SND@LHC

Design and performance

CERN Detector Seminar

January 27, 2023

LHC

Scattering and Neutrino Detector
at the LHC

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Cristóvão Vilela
on behalf of the SND@LHC Collaboration

Neutrinos at the LHC

- Studies of the potential for observing neutrinos at the LHC date back to the 90's.
  - Large flux in forward region.
  - Very high neutrino energy ($\sigma_\nu \propto E_\nu$).

  ⇒ A small-scale LHC experiment can observe neutrinos of all three types.
    - Highest energy human-made neutrinos!
- Two neutrino detectors in operation at LHC's IP1 for Run 3: SND@LHC and FASERν

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

OPEN ACCESS
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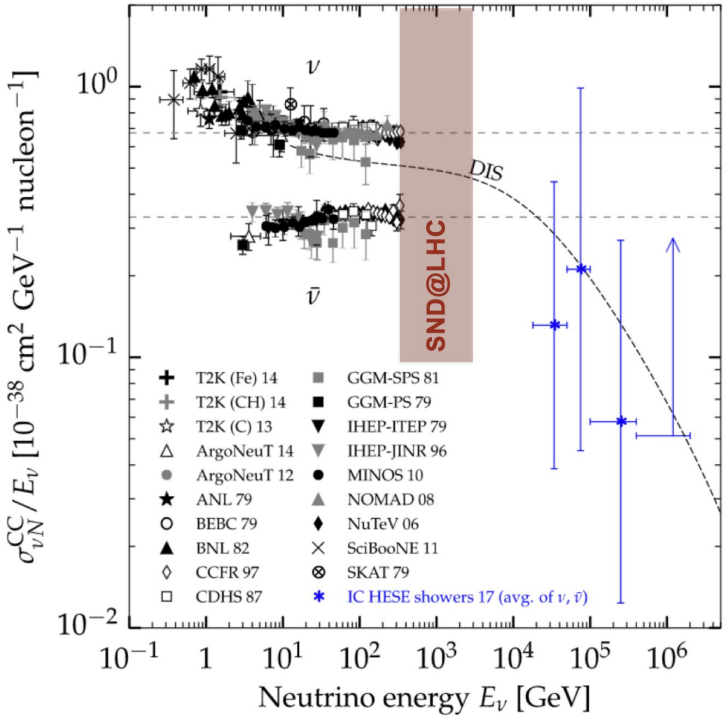
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **47** (2020) 125004 (18pp)
https://doi.org/10.1088/1361-6471/aba7ad

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

PRL 122 (2019) 041101



Detector location

Strategy:

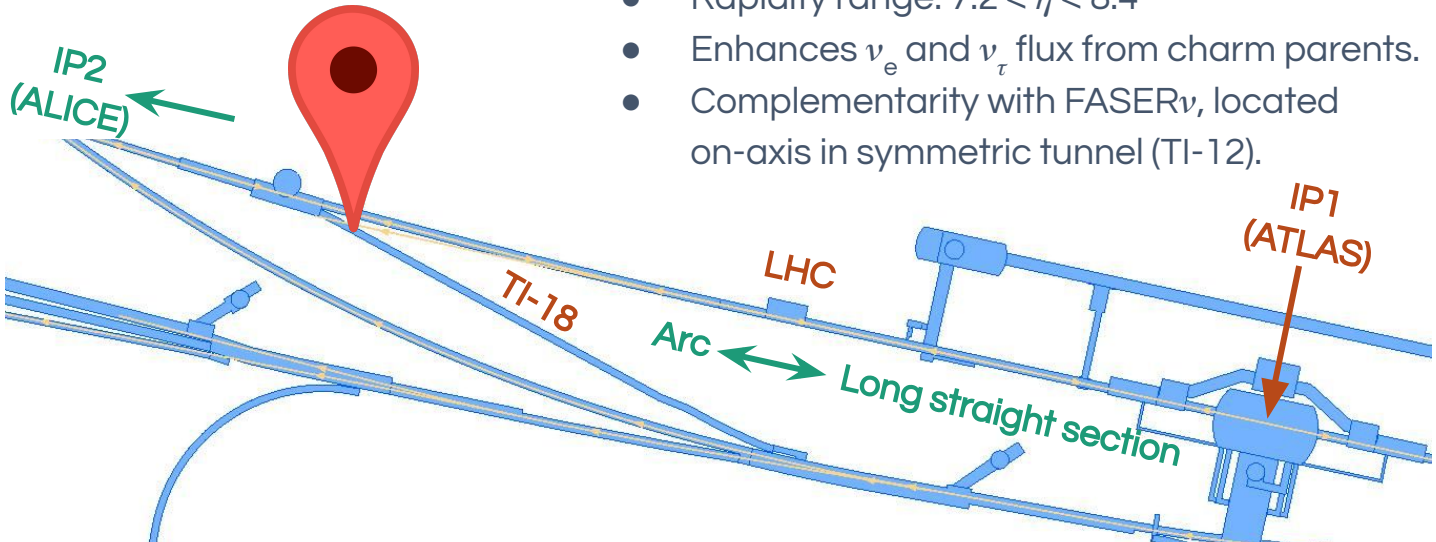
- Existing site (avoid major civil engineering).
- Enough material to shield against collision debris.
- Use LHC magnets to deflect charged particles.

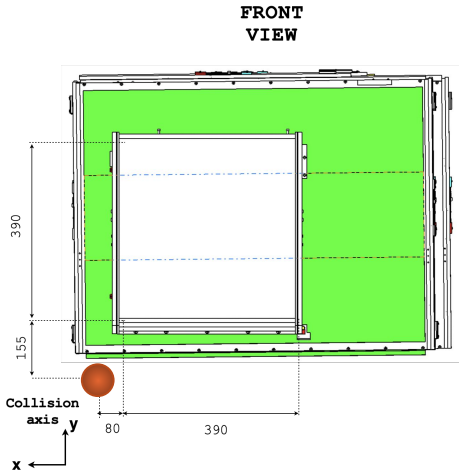
TI-18 location:

- Old LEP positron transfer line tunnel.
- 480 m away from IP1.
- 100 m of rock between detector and IP1.
- Downstream of dipole magnets.

Off-axis position:

- Rapidity range: $7.2 < \eta < 8.4$
- Enhances ν_e and ν_τ flux from charm parents.
- Complementarity with FASERν, located on-axis in symmetric tunnel (TI-12).

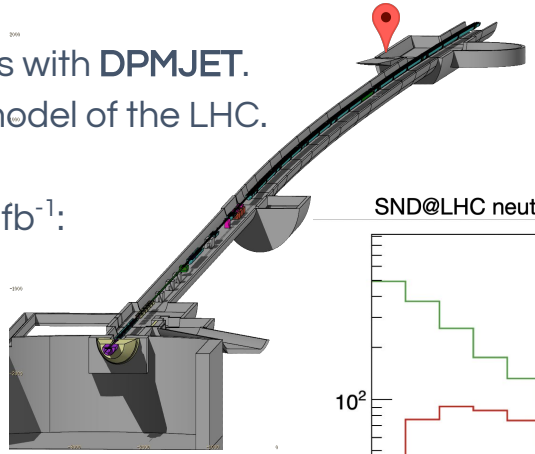


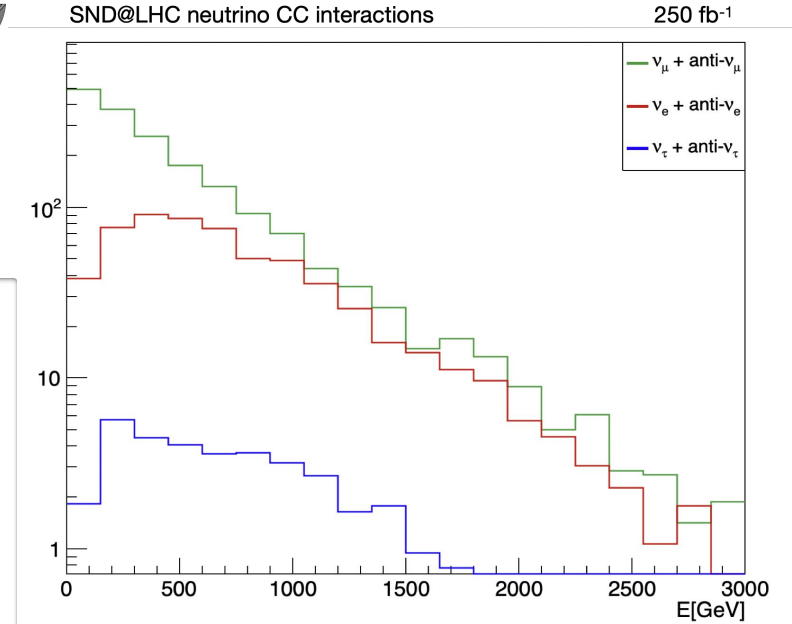


SND@LHC Physics

Expected neutrino event rates

- Model neutrino production in pp collisions with **DPMJET**.
- Propagation to SND@LHC with **FLUKA** model of the LHC.
- GENIE neutrino interaction model.
- Neutrino interactions in SND@LHC / 250 fb^{-1}:
  - $\nu_\mu + \bar{\nu}_\mu$ charged-current: 1270
  - $\nu_e + \bar{\nu}_e$ charged-current: 390
  - $\nu_\tau + \bar{\nu}_\tau$ charged-current: 30

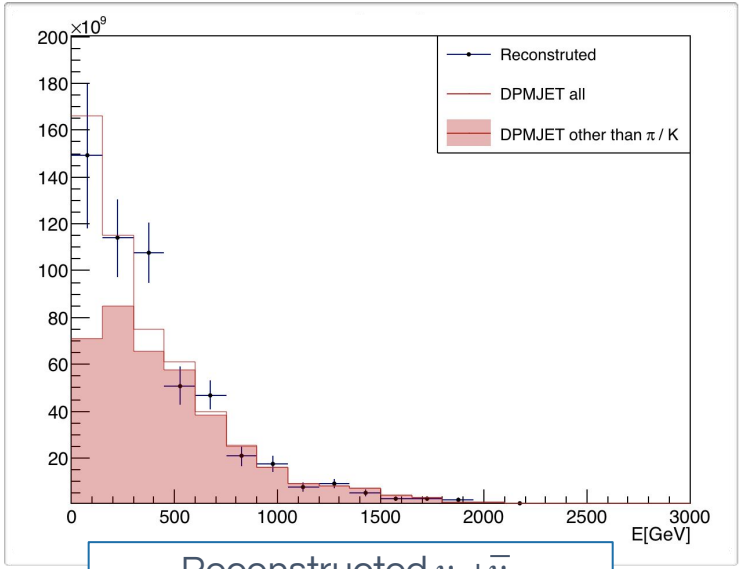




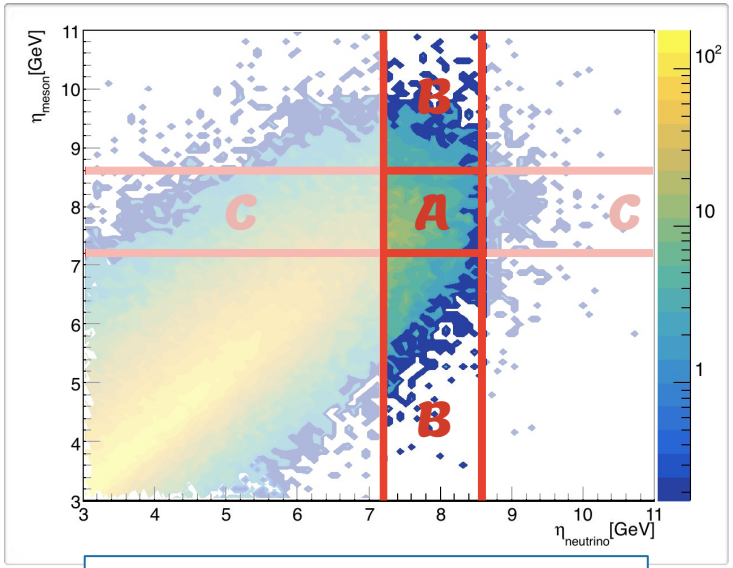
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	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

Neutrinos from charm production

- Expect 90% of $\nu_e+\bar{\nu}_e$ to originate from charm decays.
  - SND@LHC $\nu_e+\bar{\nu}_e$ are a probe of forward charm production.
  - Forward charm production measurement constrains gluon PDFs at very low x (10^{-6}).
- Impact on future higher energy hadron colliders and neutrino astrophysics.



Reconstructed $\nu_e+\bar{\nu}_e$ spectrum at SND@LHC.



Correlation between η_ν and η_c

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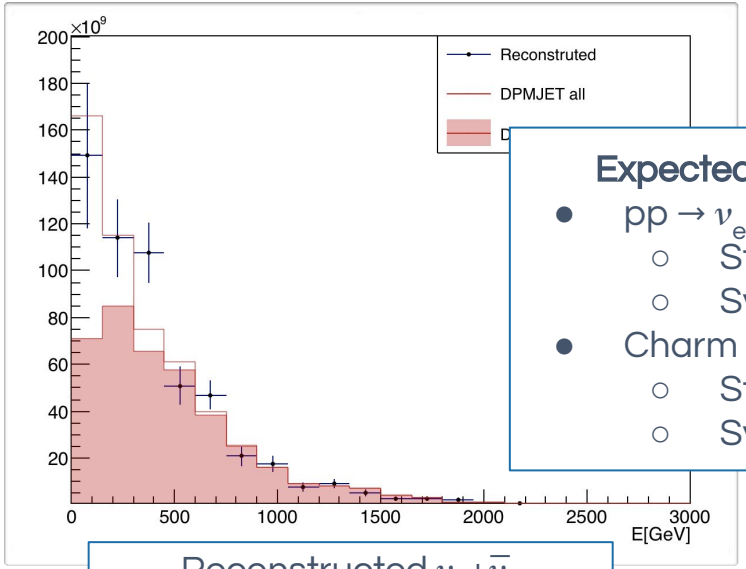
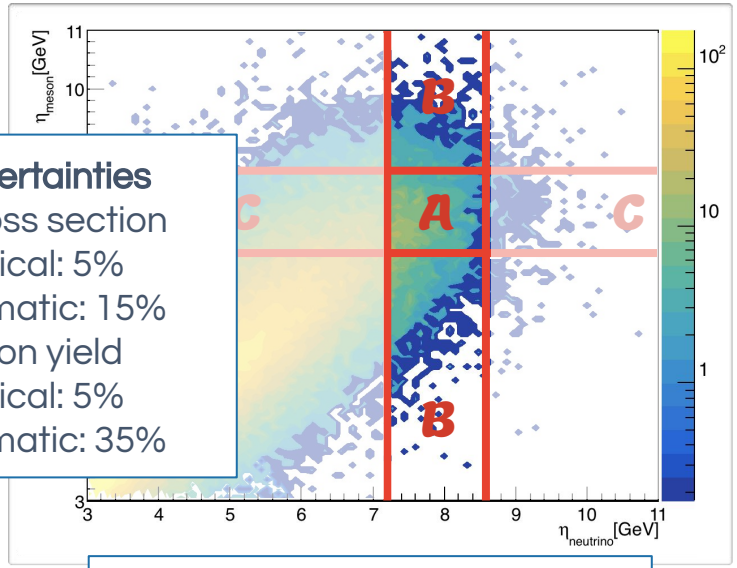


Reconstructed $\nu_e+\bar{\nu}_e$ spectrum at SND@LHC.

Expected uncertainties

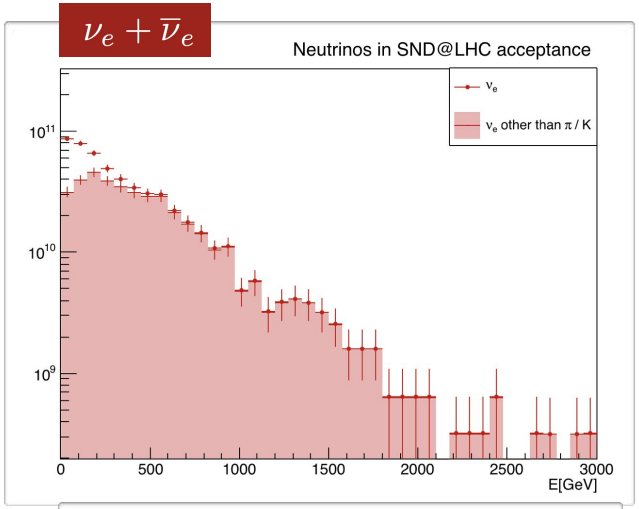
- pp → ν_eX cross section
  - Statistical: 5%
  - Systematic: 15%
- Charm hadron yield
  - Statistical: 5%
  - Systematic: 35%



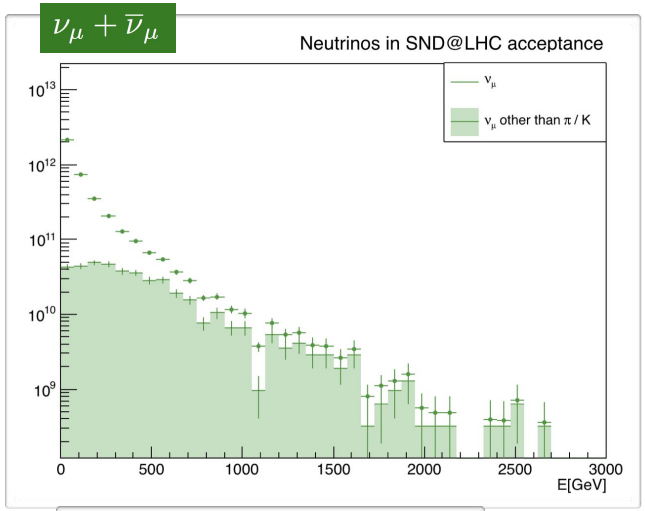
Correlation between η_ν and η_c

Lepton Flavour Universality tests

- Charm hadron decays contribute to the flux of all three types of neutrinos at SND@LHC.
- The detector has excellent flavour identification capabilities.
- Unique opportunity to test lepton flavour universality with neutrinos.
  - Take ratios of event rates: ν_e/ν_τ and ν_e/ν_μ.



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



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

π/K contamination

Lepton Flavour Universality tests

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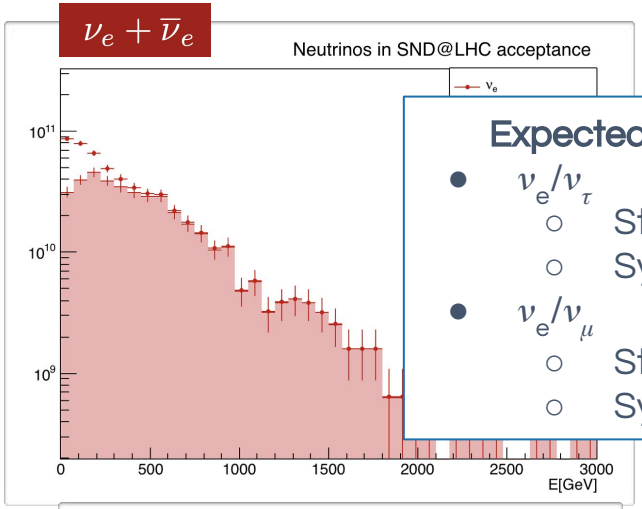

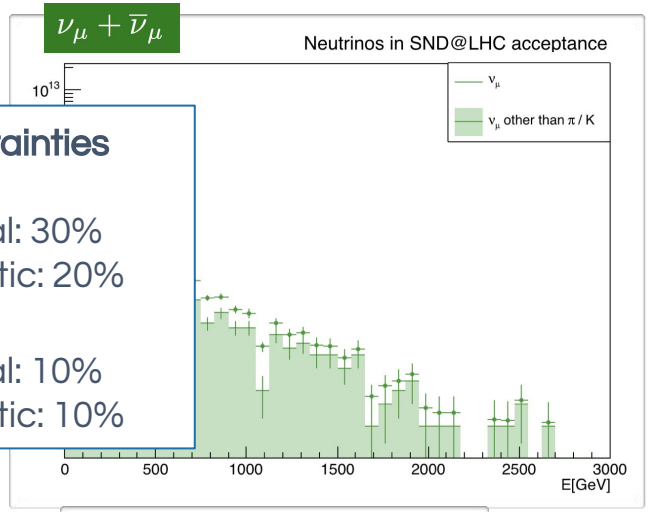

Expected uncertainties

- ν_e/ν_τ
  - Statistical: 30%
  - Systematic: 20%
- ν_e/ν_μ
  - Statistical: 10%
  - Systematic: 10%

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

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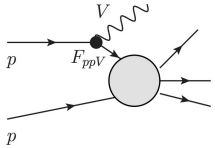
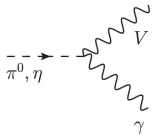
π/K contamination

Feebly interacting particles

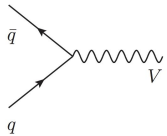
- SND@LHC is sensitive to new **dark sector** particles.



p bremmstrahlung

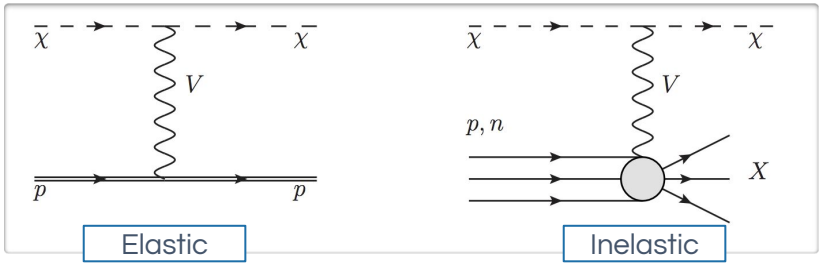


Meson decay

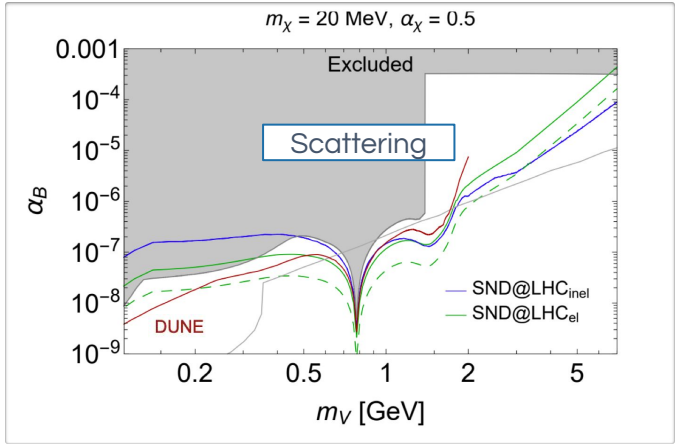


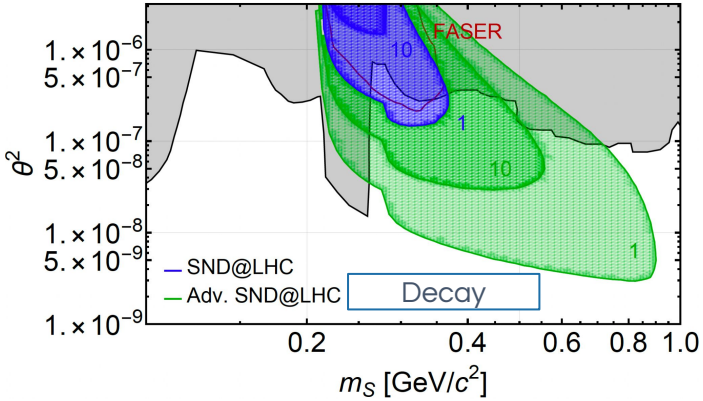
Drell-yan

- **Scattering** in the detector.
  - E.g., scalars interacting with nucleons via a leptophobic portal.



- **Decaying** in the detector.
  - Dark scalars, heavy neutral leptons or dark photons decaying into a pair of charged tracks.





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Feebly interacting particles

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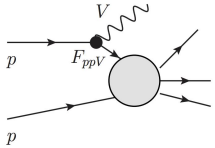

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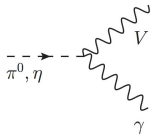
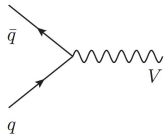


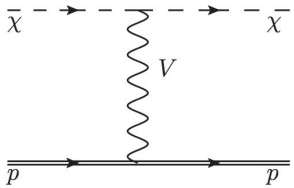
Meson decay



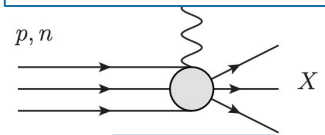
Drell-yan

- **Scattering** in the detector
  - E.g., scalars in
    via a leptophob

Signal efficiencies and backgrounds (neutrinos!) under study.

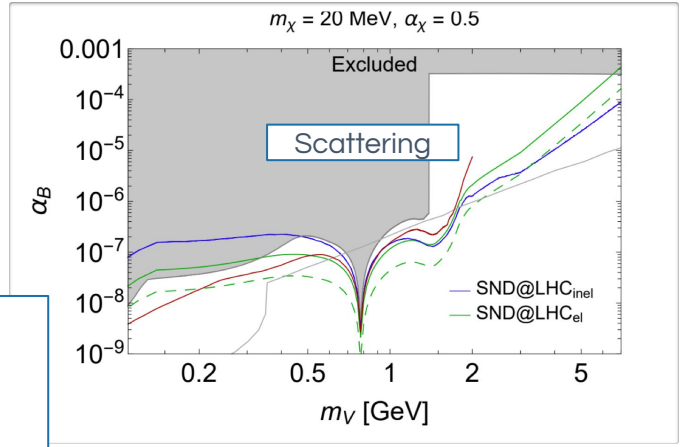


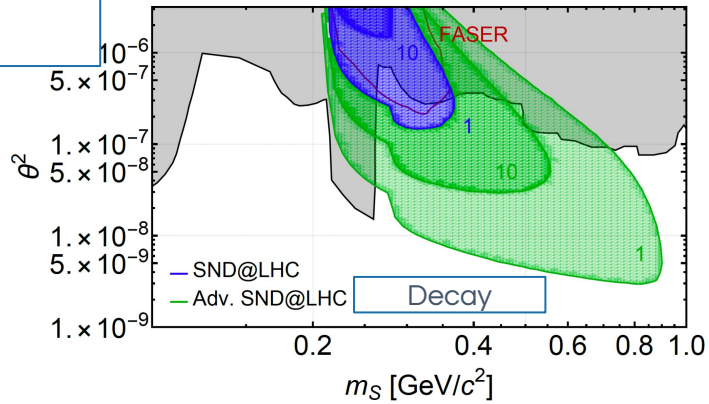
Elastic



Inelastic

- **Decaying** in the detector.
  - Dark scalars, heavy neutral leptons or dark photons decaying into a pair of charged tracks.





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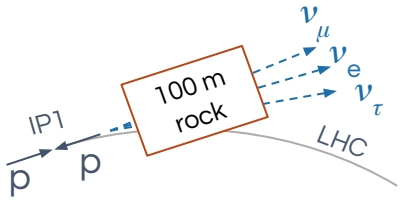
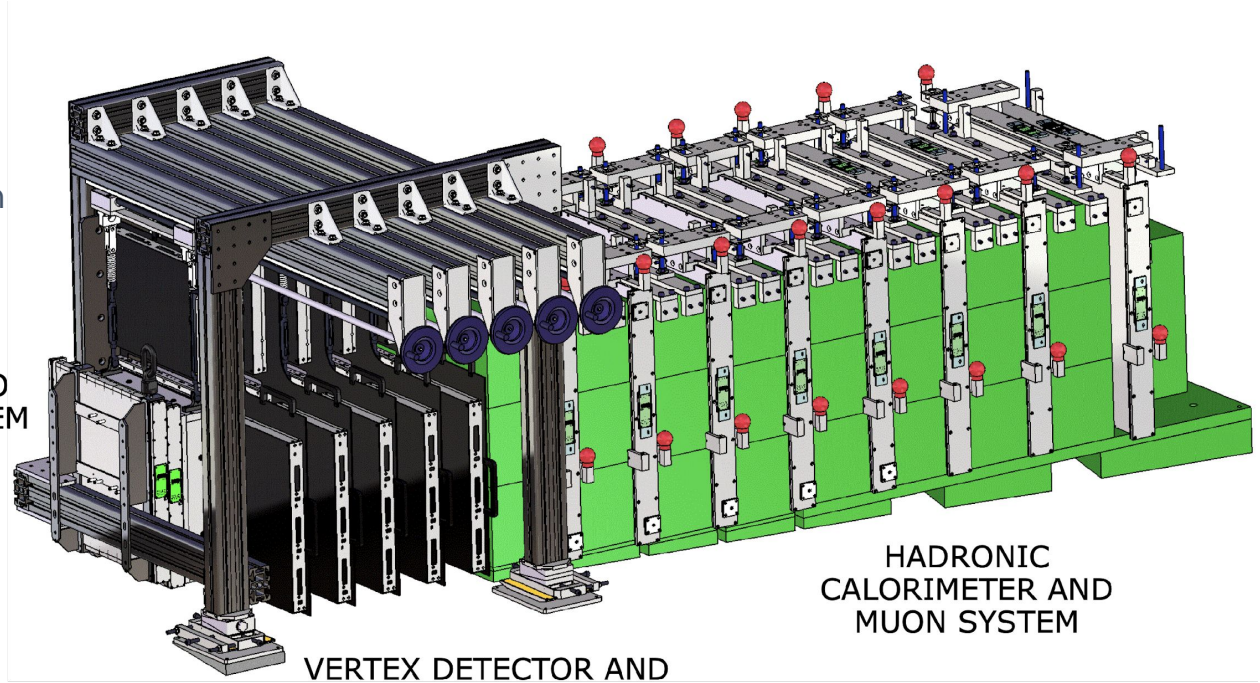
Detector design

The SND@LHC detector concept

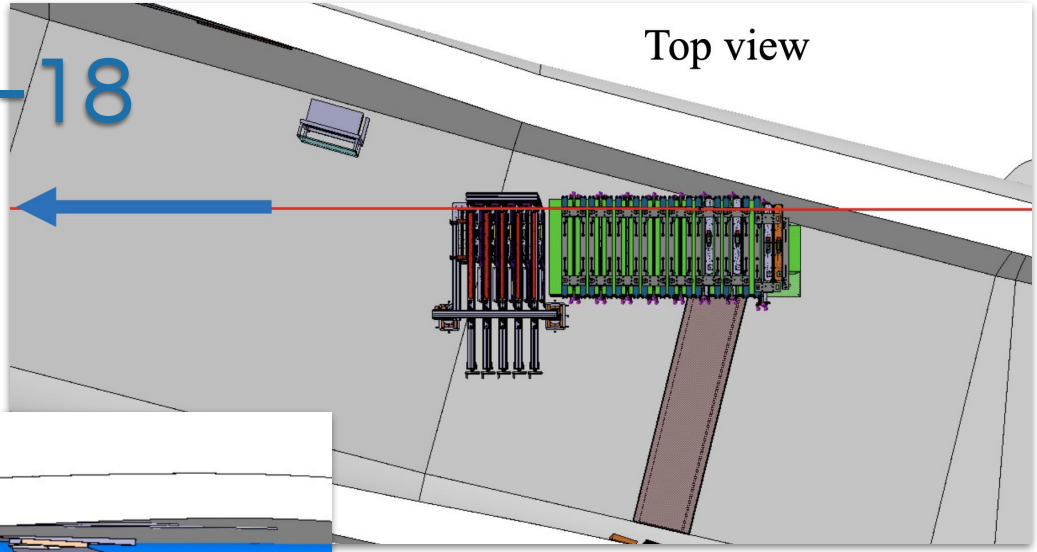
- Hybrid detector design.
- Optimized for the identification of three neutrino flavours and feebly interacting particles.

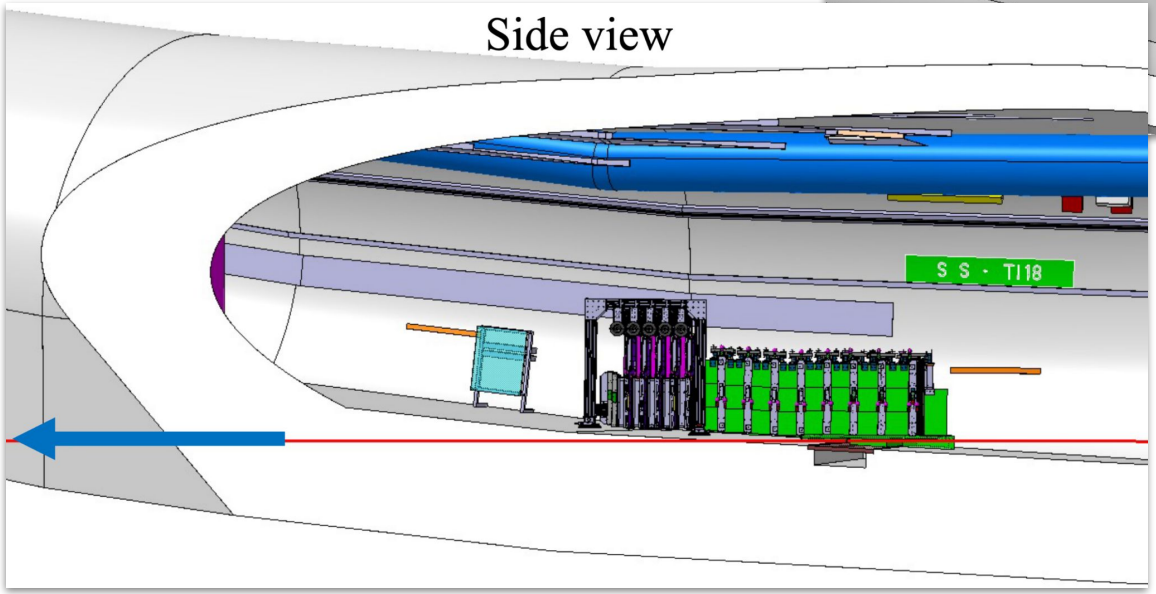




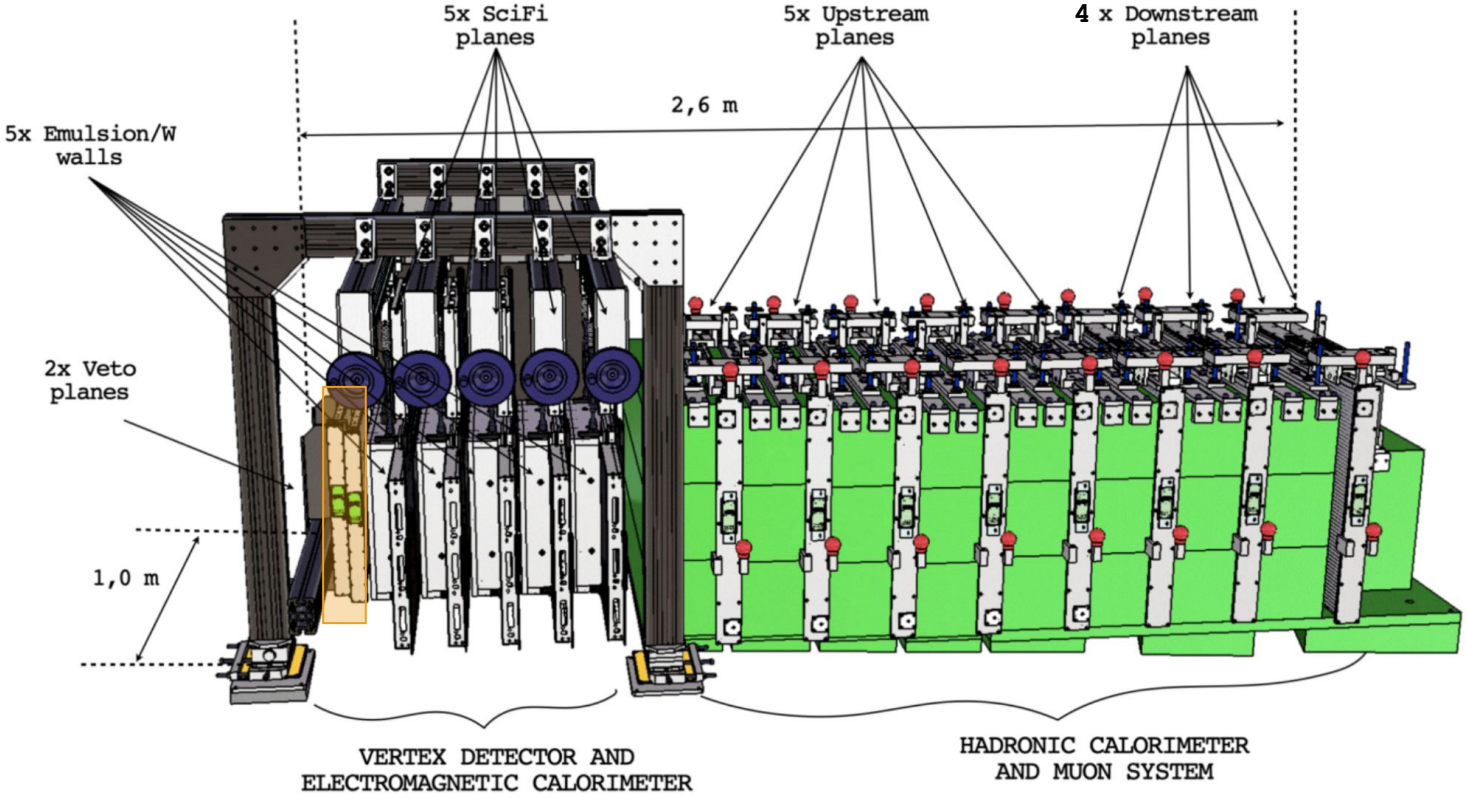
SND@LHC in TI-18

A very tight fit!





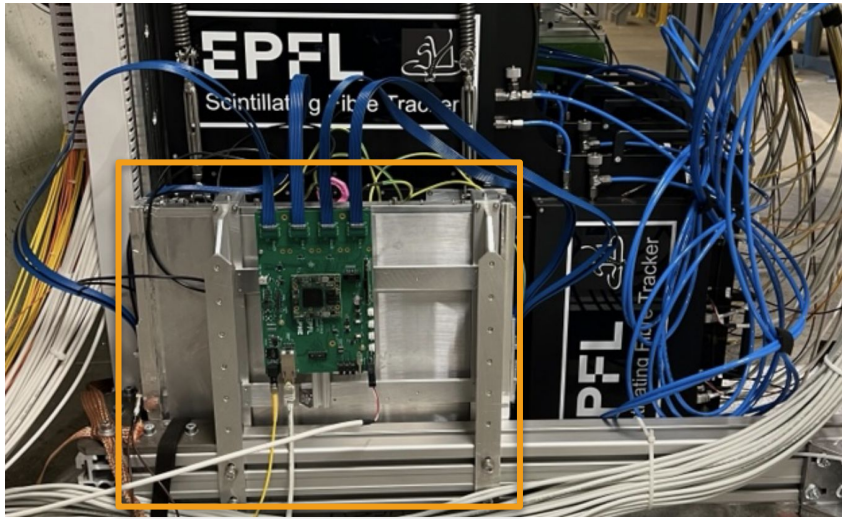
Veto system

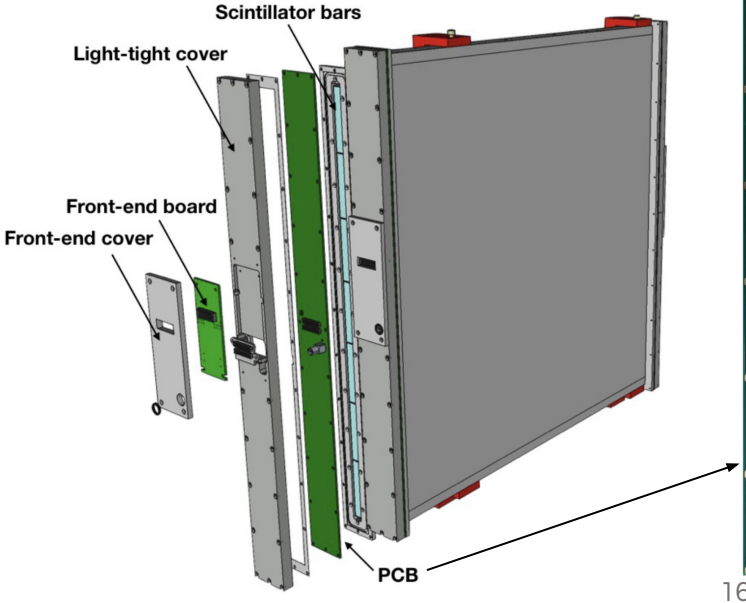


Two veto planes on upstream face of the detector.

Veto system

- Tags entering charged particles.
- Each plane is populated with 7 scintillator bars.
  - Each bar is 1 x 6 x 42 cm^3.
  - Bars are read out on both ends by 8 SiPMs, each 6 x 6 mm^2.
- Planes cover the target surface area and are vertically staggered to mitigate dead zones between bars.



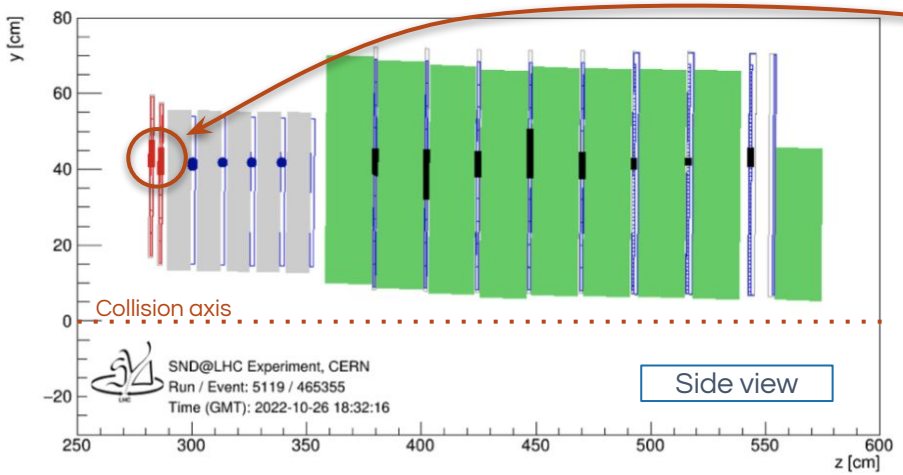


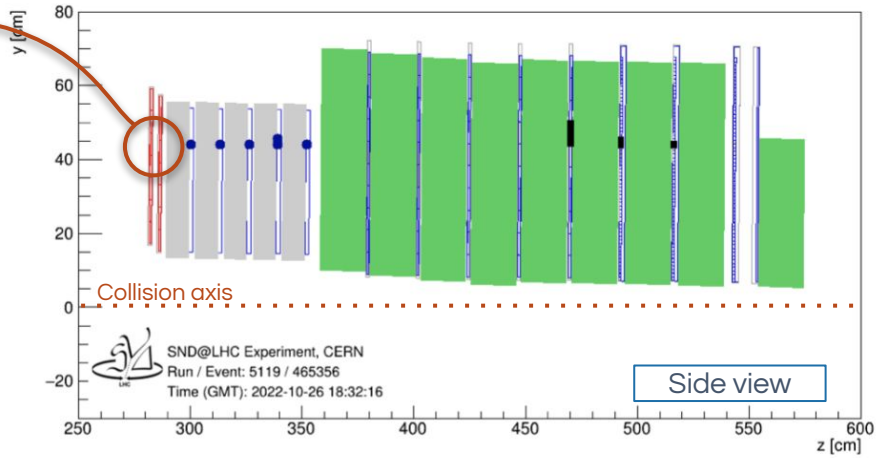
SND@LHC PRELIMINARY

Veto system performance

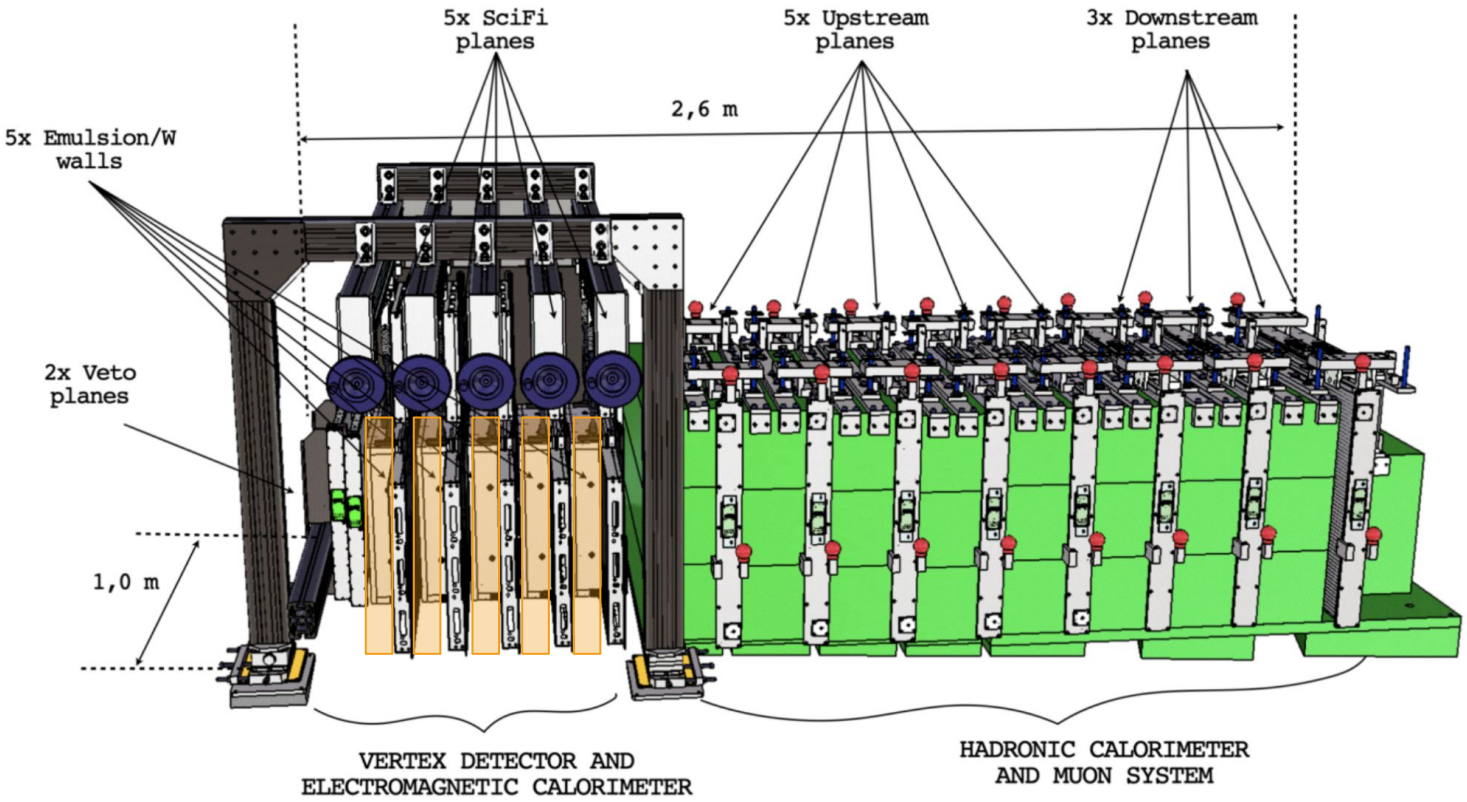
- Veto system inefficiency around 10^{-4} is observed in LHC Run 3 data.
  - Data is dominated by muon tracks originating from IP1.
- This inefficiency is dominated by the detector dead time of around 200 ns.
  - Can be mitigated by requiring that signal candidate events are isolated in time.

Inactive veto bars were hit in previous event





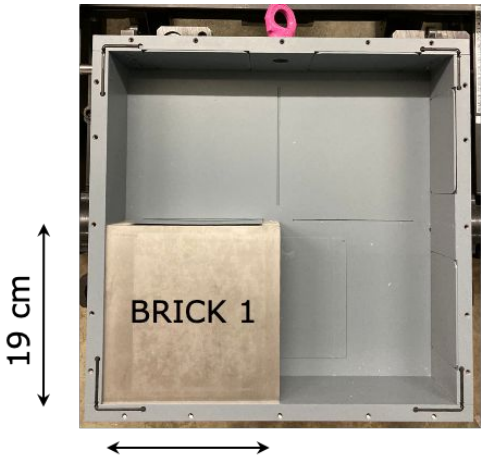
Emulsion target and vertex detector

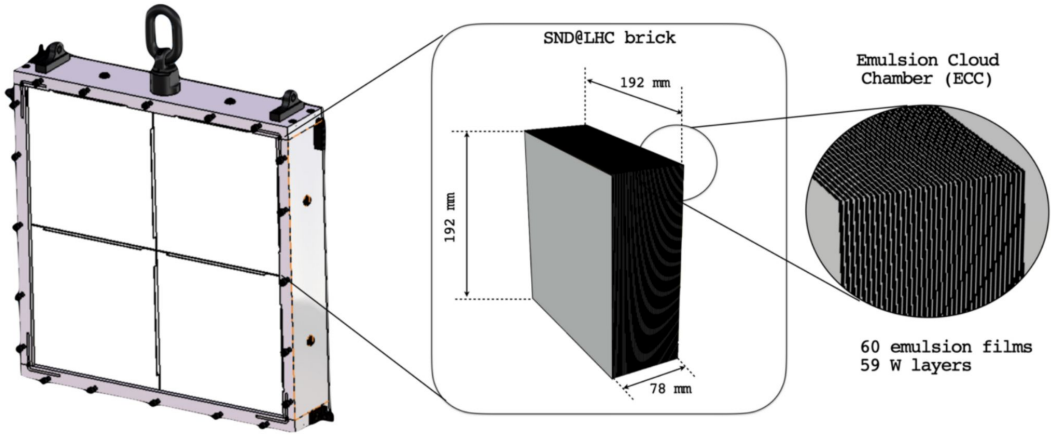


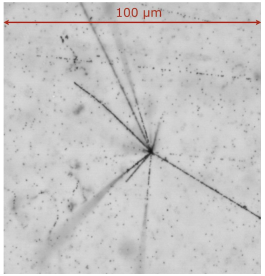
Five target walls instrumented with emulsions.

Emulsion target and vertex detector

- Emulsion cloud chamber (ECC): emulsion films interleaved with high-density passive layers.
- Each target wall is populated with four ECC bricks.
  - Each brick consists of 60 layers of emulsion (0.3 mm) and 59 layers of tungsten (1 mm).
  - Wall thickness: 78 mm (17 X_0).
  - Sensitive transverse size: 38.4 x 38.4 cm^2
- Total target mass: 830 kg
- Surrounded by acrylic and borated polyethylene enclosure to shield from neutrons and control the temperature (15 °C) and relative humidity (45 %).



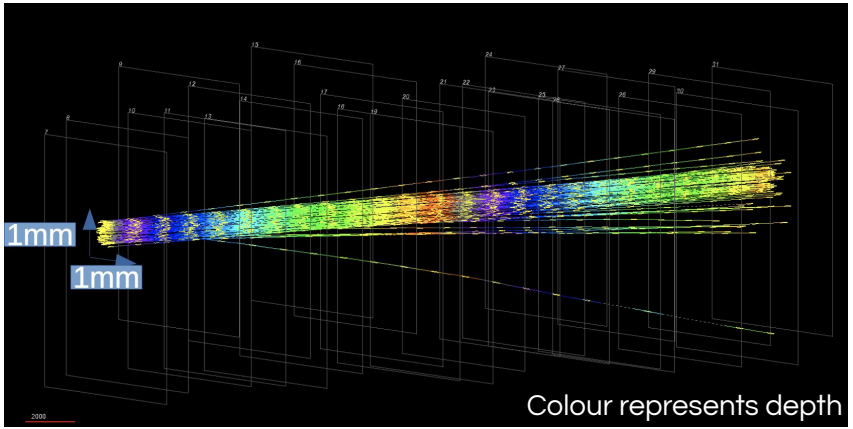




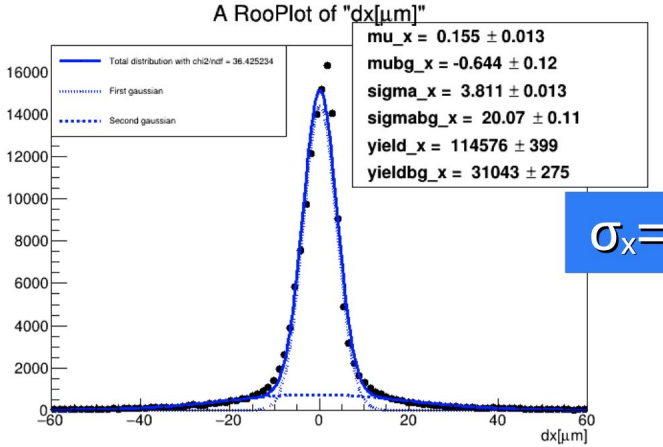
Emulsion detector performance

SND@LHC PRELIMINARY

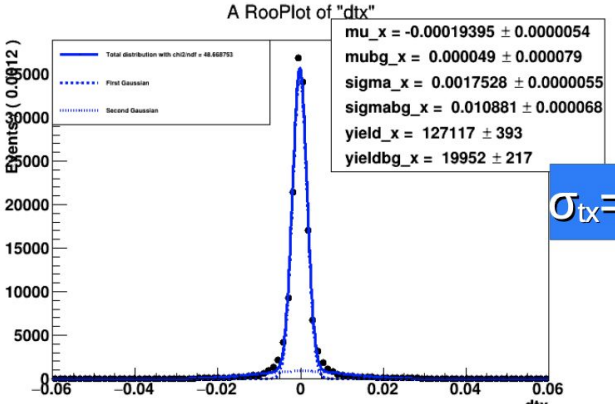
- A small portion of the target was instrumented at the start of the LHC Run 3.
- Exposed for 0.52 fb^{-1}.
  - Data consists mostly of muon tracks originating from IP1.
- Analysed to measure the muon flux with relatively low occupancy.



Tracks going through 1 x 1 mm^2 in 0.52 fb^{-1}

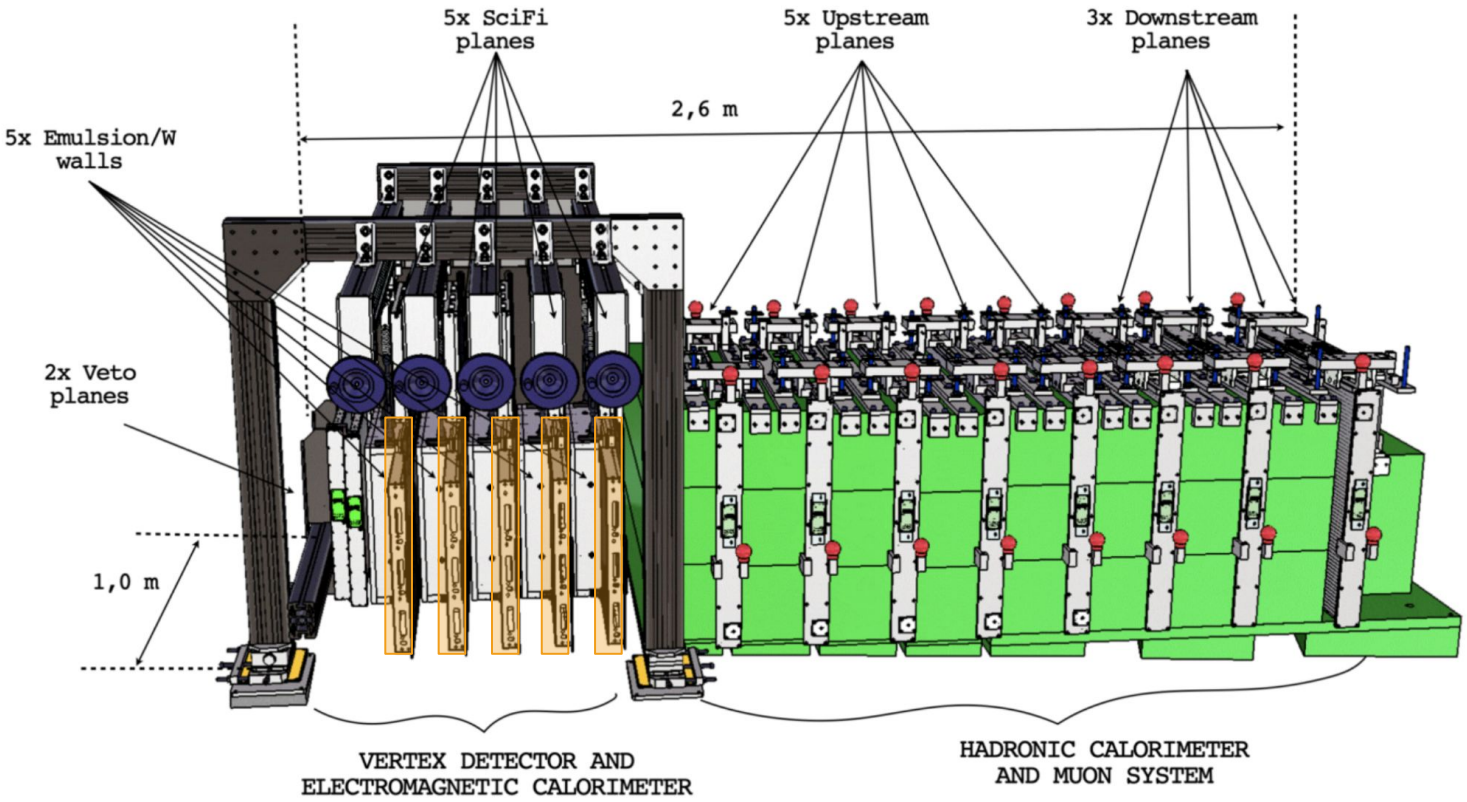


σ_x=3.8 μm



σ_{tx}=1.8 mrad

Scintillating fibre detector

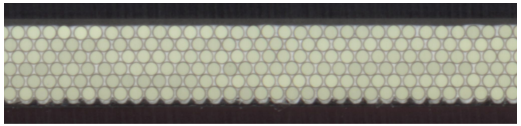


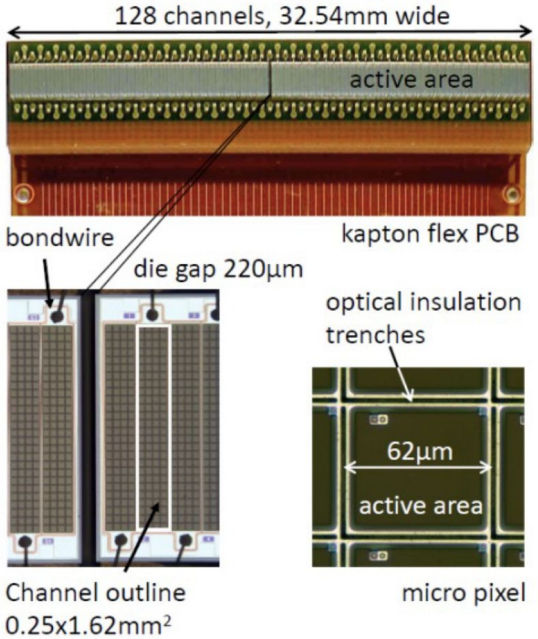
Each target wall is followed by a scintillating fibre detector station.

Scintillating fibre detector

- Role of SciFi detector:
  - **Interface** emulsion detector with electronic detectors by matching the hit pattern in the electronic detector event to a vertex in the emulsion.
  - Electromagnetic **calorimetry**.
- Six staggered layers scintillating fibres with 0.25 mm diameter are densely packed to form a **mat**.
- Each station consists of two planes: one **vertical**, one **horizontal**.
- Mats are read out by SiPM arrays with 0.25 mm channel width.

~25 p.e. per MIP crossing mat

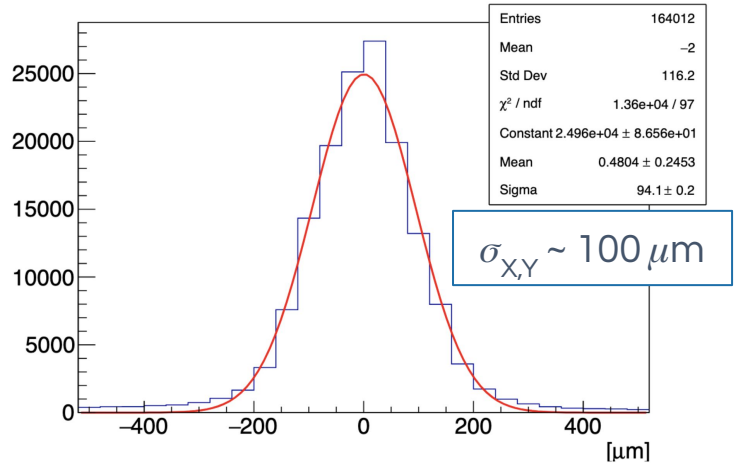




SciFi performance

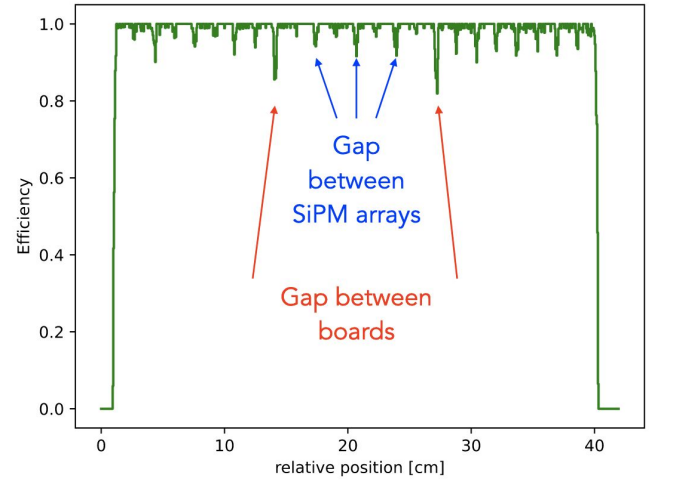
- SciFi performance measured using:
  - Test-beam muons.
  - LHC Run 3 data (dominated by IP1 muons).

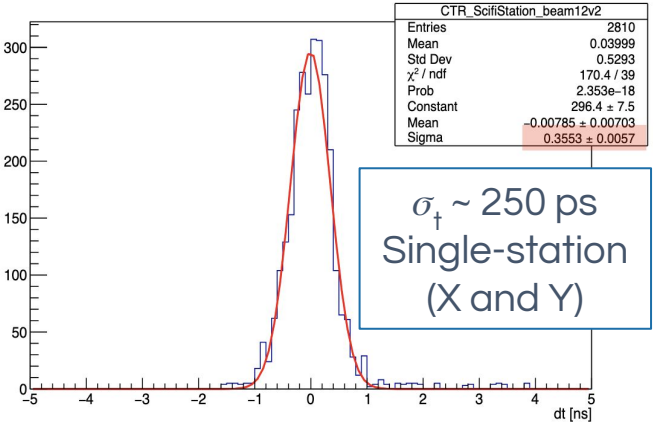
Muon test beam data



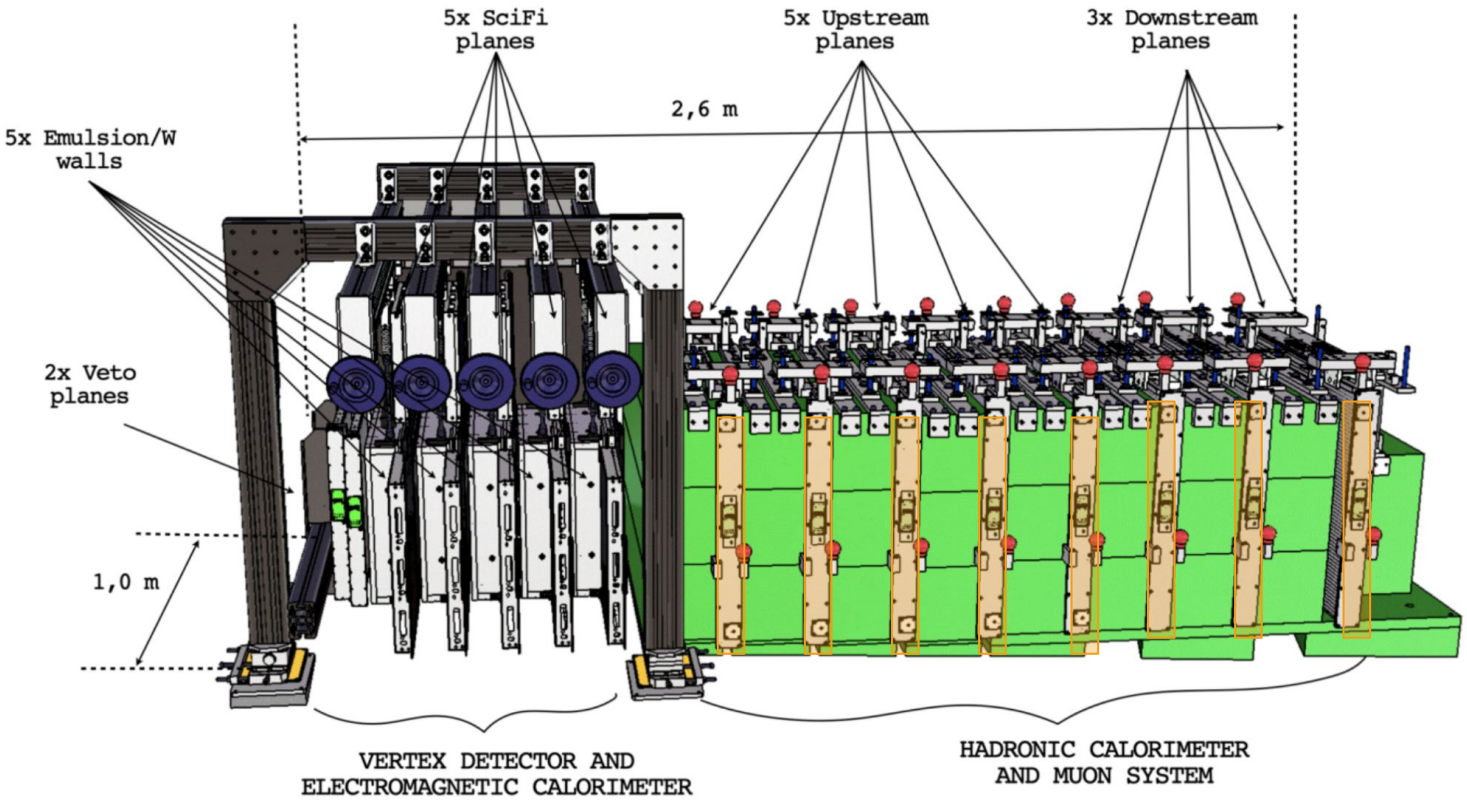
Measured without any material between stations.

Run 3 Data SND@LHC PRELIMINARY





Hadronic calorimeter and muon system

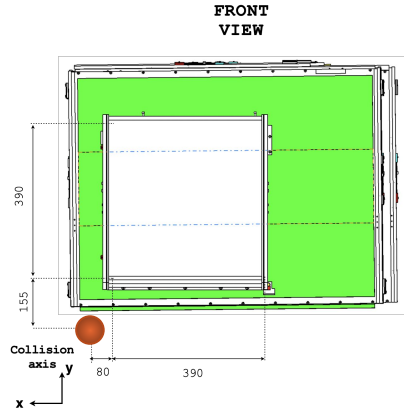


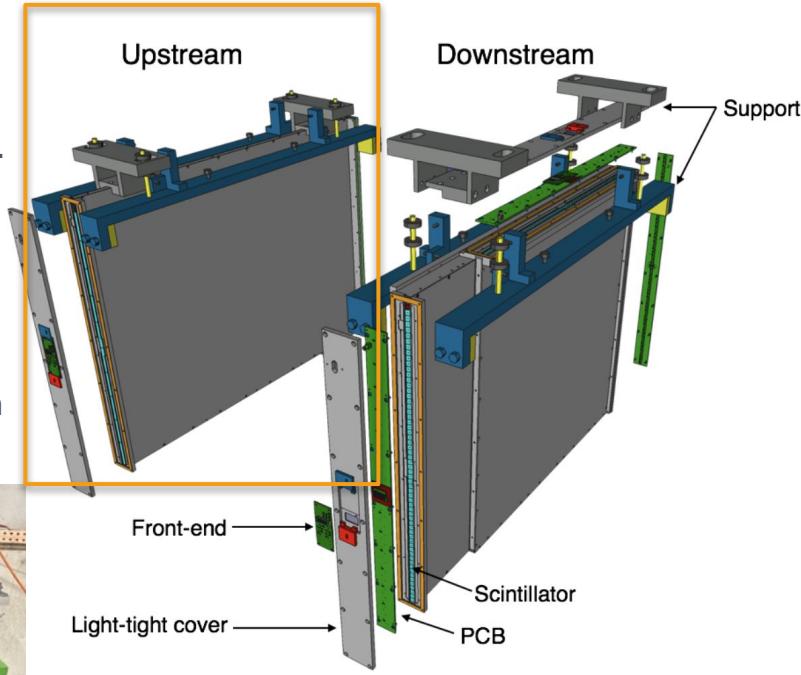
Fe-scintillator system with eight stations downstream of target.

Hadronic calorimeter and muon system

Upstream

- Most upstream five stations used for hadron calorimetry.
  - 5 x 20 cm Fe blocks: 6 λ
- Each station instrumented with 10 horizontal scintillator bars.
  - Each bar is 1 x 6 x 81 cm^3
  - Read out on both sides by 6 large (6 x 6 mm^2) and 2 small (3 x 3 mm^2) SiPMs.
    - Small SiPMs have higher pixel density and extend the dynamic range beyond the saturation of the large SiPMs.

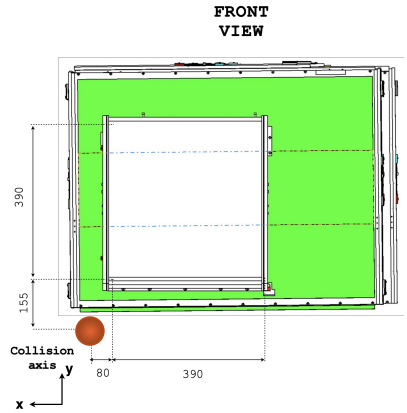


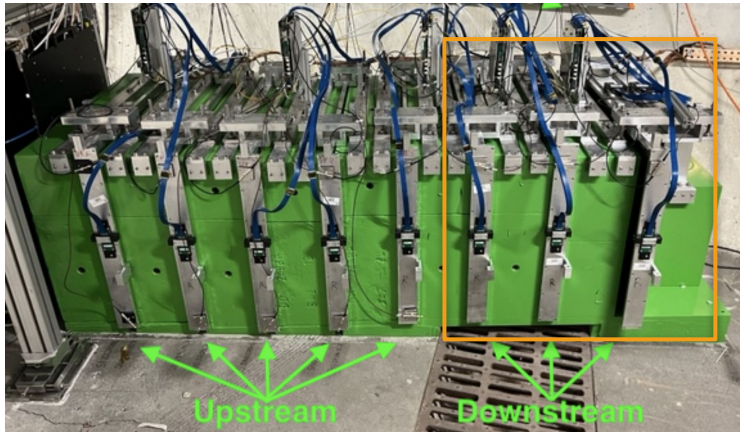


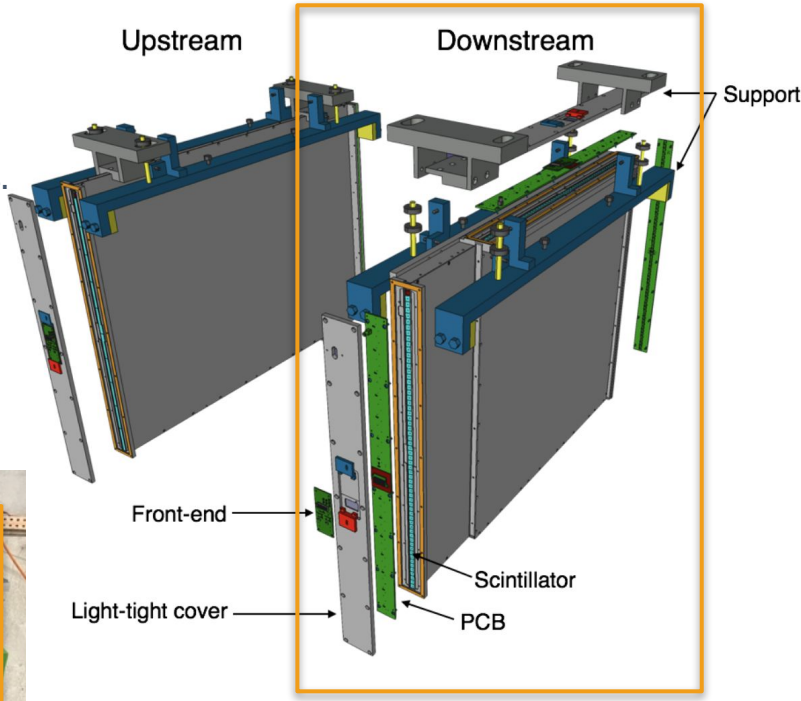
Hadronic calorimeter and muon system

Downstream

- Most downstream three stations used for muon tagging.
  - By the last station particles have traversed an average of 11 λ (including tungsten target).
- Stations instrumented with 60 horizontal and 60 vertical bars.
  - Each bar is 1 x 1 cm^2 in cross section.
    - Length: 81 cm (horizontal) or 60 cm (vertical)
  - Horizontal bars read out by 1 large SiPM on each side.
  - Vertical bars read out by single large SiPM on top.
  - Last station has one additional vertical plane.



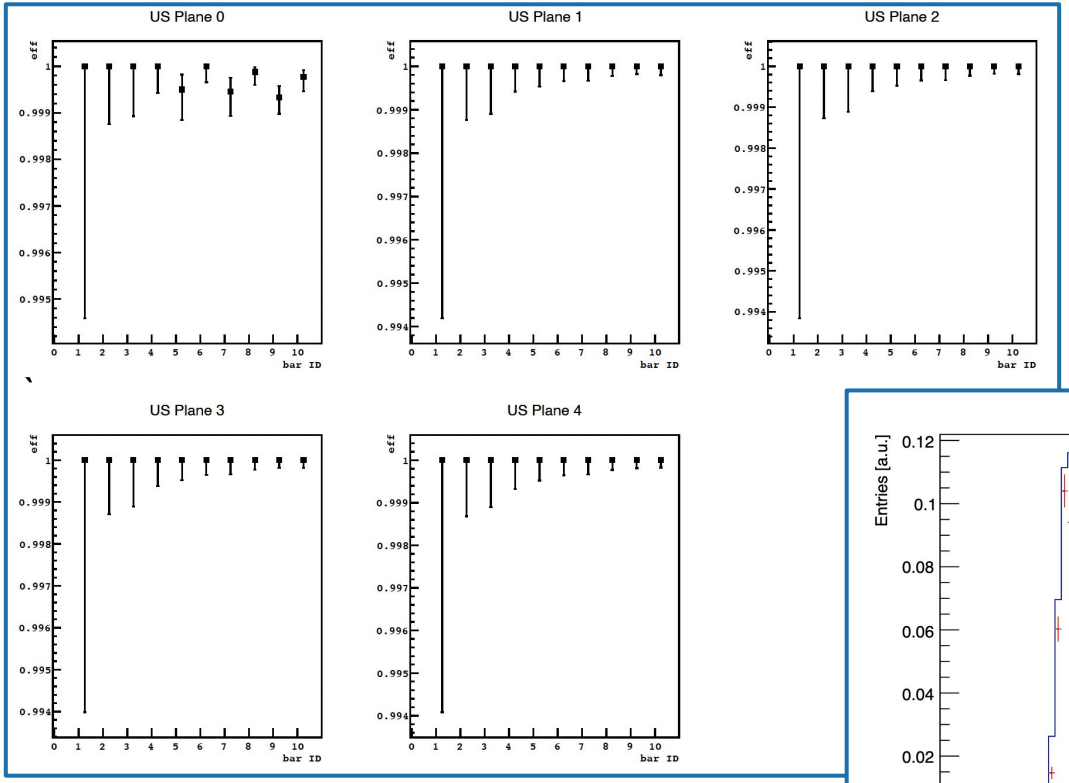




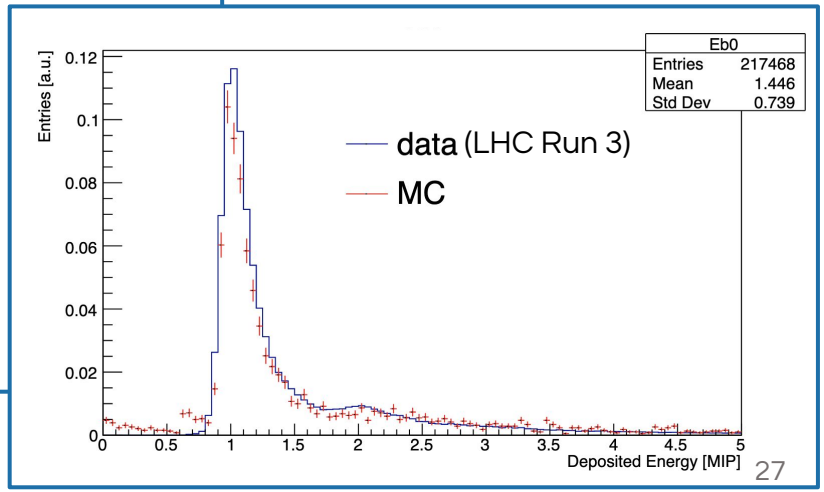
Hadronic calorimeter performance

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

SND@LHC PRELIMINARY



Good MIP energy deposition model

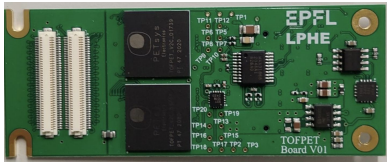


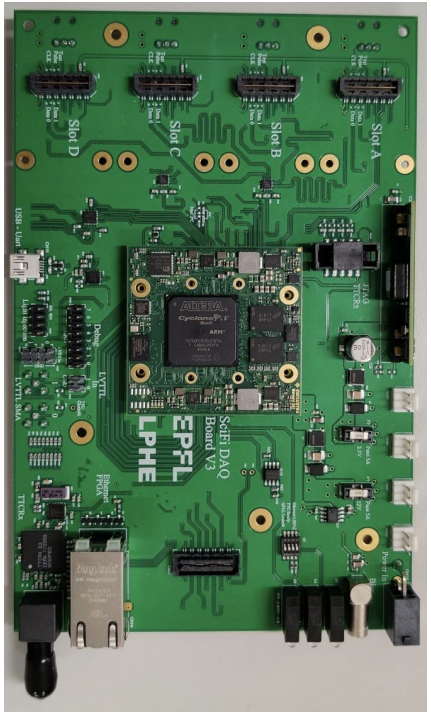
Data acquisition

- All electronic detectors are read out by TOFPET2-based front-end boards.
  - Low signal threshold: 0.5 p.e.
  - Good timing: 40 ps
  - 128 channels.

- DAQ boards based on Cyclone V FPGA.
  - Run at 160 MHz, aligned with the LHC clock.
  - Collect data from four front-end boards (512 channels).
  - Get clock from LHC time, trigger and control system (TTC) via optical fibre.
  - All hits above threshold sent to DAQ server over ethernet.

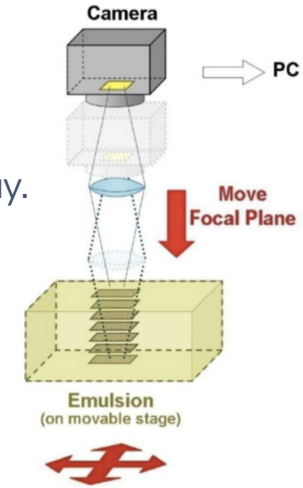
- DAQ server.
  - Receives hits from DAQ boards, 17k channels in total.
  - Runs timestamp-based event-building code.
  - Applies online noise filter conditions based on event topology.
  - Saves data to disk in ROOT format.

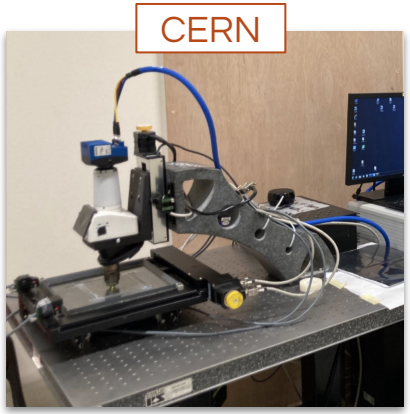


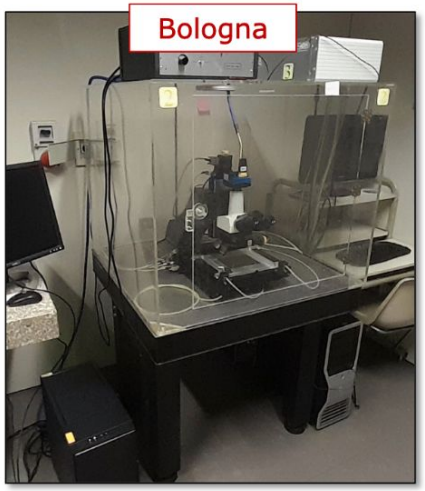


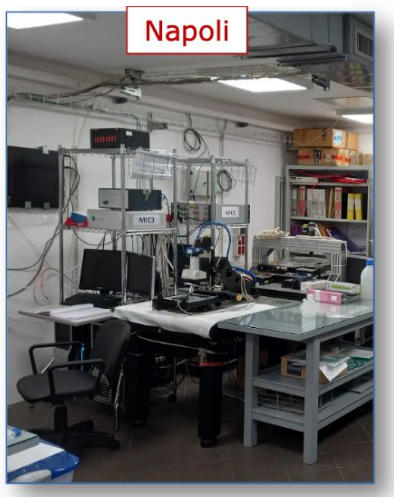
Emulsion scanning

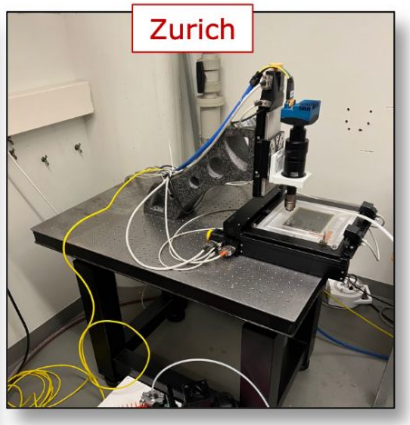
- Five emulsion scanning stations.
- Each microscope currently scans one emulsion film per day.
- Prohibitive to store raw microscope images in disk.
  - Processing the images is the bottleneck.
- Speed up foreseen:
  - More microscopes coming online.
  - Distributed data processing.











Commissioning, installation and operation

Experiment timeline

Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020

TECHNICAL PROPOSAL

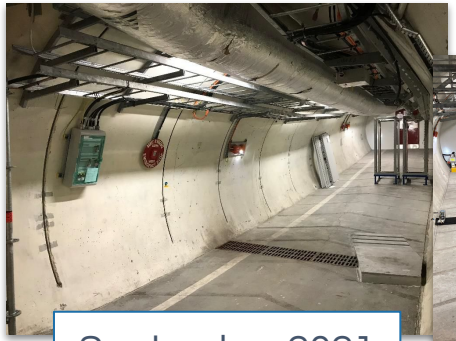
SND@LHC

January 2021

CERN approves new LHC experiment

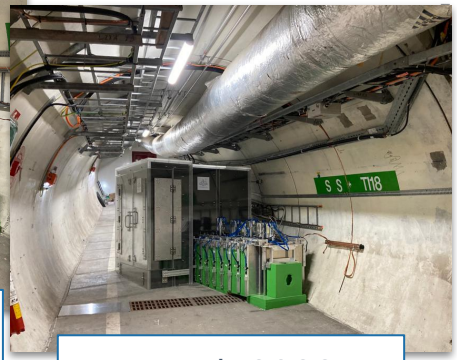
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021



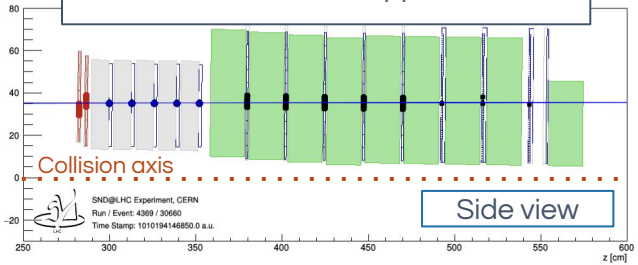
September 2021

December 2021



March 2022

Muon from 13.6 TeV pp collision



July 2022

Detector installation in TI-18

Target wall

Target and SciFi

Veto system

Muon system

Emulsion replacement

- Emulsions need to be replace every < 20 fb^{-1} to keep occupancy at acceptable level for analysis.
- Wall replacements take place during technical stops.
- Procedure takes 4 to 5 hours to complete.
  - Possible to replace the target with only a short access when necessary.

Transport

Target replacement

SciFi installation

Development

Emulsion development

Chemical bath preparation

Emulsion film development

Emulsion drying

Packaging

5 people x 11 days to develop a fully instrumented detector.

Emulsion development facility

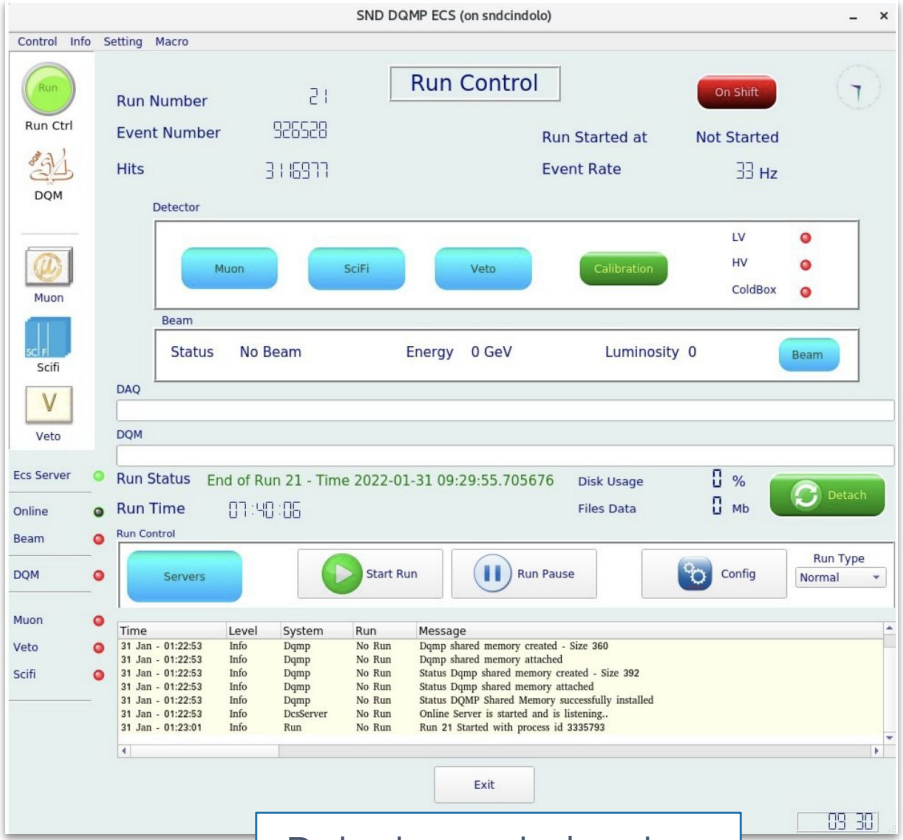
- Located at CERN, buildings 162 and 169.
- Refurbished for shared use by SND@LHC, FASERν and DsTau.

- **16** walls assembled
- **3522** emulsion films installed (130 m^2)
- **3522** emulsion films developed (130 m^2)
- **3500 L** disposed chemical solutions

Experiment operation

- Normal detector operation can be performed remotely.
  - Control system automatically recovers from most frequent hiccups.
- 24/7 data taking shifts during physics runs.
  - Shifter must be in CERN area.
  - Physical control room available.
- Emulsion preparation and development shifts.

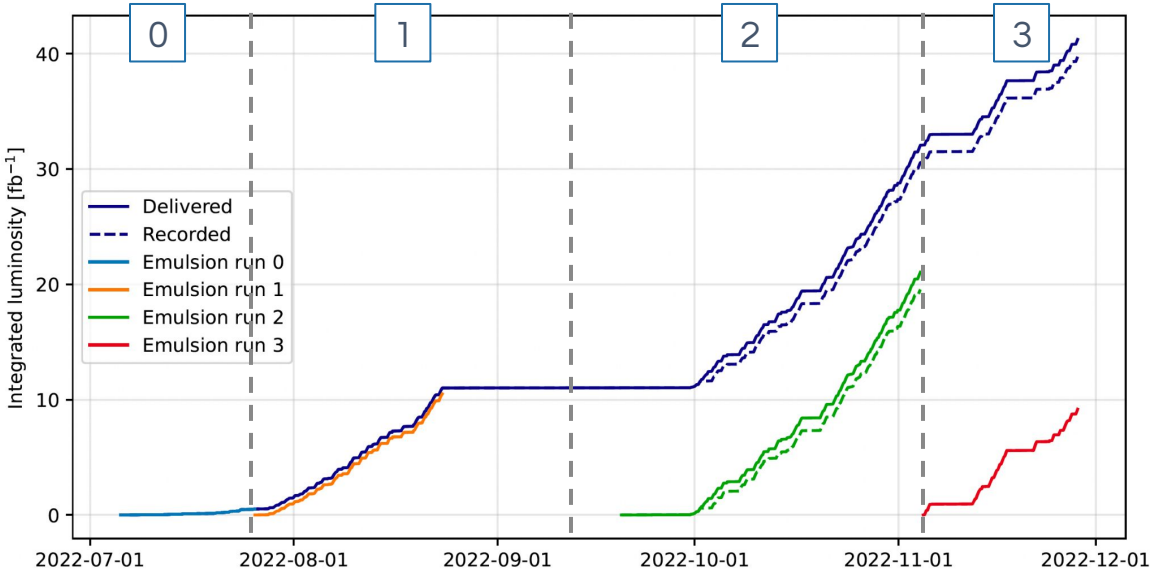
Control room in Meyrin

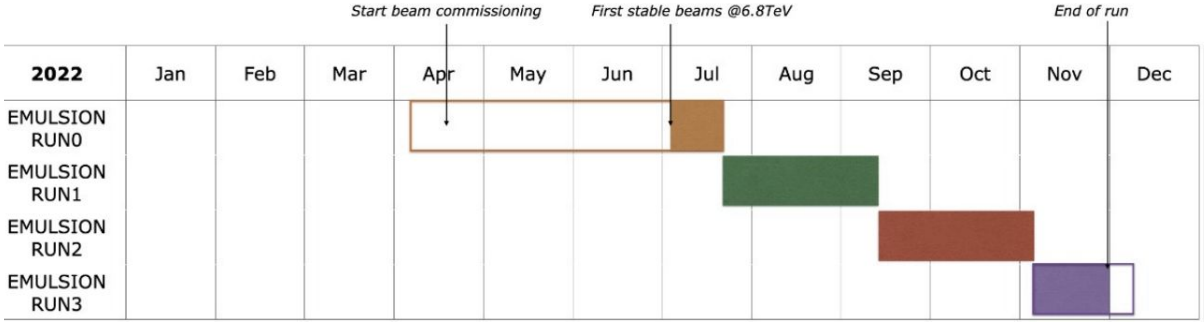


Detector control system

Data taken in Run 3

Run 3
Delivered:
41.25 fb^{-1}
Recorded:
39.74 fb^{-1} (96%)





INSTRUMENTED TARGET MASS	INTEGRATED LUMINOSITY
39 kg	0.5 fb^{-1}
807 kg	10.5 fb^{-1}
784 kg	21.1 fb^{-1}
792 kg	9.2 fb^{-1}

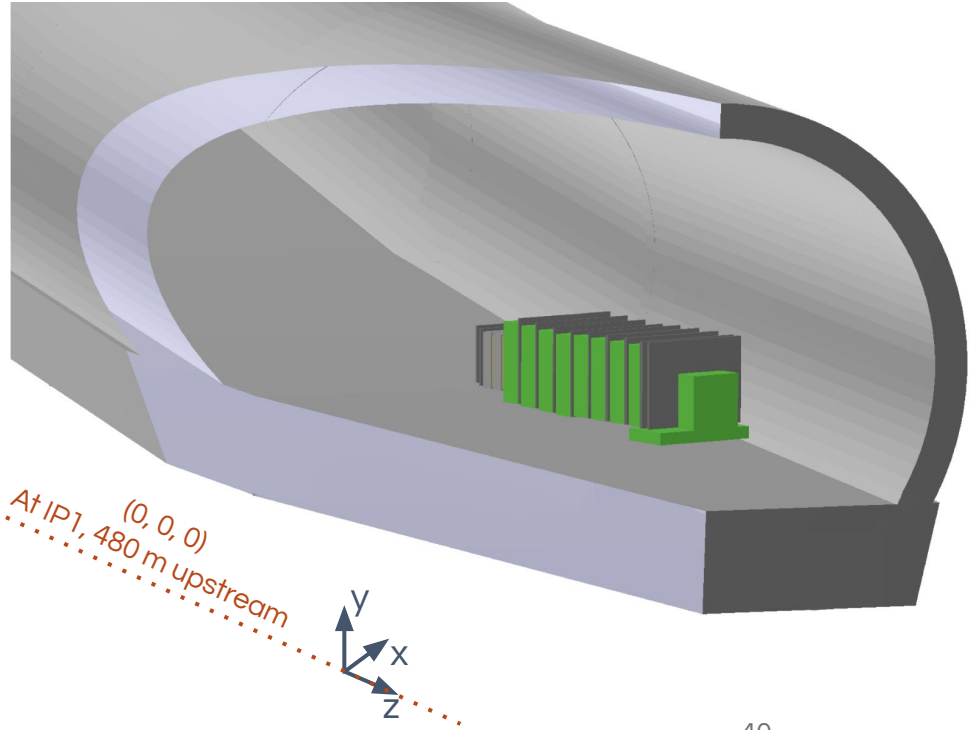
Data analysis progress

Software and analysis tools

- Fluxes at LHC TI-18 tunnel generated with DPMJET + Fluka model of the LHC.
  - Maintained by CERN Sources, Targets and Interactions Group SY/STI.

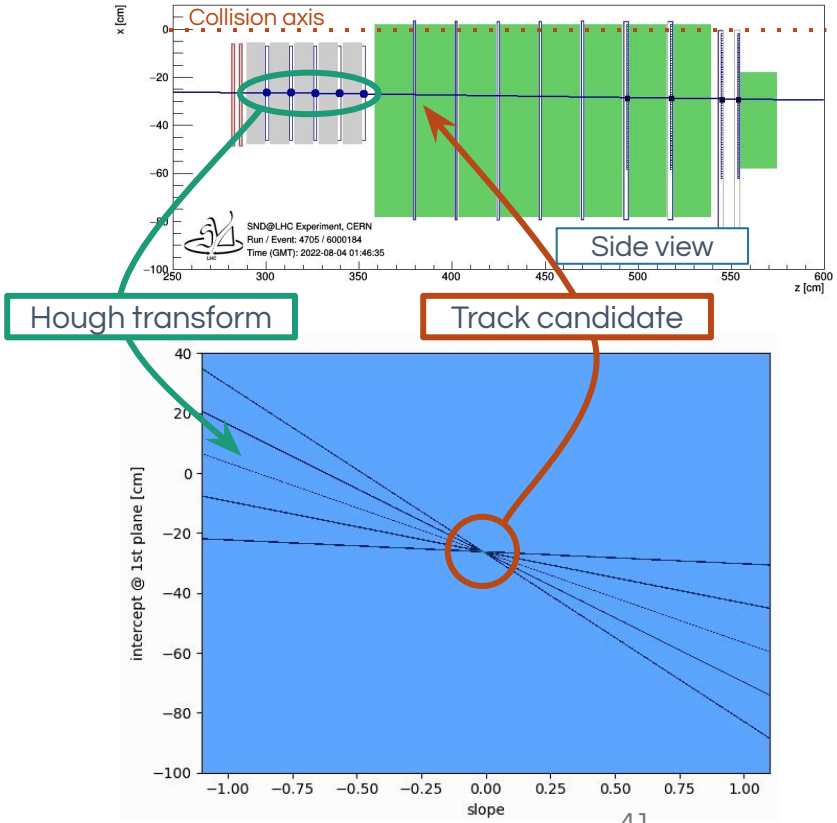
In `sndsw` FairROOT based software:

- Propagation of particles through the TI-18 tunnel and detector modeled with Geant4.
  - Digitization models.
- Neutrino event generation with GENIE.
- Muon DIS event generation with PYTHIA.
- Analysis tools:
  - Electronic detector track reconstruction.
  - Emulsion reconstruction with FEDRA.
  - Detector alignment tools.
- Online data quality monitoring.



Tracking with electronic detectors

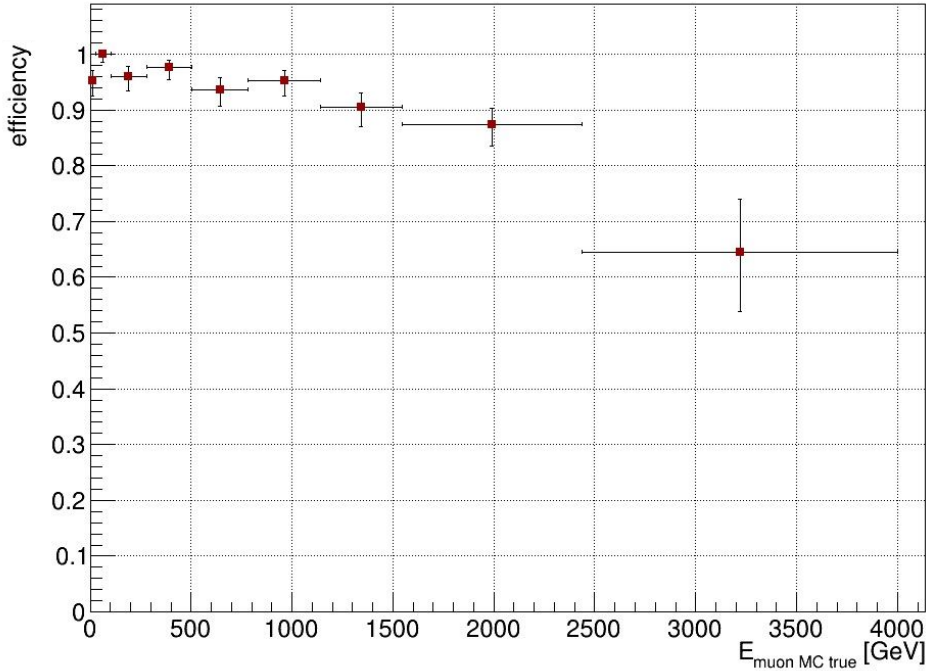
- Tracking muons with the electronic detectors plays two critical roles in the experiment:
  - Real-time muon flux measurements.
    - Background model validation.
    - Emulsion occupancy estimation.
    - Use SciFi and/or muon system.
  - Muon identification in neutrino interactions.
    - Tags ν_μ charged-current events.
    - Rely on muon system.
- Two complementary algorithms in place:
  - Simple tracking.
    - Cluster hits in each tracking plane.
    - Require a single cluster in most planes.
    - Runs faster.
  - Hough transform.
    - Identify straight-line hit patterns with Hough transform.



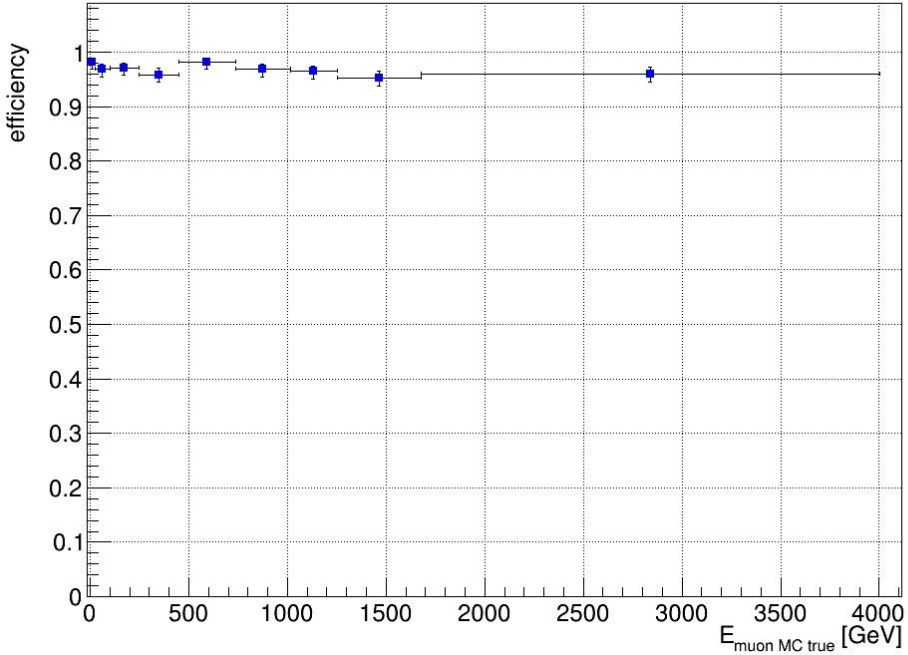
Muon tracking efficiency

SND@LHC PRELIMINARY

SciFi + Simple tracking

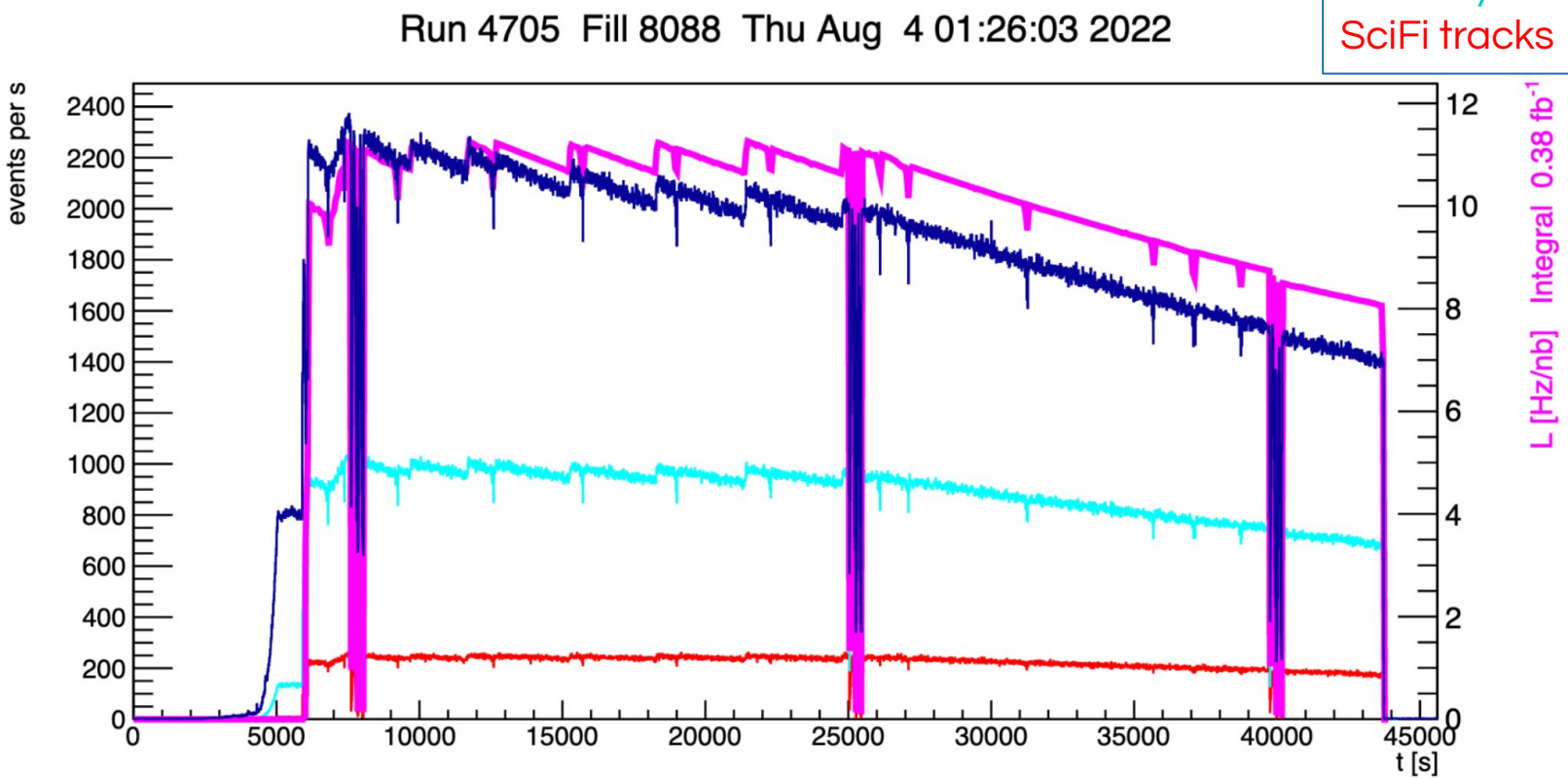


Muon system + Hough transform



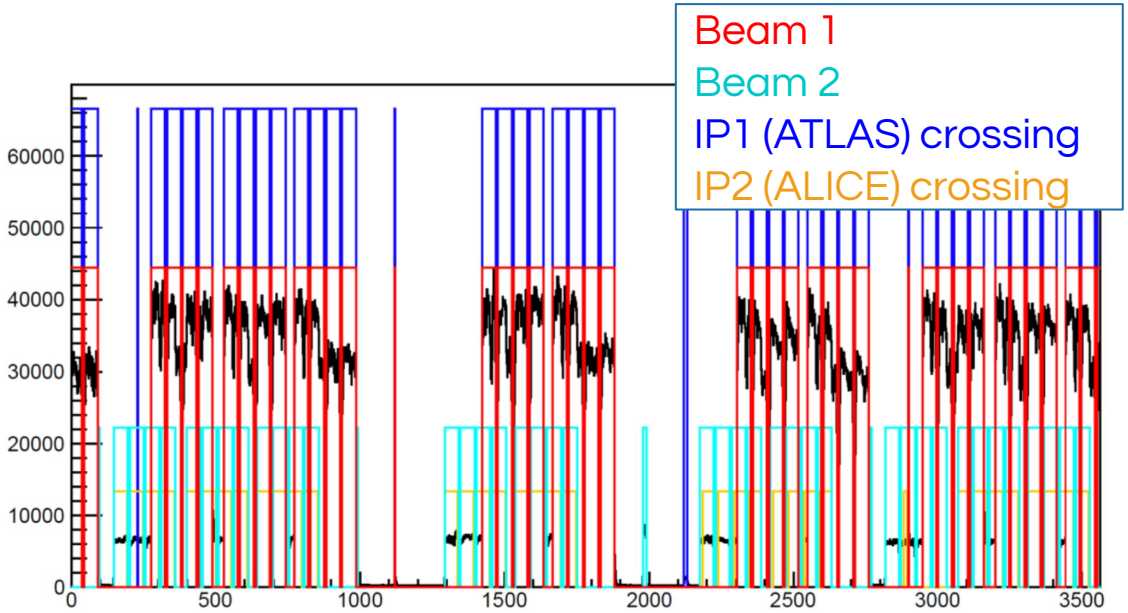
Event rates with collisions

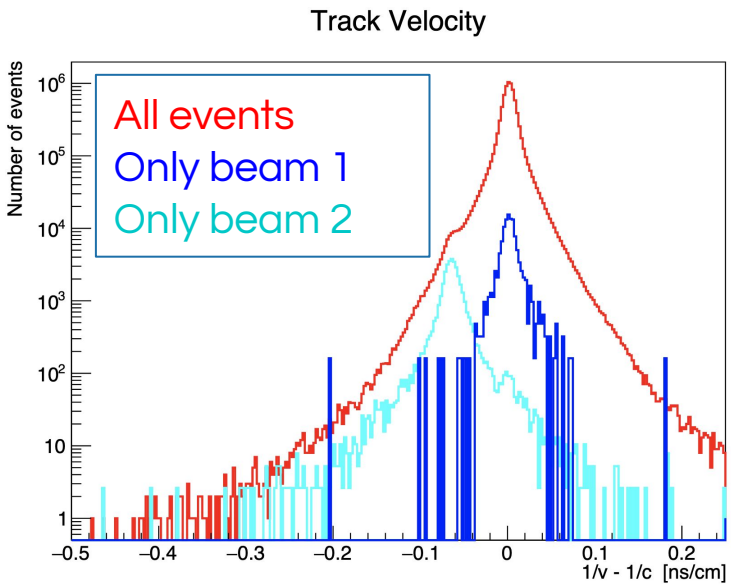
ATLAS Luminosity
SND@LHC Event rate
Muon system tracks
SciFi tracks



Bunch structure

- Event rates at SND@LHC follow the LHC filling scheme.
- Events associated to non-colliding bunches used to measure non-collision backgrounds.
  - Significant event rate induced by Beam 2 non-colliding bunches.
    - These events enter the detector from the downstream end.
    - Clearly observed in track direction measurements.

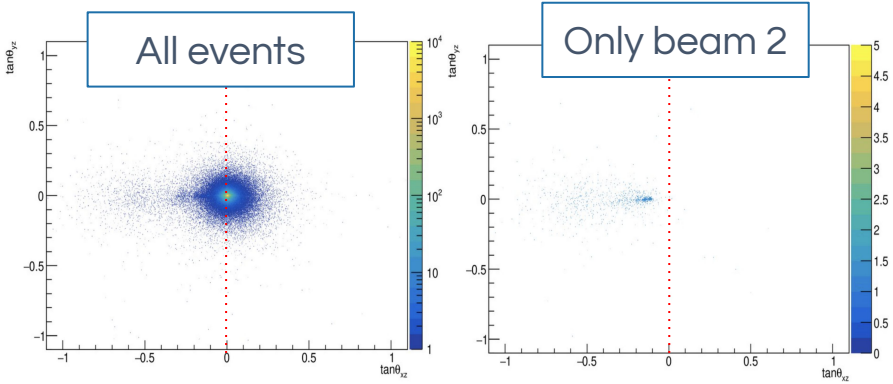


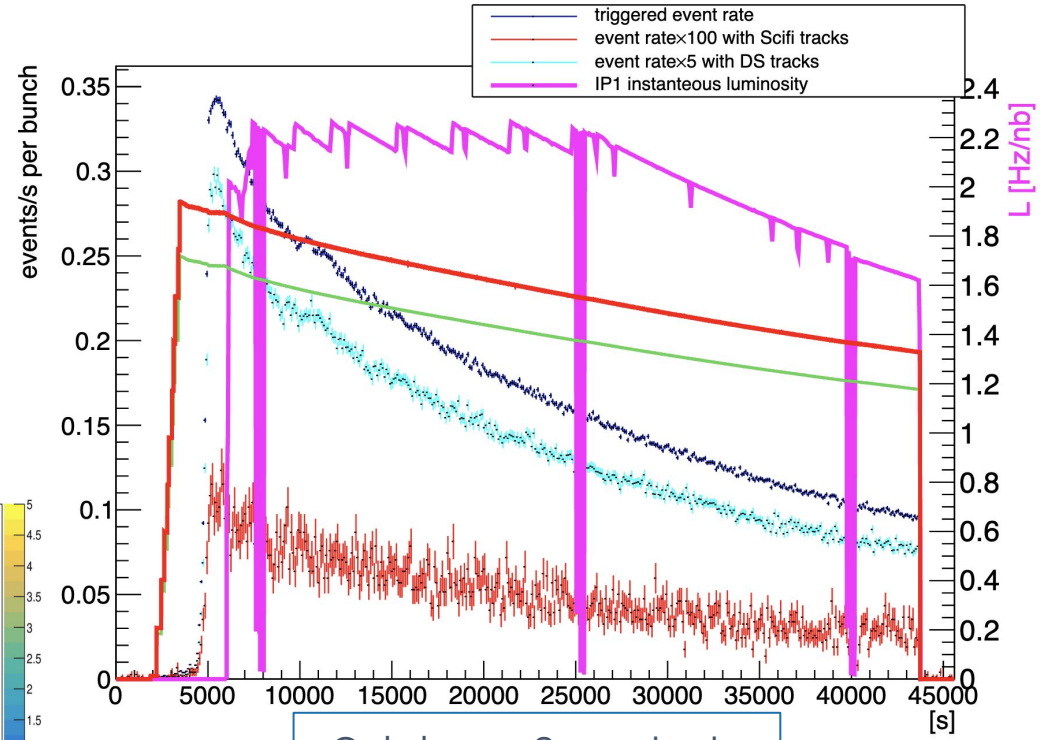


Non-colliding bunch events

SND@LHC PRELIMINARY

- Non-colliding bunch event rate drops with the fill time.
- Steeper drop than the beam intensity.
  - Most likely due to the evolution of vacuum conditions over the fill.
- Muon tracks in Beam 2 events have larger angles.
  - Muon origin under investigation.

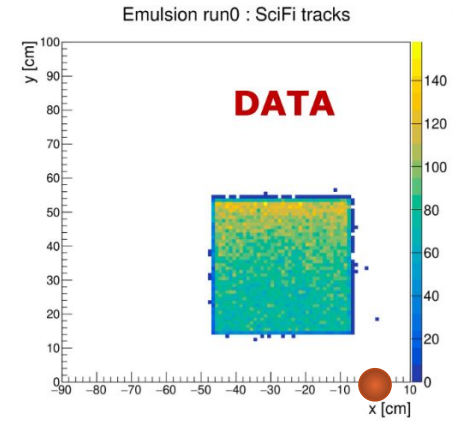




Only beam 2 event rate

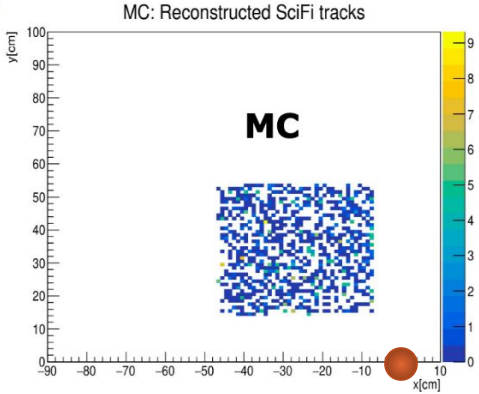
Muon flux with electronic detectors

SND@LHC PRELIMINARY



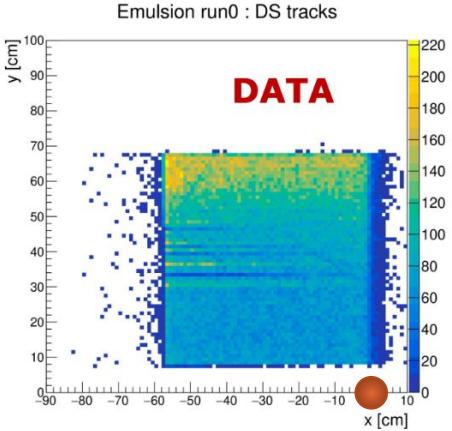
Measured muon track rate in SciFi (39x39 cm²):

1.8x10⁴ fb/cm²



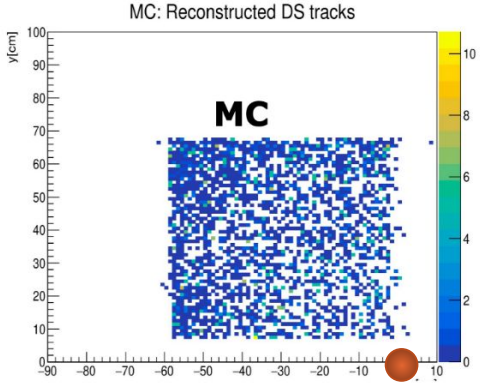
Expected muon track rate in SciFi (39x39 cm²):

3.6x10⁴ fb/cm²



Measured muon track rate in DS (60x60 cm²):

2.0x10⁴ fb/cm²



Expected muon track rate in DS (60x60 cm²):

4.4x10⁴ fb/cm²

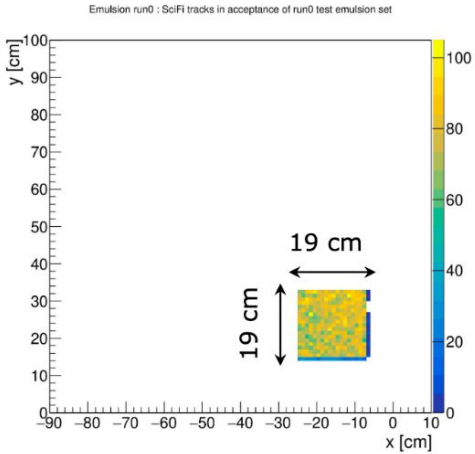
- Expect better data/MC agreement using newly updated simulation with better description of magnetic field in yokes.

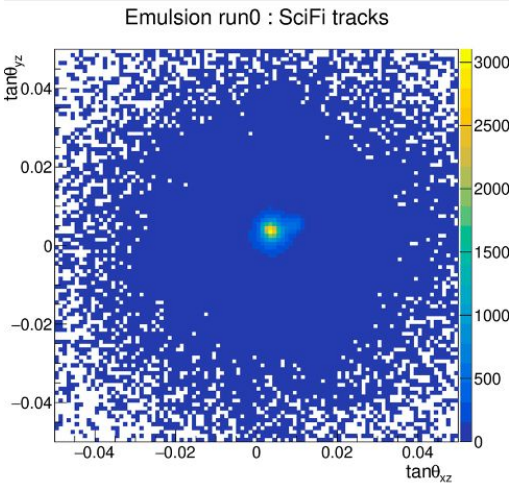
SciFi and Emulsion fluxes compared

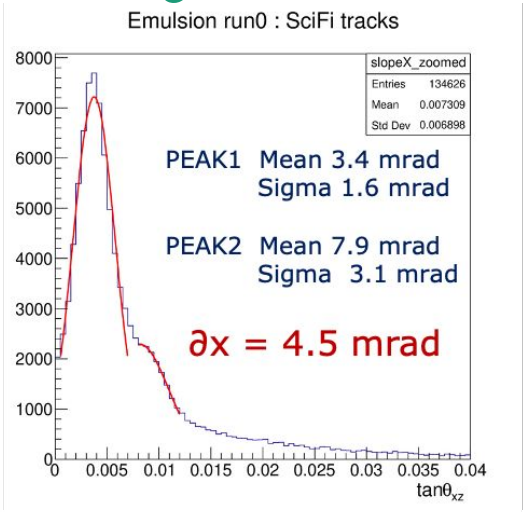
SND@LHC PRELIMINARY

SciFi

Measured rates on BRICK1 surface
1.4×10^4 fb/cm^2

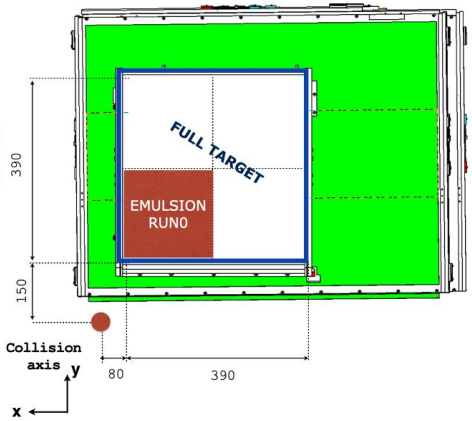


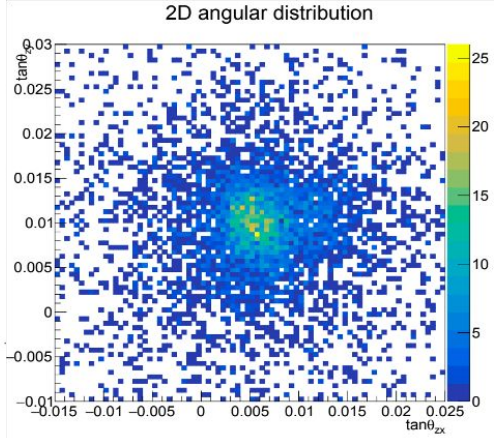


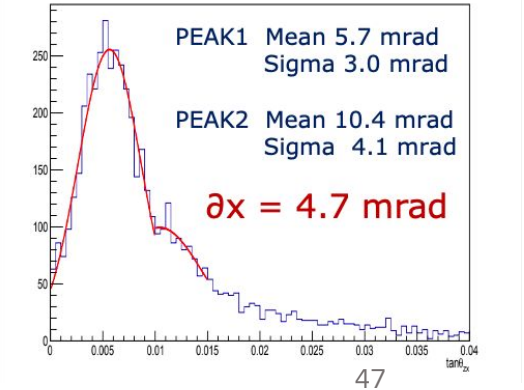


EMULSIONS

Measured rates in BRICK1
1.5×10^4 fb/cm^2



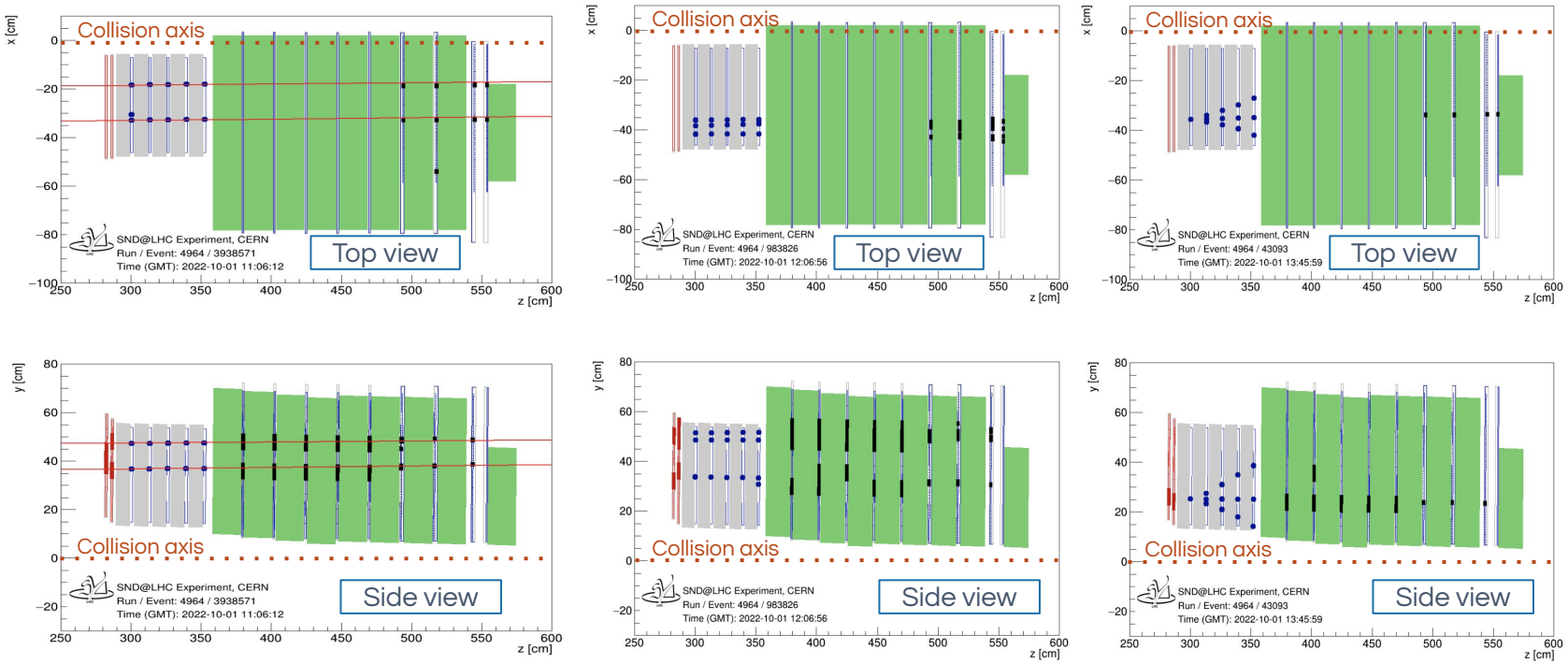




Multi-track events

SND@LHC PRELIMINARY

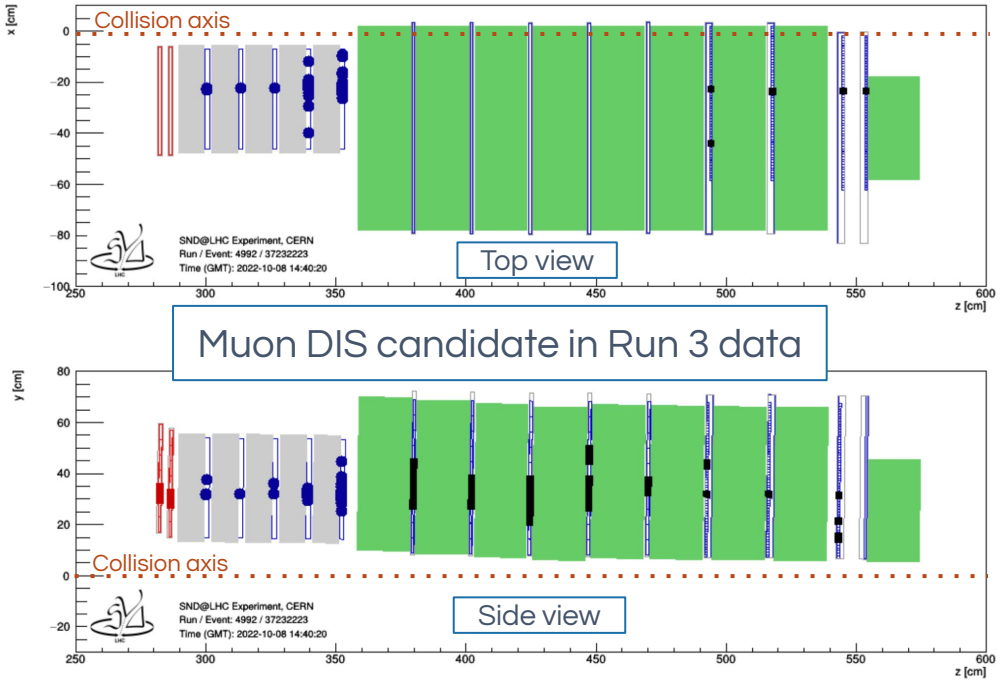
- We observe events with 2 and 3 tracks at a rate which is incompatible with pile-up.
- The origin of these events is under investigation.
  - Muon trident, pair-production, … ?



Muon deep inelastic scattering

SND@LHC PRELIMINARY

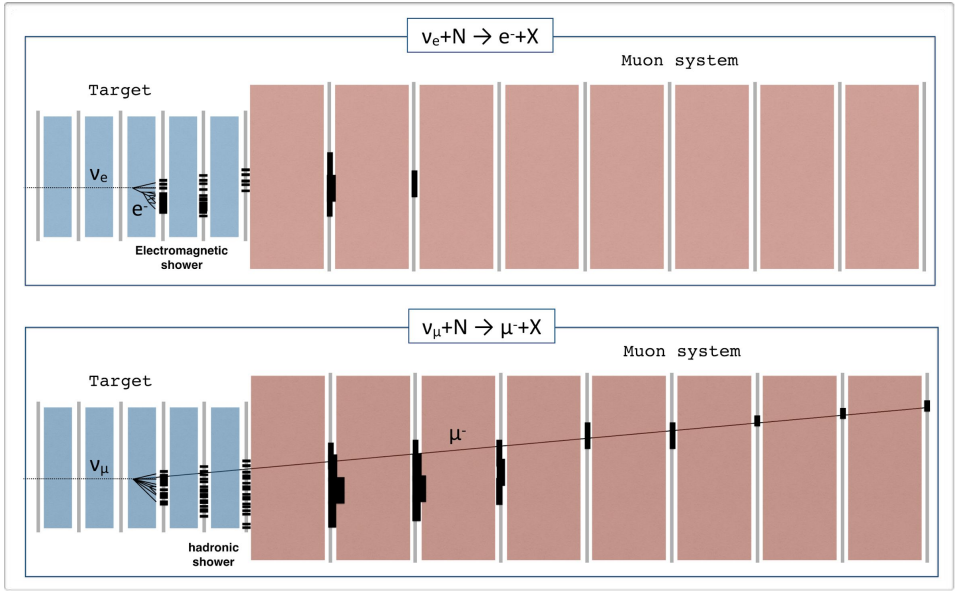
- Muon DIS is a potential source of background in neutrino measurements.
  - Can mimic charged-current ν_μ events if incoming track is missed.
  - Produce neutrons and K_L in rock upstream of the detector.
- Measure muon DIS rate in the detector to validate and constrain background model.
  - Select events with a muon track and a large hadronic shower.



Neutrino identification strategy

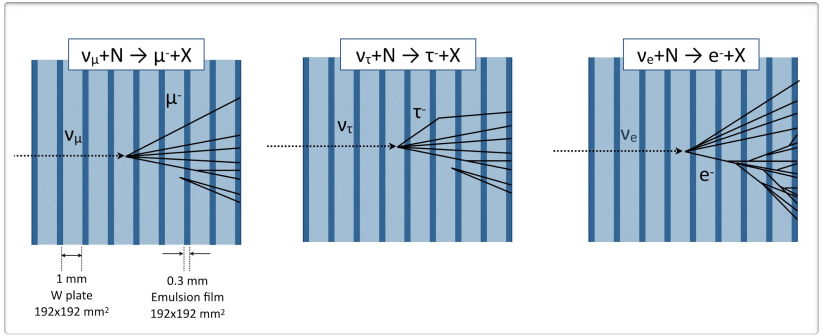
First stage

- Identify neutrino candidates in electronic detector data.
- Tag muons with muon system.
- Measure electromagnetic and hadronic energy in calorimeters.



Second stage

- Identify neutrino candidates in emulsion data.
- Tag electromagnetic showers.
- Match events to electronic detector data.
  - Timestamp events.
- Identify ν_τ!



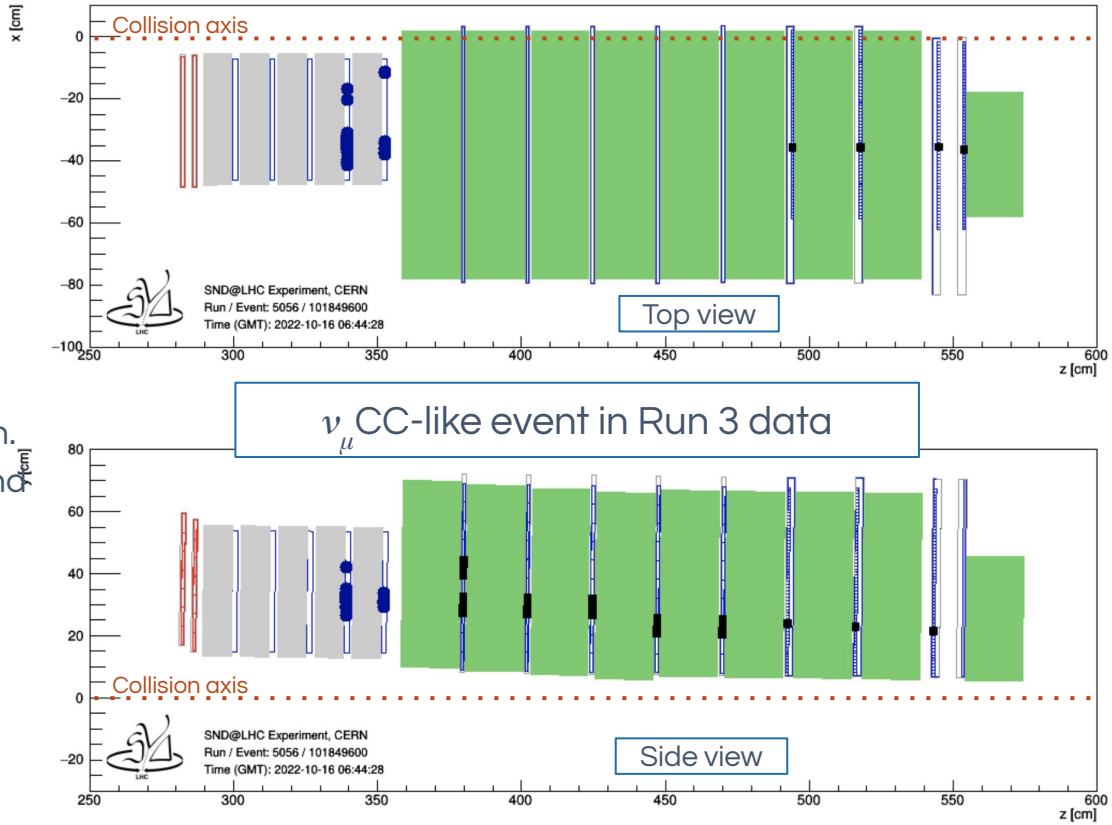
Proof-of-concept

- Identify neutrino candidates in existing electronic detector data.
- Low-efficiency, high-purity criteria.
  - "Golden sample"

Neutrino golden sample

SND@LHC PRELIMINARY

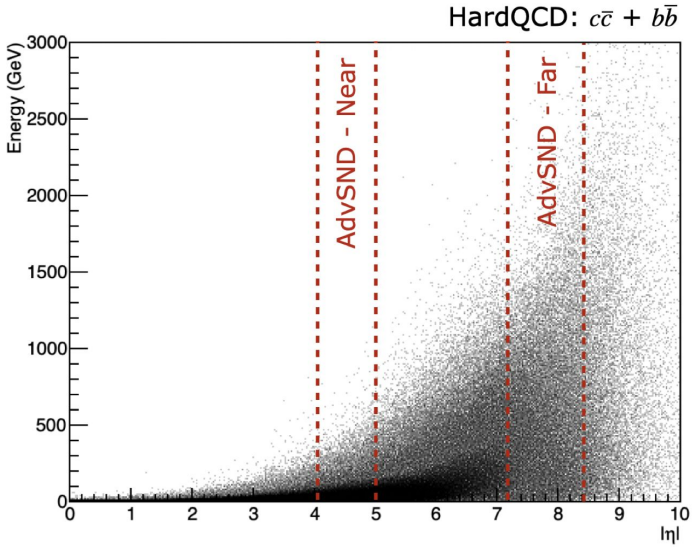
- Analyse 34 fb^{-1} of data.
  - 6.5×10^9 events
- Reduce to about 2000 events with simple cuts:
  - No activity in veto or first SciFi station.
  - Event does not start in last SciFi station.
  - Large activity in calorimeters.
  - Tight fiducial volume in target center.
  - Event corresponds to IP1 colliding bunch.
  - Event is isolated in time from previous and following event.
  - Reduction factor of 3×10^6.
- Identify a few ν_μ CC-like events by eye.
  - Work in progress to automate this step.
- Background estimation in progress.

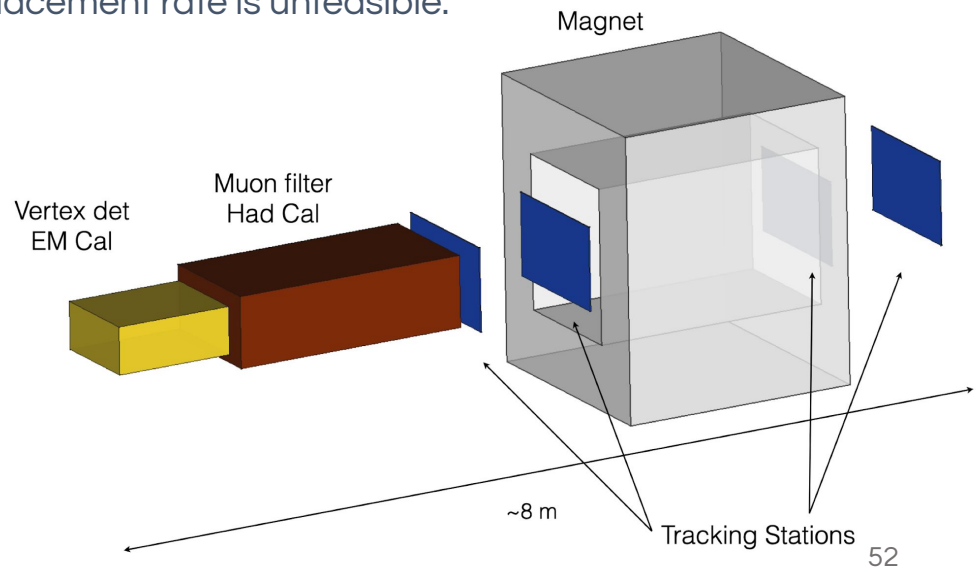


ν_μ CC-like event in Run 3 data

SND@LHC beyond Run 3

- Propose a near detector in a rapidity range overlapping with LHCb.
  - Reduce systematic uncertainty on far detector measurements using LHCb charm production measurements.
- Far detector in same rapidity range as current detector.
- Detector upgrades:
  - Tag muon sign with magnet.
  - Replace emulsion vertex detector with electronic technology.
    - HL-LHC emulsion replacement rate is unfeasible.





Summary

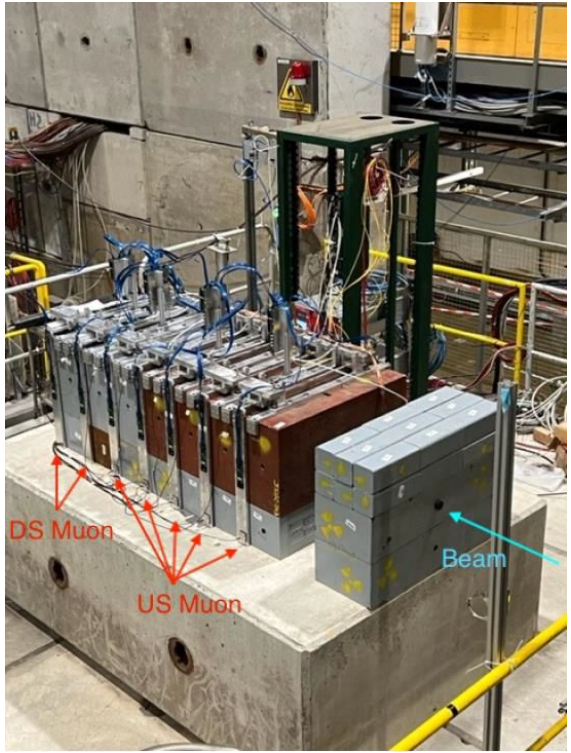
- SND@LHC has been taking data since the start of Run 3.
  - Less than two years between LoI and physics data!
  - Immense effort to build, install and commision the experiment in such a short amount of time.
- The detector is operating smoothly and collected 96% of the delivered luminosity in 2022.
- Lots of progress in the development of software and analysis tools.
- Physics analyses are now in full swing.
  - Muon DIS event candidates identified.
  - Neutrino-like events identified.
  - Multi-track events under study.
- Design and optimization of detector upgrades beyond Run 3 are underway.

Thank you for your attention!

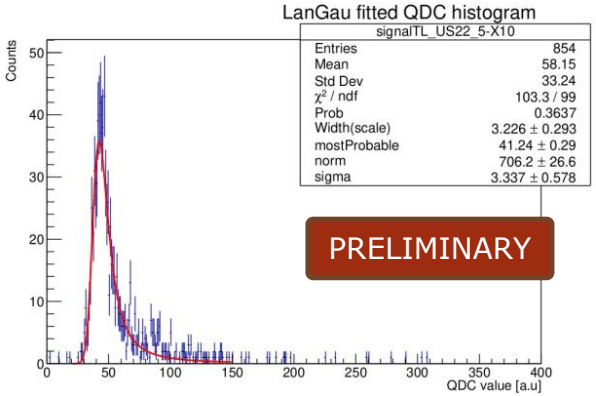
TEST BEAM WITH MUON SYSTEM

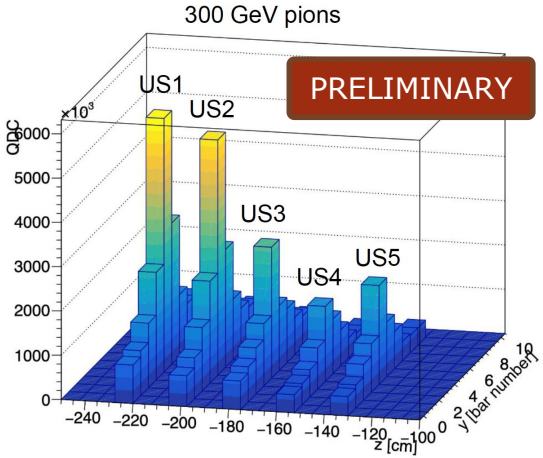
Oct 2021

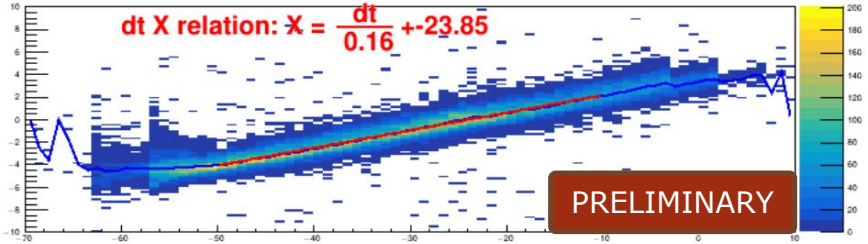
- Installation of the whole muon system at H8 in the North Area
- Energy calibration with 140, 180 240, 300 GeV pion beam



First glance at the signal







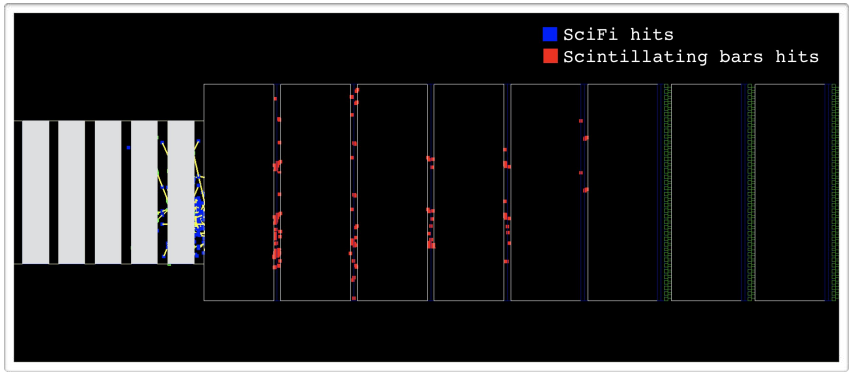
Extrapolated track X position vs mean time difference between left and right side

Position resolution:
σ_x =3.7 cm

ν_e ENERGY ESTIMATION

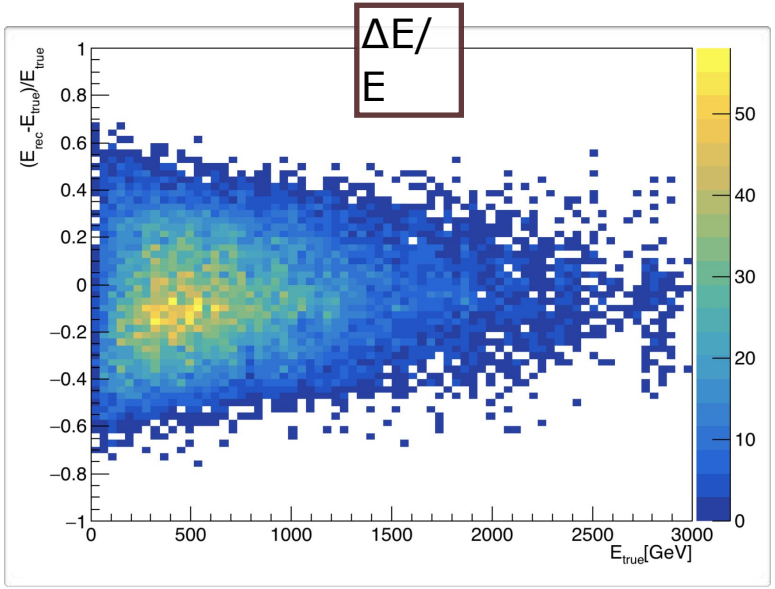
- Estimation of ν_e energy combing information from SciFi (target region) and Scintillator bars (Muon System)
- The detector acts as a non-homogeneous calorimeter

$$E_{rec} = A + B \times Nhits_{SciFi} + C \times Nhits_{Bars}$$



- Monte Carlo hits used in the current estimation
- Parameters A, B and C estimated via a gradient descent minimisation algorithm

Average resolution: 22%

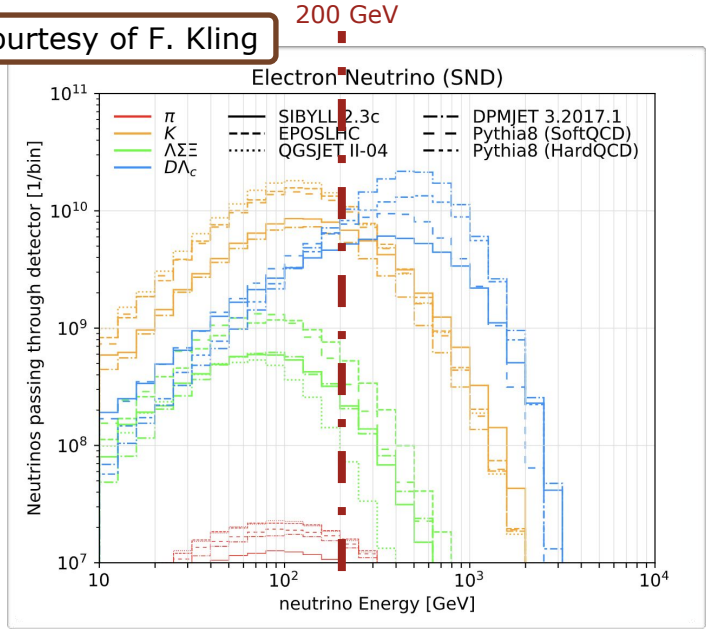


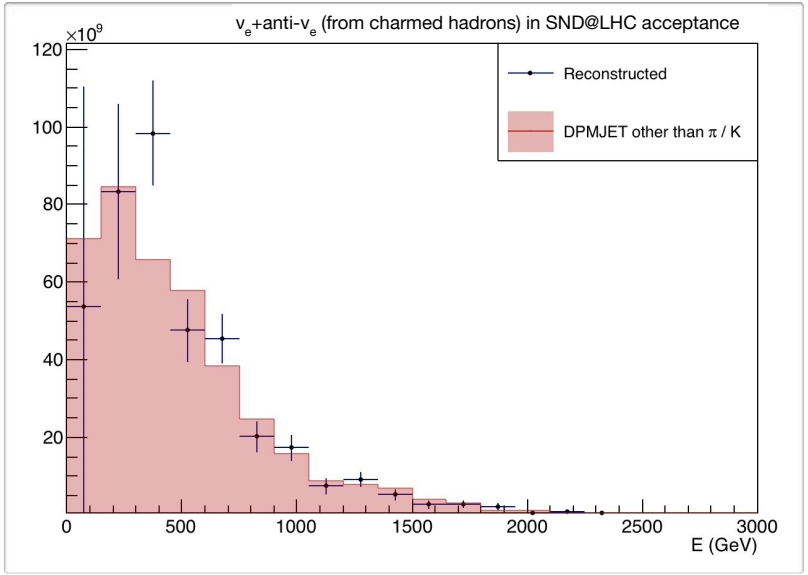
KAON CONTRIBUTION TO ν_e

- In order to extract the ν_e+anti-ν_e component from charmed hadron decay, a statistical subtraction of K component has to be performed
- The K component dominates at low energies (E<200 GeV)
- Predictions from different generators show large uncertainties (factor 2)

- This operation affects the low energy portion of the spectrum where the number of observed neutrino is lower
- The subtraction of the K component introduces an additional systematic error of **~20%**

Courtesy of F. Kling





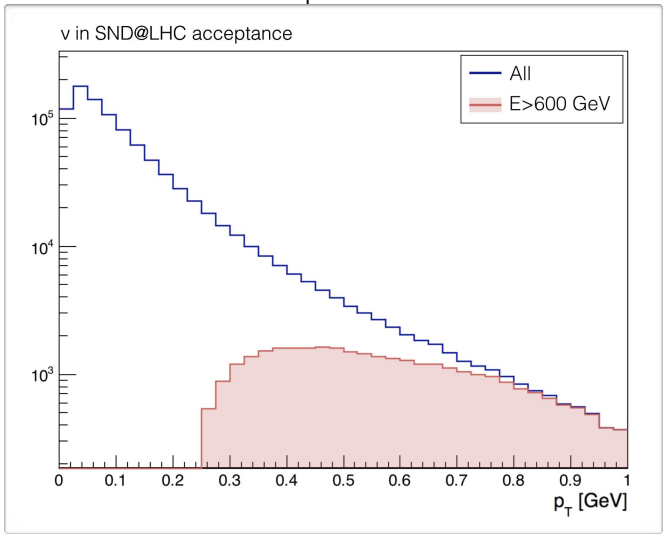
UNCERTAINTY IN PION/KAON CONTAMINATION

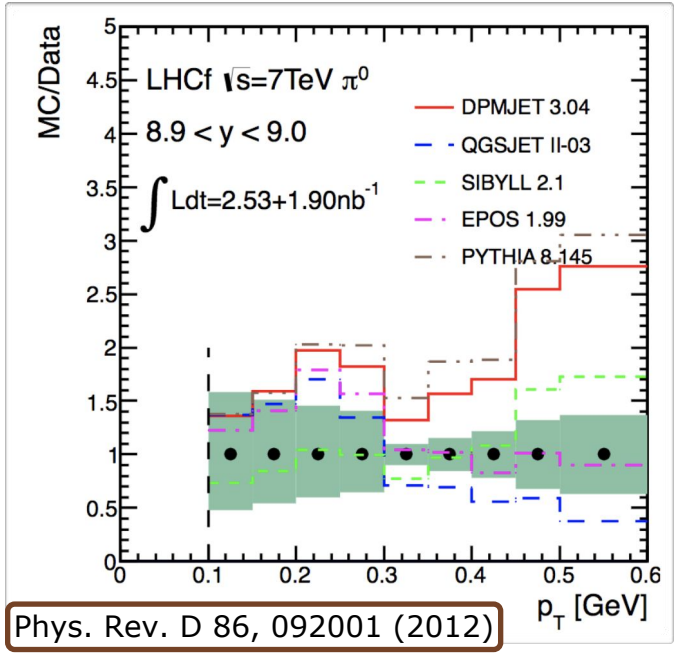
- The uncertainty in the knowledge of π/k contamination has two contributions:

1. Production of π/k
2. Propagation along beamline

- Simulation of light meson production in forward region constrained by LHCf collaboration
- Agreement better than **10%** with EPOS generator for p_T>300 GeV

- Neutrinos in SND@LHC acceptance with E>600 GeV have p_T>250 MeV





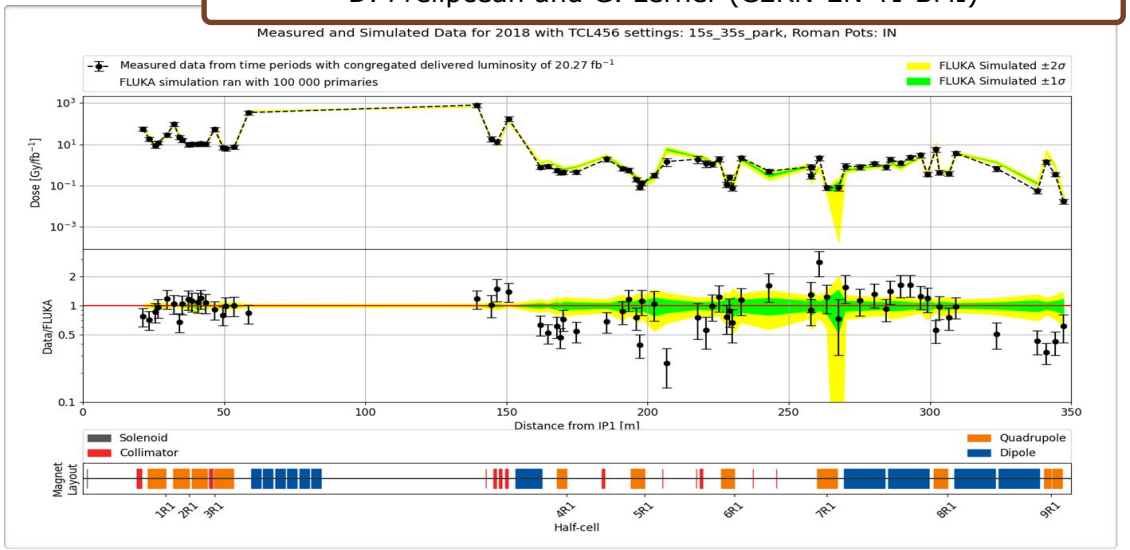
Phys. Rev. D 86, 092001 (2012)

UNCERTAINTY IN PION/KAON CONTAMINATION

- The uncertainty in the knowledge of π/k contamination has two contributions:

1. Production of π/k
2. Propagation along beamline

D. Prelipcean and G. Lerner (CERN-EN-TI-BMI)



- Charged meson propagation performed with FLUKA and show very good agreement with measurements performed along the beamline

- Measurements performed by FASER in TI18 in agreement with FLUKA predictions (2×10^4/cm^2/fb^{-1}) within errors

- SND@LHC will measure particle flux in TI18 with high accuracy, using different detectors

COMPLEMENTARITY WITH FASERnu

- Pseudo-rapidity range: η >8.8
- Main physics goals:
  - ~2000 ν_e, 7000 ν_μ, 50 ν_τ CC interactions expected *[Eur. Phys. J. C 80 (2020) 61]*
  - NC measurements could constrain neutrino non-standard interactions *[Phys. Rev. D 103, 056014 (2021)]*
  - Neutrino CC interaction with charm production ($\nu s \to l c$)
  - Study the strange quark content