SND@LHC
The Scattering and Neutrino Detector at the LHC

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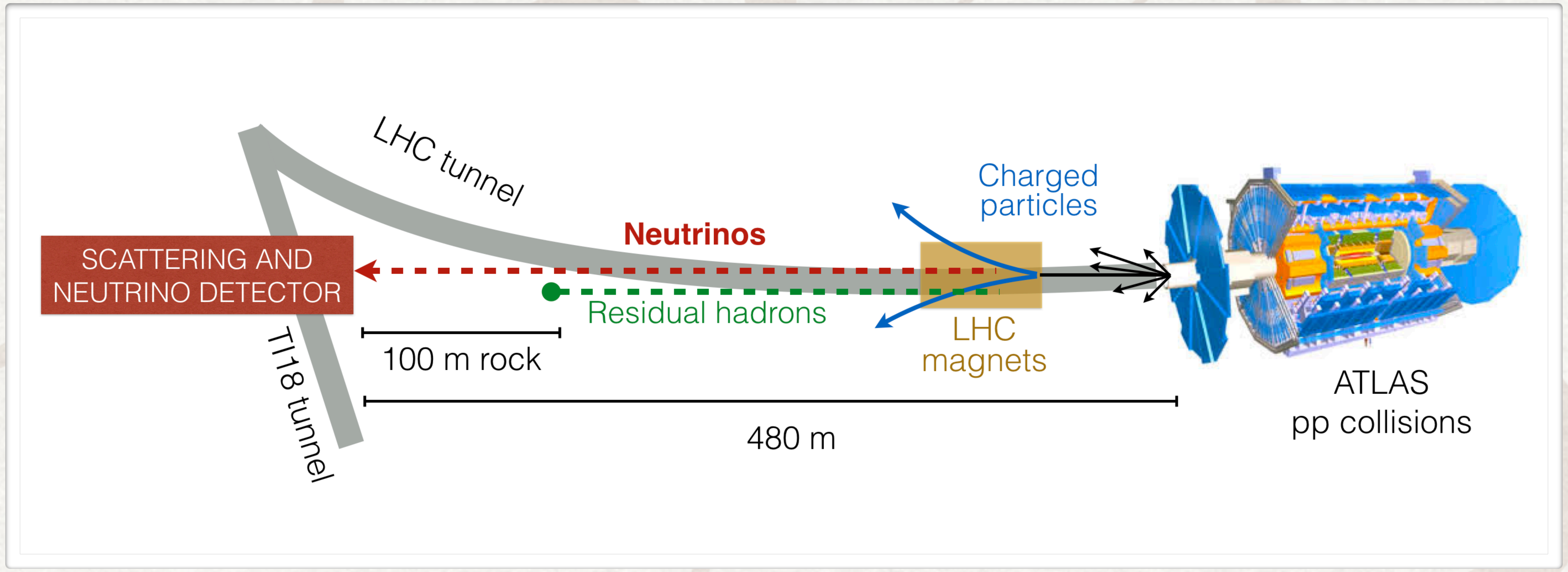
INFN Napoli

INFN NA Gr1 Meeting - 21 Dec 2021

OVERVIEW

- The SND@LHC experiment
- Neutrino physics program
- Search for feebly interacting particles
- Detector commissioning and installation



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

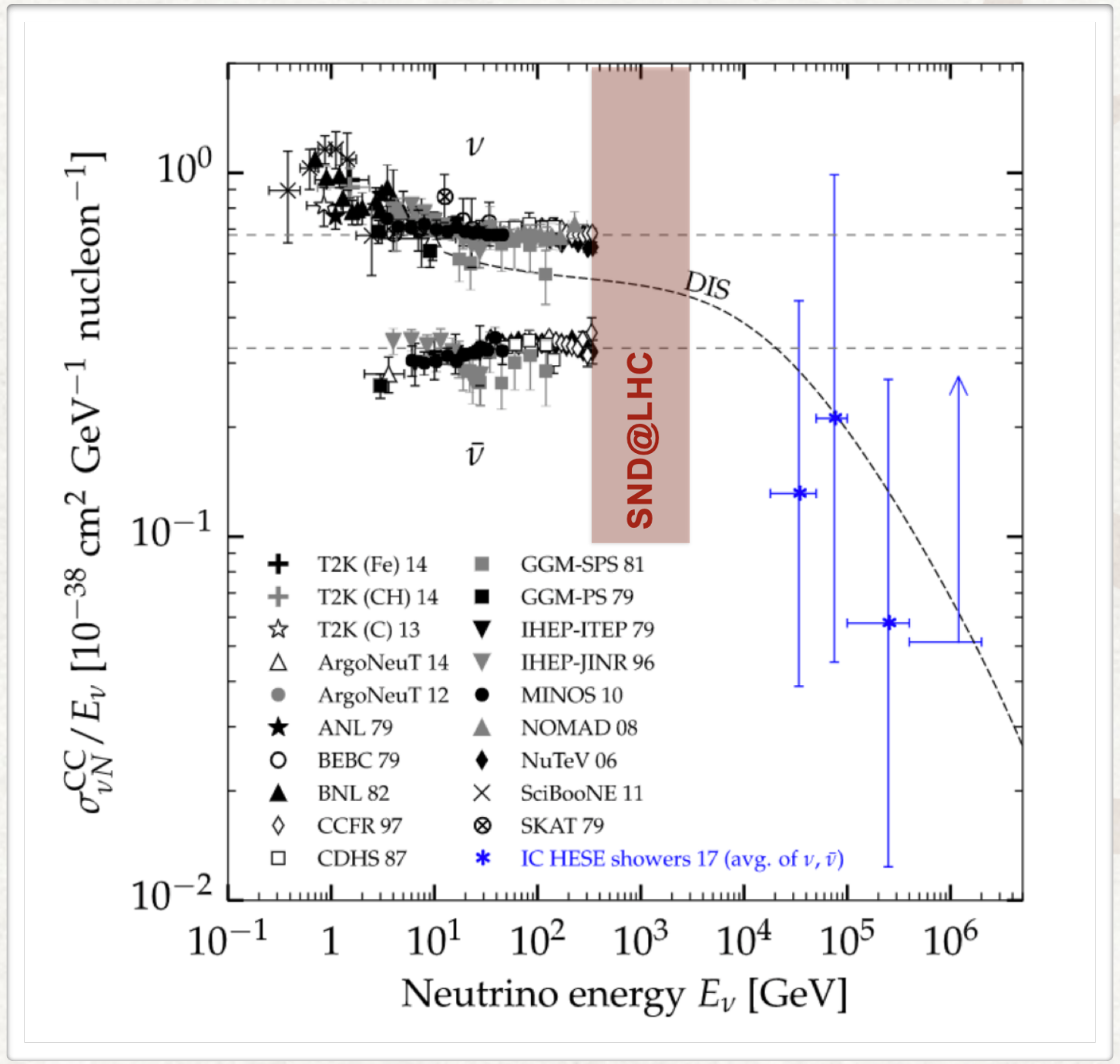
Approved by the Research Board on March 2021

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

PRL 122 (2019) 041101



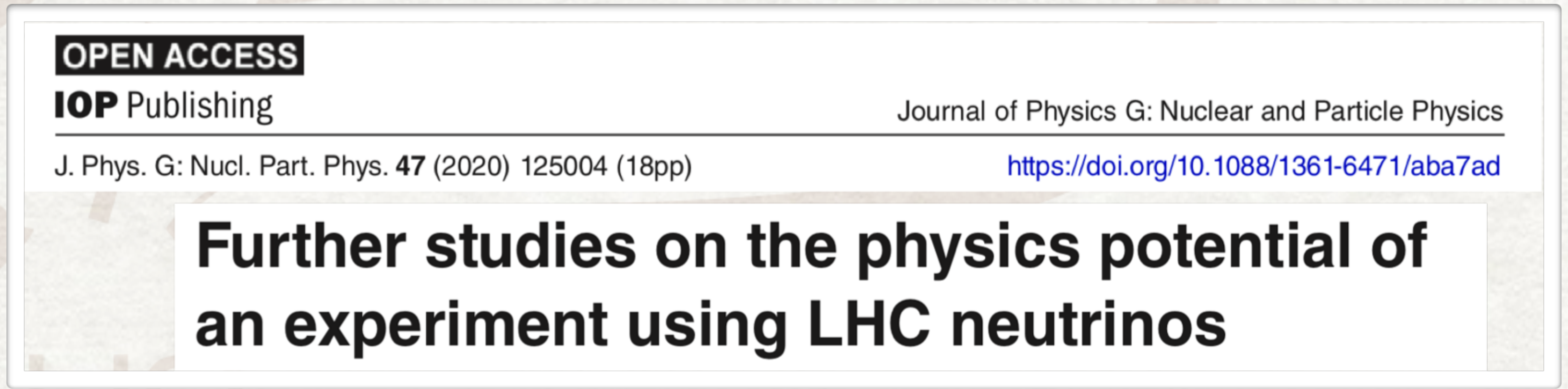
CERN is unique in providing energetic **ν** (from LHC) and measure pp →**ν**X in an unexplored domain


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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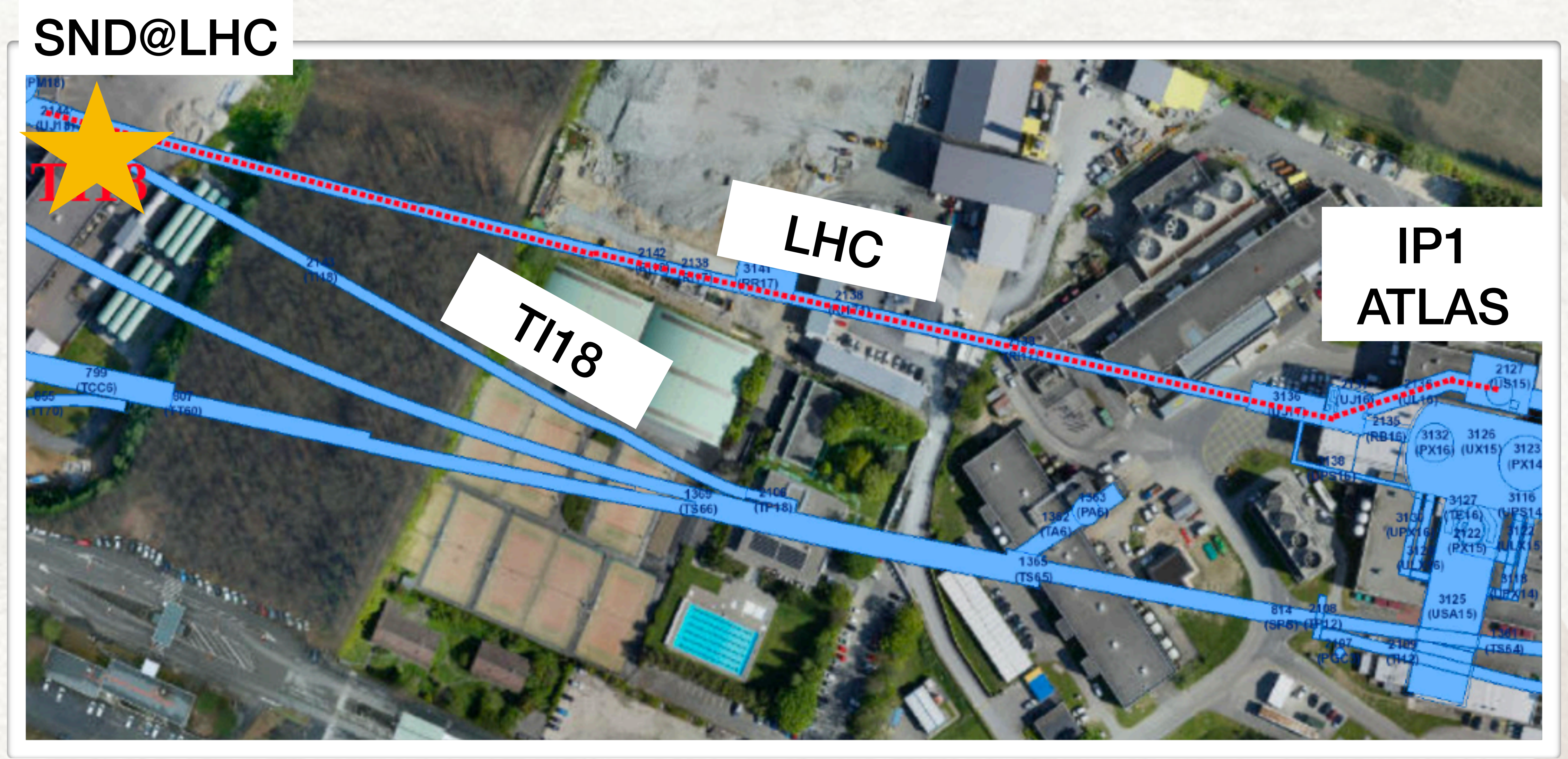
IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

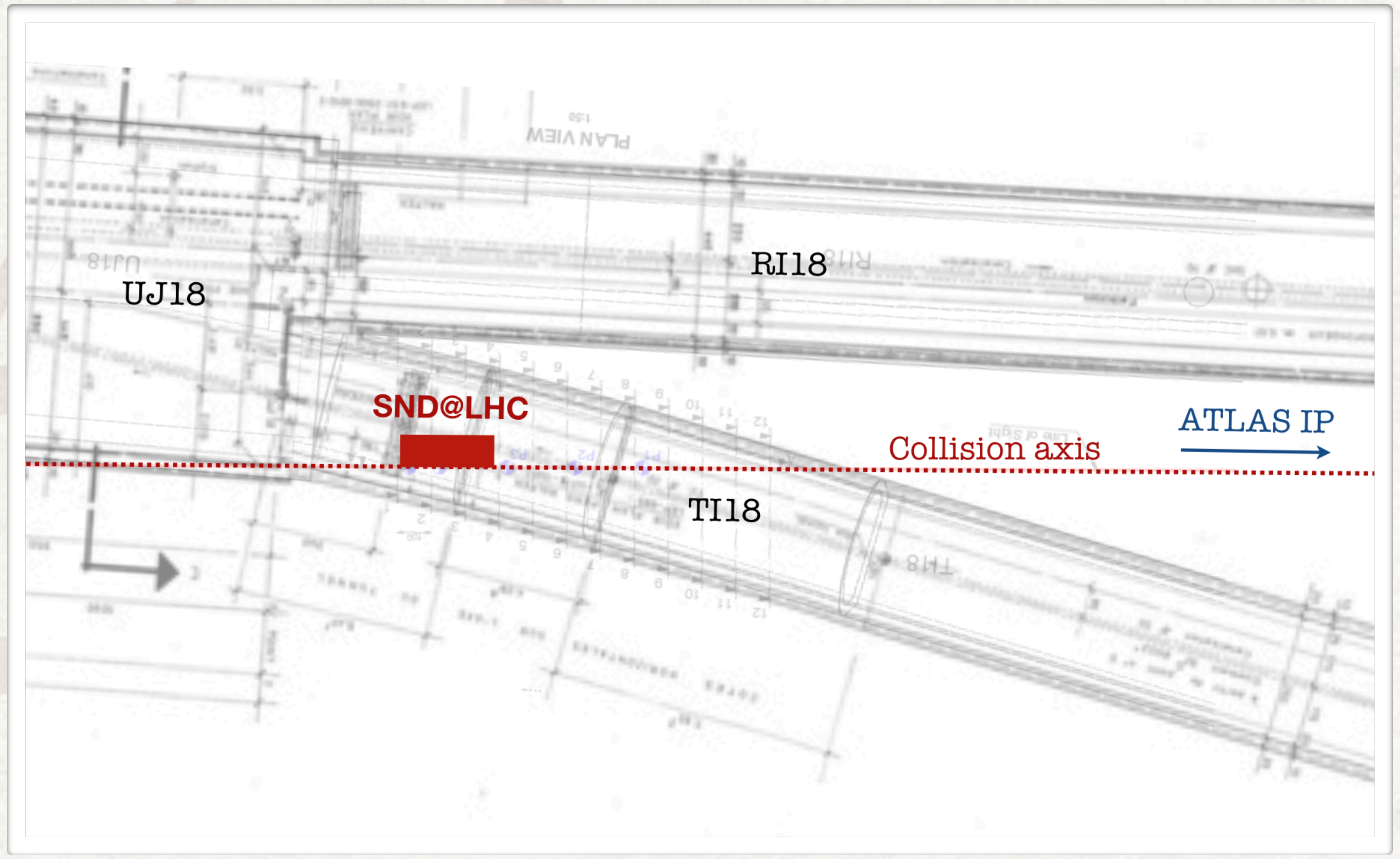
J. Phys. G: Nucl. Part. Phys. **47** (2020) 125004 (18pp) https://doi.org/10.1088/1361-6471/aba7ad

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

LOCATION



- About 480 m away from the ATLAS IP
- Tunnel TI18: former service tunnel connecting SPS to LEP
- Symmetric to TI12 tunnel where FASER is located



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

- Angular acceptance: $7.2<\eta< 8.6$

- First phase: operation in Run 3 to collect 150 fb^{-1}

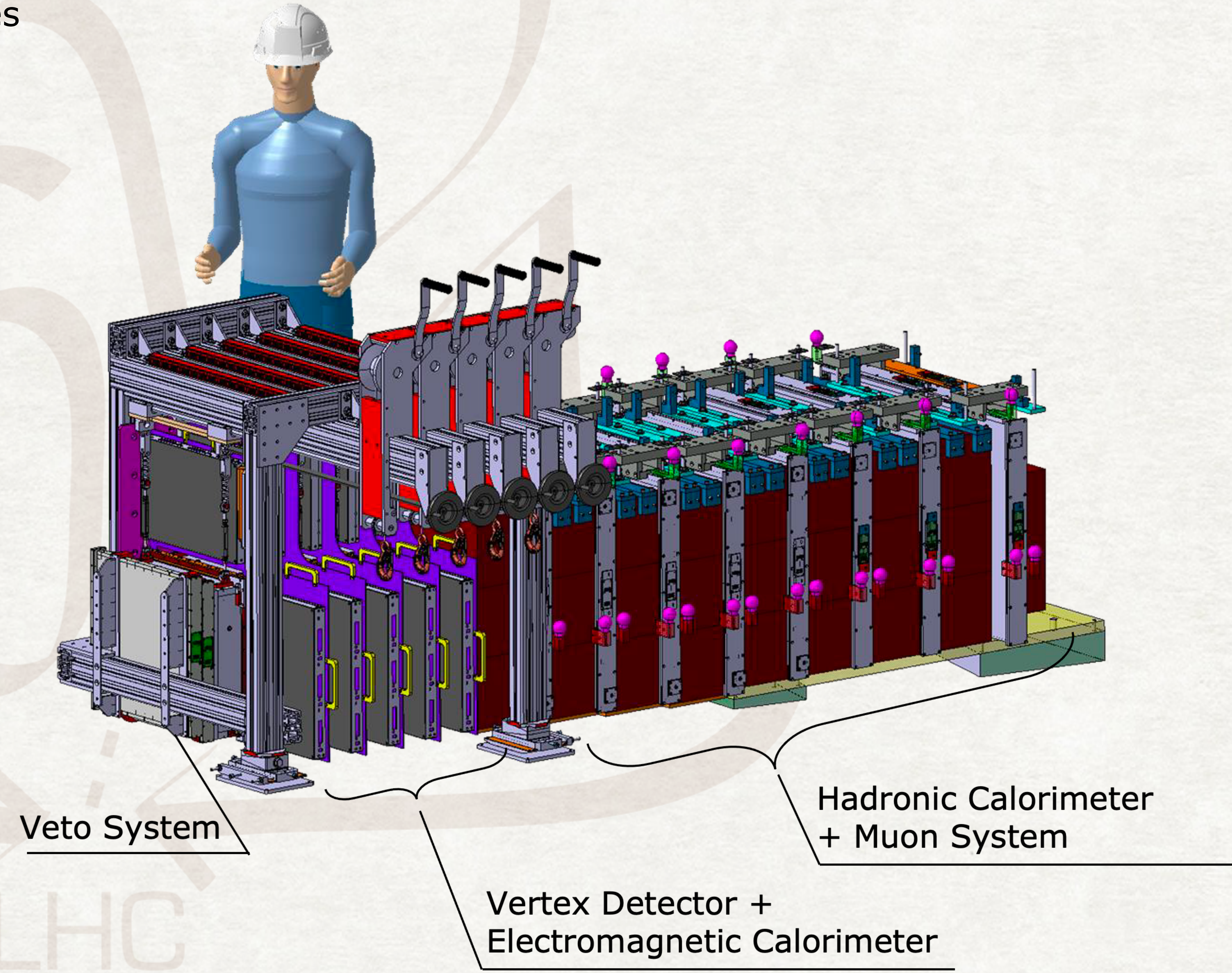
THE SND@LHC CONCEPT

Hybrid detector optimised for the identification of three neutrino flavours and for the detection of feebly interacting particles

VETO SYSTEM:
tag penetrating muons

VERTEX DET + ECAL:
- Emulsion cloud chambers (Emulsion+Tungsten) for neutrino interaction detection
- Scintillating fibers for timing information and energy measurement

MUON SYSTEM + HCAL:
Iron walls interleaved with plastic scintillator planes for fast time resolution and energy measurement



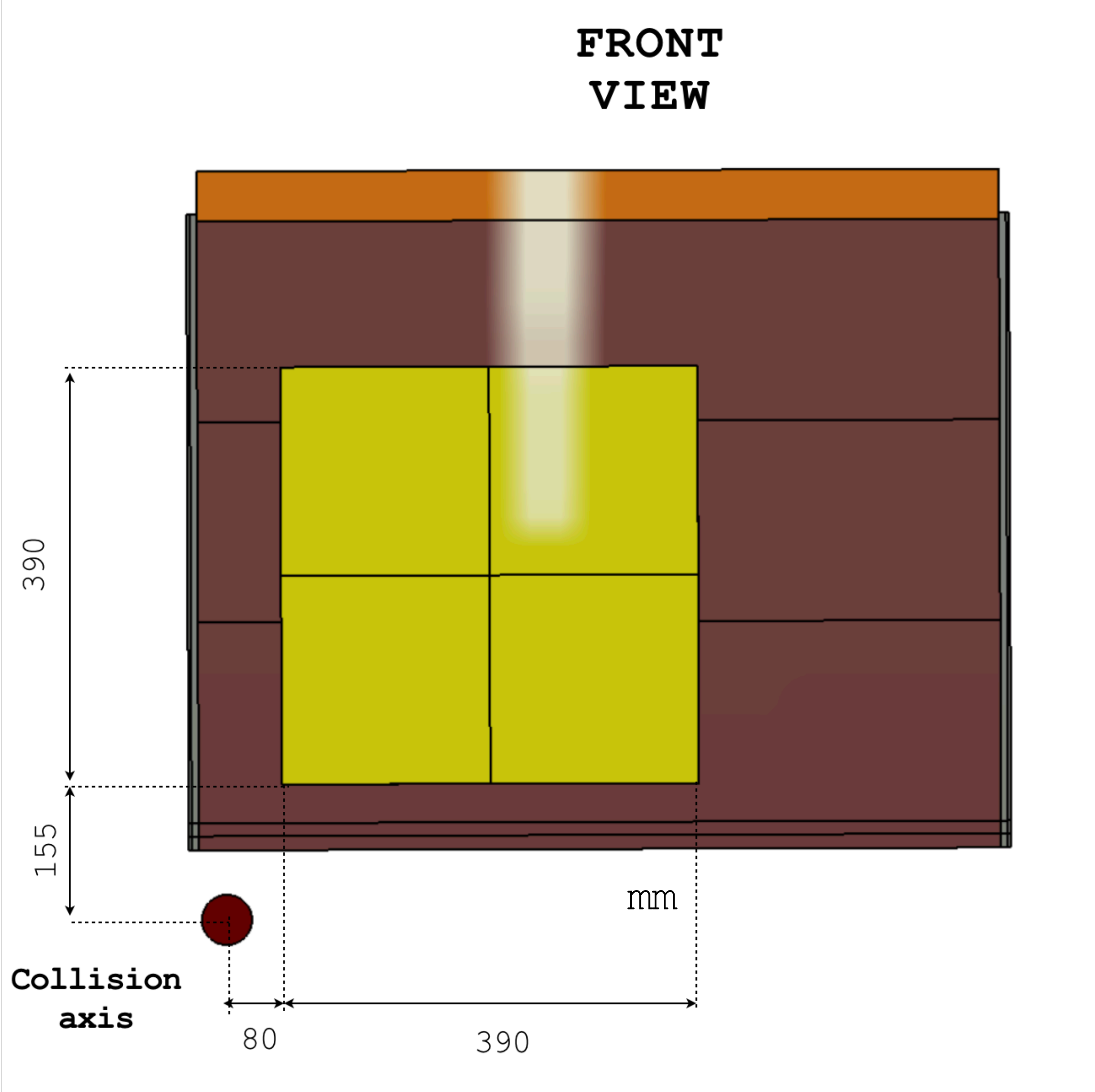
THE DETECTOR LAYOUT

- Angular acceptance: $7.2 < \eta < 8.6$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm²

Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ

Off axis location



Veto plane for charged particles in front of the target region

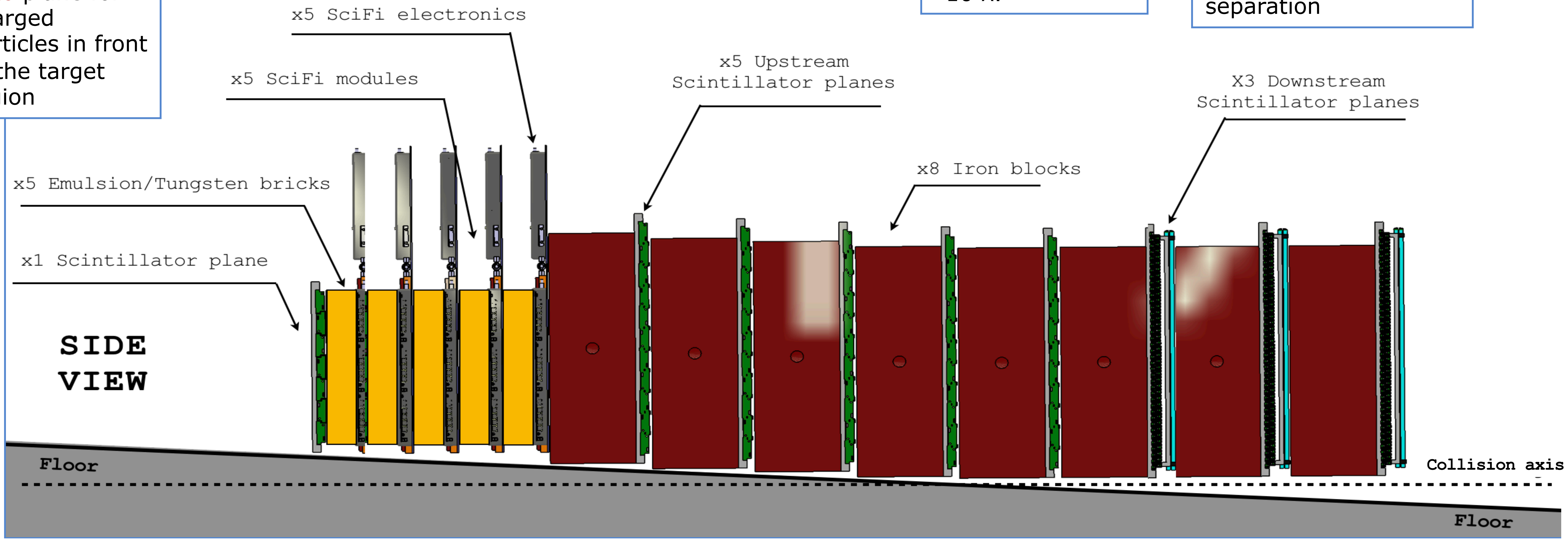
Emulsion Cloud Chamber, emulsion and W absorbers for micrometric accuracy in the detection of τ and FIPs, EM shower energy measurement.

SciFi with timing, provide time stamp to emulsion, records TOF information of events in the target region, track matching with ECCs. EM shower measurement as sampling calorimeter every ~17 X_0.

Muon system – hadronic calorimeter 8 λ, sampling every λ, with target region ~10 λ.

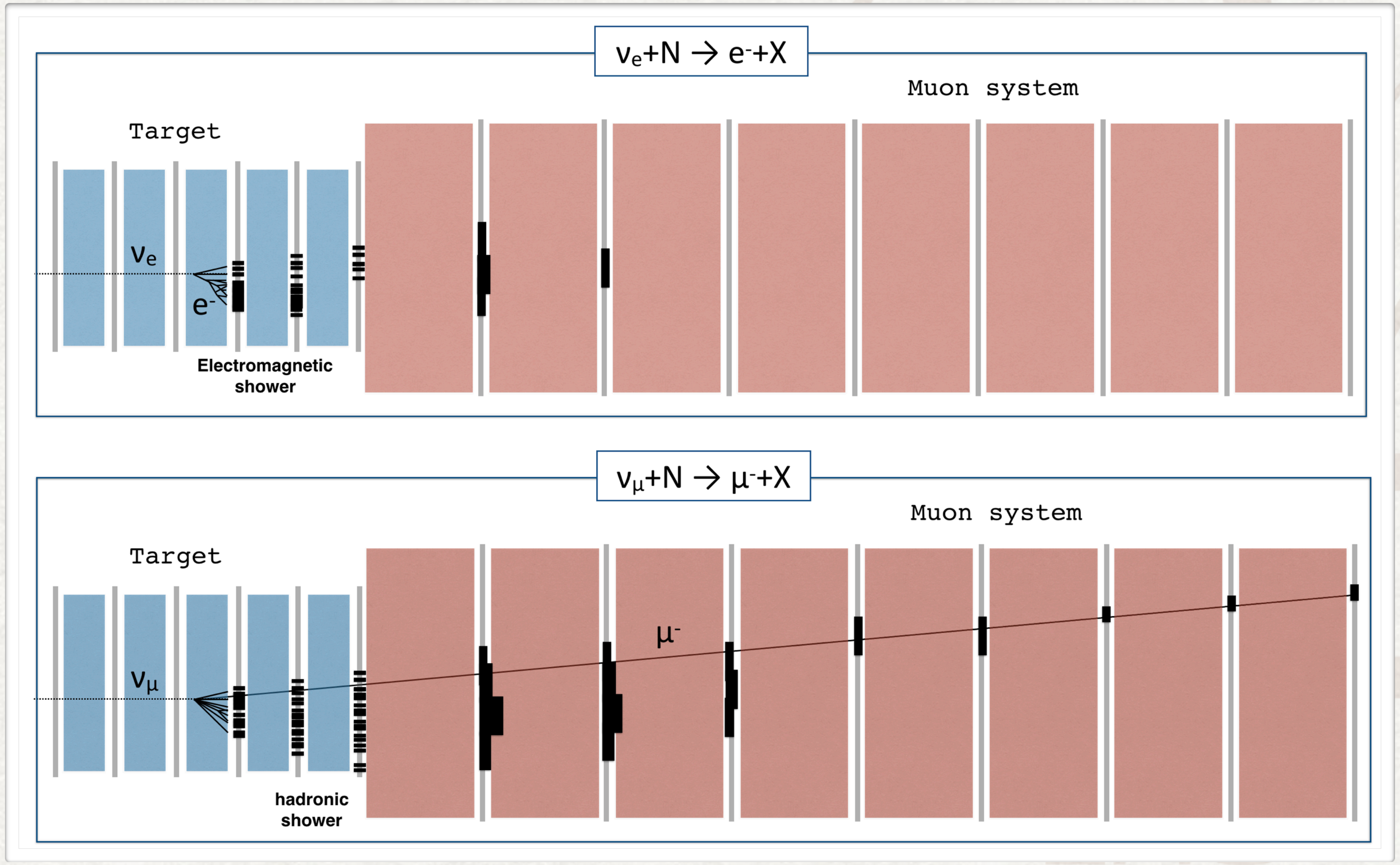
Timing upstream for the muon filtering

Timing downstream, double X-Y planes with higher granularity for muon-hadron separation

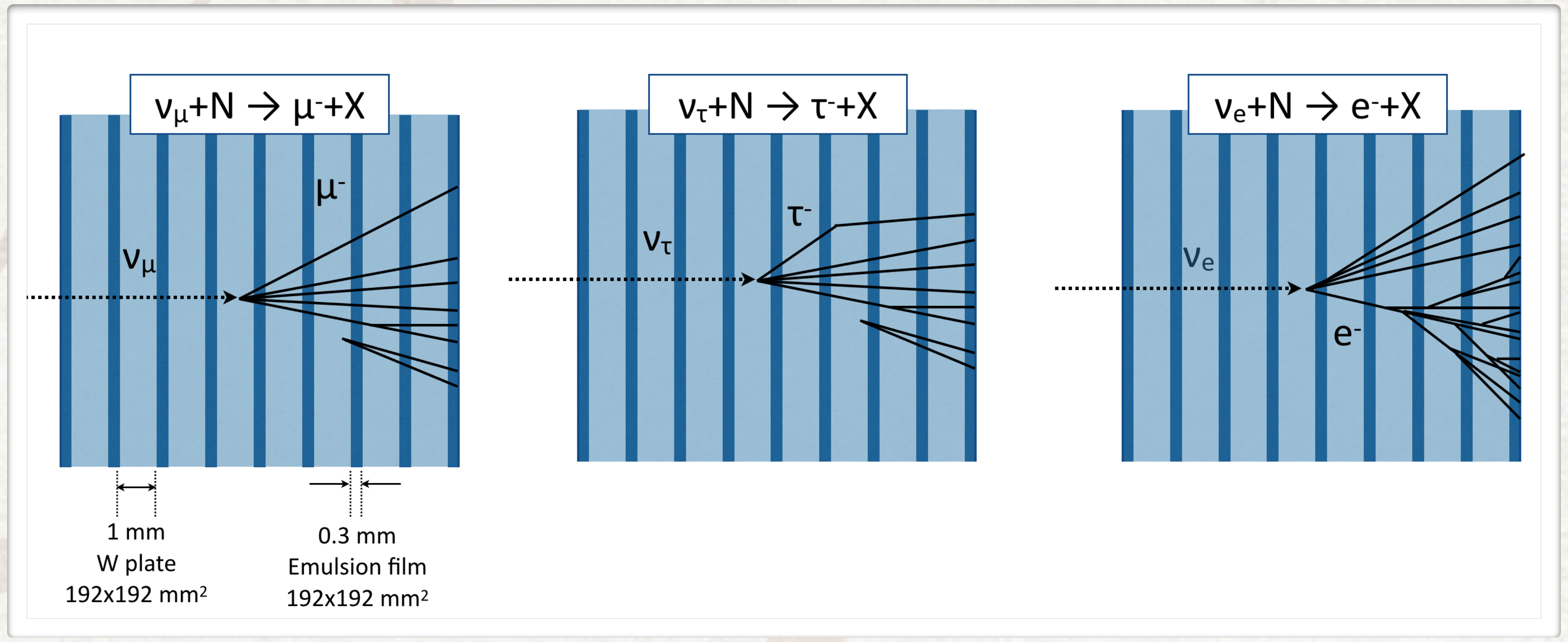


EVENT RECONSTRUCTION

- **FIRST PHASE: electronic detectors**
- Event reconstruction based on Veto, Target Tracker and Muon system
  - Identify neutrino candidates
  - Identify muons in the final state
  - Reconstruction of electromagnetic showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)



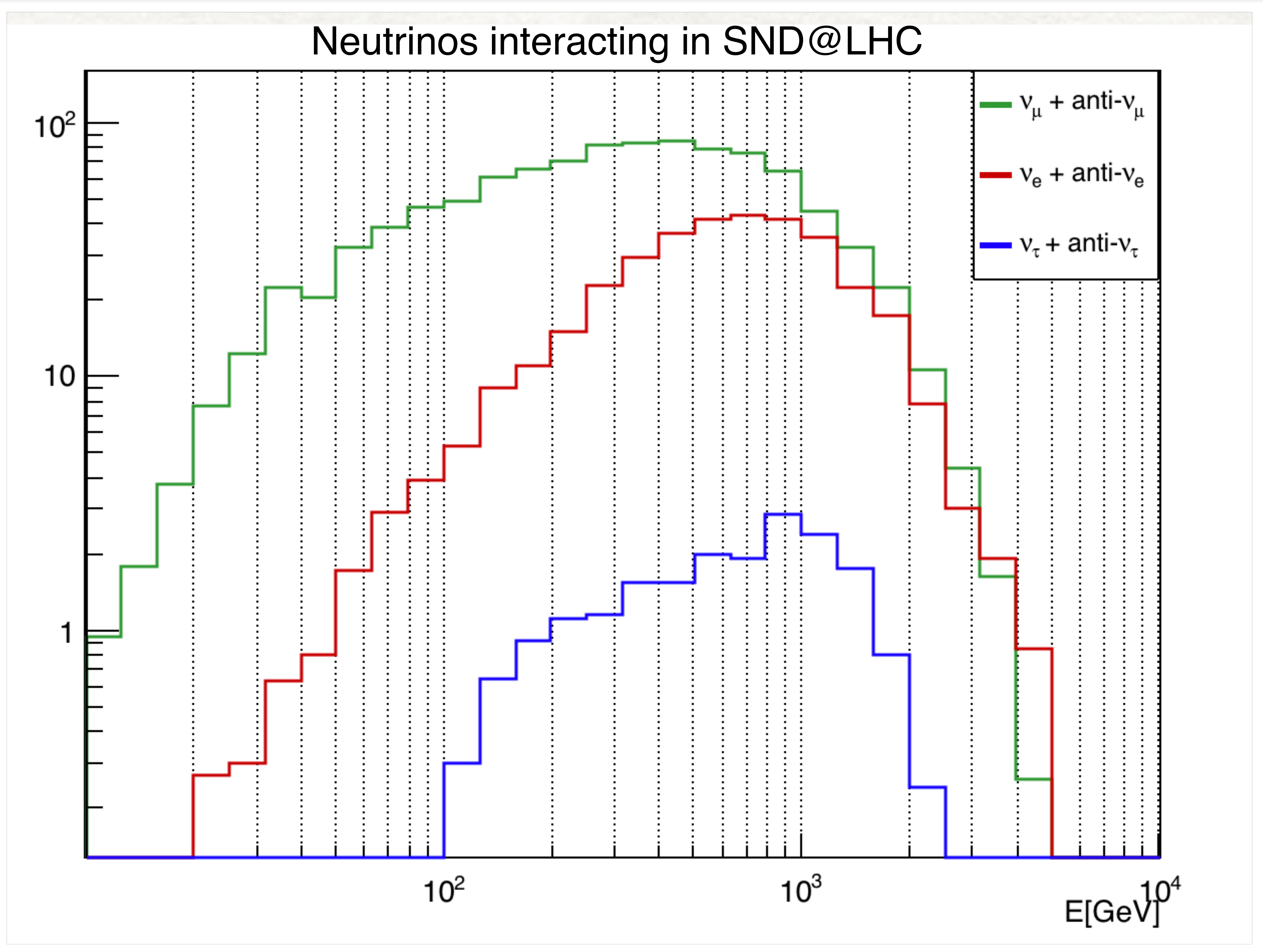
- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement



NEUTRINO EXPECTATIONS

- Expectations in 150 fb^{-1}
- Upward crossing angle

- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in FLUKA
- Particle propagation towards the detector through **FLUKA** model of LHC accelerator



Flavour	Neutrinos in acceptance $\langle E \rangle$ (GeV)	Neutrinos in acceptance Yield	CC neutrino interactions $\langle E \rangle$ (GeV)	CC neutrino interactions Yield	NC neutrino interactions $\langle E \rangle$ (GeV)	NC neutrino interactions Yield
ν_μ	145	2.1×10^{12}	450	730	480	220
$\bar{\nu}_\mu$	145	1.8×10^{12}	485	290	480	110
ν_e	395	2.6×10^{11}	760	235	720	70
$\bar{\nu}_e$	405	2.8×10^{11}	680	120	720	44
ν_τ	415	1.5×10^{10}	740	14	740	4
$\bar{\nu}_\tau$	380	1.7×10^{10}	740	6	740	2
TOT		4.5×10^{12}		1395		450

NEUTRINO PHYSICS PROGRAM IN RUN 3

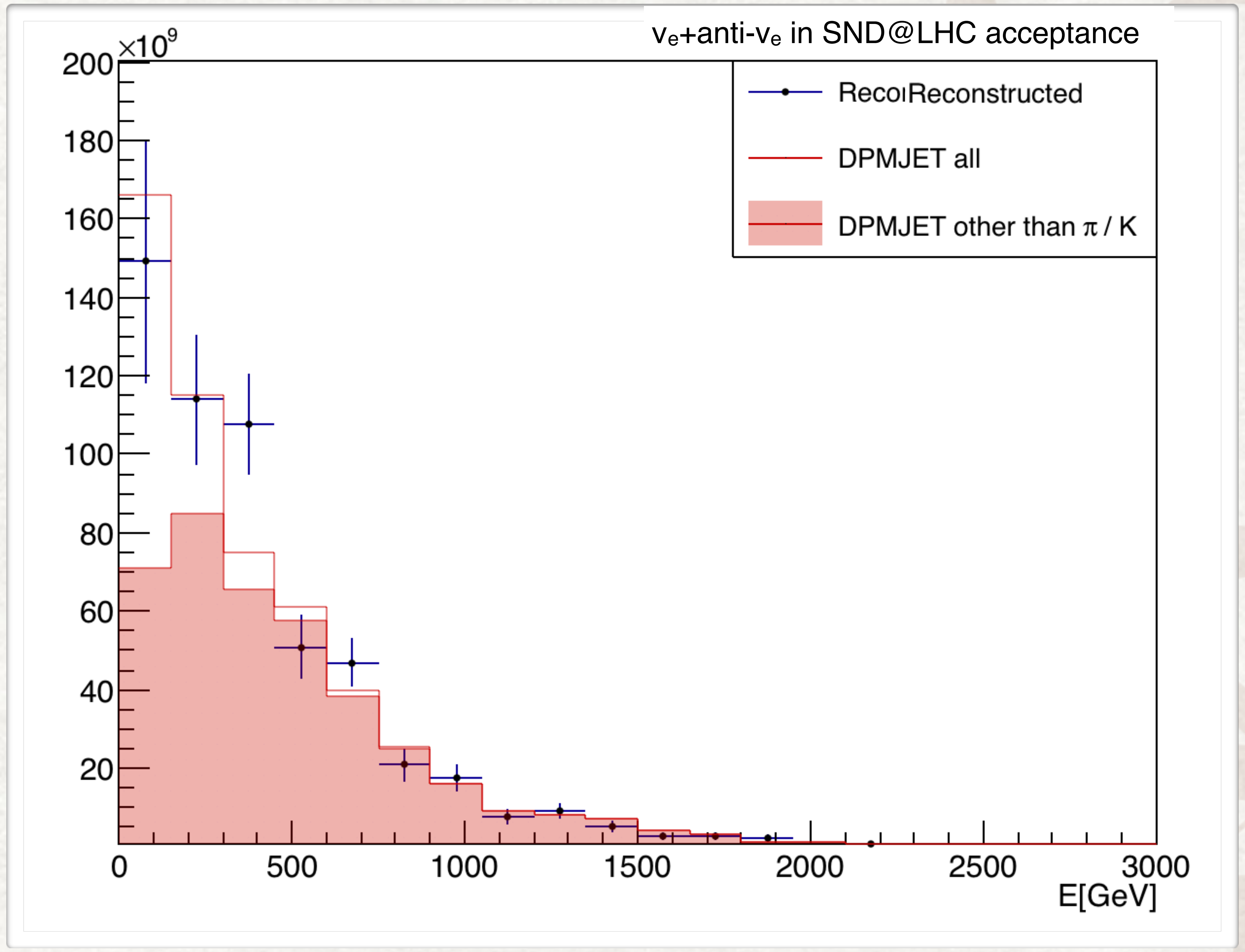
1. Measurement of the $pp \longrightarrow \nu_e X$ cross-section
2. Heavy flavour production in pp collisions
3. Lepton flavour universality in neutrino interactions
4. Measurement of the NC/CC ratio

1. MEASUREMENT OF $pp \rightarrow \nu_e X$ CROSS-SECTION

2. CHARMED HADRON PRODUCTION

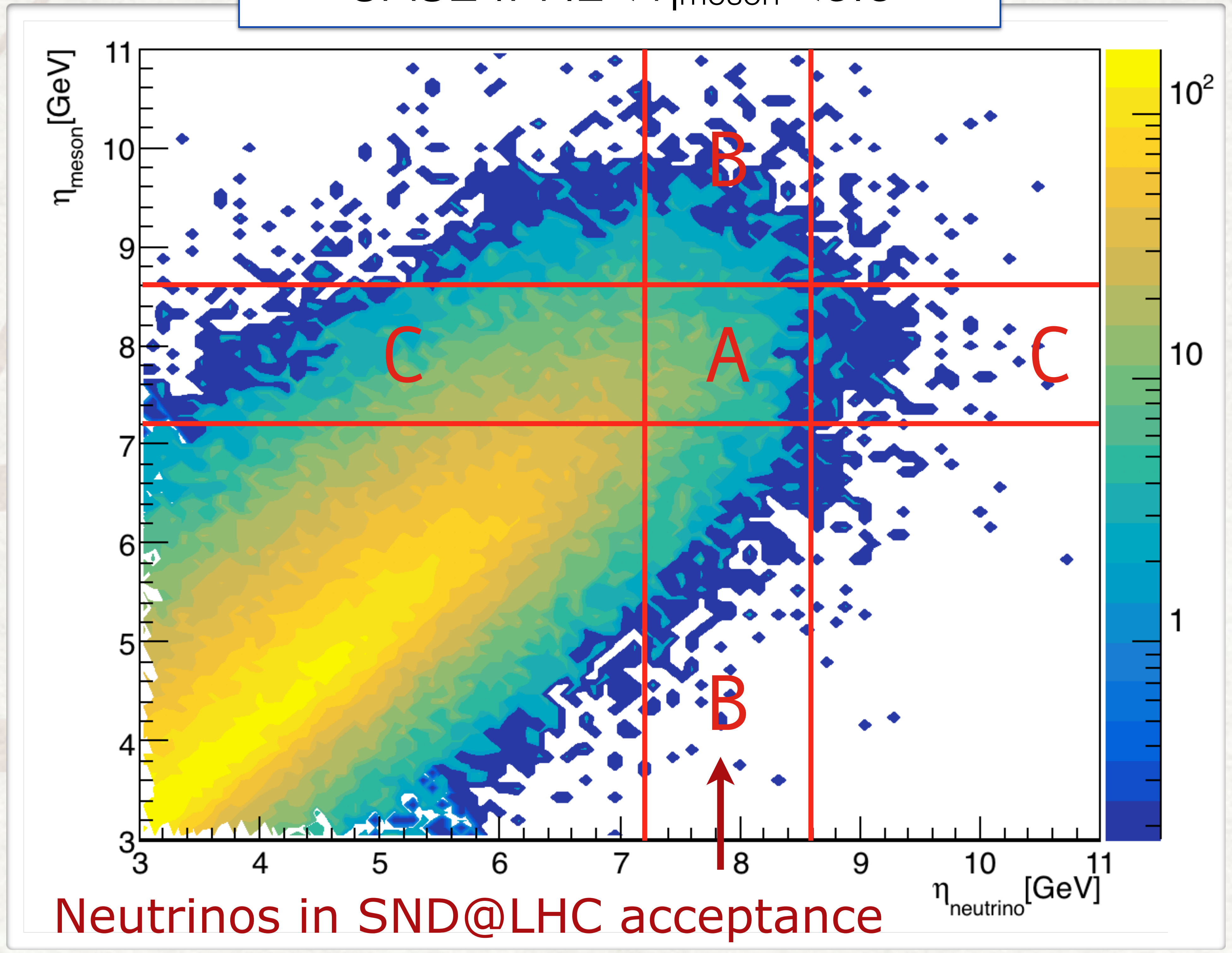
- Simulation predicts that 90% ν_e+anti-ν_e come from the decay of charmed hadrons
- Electron neutrinos can be used as a probe of the production of charm in the relevant pseudo-rapidity range after unfolding the instrumental effects

- Reconstructed spectrum of ν_e+anti-ν_e flux in SND@LHC acceptance



- Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron

CASE I: $7.2 < \eta_{meson} < 8.6$

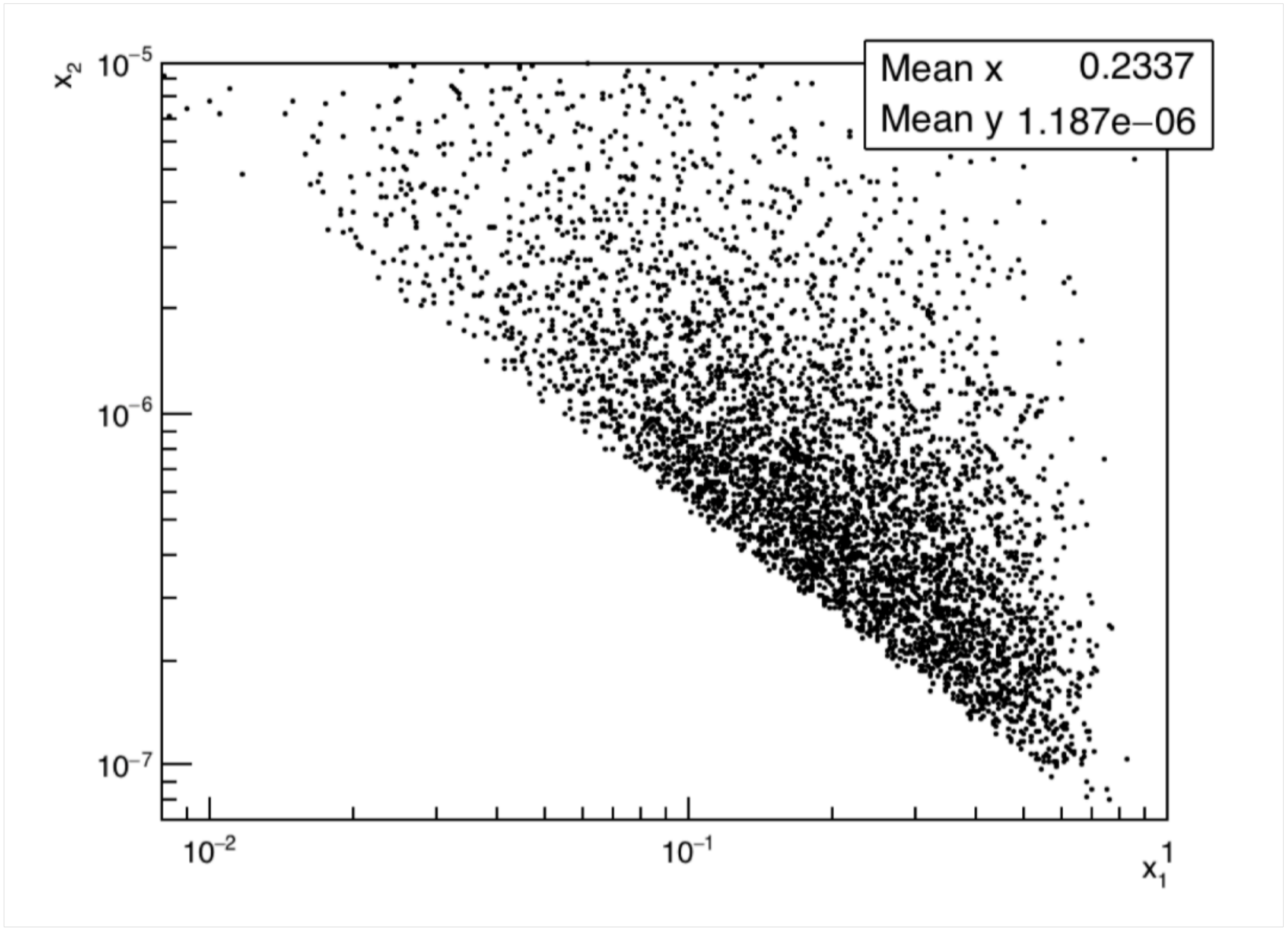


QCD MEASUREMENTS

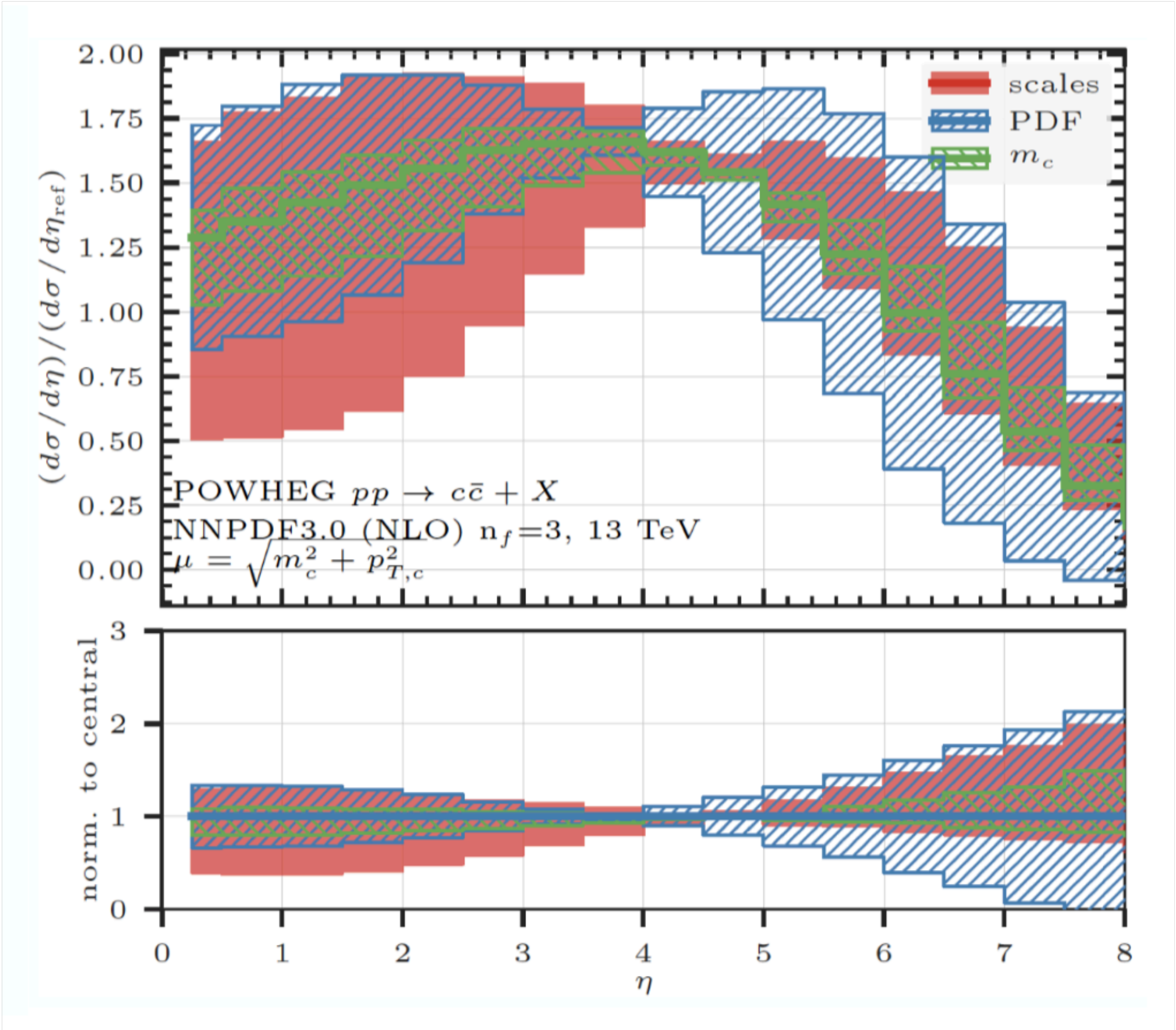
Extraction of gluon PDF in very small x-region relevant for:
- Future Circular Colliders
- predictions of high energy neutrinos production in cosmic rays

The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering

Average lowest momentum fraction: 10^{-6}



Correlation between x1 and x2 for events in the SND@LHC acceptance



Ratio between the cross-section measurements at different energies and pseudo-rapidities

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

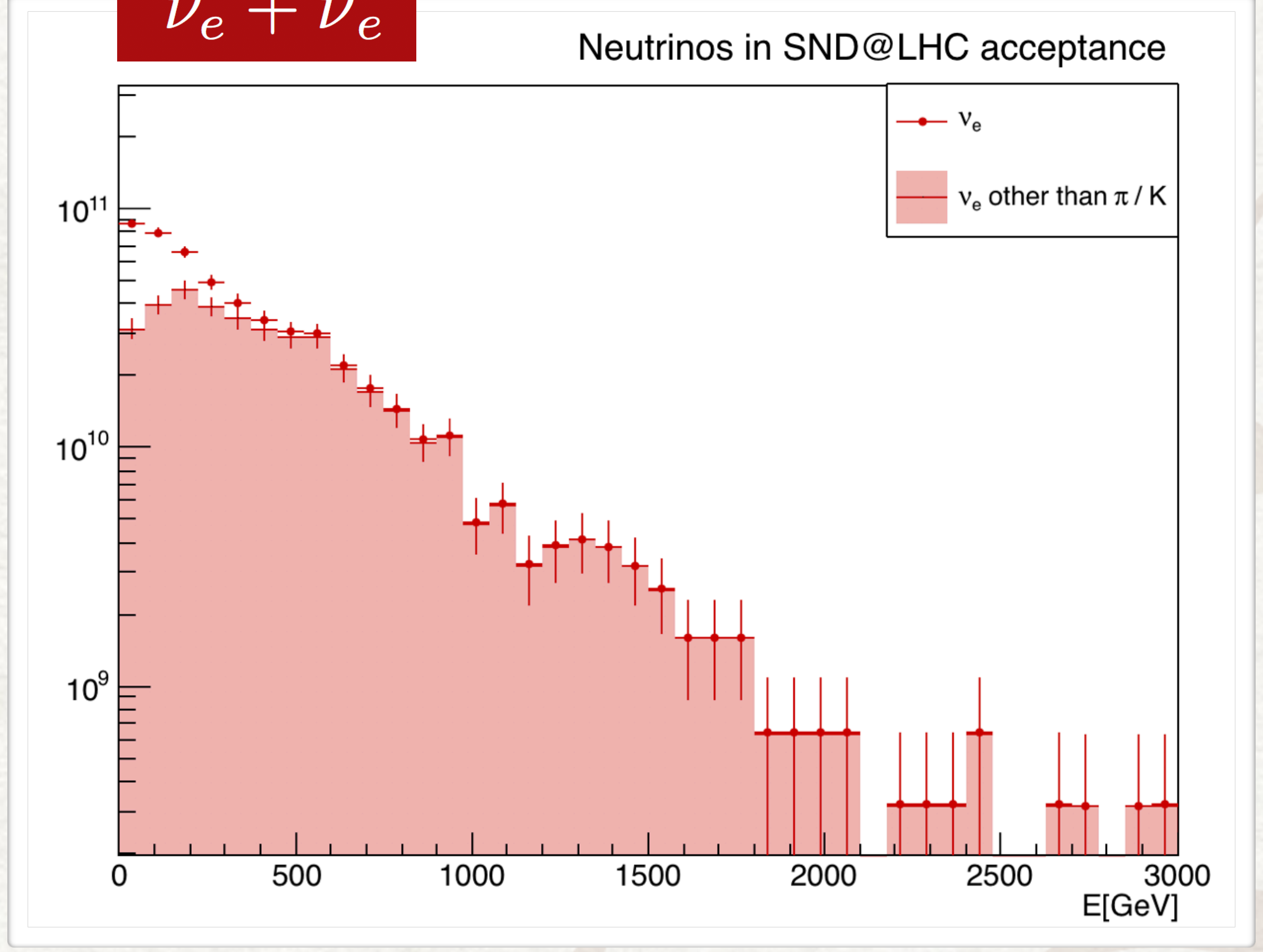
$\eta_{ref} = 4.5$

Reduction of scale uncertainties
Constraint the PDF with data

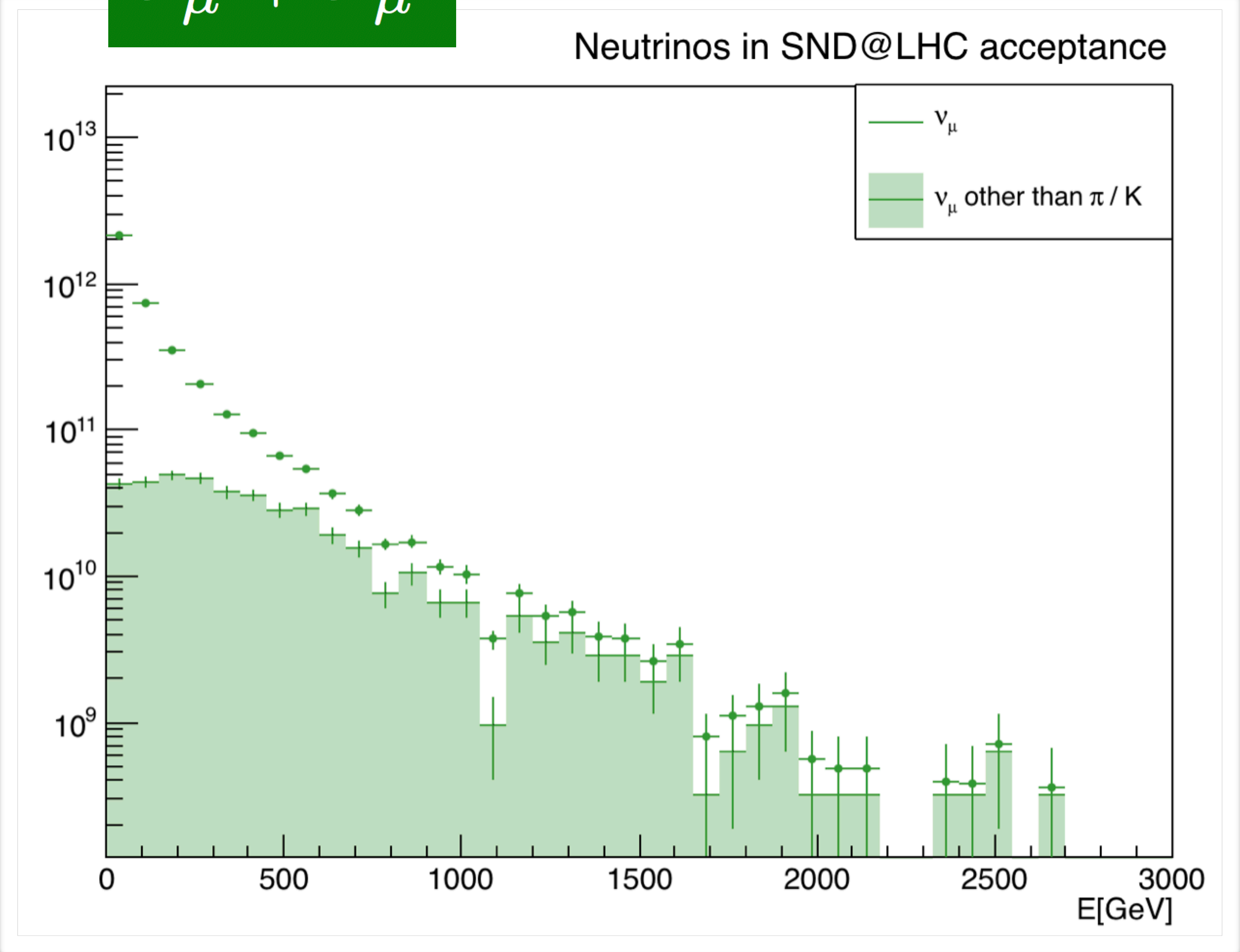
3. LEPTON FLAVOUR UNIVERSALITY TEST

- The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality (LFU)

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



$\nu_\mu + \overline{\nu}_\mu$



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

- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

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

contamination from π/k

- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV

4. MEASUREMENT OF NC/CC RATIO

- Lepton identification for the three different flavors allows to distinguish CC to NC interaction at SND@LHC
- If differential neutrino and anti-neutrino fluxes are equal, the NC/CC ratio can be written as

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

- In case of DIS, *P* can be written as

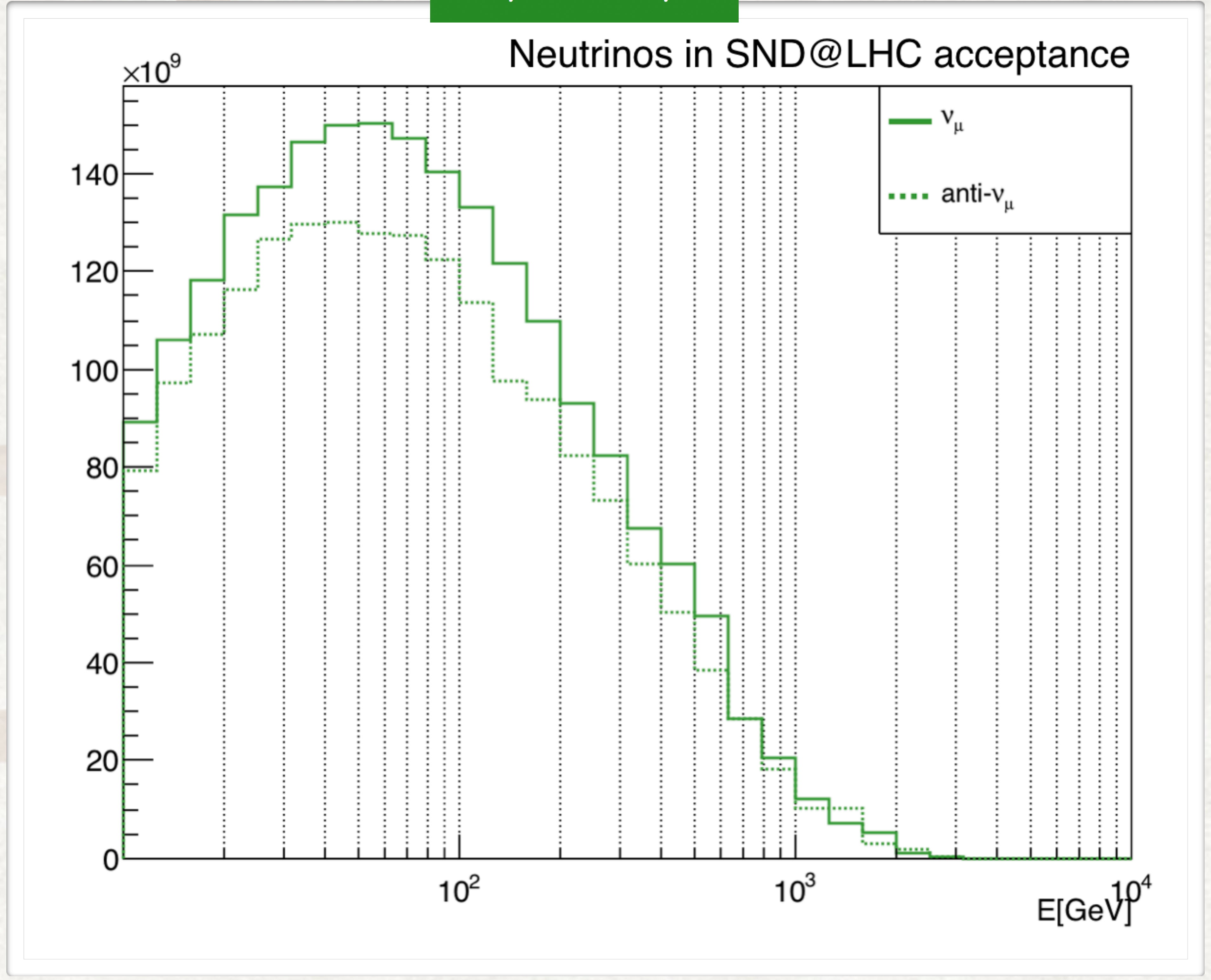
$$P = \frac{1}{2}\left\{1 - 2\sin^2\theta_W + \frac{20}{9}\sin^4\theta_W - \lambda(1 - 2\sin^2\theta_W)\sin^2\theta_W\right\}$$

For a Tungsten target λ=0.04

Rept.Prog.Phys. 79 (2016) 12, 124201

- P measurement used as an internal consistency check

ν_μ vs $\bar{\nu}_\mu$



NEUTRINO PHYSICS IN RUN 3

- Summary of SND@LHC performances

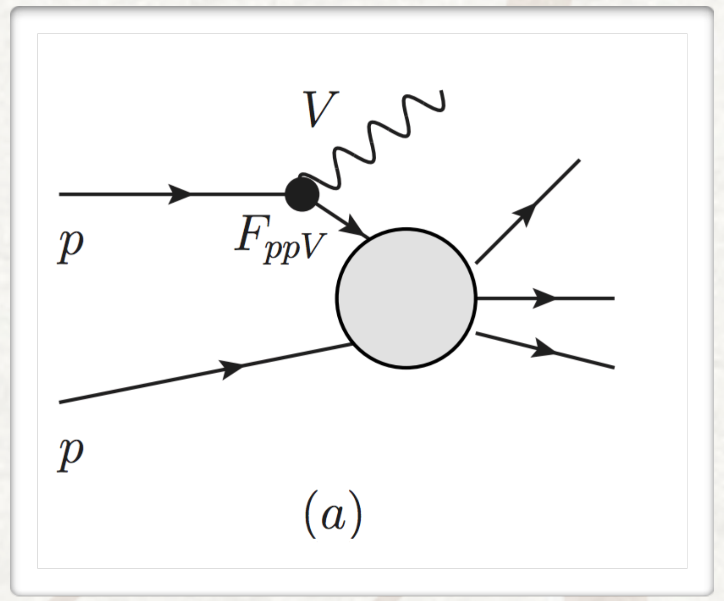
Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	20%
ν_e/ν_μ ratio for LFU test	10%	10%
Measurement of NC/CC ratio	5%	10%

FLEEBLY INTERACTING PARTICLES

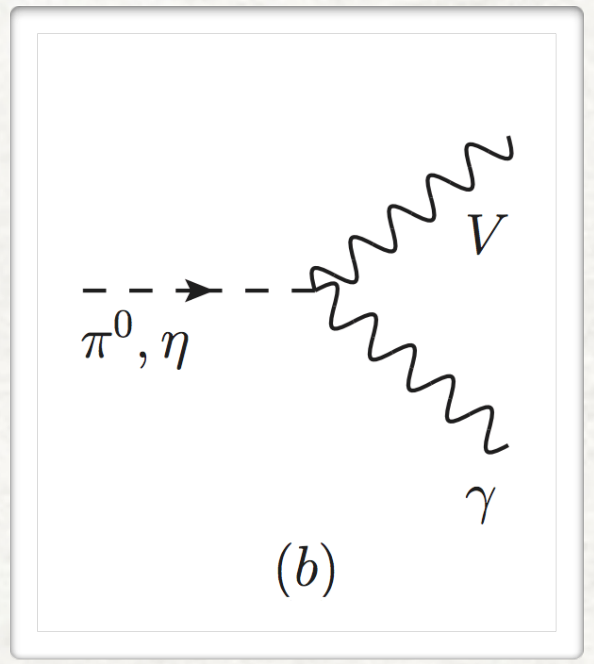
- SND@LHC experiment can explore a large variety of Beyond Standard Model (BSM) scenarios describing Hidden Sector

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

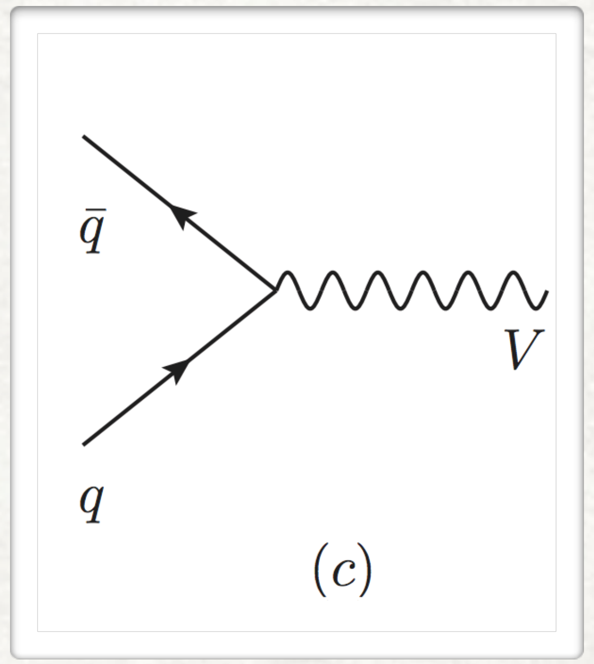
$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),$$



Proton bremsstrahlung

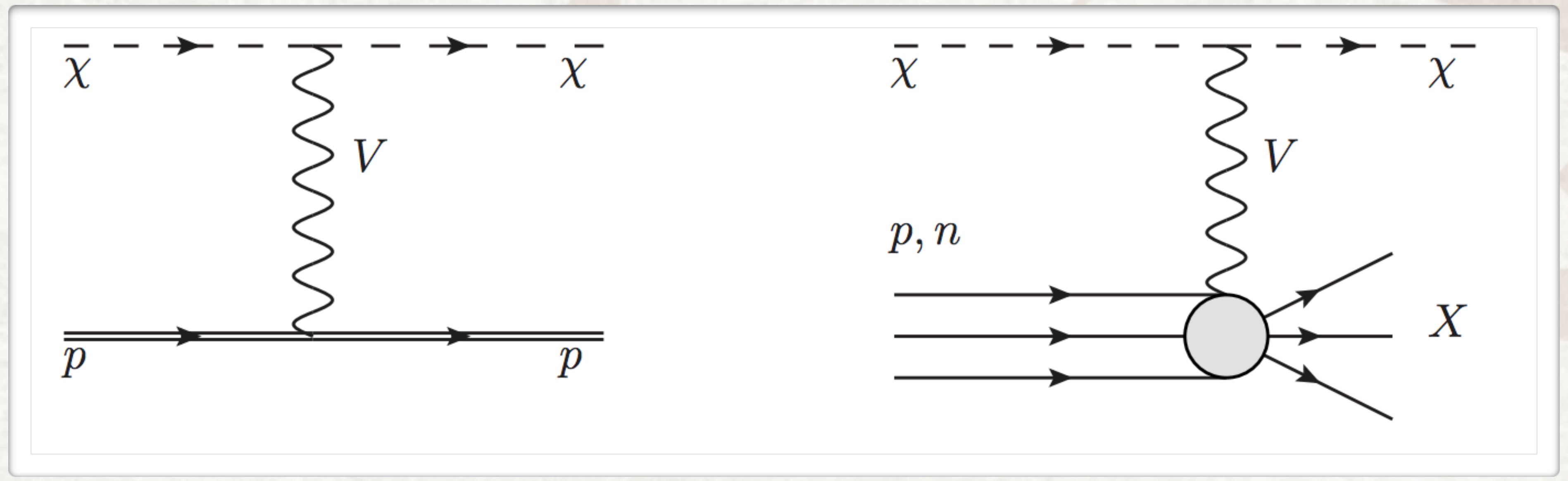


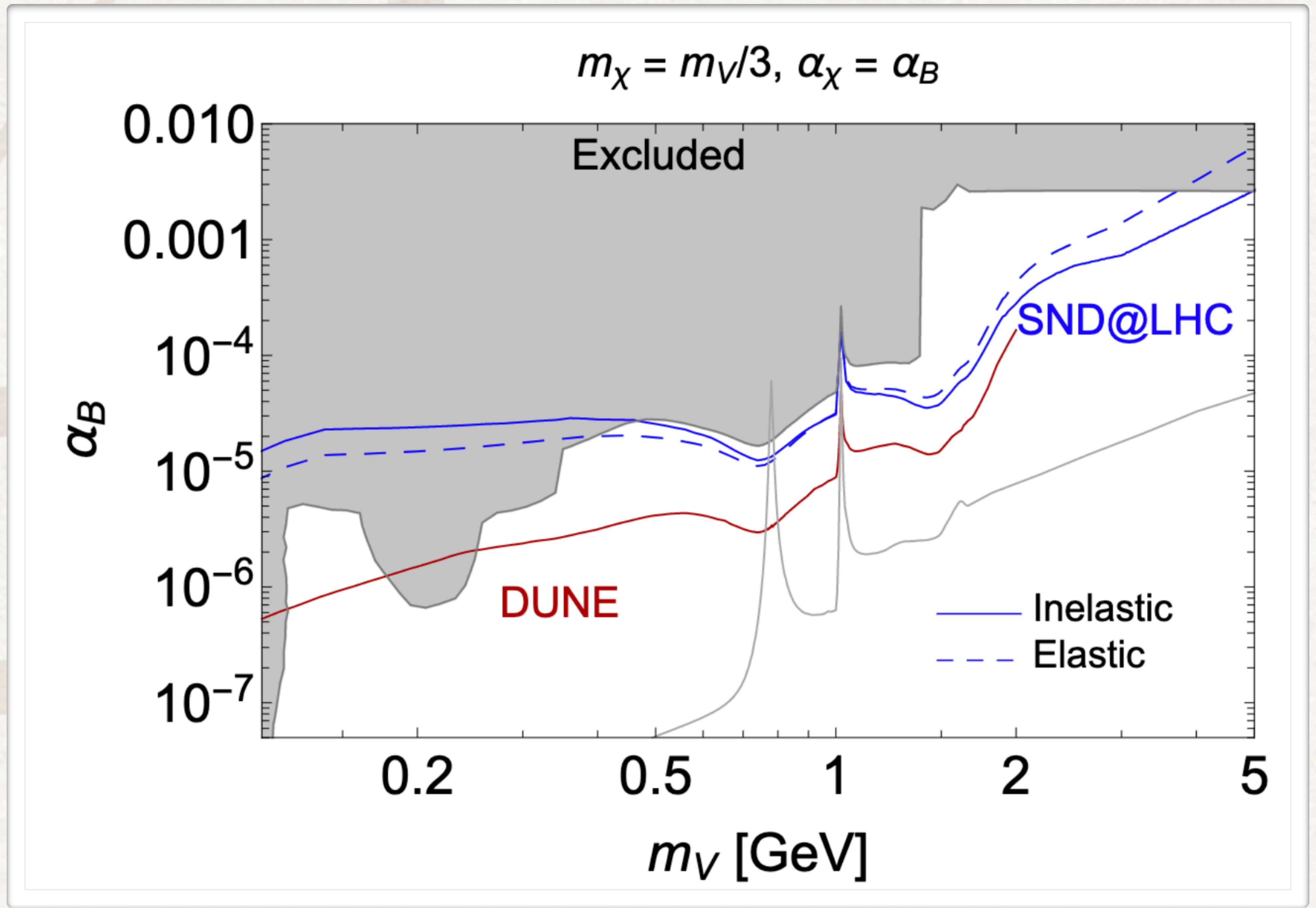
Meson decay



Drell-Yan process

Detection: χ elastic/inelastic scattering off nucleons of the target

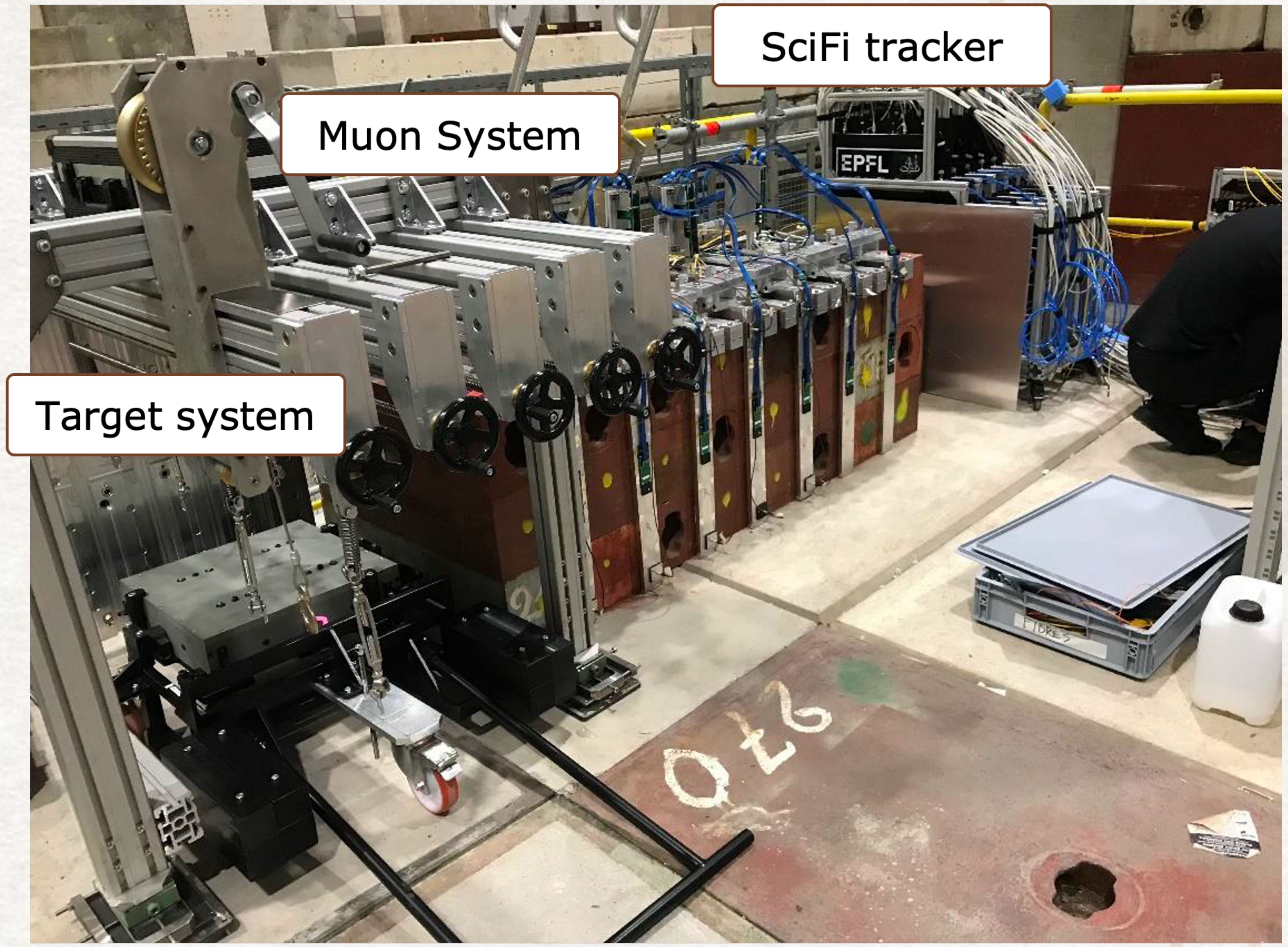


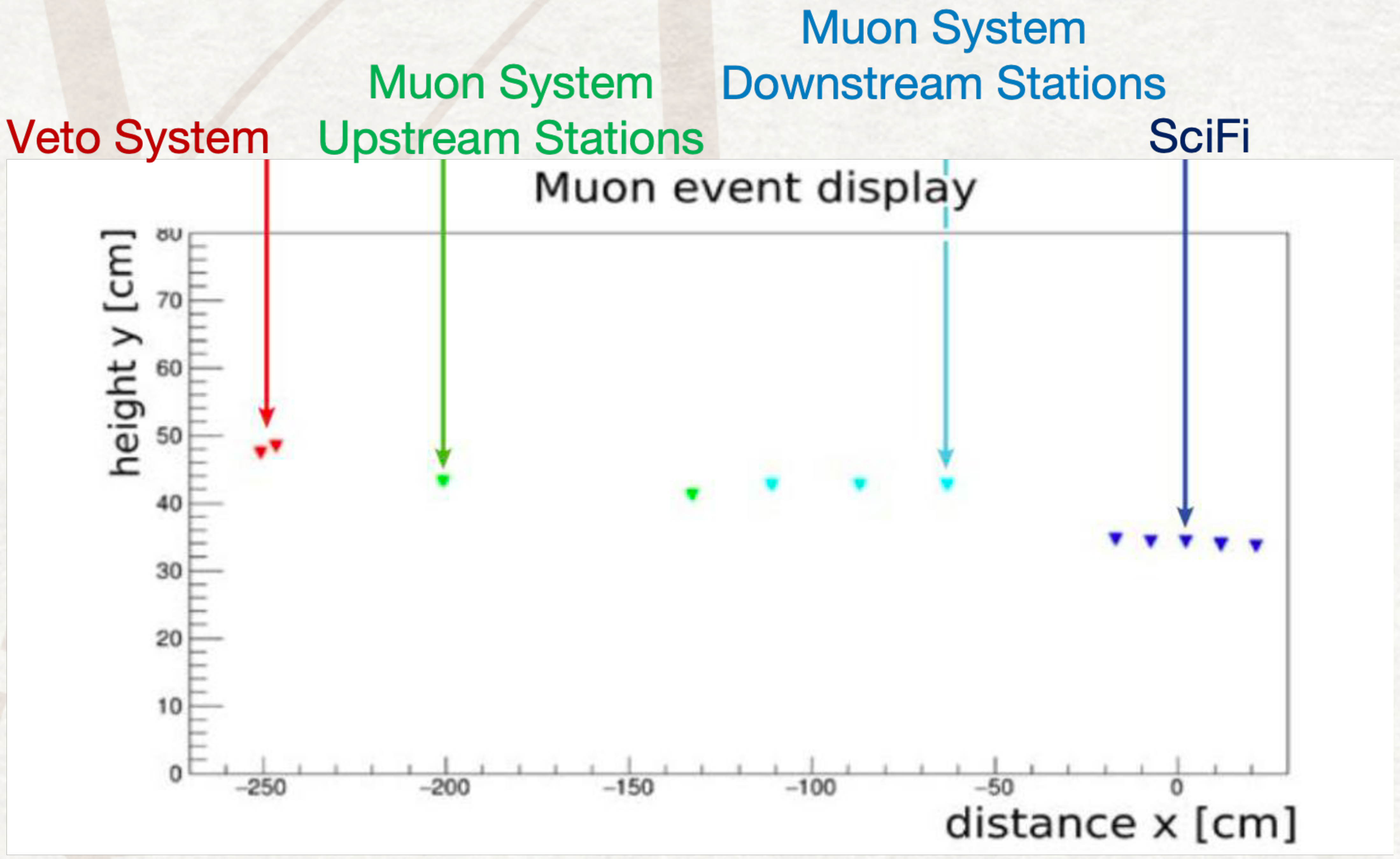


DETECTOR COMMISSIONING ON SURFACE

Sept 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

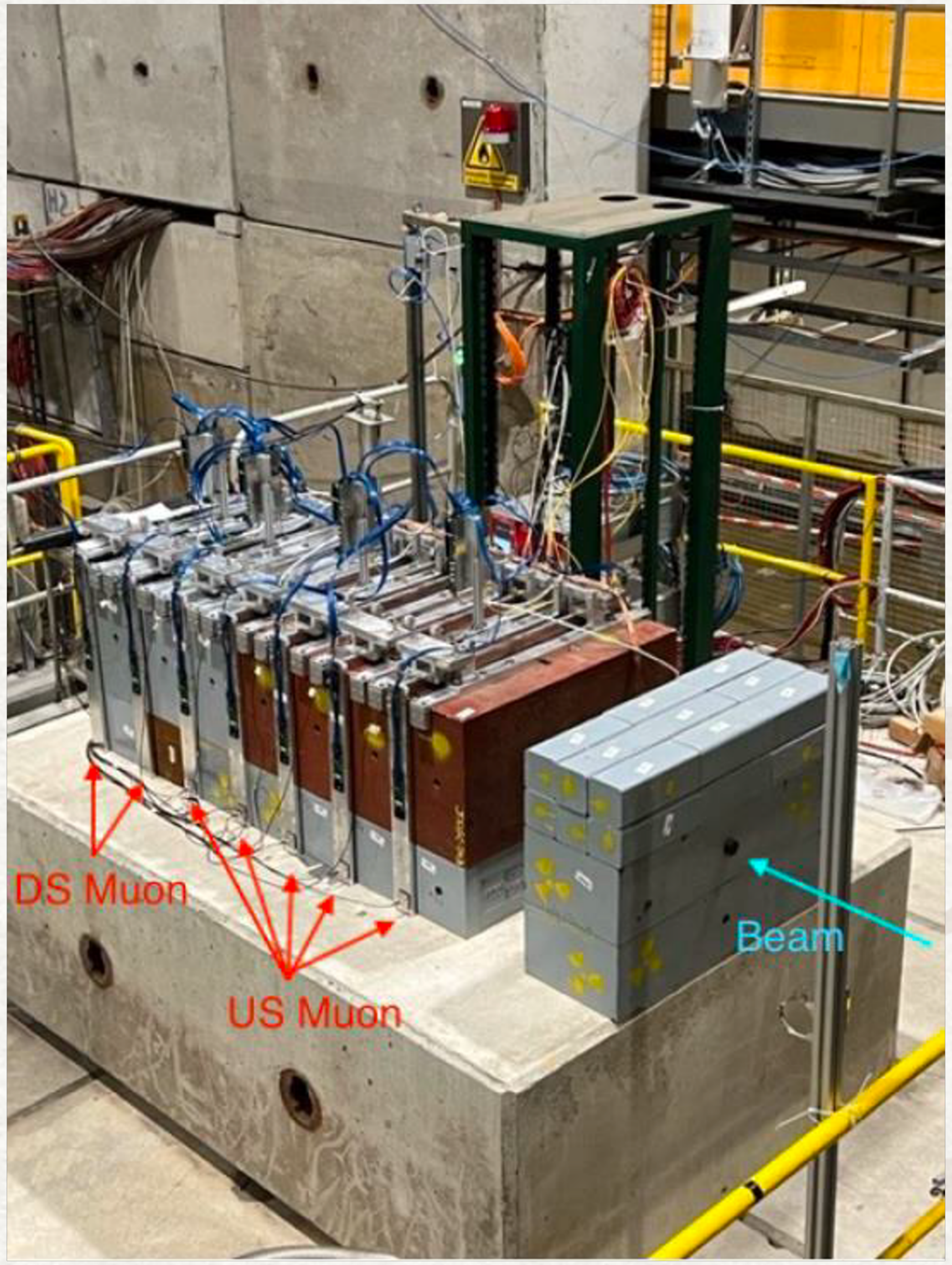




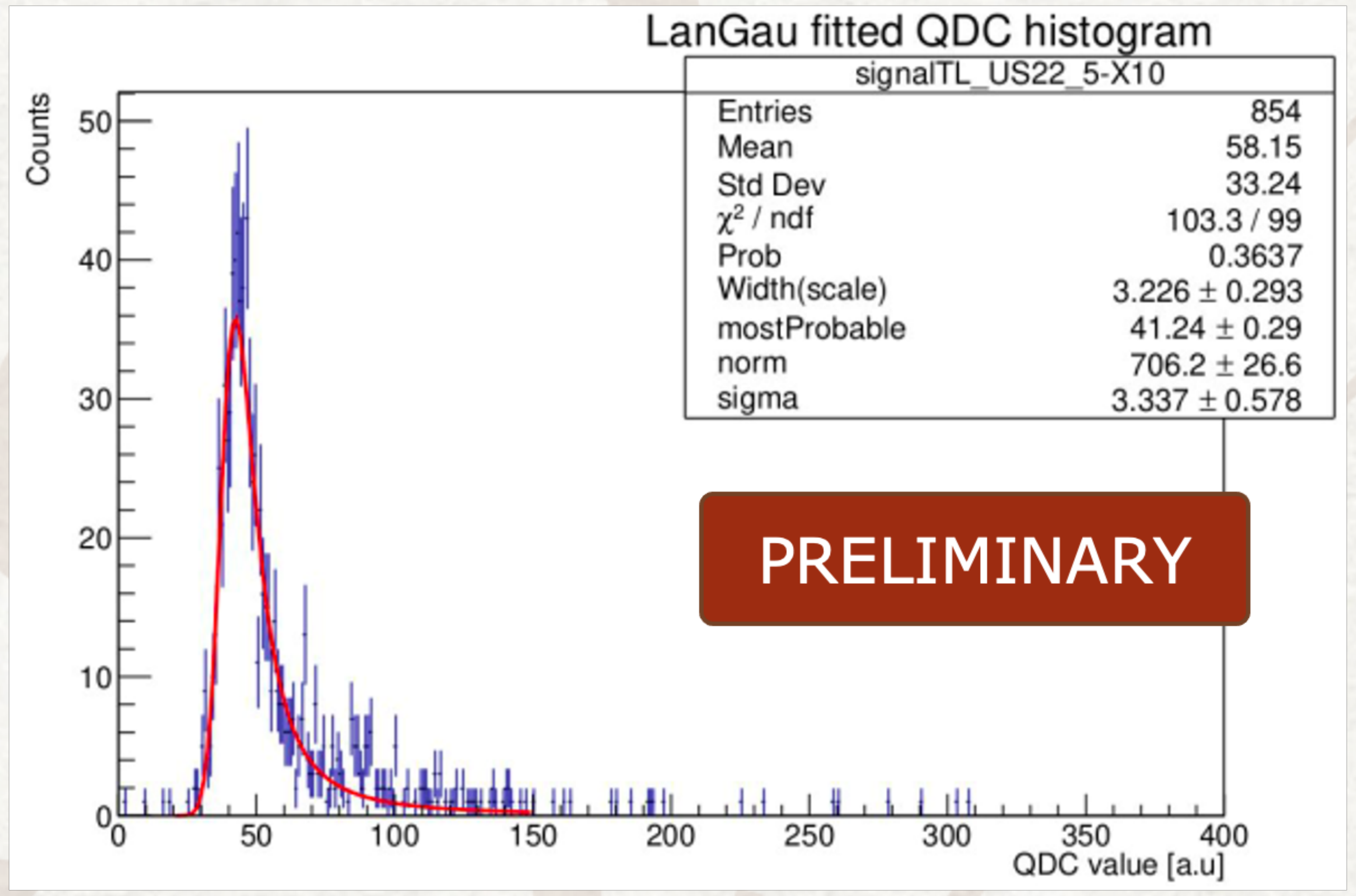
TEST BEAM WITH MUON SYSTEM

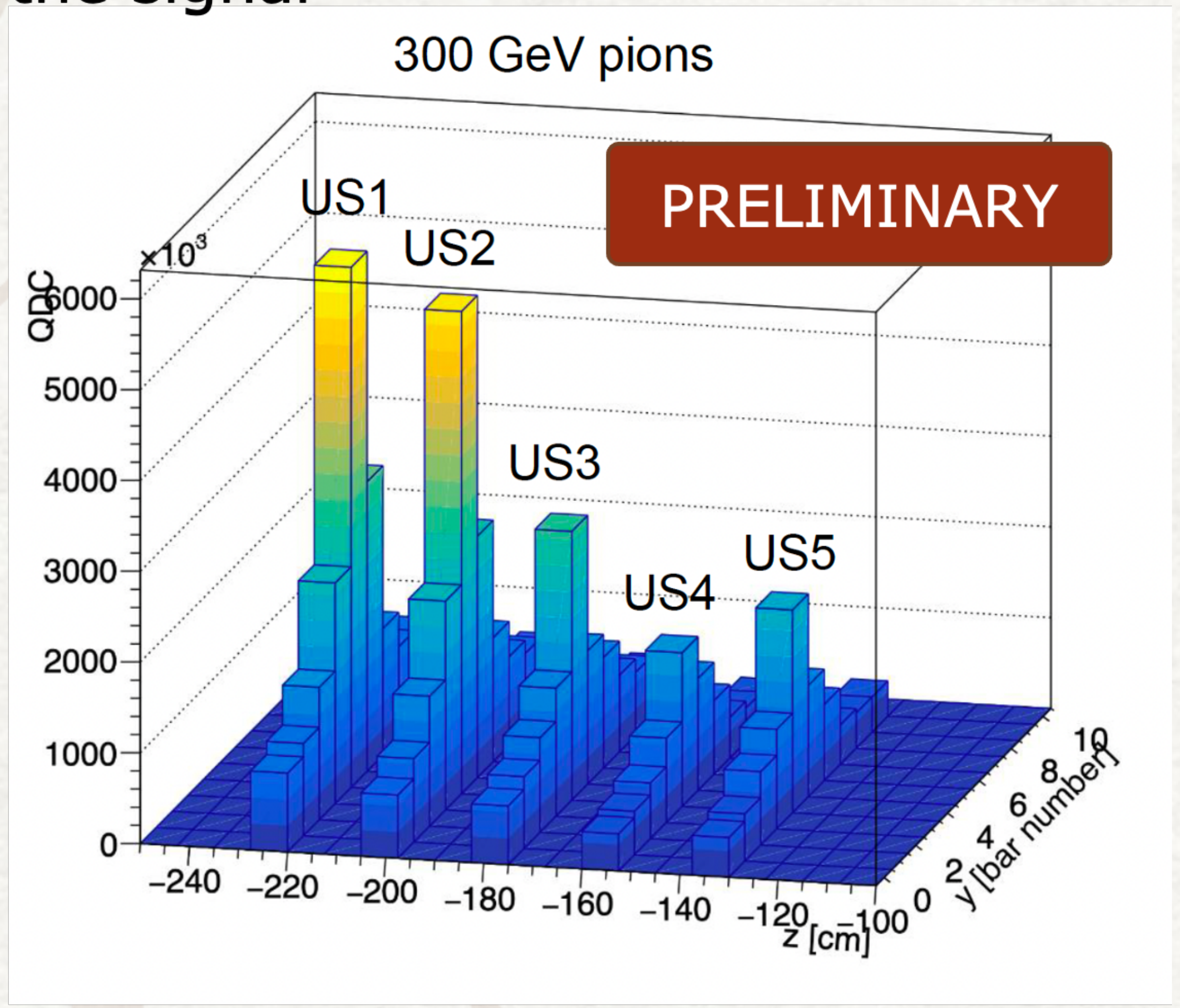
Oct 2021

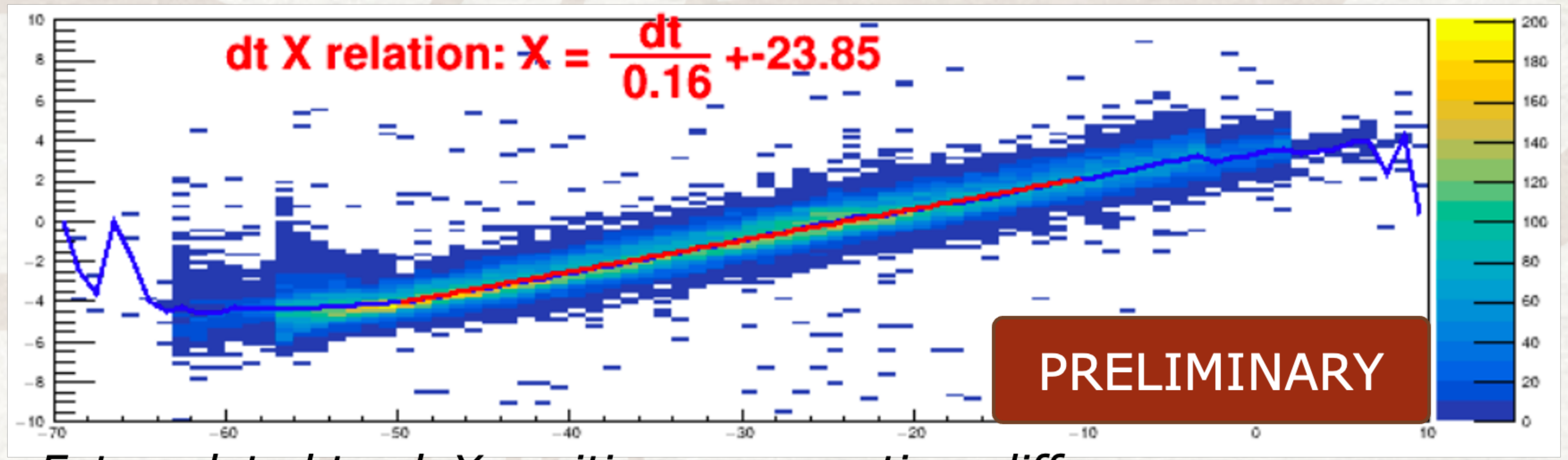
- Installation of the whole muon system at H8 in the North Area
- Energy calibration with 140, 180 240, 300 GeV pion beam



First glance at the signal







Extrapolated track X position vs mean time difference between left and right side

Position resolution:
σ_x =3.7 cm

DETECTOR INSTALLATION IN TI18

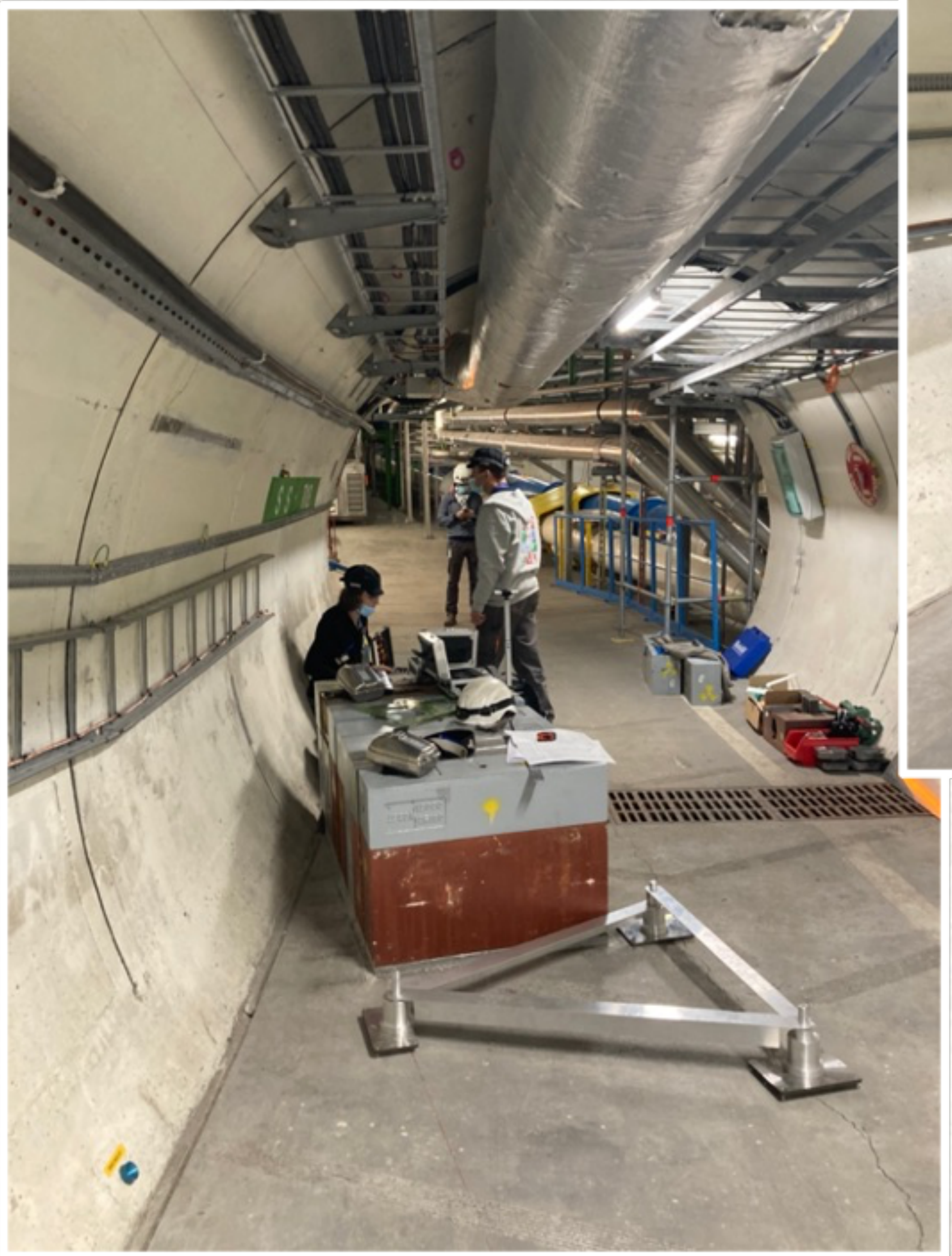
- Installation in TI18 started on November 1st
- Full detector installed on December 3rd


September 2021


December 2021

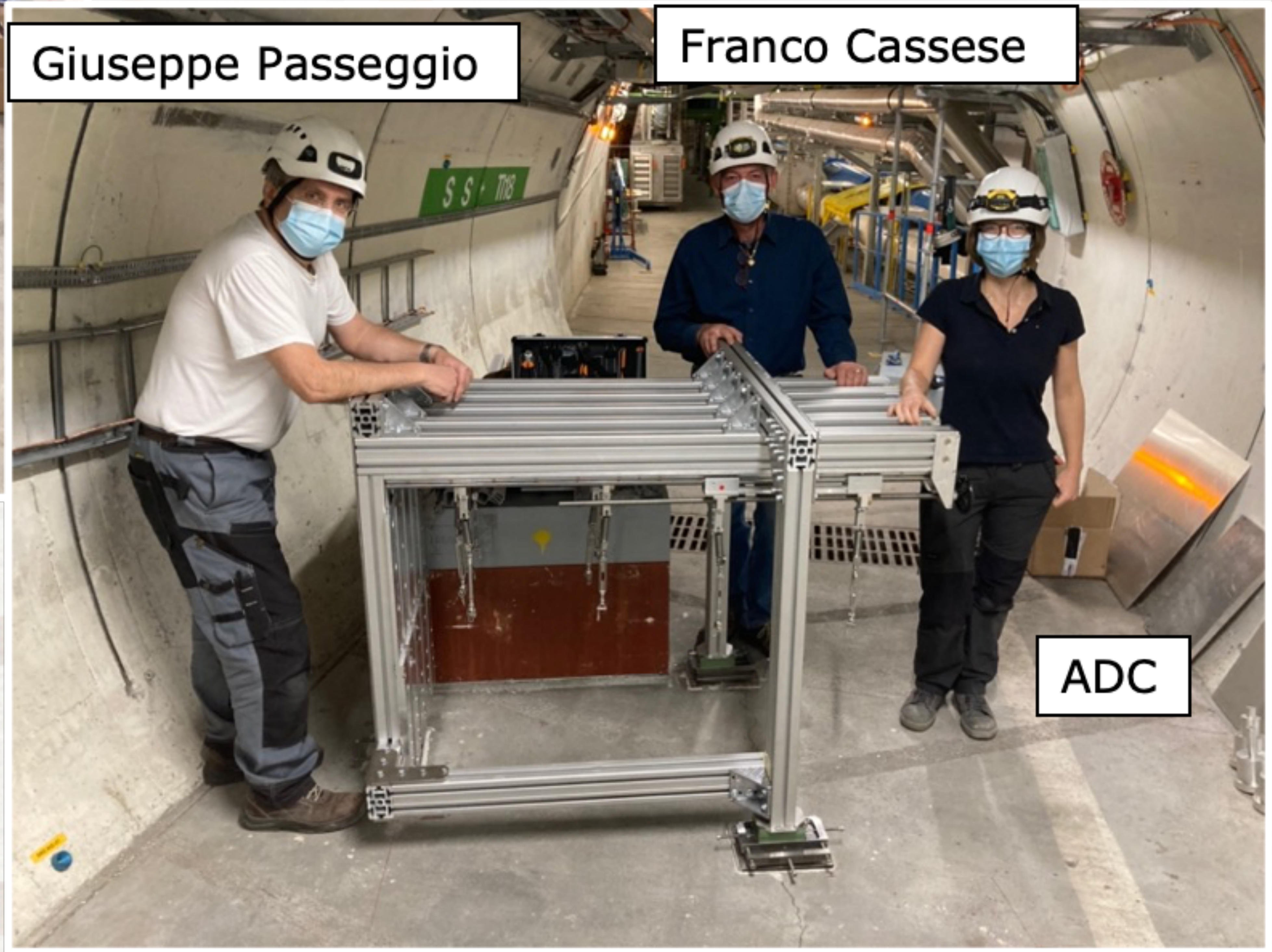
MECHANICAL STRUCTURE IN TI18

First detector element installed in TI18 after the positioning of Iron walls



Positioning of the feet in TI18
and grouting with Survey Team

Target structure installation



Target structure in its final configuration

TARGET TRANSPORTATION

Test of the complete procedure of (empty) wall transportation with the trolley

At the entrance of blg 2155 (on surface)

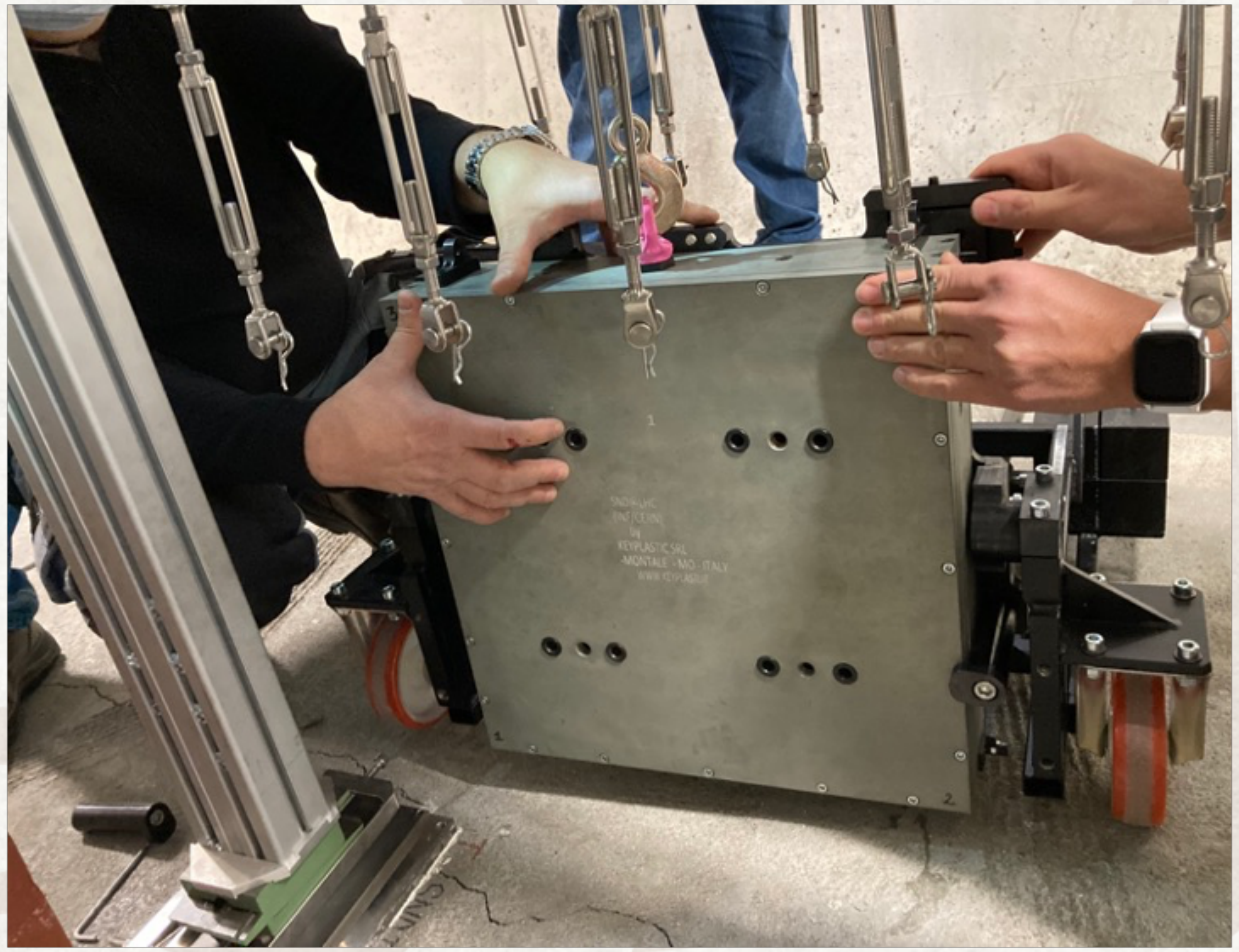
In the LHC tunnel

Passage under LHC magnets

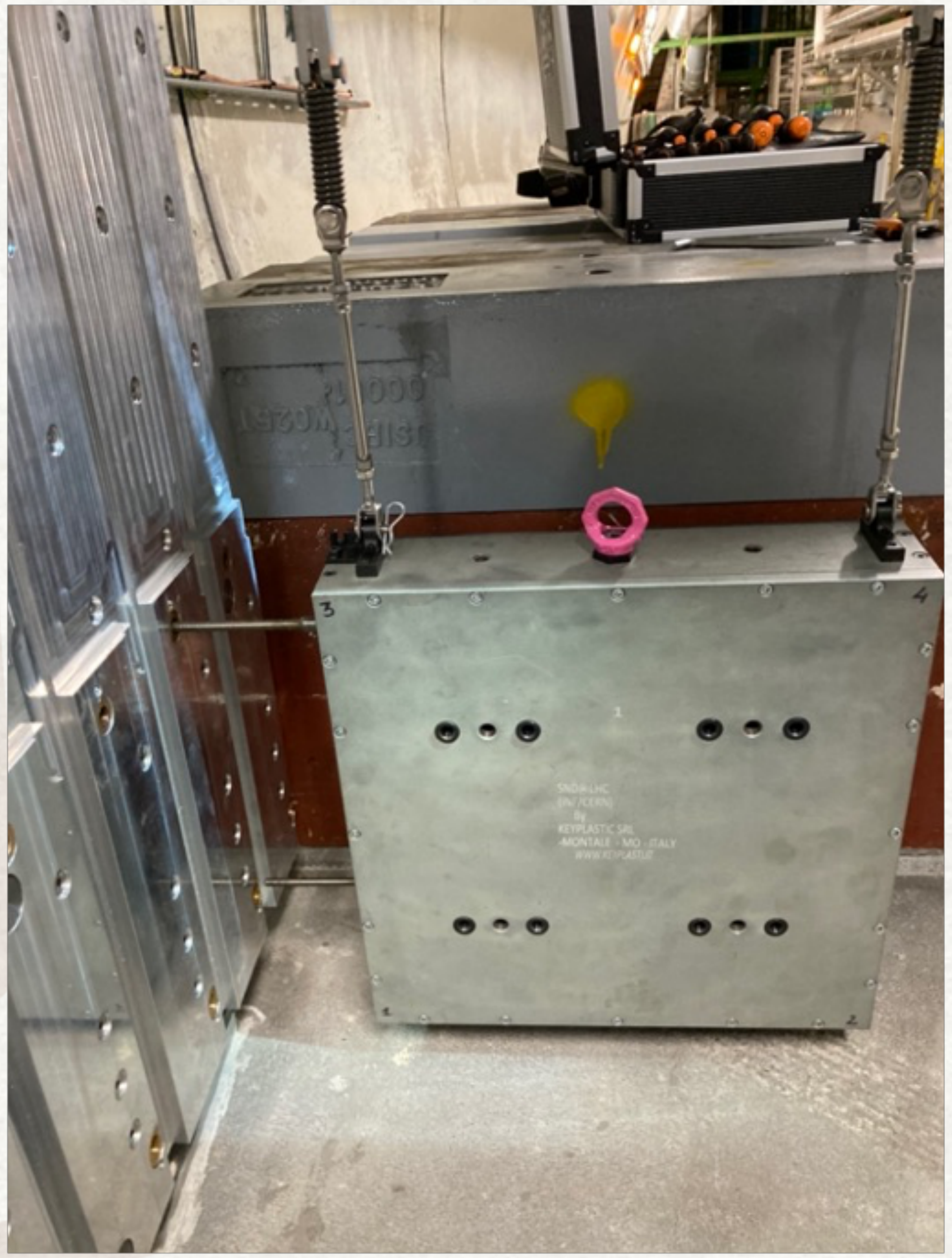
EMULSION WALL REPLACEMENT PROCEDURE

Test of the (empty) wall exchange procedure

Wall transported on the slope



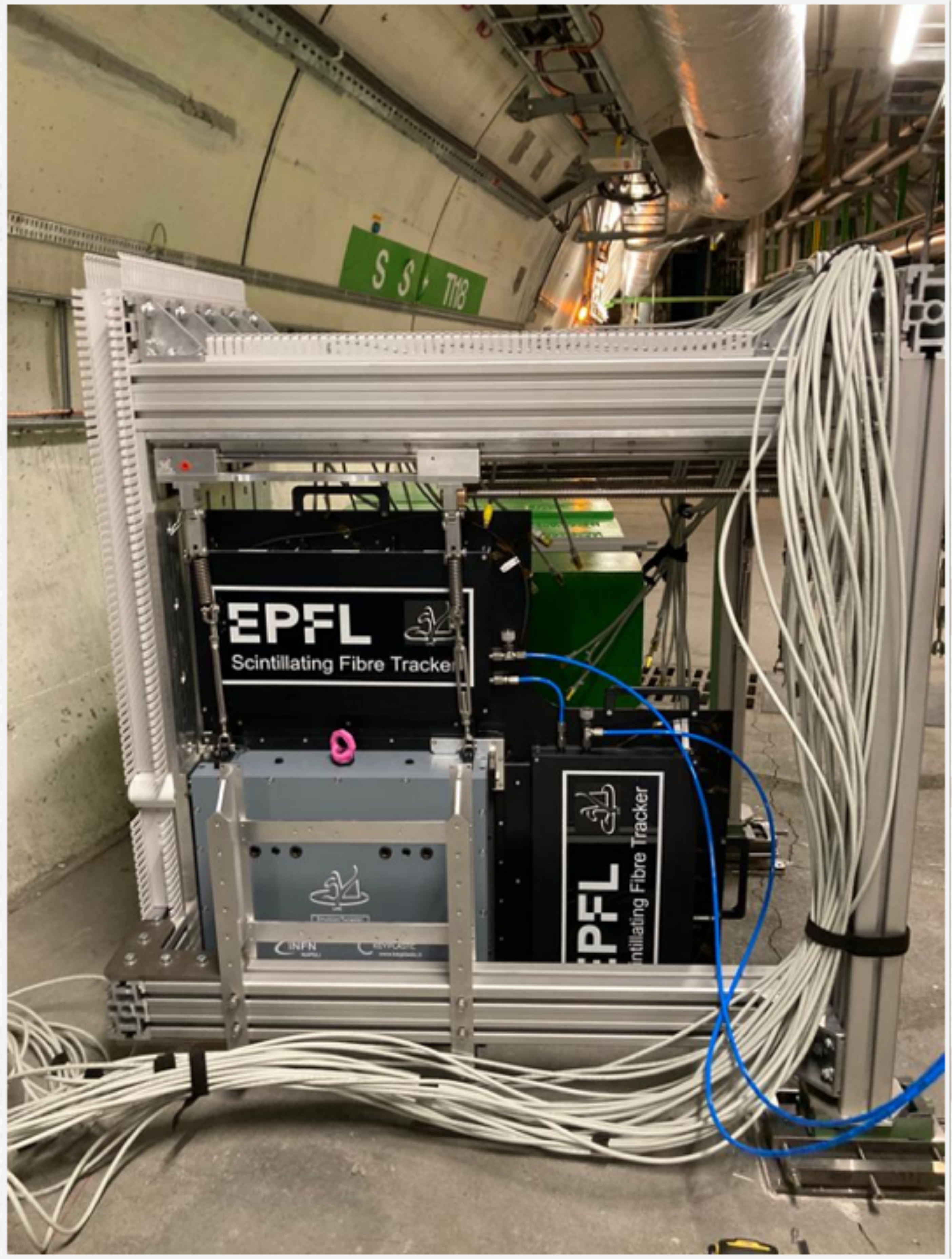
Wall insertion in the structure



Wall hanging to the structure

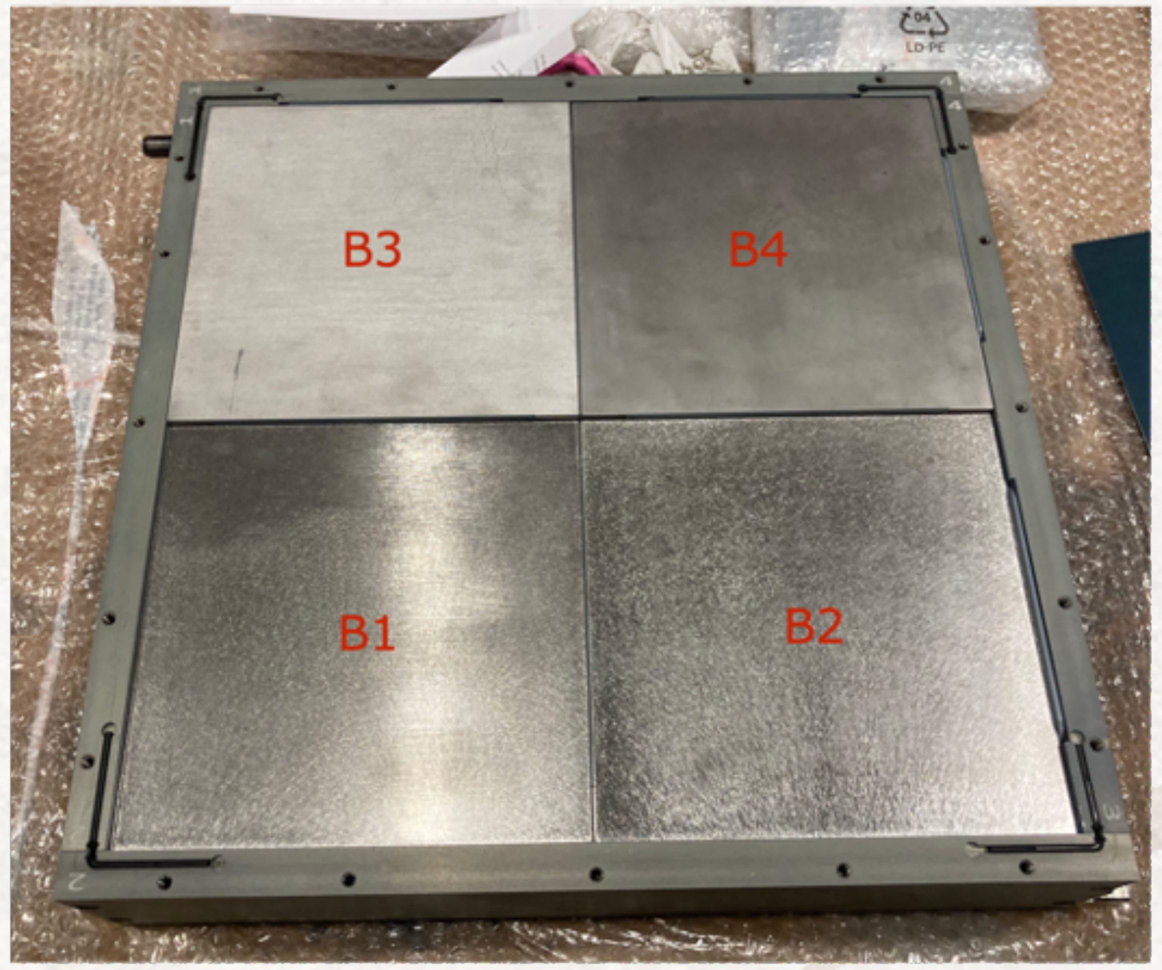
TARGET WALLS + SCIFI TRACKERS

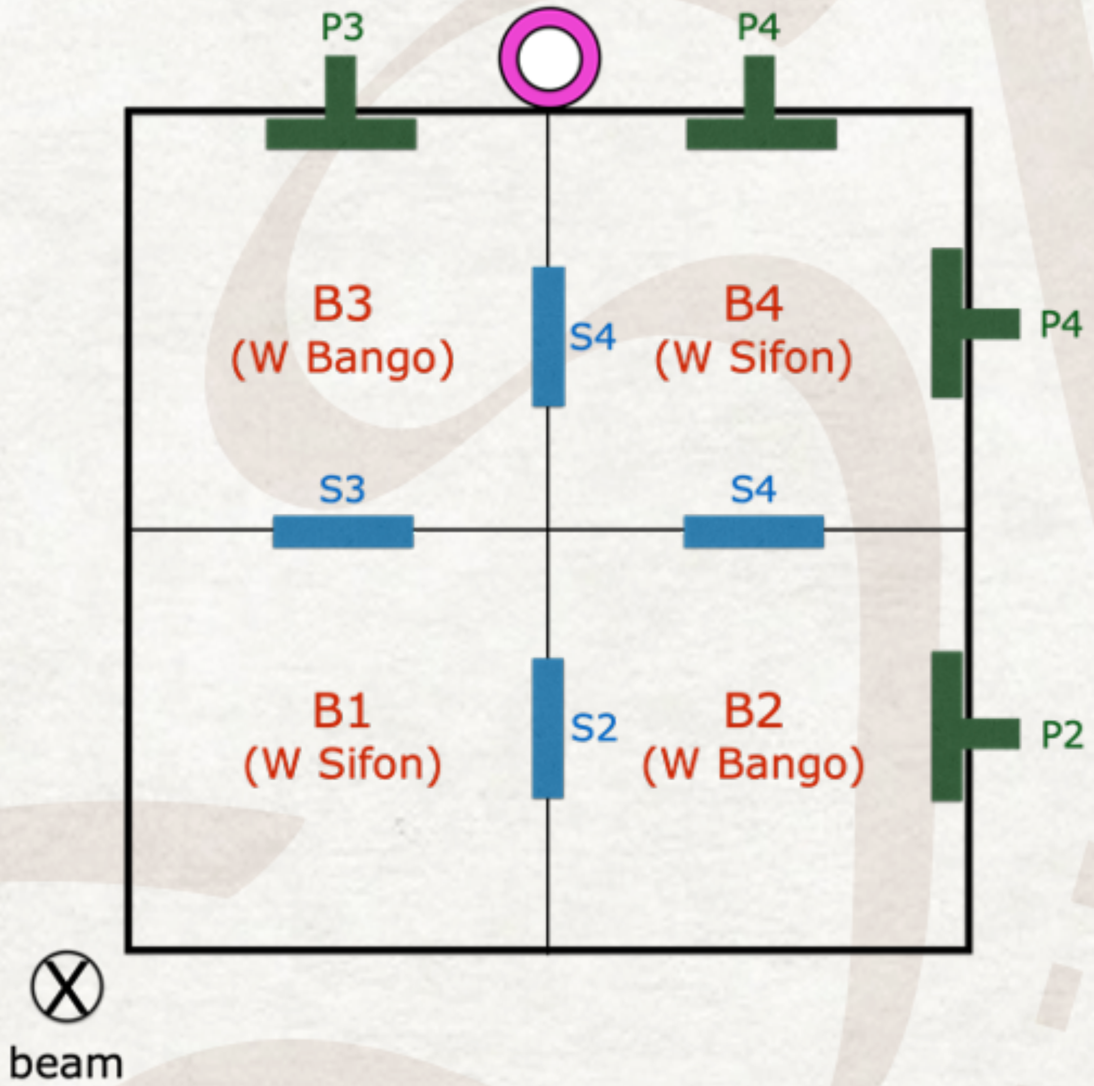
- Test of wall boxes with SciFi planes
- Small modification needed to one of the three metallic pieces used to hook the SciFi plane to the wall (thanks to Pablo)
- Installation of five walls + five SciFi planes

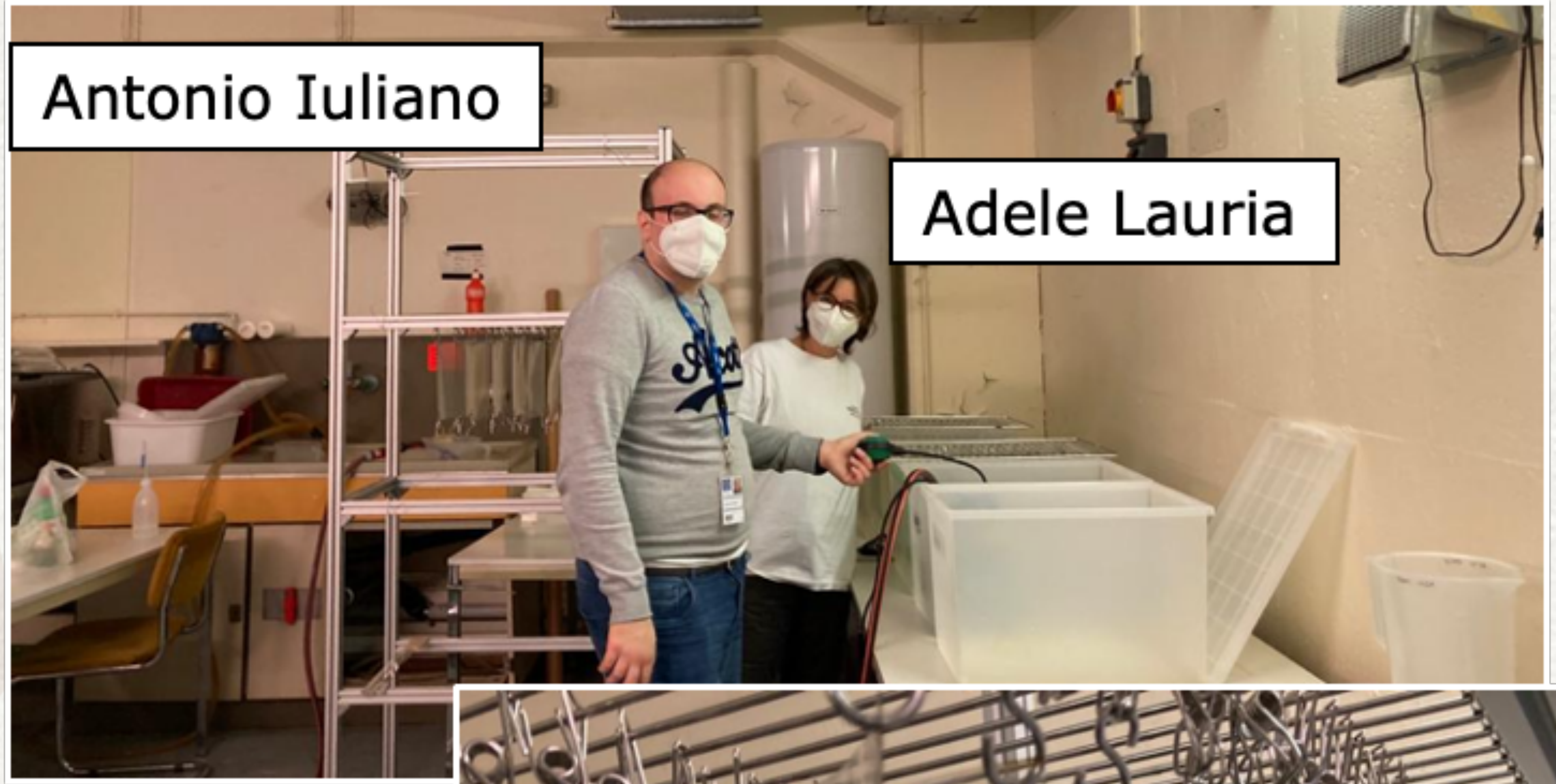


WALL COMMISSIONING WITH NUCLEAR EMULSIONS

Aim: - complete test of the wall box with tungsten and emulsions
- measure emulsion deformations, uniformity of segment recontruction in different positions of the W pile
- test alignment between consecutive emulsion films
- perform track reconstruction







Test in November 2021
- New emulsion batch produced in short time and delivered to CERN
- 30 emulsion films
- Wall commissioning performed
- **Good quality** emulsion films after development
- Scanning will be performed in Napoli Laboratory

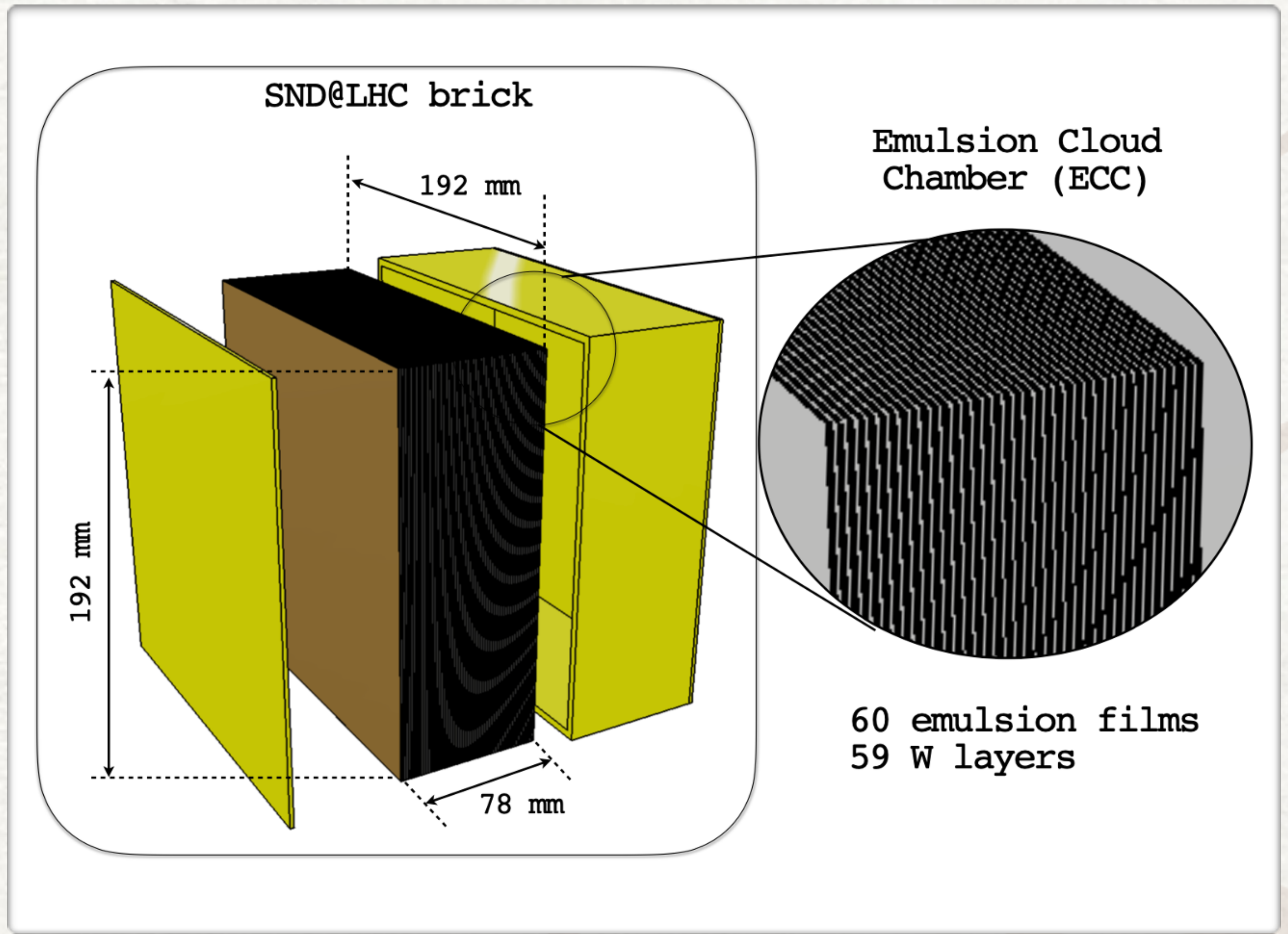
CONCLUSIONS

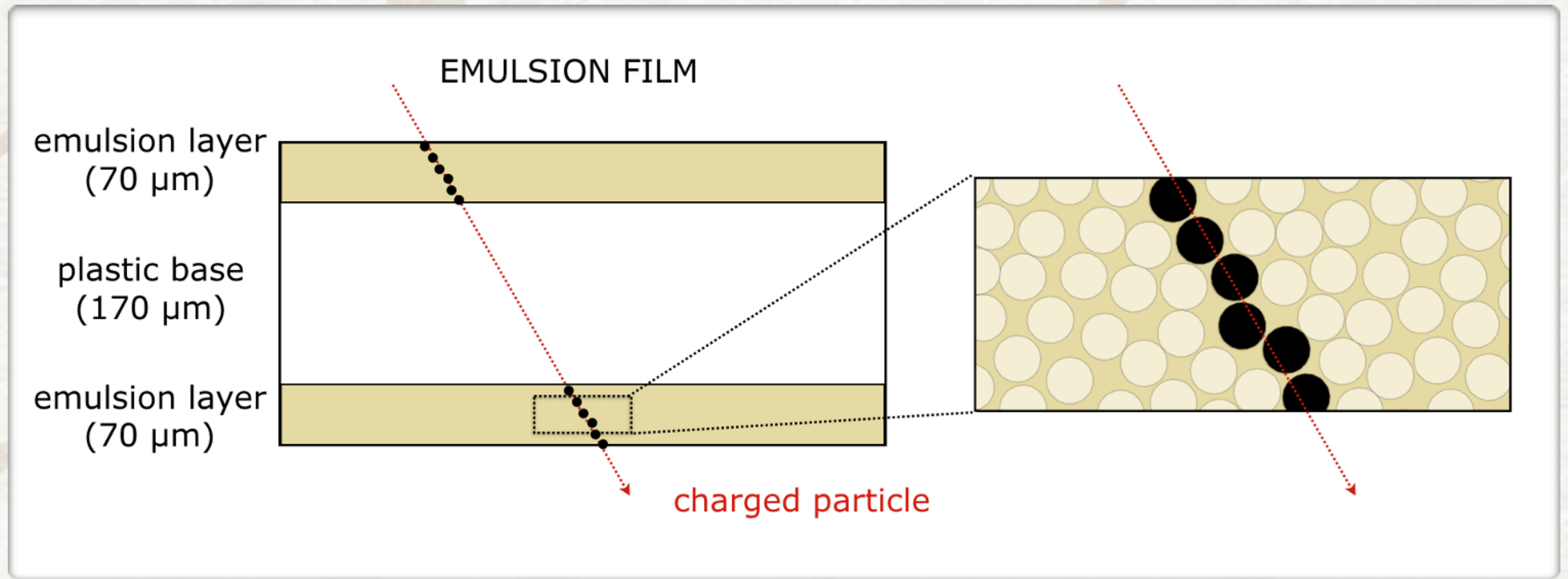
- SND@LHC is a recently approved experiment at CERN aiming at:
  - measuring neutrinos produced at the LHC in an unexplored pseudo-rapidity region
  - searching for light dark matter
- Detector installation completed
- Data taking will start in early 2022
- Possible extensions beyond Run3 under study
- Napoli responsibilities
  - Spokesperson: G. De Lellis
  - Physics Coordinator: A. Di Crescenzo
  - Project managers of emulsion target system: S. Buontempo, A. Di Crescenzo
- Tasks assigned to Napoli group
  - Neutrino MC simulation (A. Iuliano)
  - Target mechanical structure design and construction (G. Passeggio, F. Cassese)
  - Fiber optic sensors for temperature and humidity monitoring (G. Breglio)
  - Optical microscope for emulsion scanning (A. Alexandrov)
  - Emulsion data analysis

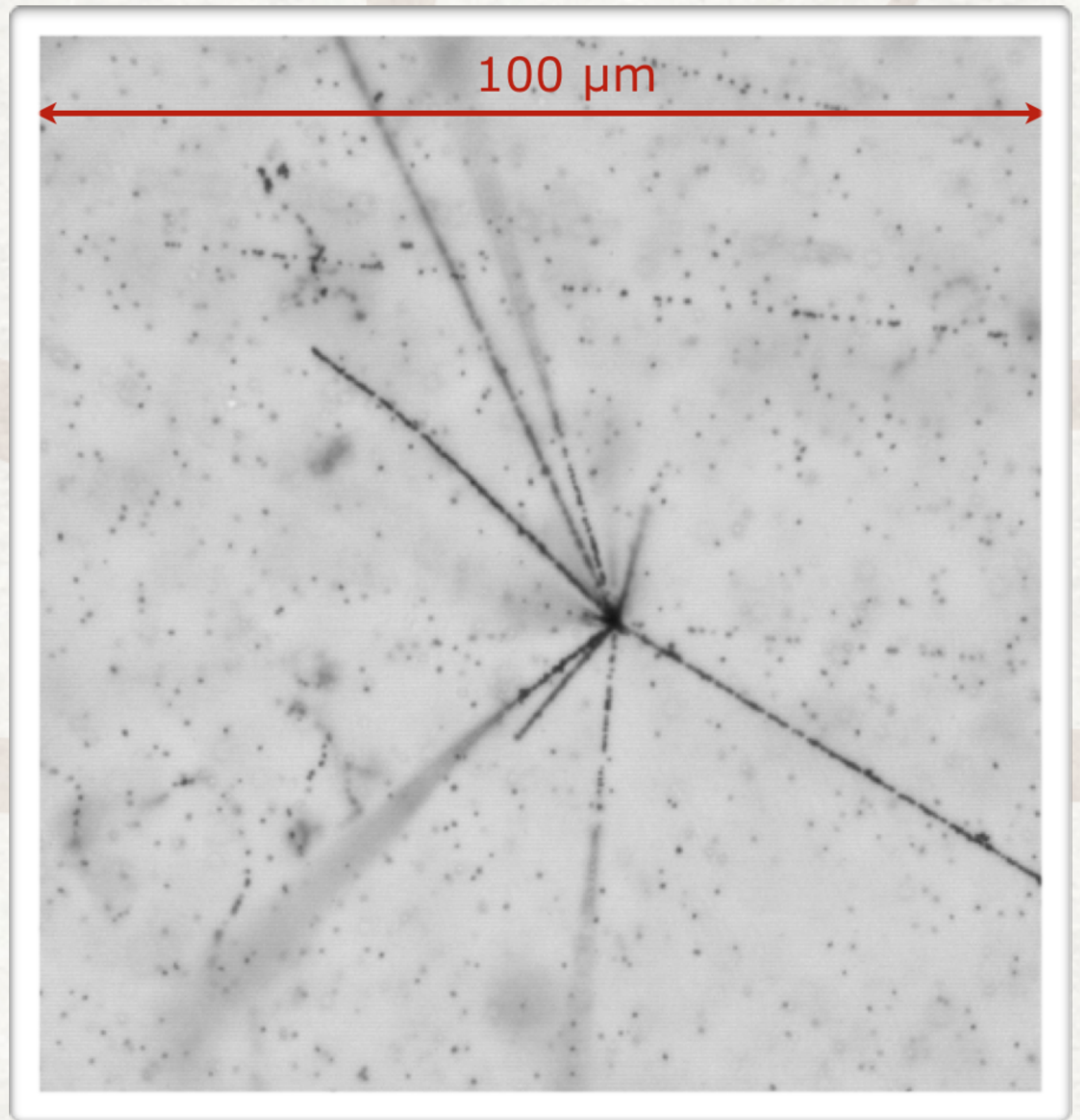
BACKUP SLIDES

EMULSION TARGET

Target assembled according to the Emulsion Cloud Chamber (ECC) technique:
Tungsten layers (1mm-thick) alternated to nuclear emulsion films



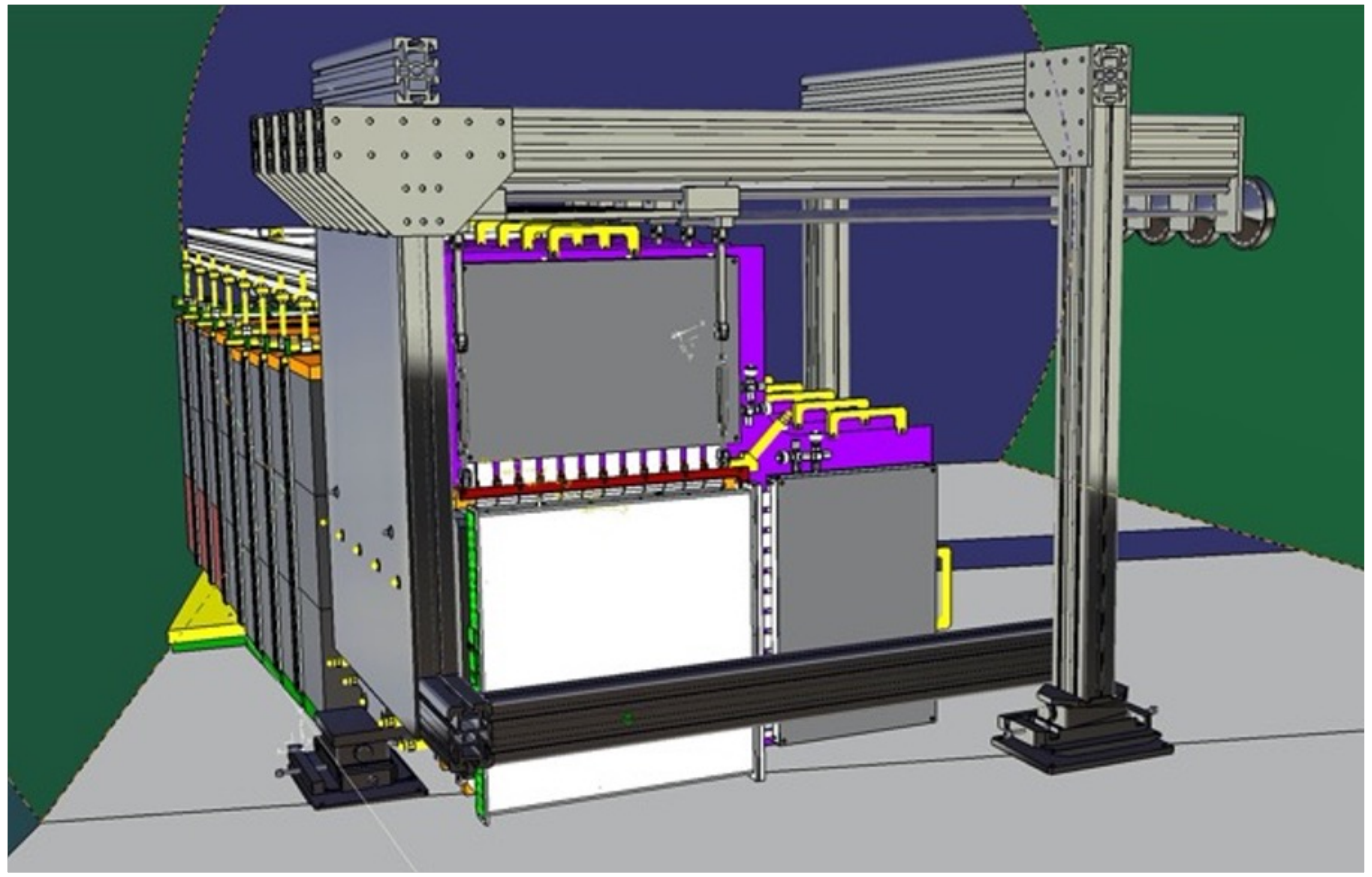


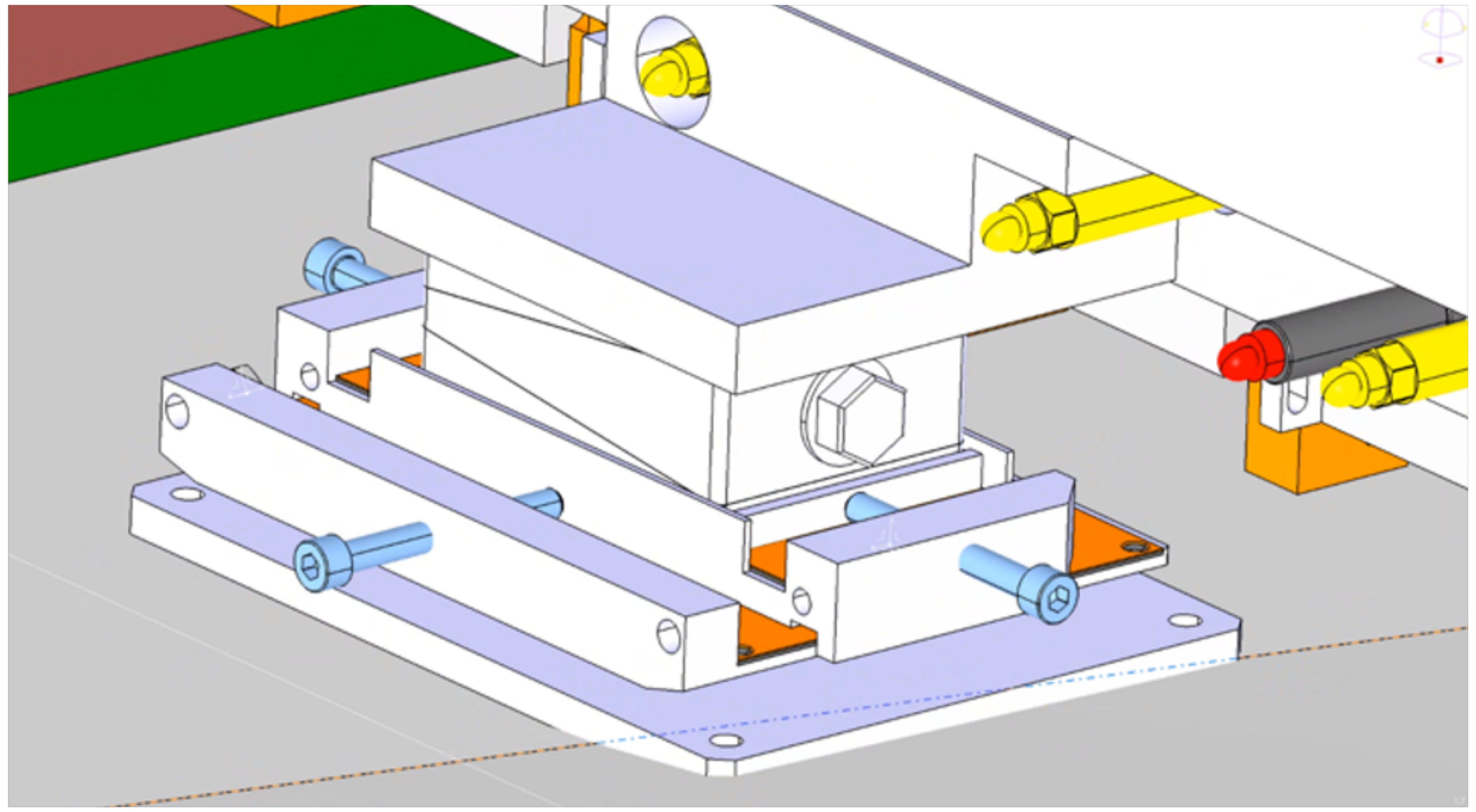


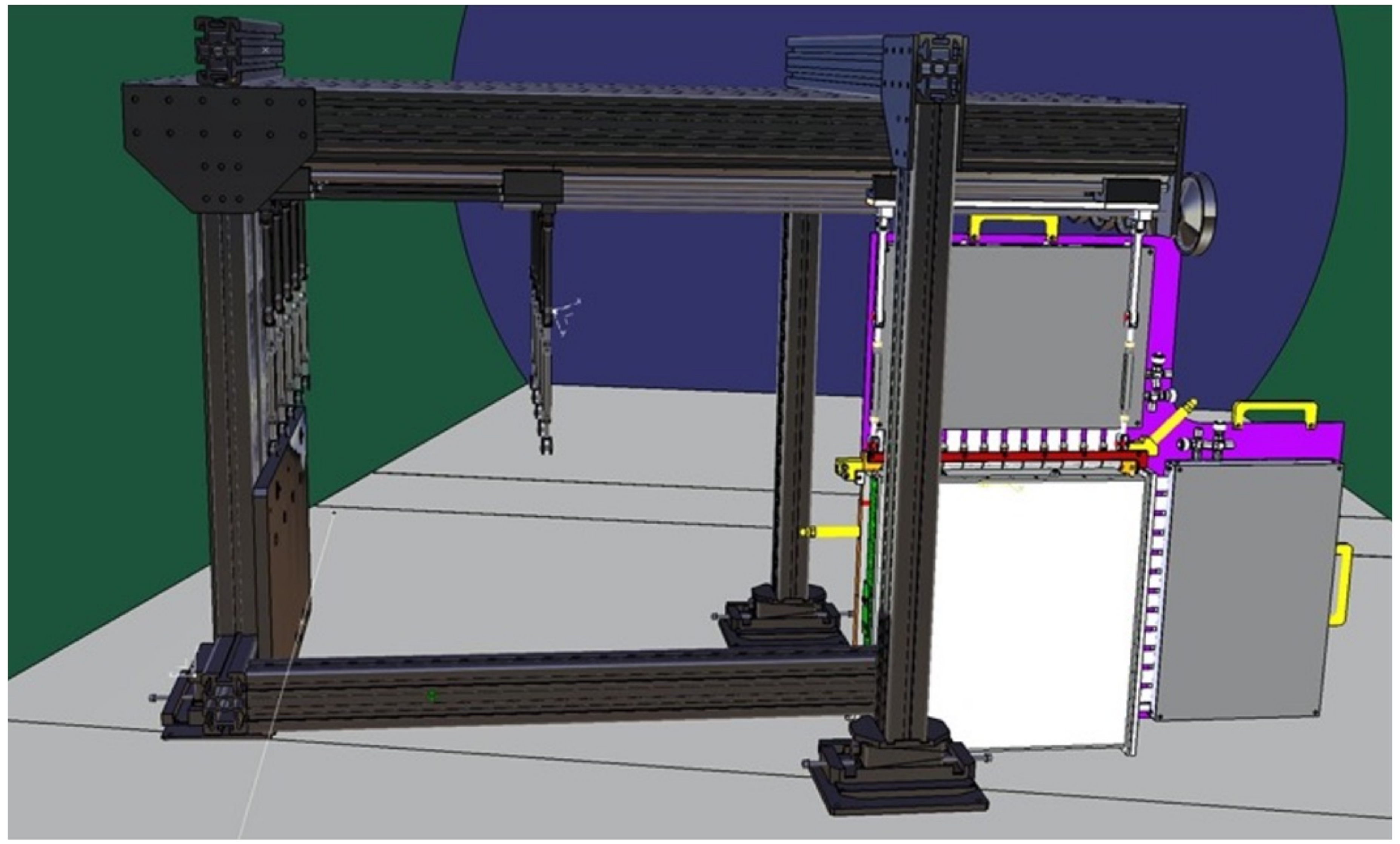
Sub-micrometric position resolution

TARGET MECHANICAL STRUCTURE

- Target walls hanging from the mechanical structure
- Horizontal displacement done by hand using mechanical worm screws
- Easy/fast/reliable wall exchange
- SciFi-to-Emulsion target precision by mechanical screws (<50 μm)
- Wall to Wall precision secured by mechanics (<50 μm)



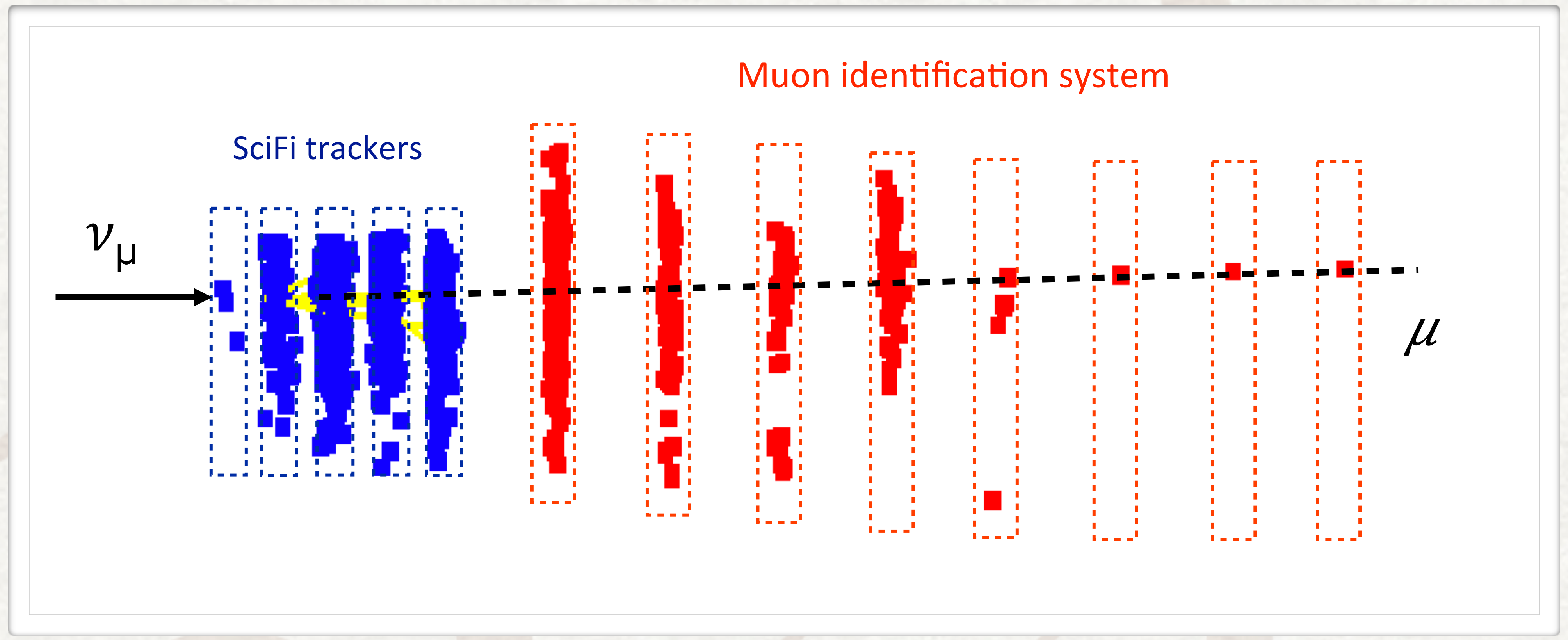




- Three adjustable feet to be placed under the structure to match with the slope of the floor in specific locations

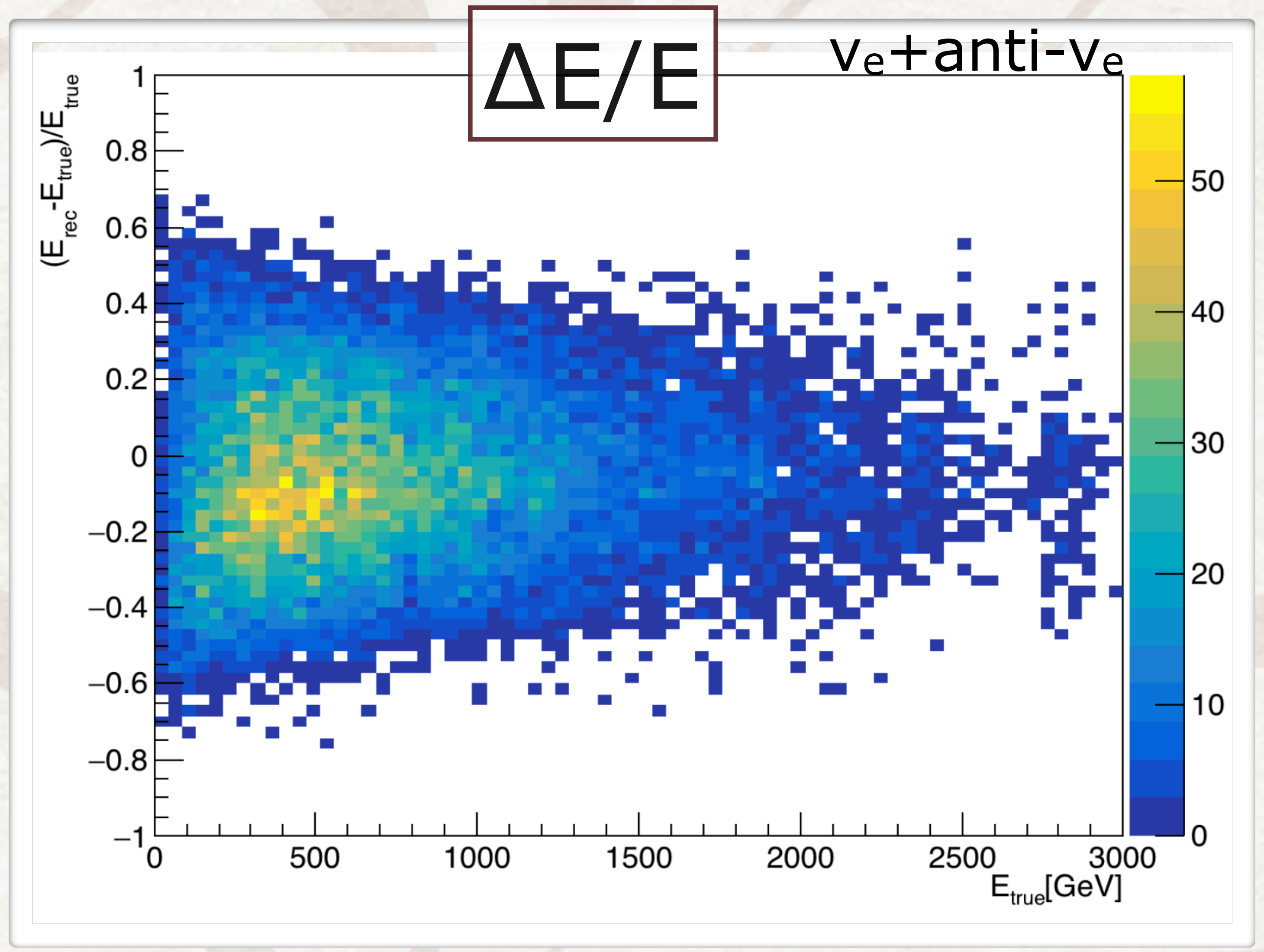
KEY FEATURES

- Muon identification
  - ν_μ CC interactions identified thanks to the identification of the muon produced in the interaction
  - Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to ν_τ detection

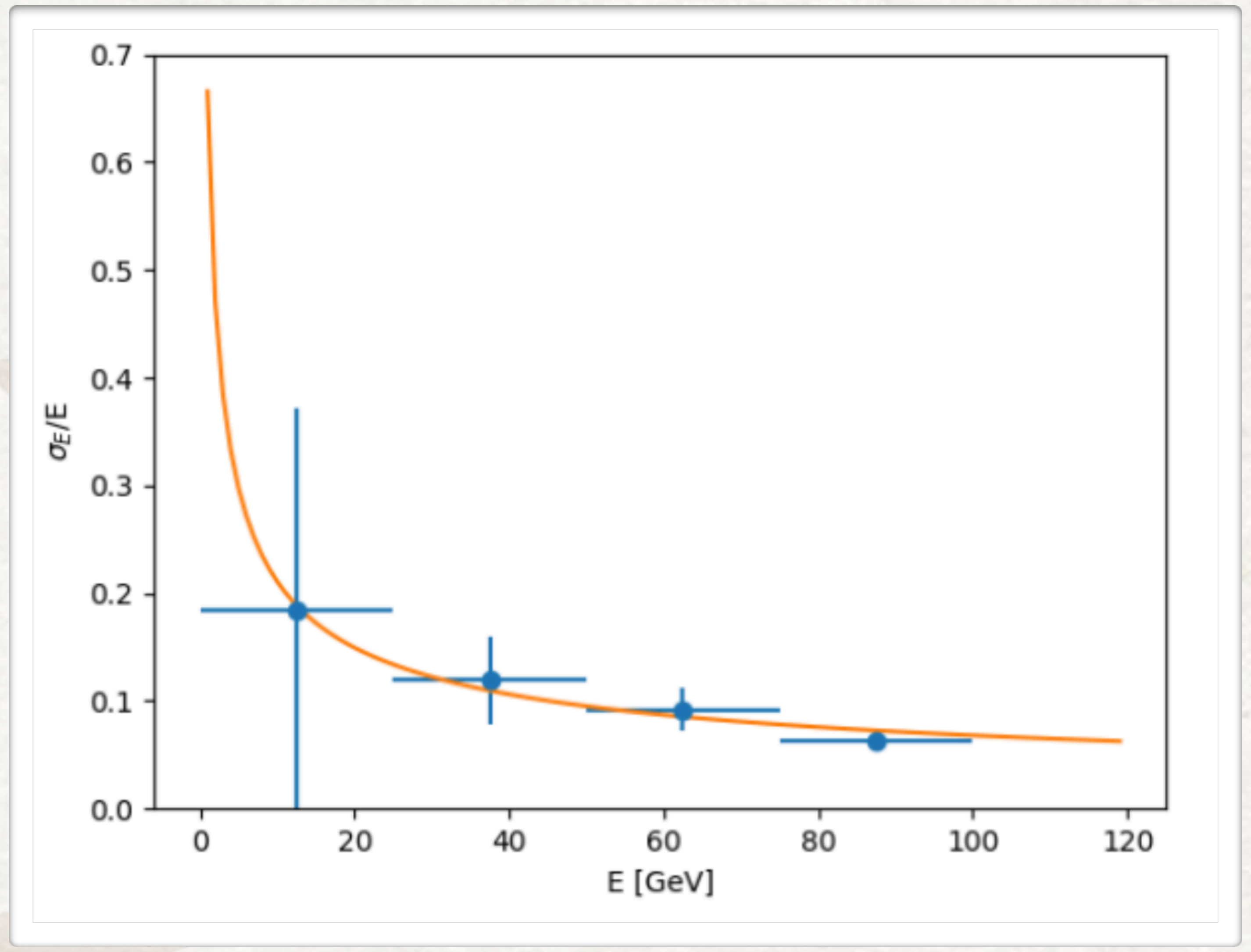


	% evts CC-DIS	% evts NC-DIS
0μ	31.1	99.6
1μ	67.6	0.27
2μ	1.1	0.06

- Energy measurement
  - The detector acts as a non-homogeneous sampling calorimeter



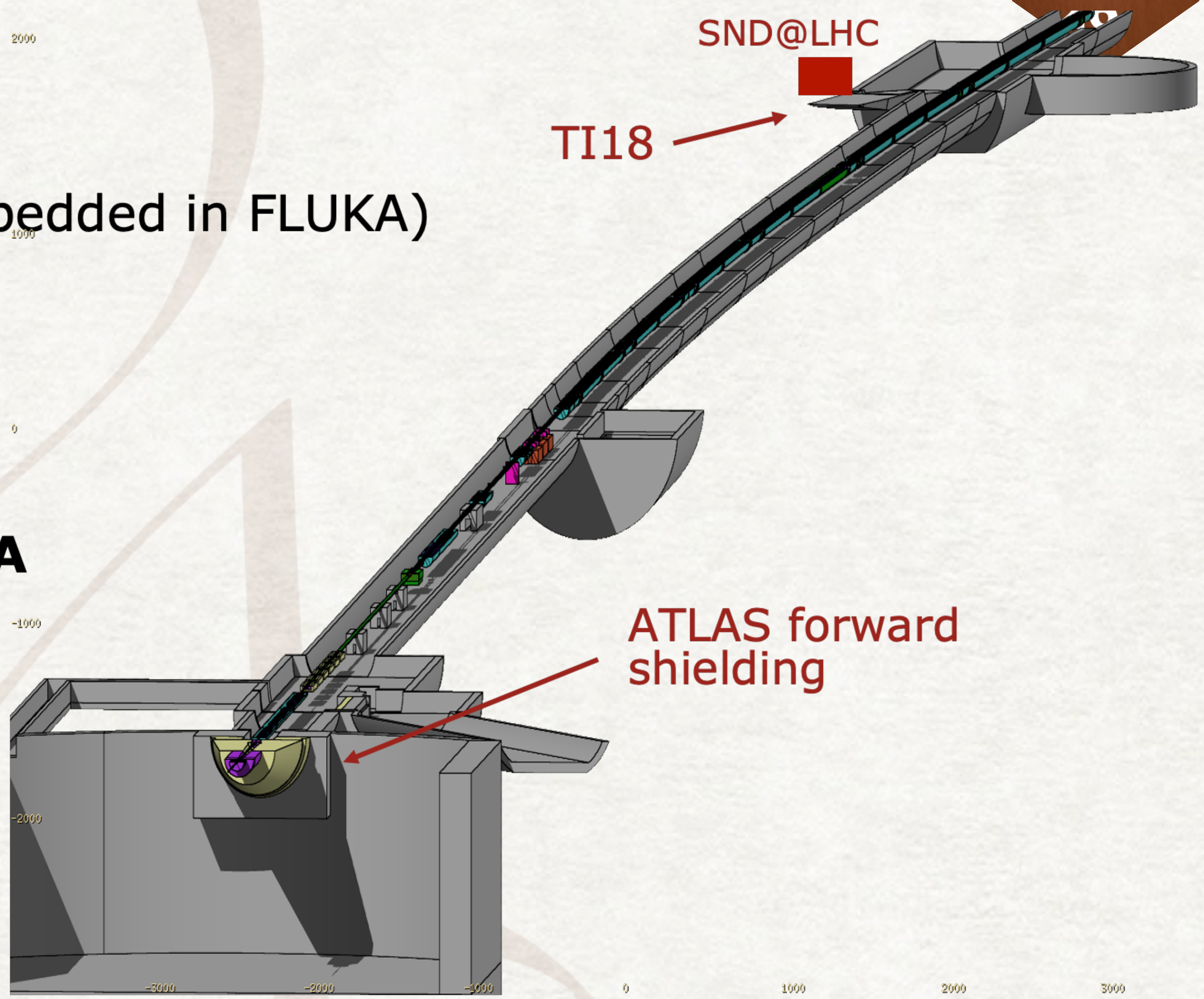
- Combing information from SciFi (target region) and Scintillator bars (Muon System)
- Average resolution on ν_e energy: 22%

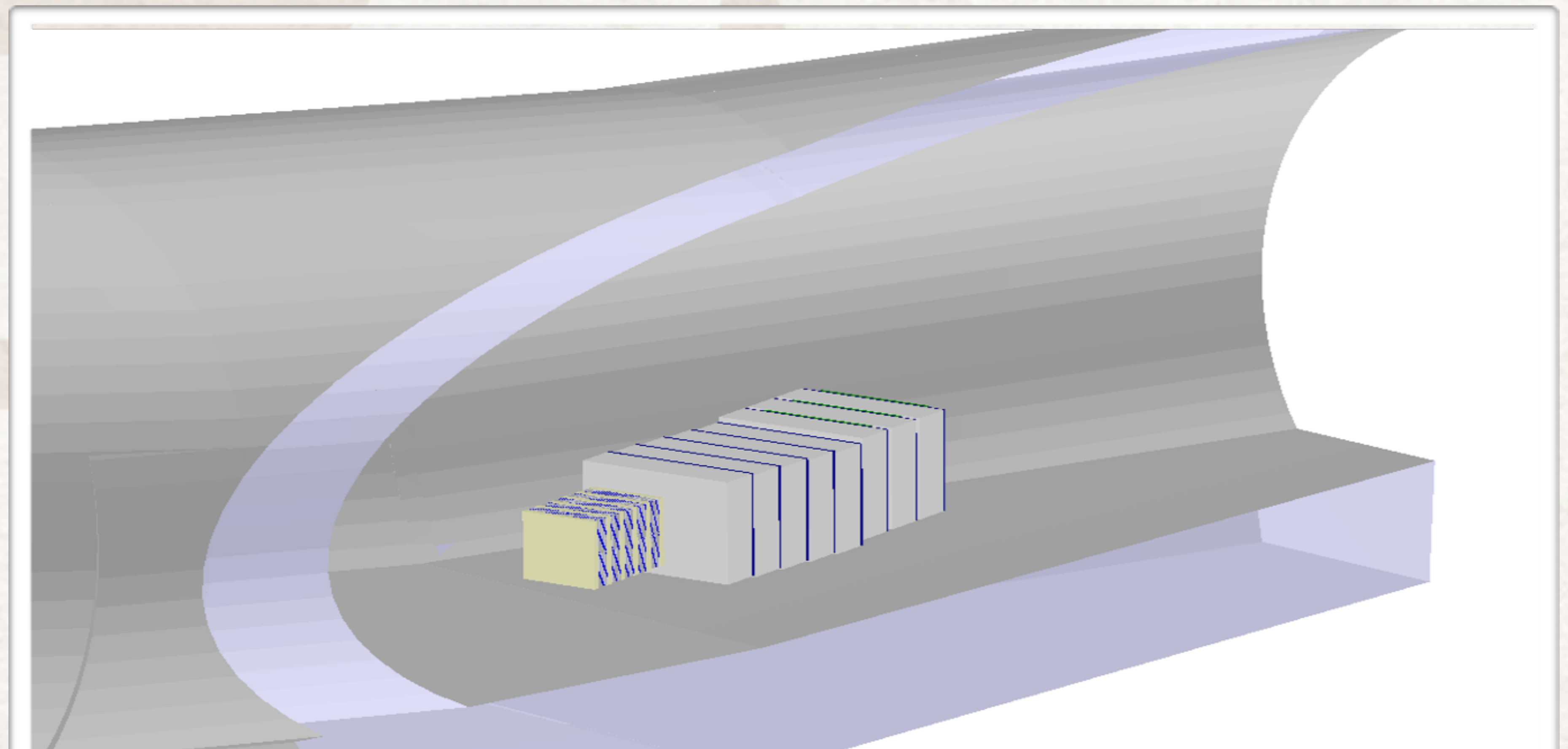


- Performance of SciFi tracker as sampling calorimeter, using a CNN
- Electron energy resolution

SIMULATION

- PRODUCTION
  - pp collisions at LHC with **DPMJET III - v10** (embedded in FLUKA)
  - √s = 13 TeV
- PROPAGATION
  - Detailed simulation of LHC beam line with **FLUKA**
  - Prediction of neutrino yields and spectra at SND@LHC location
  - Prediction of muon population in the upstream rock, 75m from SND@LHC
- DETECTOR
  - Neutrino interactions in SND@LHC material simulated with **GENIE**
  - Detector geometry and surrounding tunnel implemented in **GEANT4**

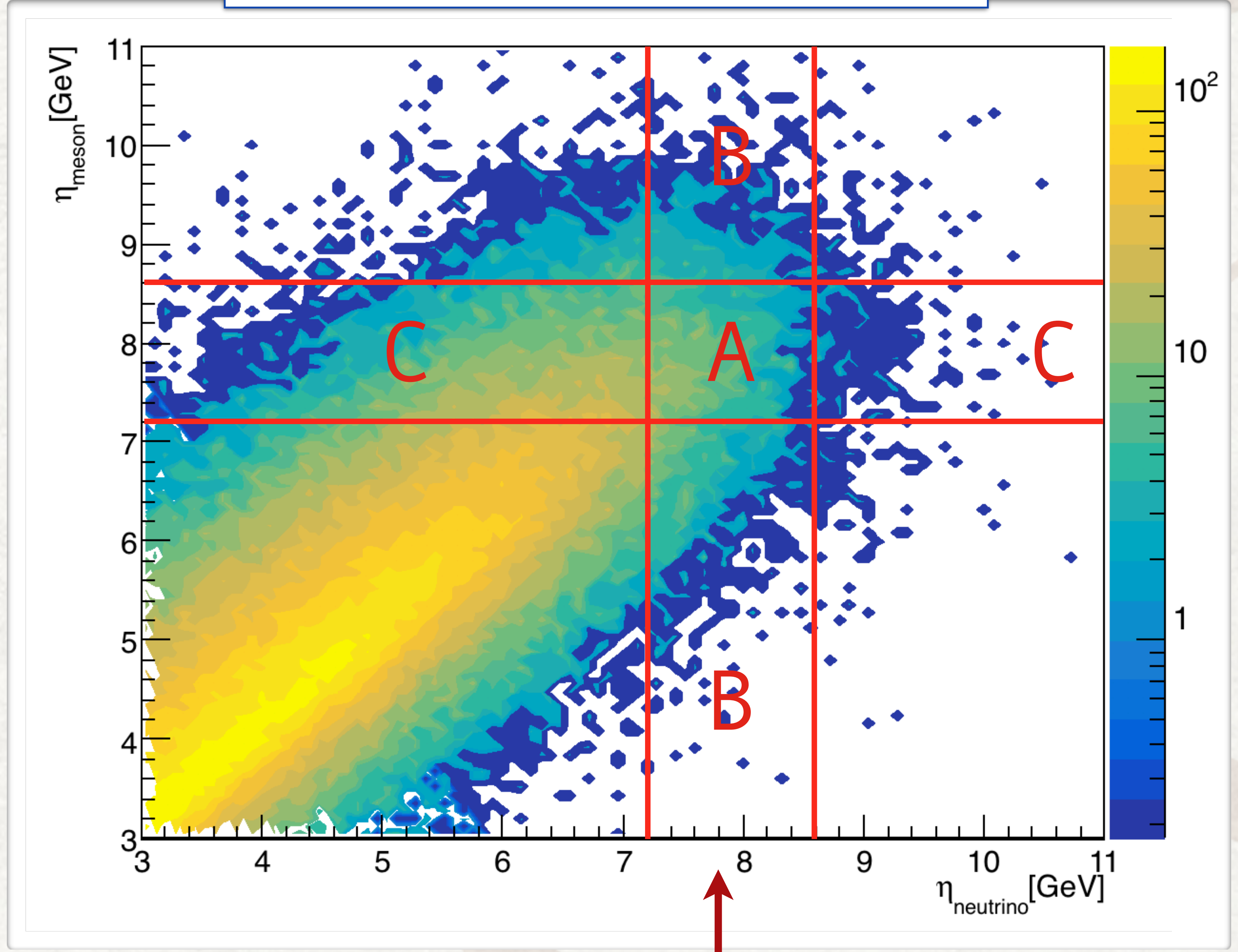




2. CHARMED HADRON PRODUCTION

- 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

CASE I: 7.2< η_{meson} <8.6



Neutrinos in SND@LHC acceptance

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

N_A/N_{A+B}

N_A/N_{A+C}

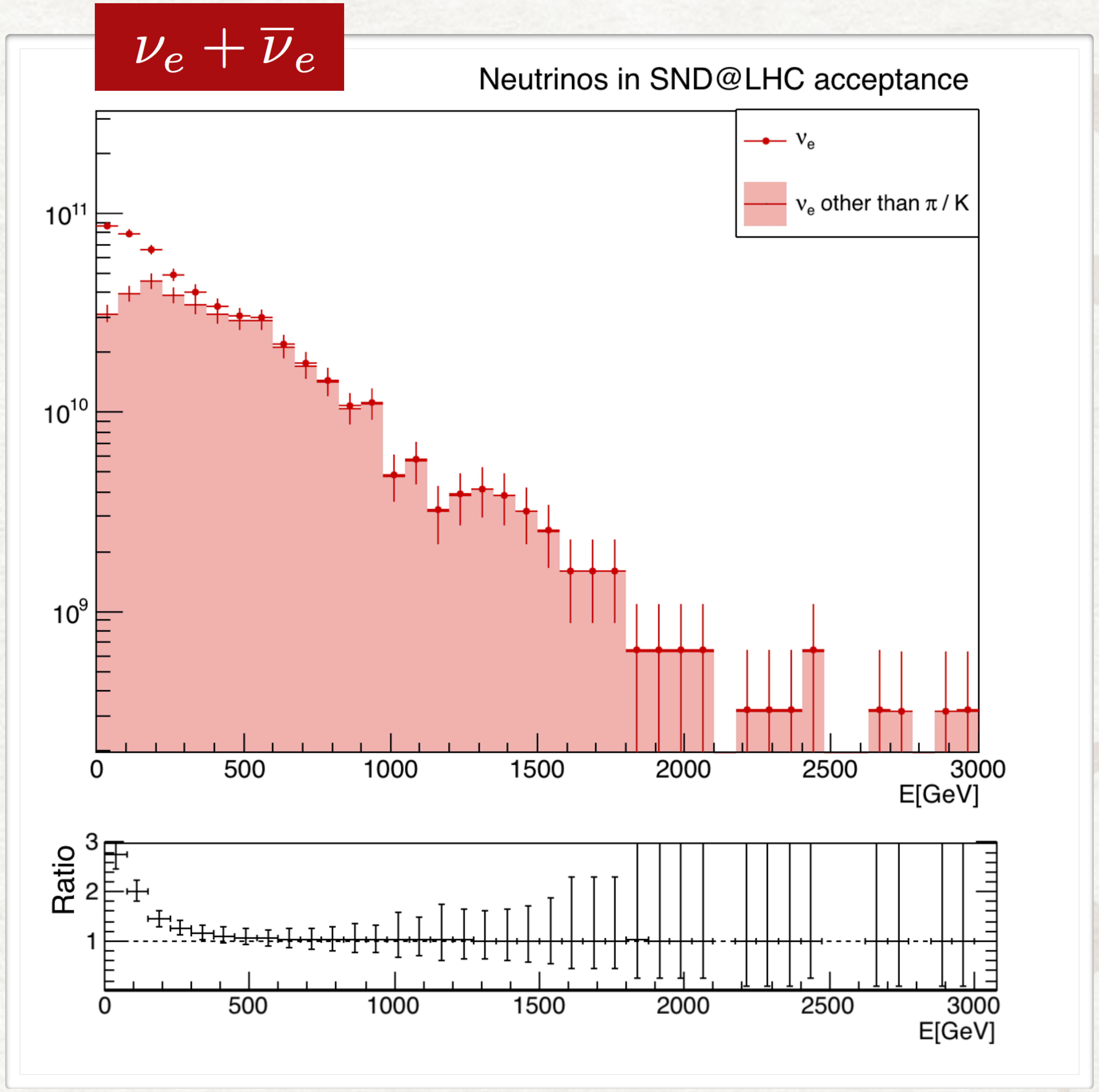
Branching ratio of charmed mesons to ν_e

- 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%**

3. LEPTON FLAVOUR UNIVERSALITY TEST

- The identification of three neutrino flavours in the SND@LHC detector offers a unique possibility to test the Lepton Flavor Universality (LFU)



- ν_τ are produced essentially only in D_s decays
- ν_e are produced in the decay of all charmed hadrons (essentially D0, D, Ds, Λc)
- The ratio depends only on charm hadronisation fractions and branching ratios
- Sensitive to ν-nucleon interaction cross-section ratio of two neutrino species

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

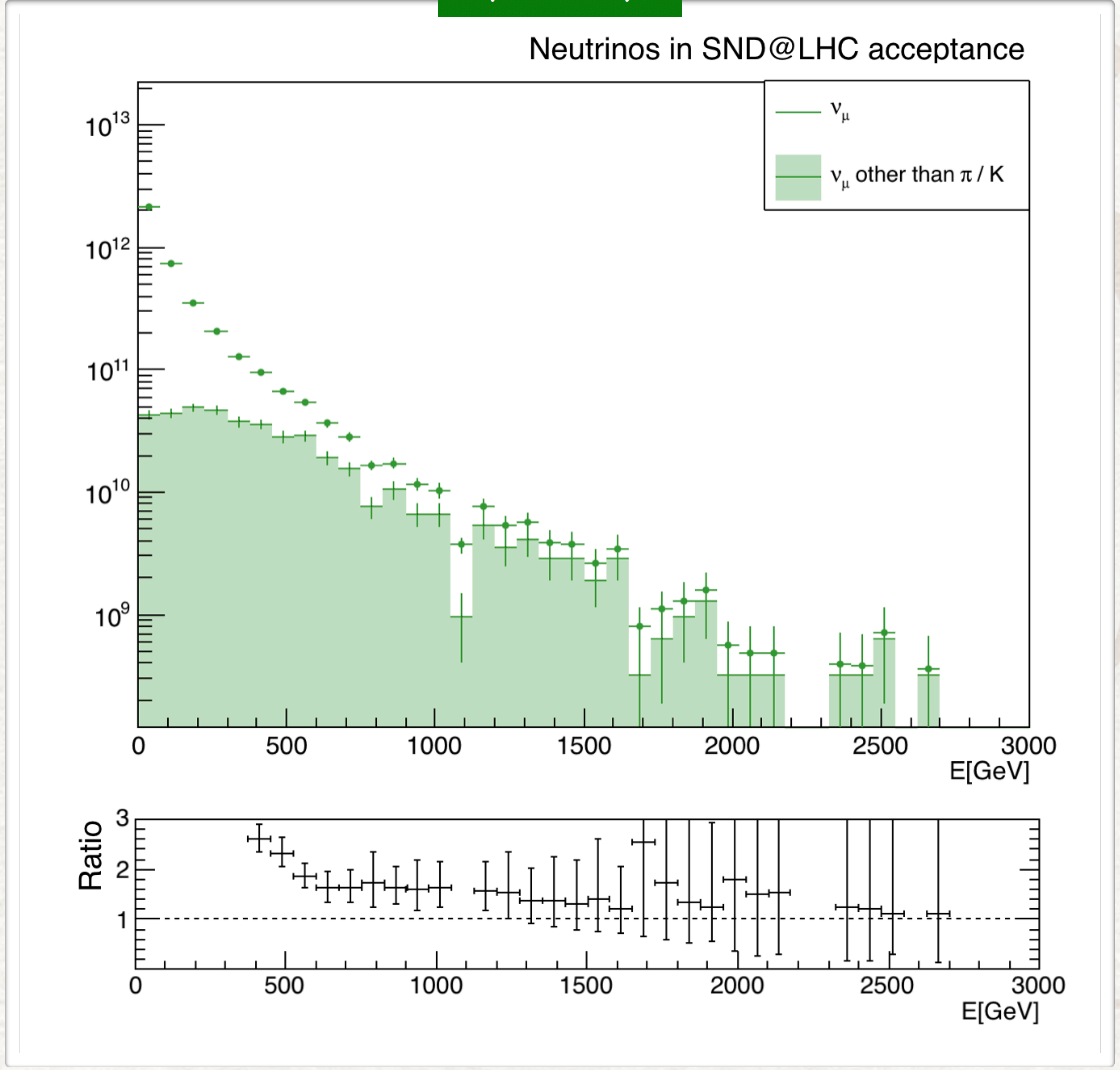
- Error on f_c and *Br* evaluated as discrepancy between values obtained in Pythia8 and Herwig generators: **20%**

- Statistical error due to low ν_τ statistics :**30%**

3. LEPTON FLAVOR UNIVERSALITY

- The ν_μ spectrum at lower energies is 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

$\nu_\mu + \overline{\nu}_\mu$



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

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

- The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU 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

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

OUTLOOK: Advanced SND

- Upgrade of the detector in view of an extended run during Run 4:
  - Magnetised region to measure charge of the muon (ν_μ/anti-ν_μ, ν_τ/anti-ν_τ in the $\tau \longrightarrow \mu$ channel)
  - Larger target region
  - Replace emulsions with electronic trackers

- Two off-axis forward detectors:
  - AdvSND1: η~8

    Reduce systematic uncertainties
  - AdvSND2: η~4.5

    Useful link to LHCb measurements

    High energy neutrino physics

- Shielded location is required