Neutrino observation with SND@LHC

Part II: First results

Seminário LIP

April 6th, 2023

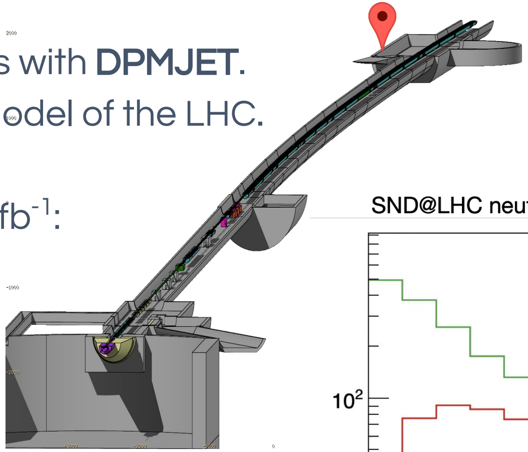
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Cristóvão Vilela

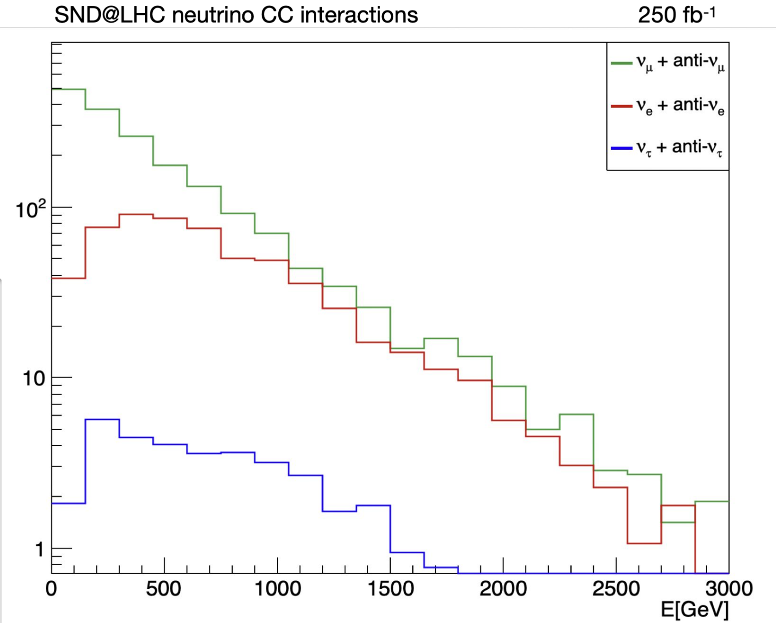
LHC neutrinos

Neutrinos in SND@LHC

- 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



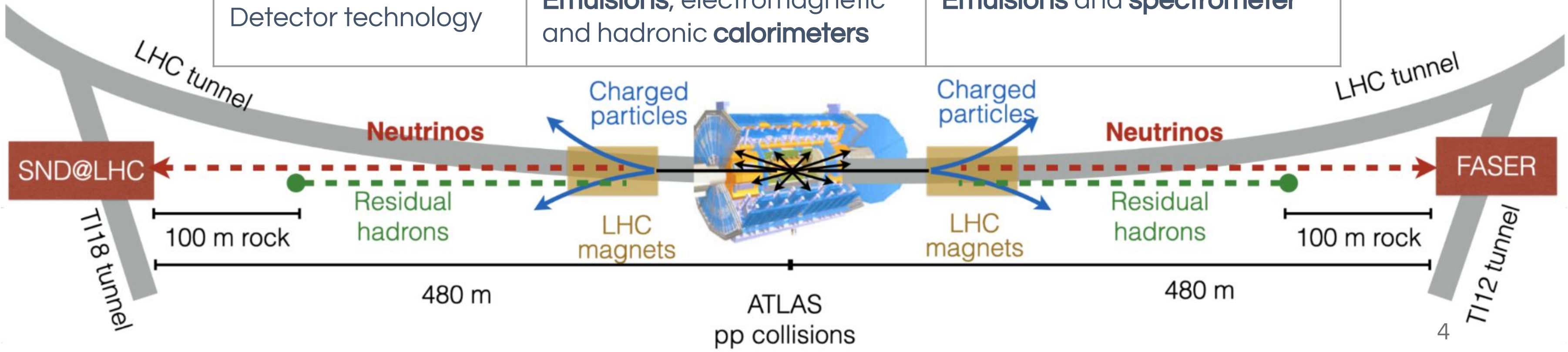
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Yield	CC neutrino interactions ⟨E⟩ [GeV]	Yield	NC neutrino interactions ⟨E⟩ [GeV]	Yield
ν_μ	130	3.0×10^{12}	452	910	480	270
$\bar{\nu}_\mu$	133	2.6×10^{12}	485	360	480	140
ν_e	339	3.4×10^{11}	760	250	720	80
$\bar{\nu}_e$	363	3.8×10^{11}	680	140	720	50
ν_τ	415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



Complementary ν LHC experiments

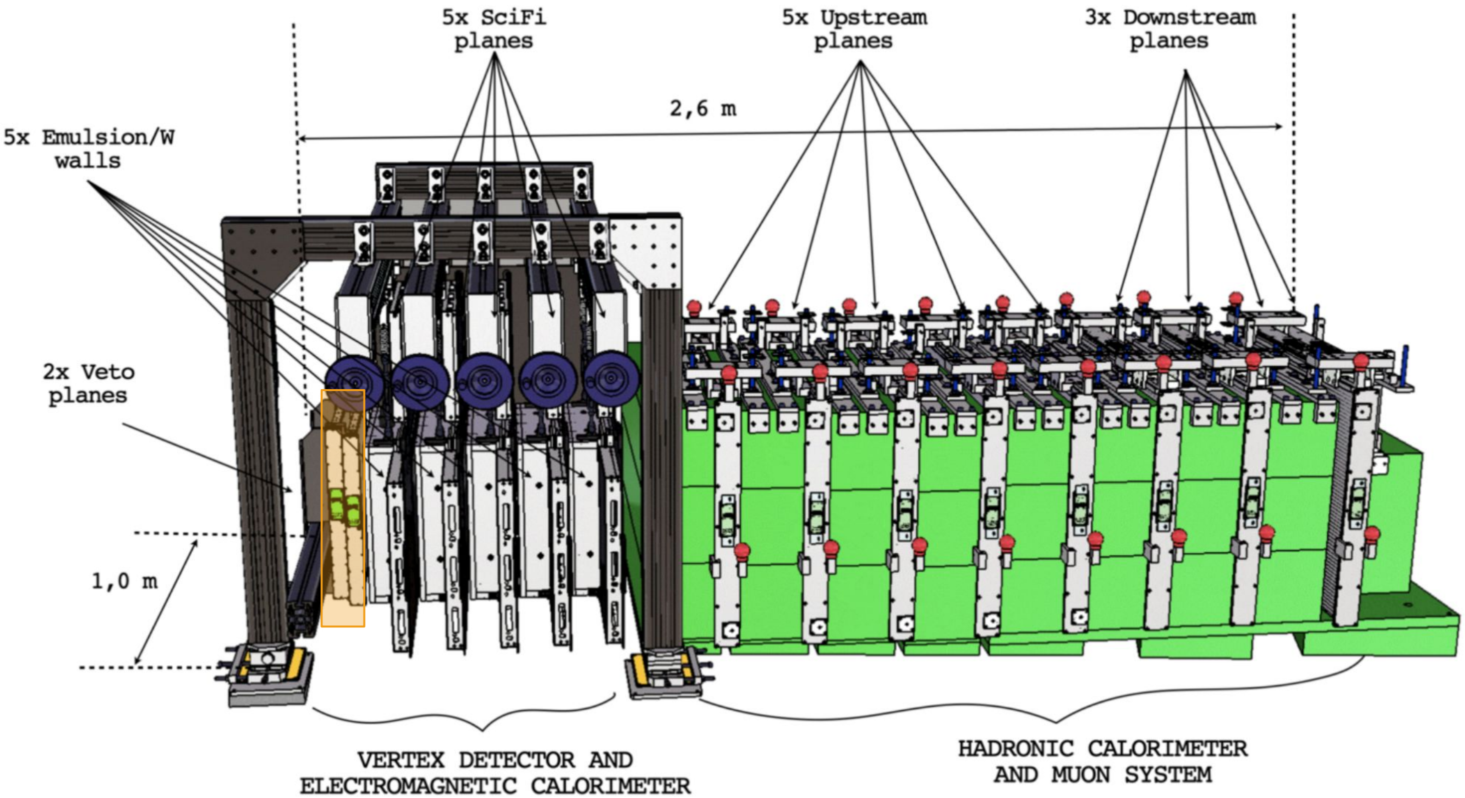
- We are not the only new kids on the block!
- **Complementary** approaches:
  - FASERnu has **larger** neutrino **flux** but can't cancel uncertainties by taking ratios.
  - Three neutrino flavours from **charm parents** at SND@LHC enables **LFU** and forward **charm production** measurements.

	SND@LHC	FASERnu
Location	**Off**-axis: $7.2 < \eta < 8.4$ ν_e, ν_μ, ν_τ from **charm decays**	**On**-axis: $\eta > 9.2$ ν_e, ν_μ, ν_τ with different parents
Detector technology	**Emulsions**, electromagnetic and hadronic **calorimeters**	**Emulsions** and **spectrometer**



A closer look at SND@LHC

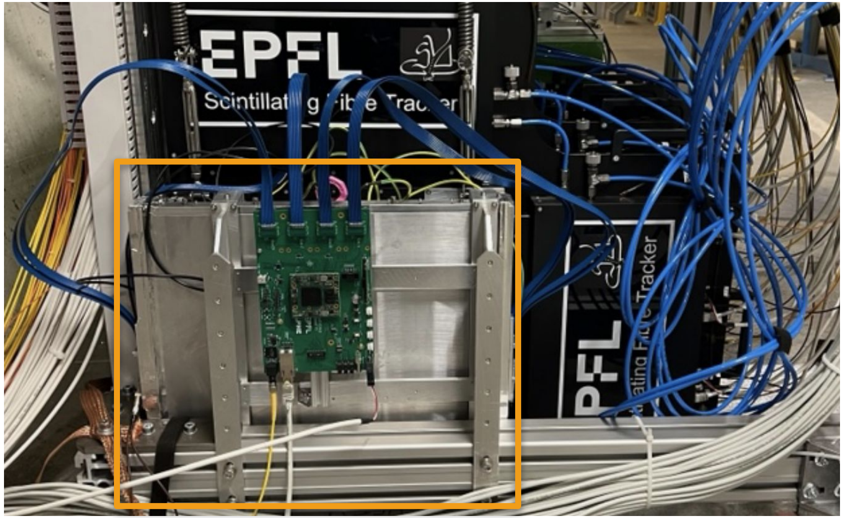
Veto system

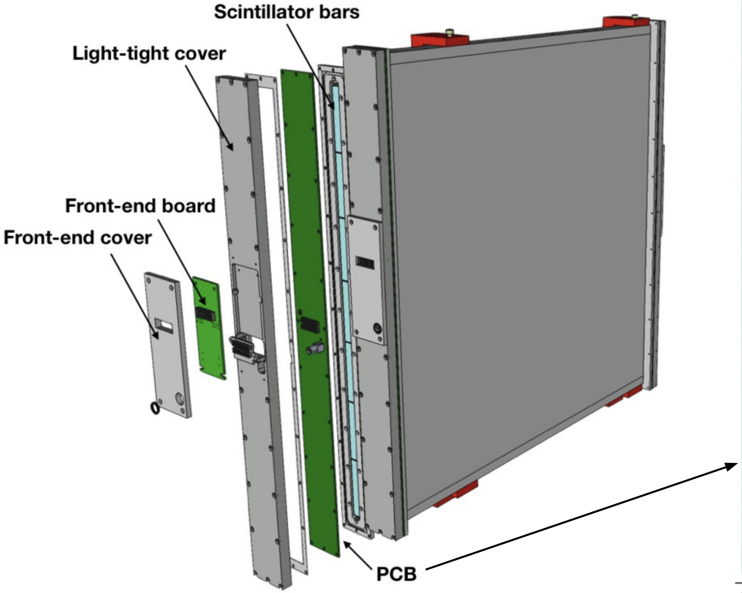


Two veto planes on upstream face of the detector.

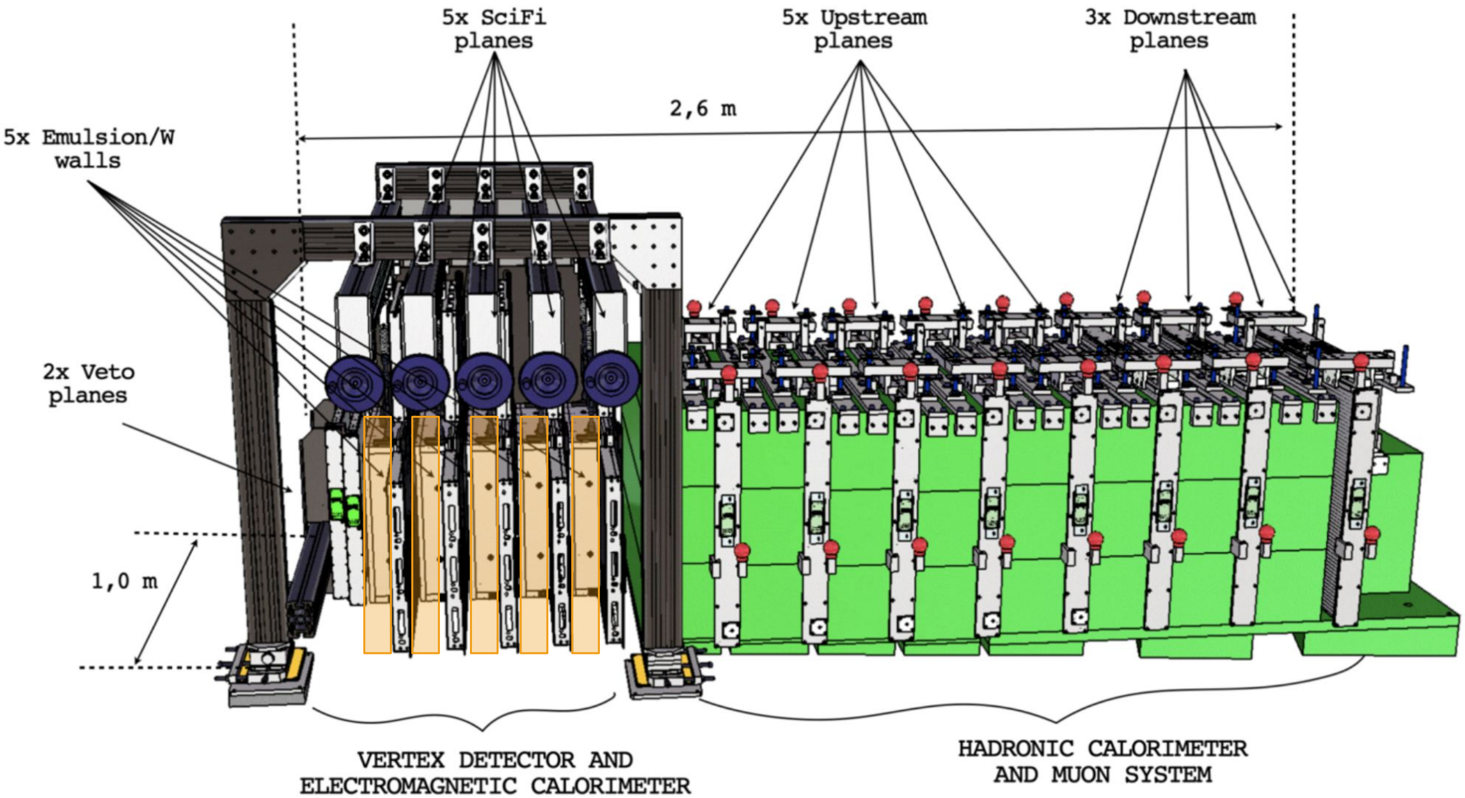
Veto system

- 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.
- Planes cover the target surface area and are vertically staggered to mitigate dead zones between bars.





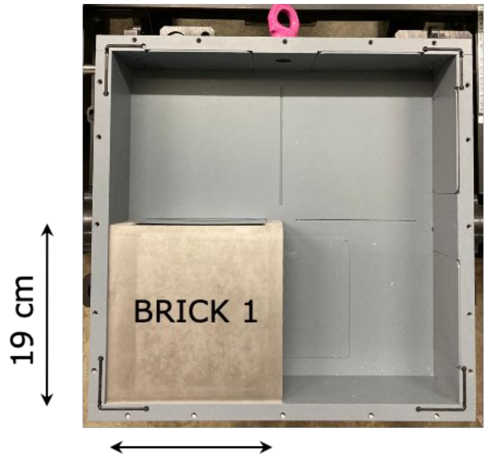
Emulsion target and vertex detector

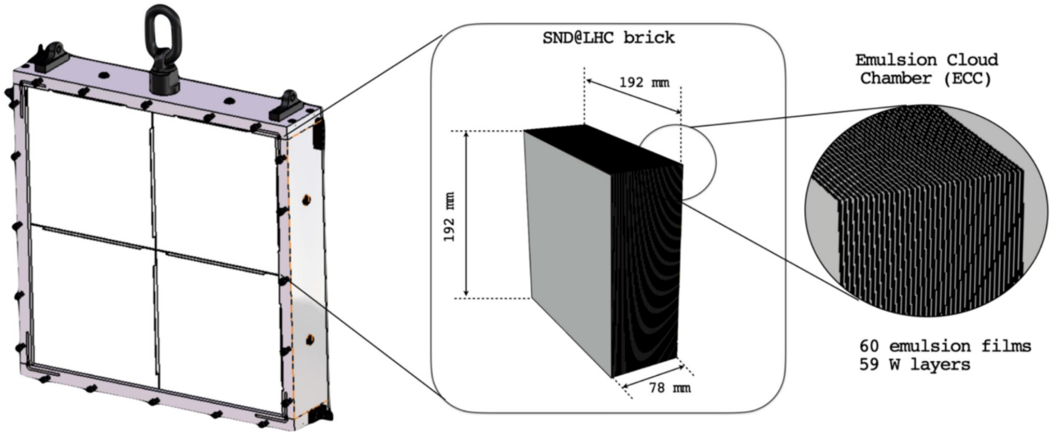


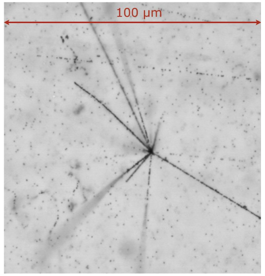
Five target walls instrumented with emulsions.

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 %).



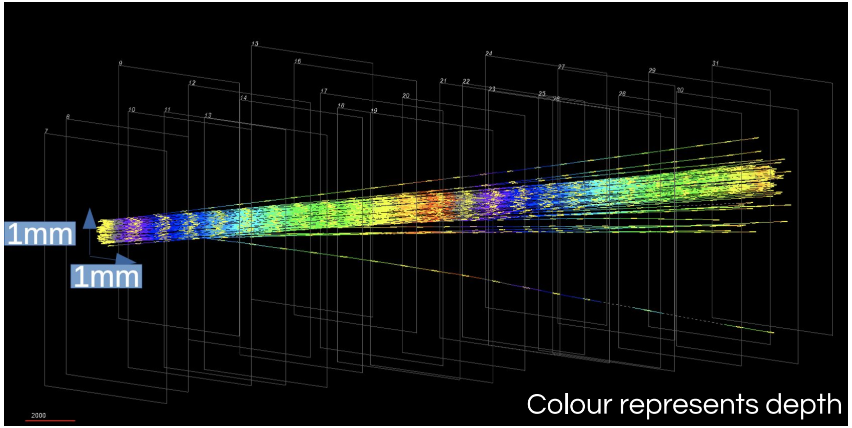




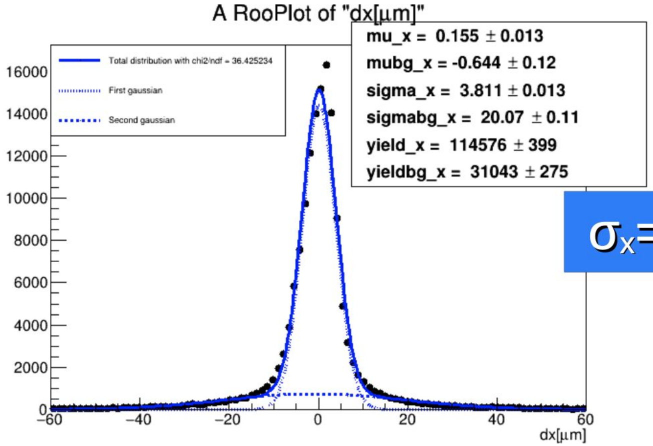
Emulsion detector performance

SND@LHC PRELIMINARY

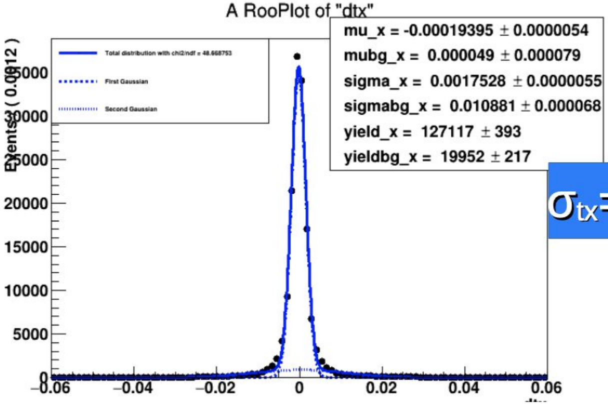
- A small portion of the target was instrumented at the start of the LHC Run 3.
- Exposed for 0.52 fb^{-1}.
  - Data consists mostly of muon tracks originating from IP1.
- Analysed to measure the muon flux with relatively low occupancy.



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

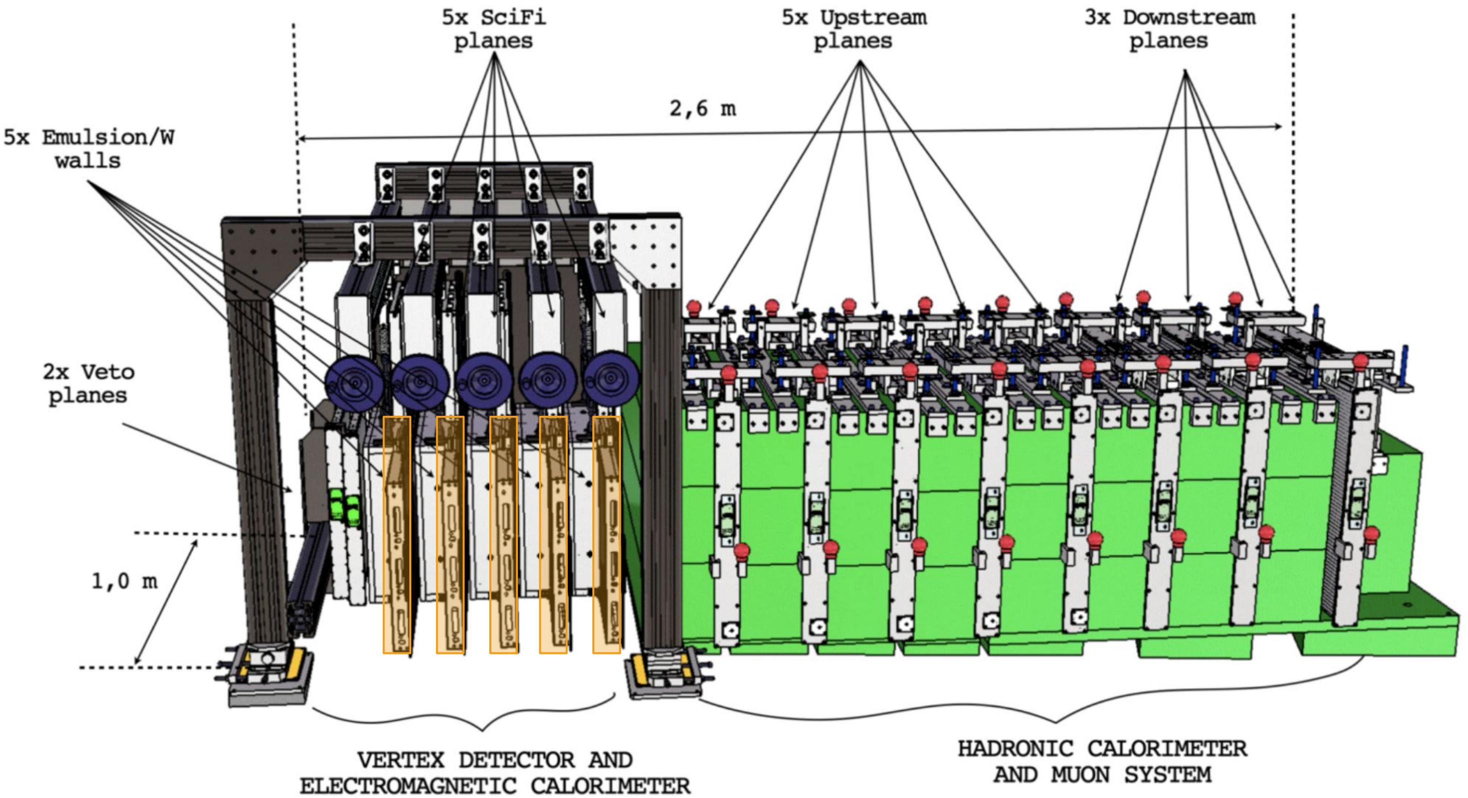


σ_x=3.8 μm



σ_{tx}=1.8 mrad

Scintillating fibre detector

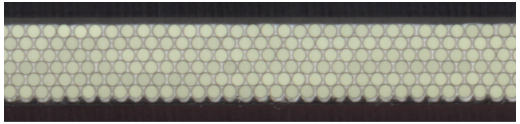


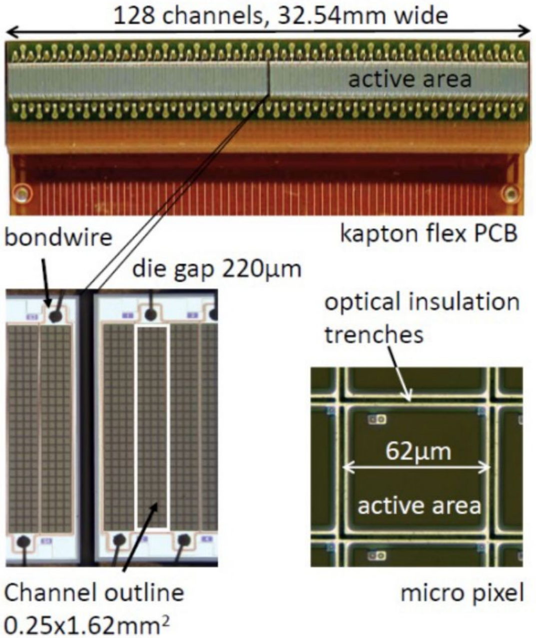
Each target wall is followed by a scintillating fibre detector station.

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

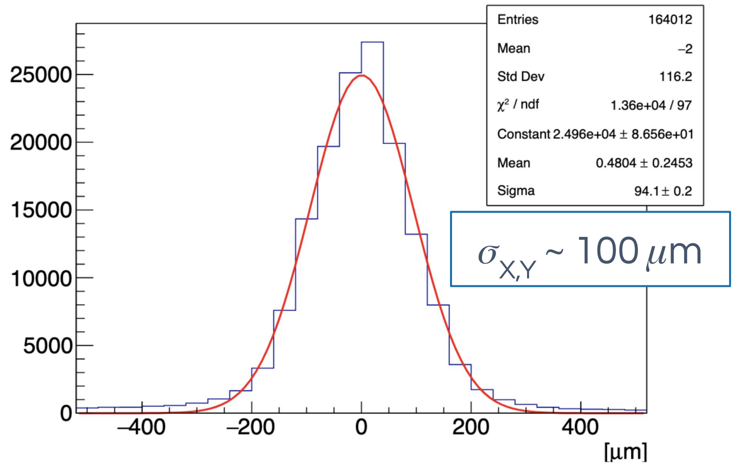




SciFi performance

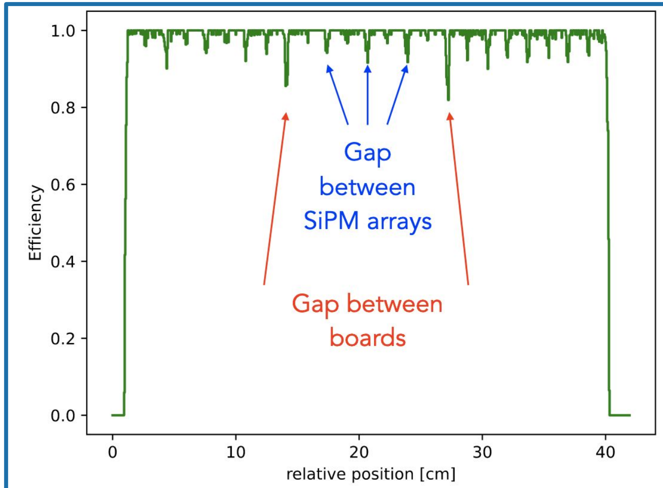
- SciFi performance measured using:
  - Test-beam muons.
  - LHC Run 3 data (dominated by IP1 muons).

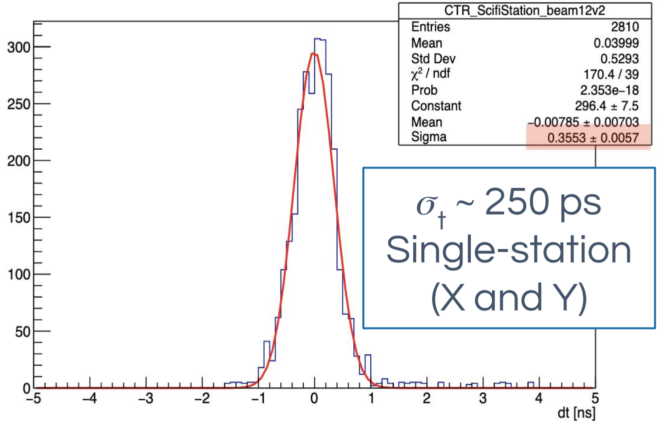
Muon test beam data



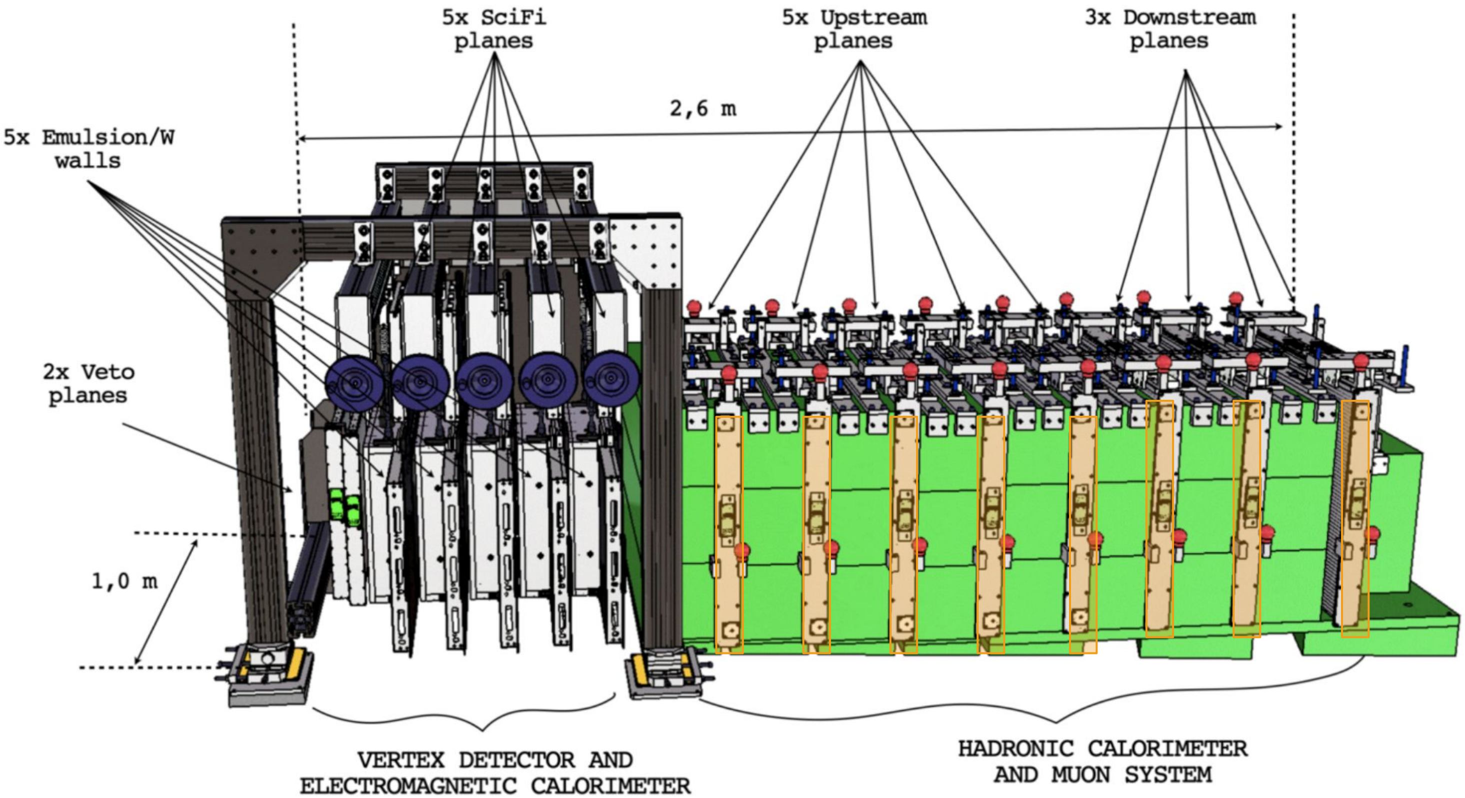
Measured without any material between stations.

Run 3 Data SND@LHC PRELIMINARY





Hadronic calorimeter and muon system

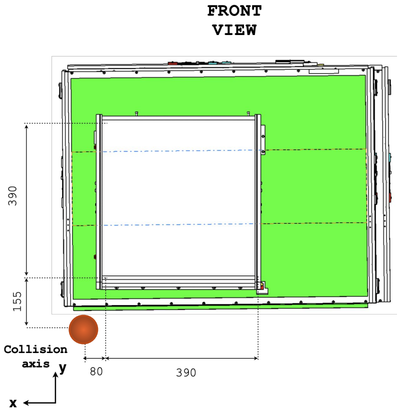


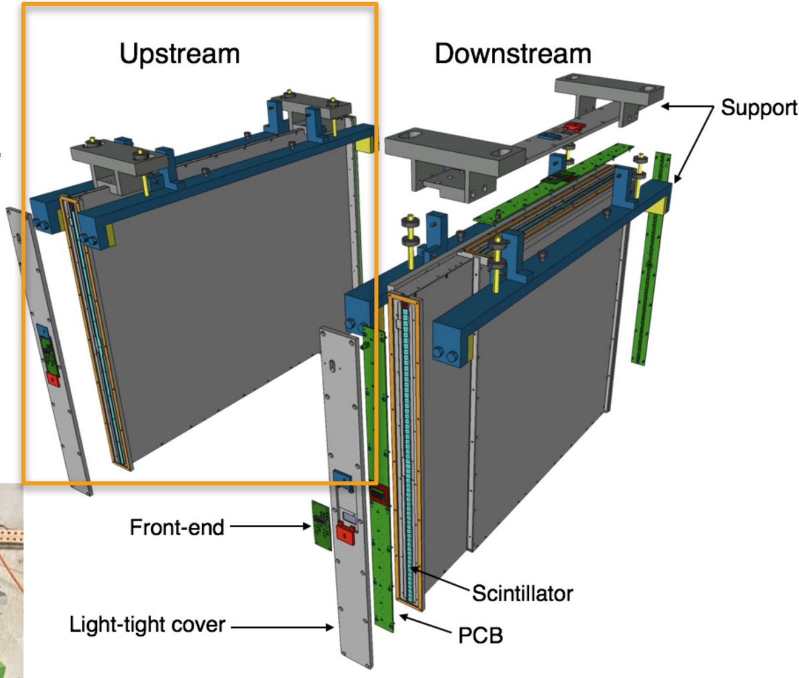
Fe-scintillator system with eight stations downstream of target.

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 and 2 small SiPMs.
    - Small SiPMs have higher pixel density and extend the dynamic range beyond the saturation of the large SiPMs.

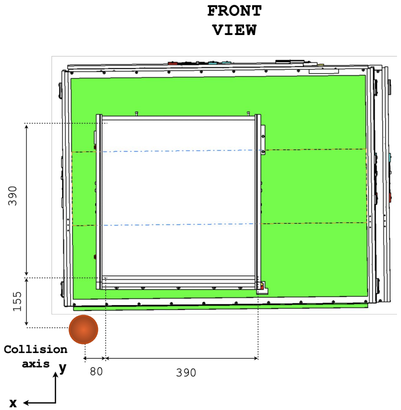


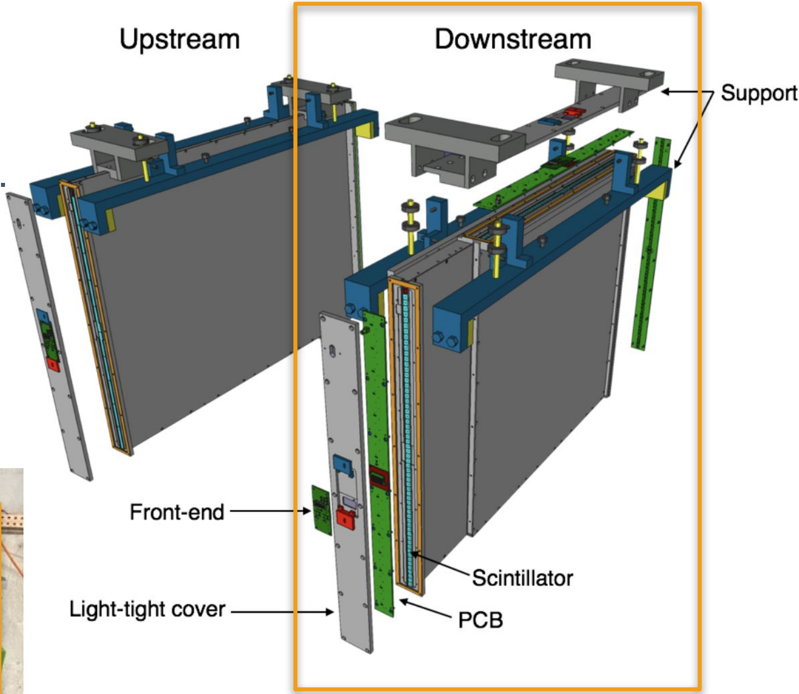


Hadronic calorimeter and muon system

Downstream

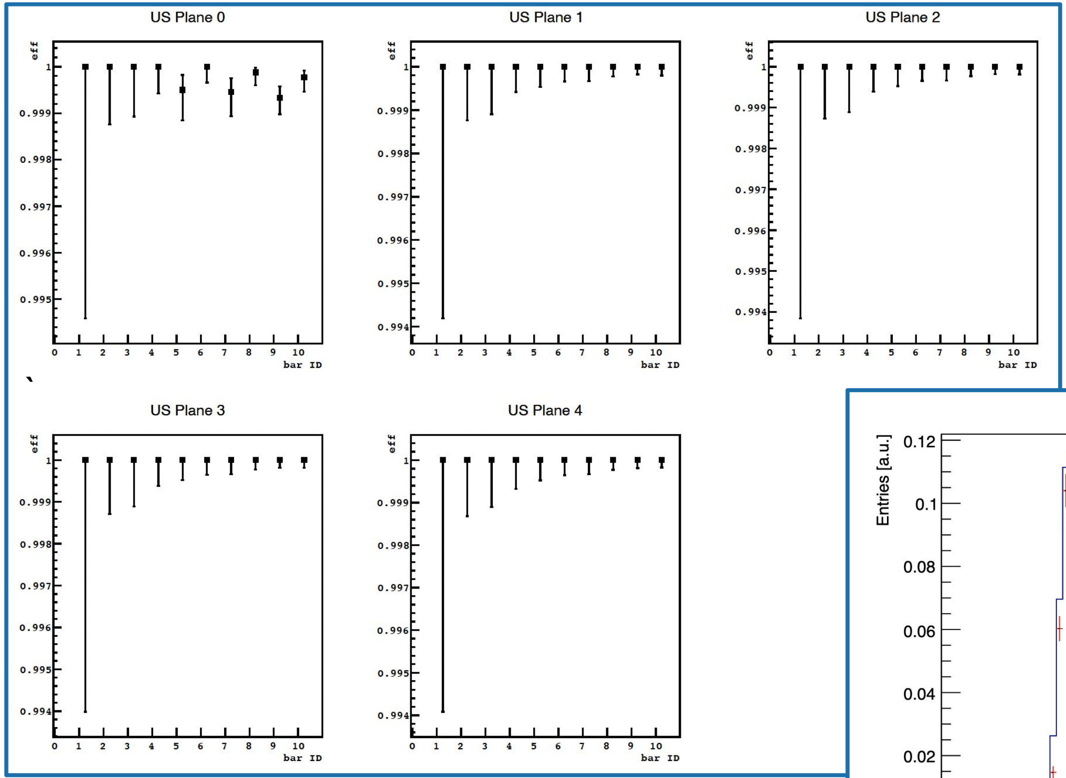
- Most downstream three stations used for muon tagging.
  - By the last station particles have traversed an average of 11 λ (including tungsten target).
- Stations instrumented with 60 horizontal and 60 vertical bars.
  - Each bar is 1 x 1 cm^2 in cross section.
  - Horizontal bars read out on both sides.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





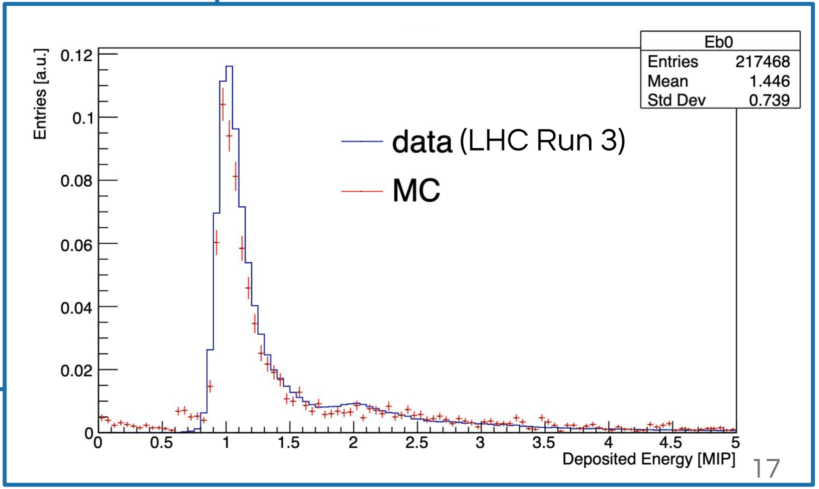
Hadronic calorimeter performance

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



SND@LHC PRELIMINARY

Good MIP energy deposition model

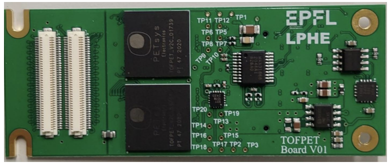


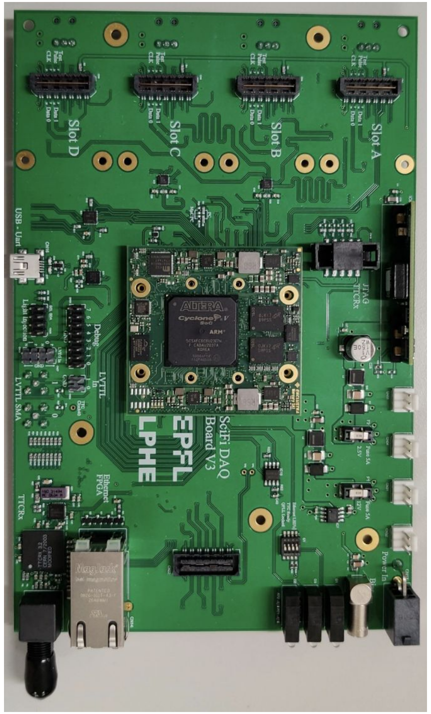
Data acquisition

- 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.

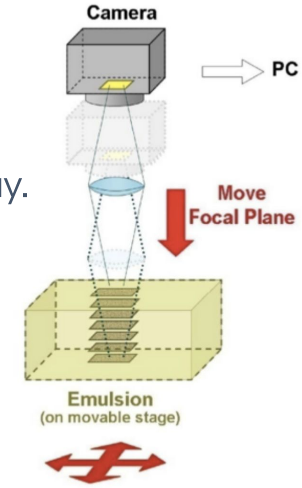
- DAQ server.
    - Receives hits from DAQ boards, 17k channels in total.
    - Runs timestamp-based event-building code.
    - Applies online noise filter conditions based on event topology.
    - Saves data to disk in ROOT format.



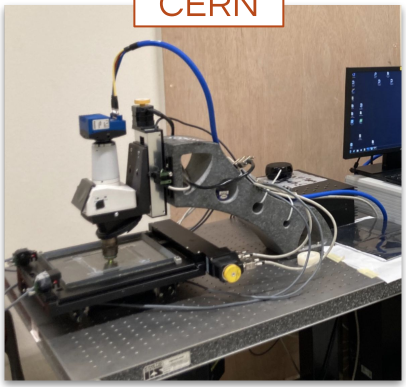


Emulsion scanning

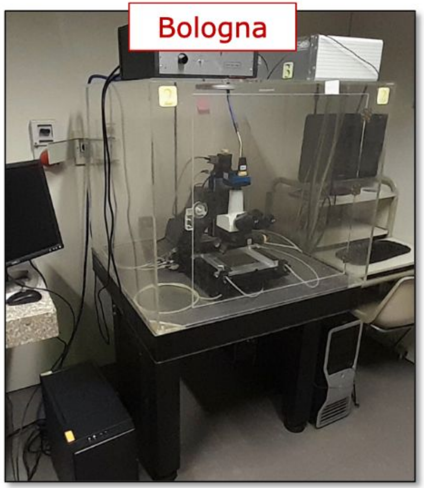
- Five emulsion scanning stations.
- Each microscope currently scans one emulsion film per day.
- Prohibitive to store raw microscope images in disk.
  - Processing the images is the bottleneck.
- Speed up foreseen:
  - More microscopes coming online.
  - Distributed data processing.



CERN

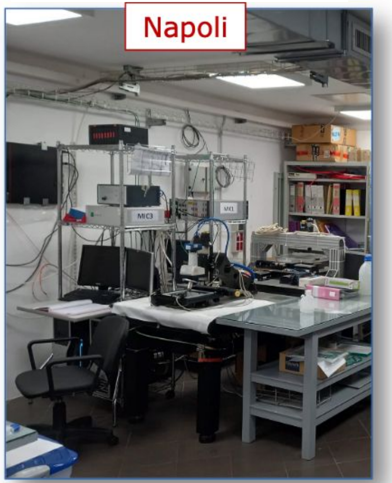


Bologna

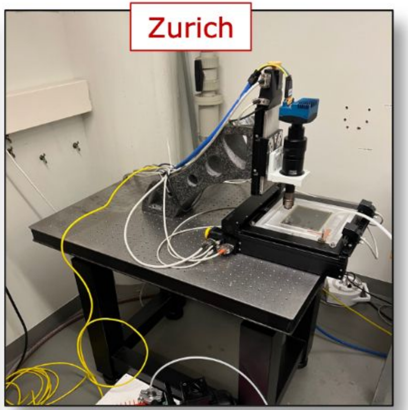


Lebedev

Napoli



Zurich

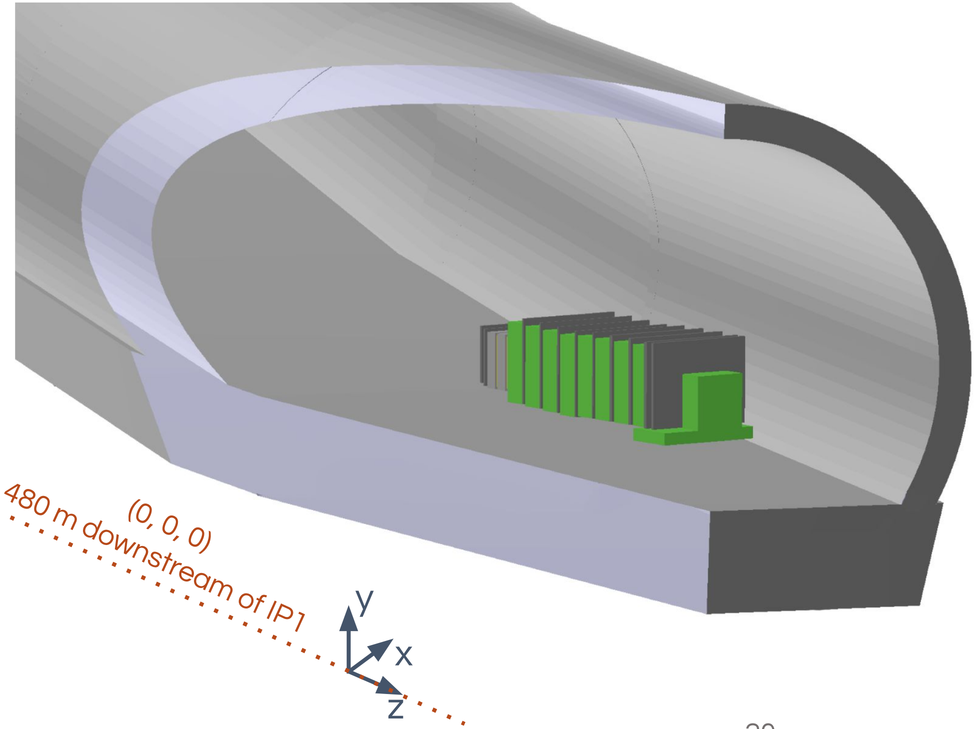


Software and analysis tools

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

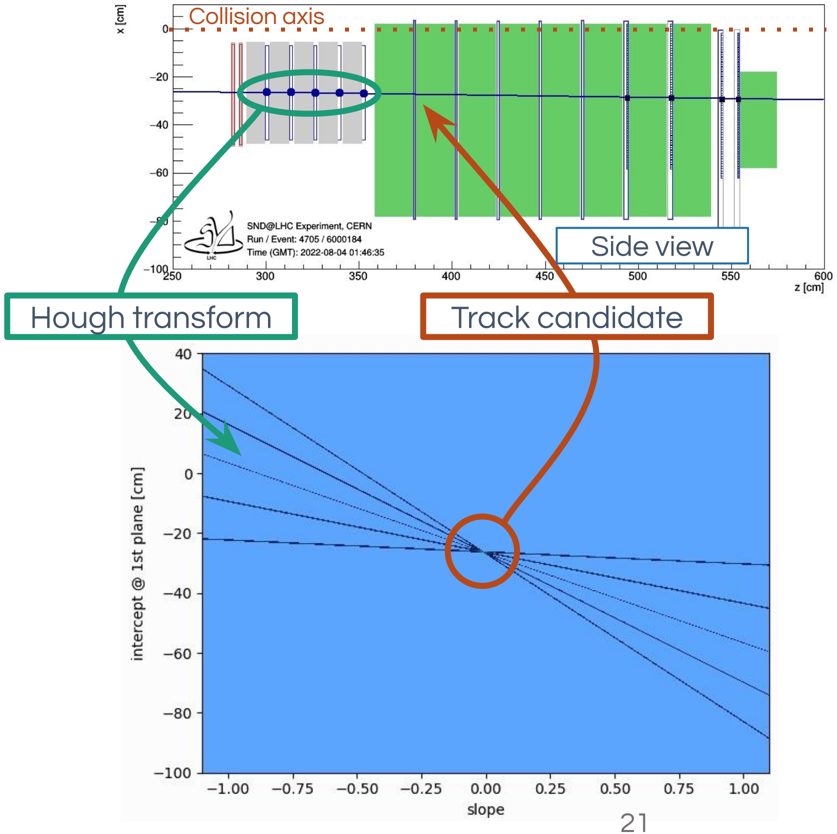
In `sndsw` FairROOT based software:

- 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.



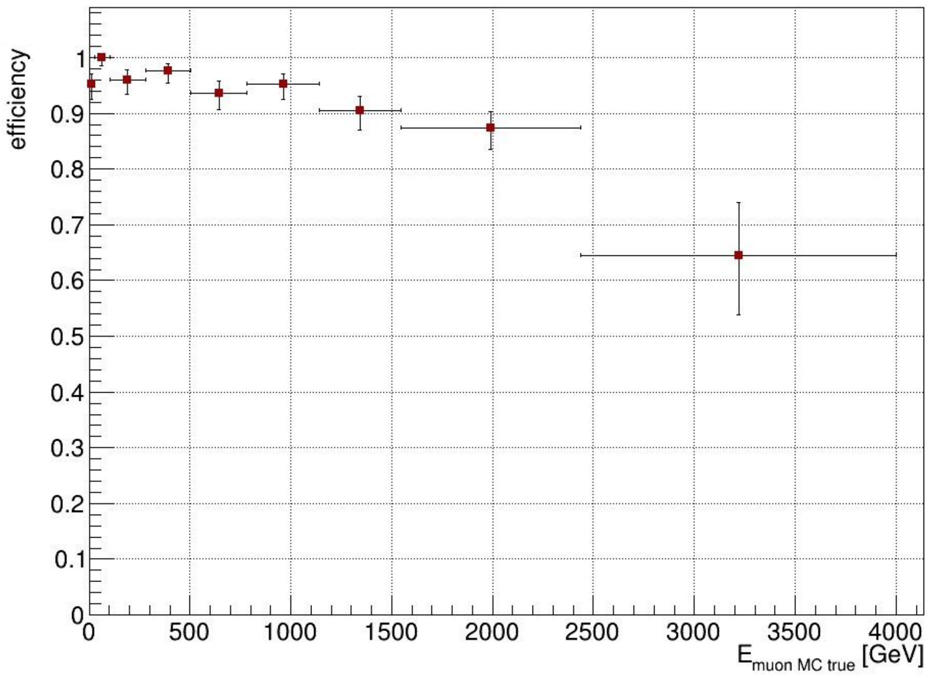
Tracking with electronic detectors

- 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 only.
- 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.

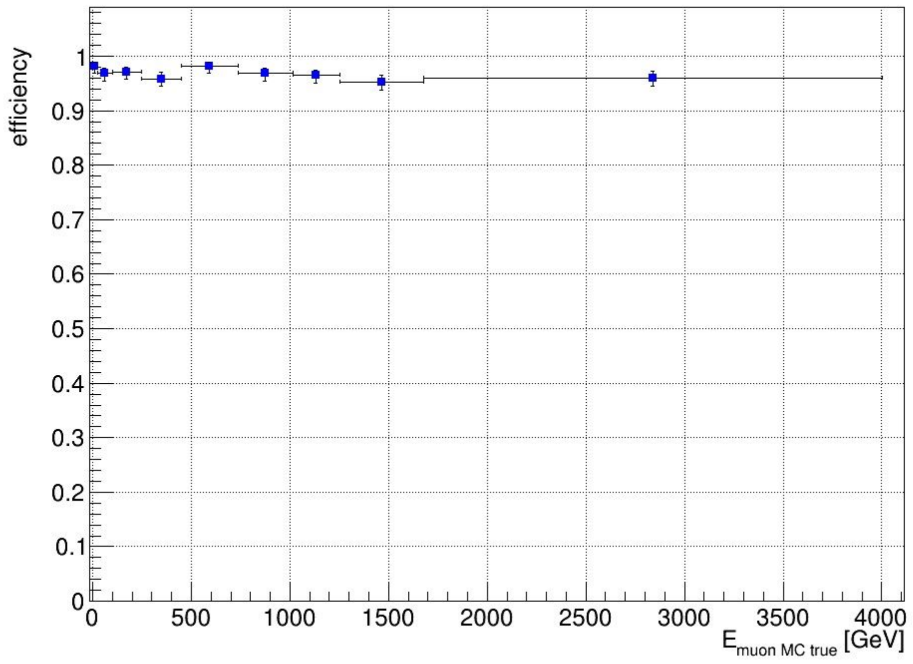


Muon tracking efficiency

SciFi + Simple tracking



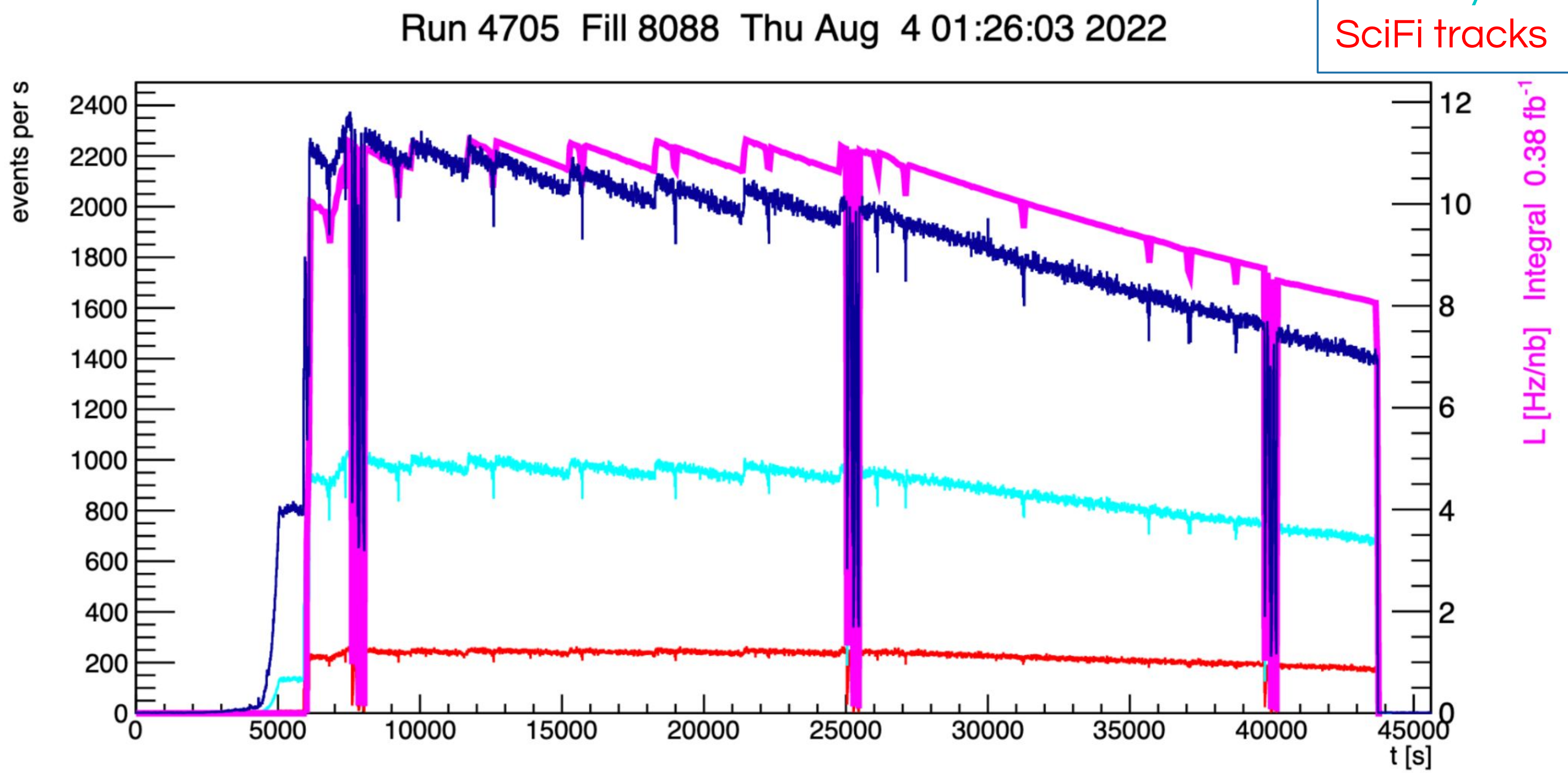
Muon system + Hough transform



SND@LHC data

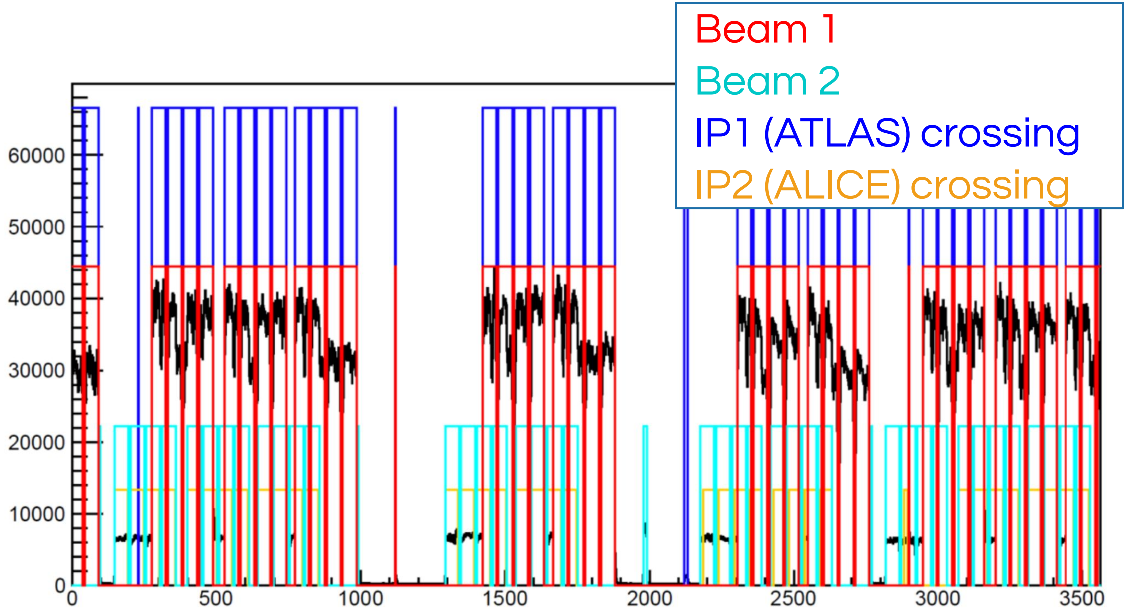
Event rates with collisions

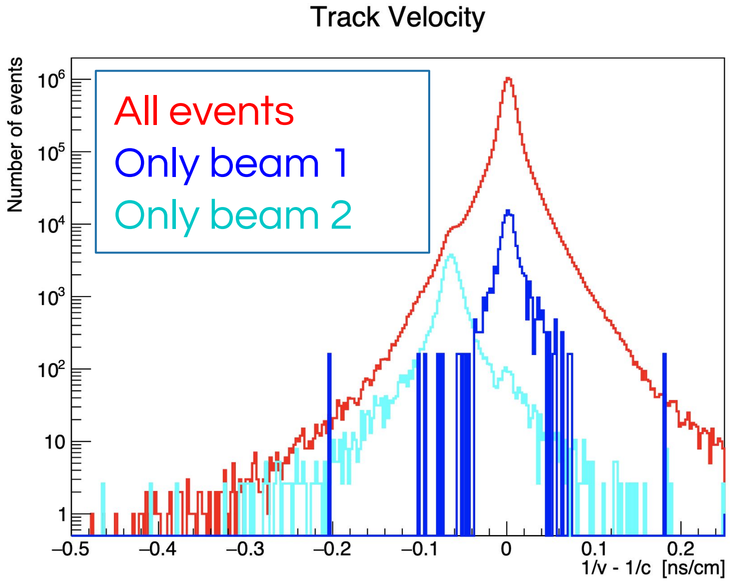
ATLAS Luminosity
SND@LHC Event rate
Muon system tracks
SciFi tracks



LHC 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.

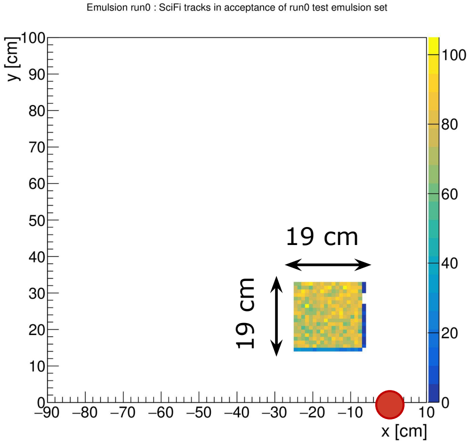


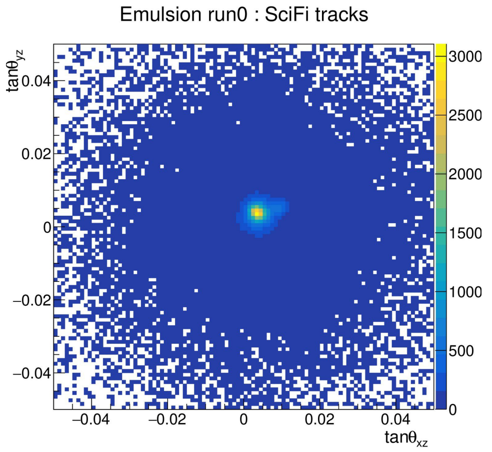


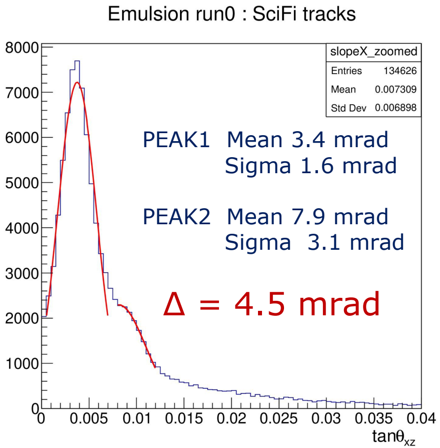
Muon flux measurement

SciFi

Measured rates on BRICK 1 surface
$1.6\text{x}10^{4}$ cm^{-2}/fb^{-1}

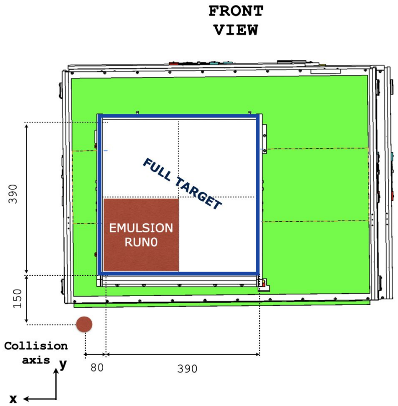


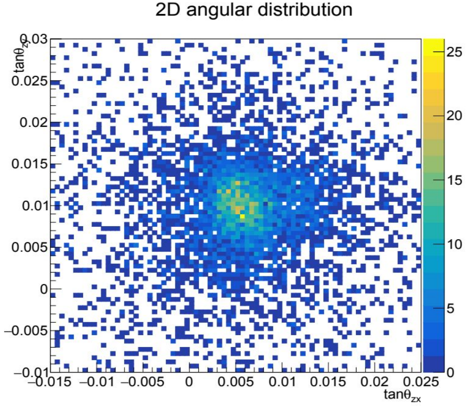


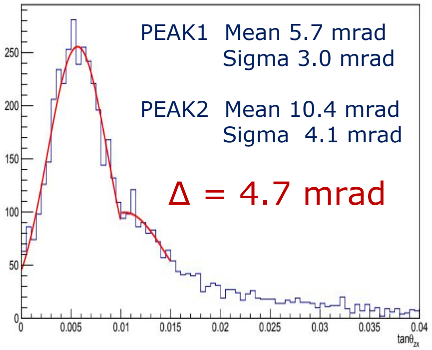


Emulsions

Measured rates in BRICK 1
$1.5\text{x}10^{4}$ cm^{-2}/fb^{-1}

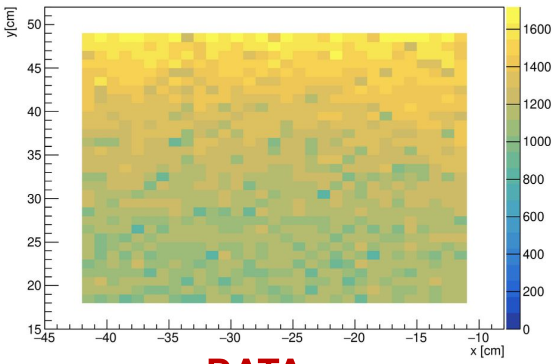






Muon flux compared to the MC

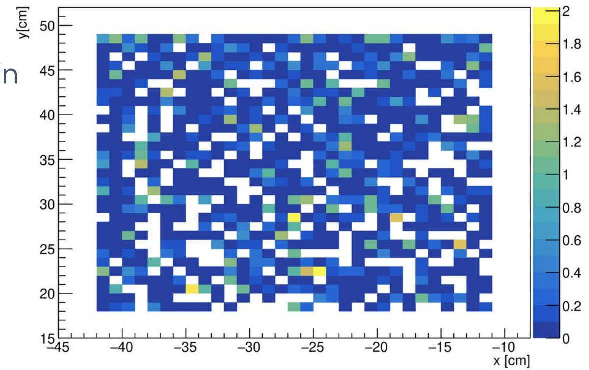
DATA



Measured muon track rate in SciFi (31x31 cm^2):

$(1.60 \pm 0.01_{stat})\times10^4$ cm^{-2}/fb^{-1}

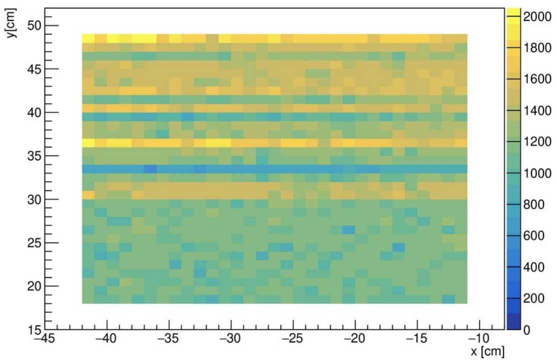
MC



Expected muon track rate in SciFi (31x31 cm^2):

$(1.57 \pm 0.10_{stat})\times10^4$ cm^{-2}/fb^{-1}

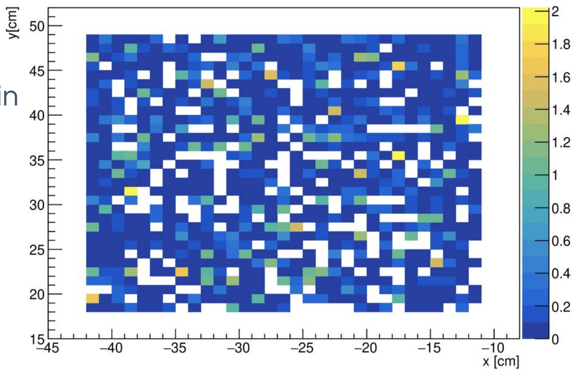
DATA



Measured muon track rate in Muon system (31x31 cm^2):

$(1.67 \pm 0.01_{stat})\times10^4$ cm^{-2}/fb^{-1}

MC



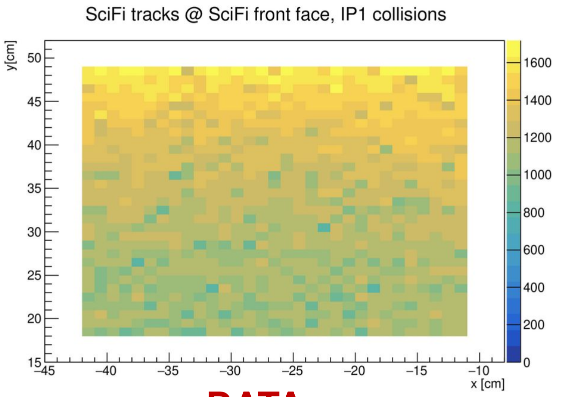
Expected muon track rate in Muon system (31x31 cm^2):

$(1.59 \pm 0.10_{stat})\times10^4$ cm^{-2}/fb^{-1}

SND@LHC PRELIMINARY

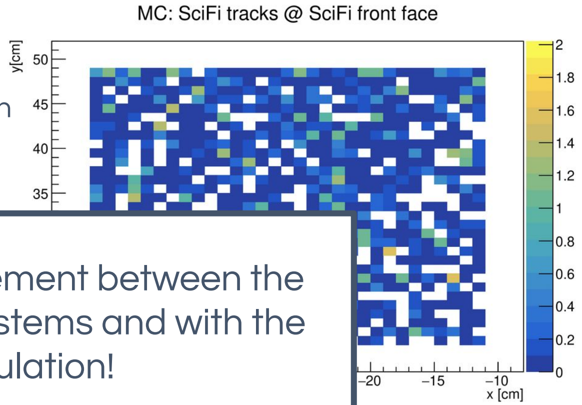
Muon flux compared to the MC

DATA



Measured muon track rate in SciFi (31x31 cm^2):

MC

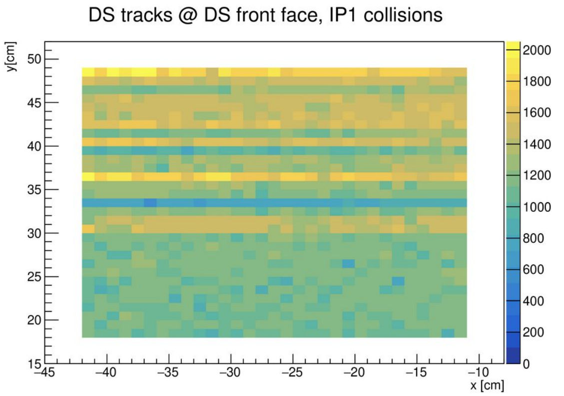


Expected muon track rate in SciFi (31x31 cm^2):

$(1.57 \pm 0.10_{stat})\text{x}10^4$ cm^{-2}/fb^{-1}

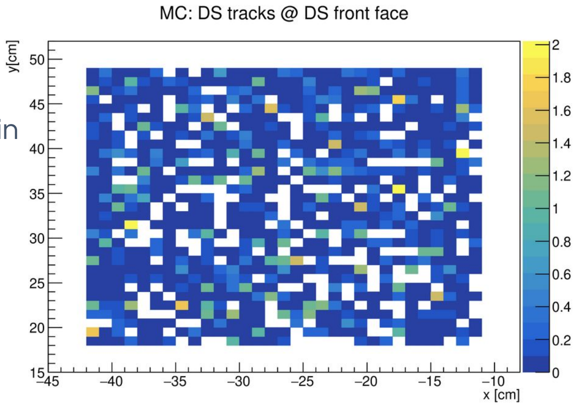
Excellent agreement between the detector subsystems and with the simulation!

DATA



Measured muon track rate in Muon system (31x31 cm^2):

$(1.67 \pm 0.01_{stat})\text{x}10^4$ cm^{-2}/fb^{-1}



Expected muon track rate in Muon system (31x31 cm^2):

$(1.59 \pm 0.10_{stat})\text{x}10^4$ cm^{-2}/fb^{-1}

Observation of collider neutrinos

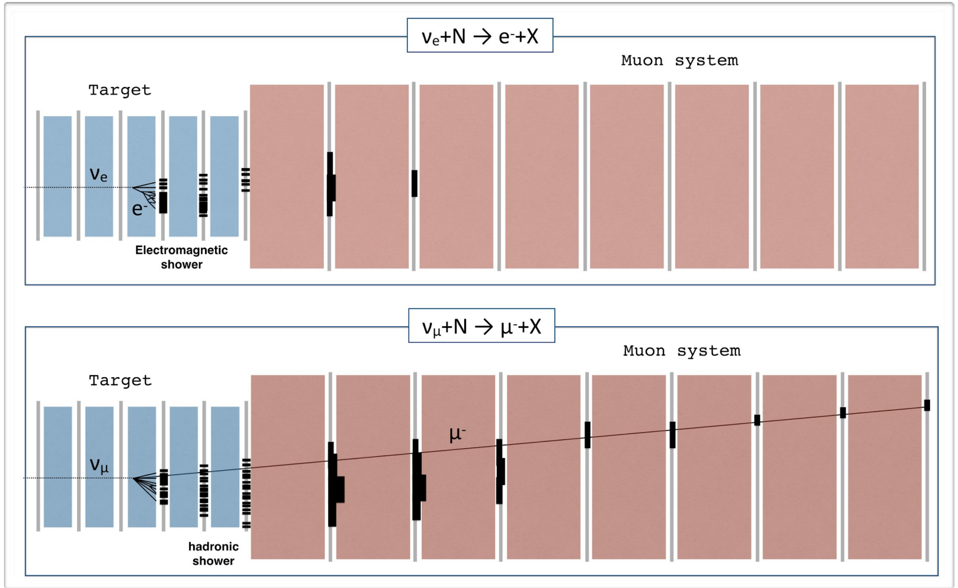
Neutrino identification strategy

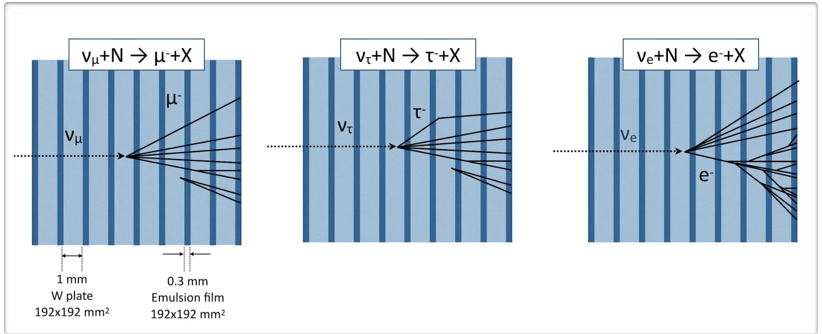
First stage

- 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!





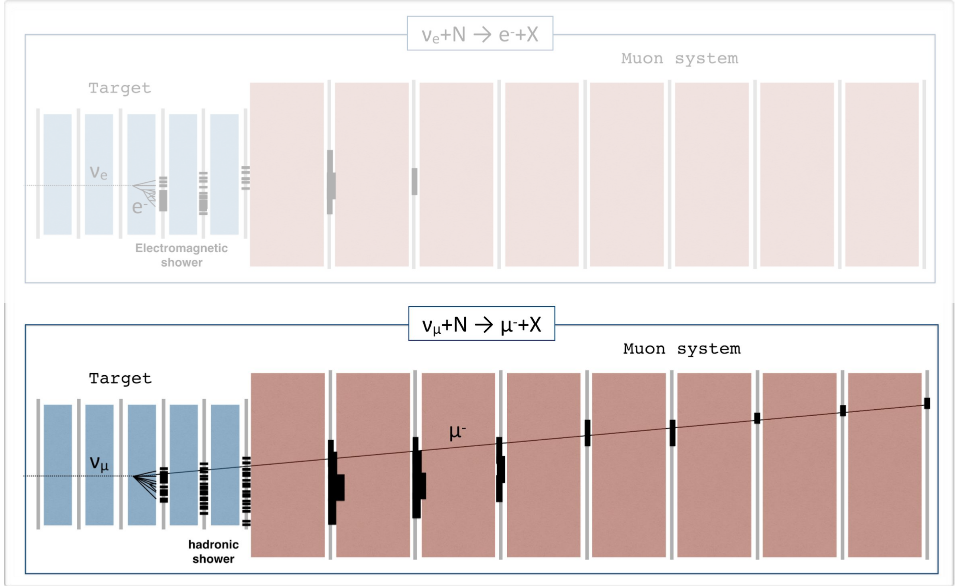
Neutrino identification strategy

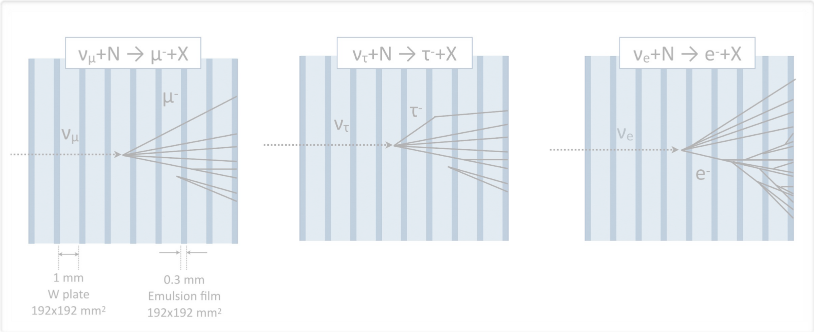
First stage

- 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!





First analysis strategy:

- Identify ν_μ candidates in existing electronic detector data.
- Apply stringent cuts to reduce the background as much as possible.

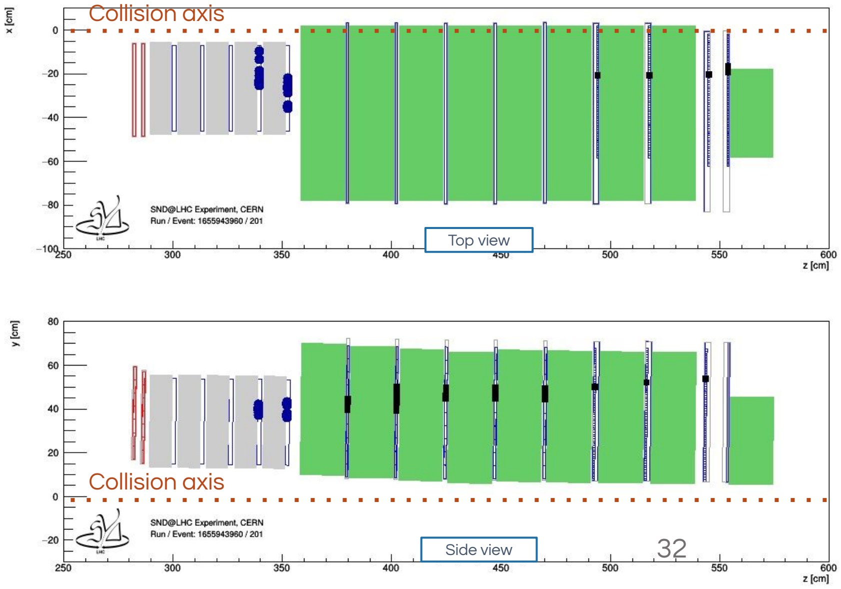
Selecting neutrino events

Full Run 3 **2022** dataset.

- 39 fb^{-1} recorded.
- 10^9 events, mostly through-going muons.

Event selection

- Fiducial volume
  - Vertex in target walls 3 or 4
  - Accept events only in tight cross-sectional area
- Neutrino selection
  - Large activity in SciFi detector
  - Large activity in hadronic calorimeter
  - Track reconstructed in downstream muon system
  - Hit times consistent with event originating from the interaction point.



ν_μ CC simulation

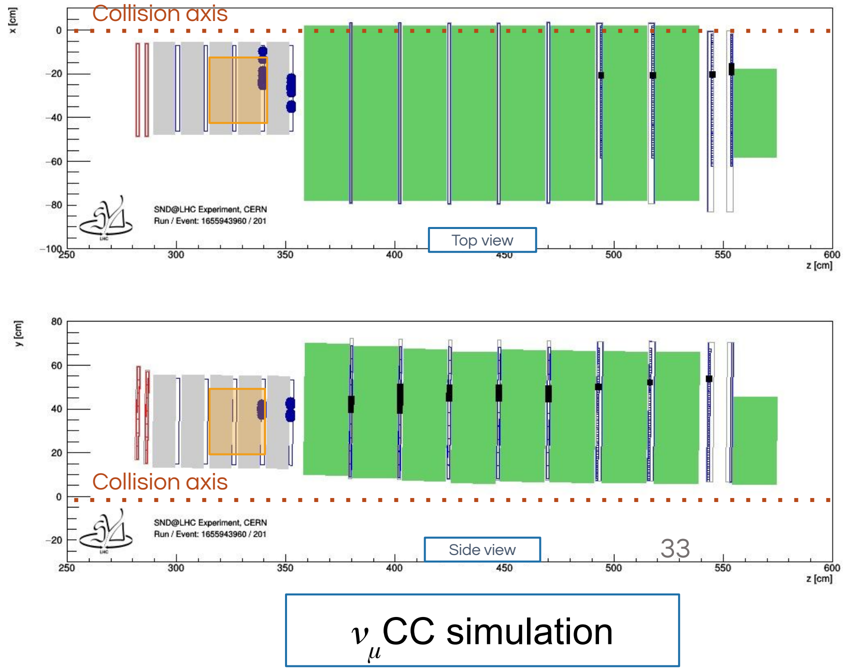
Selecting neutrino events

Full Run 3 **2022** dataset.

- 39 fb^{-1} recorded.
- 10^9 events, mostly through-going muons.

Event selection

- Fiducial volume
  - Vertex in target walls 3 or 4
  - Accept events only in tight cross-sectional area
- Neutrino selection
  - Large activity in SciFi detector
  - Large activity in hadronic calorimeter
  - Track reconstructed in downstream muon system
  - Hit times consistent with event originating from the interaction point.



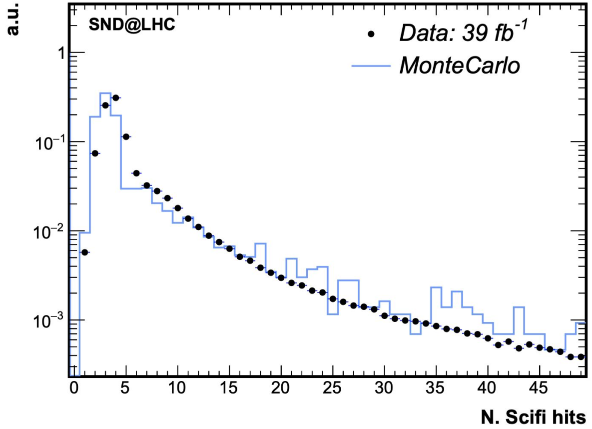
Selecting neutrino events

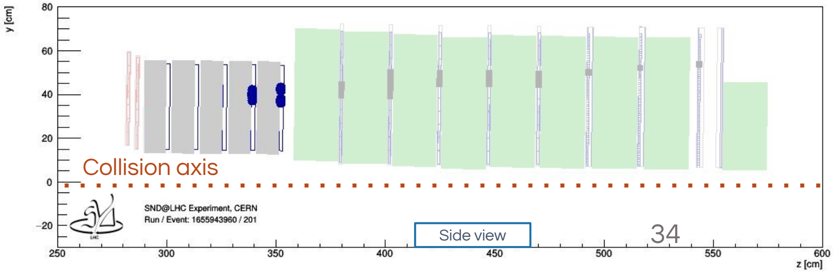
Full Run 3 **2022** dataset.

- 39 fb^{-1} recorded.
- 10^9 events, mostly through-going muons.

Event selection

- Fiducial volume
  - Vertex in target walls 3 or 4
  - Accept events only in tight cross-sectional area
- Neutrino selection
  - Large activity in SciFi detector
  - Large activity in hadronic calorimeter
  - Track reconstructed in downstream muon system
  - Hit times consistent with event originating from the interaction point.





ν_μ CC simulation

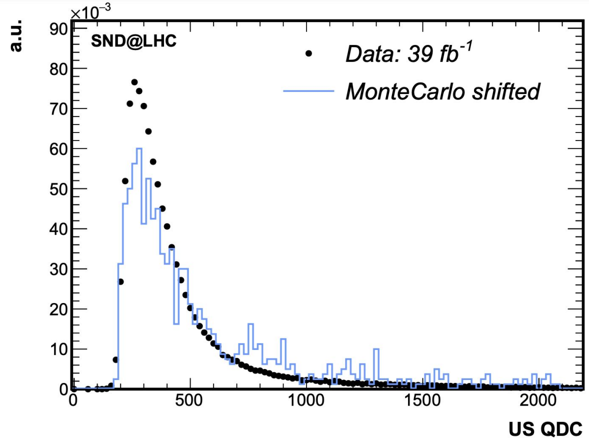
Selecting neutrino events

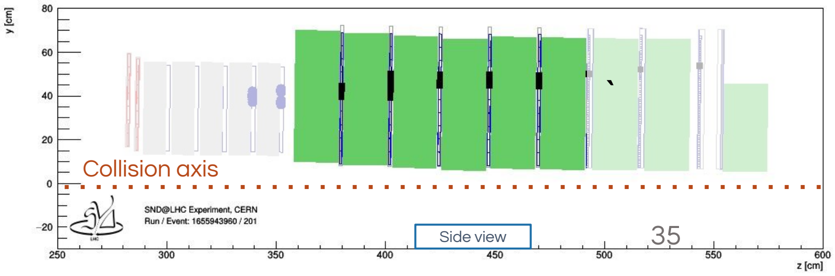
Full Run 3 **2022** dataset.

- 39 fb^{-1} recorded.
- 10^9 events, mostly through-going muons.

Event selection

- Fiducial volume
  - Vertex in target walls 3 or 4
  - Accept events only in tight cross-sectional area
- Neutrino selection
  - Large activity in SciFi detector
  - Large activity in hadronic calorimeter
  - Track reconstructed in downstream muon system
  - Hit times consistent with event originating from the interaction point.





ν_μ CC simulation

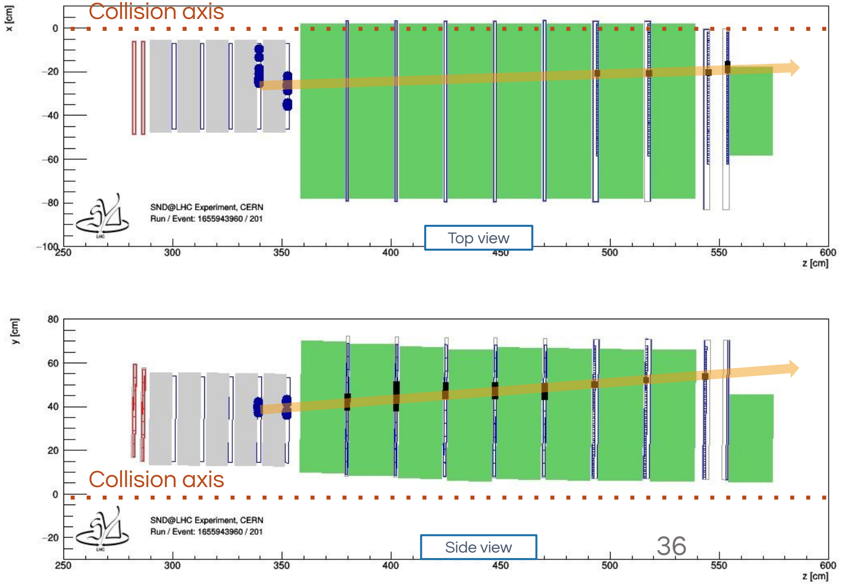
Selecting neutrino events

Full Run 3 **2022** dataset.

- 39 fb^{-1} recorded.
- 10^9 events, mostly through-going muons.

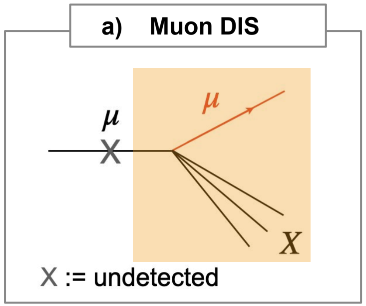
Event selection

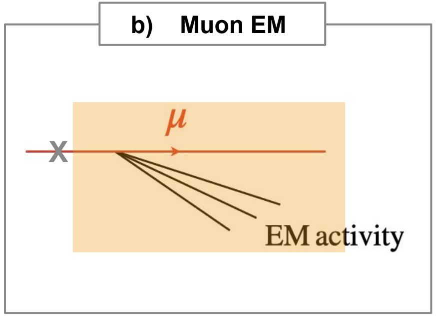
- Fiducial volume
  - Vertex in target walls 3 or 4
  - Accept events only in tight cross-sectional area
- Neutrino selection
  - Large activity in SciFi detector
  - Large activity in hadronic calorimeter
  - Track reconstructed in downstream muon system
  - Hit times consistent with event originating from the interaction point.



ν_μCC simulation

Entering muon background





$$N_{\mu}^{bkg} = \underbrace{N_{\mu}}_{\text{Number of muons in acceptance}} \times \underbrace{(1-\epsilon_{Veto}) \times (1-\epsilon_{SciFi1}) \times (1-\epsilon_{SciFi2})}_{\text{Veto and SciFi inefficiency}} = 10^{-2}$$

Number of muons in acceptance

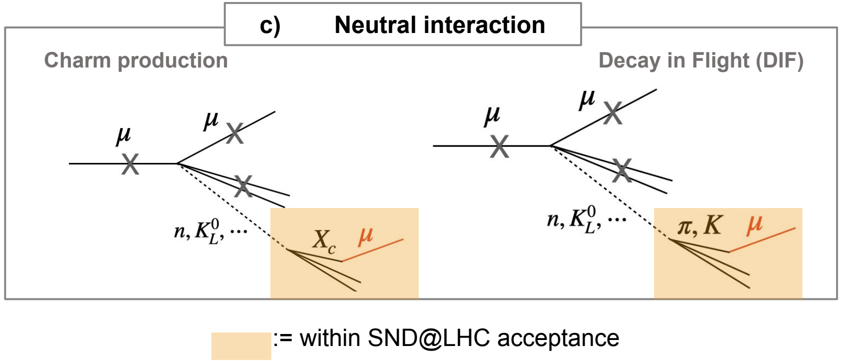
$$N_{\mu} = \frac{28 \times 10^{6}}{fb^{-1}} \times 39\, fb^{-1} = 1.1 \times 10^{9}$$

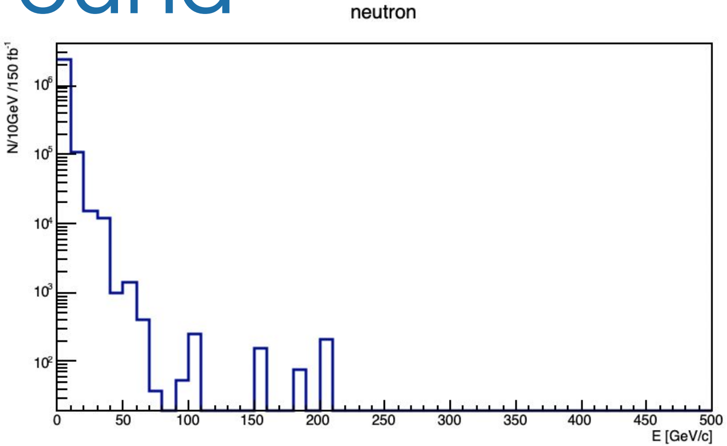
Veto and SciFi inefficiency

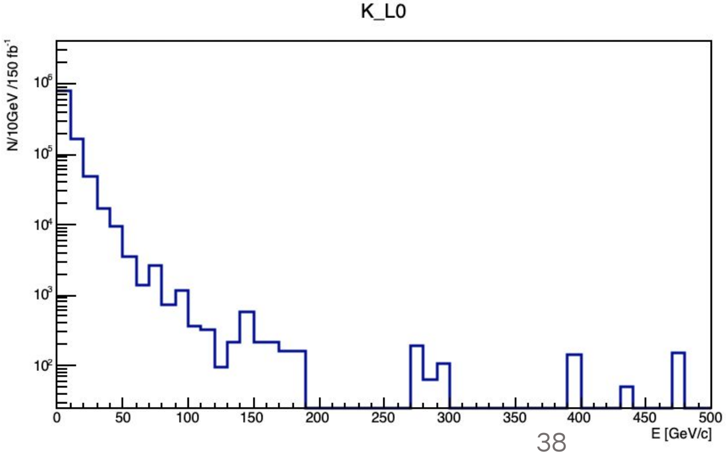
$$(1-\epsilon_{Veto}) \times (1-\epsilon_{SciFi1}) \times (1-\epsilon_{SciFi2}) \sim 10^{-11}$$

Negligible background with tight fiducial volume criteria

Neutral hadron background







Expect a total of around **0.2** neutral hadron events

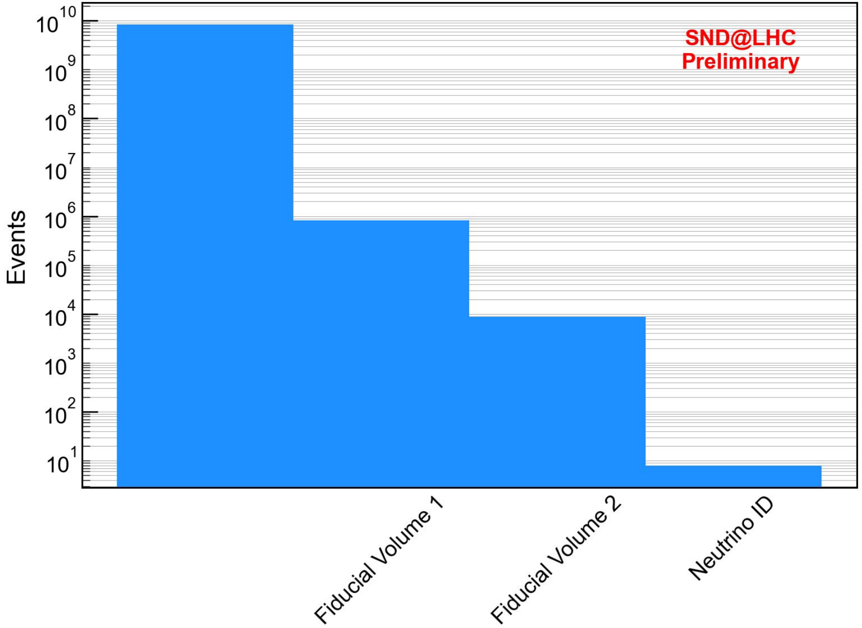
- Neutrons: 0.6
- K^0: 0.12

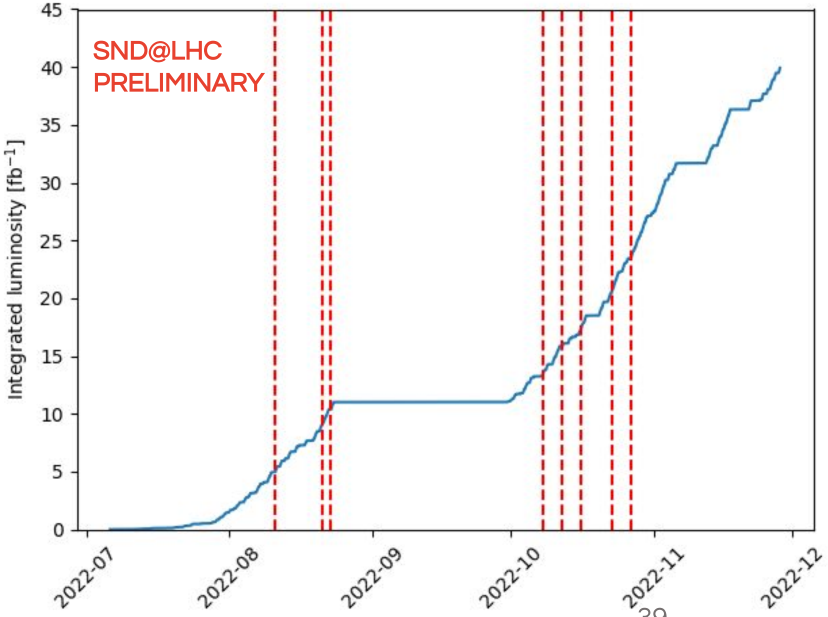
Mostly due to pion decay-in-flight.

Systematic uncertainty estimation is ongoing.

Observed events

- **Number of ν_μ candidate events in the data:** **8** (5 expected)
- Expected background: **0.2** events
- Statistical significance of around 5 σ
  - Pending final systematic uncertainty on background rate.
- Results announced at [Moriond (EW)]() where FASERnu also reported the observation of 153 ν_μ candidate events with very high statistical significance.

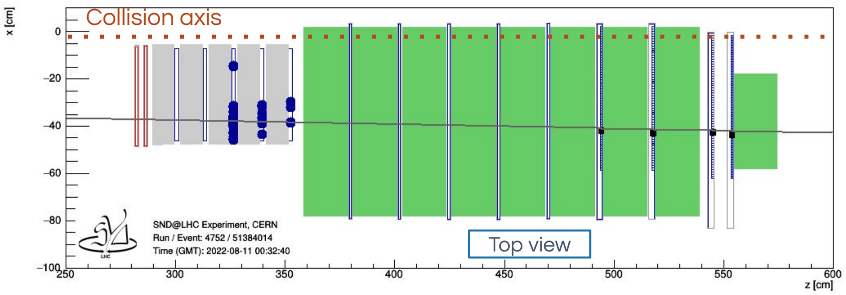


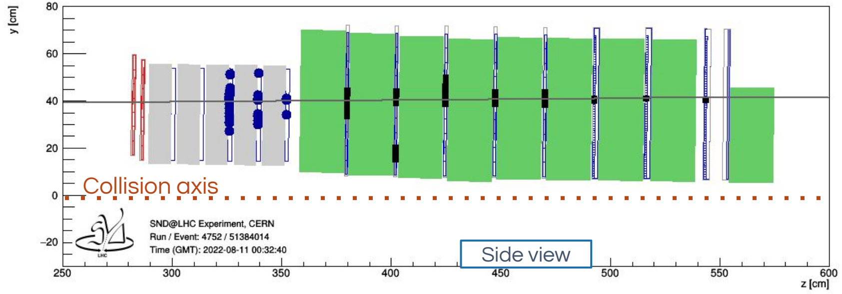


Observed events

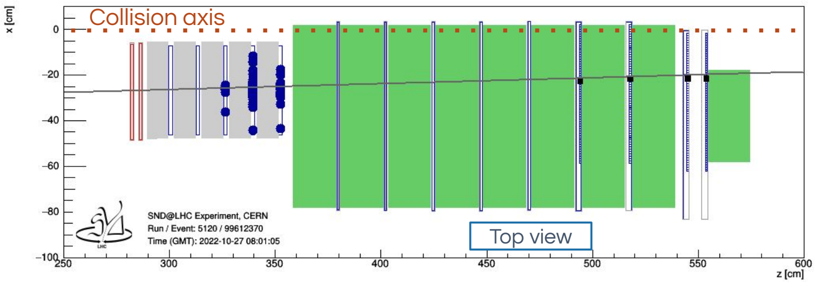
ν_μ CC candidate events in Run 3 data

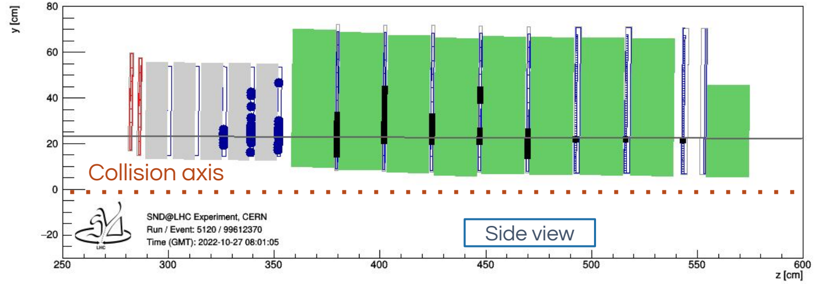
Aug 11th 2022



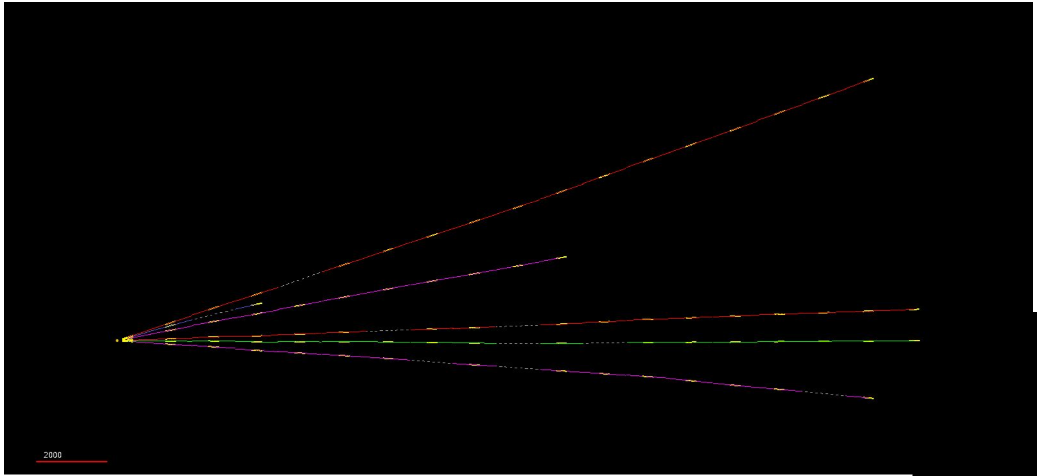


Oct 27th 2022



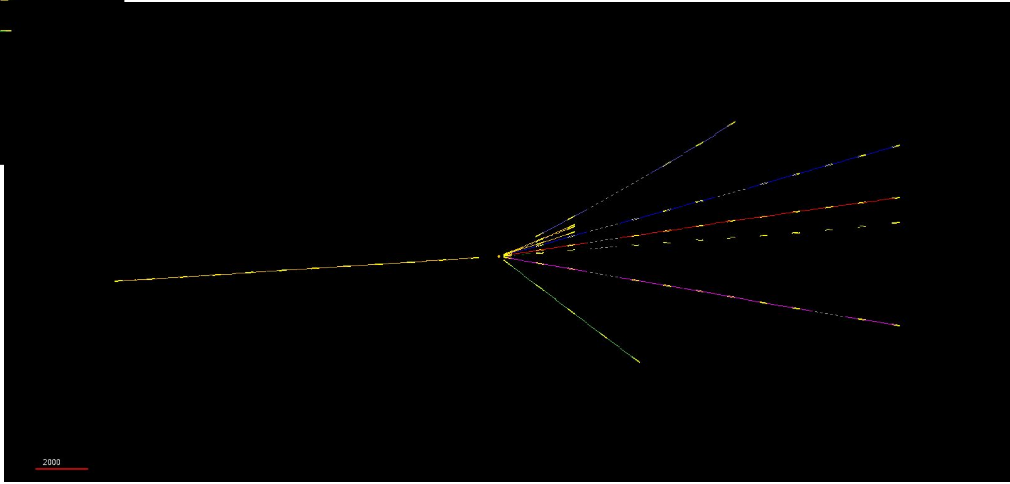


Preview of emulsion data: vertices



← Neutral vertex candidate

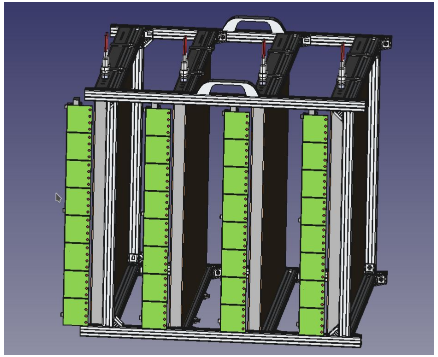
Charged particle interaction candidate →

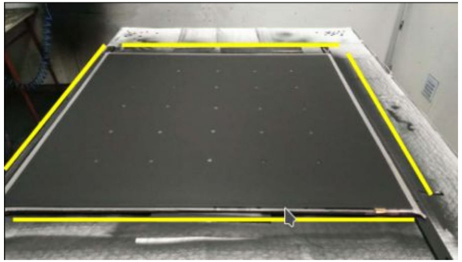


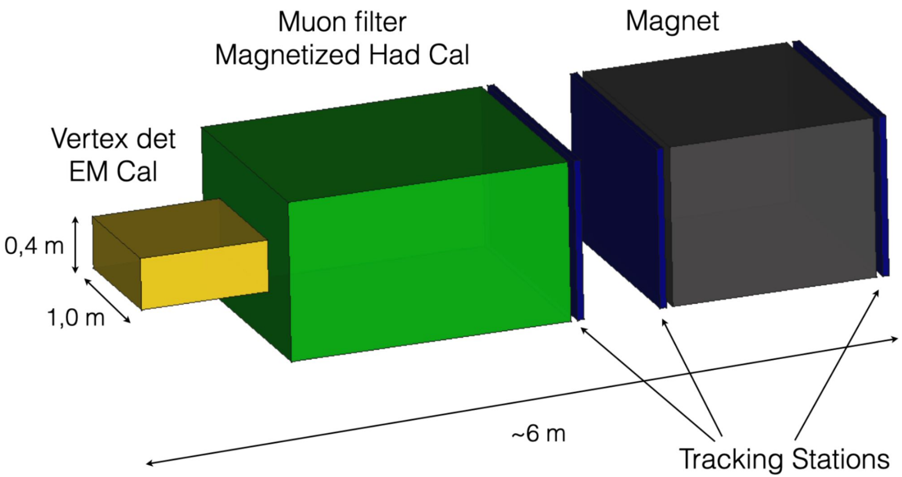
SND@LHC upgrade

- **Upgrade** plan for SND@LHC detector for the **high-luminosity** LHC.
  - Upgraded detector will be in the current location or in the proposed Forward Physics Facility.
- Replace emulsion with **electronic vertex detector**.
  - Excellent resolution required for ν_τ → silicon.
- Add iron-core **muon spectrometer**.
  - Improved ν_μ energy measurement and ν/anti-ν separation.

- **LIP** will install and operate **sealed-RPC** prototype telescope in the SND@LHC tunnel.
  - Expect first data in **2023**!
- **Validate muon flux** model in different positions.
  - Input for upgraded detector positioning.

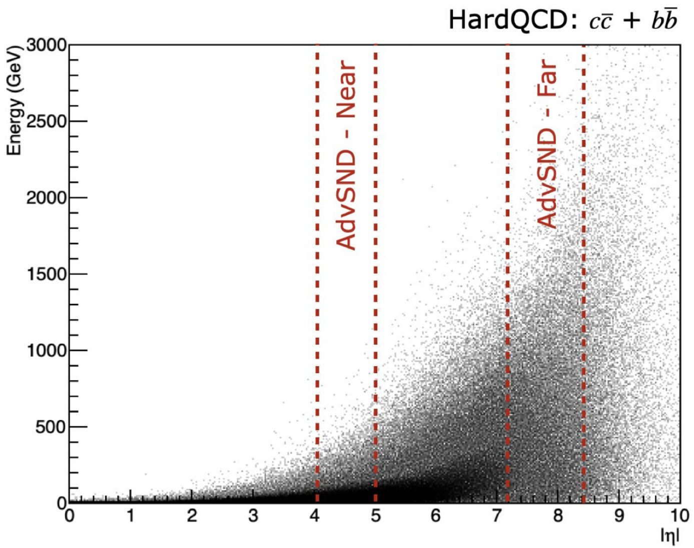


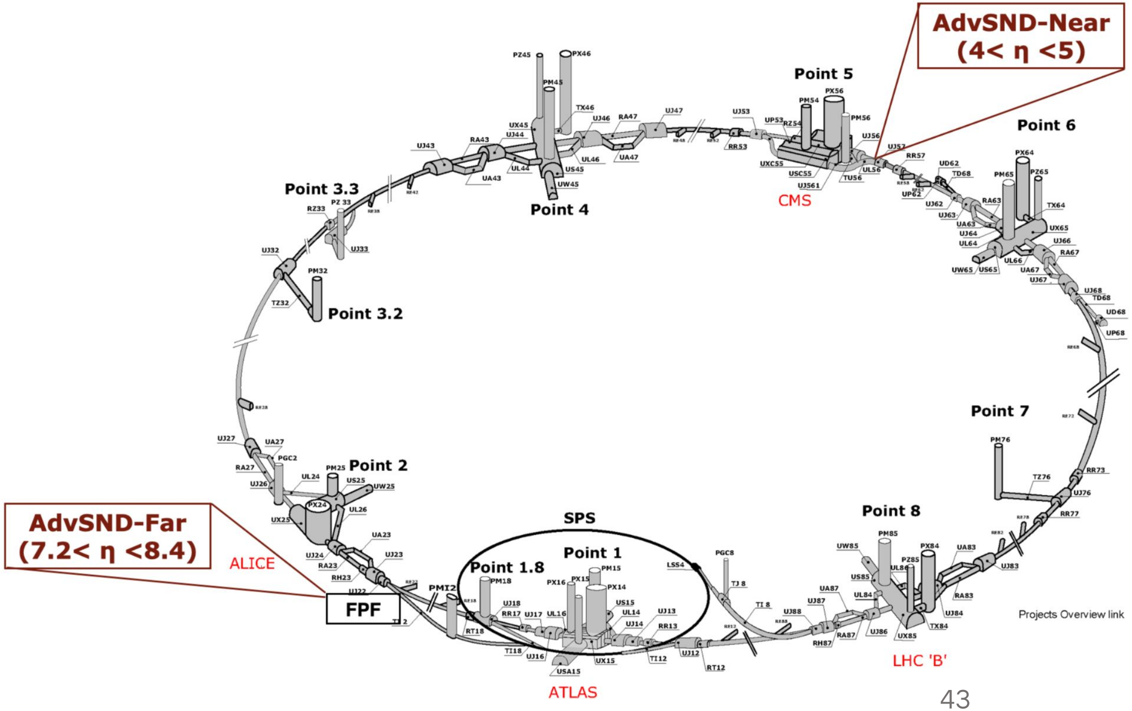




A near detector for SND@LHC

- Propose a near detector in a rapidity range overlapping with LHCb.
    - Reduce systematic uncertainty on far detector measurements using LHCb charm production measurements.





Summary

- SND@LHC announced its **first results** only **two years** after the experiment was approved**.**
  - Detector built, installed and commissioned in **record time**.
    - **LIP** was involved in the construction and commissioning of the hadronic calorimeter and muon system.
  - Excellent detector performance in 2023, with 96% of delivered luminosity recorded.

- Together with FASERnu, **SND@LHC** announced the **first observation** of neutrinos produced in proton-proton collisions.
  - Eight events observed on a background of 0.2, with a significance of around 5 σ.
  - This result marks the **start of an exciting research program with LHC neutrinos**.

- An **upgrade** plan is being developed to take SND@LHC beyond Run 3 of the LHC.
  - Improved detector at the current location, and an additional detector in a lower rapidity range.
- **LIP**'s **sealed-RPC** prototype to be installed in the SND@LHC tunnel and start taking **data** in **2023**.

Thank you for your attention!

Supplementary slides

Cutflow detail

Fiducial Volume 1

A. No veto hits
B. No hits in the first SciFi planes
C. Interaction vertex not in 5th wall.
D. Average SciFi channel in [200, 1200] (ver) and [300, 1336] (hor).
   Corresponds to [5, 8.4] cm from sides, 7.25 cm from bottom and 5 cm from top.
E. Average DS bar number in [70, 105] (ver) and [10, 50] (hor).
   Corresponds to [10, 15] cm from sides, 10 cm from bottom and 10 cm from top.

Fiducial Volume 2

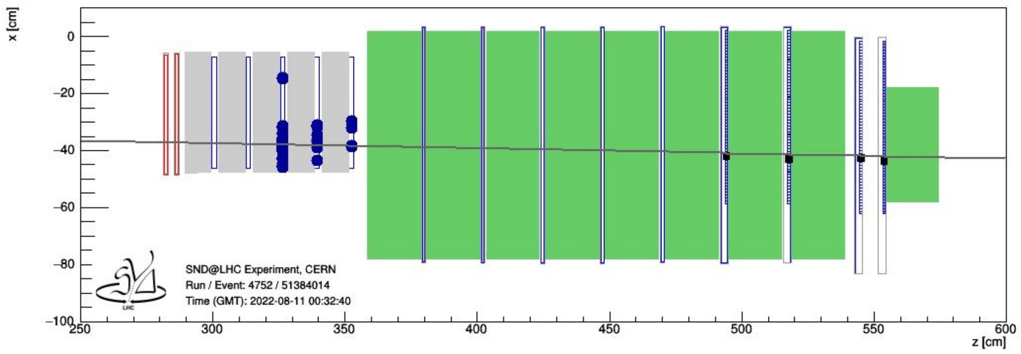
F. At least two consecutive SciFi planes hit
G. If there is a DS hit, all US planes must be hit.
H. Previous event more than 100 clock cycles (625 ns) away.
I. No hits in the second SciFi planes

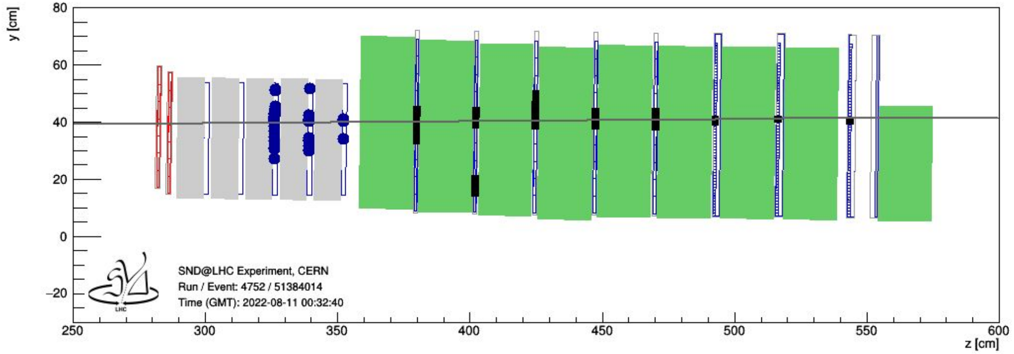
Neutrino ID

J. Latest DS hit time must be after earliest SciFi hit time.
K. Event has one reconstructed DS track.
L. DS track intersects first SciFi plane > 5 cm away from the detector edge.
M. Average DOCA of track to SciFi hits must be < 3 cm in both horizontal and vertical planes.
N. More than 35 SciFi hits.
O. US total QDC larger than 600 (700) for data (MC).

ν_μ CC-like candidate event in Run 3 data

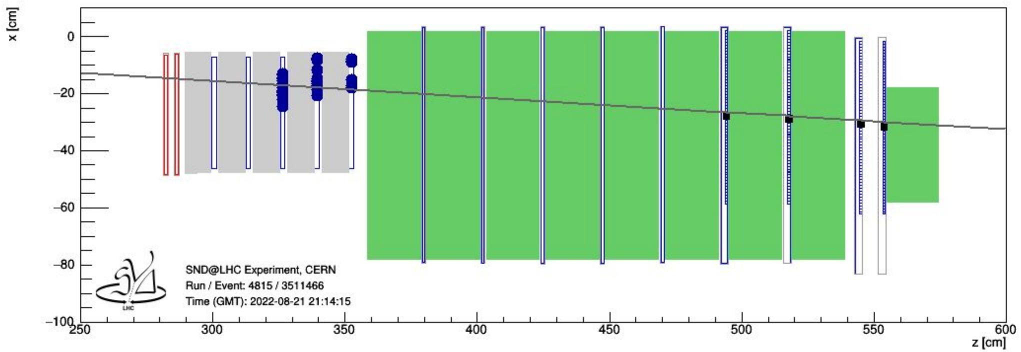
2022 Aug 11th

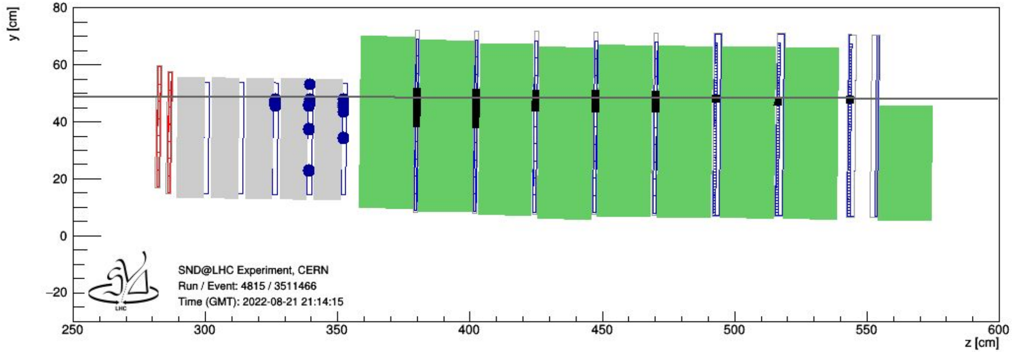




ν_μ CC-like candidate event in Run 3 data

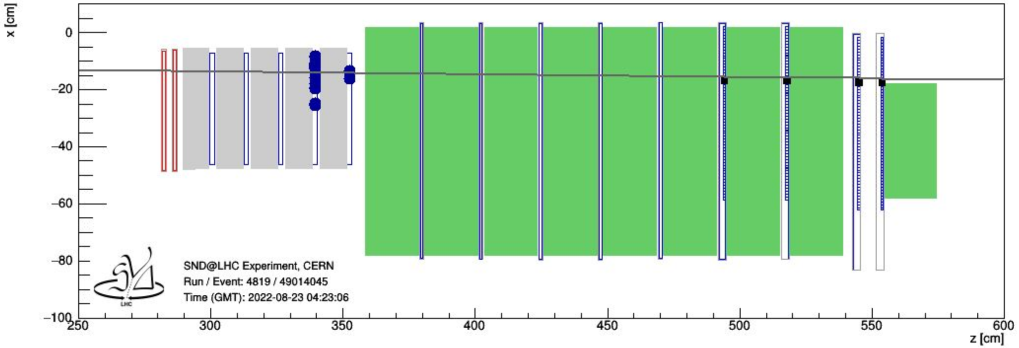
2022 Aug 21th

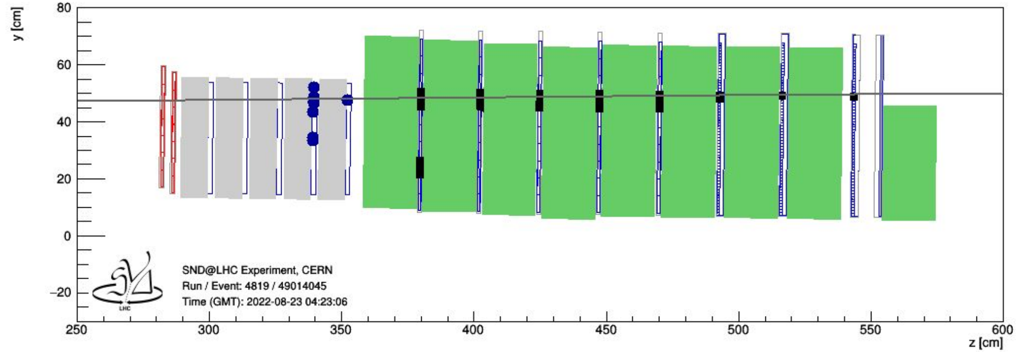




ν_μ CC-like candidate event in Run 3 data

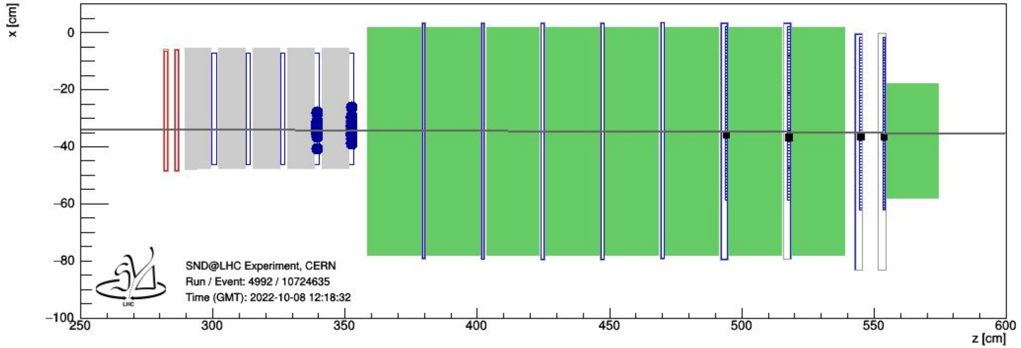
2022 Aug 23rd

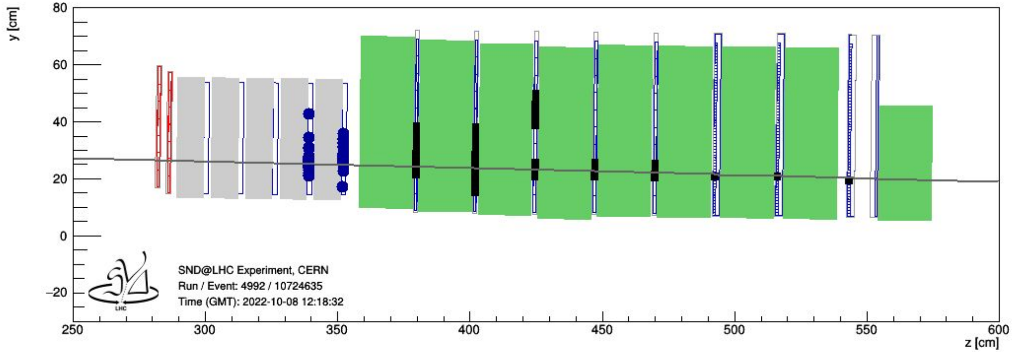




ν_μ CC-like candidate event in Run 3 data

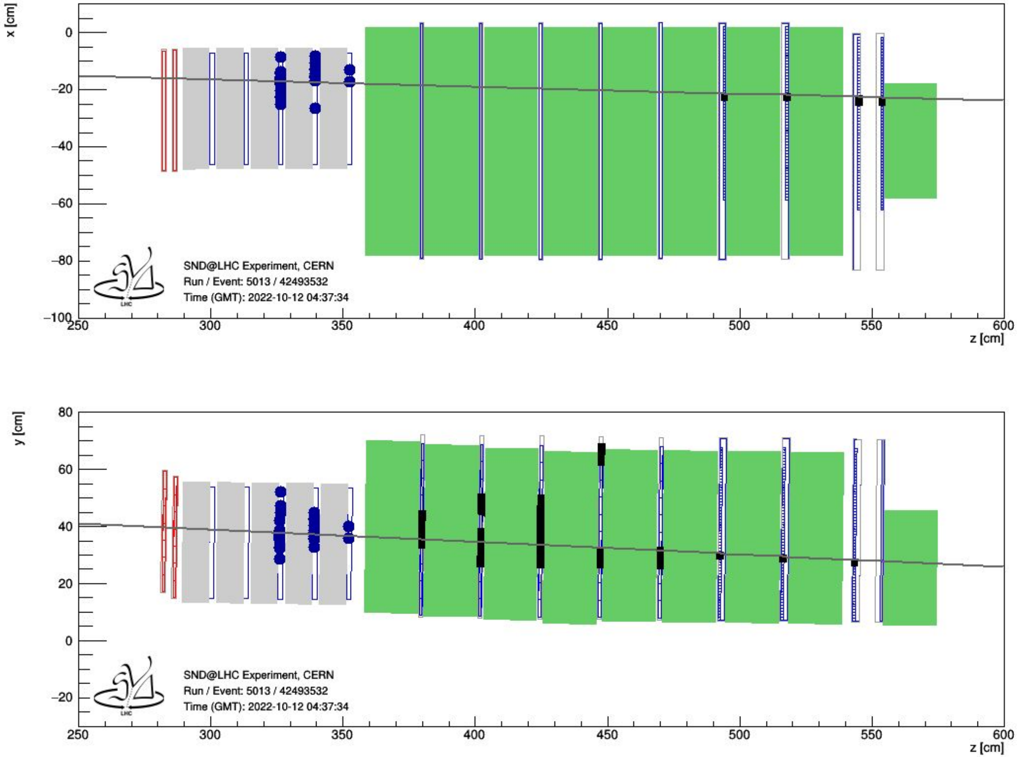
2022 Oct 10th





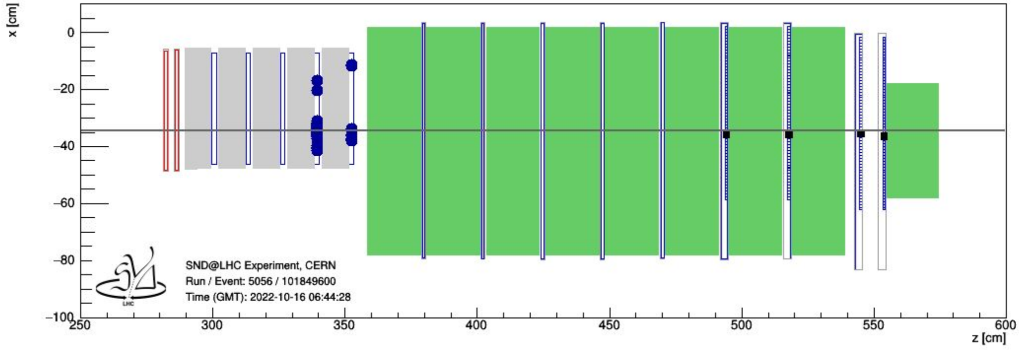
ν_μ CC-like candidate event in Run 3 data

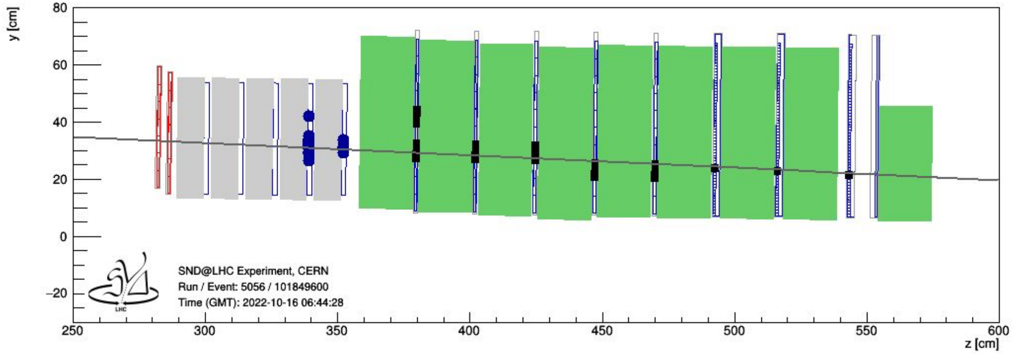
2022 Oct 12th



ν_μ CC-like candidate event in Run 3 data

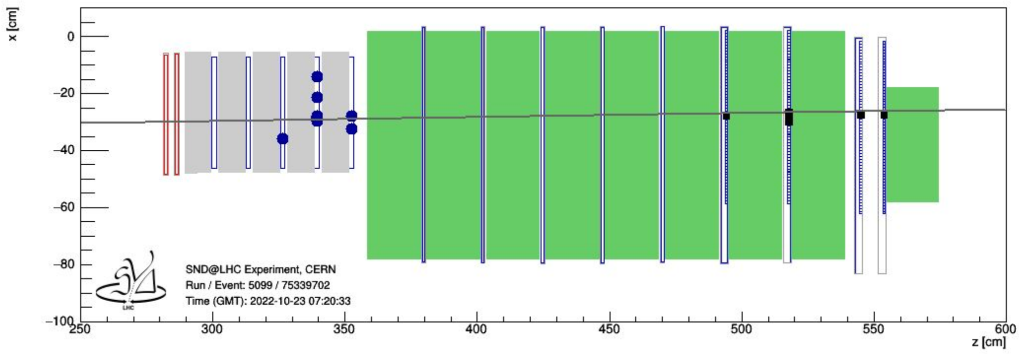
2022 Oct 16th

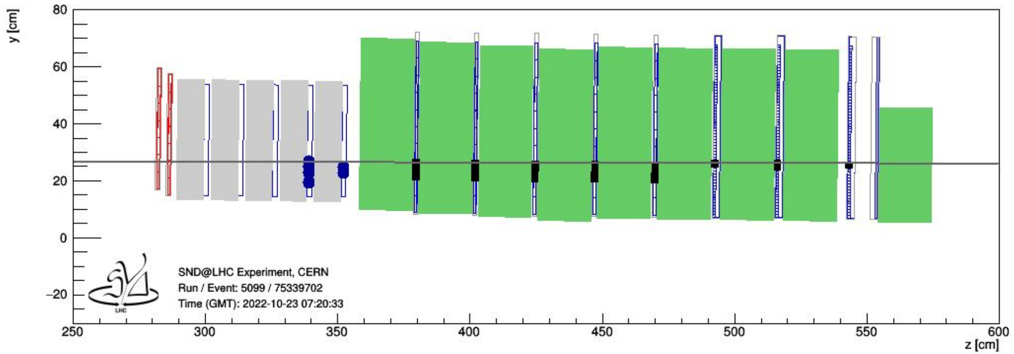




ν_μCC-like candidate event in Run 3 data

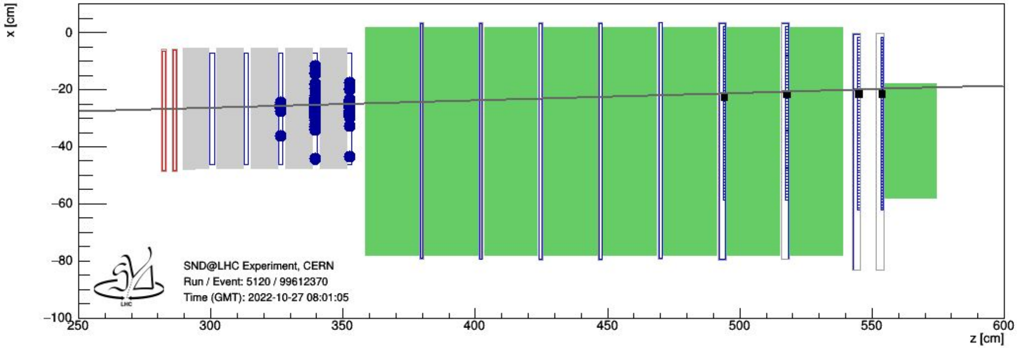
2022 Oct 23rd

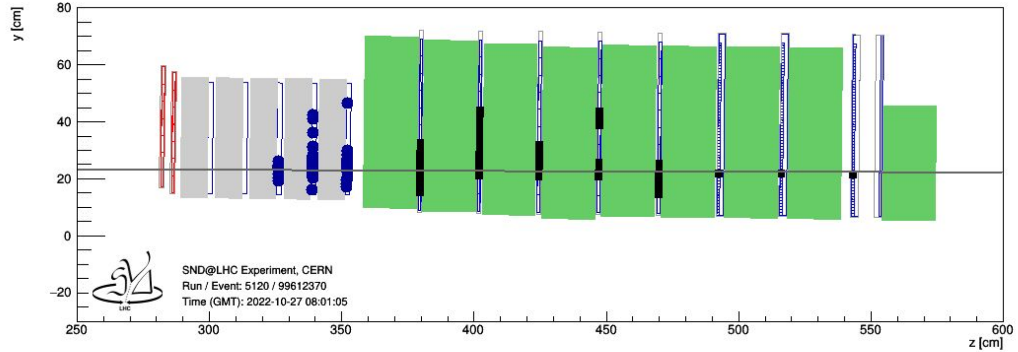




ν_μ CC-like candidate event in Run 3 data

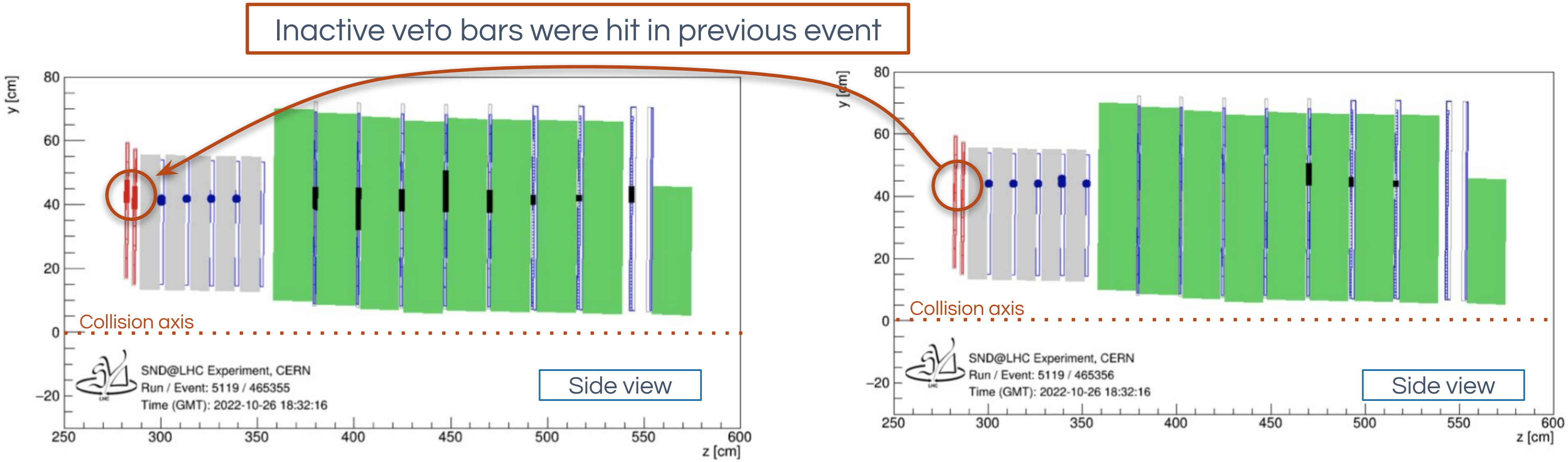
2022 Oct 27th





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.

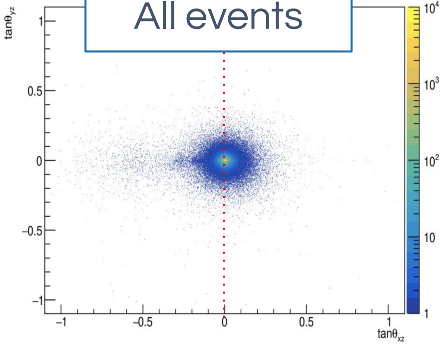


Non-colliding bunch events

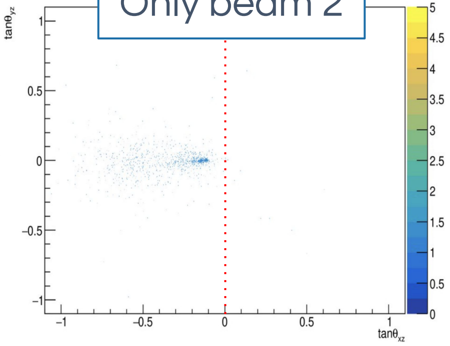
SND@LHC PRELIMINARY

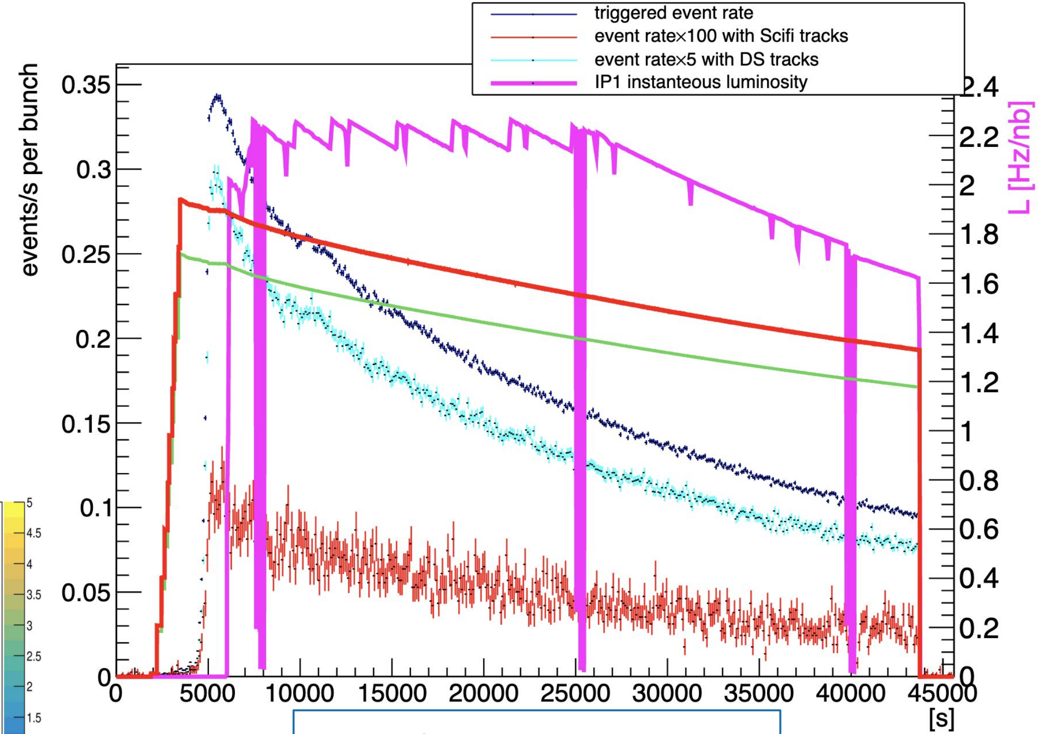
- Non-colliding bunch event rate drops with the fill time.
- Steeper drop than the beam intensity.
  - Most likely due to the evolution of vacuum conditions over the fill.
- Muon tracks in Beam 2 events have larger angles.
  - Muon origin under investigation.

All events



Only beam 2





Only beam 2 event rate