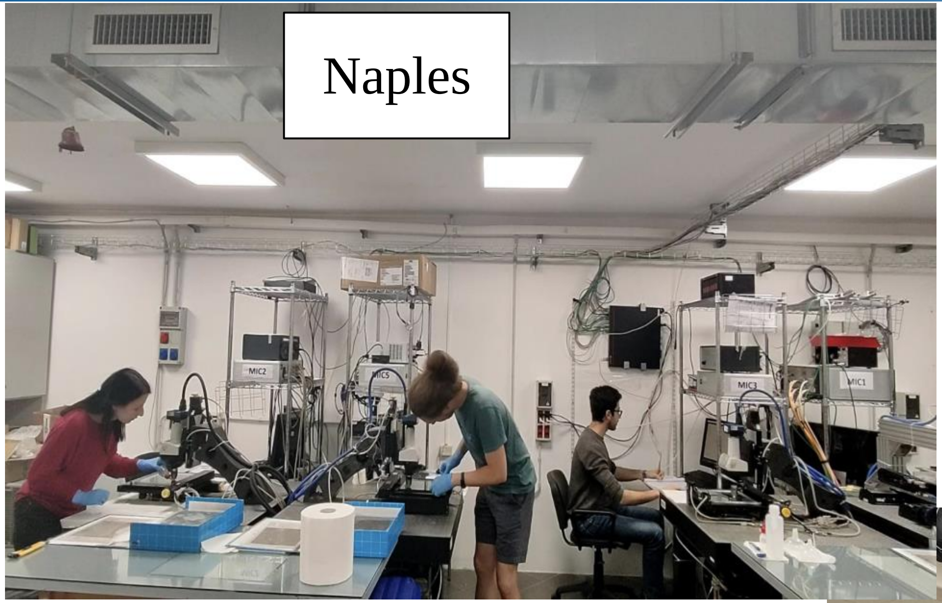
- 122 fb^{-1} Electronic detectors
- 92 fb^{-1} Emulsions

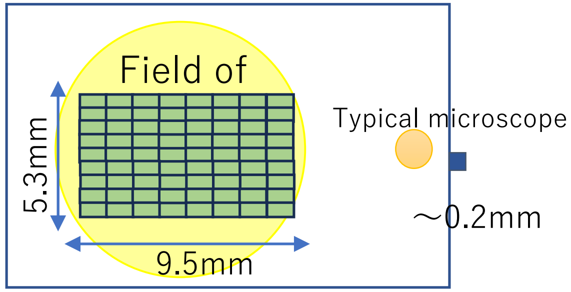


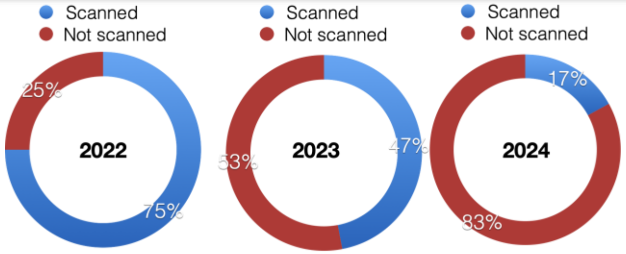
2025						
251	TARGET 15	RUN17	11-Mar-25	06-Jun-25	797 kg	14.2 fb^{-1}
252	TARGET 16	RUN18	06-Jun-25	23-Jul-25	797 kg	15.6 fb^{-1}
253	TARGET 17	RUN19	23-Jul-25	07-Aug-25	797 kg	13.6 fb^{-1}
254	TARGET 18	RUN20	07-Aug-25	25-Aug-25	598 kg	17.9 fb^{-1}
255	TARGET 19	RUN21	25-Aug-25	17-Sep-25	598 kg	15.8 fb^{-1}
256	TARGET 20	RUN22	17-Sep-25	01-Oct-25	598 kg	14.9 fb^{-1}

Emulsion film scanning stations in the Collaboration

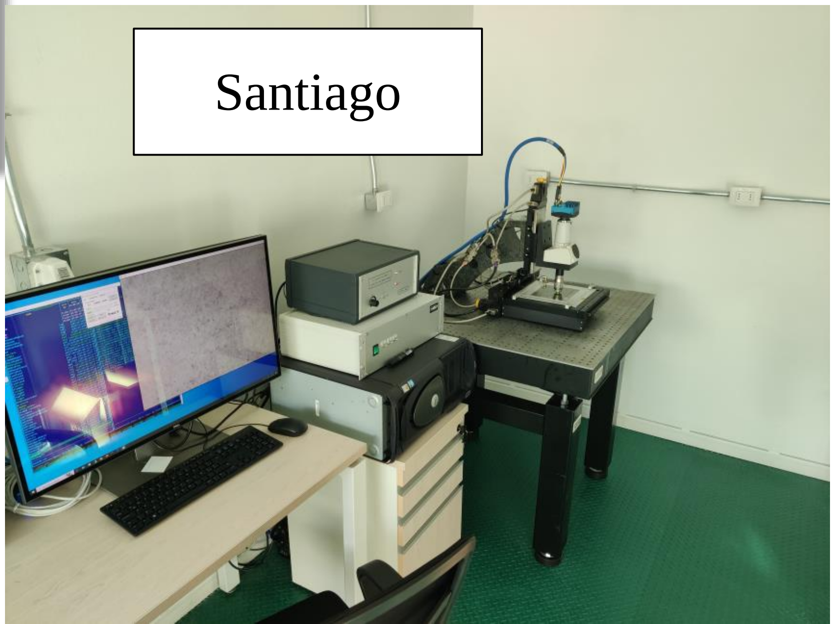
1) **Bologna:** 2 systems, 4 films/week
2) **CERN:** 4 systems, 40 films/week
3) **Napoli:** 3 systems, 26 films/week
4) **LNGS:** 2 systems, 3 films/week
5) **Salerno:** 1 system under test
6) **Santiago:** 1 system, 3 films/week
7) **Nagoya:** ~800 films so far

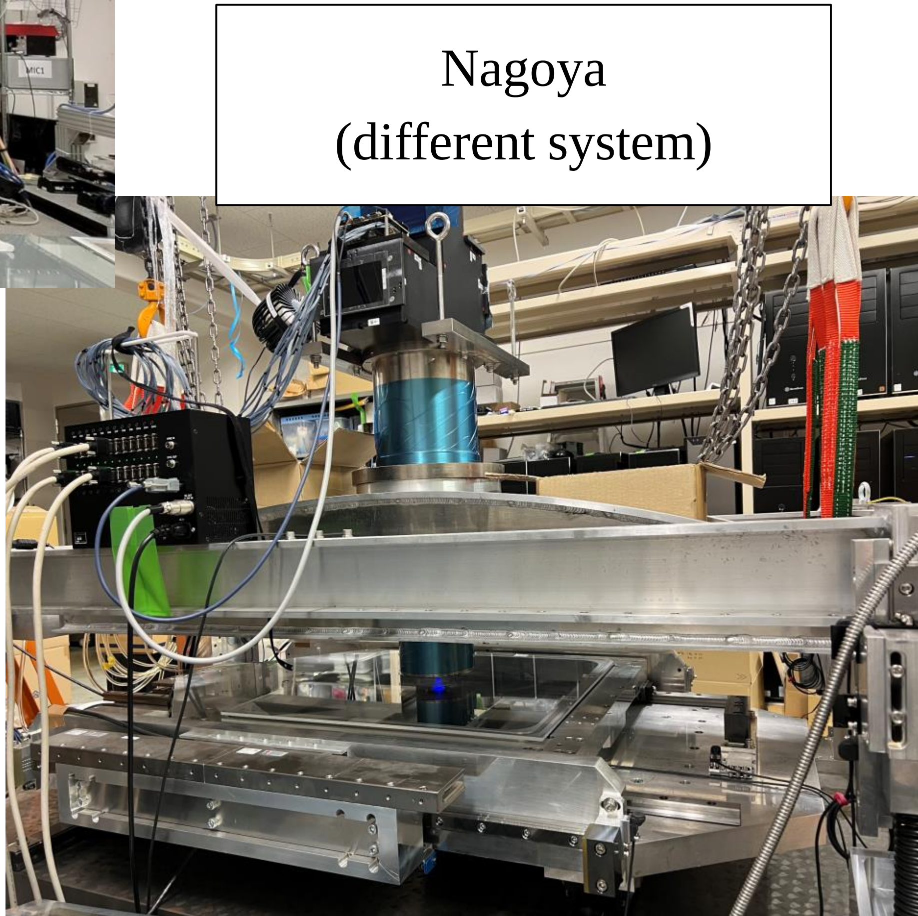






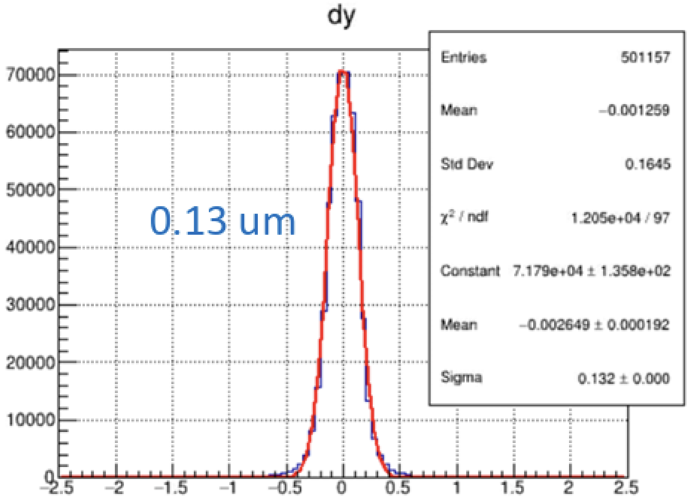
Scanning completed
800 kg x 60 fb^{-1}

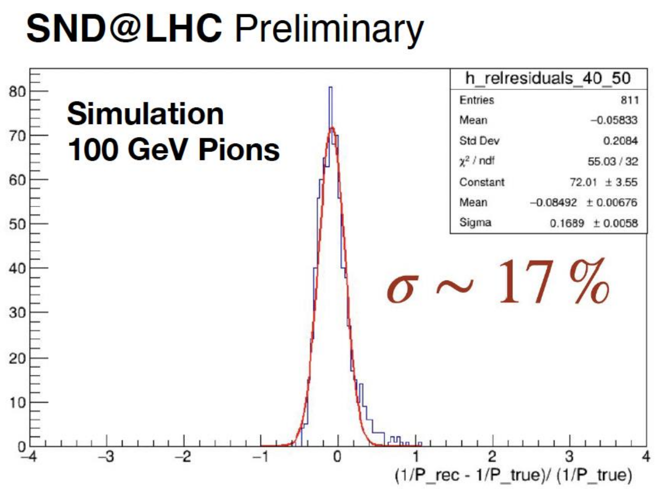


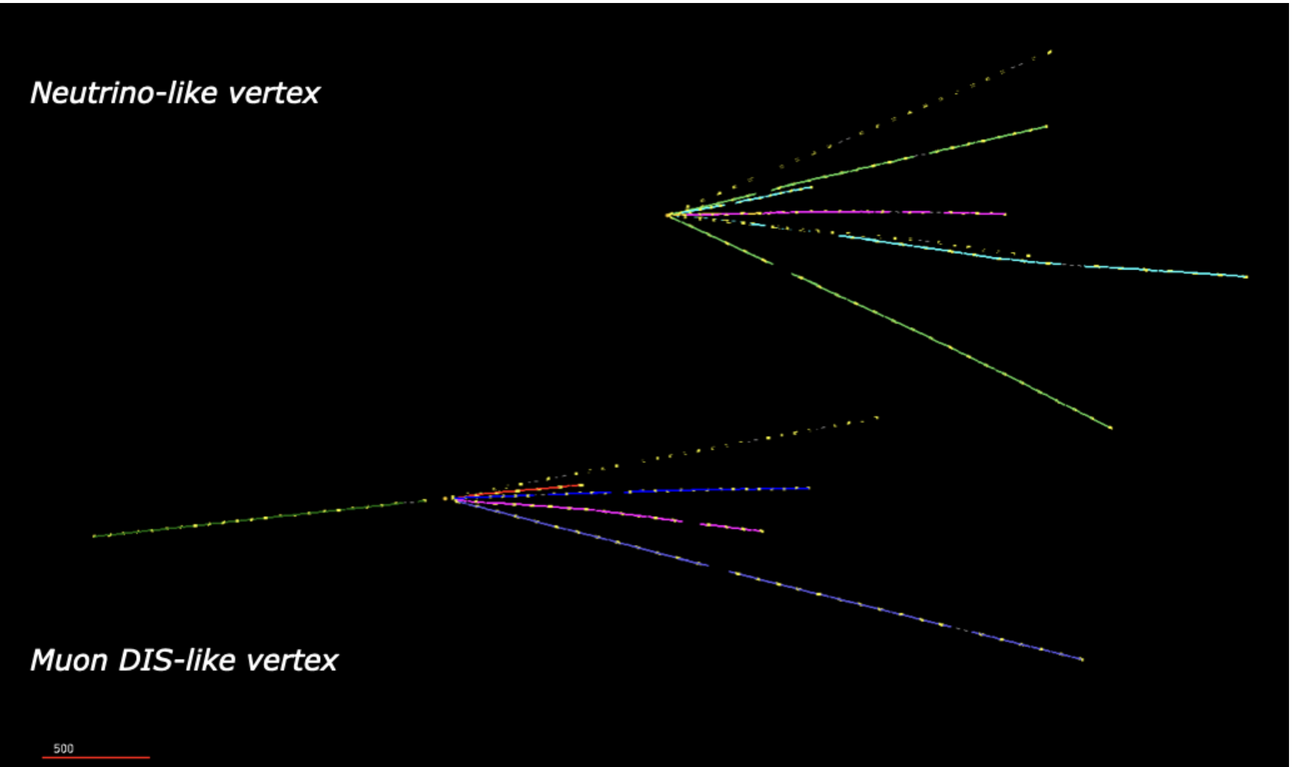


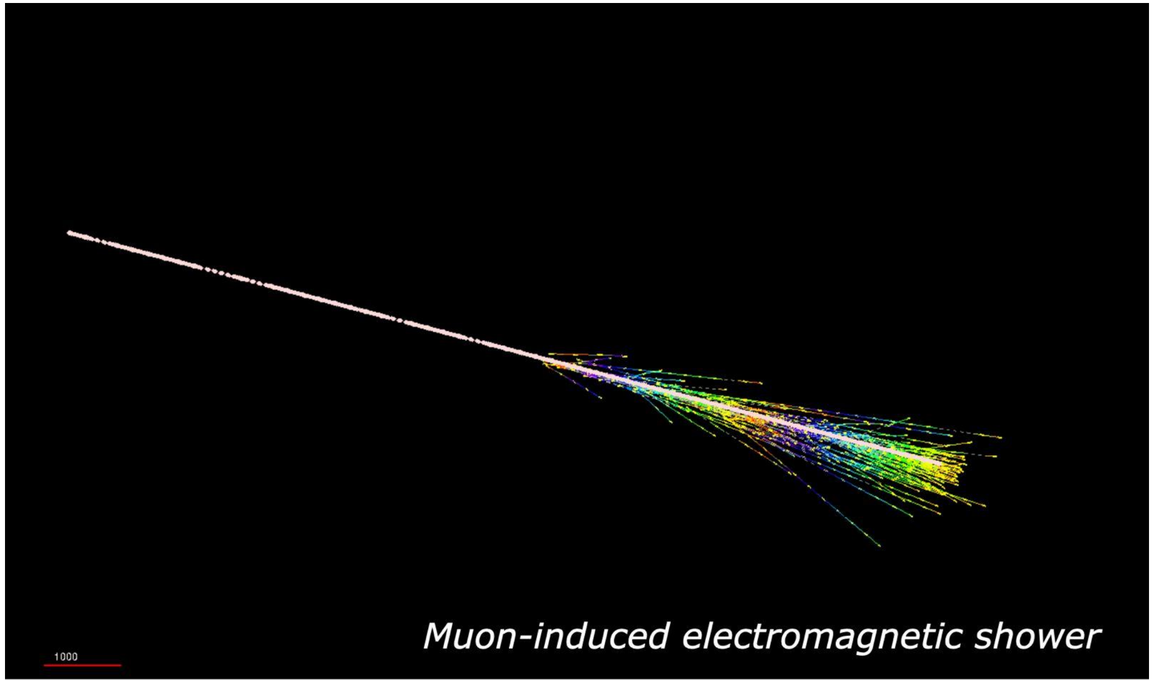
EMULSION DATA ANALYSIS

- Momentum measurement with Mutiple Coulomb Scattering
  - 15÷20% resolution for charged pions
- Electromagnetic shower identification and energy measurement
  - 25% energy resolution
- Identification of charged and neutral vertices

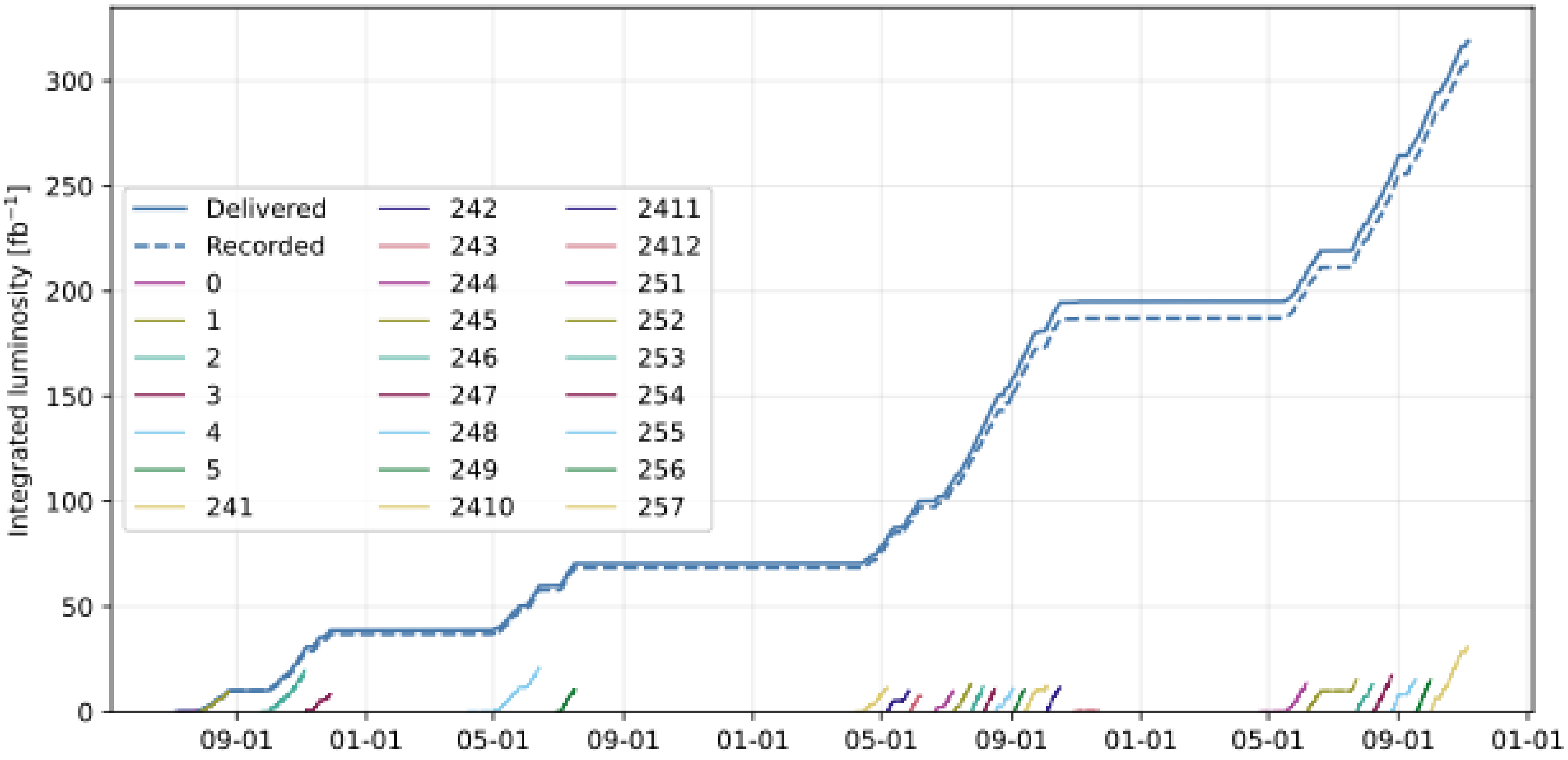








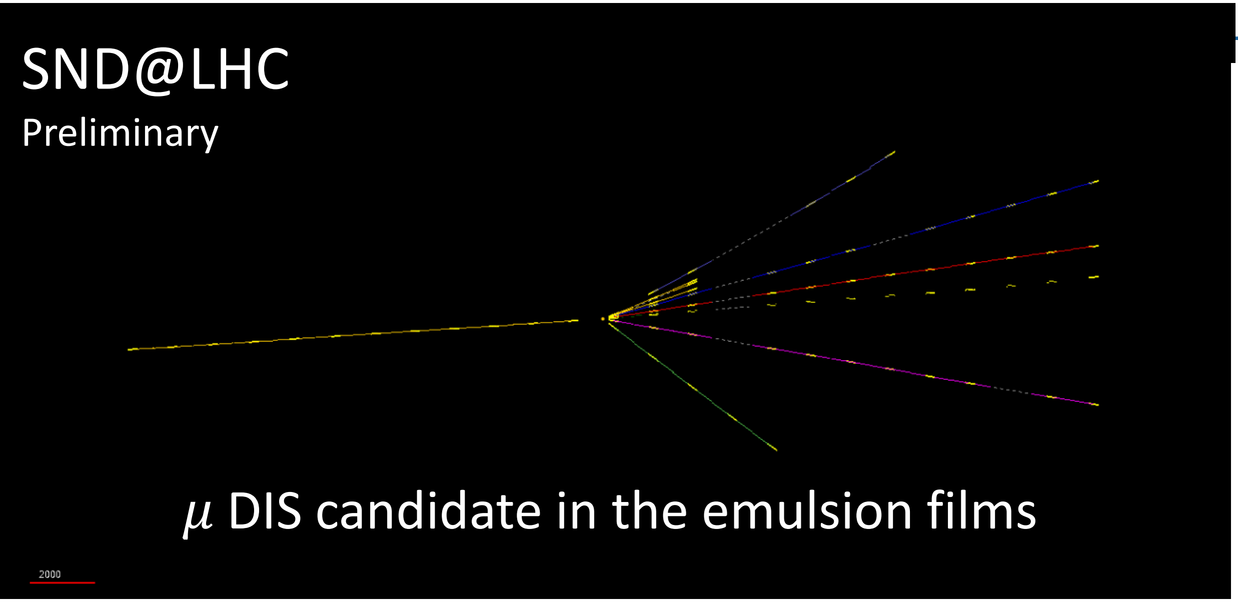
Integrated luminosity



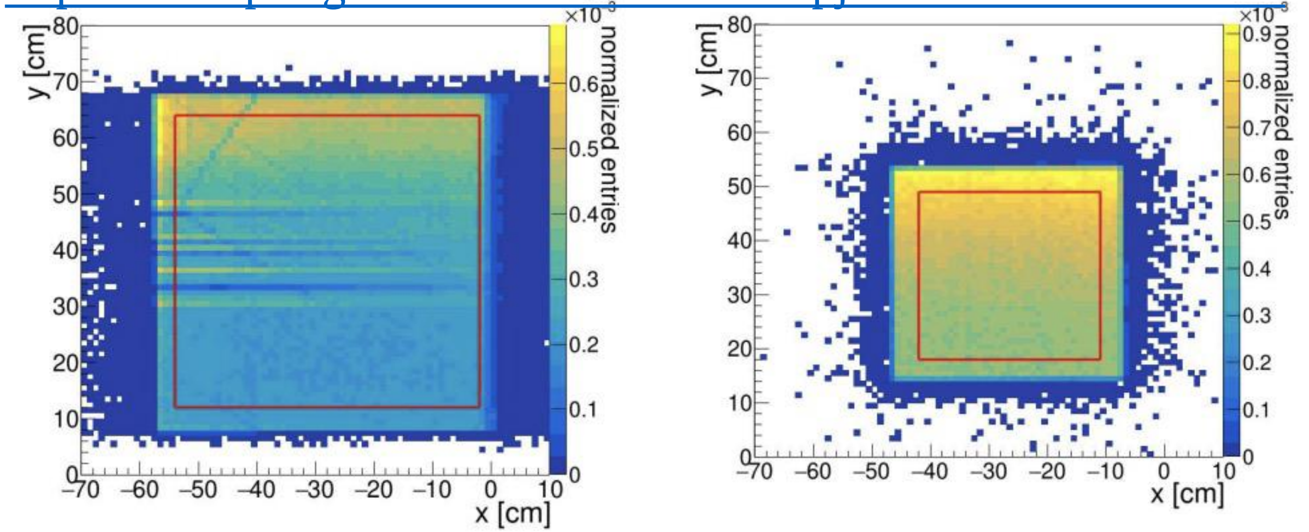
Integrated luminosity: delivered 319 fb^{-1} , recorded 309 fb^{-1} (122 fb^{-1} in 2025)
efficiency 97% (2022 95%, 2023 99.7%, 95.3% in 2024, 98.5% in 2025)

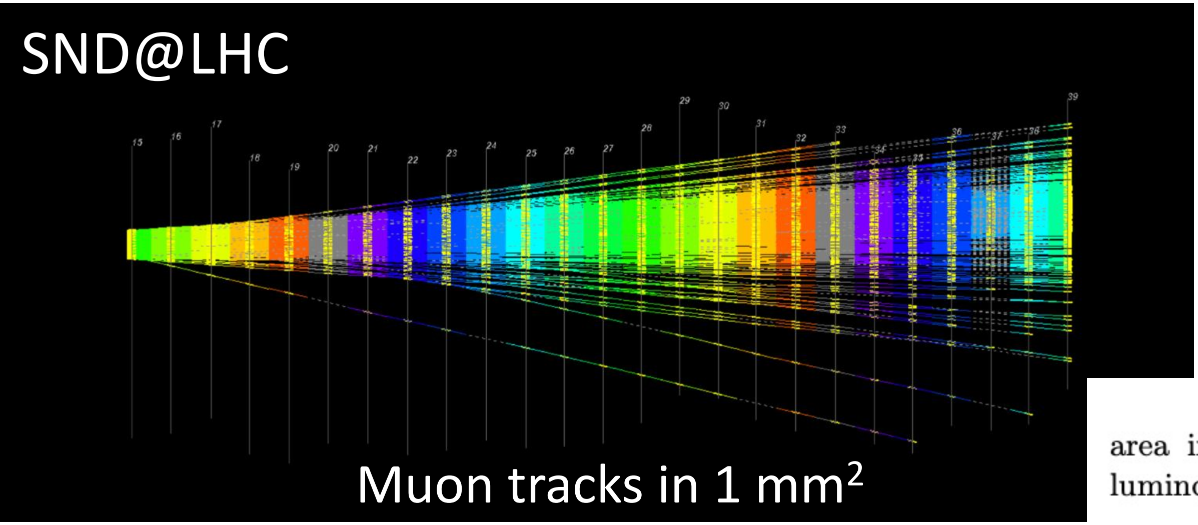
Data analysis

Muon flux measurement



https://link.springer.com/article/10.1140/epjc/s10052-023-12380-3





SND@LHC measure muon flux in 3 different detector systems (emulsion, SciFi and Muon System).
Flux seen to increase with vertical distance from LOS.
FLUKA simulation estimate of flux ~20% lower than measurement.

10^5 tracks/cm^2 in 10 fb^{-1} exposure

The muon flux per integrated luminosity through an 18×18 cm^2 area in the emulsions is $\mathbf{1.5 \pm 0.1}(\text{stat}) \times \mathbf{10^4}$ fb/cm^2. The measured muon flux per integrated luminosity through a 31×31 cm^2 central SciFi area is

$$\mathbf{2.06 \pm 0.01}(\text{stat}) \pm \mathbf{0.12}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2,$$

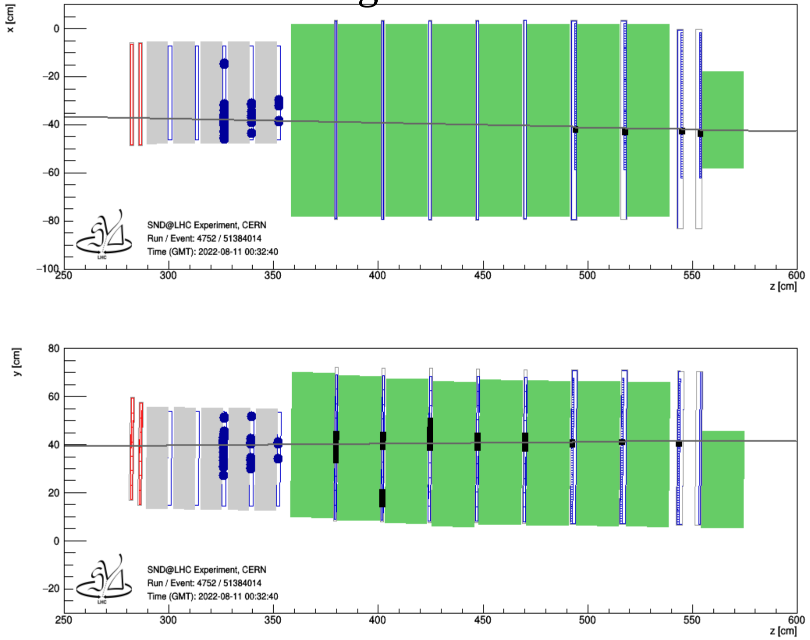
while for the downstream muon system the flux is

$$\mathbf{2.35 \pm 0.01}(\text{stat}) \pm \mathbf{0.10}(\text{sys}) \times \mathbf{10^4}\ \text{fb/cm}^2$$

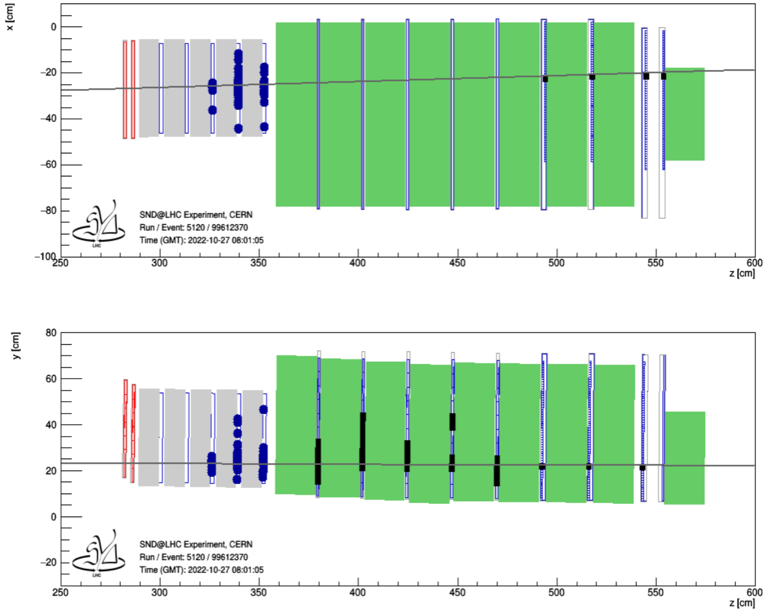
for a 52×52 cm^2 central detector region.

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



Oct 27th 2022

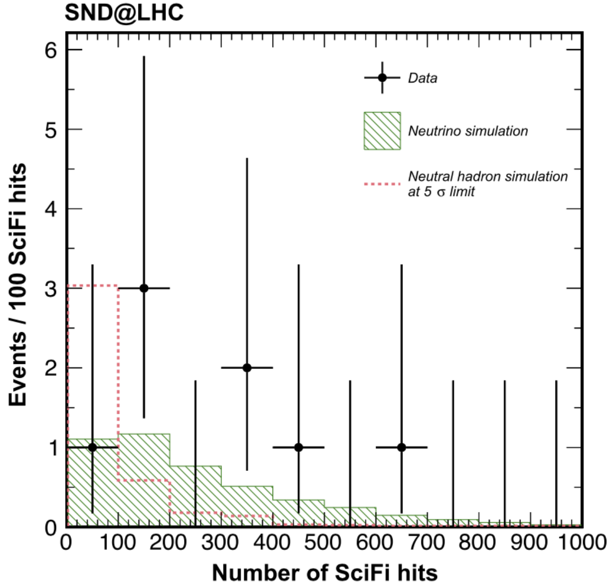


Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)

Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023



Distribution of SciFi hits for ν_μ candidates with the MC expectation for ν events and background (augmented to the 5 sigma level)

8 observed events and an expected background

$$(8.6 \pm 3.8) \times 10^{-2}$$

Background only hypothesis probability:

$$P = 7.15 \times 10^{-12}$$

6.8 σ observation

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

Observation of 0μ (ν_e CC and ν NC) events with 2022-23 data

PHYSICAL REVIEW LETTERS **134**, 231802 (2025)
https://journals.aps.org/prl/abstract/10.1103/r2qy-9hft

Neutral hadron background

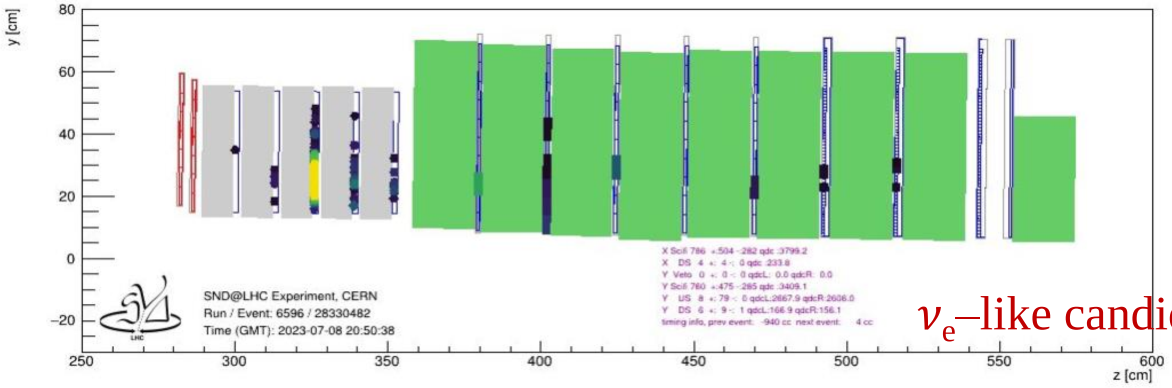
- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
- Events **expected in signal region**: **0.01**

Neutrino background

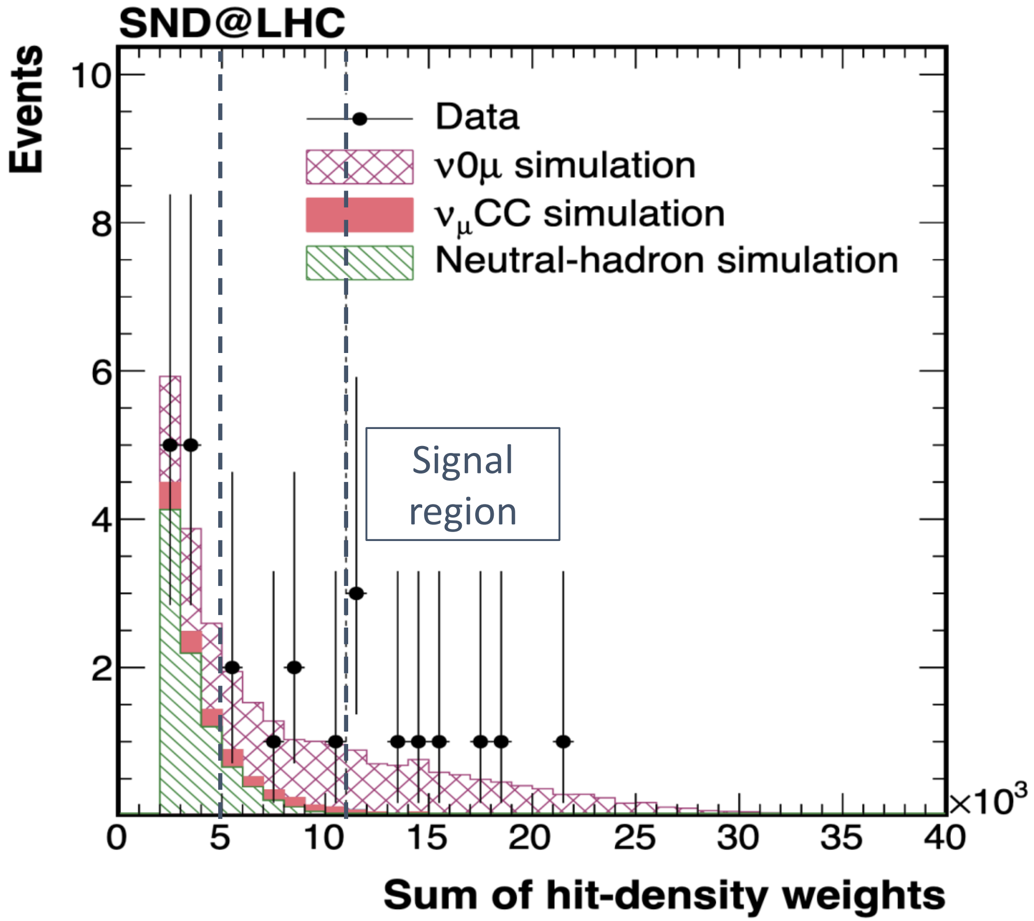
- ν_μ CC interactions are the dominant background, with **0.30** expected events
- ν_τ CC1μ interactions expected: 0.002

0μ observation significance

- **Total expected background: 0.32 ± 0.06 events**
- **Expected signal: 7.2 events**
  - 4.9 ν_eCC, 2.2 NC, 0.1 ν_τCC
- **Expected significance: 5.5 σ**



ν_e–like candidate



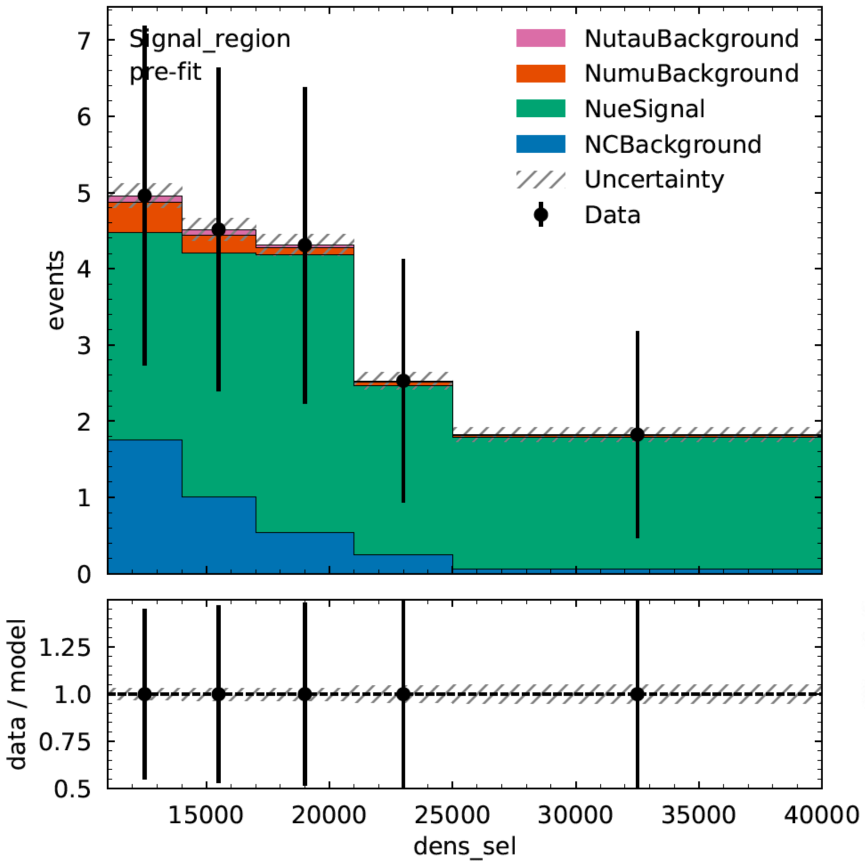
Number of events observed: 9

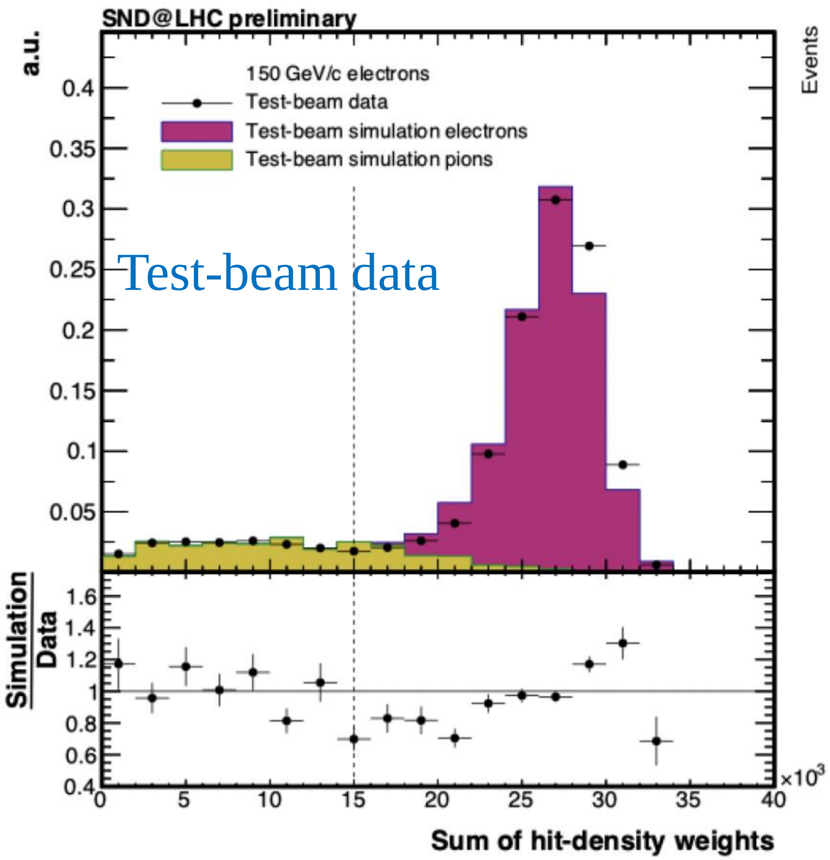
Observation significance: 6.4 σ

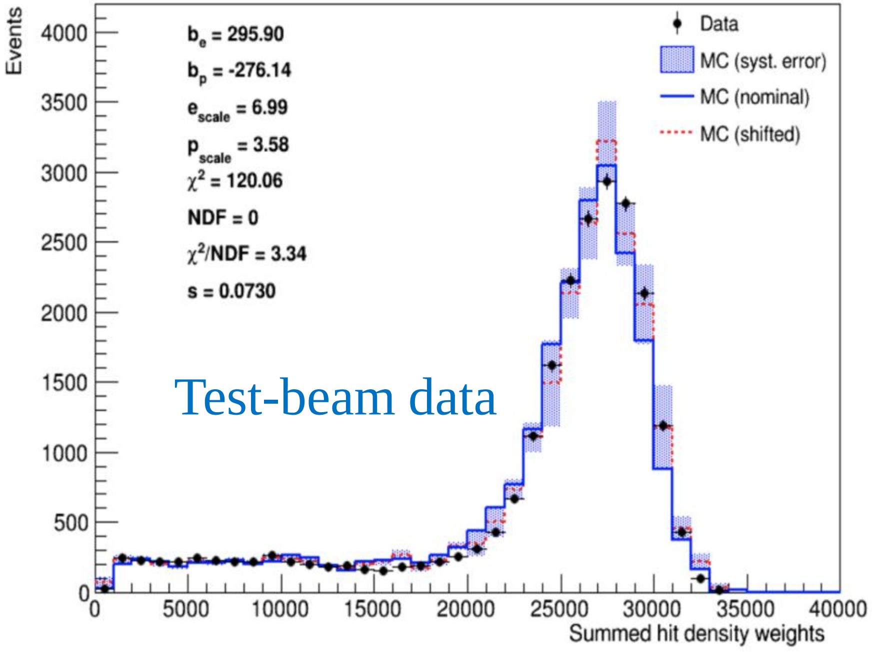
ν_e CC search with electronic detectors

- Follow up on SciFi-based identification of "0μ" neutrino events [PRL 134, 231802 (2025)]. Expect 5σ sensitivity to ν_eCC with 2022-2024 data and binned likelihood analysis.
- Systematic uncertainty on the shape of the discriminating variable evaluated using test-beam data.
- Statistical data analysis implementation ongoing using the "cabinetry" framework (Scikit-HEP).

SIMULATION







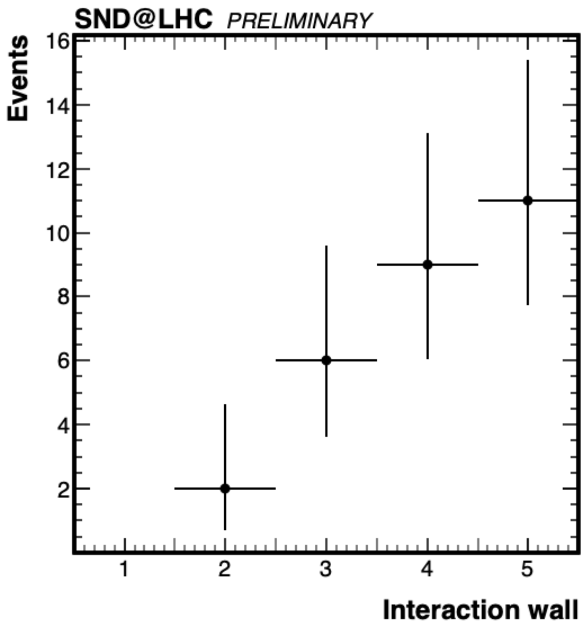
Updated ν_μ results (2022-2023 data) with electronic detector

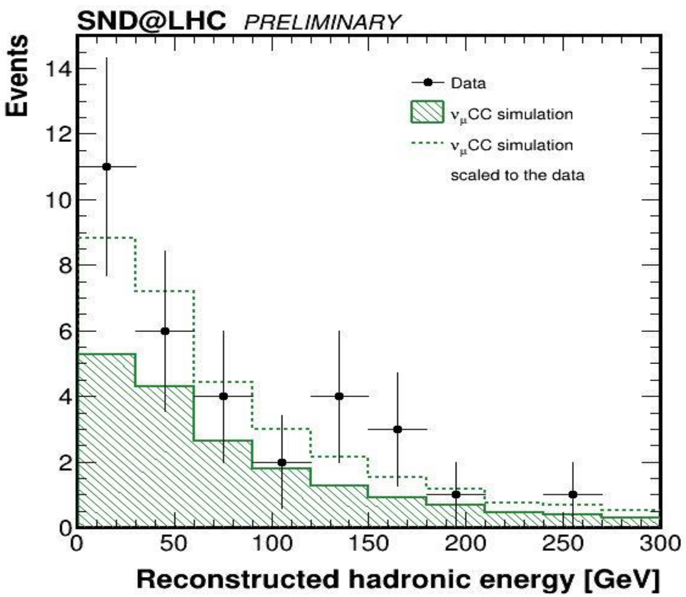
Period		Luminosity	Survival Rate	Inefficiency		μ Background
				Veto	SciFi	
2022	1	1.21 fb^{-1}	4.13×10^{-3}	3.03×10^{-4}	2.50×10^{-4}	7.88×10^{-2}
	2	14.00 fb^{-1}	5.57×10^{-3}	7.00×10^{-4}	1.06×10^{-4}	1.18
	3	7.12 fb^{-1}	6.21×10^{-3}	3.03×10^{-4}		2.75×10^{-1}
	4	1.58 fb^{-1}	6.41×10^{-3}	1.04×10^{-5}		2.08×10^{-3}
	5	5.72 fb^{-1}	5.07×10^{-3}	3.98×10^{-7}		2.89×10^{-4}
	6	9.01 fb^{-1}	5.50×10^{-3}	4.40×10^{-7}		5.28×10^{-4}
2023	1	11.60 fb^{-1}	4.02×10^{-4}	4.40×10^{-5}	1.18×10^{-4}	8.96×10^{-5}
	2	9.68 fb^{-1}	4.30×10^{-3}	4.05×10^{-7}		4.73×10^{-4}
	3	10.50 fb^{-1}	2.81×10^{-3}	9.00×10^{-8}		1.18×10^{-4}
Total		70.43 fb^{-1}	-	-	-	1.53

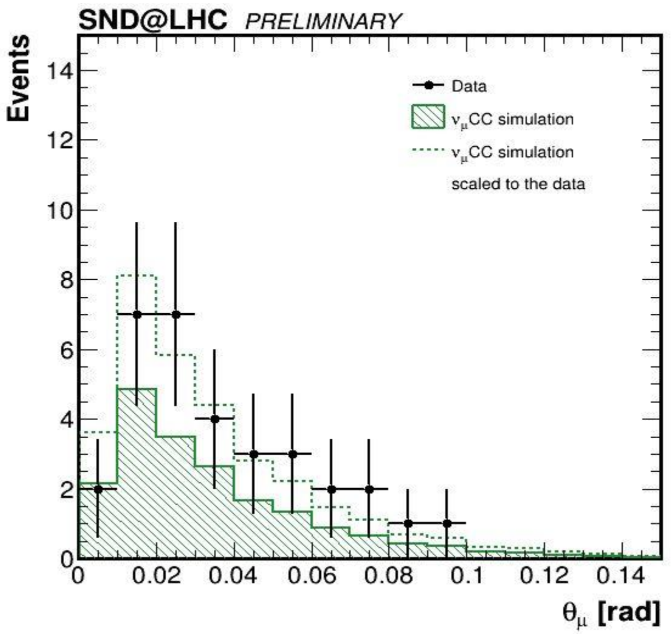
Events expected in 68.6 fb^{-1}

- Signal: $19\ ^{+5.7}_{-3.8}$ (prod) $^{+1.6}_{-6.6}$ (sel)
- Neutral hadrons: 0.25 ± 0.06
- Unidentified muons: 1.5 ± 0.3

31 events observed

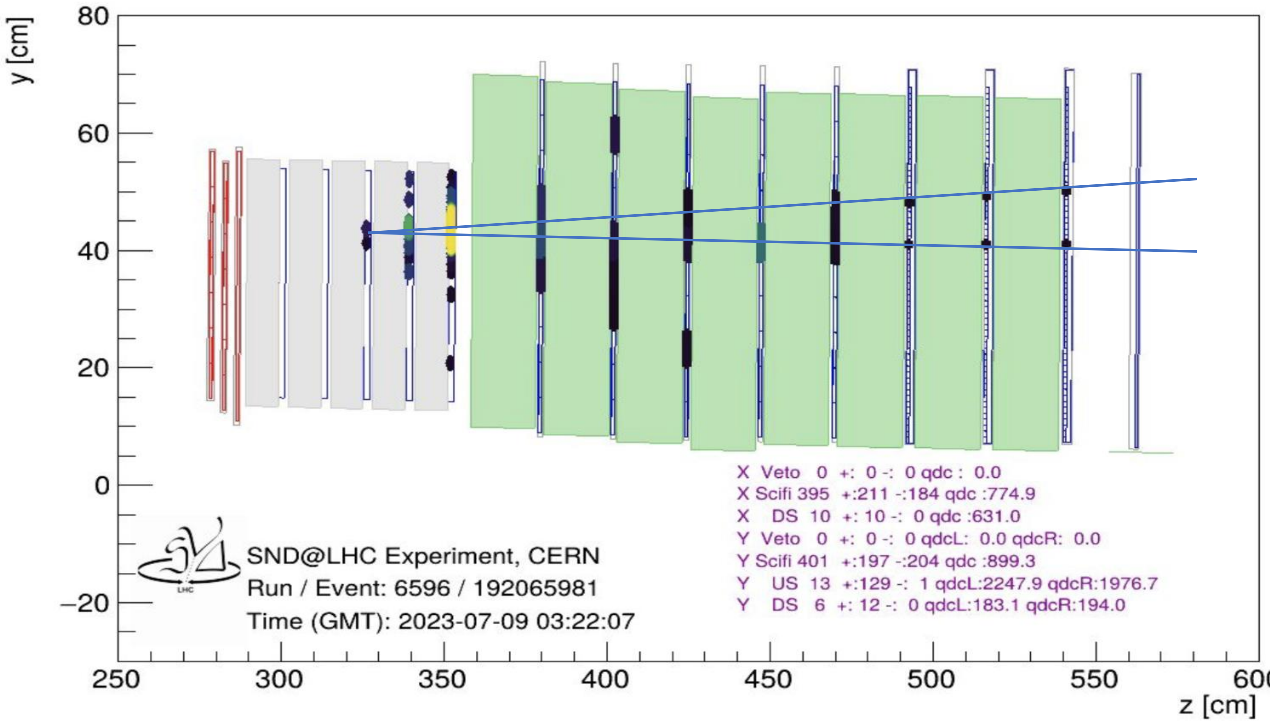


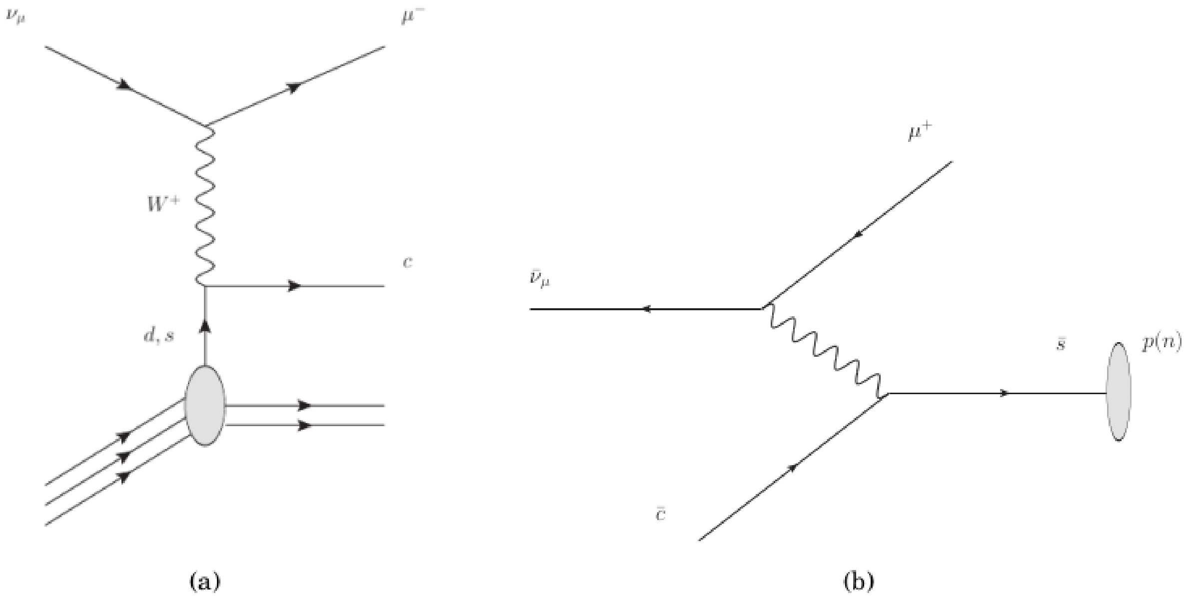




Hints for neutrino induced charm production

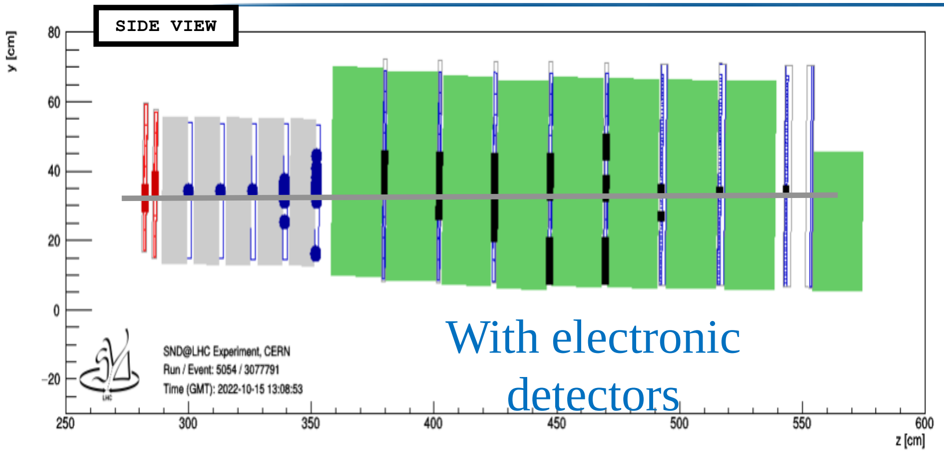
- A 2-muon event is observed in the selected events in the 2023 data sample.
- Expect the main contribution from neutrino induced charm production and subsequent muonic decay of the charmed hadron
  - Investigating the potential for a follow-up analysis to measure 2-muon/1-muon ratio using the 2022 – 2025 data (+340% more luminosity).



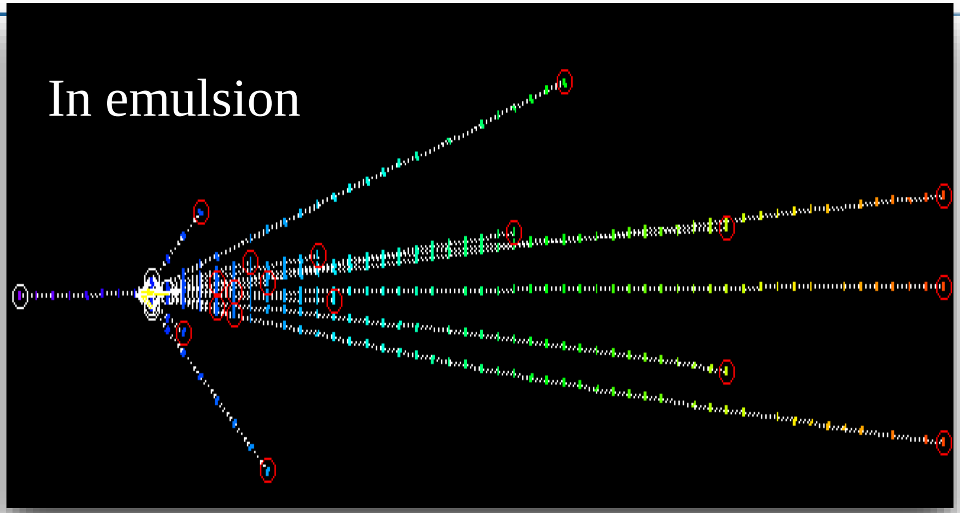


Ongoing effort to optimize selection for 2024-2025 data with 3rd veto plane.

Study of muon Deep Inelastic Scattering

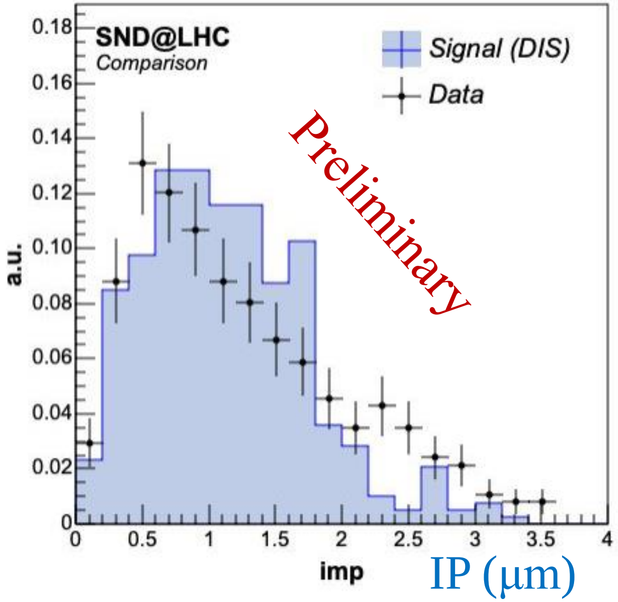


With electronic detectors

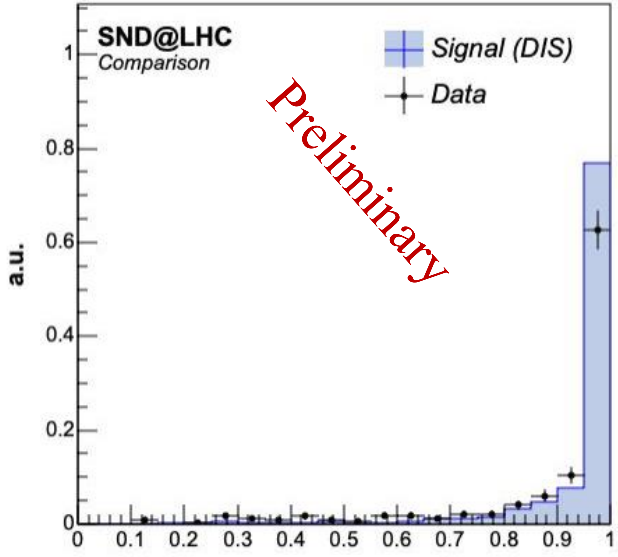


Expected signal: 870
Background: 1030±360

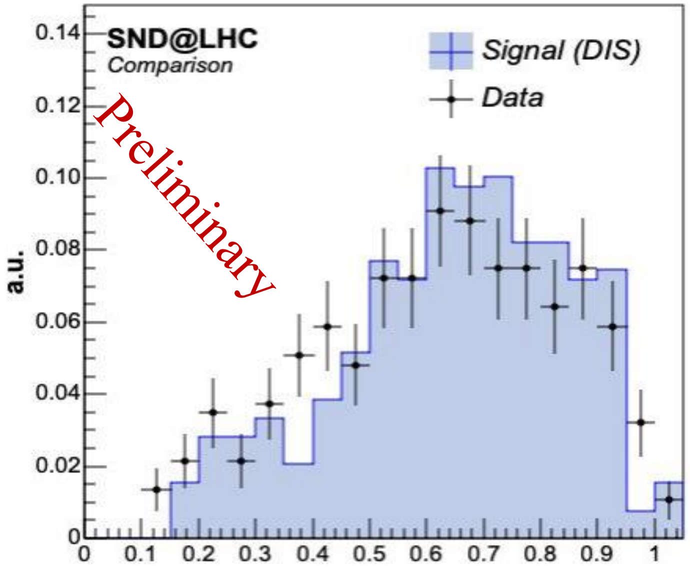
Observed events : 1741
Expected events : 1900 ± 360



IP (µm)



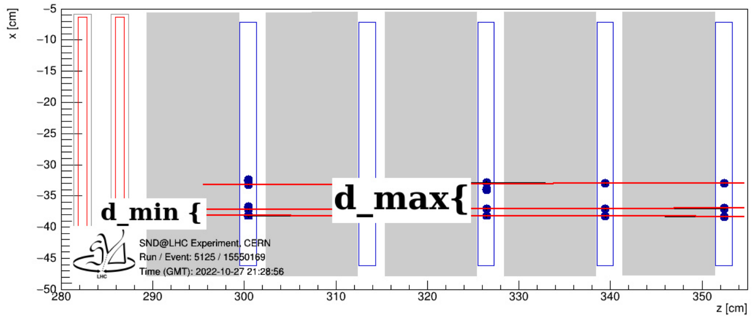
VTX prob

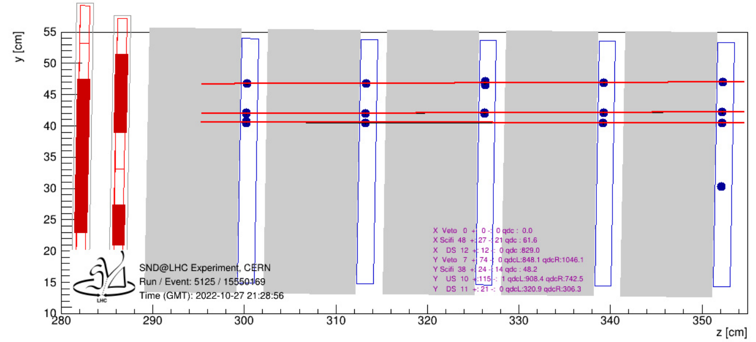


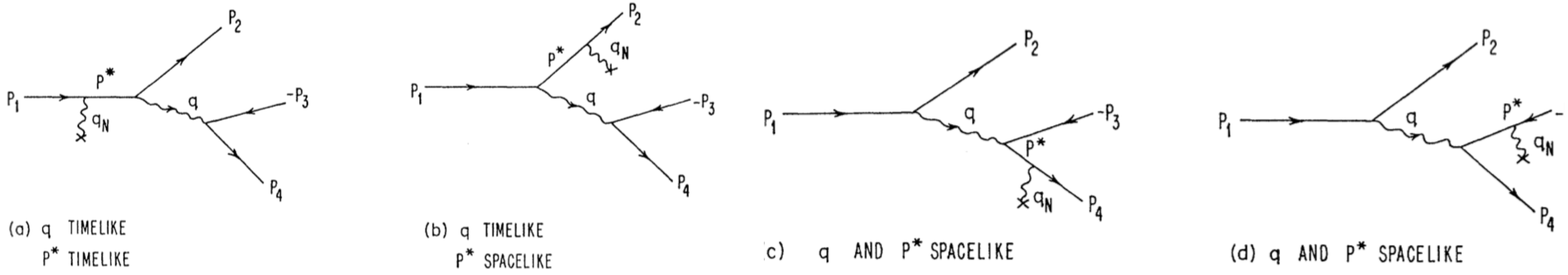
Relative length of the track in the brick

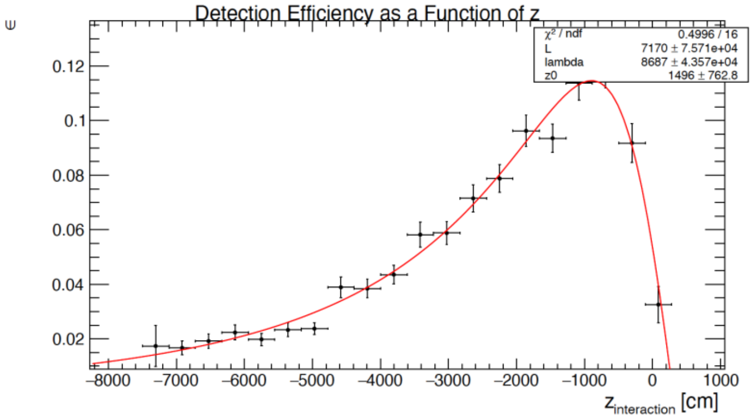
Trident process in the surrounding rock

- $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
  - Studied in the 60's and 70's, Muon Tridents, J.D. Bjorken(SLAC), M.C. Chen, Observation of Muon Trident Production in Lead and the Statistics of the Muon
  - Due to identical muons, sensitive to Fermi statistics
  - With 10 GeV muon beam, measured 60 nb per lead nucleon
- "Background": bremsstrahlung followed by γ-conversion
  $$\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma, \gamma + N \rightarrow N + \mu^{+}\mu^{-}$$
- Process introduced in GEANT4 in 2022 (improving now with our feedback)
- Rate inconsistent with coincidence muons (already with 2 muons)

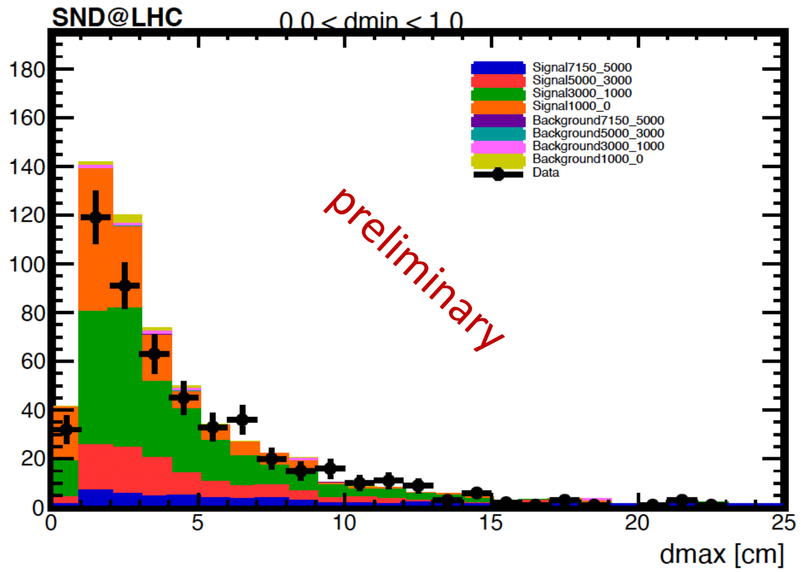




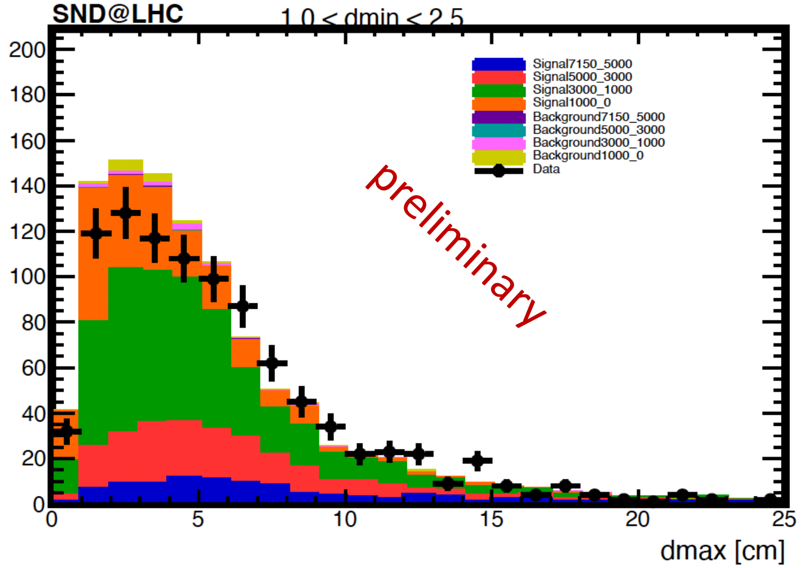


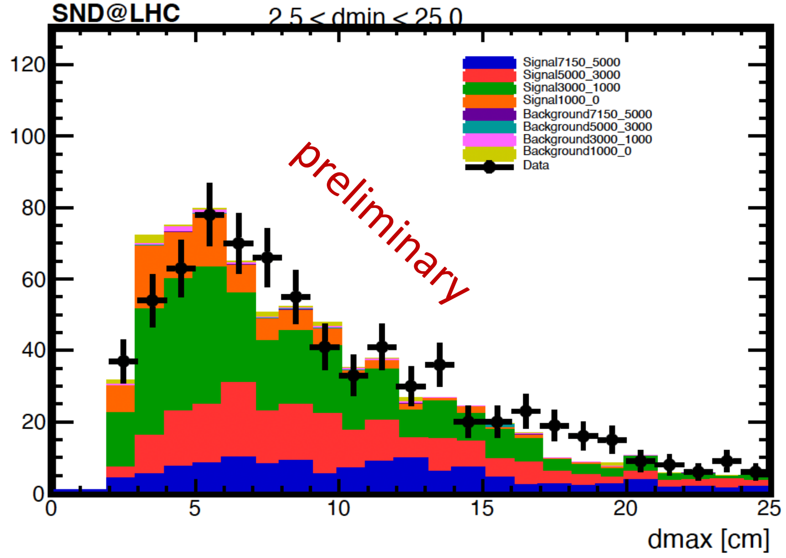


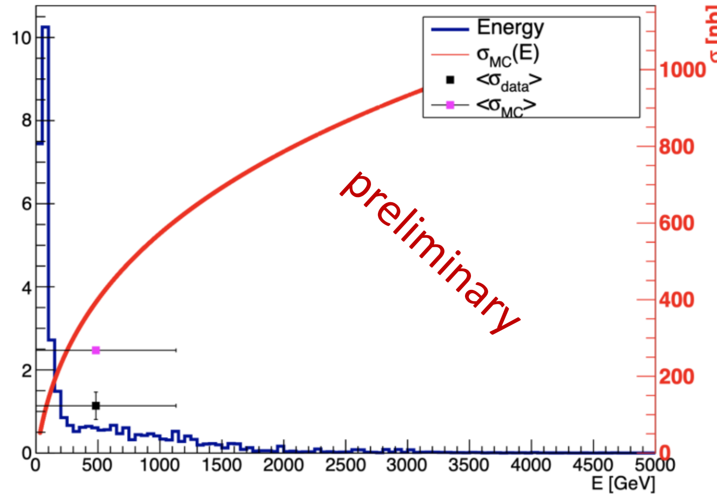
Preliminary results on the muon trident



- Disagreement with Geant4 prediction.
  - SND@LHC: 129 ± 39 nb
  - Geant4: 281 nb
- A new Geant4 version of the process with some improvements was released in December 2025

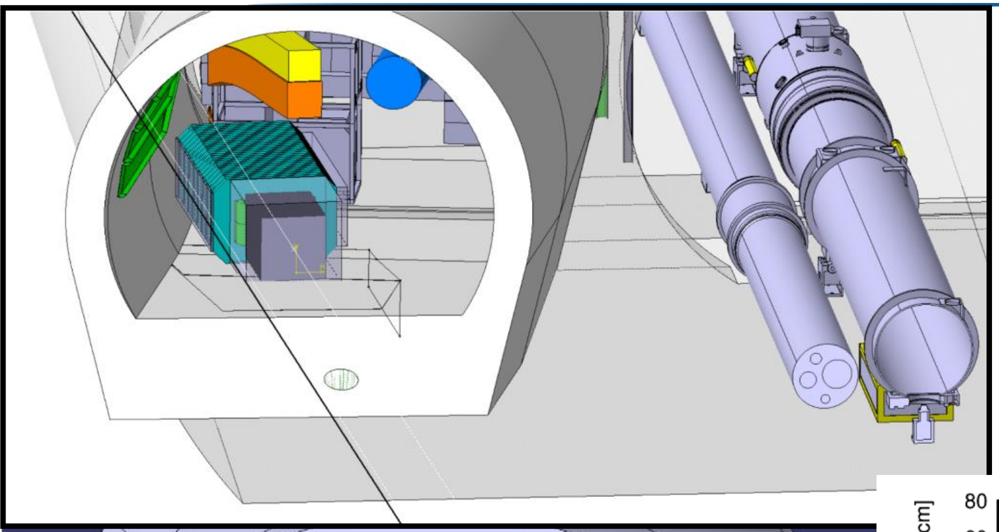


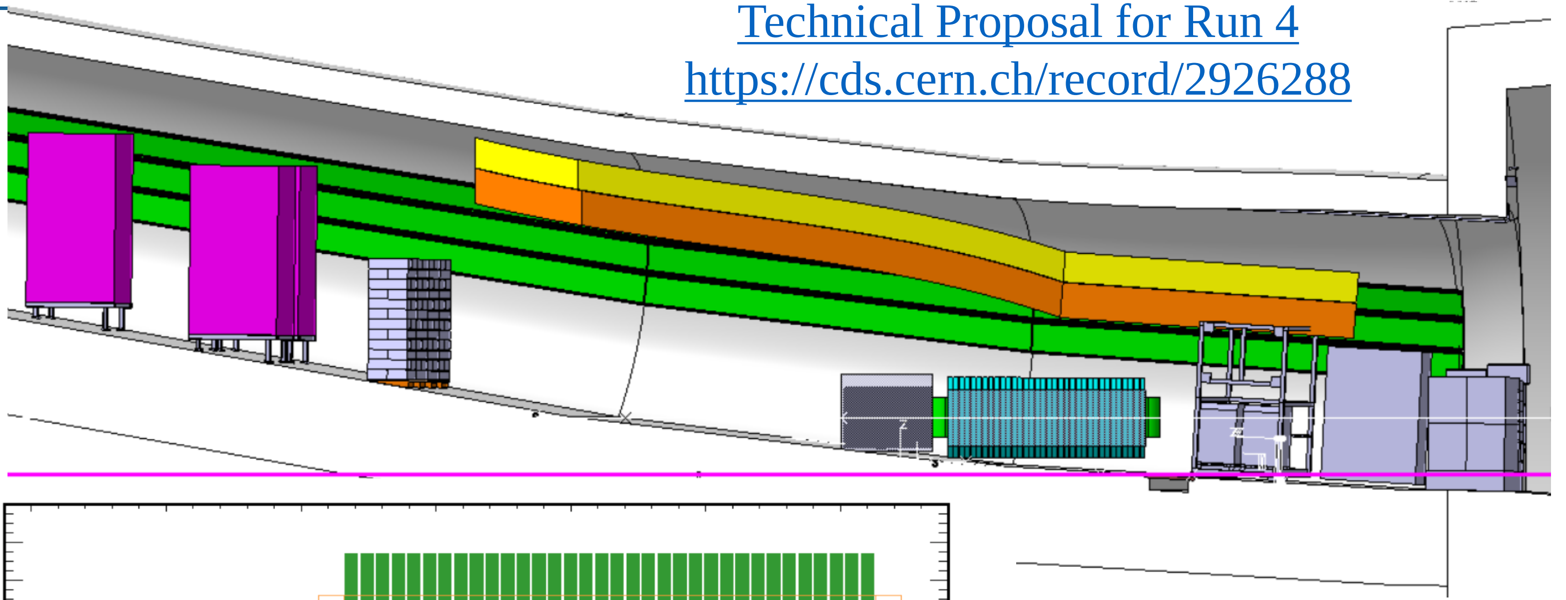




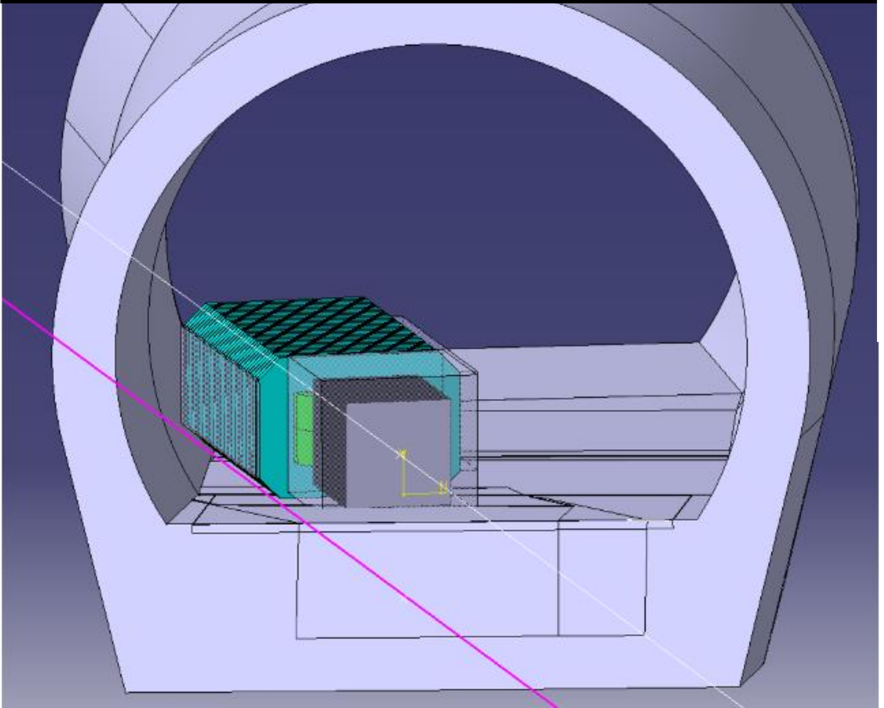
SND@LHC UPGRADE FOR HL-LHC

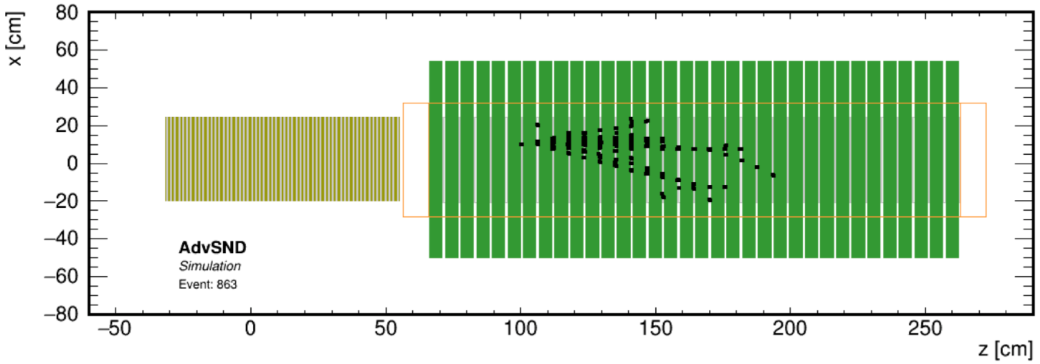
Detector for the High Luminosity Runs





[Technical Proposal for Run 4](https://cds.cern.ch/record/2926288)
https://cds.cern.ch/record/2926288

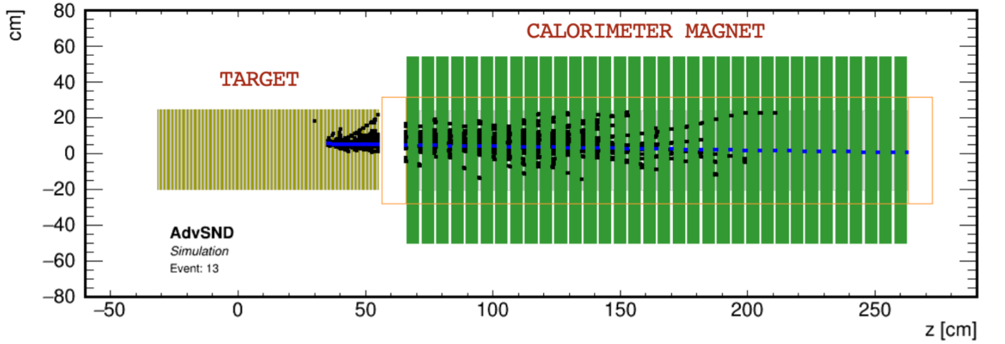




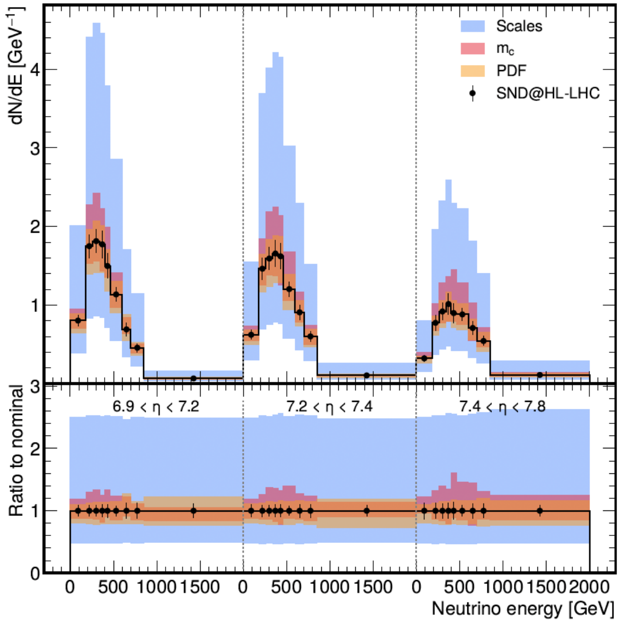
Approved in June 2025

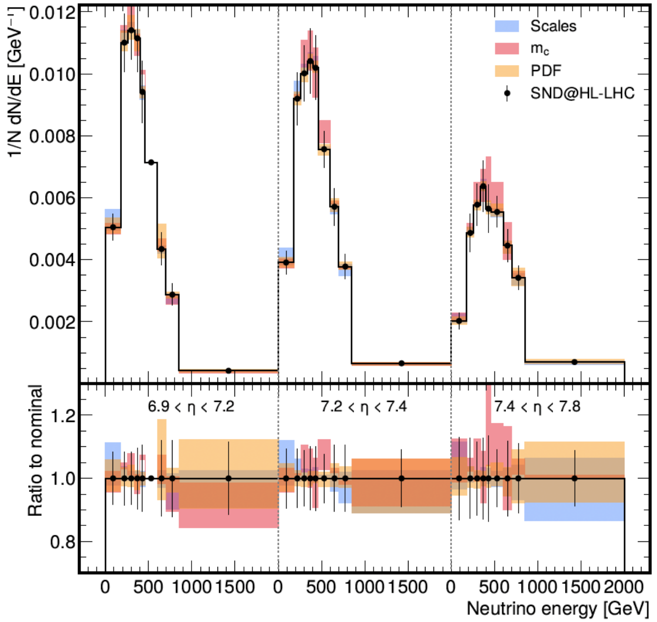
3000 fb^{-1} and the +250 μrad-H

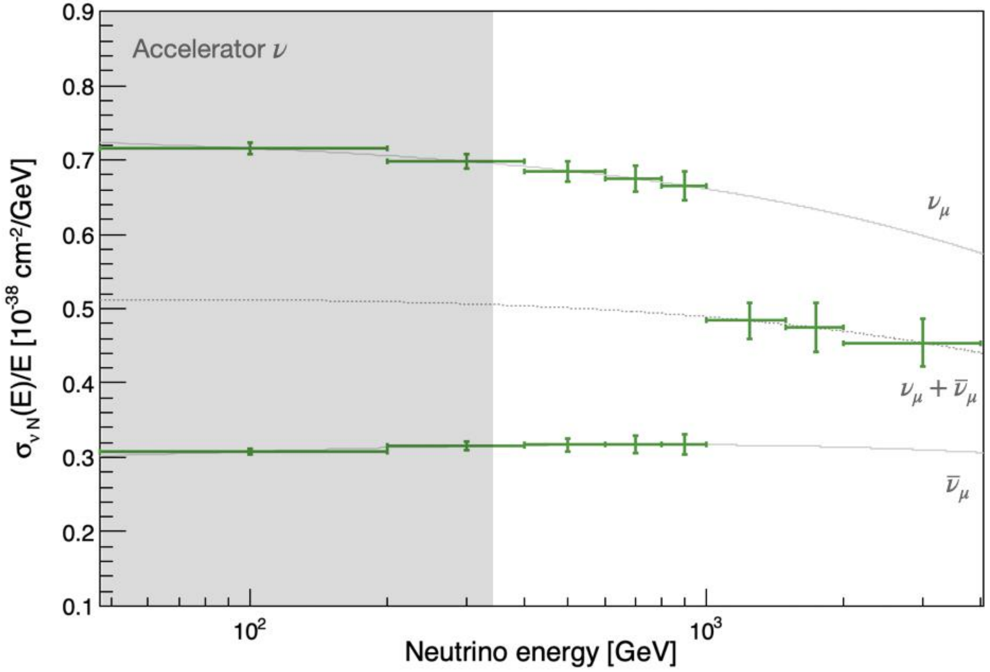
Flavour	Target	HCAL	Target+HCAL
$\nu_\mu+\bar{\nu}_\mu$	1.5×10^4	8.8×10^3	2.4×10^4
$\nu_e+\bar{\nu}_e$	3.4×10^3	2.1×10^3	5.5×10^3
$\nu_\tau+\bar{\nu}_\tau$	2.8×10^2	1.7×10^2	4.5×10^2
Tot	1.9×10^4	1.1×10^4	3.0×10^4



Physics case in the High-Luminosity era in a nutshell







- *Energy and η distribution of (charm-induced) νe CC interactions*
- *Left: event yield. Right: normalized to an arbitrarily chosen reference bin*

Extending ν cross-section measurements to a few TeV

Run3

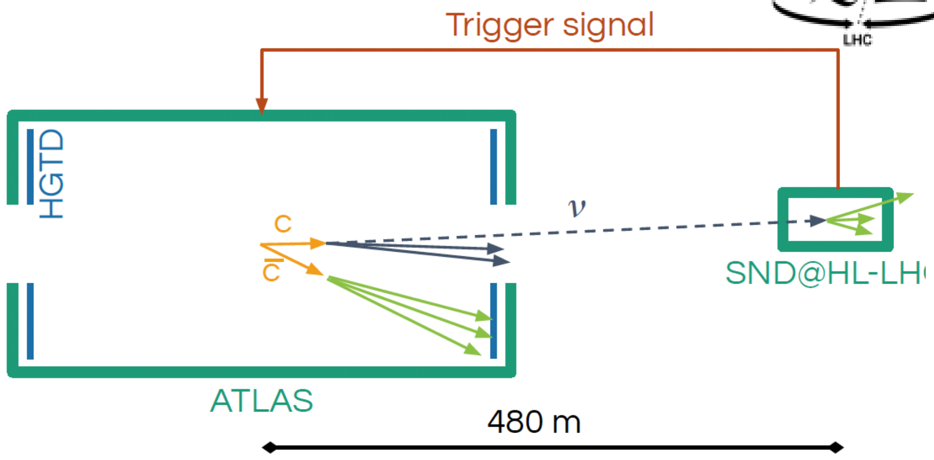
Measurement	Uncertainty Stat.	Sys.	Uncertainty Stat.	Sys.
Gluon PDF	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	< 5%
ν_μ and $\overline{\nu}_\mu$ cross-section	-	-	1%	5%

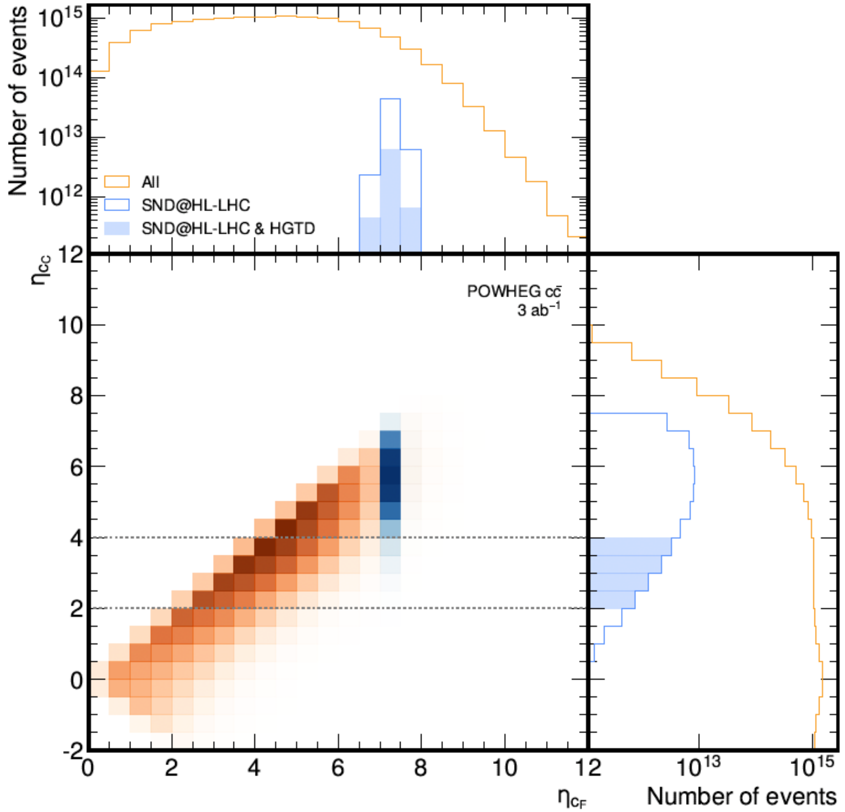
HL

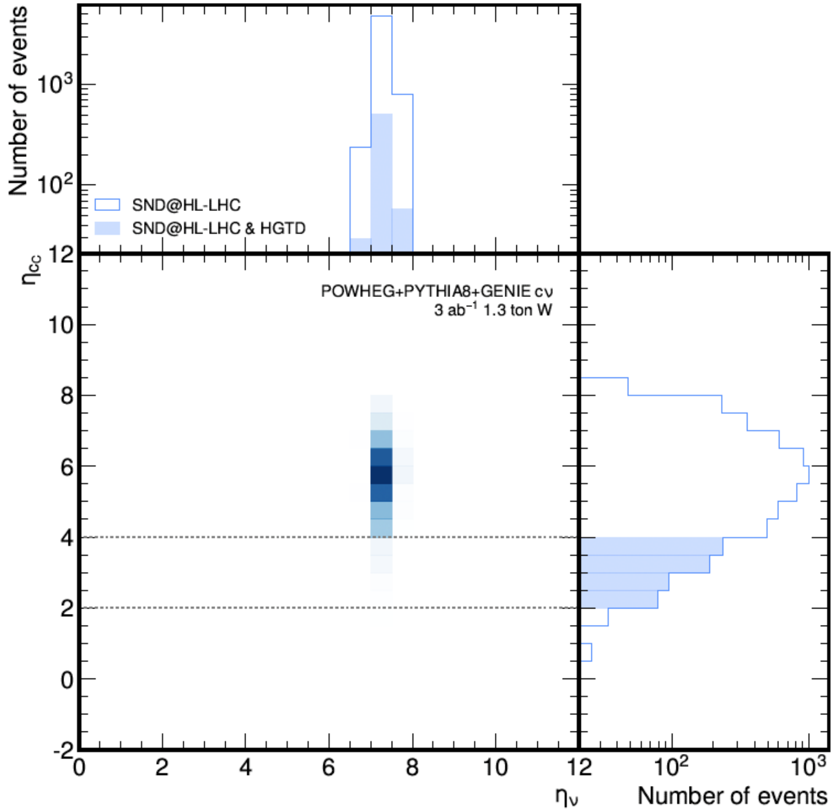
Technical Proposal for Run 4
https://cds.cern.ch/record/2926288

ν tagging: triggering ATLAS with ν events

- Forward charm producing a neutrino
- Less-forward charm being detected in ATLAS
- In ~ 10÷15% of ν events, the partner charm is in the ATLAS acceptance ($2 < \eta < 4$)



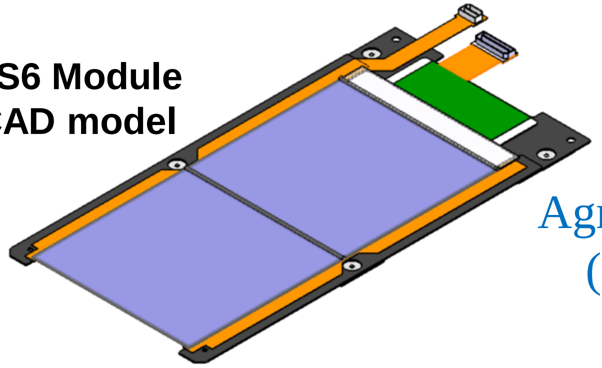


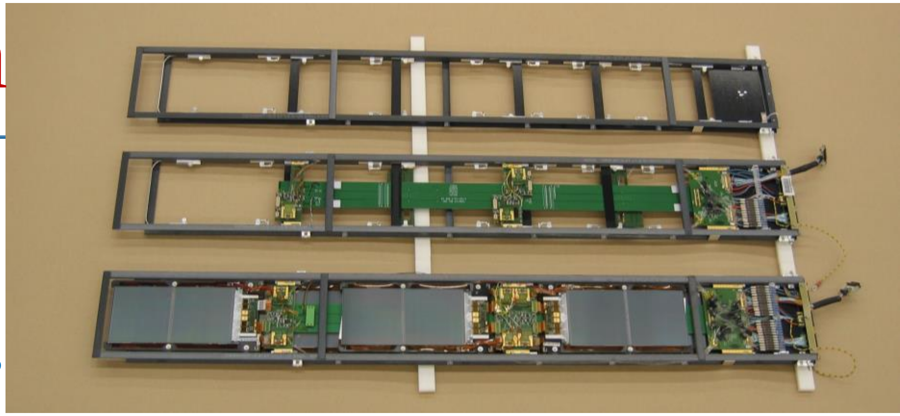


- **Number of events in 3 ab^{-1}: ~1000**

Detector modules and a 40 x 40 cm^2 station

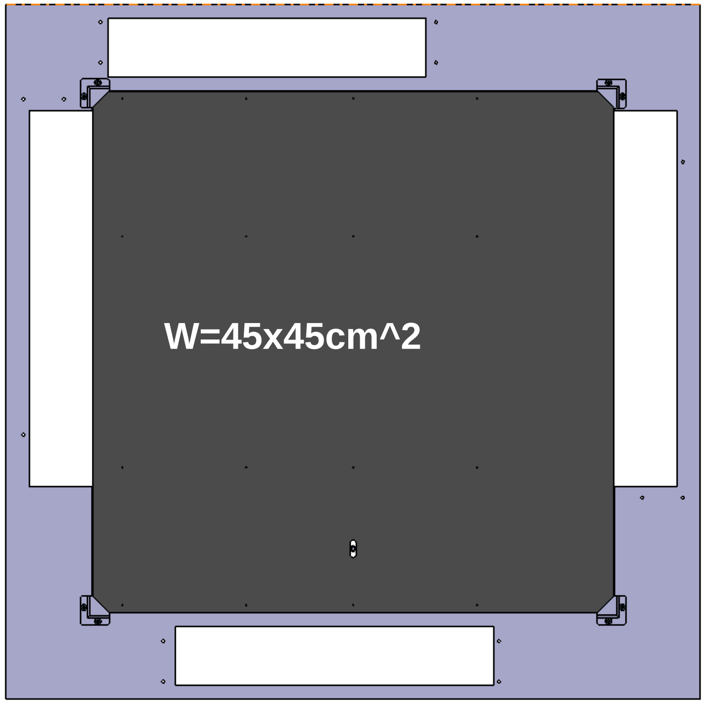
SS6 Module
CAD model

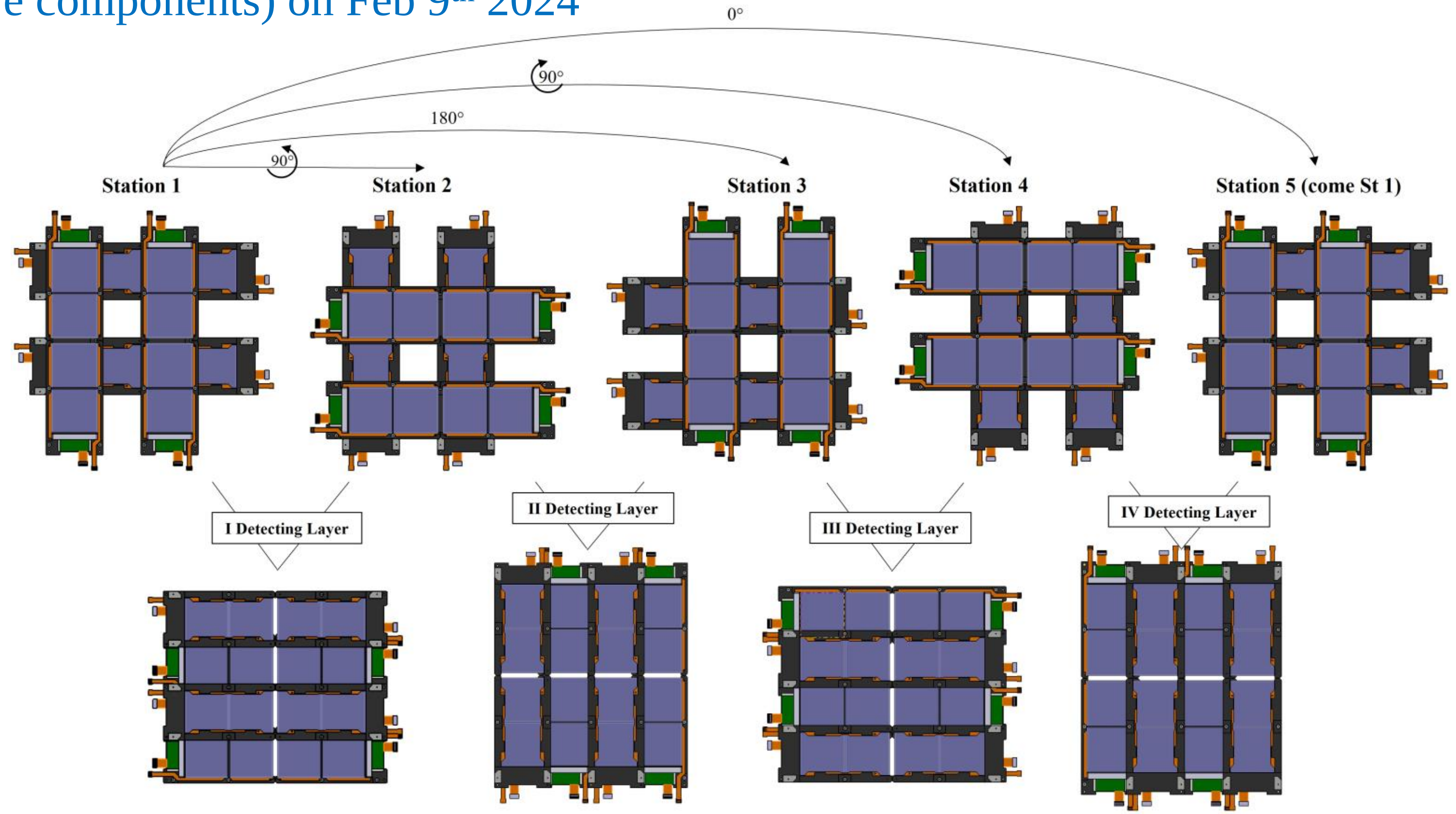




Agreement with CMS to reuse their TOB modules (and their spare components) on Feb 9th 2024

Steel Frame and W Slab

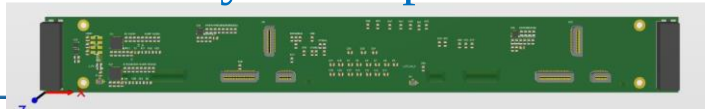


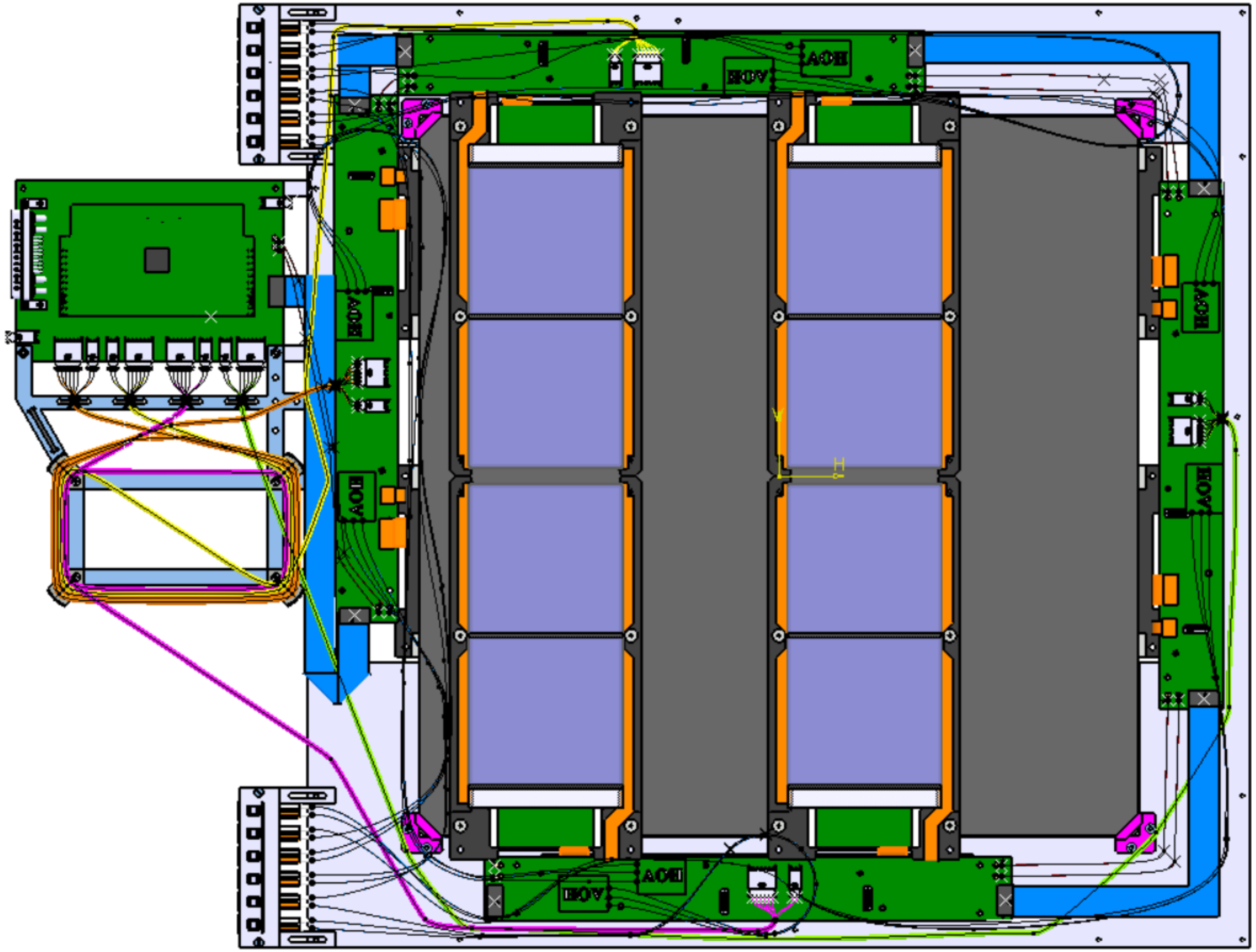


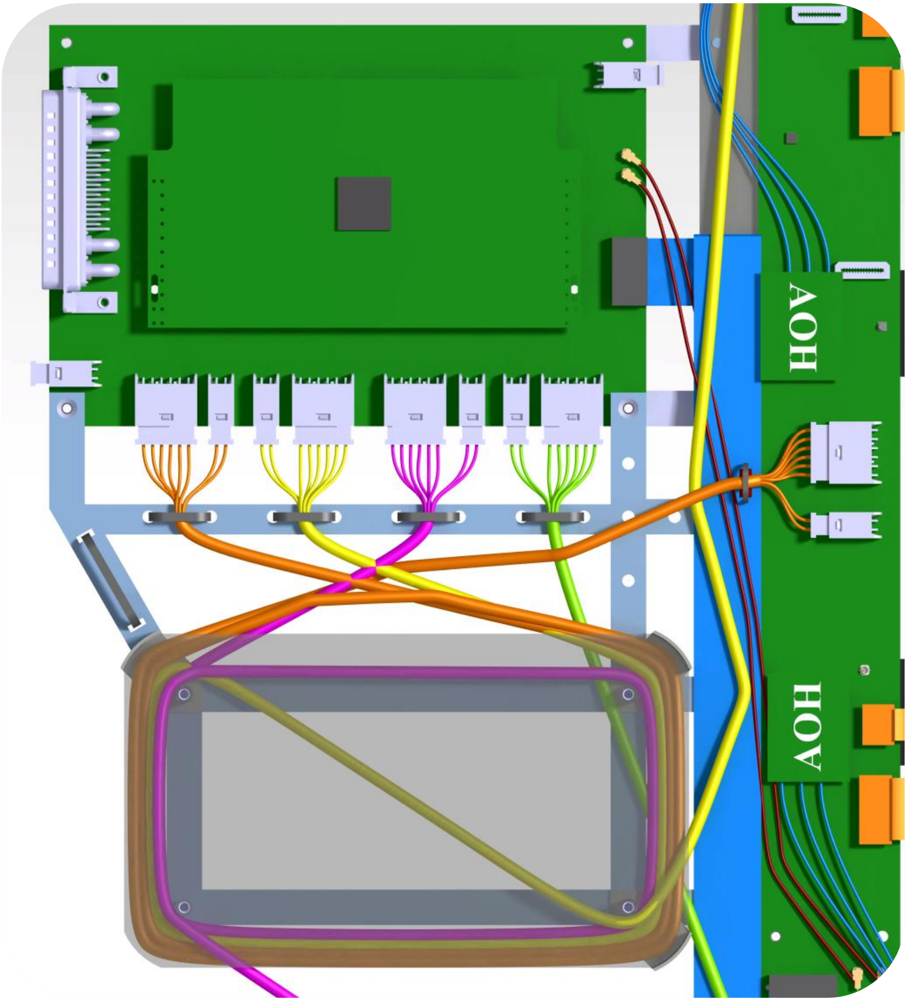
Tungsten in the target as passive layer with 5 cm iron slabs in the HCAL

The station: assembling sequence

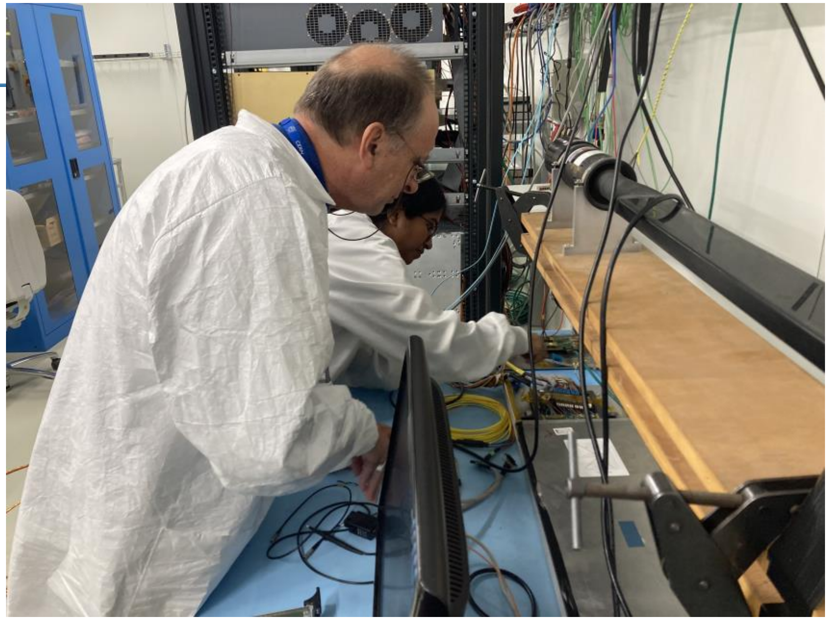
Newly developed ROB



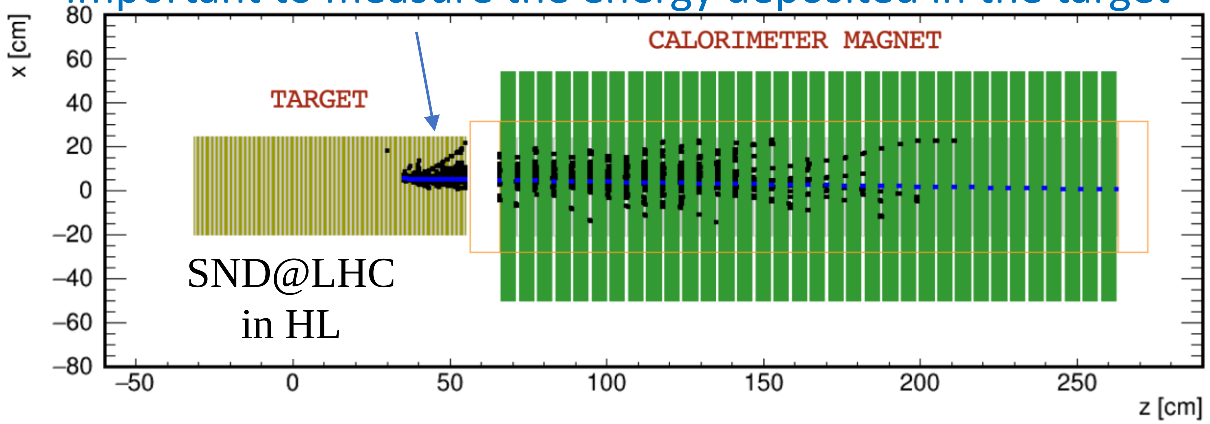




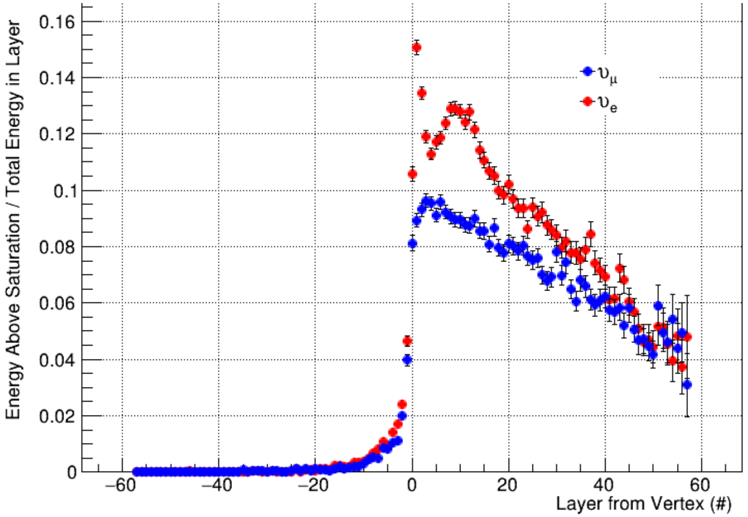
Tests at CERN and detector response simulation



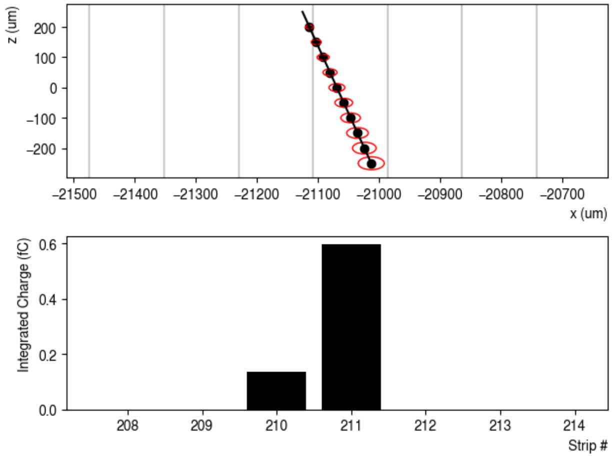
Important to measure the energy deposited in the target

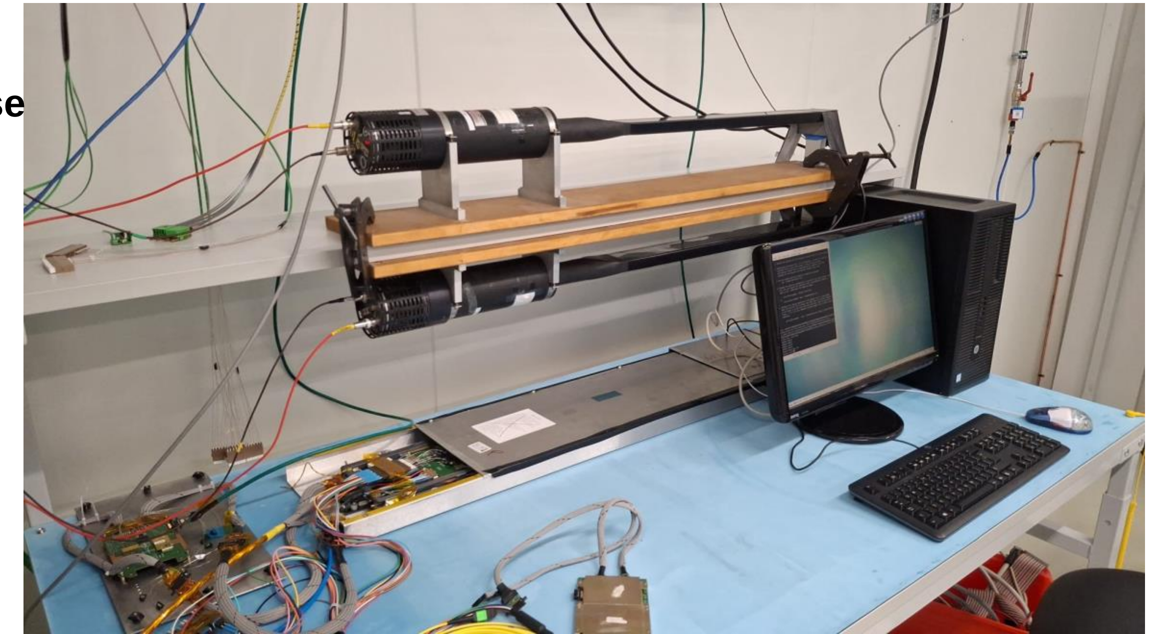


Fractional energy lost due to saturation



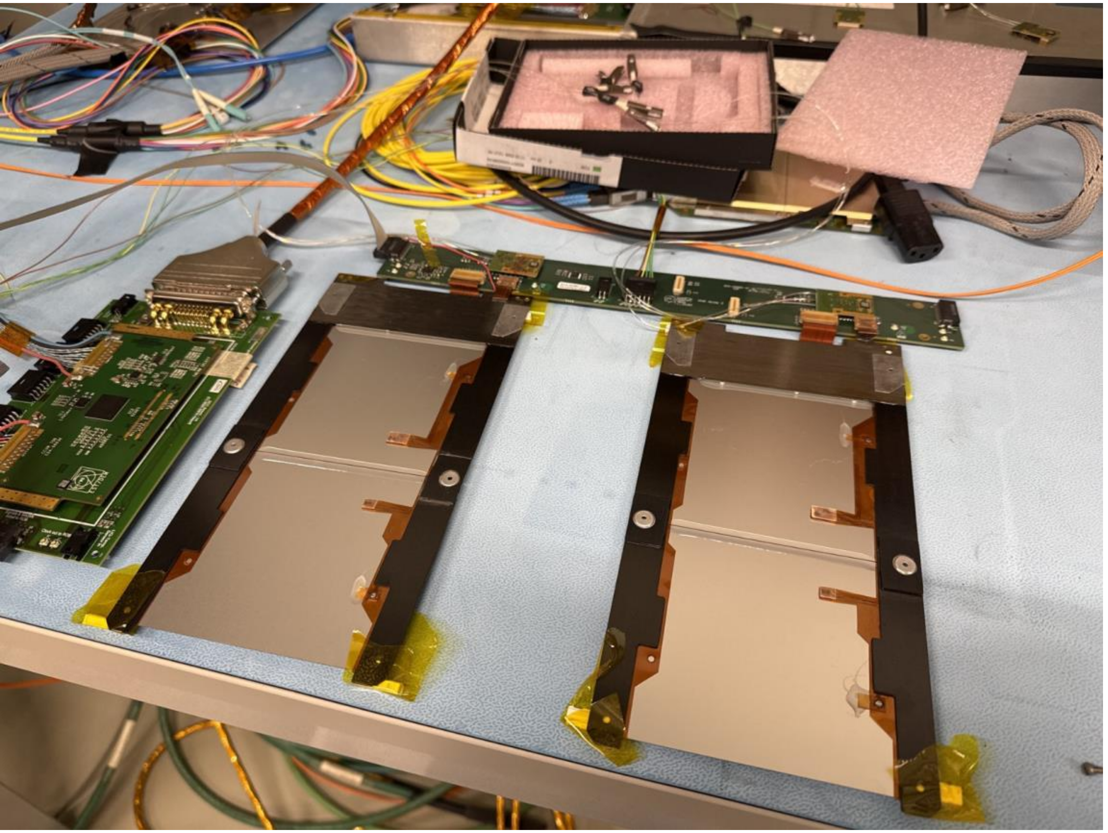
Simulation of Detector Response

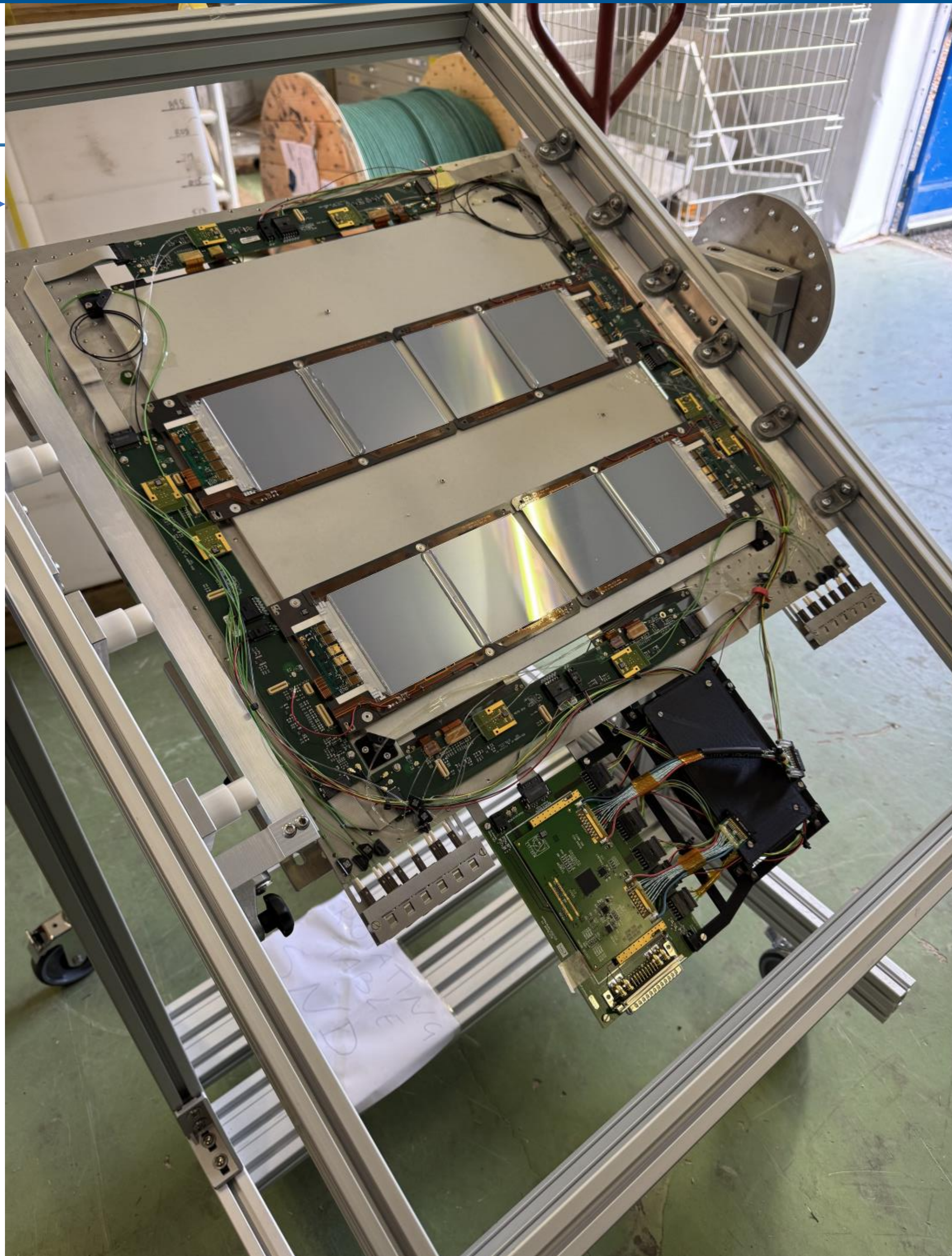




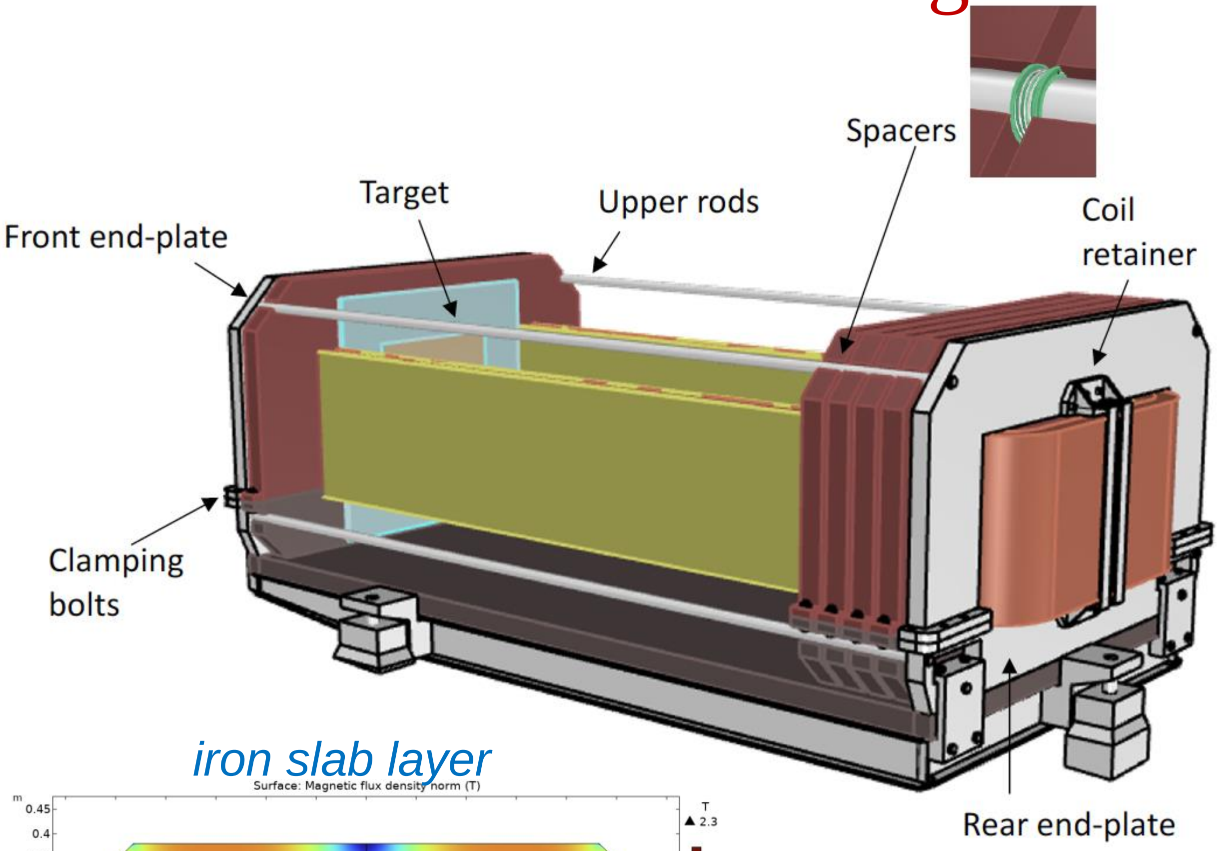
Silicon/W detector design

- Mechanical design fully validated
- Tools being built: rotation platform assembled
- Electronics tests have validated the newly produced boards

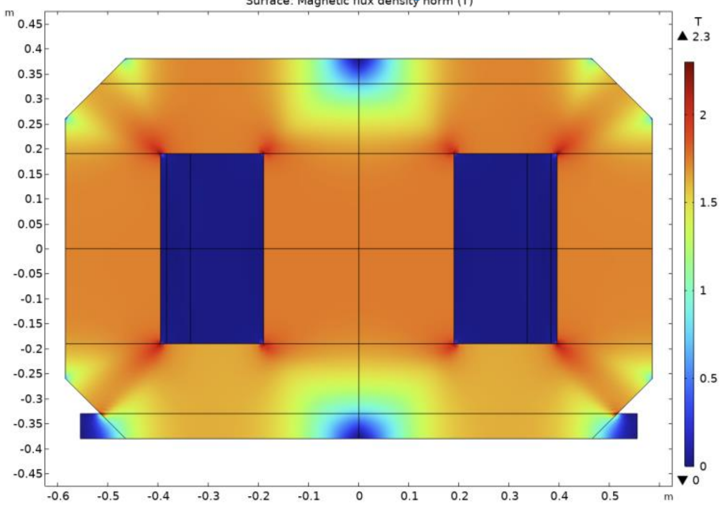


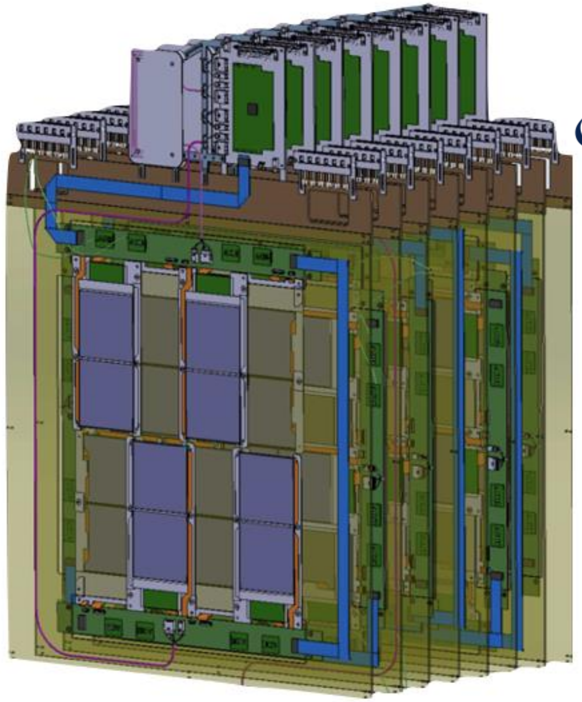


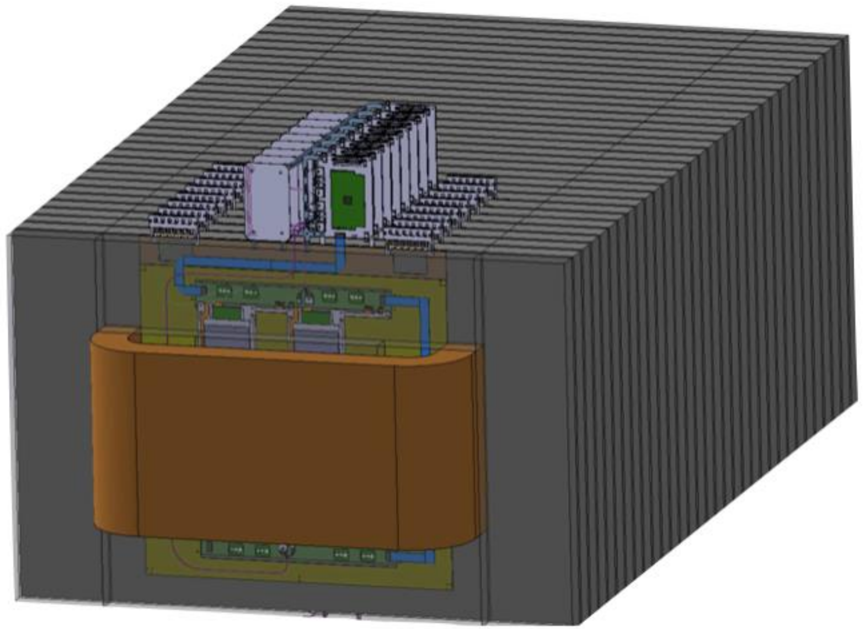
Silicon detector for the magnetised tracking calo



iron slab layer



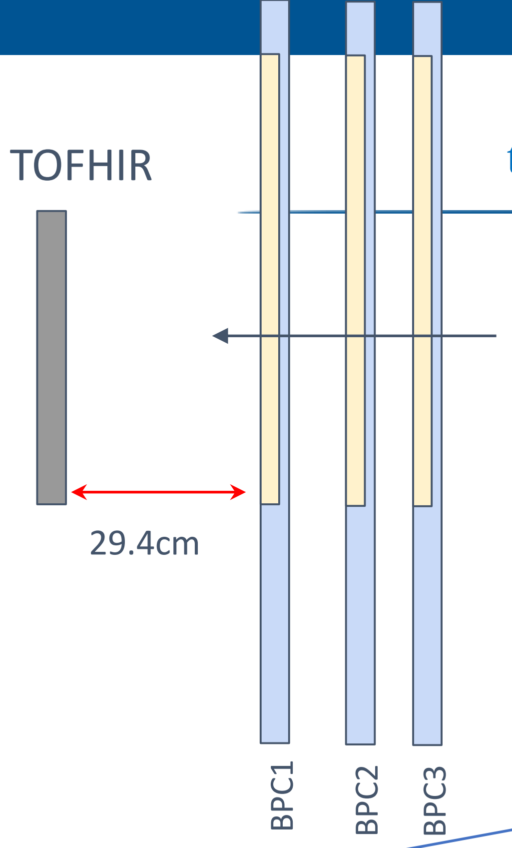




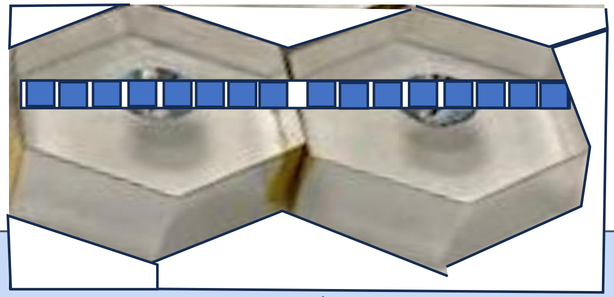
Progress on the design of the magnet
Progress on the design of silicon modules

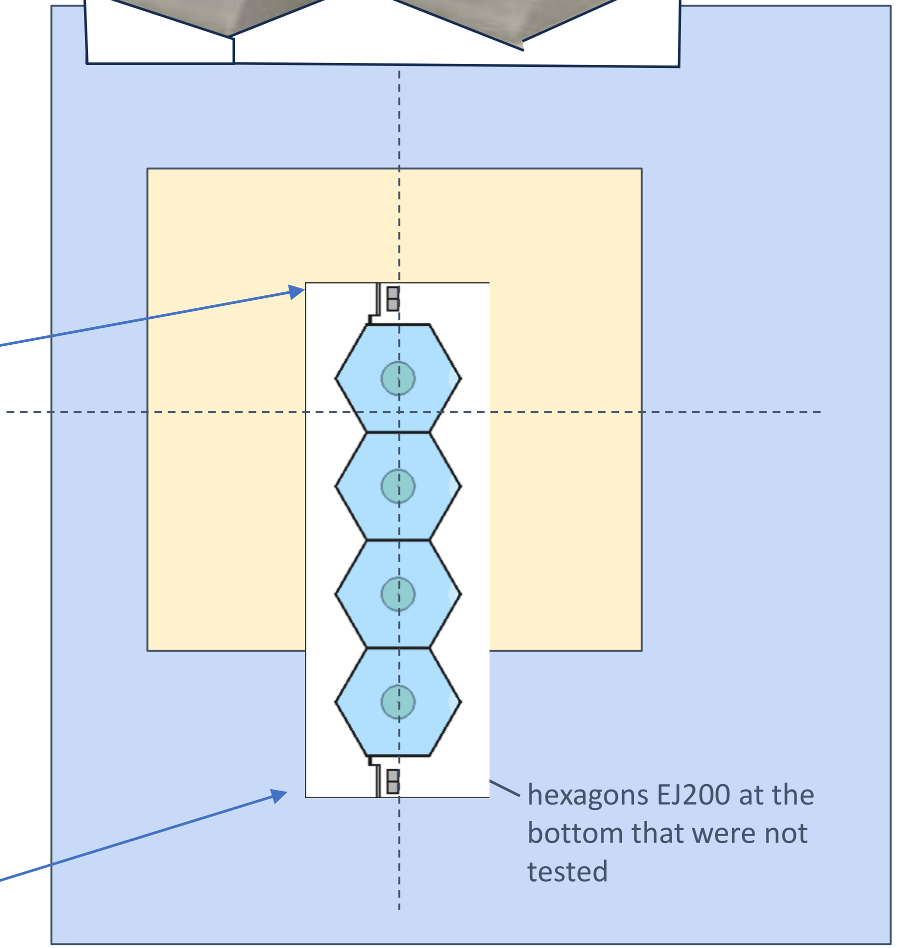
Timing detector (<50 ps) developments

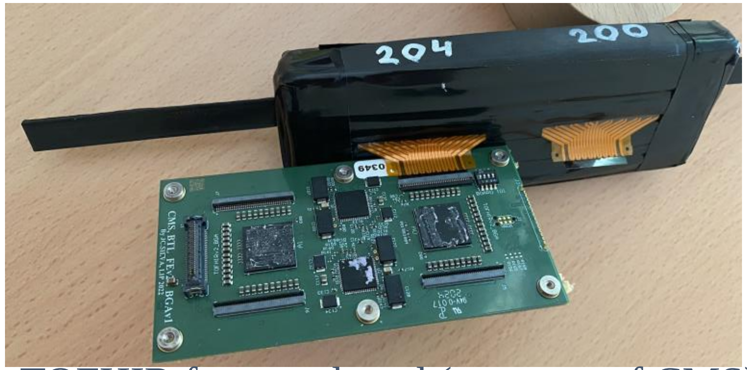
two hexagonal cells readout by the CMS SiPM barrette used for their timing layer



16 3x3 mm^2 SiPM (25 µm pixel) glued to the center of the two cells



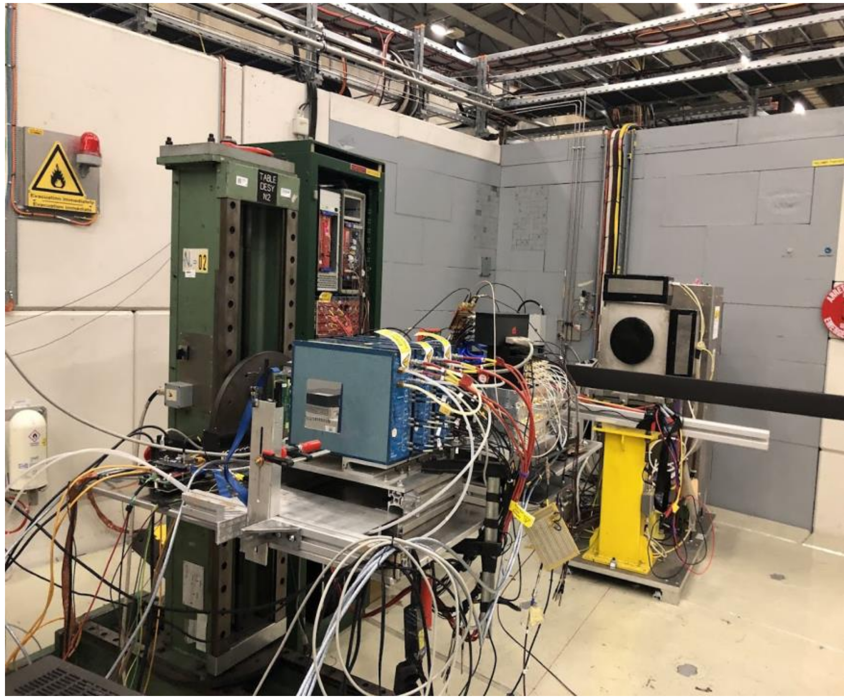




TOFHIR front-end card (courtesy of CMS)

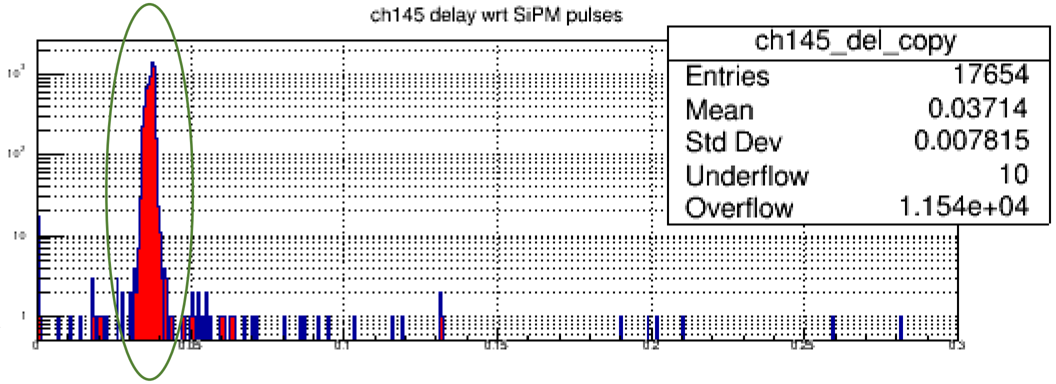
Barrette with 16 SiPMs (courtesy of CMS)

Setup at the PS T10 in October 2025



Timing detector developments: first look at the data

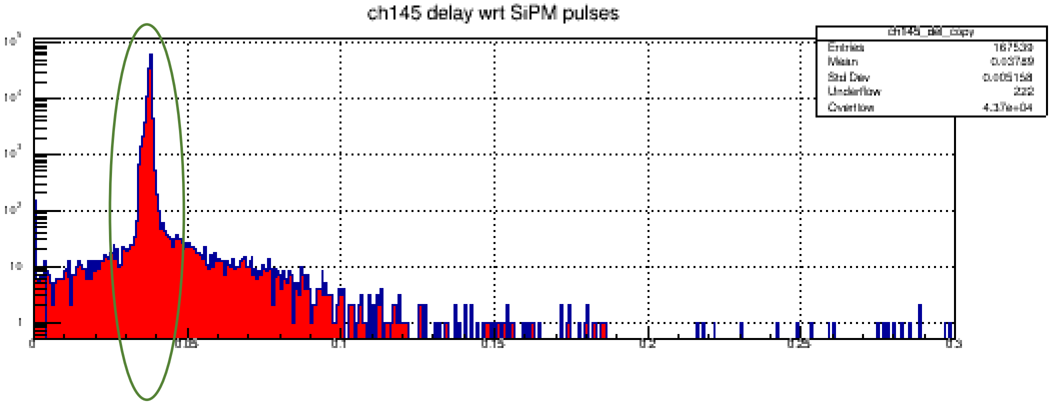
Run 135:
1.5 GeV/c π,
with W target
("scatterer")



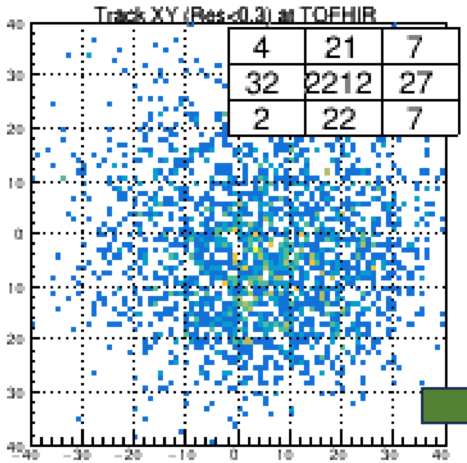
Use only events with both Beam chambers and TOPHIR signals

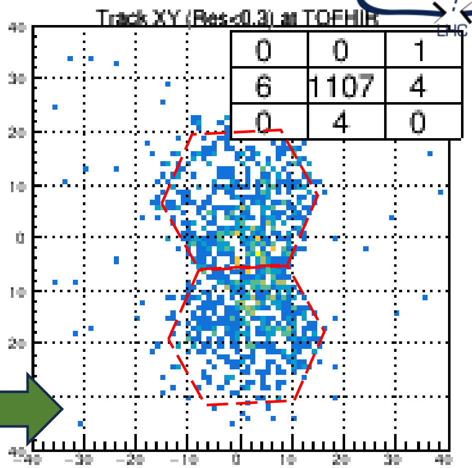
Note log scale!

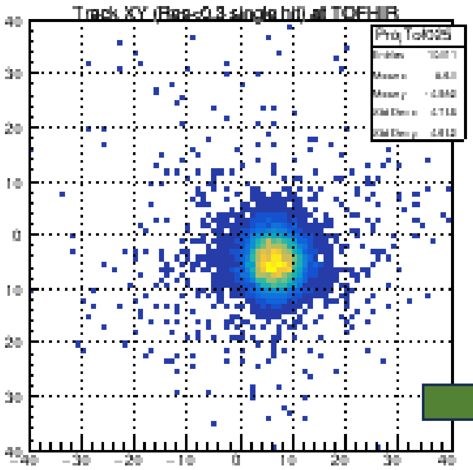
Run 131:
5 GeV/c π,
no target



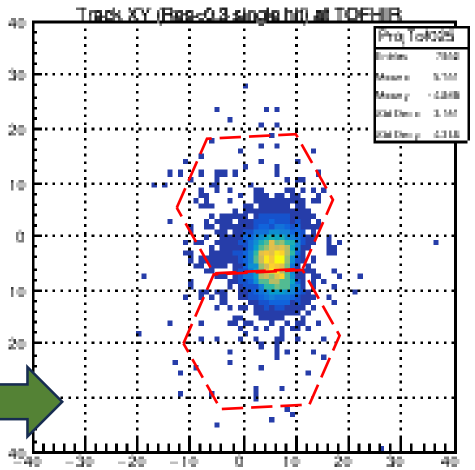
Note: all SiPM channels in a matched event are counted here. Background "base" to be investigated, perhaps Δ-electrons







ALL well reconstructed tracks



Well reconstructed tracks for TOFHIR events with correlated ch145 and SiPM hits

Neutrino and hidden sector physics at the SPS

The SHiP experiment at the intensity frontier

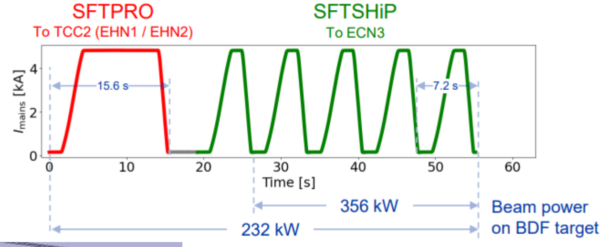
The SHiP/NA67 experiment at CERN

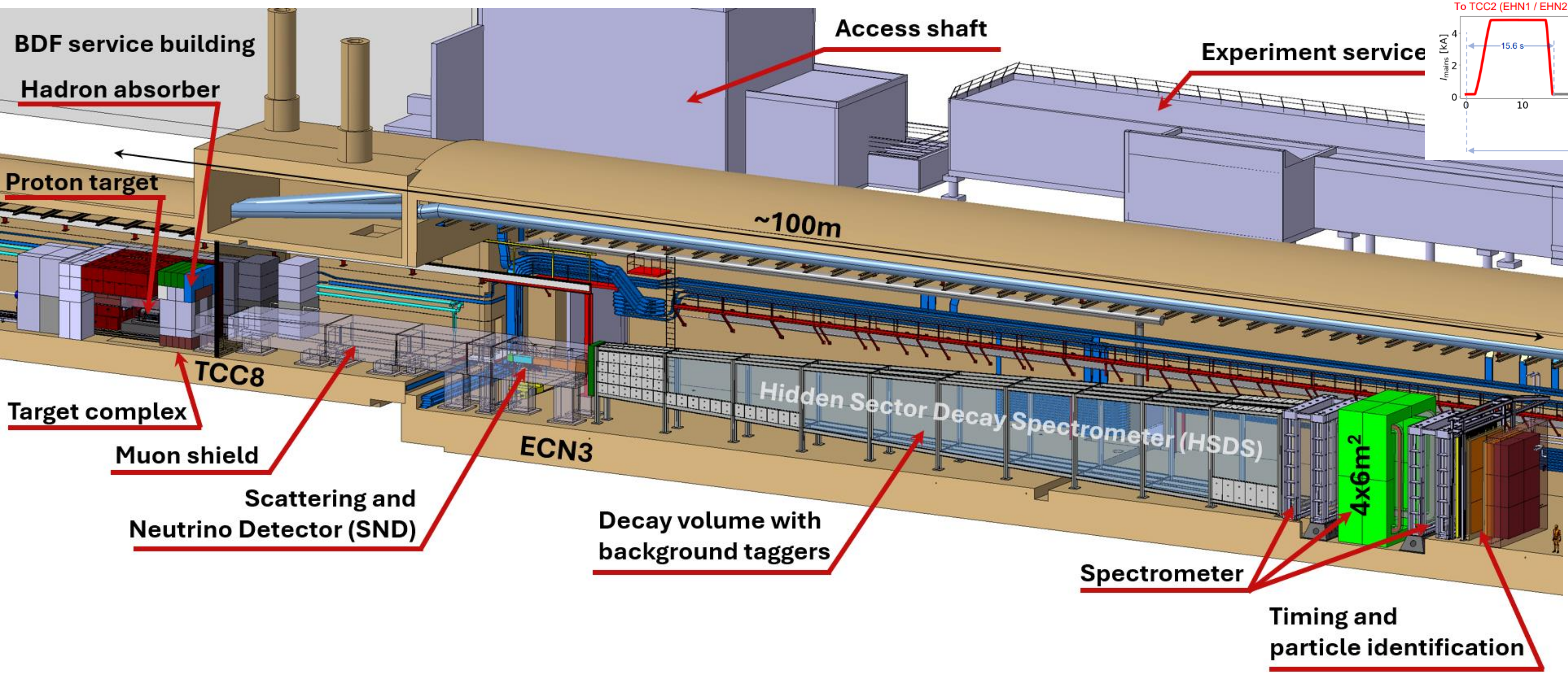
TP in 2015: http://cds.cern.ch/record/2007512/files/SPSC-P-350.pdf

EPJC (2022) 82:486

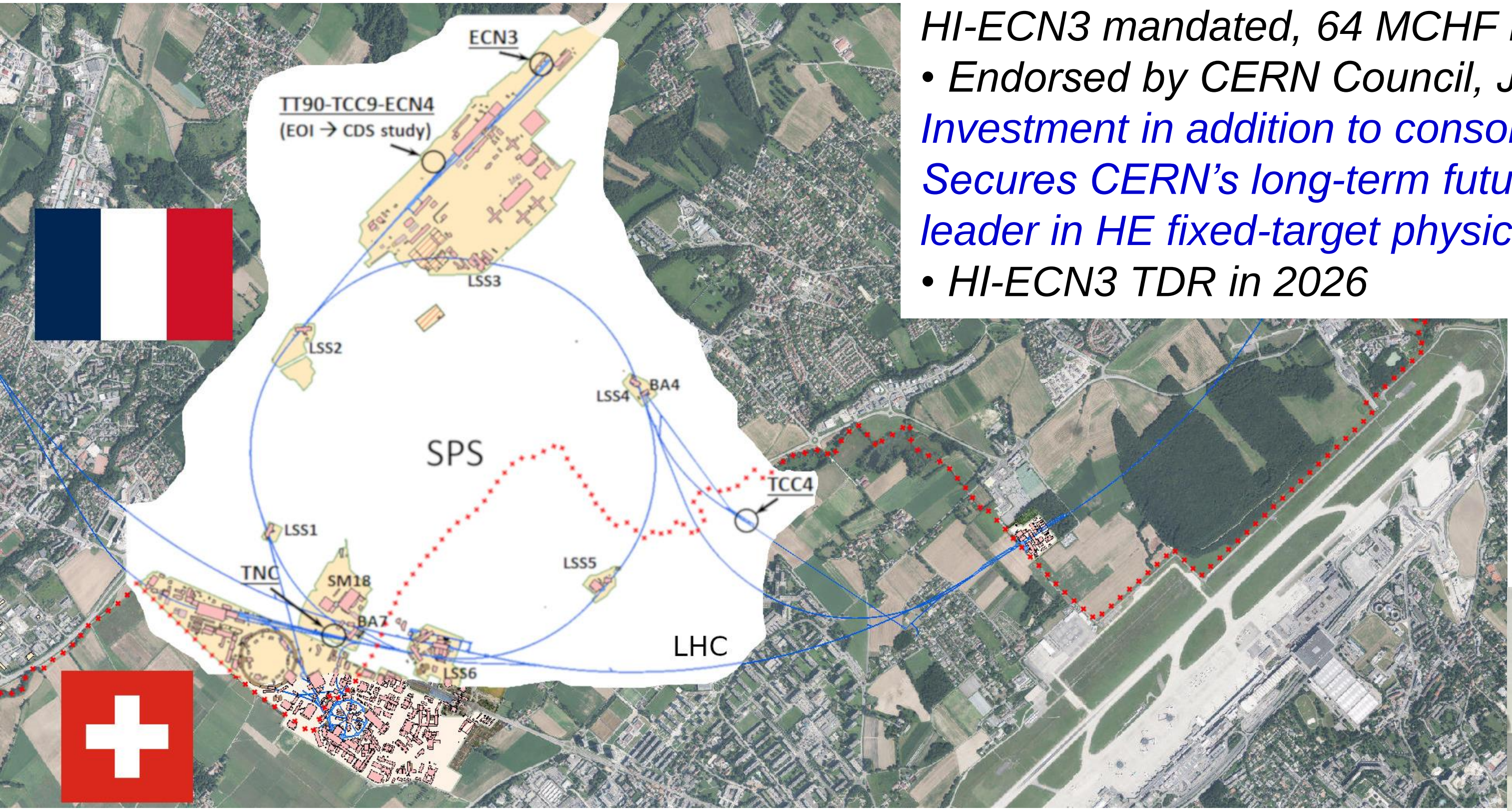
Experiment approved by the Research Board in March 2024

Nominal Design Parameter	Value
Beam type	proton
Beam momentum [GeV/c]	400
Beam pulse intensity [$\times 10^{13}$ p]	4.0
Spill length [s]	1
Beam pulse power [kW]	2560
Average beam power [kW] (7.2 s)	356
POT [$\times 10^{20}$ p over 15 years]	6.0





High Intensity ECN3 project

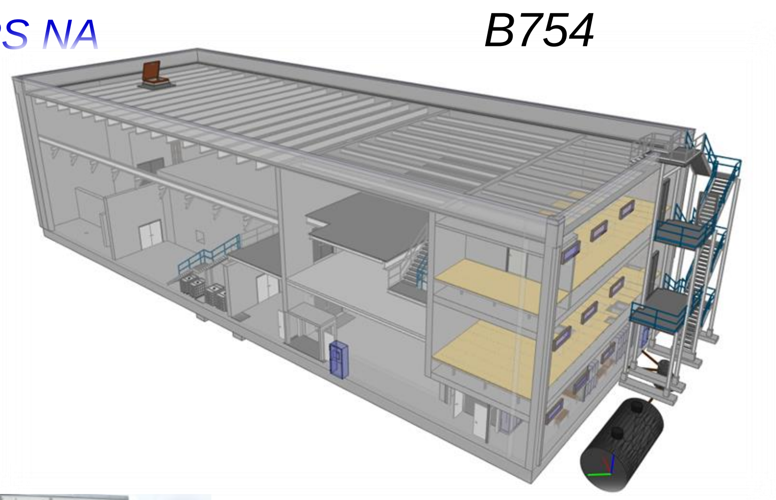


HI-ECN3 mandated, 64 MCHF in CERN MTP 2024

- *Endorsed by CERN Council, June 2024*

Investment in addition to consolidating the SPS NA
Secures CERN's long-term future as world leader in HE fixed-target physics

- *HI-ECN3 TDR in 2026*

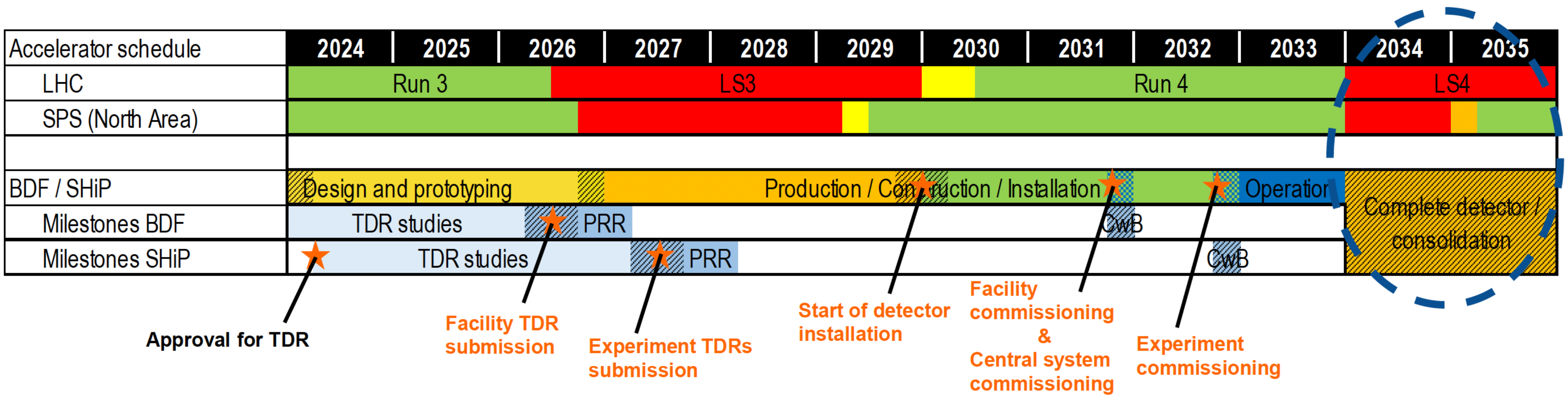


It is happening!

Ground broken & worksite prepared (before LS3) for construction of B754 complete and Infrastr. Request Proposal design study complete, Mkt Survey released, Inv. Tender drafted EDMS 3352794

B911 doors modified and network trench installed to divert services around future car park extension

BDF/SHiP schedule: 15 years of data taking



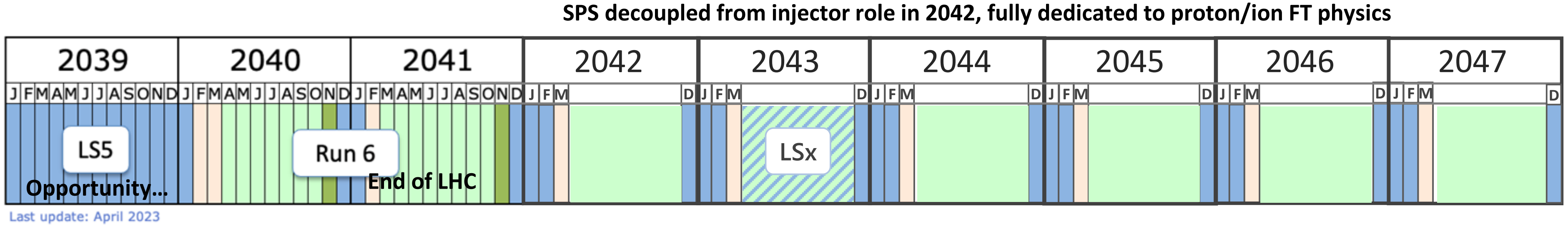
Construction / installation of facility and detector is decoupled from NA operation

Important to start data taking >1 year before LS4

Several upgrades/extensions of the BDF/SHiP in consideration over the operational life

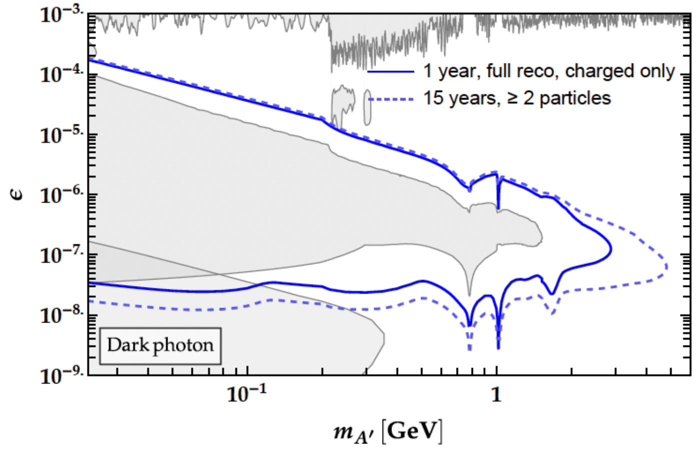
SPS decoupled from injector role in 2042, fully dedicated to proton/ion FT physics

Operation till 2047

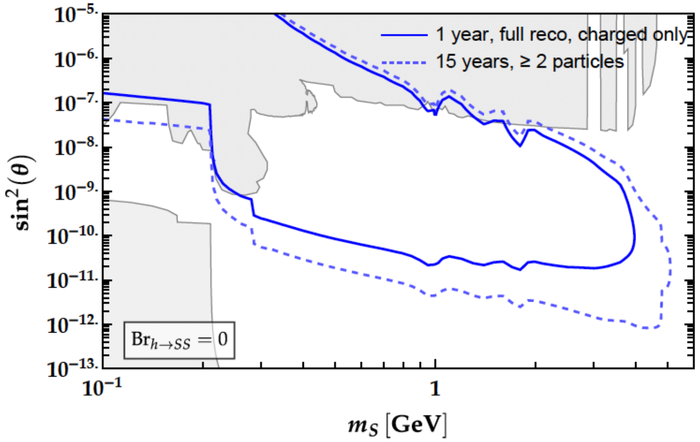


Prospects for the first run in 2033

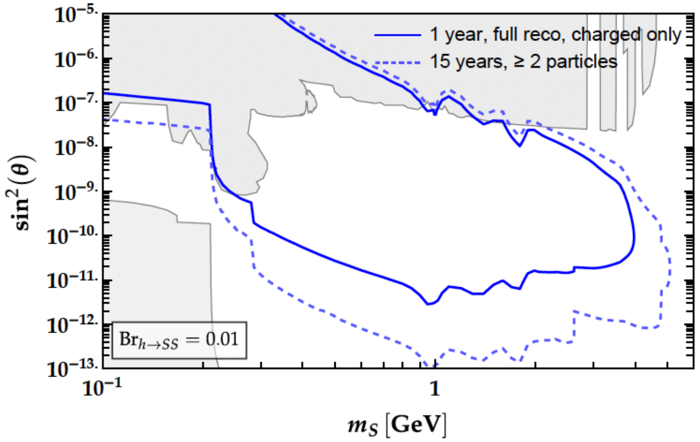
BC1 (dark photons)



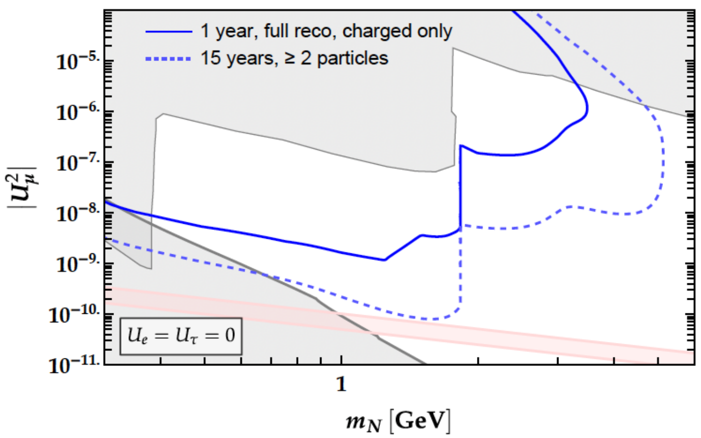
BC4 (scalars without hSS coupling)



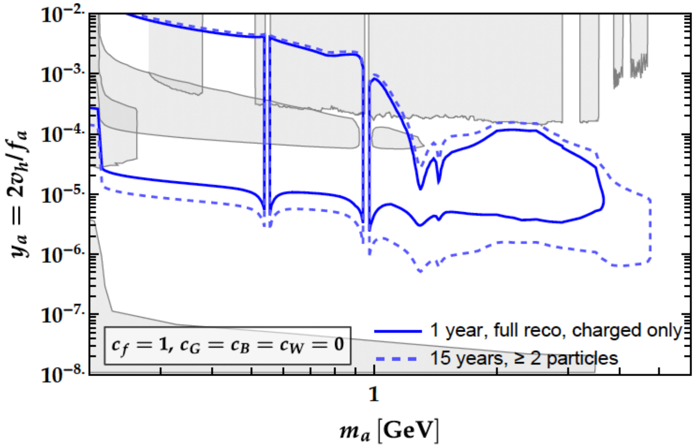
BC5 (scalars with hSS coupling fixed such that $\mathrm{Br}(h \to SS) = 0.01$)



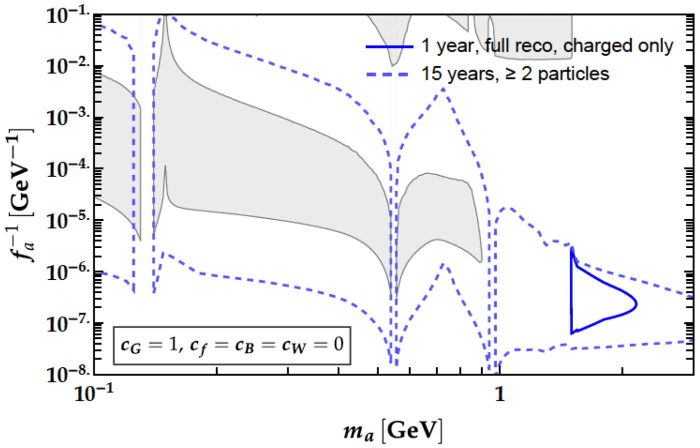
BC7 (heavy neutral leptons mixing with ν_e)



BC10 (axion-like particles with universal couplings to fermions)



BC11 (axion-like particles coupled to photons)



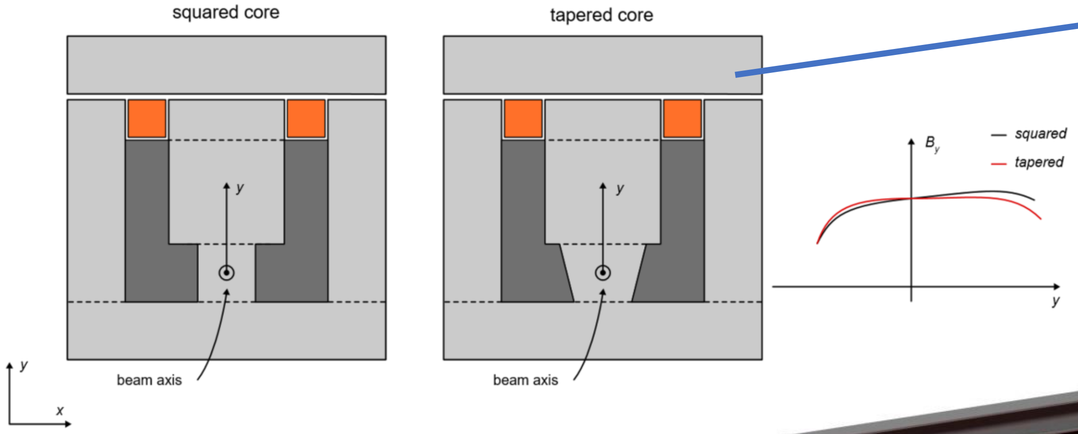
—— after **one year** of data taking (4×10^{19} PoT) with the SHiP detector in **2033** using **only fully reconstructed final states with charged particle tracks**.

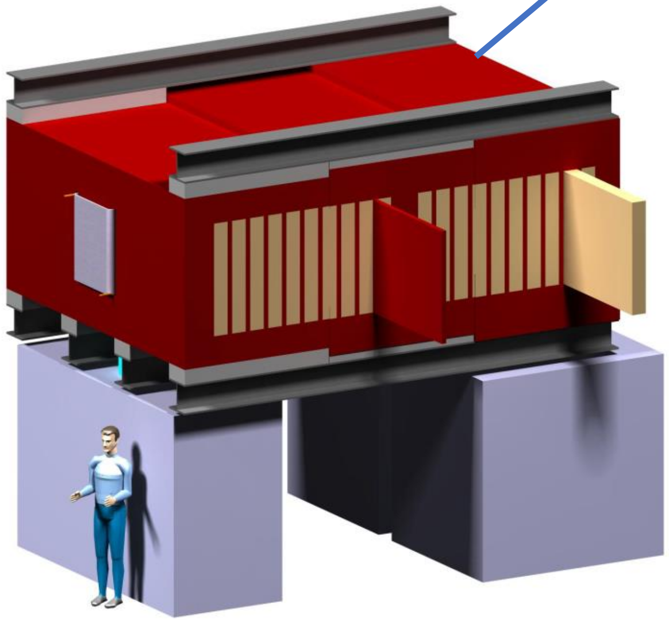
\- - - after **15 years** of running (6×10^{20} PoT), including **all final states**.

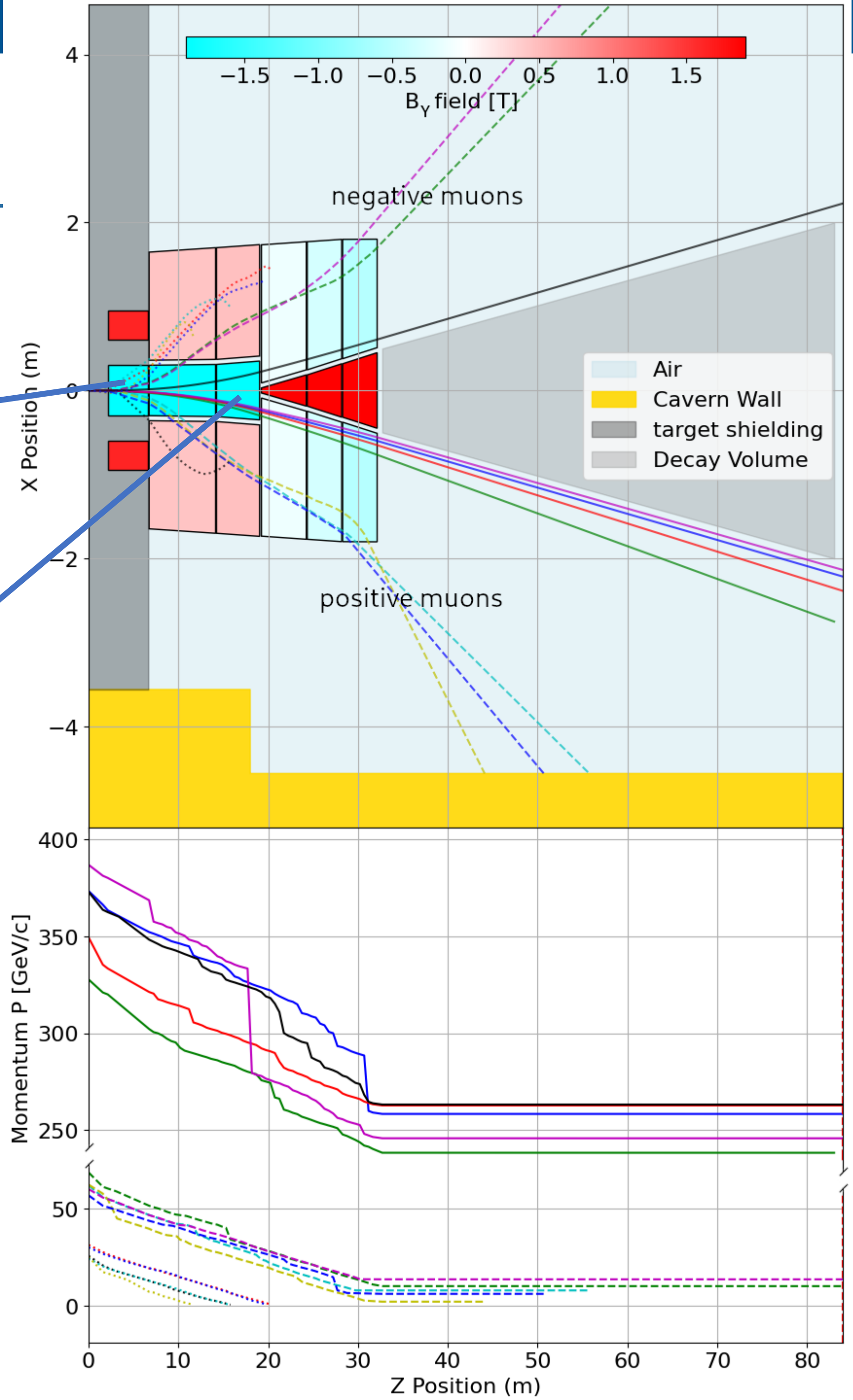
Progress on the muon shield

Conceptual design studies

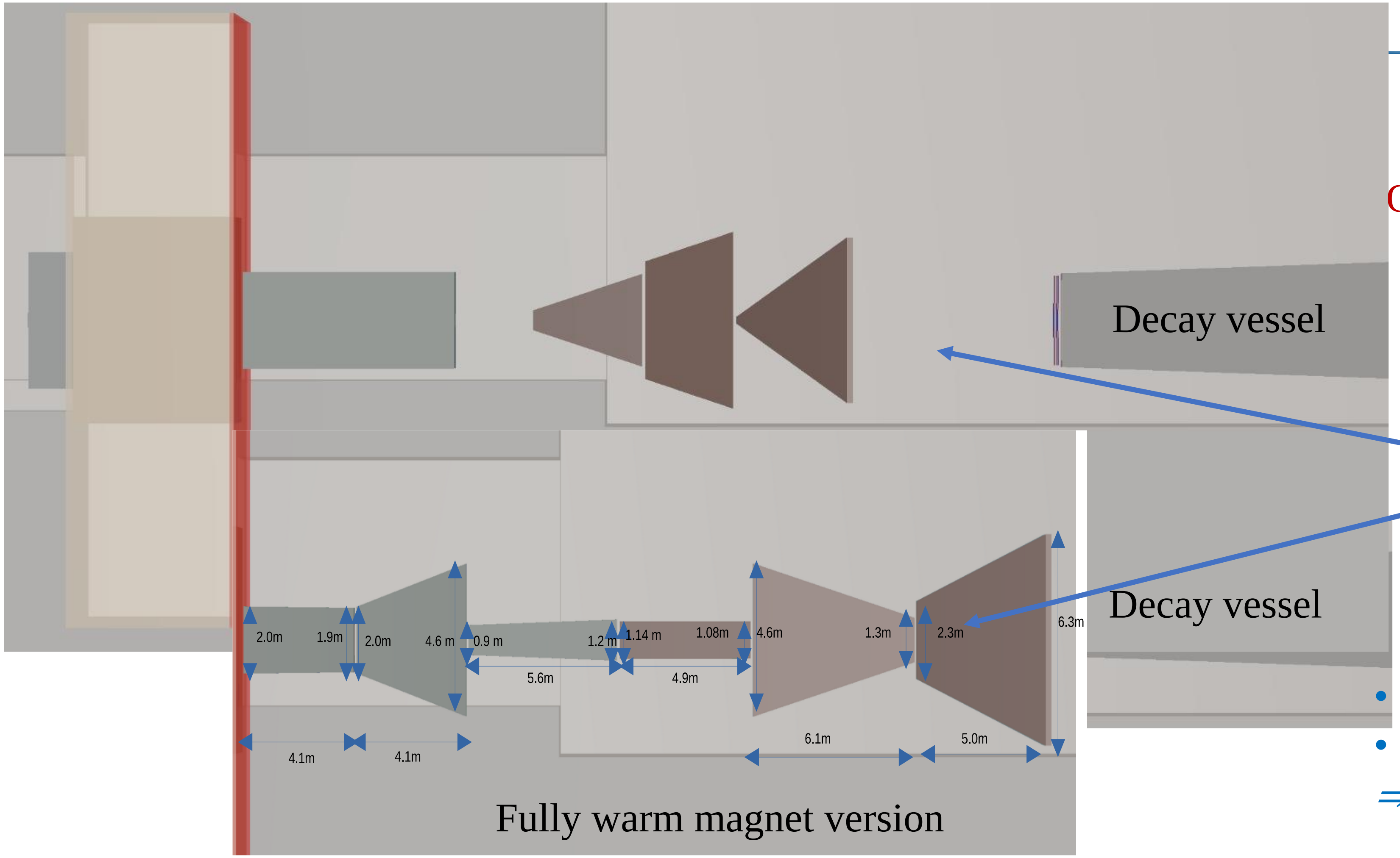
- *MHS eng. design taken over by CERN/TE-MSC-NCM*
- *Started SND integration studies*
- *Started developing concept of 4.8 m long Tuned Return Yoke (TRY) magnet*







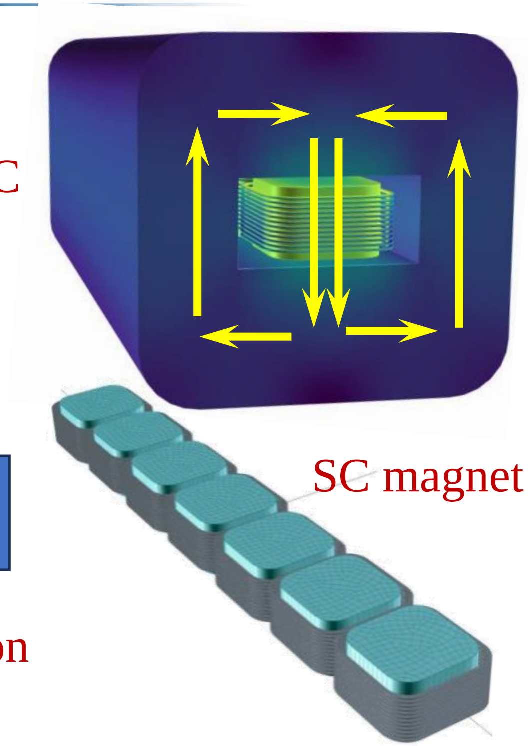
Muon shield versions and SND detector embedded therein



Ongoing R&D on SC magnet with HTS technology for a hybrid version

SND

Fully warm version

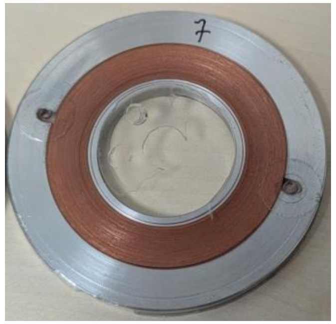


SC magnet

- *estimated cost of a 5 T/7 m SC magnet*
- *desired start date of SHiP experiment (2032)*

⇒ *"hybrid" MS appears extremely challenging*

dummy coil during insertion into impregnation mold and after vac-pressure impregnation



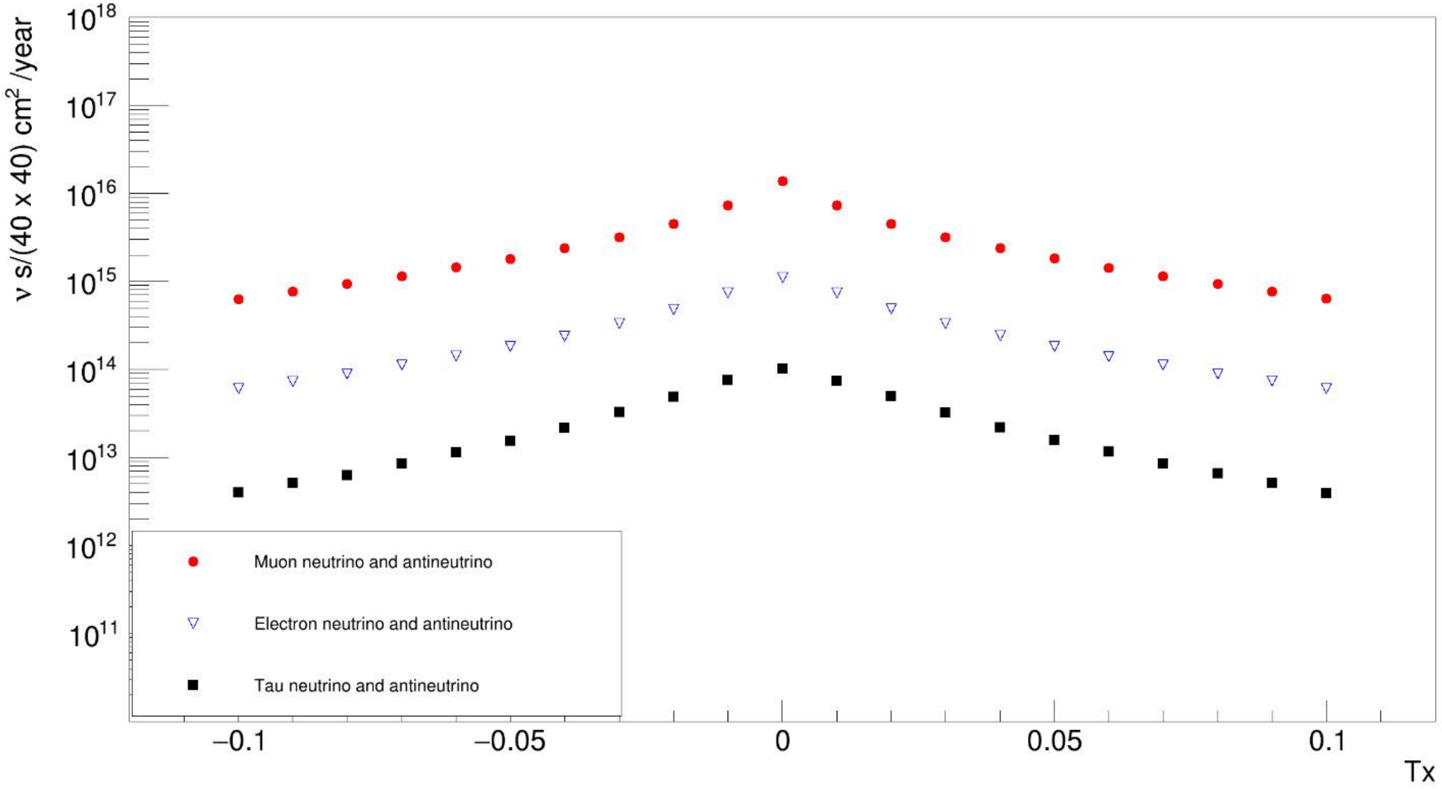
SND requires a muon spectrometer (magnet) → embed it within the magnetised iron of the muon shield

Scope of the SND detector and guidelines to its design

- Profit of the huge flux of neutrinos of all types to study neutrino interactions
- Emphasis on the unexplored ν_τ and anti- ν_τ and ν_e and anti-ν_e
- Study neutrino-induced charm production ([1] and [2]) to e.g. improve the knowledge of the strange quark content of nucleons

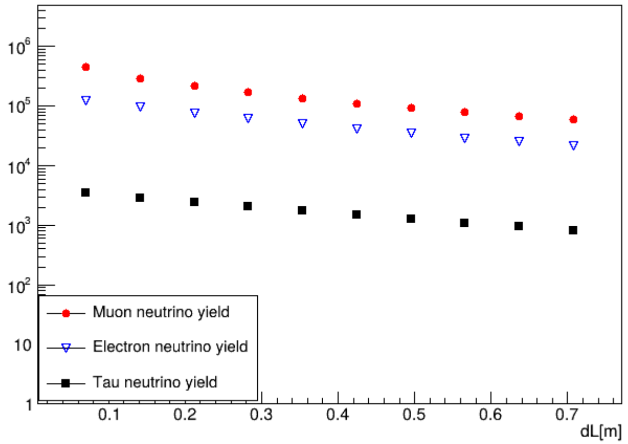
[1] https://www.sciencedirect.com/science/article/abs/pii/S0370157304002984?via%3Dihub

[2] https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.70.1341

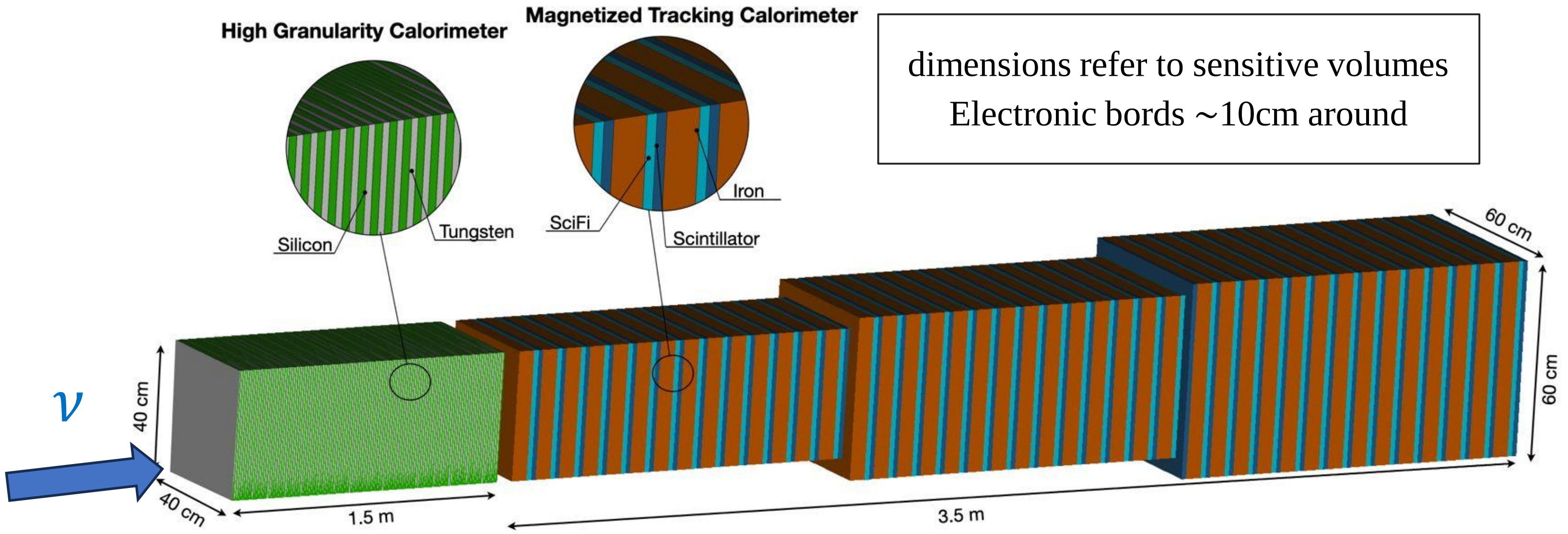


- Centred along the beam axis
- Optimal longitudinal location: upstream of the decay vessel
- Compact: ton scale

Very compact detector



SND detector concept, in full synergy with SND@LHC

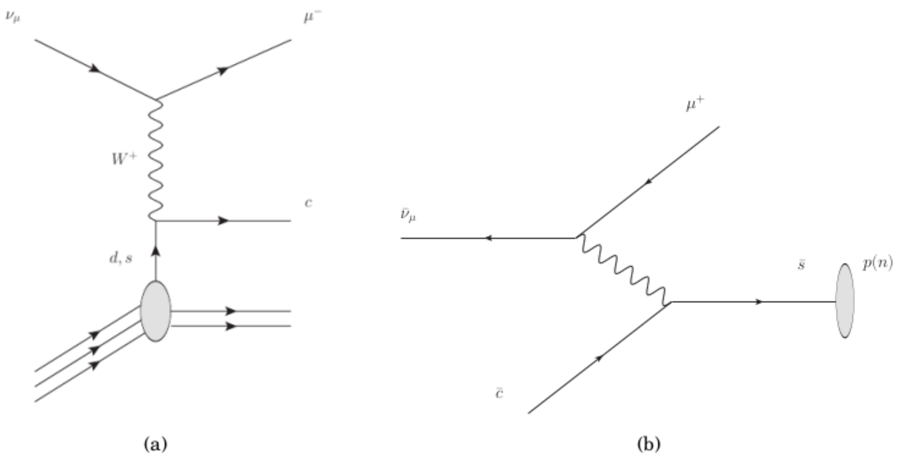


dimensions refer to sensitive volumes
Electronic bords ~10cm around

HIGH GRANULARITY CAL	
Tungsten	120
Silicon	120
Weight	1.3 tonnes

MAGNETIZED TRACKING CAL	
Iron	42
Scintillator	42
SciFi	42
Weight	4.2 tonnes

42 Fe slabs, 5 cm each
$\gtrsim 10\ \lambda$
$\int B dl \gtrsim 3$ Tm



ν-induced charm production

1.3 W tons in the Si/W

Interactions/year (i.e. 4.5 x 10^{19} pot)

	CC DIS (W)	Charm CC DIS (W)
N_{ν_e}	6.8×10^4	4.1×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3
N_{ν_τ}	2.1×10^3	1.2×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1

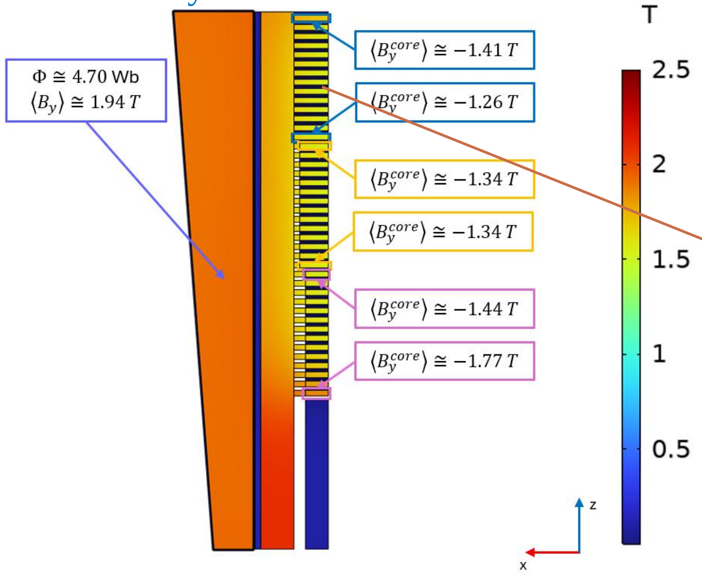
4.2 Fe tons in the MTC

Interactions/year

	CC DIS (Fe)	Charm CC DIS (Fe)
N_{ν_e}	1.6×10^5	9.8×10^3
N_{ν_μ}	4.6×10^5	2.0×10^4
N_{ν_τ}	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	3.8×10^3	2.1×10^2

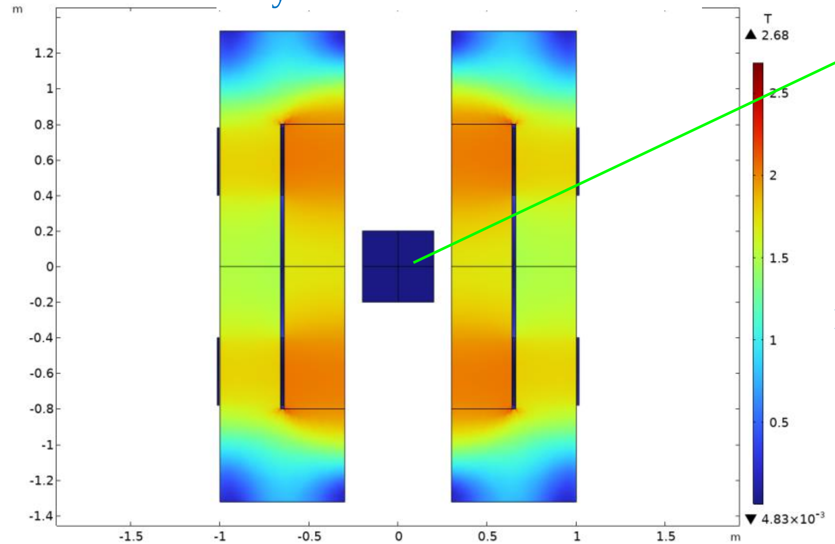
A design to allow inserting/handling the detector modules:

B_y field (top view)

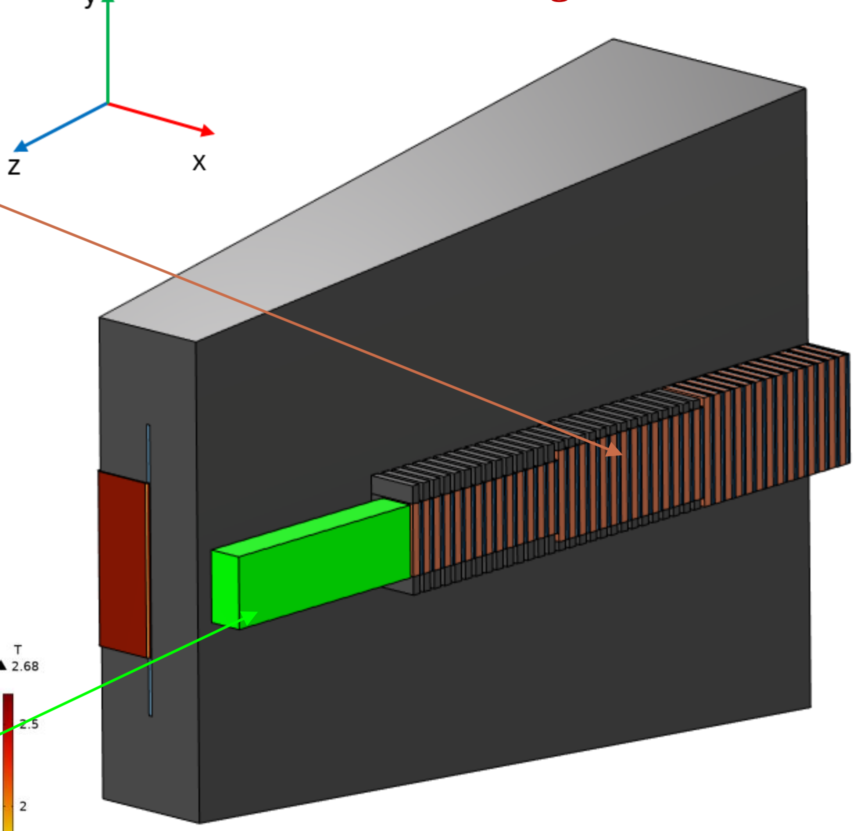


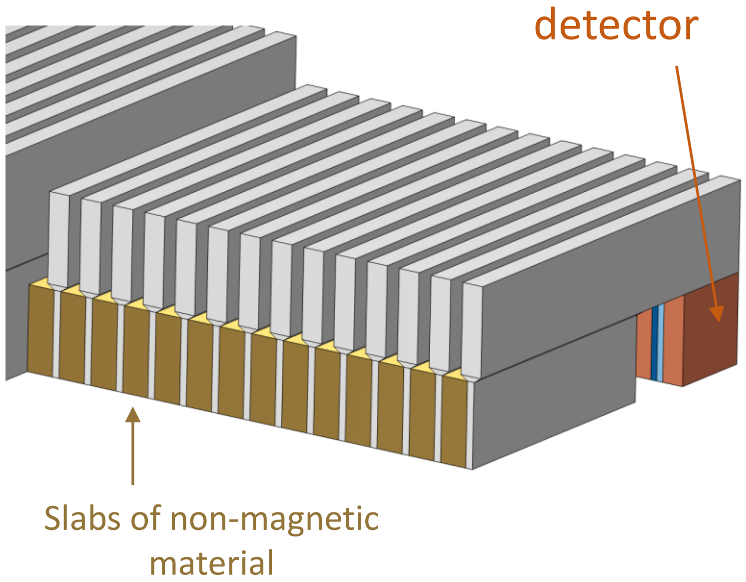
(modified X-section case)

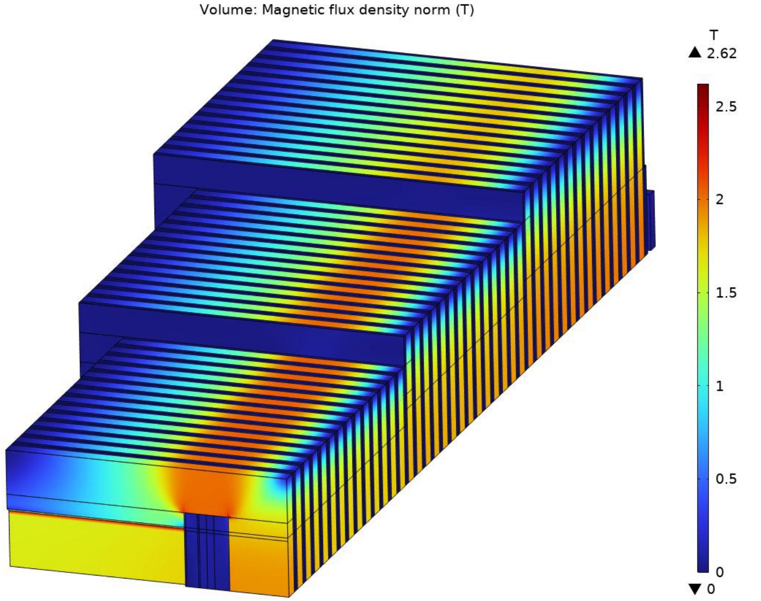
B_y field (front view)



distinct outer legs and core







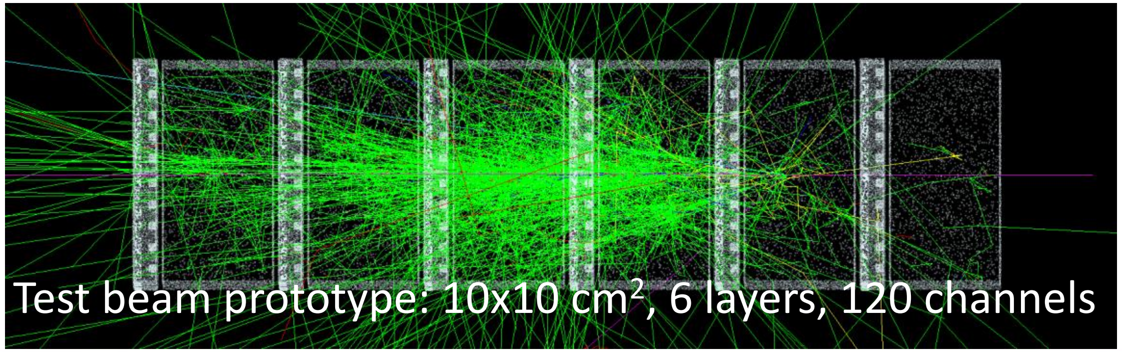
TRY concept: outer legs to deflect outwards mid momentum muons and continue degrading their total momentum by energy loss. Better achieved with a sideways extended region of dense material with moderate magnetic field.

Scintillating pads: energy resolution and tests

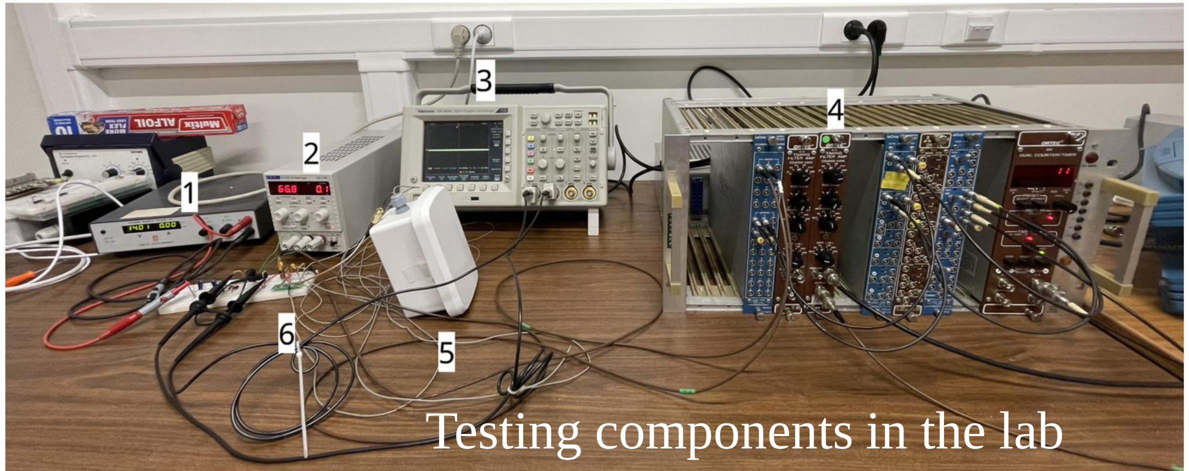
Expect 0.6/sqrt(E) for π and 0.31/sqrt(E) for e, dominated by statistical fluctuations

- π resolution limited by the constant term due to shower leakage (lateral and longitudinal) → define acceptance
- sufficient containment of EM showers over the full energy range

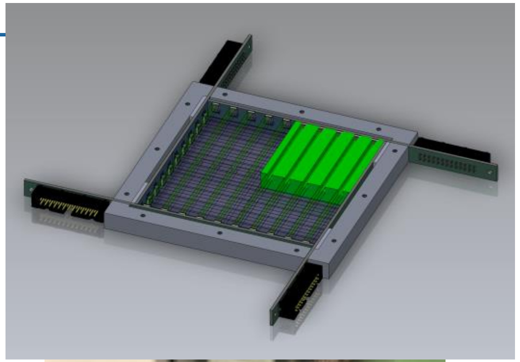
Test beam foreseen in Spring 2026 at PS and SPS

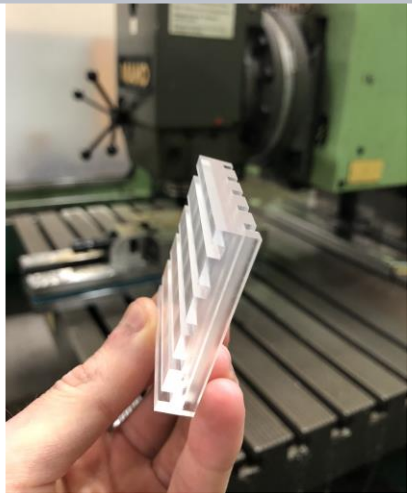


Test beam prototype: 10x10 cm^2, 6 layers, 120 channels

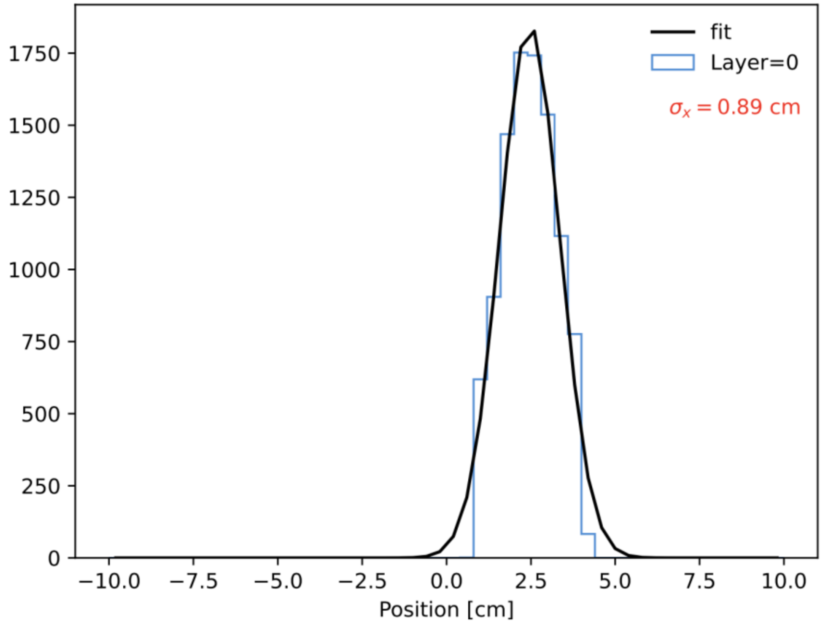


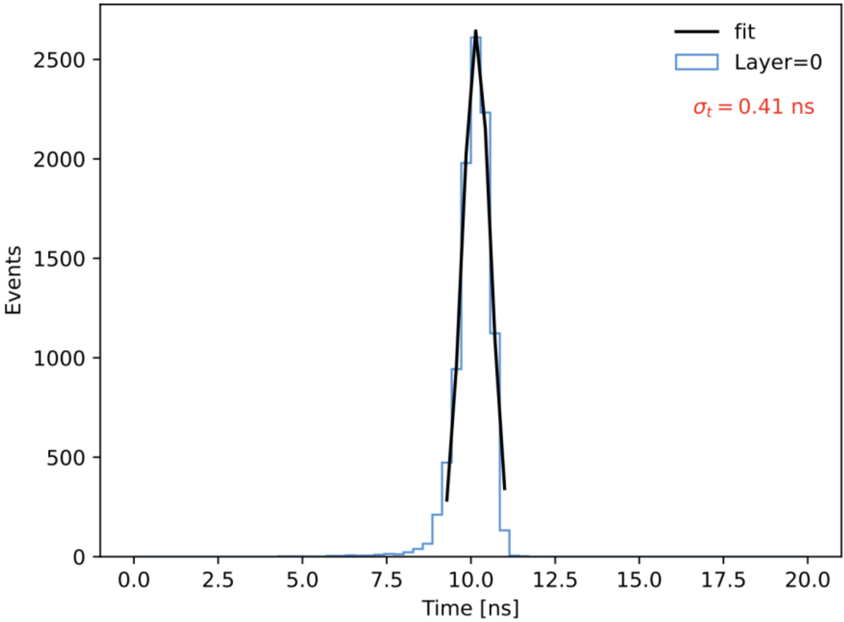
Testing components in the lab



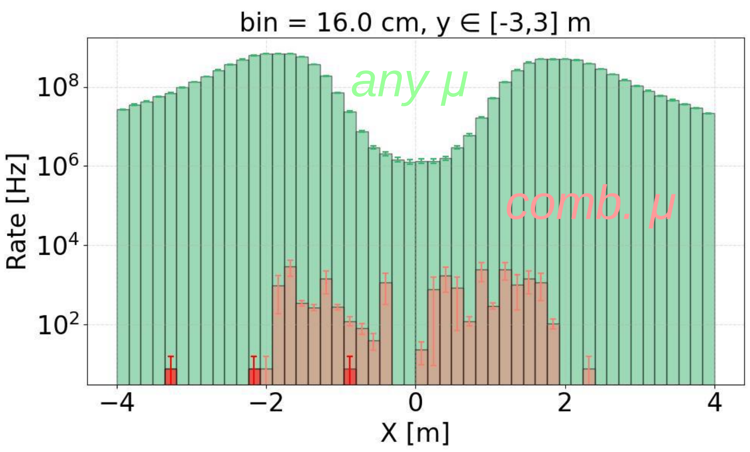


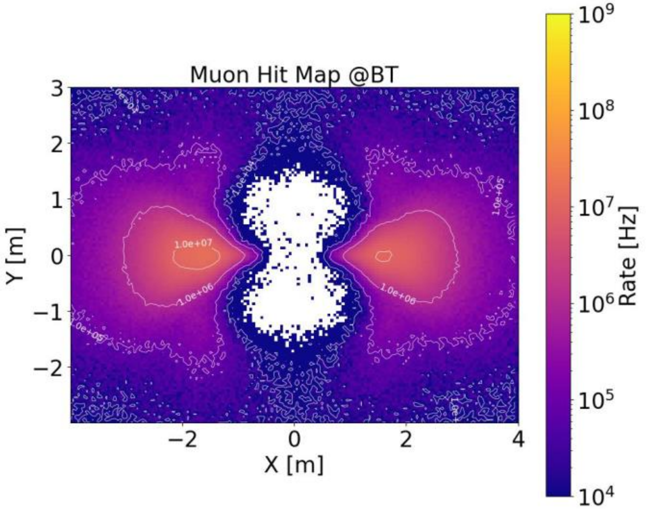
- Wrap the whole scintillator plane in reflective material (Mylar)
- Improve light transmission from one tile to another using optical grease (EJ-552)





Upstream background tagger





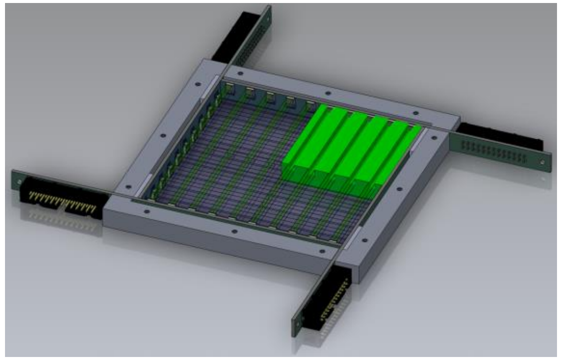
Main suppression factor of μ comb. is by timing cut ~ 3.4 x 10^{-10}
Studied μ comb. bkg for several MS variants
⇒ ϵ_{tag} > 99% (per track)
Still to be studied: track matching, false vetoing

Upstream BT:
Tag combinatorial bkg and inelastic before Decay Volume

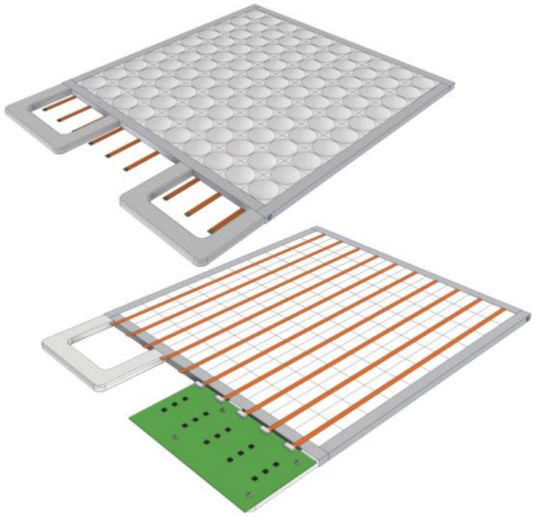
- *Will likely require a good time and spatial resolution (including direction)*
- *Considering a combination of:*

(a) scintillating tiles:

- ❑ *time resolution of 200 ps can be achieved with scint. tiles of 5x5 cm^2*
- ❑ *detector must cope with rate of charged particles of up few MHz/tile*
- ❑ *evaluating different readout schemes*



WLS-fiber coupled (2 ends)

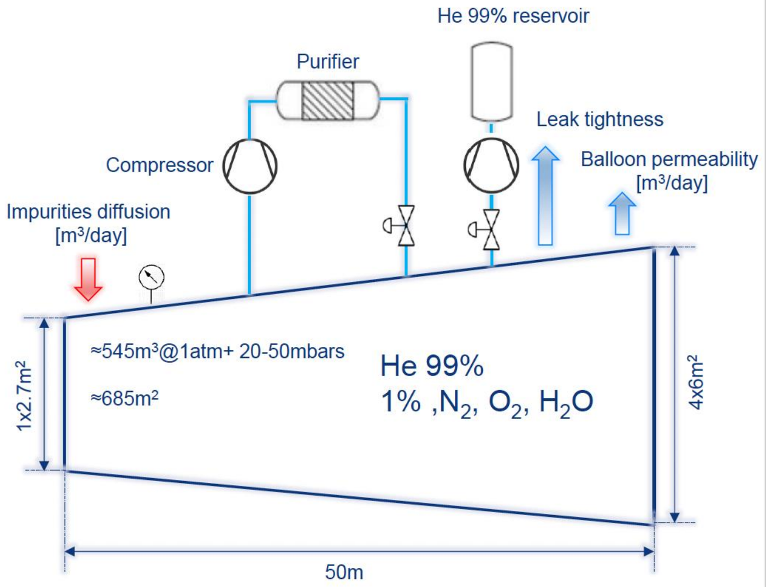


individual SiPM

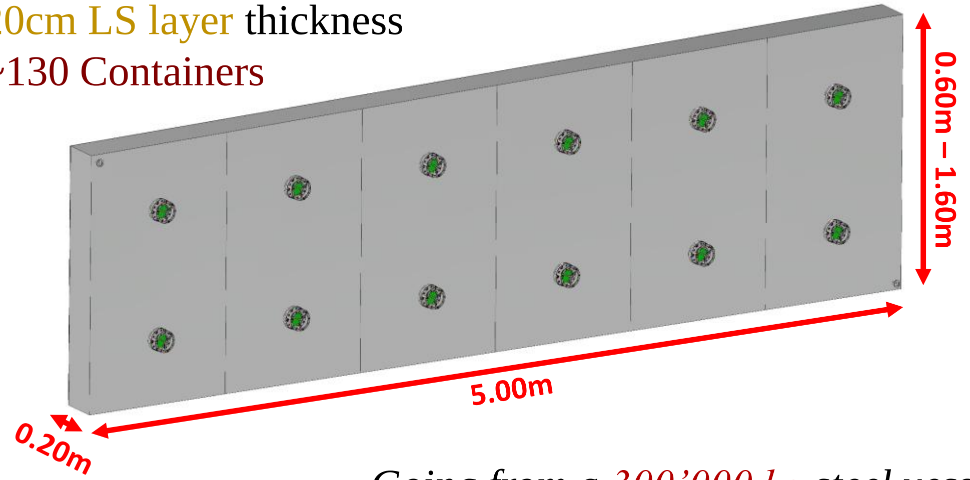
(b) straw tubes: started studies to define requirements (rate, material effects on bkg / resolution / efficiency)

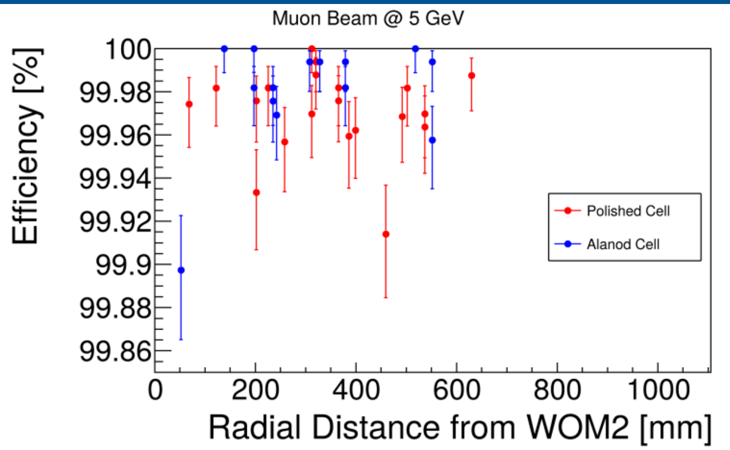
- *After we have fixed MS design, study rate at vertical plane between MS and DV*
- *Design a tagging system that covers as much as possible this plane (rate limits!)*

Decay vessel and the surrounding veto system



6 Interconnected liquid scintillator filled cells
Welded from large sheets of polished AW 5083 (AlMg4.5)
20cm LS layer thickness
~130 Containers





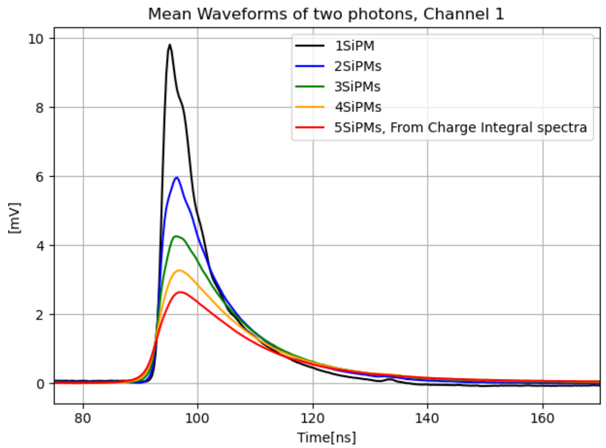
Empty weight: max. 395kg

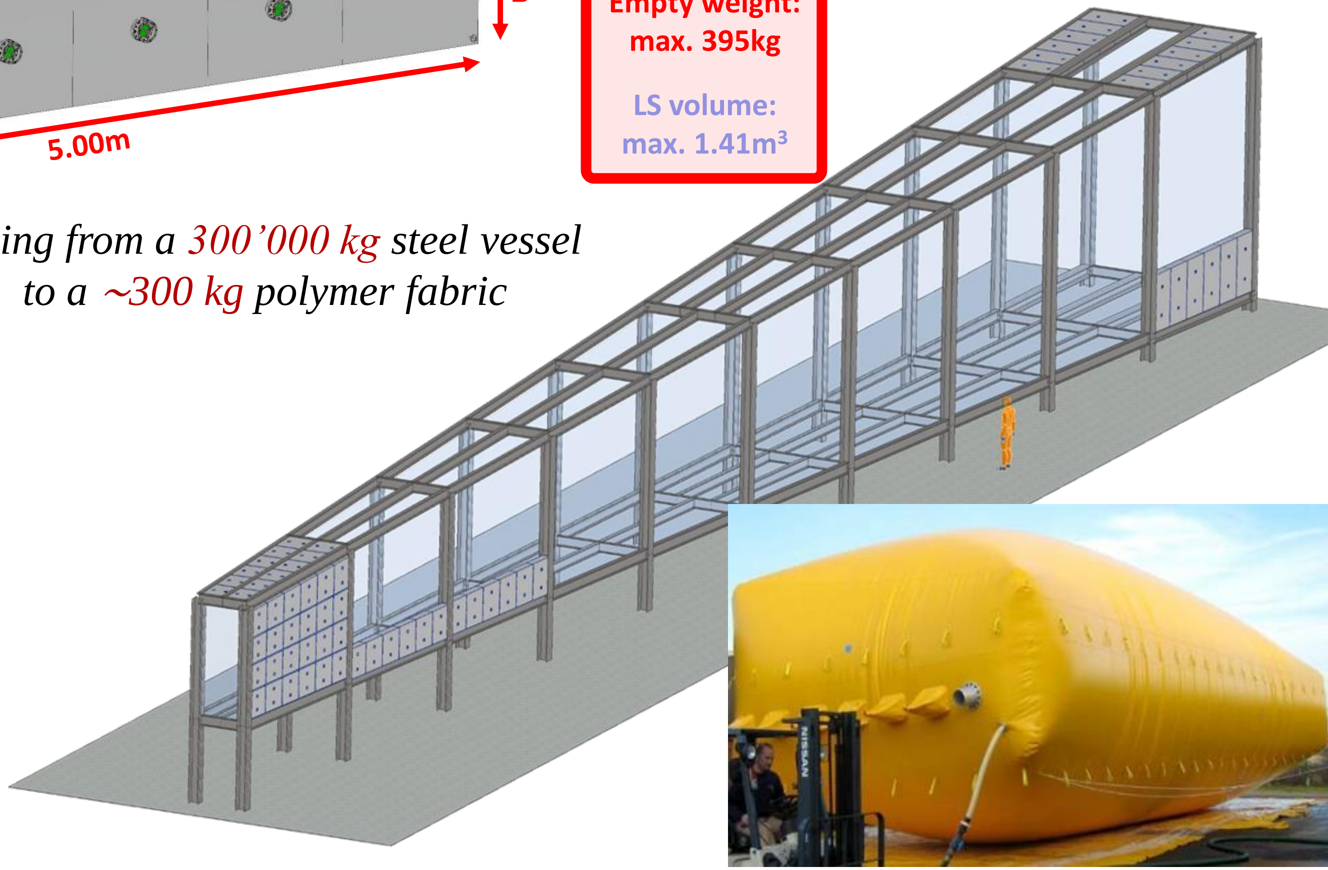
LS volume: max. 1.41m³

Going from a 300'000 kg steel vessel to a ~300 kg polymer fabric

0.3-0.4 mm thick

Waveforms by 2 photons, for one channel





Spectrometer magnet with HTS technology

Proof-of-Principle

Magnet based on MgB_2 cable (wire same as HL-LHC SC Link)

Indirect cooling – Cryocooler+Cryofan – GHe ~20K

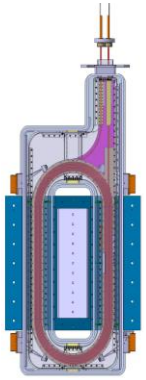
EESD1: coil pack concept validated

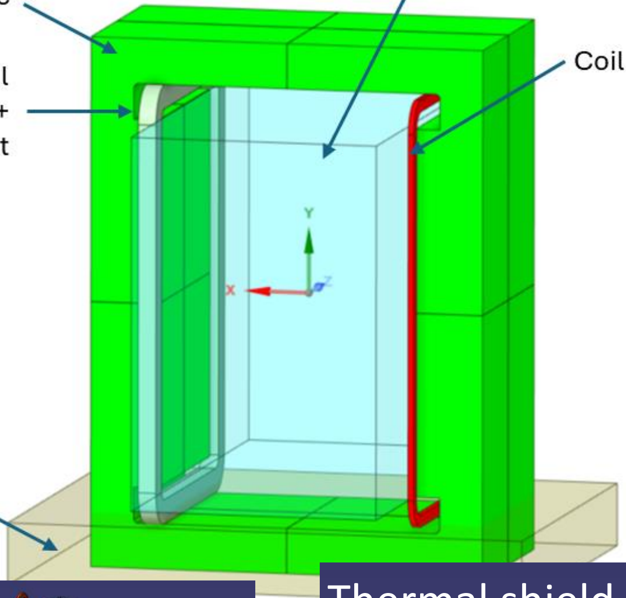
ESSD2: Validate cooling concept + operation with current leads

From Proof-of-Principle

Energy-Efficient Superferric Dipole

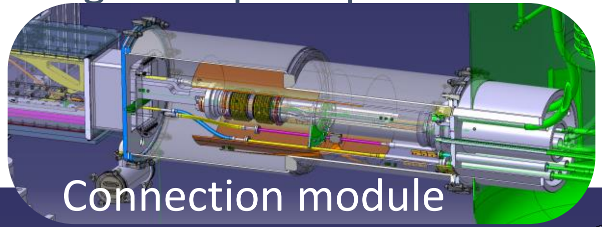
~ 1m

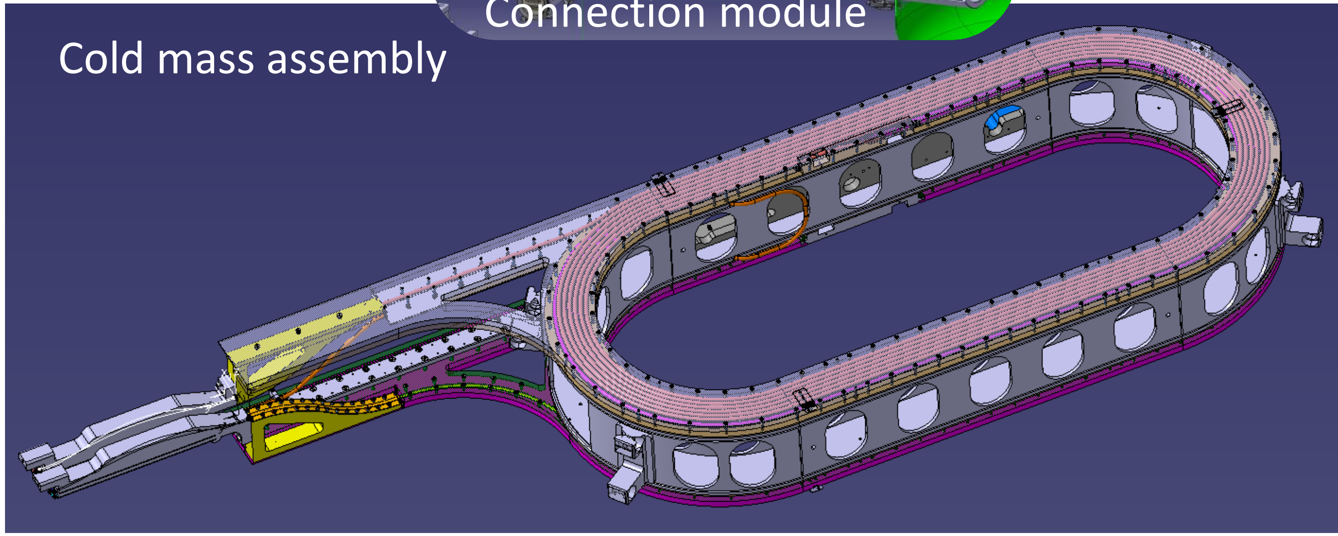


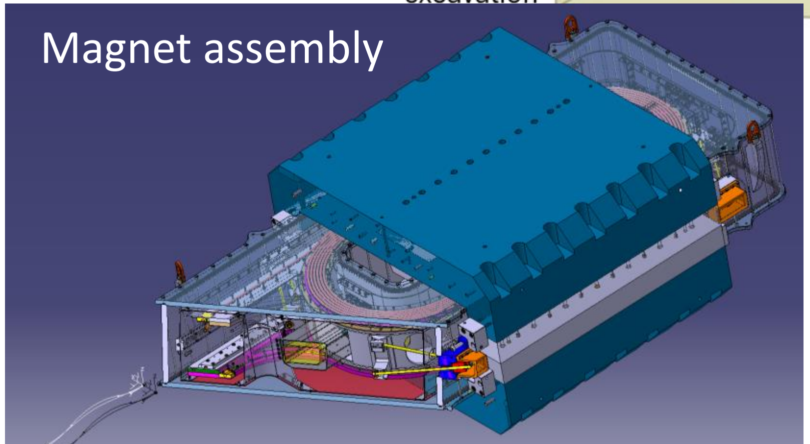


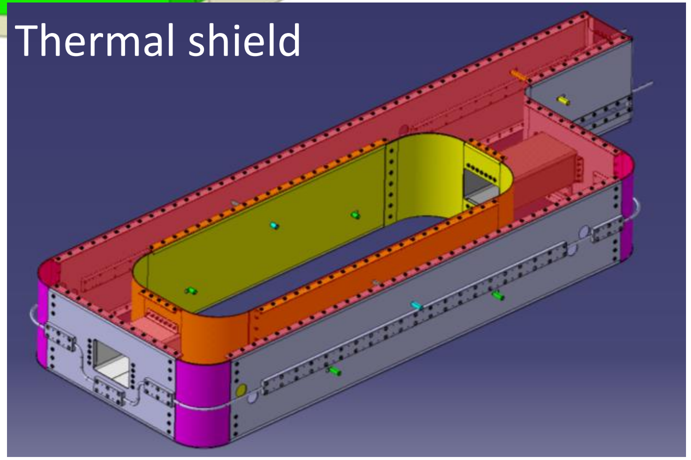
To Full-Scale Magnet

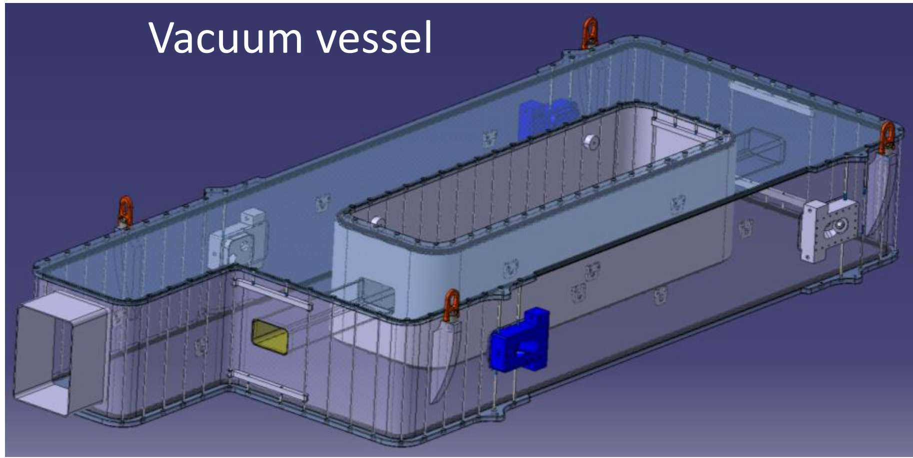
~ 5m (Z) x ~ 7.5m (Y)



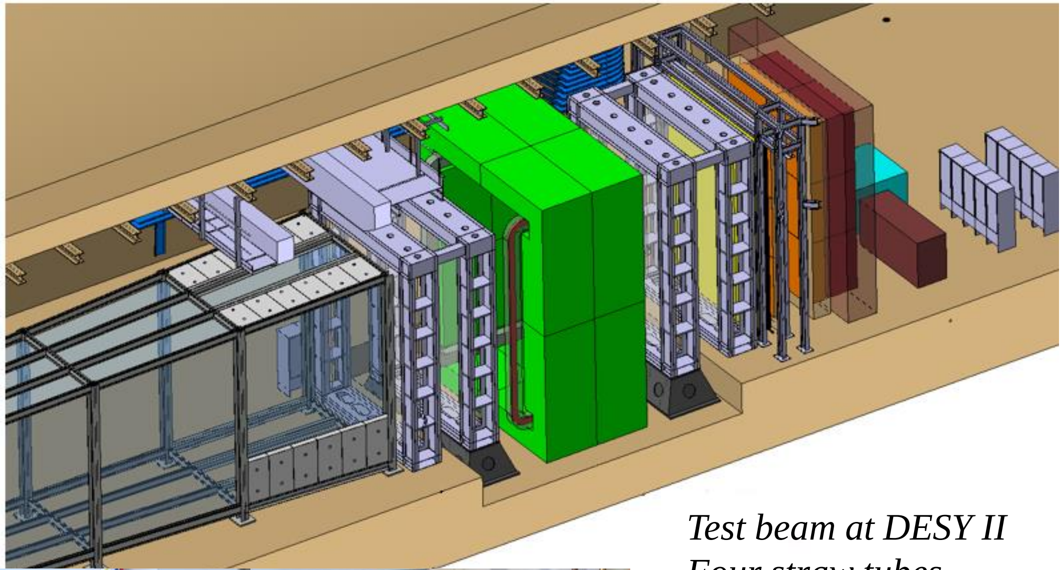




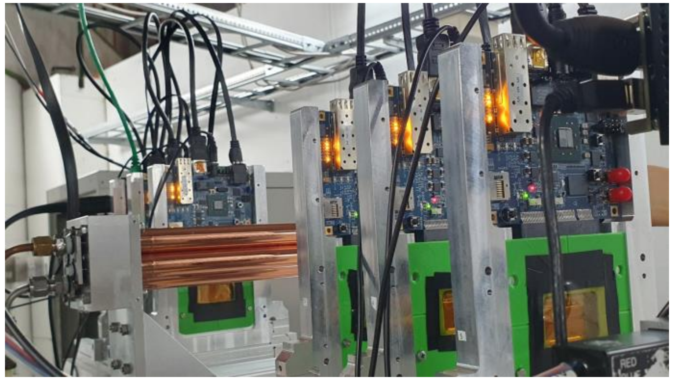


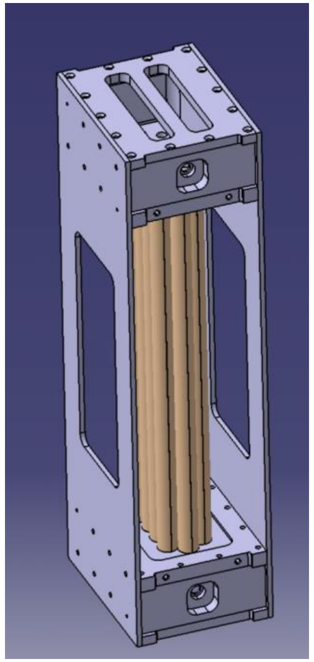


Straw tracker developments for the spectrometer

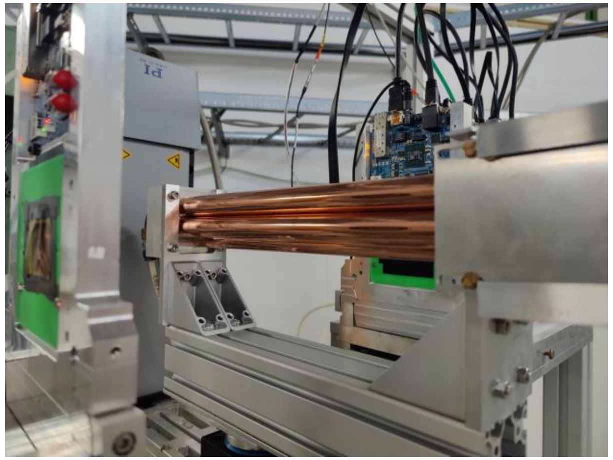


Four identical stations, aperture of 4m x 6m
300 tubes on top, 8 layers per station
2400 straws per station → almost 10000 channels
Modules of 2 x16 straws (32 cm high)



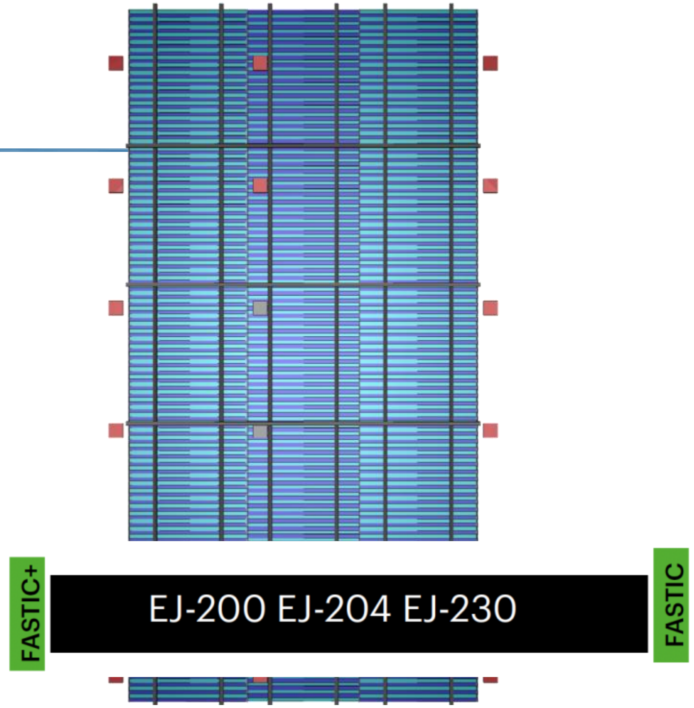


Test beam at DESY II
Four straw tubes
30 cm long, 2cm diameter
30 μm wire
80/20 Ar/CO2
at ambient pressure
Readout with SAMPIC

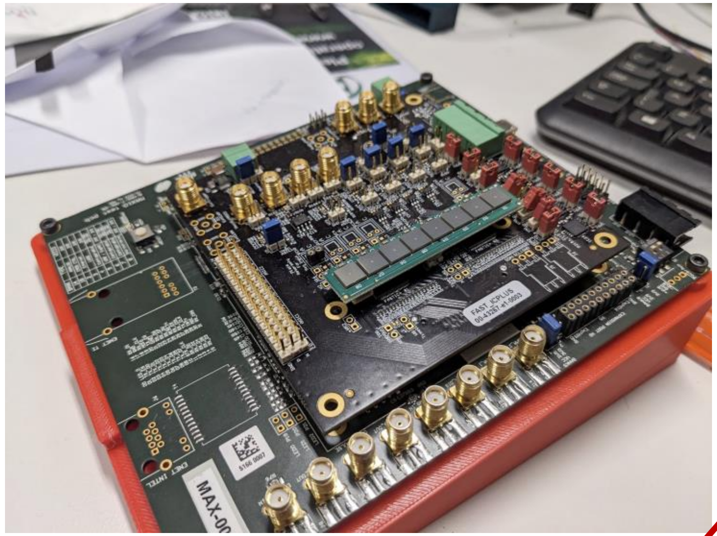


Timing detector

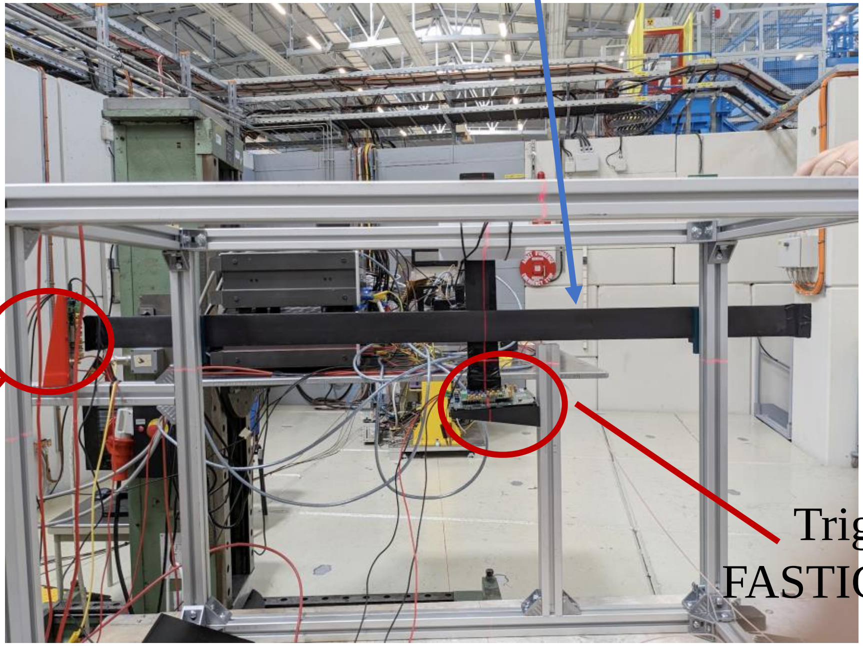
- Provide precise timing (<100 ps) of each track to reject combinatorial background
- Plastic scintillator characteristics
  - Three-column setup with EJ200 plastic bars of 140cm × 6cm × 1cm, providing 0.5cm overlap
  - Readout on both ends by array of eight 6×6 mm^2 SiPMs, 8 signals summed up
  - 330 bars and 660 channels



FASTIC with 25ps TDC embedded

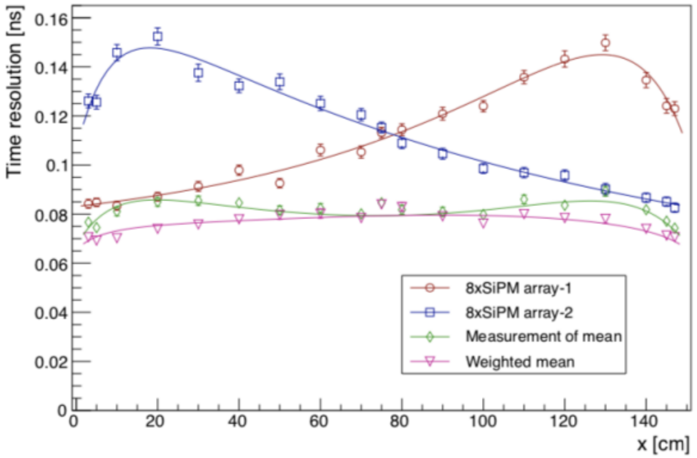


Test beam in Sep 2025 at CERN T10



Trigger IN
Beam Counter

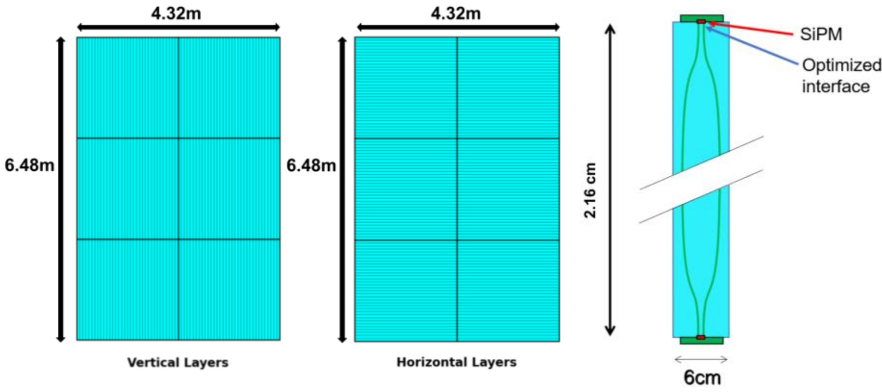
Trigger IN
FASTIC- Fast OR

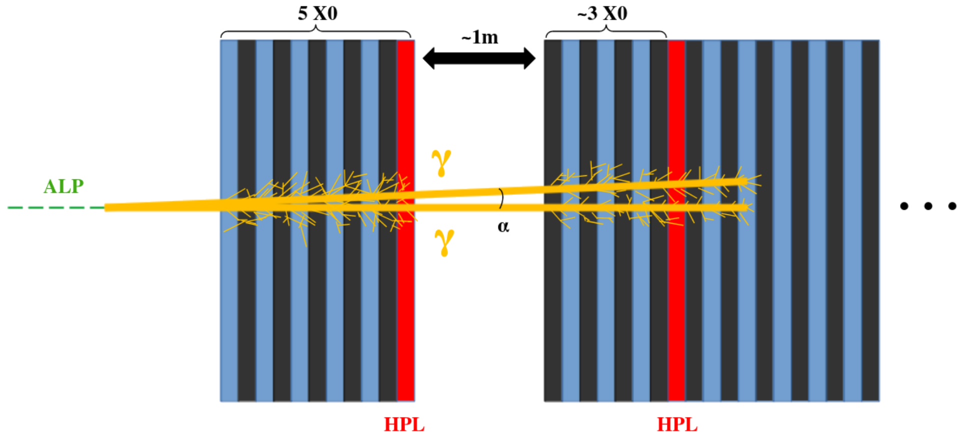


NIM A 979 (2020) 164398

Calorimeter and Particle ID system

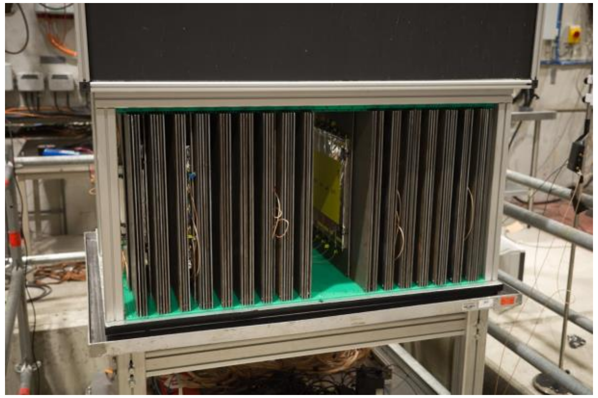
- *PID composed of sampling ECAL and HCAL based on scintillators readout by SiPMs*
- *ECAL based on the SplitCal concept to reconstruct neutral (γγ) final states*
- *Thin scintillator bars*
- *GEMs (High Precision Layers)*
- *Detector built in 6 hexants for modularity*
- *Needs to reconstruct MIPs and large showers*

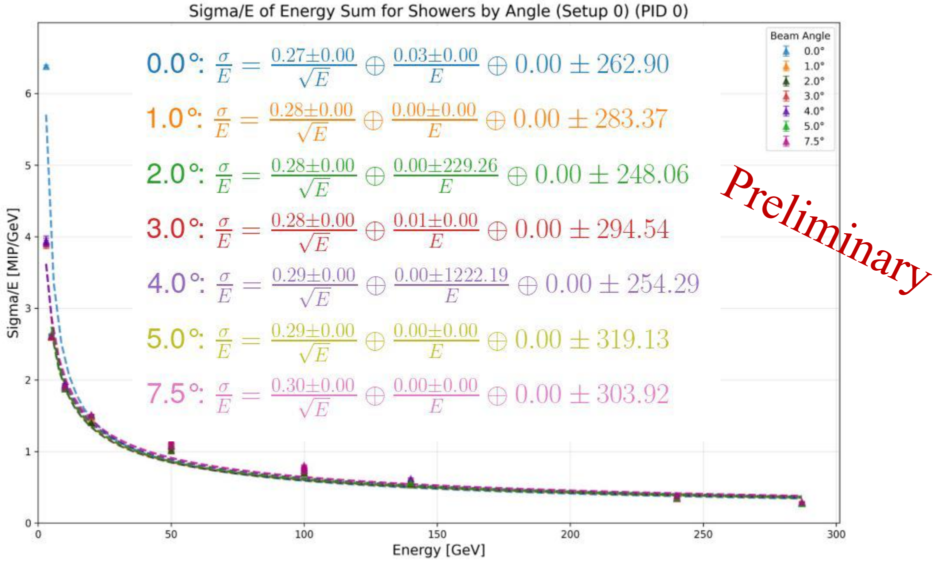


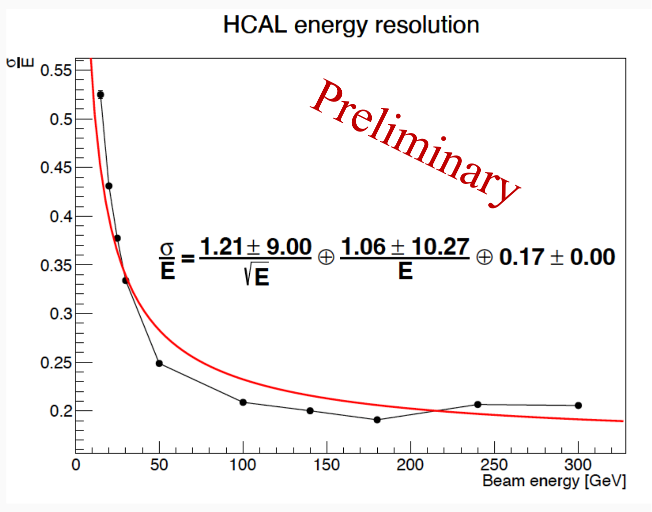


Test beam in May 2025 at SPS

- *ECAL prototype: 17 active layers, 20 X^0, 112 cm total depth with central 20 cm split*
- *Prototype included thin and wide scintillator bars*







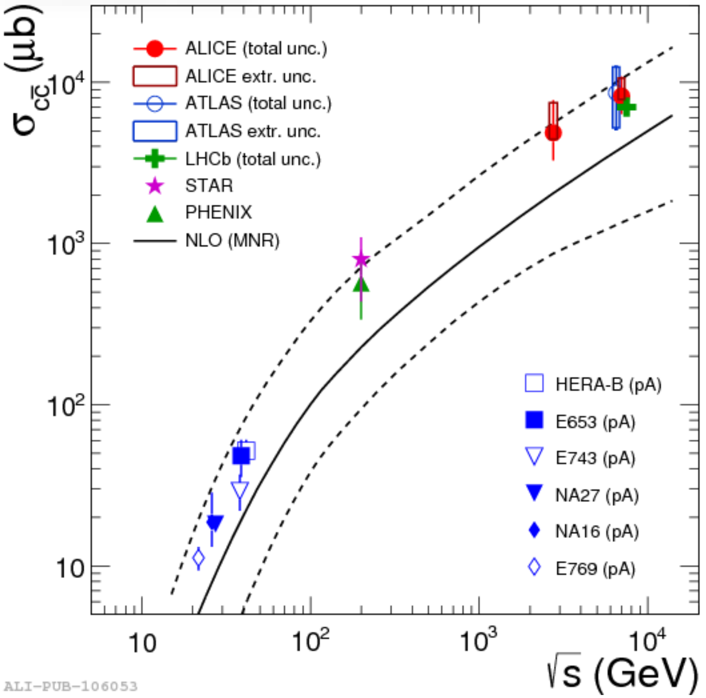
ν_τ cross-section measurement

When the τ charge is identified, expected statistical accuracy ~ 2%

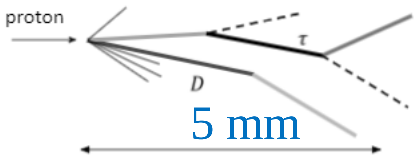
Charm production cross-section at 400 GeV: NA27 experiment (10%)

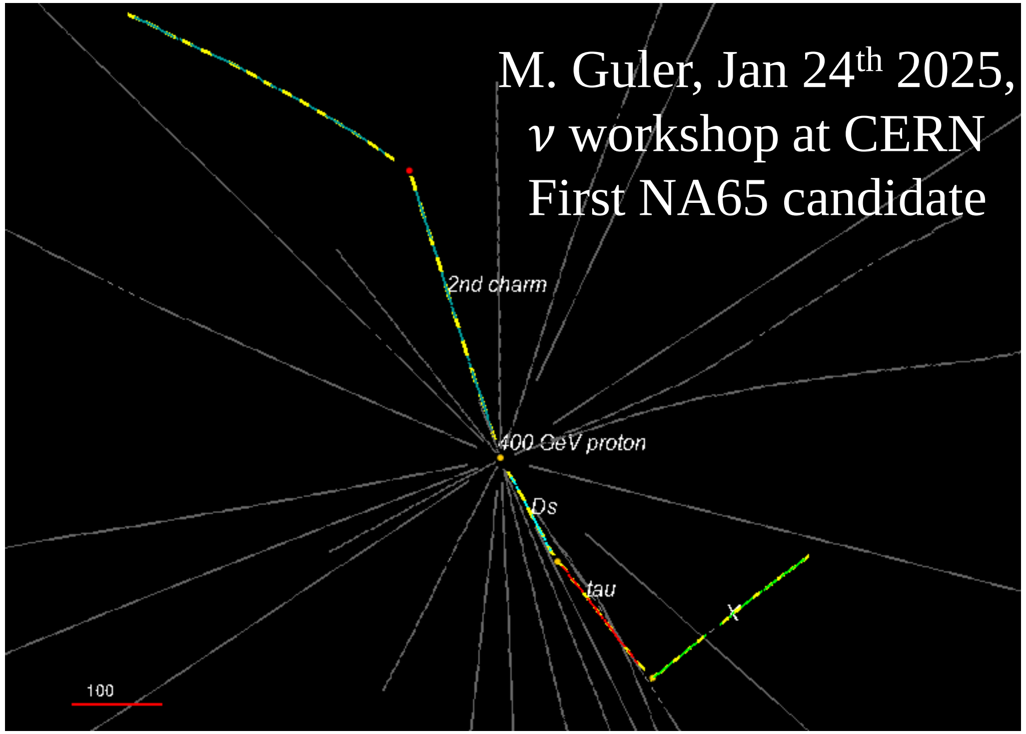
	exp NA27
$\sigma[\mu b]$	18.1 ± 1.7

Experiment	D^+/D^0	$D^0(\text{from } D^*)/D^0$	D_s^+/D^0
WA92: 350 GeV π^- on Cu	0.423 ± 0.012	0.280 ± 0.015	0.160 ± 0.037
WA92: 350 GeV π^- on W			0.183 ± 0.068



NA65 schematic





D_s uncertainty large, BR ($D_s \rightarrow \tau\, \nu_\tau$) = (5.32±0.11)% (2% small)

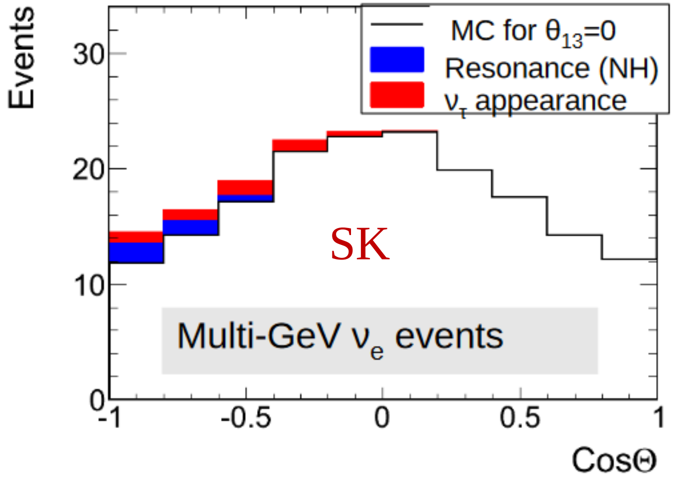
NA65 measuring p p → X D_s → τ in a thin target

NA65 expects 1000 events → potentially ~3%

Measure the J/ψ → μ+μ- $(5.961 \pm 0.033)\%$ in a thick/thin target at 400 GeV (and a few other energies)

Impact of ν_τ measurements on oscillation studies: SK/HK and IceCube

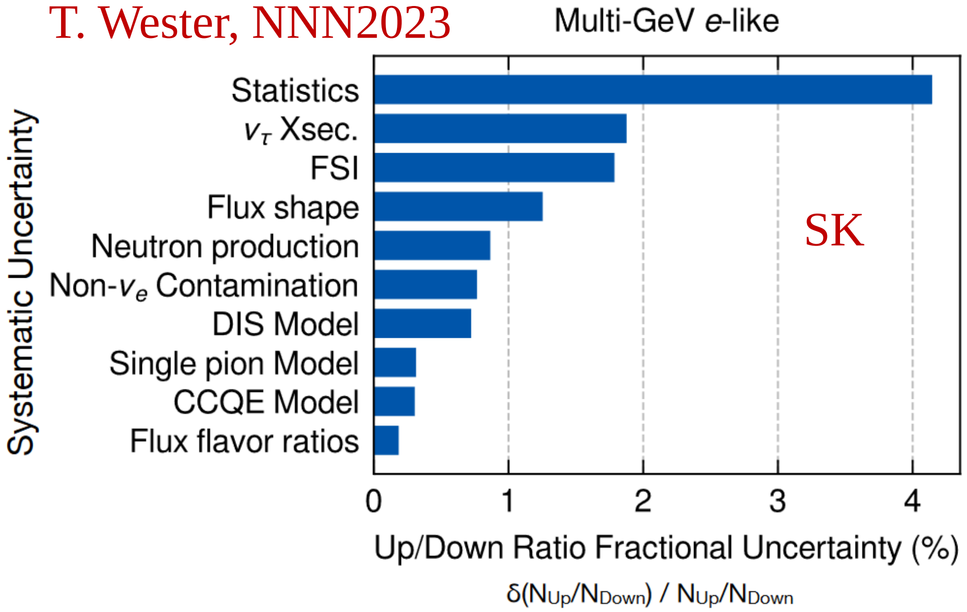
C. Bronner,
https://indico-sk.icrr.u-tokyo.ac.jp/event/5223/



M. Scott (Imperial College)

Mass ordering sensitivity from upward-going, multi-GeV electron-like samples
- ν_τ cross-section uncertainty dominant systematic
- Hyper-K will have stat error <2%

T. Wester, NNN2023

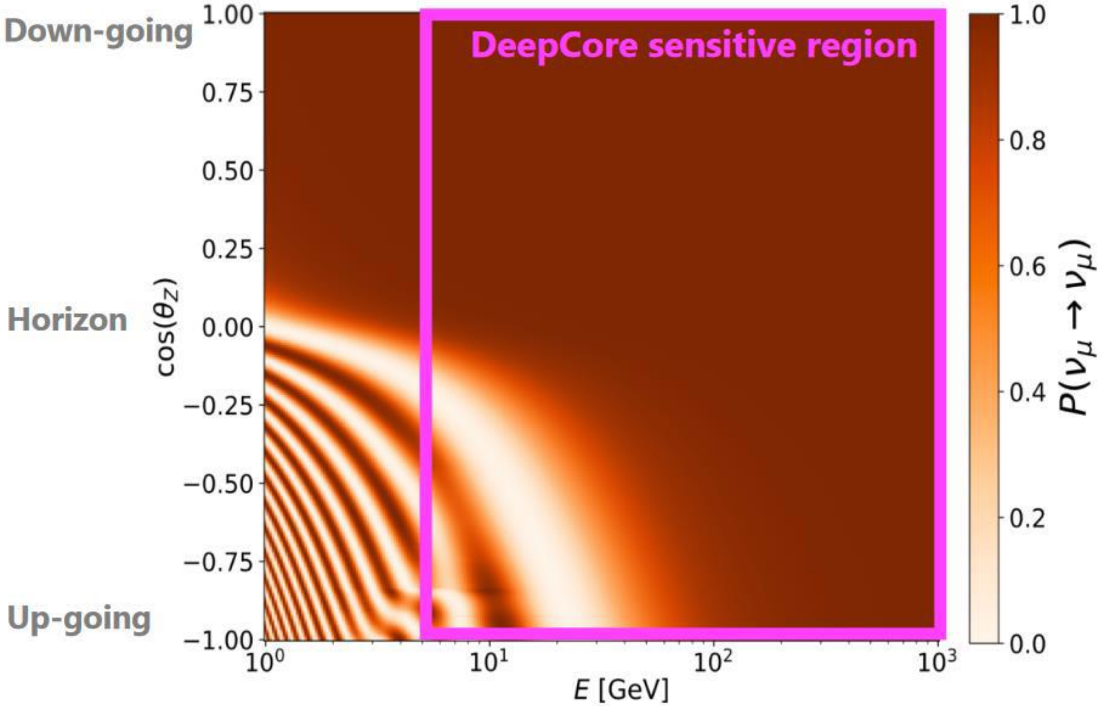


ICECUBE

- Largest particle detector in existence (1Mt)
- Limited at low energy threshold ~ 10GeV
- Above threshold of τ production –can measure ν_τ appearance

IceCube-gen2 completed in 2032

T. Stuttard, NuFact 2019

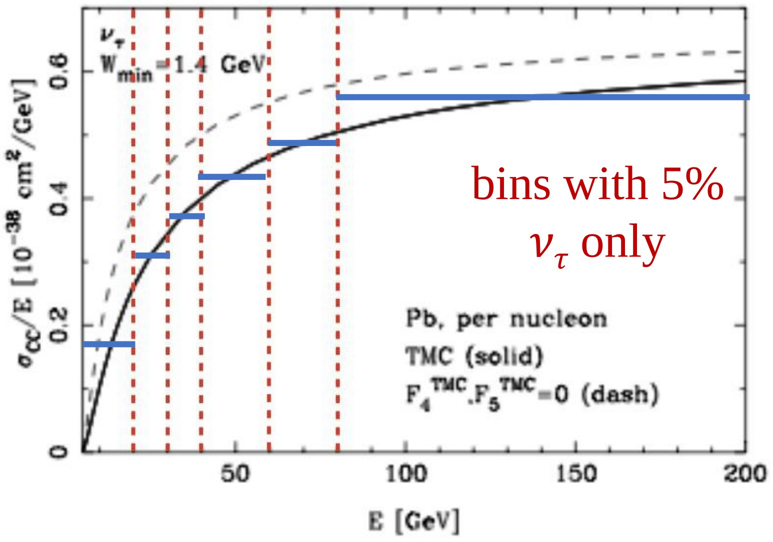


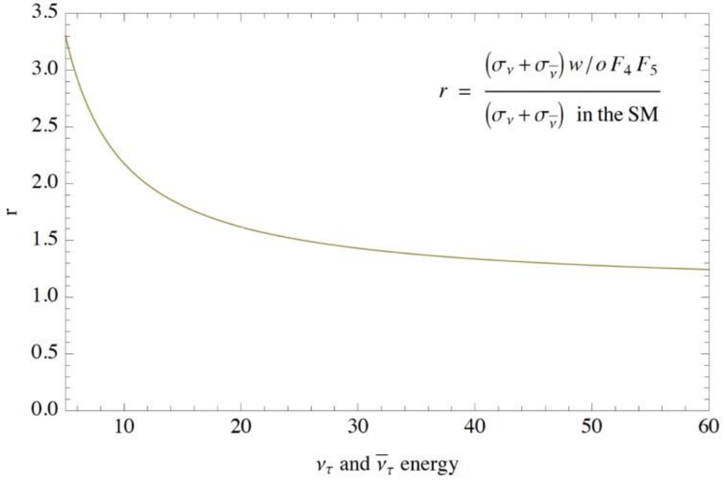
F4/F5 structure functions

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

C. Albright and C. Jarlskog, NP B84 (1975)

- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV





Rep. Prog. Phys. 79 (2016) 124201

About 3×10^4 detected events below 60 GeV

Evidence for F_5 can be assessed quickly

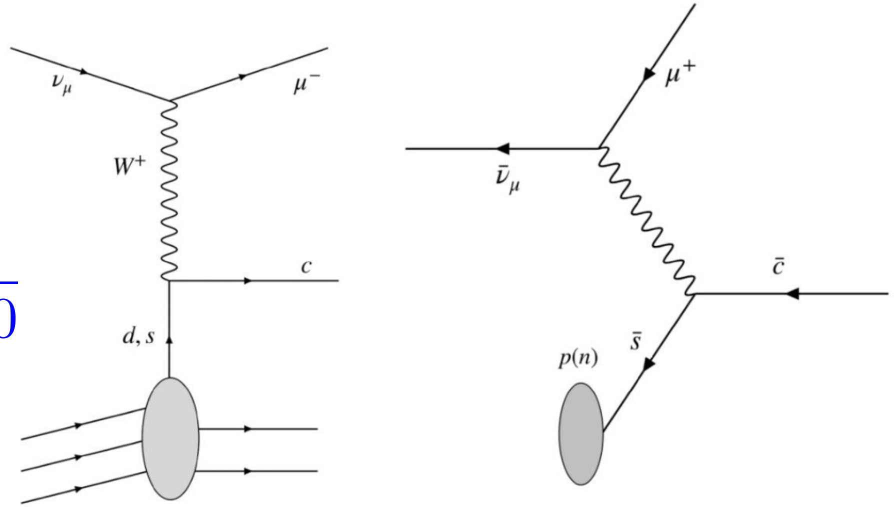
Measurement of F4/F5 ∽5% accuracy

→ differential measurement as a function of x and Q^2

Charm physics with neutrinos

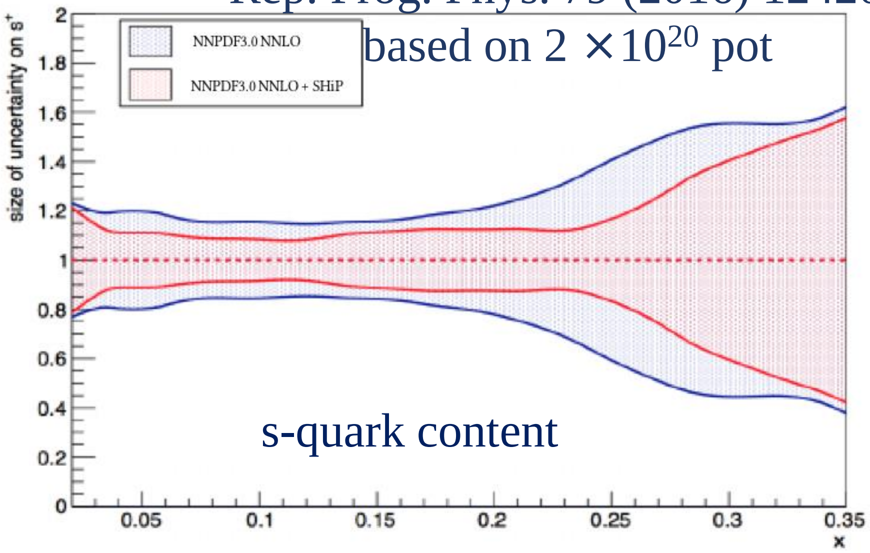
Physics Reports 399 (2004) 227–320

$$\left|\frac{V_{cd}}{V_{cs}}\right|^2 \simeq \frac{1}{20}$$



Rep. Prog. Phys. 79 (2016) 124201

based on 2 $\times 10^{20}$ pot



Charm production via anti-neutrinos dominated by s-bar quarks

Charm production via neutrinos shared ~50/50 between d (valence) and s (sea)

	<E> (GeV)	CC DIS with charm prod	Charm fractions (%)
N_{ν_μ}	57	3.5×10^5	4.4
N_{ν_e}	71	1.7×10^5	6.0
$N_{\bar{\nu}_\mu}$	50	0.7×10^5	3.8
$N_{\bar{\nu}_e}$	60	0.3×10^5	5.3
total		6.2×10^5	

V_{cd} Measurements by BESIII and CLEO

$D^+ \to \mu^+\nu$ and $\tau^+\nu$

$$|V_{cd}| = 0.2181 \pm 0.0049 \pm 0.0007$$

Earlier measurements by νs (CDHS, CCFR, CHARM II): subtraction of ratios of two-muon events in ν and anti-ν interactions, combined with B_μ

CHORUS: 2013 ν-induced charm events, limited by anti-ν being a contamination (32 events)

CHORUS

$$\mathcal{B}_\mu = 0.085 \pm 0.009 \pm 0.006$$

$$|V_{cd}| = 0.230 \pm 0.011$$

(PDG 2022 value from neutrinos)

SHiP can measure V_{cd} with <2% accuracy, comparable/better than other methods!

Reach ν physics program and most sensitive FIB searches at CERN

https://home.cern/news/news/physics/new-lhc-experiments-enter-uncharted-territory

New LHC experiments enter uncharted territory

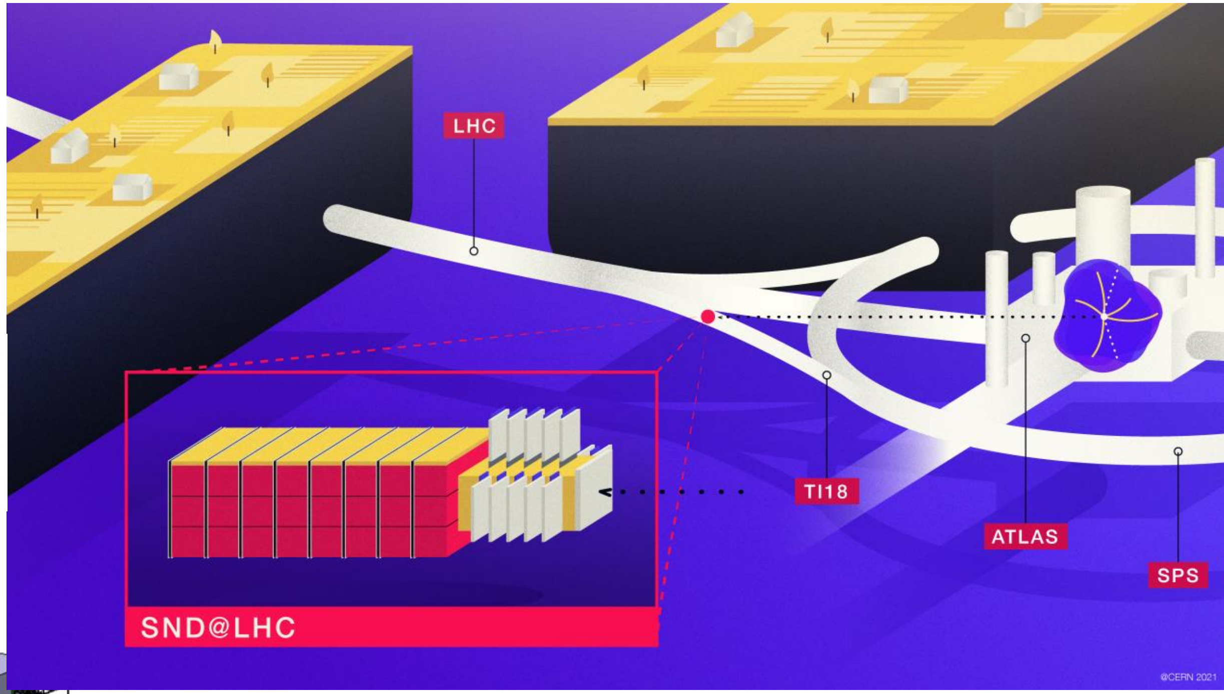
NEUTRINOS | NEWS

Collider neutrinos on the horizon

2 June 2021

https://cerncourier.com/a/collider-neutrinos-on-the-horizon/

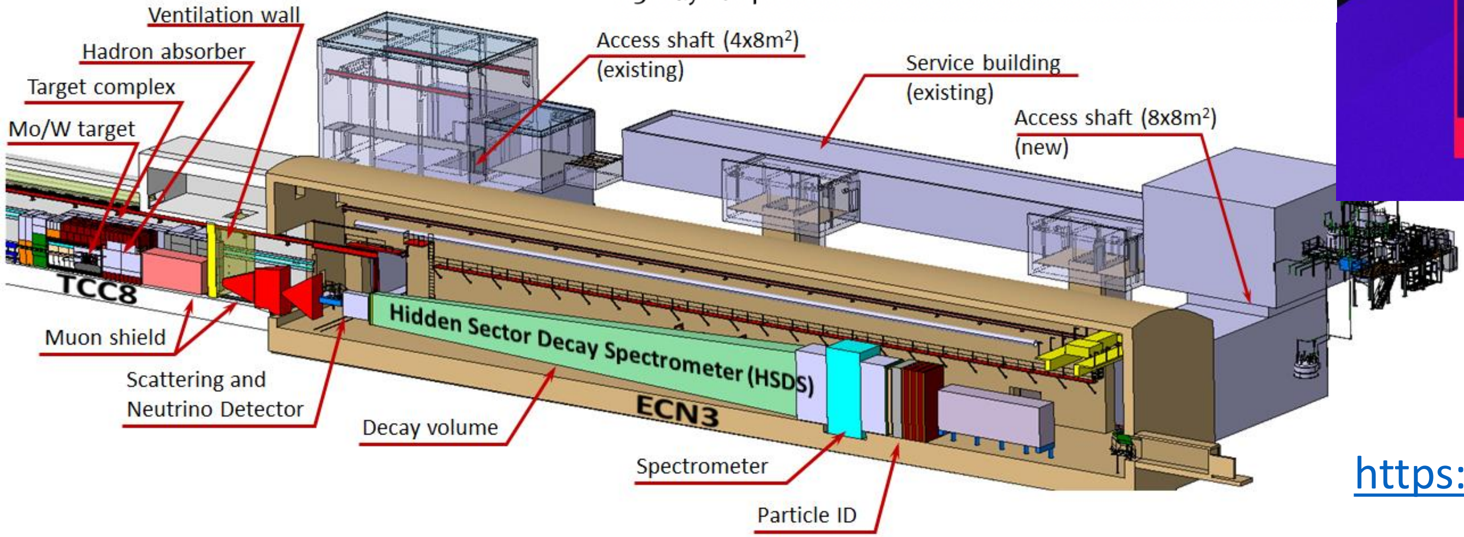
CERNCOURIER | Reporting on international high-energy physics



SEARCHES FOR NEW PHYSICS | NEWS

SHiP to chart hidden sector

3 May 2024



https://cerncourier.com/a/ship-to-chart-hidden-sector/