New neutrino experiments at the LHC

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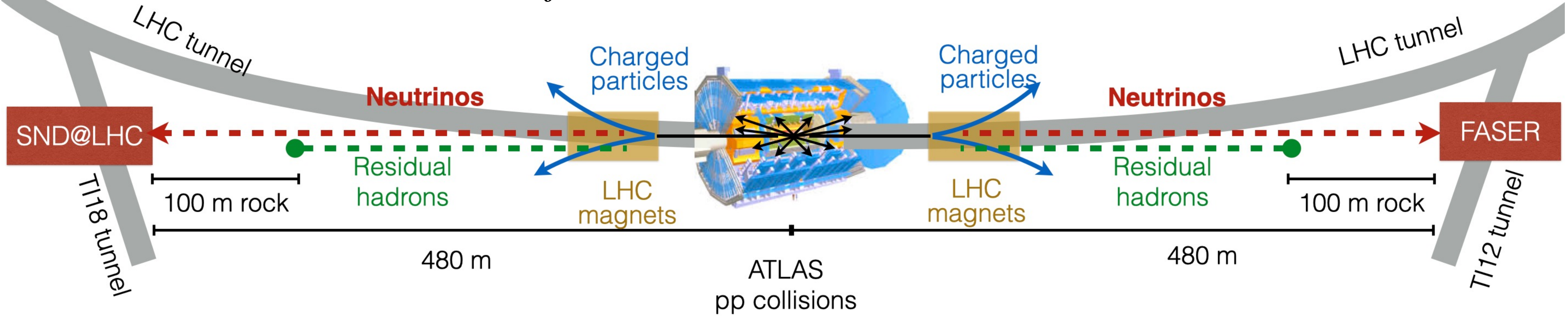
With contributions from the FASER and SND@LHC Collaborations



Heavy Quarks and Leptons, Warwick, September 16th 2021

OVERVIEW

- *Motivation*
- *Neutrino physics program*
- *The FASERν and SND@LHC experiments taking data in 2022-2024*
- *Status of detector construction and installation*

FASERν Technical Proposal, Nov 27th 2019
http://cds.cern.ch/record/2702868/files/LHCC-P-015.pdf

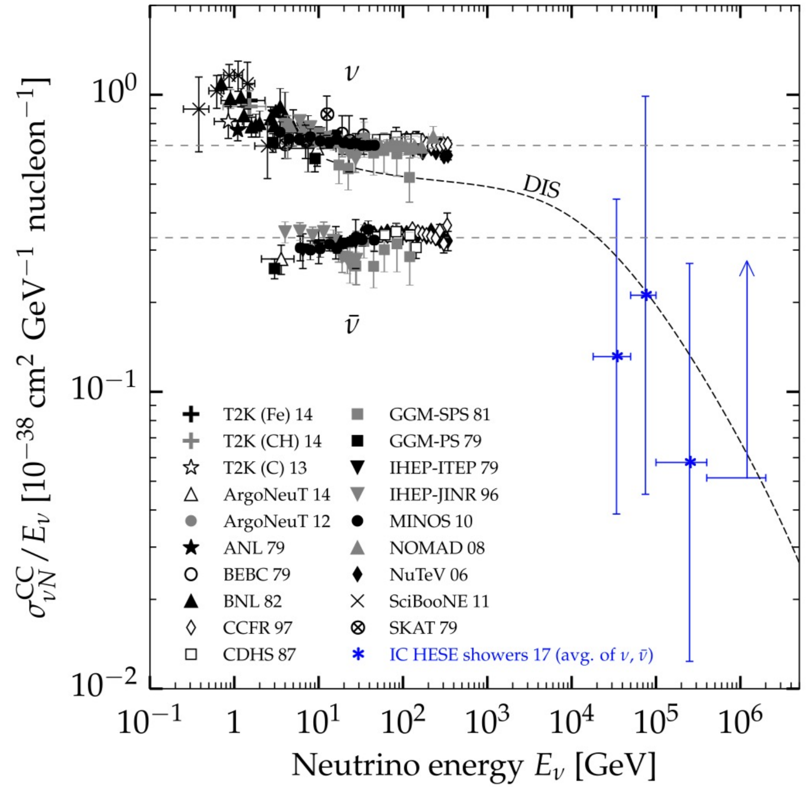
SND@LHC Technical Proposal Jan 22nd 2021
https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf

MOTIVATION

Neutrino physics at the LHC

- Klaus Winter, 1990, observing tau neutrinos at the LHC
- A. De Rùjula, E. Fernandez and J. J. Gòmez-Cadenas, 1993, Neutrino fluxes at LHC
- F. Vannucci, 1993, neutrino physics at the LHC
- [http://arxiv.org/abs/1804.04413 April 12th 2018](http://arxiv.org/abs/1804.04413), First paper on feasibility of studying neutrinos at LHC

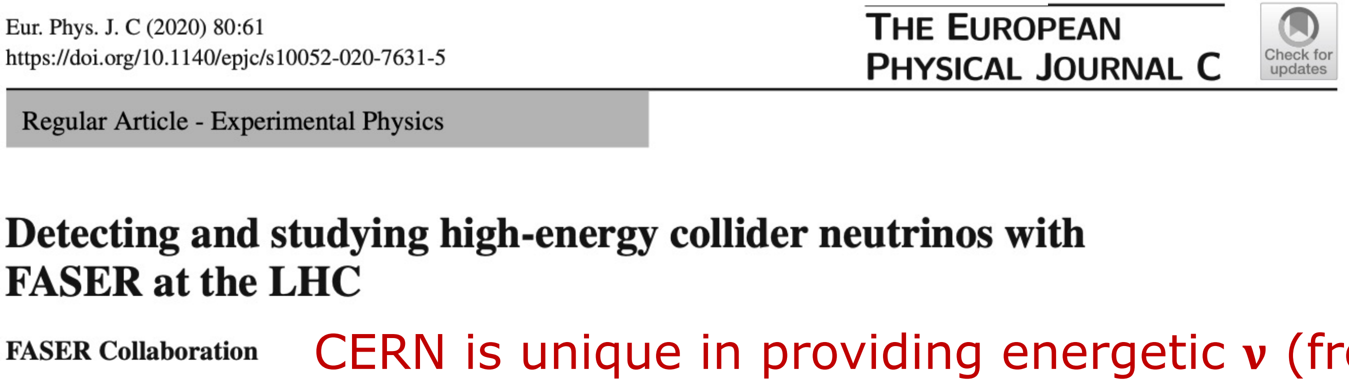
PRL 122 (2019) 041101



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

Physics potential of an experiment using LHC neutrinos

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



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

Regular Article - Experimental Physics

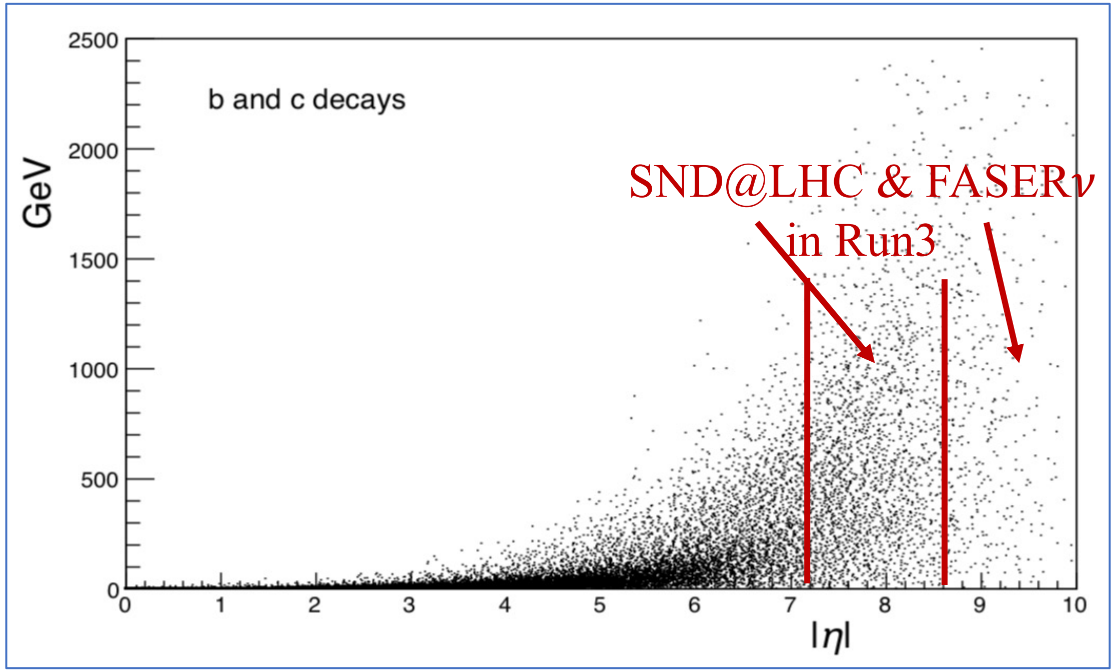
Detecting and studying high-energy collider neutrinos with FASER at the LHC

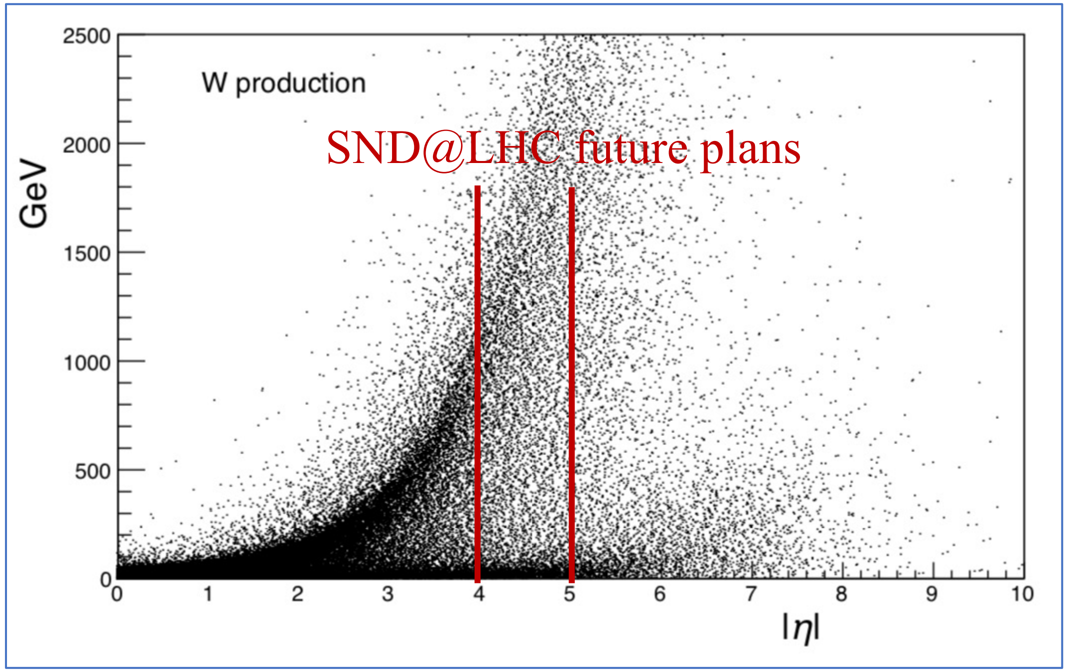
FASER Collaboration

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

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%





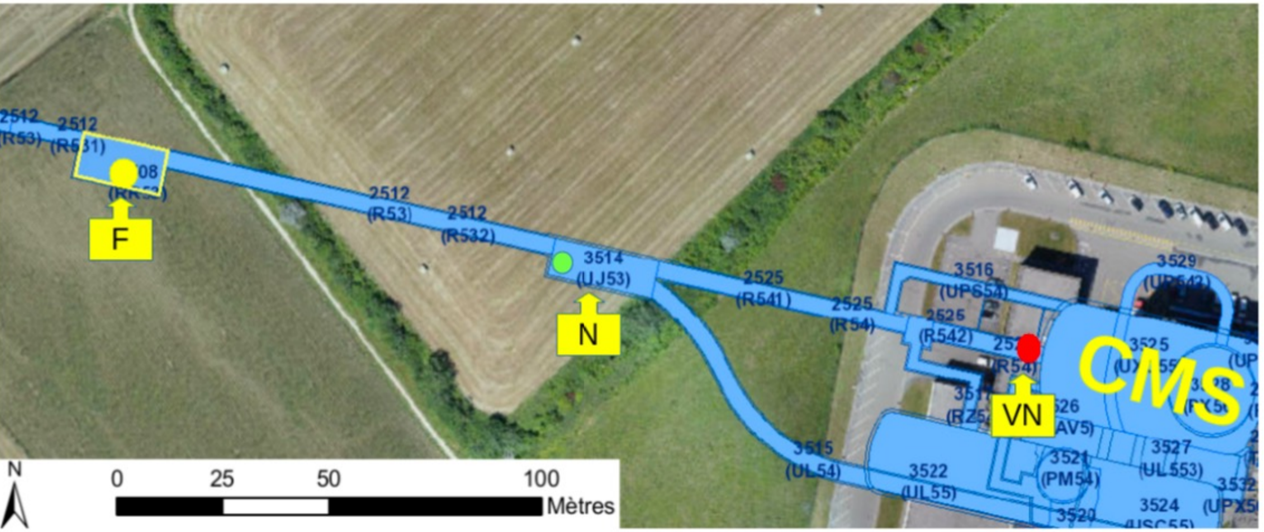
Mostly for η < 5

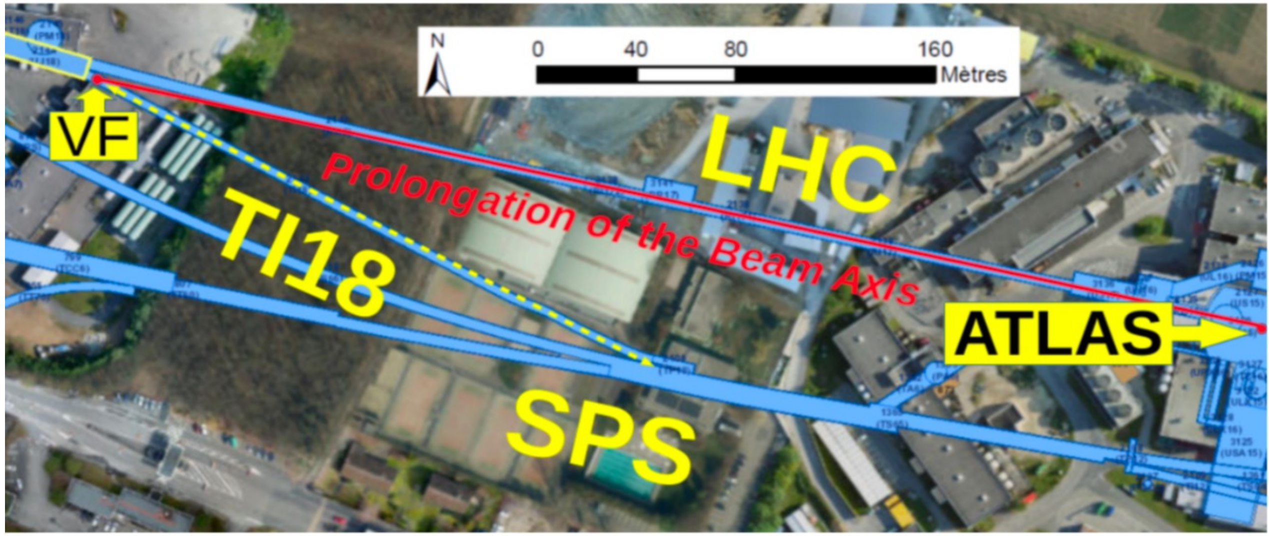
Plots show the scatter plots of ν energy versus η, per event

- FASER is on-axis while SND@LHC is off-axis
- W decays could be tagged at IP detectors → 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 (FASERν measurements)



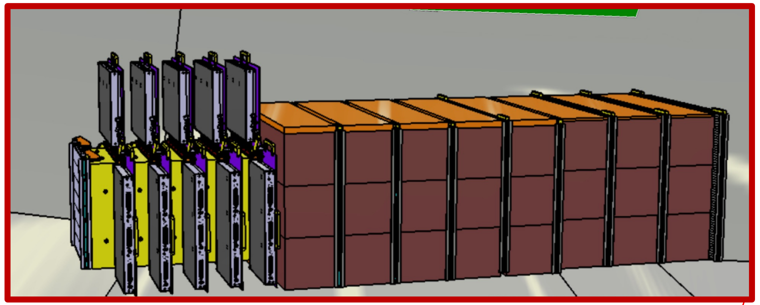


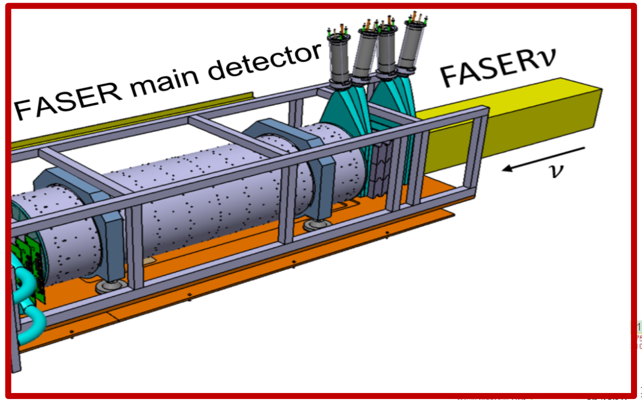
Journal of Physics G 46 (2019) 115008

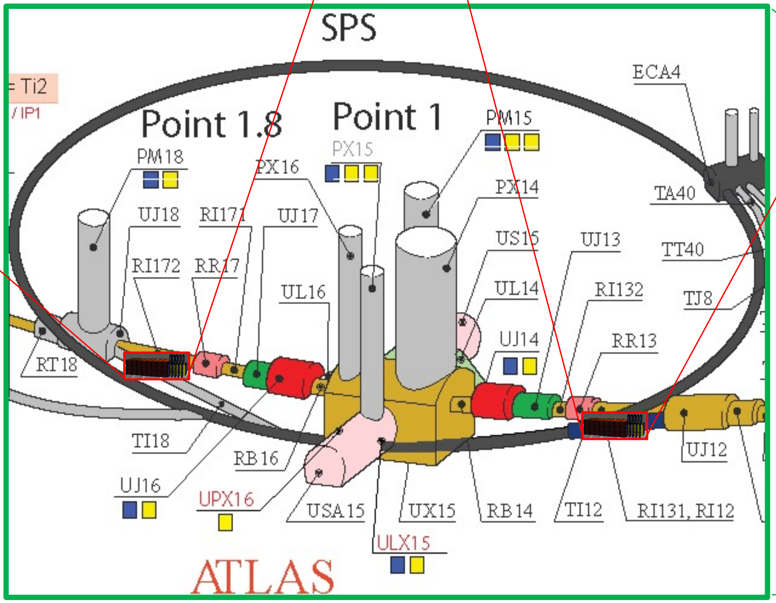
LOCATION

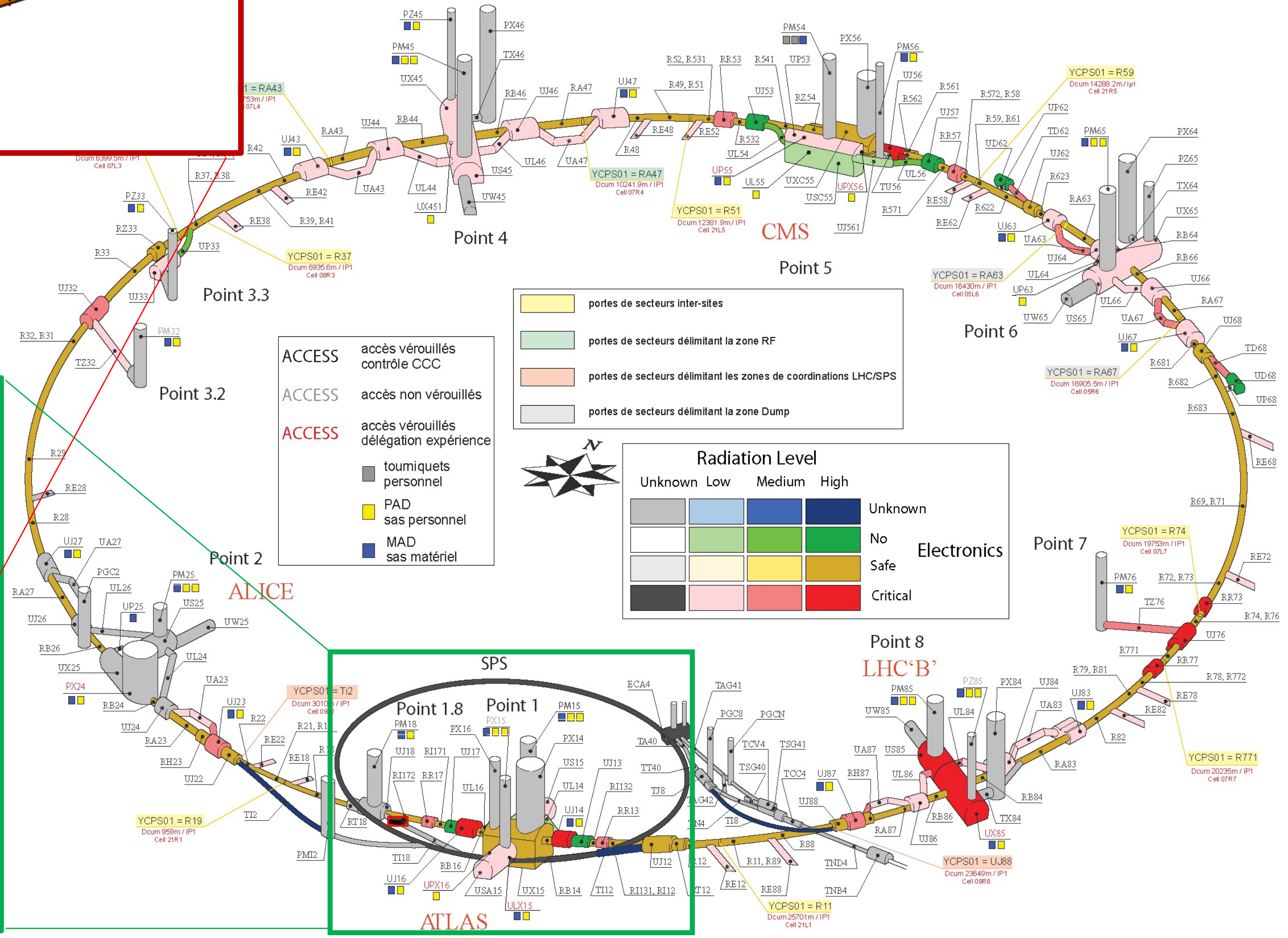
Tunnels TI12 (FASERν) and TI18 (SND@LHC): former transfer tunnels connecting SPS to LEP

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





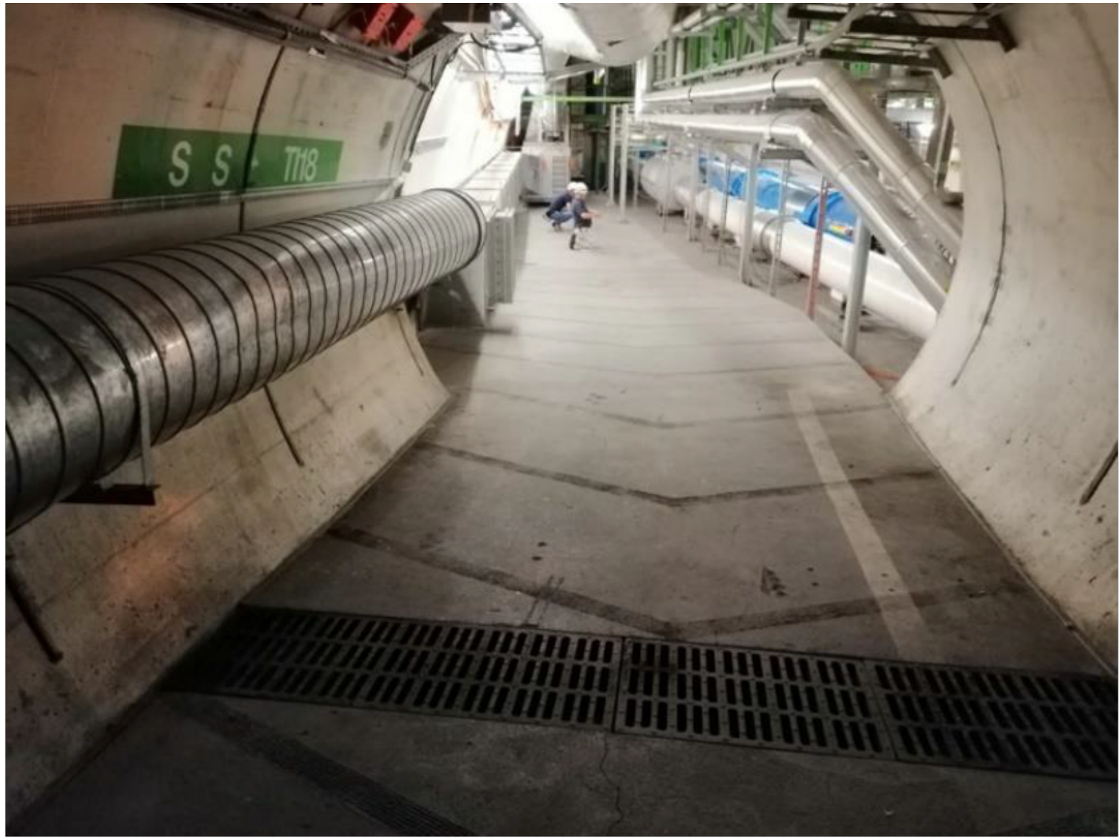




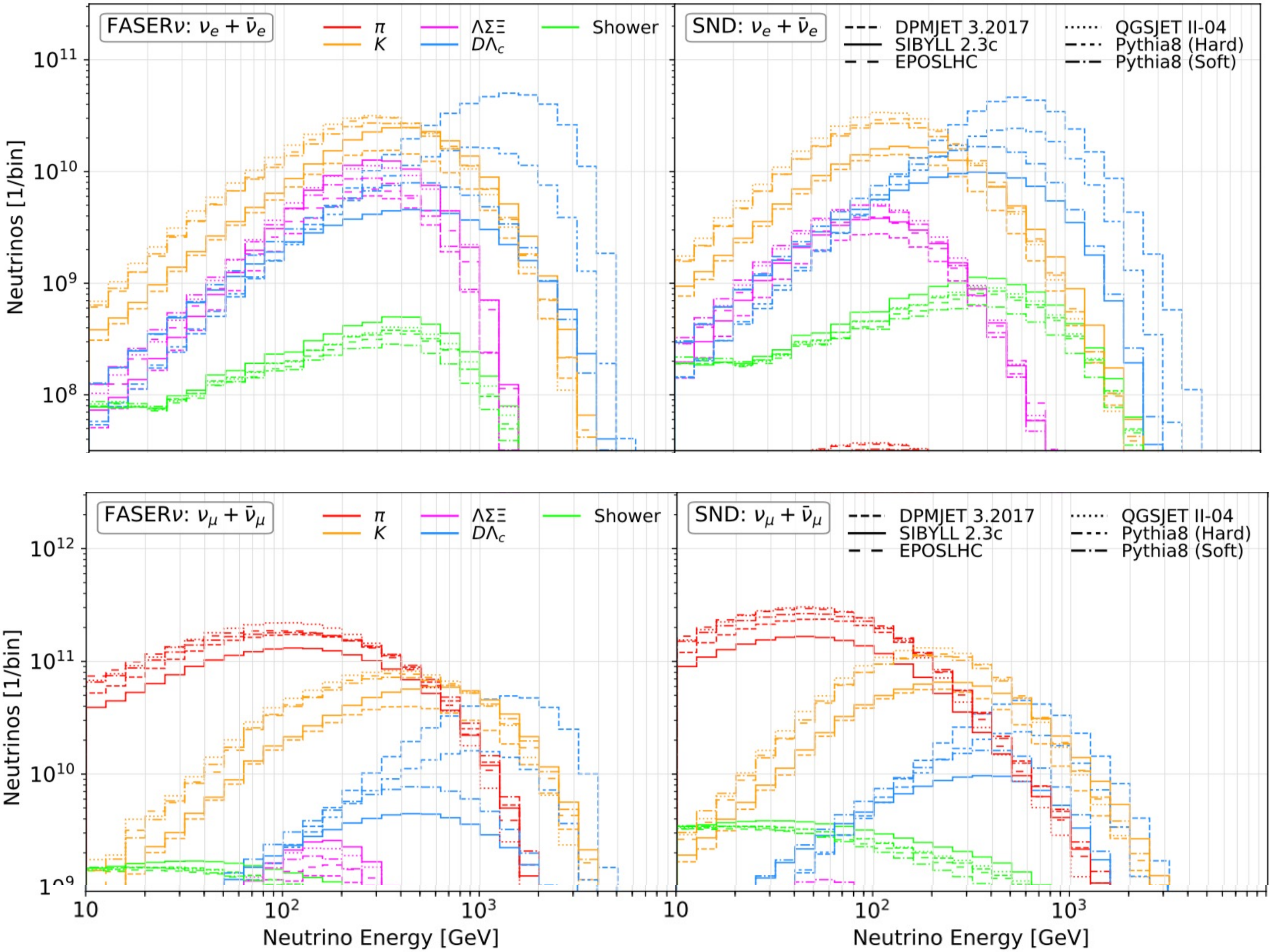
The tunnels

E.g. the TI18 tunnel

The LHC seen from the TI18 tunnel



Comparison of the neutrino fluxes and sources



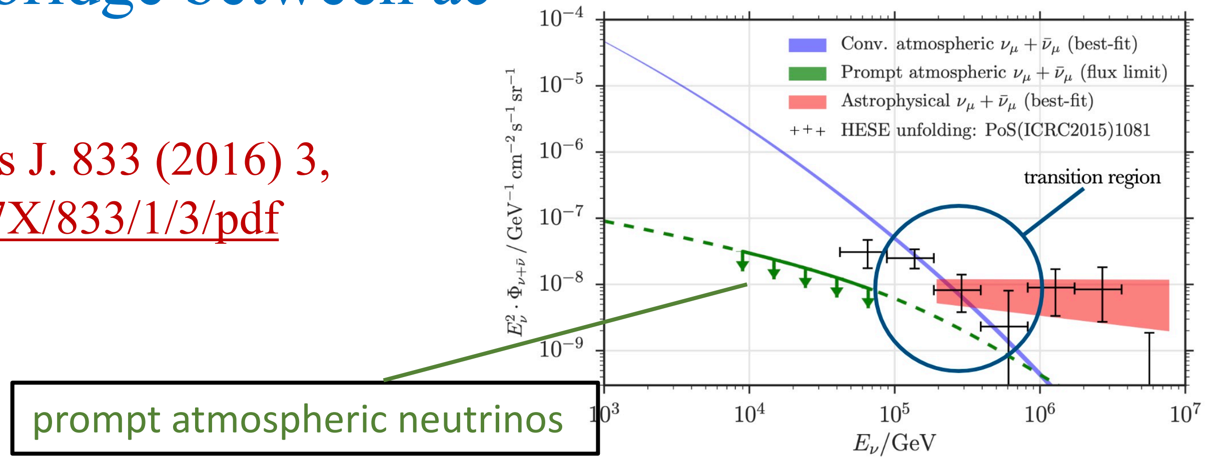
Felix Kling,
https://arxiv.org/pdf/2105.08270.pdf

Global physics goals

- Ultimate goal: study neutrino interactions (cross-section) 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

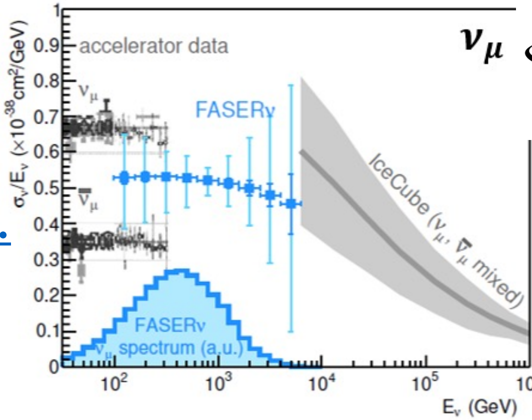
7+7 TeV *p*-*p* collisions correspond to 100 PeV proton interaction for a fixed target

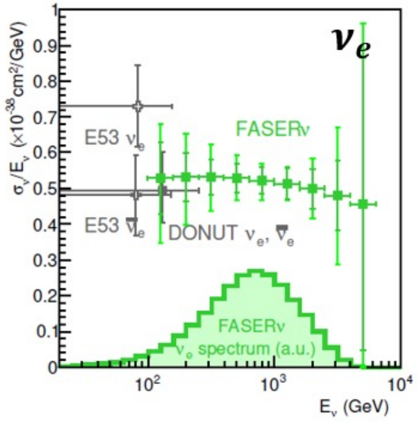


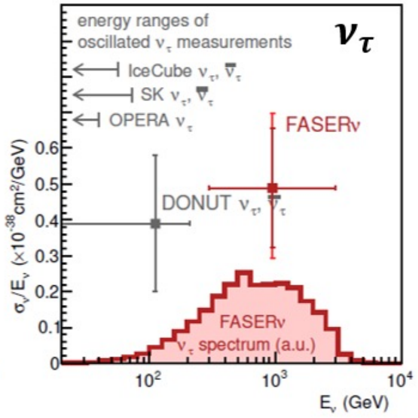
Faserν main physics goals

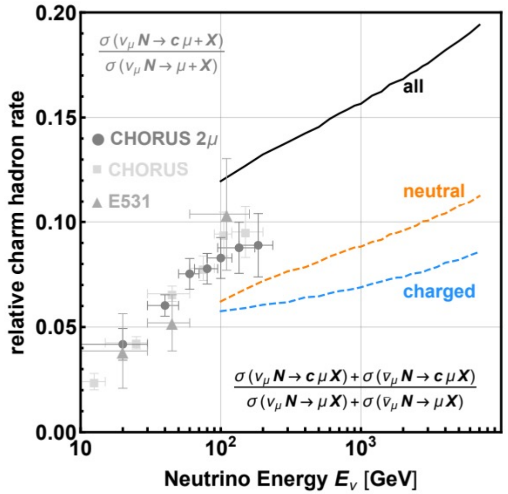
$\eta > 8.8$, $\vartheta < 0.3$ mrad

- Cross section measurements at the TeV scale
- ~2000 ν_e, 7000 ν_μ, 50 ν_τ CC interactions expected, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310
- NC measurements could constrain neutrino non-standard interactions, Phys. Rev. D 103, 056014 (2021), arXiv:2012.10500
- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
    - Study the strange quark content
    - Relevant to predict the W production at the LHC



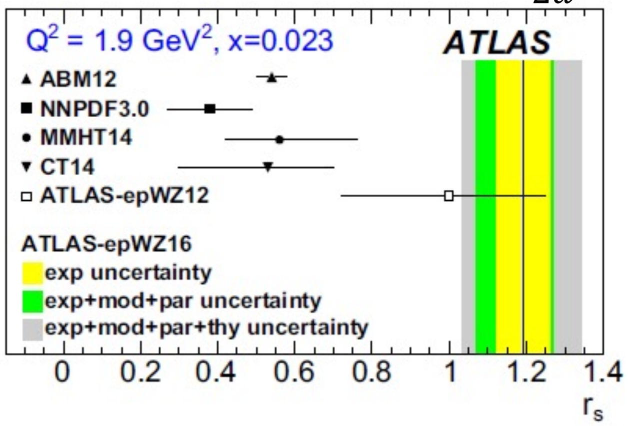






Eur. Phys. J. C77 (2017) 367

$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$

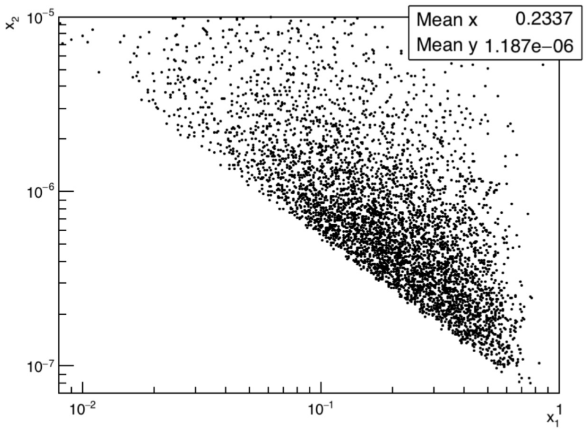


SND@LHC main physics goals

$7.2 < \eta < 8.6$, $0.4 < \vartheta < 1.5$ 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%
NC/CC ratio	5%	10%

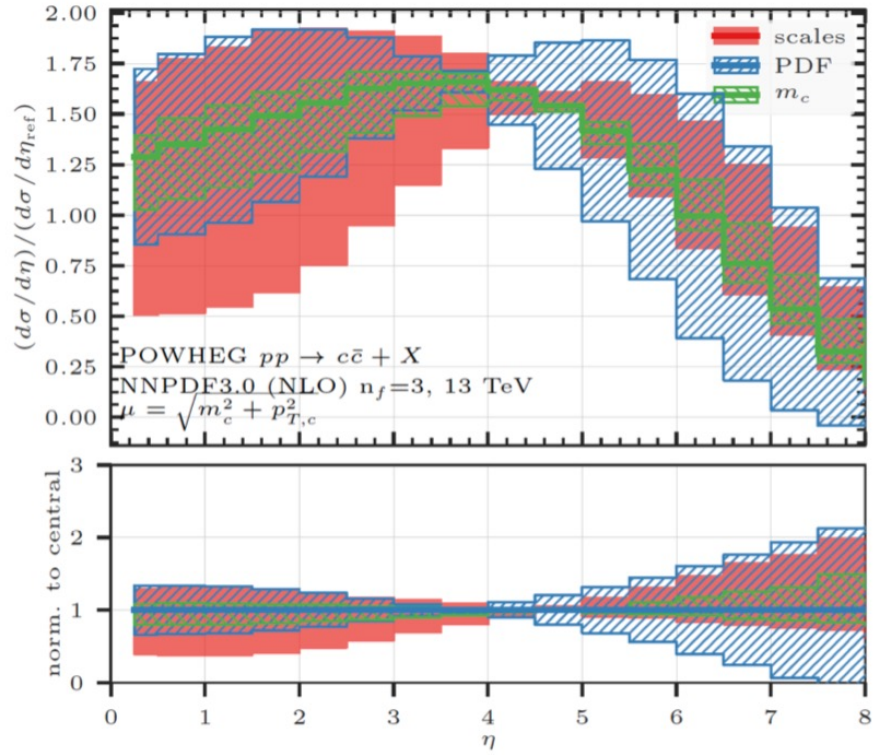
Extraction of the gluon PDF in a *x*-region relevant for Future Circular Colliders



- Expectations in 150 fb^{-1} (50/50 upward/downward crossing angle)

Flavour	CC neutrino interactions ⟨E⟩ [GeV]	CC Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC Yield
ν_μ	452	606	480	182
$\bar{\nu}_\mu$	485	248	480	93
ν_e	760	182	720	54
$\bar{\nu}_e$	680	97	720	35
TOT		1133		364

~ 20 ν_τ CC interactions expected

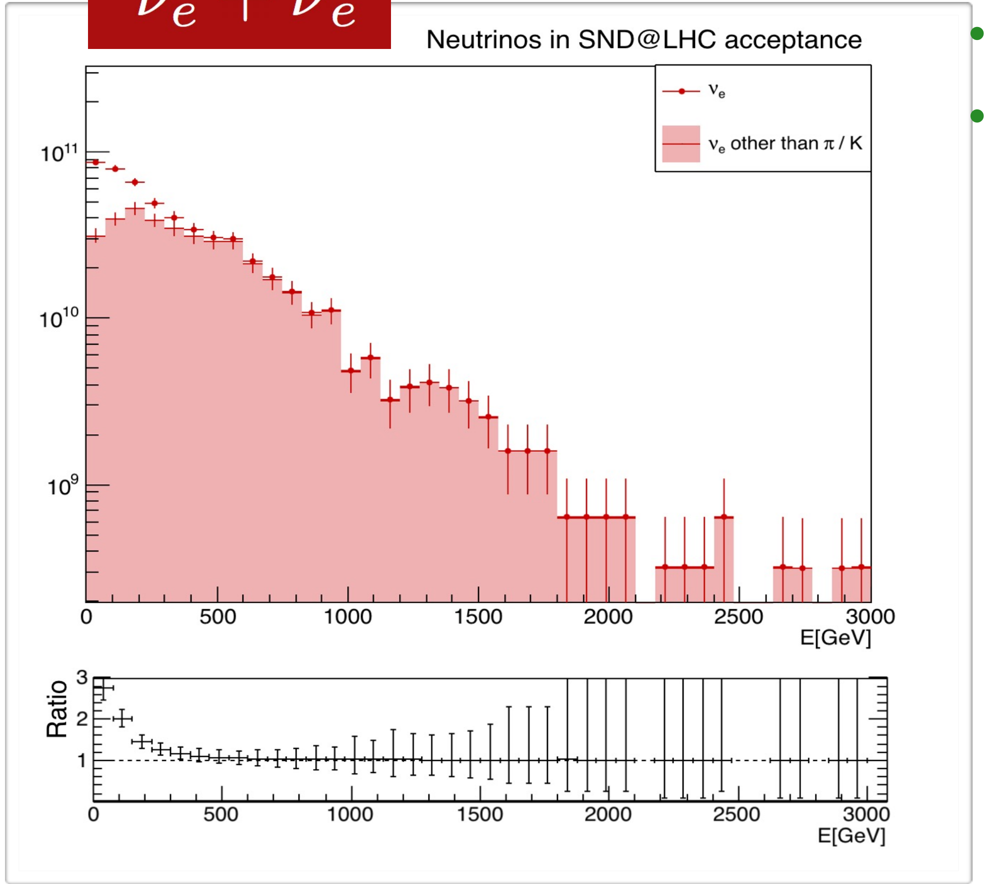


$$R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)} \qquad \eta_{ref} = [4, 4.5]$$

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

$\nu_e + \overline{\nu}_e$

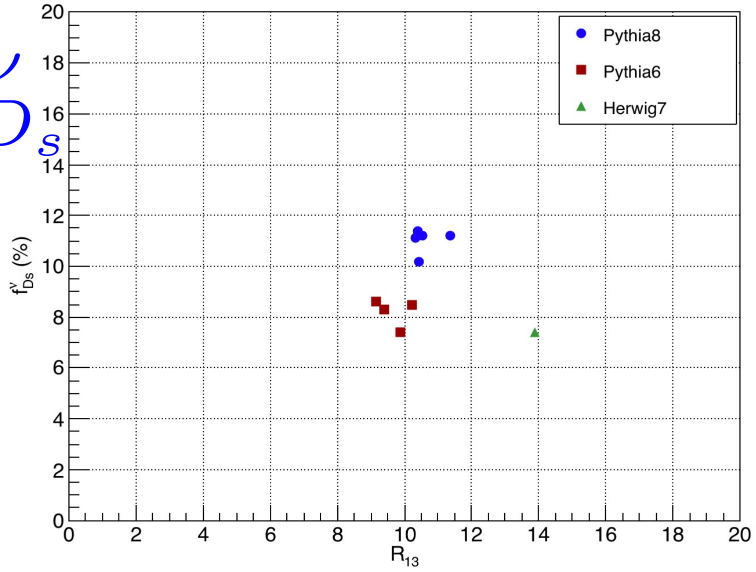


$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

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

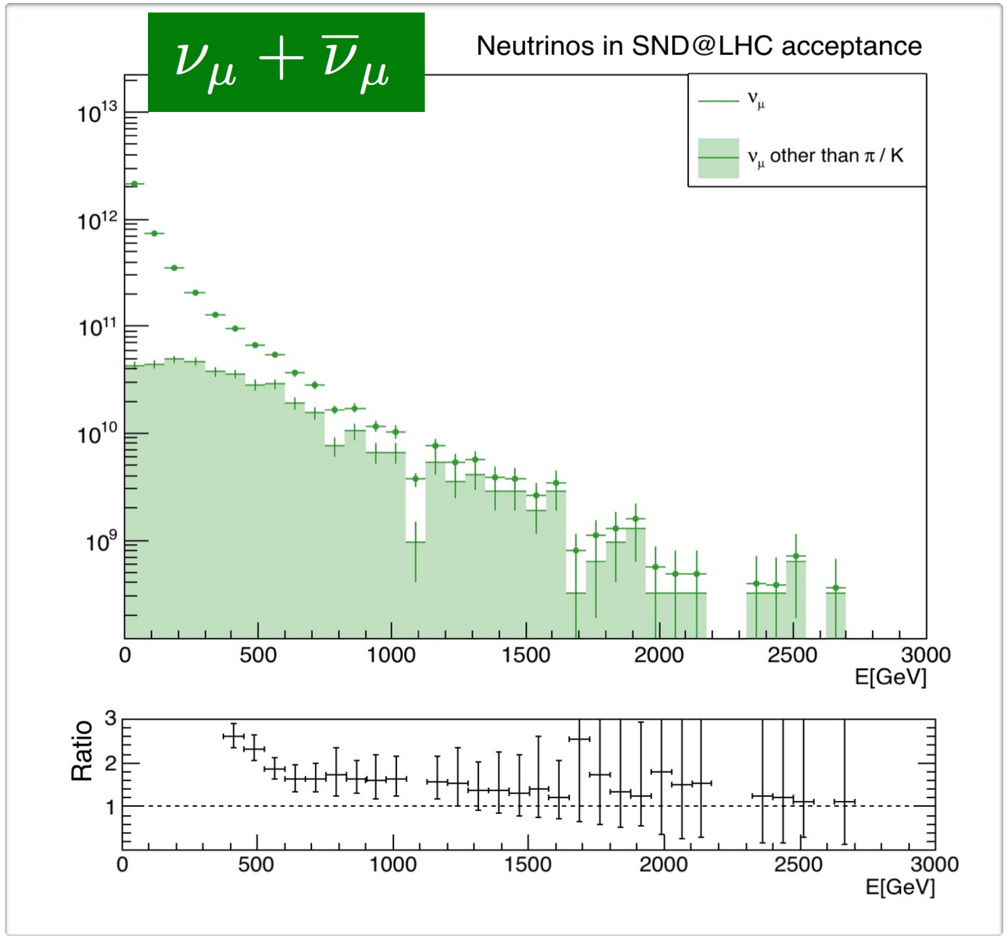
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**
- **30%** error due to ν_τ statistics

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



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



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

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

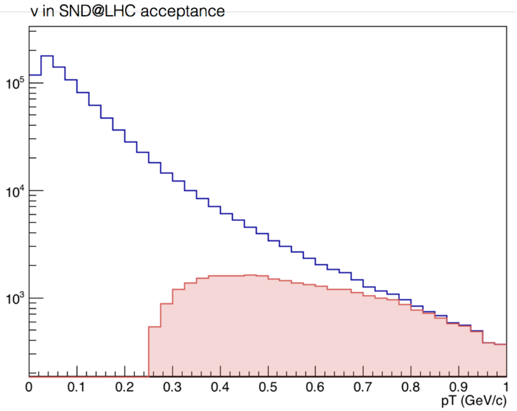
$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

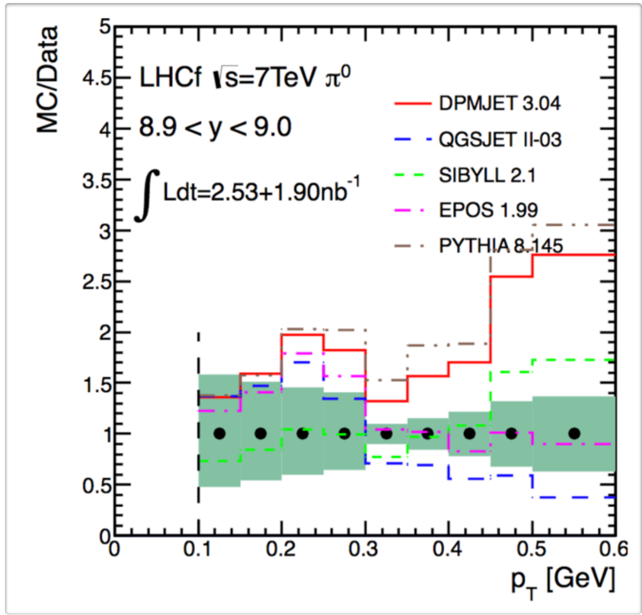
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

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

contamination from π/k

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





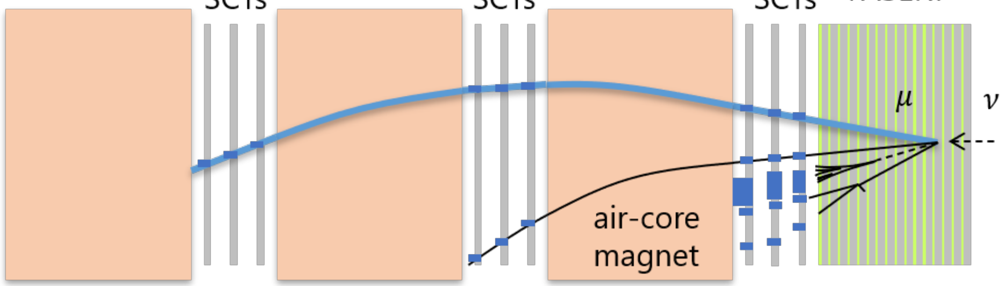
Phys. Rev. D 86, 092001 (2012)

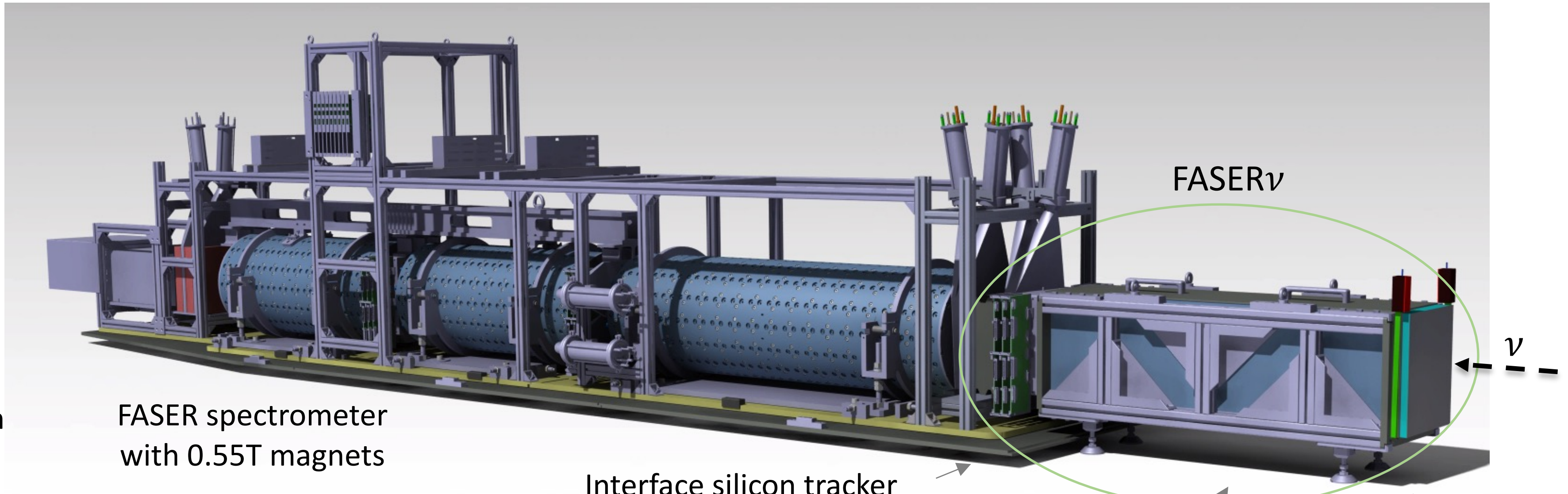
Detectors

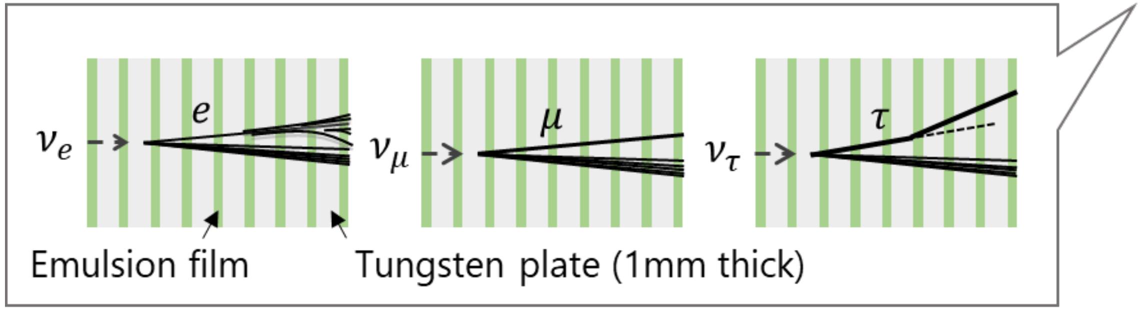
The FASERν detector

FASER (new particle searches) approved by CERN in Mar 2019
FASERν (neutrino measurements) approved by CERN in Dec 2019

- **Emulsion/tungsten detector, interface silicon tracker, and veto station** will be placed in front of the FASER main detector.
- Allow to distinguish **all flavor of neutrino interactions**
  - **Muon identification** by their track length in the detector ($8\lambda_{int}$)
  - **Muon charge identification** with hybrid configuration → distinguishing ν_μ and $\bar{\nu}_\mu$
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables





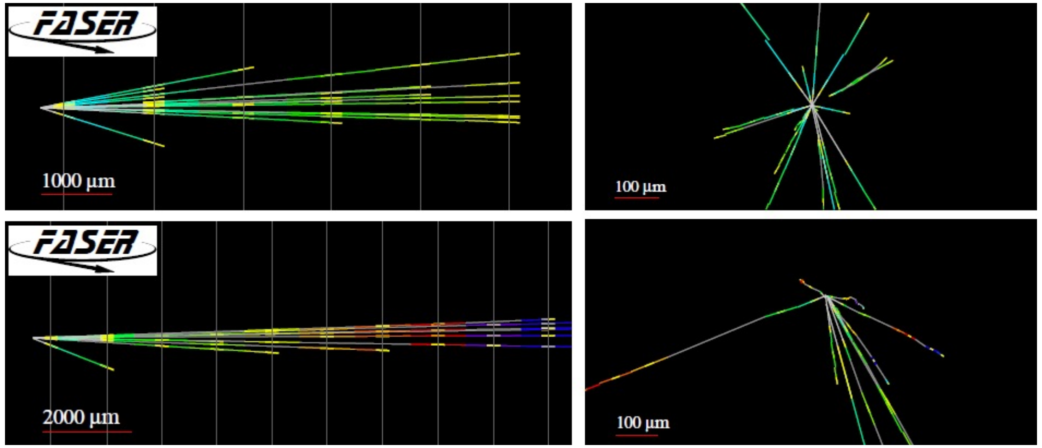


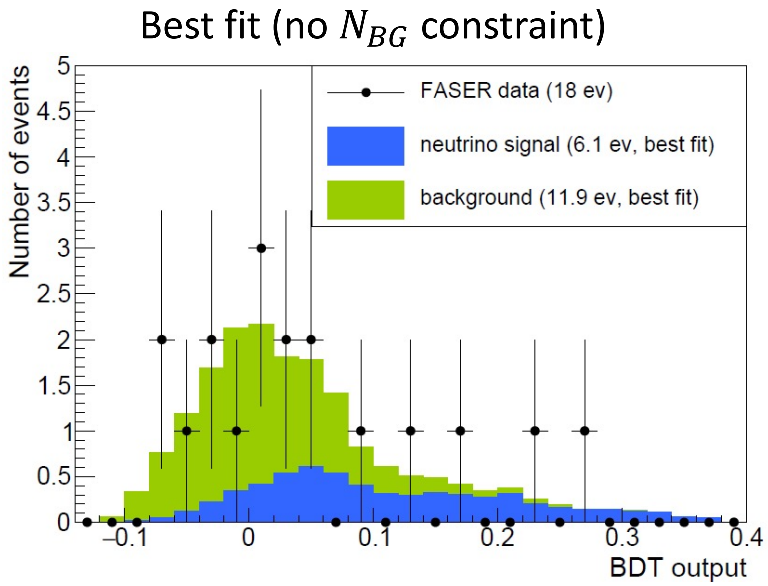
Emulsion/tungsten detector
- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm^2, 1.1 m long, 1.1 tons detector ($220X_0$)

First neutrino interaction candidates at the LHC

arXiv:2105.06197

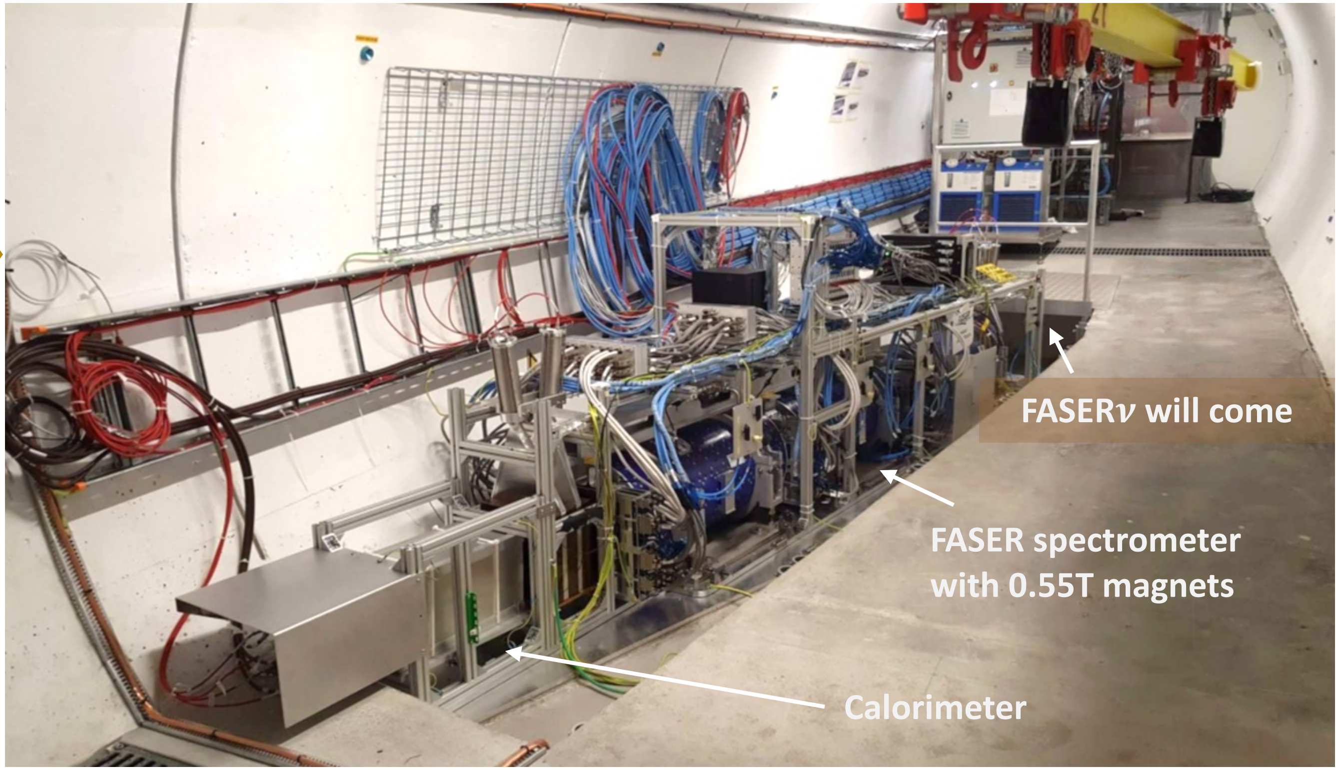
- Analyzed target mass of 11 kg, exposed in 2018
- 18 neutral vertices were selected
  - Selecting at least 5 charged particles
  - Expected signal $3.3^{+1.7}_{-0.9}$ events, BG 11.0 events
- Excess of neutrino signal over the background observed (BDT analysis) with 2.7σ significance
- First indication of neutrinos at the LHC with a small detector, without any VETO plane in front, unlike in the upcoming Run3





Preparation towards LHC Run-3

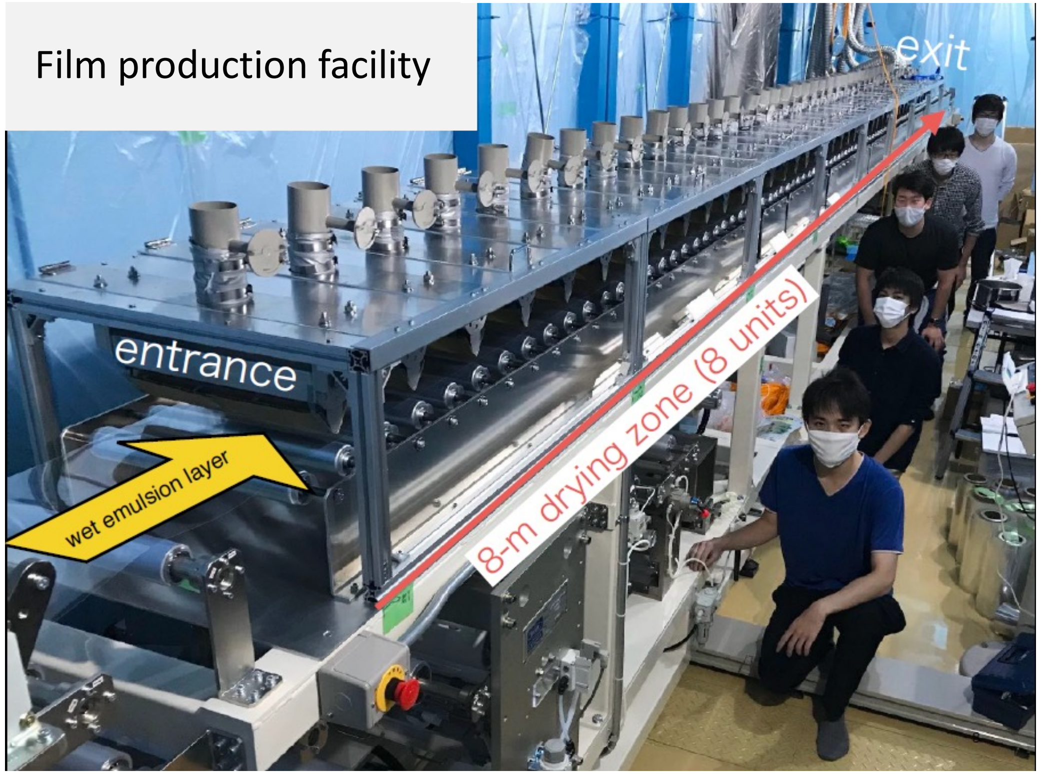
The TI12 area



The FASER main detector was successfully installed into the TI12 tunnel in March 2021.

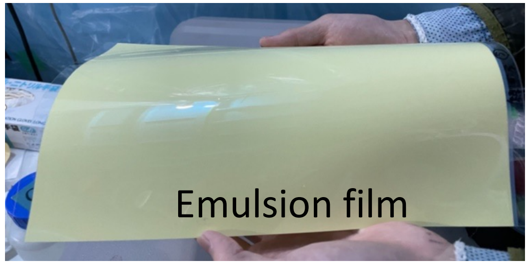
Emulsion detector preparation

- Emulsion gel and film production facilities in Nagoya (Japan) set up in 2020
- Testing gel and film mass production
- Testing produced films with cosmic rays



Film production facility


Tungsten plate

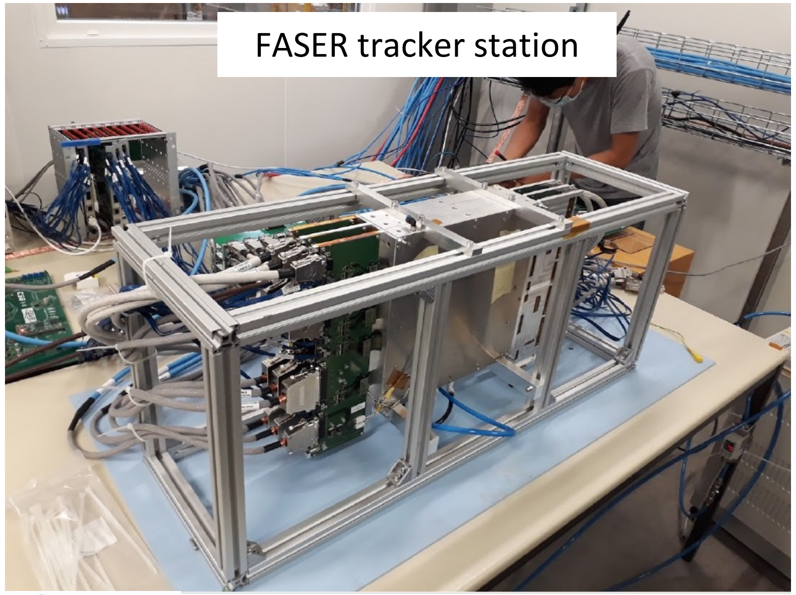

Emulsion film

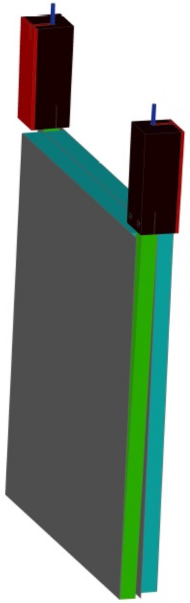
FASERν box and installation test in the tunnel

Interface tracker (IFT) and veto system

- **IFT** will use the same design as the tracker station in the FASER spectrometer.
  - Silicon strip detector with ATLAS SCT barrel modules
    - 80 μm strip pitch, 40 mrad stereo angle
    - Position resolution ~17 μm and ~ 580 μm in the 2 coordinates
  - Electrical qualification as well as assembly of the planes/station completed.
  - The beam test has been performed at the H2 beamline in the CERN SPS North Area.

- **Veto station** consists of two 2-cm scintillators and WLS (Wavelength Shifting) bars with two PMTs.
  - The PMTs tested.
  - Scintillators assembled and under test with cosmic rays





Veto dimension 30×35 cm^2

SND@LHC DETECTOR LAYOUT

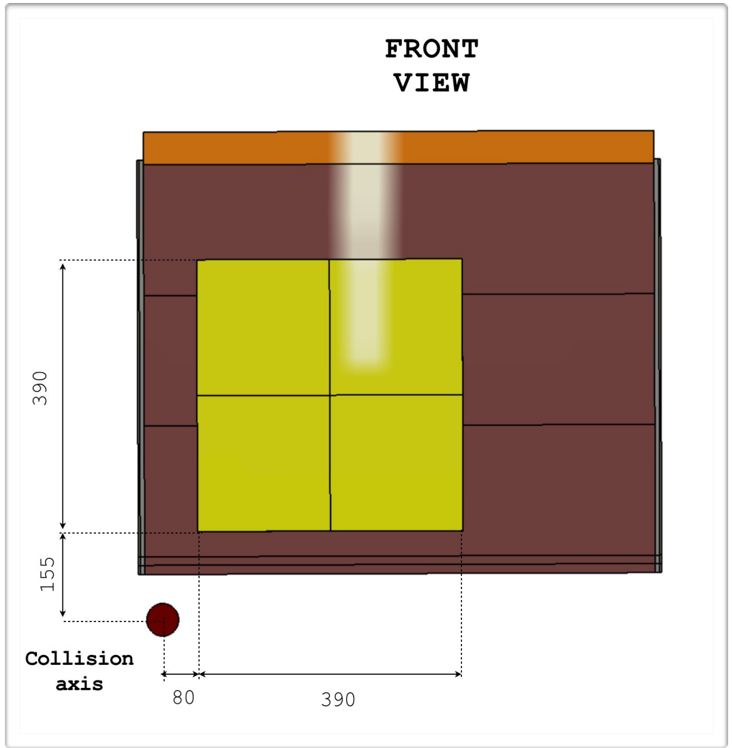
- Angular acceptance: 7.2< η < 8.6
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm^2

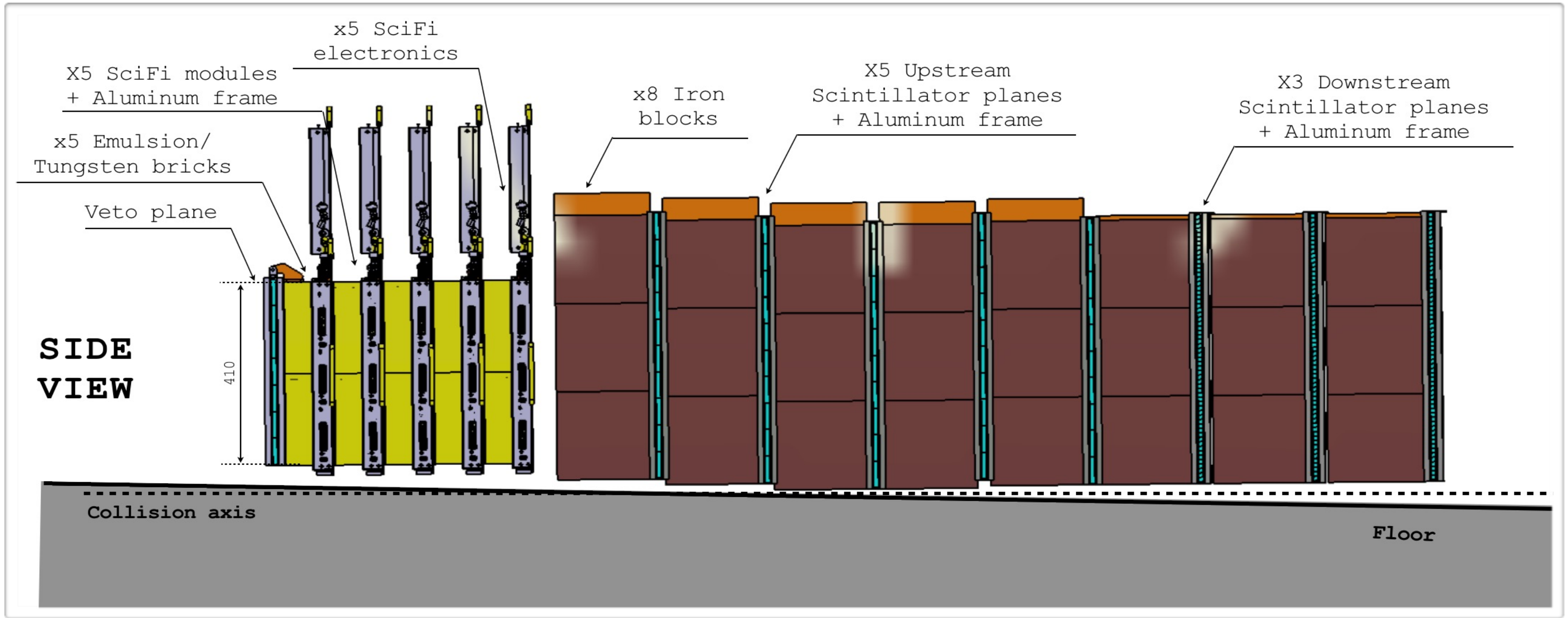
Veto Plane, Target Region (emulsion & tungsten), Muon system/Had Calo

Off axis location

Electromagnetic calorimeter
On average ~40 X_0

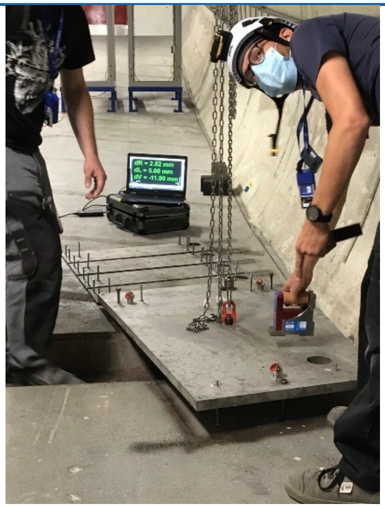
Hadronic calorimeter
On average ~11 λ





Experimental area preparation in TI18

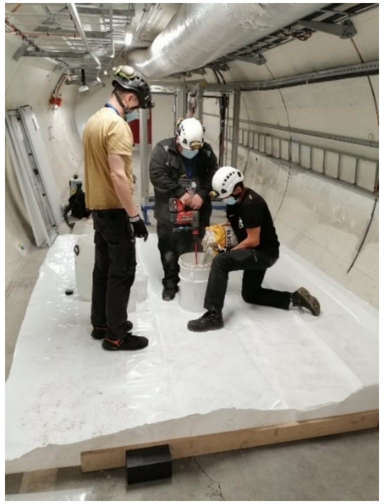
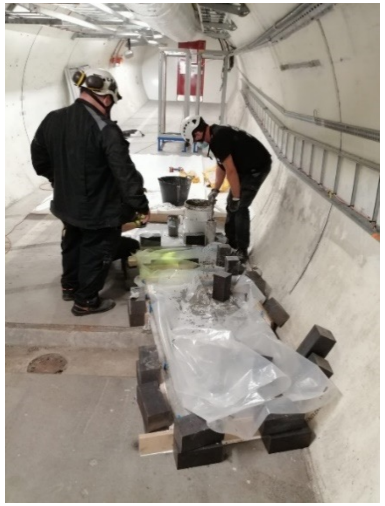
LHC
Scattering and Neutrino Detector
at the LHC


Survey and positioning of baseplates for muon filters

Underground racks

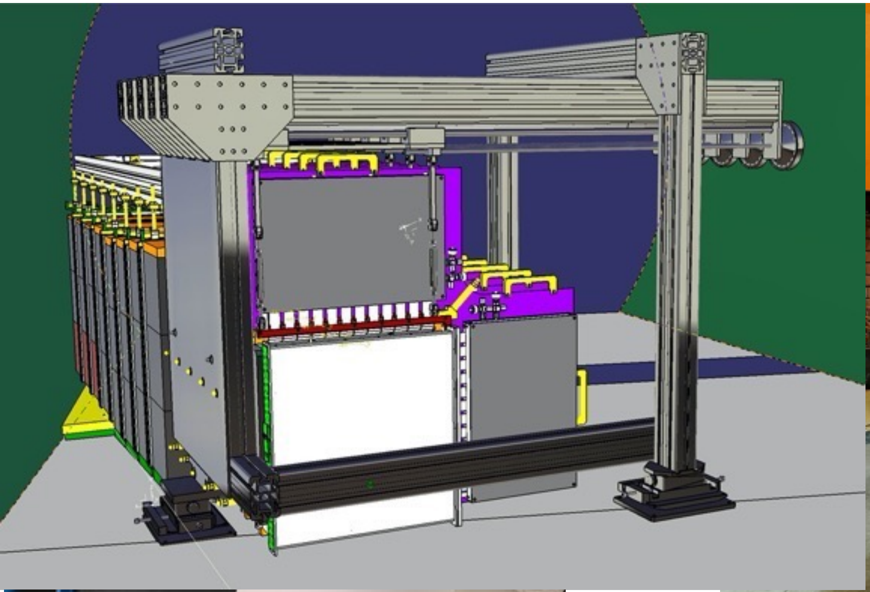
Optical fibres between surface and underground racks

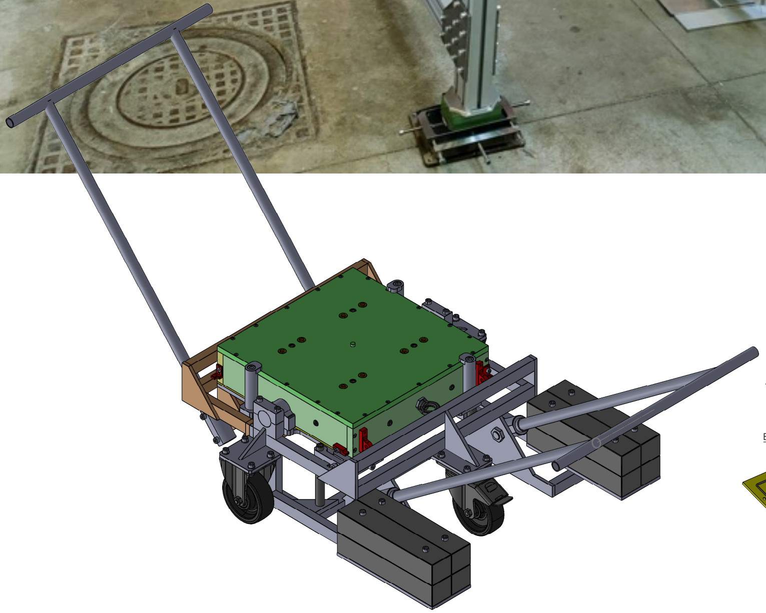

Formworks and grouting of baseplates

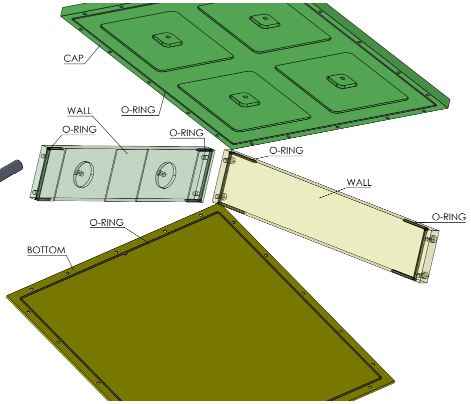
Mechanical structure and ν target/vertex construction

Scattering and Neutrino Detector at the LHC



Wall box for emulsion/tungsten

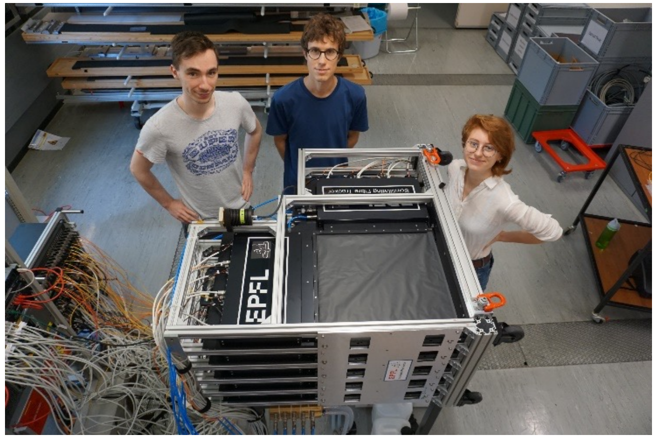


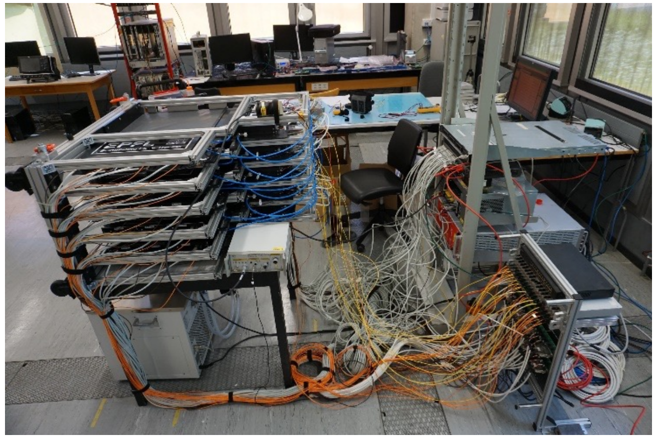


Adjustable feet

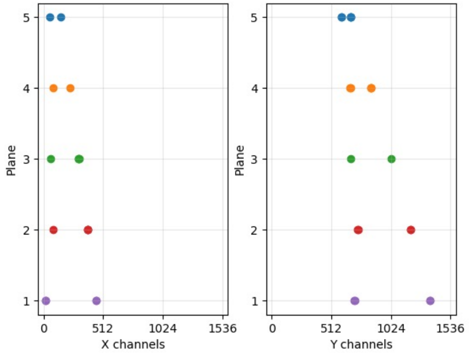
Detector construction: SciFi and Muon stations

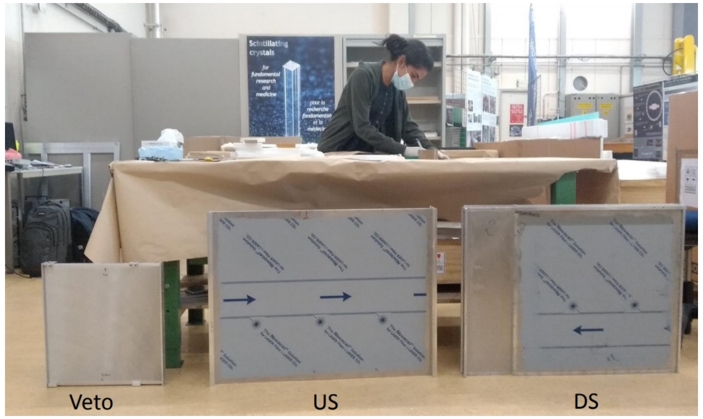
LHC
Scattering and Neutrino Detector at the LHC

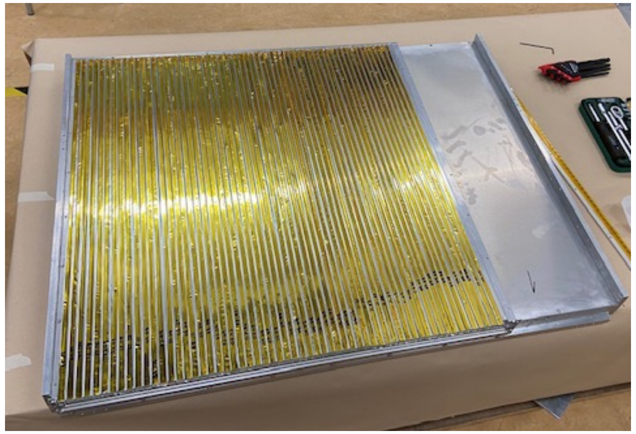




e-pair candidate



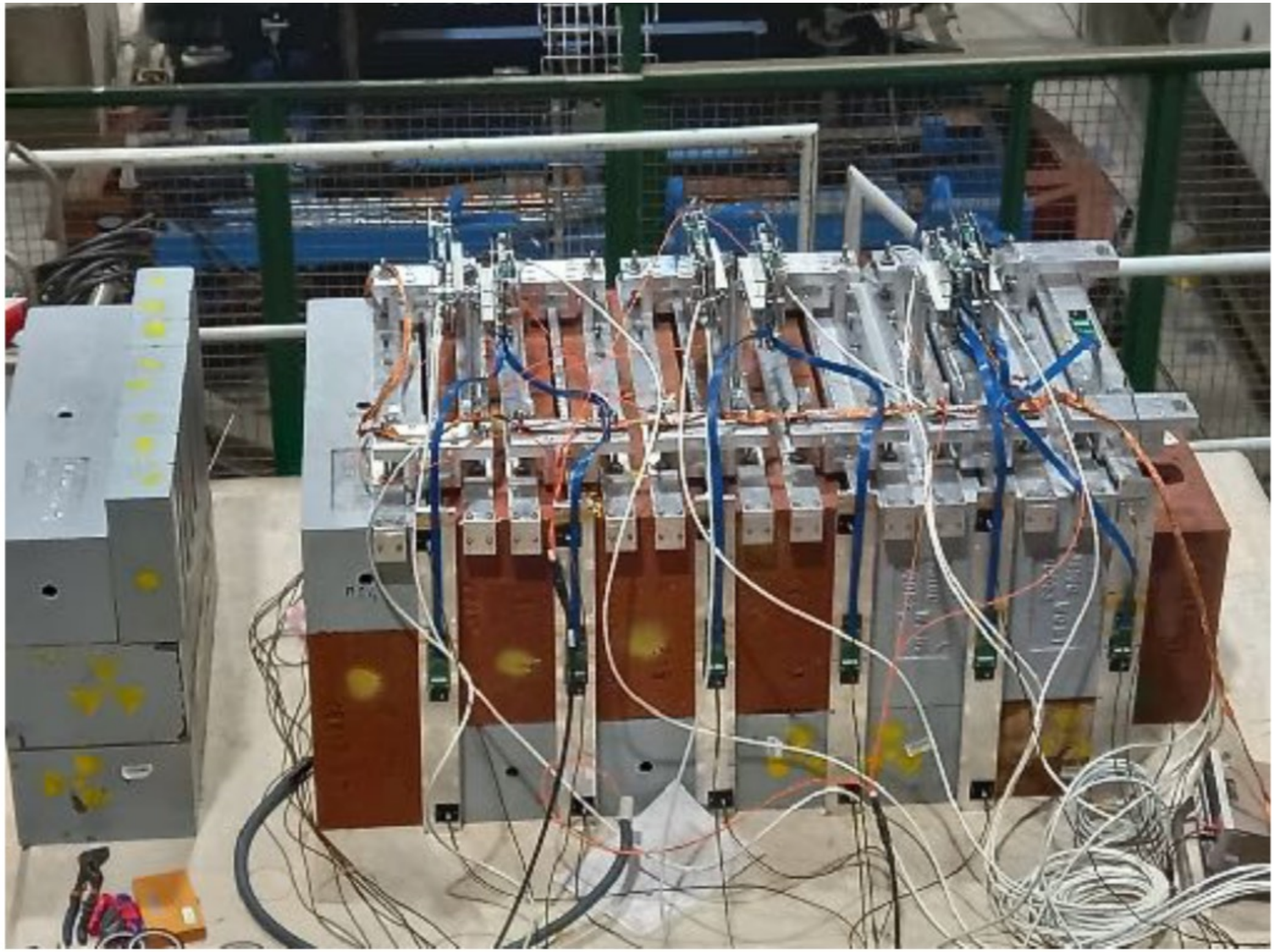




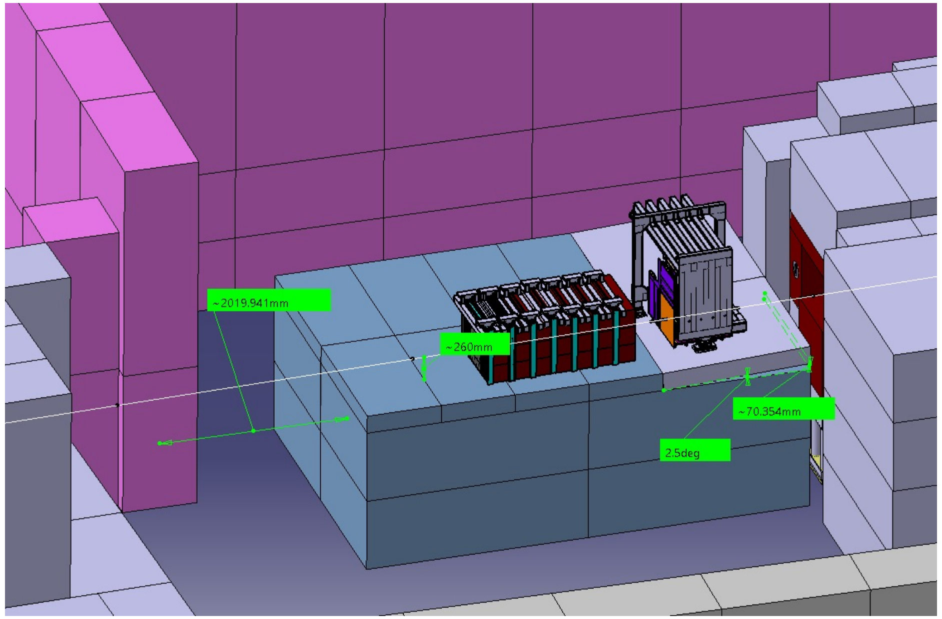
Commissioning of the detector

Scattering and Neutrino Detector at the LHC

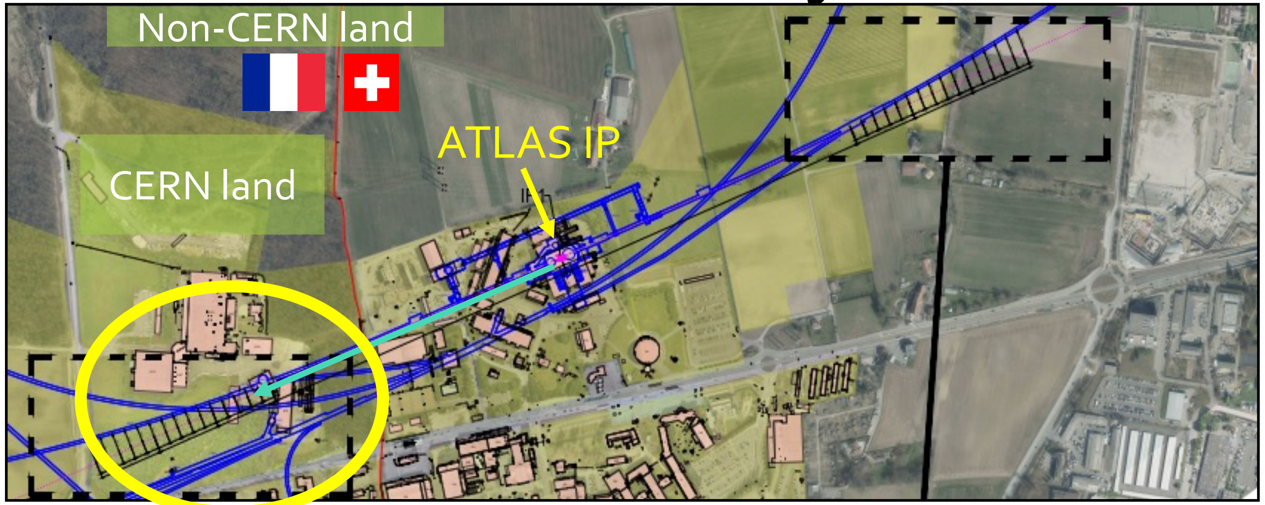
Test beam in H8 for SND-muon/HCAL for energy calibration, performed in Sep 1-5



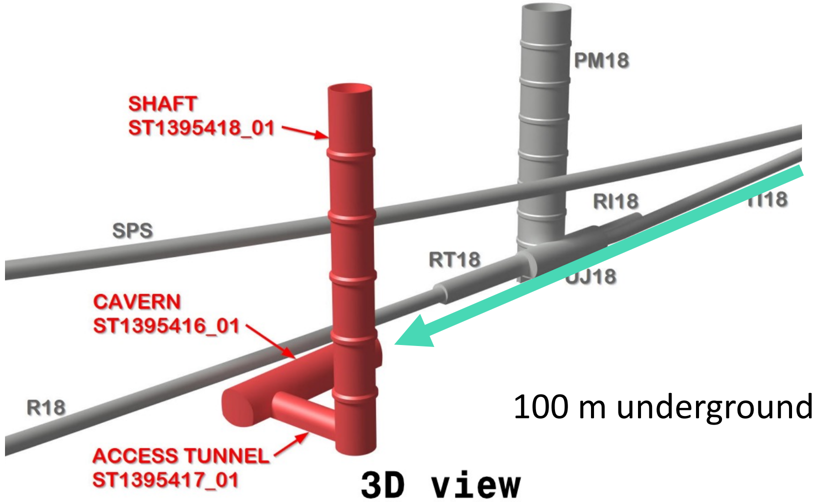
Commissioning of the detector on surface at H6 in October



The new Forward Physics Facility (FPF): FASERν2 and AdvSND

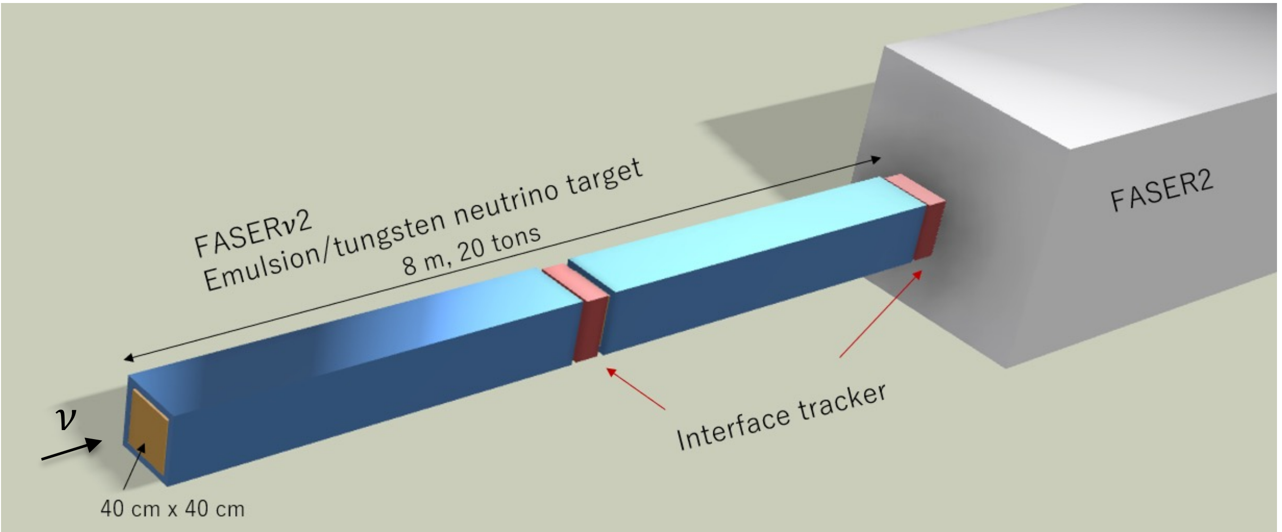


- FPF for the HL-LHC proposed to house a suite of experiments to enhance the LHC physics potential for BSM physics searches, neutrino physics and QCD.
- FASERν2 designed to carry out precision ν_τ measurements and heavy flavour physics studies
  - $\sim$2300 (SIBYLL) / $\sim$20000 (DPMJET) ν_τ interactions are expected
- AdvSND with two off-axis forward detectors
  - •SND1: $\eta \sim$ 8 Reduce systematic uncertainties
  - •SND2: $\eta \sim$ 4.5 link to LHCb measurements & high-energy neutrino physics



100 m underground

3D view



New era of collider neutrinos started!

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

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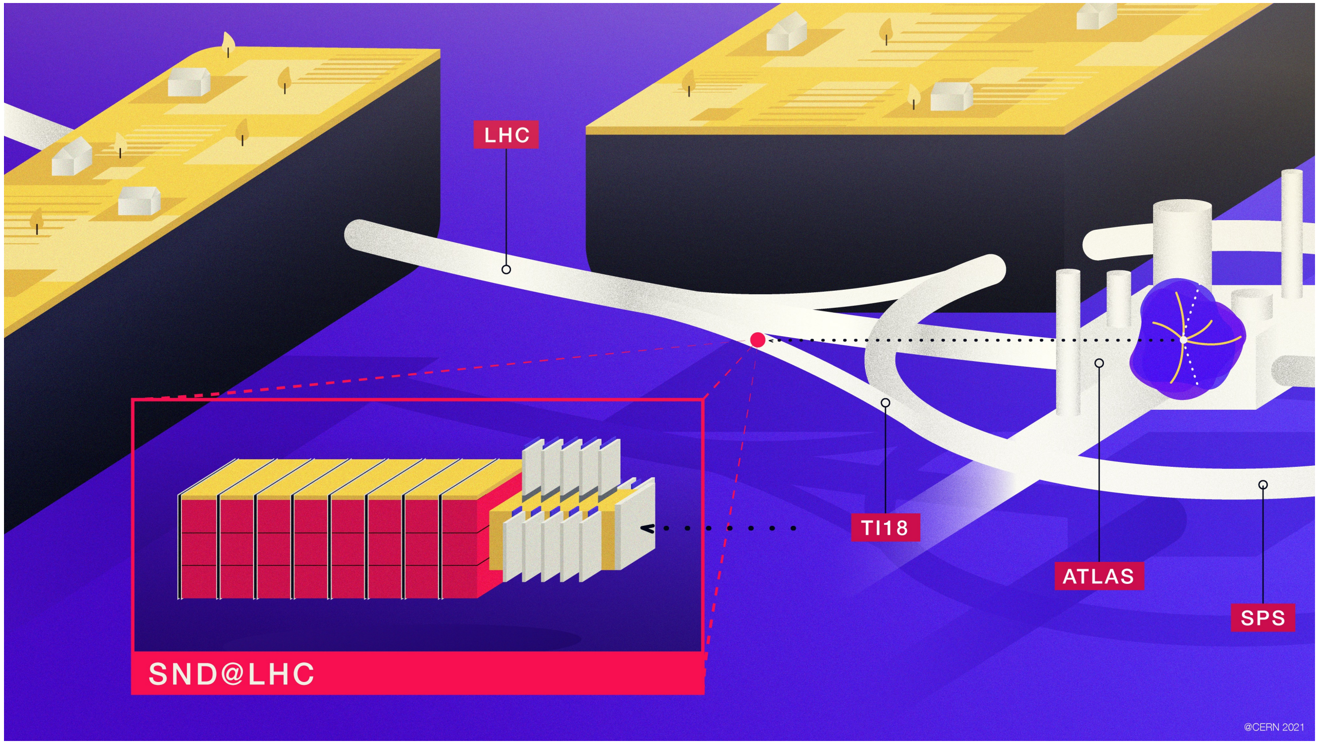
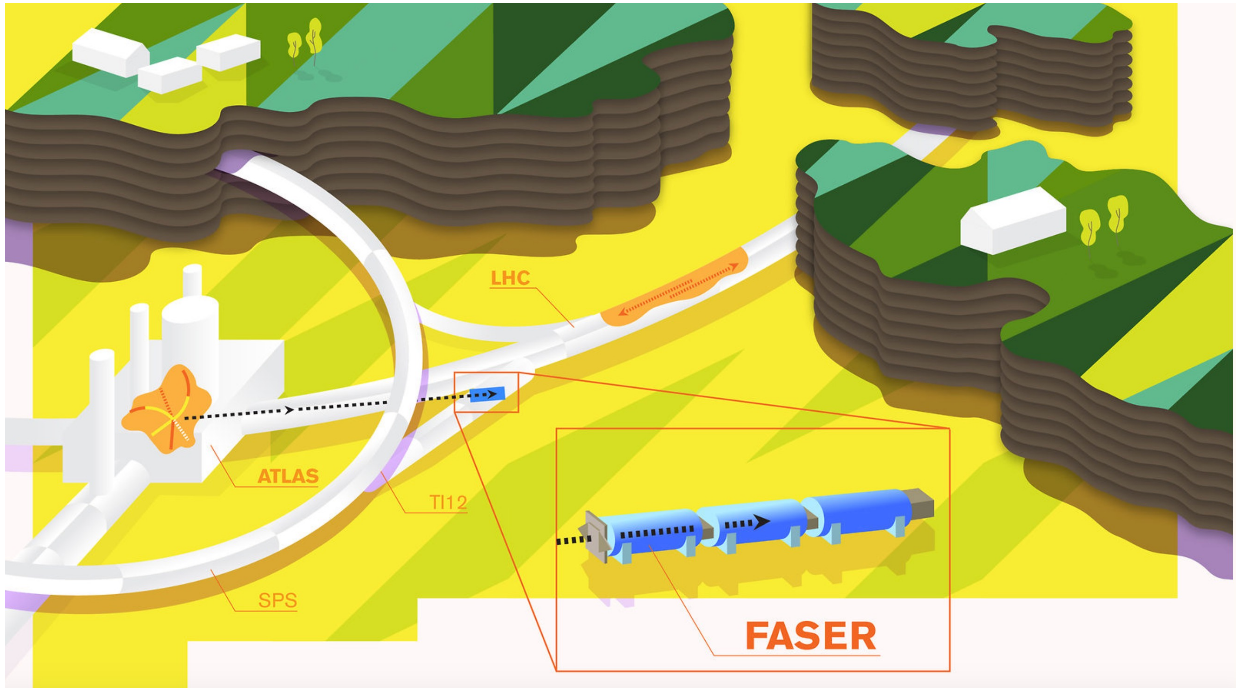
NEUTRINOS | NEWS

Collider neutrinos on the horizon

2 June 2021





https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc

Stay tuned! Both experiments will start taking data in 2022!