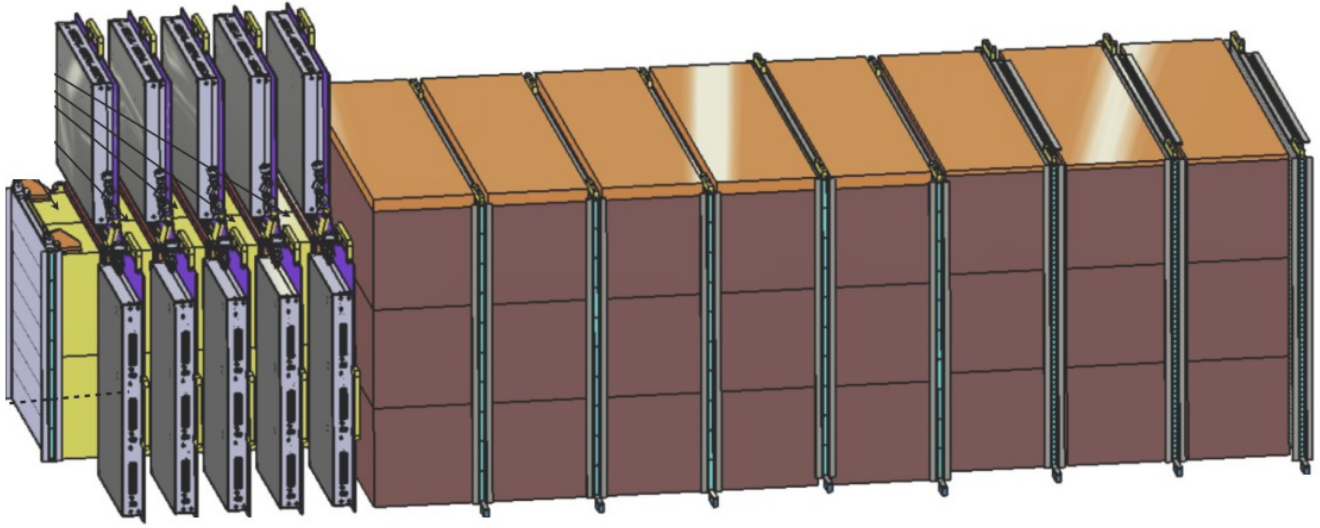
# The Scattering and Neutrino Detector at the LHC



Simona Ilieva
for the SND@LHC collaboration
Sofia University St. Kliment Ohridski

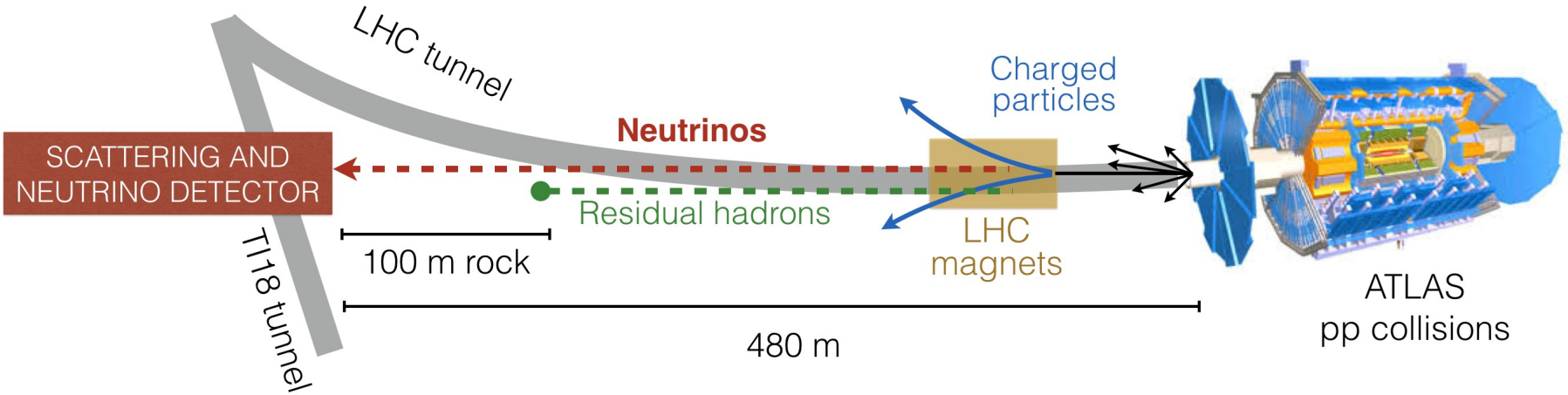
**6th ComHEP**
**30/11/2021**

LHC
Scattering and Neutrino Detector
at the LHC

# Outline

- Overview and Motivation
- The SND@LHC detector
- Physics concepts
- Current status

# **S**cattering and **N**eutrino **D**etector @ **LHC**

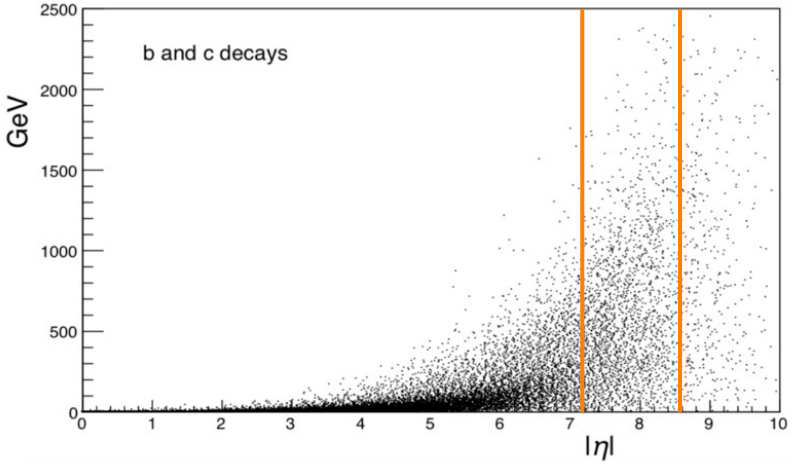



- Compact experiment observing forward-going neutrinos emerging from LHC interactions
- Off-axis detector located 480m downstream of the ATLAS interaction point (IP1) in the TI18 tunnel
- Experiment approved by CERN Research Board in March 2021

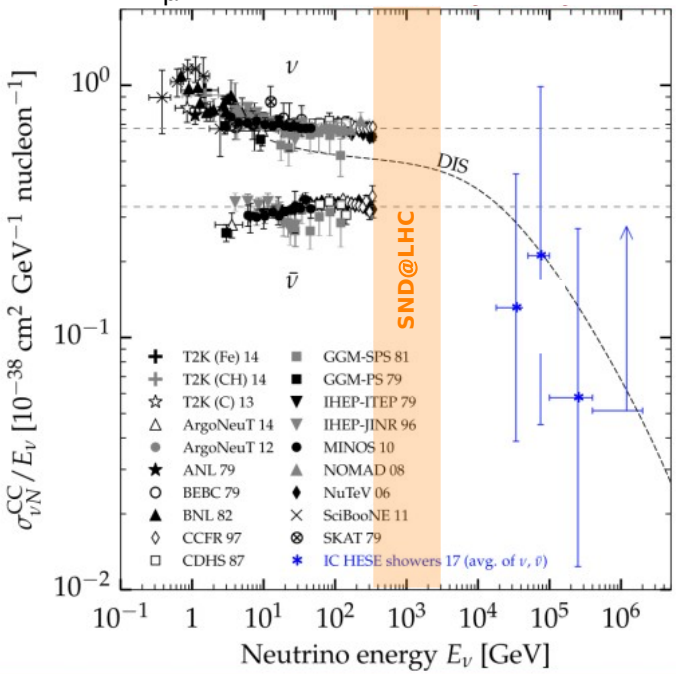
  **https://snd-lhc.web.cern.ch/**
- Collaboration of 180 members from 24 institutes in 13 countries and CERN

# Motivation

- Unlocking the potential of LHC neutrinos:
  - E range is few hundred GeV to a few TeV
- 150 $fb^{-1}$ luminosity for the LHC Run 3 and 1-tonne detector mass located in TI18 result in 2000 high-energy neutrino interactions
  - all three neutrino flavours
  - pseudorapidity range $7.2 < \eta < 8.6$
- Large neutrino flux in forward direction covering a wide energy range




- High neutrino energies → relatively large neutrino interaction xsec
- Measure charmed-hadron production indirectly through $\nu_e$ and $\nu_\tau$ in an unexplored domain
- $\nu_\mu$ originate mainly from charmed-hadron decays, low-energy $\nu_\mu$ also from π and K decays



# Physics goals

## Neutrino physics at LHC energies

- $\sigma_{pp \to \nu X}$ in $7.2 < \eta < 8.6$ range
- $\nu_e$ as a probe of charm quark production
- Lepton universality test: $\nu_\tau/\nu_e$ and $\nu_\mu/\nu_e$
- Measurement of the NC/CC ratio

## Search for new physics

- Direct search for feebly interacting particles (FIP) through their scattering

$$\chi + p/e \to \chi + p/e$$
$$\chi + p/n \to \chi + X$$

# Overview of the detector

## Upstream veto plane

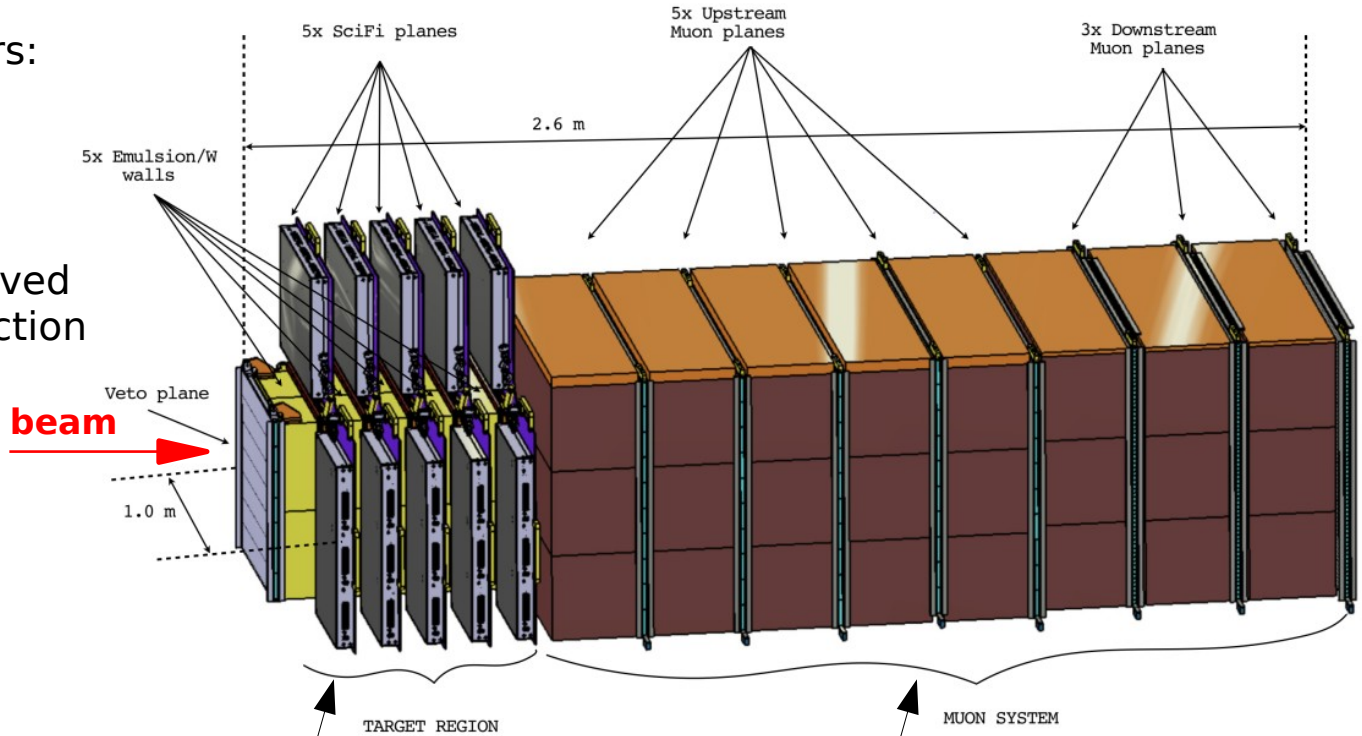
- Single plane of scintillating bars: tag incoming muons

## Target region

- Emulsion cloud chambers: tungsten target plates interleaved with emulsion: neutrino interaction detection (vertexing)
  - Target mass 830kg
- Scintillating fiber planes: time-stamp, position measurement
- Together: EM shower energy measurement

## Muon system

- Plastic scintillator planes inter-changed with iron walls: time and energy measurement

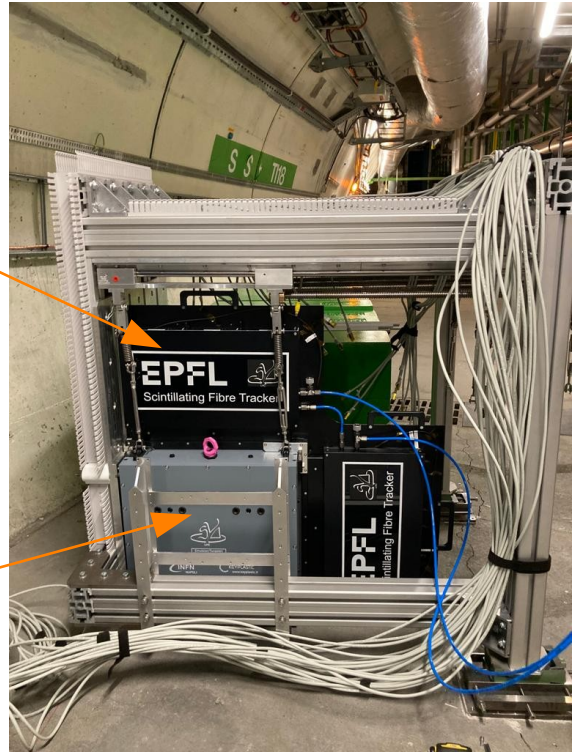



Vertex detector + ECAL
sampling every $10X_0$ to ~$40X_0$

HCAL + muon ID system
sampling every λ to 8 λ,
(with target region ~10 λ)

# SND@LHC detector in TI18: installation ongoing

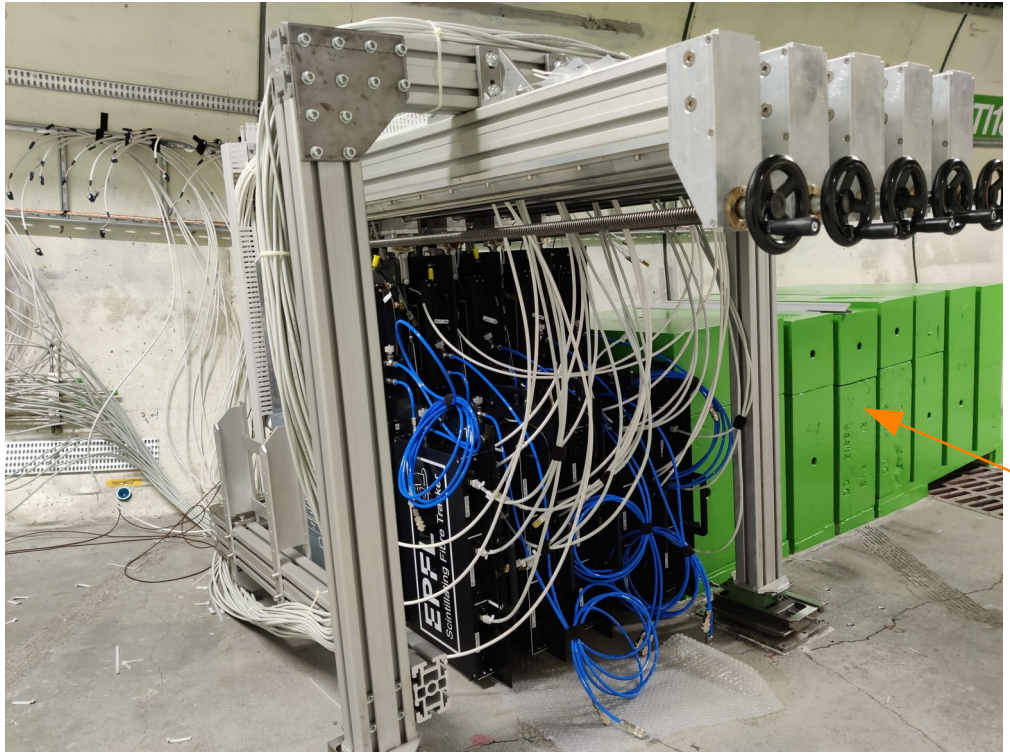
Front view




SciFi readout electronics

Emulsion Cloud Chamber

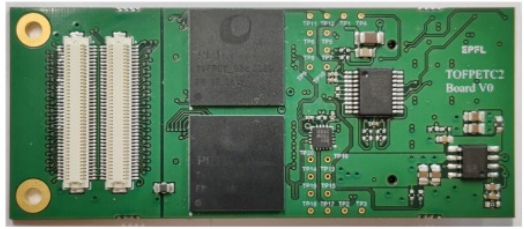
Side view



Iron walls (part of the muon system)

# Data acquisition

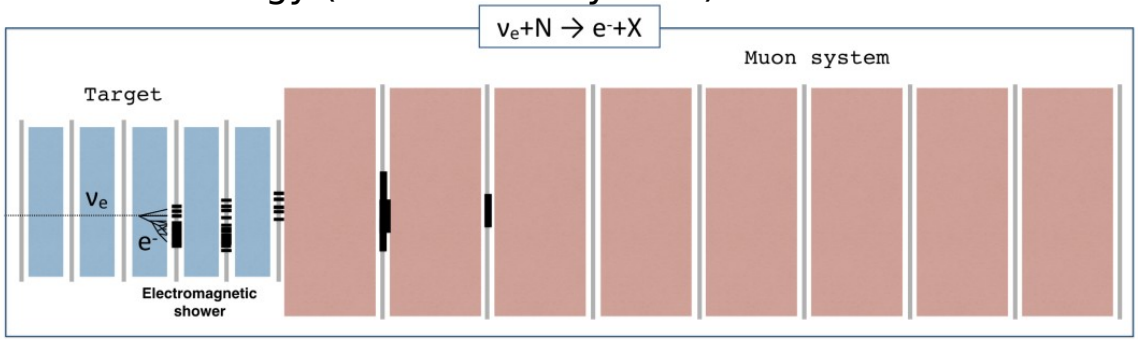
- Two types of active sub-systems:
  - Scintillator bars read out by SiPMs - veto and muon systems
  - Scintillating fibers read out by SiPMs, - SciFi tracker
- 36 identical DAQ boards synchronized with the LHC bunch crossing clock
- Trigger-less: all hits are recorded
  - hits with same time stamp grouped into events
  - basic online signal processing for data quality monitoring
- Noise reduction: setting of signal threshold (3.5 ph.e.)
  - online: events must produce signals in a minimum number of boards

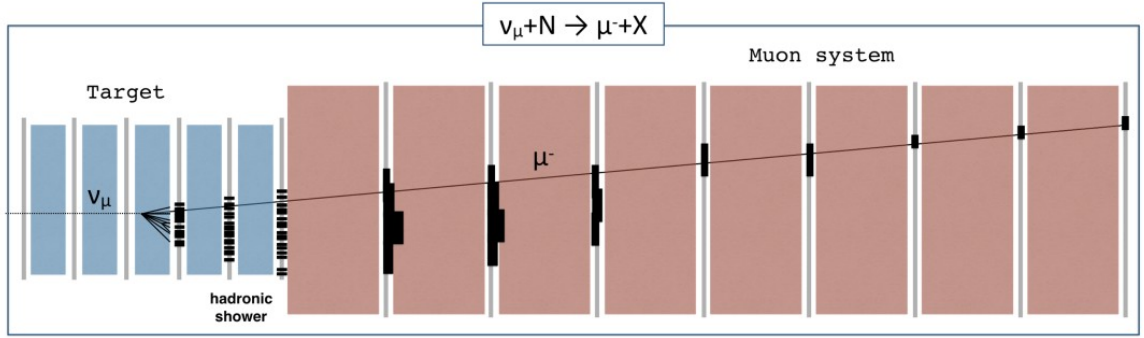



# Data reconstruction

**First phase**: online; using response of <u>electronic detectors</u>

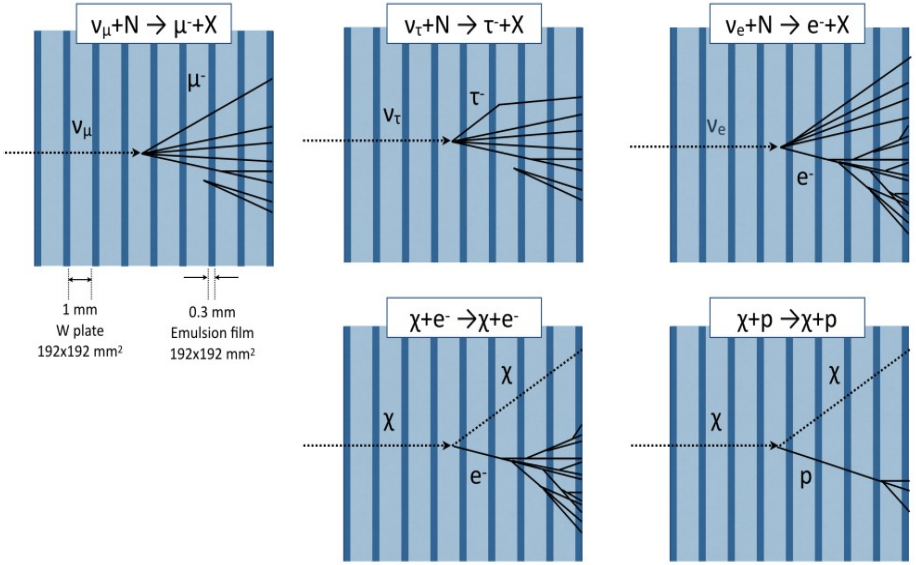
- Identify $\nu$ interaction and FIP scattering event candidates
- Muons (spanning to the DS muon stations)
- EM showers (limited to SciFi)
- $\nu$ energy (SciFi+Muon system)




**Second phase**: <u>nuclear emulsion</u> data – about 6 months exposure, then 6 months for scanning of films

- EM showers
- $\nu$ vertex reconstruction
- identify $\nu_\tau$
- match with candidates from electronic detectors

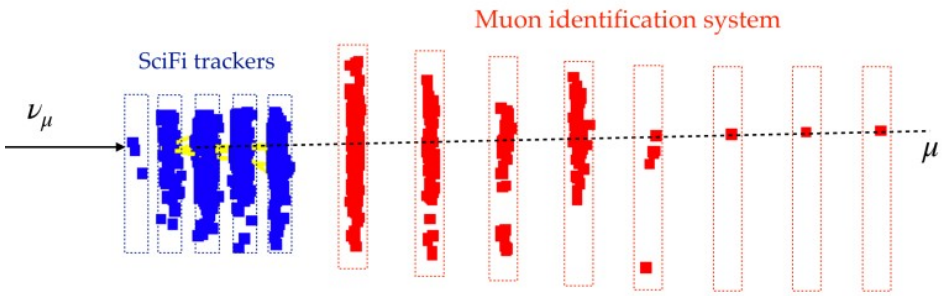


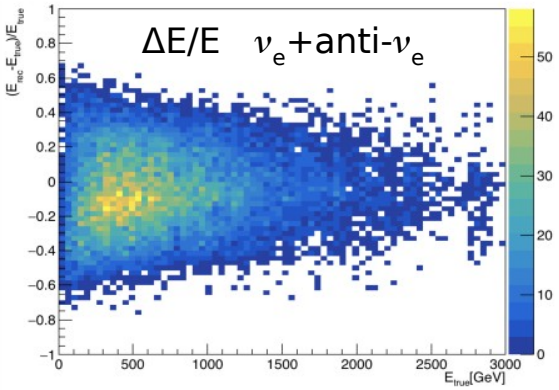
# Key detector features

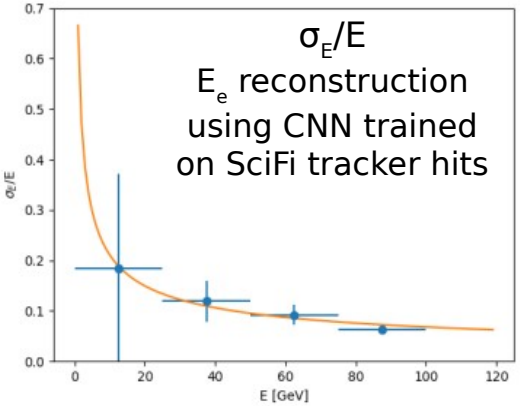
| | % evts CC-DIS | % evts NC-DIS |
|---|---|---|
| $0\mu$ | 31.1 | 99.6 |
| $1\mu$ | 67.6 | 0.27 |
| $2\mu$ | 1.13 | 0.06 |
| $3\mu$ | 0.1 | 0.03 |
| $> 3\mu$ | 0.01 | 0 |

## Muon Identification

- $\nu_\mu$ CC interactions identified by detection of muons produced in target interactions
- Muon ID at $\nu$ vertex crucial to identify charmed hadron production, latter form background to $\nu_\tau$ detection if primary muon is not identified



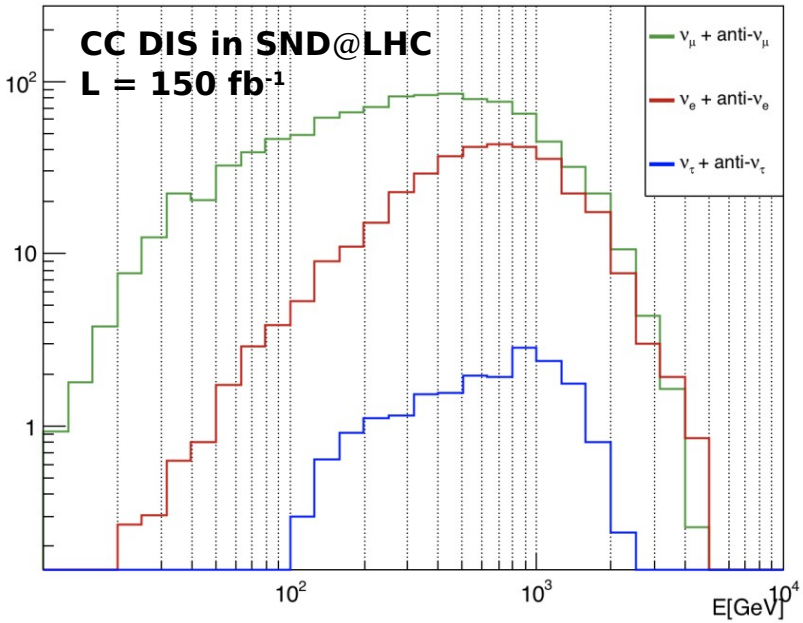




## Energy measurement

- Whole detector acts as a non-homogeneous sampling calorimeter
  - combine information from the SciFi tracker of the Target region and the scintillator bars of the Muon system
  - overall fractional resolution is 22%
- Energy reconstruction technique using convolutional neural networks (CNN) is under development

# Expected neutrino flux and interactions




Number of neutrinos in the SND@LHC acceptance

| Flavour | Neutrinos in acceptance ⟨E⟩ [GeV] | Neutrinos in acceptance Yield | CC neutrino interactions ⟨E⟩ [GeV] | CC neutrino interactions Yield | NC neutrino interactions ⟨E⟩ [GeV] | NC neutrino interactions Yield |
|---|---|---|---|---|---|---|
| $\nu_\mu$ | 145 | $2.1 \times 10^{12}$ | 450 | 730 | 480 | 220 |
| $\bar{\nu}_\mu$ | 145 | $1.8 \times 10^{12}$ | 485 | 290 | 480 | 110 |
| $\nu_e$ | 395 | $2.6 \times 10^{11}$ | 760 | 235 | 720 | 70 |
| $\bar{\nu}_e$ | 405 | $2.8 \times 10^{11}$ | 680 | 120 | 720 | 44 |
| $\nu_\tau$ | 415 | $1.5 \times 10^{10}$ | 740 | 14 | 740 | 4 |
| $\bar{\nu}_\tau$ | 380 | $1.7 \times 10^{10}$ | 740 | 6 | 740 | 2 |
| TOT | | $4.5 \times 10^{12}$ | | 1395 | | 450 |

- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in **FLUKA**
  - Tau neutrino production with **PYTHIA8**
- Particle propagation towards detector with the **FLUKA** model of LHC
- Neutrino interactions inside the detector simulated using **GENIE**

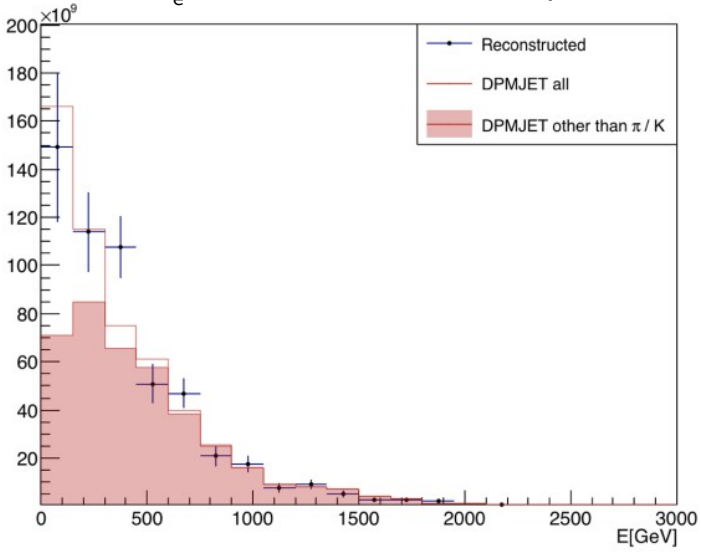
# Physics performance: neutrino physics

## Charmed-hadron production in pp collisions

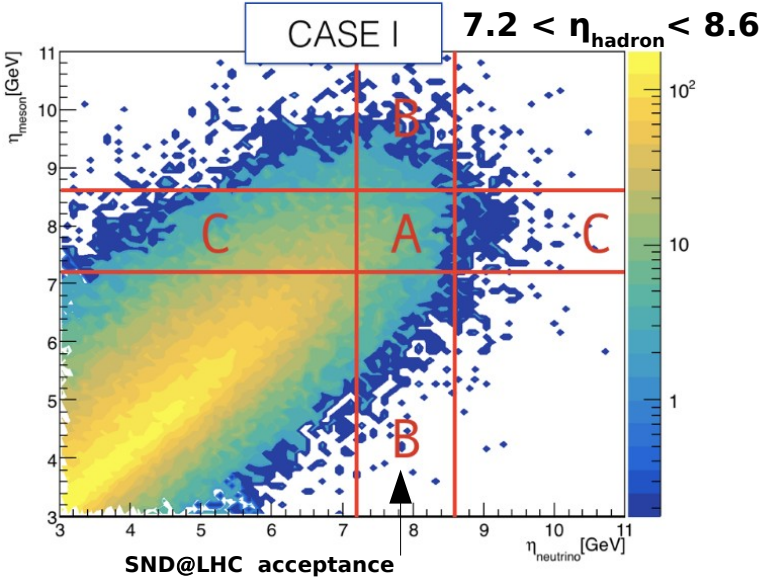
Simulation predicts that 90% $\nu_e$ +anti-$\nu_e$ come from the decay of charmed hadrons

- Measurement of $\sigma_{pp \to \nu_e X}$

Reconstructed energy spectrum of $\nu_e$ and anti-$\nu_e$ in the SND@LHC acceptance



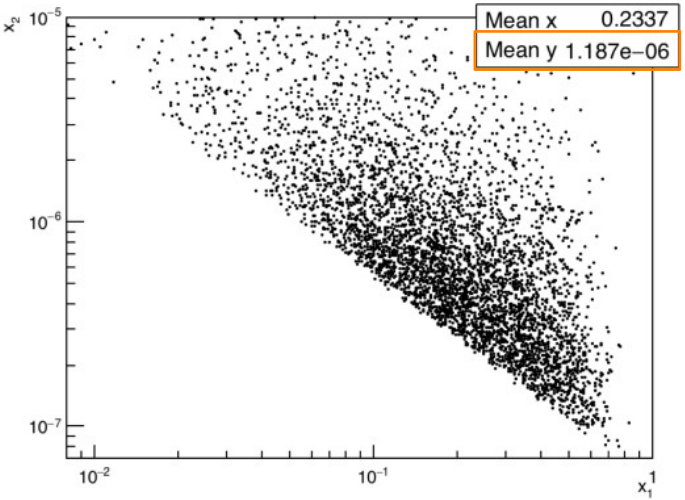

- Derivation of the charmed-hadron yield from the $\nu_e$ flux
  - based on angular correlation between $\nu_e$ and parent charmed hadron



# Physics performance: neutrino physics

## Charmed-hadron production in pp collisions: QCD measurements

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

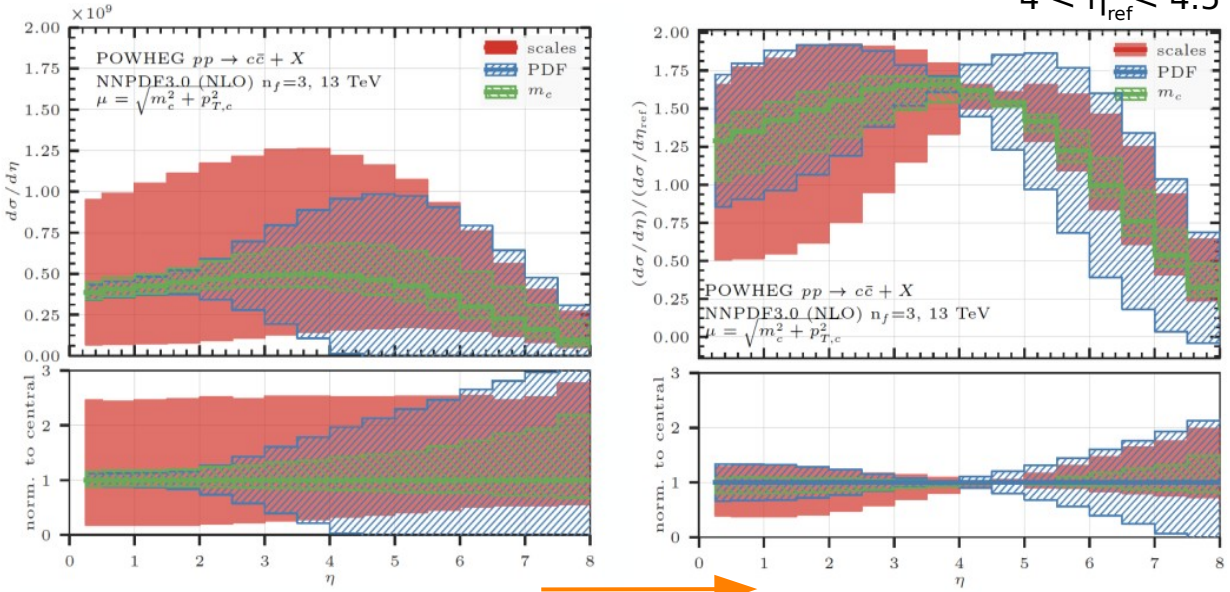



Correlation between $x_1$ and $x_2$ momentum fractions for events in the SND@LHC acceptance

Extraction of gluon PDF in very small x-region relevant for Future Circular Colliders

Constrain PDF with data: $R = \frac{d\sigma/d\eta(13\,TeV)}{d\sigma/d\eta_{ref}(7\,TeV)}$

$4 < \eta_{ref} < 4.5$



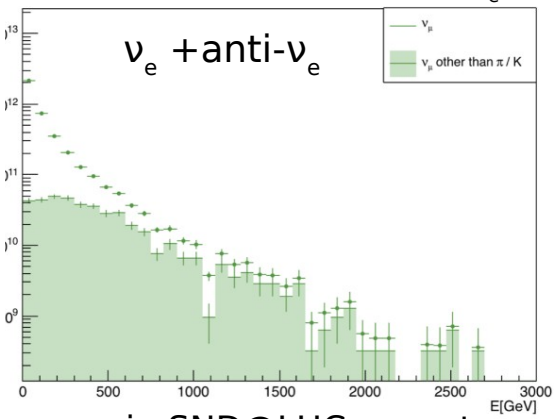

reduction of the scale uncertainty

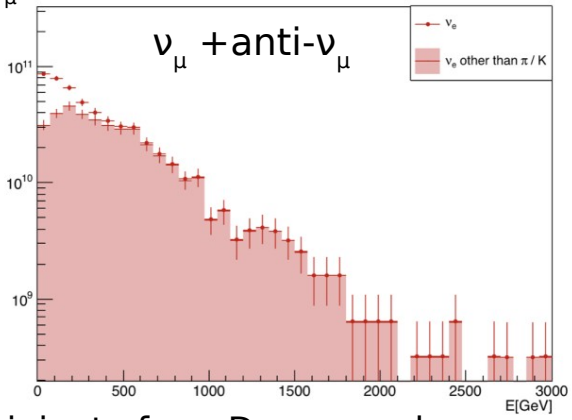
# Physics performance: neutrino physics

## Lepton flavour universality test

Identification of three neutrino flavours in the SND@LHC detector

Energy spectrum of $\nu_e$ and $\nu_\mu$ in the SND@LHC acceptance




- $\nu_\tau$ in SND@LHC acceptance originate from $D_s$ meson decays
- Sensitive to $\nu$ - nucleon cross section ratio for $\nu_\tau$ and $\nu_e$

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

- The measurement of the $\nu_e/\nu_\mu$ ratio can be used as a test of the LFU for E > 600 GeV

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

$\omega_{\pi/K}$ is the $\nu_\mu$ contamination from $\pi$/K
- flat above 600 GeV

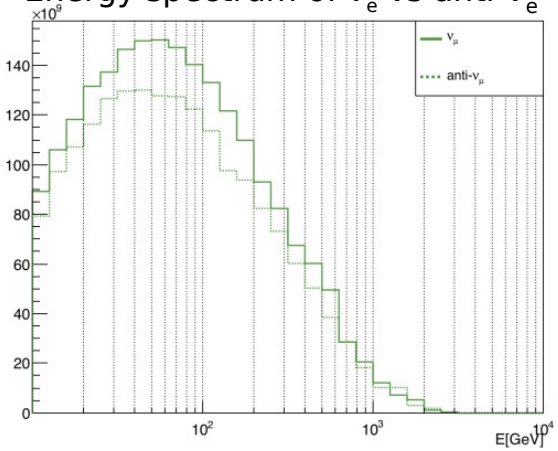
## NC/CC ratio

Lepton flavour identification in the SND@LHC detector

- If differential $\nu$ and anti-$\nu$ energy spectra are equal, NC/CC ratio (P) is

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

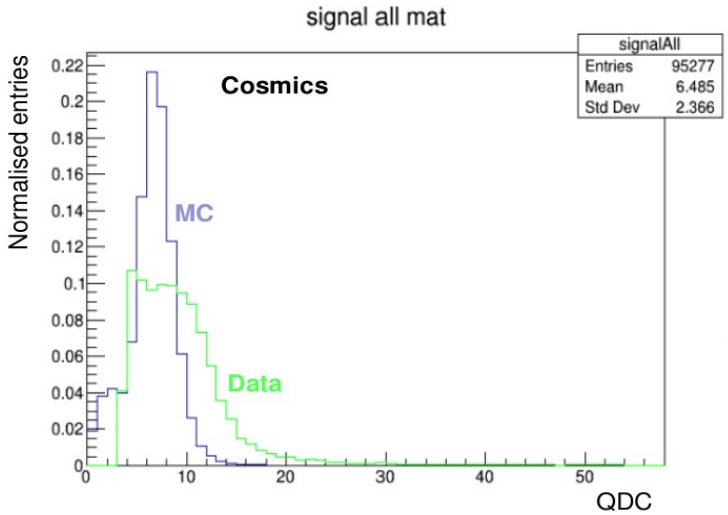
Energy spectrum of $\nu_e$ vs anti-$\nu_e$



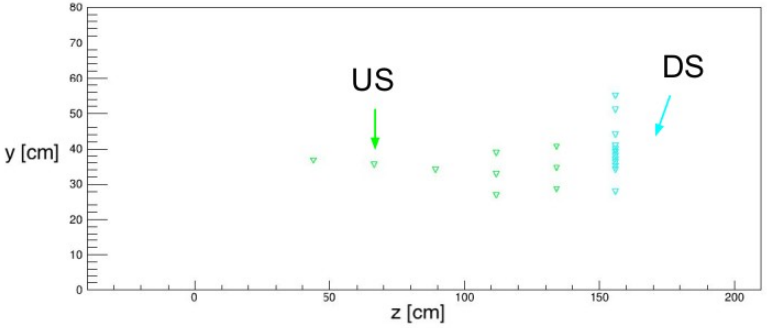

- Compare measured P with the SM expectation
  - NC/CC ratio used as an internal consistency check

# Detector commissioning and tests

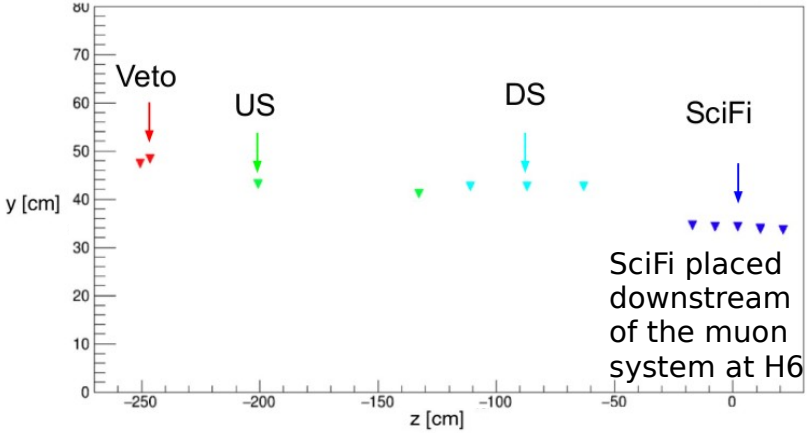
- Successful tests of the SciFi tracker/ECAL using cosmic ray muons (Aug 2021): first test of DAQ and event building, MC parameter tunning
- Test Scifi tracker and also all detectors on muon beam at the CERN SPS H6 beamline - check electronics response
- Test with HCAL/Muon system on pion beam at the CERN SPS H8 beamline (Sep-Oct 2021) - calibration of E measurement with HCAL, important for MC tunning
- Detector installation on site started on Nov 1 and is currently ongoing




EM shower @ H8



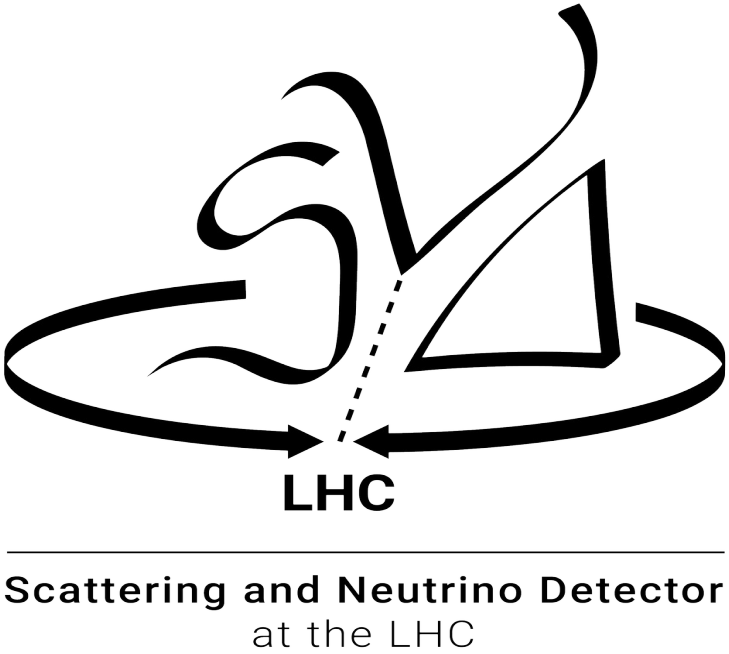

Muon event @ H6



# Summary

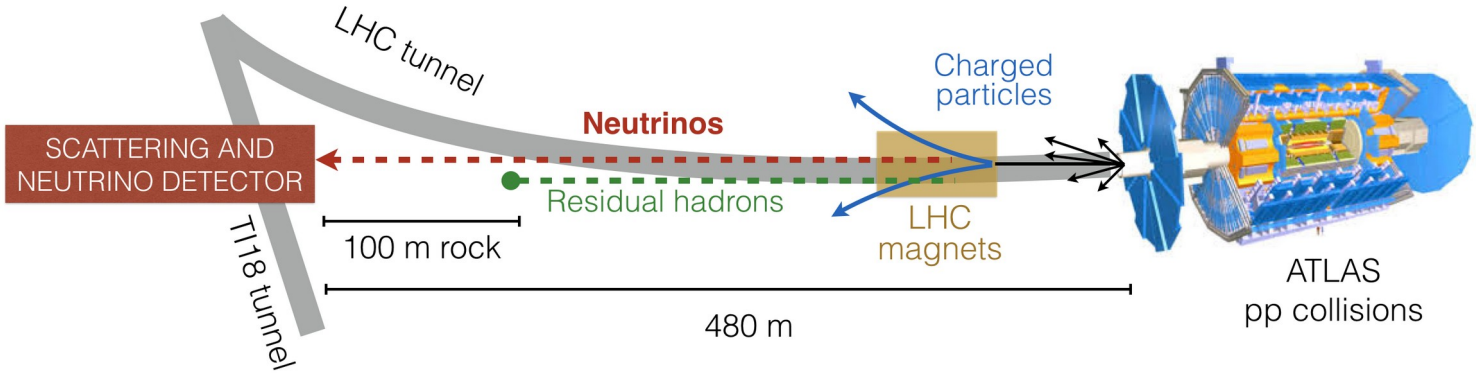
- SND@LHC is on schedule and detector installation is ongoing
- Plan to start taking data in 2022!
- Detector optimized for neutrino searches in a region where they act as a probe of heavy (mostly charm) quark production
- Searches for new particles, sensitivity under evaluation
- A new era of collider neutrino physics is just starting!

# Acknowledgements




This work is supported by the Bulgarian Ministry of Education and Science within the National Roadmap for Research Infrastructures 2020-2027, contract No. D01-374/18.12.2020

# Location




- TI18 tunnel: former service tunnel connecting SPS to LEP
- Symmetric to TI12, where FASER is located
  - In situ background measurement performed by the FASER Collaboration
- About 480m away from ATLAS IP:
  - ~100m of rock serve as a shield
  - Charged particles deflected by LHC magnets

**Installation in TI18**

# Backgrounds in the TI18

- Exists a detailed FLUKA simulation of proton beams transport along the LHC
  - rate in SND@LHC acceptance: $2 \times 10^4$ particles/cm$^2$/fb$^{-1}$
- Measured particle fluxes in TI18 for FASER during Run 2: $1.2-1.9 \times 10^4$ particles/cm$^2$/fb$^{-1}$
- Backgrounds essentially composed of
  - Muons: only those with E >30 GeV reach the detector:
    - veto detector to tag them
    - exchange emulsion every 25fb$^{-1}$
  - Neutrons and $K_L$s from muon DIS in rock: mimic neutrino NC
  - Thermal neutrons
    - Coming from proton beam interaction with the residual gas inside the LHC vacuum pipe, beam 2 contributes more
      - 50% are thermal neutrons at ~0.025 eV
    - Total flux is $2.8 \times 10^8$ particles/cm$^2$/year
      - allows using non-radiation-hard electronic devices
      - place neutron shield around the emulsion detector

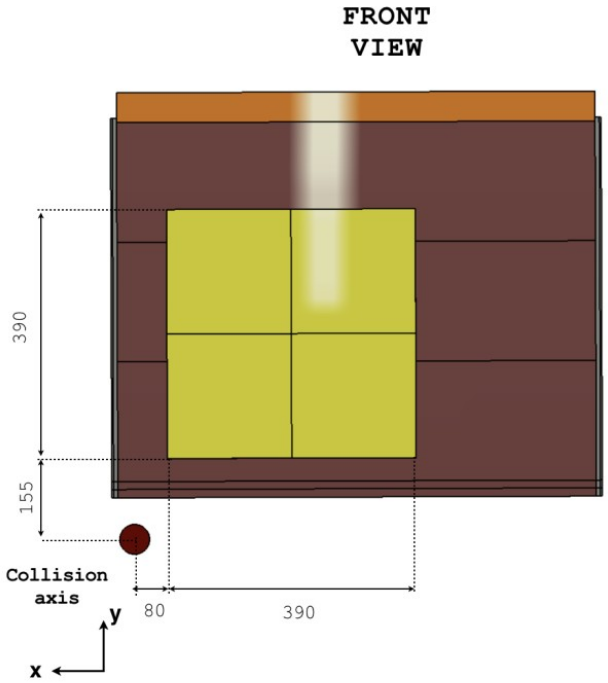
| particles/fb$^{-1}$ | E>10 GeV | E>100 GeV | E>200 GeV | E>500 GeV |
|---|---|---|---|---|
| $K_L$ | 48 | 11.7 | 4.4 | 0.5 |
| neutron | 17 | 5.4 | 2.0 | 0.5 |
| anti-neutron | 12 | 3.3 | 1.5 | 0.1 |

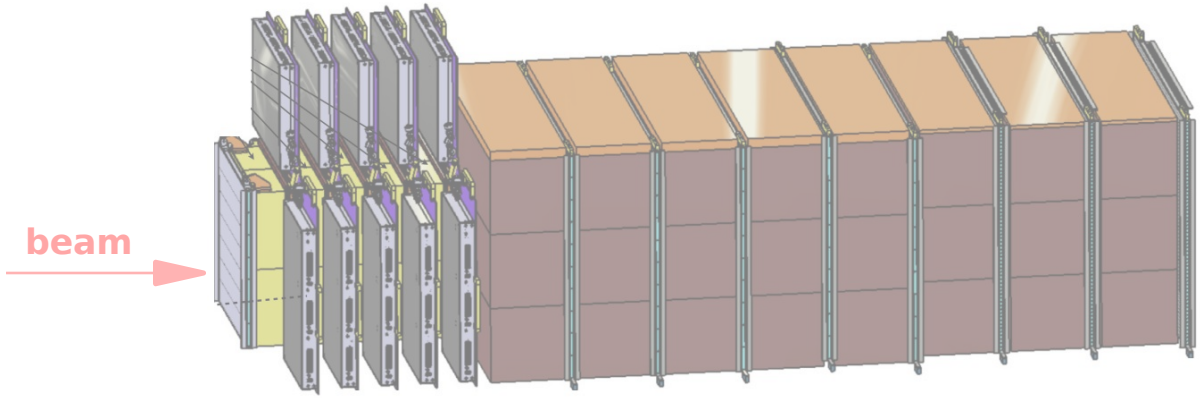
# Off-axis position

- Detector is off-axis wrt the collision axis: neutrino yields depend on the pp beams crossing angle ( ±150 mrad )

| case | Upward beam crossing | Downward beam crossing | 0 beam crossing angle |
|---|---|---|---|
| N observed υ interactions wrt nominal (0 angle) | 18% | -22% | - |
| η | 7.3 – 9.0 | 7.1 – 8.3 | 7.2 – 8.6 |

background control



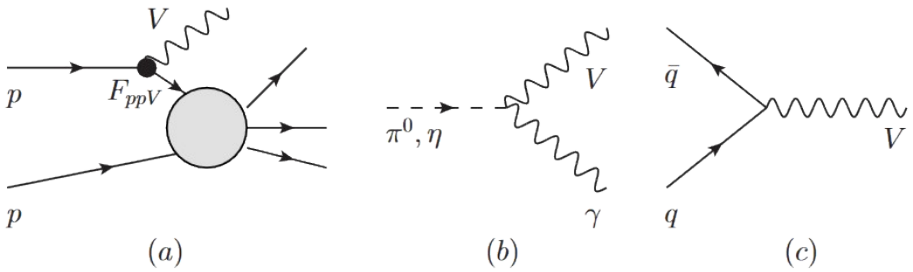
# Physics performance: neutrino physics

Summary of physics results: expected precision

| Measurement | Uncertainty Stat. | Sys. |
|---|---|---|
| $pp \to \nu_e X$ cross-section | 5% | 15% |
| Charmed hadron yield | 5% | 35% |
| $\nu_e/\nu_\tau$ ratio for LFU test | 30% | 22% |
| $\nu_e/\nu_\mu$ ratio for LFU test | 10% | 10% |
| NC/CC ratio | 5% | 10% |

# Physics performance: new physics searches

Mediator (V) production channels: $pp \to V + X$




proton bremsstrahlung

decay of unflavoured mesons

Drell-Yan process

$$V \to \chi\chi$$

Mediator decays to
- a scalar particle χ coupled to the Standard model via a *leptophobic portal* :

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

$J^B_\mu$ baryonic current $\quad J^B_\mu = \frac{1}{3} \sum \bar{q} \gamma_\mu q$

χ scattering off nucleons : number of events scales as $\alpha_B^3$