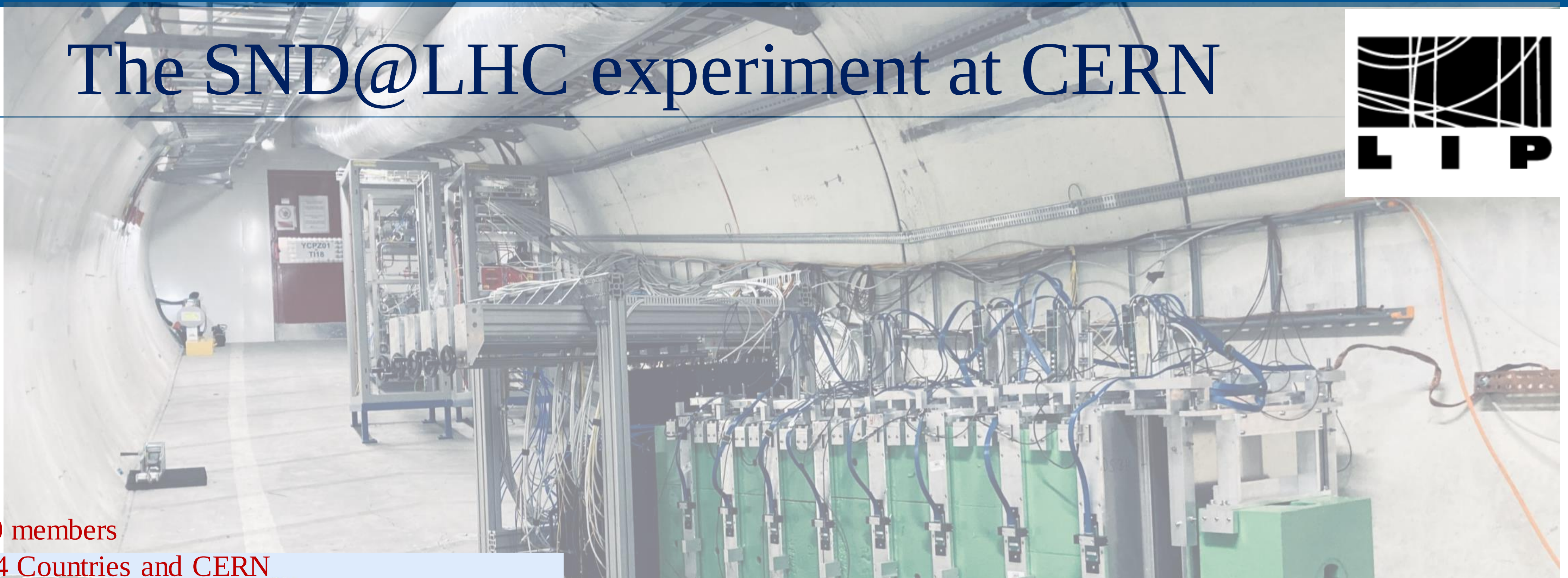
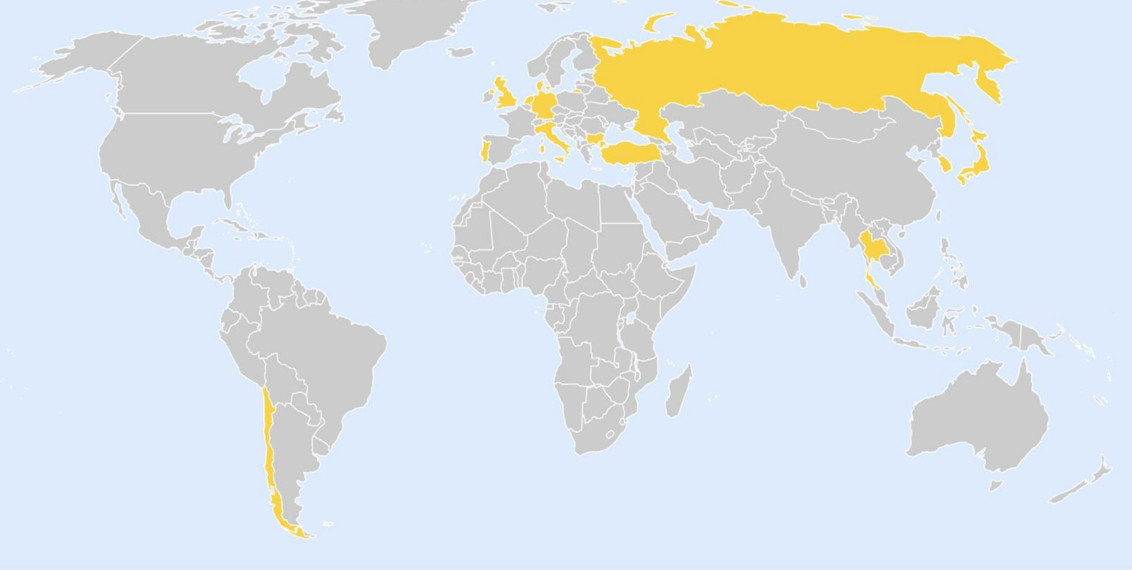
The SND@LHC experiment at CERN

Scattering and Neutrino Detector at the LHC



Collaboration: 150 members

24 Institutes in 14 Countries and CERN



Tiziano Camporesi

LIP, Lisbon

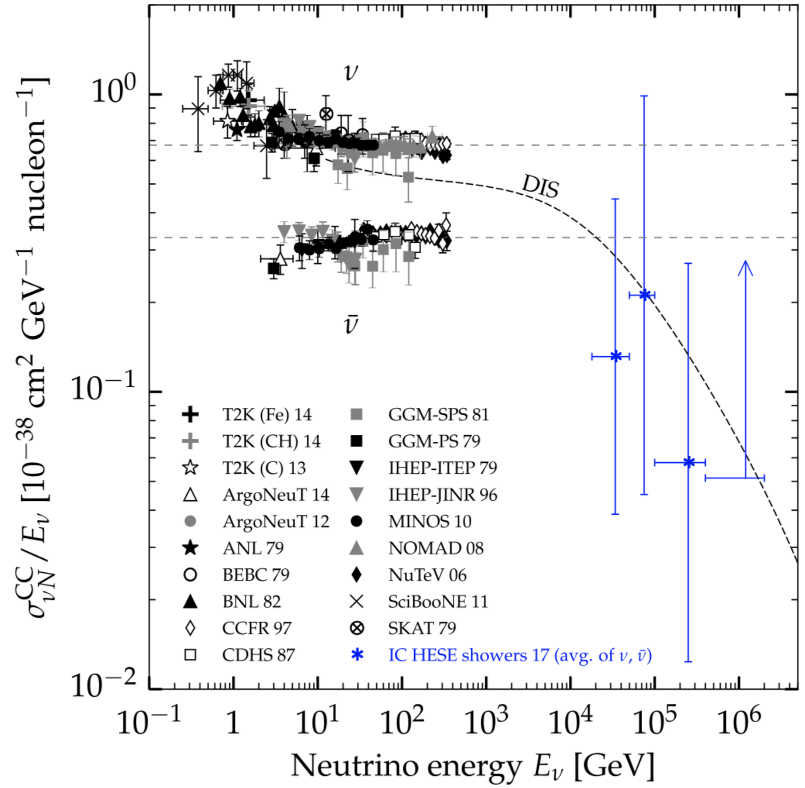
PSI Seminar, Villigen, 29th Feb 2024

Neutrino physics at the LHC: ideas and motivation

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, 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]

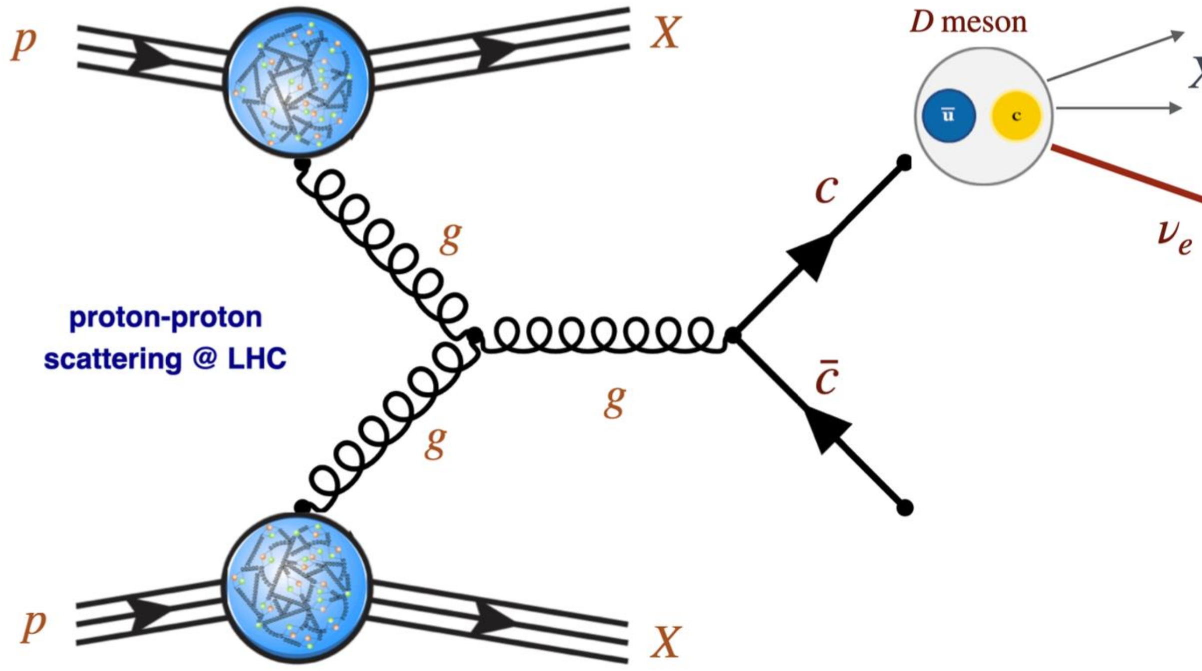
Eur. Phys. J. C (2020) 80:61
https://doi.org/10.1140/epjc/s10052-020-7631-5
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Regular Article - Experimental Physics

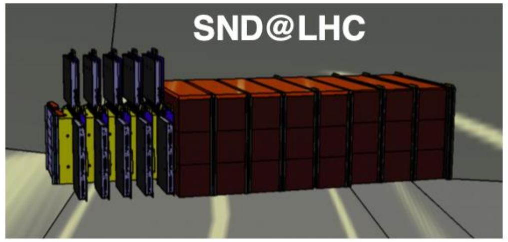
Detecting and studying high-energy collider neutrinos with FASER at the LHC

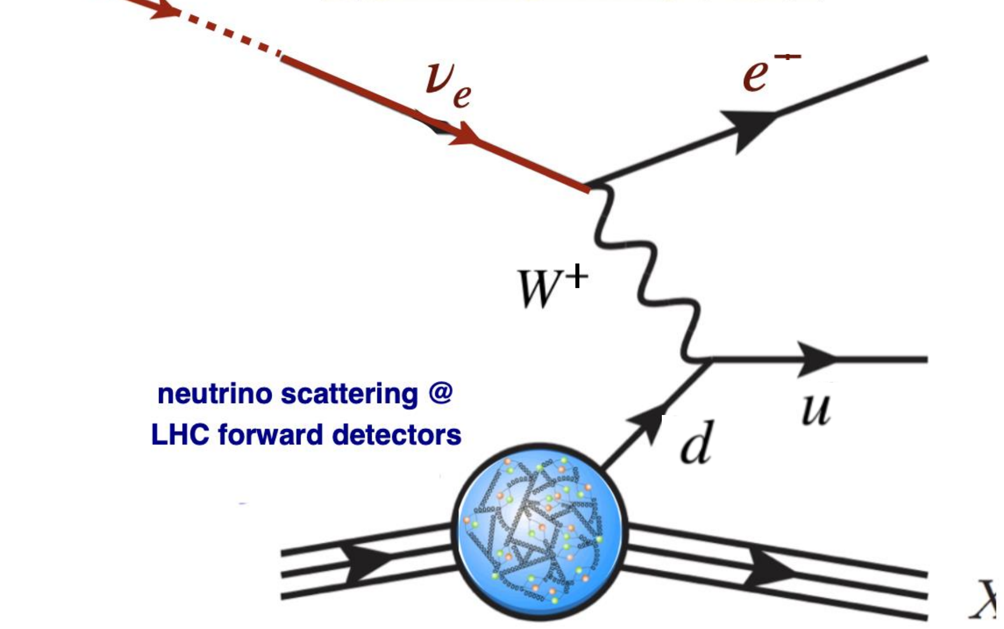
FASER Collaboration

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

High energy neutrino production at LHC





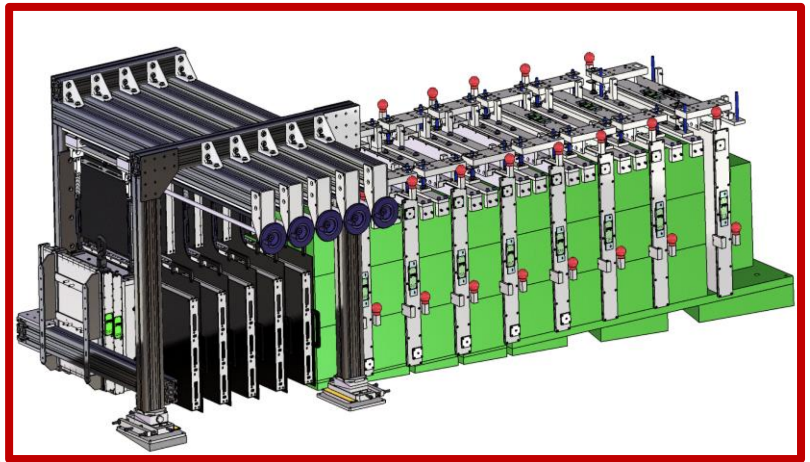


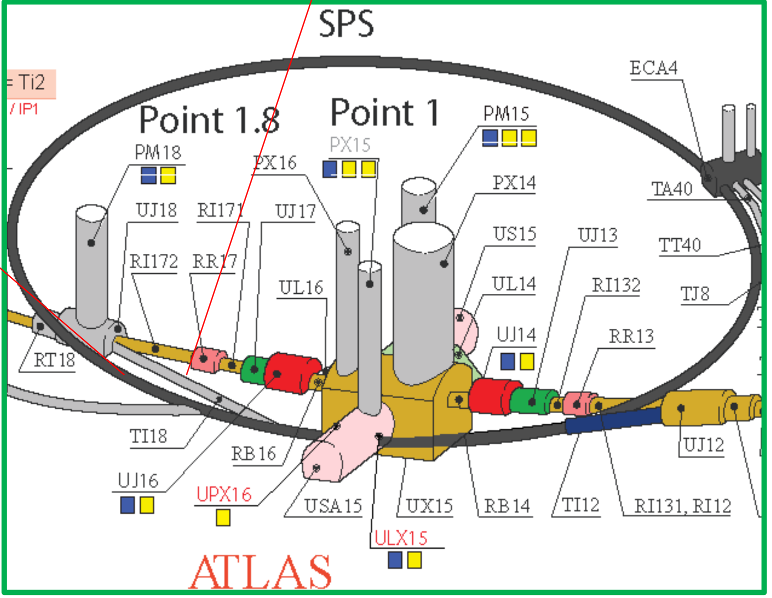
D meson produced with high boost : exploring gluon PDF in unchartered domain $X<10^{-5}$
Charm mesons (leptonic decays of D, D_s produce all types of neutrinos)

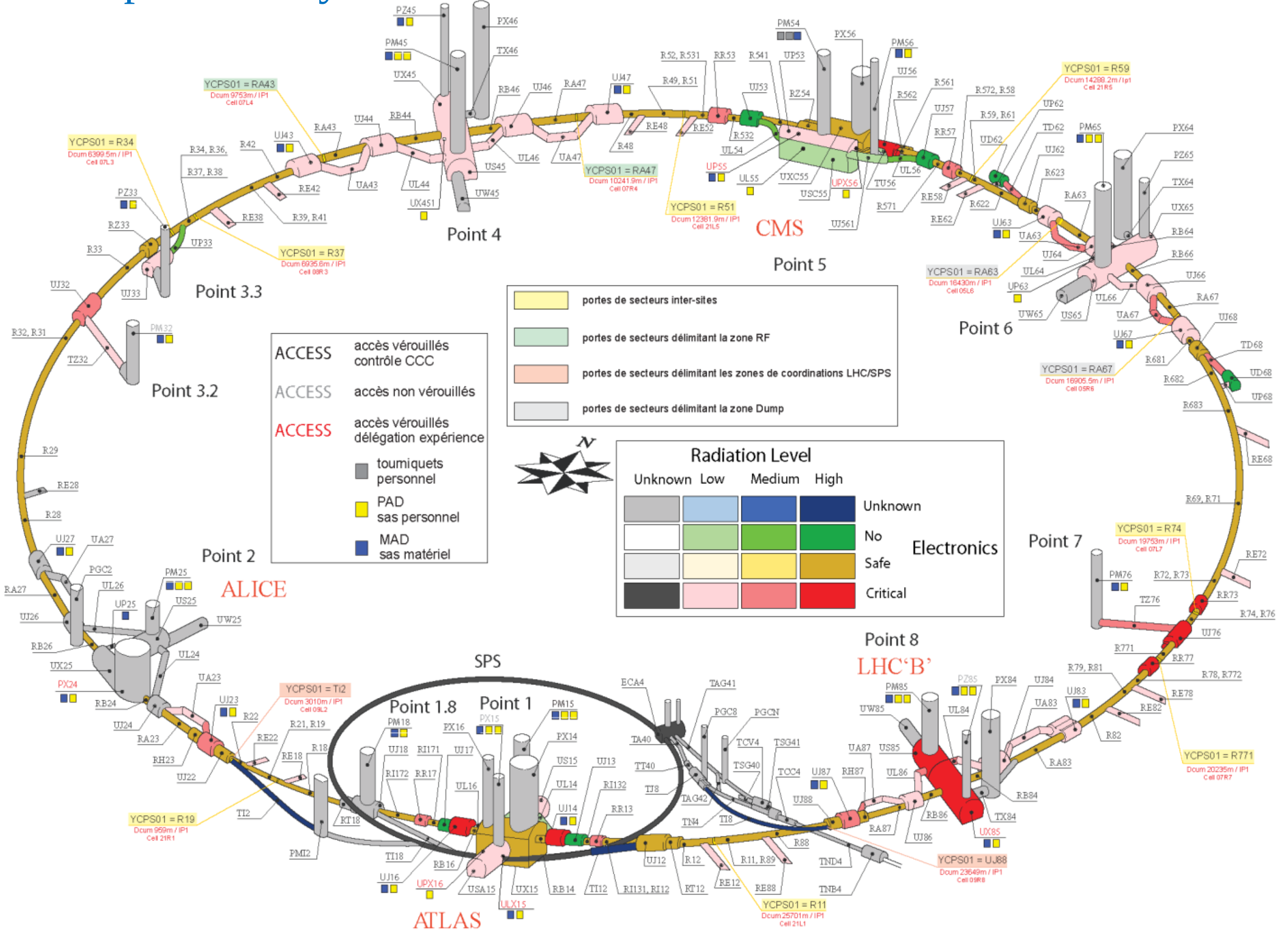
Location: TI18, transfer tunnel connecting SPS to LEP

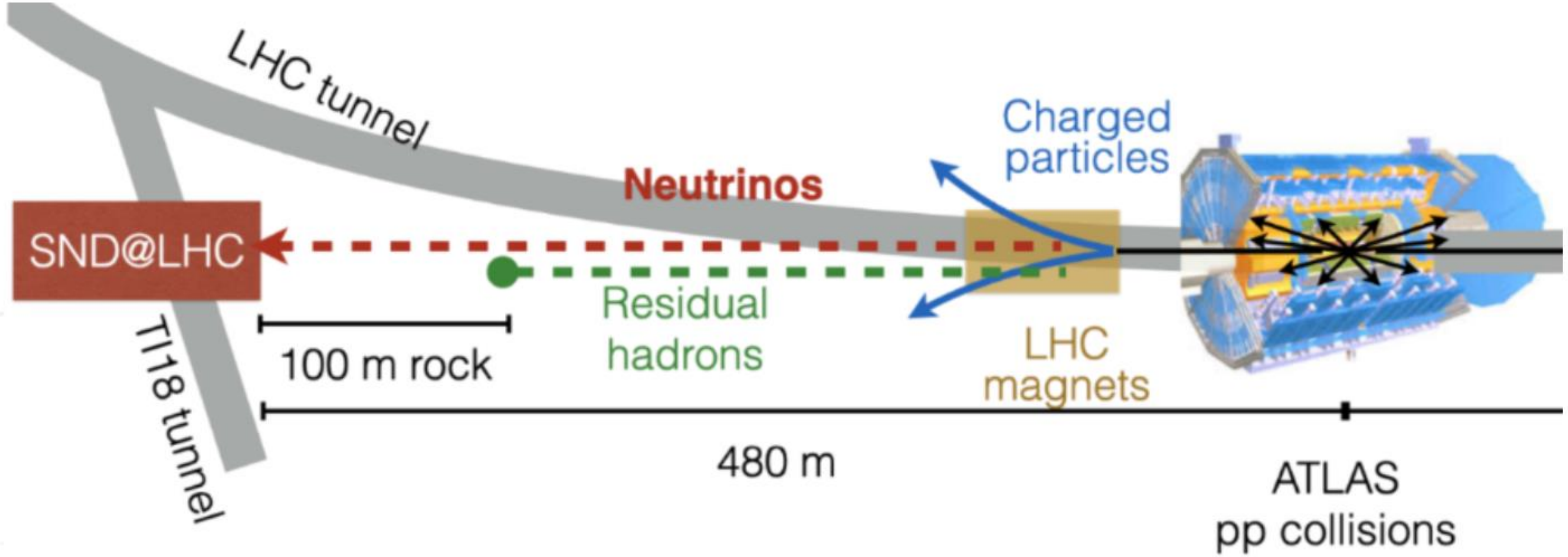
Scattering and Neutrino Detector at the LHC

- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock








LHC tunnel
Charged particles
Neutrinos
SND@LHC
Residual hadrons
LHC magnets
100 m rock
TI18 tunnel
480 m
ATLAS
pp collisions

Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

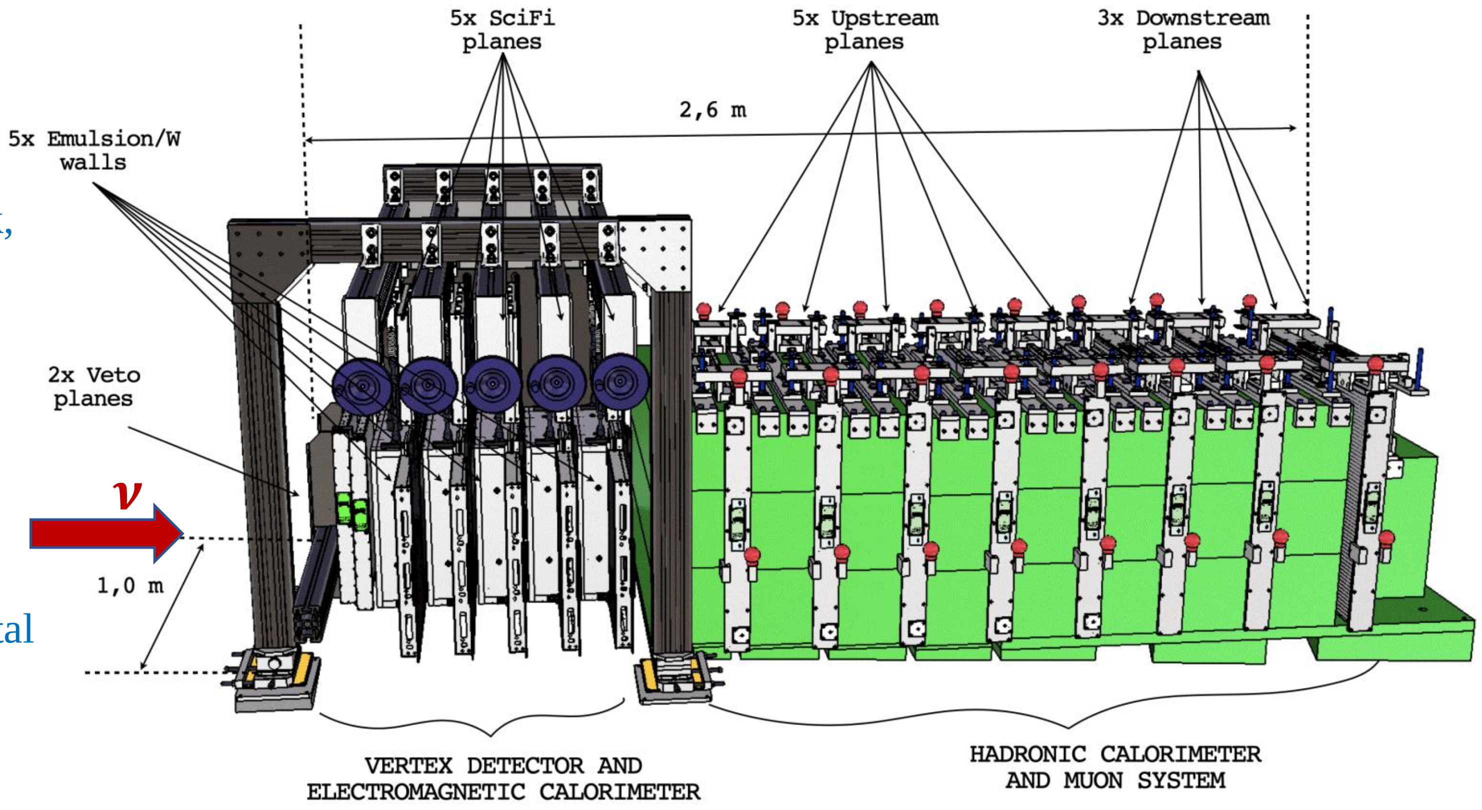
VETO PLANE:
tag penetrating muons

NEUTRINO TARGET & VERTEX DETECTOR:
- Emulsion cloud chambers (60 emulsion films, 300μm thick, interleaved by 1mm thick tungsten plates).

E.M. CAL
- 250μm Scintillating fibres for timing information and e.m. energy measurement: embedded in W target at regular intervals

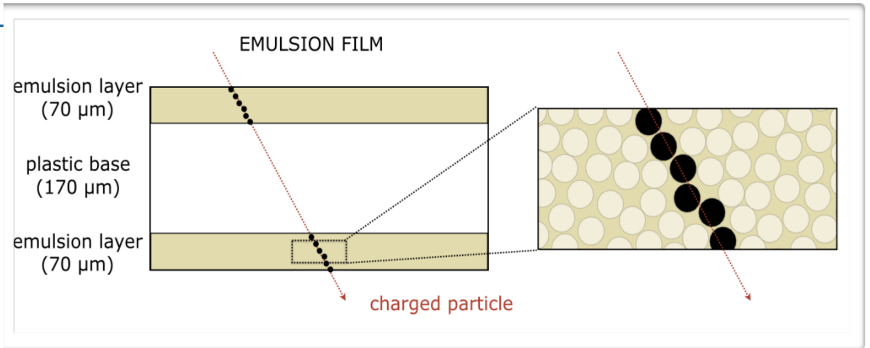
HADRONIC CALO:
iron walls interleaved with plastic scintillator planes for a total of about 11 λ

MUON IDENTIFICATION SYSTEM:
3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking



Neutrino target

Submicron resolution
Milliradians angular resolution



Angular acceptance: 7.2< η < 8.4

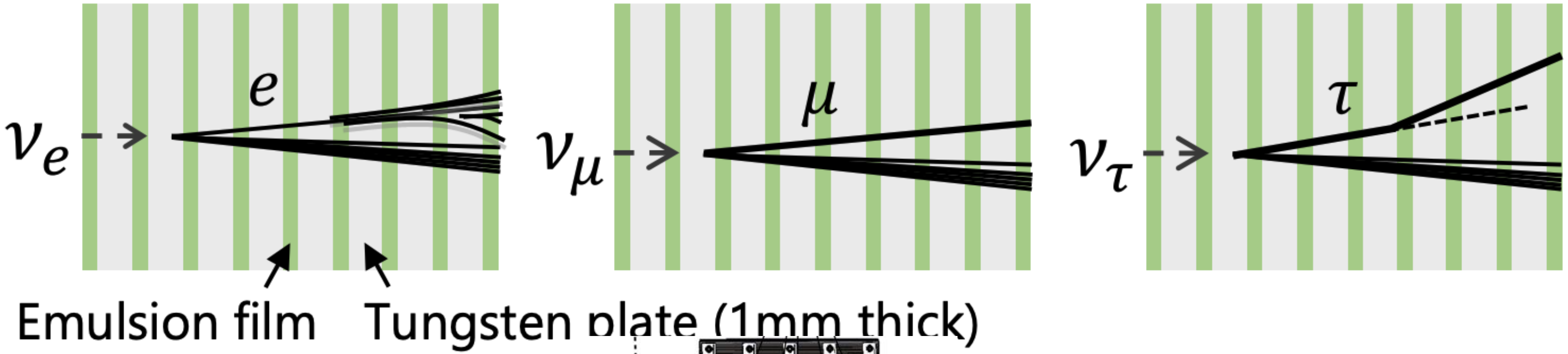
5 Walls comprising 60 Emulsions interleaved with 1 mm tungsten plates

Total emulsion surface 44m^2

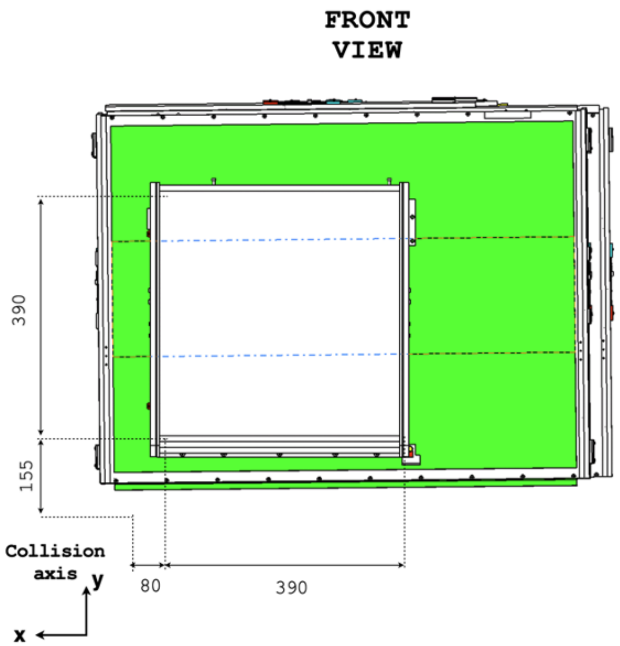
Total weight of target 830 Kg

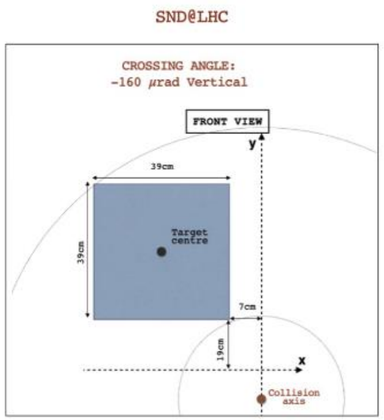
Surface: 390x390 mm^2

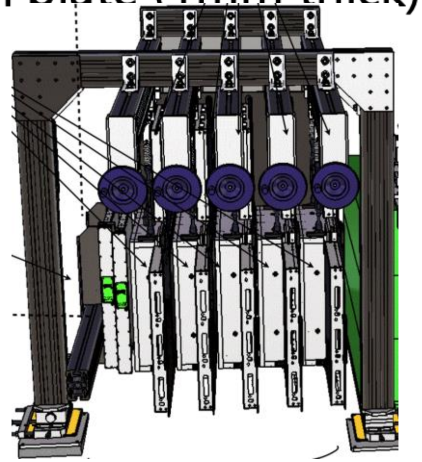
Detection of neutrino interactions in emulsion detector



Off axis location determined by TII8 layout







EVENT RECONSTRUCTION

FIRST PHASE: electronic detectors

Event reconstruction based on Veto, Target Tracker (TT) and Muon system/HCAL

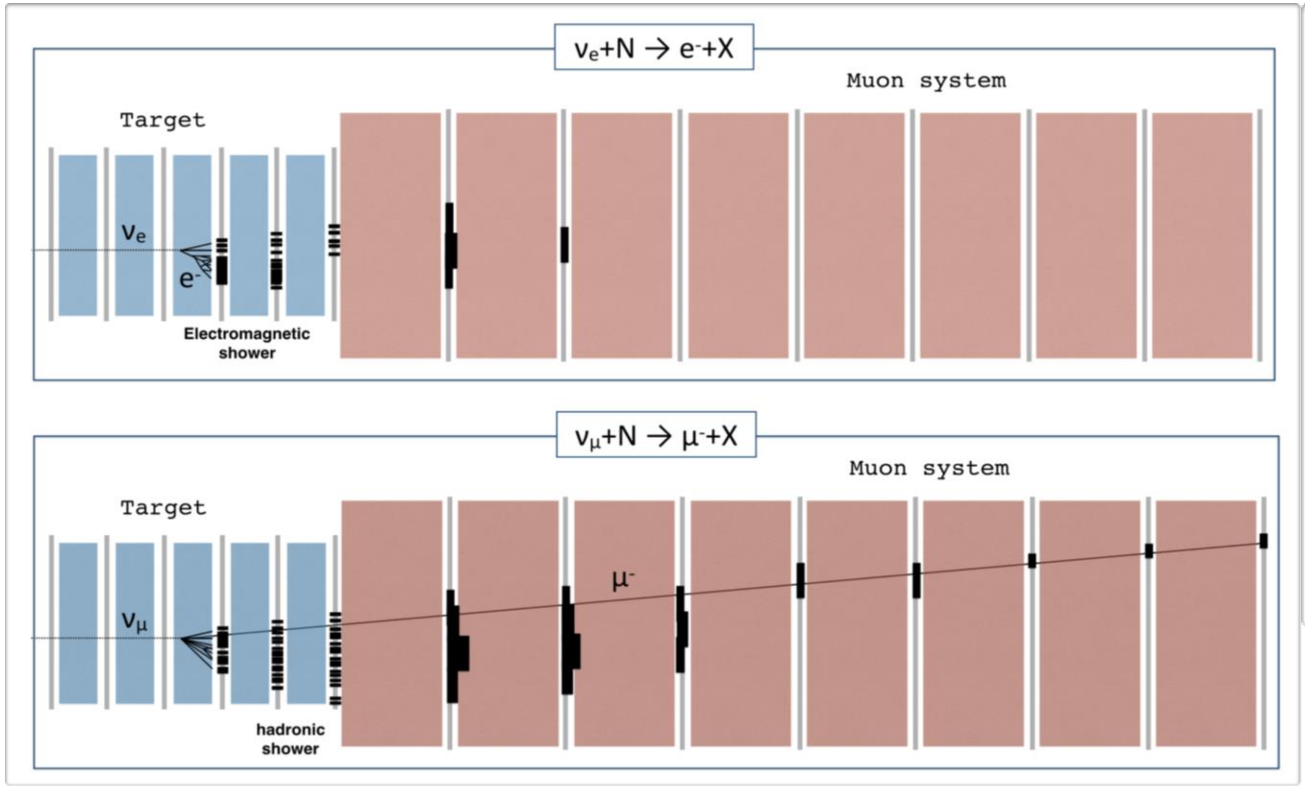
- ν candidates
- μ ID
- E.m. shower reconstruction (SciFi)
- ν energy (SciFi+Muon system/HCAL)

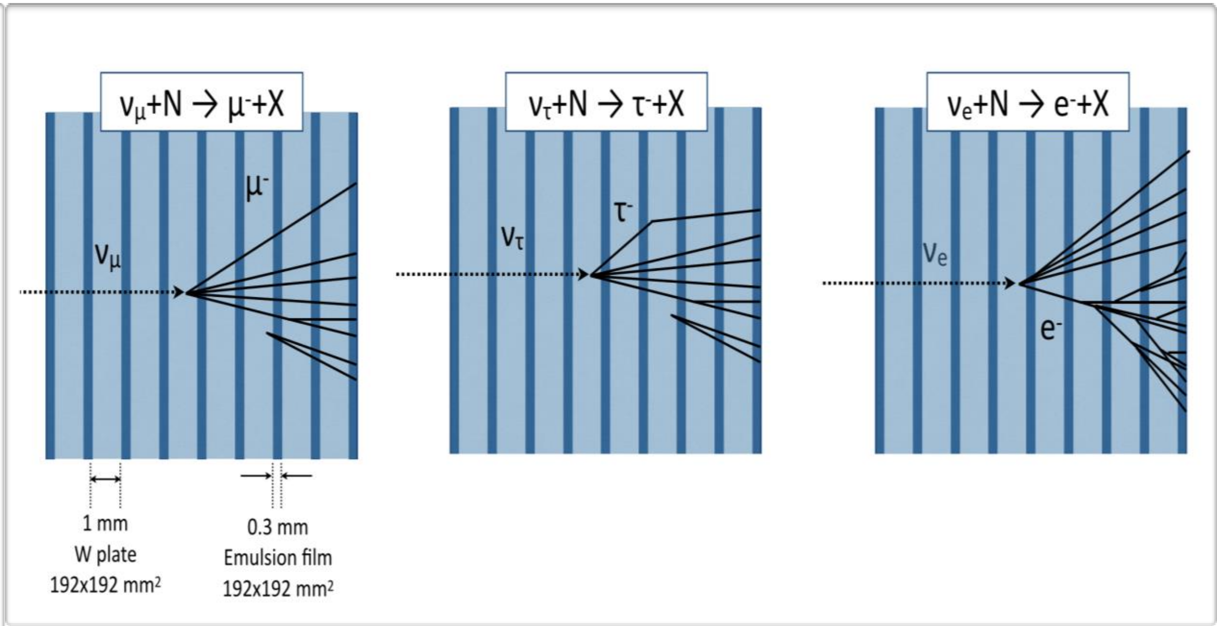
SECOND PHASE: nuclear emulsions

After subtracting the through going muon tracks

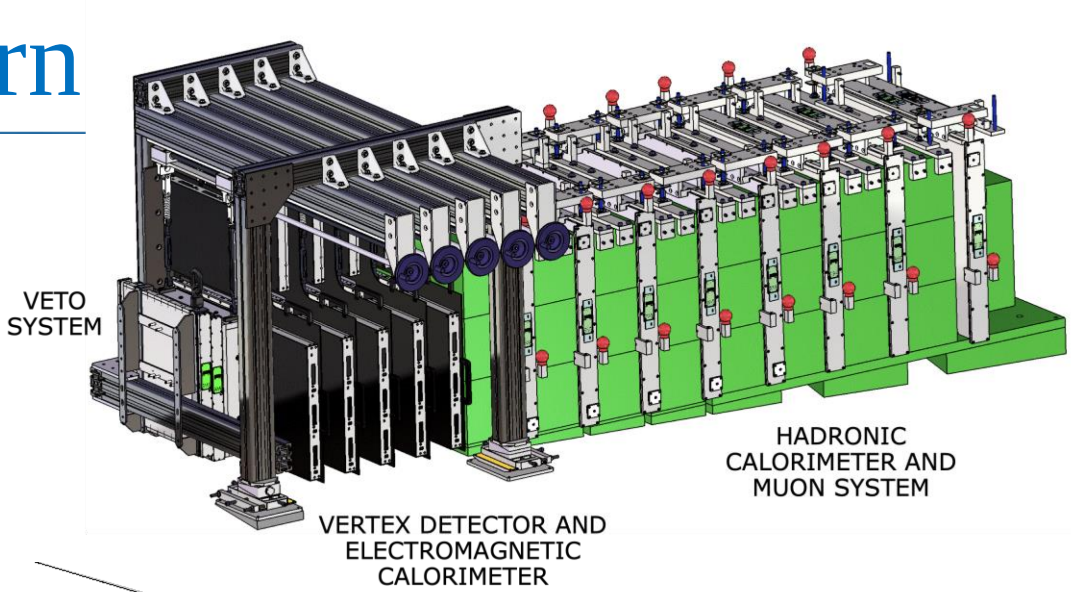
Event reconstruction in the emulsion target

- E.m. shower id with e/π^0 separation
- ν and 2ry vertex reconstruction
- Match emulsion and elec. Det. (time stamp)
- Complement TT for e.m. energy measurement

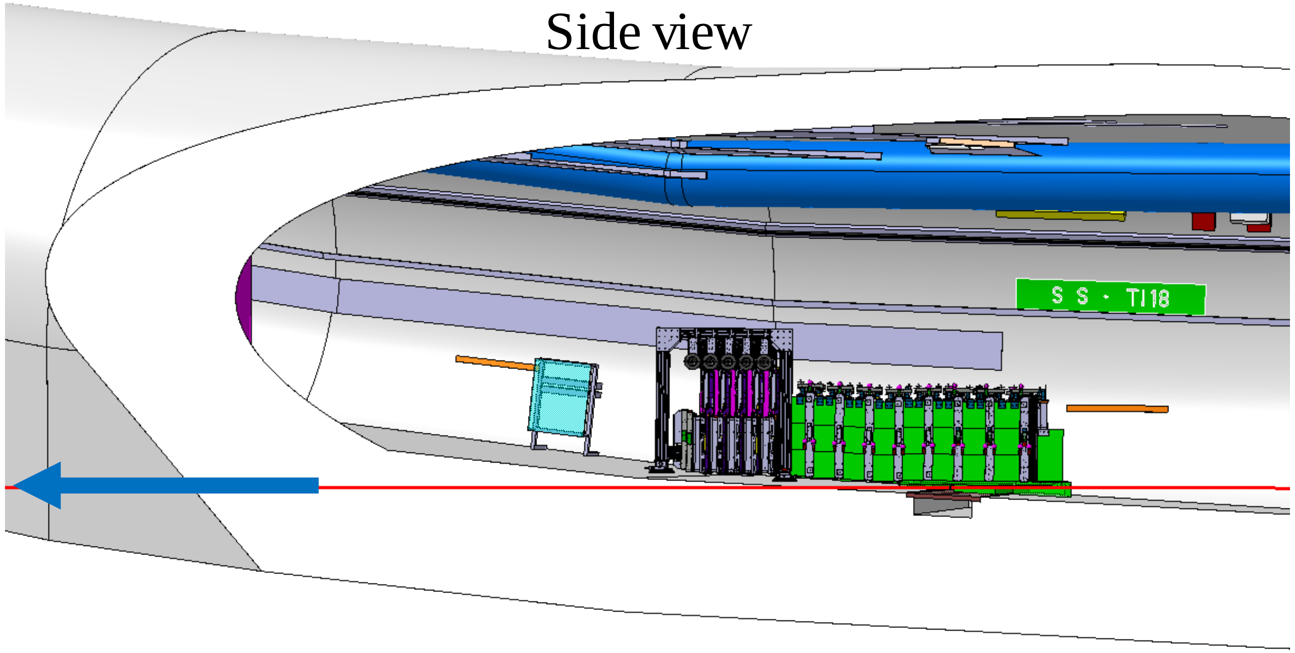




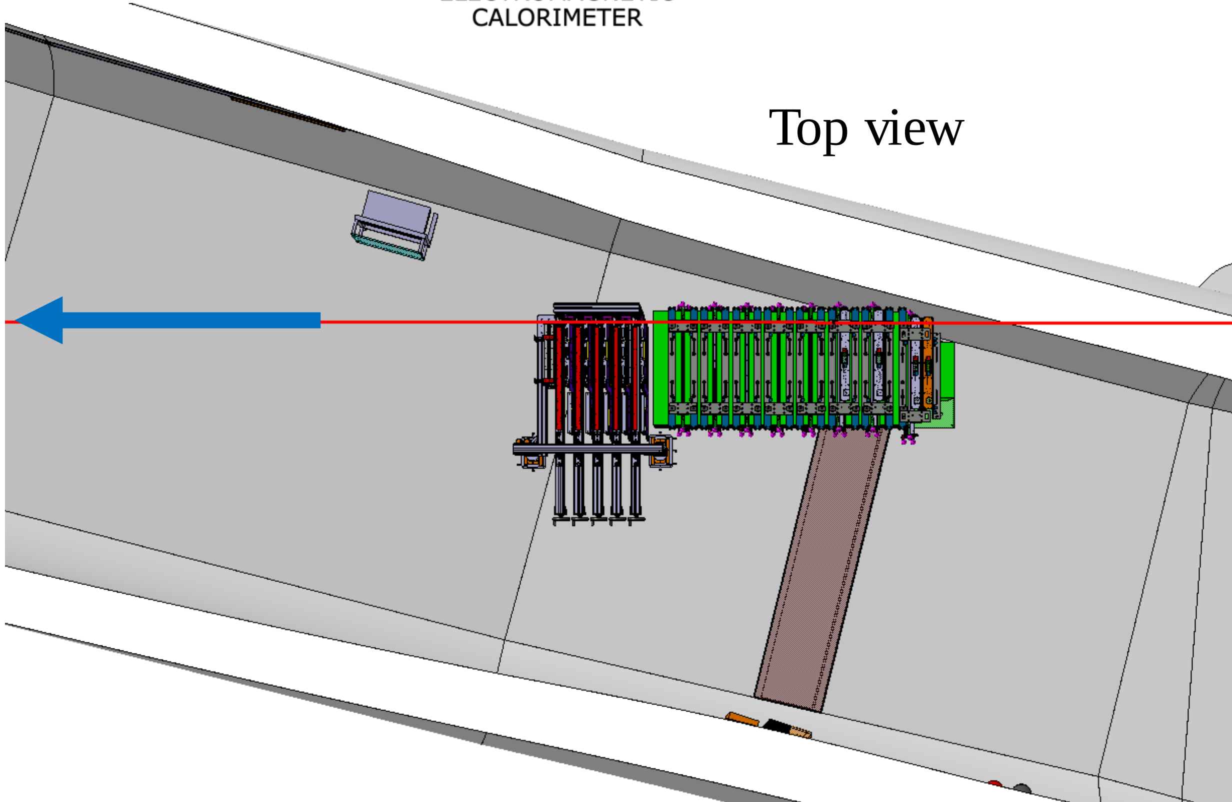
SND@LHC in the TI18 cavern



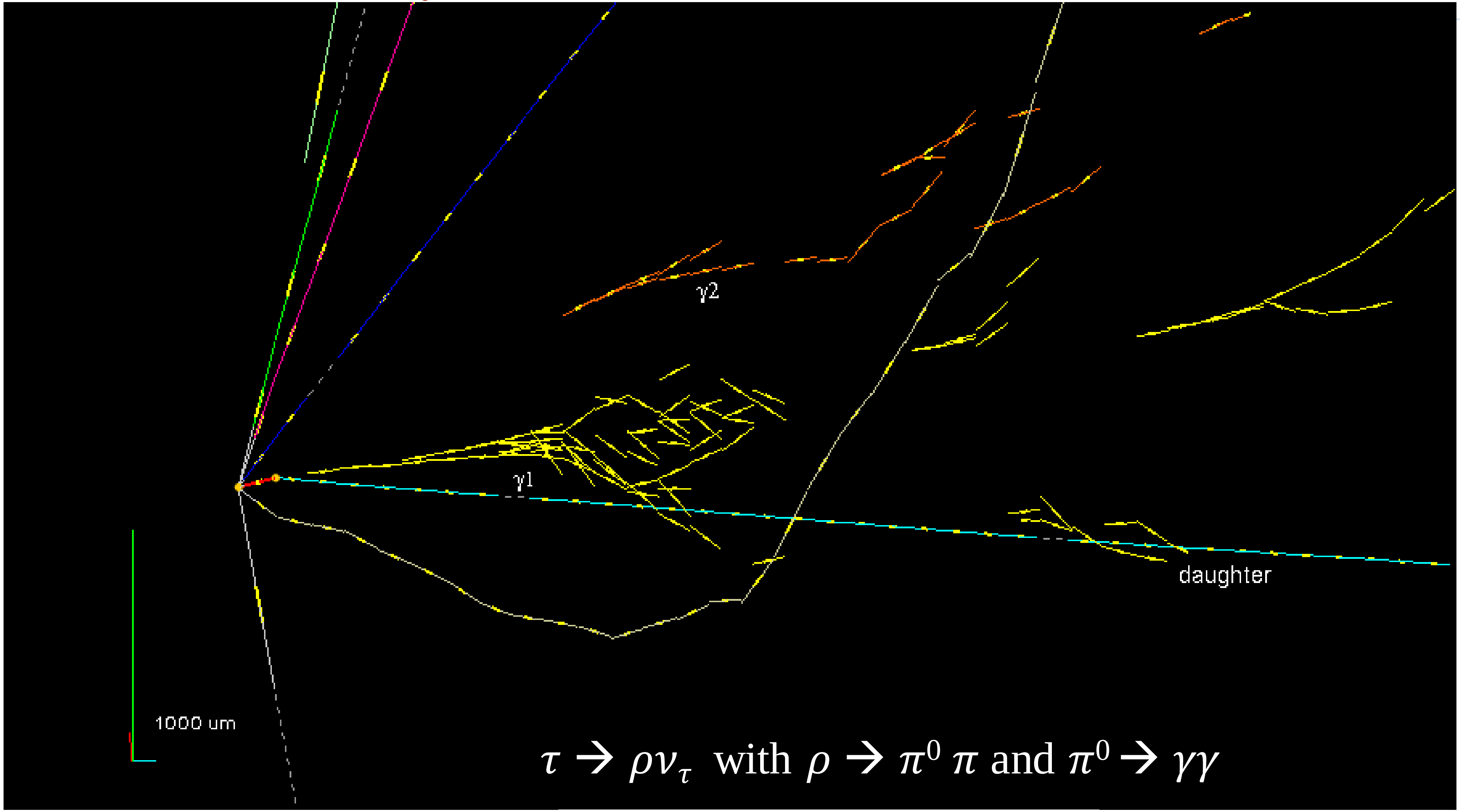
Side view



Top view



The First ν_τ Candidate in OPERA



$\tau \rightarrow \rho\nu_\tau$ with $\rho \rightarrow \pi^0\,\pi$ and $\pi^0 \rightarrow \gamma\gamma$

Physics Letters B691 (2010) 138

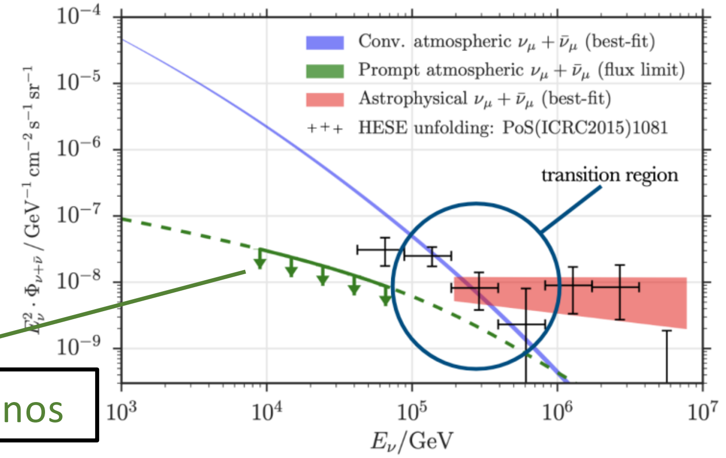
Physics goals

- Study neutrino interactions (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 → SND@LHC acting as a bridge between accelerator and astroparticle physics

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

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

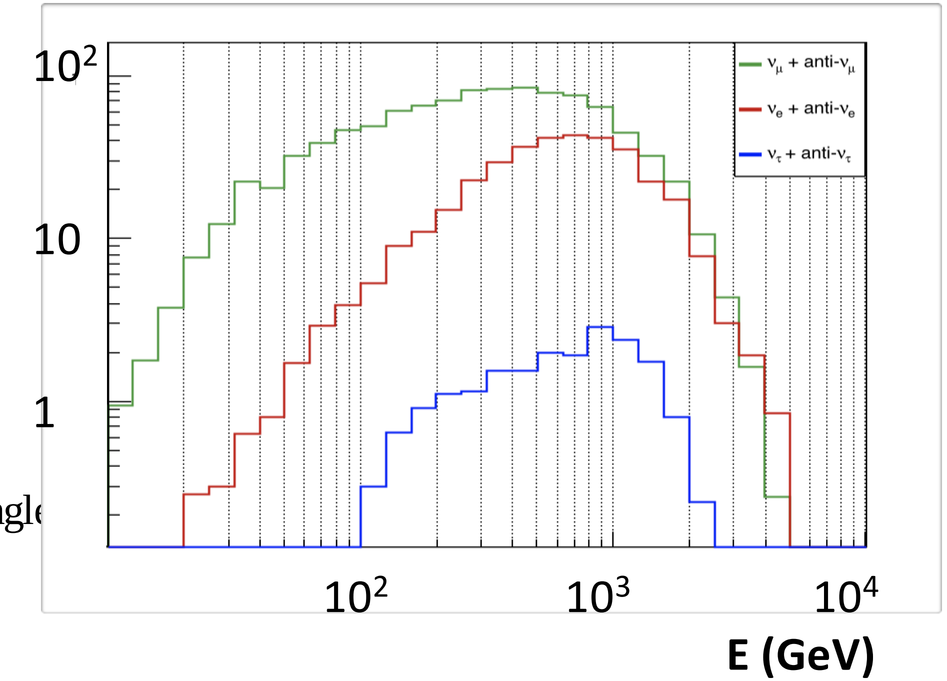
prompt atmospheric neutrinos



NEUTRINO DIS INTERACTIONS

$7.2 < \eta < 8.4,\ 0.4 < \vartheta < 1.5$ mrad

- **DPMJET3** embedded in FLUKA for neutrino production @ LHC
- Particle propagation towards the detector through the LHC **FLUKA** model
- **GENIE** used to simulate neutrino interactions in the detector target



Interacting Neutrinos

- Expectations in LHC RUN3 (290 fb^{-1}) (43/57 upward/downward crossing angle

	CC neutrino interactions		NC neutrino interactions	
Flavour	⟨E⟩ [GeV]	Yield	⟨E⟩ [GeV]	Yield
ν_μ	450	1028	480	310
$\bar{\nu}_\mu$	480	419	480	157
ν_e	760	292	720	88
$\bar{\nu}_e$	680	158	720	58
ν_τ	740	23	740	8
$\bar{\nu}_\tau$	740	11	740	5
TOT		1930		625

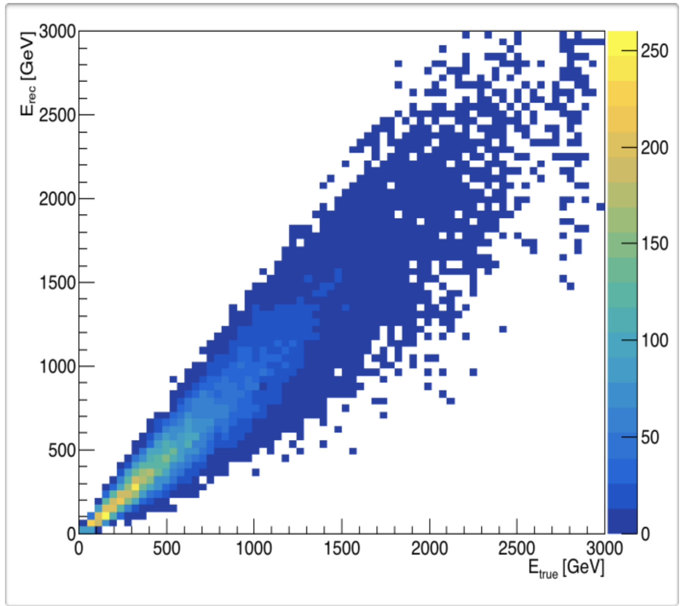
~ 30 ν_τ CC interactions expected

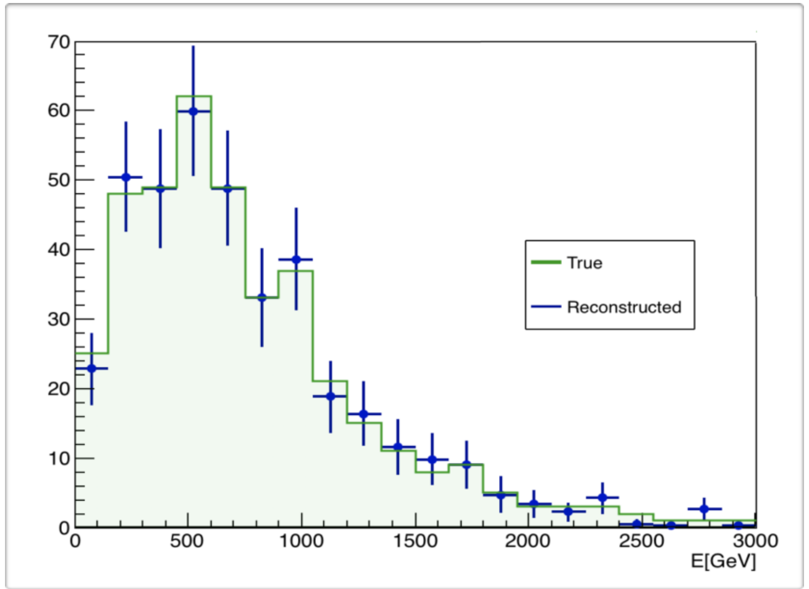
NEUTRINO PHYSICS PROGRAMME

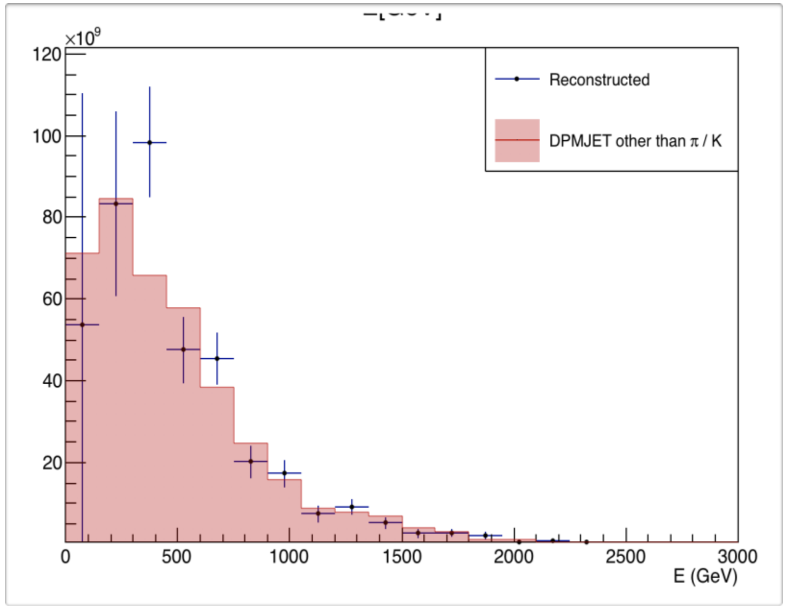
1. Measurement of the $pp \longrightarrow \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions
4. Measurement of the NC/CC ratio as a control sample

1. Measurement of pp⟶ν_eX cross-section and charm

- 90% ν_e & anti-ν_e from the decay of charmed hadrons
- ν_e as a probe of charm production in this η range after unfolding instrumental effects
- Unfolding the *measured* energy spectrum to retrieve the *true* energy, deconvolution of ν (SM) cross-section (**15%**)
- Subtract kaon component dominating at low energies (E<200 GeV), different event generators up to a factor 2
- Procedure introduces an additional systematic uncertainty of **~20%** on the overall yield

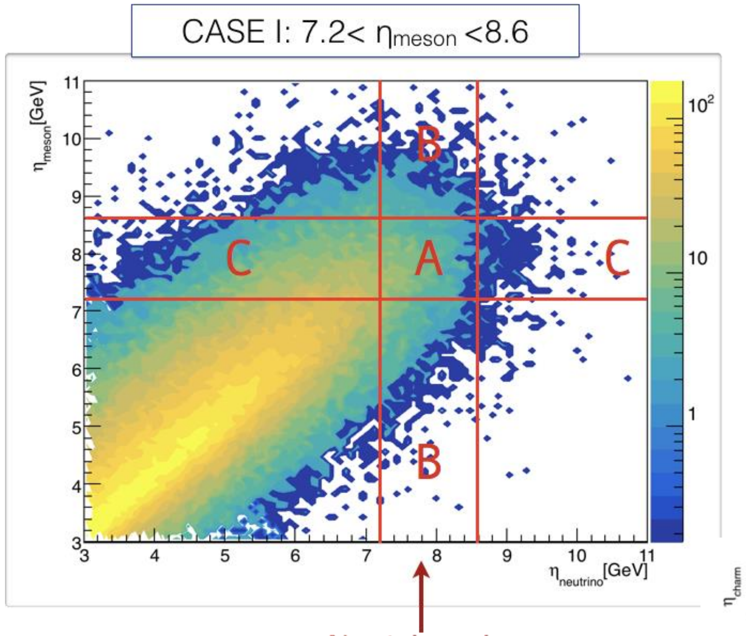






2. CHARMED HADRON PRODUCTION

- Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron
- Evaluation of the migration by defining regions in the pseudo-rapidity correlation plot



Neutrinos in SND@LHC acceptance

$$N(c\text{−mesons}) = N(\nu_e + \overline{\nu}_e)^{\text{charm}} \times \frac{f_{AB}}{f_{AC}} \times \frac{1}{Br(c \rightarrow \nu_e)}$$

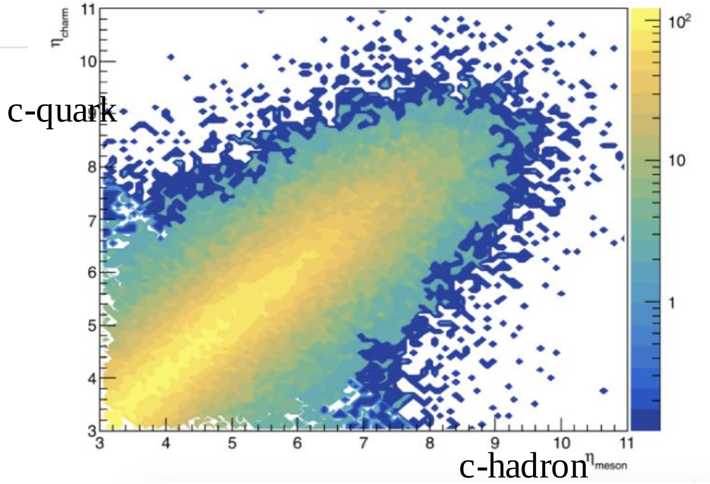
N_A/N_{A+B}

N_A/N_{A+C}

Branching ratio of charmed mesons to ν_e

- Fractions f_{AB} and f_{AC} evaluated using leading order computations+Pythia8 parameters for cc-bar production at 13 TeV
- Variation of parameters that describe charm production and hadronisation show that the ratio f_{AB}/f_{AC} is stable within **20-30%**

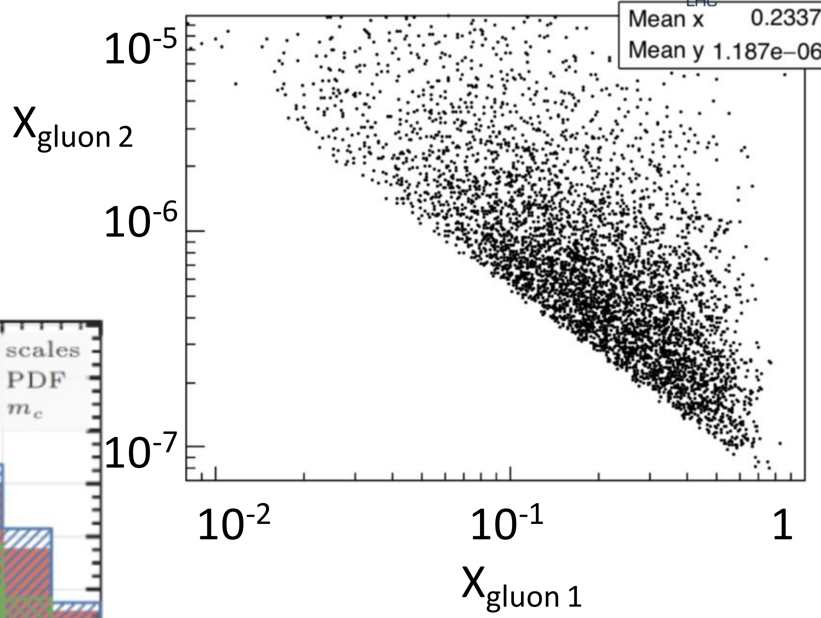
Statistical uncertainty ~5%
Systematic uncertainty ~35%

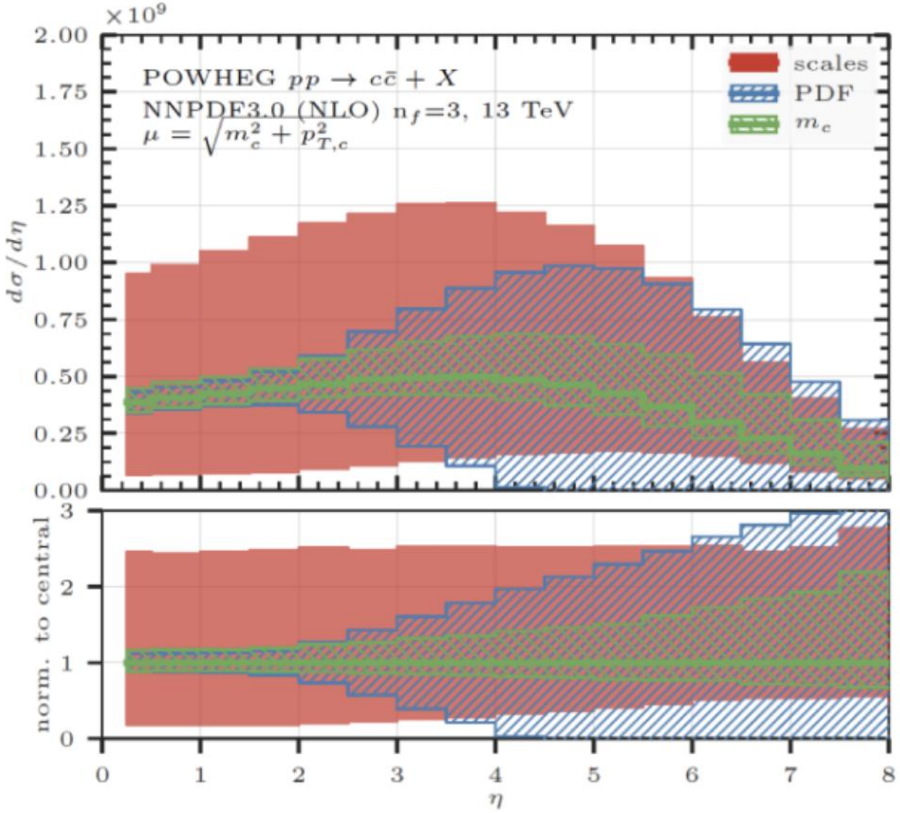


The measurement of charmed hadrons can be translated into a measurement of the corresponding open charm production in the same pseudo-rapidity range given the straight correlation between the hadron and its parent charm quark

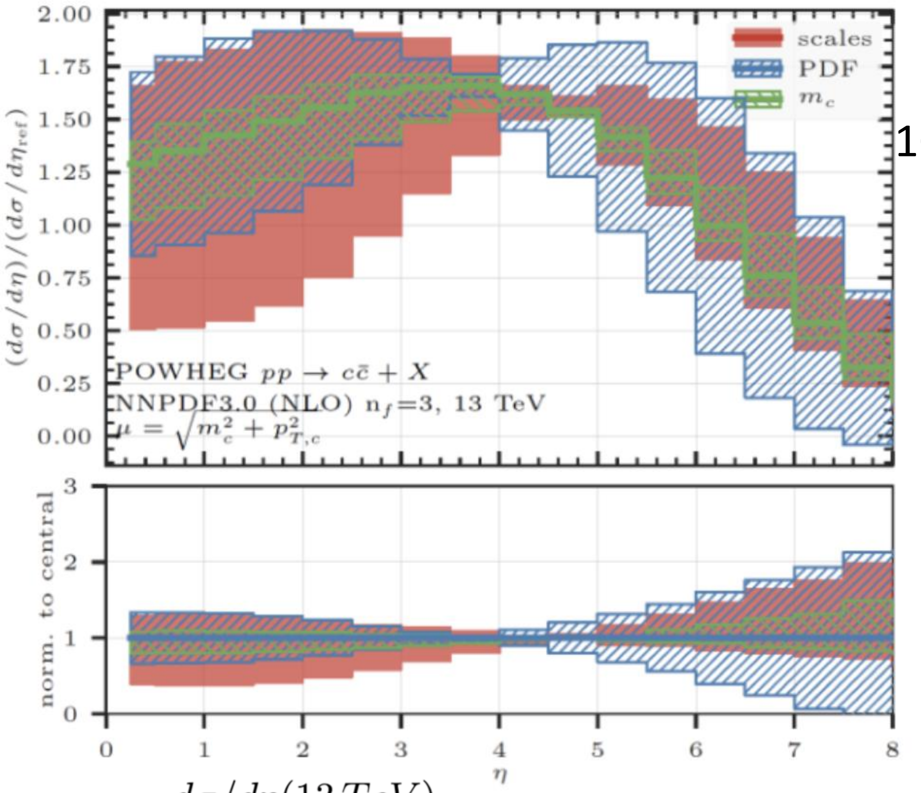
Extraction of the gluon PDF

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





dσ/dη at 13 TeV

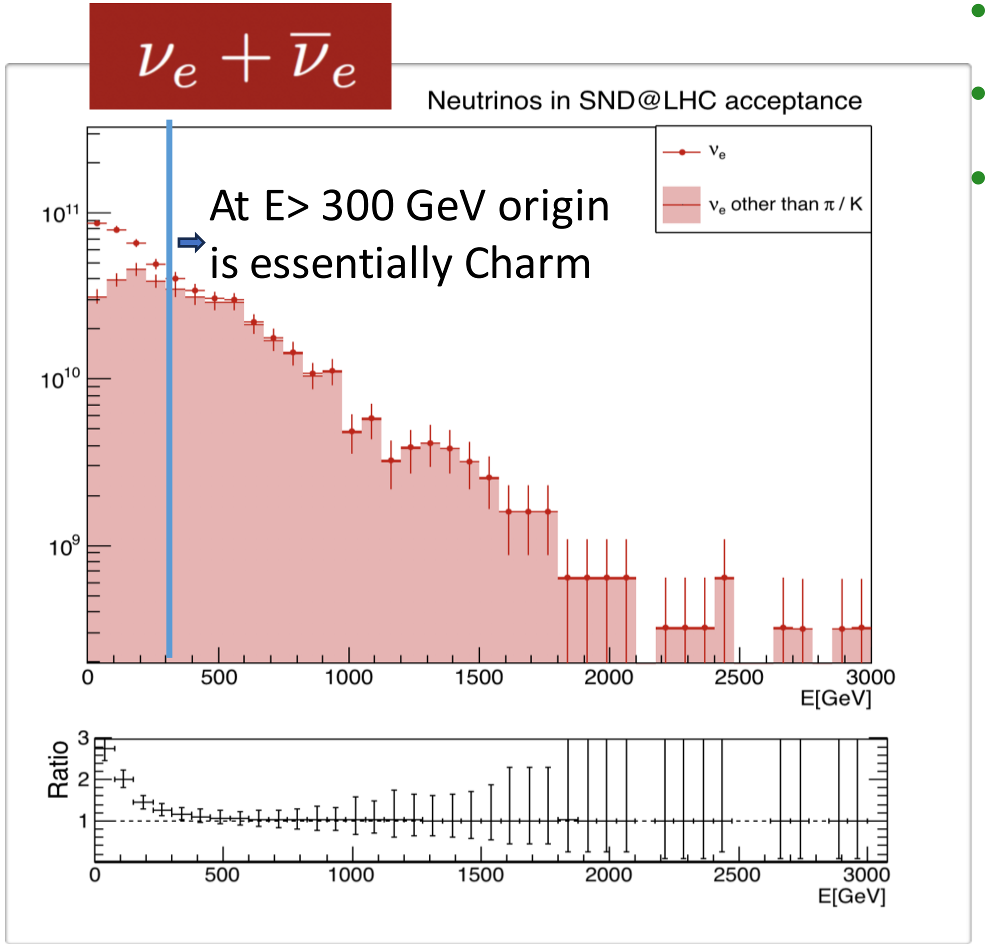


$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$$

η_{ref} = [4,4.5]

3. Lepton flavour universality test in ν interactions

- The identification of 3 ν flavours offers a unique possibility to test LFU in ν interactions



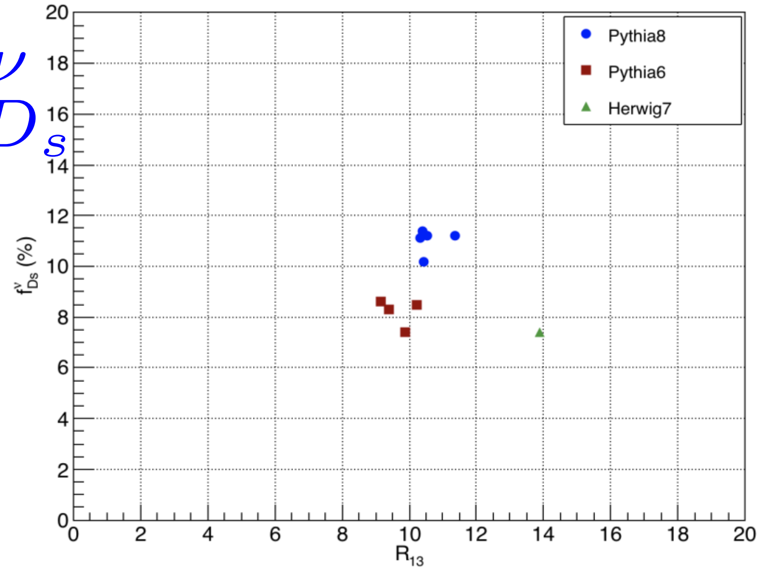
- ν_τ produced essentially only in D_s decays
- ν_e produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
- The ratio depends only on charm hadronisation fractions
- Sensitive to ν-nucleon cross-section ratio

$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

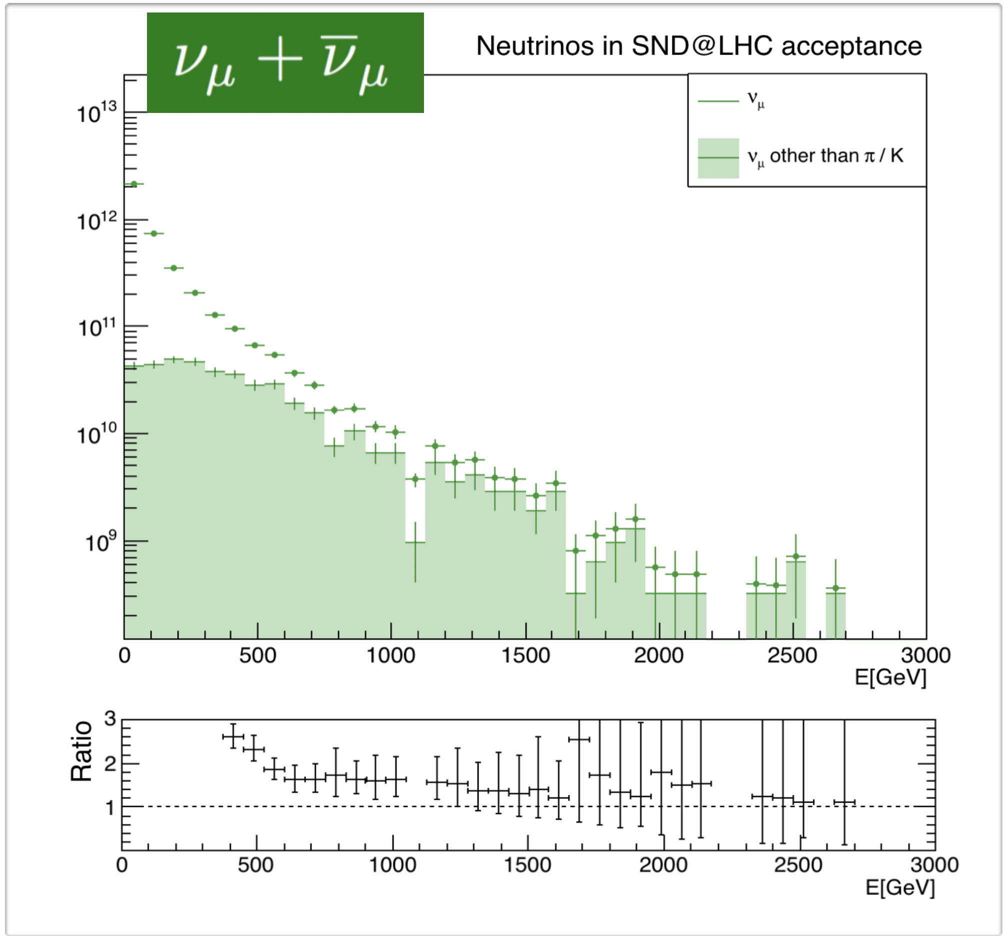
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **20-30%** error due to ν_τ statistics

$f^{\nu}_{D_s}$



3. Lepton flavour universality test in ν interactions

- ν_μ spectrum at low energies dominated by neutrinos produced in π/K decays
- For E>600 GeV the contamination of neutrinos from π/K keeps constant (~35%) with the energy



$$N(\nu_\mu + \bar{\nu}_\mu)[E > 600\,GeV] = 294 \quad \text{in } 150\ \text{fb}^{-1}$$

$$N(\nu_e + \bar{\nu}_e)[E > 600\,GeV] = 191 \quad \text{in } 150\ \text{fb}^{-1}$$

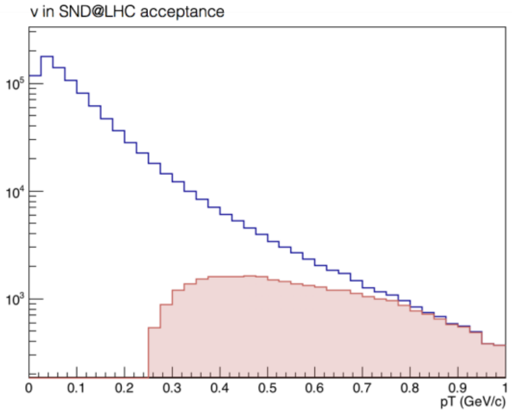
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

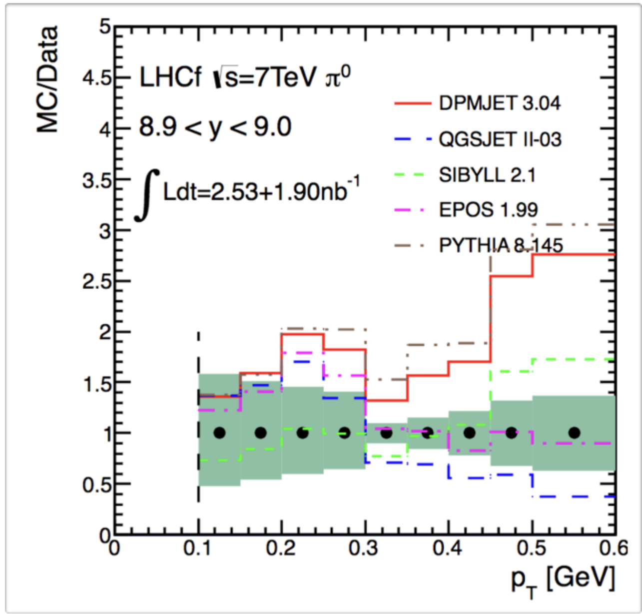
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

$$R_{12} = \frac{N_{\nu_e+\bar{\nu}_e}}{N_{\nu_\mu+\bar{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

contamination from π/k

- Statistical error: **10%**
- Systematic uncertainty from the knowledge of π/k contamination: **10%**





Phys. Rev. D 86, 092001 (2012)

4. The NC/CC RATIO as a consistency check

- Lepton identification allows to distinguish between CC and NC interactions
- If differential ν and anti-ν fluxes are equal, the NC/CC ratio can be written as

$$P = \frac{\sum_i \sigma_{NC}^{\nu_i} + \sigma_{NC}^{\bar{\nu}_i}}{\sum_i \sigma_{CC}^{\nu_i} + \sigma_{CC}^{\bar{\nu}_i}}$$

- For DIS, P can be written as

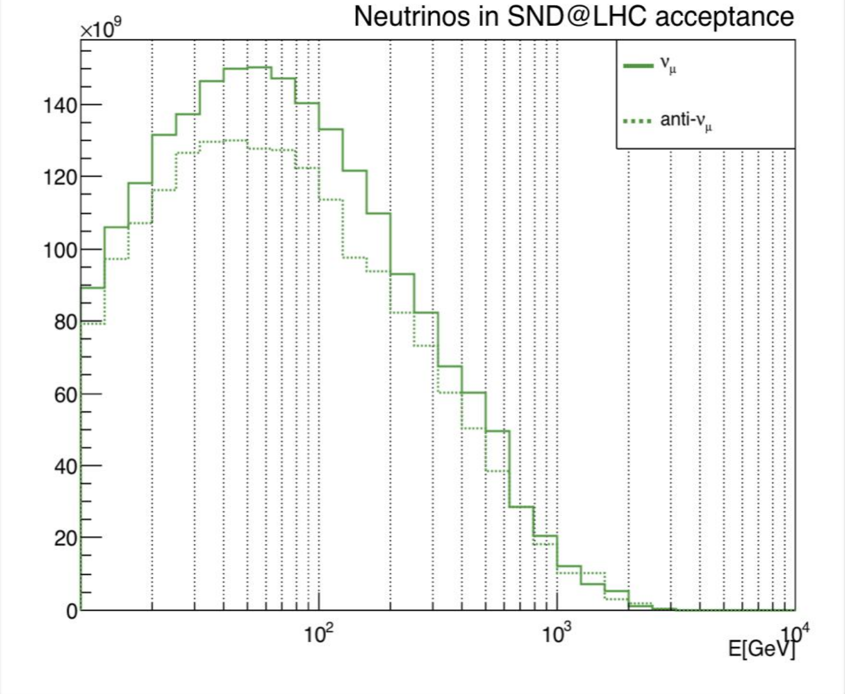
$$P = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda(1 - 2\sin^2\theta_W)\sin^2\theta_W\right\}$$

- where λ originates from the non-isoscalarity of the target, a correction factor of ~1%

- For a Tungsten target λ=0.04

- **Statistical** uncertainty given by the number of observed CC and NC interactions: **5%**
- **Systematic** uncertainty:
- asymmetry between ν and anti-ν spectra mainly in the ν_μ spectrum at low energies. Contribution to the error **<2%**
- CC to NC migration and neutron background subtraction: **10%**

ν_μ vs $\overline{\nu}_\mu$



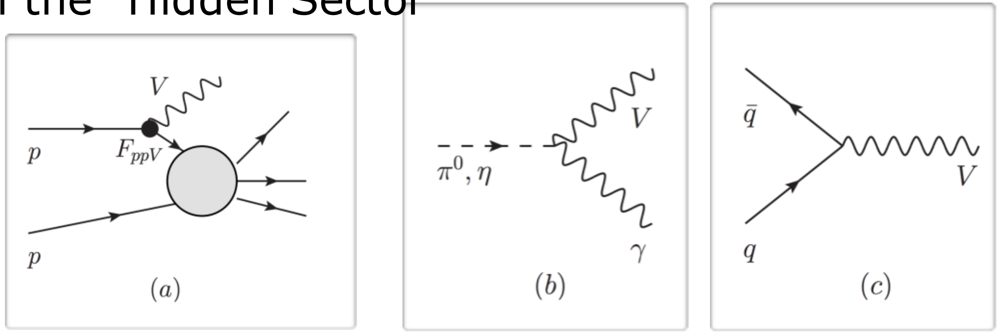
Important internal consistency test

FEEBLY INTERACTING PARTICLES

- SND@LHC can explore a large variety of BSM scenarios within the "Hidden Sector"

As an example, we report here

$$\mathcal{L}_{\text{leptophob}} = -g_B V^{\mu} J^{B}_{\mu} + g_B V^{\mu}(\partial_{\mu}\chi^{\dagger}\chi + \chi^{\dagger}\partial_{\mu}\chi),$$

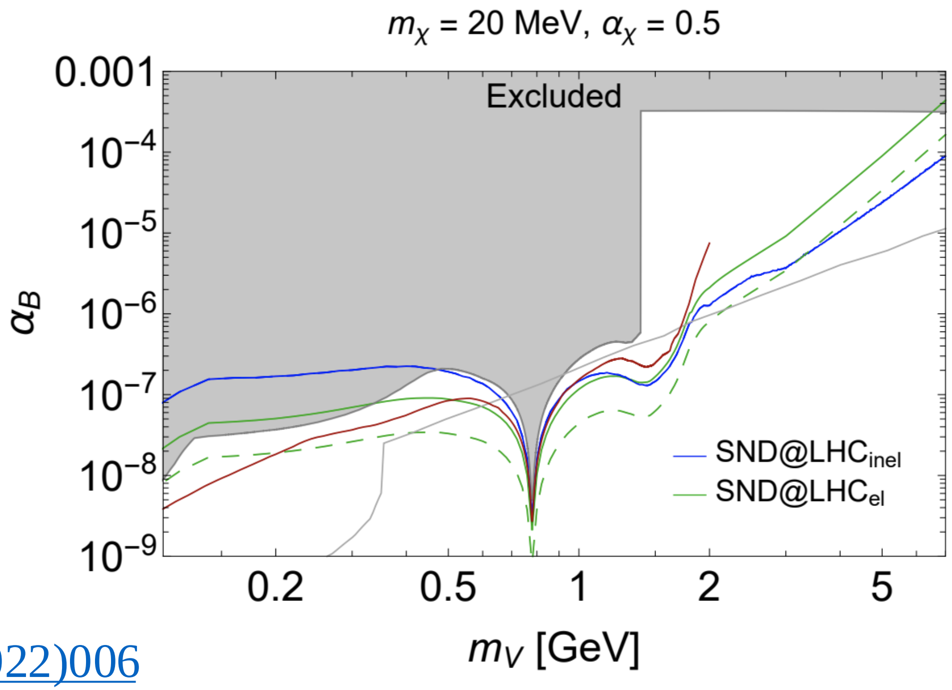


Proton bremsstrahlung | Meson decay | Drell-Yan process

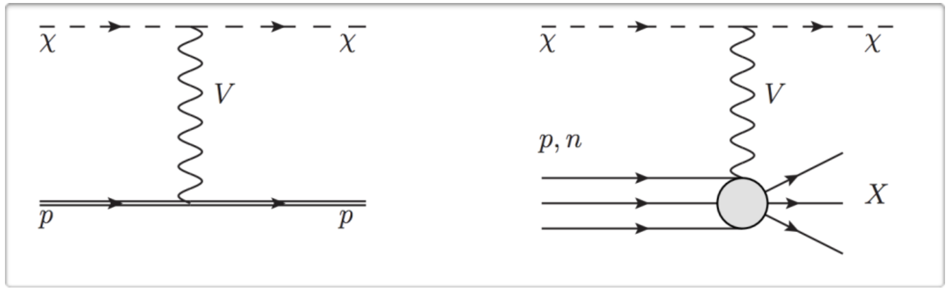
Production: we consider a scalar χ particle coupled to the Standard Model via a leptophobic portal

Current limits: CDF monojets, J/Ψ BES, E949
K rare decays, π^0 decays Brookhaven

Observed as excess NC like events

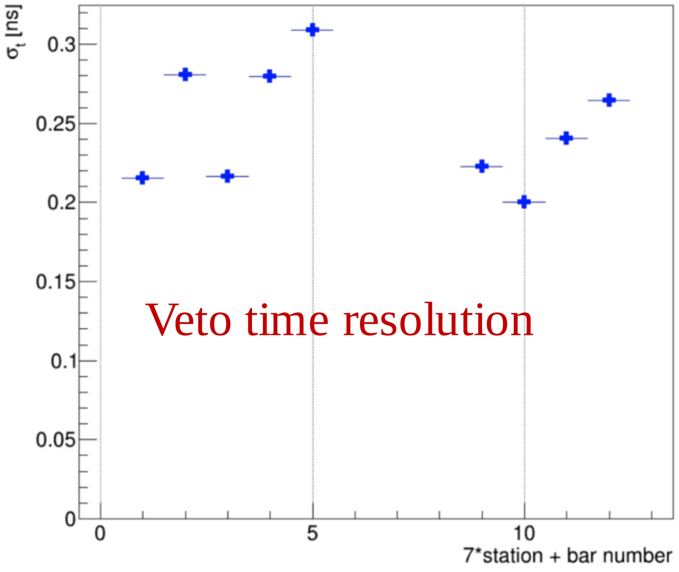


Detection: χ elastic/inelastic scattering off target nucleons



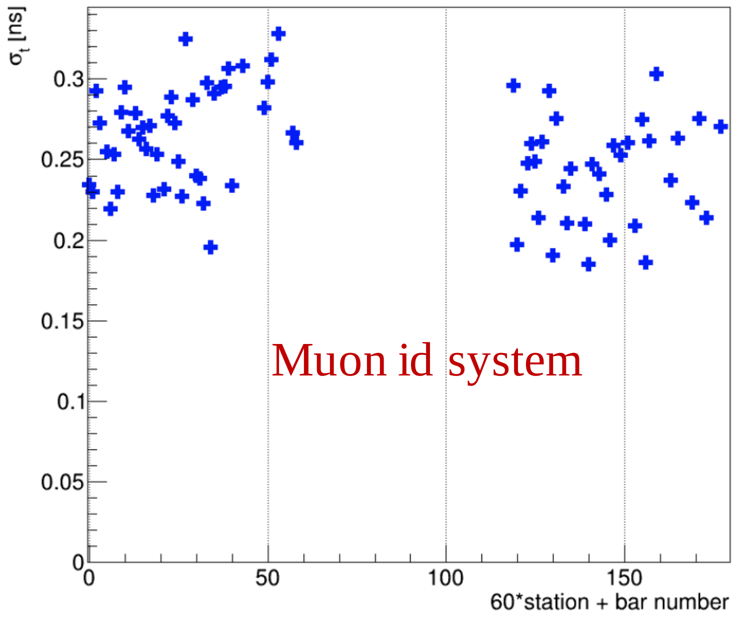
https://link.springer.com/article/10.1007/JHEP03(2022)006

Some detector performance

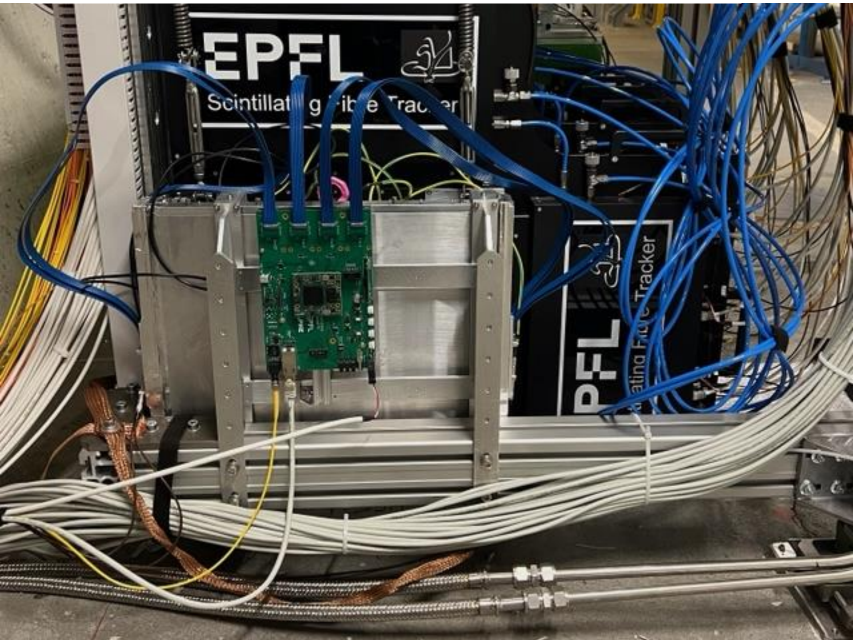


$<\sigma_t> = 245$ ps , *i.e.* ∽ 170 ps per end including a binning effect of 70ps

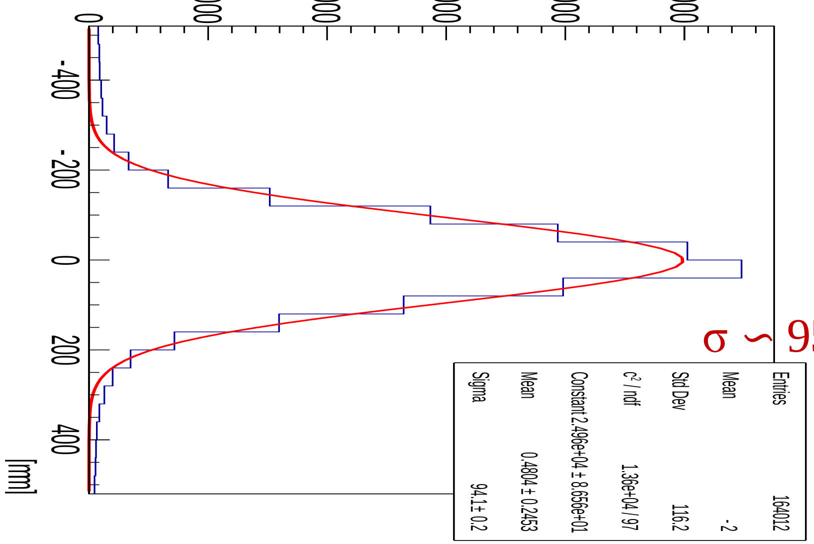
Downstream stations timing resolution



Timing resolution in H bars

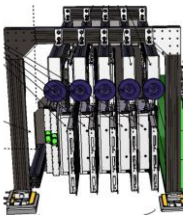


SciFi position resolution

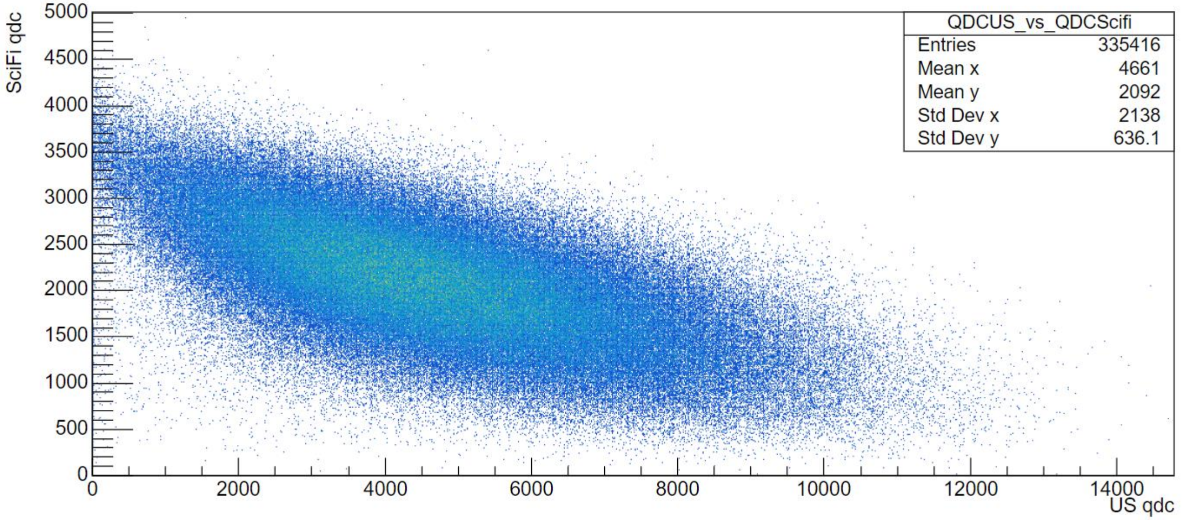


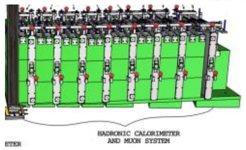
σ ∽ 95 μm

Results on energy resolution



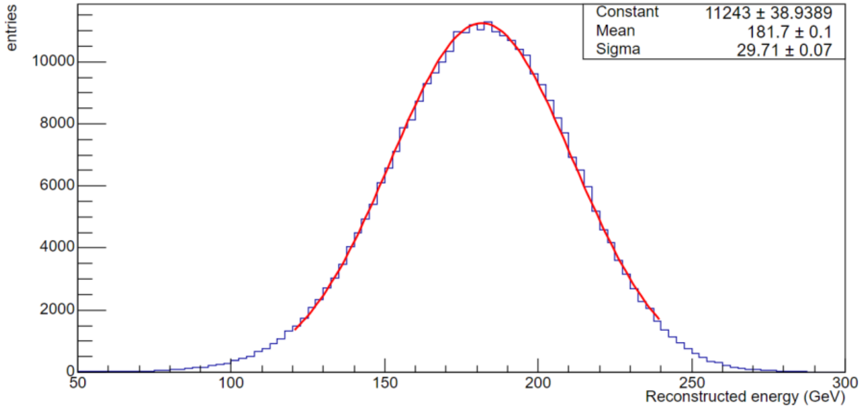
SciFi



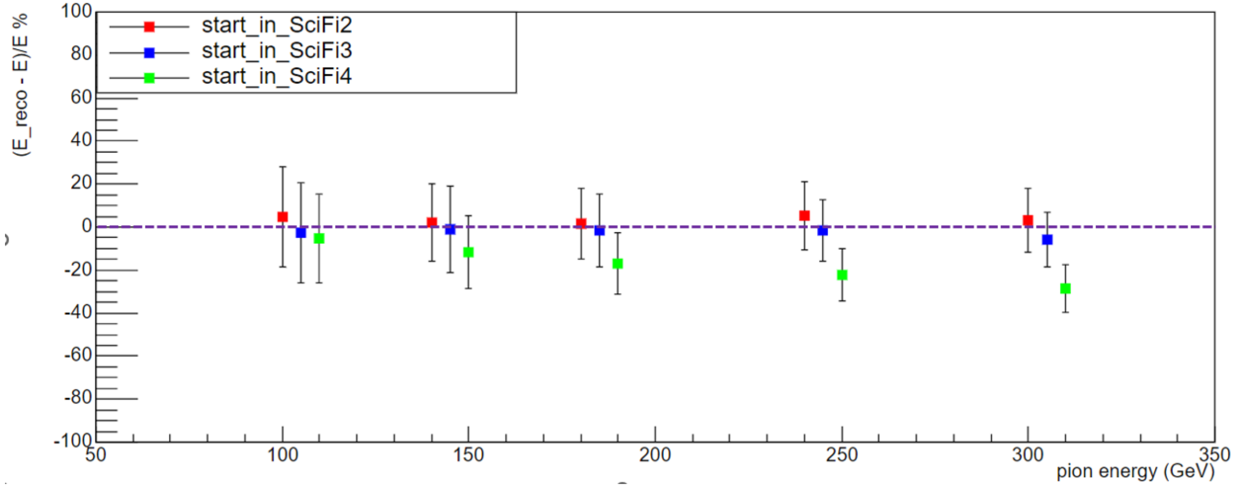


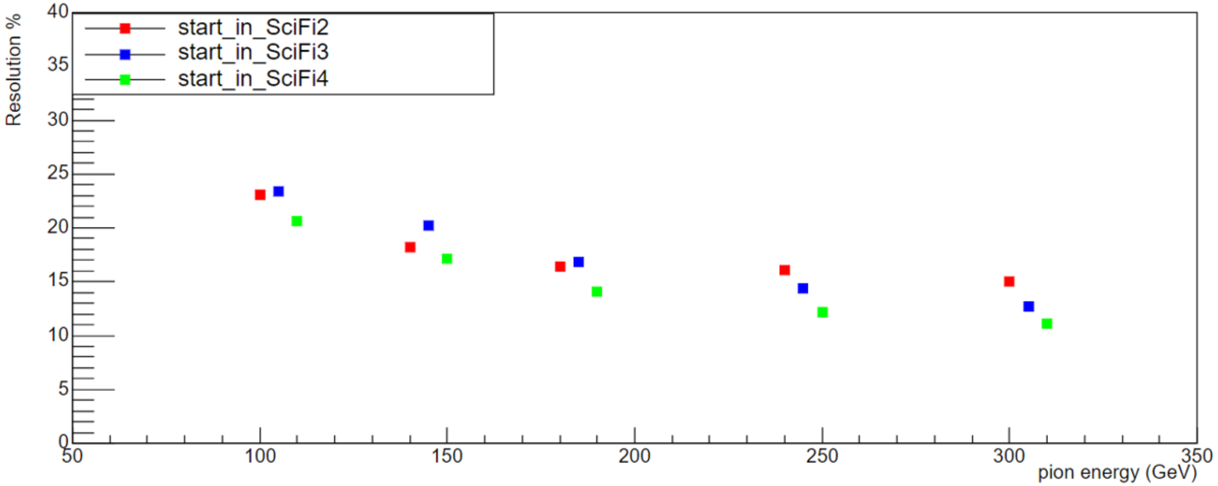
Hcal

Reconstructed energy for 180 GeV π



Deviations from linearity for showers originated in the last λint of the target and E > 150 GeV → saturation in US





Detector installation in TI18

- Started on November 1st 2021
- Electronic detector completed on December 3rd 2021
- Neutron shield completed on March 15th 2022
- First emulsion films in the target on April 7th 2022

September 2021

December 2021

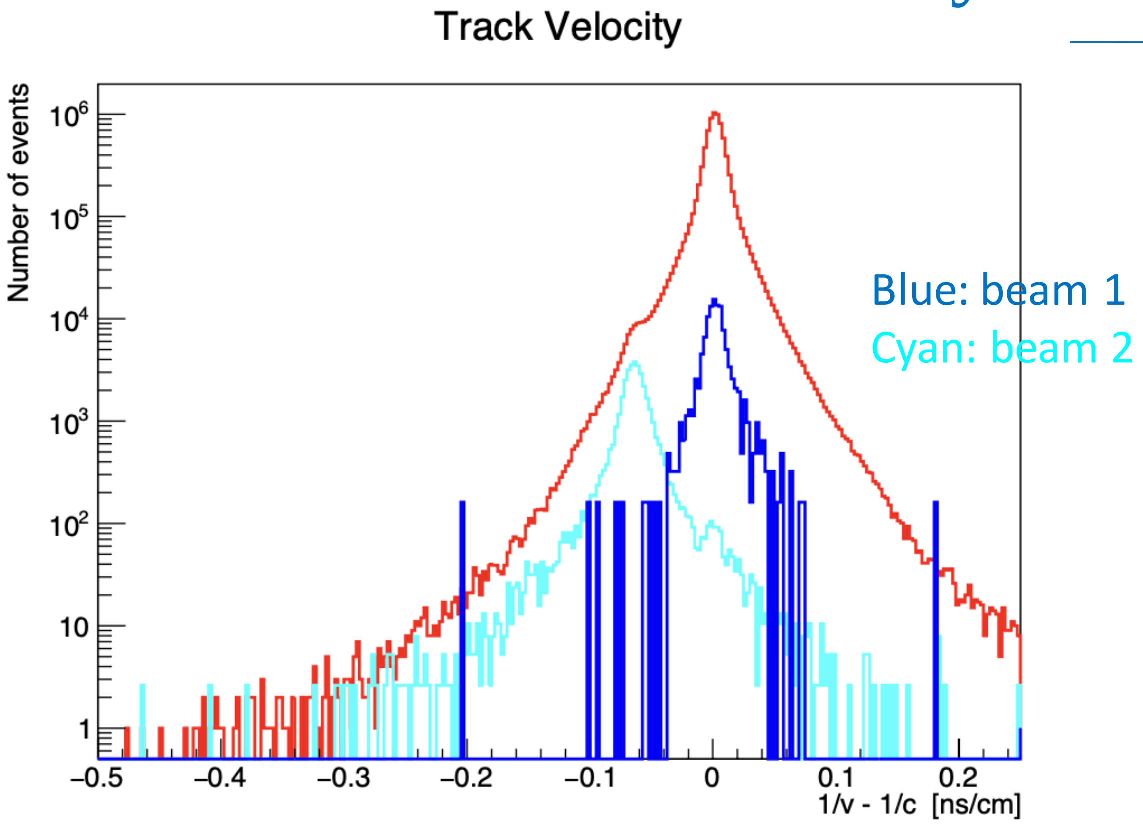
March 2022

12 months from LHCC approval
to working experiment !

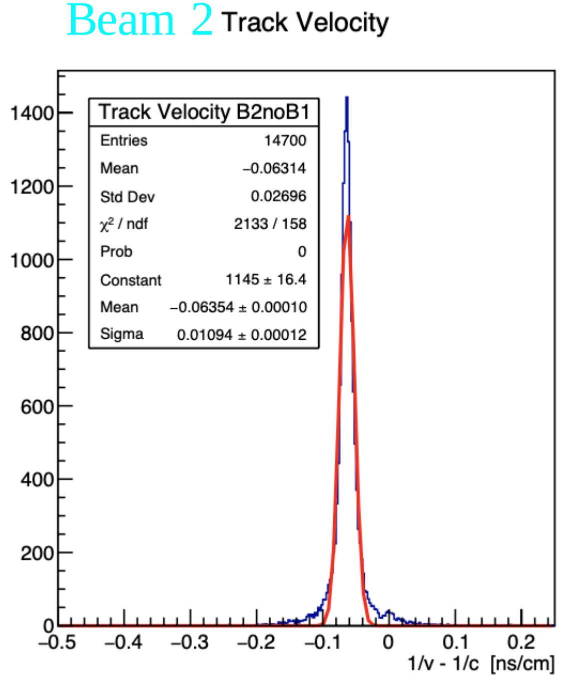
Fully installed detector pointing to the IP

View of the machine towards the IP1 (left) and of the detector in TI18 (right)

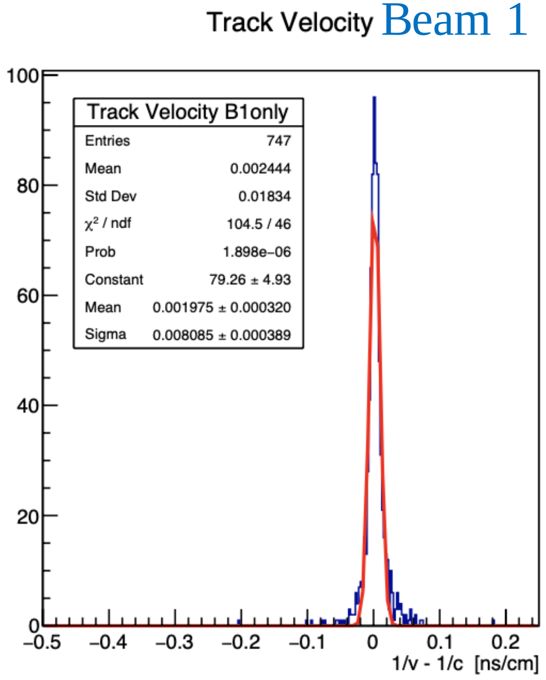
Use bunch structure to study event features: the track direction



Beam 2



Beam 1



track type	beam 1	beam 2	no beam
Run 4705			
Scifi	1.41%	0.44%	0.02%
DS	1.10%	1.13%	0.04%
Run 4654			
Scifi	1.30%	0.41%	0.01%
DS	0.98%	1.03%	0.02%
Run 4661			
Scifi	1.20%	0.34%	0.01%
DS	0.90%	0.86%	0.05%

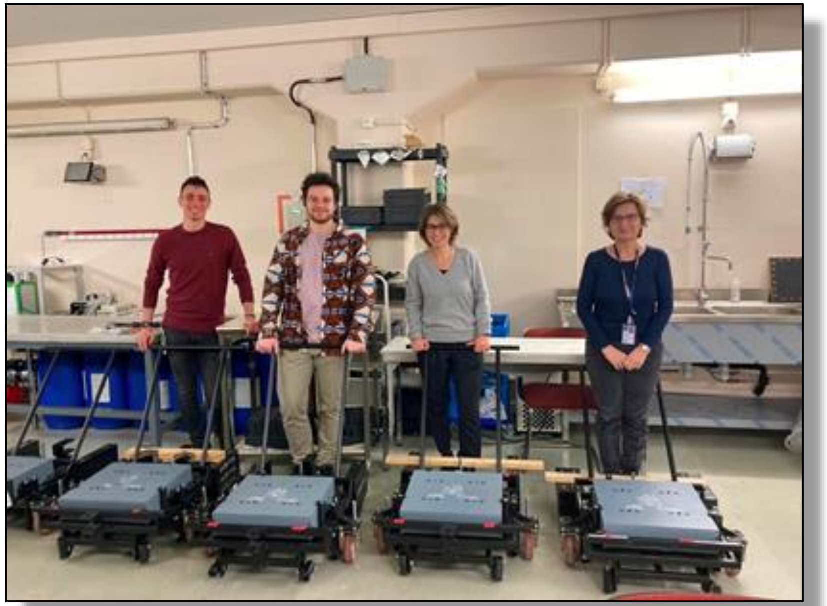
Table 1: Background rates for different runs.

Background on target tracks < 2%

Emulsion replacements in 2023

- Mass of target #4: **797 kg**
- **1158** films (70% Nagoya+30% Slavich)
- Assembly: March 16th-19th
- Installation: **March 20th**
- Extraction: **June 23rd**
- Emulsion development: July 4th-17th
- Time for underground operation: 4 hours

- Mass of target #5: **784 kg**
- **1140** films (100% Nagoya)
- Assembly: March 16th-19th
- Installation: **June 23rd**
- Extraction: **July 27th**
- Emulsion development: August 12th-25th
- Time for underground operation: 4 hours

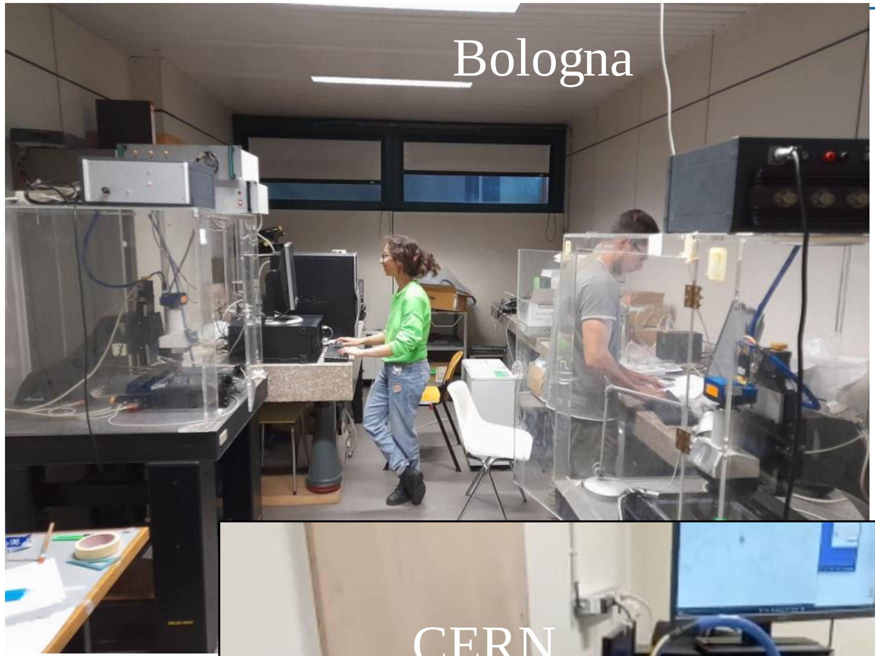


Target assembly

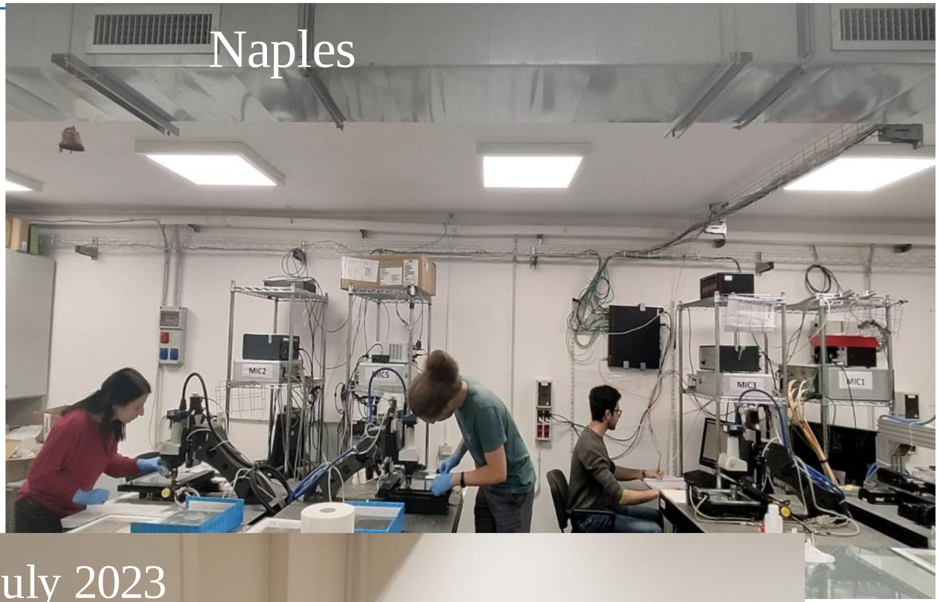
Target installation

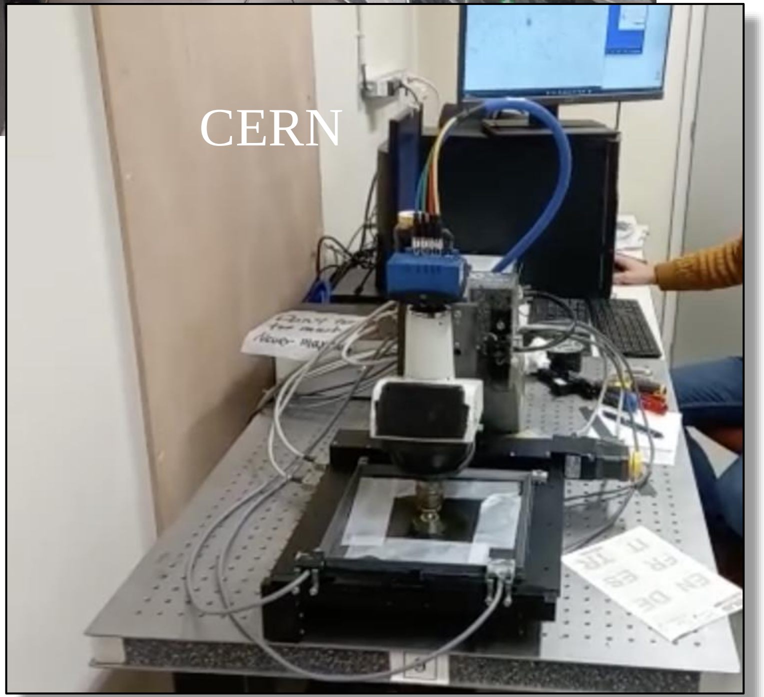
Emulsion development

Emulsion scanning stations



Bologna: 2 systems
Napoli: 2 systems
CERN: 2 systems + 2 upgrades operational in Dec

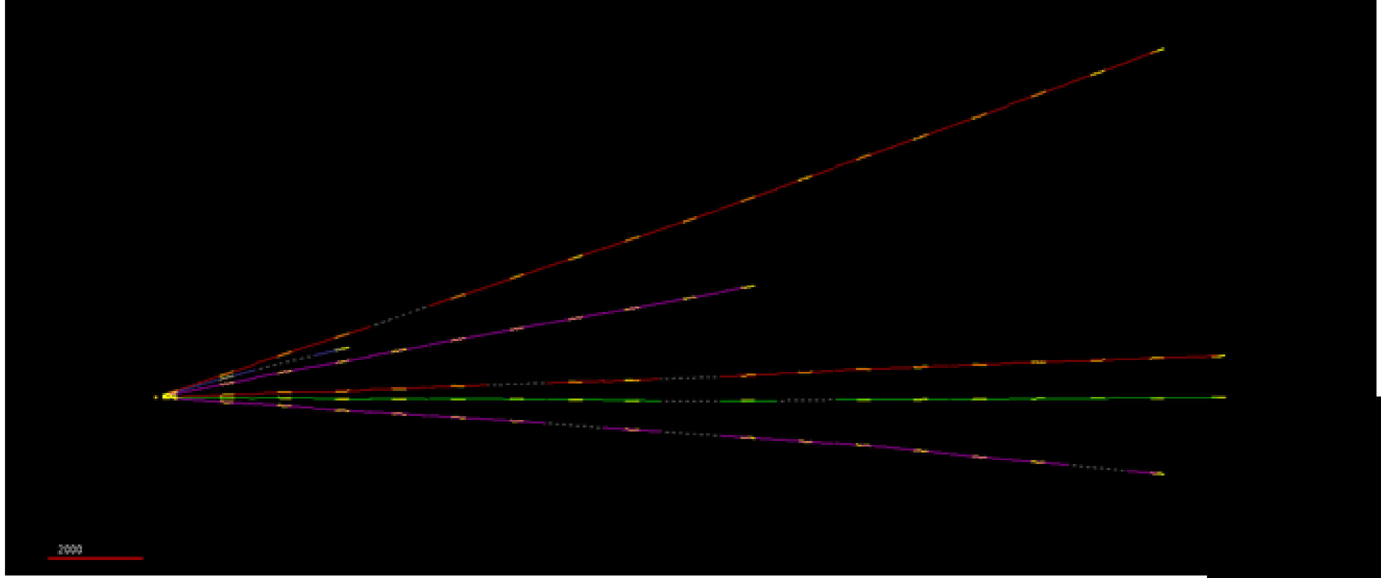




Track and vertex reconstruction in emulsion

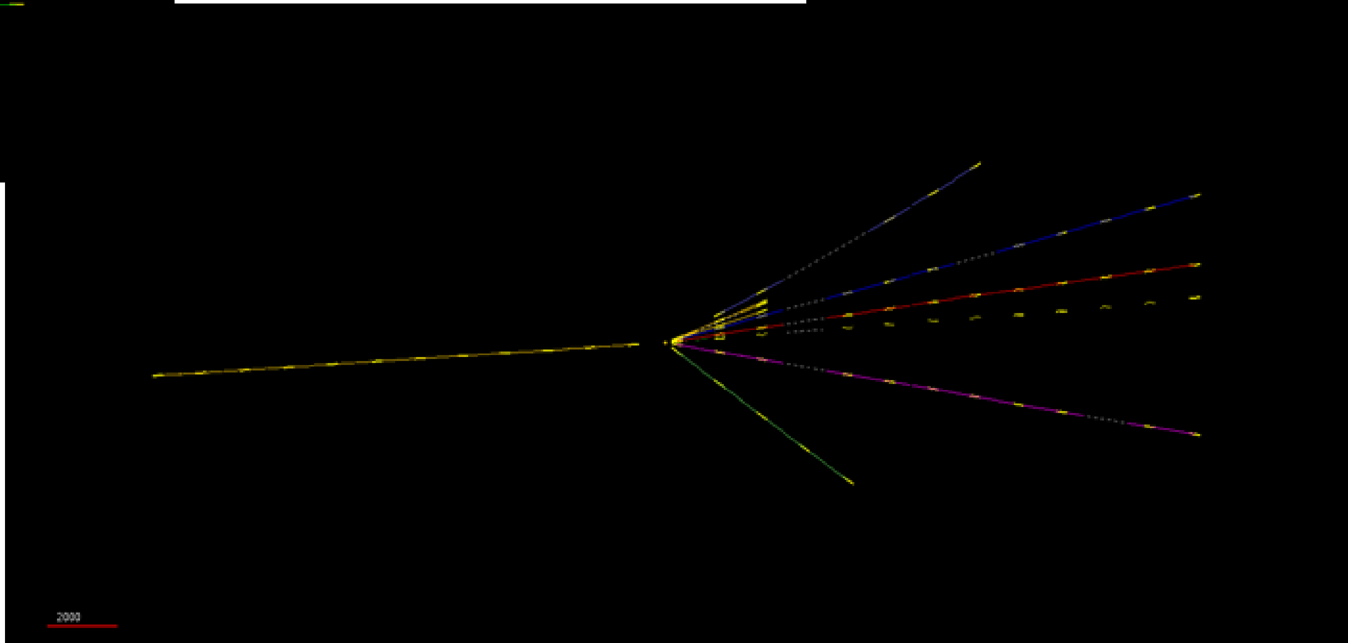
- Neutrino-like vertex

- Vertex plate: 13
- Track multiplicity: 6
- Average #segments: 13
- Average IP: 0.2 um



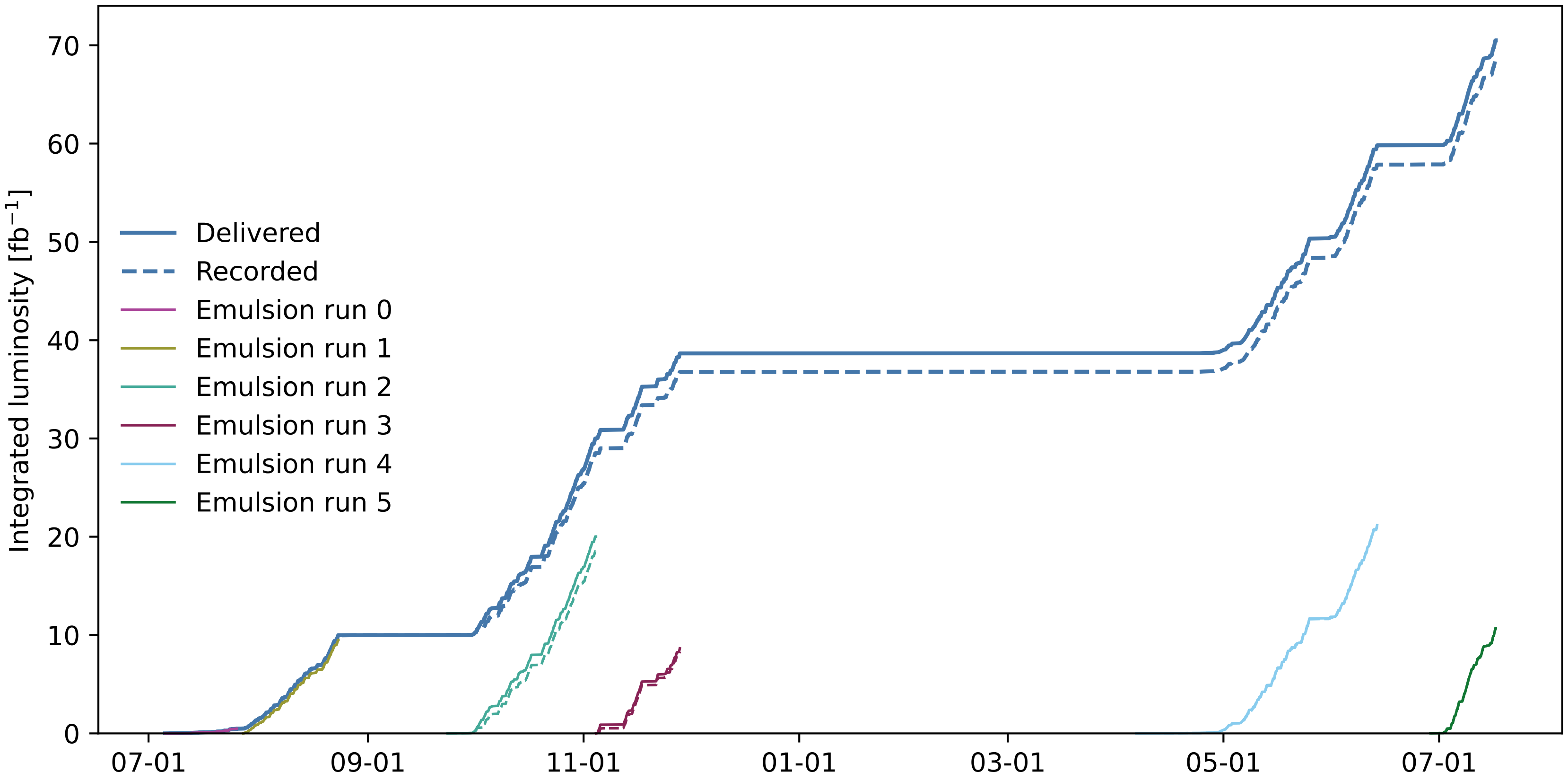
- Muon DIS-like vertex

- Vertex plate: 19
- Track multiplicity: 11
- Average #segments: 7
- Average IP: 5 um



Data analysis

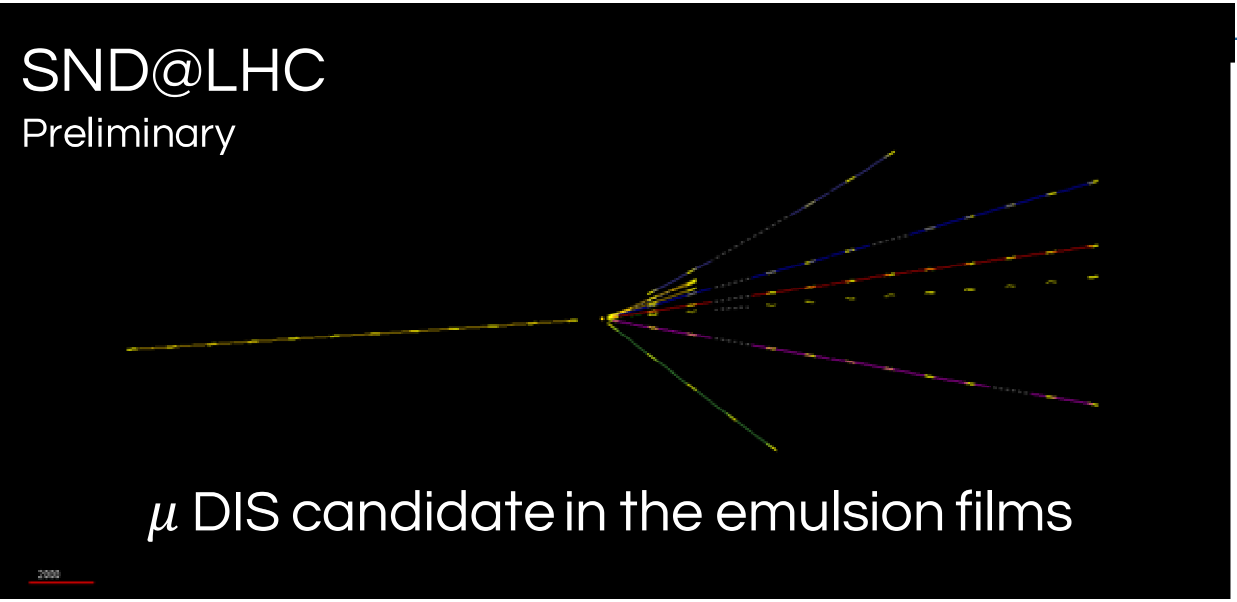
Integrated luminosity

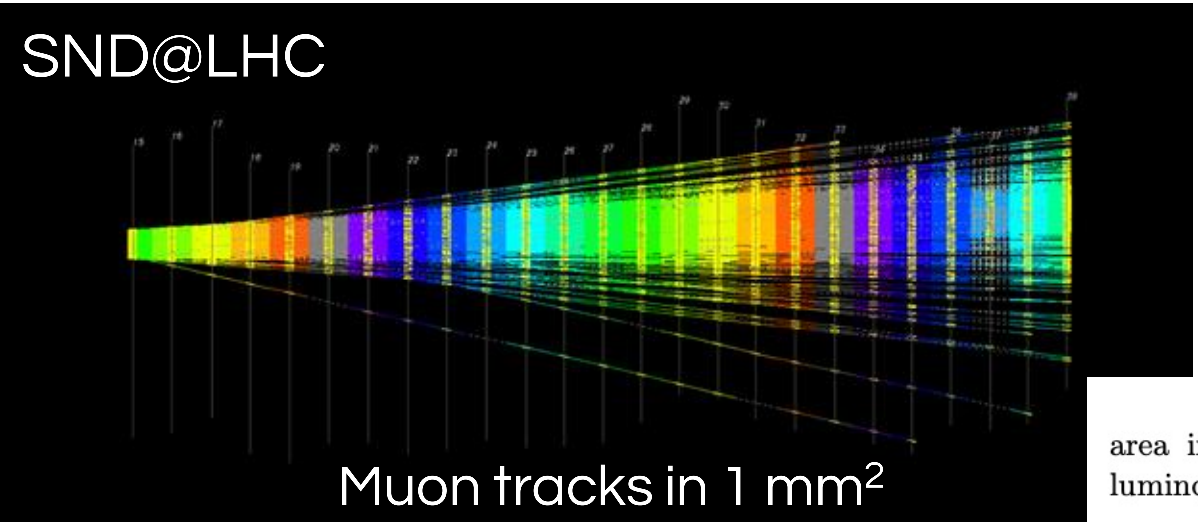


Integrated luminosity: 70.5 fb^{-1}

Recorded efficiency 97.3% (2022 95%, 2023 99.7%)

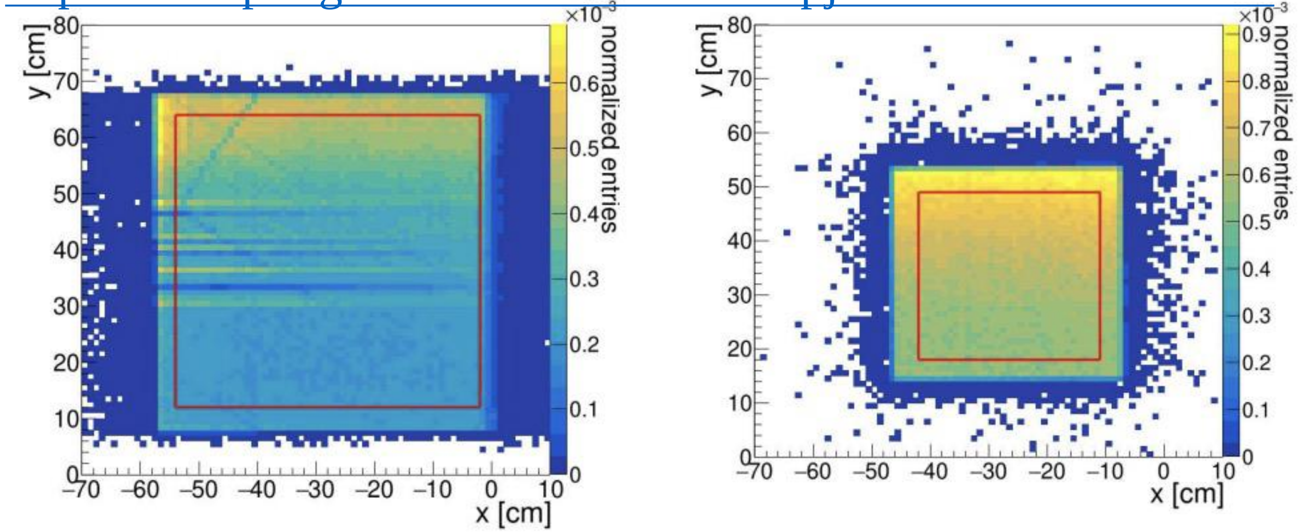
Muon flux measurement and emulsion analysis





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

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 Line of sight.

FLUKA simulation estimate of flux ~20-25% lower than measurement.

The muon flux per integrated luminosity through an 18×18 cm^2 area in the emulsions is $\mathbf{1.5 \pm 0.1}$(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

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

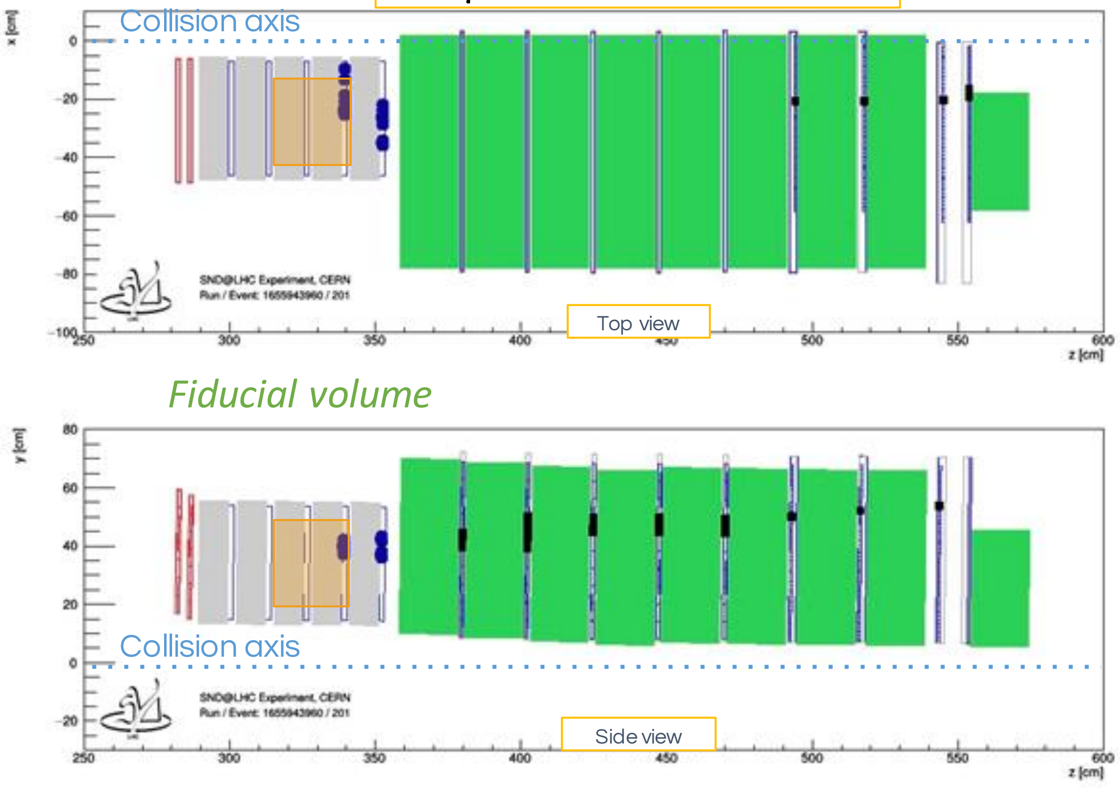
for a 52×52 cm^2 central detector region.

Neutrino observation with electronic detectors

- Analysis strategy:
  - Full Run 3 **2022 dataset**: recorded luminosity of 36.8 fb^{-1}
  - Observe ν_μ **Charged Current** interactions with **electronic detectors only**
  - **Maximise S/B**, counting-based approach: initial S/N ~ 10^{-8} down to 100
  - ~10^9 muon events: **strong rejection power** to reach negligible background level

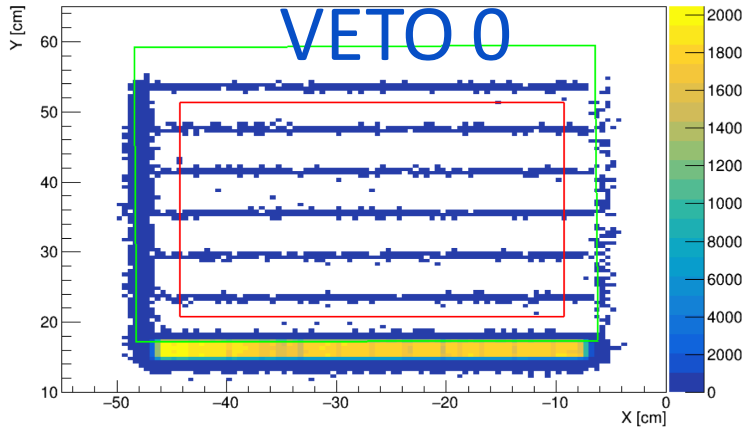
- Signal selection:
  - **Fiducial Volume (1, 2)** cuts
    - **Neutral vertex**, located in the 3rd or 4th target wall
    - Select fiducial cross-sectional area to reject background entering from the side
  - **Neutrino ID** cuts
    - Require "large" E.M. (SciFi) and hadronic activity (HCAL)
    - Event produced upstream (timing)
    - **Muon** reconstructed and **isolated** in the Muon system

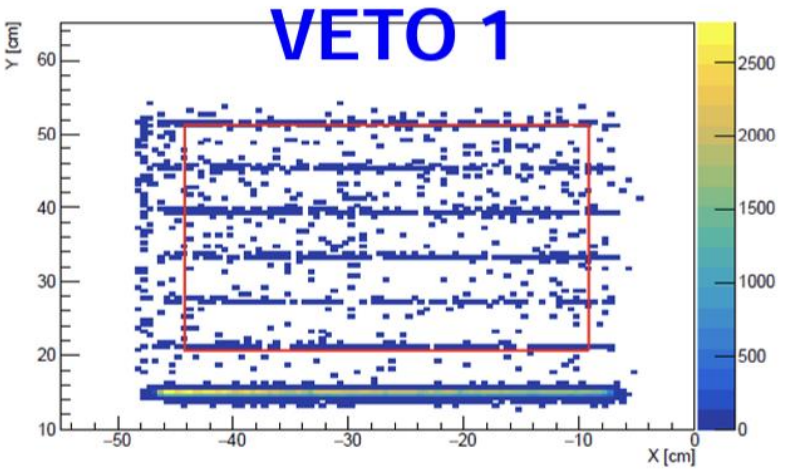
ν_μCC simulation



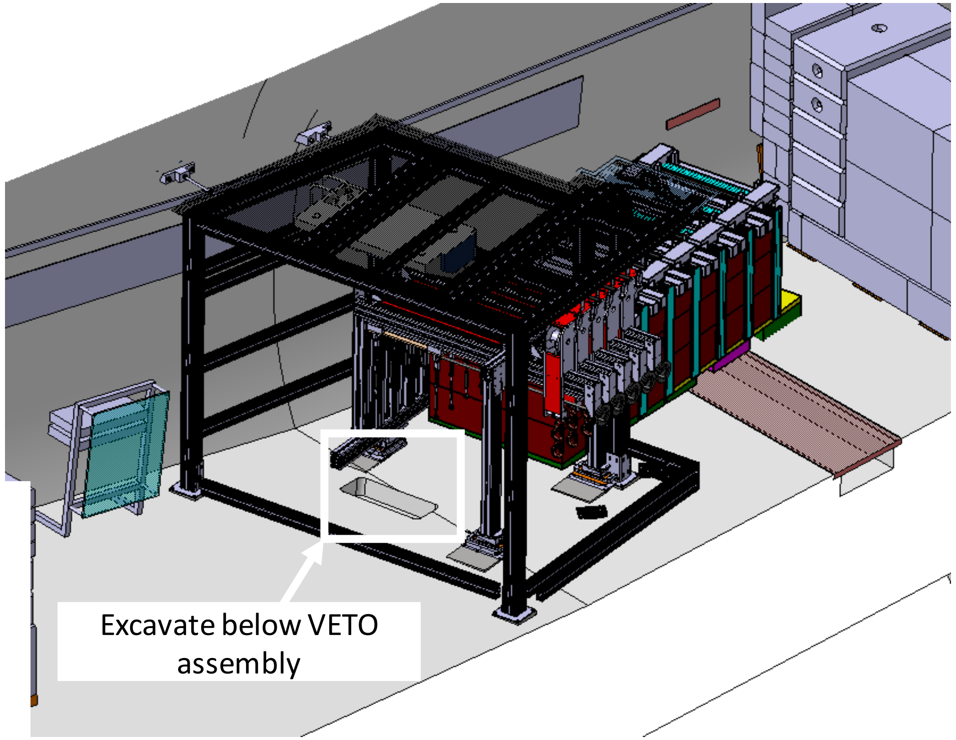
Upgrade of the veto system during 2023-2024 YETS

Extrapolated SciFi track position
when no signal in Veto 0 or 1





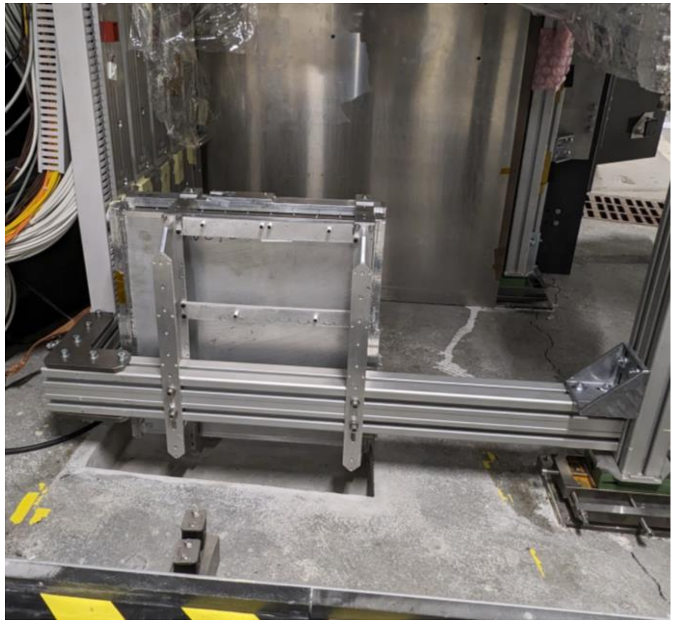
Pit excavation for the new VETO assembly



3D integration model of SND@LHC in TI18

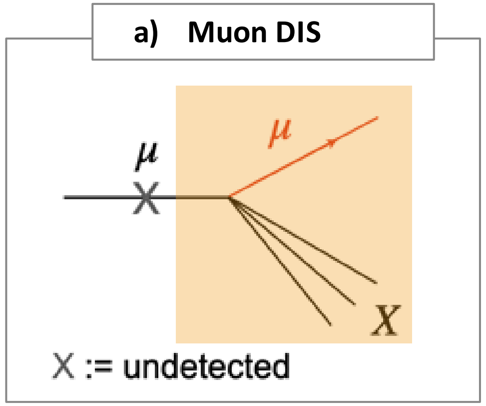
Side view of new VETO assembly and excavated pit

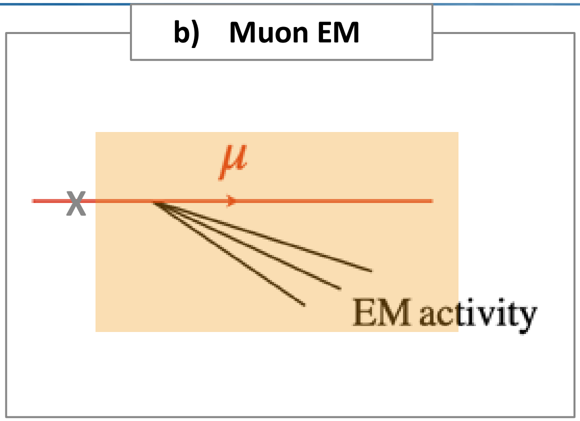
Upgraded and relocated VETO assembly



- Recover fiducial volume, on all 3 sides, by also lowering the position
- Add a third layer to avoid losing the first target wall for the acceptance

Background evaluation



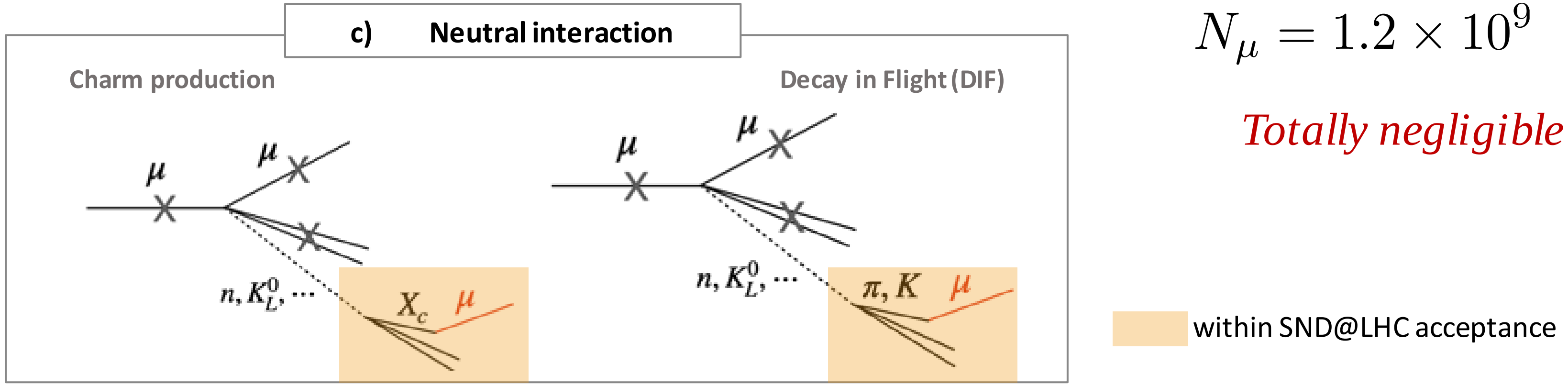


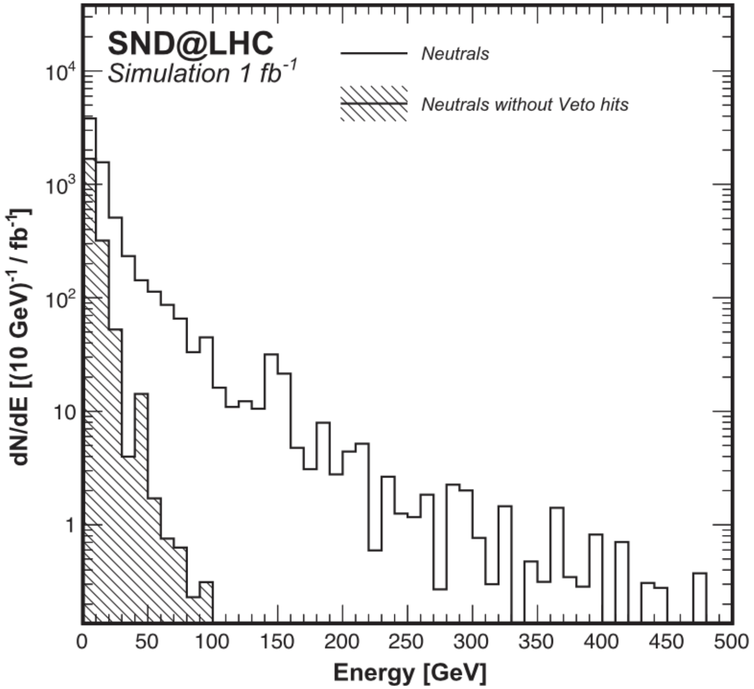
- Muon induced background: undetected muons entering the target (2022 Run3 data)

$$N_{bkg} = N_\mu \left(1-\varepsilon_{veto}\right) \times \left(1-\varepsilon_{SciFi1}\right) \times \left(1-\varepsilon_{SciFi2}\right) = 5.3 \times 10^{-12} N_\mu$$

$$N_\mu = 1.2 \times 10^9$$

Totally negligible



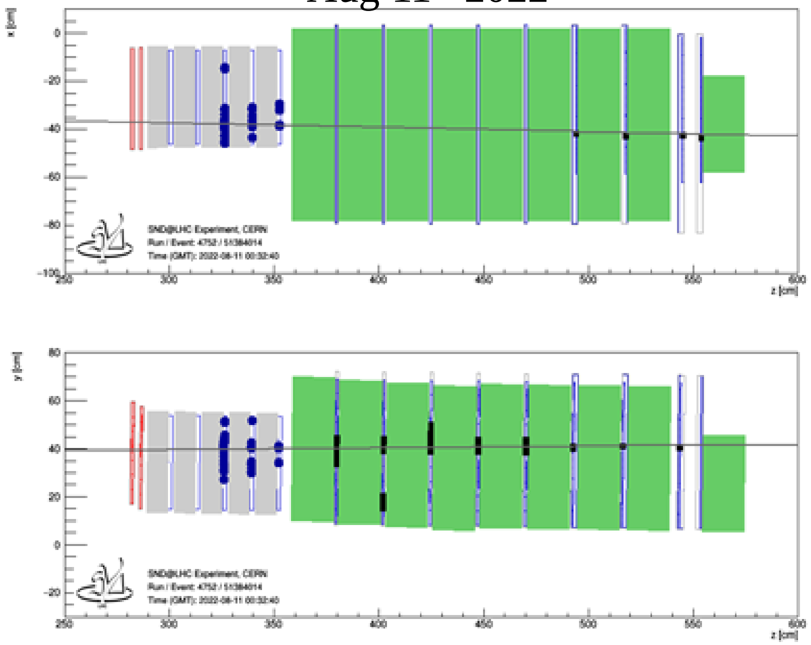


- Muon-induced neutral interactions in rock

$$N^{\text{bkg}}_{\text{neutrals}} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}} = (8.6 \pm 3.8) \times 10^{-2}$$

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



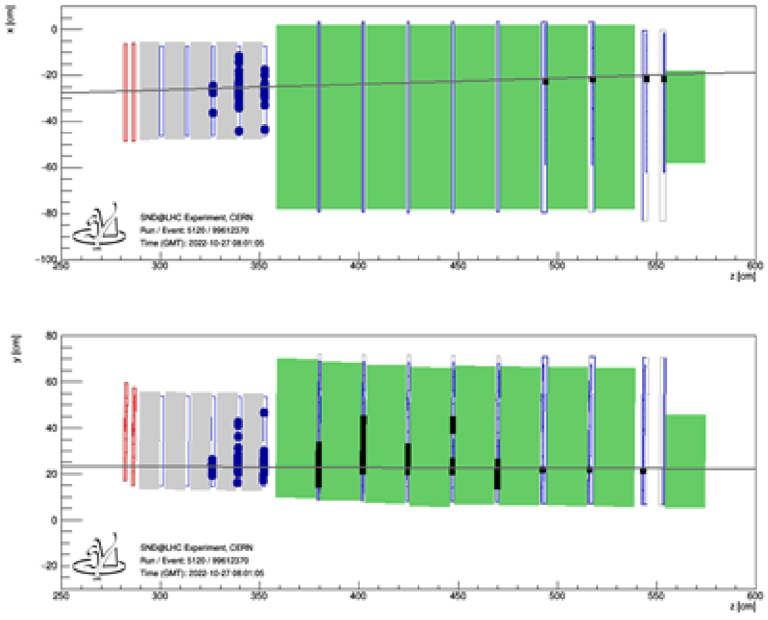
Editors' Suggestion

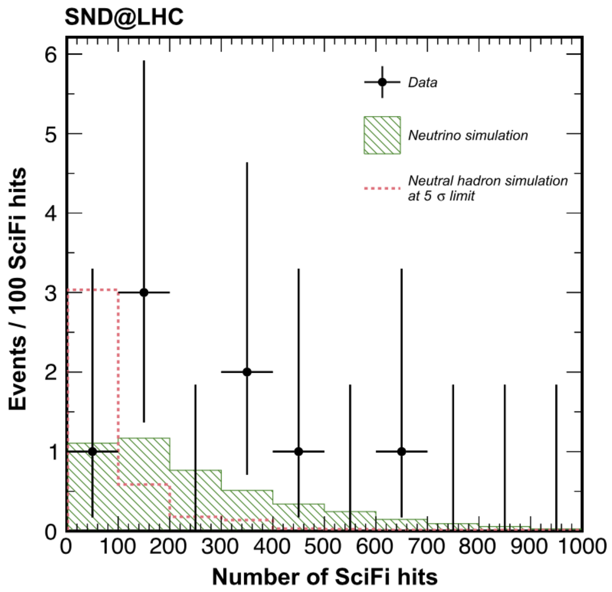
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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

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

Oct 27th 2022





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

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

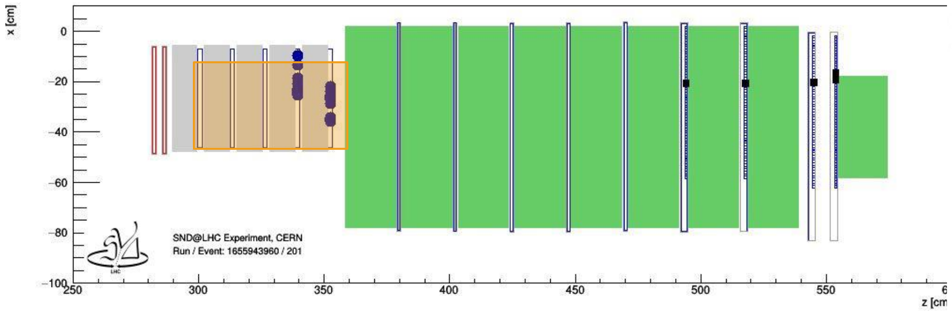
Background only hypothesis probability:

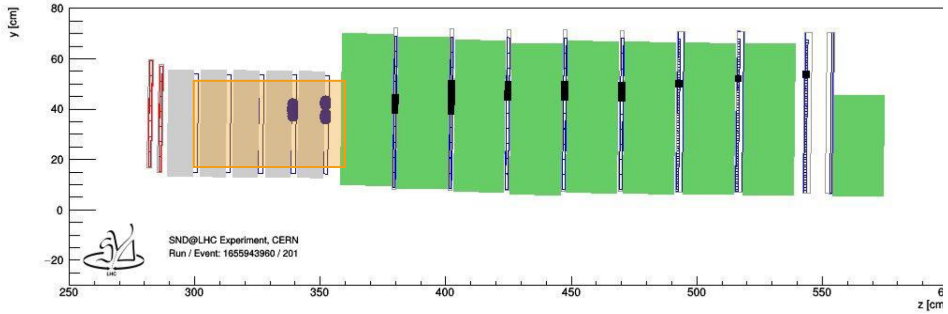
$$P = 7.15 \times 10^{-12}$$

6.8 σ observation

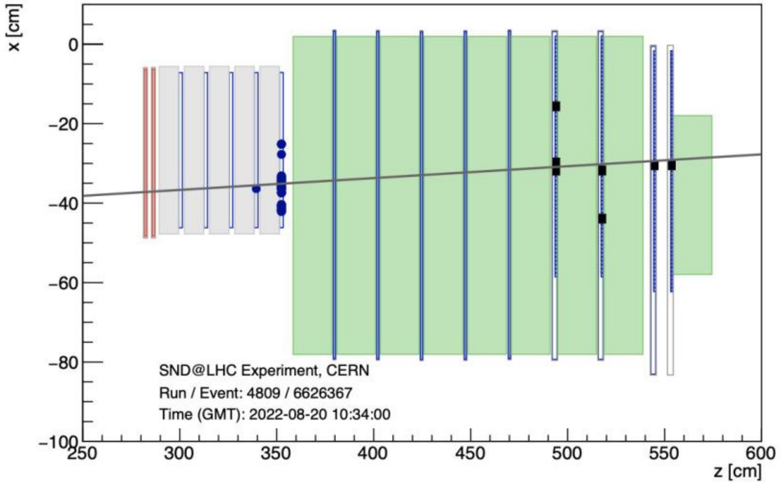
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

Muon neutrino selection with 2022-2023 data in an extended volume (wall 2 and 5 included)

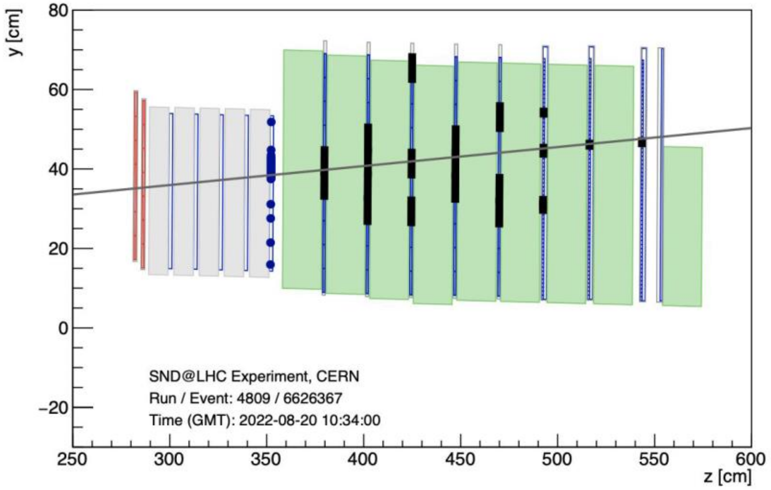


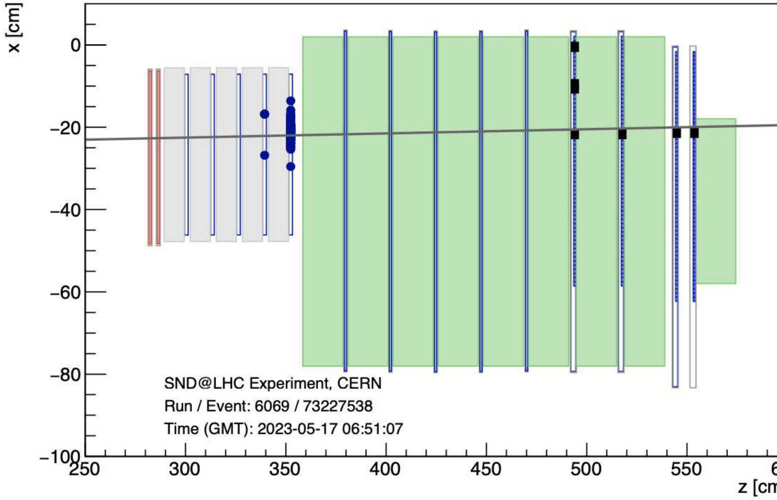


32 events: 15 in 2022 and 17 in 2023

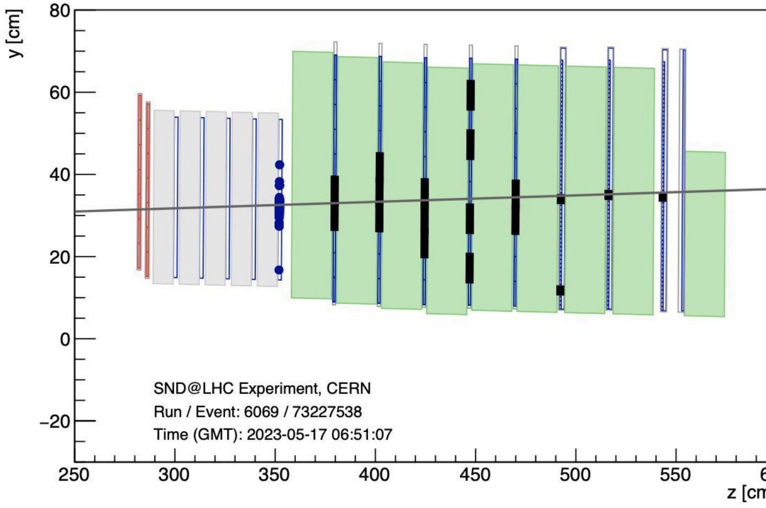


New 2022 event

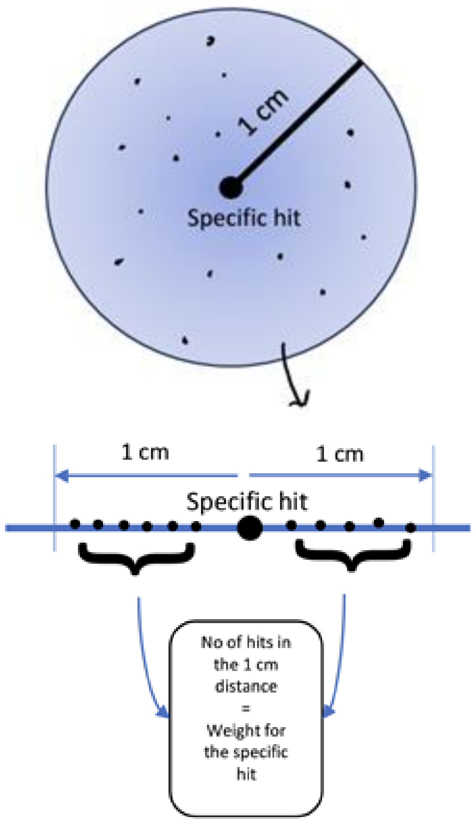




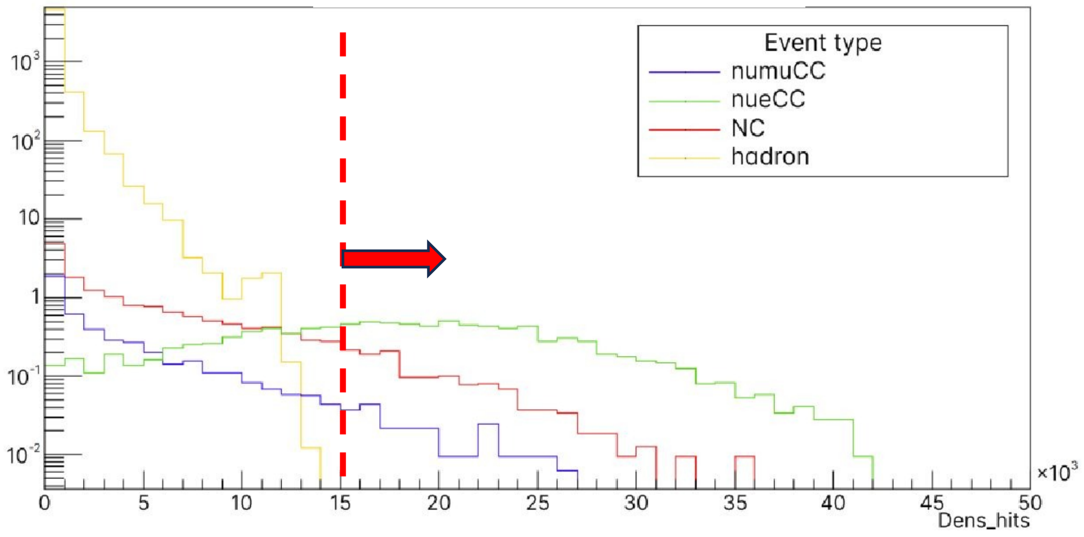
2023 event



Electron neutrino and neutral current identification



Hit density distribution

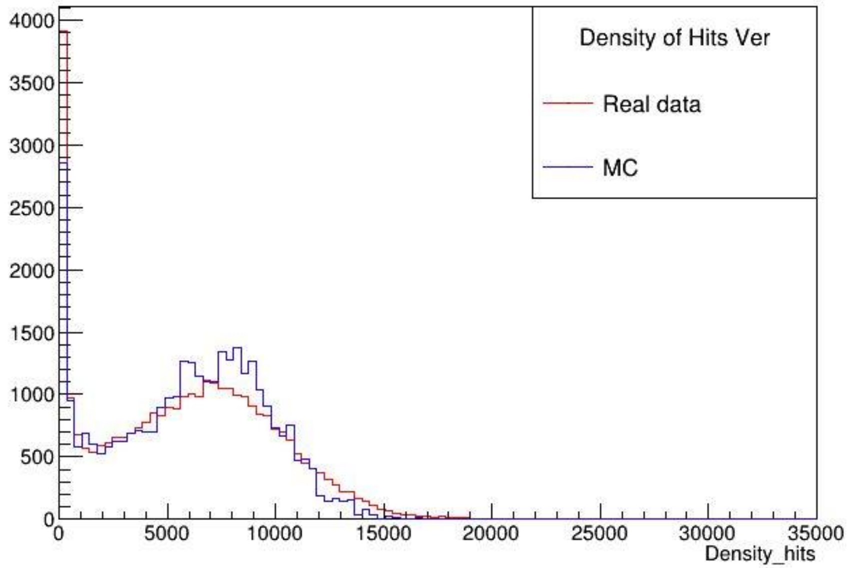


- Signal selection based on topological and calorimetric information
- Discriminating variable: density of hits in SciFi

- Density of his > 12000
  - negligible neutral hadron background
- Density of hits > 25000
  - dominated by ν_e CC events

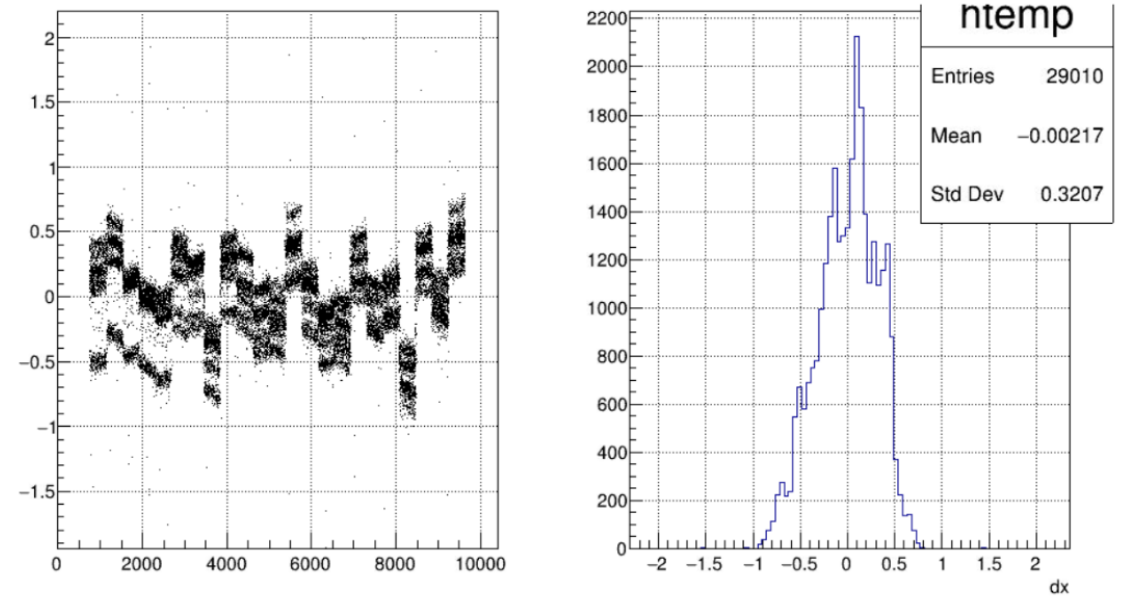
With a cut at 15000:
1.61 NC
0.29 ν_μ CC
7.1 ν_e CC

SciFi hit density distribution in Test Beam

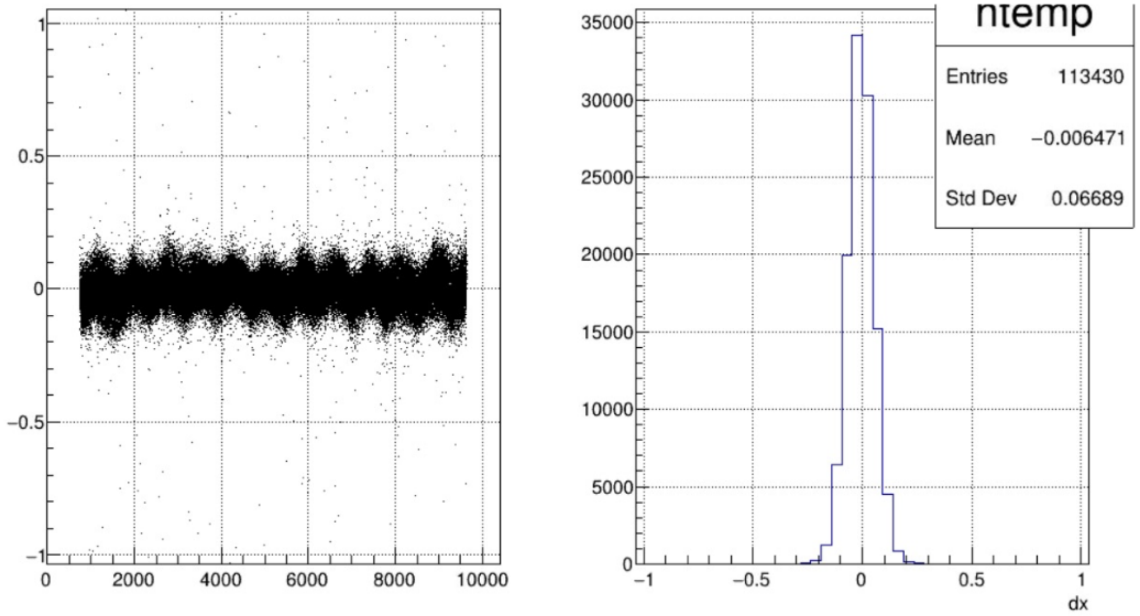


(Amazing) Resolution of emulsions

Reproducibility: high-frequency oscillation due to mechanics and environmental parameters, up to ~0.3 μr



New software corrections applied thanks to the tracks in the overlap of adjacent views → 0.07 μm



This corresponds to 0.5 μm resolution over the full muon track extrapolation

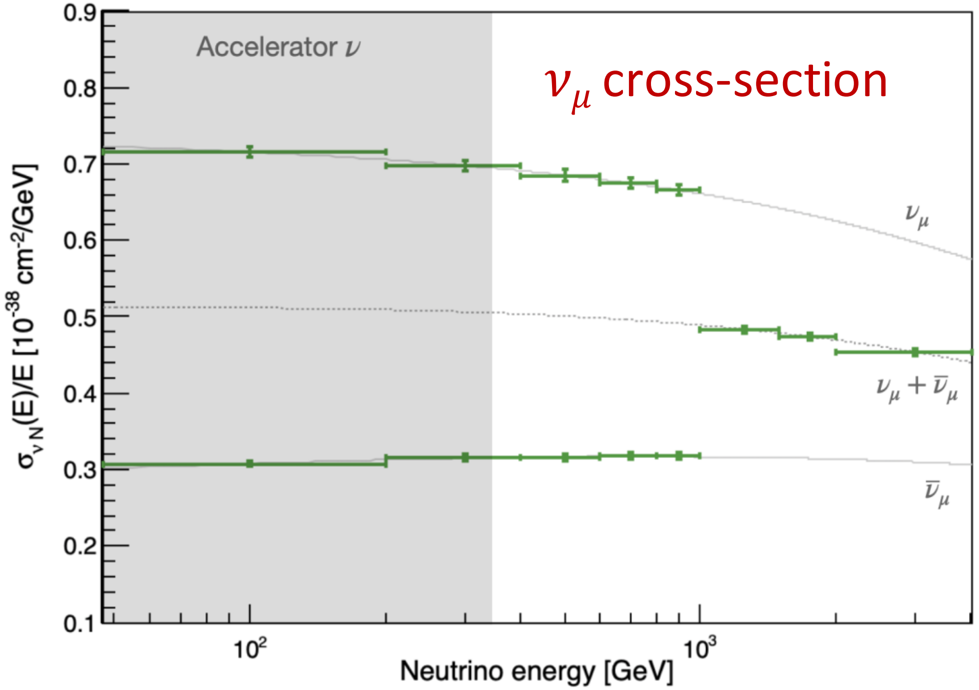
….which is ok to be able to reconstruct all the throughgoing muons who are typically separated by ~10 μm (for a 20 fb^{-1} exposure)

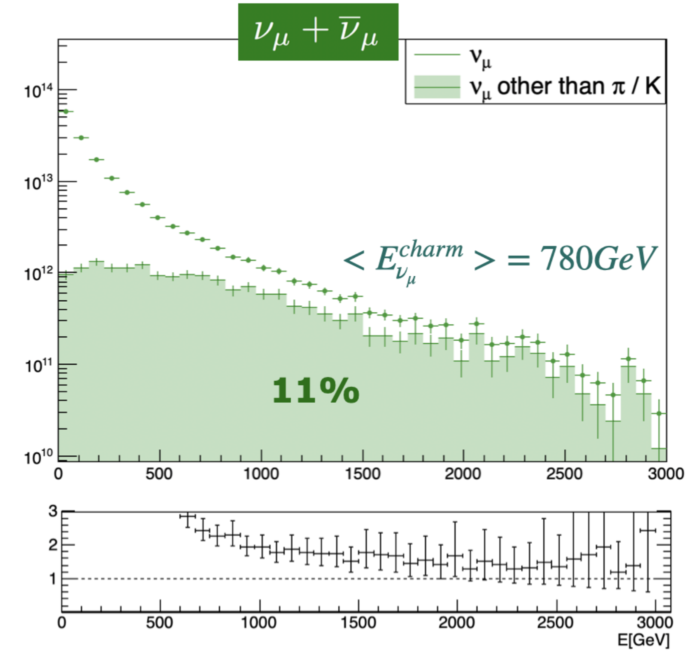
SND@LHC UPGRADE TOWARDS HL-LHC

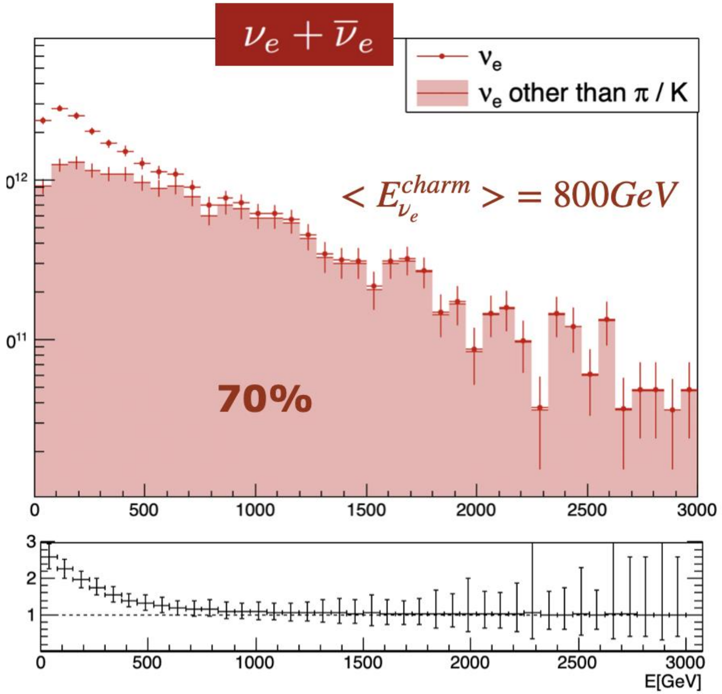
Scattering and Neutrino Detector
at the LHC

High Lumi LHC Physics performance in TI18

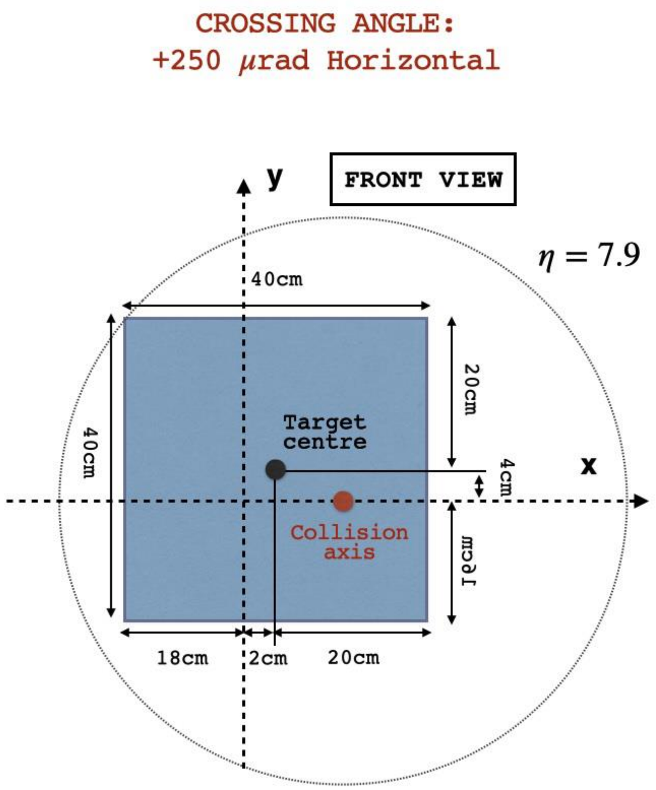
Flavour	ν in acceptance All	ν in acceptance not from π/k	CC DIS All	CC DIS not from π/k	NC DIS All	NC DIS not from π/k
ν_μ	8.6×10^{13}	8.2×10^{12}	$7.7{\times}10^4$	$2.1{\times}10^4$	$2.3{\times}10^4$	$6.4{\times}10^3$
$\bar{\nu}_\mu$	7.0×10^{13}	9.6×10^{12}	$2.8{\times}10^4$	$1.1{\times}10^4$	$1.0{\times}10^4$	$4.2{\times}10^3$
ν_e	1.3×10^{13}	9.1×10^{13}	$2.7{\times}10^4$	$2.3{\times}10^4$	$8.1{\times}10^3$	$7.0{\times}10^3$
$\bar{\nu}_e$	1.3×10^{13}	9.2×10^{13}	$1.2{\times}10^4$	$1.1{\times}10^4$	$4.5{\times}10^3$	$3.9{\times}10^3$
ν_τ	7.3×10^{11}	7.3×10^{11}	$1.3{\times}10^3$	$1.3{\times}10^3$	$4.3{\times}10^2$	$4.3{\times}10^2$
$\bar{\nu}_\tau$	9.4×10^{11}	9.4×10^{12}	$7.4{\times}10^2$	$7.4{\times}10^2$	$3.0{\times}10^2$	$3.0{\times}10^2$
Tot	1.8×10^{14}	2.9×10^{13}	$1.5{\times}10^5$	$6.8{\times}10^4$	$4.7{\times}10^4$	$2.1{\times}10^4$

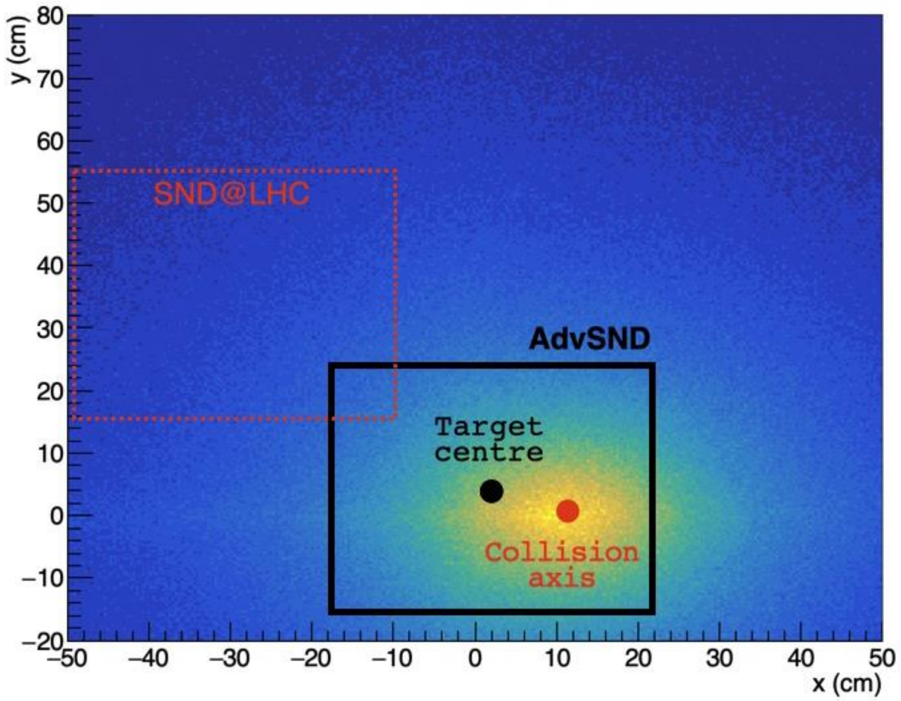






Geometrical configuration in Run 4: off-axis with an improved acceptance to cope with statistical limitations of Run 3





Account for the crossing angle in the horizontal plane in Run 4

Main points of the upgrade:

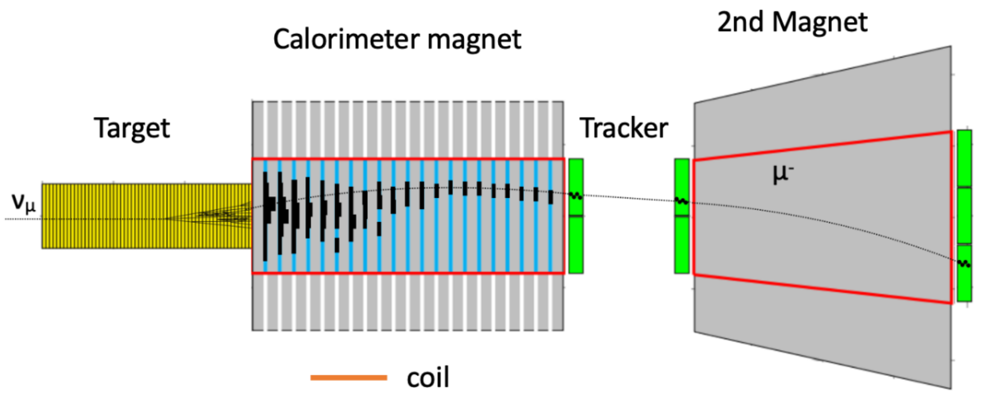
Better transverse position while keeping the off-axis characterization

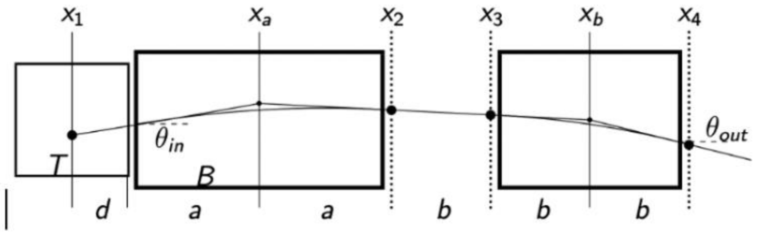
Replace emulsion technology in the target to withstand the high μ-rate of HL-LHC without need for frequent access as it is in Run 3

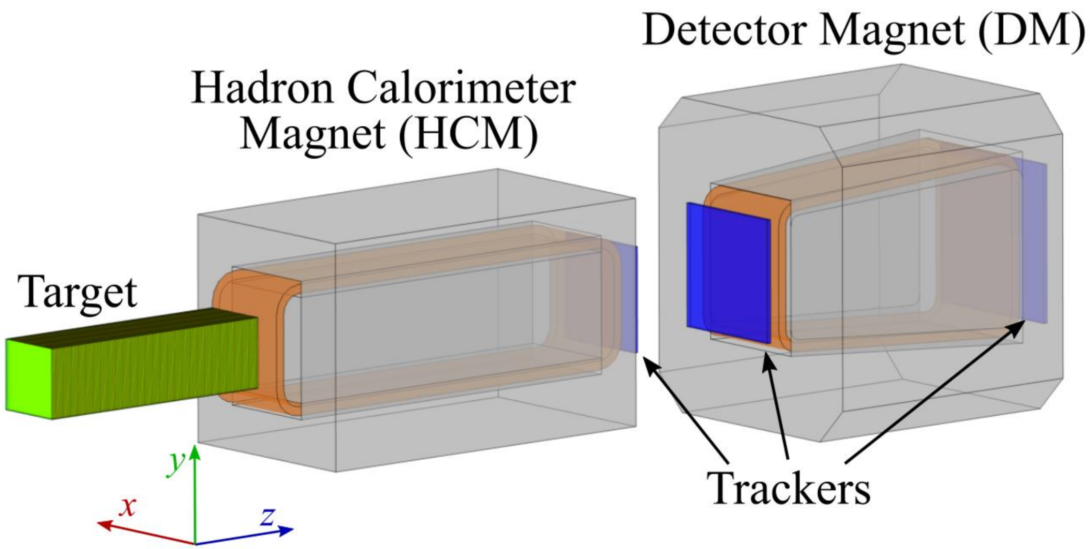
Add a magnetised spectrometer for the muon charge and momentum measurement (energy and ν/ν-bar separation)

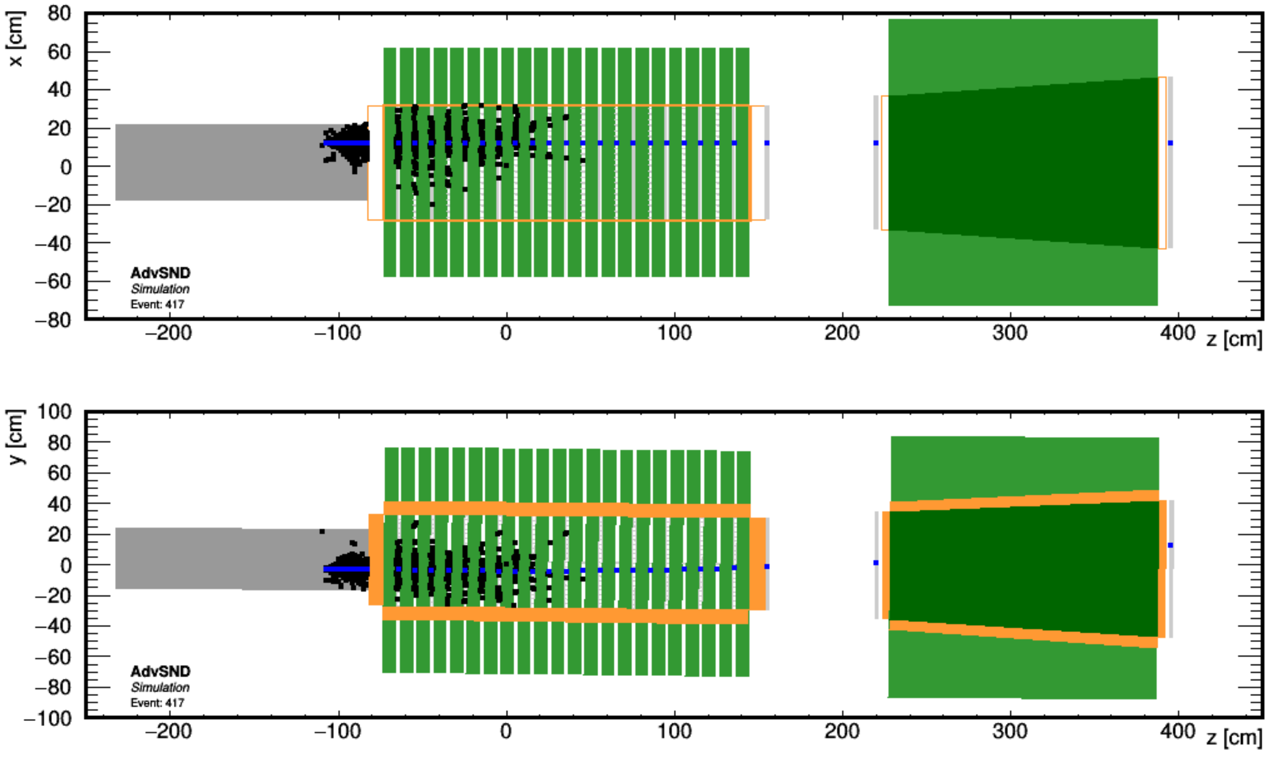
Overview of the upgraded detector

LHC
Scattering and Neutrino Detector at the LHC

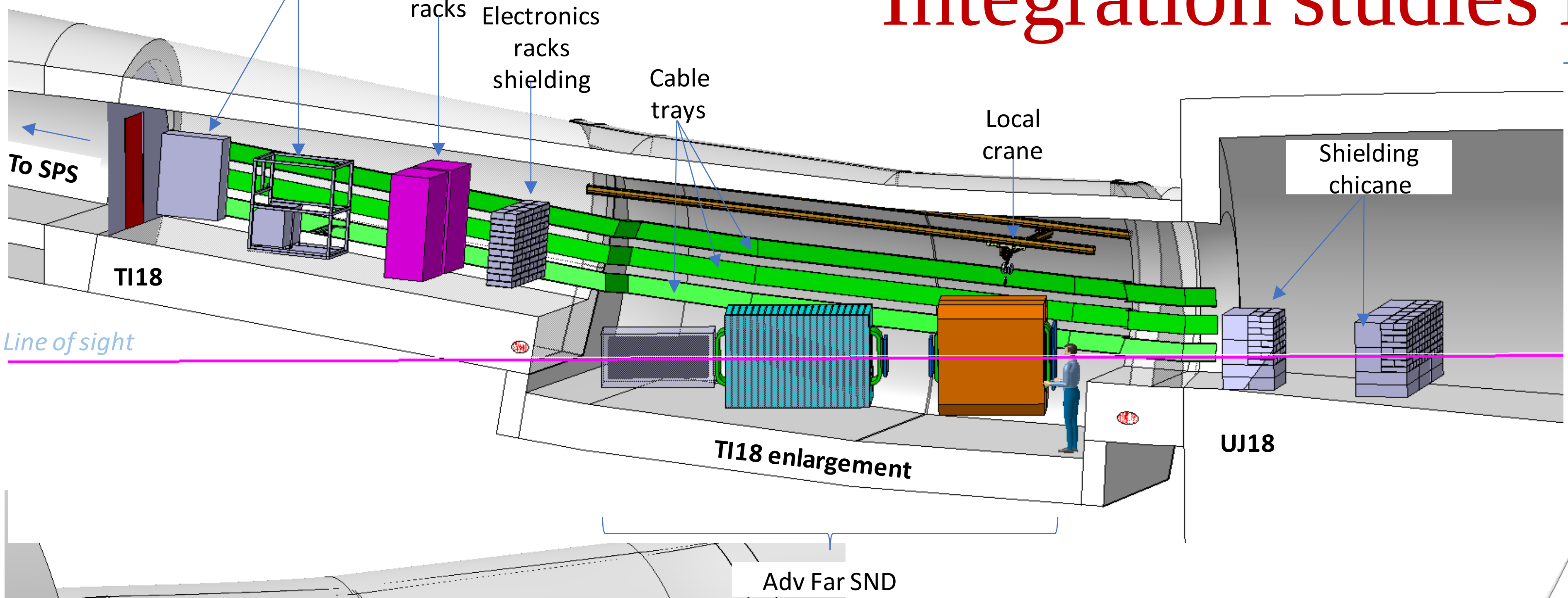


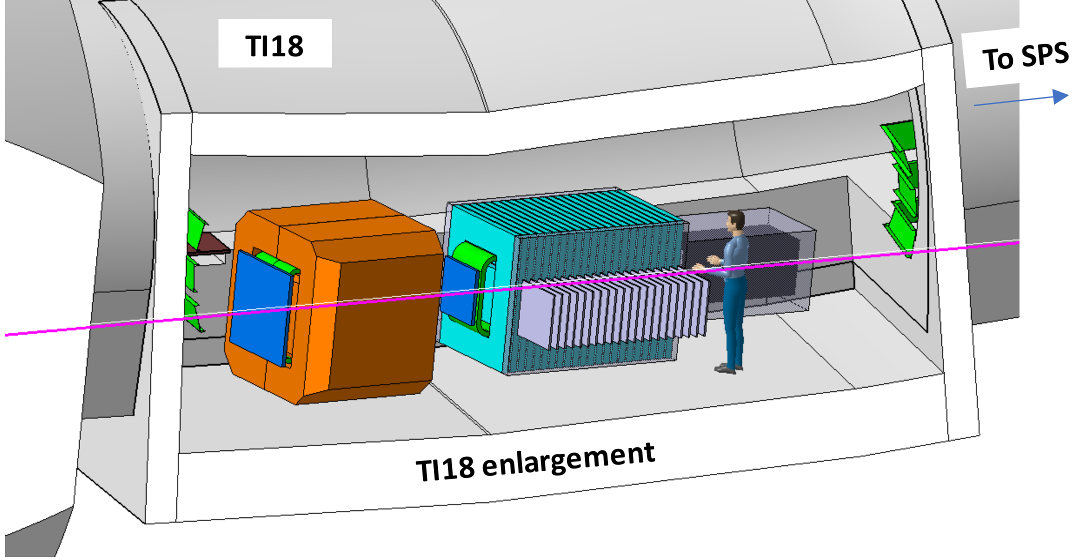


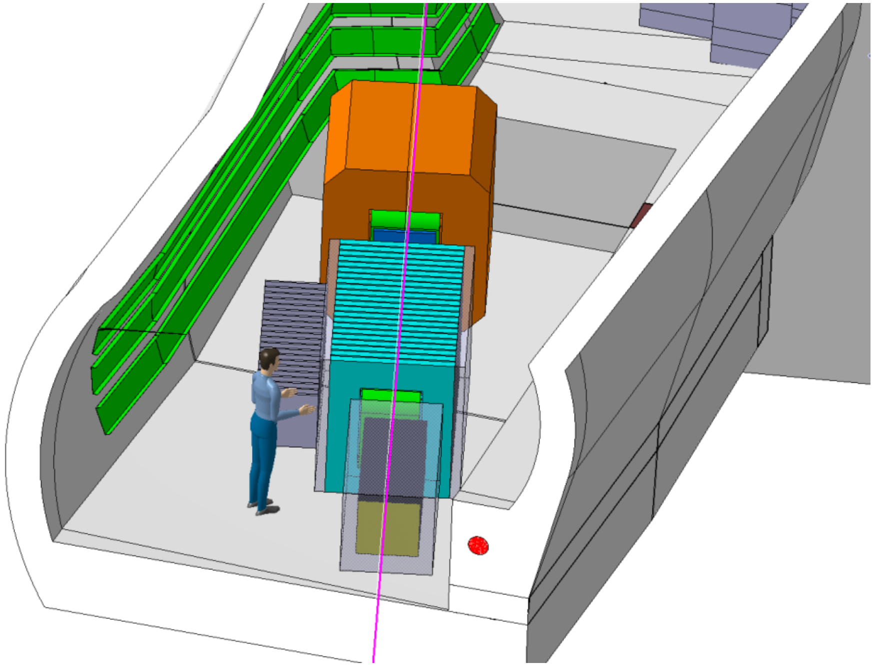




Integration studies in TI18

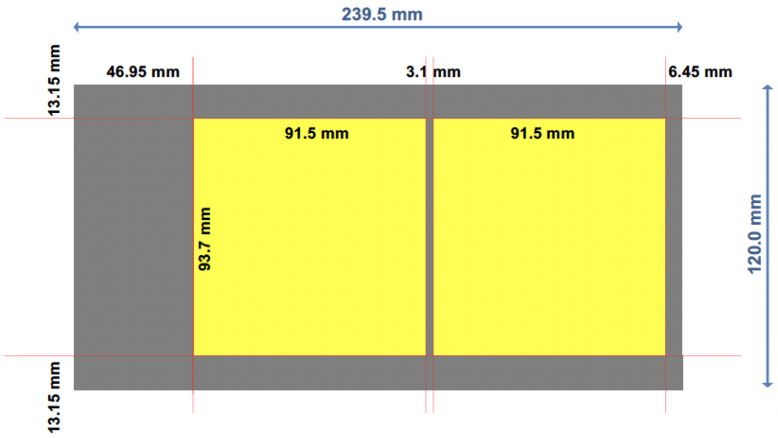






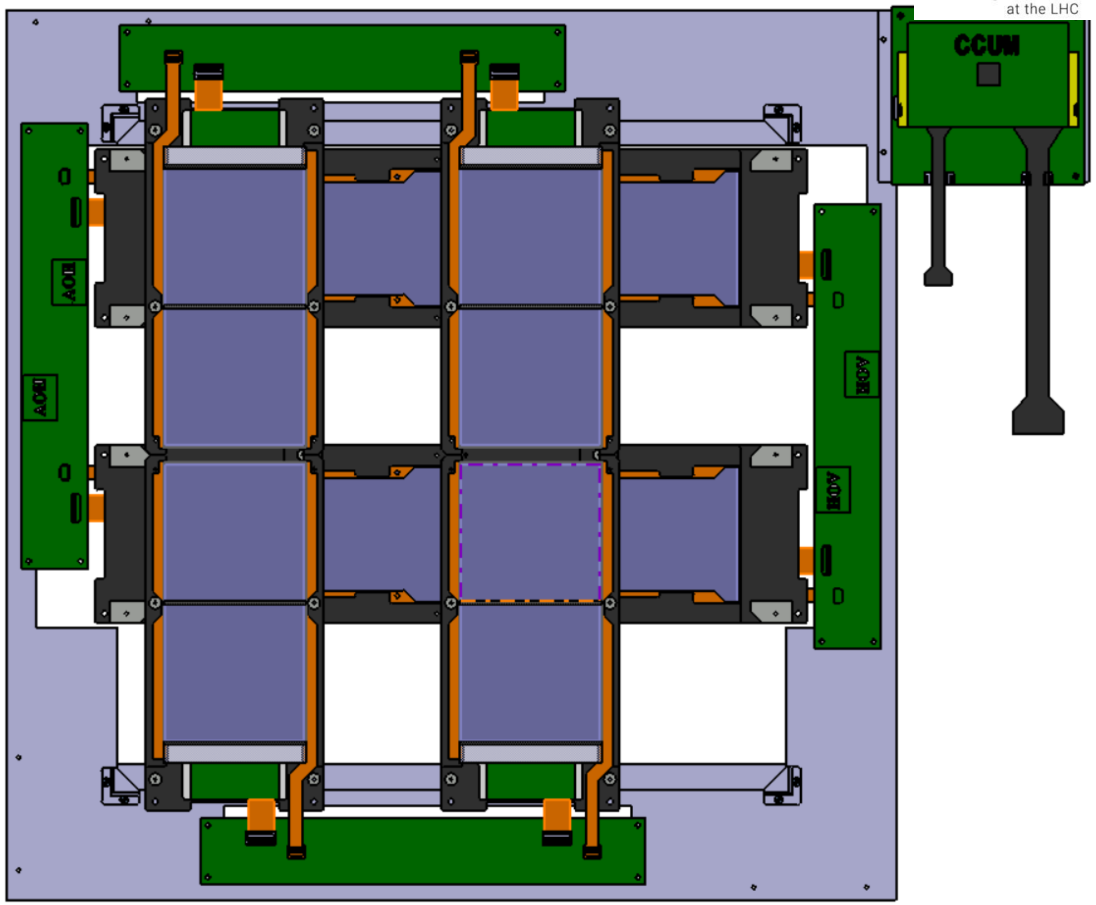
LHC
Scattering and Neutrino Detector
at the LHC

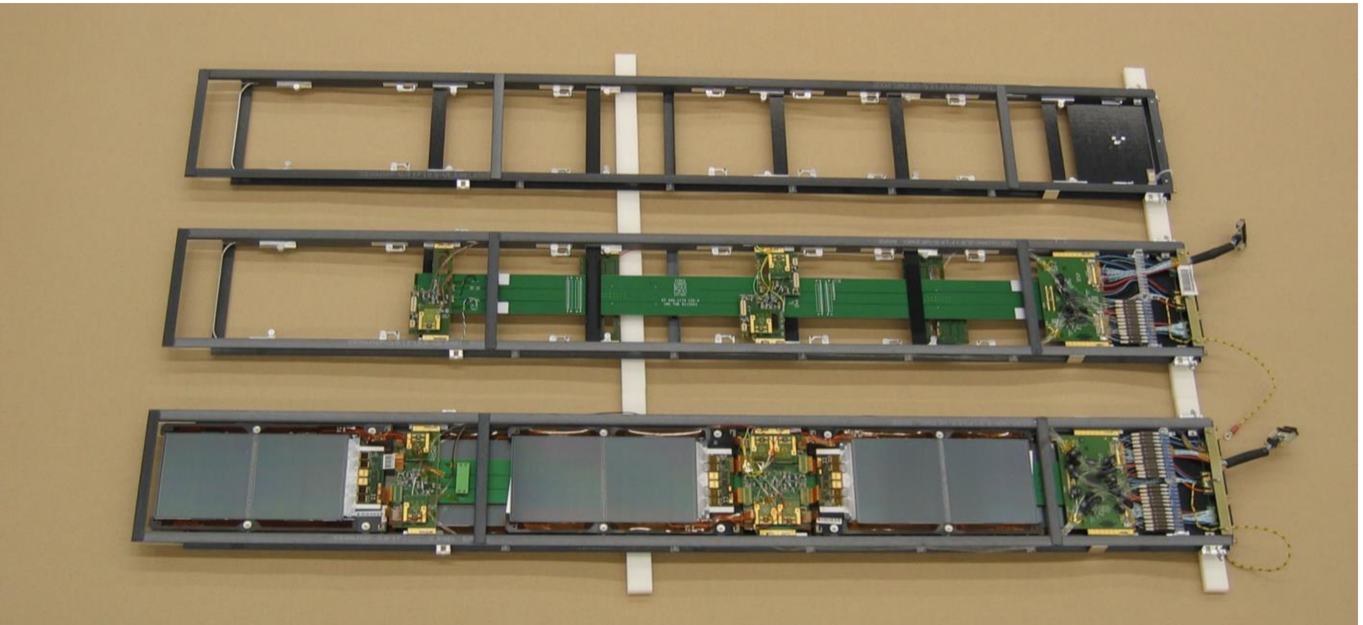
CMS silicon trackers as a vertex/ECAL detector



One module

One station with 8 modules (shown without the embedded tungsten plates)

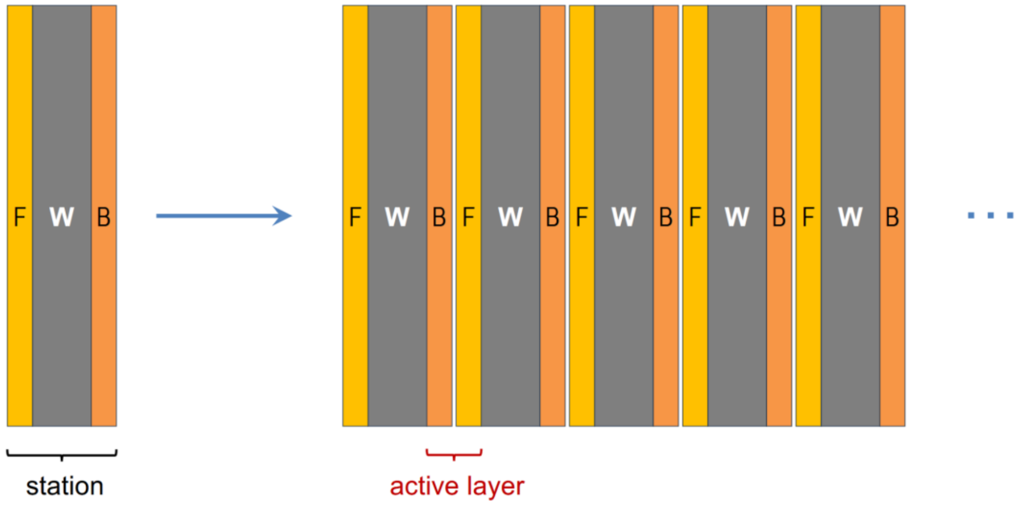


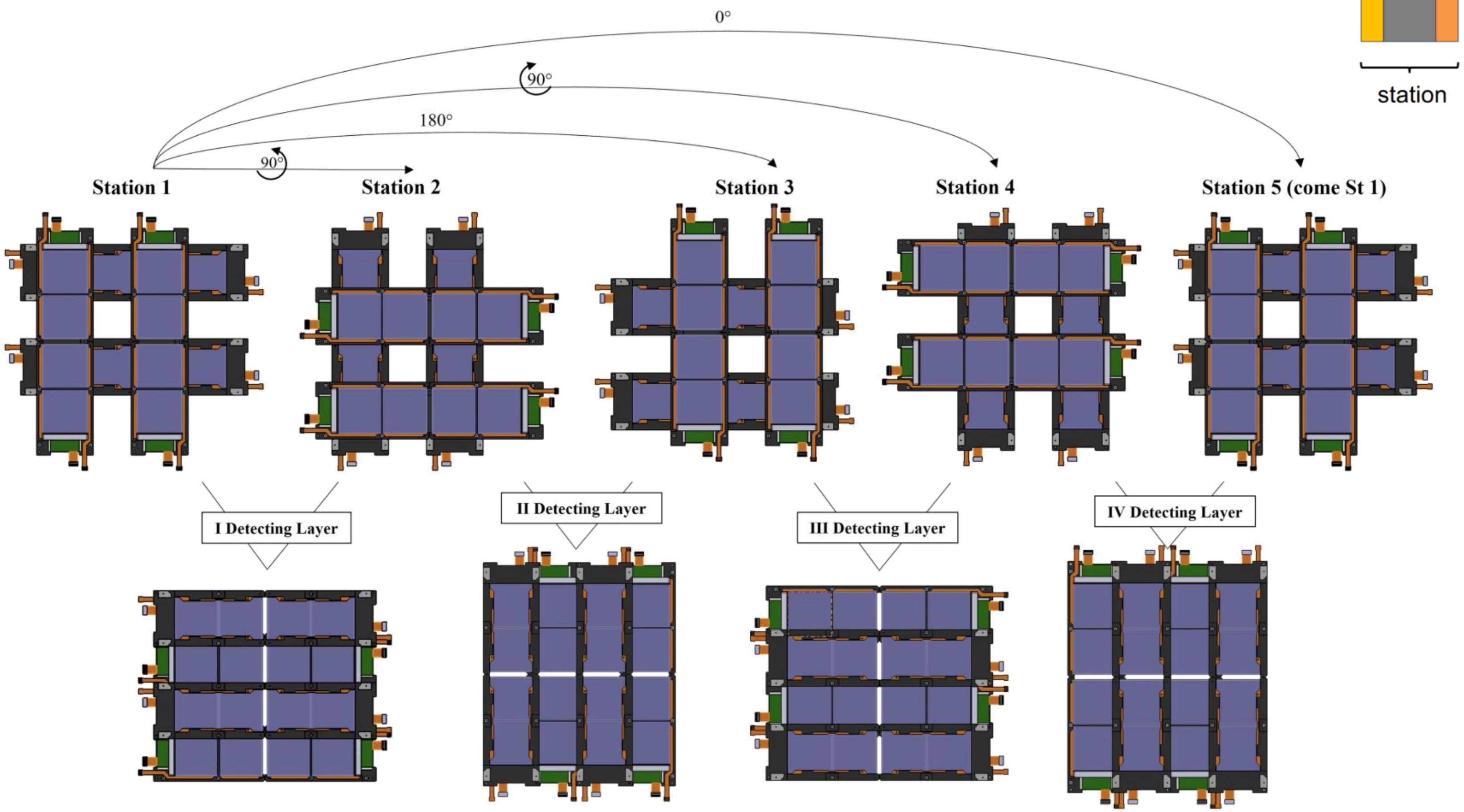


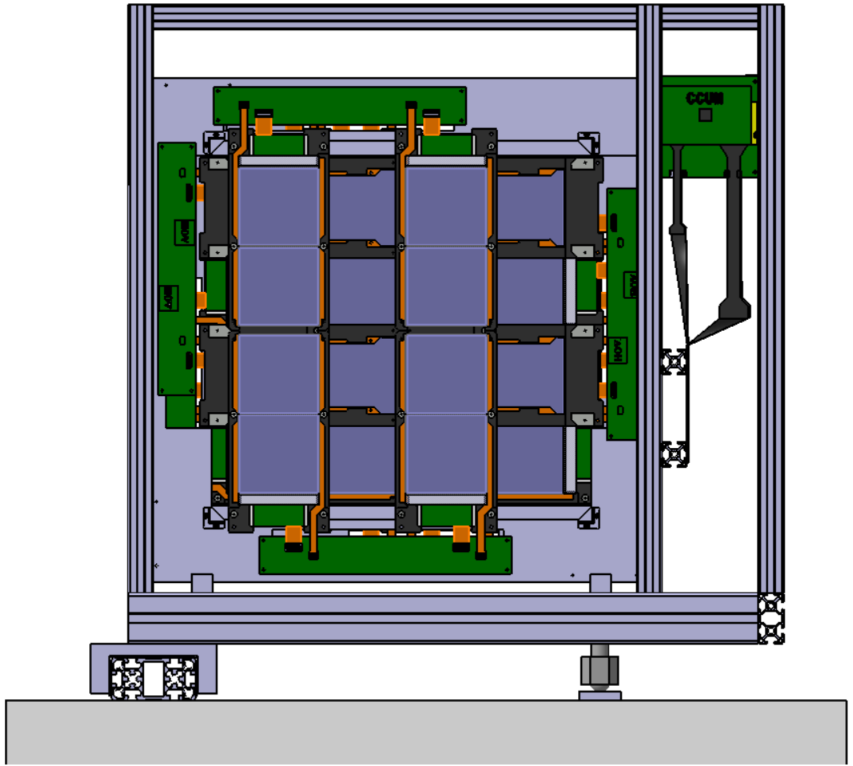
Agreement with CMS to reuse their TOB modules
(and their spare components)
CMS Board approved the request on Feb 9th 2024

Structure of the different stations

One detecting layer is "hermetic"

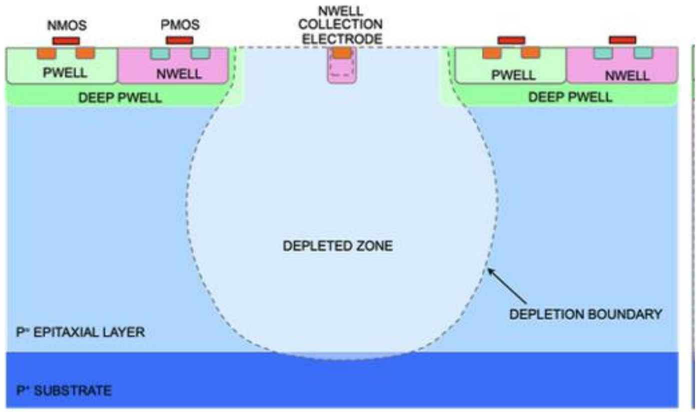




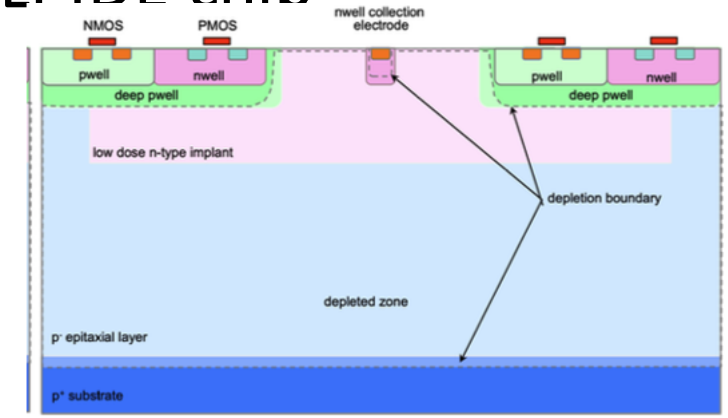


Option: Pixel layers

Option : pixel layers



- Use ALICE ITS3 upgrade development
- Alice pioneered the development of Monolithic Active Pixel Sensors Silicon (MAPS), i.e. pixel detector integrated with the CMOS digital readout for its ITS2 tracker based on the ALPIDE chip
- Improved rad hardness
- And R&D on using Stitching to develop large area detector



The ITS3 large scale Stitched CMOS MAPS
MOnolithic Stitched Sensor (MOSS)

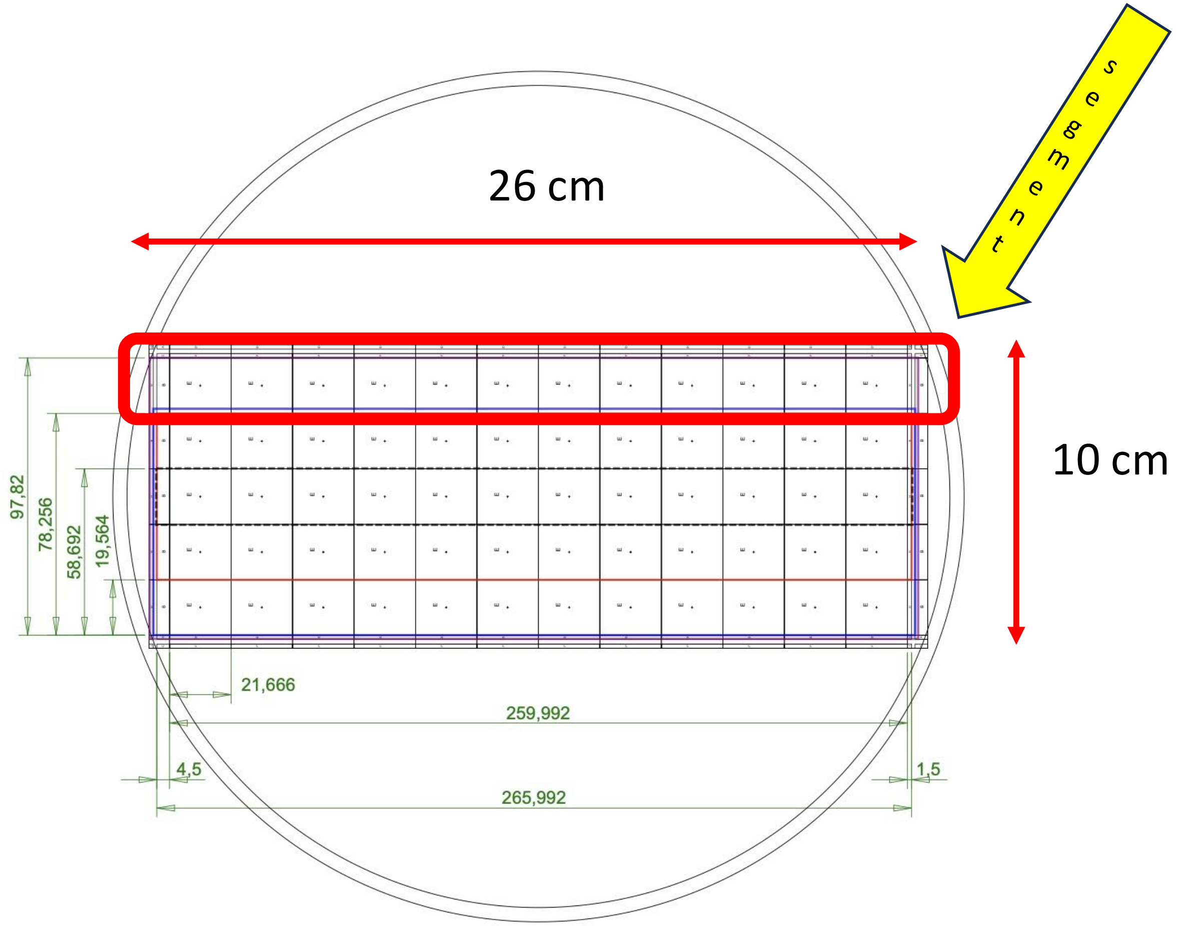
- The major innovation for the ITS3 upgrade is the adoption of stitching: stitching is an industrial procedure to connect reticle sized (30 mm × 30 mm) ASICs with each other to propagate power and signals and thus create wafer scale sized sensors. In the most extreme case, this allows the suppression of the High Density Interconnect circuitry which is standard in the traditional silicon pixel detectors in the sensitive area.
- The proposed detector modules will be using the whole surface of a 12 inches wafer to make modules which are 26x10 cm in size (with ~20x20 μm^2 pixels)

Floor plan for ITS3 MOSS

Made of 5 segments which can be diced separately (in our case we would use the whole 5 segment module)

Each segment has at the edge the circuitry which contains supply pads and differential I/O pads for the control and data readout interconnects.

Each segment has 8 data links (compatible with LPGBT) which can be configured depending on the expected data rate (in our case the data volume is likely to be dominated by intrinsic noise) so we should be able to read each segment with 4 fibers

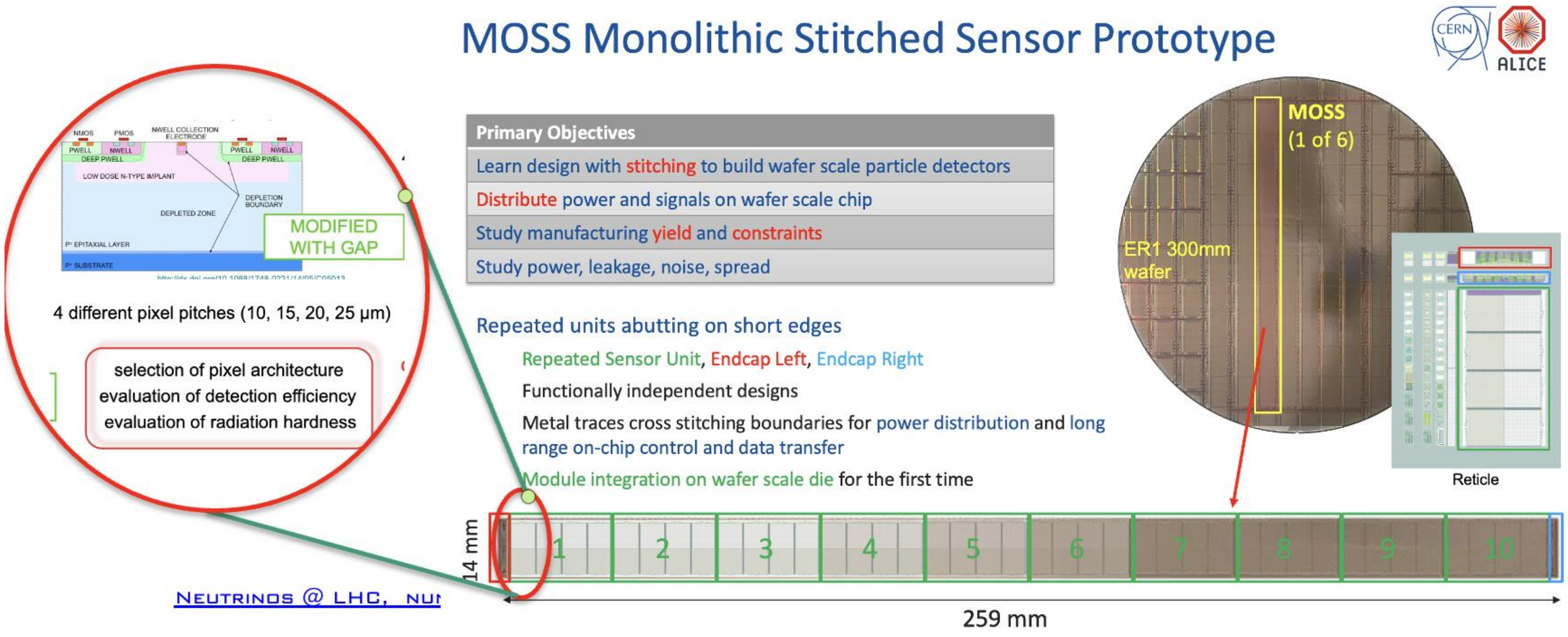


Possible implementation in ADVSND

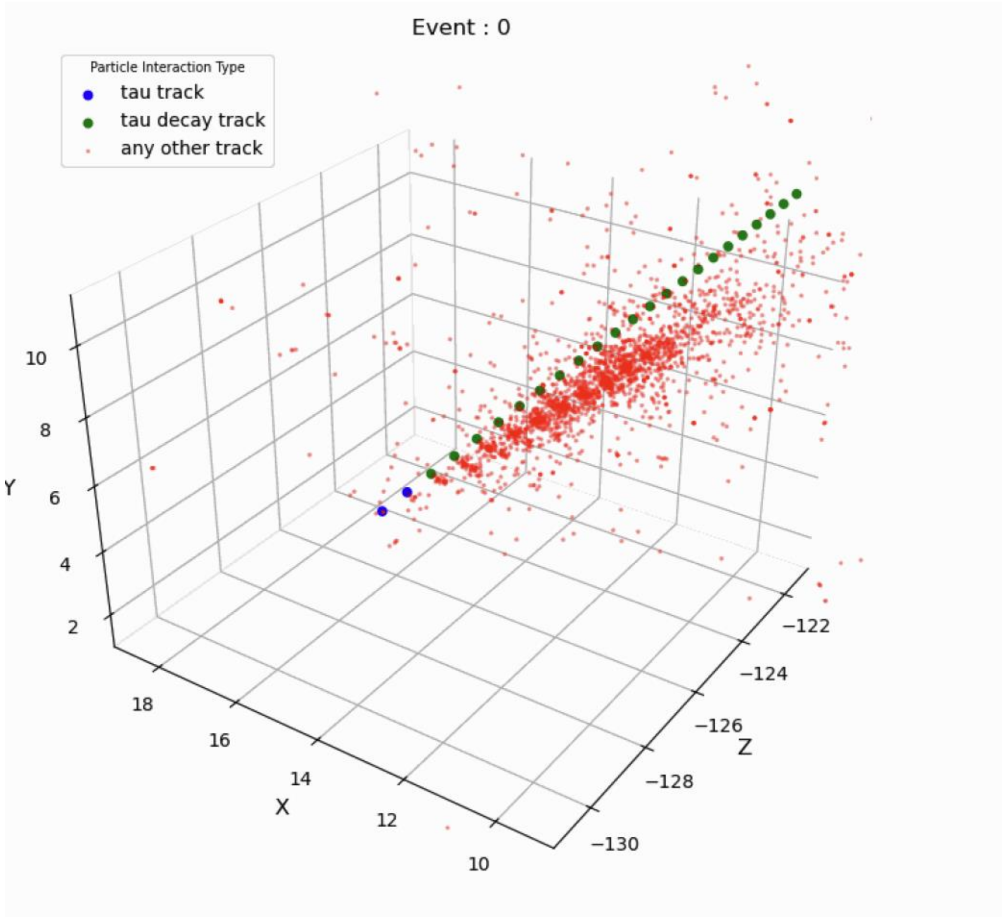
- Replace planes of SI strip: for one plane use 8 MOSS modules arranged horizontally and with 12 cm central overlap (allowing in this area the formation of tracklets !)
- Our application is simpler than for ALICE: no need to thin the wafer,no problem with material (can couple to simple PCB instead of fancy flex circuitry) , full access on the side of the detector for connecting services.
- Each module coupled to a relatively simple PCB which would have Voltage distribution and LPGBT optical drivers

Will MOSS detector be available ?

ALICE has already got back the first prototype wafer aimed to validate the Stitching principle..and it works!
Aim to submit a full detector size (26x10 cm) by end of 2024 and foresees an additonal iteration to get detector grade wafers for end 2025 in order to have detectors to be installed in LS3



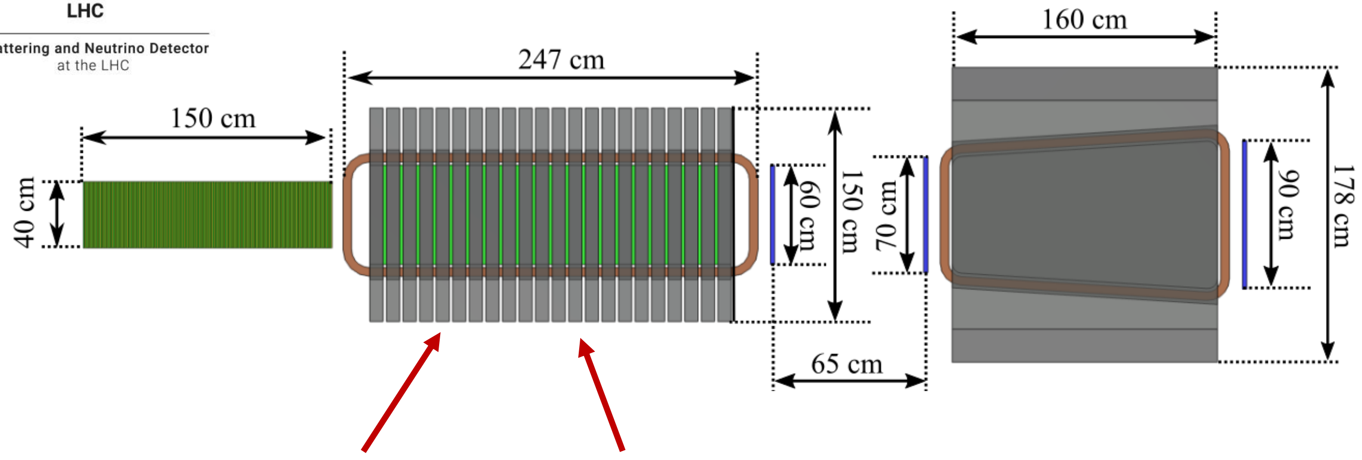
How would a ν_τ interaction look like ?



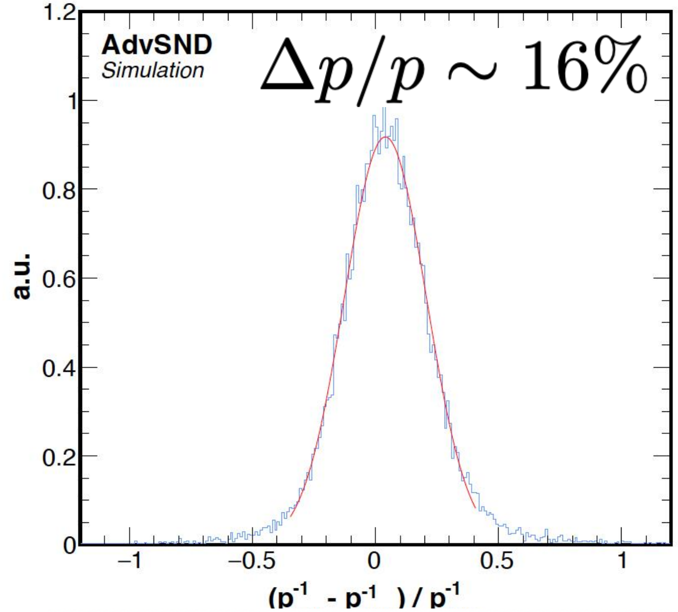
- τ decay to μ and sampled every 8 mm (with 4mm W absorbers layers)

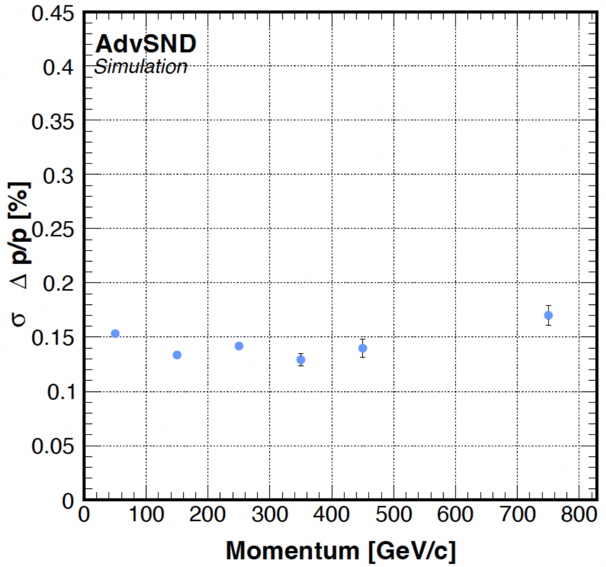
Size of the hits representation is larger than the size of the pixel

HCAL and μ spectrometer

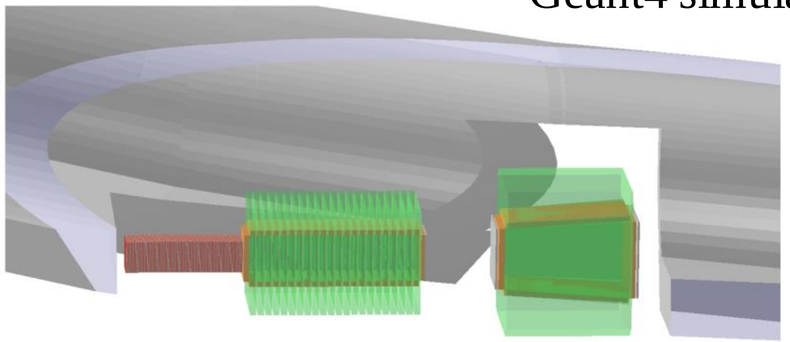


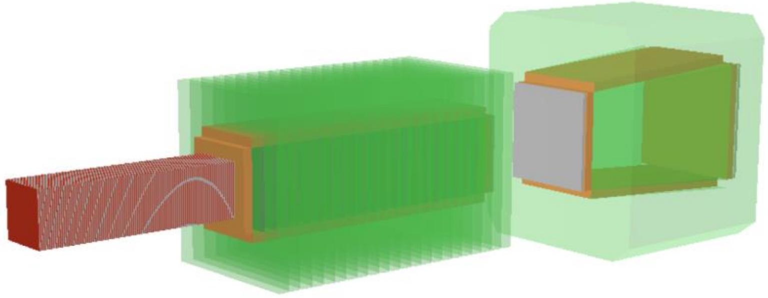
Magnetised Iron slabs interleaved with scintillating bar planes



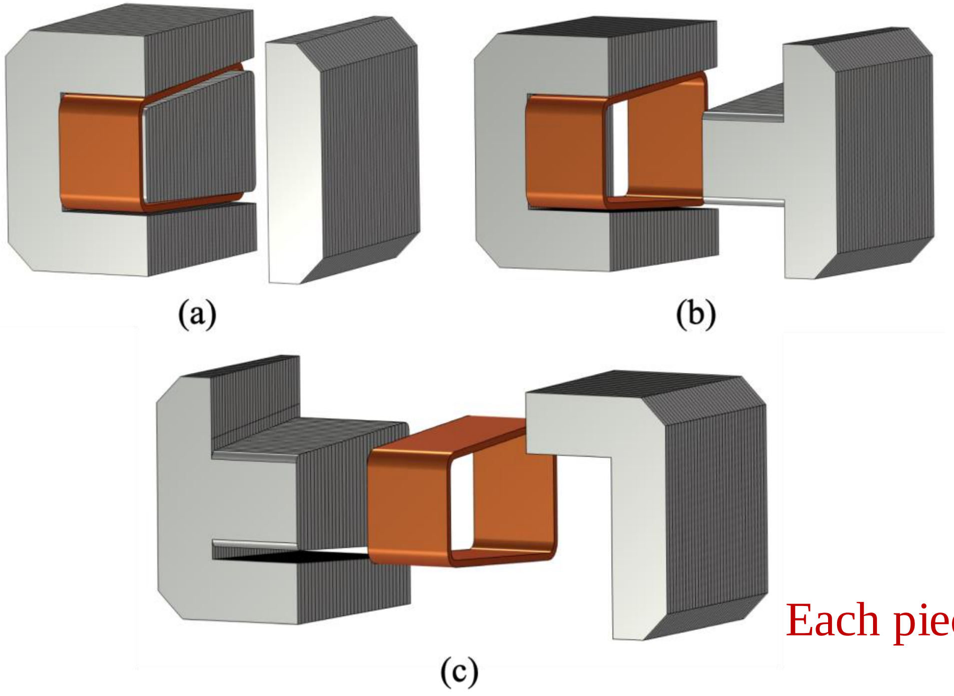


Geant4 simulation



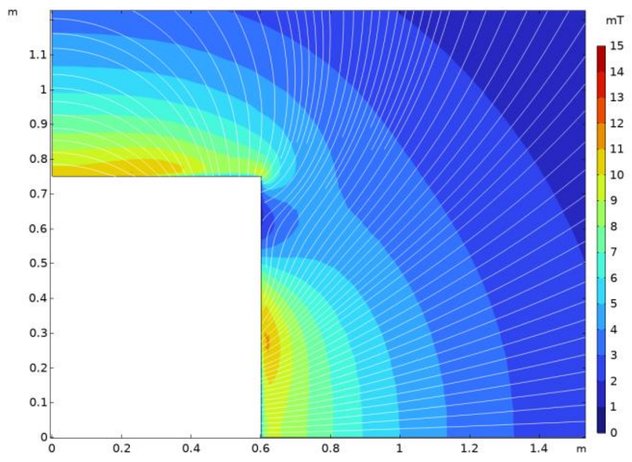


Magnet made of iron pieces to ease transportation and assembly on site

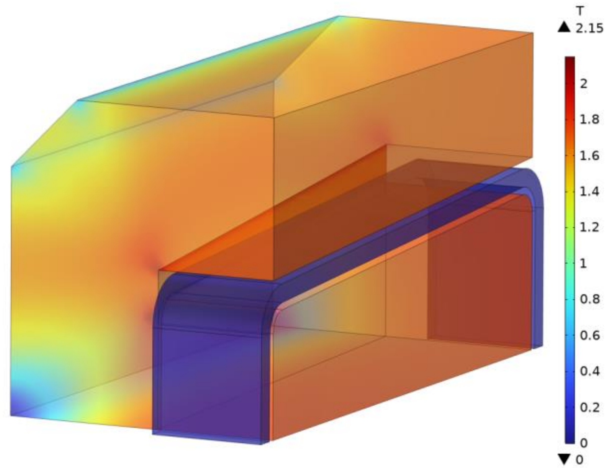


Each piece within 1.0 ton

Stray field well below operational limits



Magnetic flux density



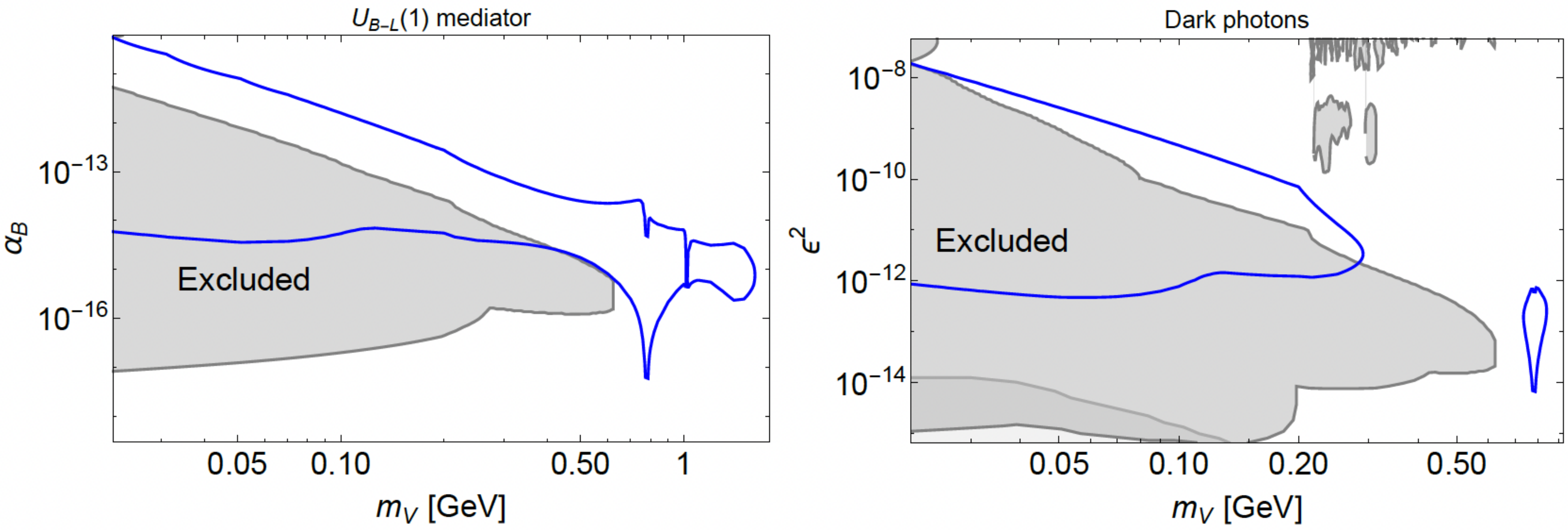
HCM

Stray field [@ iron surface, @ d >2m]	[mT]		[$\lesssim 10 \lesssim 1$]
Voltage at the coil terminals	[V]	V	3.1
Electrical current	[A]	I	500
Current density	[A/mm^2]	J	0.75
Magnetomotive force	[kA]	$\mathcal{F} = NI$	18
Electrical power	[kW]	P	1.5
Total conductor mass	[t]	m_{Cu}	1.3
Mass of a single iron slab	[t]	$\frac{m_{\mathrm{Fe}}}{22}$	1.02
Total iron mass	[t]	m_{Fe}	22.5

DM

Stray field [@ iron surface, @ d >2m]	[mT]		[$\lesssim 10 \lesssim 1$]
Voltage at the coil terminals	[V]	V	3.0
Electrical current	[A]	I	500
Current density	[A/mm^2]	J	0.74
Magnetomotive force	[kA]	$\mathcal{F} = NI$	21.0
Electrical power	[kW]	P	1.5
Total conductor mass	[t]	m_{Cu}	1.25
Total iron mass	[t]	m_{Fe}	33

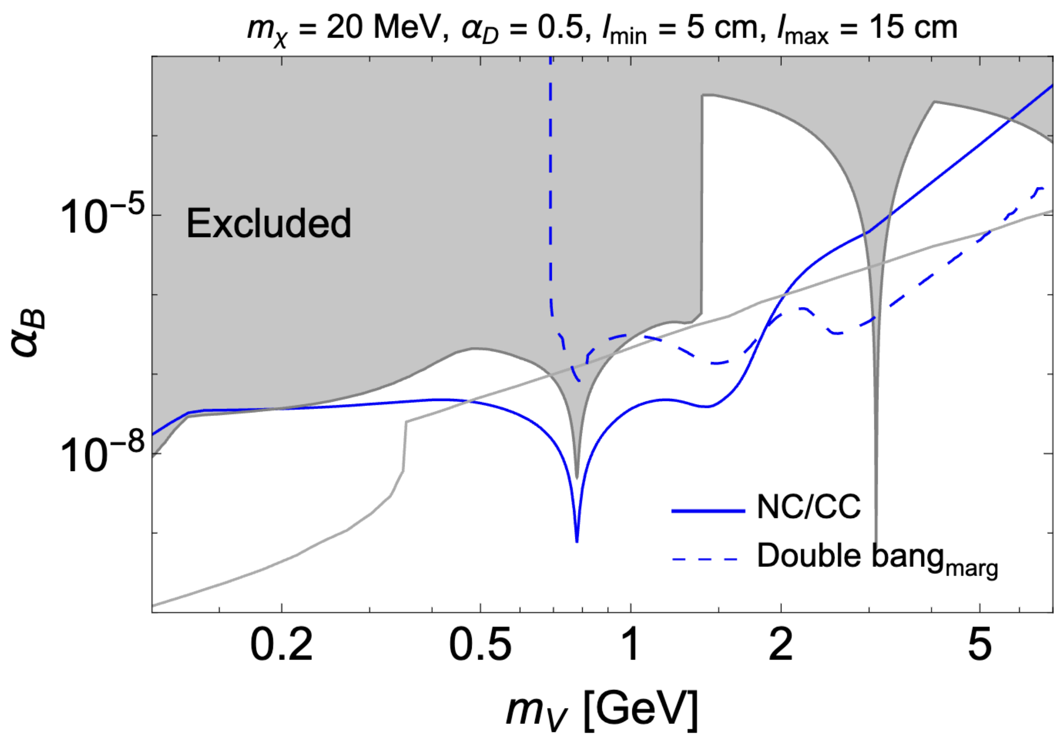
Sensitivity to FIPs (decay)



AdvSND particularly suited to detect FIPs with relatively short proper lifetimes ($c\tau \ll 400$ m). The substantial boost increases their decay lengths ($\gamma c\tau$) → reach and decay within the SND detector.

Dark photons and $B - L$ mediators, with lifetimes not yet ruled out by previous experiments, fall within this category. Within the mass range of $m \lesssim 1$, GeV , they are mainly produced through decays of π^0, η mesons, and proton bremsstrahlung. Upon reaching the detector, they may decay into either a lepton pair or a bunch of hadrons, mirroring the interaction characteristics of ρ^0, ω mesons

Sensitivity to dark matter (scattering)



$$\chi + p/n \to \chi + \text{hadrons},$$

EDM signature

$$\chi + p/n \to \chi' + \text{hadrons}, \quad \chi' \to \chi + \text{hadrons}$$

IDM signature

LDM coupled to a baryonic mediator: elastic DM model (EDM, solid blue), where the signature is an increase of the NC/CC ratio due to scatterings, and the inelastic DM model (IDM, dashed blue), with the signature being "double bang" – a scattering with the subsequent displaced decay

Only inelastic scattering off protons considered. For the EDM signature, 10% accuracy in the NC/CC measurement is assumed. IDM signature: for the first bang, a minimal energy deposition of 600 MeV is required; the minimal/maximal displacements l_{min} and l_{max} range between 5 and 15 cm; the lighter particle mass is assumed to be m_χ = 20 MeV, to avoid the direct detection constraints on DM for the EDM case that become relevant at masses ≳ 100 MeV (bounds absent in the IDM case), while the marginalization is made over the mass splitting between χ' and χ

New era of collider neutrinos started!

LHC
Scattering and Neutrino Detector
at the LHC

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

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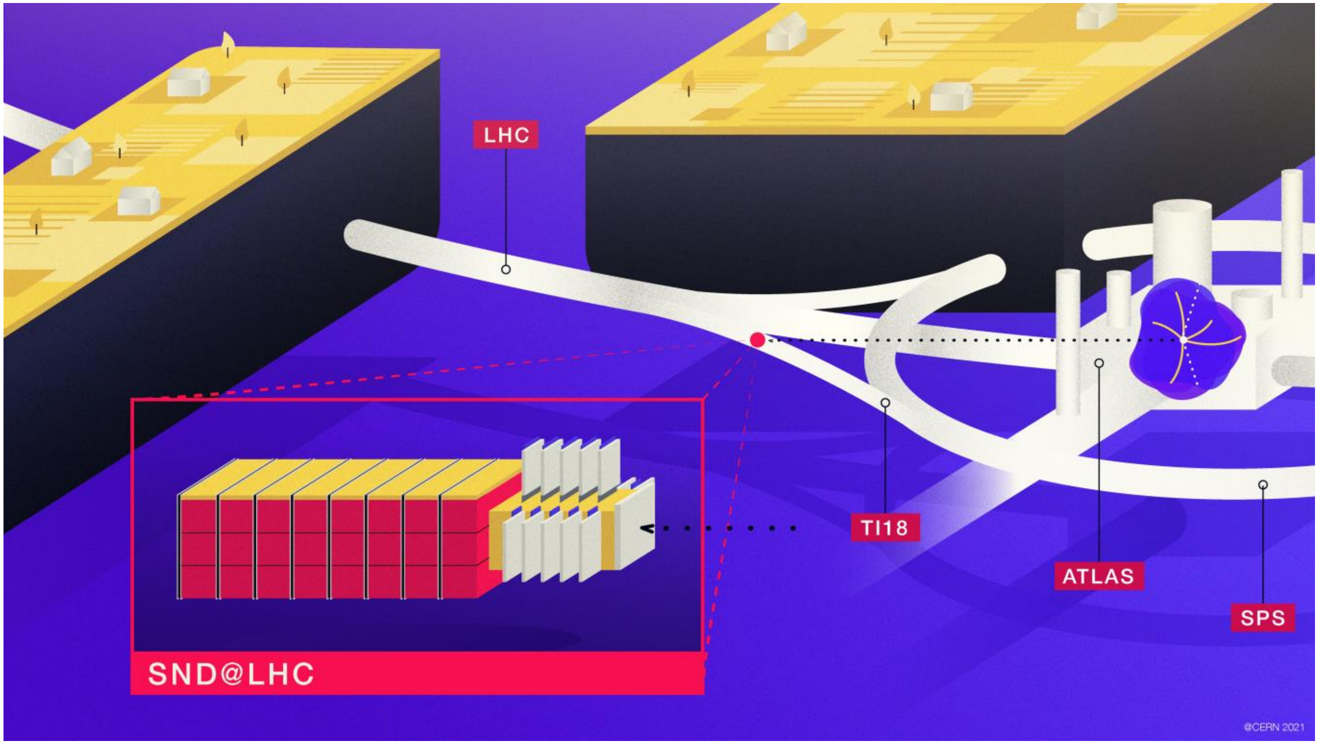
NEUTRINOS | NEWS

Collider neutrinos on the horizon

2 June 2021



Stay tuned!

Backup

Detector(s) concept to extend the physics case in HL-LHC

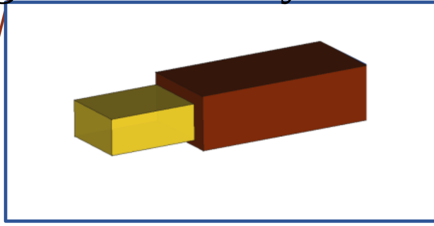
AdvSND-Far in TI18 (Run 4)

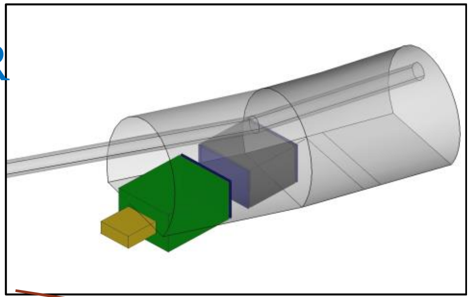
- Improve statistics, reduce systematics
- Separate ν from ν-bar
- Charm production measurements
- LFU

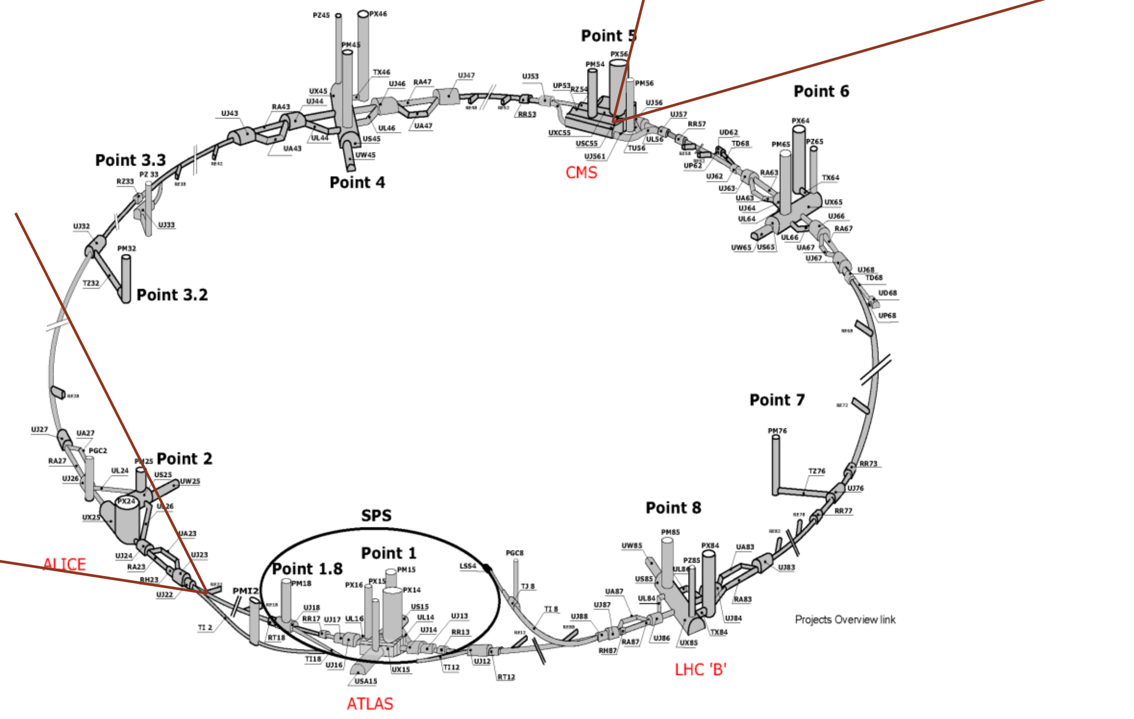
AdvSND-Near in UJ57/UJ56 (Run 5)

- Overlap with LHCb η where c/b measured
- Reduce sys uncertainties for the FAR
- ν cross-section

AdvSND-Near: $4.0 < \eta < 4.5$
Other η region covered by LHCb







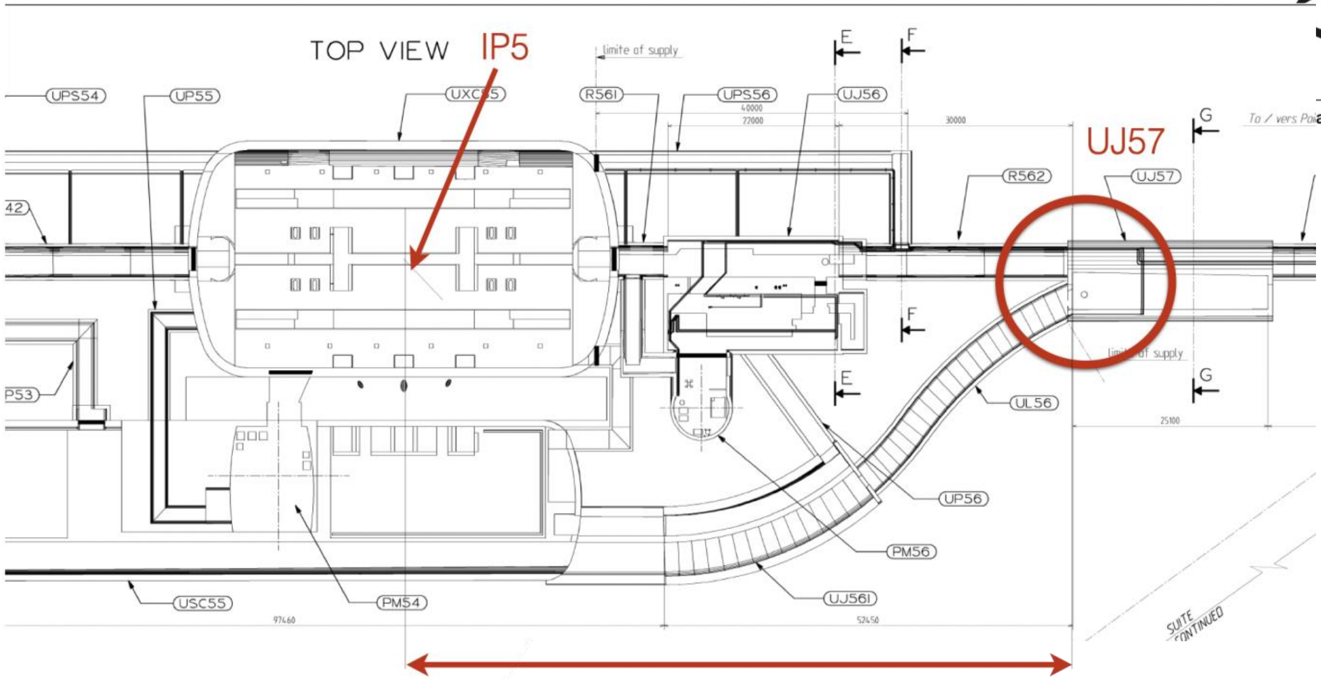
AdvSND-Far: $\eta > 7.9$

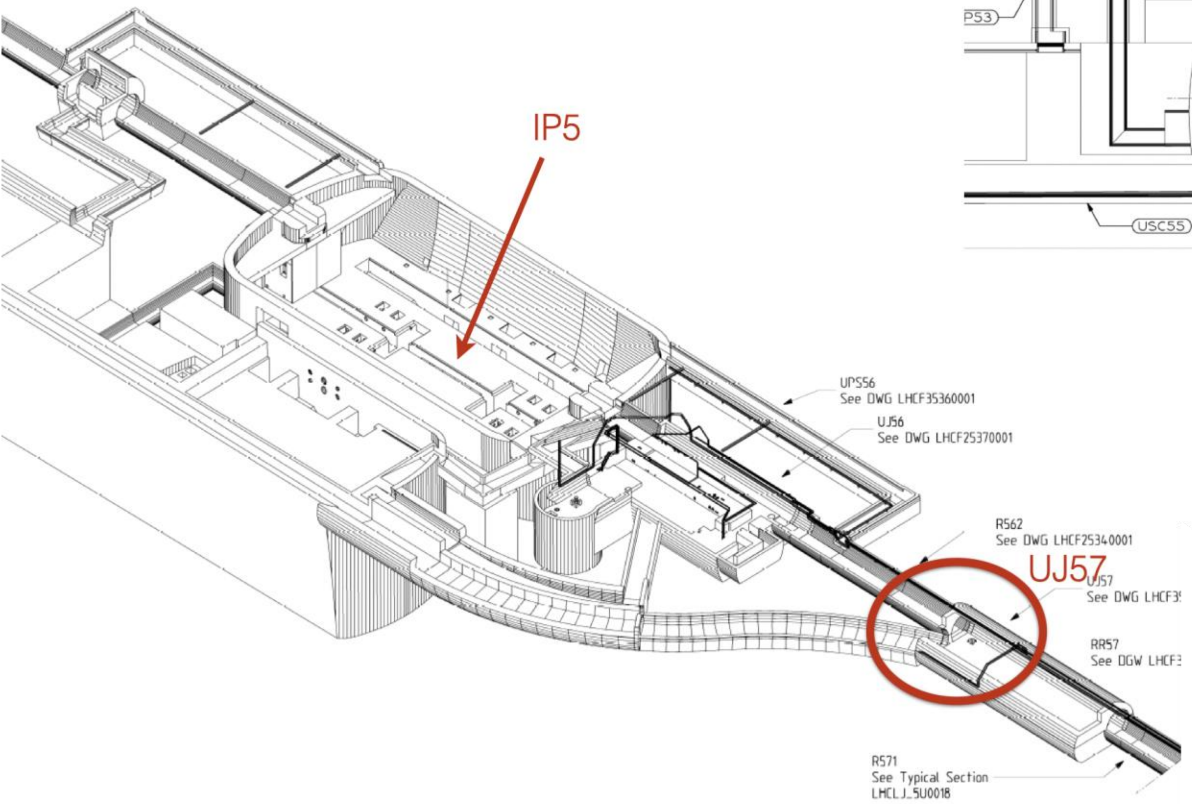
Studies for the NEAR detector (Run 5)

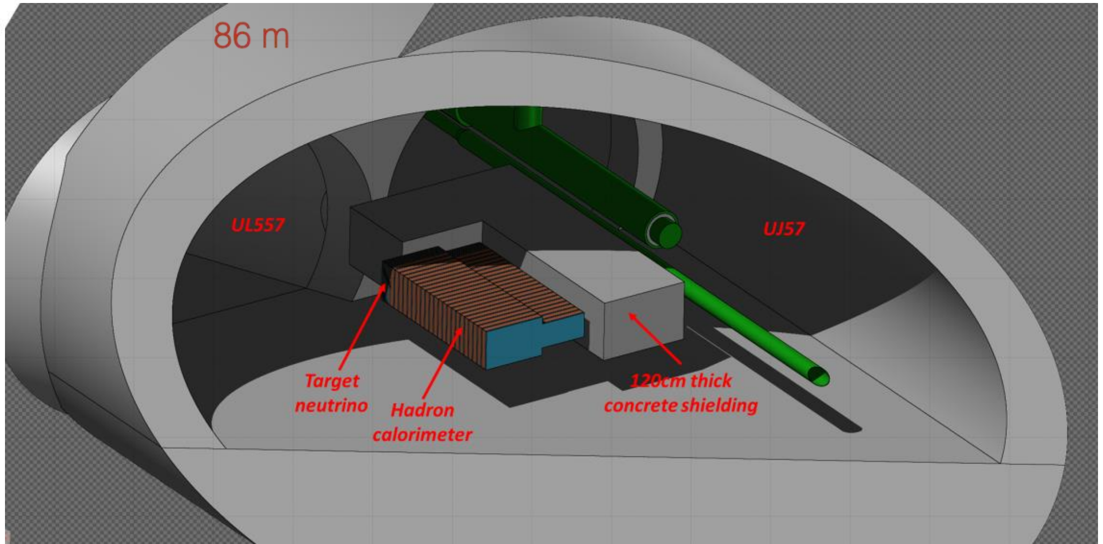
LHC
attering and Neutrino Detector
at the LHC

UJ57 tunnel at 86 m from CMS IP

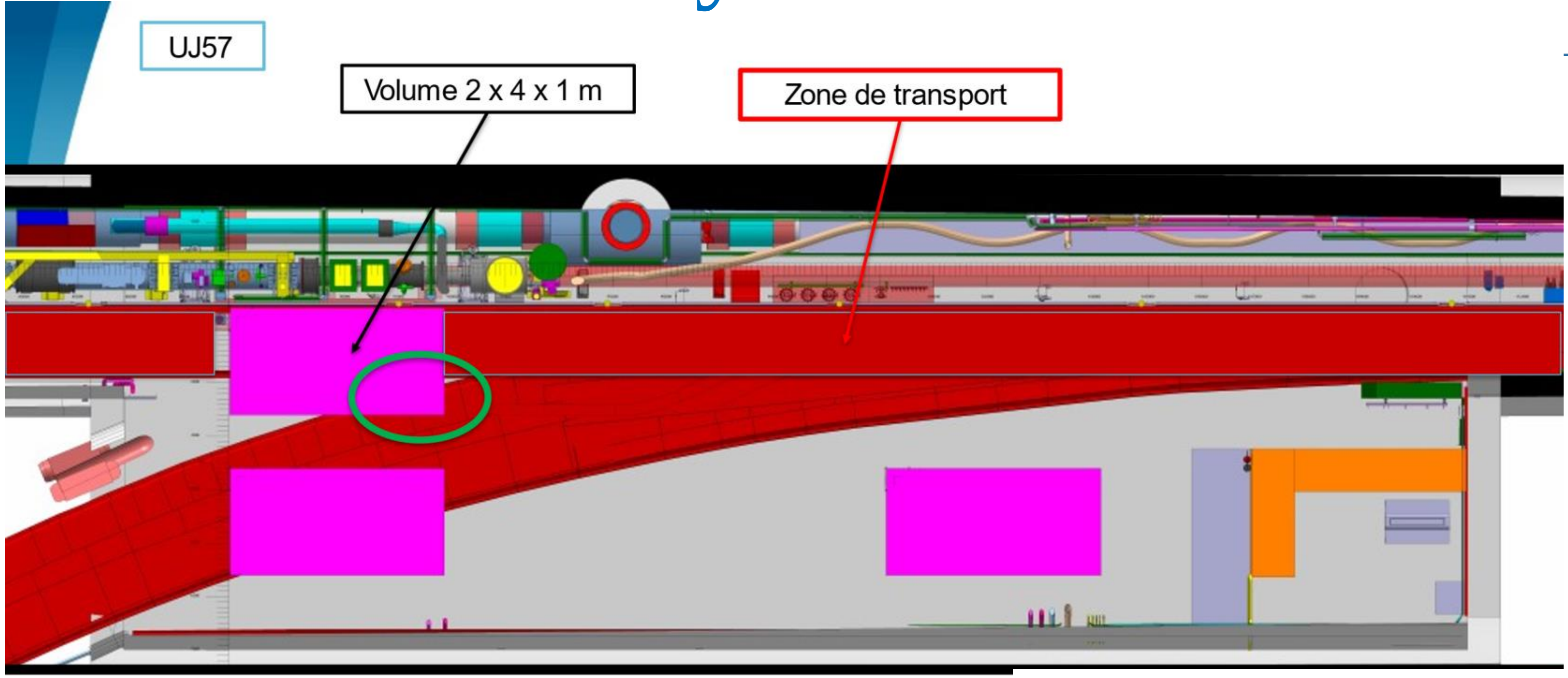
Sufficiently close to allow triggering CMS (→ 4π view of the event)





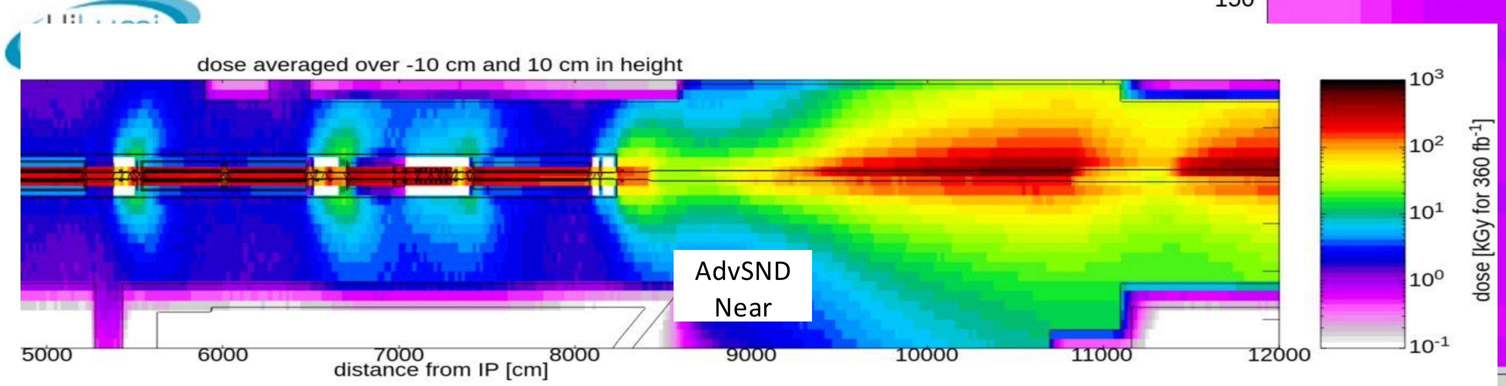


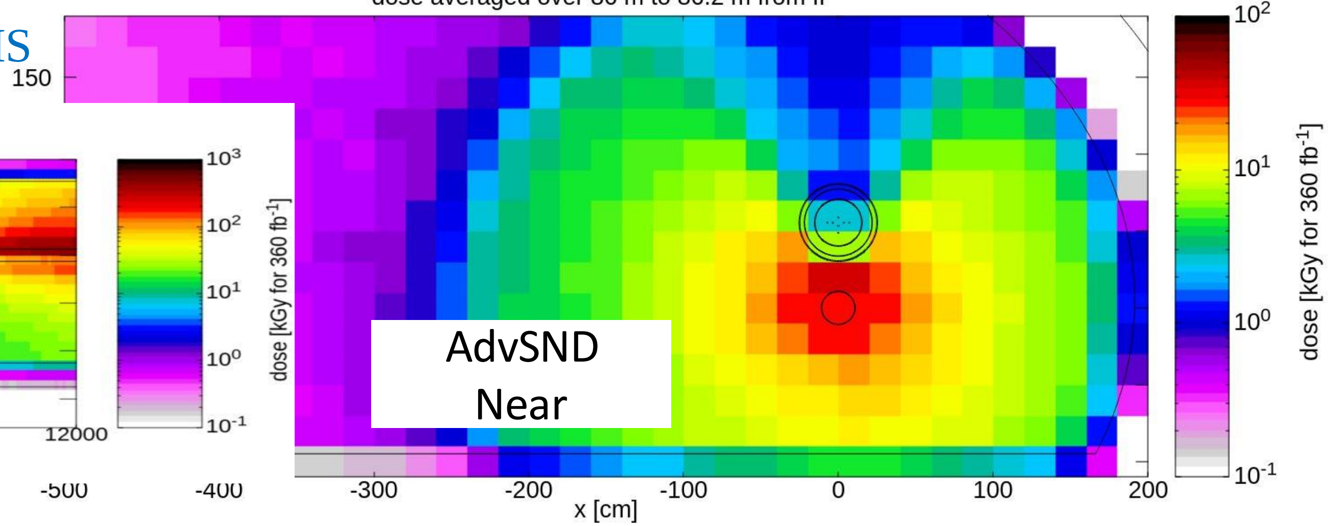
Preliminary studies of the NEAR detector



Dose distribution in the transverse plane, 86 m from CMS

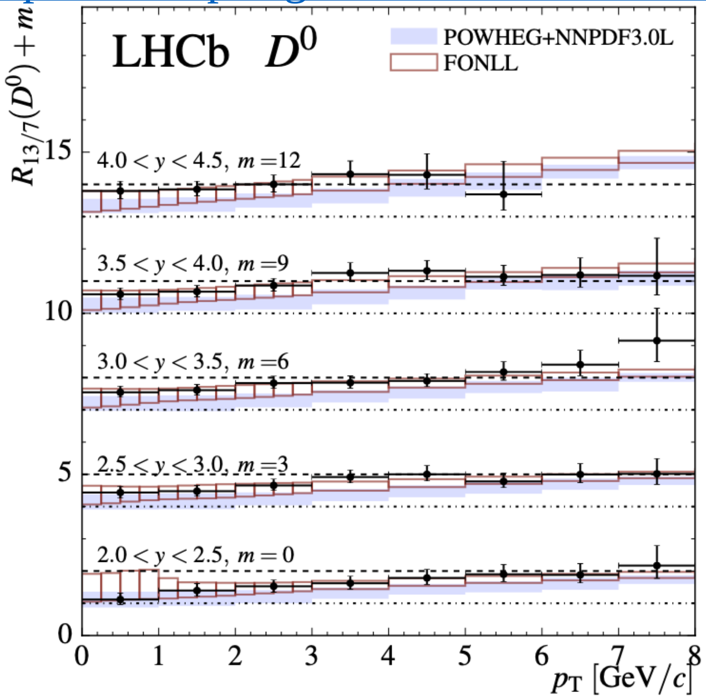
Dose distribution along the beamline vs distance from CMS

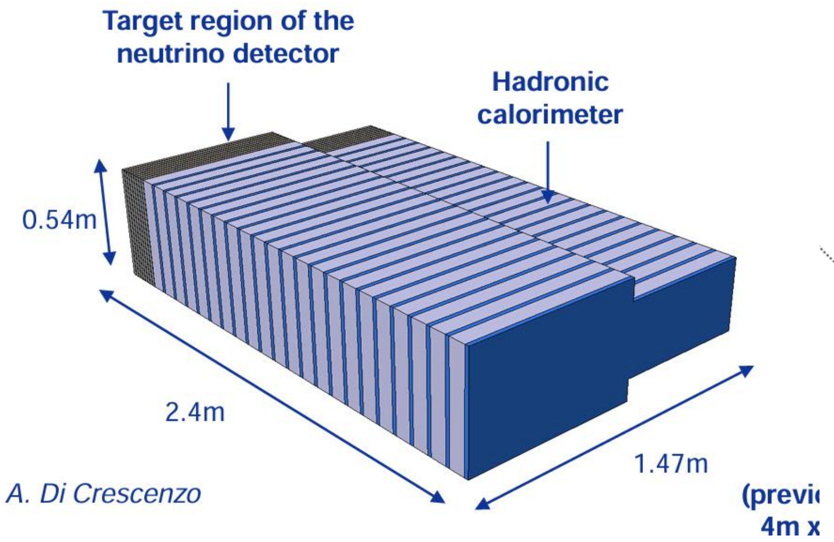


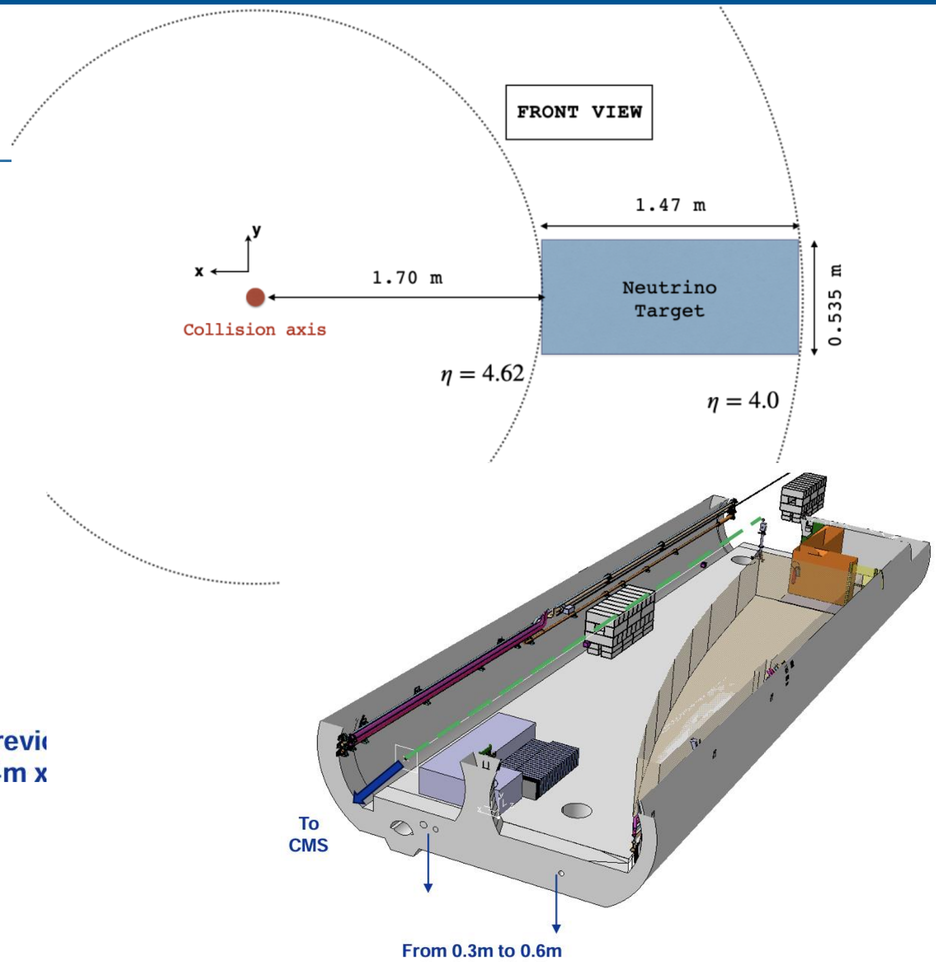


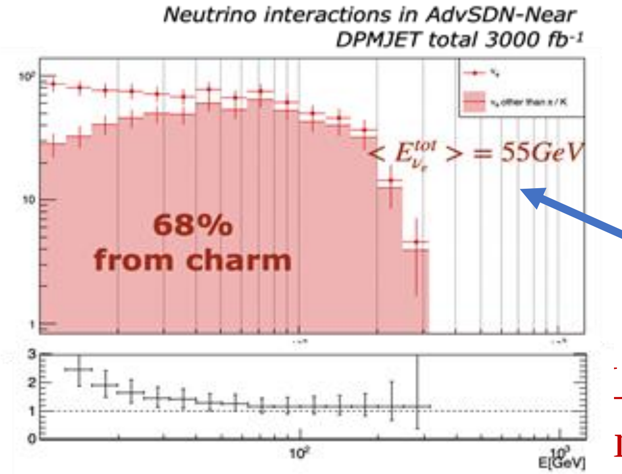
LHCb measurements and ν

https://link.springer.com/article/10.1007/JHEP05(2017)074









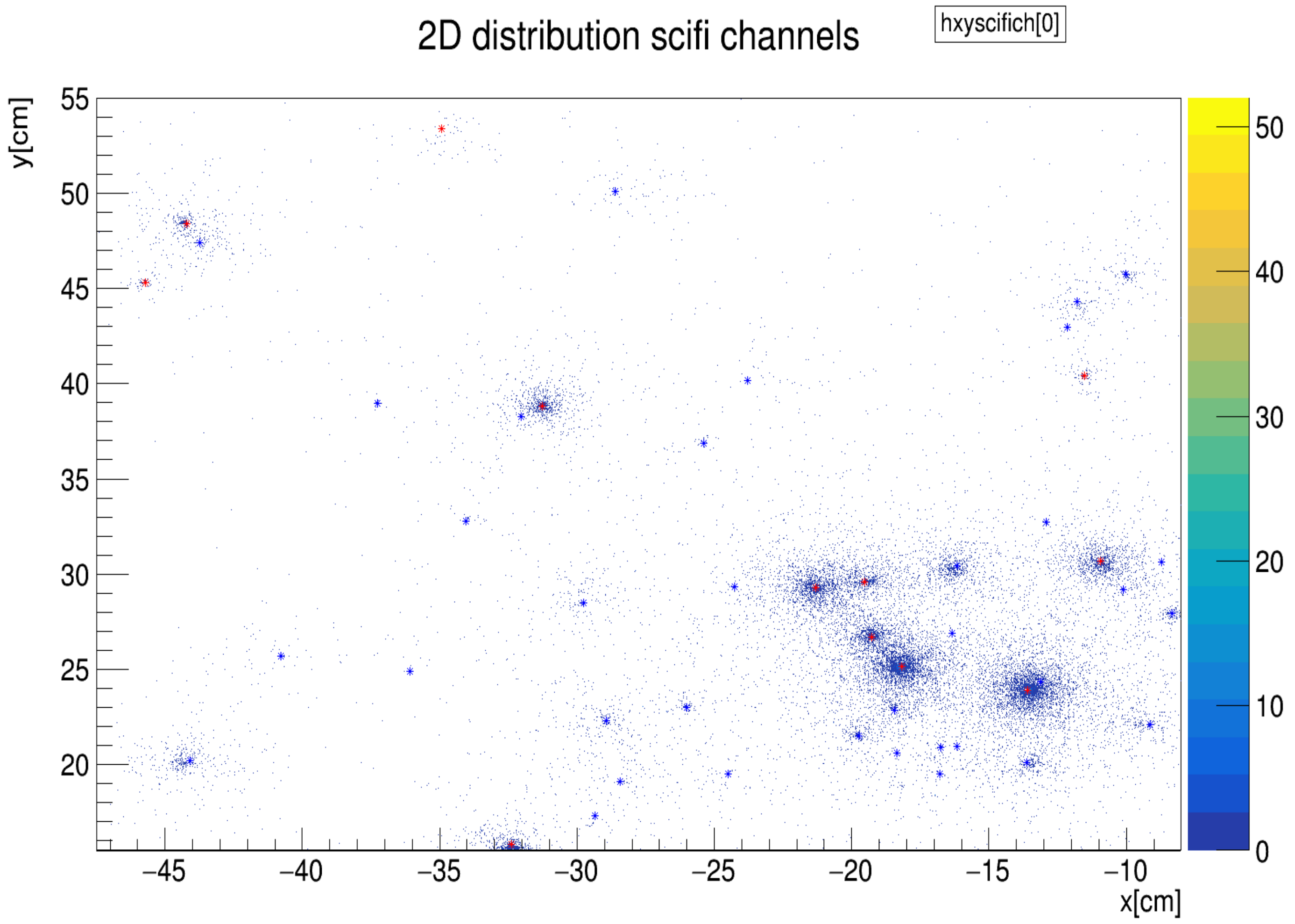
LHCb ~ 180k charmed hadrons
n the 4 to 4.5 η range → ~ 18k ν_e

Flavour	CC DIS Interactions (3000 fb^{-1}) total (DPMJET)	cc-bar (DPMJET)	cc-bar (PYTHIA8)	bb-bar (PYTHIA8)
$\nu_\mu + \bar{\nu}_\mu$	1.7x10^4	1.0x10^3	0.9x10^3	47
$\nu_e + \bar{\nu}_e$	1.8x10^3	1.1x10^3	1.0x10^3	50
$\nu_\tau + \bar{\nu}_\tau$	75	75	75	10
Total	**1.9x10^4**	**2.2x10^3**	**2.0x10^3**	**107**

SCINTILLATING FIBRES

Emulsion-SciFi alignment

Expected neutrino CC DIS interactions in a single wall in 25fb^{-1}: 35 ν_μ, 12 ν_e



Hit map on the SciFi plane immediately downstream of the emulsion/tungsten wall

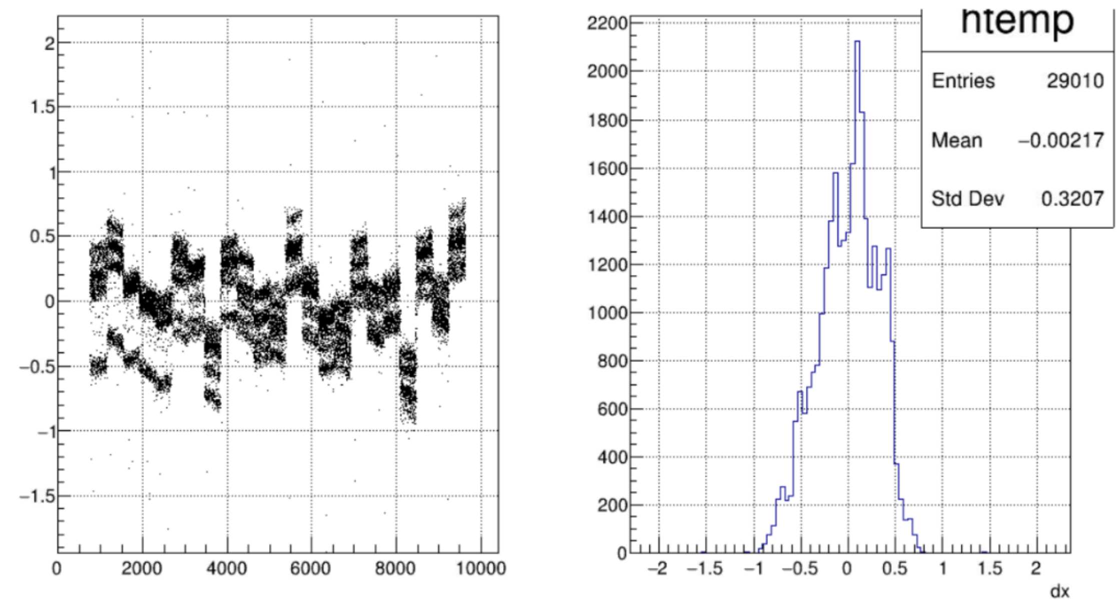
TARGET WALL INSTALLATION ON APRIL 7TH

LHC
Scattering and Neutrino Detector at the LHC

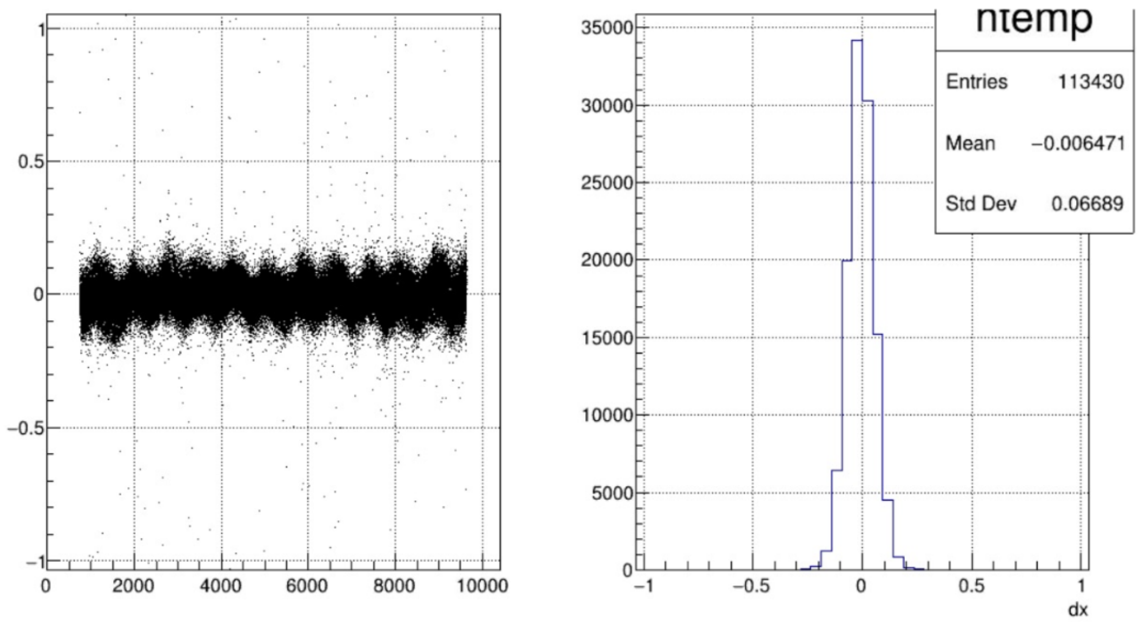
¼ of one wall (the central one) equipped with nuclear emulsions

(Amazing) Resolution of emulsions

Reproducibility: high-frequency oscillation due to mechanics and environmental parameters, up to ~0.3 μm



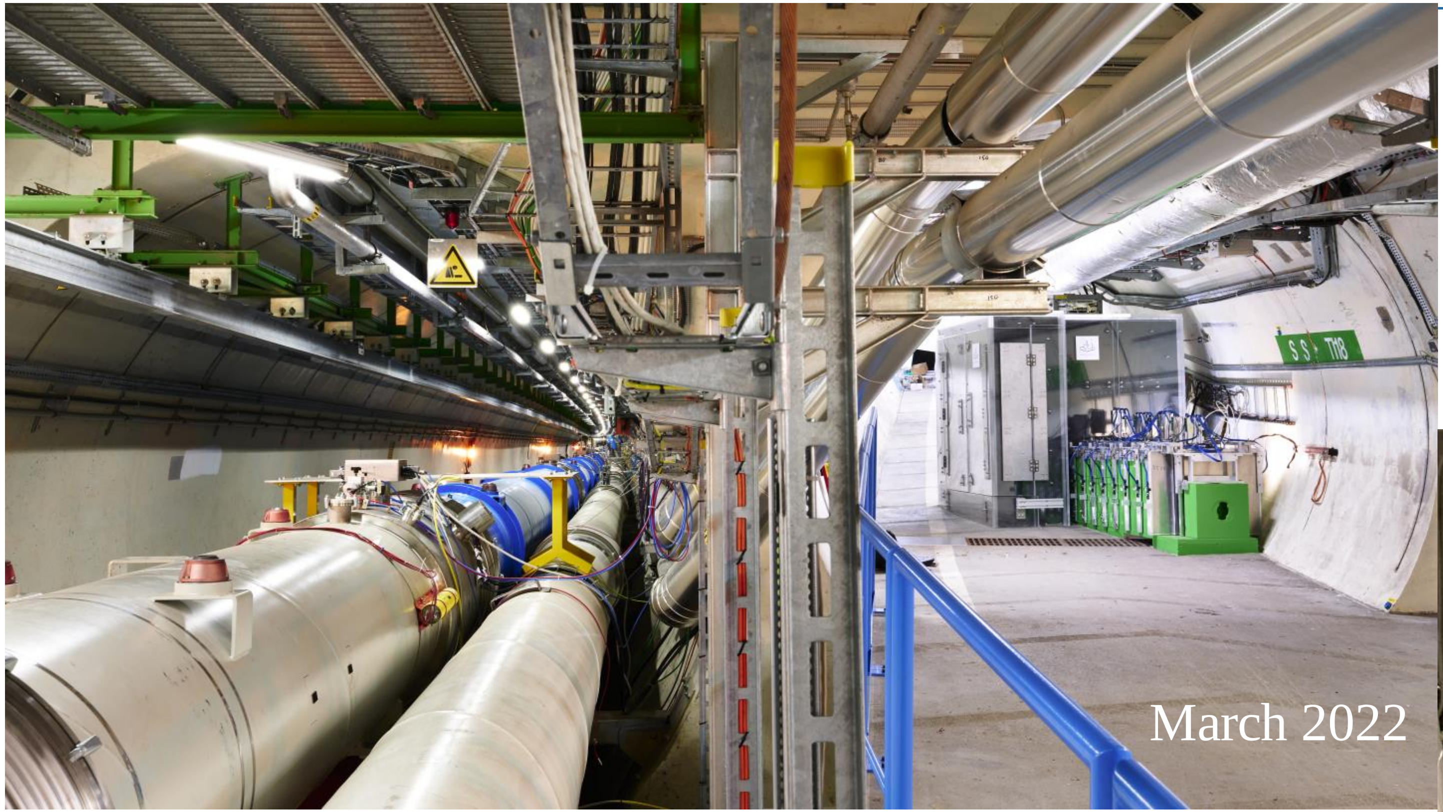
New software corrections applied thanks to the tracks in the overlap of adjacent views → 0.07 μm



This corresponds to 0.5 μm resolution over the full muon track extrapolation

….which is ok to be able to reconstruct all the throughgoing muons who are typically separated by ~10 μm (for a 20 fb^{-1} exposure)

Detector view in 2022 and in 2023



March 2022

March 2023