Status of the SND@LHC experiment

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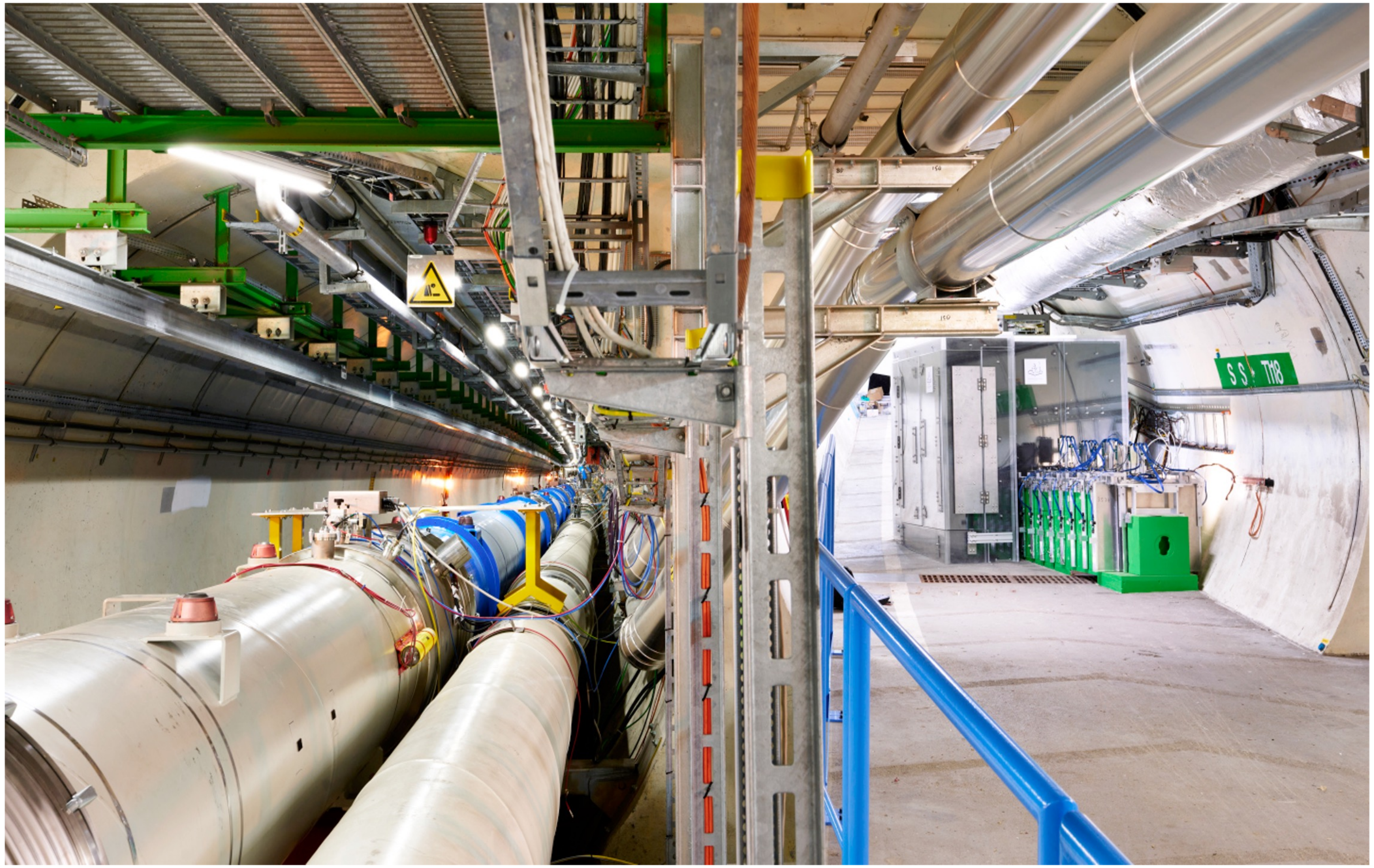
LHC
Scattering and Neutrino Detector
at the LHC



Neutrino production at LHC

An old Idea: A. De Rùjula, R. Rükl, 1984, Neutrino And Muon physics in the collider mode of future accelerator,CERN-TH-3892-84

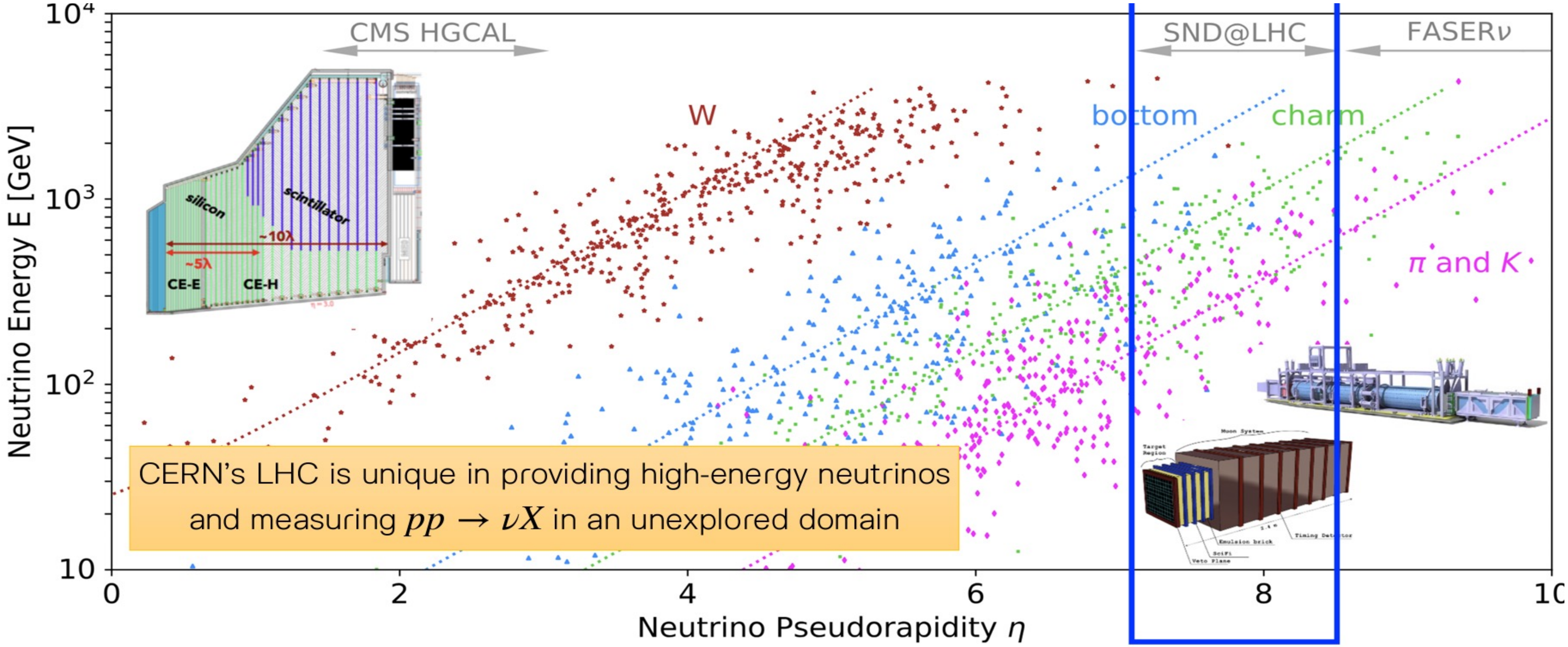
Which has become reality

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

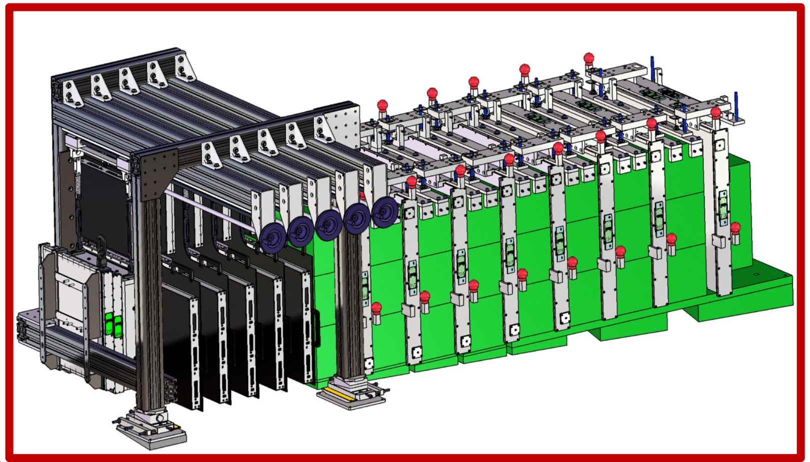
N Beni[1], M Brucoli[2], S Buontempo[5], V Cafaro[4], G M Dallavalle[4,8], S Danzeca[2], G De Lellis[2,3,5], A Di Crescenzo[3,5], V Giordano[4], C Guandalini[4], D Lazic[6], S Lo Meo[7], F L Navarria[4] and Z Szillasi[1,2]

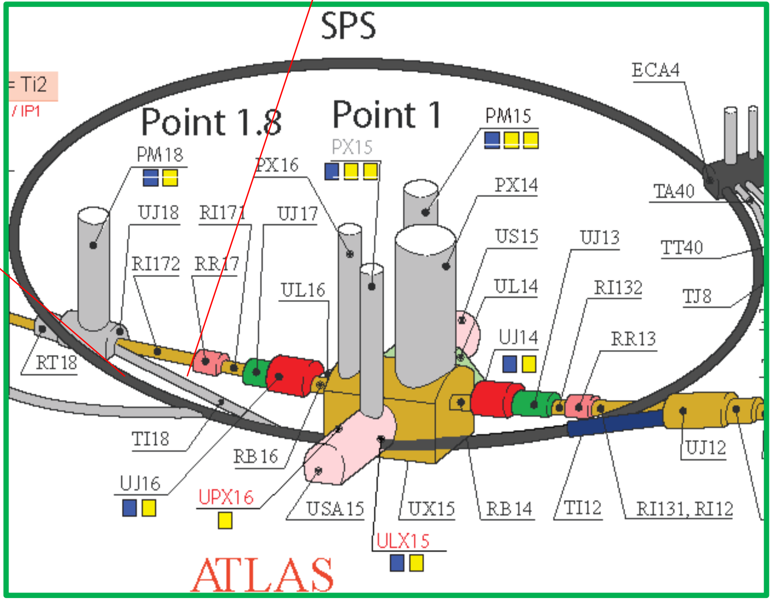


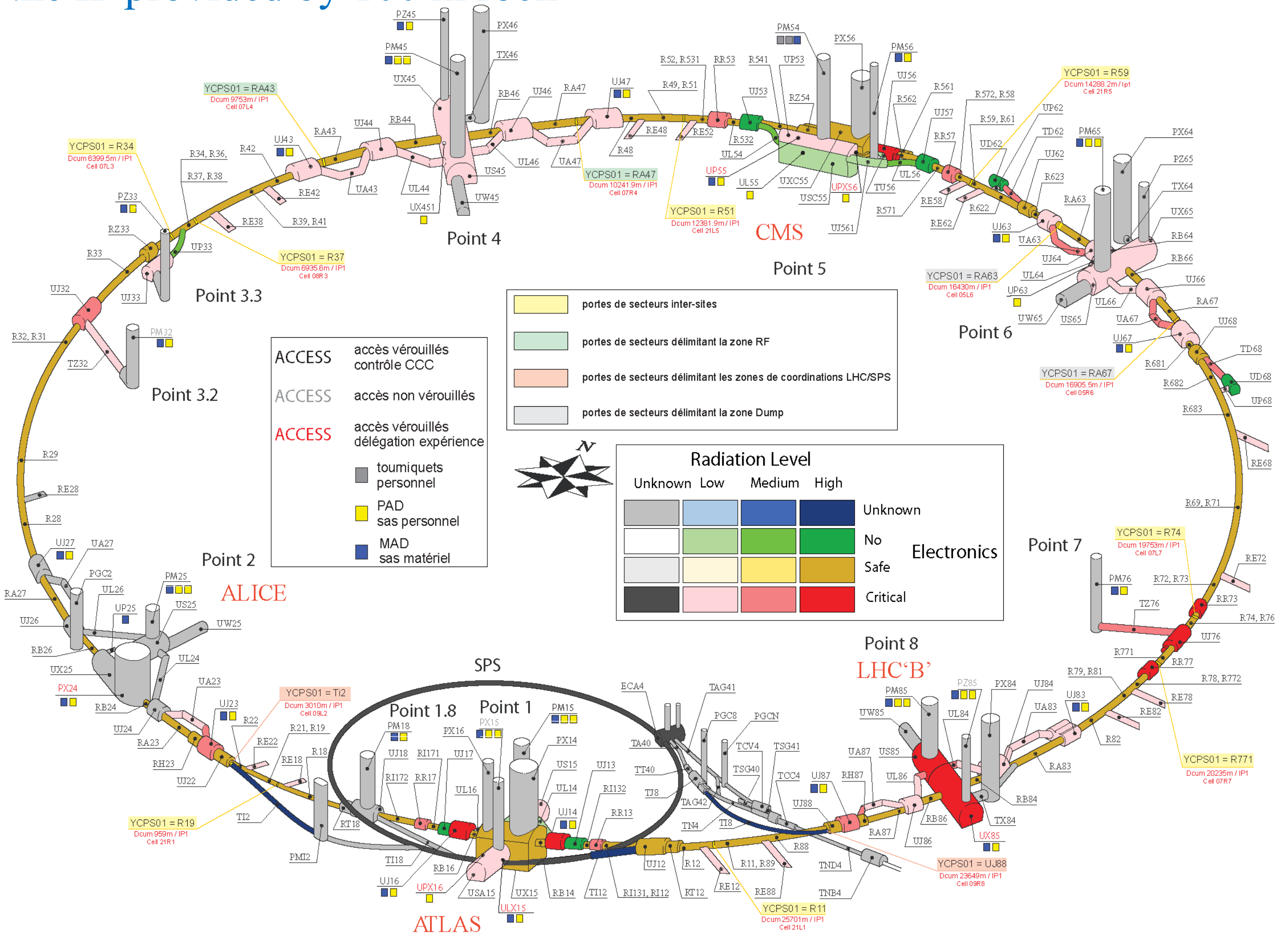
Location: TI18, transfer tunnel connecting SPS to LEP

LHC
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







Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

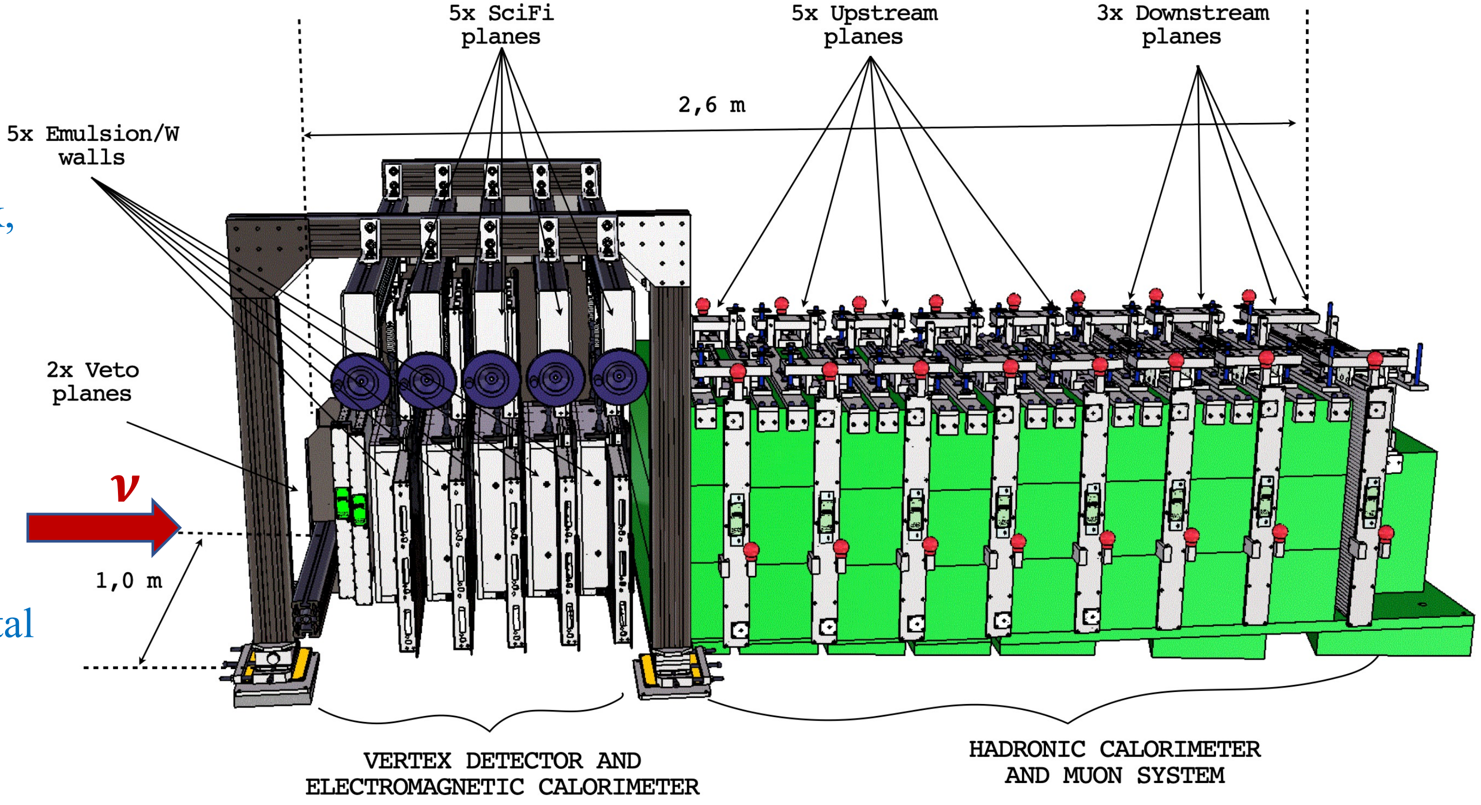
VETO PLANE:
tag penetrating muons

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

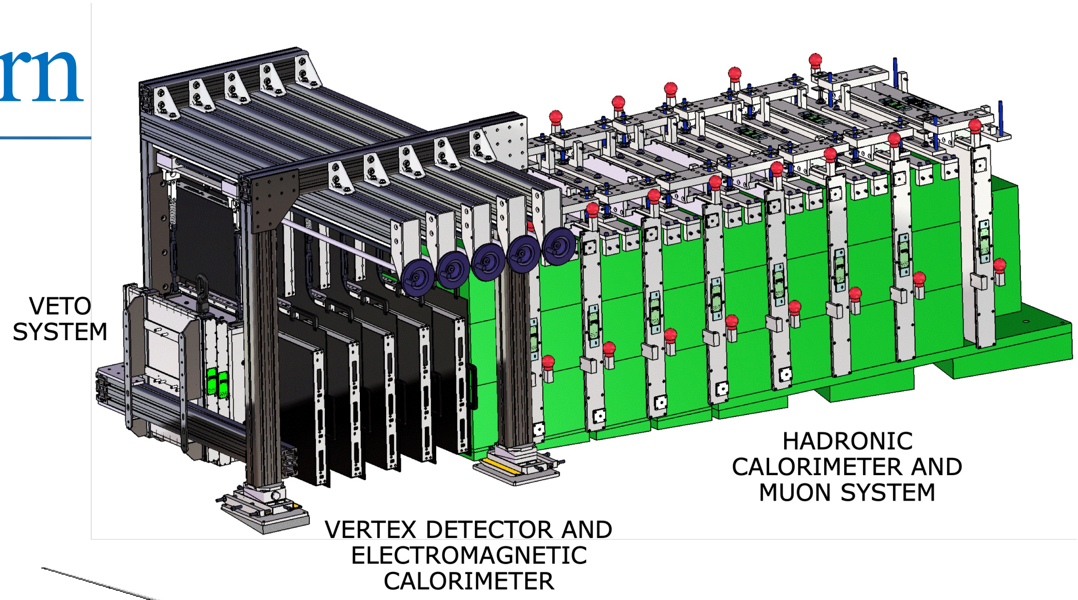
E.M. CAL
- 250μm Scintillating fibres for timing information and e.m. energy measurement

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

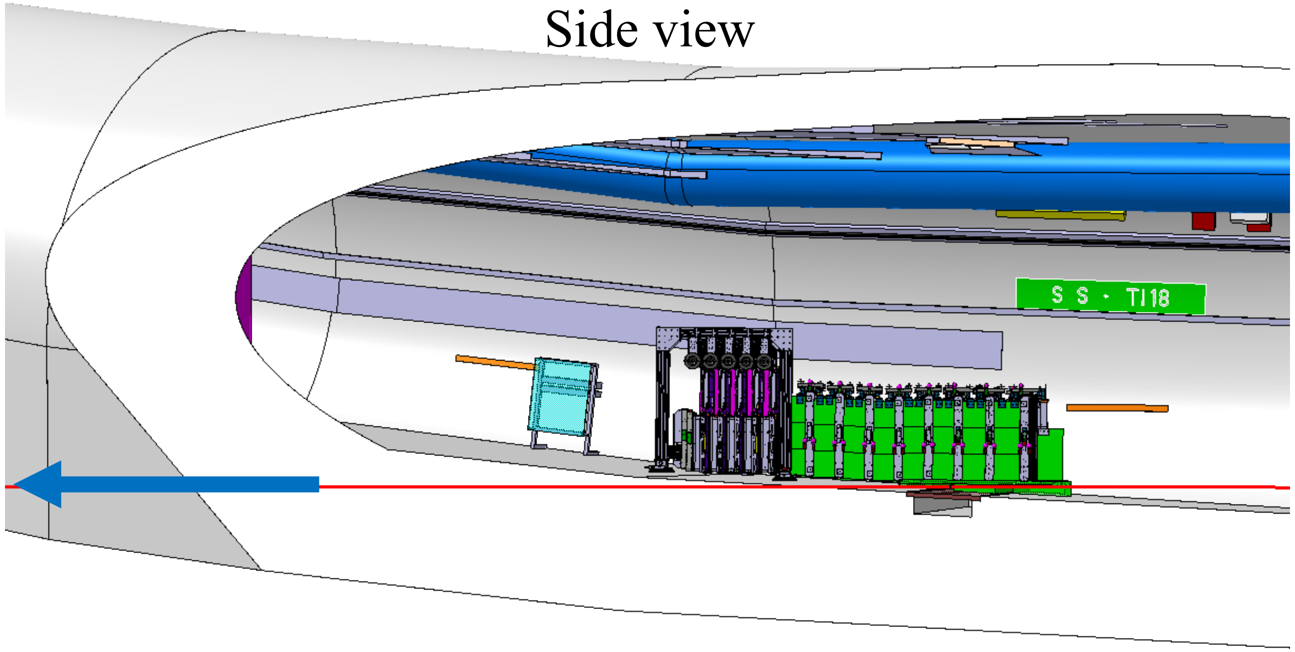
MUON IDENTIFICATION SYSTEM:
3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking



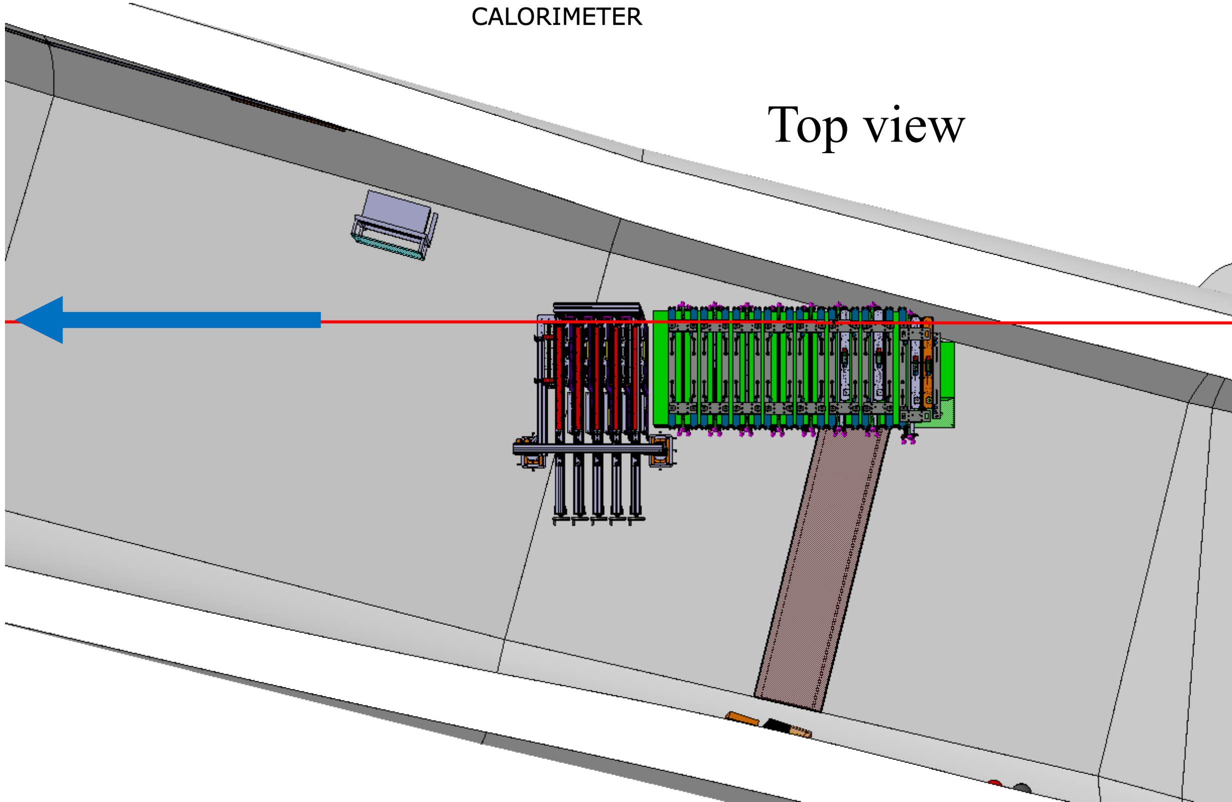
SND@LHC in the TI18 cavern



Side view



Top view

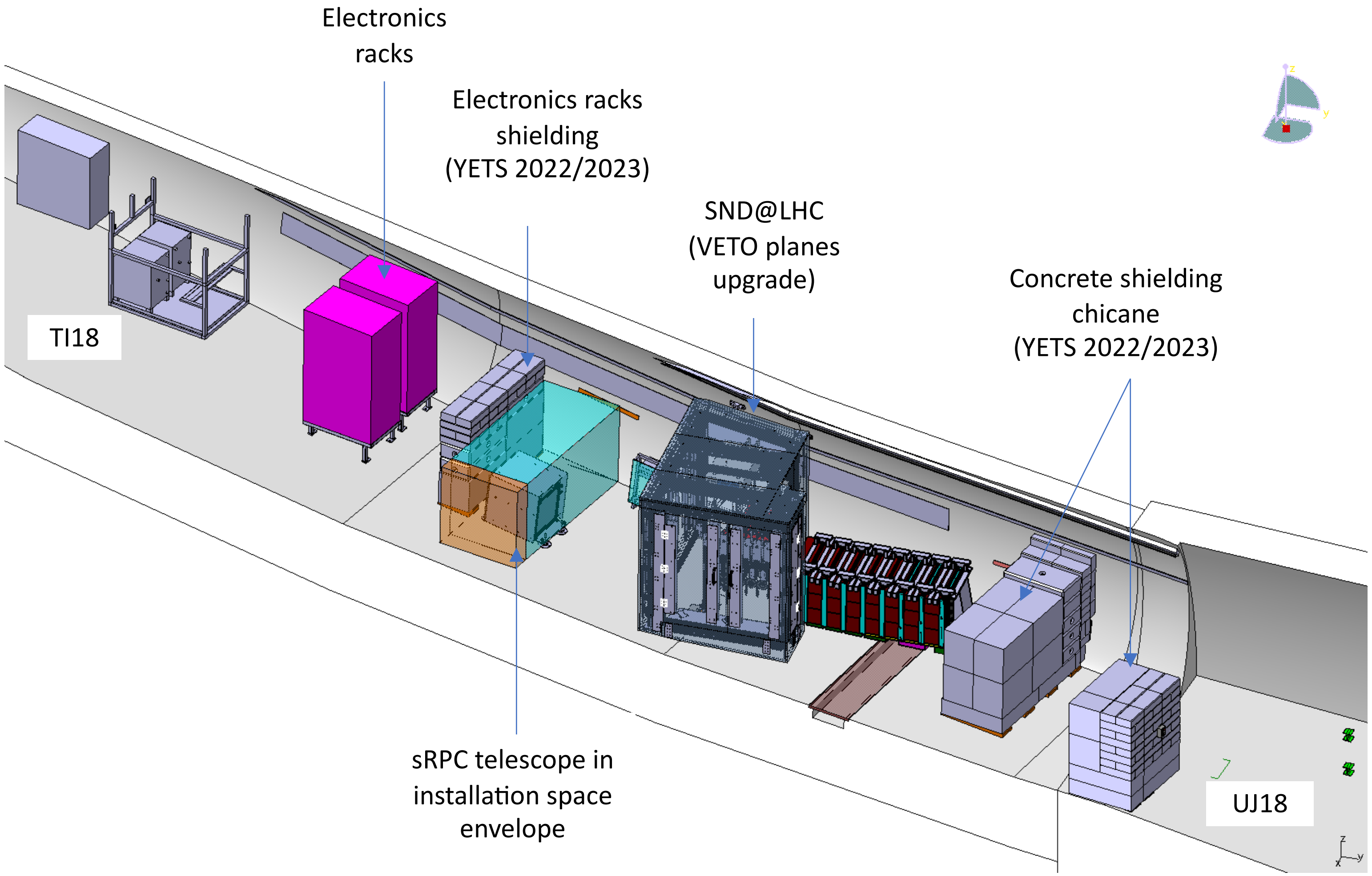


Different activities during YETS

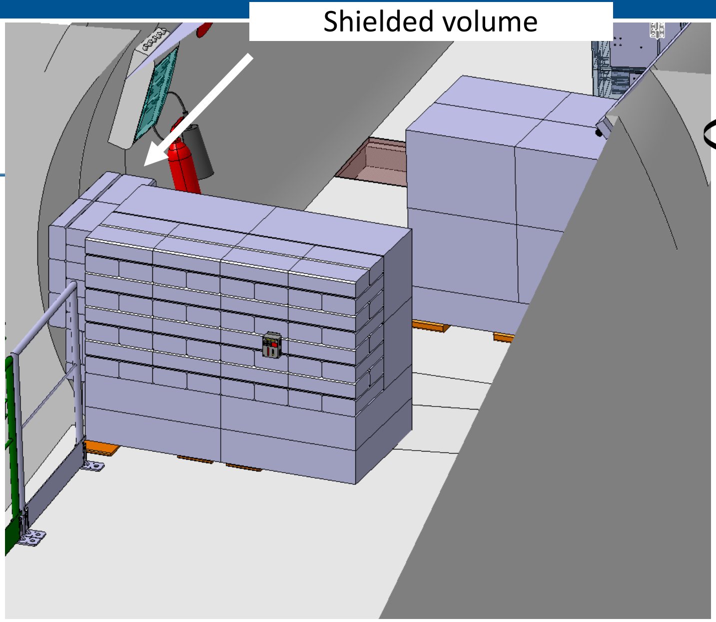
Concrete shielding chicane

Installation of sRPC telescope

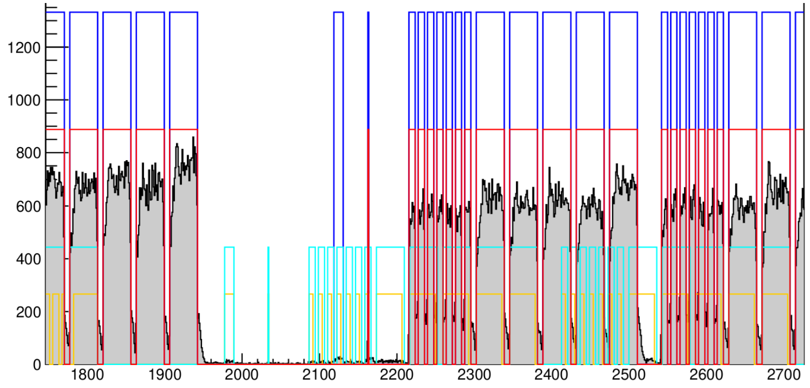
VETO planes upgrade



Concrete shielding



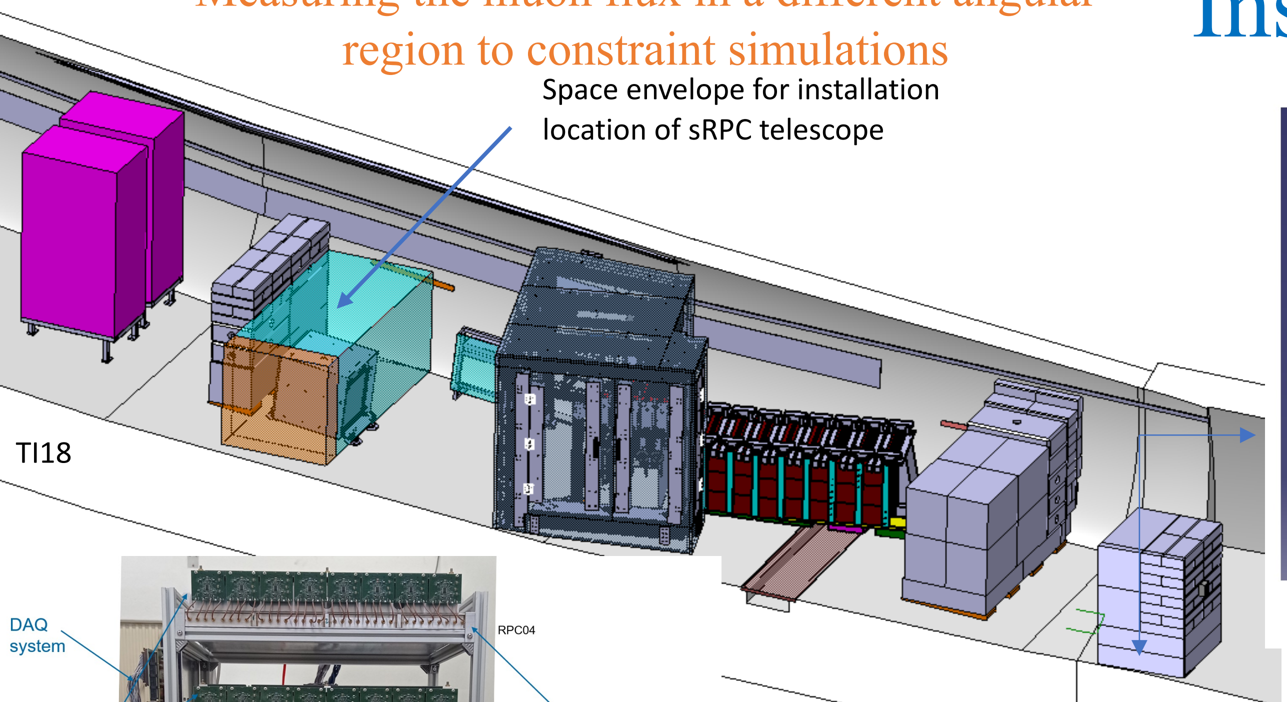
Further improvement expected w.r.t. the background rejection power already achieved last year

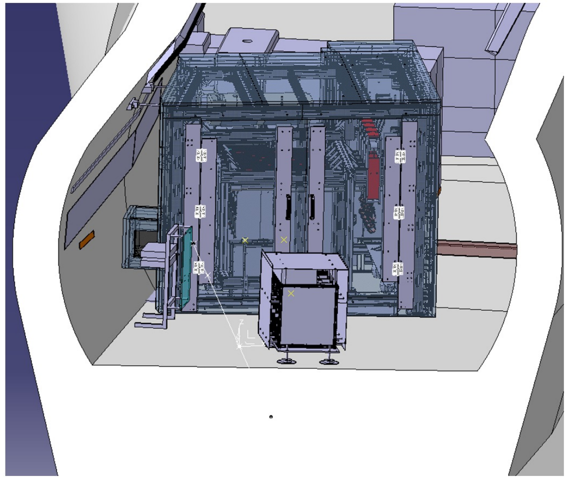


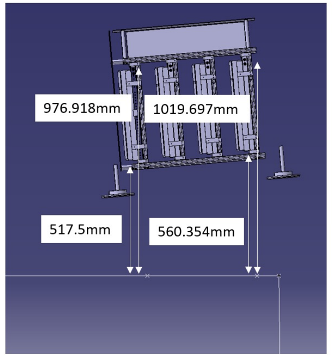
Installation sRPC telescope

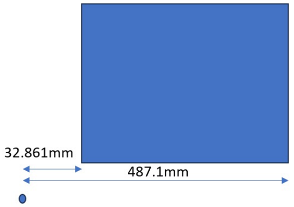
Measuring the muon flux in a different angular region to constraint simulations

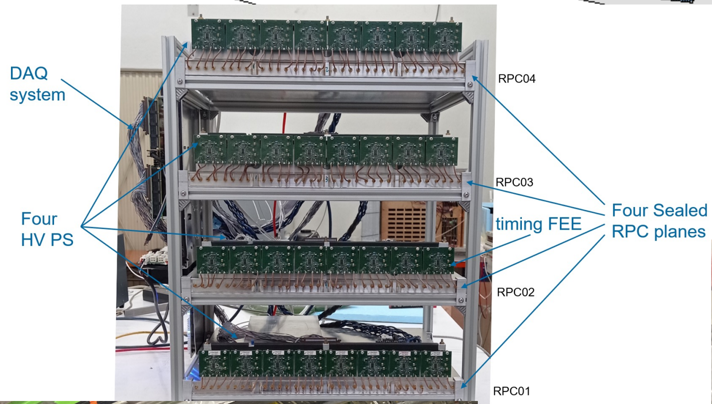
$6.7 < \eta < 7.5$

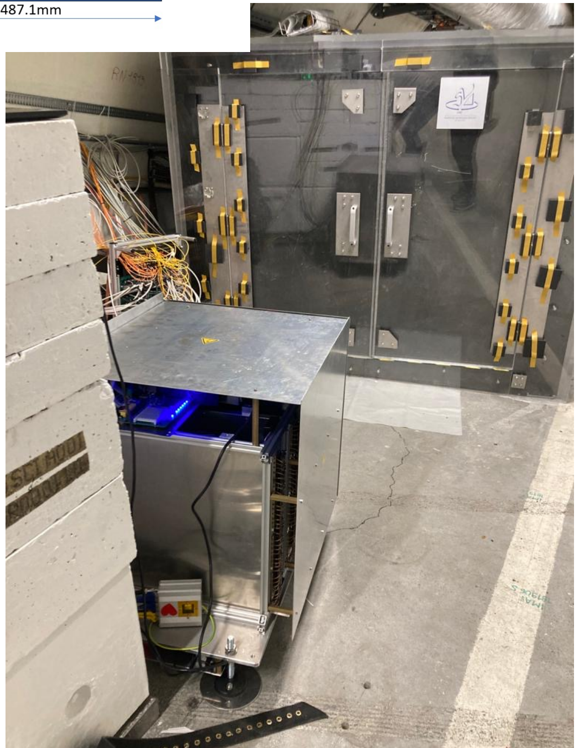






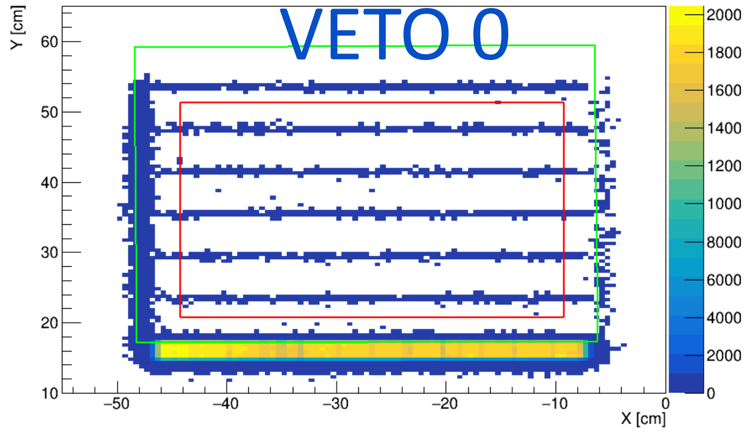


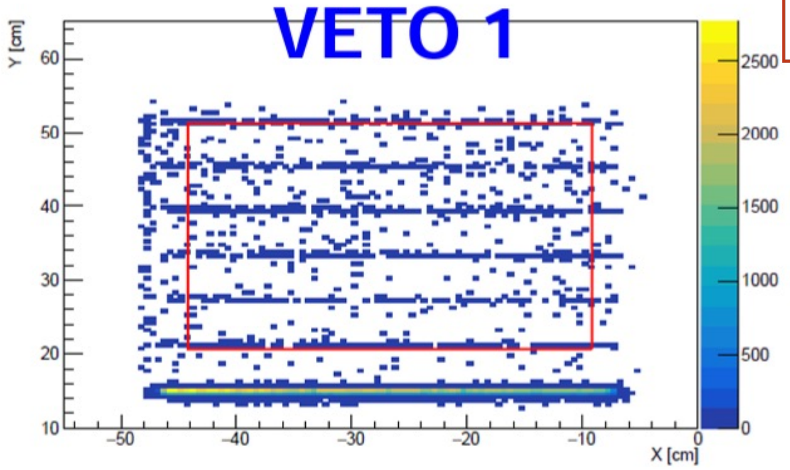


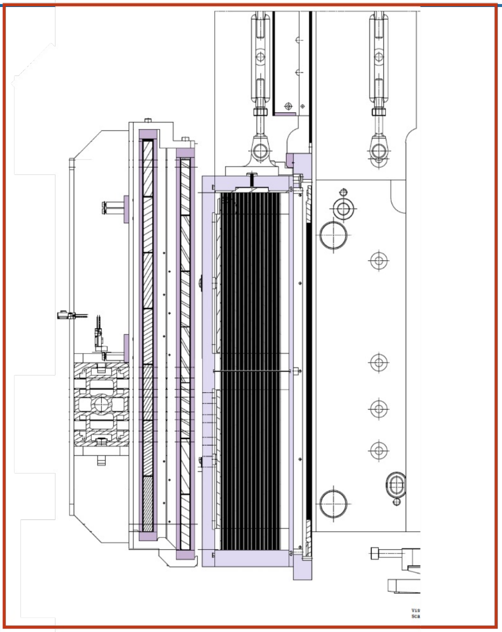


Upgrade of the veto system during 2023-2024 YETS

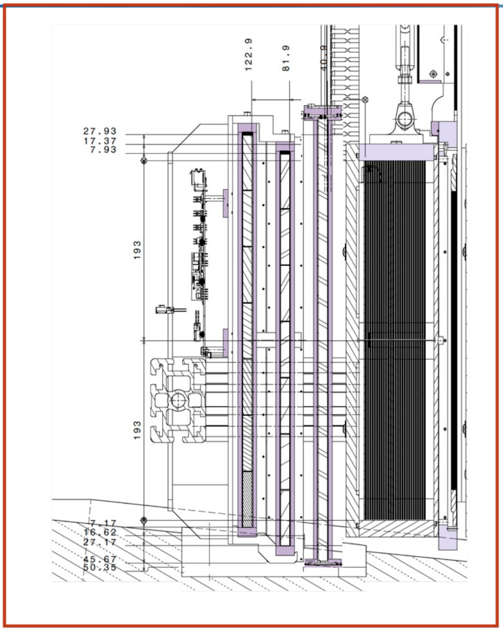
Extrapolated SciFi track position
when no signal in Veto 0(1)



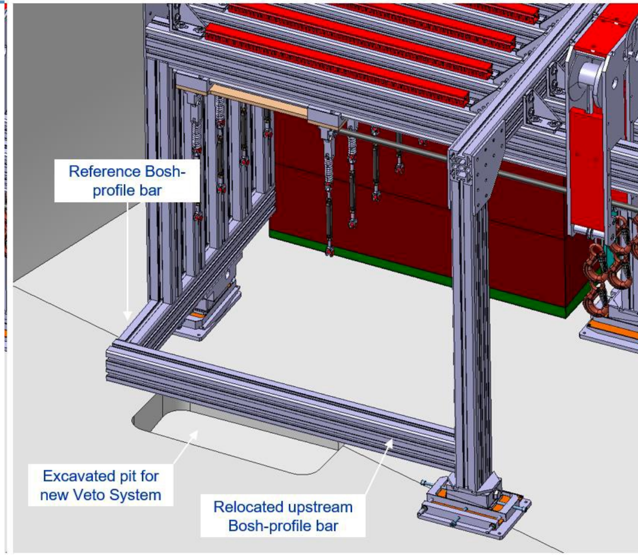




Previous layout: two planes with H bars

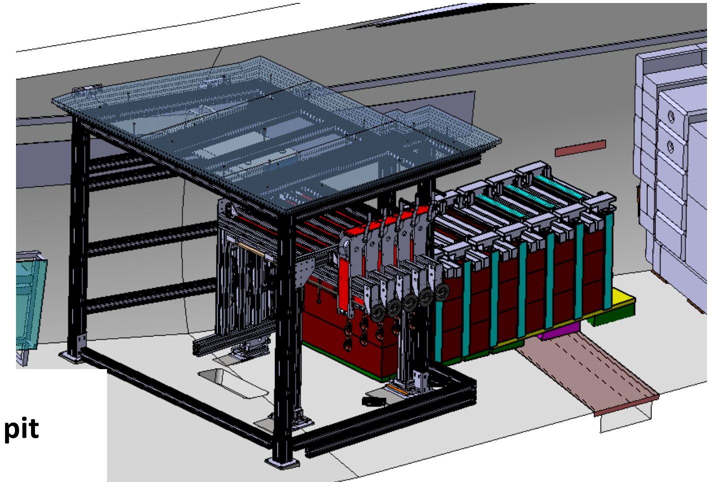


Upgraded layout: third plane with vertical bars



3D integration model (YETS 2023/2024)

Recover fiducial volume, both longitudinally and in the transverse plane
Add a third layer to avoid loosing the first target wall and lower their position to cover the full transverse plane

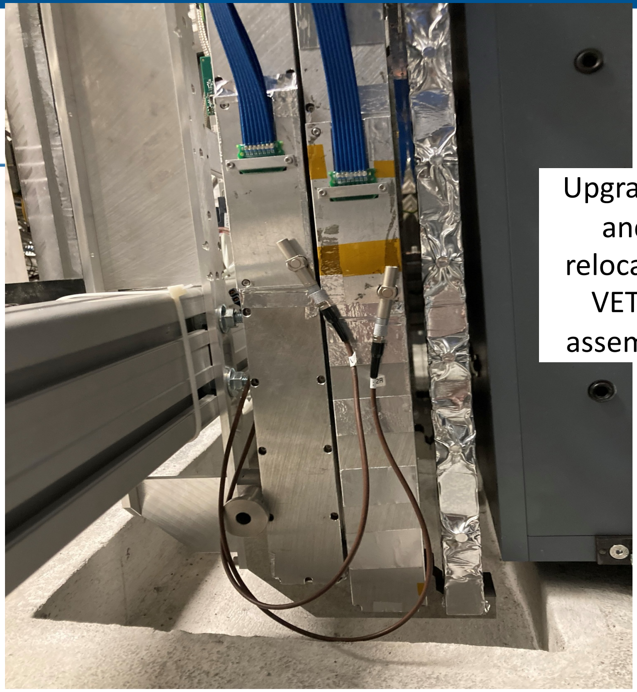


Excavated pit

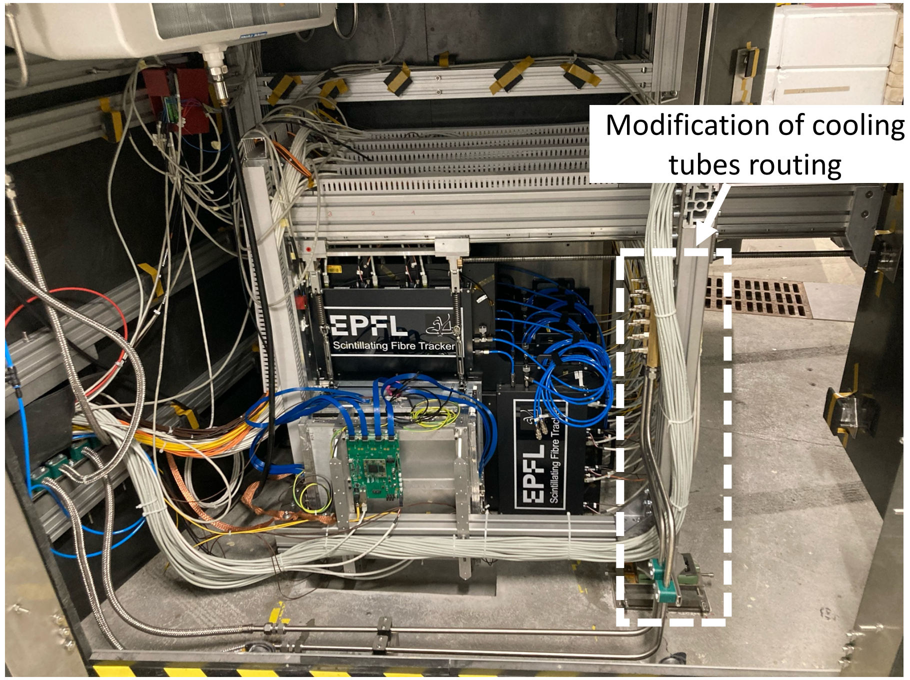
Preparation, excavation and installation

View of transported material to execute excavation works

View of low-speed core drilling and direct dust removal

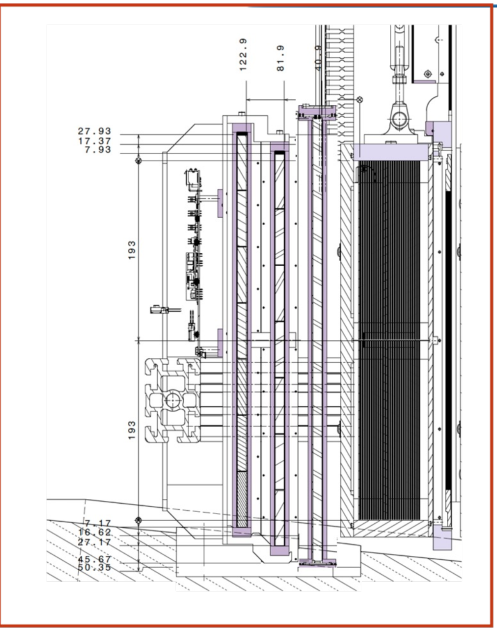


Upgraded and relocated VETO assembly



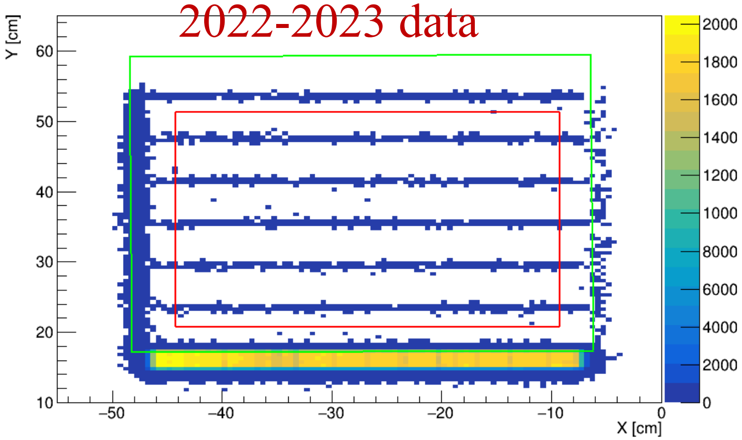
Modification of cooling tubes routing

Veto inefficiency with the new configuration

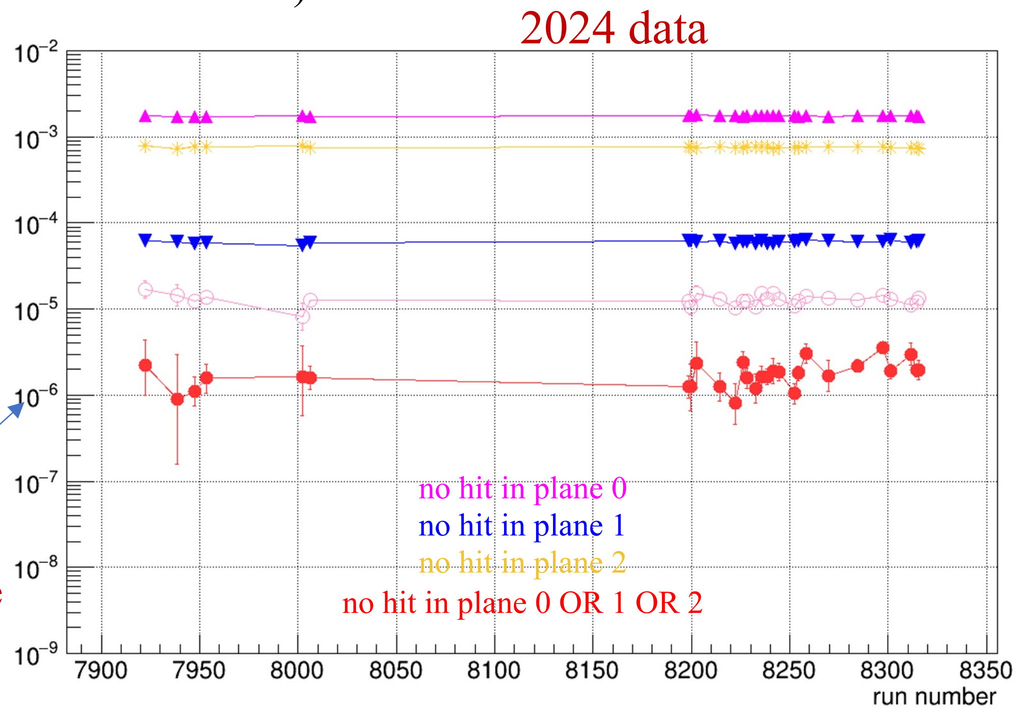


Upgraded layout: third plane with vertical bars

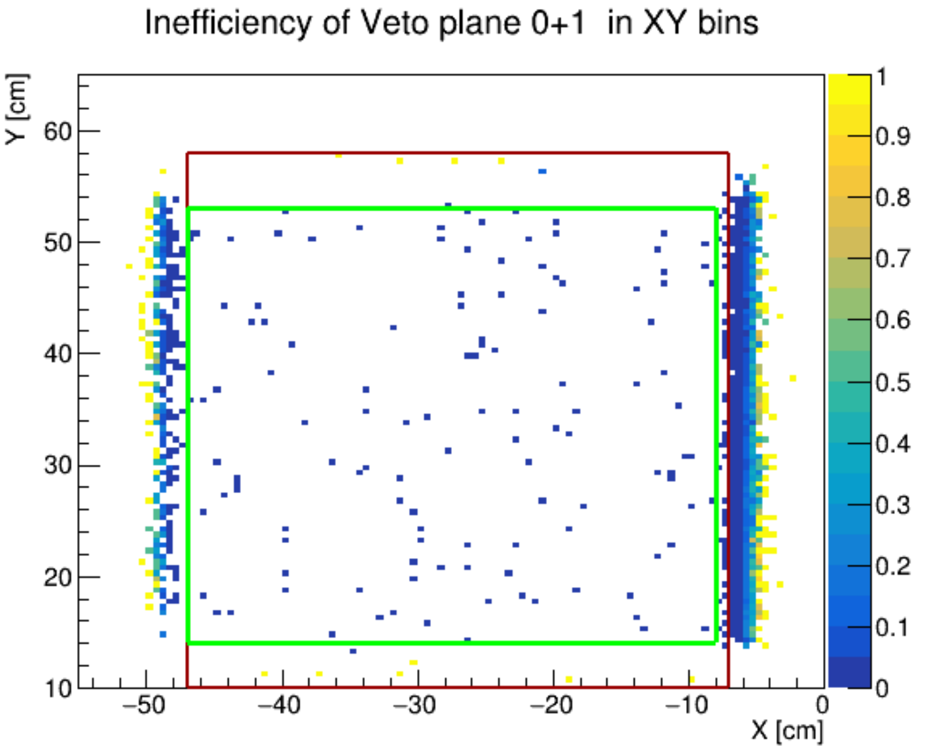
- Data corresponding to the first installed target
  - 21st March - 6th May 2024, recorded luminosity is ~12fb^{-1}
  - Detector fully aligned in this period
- A few hiccups with loss of synchronicity → run without LHC clock and/or phase alignment
  - Affected runs amounting to 1.18fb^{-1} excluded from current analysis
- 2.7x10^{8} events with tracks used for this first study (10fb^{-1})
  - Events with a reconstructed SciFi track, particles from the IP1 side. To mitigate dead time issues, require no previous event in 100 cc (625ns) (99.6% of all events)

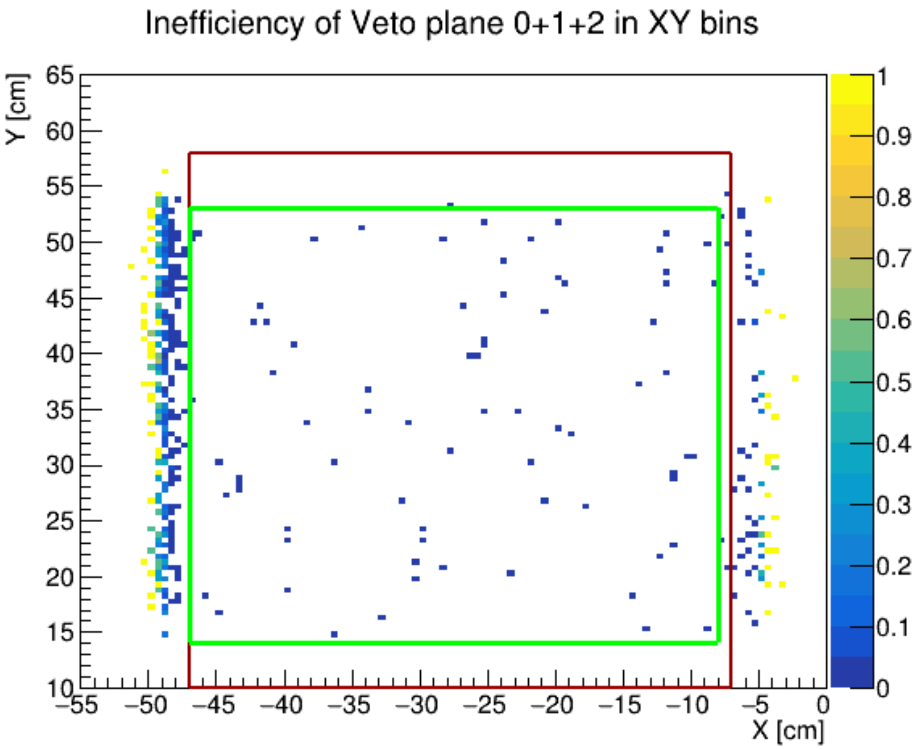


Gained one order of magnitude for the whole system, i.e. without any geometrical cut



XY fiducial volume with current veto stations





Red rectangle represents the geometrical cut:
-47 cm <X< -7 cm
10 cm <Y< 58 cm
area of **40x48cm² > target**

Geometrical cut for 2022-2023 data → **35x27cm²**

Now covering the whole target region (green square)

Expected increase in the neutrino yield is **a factor of 5!**

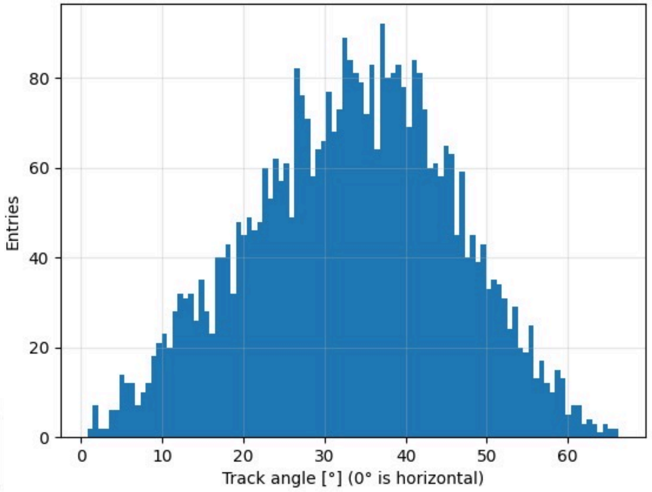
Preliminary inefficiency
Work in progress

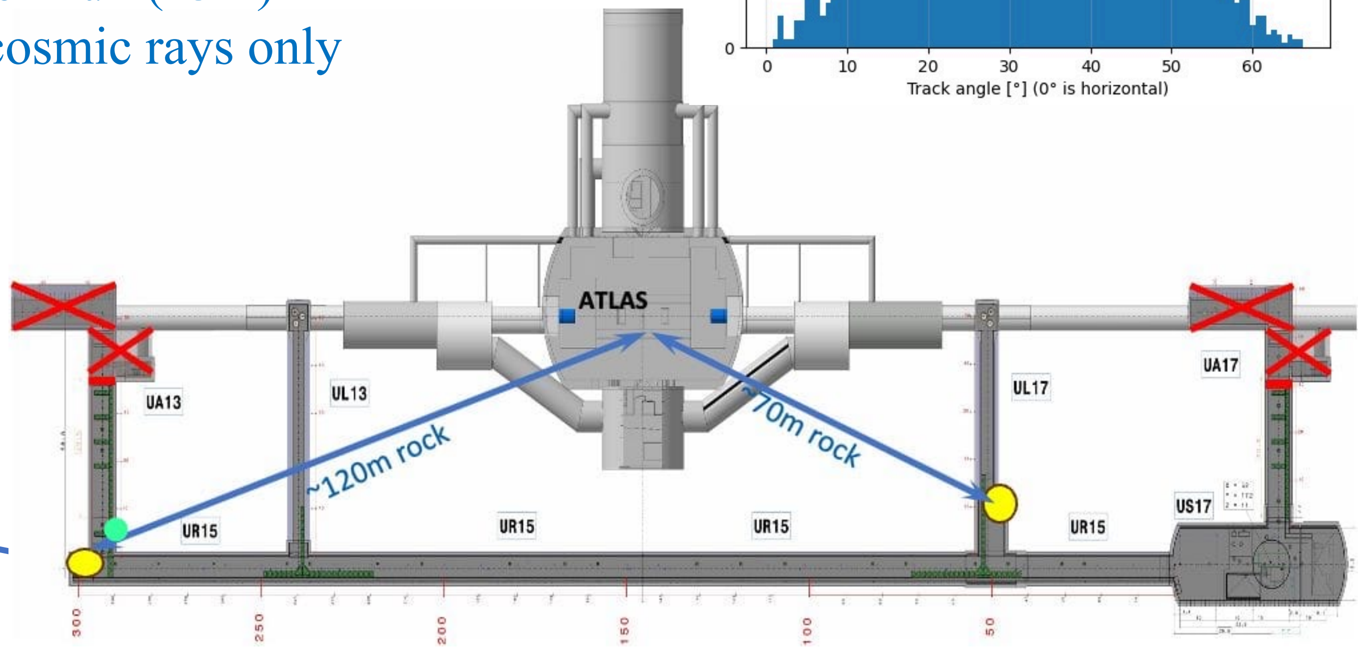
All planes
6.19E-07

New emulsion storage location

- Temporarily store SND@LHC and FASER emulsion in HL-LHC P1 underground galleries. Significantly more convenient and practical than CNGS access tunnel
  - Two locations identified (in yellow), h~1.6, ~10-15m above ATLAS IP
  - Accessible (without radiation badge) anytime, elevator with 3t capacity
  - SciFi detector with Wifi readout installed to measure muon rate during collisions

Measured muon rates
During 0.77 fb^{-1} run (13 h)
Consistent with cosmic rays only

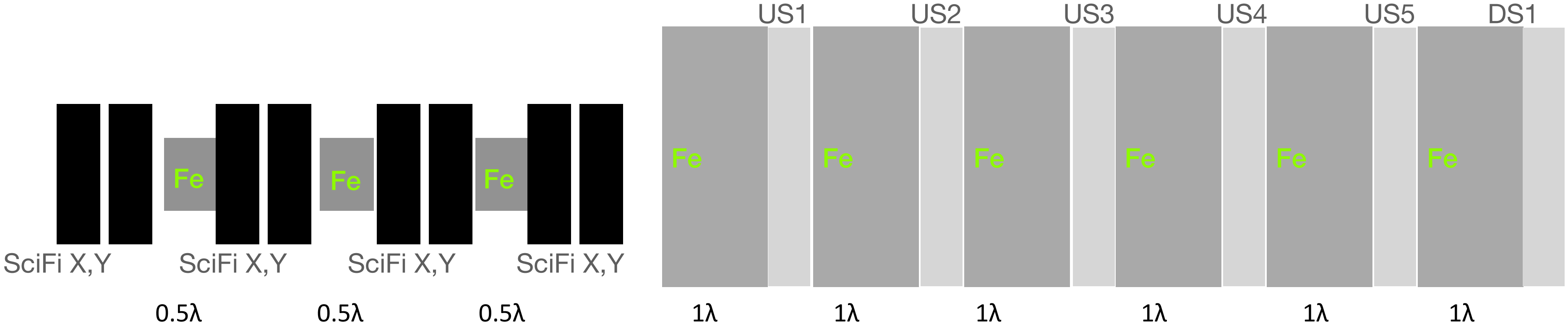




Towards energy calibration

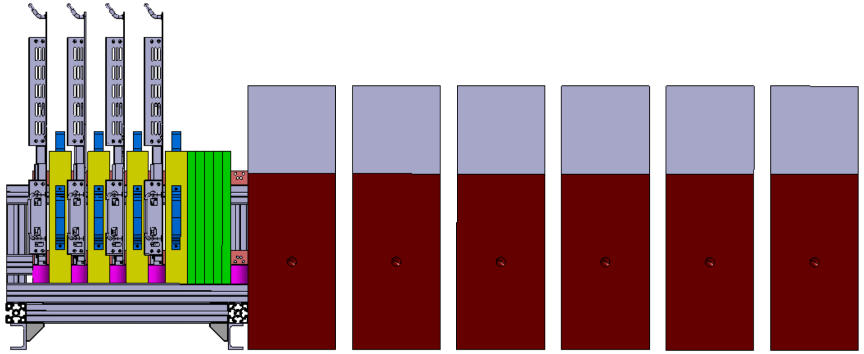
Target instrumented with SciFi stations to get the shower origin

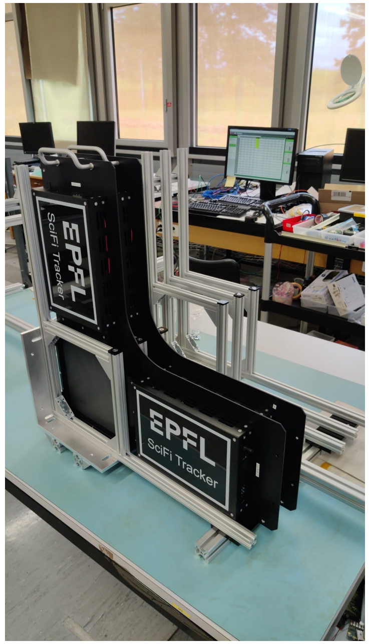
All 5 US stations and just 1 DS



data taking in H8 in August 2023

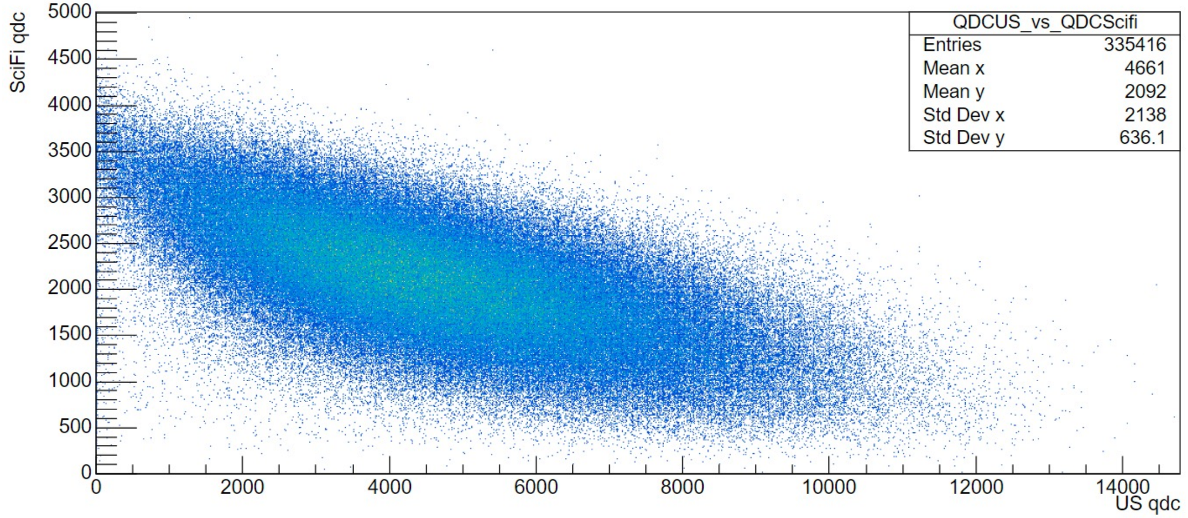
Bologna group → see Marco's talk



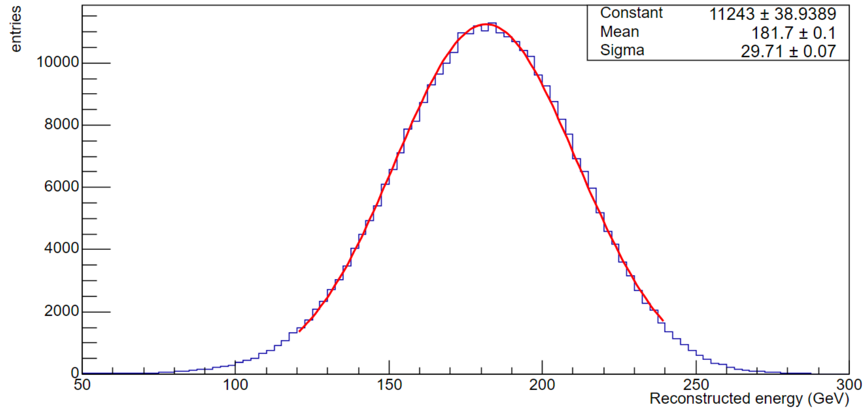


Finding on energy resolution

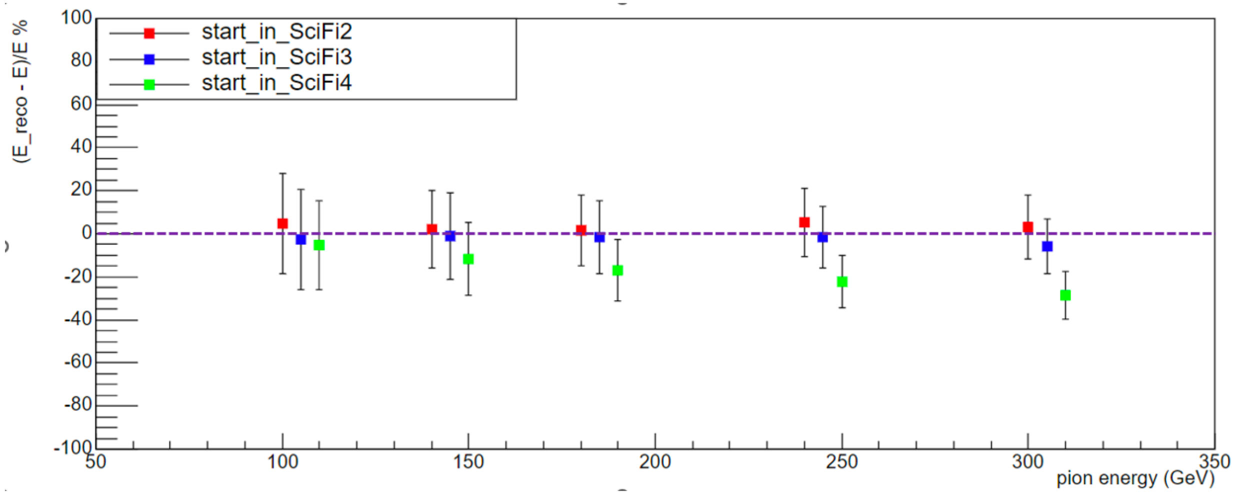
LHC
Scattering and Neutrino Detector at the LHC

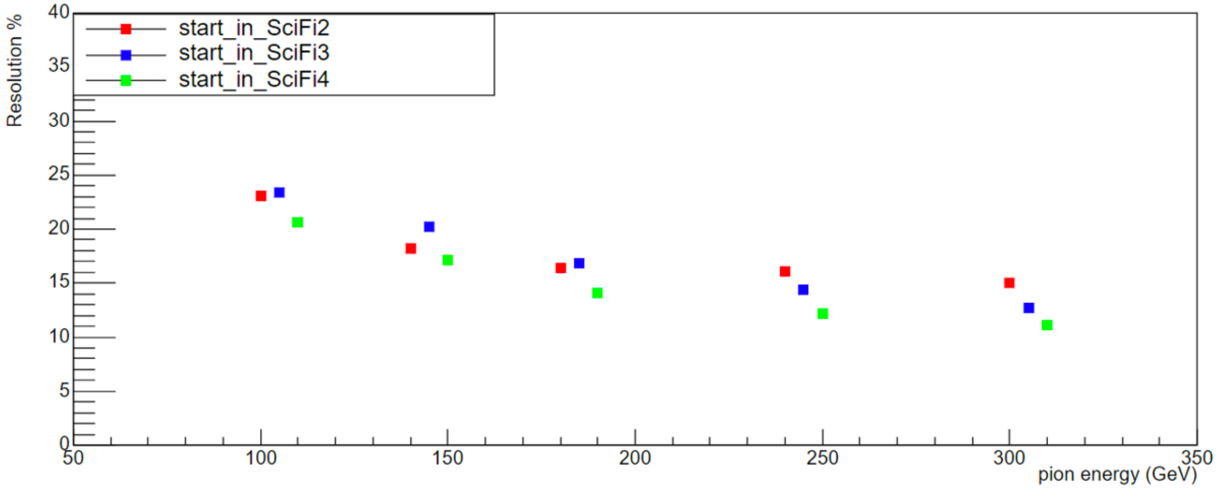


Reconstructed energy for 180 GeV π



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





Muon flux (background) measurement in 2024 → See Simona's talk

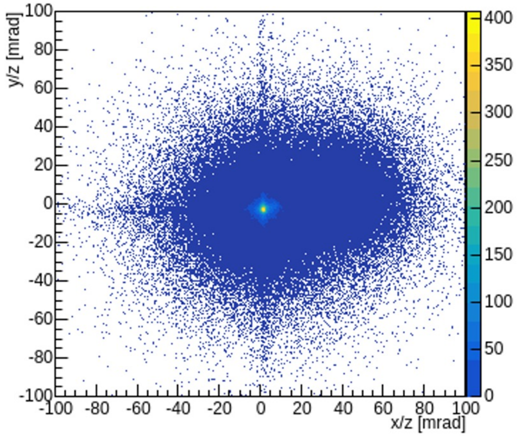
Due to new RP optics for the upward beam crossing angle, muon rates at the detector doubled wrt 2022-2023

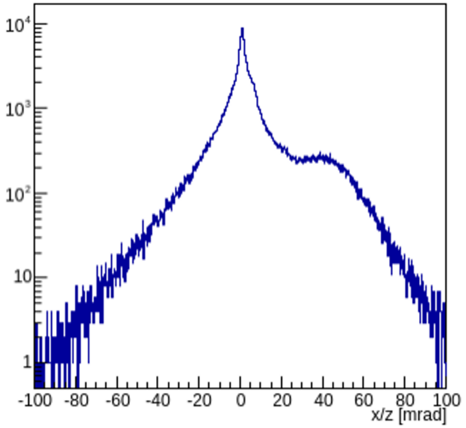
2024

- muons in SciFi 596 Hz ; 3.92x1e4 fb/cm^2
- muons in DS: 1836 Hz ; 5.10x1e4 fb/cm^2

2022-2023

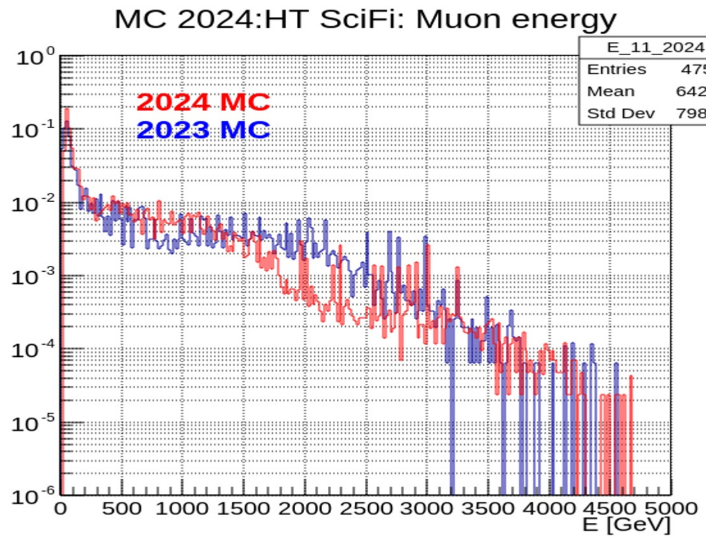
- muons in SciFi 300 Hz ; 2.06x1e4 fb/cm^2
- muons in DS: 850 Hz ; 2.35x1e4 fb/cm^2





A secondary peak @40mrad in the horizontal plane consistent with LEHR.11R1 collimator 65m upstream of the detector - was also present during the 2023 ion run too.

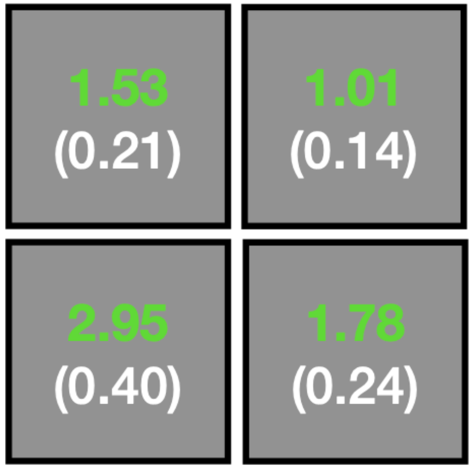
- MC predictions for the 2024 upward crossing angle
  - Q4 off, Q5 on, TCL6@1.6mm 767Hz muons
    - increase is mainly due to muons in the TeV energy range (compared to 2023 downward-crossing case with Q4 on)
- MC predictions for the 2025 downward crossing angle
  - Q4@15 T/m(not the maximum): 763 Hz muons
  - Q4 off : 725 Hz muons



- With a doubled muon rate, emulsion replacement becomes very frequent and incompatible with the emulsion production plans
- Production already extended from 4 to 5 batches in 2024

Adopt a new strategy to mitigate the loss

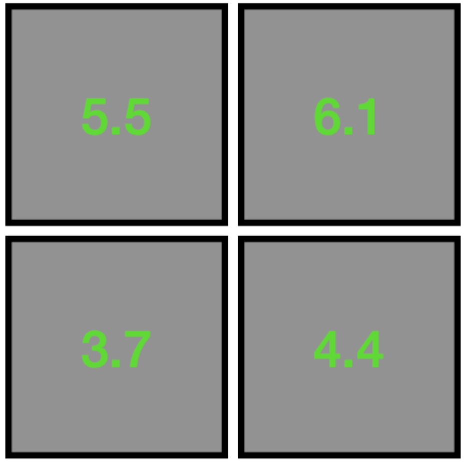
Neutrino events



Neutrino events of CC interactions in 1fb^{-1}

Muon flux

Numbers are in 10^4 fb/cm^2



Bottom bricks with the highest neutrino yield (65%) and the lowest muon flux (factor 1.6 between brick 1 and 4)

→ Instrument half target and try to replace as many targets as possible

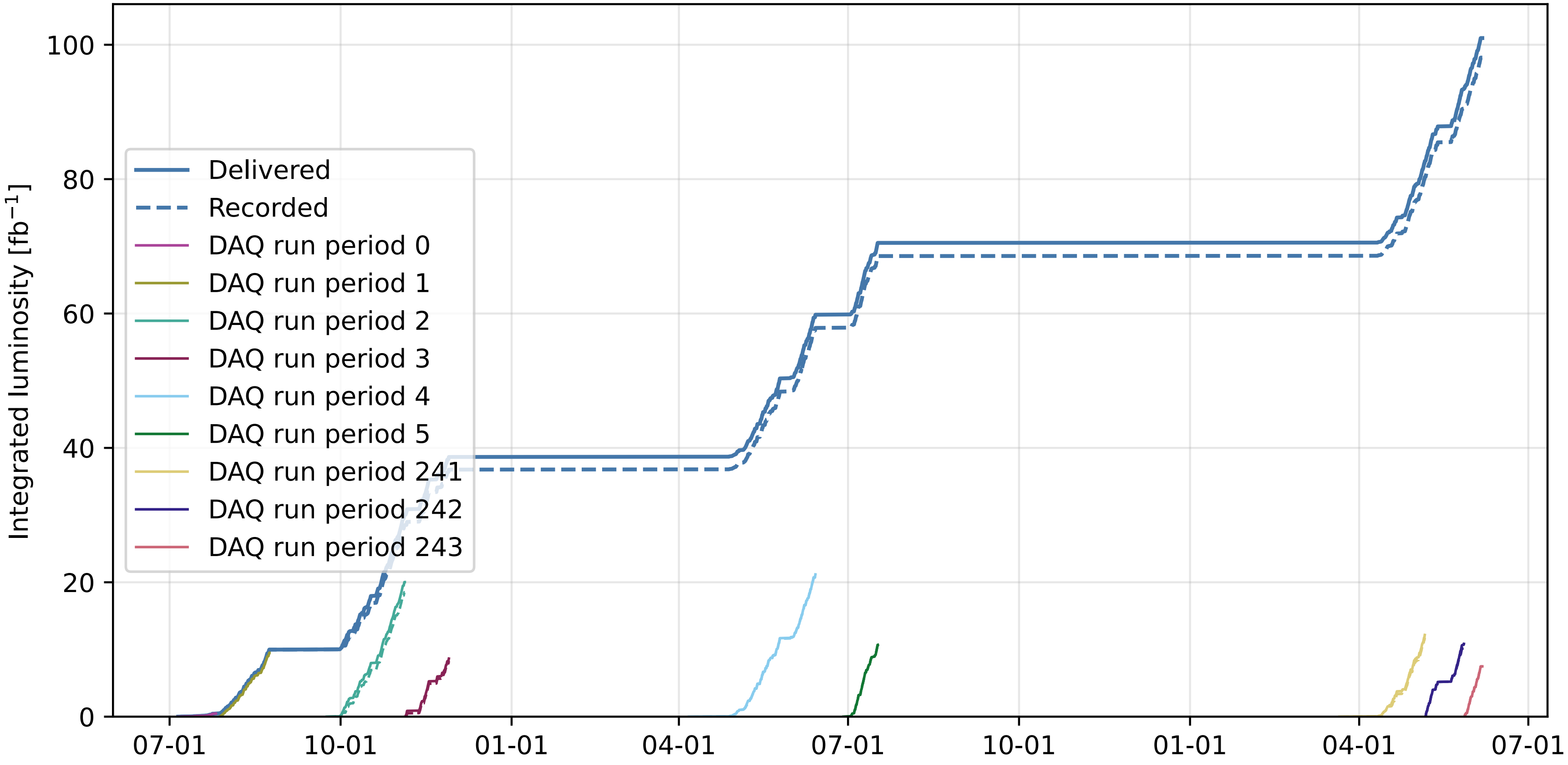
→ Withstand up to 12 fb^{-1}. Agreed the following with the LPC: on our side we grant the maximum flexibility, with a team ready to replace emulsions on a very short notice (down to a few hours) before the maximum background yield is reached. On the LPC side, they make sure we don't exceed 12 fb-1 (and we gather a minimum of 9 fb^{-1})

→ Example of implemented flexibility: on May 27th warned at 8:30 am → team underground at 10:30 am

→ With this strategy we gain about 60% in terms of neutrino yield

Data analysis

Integrated luminosity



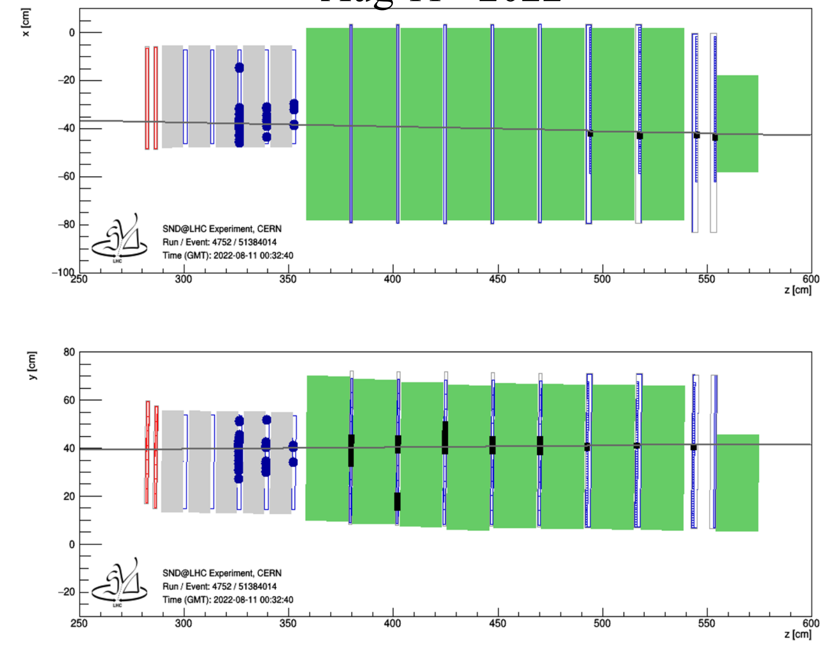
Integrated (recorded) luminosity: 101.0 (98.1) fb^{-1}

Recorded efficiency 97% (2022 95%, 2023 99.7%, 2024 96.7%)

29.5/30.5 fb-1 in 2024

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



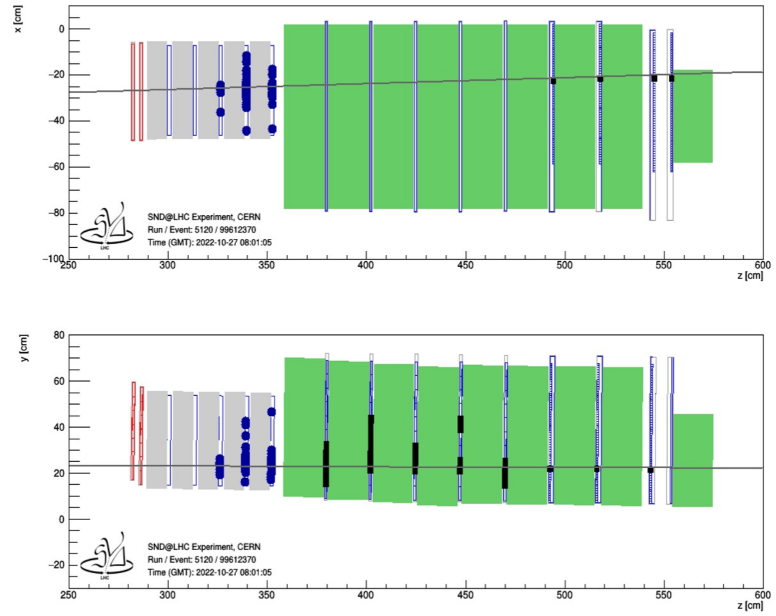
Editors' Suggestion

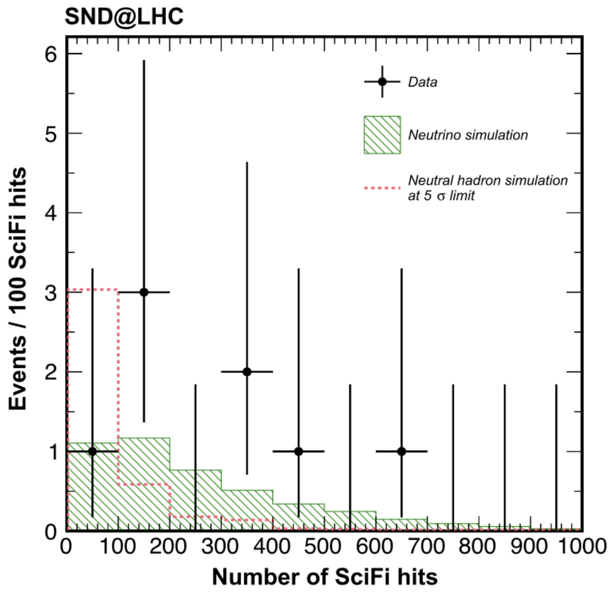
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

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

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

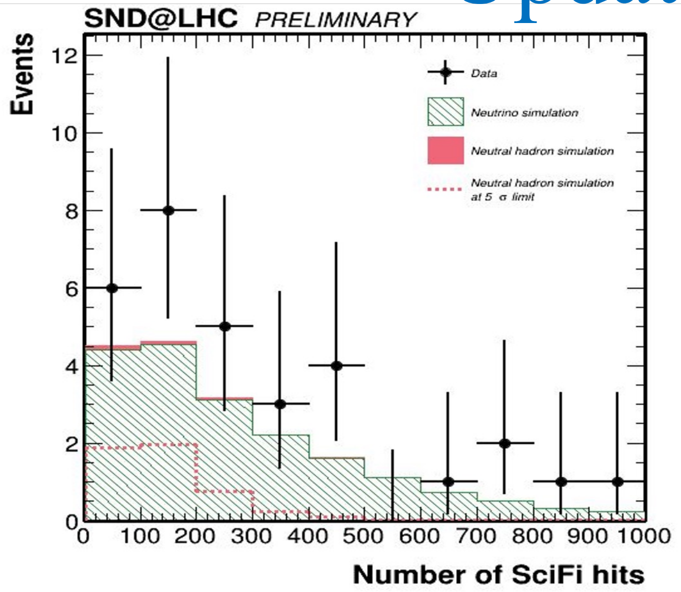
Background only hypothesis probability:

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

6.8 σ observation

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

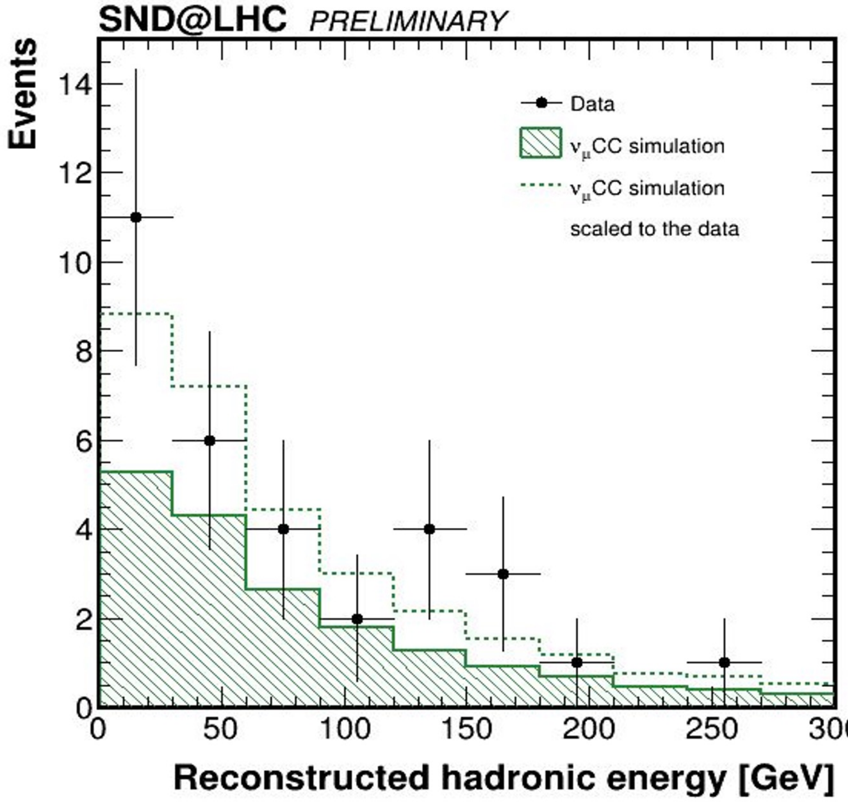
Updated muon neutrino results (2022-2023)

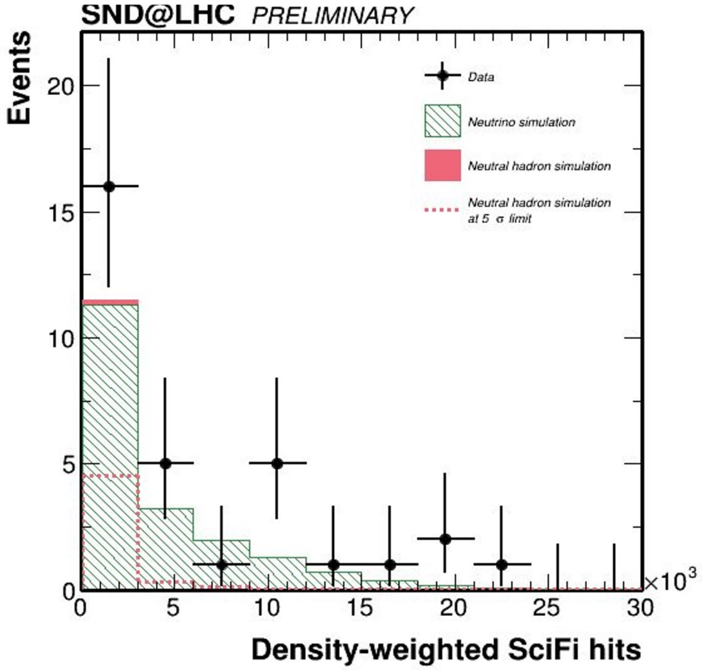


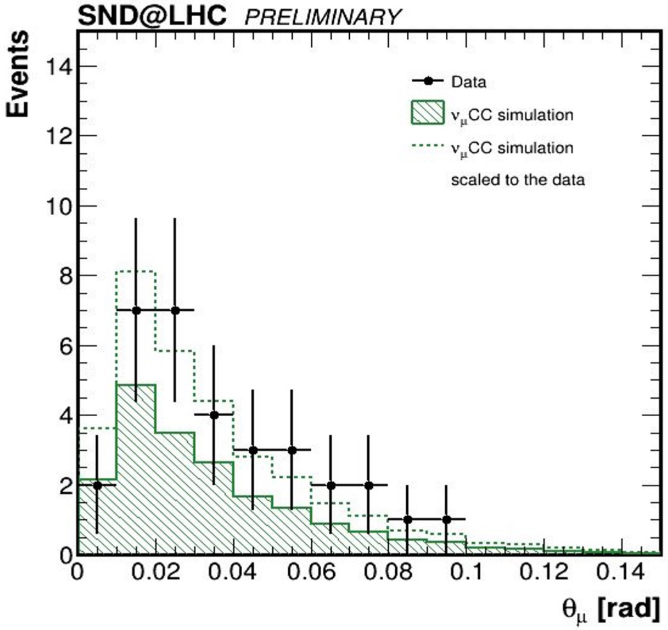
Events expected in 68.6 fb^{-1}

- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

32 events observed







Observation of 0μ neutrino events

Neutral hadron background

- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
  - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region**: **0.01**

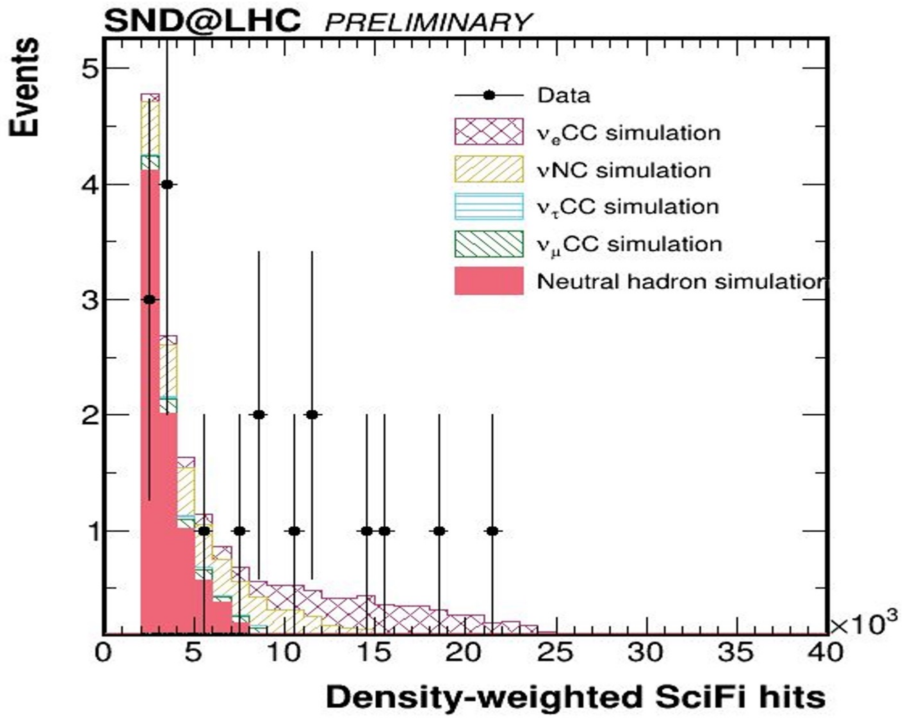
Neutrino background

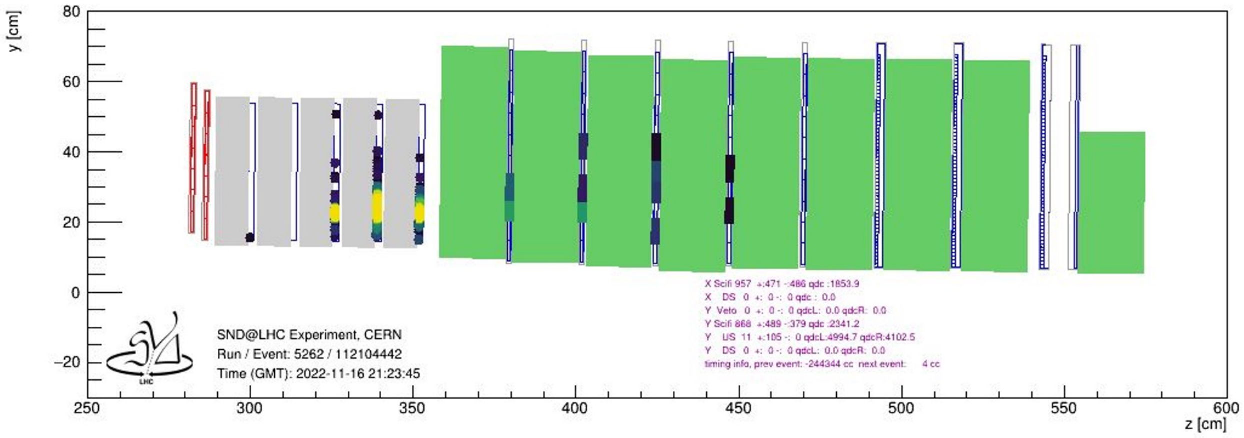
- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC interactions expected: **0.01**

0μ observation significance

- **Total expected background: 0.14 ± 0.07 events**
- **Expected signal: 4.7 events**

Number of events observed: 6
Observation significance 5.5 σ



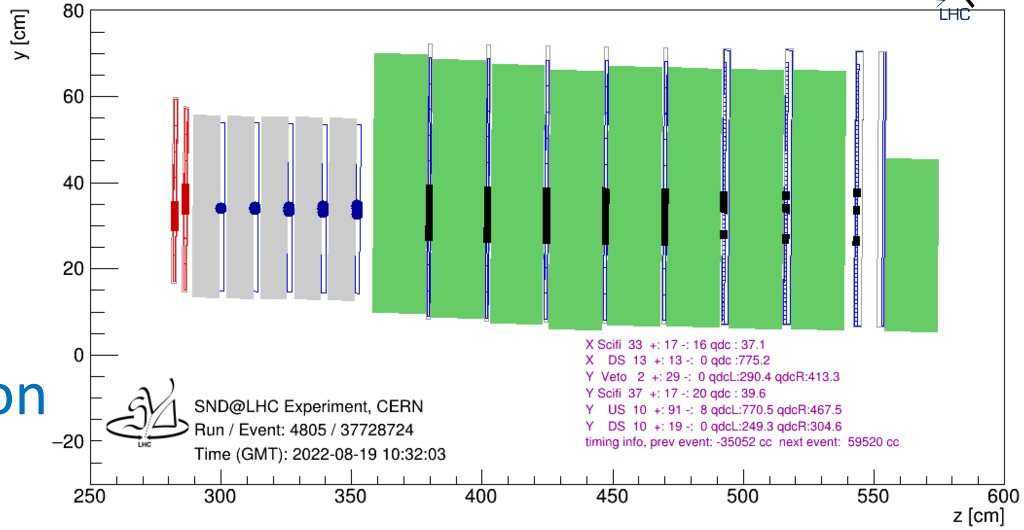


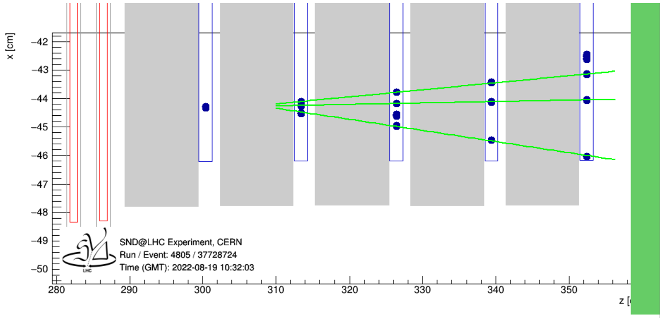
Trident process in the neutrino target

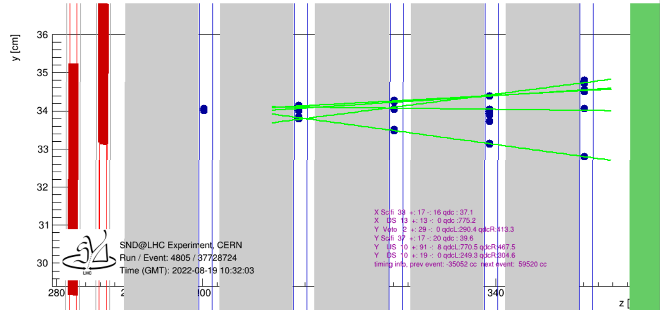
- $\mu^{\pm} + N \rightarrow \mu^{+}\mu^{-}\mu^{\pm} + N$
  - Studied in the 60's and 70's, Muon Tridents, J.D. Bjorken(SLAC), M.C. Chen, Observation of Muon Trident Production in Lead and the Statistics of the Muon
  - Due to identical muons, sensitive to Fermi statistics
  - With 10 GeV muon beam,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

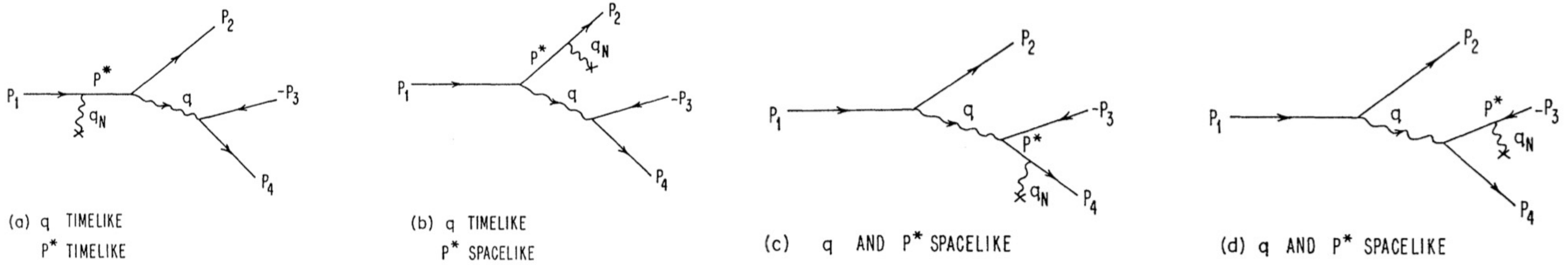
$$\mu^{\pm} + N \rightarrow \mu^{\pm} + N + \gamma, \gamma + N \rightarrow N + \mu^{+}\mu^{-}$$

- Process introduced in GEANT4 in 2022
- In 2022 data, 137 events observed with 3 tracks and 1 vertex
- Expect from simulation 85 events (2/3 due to γ-conversion and 1/3 genuine trident)





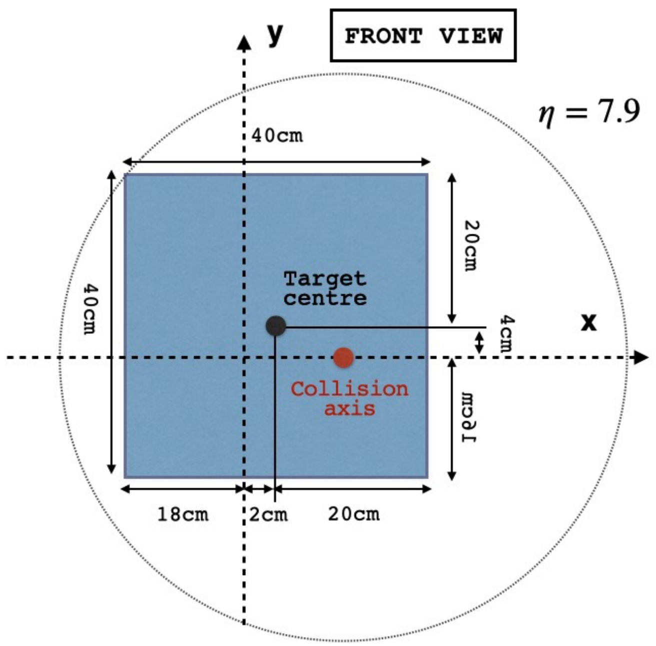


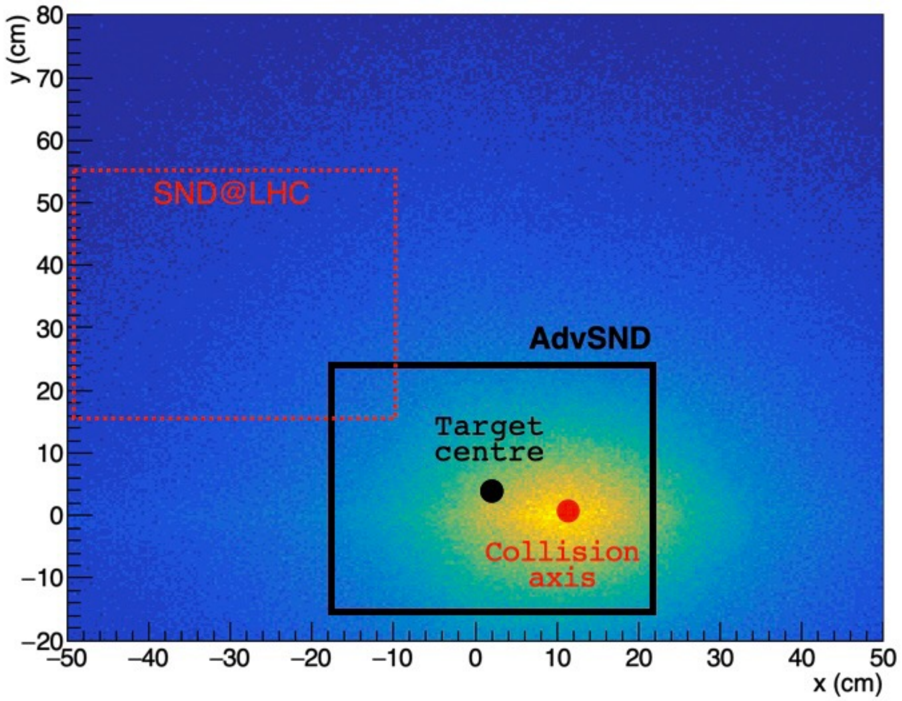


SND@LHC UPGRADE TOWARDS HL-LHC

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

CROSSING ANGLE:
+250 μrad Horizontal





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

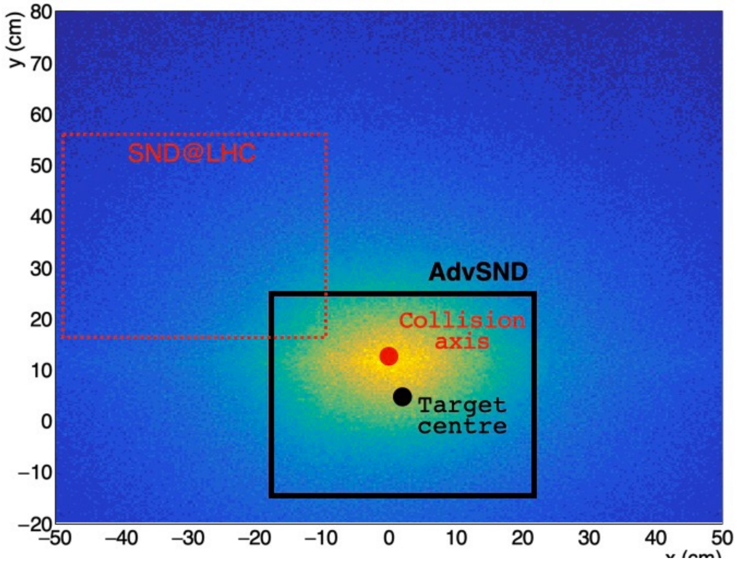
Main points of the upgrade:

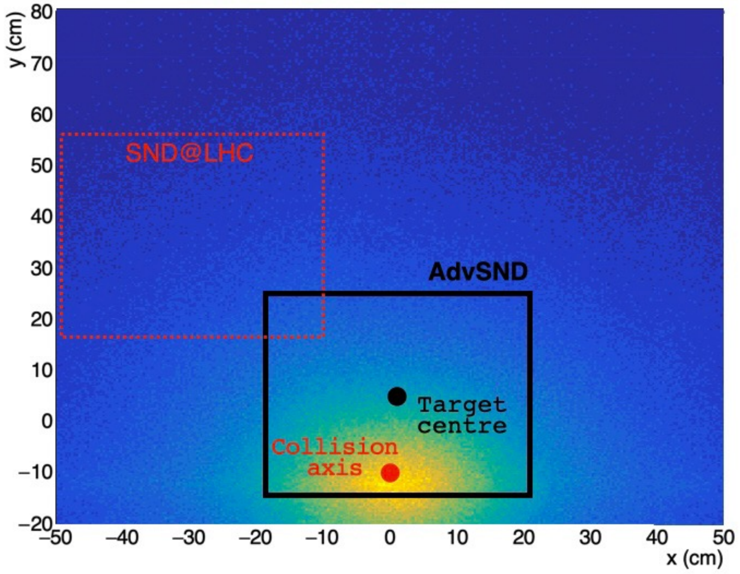
Better transverse position while keeping the off-axis characterization (with some useful overlap with FASER)

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)

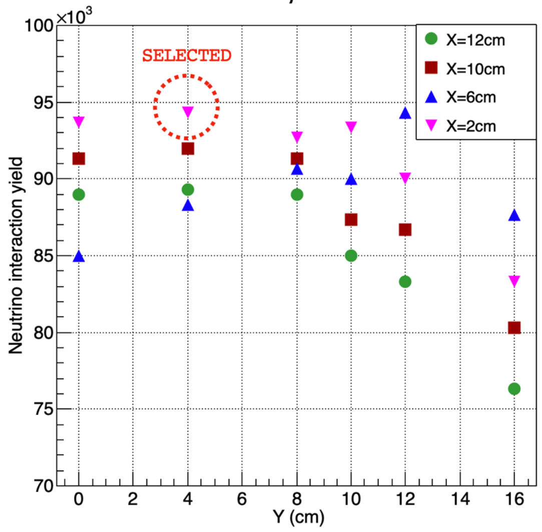
Crossing angle and optimal detector configuration



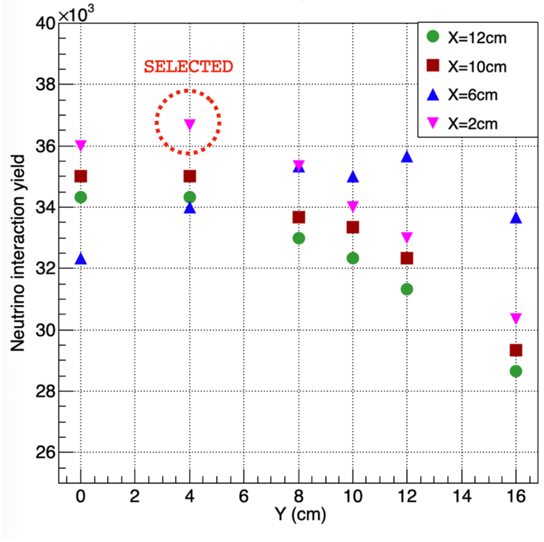


Beyond Run 4 the crossing angle can change from the H to V plane

ν_μ

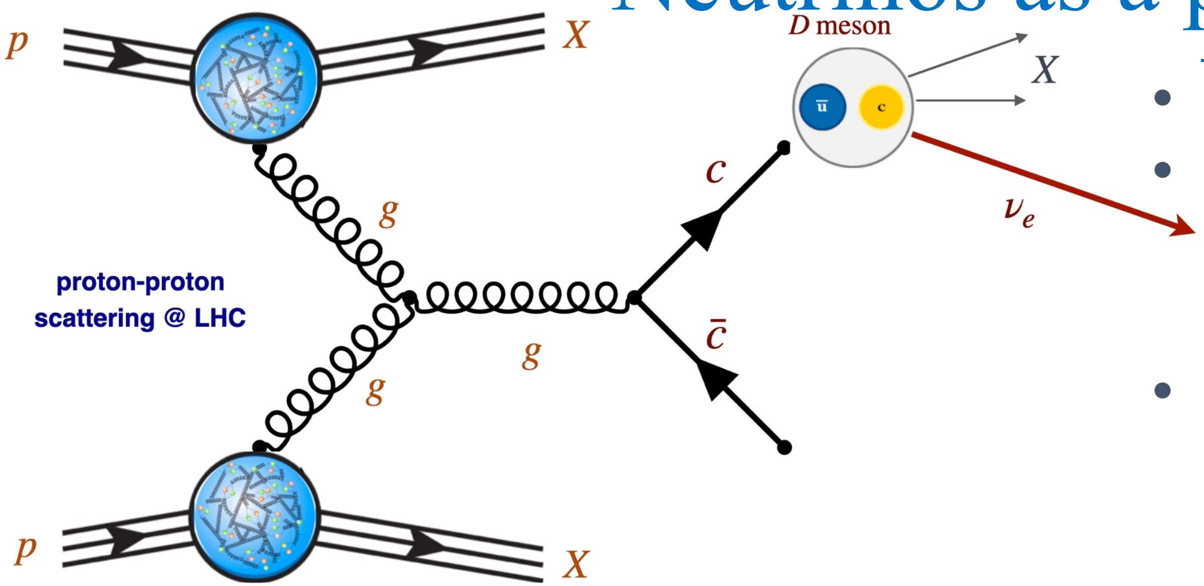


ν_e

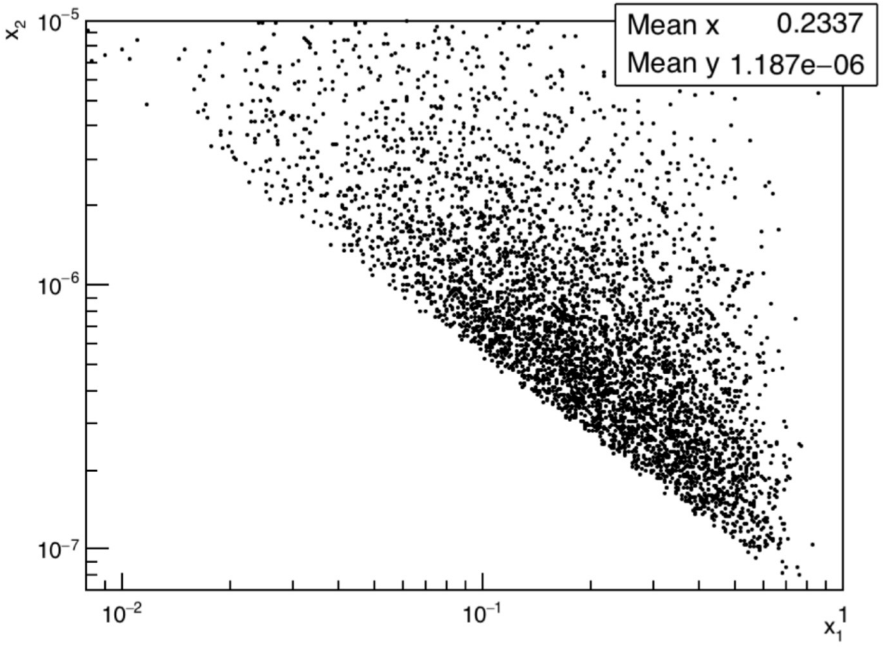


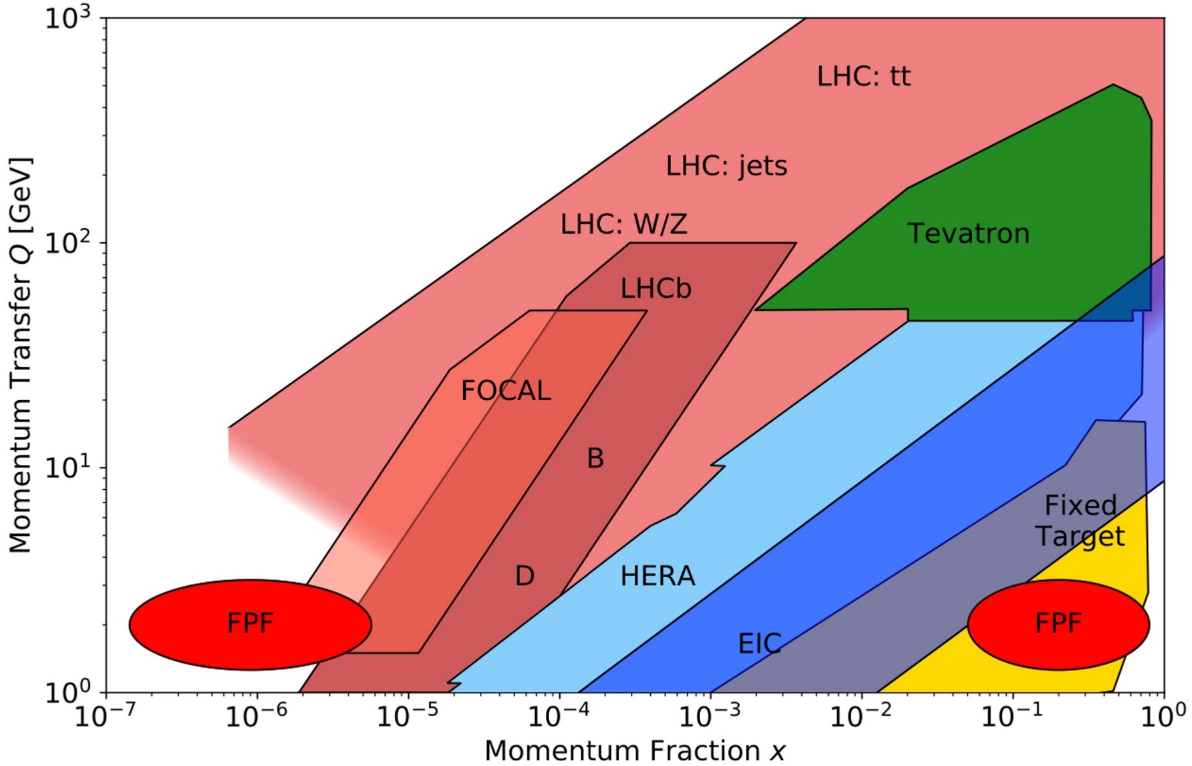
The chosen configuration maximises the average of the three possible configurations for all neutrino species as well as for those produced in charmed hadron decays

Neutrinos as a probe of charm production

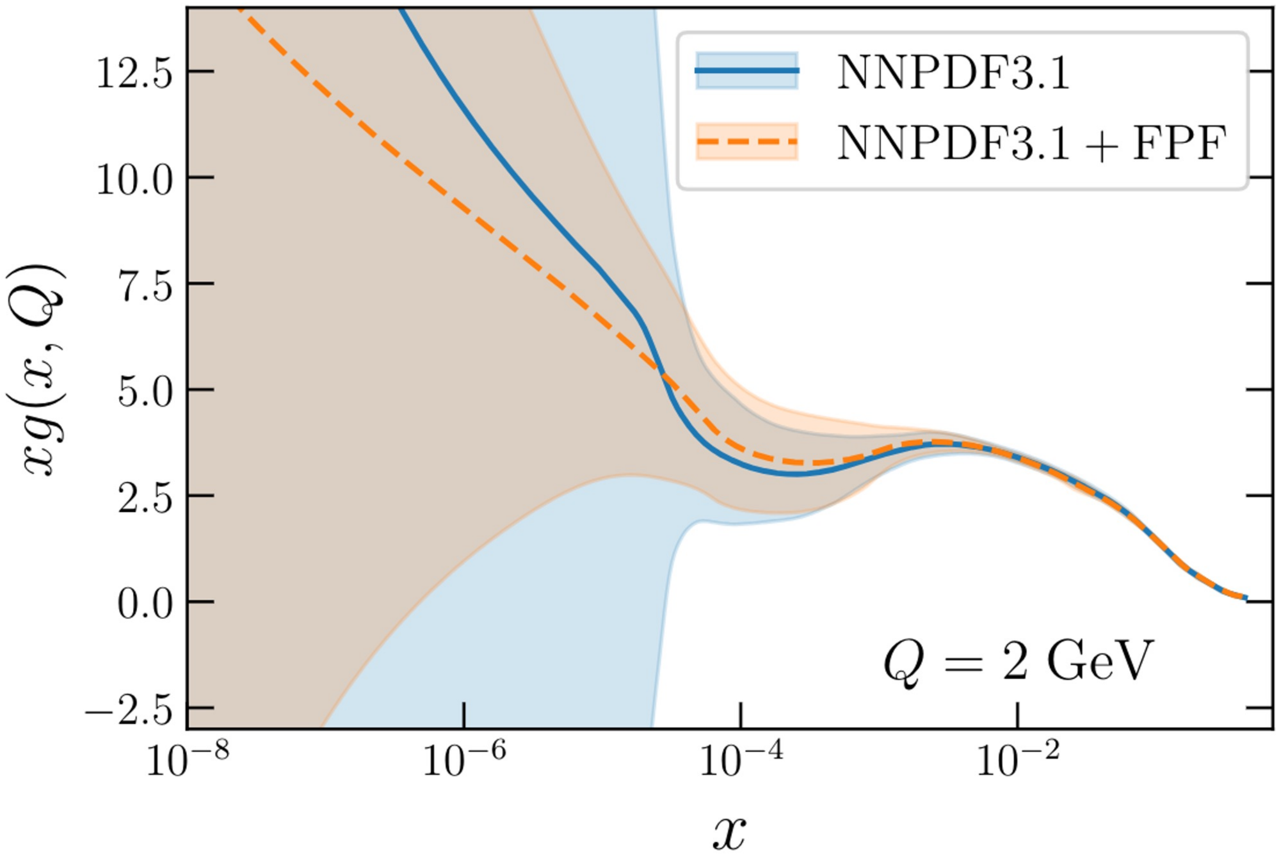


- Dominant partonic process: **gluon-gluon** scattering.
- SND@LHC will constrain the gluon PDF in the **very small x** region.
  - Only LHC neutrinos have sensitivity in this region.
- Relevant for **FCC-pp**, **ultra-high energy neutrinos** and **cosmic rays**.





New observables for gluon PDF



- The *high statistics* of HL-LHC will allow for *binning* the data, for example, in *rapidity*.
- Recent theory developments show that powerful constraints on the gluon PDF can be obtained by taking *ratios* of *rapidity* bins within a single experiment.

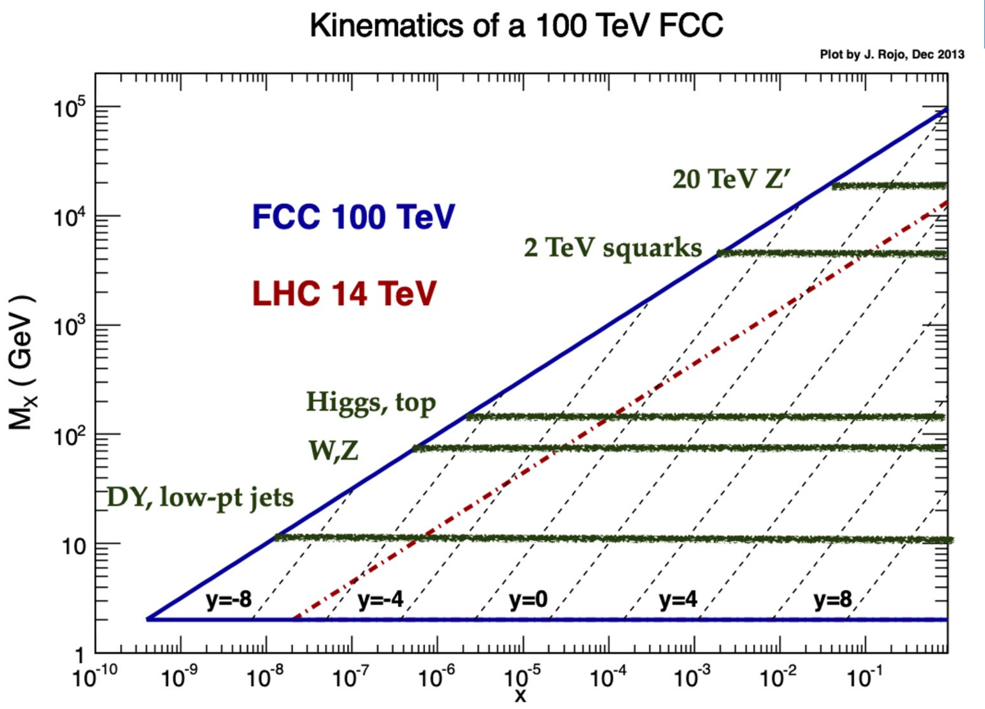
J. Rojo CERN-TH Colloquium 11/2023

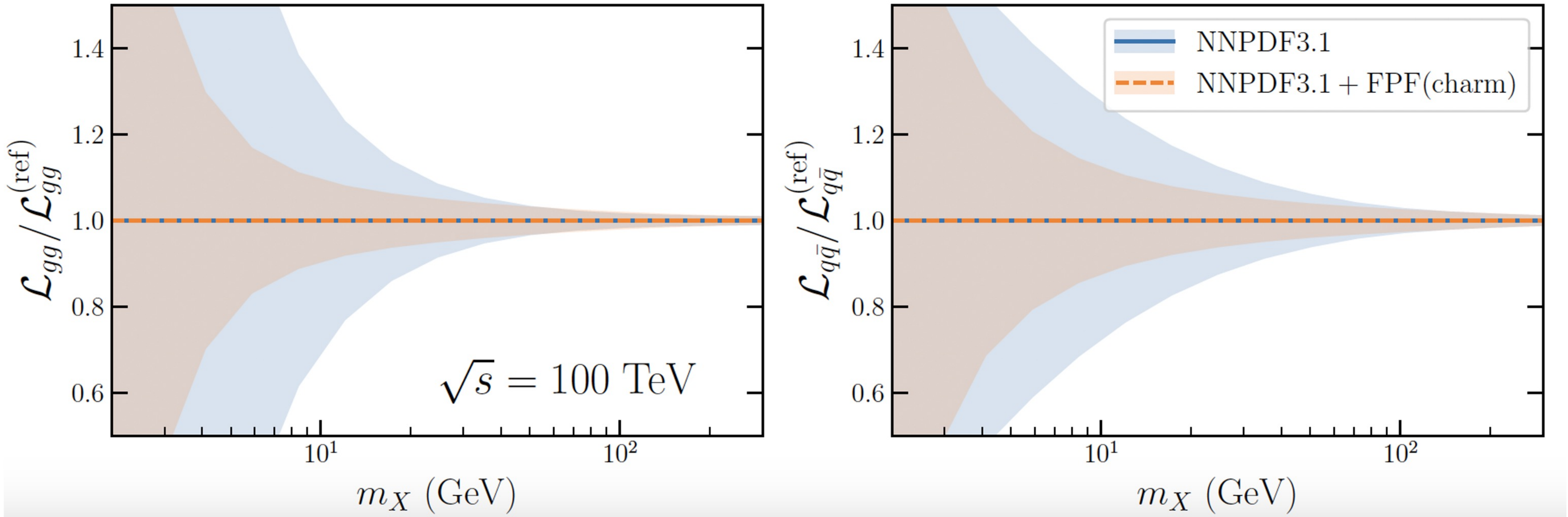
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- *Systematic uncertainty* on Advanced SND gluon PDF constraints will be *smaller* than the conservative estimate in the LoI.

Implications for FCC-pp

- Much of the *FCC-pp* physics will be produced at very *small x*.
  - Even electroweak and Higgs measurements will be sensitive to *small-x QCD*.
- Current estimates show a *large reduction* in FCC-pp *cross sections* with *constraints* from the *HL-LHC neutrino* data.

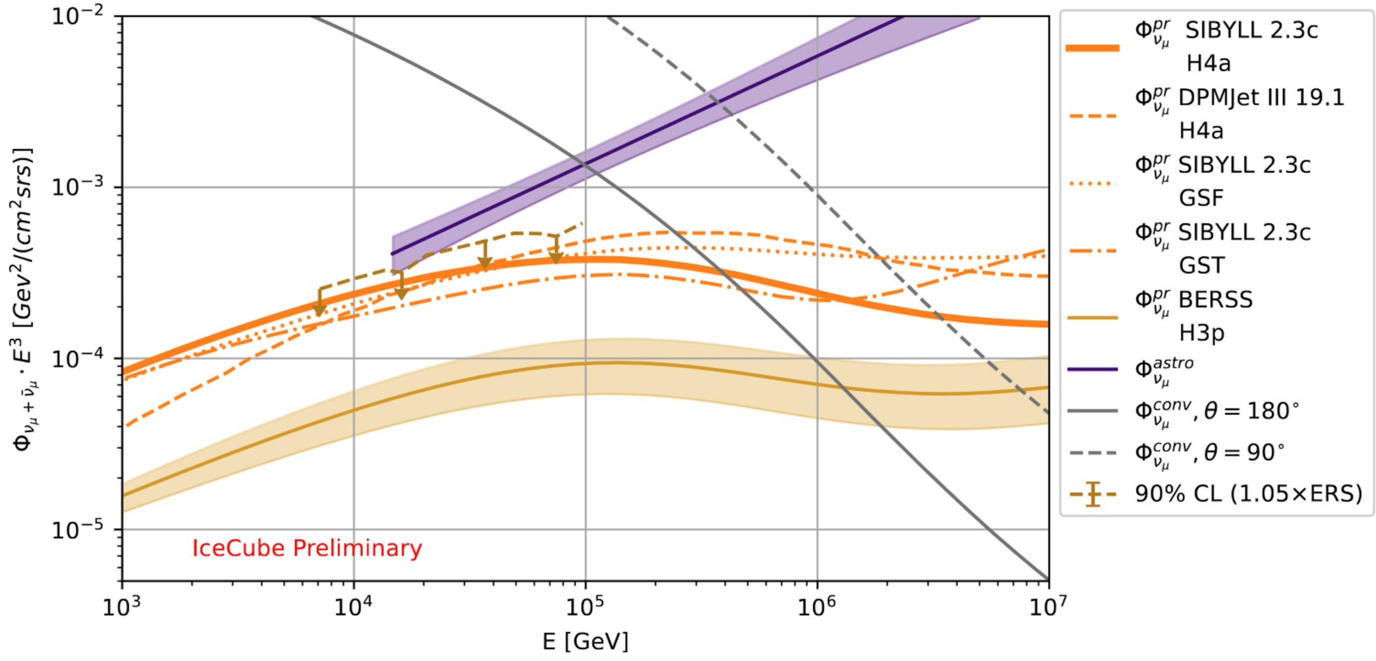




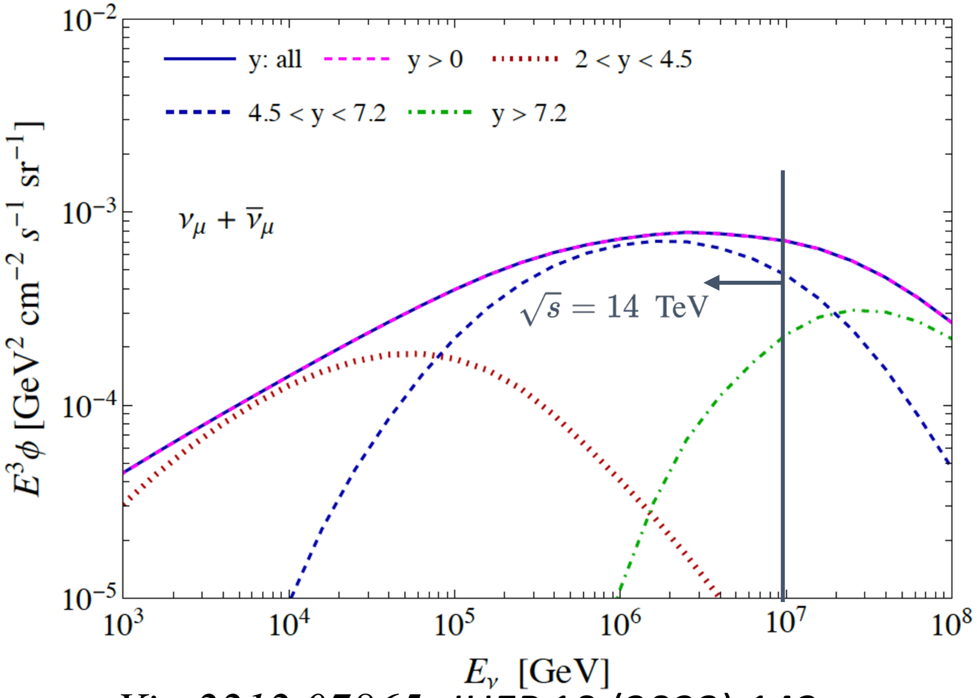
Implications for astroparticle physics

- The *prompt* flux of atmospheric neutrinos, originating from charm decays, is not known.
  - This is an important component in the *transition region* between *atmospheric* and *astrophysical* neutrino flux.
- LHC neutrinos originating from *charm* hadrons with η > ~ 7 correspond to atmospheric neutrino energies up to **10^7 GeV**, in the *transition region*.

Current IceCube limits on the prompt neutrino flux, along with model predictions.



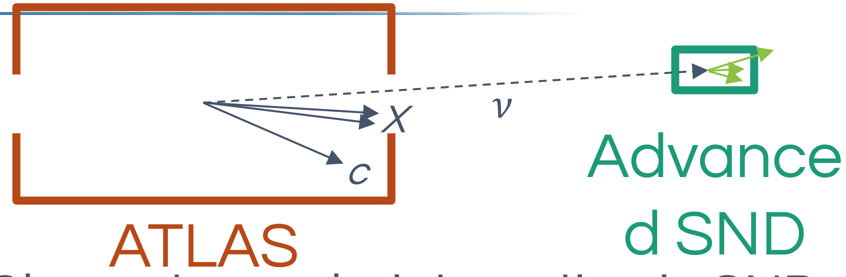
Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



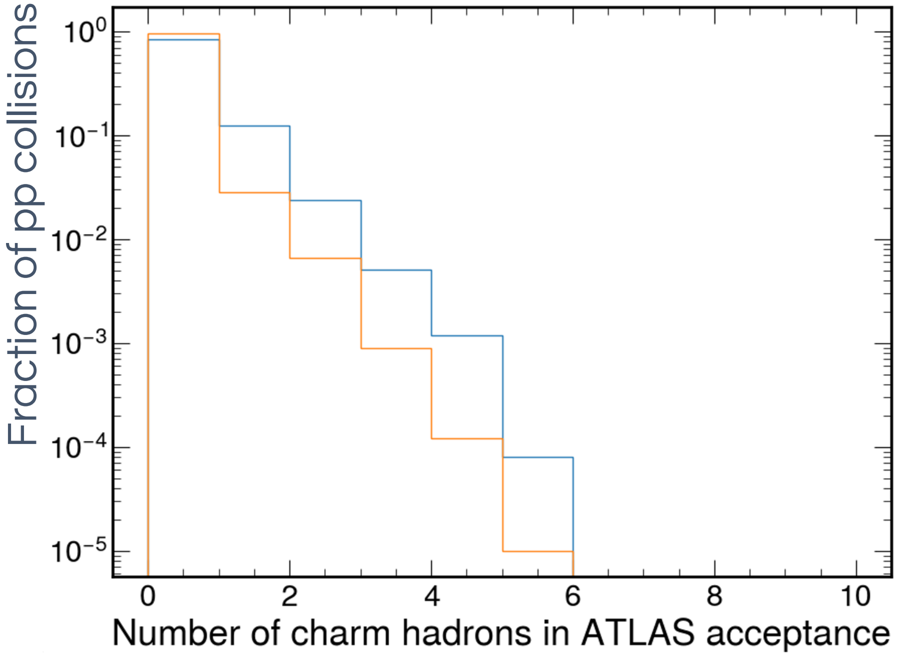
arXiv:2212.07865, JHEP 10 (2023) 142
https://doi.org/10.1007/JHEP10(2023)142

Exploring correlations with ATLAS

- The HL-LHC may be a ***golden opportunity*** to detect the ***production*** and ***interaction*** of neutrinos in the ***same event***.
  - The ATLAS Phase-II Level 0 ***trigger buffer*** (10 us) comfortably allows for a 500m round trip.
    - It's ***feasible*** for SND to ***trigger*** the ATLAS detector.
  - With the expected high statistics, it will be possible to measure processes that amount to only a few % of the neutrino interaction rates.
- Preliminary studies indicate an ***enhancement*** by a factor of ~4 of ***charm hadrons*** in the ***ATLAS*** acceptance given a ***neutrino*** detected in Advanced SND.
  - Beating the ***pile-up*** is the main challenge.
    - ***Timing resolution ~ 50 ps*** is critical.



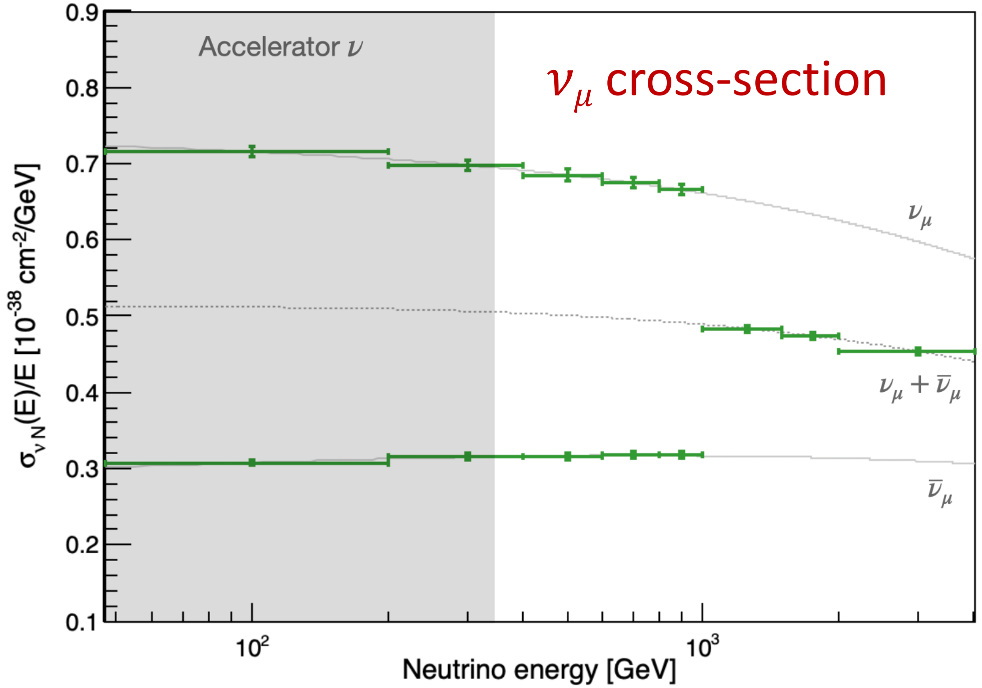
Charm-tagged ν interacting in SND

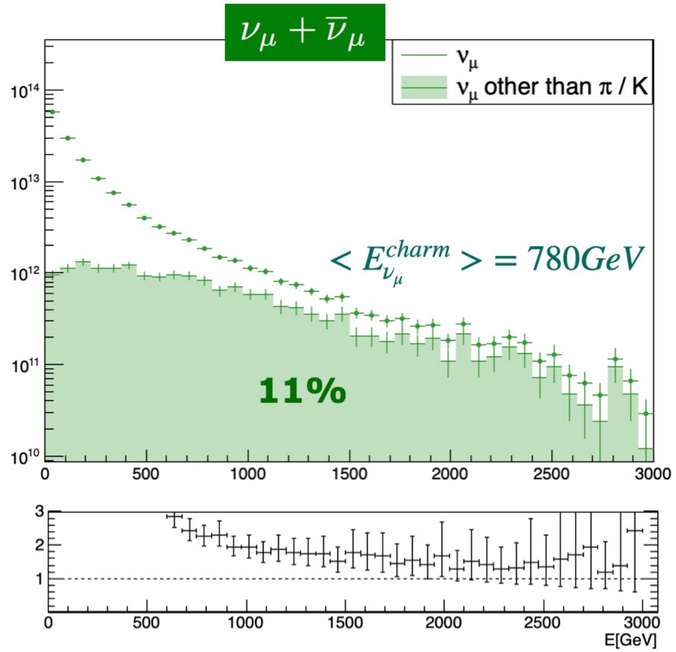


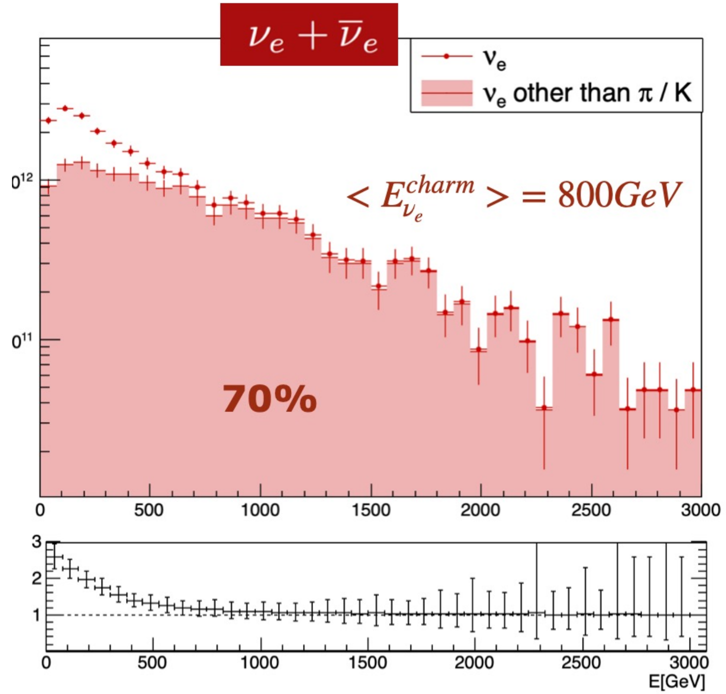
These conditions ***will not occur again*** in the next decades!

Physics performance in TI18

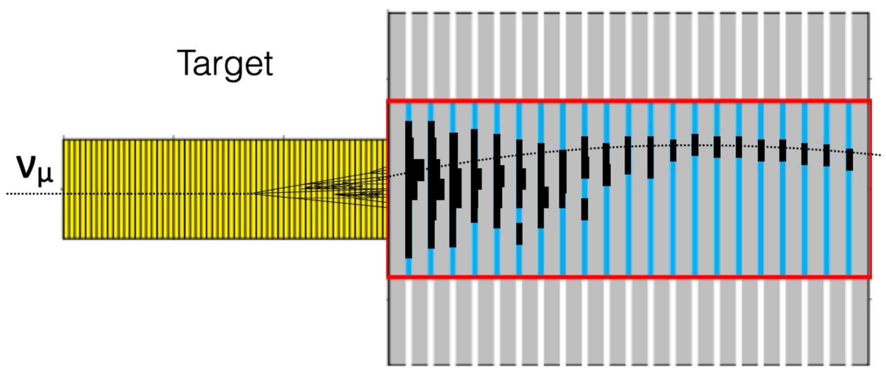
Flavour	ν in acceptance All	ν in acceptance not from π/k	CC DIS All	CC DIS not from π/k	NC DIS All	NC DIS not from π/k
ν_μ	8.6×10^{13}	8.2×10^{12}	7.7×10^4	2.1×10^4	2.3×10^4	6.4×10^3
$\bar{\nu}_\mu$	7.0×10^{13}	9.6×10^{12}	2.8×10^4	1.1×10^4	1.0×10^4	4.2×10^3
ν_e	1.3×10^{13}	9.1×10^{13}	2.7×10^4	2.3×10^4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

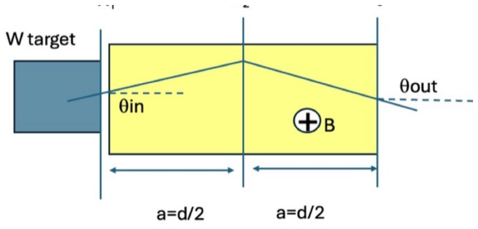






Overview of the upgraded detector



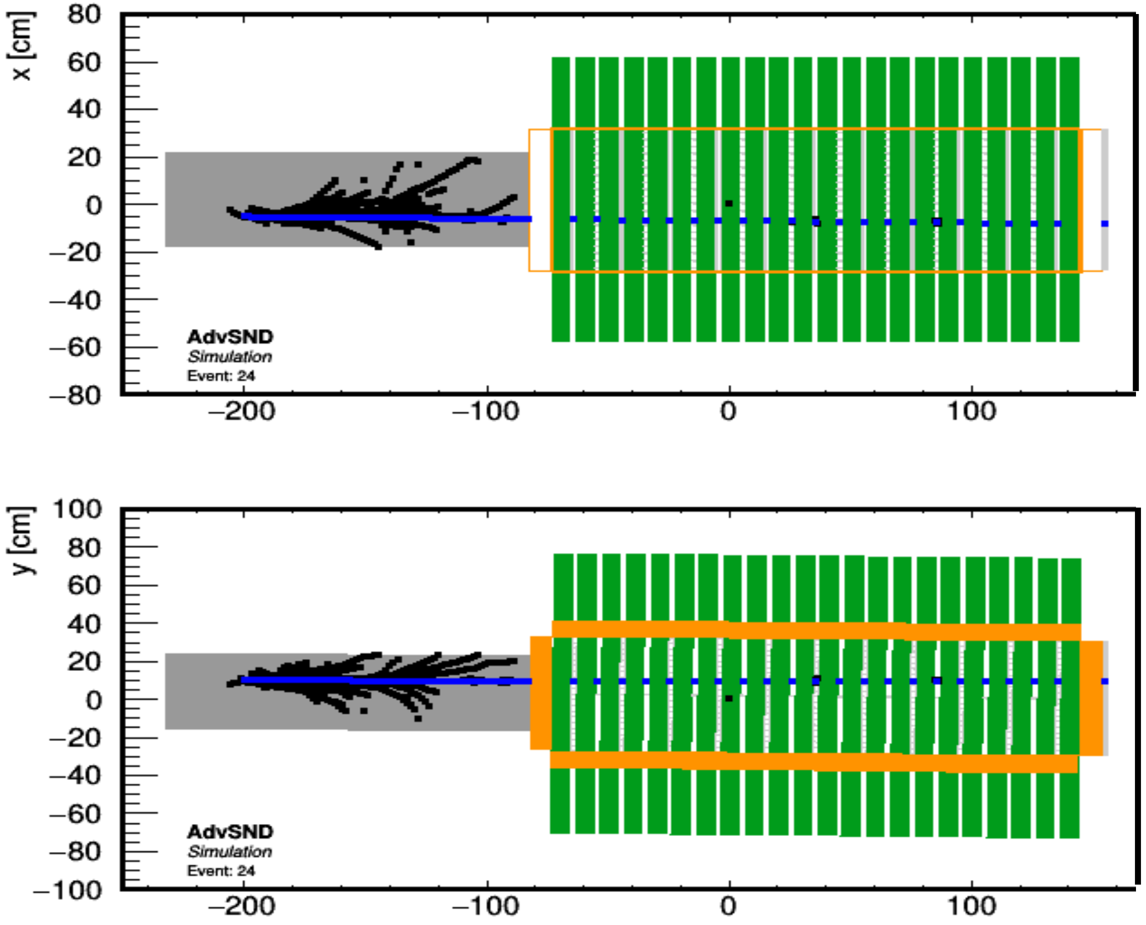


$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \simeq \rho\frac{\theta^2}{8} = 0.3\frac{BL^2}{8p}$$

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \sqrt{\frac{3}{2}}\frac{8p\sigma_x}{0.3BL^2}$$

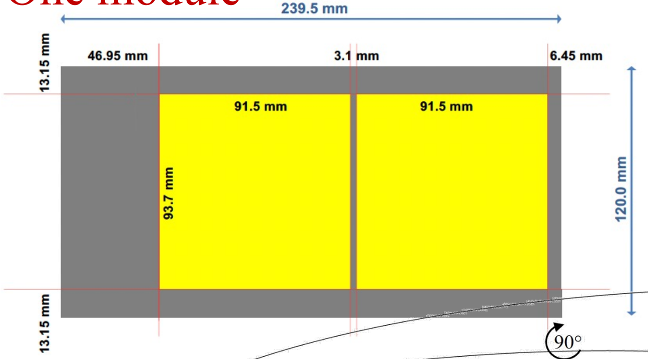
$$\frac{\Delta p}{p} \sim 21\%\ at\ 1\ TeV$$

Compact version with magnetised calorimeter

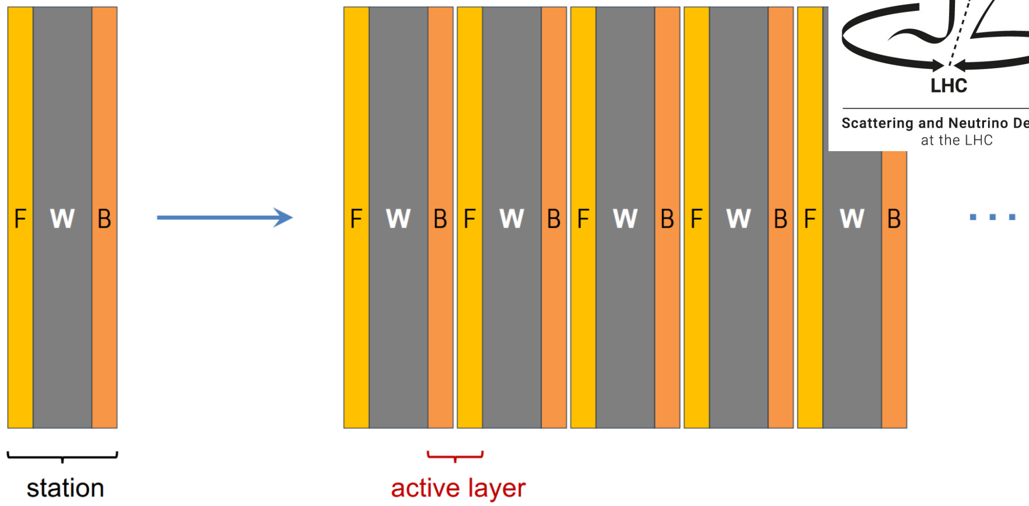


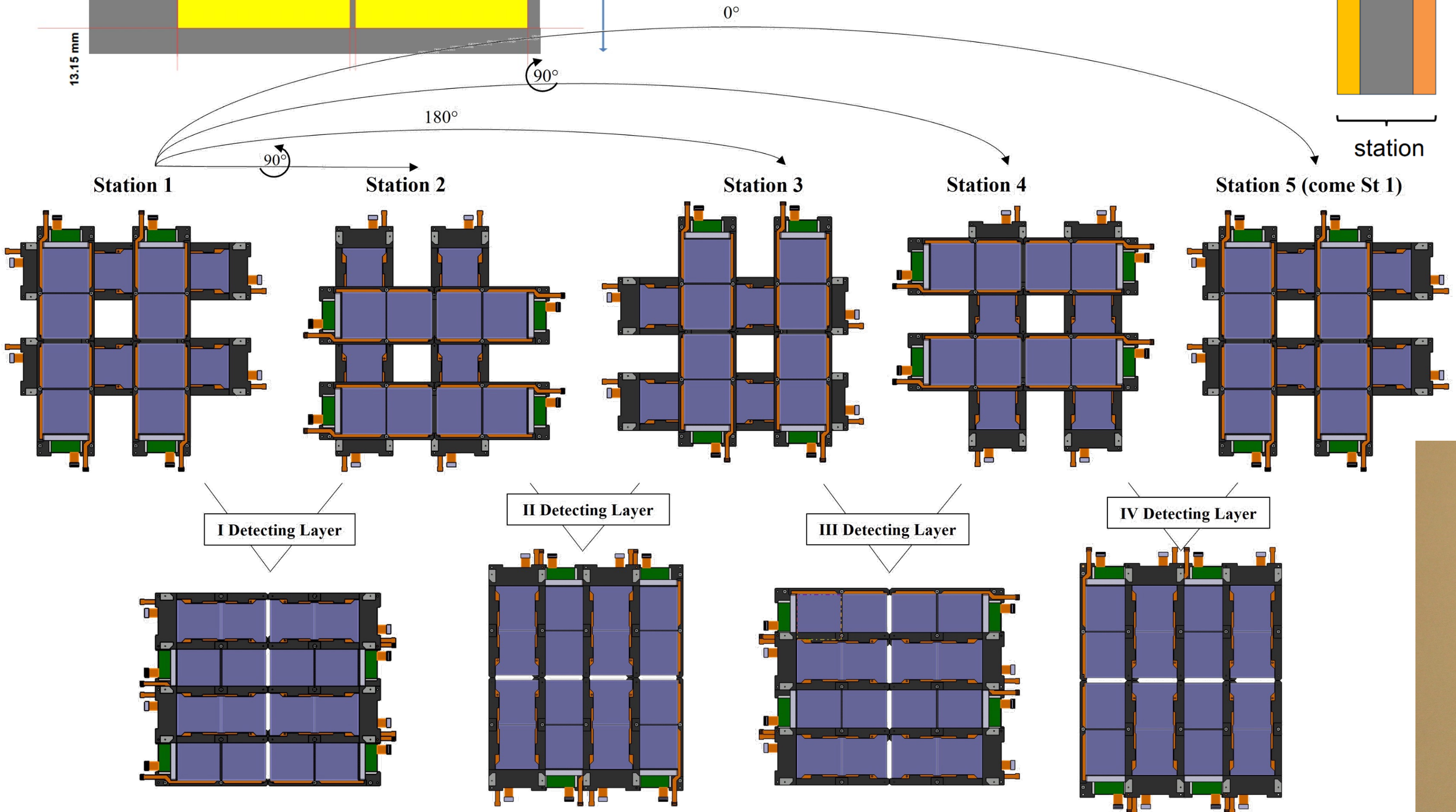
CMS silicon trackers as a vertex/ECAL detector

One module

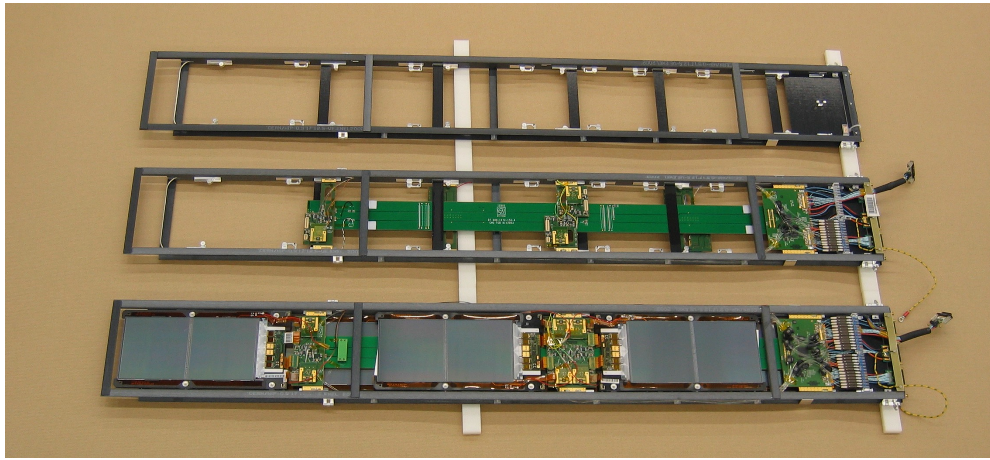


One station with 8 modules





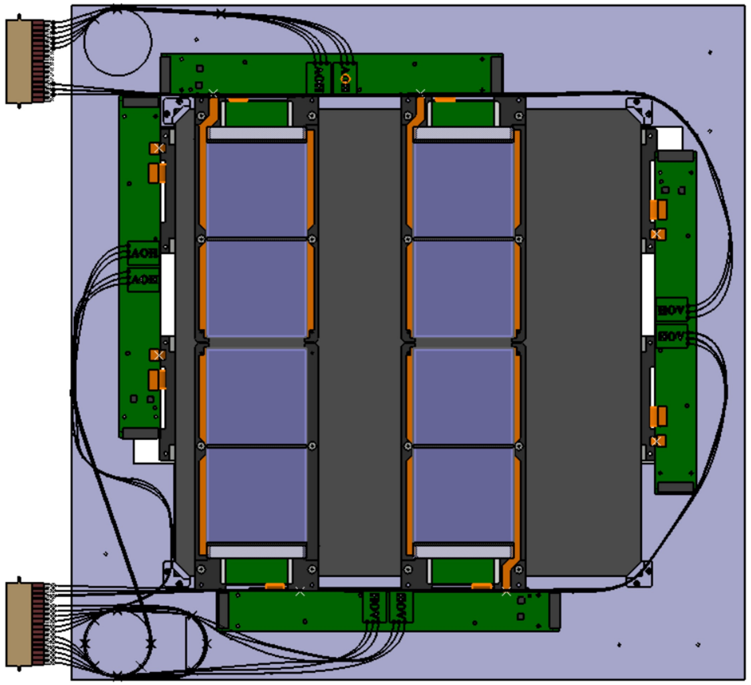
Agreement with CMS to reuse their TOB modules (and their spare components) approved by the CMS Board on Feb 9th 2024

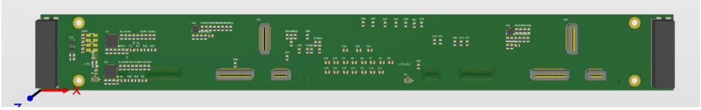


One detecting layer is “hermetic”

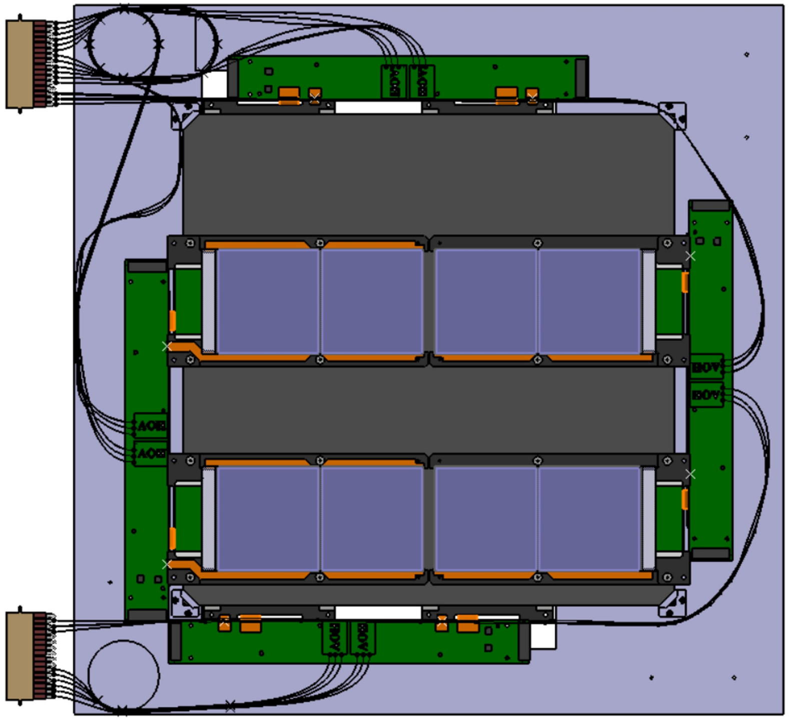
Mechanics and electronics

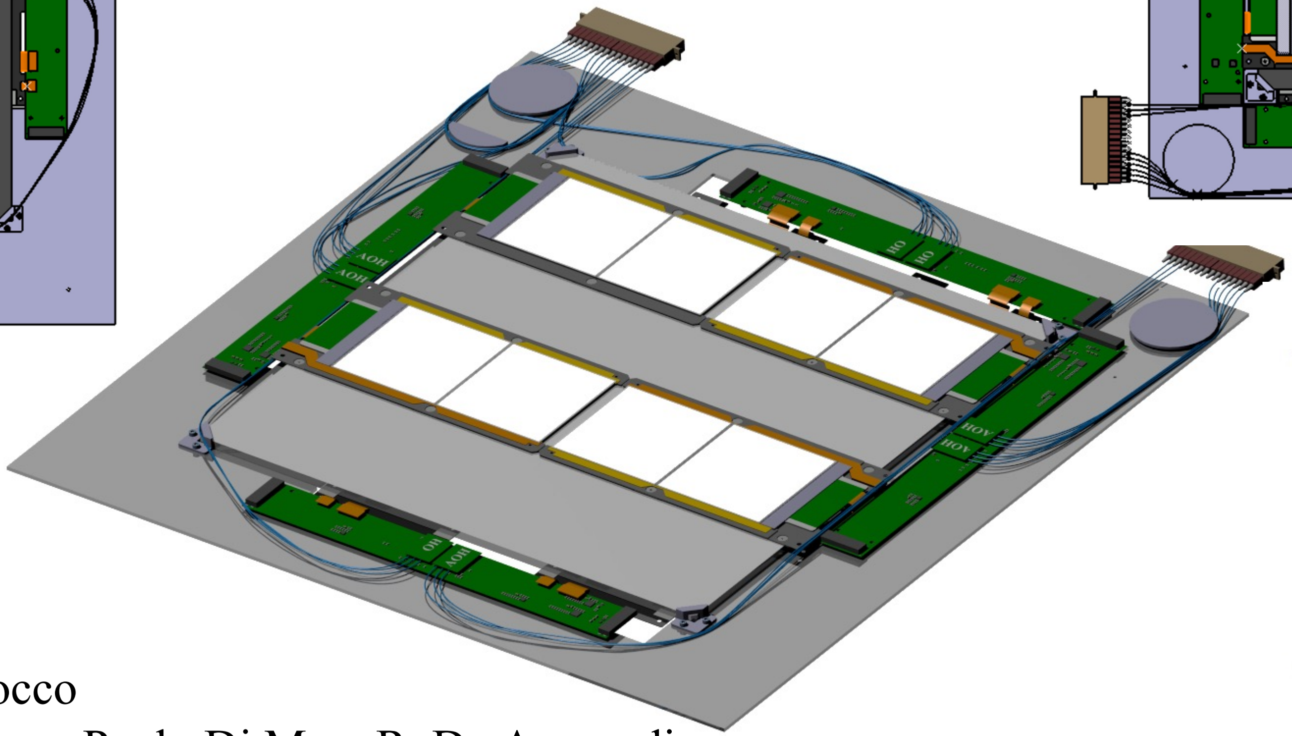
Station-1

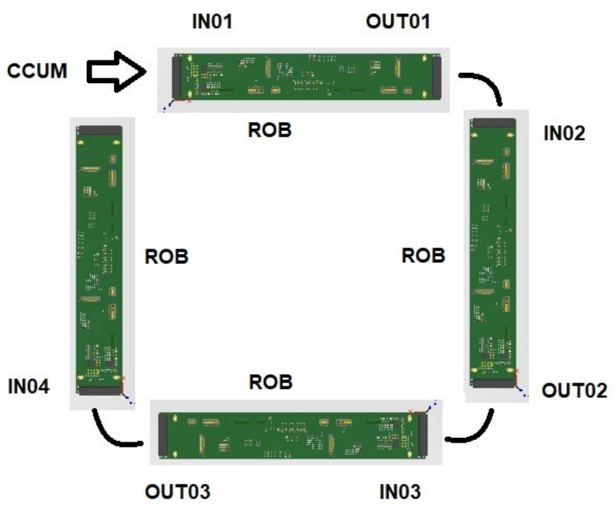




Station-2







INFN Napoli

Mechanical design: Alcide Bertocco
Electronics design: Alfonso Boiano, Paolo Di Meo, R. De Asmundis

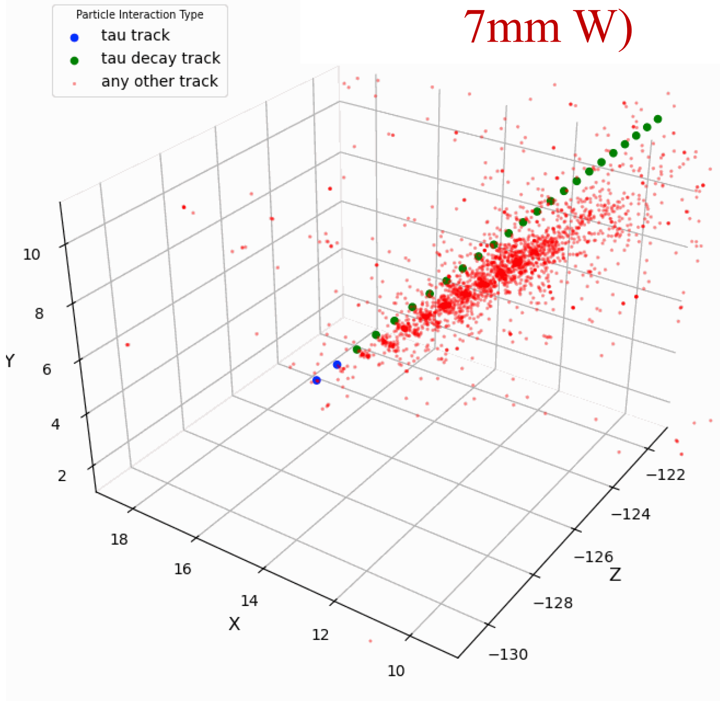
Silicon pixel planes from ALICE ITS2

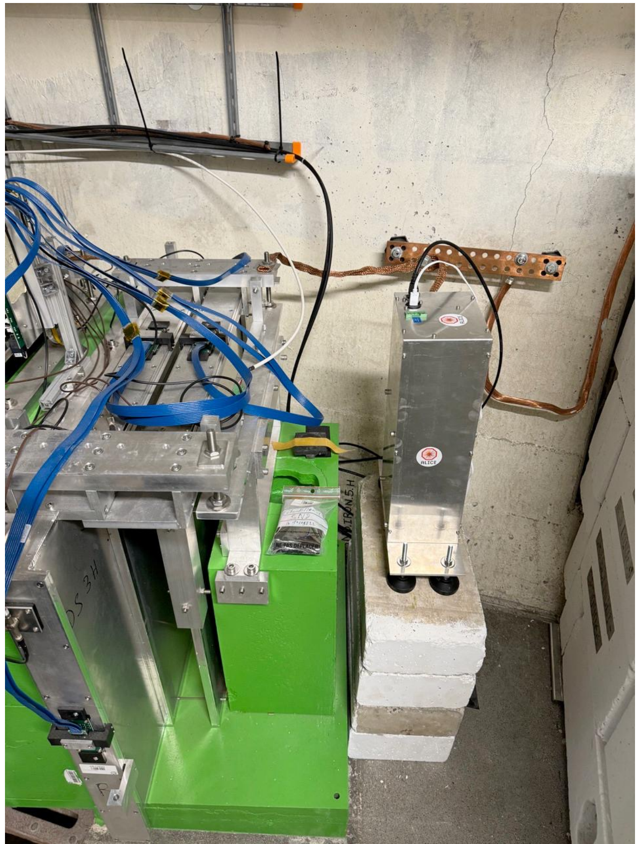
LHC
Scattering and Neutrino Detector at the LHC

170 modules left from the ITS2 production. The majority has defects at the percent level (max 1 chip out of 14)

Each module contains 2x7 ALPIDEs, covering an active area of about 2.7x21 cm (the active area of ALPIDE is not the full 1.5 cm). So for 40x40 cm^2, need 15x2=30 modules → 4 stations

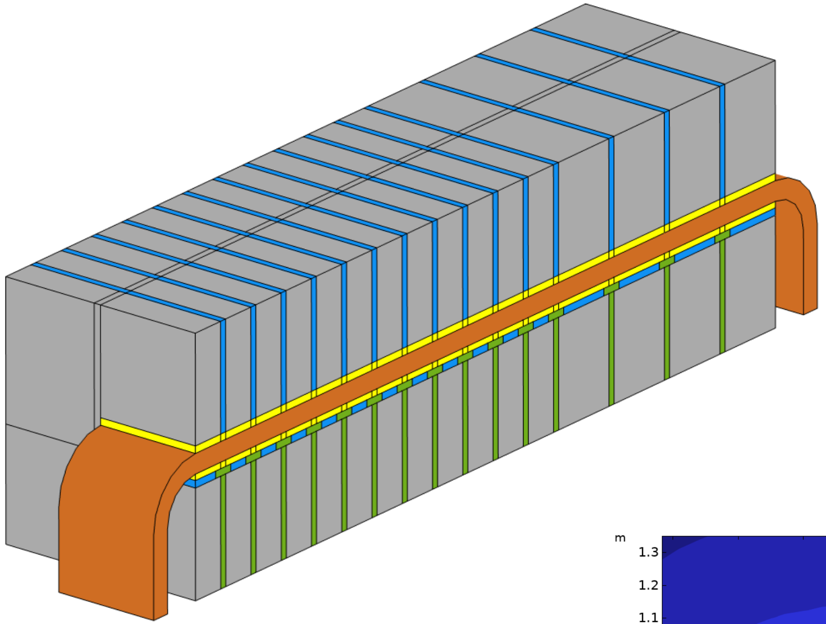
τ decay to μ, sampled every 11 mm (with 7mm W)

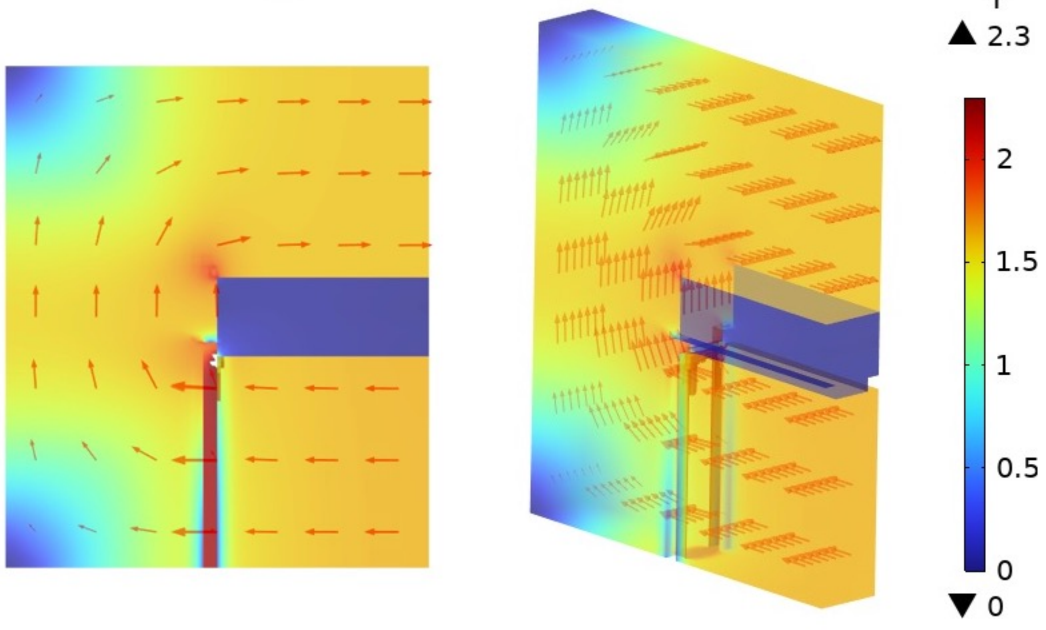




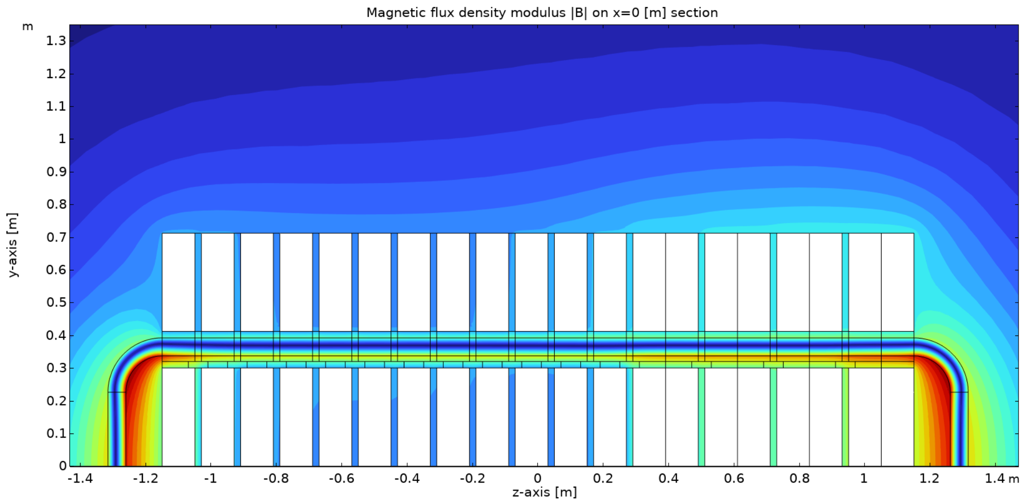
Magnet design

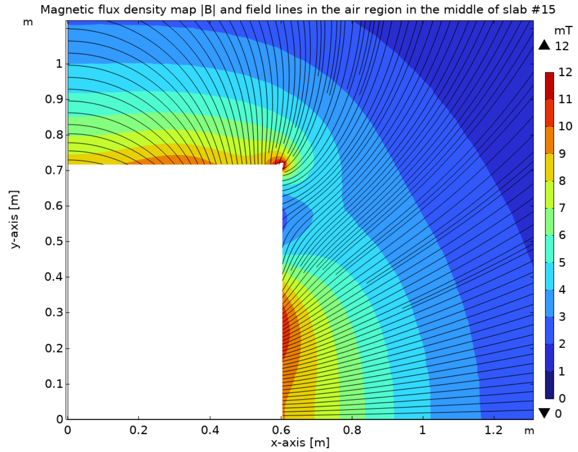
R. Albanese[1,7], D. Centanni[2,7], G. De Lellis[3,7], D. Davino[4,7], M. de Magistris[2,7],
A. Di Crescenzo[3,7], A. Iaiunese[2,7], *V.P. Loschiavo*[4,7], *R. Fresa*[5,7],
B. V. Scalera[2,7], W. Schmidt-Parzefall[6], A. Quercia[1,7], C. Visone[1,7]



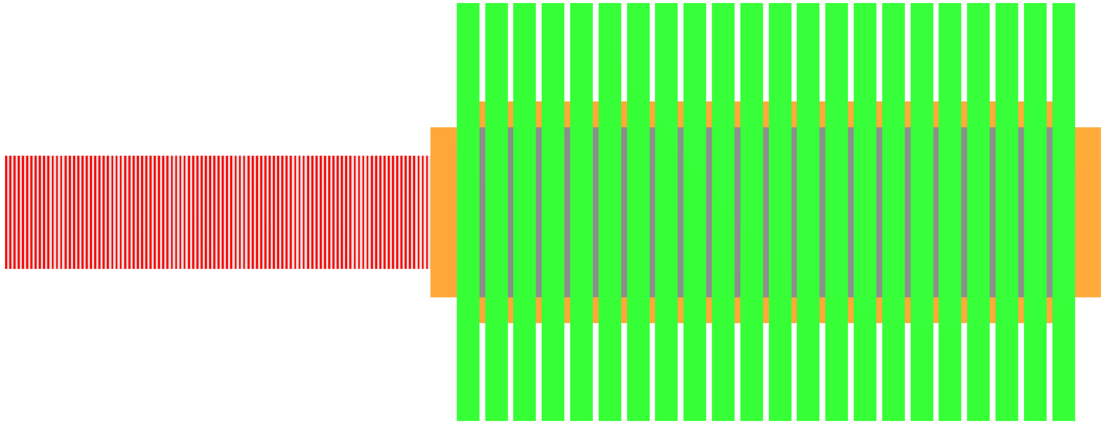


Stray field outside

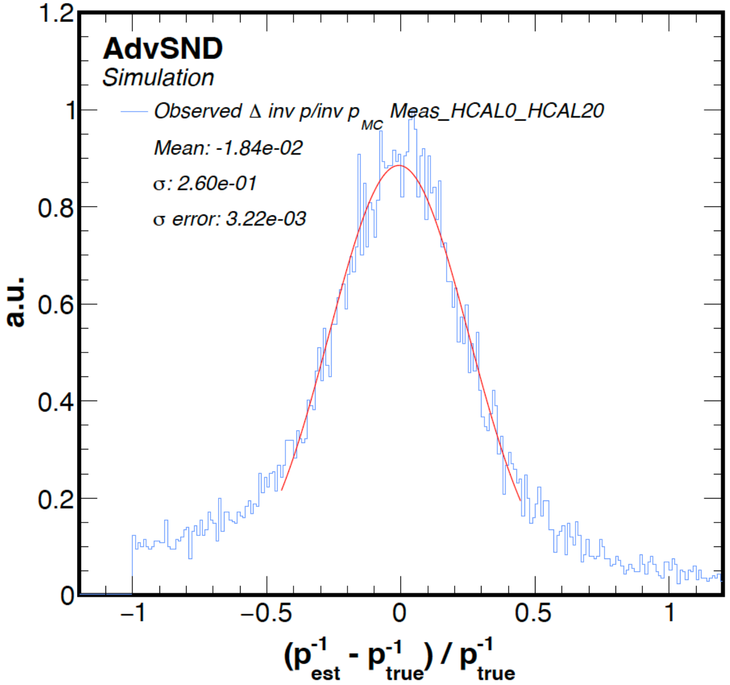


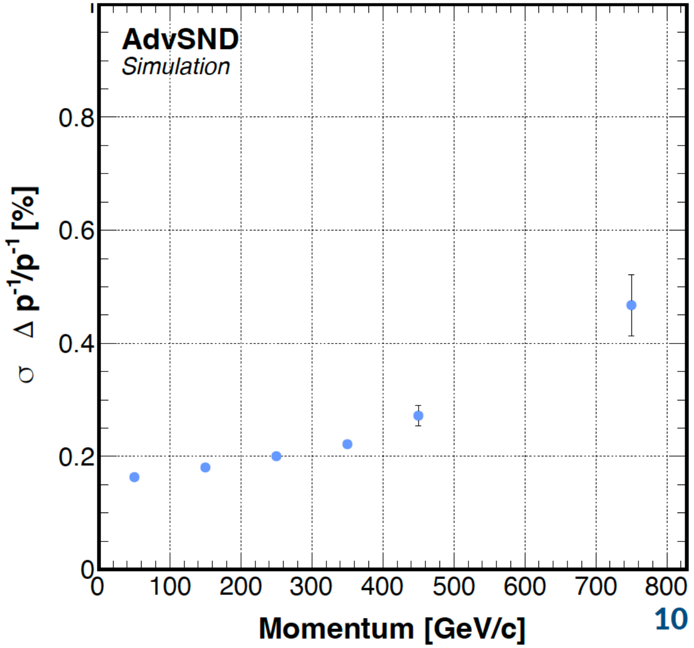


Preliminary performance of the muon spectrometer

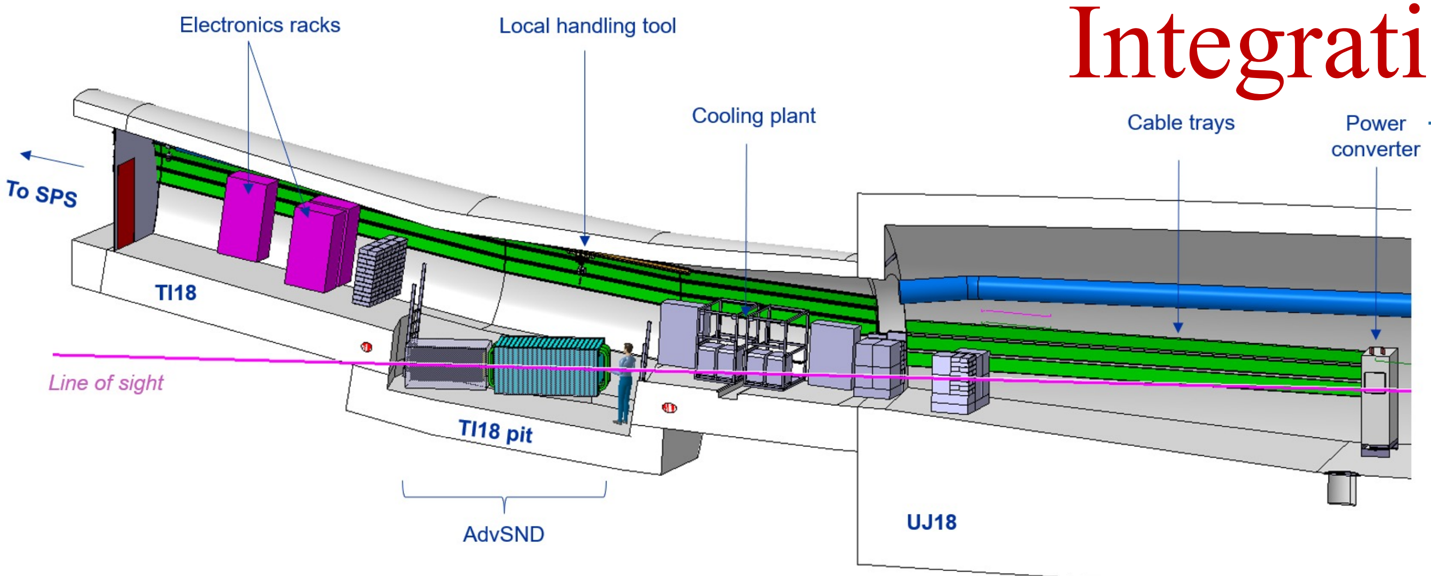


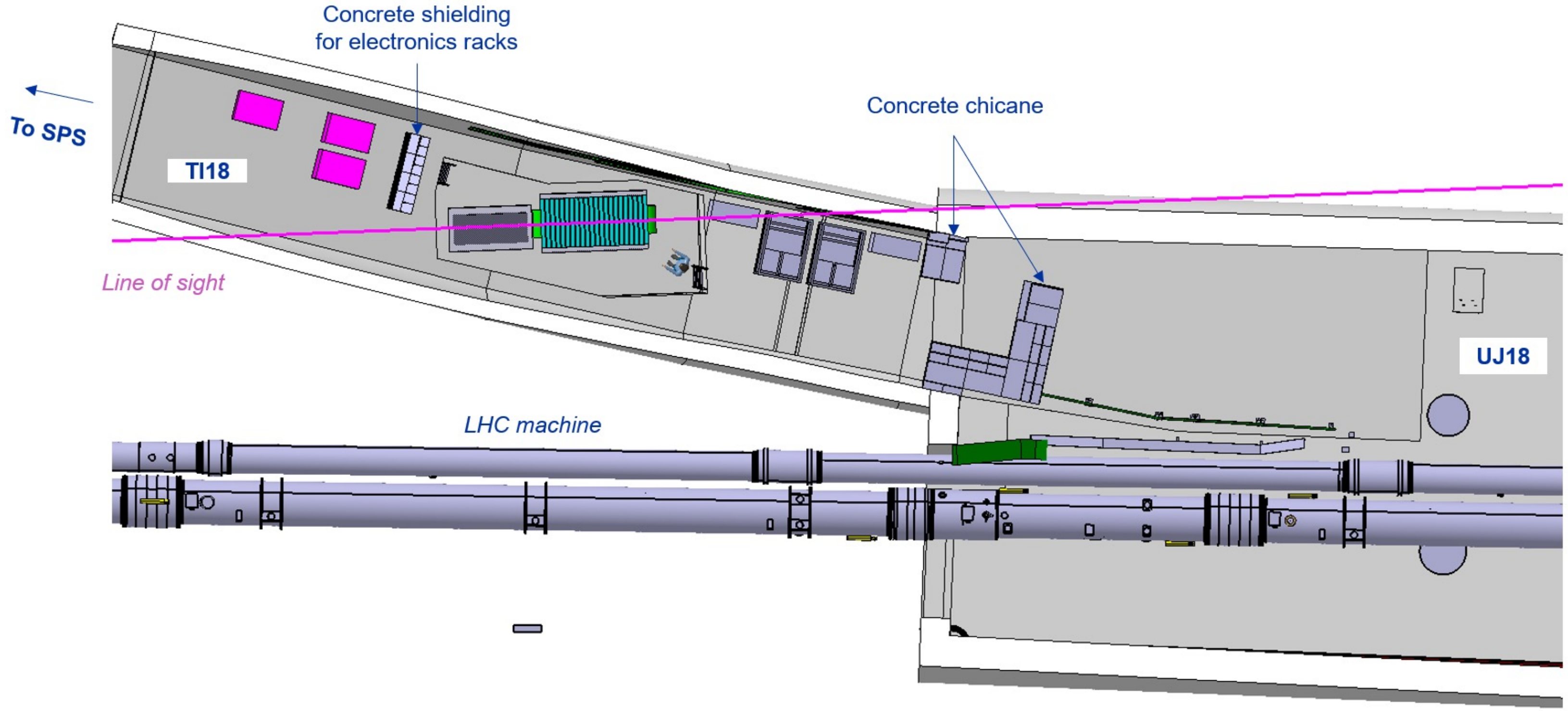
Measuring the angular deflection





Integration studies in TI18





Integration studies in TI18

LHC
Scattering and Neutrino Detector
at the LHC