The new era of accelerator neutrinos: the SND@LHC experiment

LHC
Scattering and Neutrino Detector at the LHC

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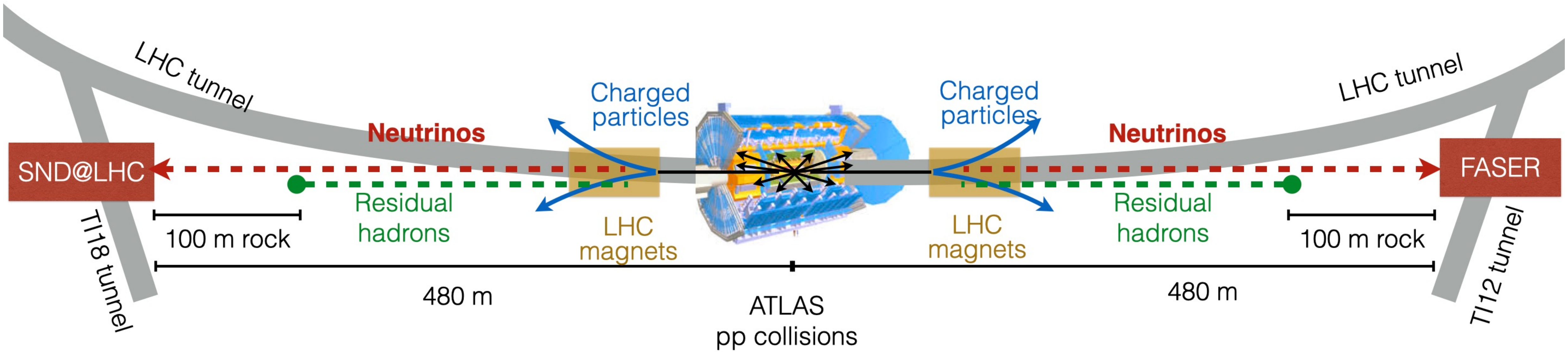
On behalf of the SND@LHC Collaboration

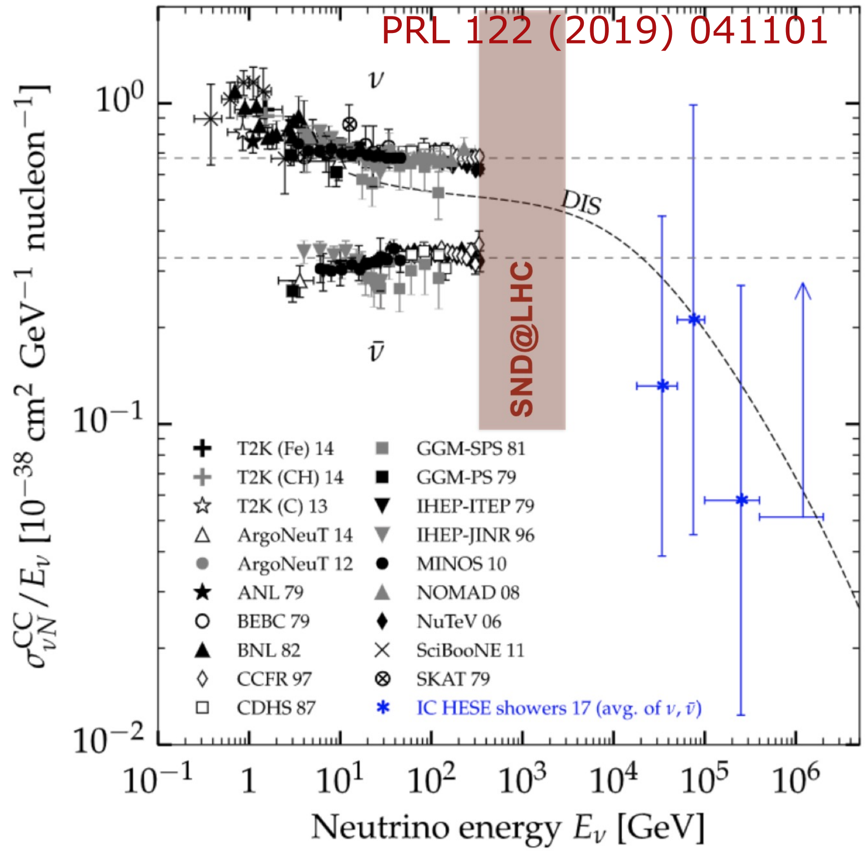


8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics, Anacapri, June 11th 2022

MOTIVATION

Neutrino physics at the LHC

- A. De Rujula and R. Ruckl. 1984, Neutrino and muon physics in the collider mode of future accelerators
- Klaus Winter, 1990, observing tau neutrinos at the LHC
- A. De Rùjula, E. Fernandez and J. J. Gòmez-Cadenas, 1993, Neutrino fluxes at LHC
- http://arxiv.org/abs/1804.04413 April 12th 2018, First paper on feasibility of studying neutrinos at LHC



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]

Further studies on the physics potential of an experiment using LHC neutrinos

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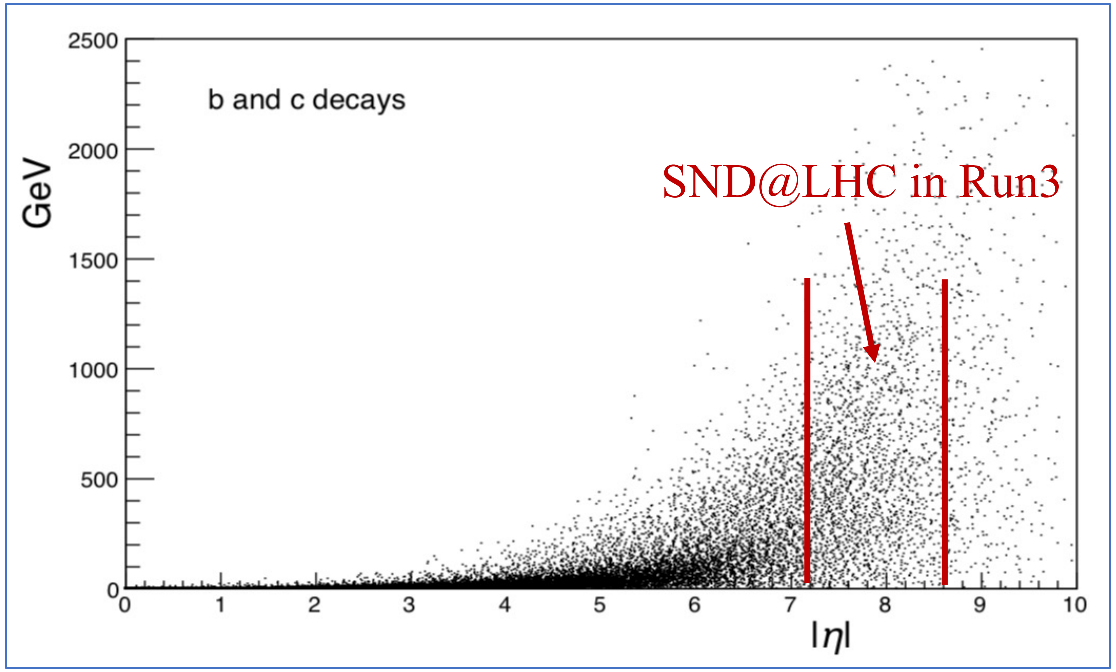
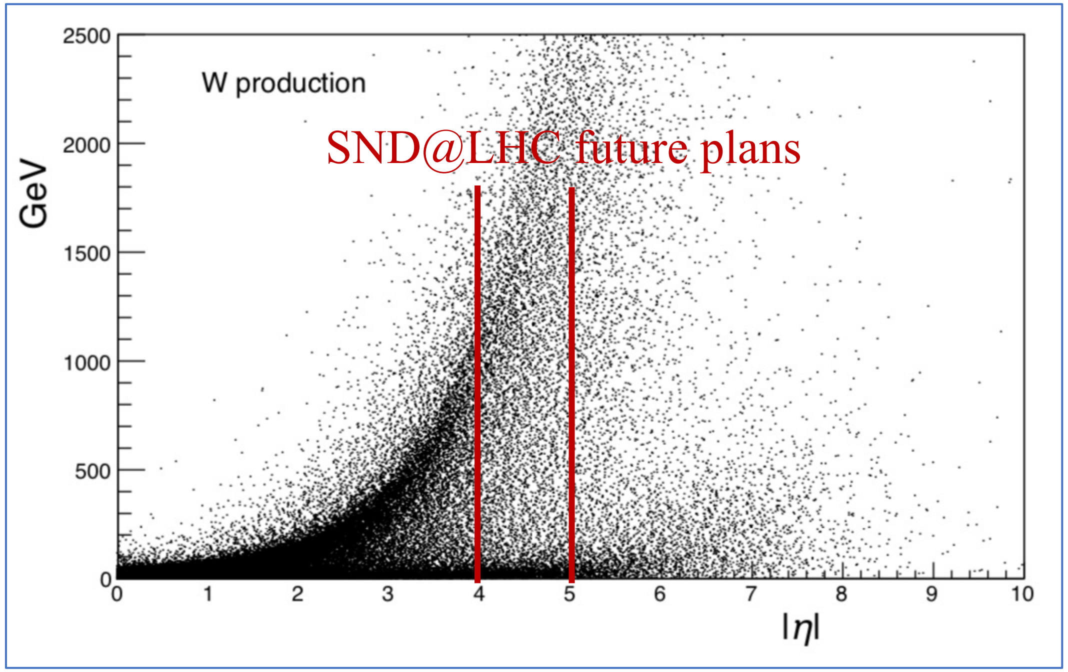
CERN is unique in providing energetic **ν** (from LHC) and measure pp → **ν**X in an unexplored domain

Neutrinos from b, c and W

ν_τ ~5% for 6.5< η <9 Journal of Physics G 46 (2019) 115008 Br (ν_τ) ~ 33%





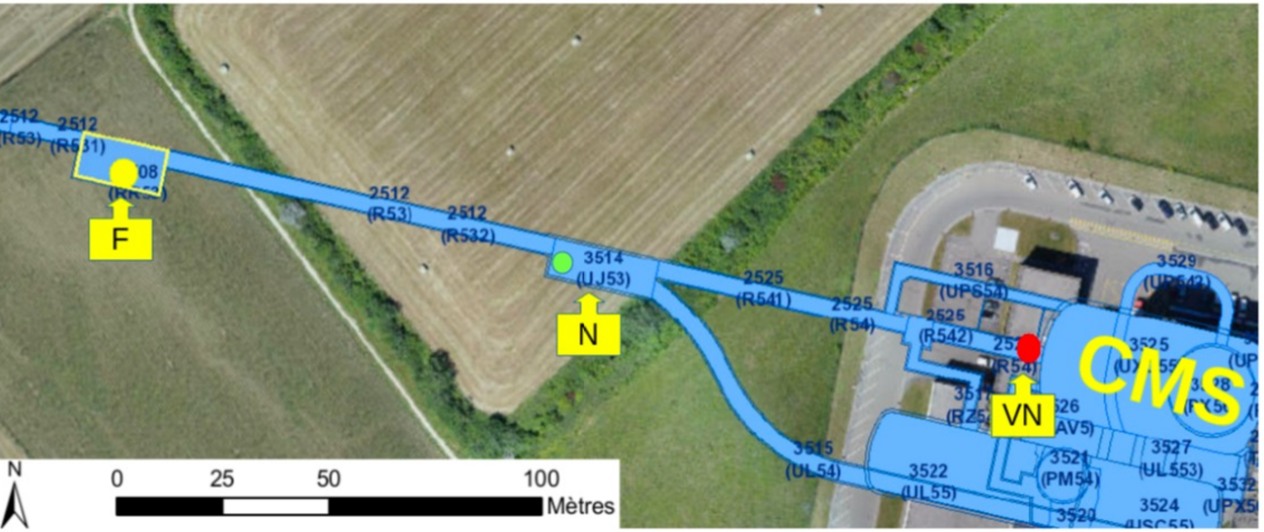
Mostly for η < 5

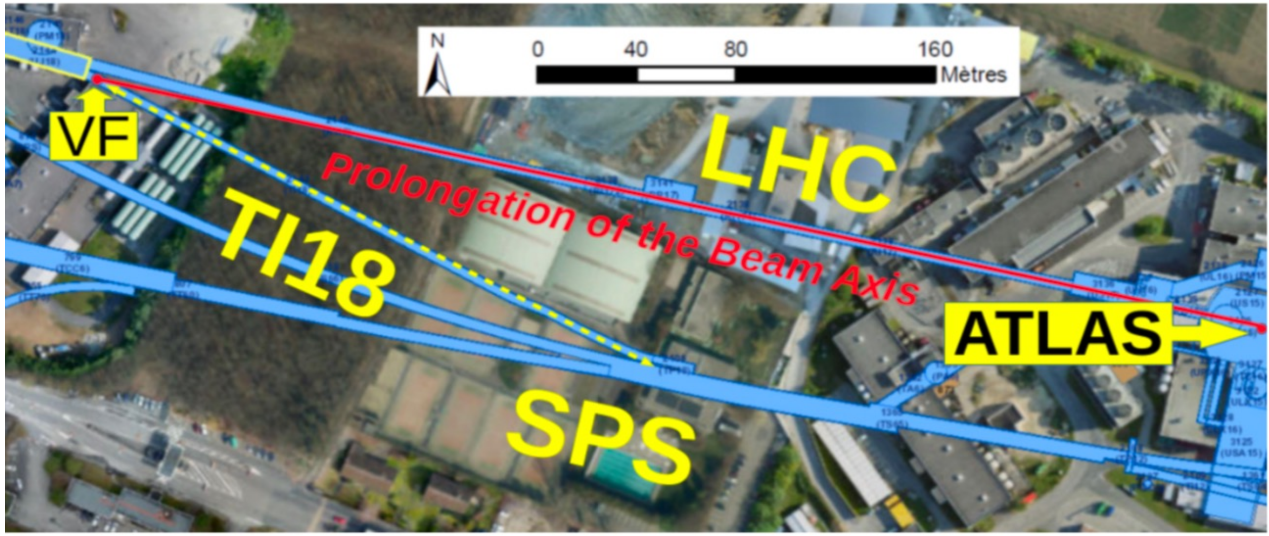
Plots show the scatter plots of ν energy versus η

- SND@LHC is off-axis
- Important benchmark of charm production in the $4 < \eta < 5$ range → future plans

Investigating the background for a neutrino detector in different locations with a measurement campaign

VN = Q1 in S45 at 25m
N = UJ53 and UJ57 at 90-120m
F = RR53 at 237m
VF = TI18 at 480m

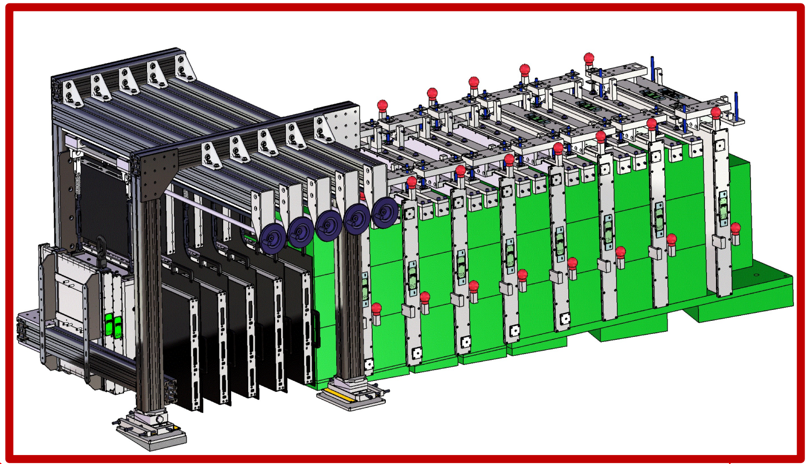


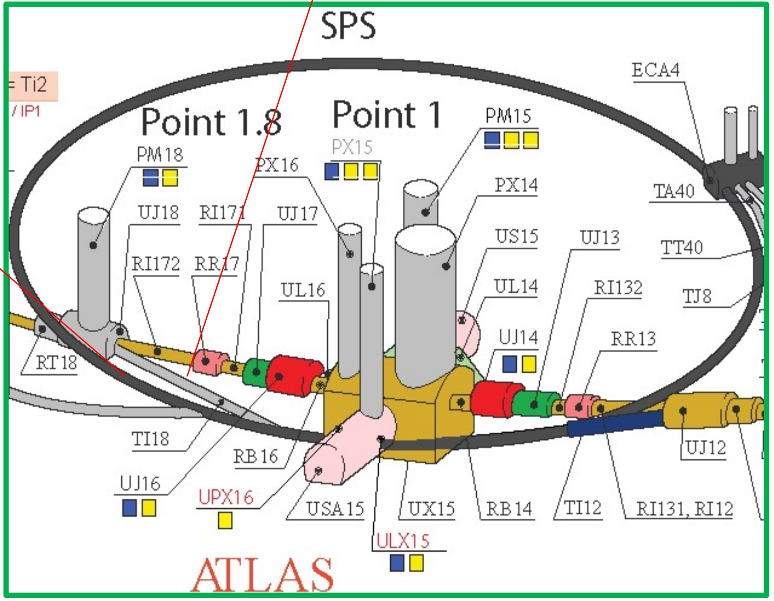


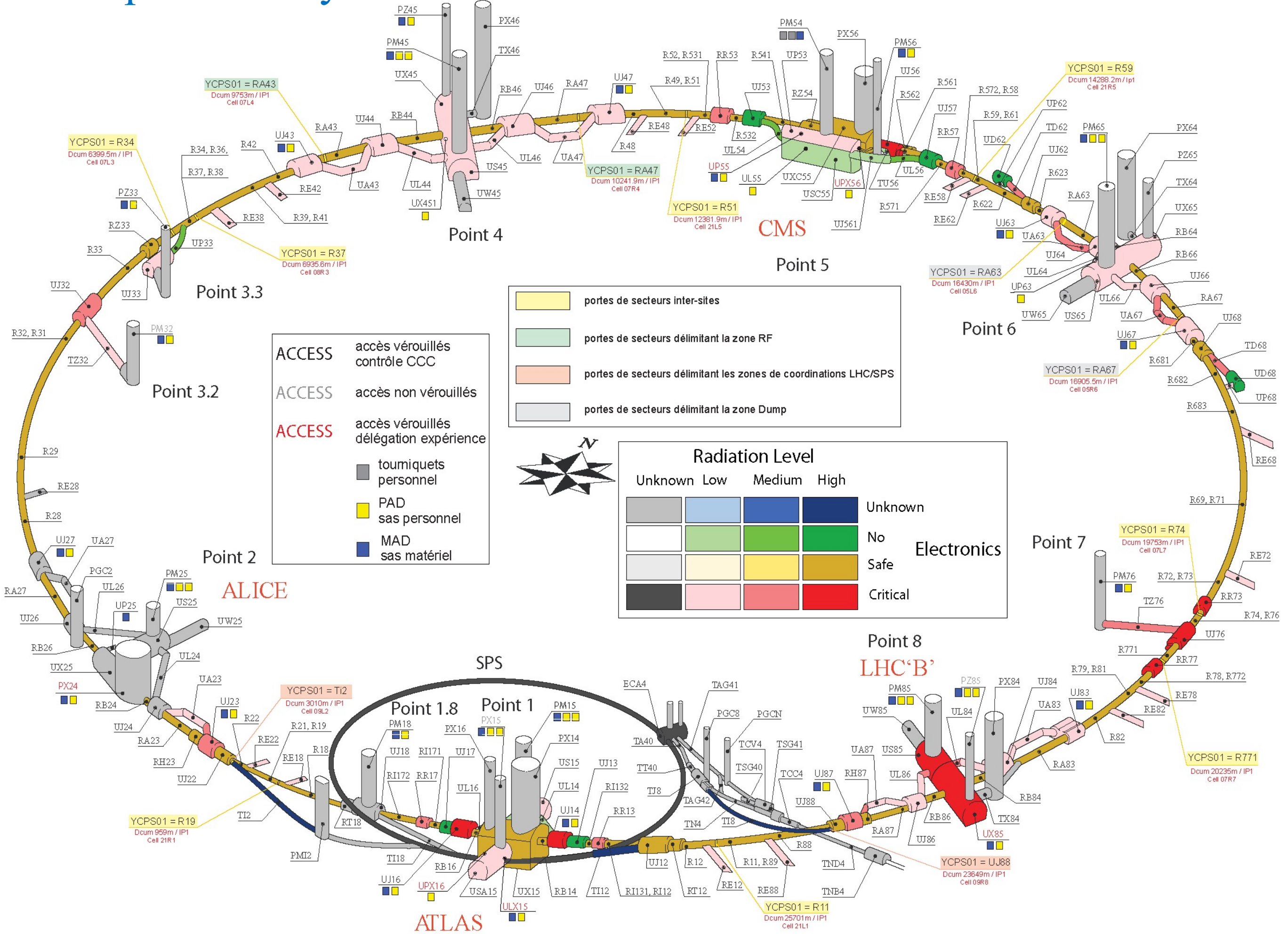
[Journal of Physics G 46 (2019) 115008](#)

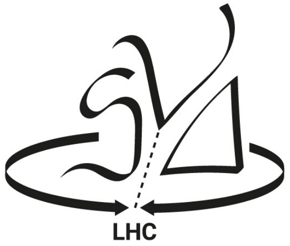
Location: TI18, transfer tunnel connecting SPS to LEP

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



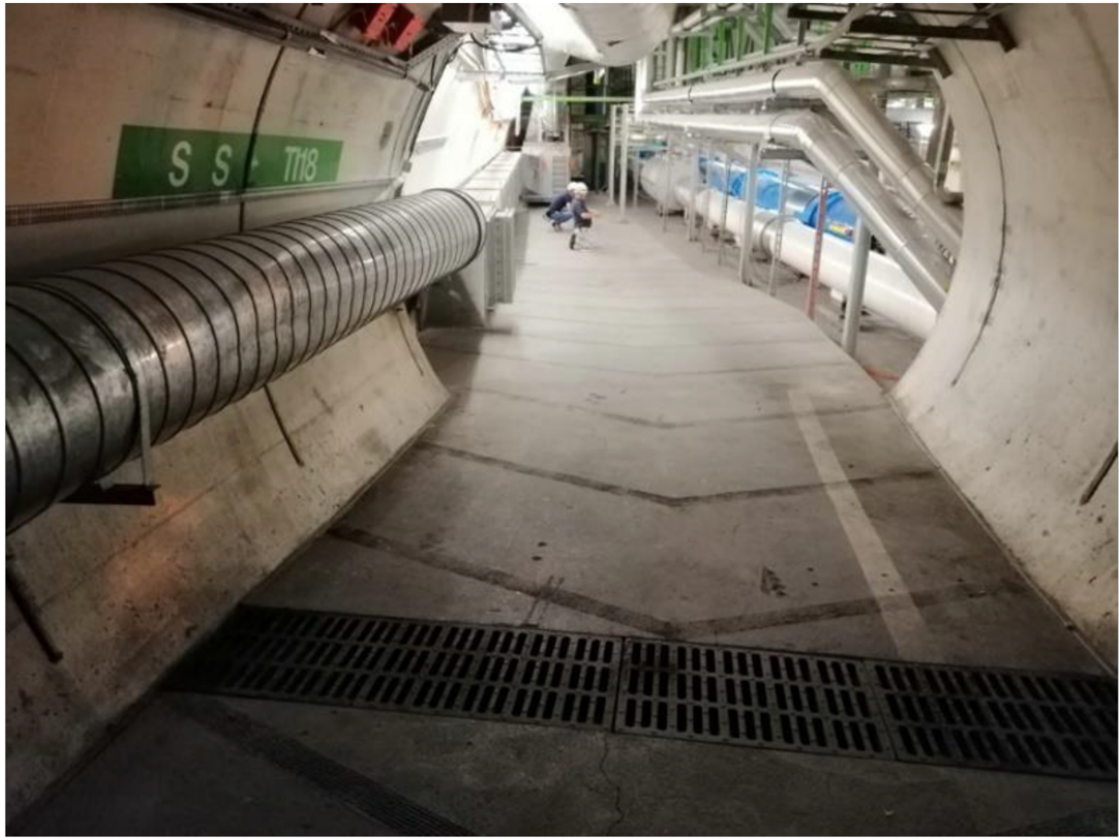






The TI18 tunnel at the end of 2020

The LHC seen from the tunnel



Experiment concept

Hybrid detector optimised for the identification of all three neutrino flavours

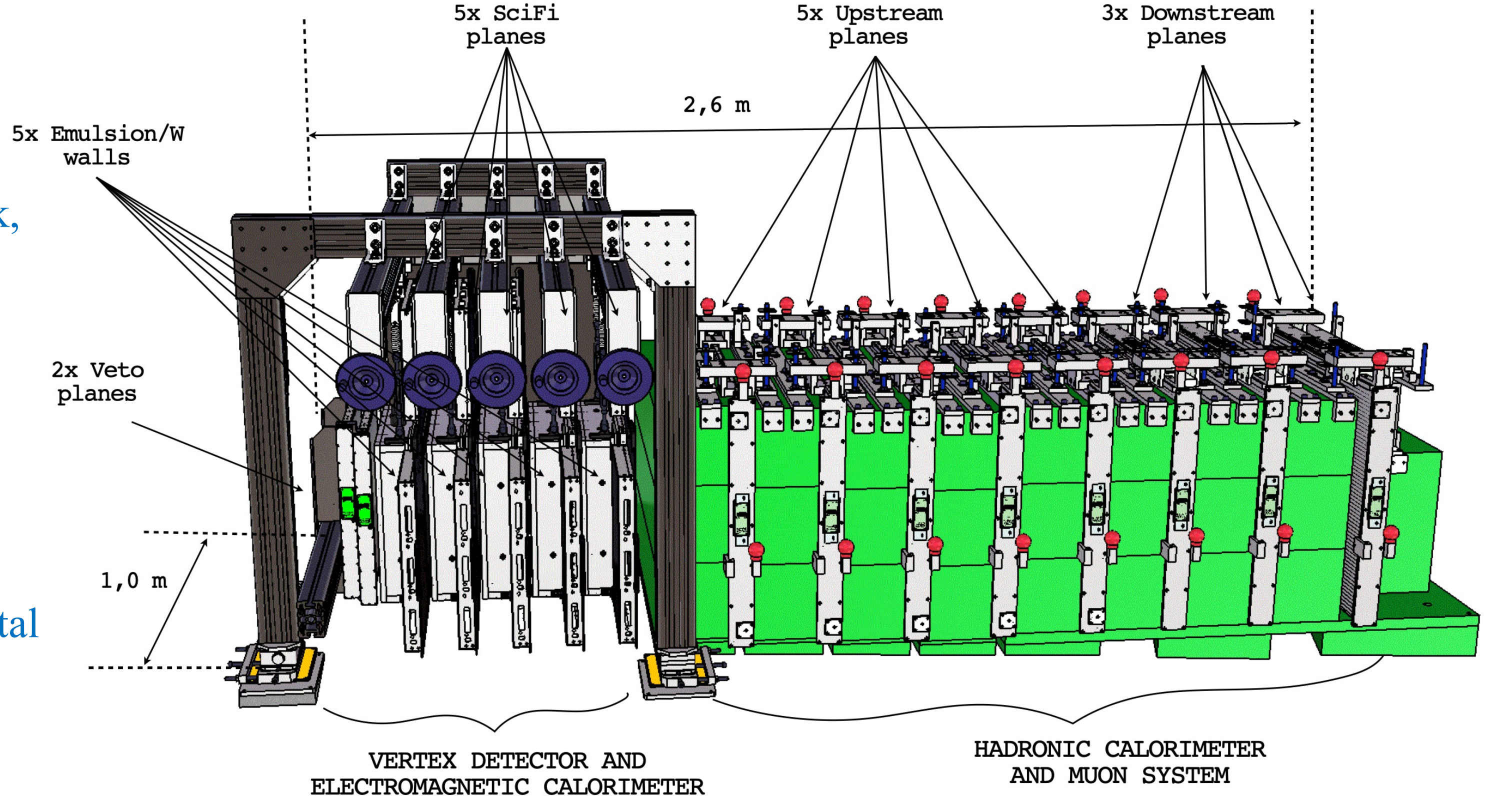
VETO PLANE:
tag penetrating muons

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

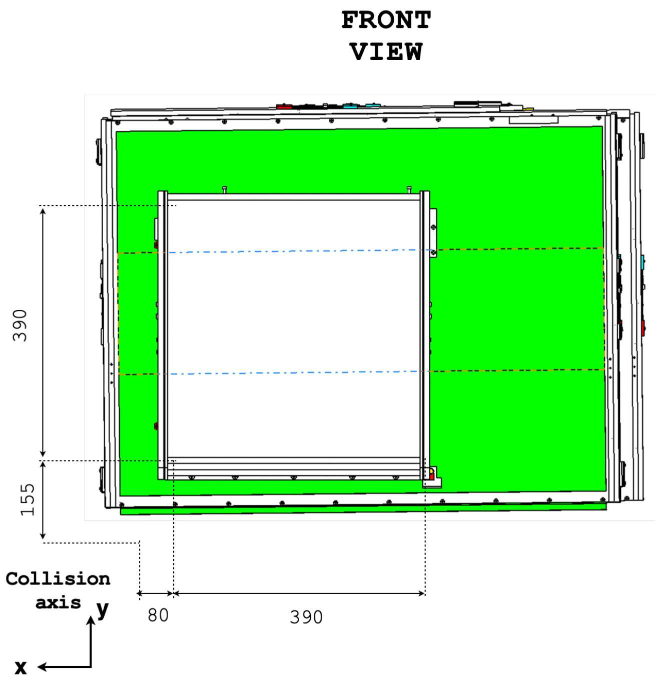
MUON IDENTIFICATION SYSTEM:
3 most downstream plastic scintillator stations based on fine-grained bars, meant for the muon identification and tracking



Detector layout

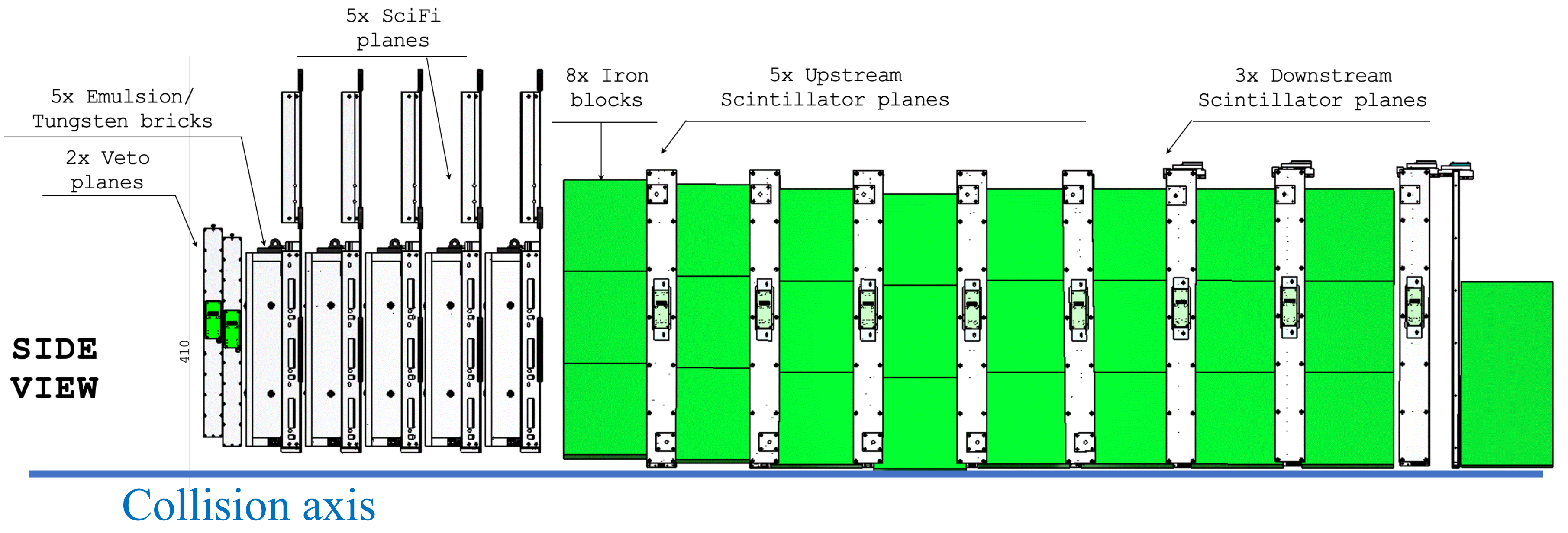
- Angular acceptance: $7.2 < \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

Off axis location

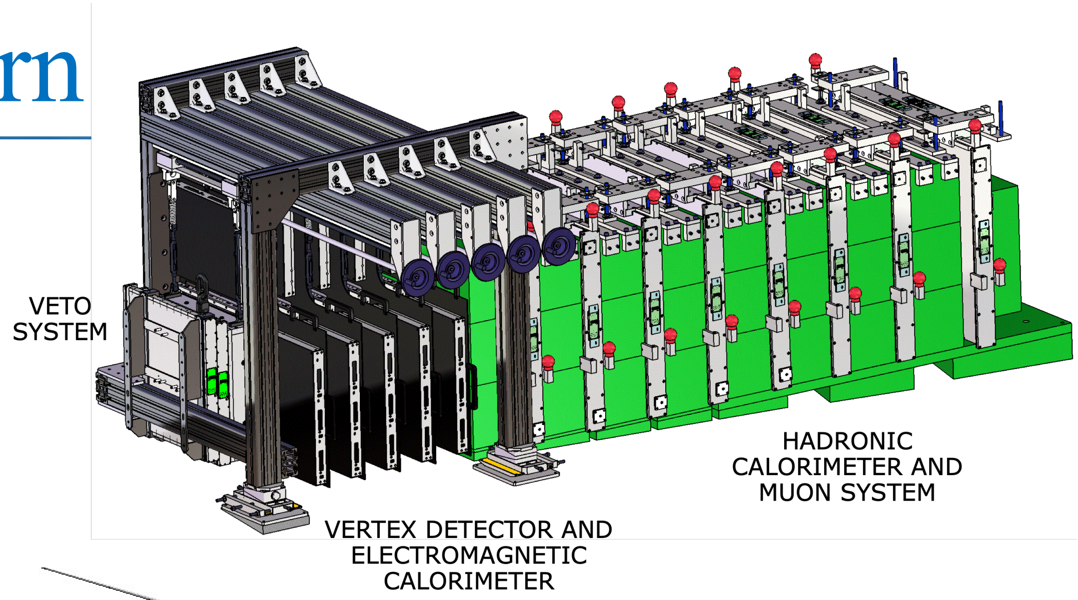


Electromagnetic calorimeter
~40 X_0

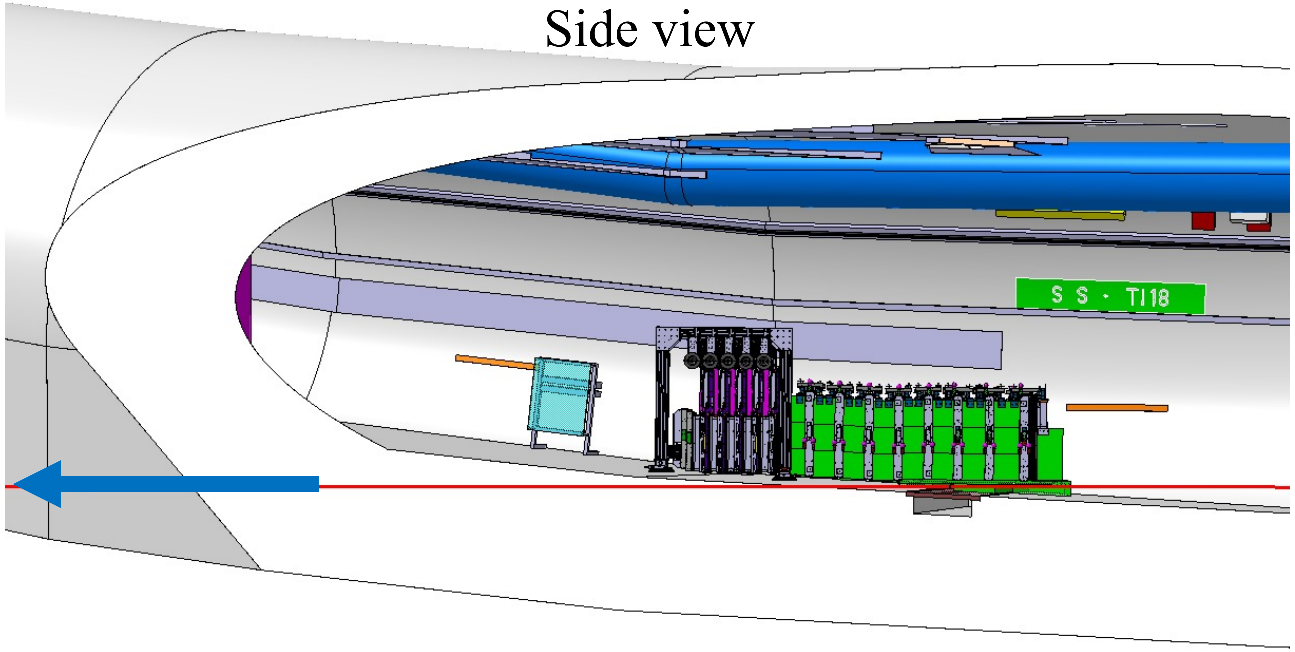
Hadronic calorimeter
~11 λ



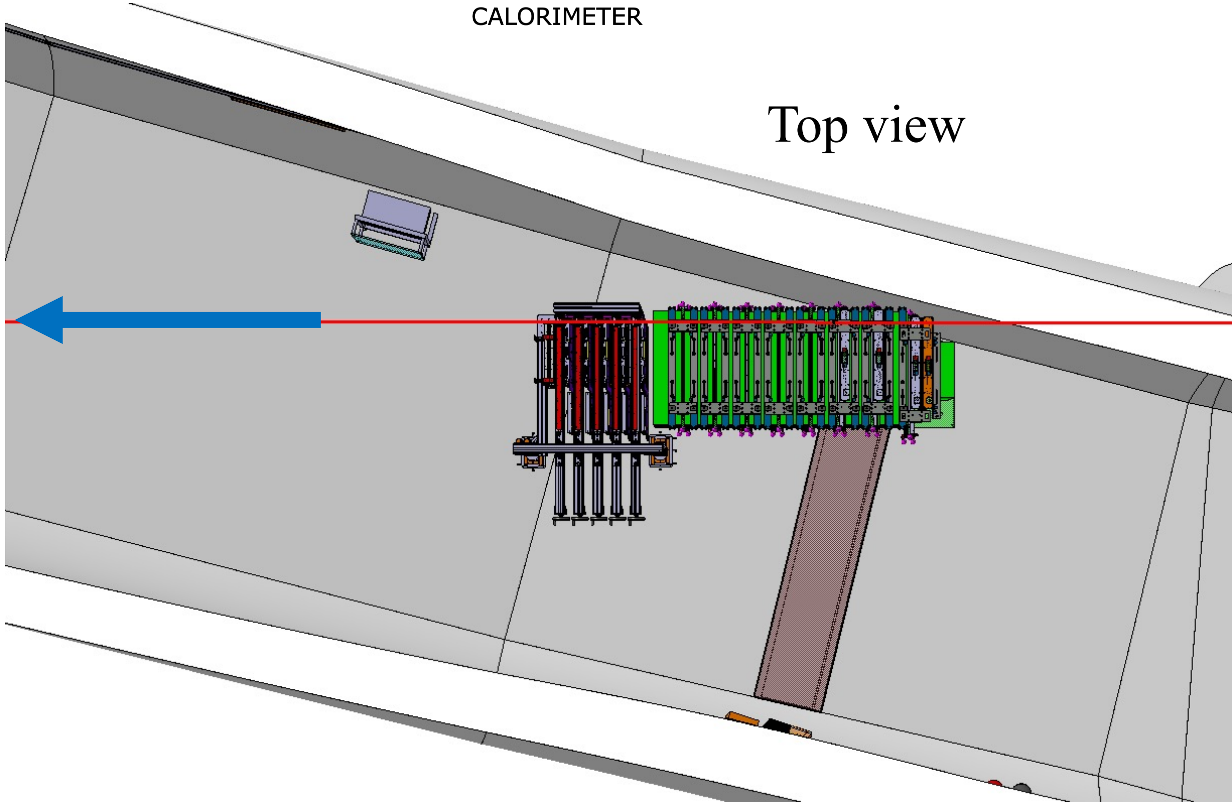
SND@LHC in the TI18 cavern



Side view



Top view

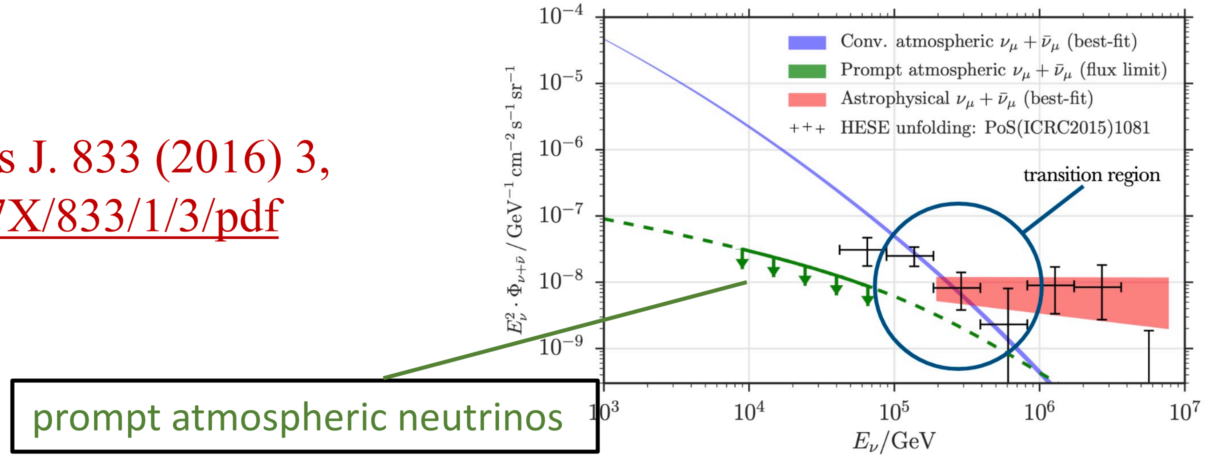


Physics goals

- 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, e.g. in some angular region ν_e production dominated by charm decays → measuring charm production in pp collisions in the forward region
- Manyfold interest for the charm measurement in pp collision at high η
- 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



LHC
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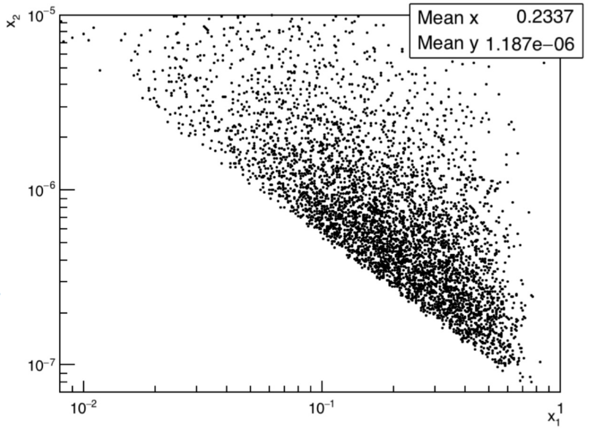
Physics goal: charm production

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

Measurement	Uncertainty Stat.	Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	22%
ν_e/ν_μ ratio for LFU test	10%	10%

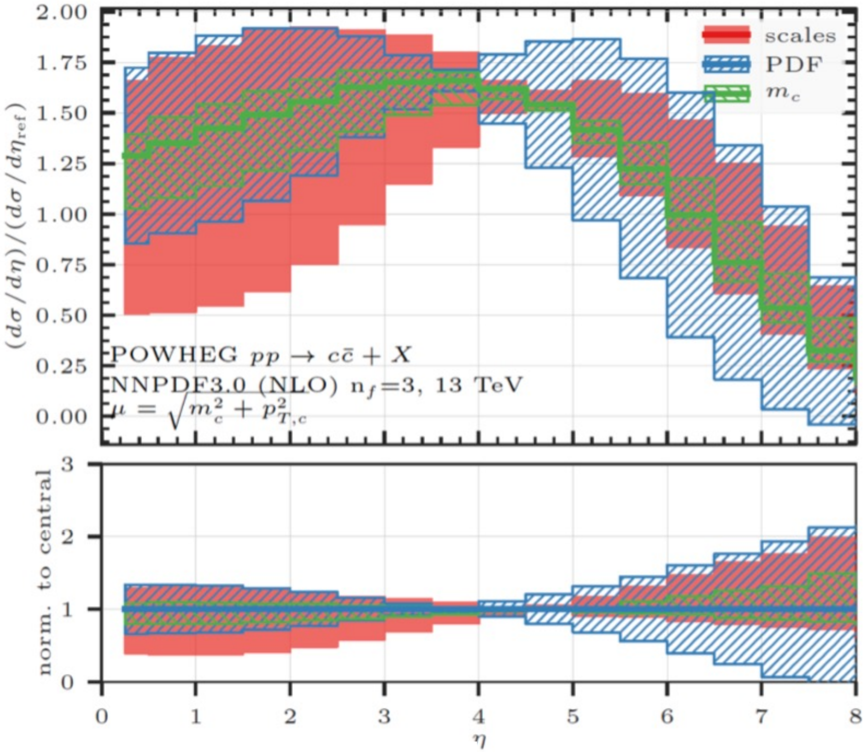
Gluon PDF in an x-region relevant for FCC and atmospheric neutrinos



- Expectations in 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

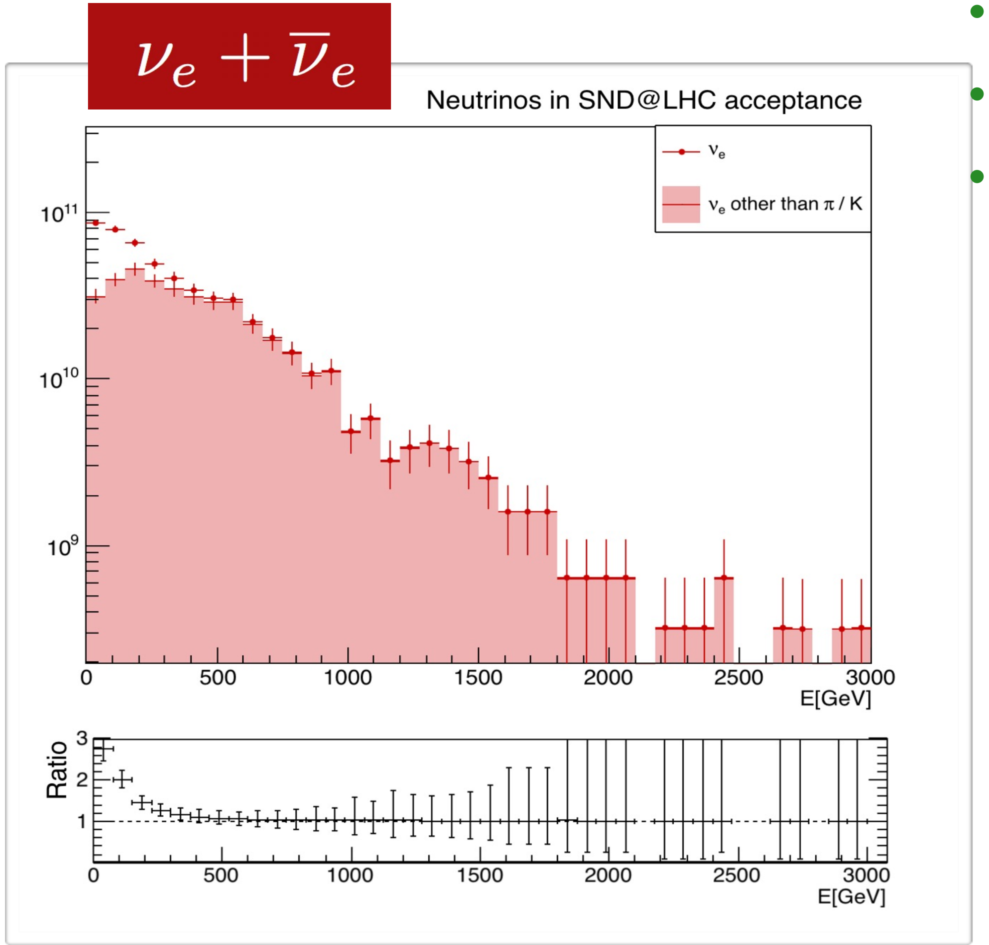
$\sim 30\ \nu_\tau$ CC interactions expected



$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)} \qquad \eta_{ref} = [4, 4.5]$$

Lepton flavour universality test in ν interactions

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



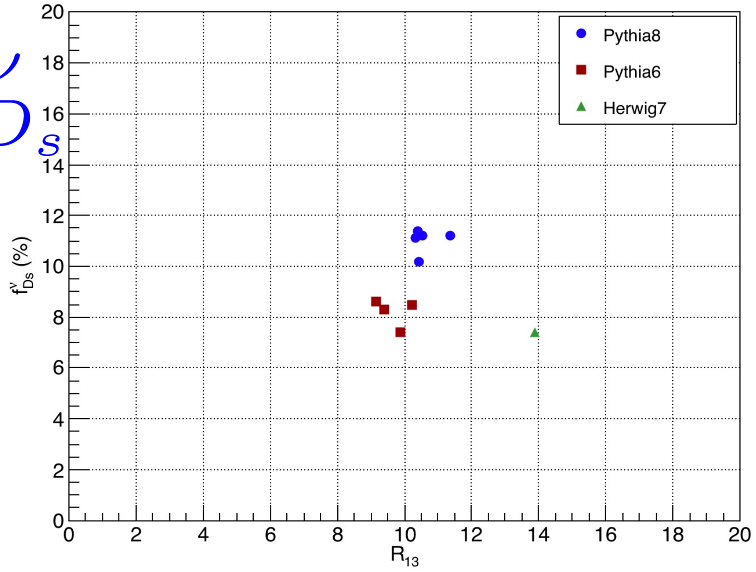
- ν_τs produced essentially only in D_s decays
- ν_es produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
- The ratio depends only on charm hadronisation fractions
- Sensitive to ν-nucleon cross-section ratio

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

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

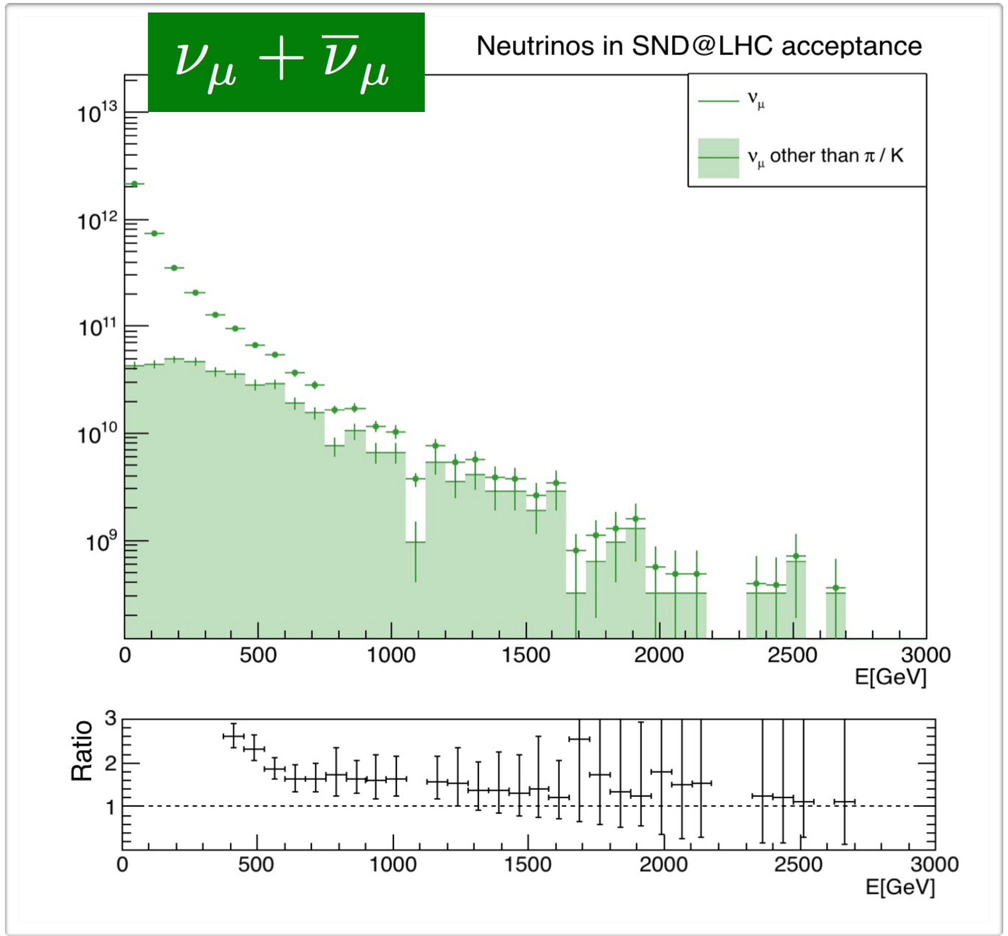
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **20%** error due to ν_τ statistics

$f_{D_s}^{\nu}$



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



$$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\,GeV] = 294 \quad \text{in 150 fb}^{-1}$$
$$N(\nu_e + \overline{\nu}_e)[E > 600\,GeV] = 191 \quad \text{in 150 fb}^{-1}$$

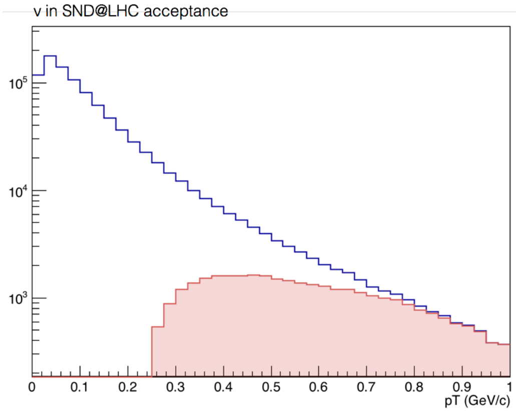
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

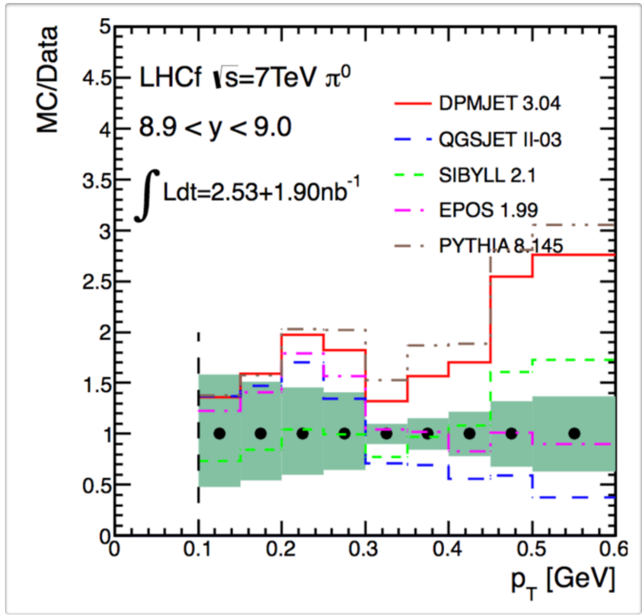
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

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

contamination from π/k

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





Phys. Rev. D 86, 092001 (2012)

Summary of the experiment main milestones

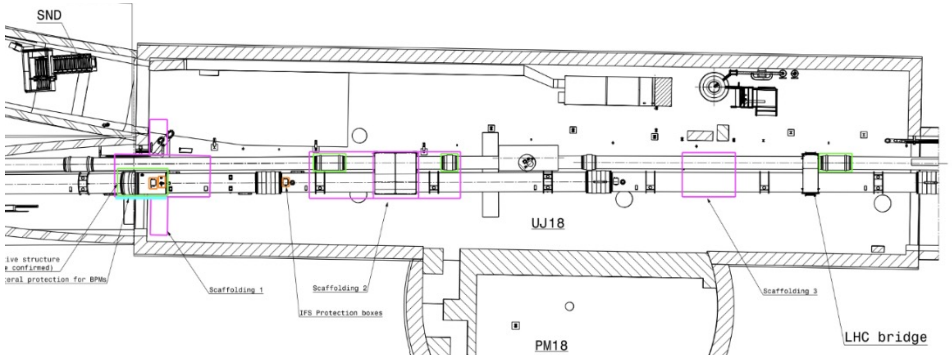
- Submission of the Letter of Intent Aug 27th, 2020
- Submission of the Technical Proposal Jan 22nd, 2021
- Approval by CERN RB: Mar 2021
- Experimental area & infrastructure: Jun 28 – end Aug
- Detector construction completion: Oct 13
- Detector surface commissioning: Sep - Oct
- Test beams: Sep 1-5, Oct 1-6
- Start of detector installation in TI18: Nov 1
- Turn on and global commissioning: Dec 7
- Detector commissioning and debugging: Jan-Feb
- Installation of the neutron shield: Mar 15
- Installation of the first emulsion films: Apr 7
- First data from "splash"/collision: Apr 22nd

SND@LHC Technical Proposal
https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

Experimental area and infrastructure preparation

- Installation of protective tables and boxes on bellows, instrumentation and feedthroughs

- Installation of scaffolding



Experimental area and infrastructure preparation

- Preparation for transport channel, electricity and lights, displacement of electrical box on footbridge

- Installation of QRL protection and load test

Experimental area preparation in TI18

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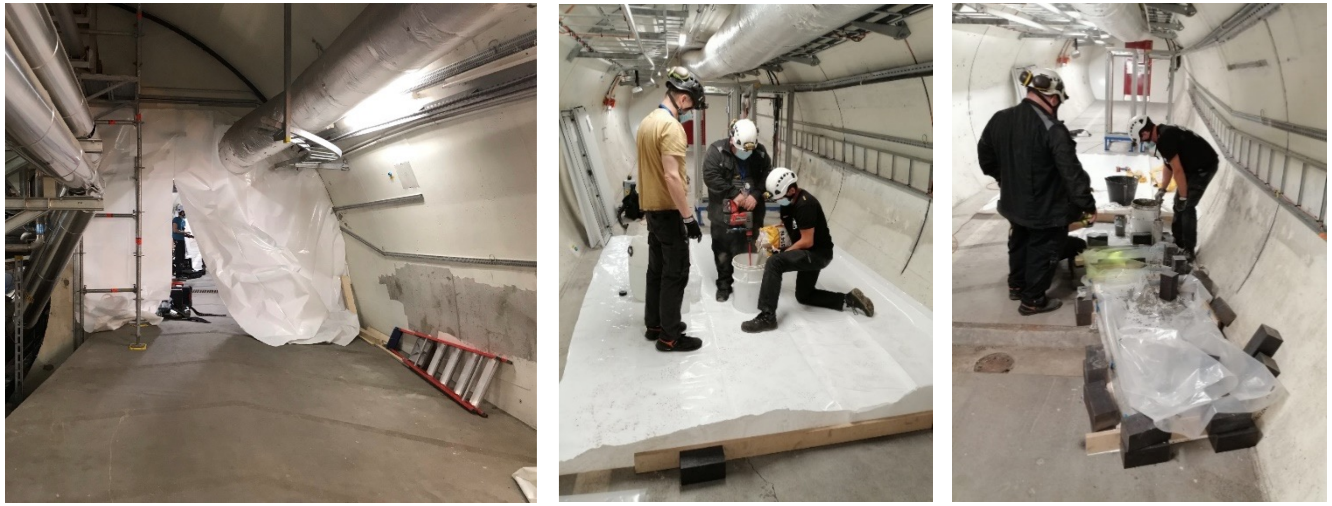
Scattering and Neutrino Detector
at the LHC

Survey and positioning of baseplates for muon filters

Underground racks

Optical fibres between surface and underground racks



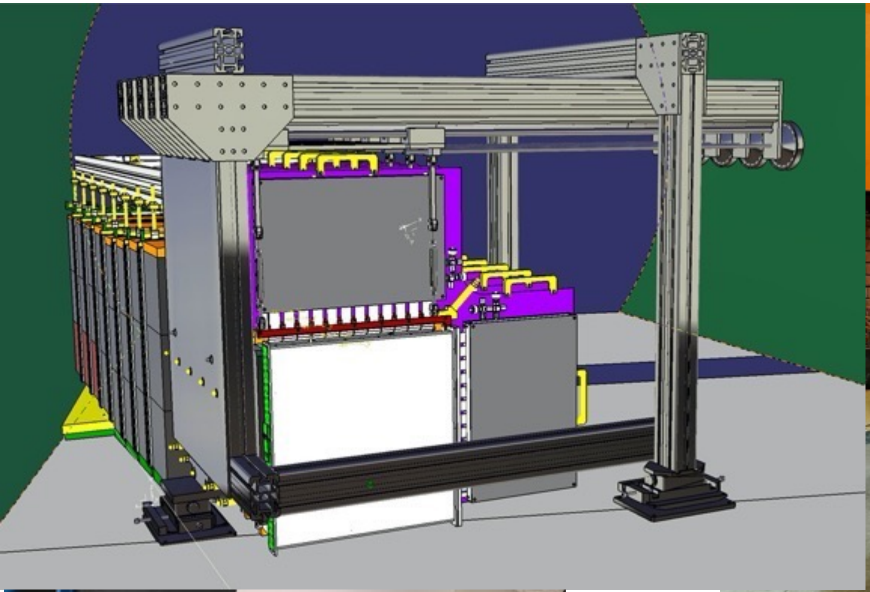
Formworks and grouting of baseplates

Detector construction and commissioning

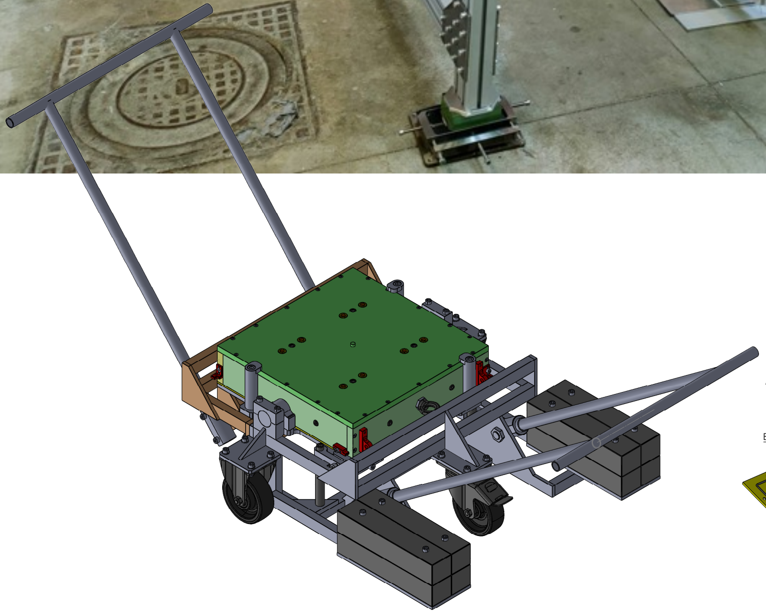
Mechanical structure and ν target/vertex construction

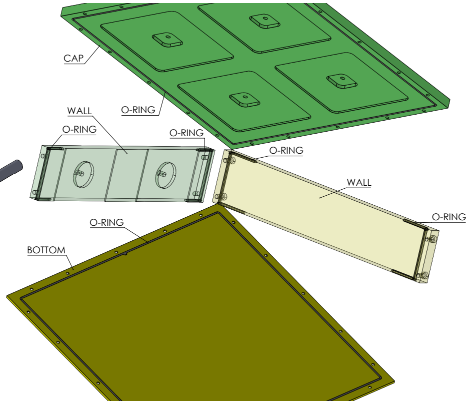
LHC

Scattering and Neutrino Detector
at the LHC



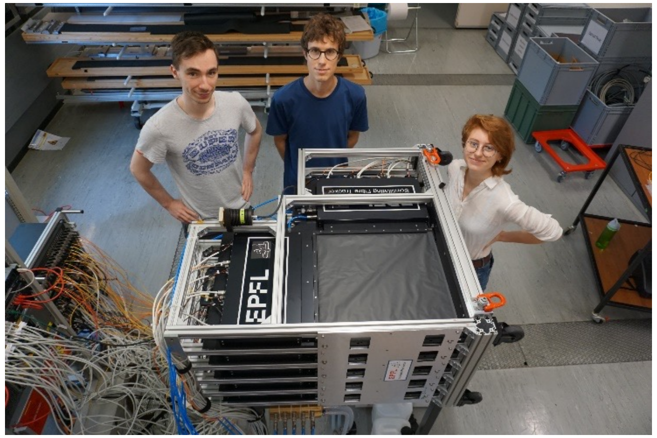
Wall box for emulsion/tungsten

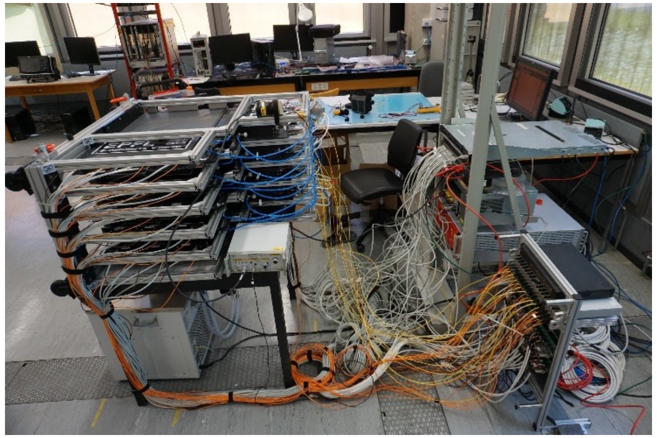


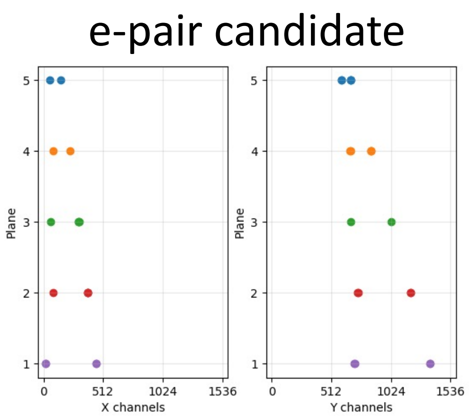


Adjustable feet

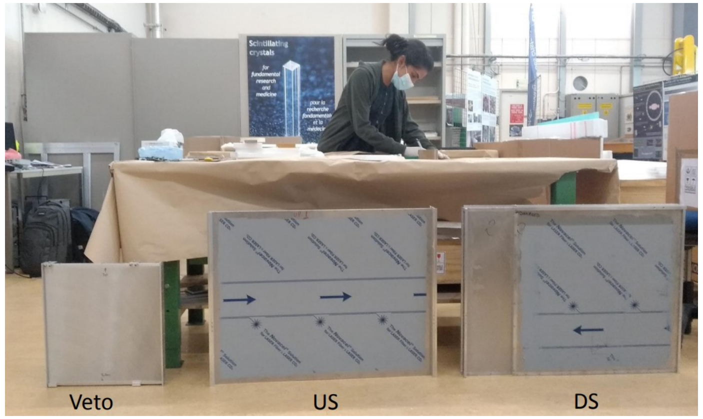
SciFi and Muon id system construction

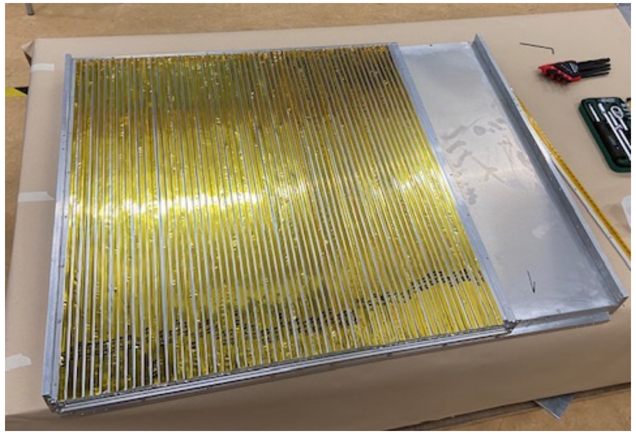






Scattering and Neutrino Detector at the LHC



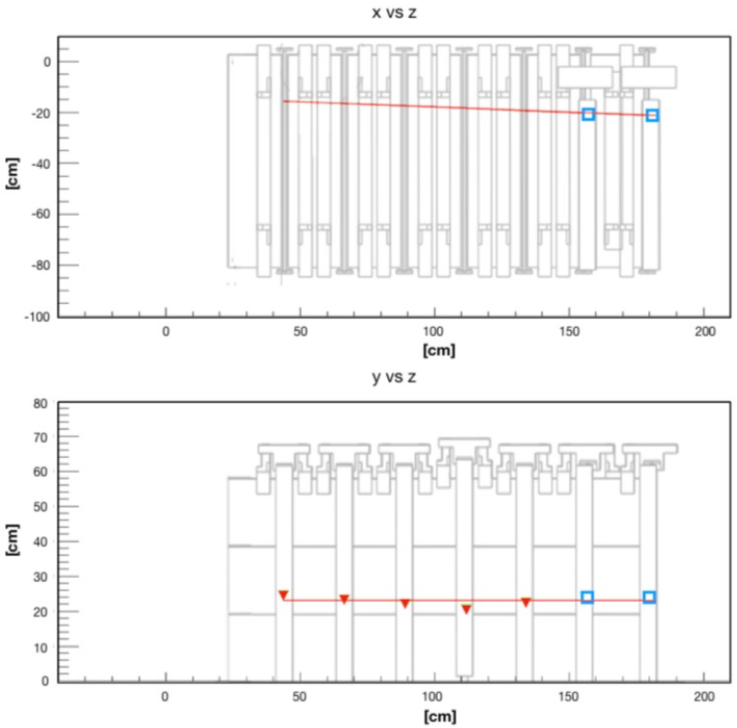


TEST BEAM WITH HCAL/MUON SYSTEM

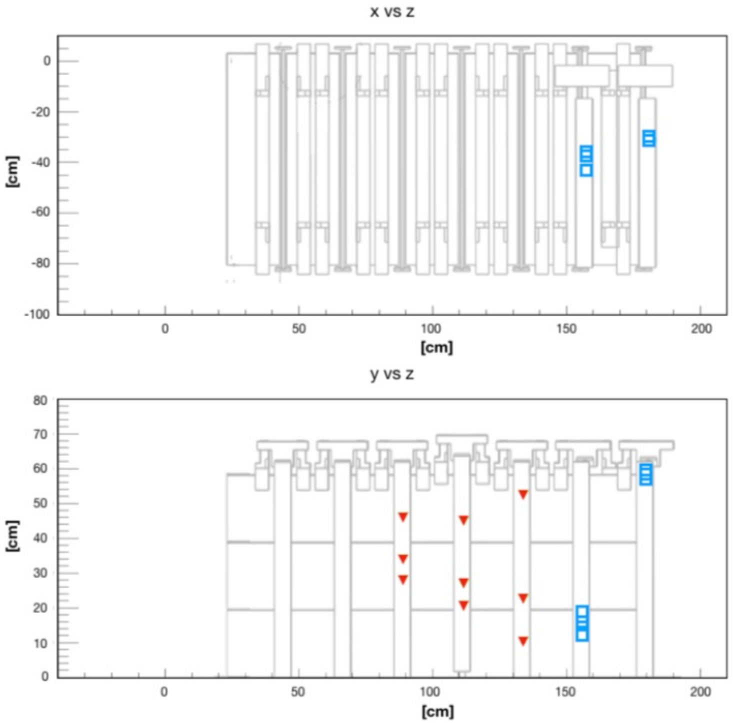
Oct 2021

- Installation of the whole muon system at H8 in the North Area
- Energy calibration with 140, 180 240, 300 GeV pion beam
- Useful for the development/debugging of the online system

Passing through muon



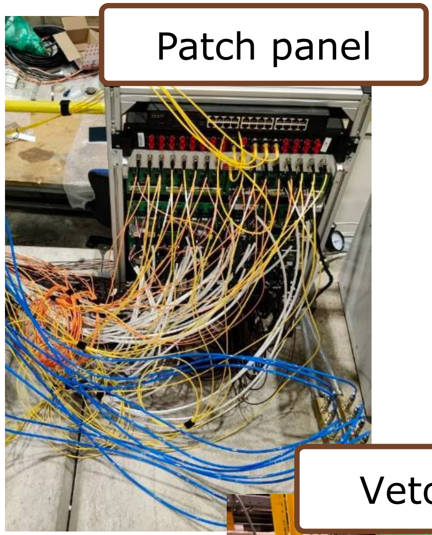
π interaction

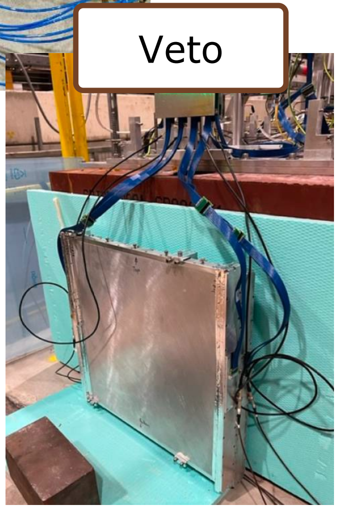


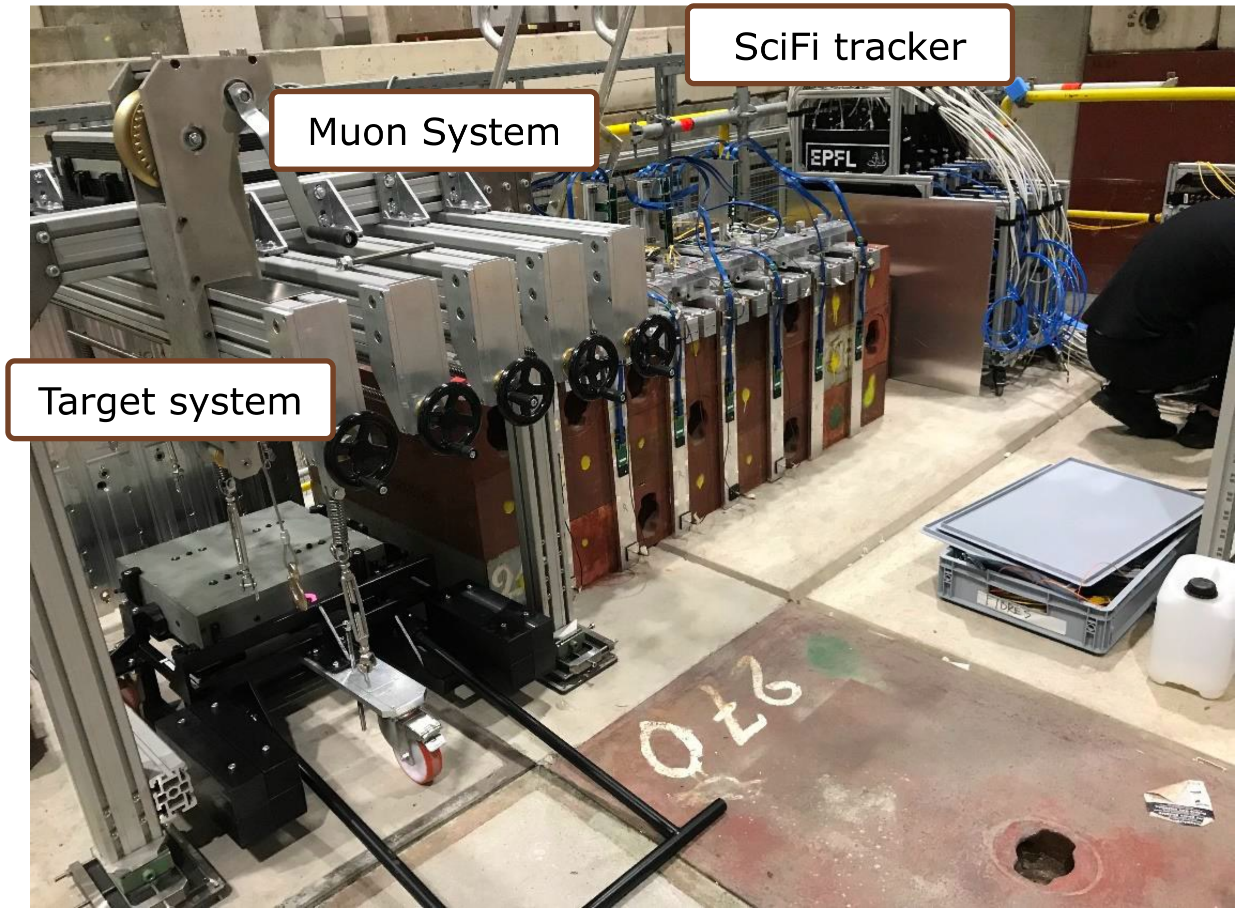
SURFACE COMMISSIONING

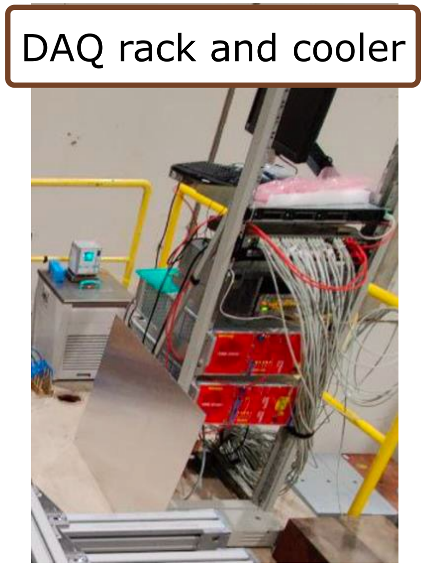
October 2021

- Full assembly of the detector at H6 in the North Area
- Target on a 2.5 degree slope to simulate the TI18 floor inclination
- Successful mechanical test of all subsystems
- Data taking with muon beam

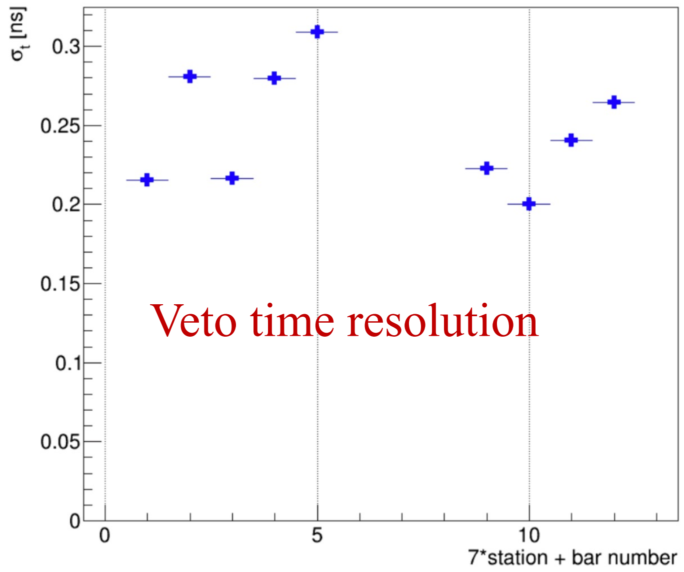






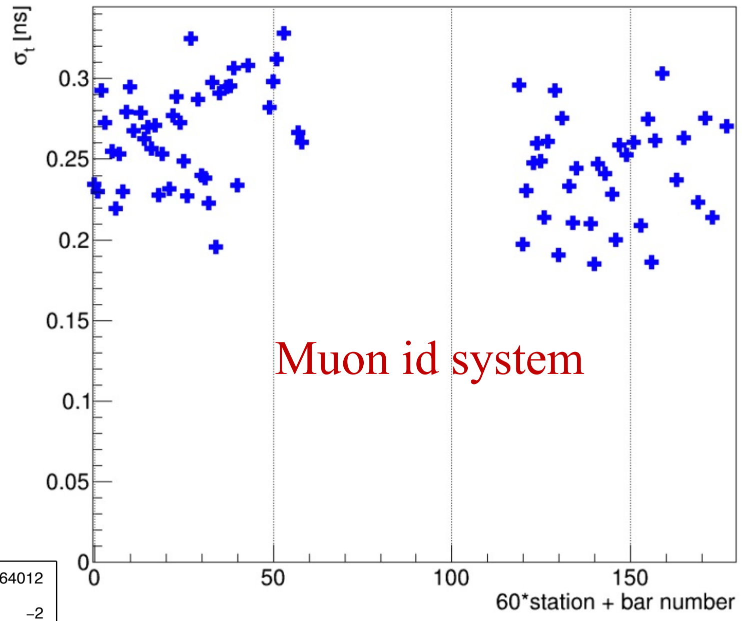


Detector Performance

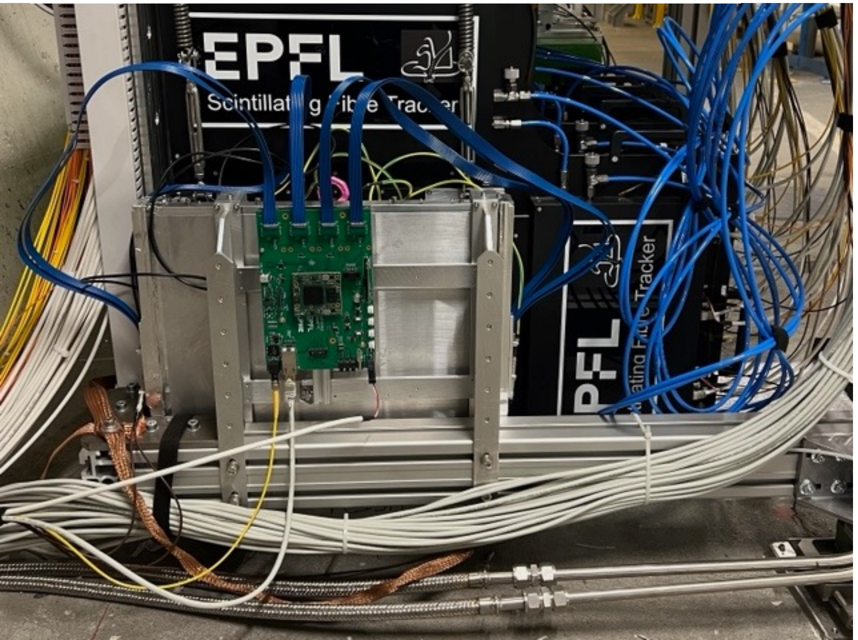


$\langle\sigma_t\rangle = 245$ ps , *i.e.* ∽ 170 ps per end including a binning effect of 70ps

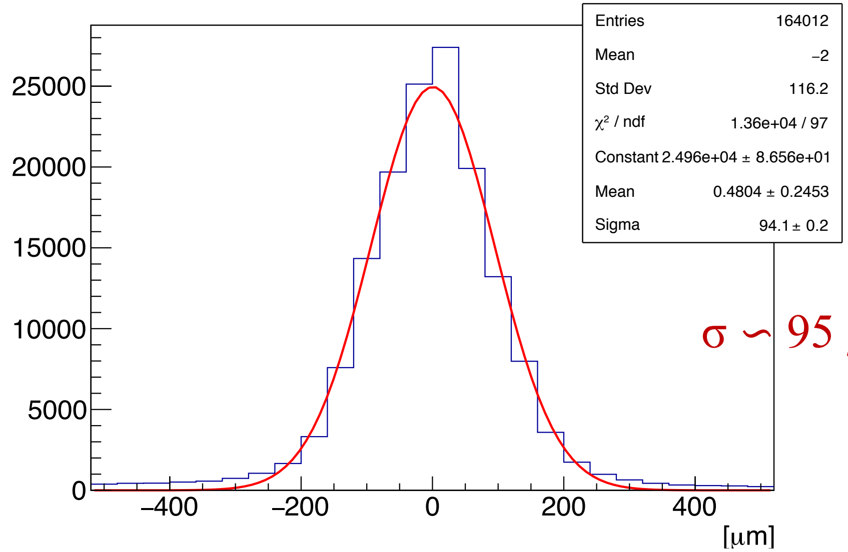
Downstream stations timing resolution



Timing resolution in H bars



SciFi position resolution



$\sigma \backsim 95\ \mu m$

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

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

Fully installed detector pointing to the IP

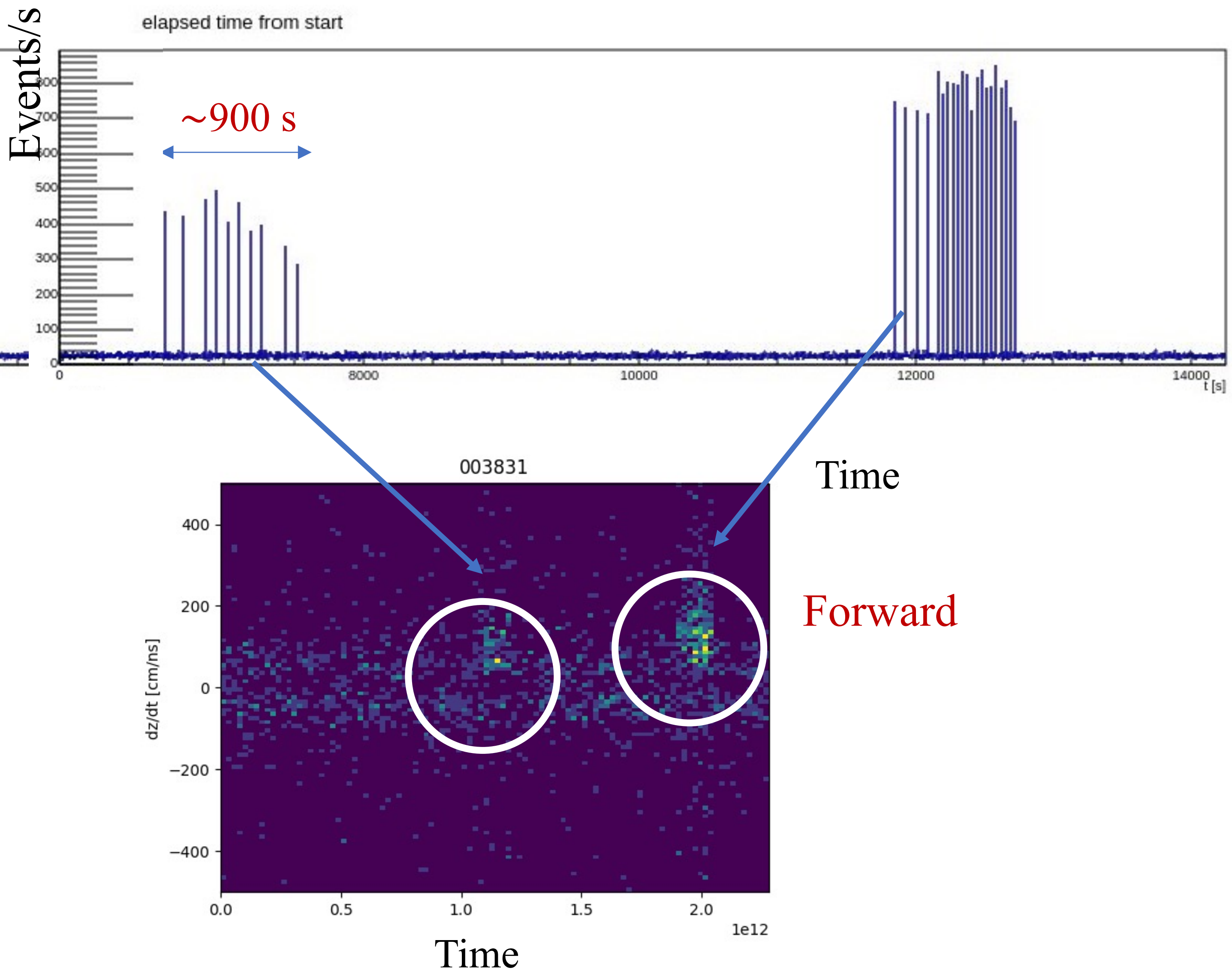
Scattering and Neutrino Detector at the LHC

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

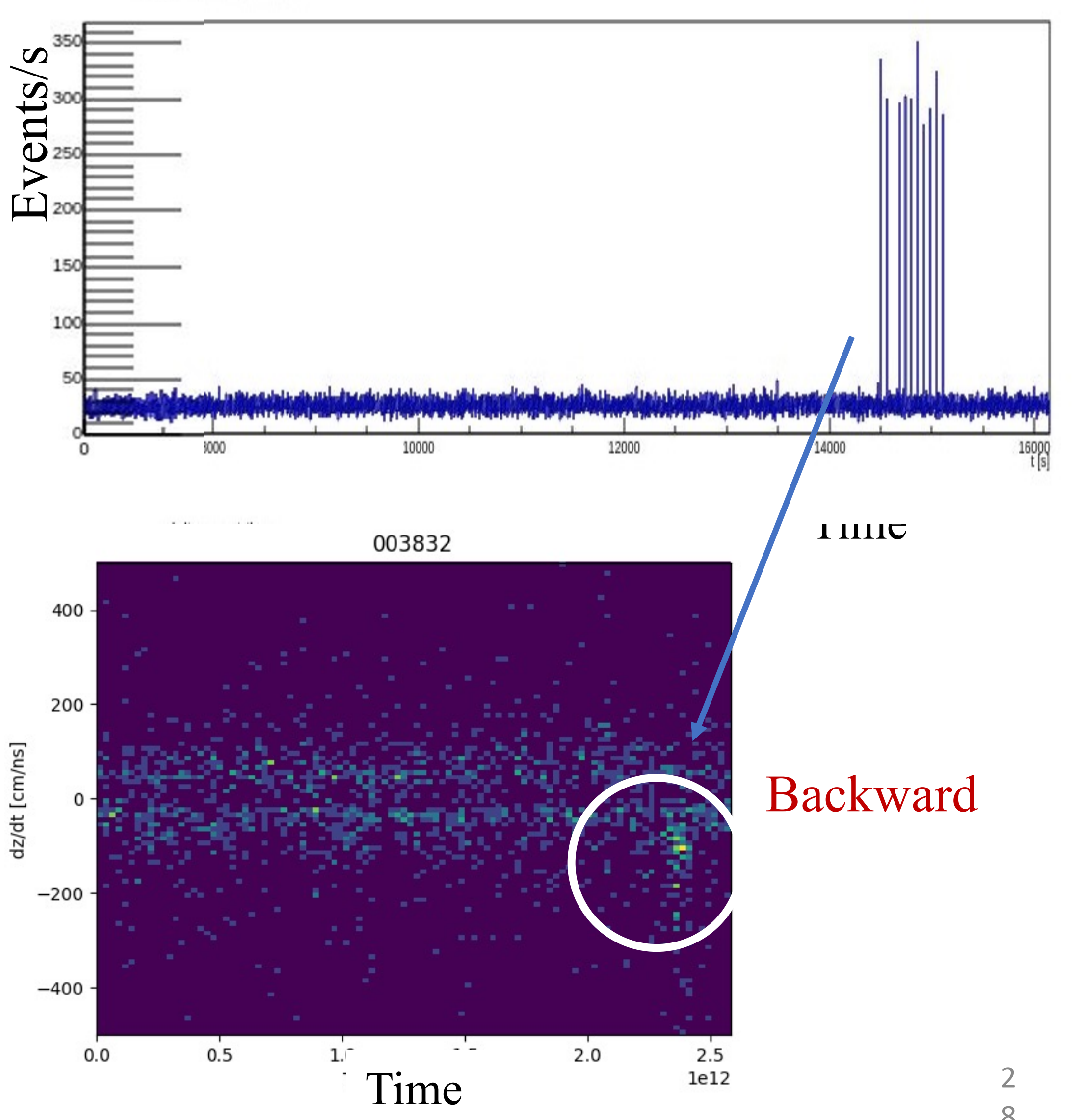
Start of data taking

Speed distribution of the "splash" events on May 7th

Beam 1 on ATLAS tertiary collimator

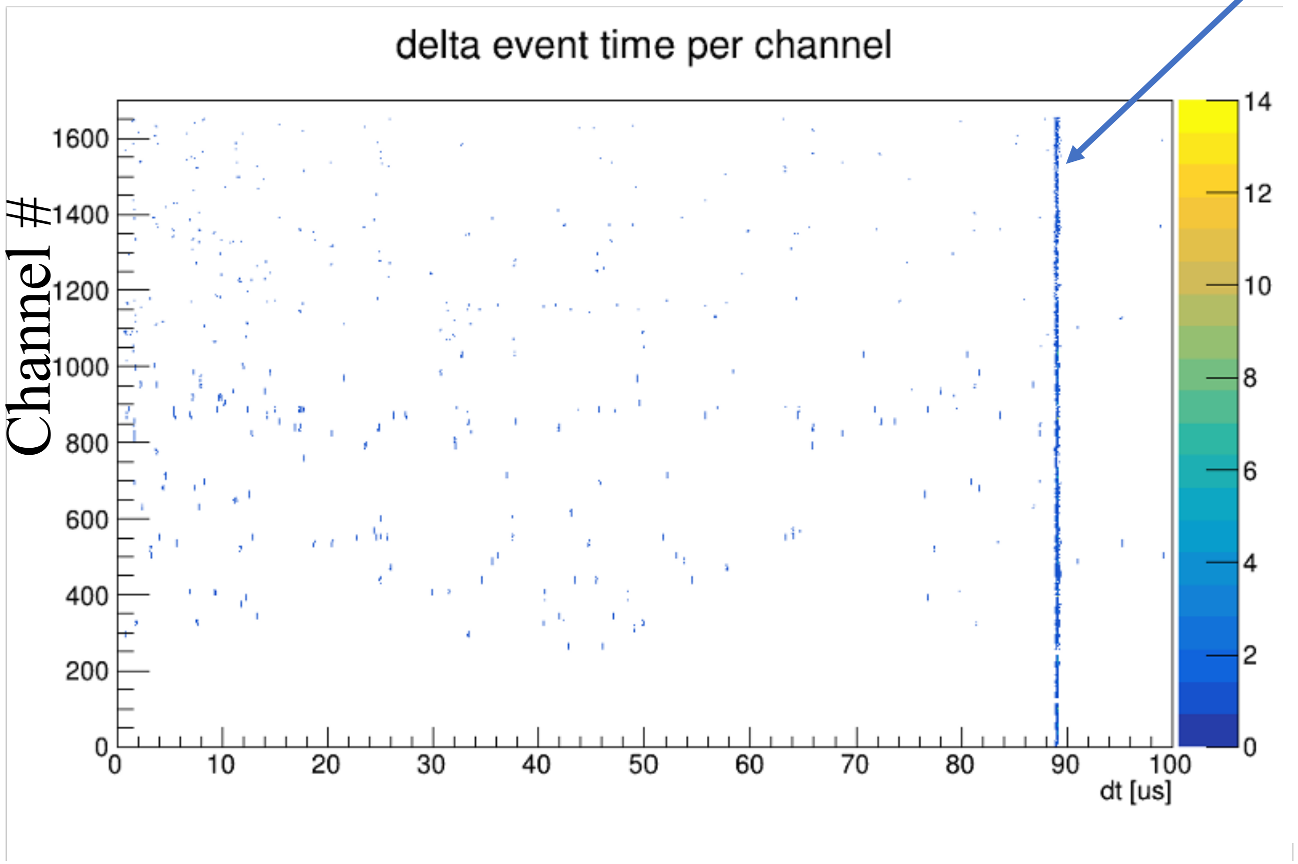


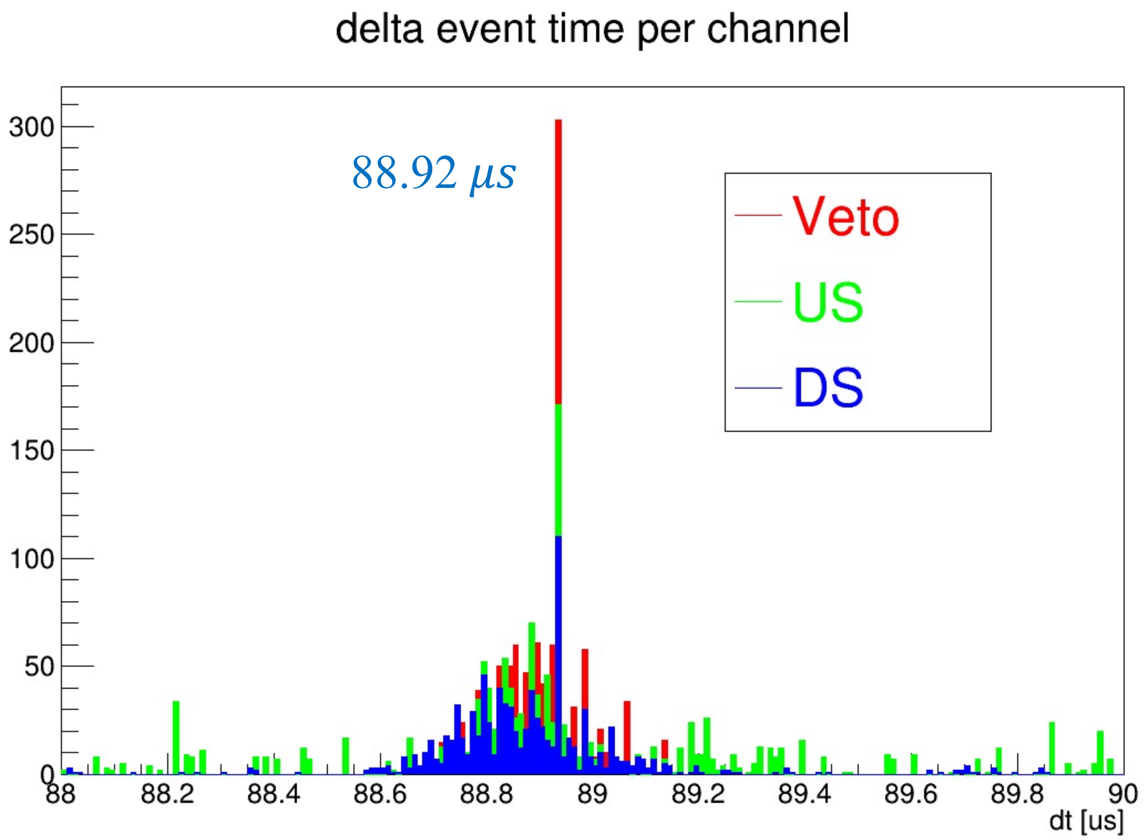
Beam 2 on ALICE tertiary collimator



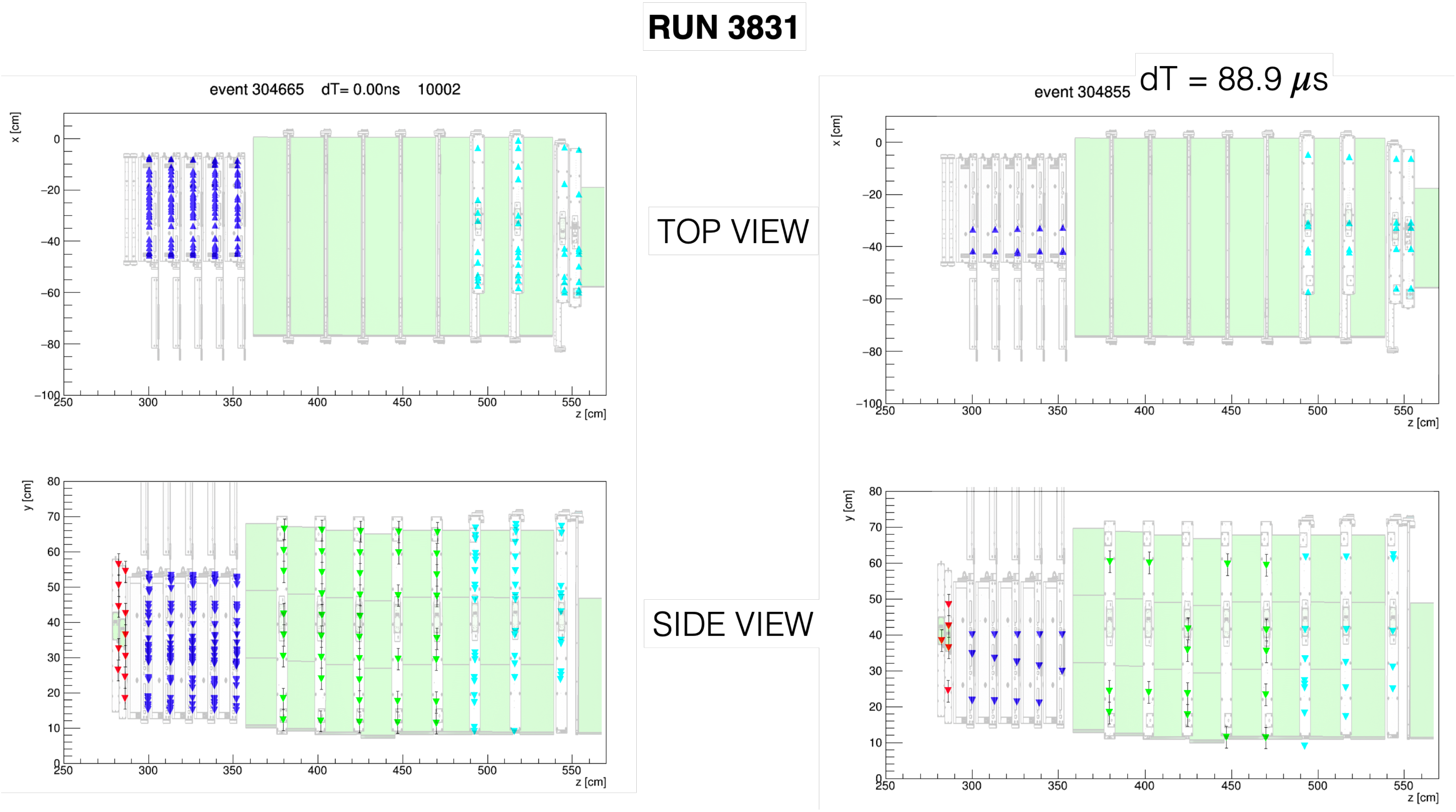
LHC "splashes"

Δt of a given channel, signal at the LHC revolution time, ring = 26659 m, one turn = 88.92 μs





LHC "SPLASHES" FROM IP1: FIRST AND SECOND TURN



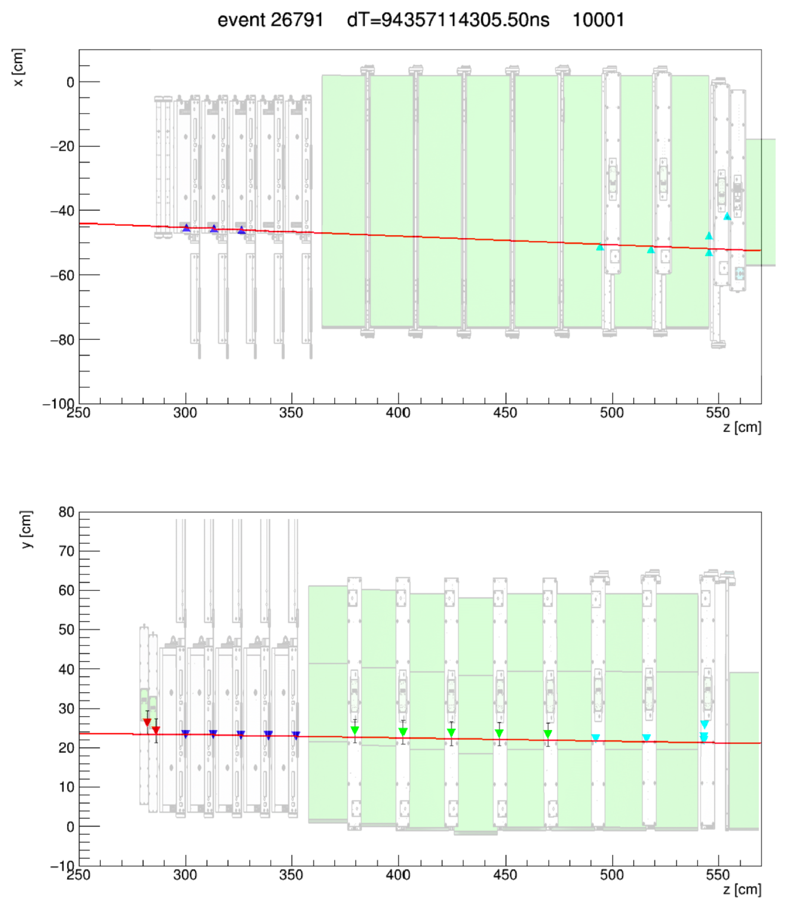
FIRST COLLISIONS IN IP1 AMONG COSMIC-RAYS

Scattering and Neutrino Detector at the LHC

Muons from 450 GeV pp collisions and cosmic-rays

RUN 3986

A muon from IP1 collisions

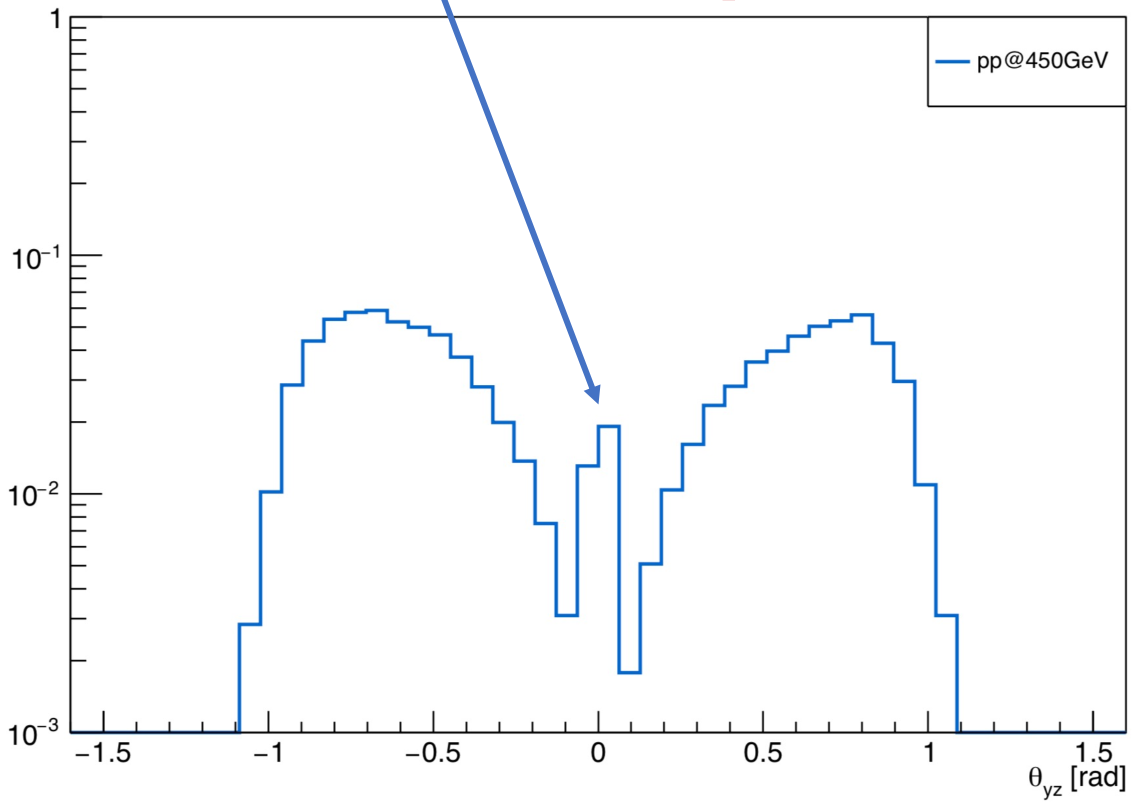


TOP VIEW

SIDE VIEW

Start seeing muons from the IP in the typical cosmic-ray shape

YZ slope



New era of collider neutrinos started!

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

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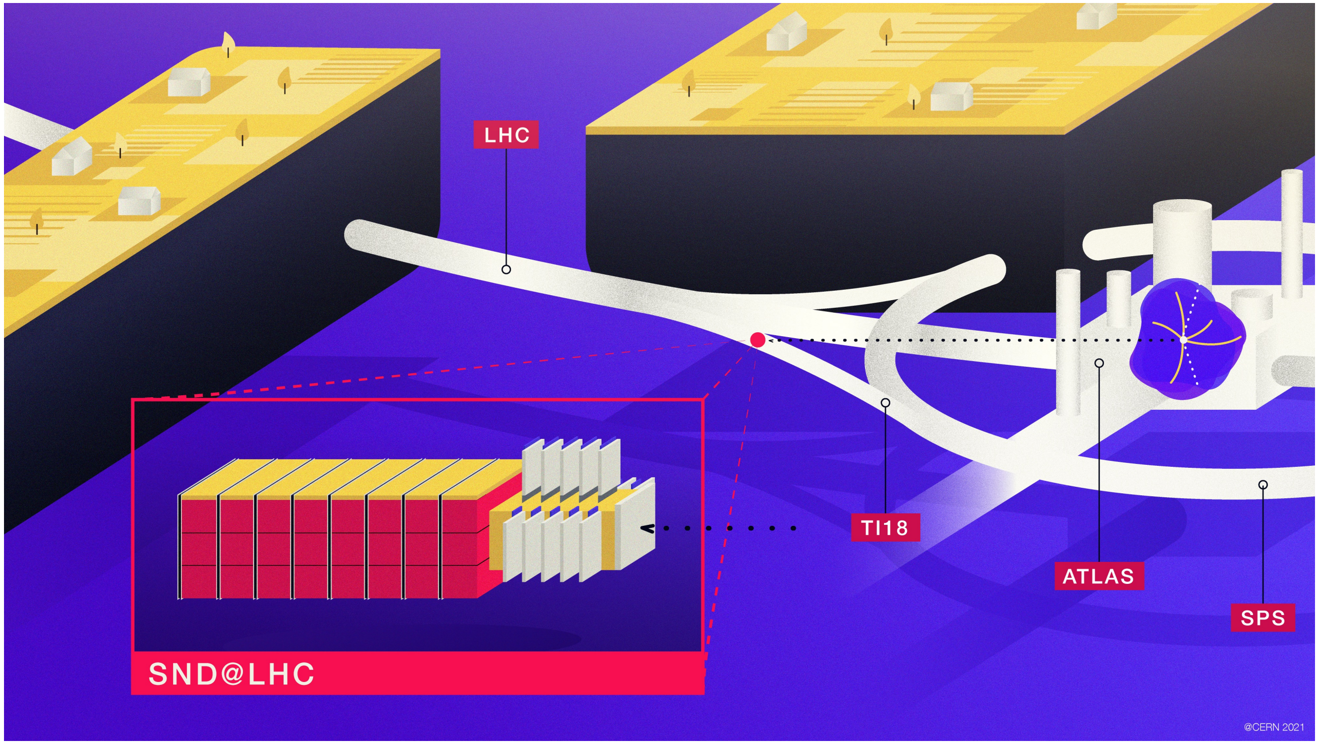
NEUTRINOS | NEWS

Collider neutrinos on the horizon

2 June 2021



Stay tuned! Data taking just started!

LHC Run3: 2022-2025