SND: A new neutrino detector at the LHC

Federico Lasagni Manghi on behalf of the SND@LHC collaboration

Innovative Detectors Technologies and Methods, 12-14 Sep 2023, Lisboa

Overview and references

- Neutrino research and neutrinos @ LHC
  - Comparison with cosmics and accelerator experiments
- SND goals and design strategies
- The detector
  - Veto, emulsions, calorimetry and muon tracking
  - DAQ and online system
- Results
- Current activities and future upgrades

LHC

Scattering and Neutrino Detector
at the LHC

Techincal proposal:
https://cds.cern.ch/record/2750060/files/LHCC-P-016.pdf
Neutrino observation:
https://doi.org/10.1103/PhysRevLett.131.031802

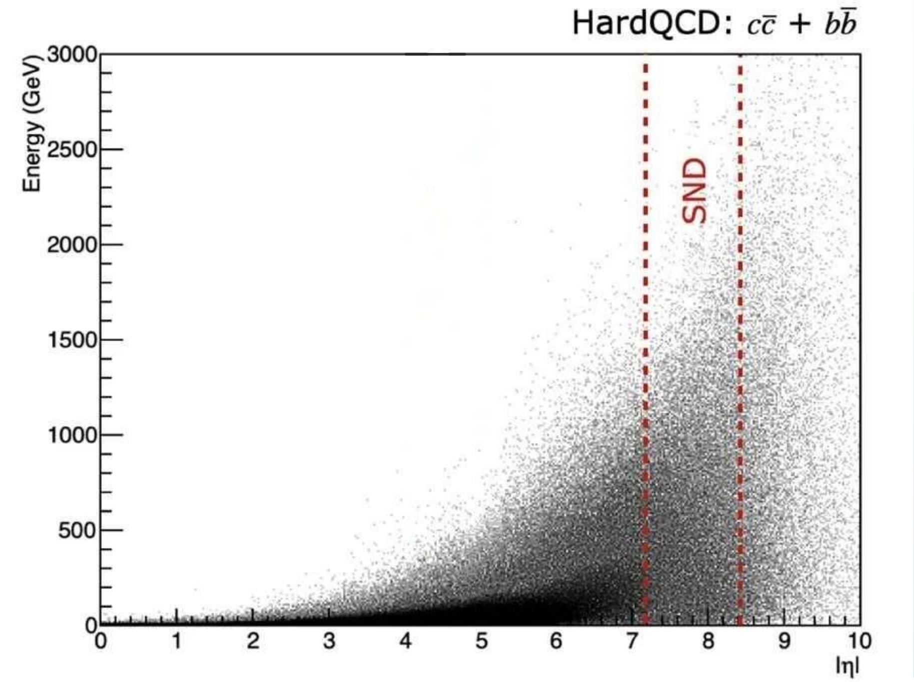
Neutrinos @ LHC

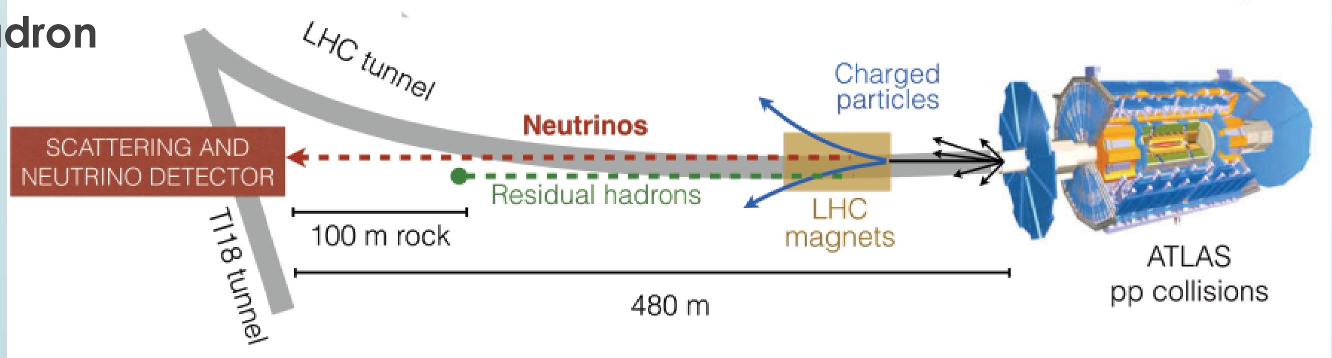
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield	NC neutrino interactions ⟨E⟩ [GeV]	Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	760	250	720	80
$\bar{\nu}_e$	363	3.8×10^{11}	680	140	720	50
ν_τ	415	2.4×10^{10}	740	20	740	10
$\bar{\nu}_\tau$	380	2.7×10^{10}	740	10	740	5
TOT		4.0×10^{12}		1690		555

- Large ν flux at LHC
- $\sigma DIS_\nu \propto E_\nu (E_\nu \in [10^2, 10^3]$ GeV)
- Small detectors can capture a sizeable number of interactions (for ex: @250 fb^{-1})

Two experiments are active at opposing sides of the ATLAS interaction point IP1:

- FASERν $\eta > 9$
- SND@LHC $7.2 < \eta < 8.4$
  - **Maximised charmed (and b) hadron contribution**
  - Located at TI18, 480 m away from the ATLAS IP





Goals and deisgn strategies

Goals:

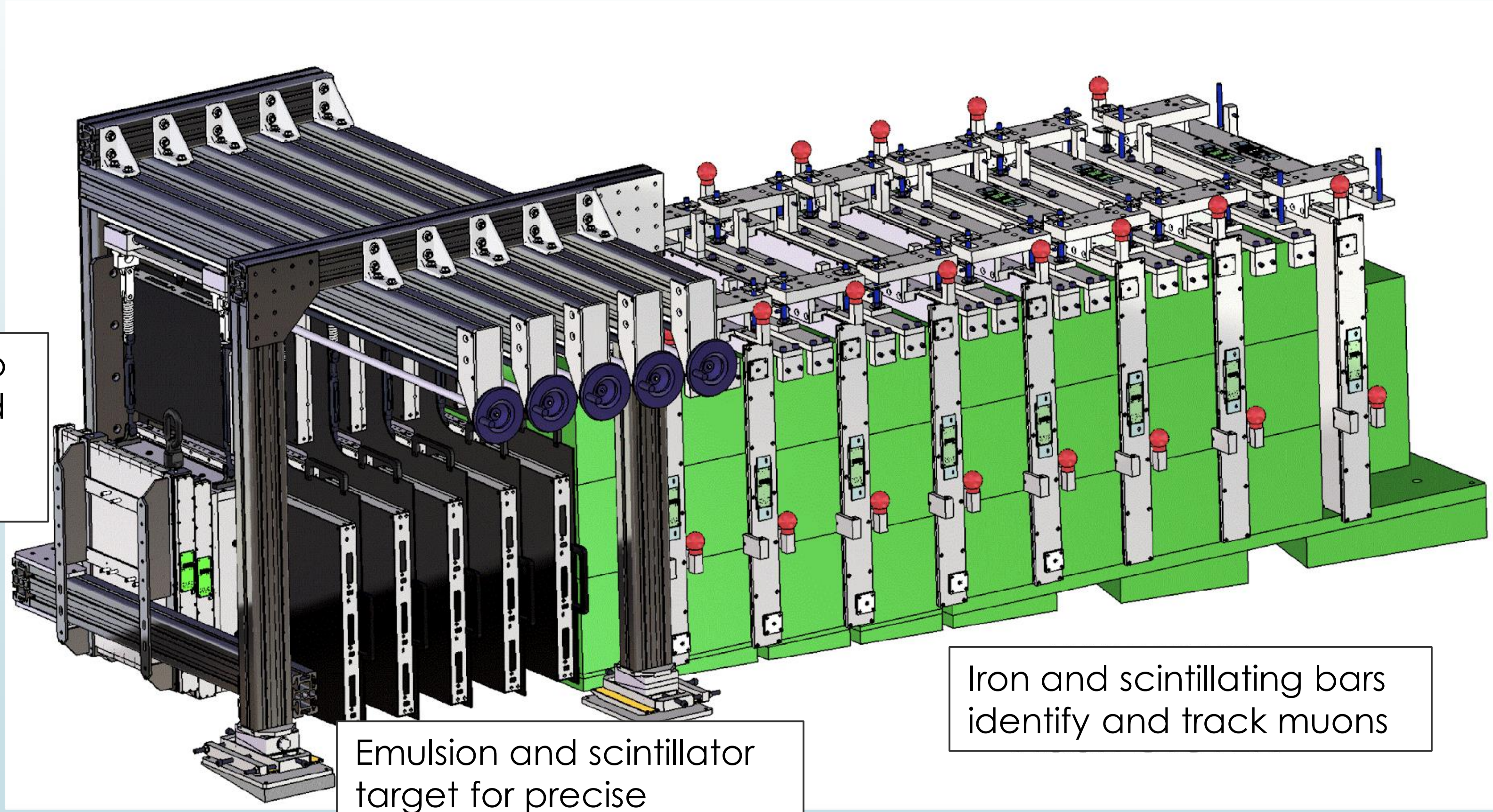
- **Charmed-hadron production in pp collisions**
- **Lepton flavour universality test in ν interactions**
  - Requires identification of ALL neutrino flavors with high efficeincy
- **Measurement of the NC/CC ratio**
- **Search for Feebly Interacting Particles (relic Dark Matter candidates):**
  - Direct scattering off electrons complementary to missing Et searches

Detector design:

- a VETO system to reject background
- a timestamp and energy measurement system
- a vertex detector with enough resolution to disentangle the neutrino-interaction vertex from the one of the tau-lepton decay;
- a muon system to identify the muon produced in ν_μ CC interactions and in the muonic decay of the tau lepton.

Detector design

Hybrid design combining nuclear emulsion technology and electronic detectors



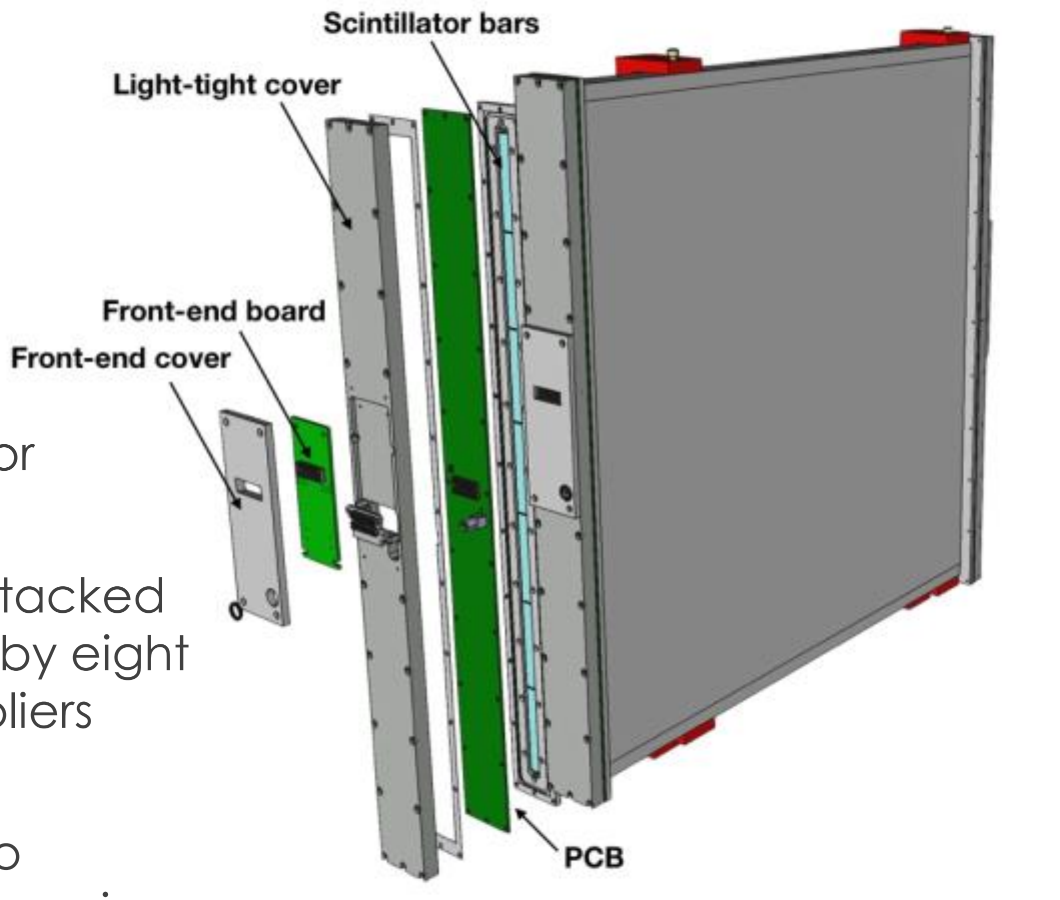
Veto scintillation planes to remove direct muons and particles produced in the rock interactions

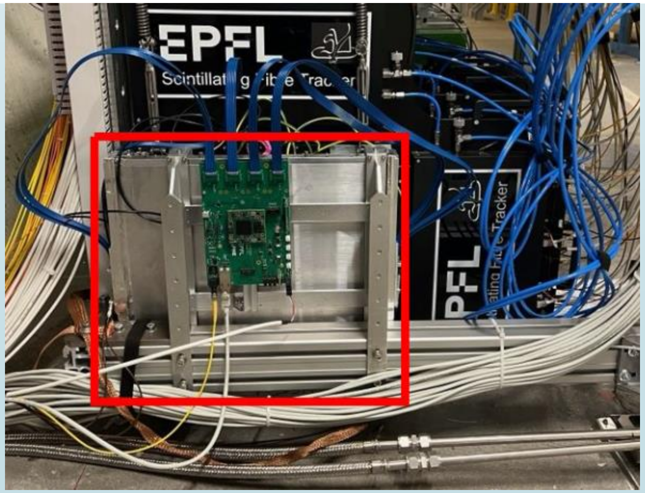
Emulsion and scintillator target for precise vertexing, calorimetry and timing

Iron and scintillating bars identify and track muons

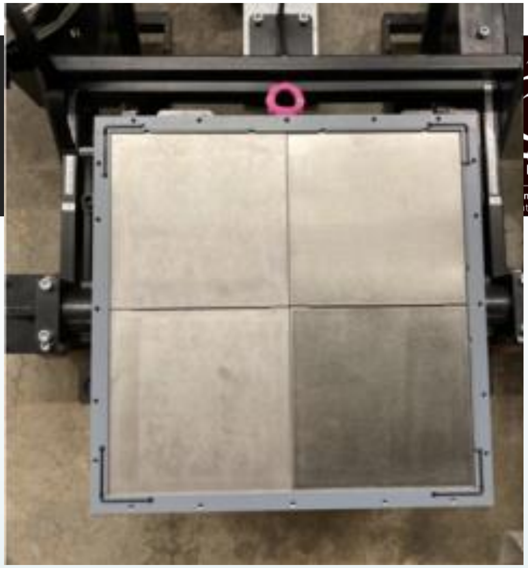
Veto

- Rejects charged particles entering the detector acceptance, mostly muons coming from IP1
- Two parallel planes, located 4.3 cm apart, of stacked EJ-200 scintillating bars read out on both ends by eight Hamamatsu S14160-6050HS silicon photomultipliers (SiPMs) mounted on a custom PCB
- Inefficiency of the coincidence of the two veto detector planes, was estimated at 7.0×10^{-7} (worse in the first period of data taking)
- Mostly due to SiPM dead-time

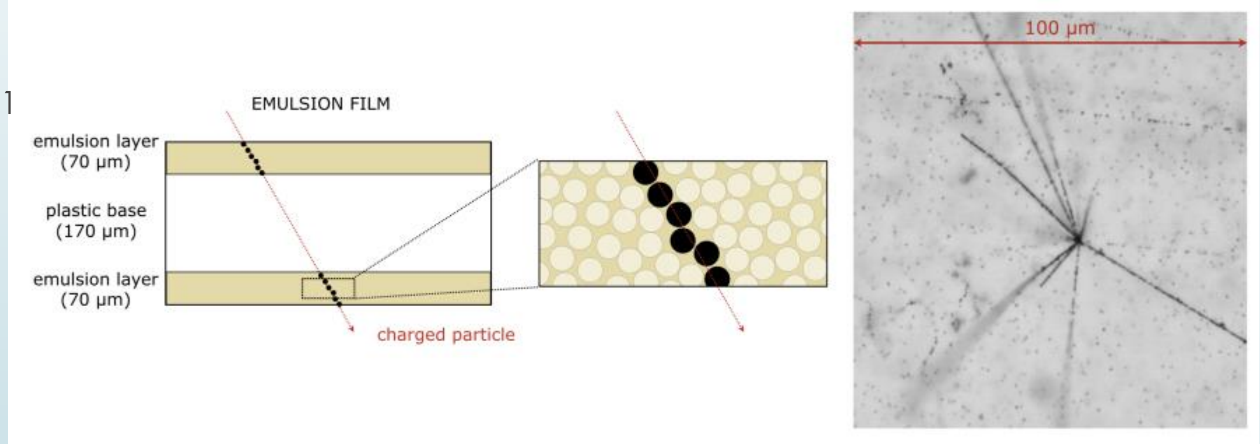




Target and vertex detector

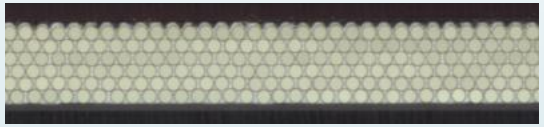


- Target based on the Emulsion Cloud Chamber (ECC) technique
- 5 emulsion brick walls, each made of 4 bricks:
  - Every 192 × 192 mm^2 brick is made of 60 films and 59 1mm tungsten layers
- Emulsions are replaced every $\sim 20\ fb^{-1}$
- Read one by one using automated optical microscopes
- Resolutions: sub-micrometric position and milliradian angular
- A neutron shield and cold box was built to protect the emulsions

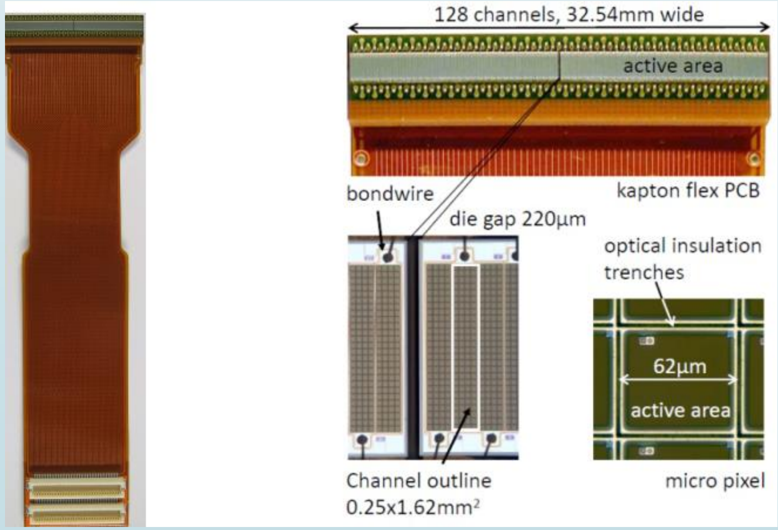


SciFi and EM calorimetry

- The Target Tracker system is made of five scintillating fibre (SciFi) planes interleaving the five target walls with a ~150 µm spatial and 250 ps time resolutions
- The fibre mat is composed of six layers of fibres glued with a titan oxide loaded epoxy glue to suppress cross talk between fibres.



- Readout:
  - S13552 SiPM multichannel arrays by Hamamatsu at the end of the fibre module
  - Kapton flex PCB holding the photo-detector



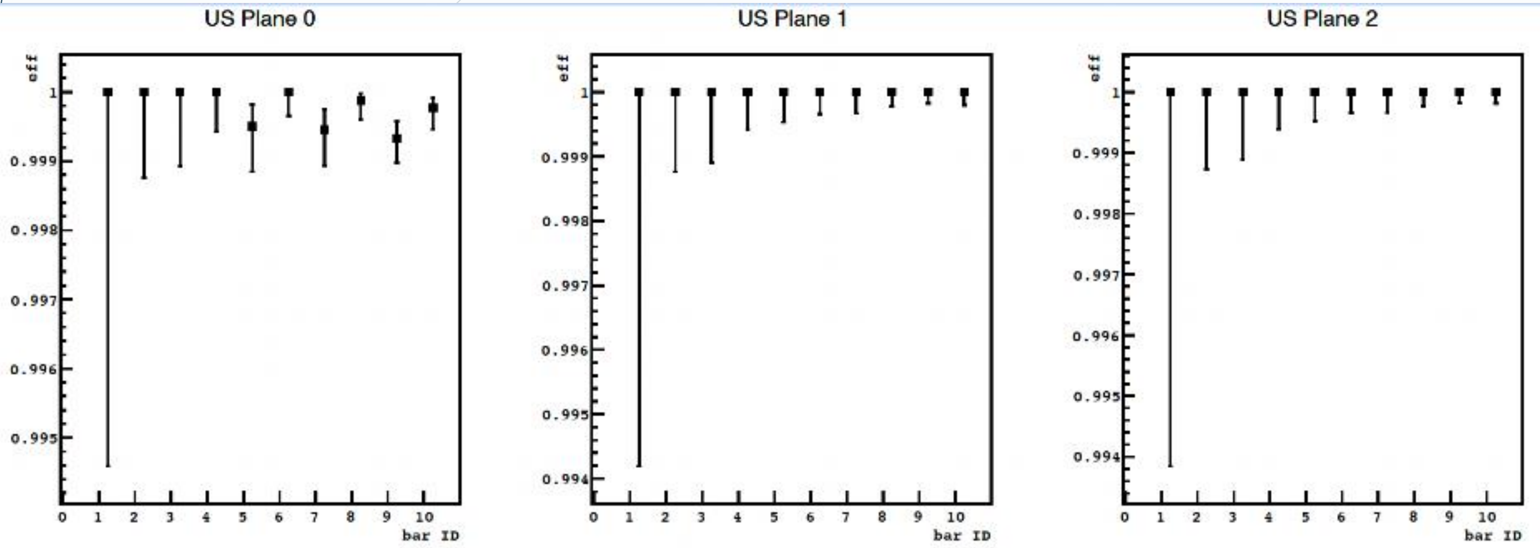
- Emulsion and SciFi make up a sampled electromagnetic calorimeter with an average thickness of about 40 X_0
- (see Guilherme's talk for details and performance)

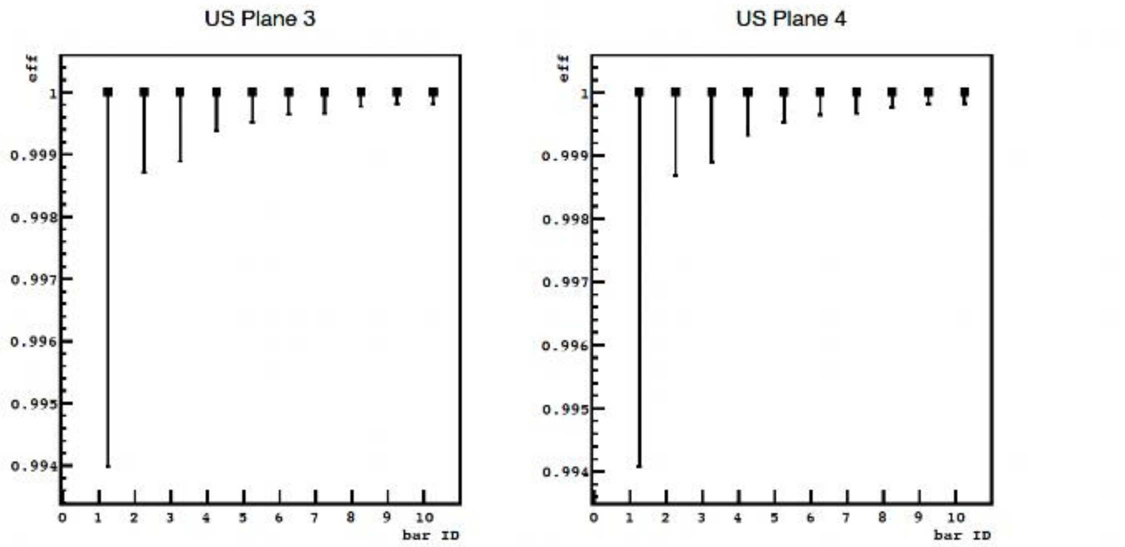
https://indico.lip.pt/event/1491/contributions/5115/attachments/4137/6476/IDTM_SND_SciFi.pdf

Muon system and hadronic calorimeter

- Eight layers of scintillating planes interleaved with 20 cm-thick iron slabs
- Passive material thickness 9.5λint (11λint total)
- The first five upstream layers (US) are made of 6 cm-thick horizontal scintillating bars
- The last three downstream layers (DS), made of fine-grained horizontal and vertical scintillating bars
- The DS layers act as precision tracking for the muons, identified as the tracks that cross all layers
  - spatial resolution of less than 1 cm

Calorimeter preliminary performance

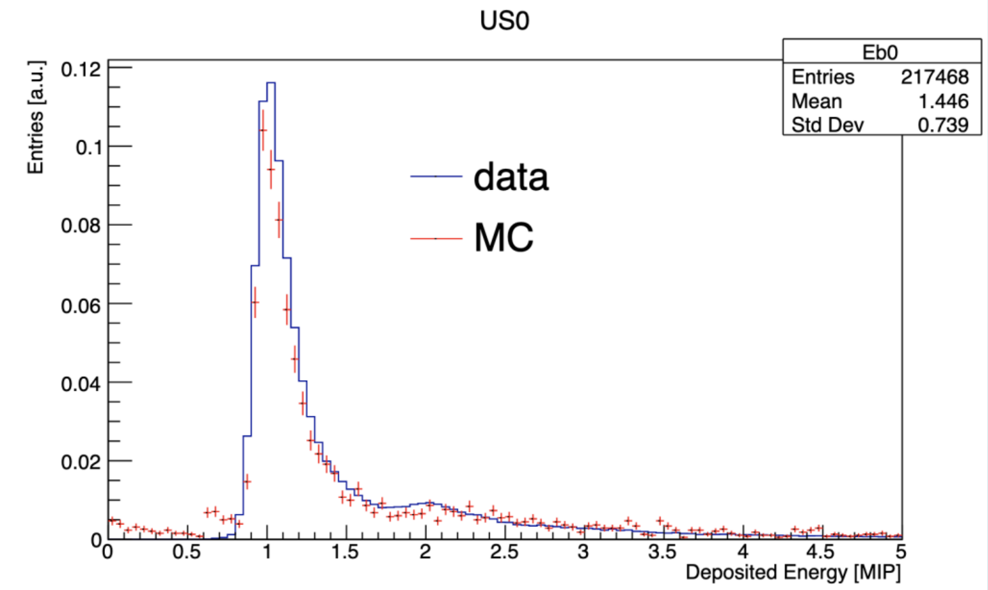




Preliminary Run 3 studies

Very high efficiency in upstream detector measured with LHC Run 3 data

Good MIP energy deposition model

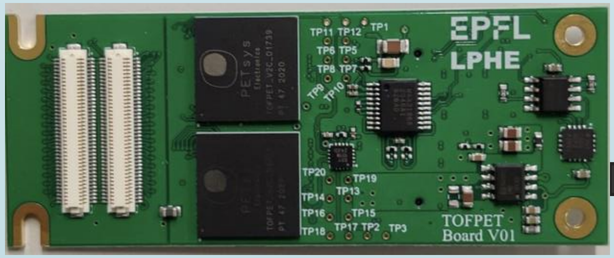


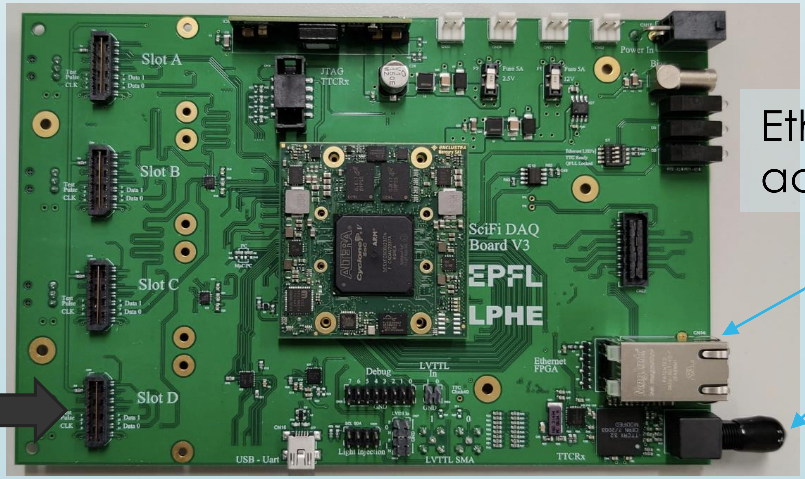
The detector

DAQ and online system

- Sub-systems are read out with the same DAQ electronics:
  - 37 DAQ boards based on the Mercury SA1 module from Enclustra featuring an Altera Cyclone V FPGA
  - Up to four front-end (FE) boards per DAQ board, based on the TOFPET2 ASIC, by PETsys
  - Up to 512 read out channel per DAQ board
- TTC system receiving LHC clock and orbit data for synchronization
- Online luminosity taken from the data stream from ATLAS to LHC

SiPM connectors





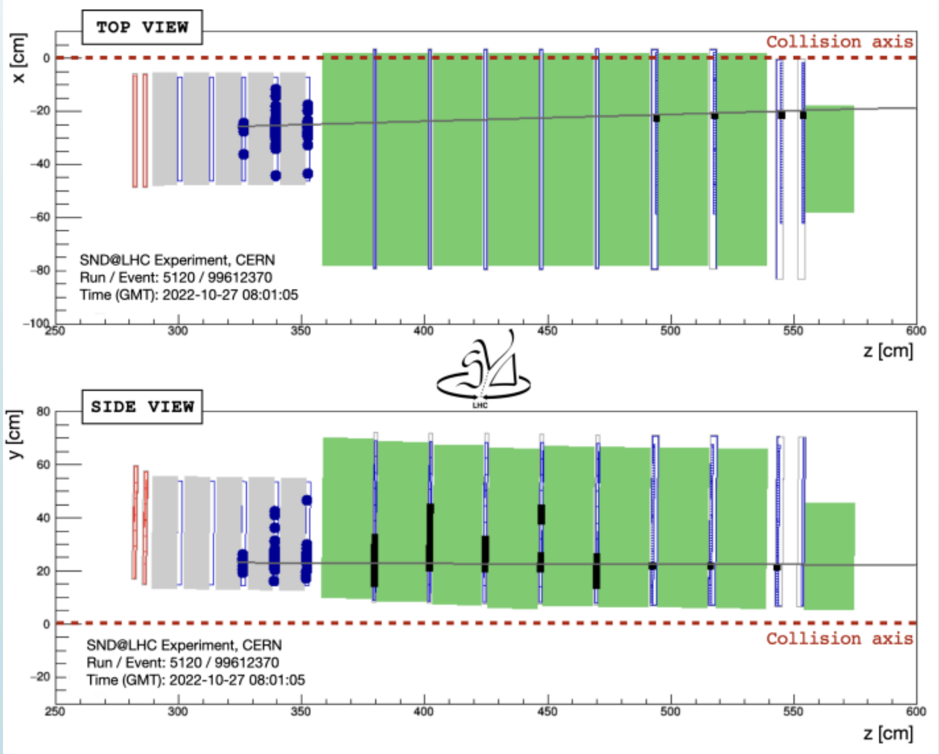
Ethernet acquisition

Optical TTC: LHC clock and timing info

Neutrino observation

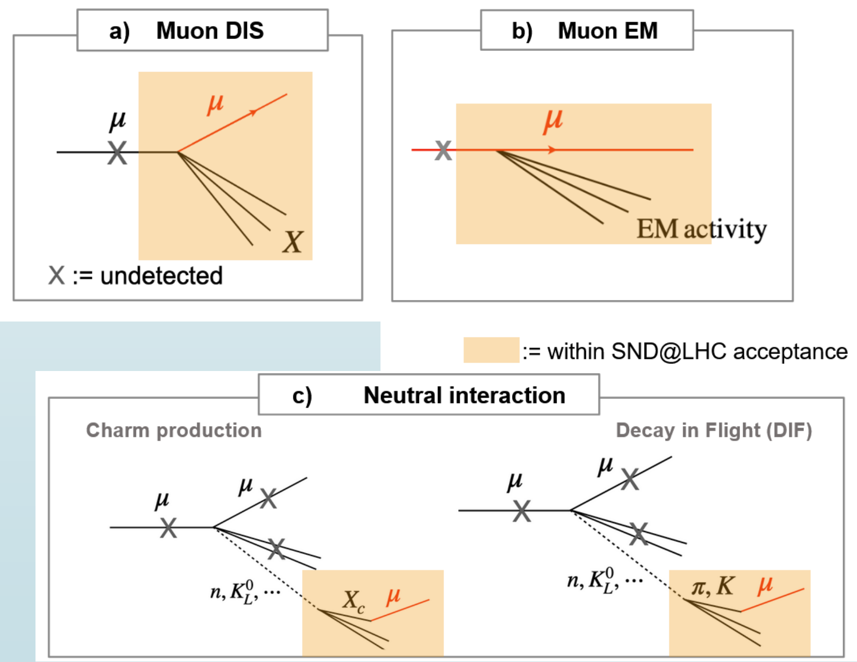
- Published paper on the 2022 pp data at 13.6 TeV (https://doi.org/10.1103/PhysRevLett.131.031802)
- Delivered integrated luminosity during this period, estimated by ATLAS, was 38.7 fb^{-1}
  - 36.8 fb^{-1} recorded (95% up-tim)
  - The data set comprises a total of 8.3×10^{9} events.
- First observation of ν_μ CC interactions, using the data from the electronic detectors
- High energy of the ν_μ s -> dominant CC process = deep inelastic scattering (CCDIS)
- Signature: isolated muon track in the muon system associated with a hadronic shower detected in the SciFi and hadronic calorimeter

Candidate event →



Analysis and backgrounds

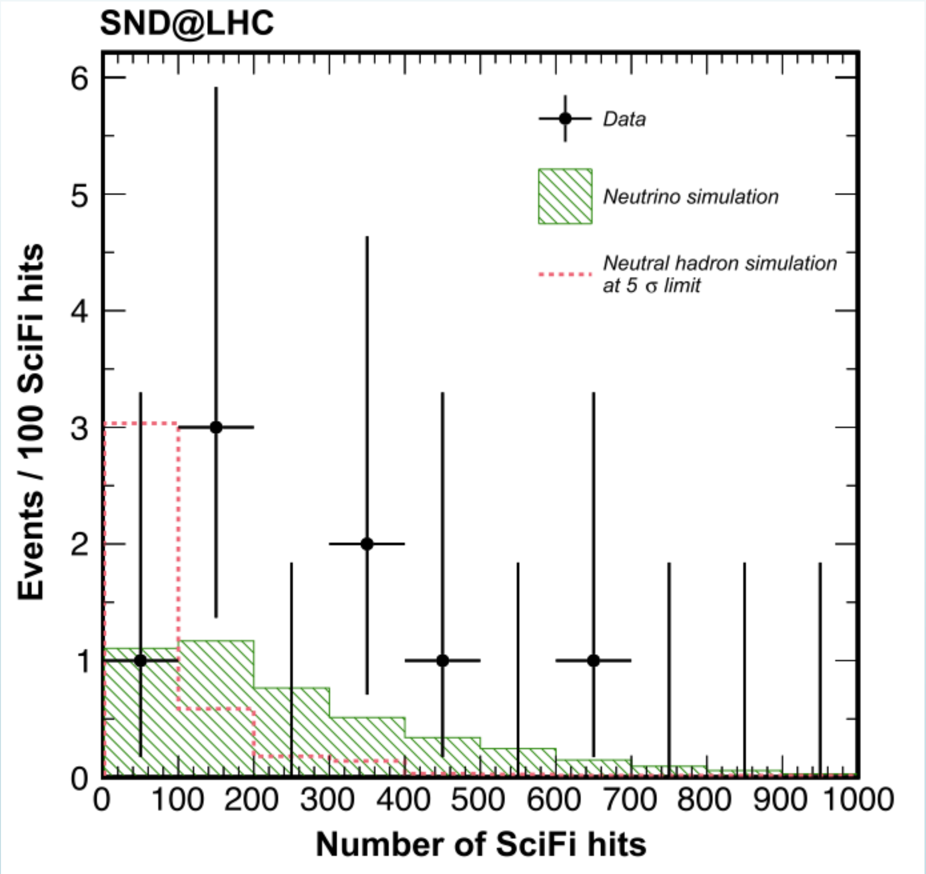
- Cuts are applied on the hit multiplicity in the veto and SciFi planes:
  - Select events in the 3rd or 4th target wall and consistent with a neutral particle interaction.
  - Discard events at the edge of the detectors: 25 × 26 cm^2 xy fiducial area, ε= 7.5%
- Large hadronic activity in the calorimeter and clean outgoing muon track from p1
- Overall rejection factor 10^9, efficiency on the ν_μ CCDIS Monte Carlo sample: 2.7%
- Background: $(8.6 \pm 3.8) \times 10^{-2}$ dominated by neutrons and K_L^0 s, 44% uncertainty



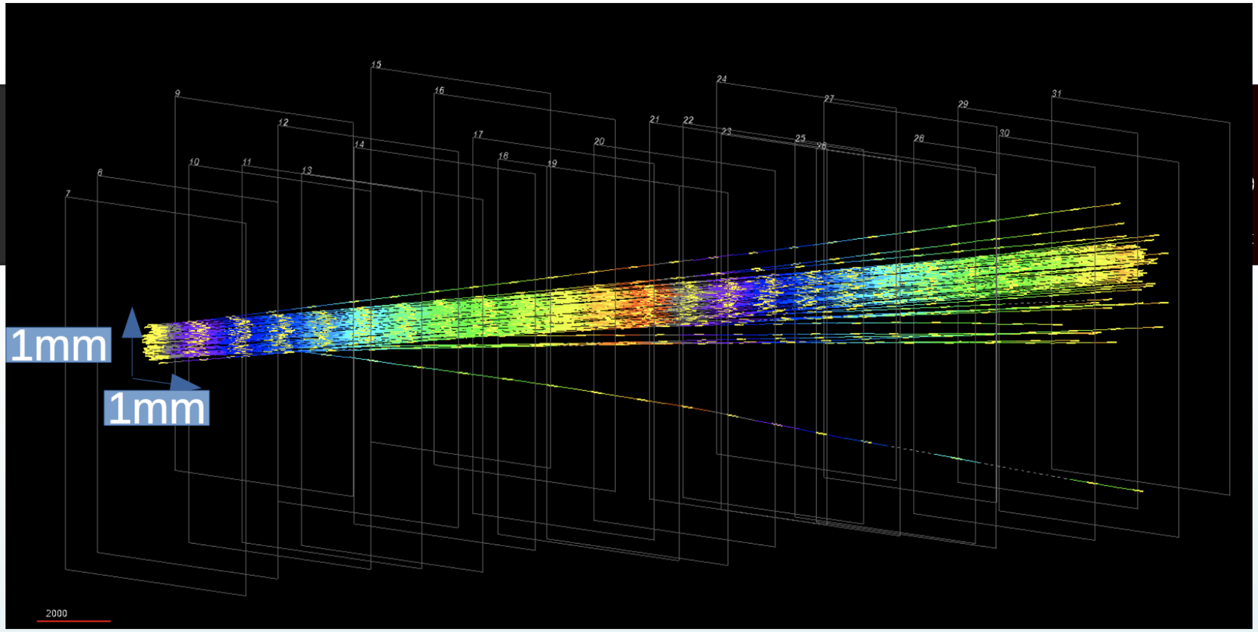
Result

- 8 $\nu\mu$ CCDIS candidates identified, 4.5 expected, <1% contamination
- Neutrals have fewer SciFi hits
  - Not used in the selection, but powerful discriminant
- Exclusion of the background-only hypothesis at the level of 6.8 standard deviations
- First observation in the $7.2 < \eta < 8.4$ region

Now onto the 2023 data (31.8 fb^{-1}, 99.7% uptime)

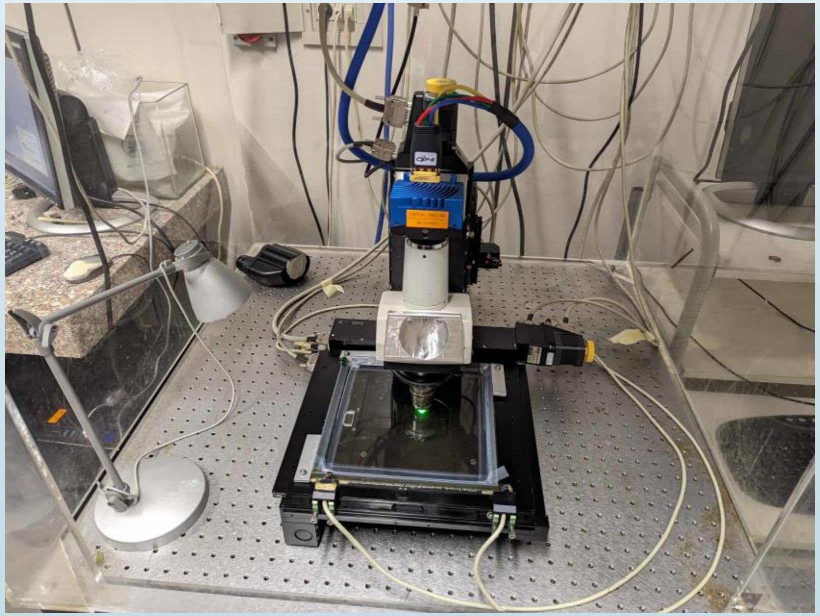


Emulsion scans



Tracks going through 1 x 1 mm2 in 0.52 fb-1

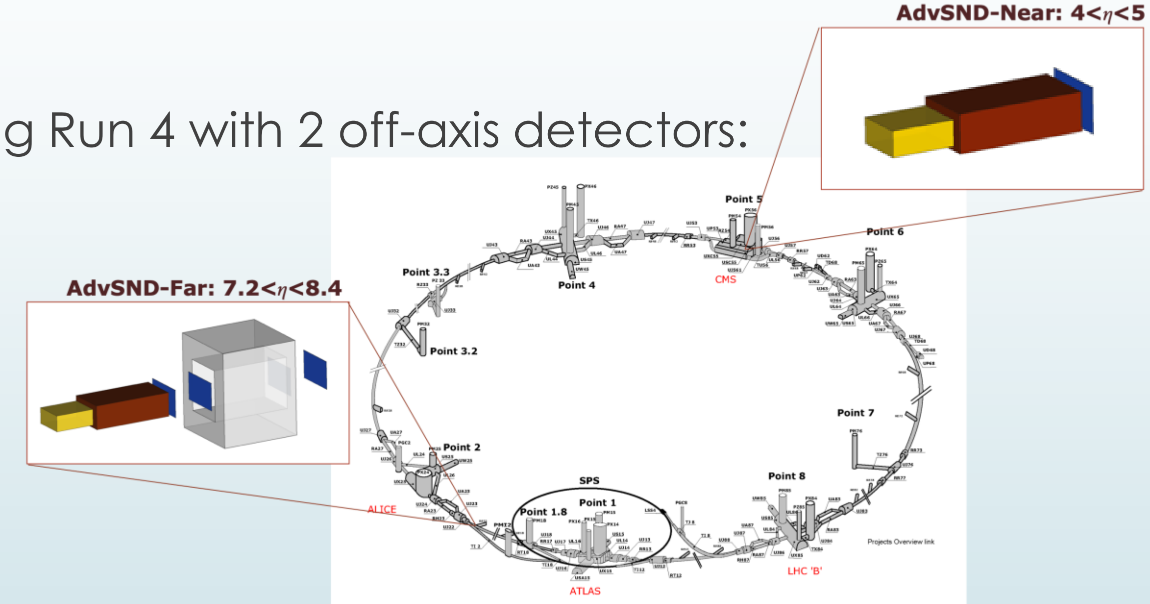
- Emulsion films swapped every 20 fb^{-1}
- Automated scanning process using optical microscopes
  - @ CERN, Bologna, Lebedev, Napoli
- In the process of increasing the number of microscopes
  - Each one scanning one film per day
  - Analysis of the emulsion data under way

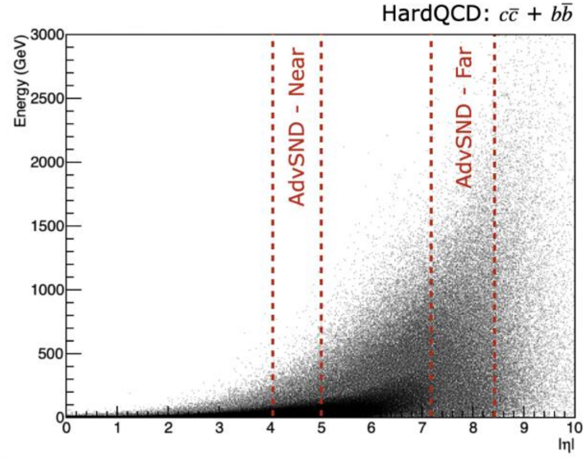


Upgrade for HL-LHC

Upgrade of SND@LHC - extended run during Run 4 with 2 off-axis detectors:

- AdvancedSND-Far: $7.2<\eta<8.4$
  - Acceptance similar to SND@LHC
  - Charm production measurements
  - Lepton flavour universality
- AdvanceSND-Near: $4<\eta<5$
  - Overlap with LHCb pseudo-rapidity coverage
  - Reduction of systematic uncertainties
  - Provide normalization for neutrino physics studies
  - Neutrino cross-section measurements





Conclusions

- Accelerator neutrinos can cover an energy range that was not probed in other kinds of experiments
- High cross section and flux allow observations with relatively compact detectors
- SND@LHC has a wide physics program thanks to the hybrid electronic and emulsion design
- The observation of muon neutrinos using the electronic detectors was published
  - 8 neutrinos observed with <1% estimated BG contamination
- Emulsion scans are in in progress to get precision vertex reconstruction
- For HL-LHC a double detector is planned, covering a complementary η range

Thank you for your attention!

LHC

Scattering and Neutrino Detector
at the LHC

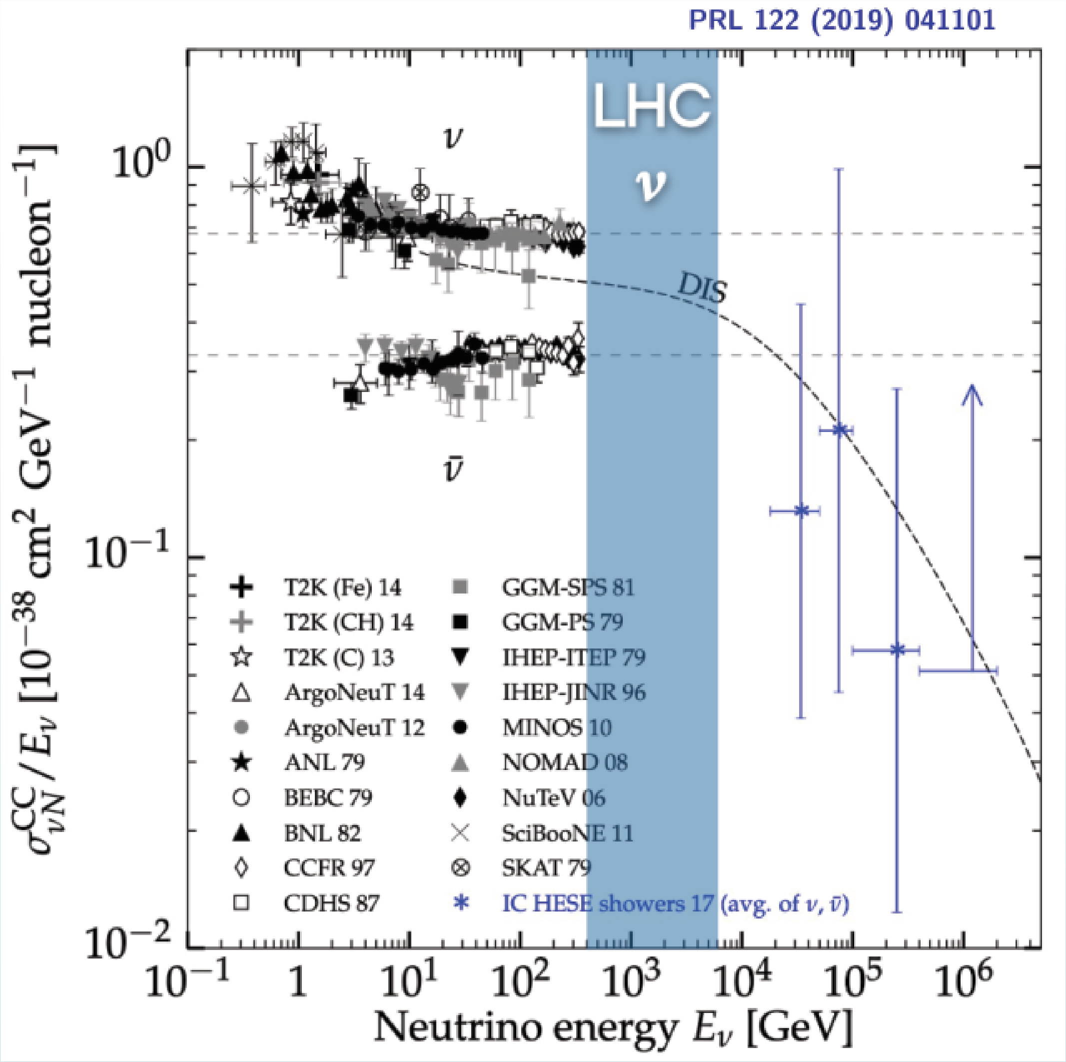
Backup

LHC

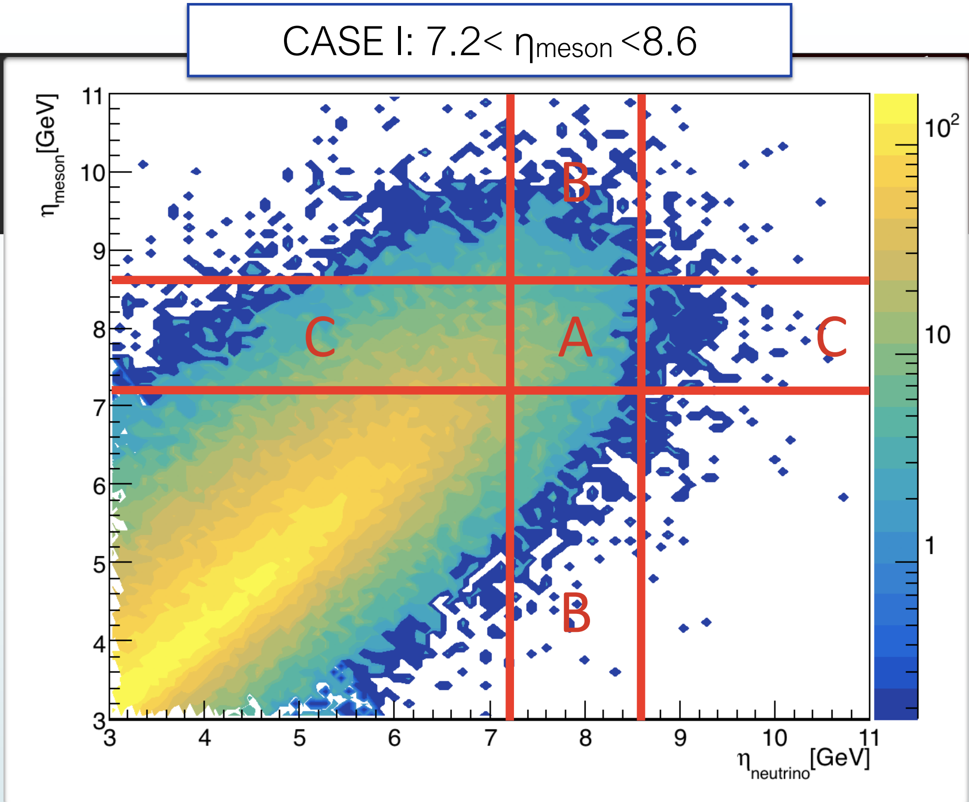
Scattering and Neutrino Detector
at the LHC

Neutrinos

- Interest in neutrinos at the LHC since the ‘80s
- Low energy neutrino interactions studied extensively in many experiments
  - Nuclear PP, solar, etc
- Very high enery cosmic neutrinos recently published by Ice Cube
- At high neutrino energy ($E_\nu \in [10^2, 10^3]$ GeV), $\sigma DIS_\nu \propto E_\nu$



Goals



Charmed-hadron production in pp collisions

- ν_e as a probe of the charm production
- Leading contribution to the uncertainty: 35% systematic error due to the K contribution, unfolding and simulation uncertainties

Lepton flavour universality test in ν interactions

- ν_e/ν_τ depends only on the c hadronisation fractions and decay BRs -> can be considered a lepton flavour universality test in neutrino interactions (30% accuracy)
- ν_e/ν_μ ratio as a lepton flavour universality test in neutrino interactions (15% err)

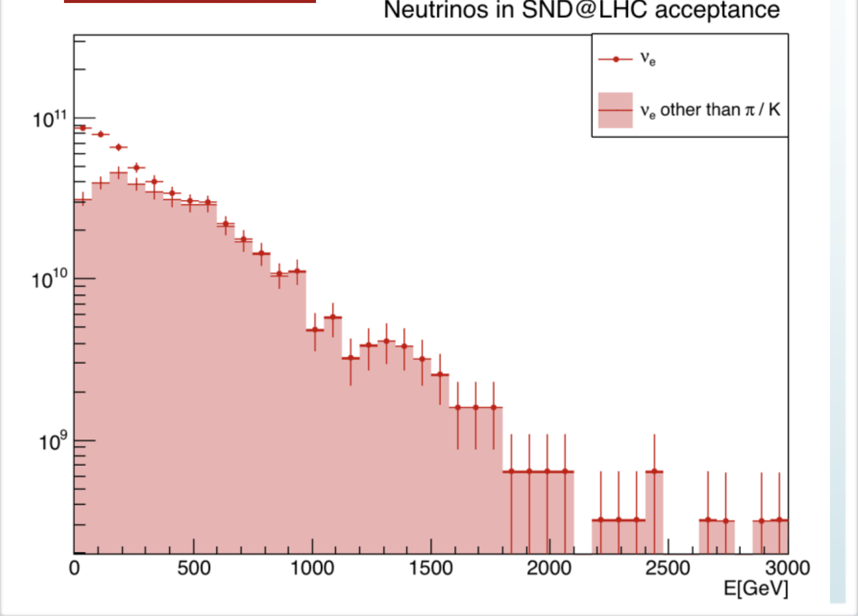
$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i} \tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s} \tilde{Br}(D_s \to \nu_\tau)},$$

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

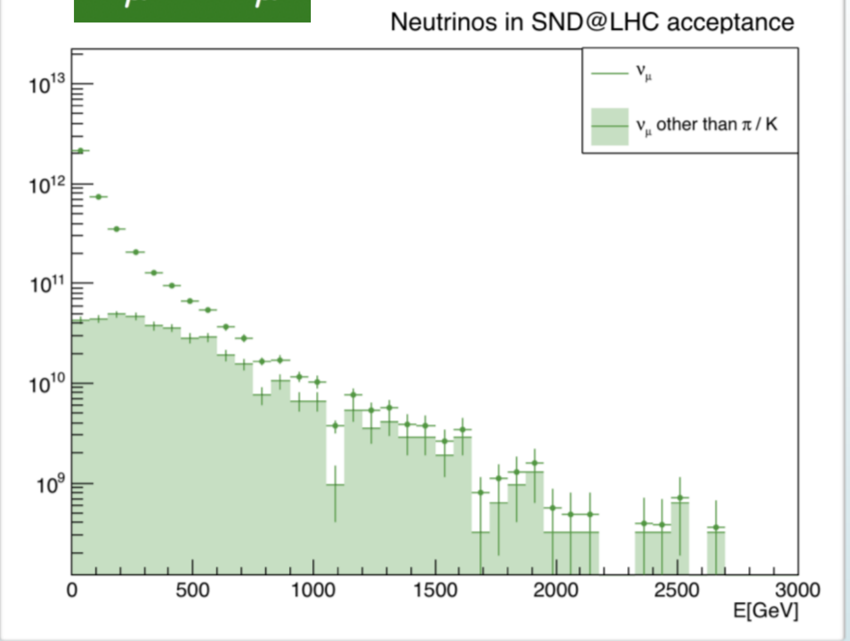
contamination from π/k

Lepton Flavour Universality Test

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



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



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

contamination from π/k

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

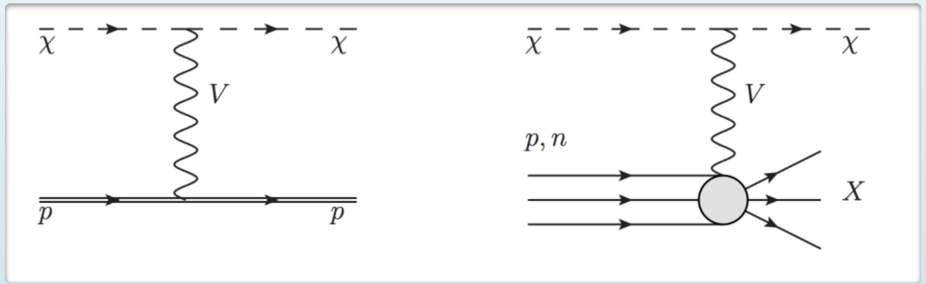
The measurement of the ν_e/ν_μ ratio can be used as a test of the LFU for E>600 GeV

Feebly interactive particles

1. Scattering

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

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



2. Decay of dark scalars, HNLs, dark photons

Production: dark scalars produced in the decay of B mesons, HLNs in the decay of B and D mesons, dark photons via leptophobic mediator

Detection: Decays in a pair of charged tracks or monophotons