Observation of collider neutrinos with FASER and SND@LHC

Scattering and Neutrino Detector at the LHC

30th Anniversary of the Rencontres du Vietnam
Windows on the Universe 2023
Quy Nhon

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Cristóvão Vilela
on behalf of the **FASER** and **SND@LHC** Collaborations

Neutrinos at the Large Hadron Collider

- Initial studies on **neutrino detection at the LHC** date back to the 80s.
  CERN-1984-010-V-2.571; Nucl. Phys. B405, 80; LPNHE-93-03
  - Back then, seen as an opportunity to discover the ν_τ.

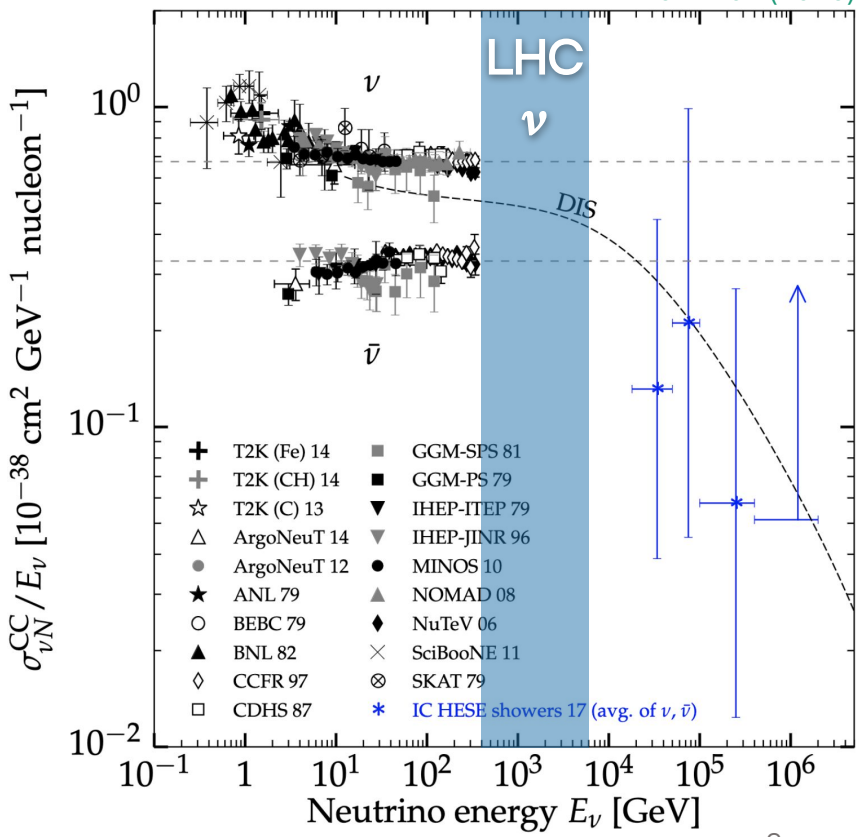
- **Large flux** of neutrinos in the forward region.
- Very **high neutrino energy** ($\sigma_\nu \propto E_\nu$).

⇒ A small-scale LHC experiment can observe neutrinos of all **three types**.

  - Highest energy human-made neutrinos!

- Two neutrino experiments in operation at the ATLAS interaction point since June 2022:
  SND@LHC and **FASER*ν***

PRL 122 041101 (2019)



Physics with LHC neutrinos

Neutrino interactions

- Measure $\boldsymbol{\nu}$ **interactions** in unexplored ~TeV energy range.
- Large yield of ν_τ will more than double existing data.
  - About 20 events observed by DONuT and OPERA.
- First observation of $\overline{\boldsymbol{\nu}_\tau}$.

QCD

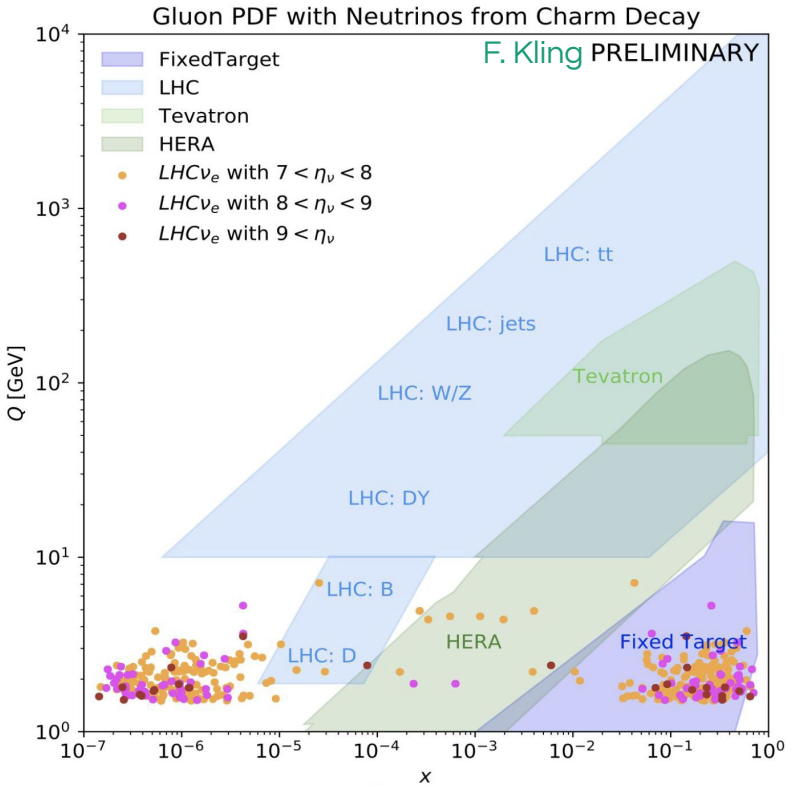
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x**.

Flavour

- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**.

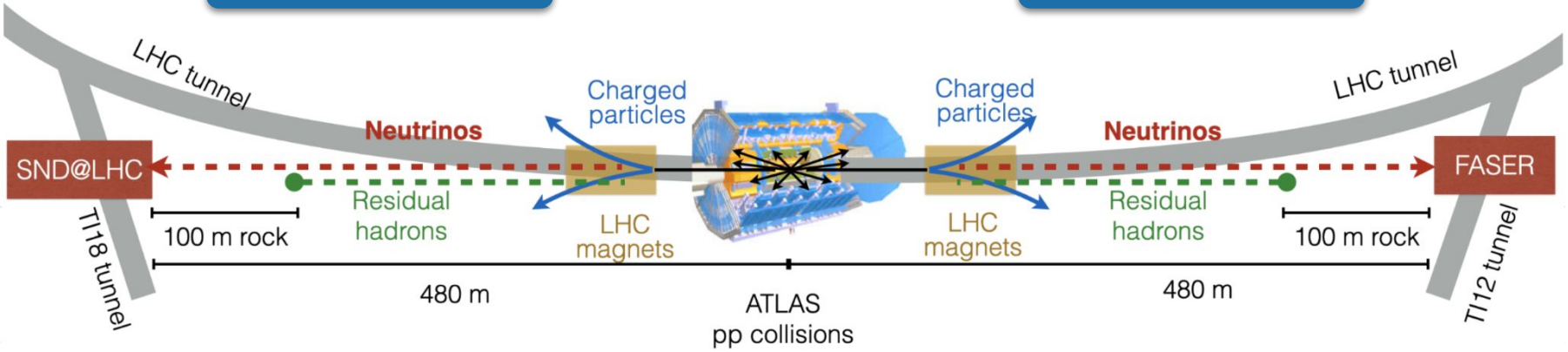
Beyond the Standard Model

- Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.



SND@LHC in TI18

FASER in TI12

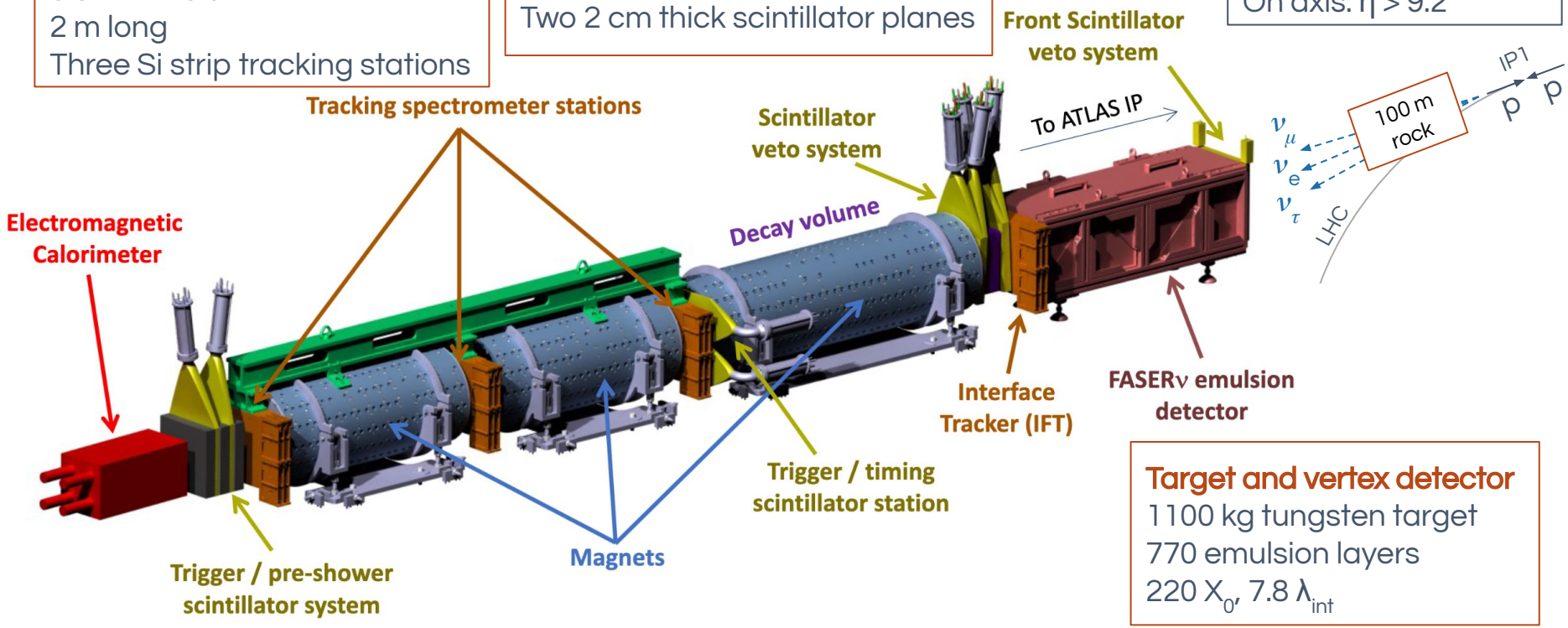


ForwArd Search ExpeRiment

Spectrometer
0.57 T B field
2 m long
Three Si strip tracking stations

Front veto system
Two 2 cm thick scintillator planes

Aperture: 20 cm
Length: 7 m
On axis: $\eta > 9.2$



Target and vertex detector
1100 kg tungsten target
770 emulsion layers
220 X_0, 7.8 λ_{int}

arXiv:2207.11427

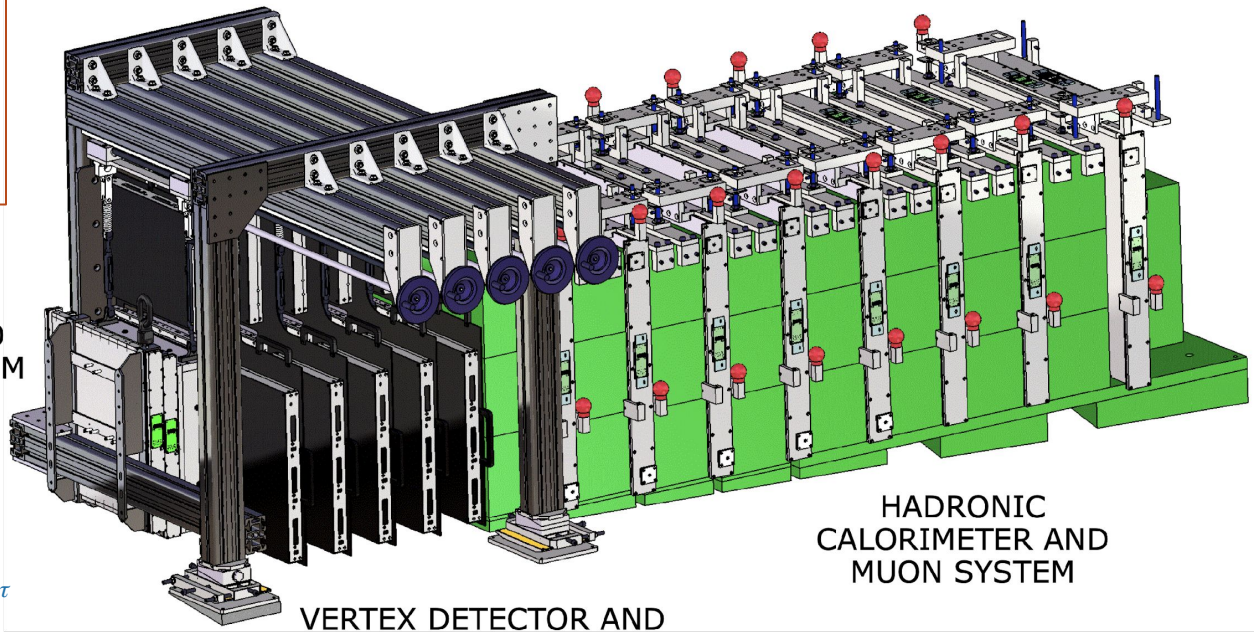
Scattering and Neutrino Detector at the LHC

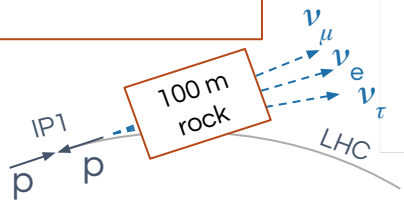
Veto system
Two 1 cm thick scintillator planes.

Target, vertex detector and ECal
830 kg tungsten target.
Five walls x 59 emulsion layers
+ five scintillating fibre stations.
84 X_0, 3 λ_{int}

HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer granularity to track muons.
9.5 λ_{int}

Cross-sectional area: 40 x 40 cm^2
Length: 2.6 m
Off-axis: $7.2 < \eta < 8.4$

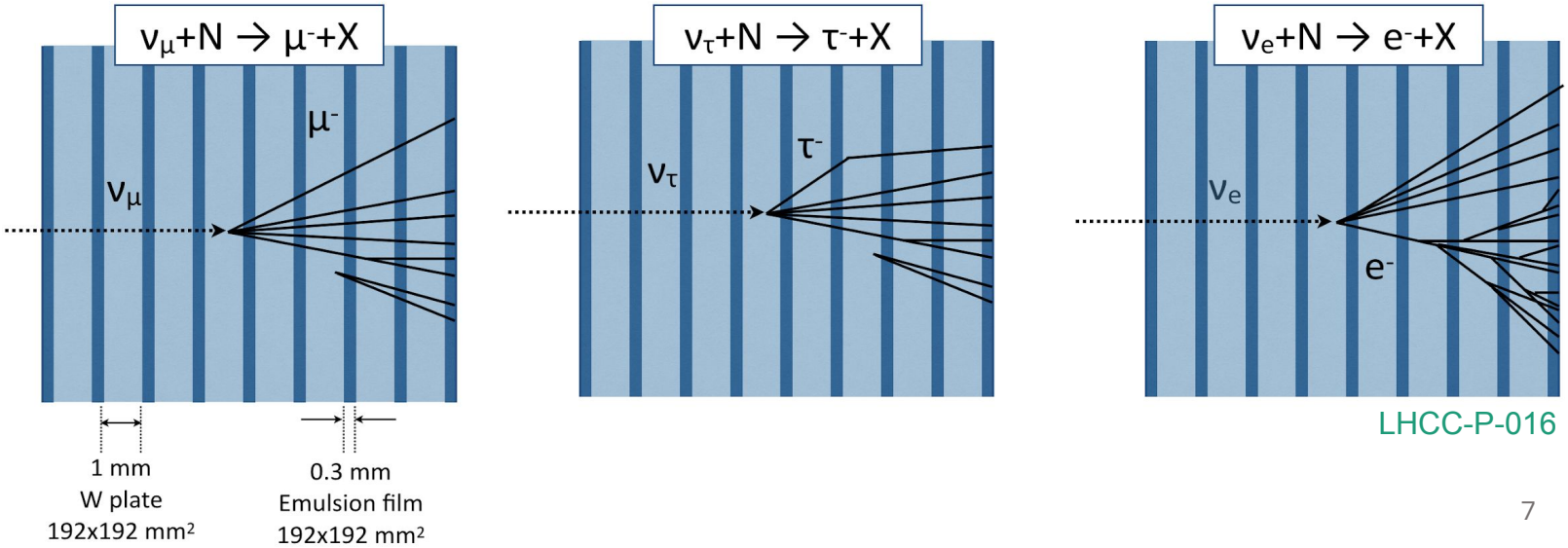




arXiv:2210.02784

Neutrino identification with emulsions

- **Micrometric resolution** of emulsion detectors allows for **excellent neutrino identification**.
  - **Essential** for the identification of the **secondary vertex** associated to ν_τ,
- However:
  - **No timing** information (emulsions integrate ~months of data).
  - Limited ability to identify **muon tracks**.
  - Limited ability to measure **hadronic showers**.
- Must be complemented with **electronic detector data**.

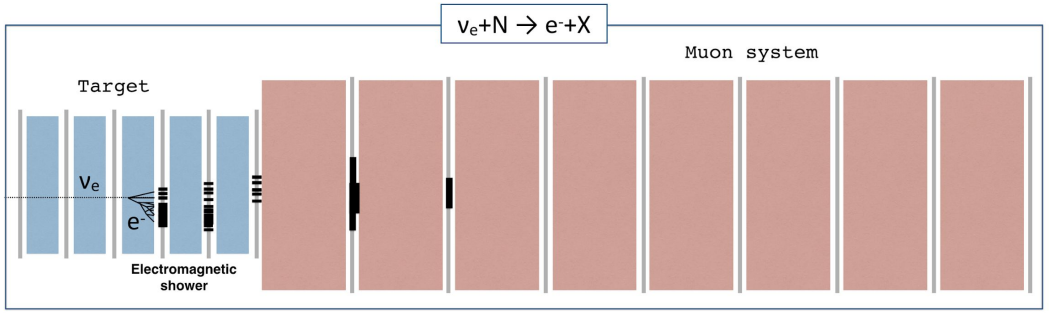


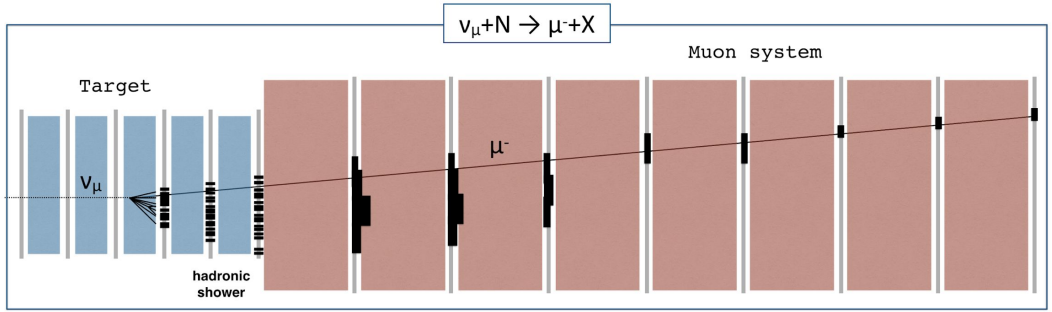
LHCC-P-016

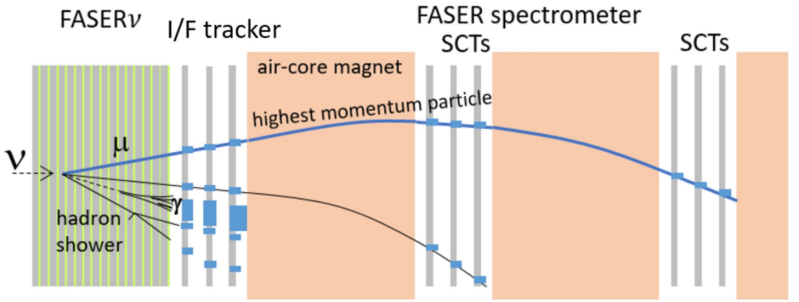
Neutrino event reconstruction strategies

SND@LHC

- Use **scintillating fibre** hit pattern to **match** electronic detector events to emulsion detector vertices.
- Measure **showers** with **ECal** and **HCal**.
- Tag muon tracks with the **muon system**.







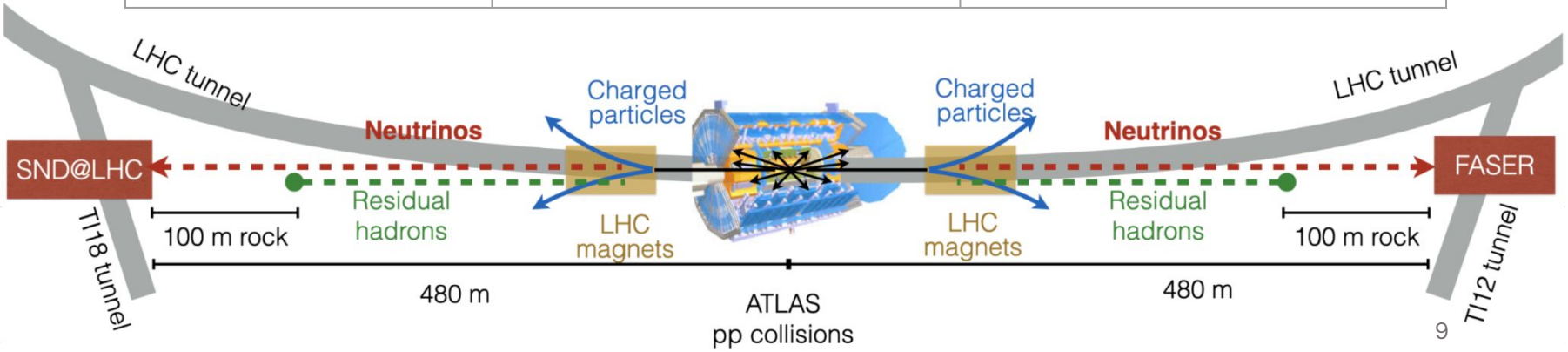
FASER

- Use **interface tracker** to **match** electronic detector events to emulsion detector vertices.
- Measure **track momenta** with **spectrometer**.
- **Muon tagging** based on absence of hadronic interactions in the tungsten and track momentum.

Initial analyses of both experiments use only the electronic detector data.
This talk

Two complementary LHC ν experiments

	SND@LHC	FASER
Location	**Off-axis**: $7.2 < \eta < 8.4$ Enhances **charm** parentage	**On-axis**: $\eta > 9.2$ Enhances **statistics**
Target	**800 kg** of tungsten	**1100 kg** of tungsten
Detector technology	**Emulsion vertex detector**, electromagnetic and hadronic **calorimeters**	**Emulsion vertex detector** and **spectrometer**



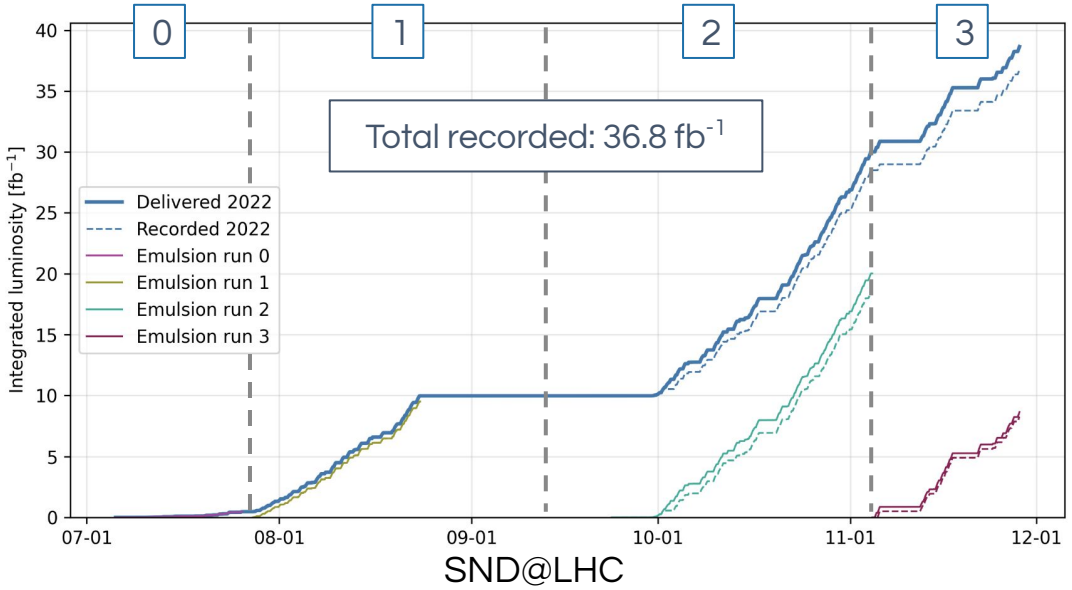
Observation of collider neutrinos

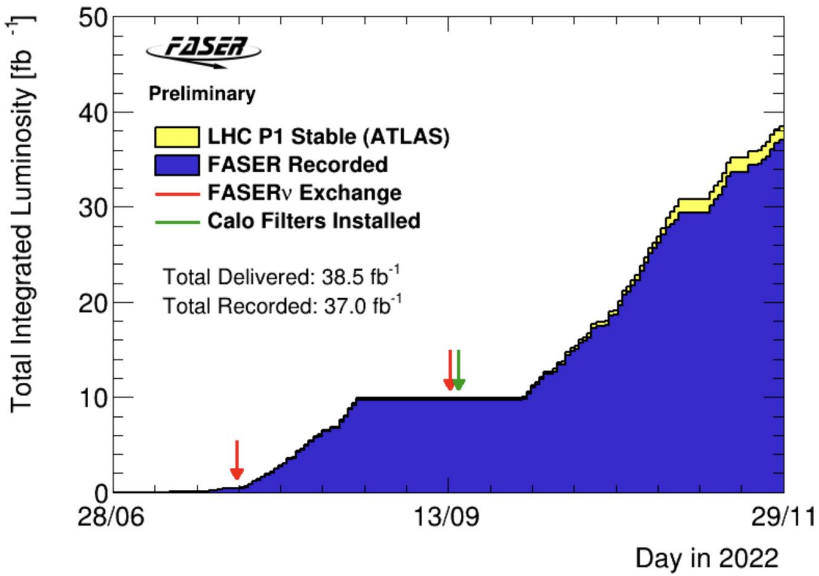
Analyses of SND@LHC and FASER **electronic detector** data collected in 2022

PRL 131, 031801 (2023) PRL 131, 031802 (2023)

Proton-proton collision data in 2022

- Both experiments operating since the start of Run 3 of the LHC.
- Extremely successful data-taking campaigns in 2022.
  - Electronic detectors uptime of ~95%.
- Three emulsion detector exchanges in SND@LHC and two in FASER.





Another ~30 fb^{-1} collected in 2023!

SND@LHC event selection

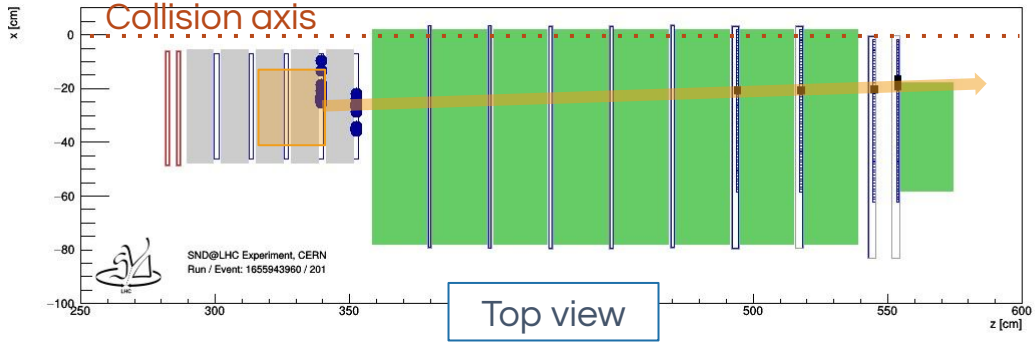
Fiducial volume

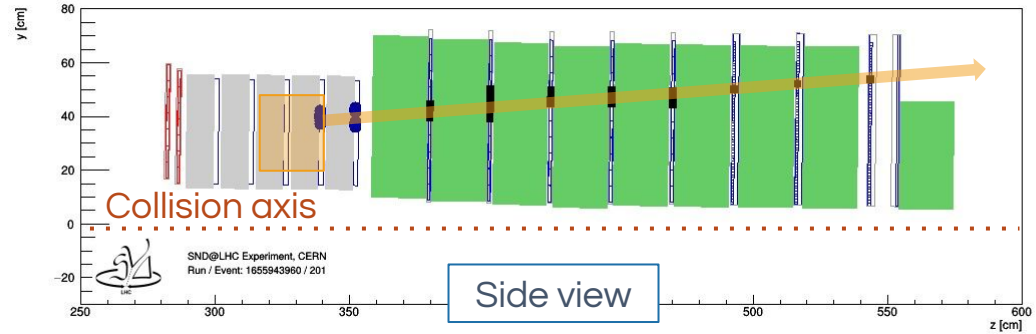
- Neutral vertex 3th or 4th wall.
- Reject side-entering backgrounds.
- Signal acceptance: 7.5%

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 36%

Number of ν_μ CC events expected in 36.8 fb^{-1} after cuts: 4.2



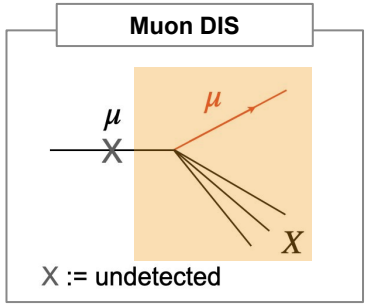


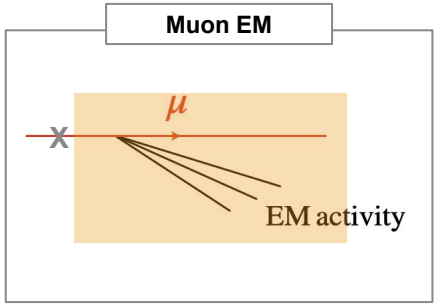
ν_μ CC simulation

SND@LHC backgrounds

Entering muons

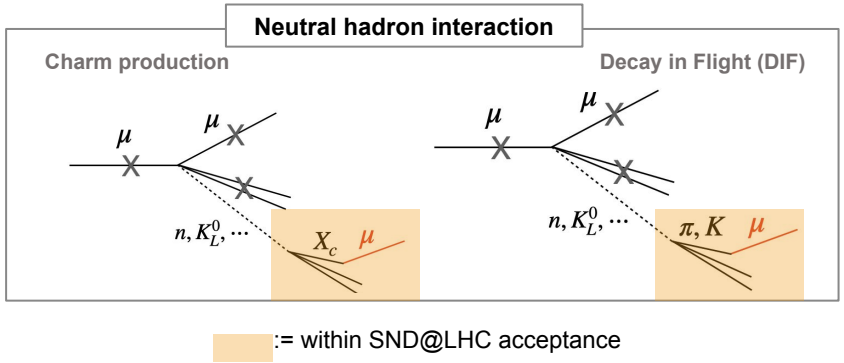
- Incoming muon track may be missed due to detector inefficiency.
- Shower induced by DIS or EM activity.
- Number of muons in acceptance: 5 x 10^{8}
  SNDLHC-NOTE-2023-001
- Detector inefficiency: 5 x 10^{-12}
  - Two veto and two scintillating fibre planes.
- **Negligible** background with tight fiducial volume.





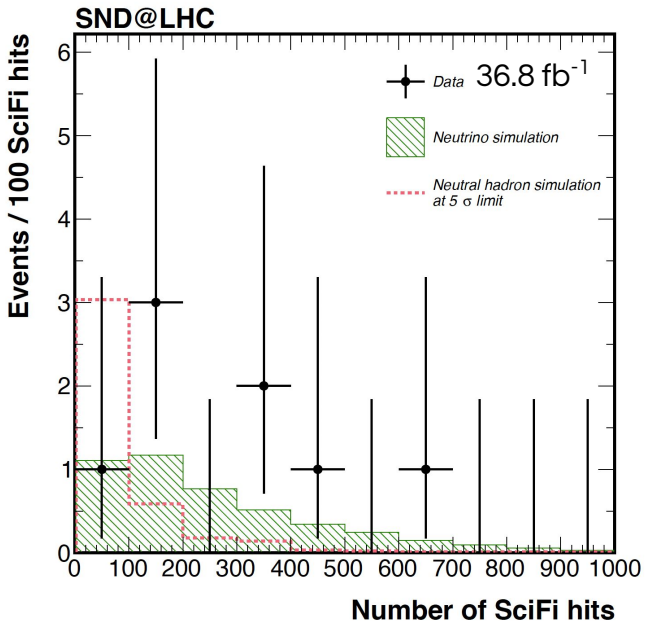
Neutral hadrons

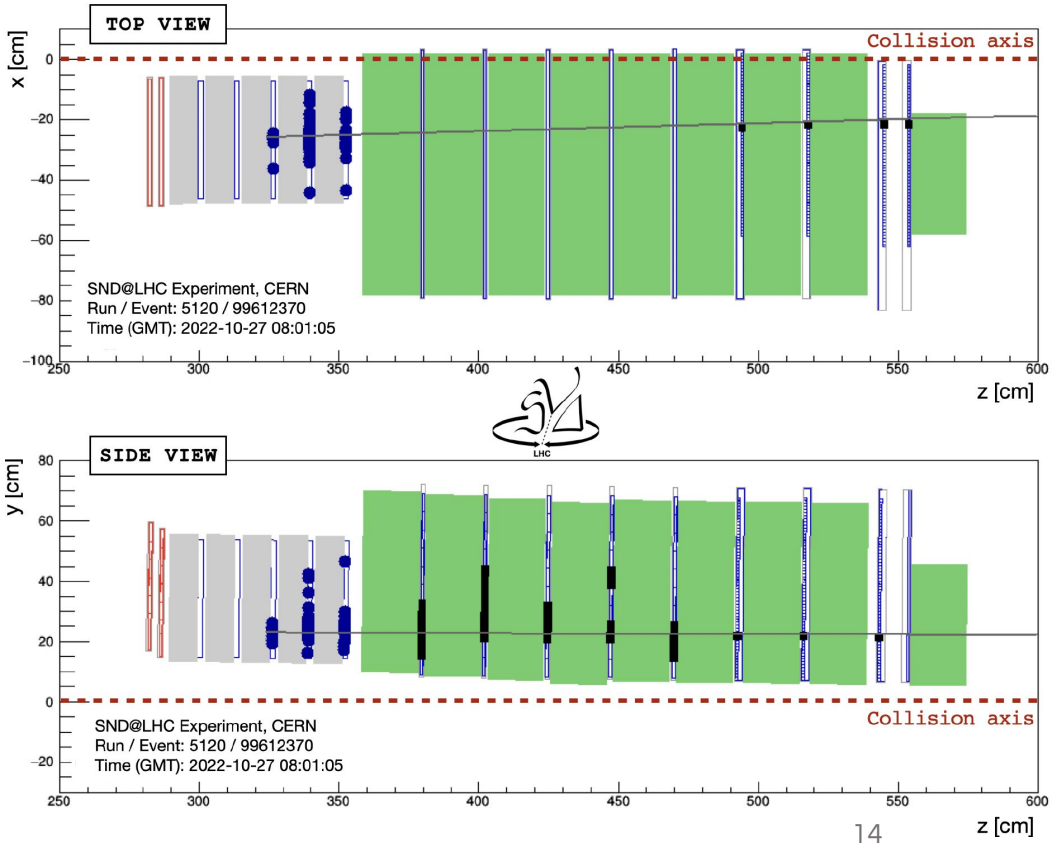
- Neutral hadrons are produced in muon DIS in materials upstream of the detector.
- Muon from pion decay-in-flight or charm production.
- Expect a total of **(8.6 ± 3.8) x 10^{-2}** background events due to neutral hadrons.



SND@LHC neutrino observation

Observed eight neutrino event candidates with a statistical significance of 6.8 σ

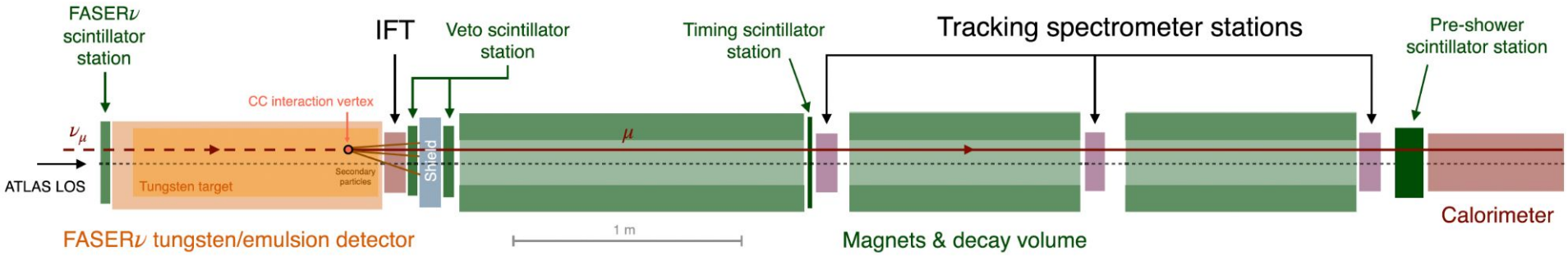




FASER event selection

- Event in time with collision and good data quality.
- No signal (< 40 pC) in the two front veto scintillators.
- Signals (> 40 pC) in all the scintillators downstream of the decay volume.
- Exactly one good fiducial track:
  - p > 100 GeV/c
  - r < 120 mm at the front veto

Number of ν_μ CC events expected in 35.4 fb^{-1} after cuts: 151 ± 41



FASER backgrounds

Entering muons

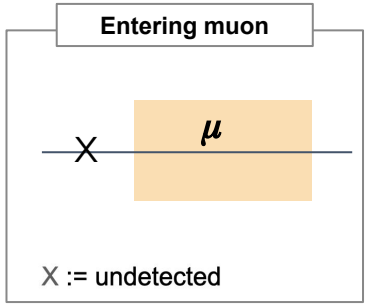
- Incoming muon track missed due to detector inefficiency.
- Expect (3.7 ± 2.5) x 10^{-7} events.
  - Estimated from events with only one scintillator plane firing.

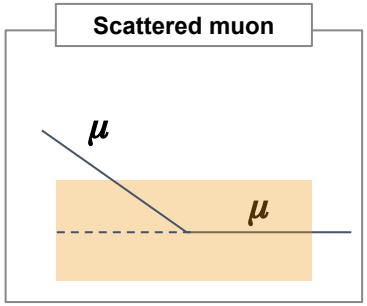
Scattered muons

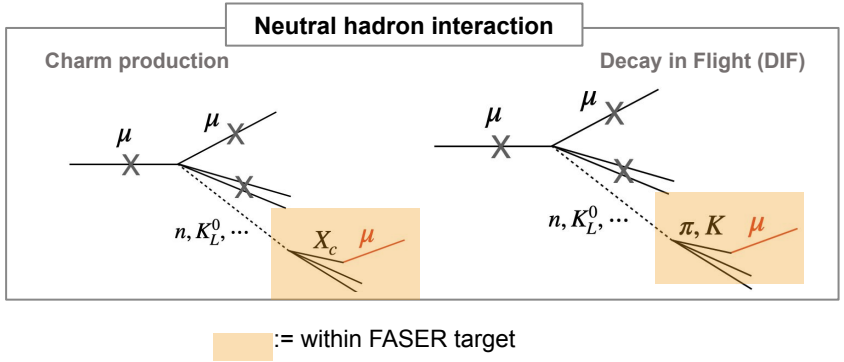
- Muon scattered in the target misses the veto planes.
- Expect **0.08 ± 1.83** events.
  - Estimated from control sample.

Neutral hadron interaction

- Neutral hadrons produced in muon DIS in materials upstream of the detector.
- Expect O(300) hadrons with E > 100 GeV.
  - Most are absorbed in the target.
- Expect **0.11 ± 1.83** events.



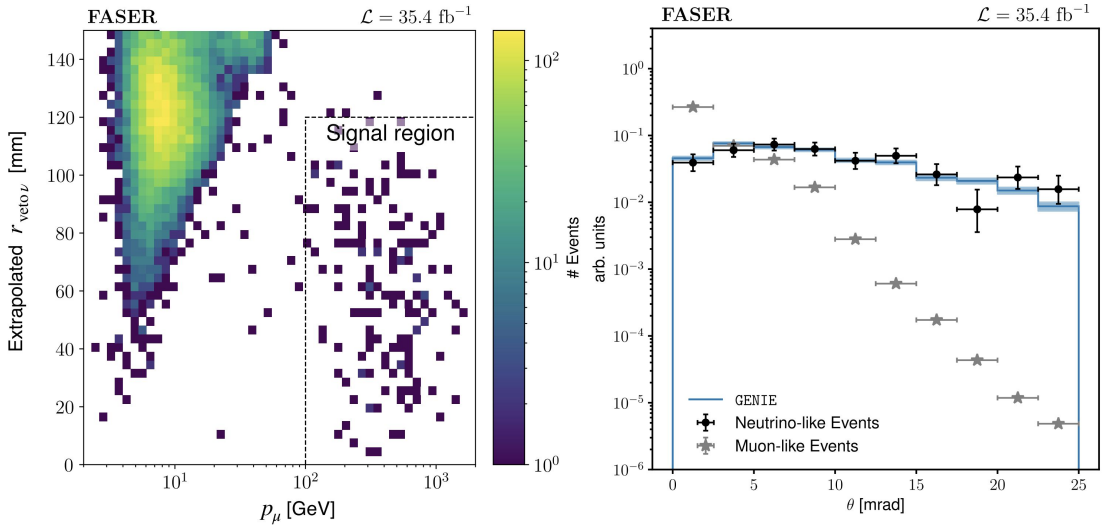


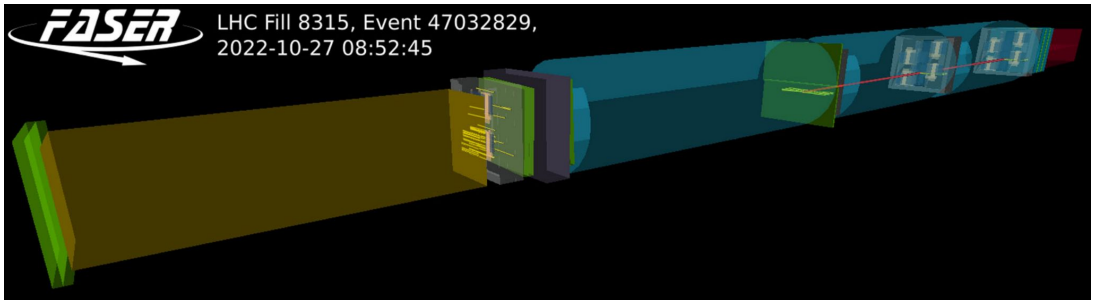


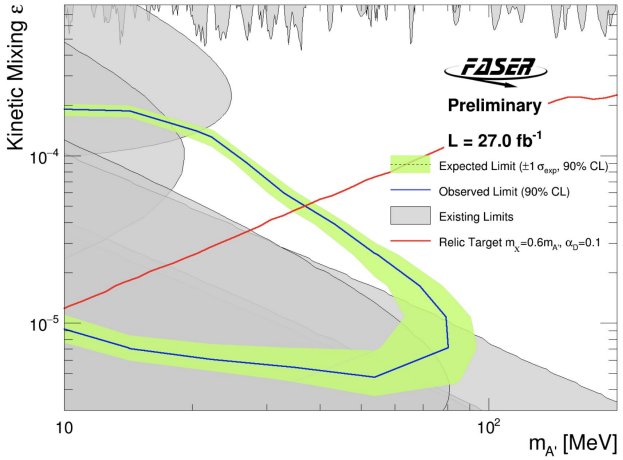
FASER neutrino observation

Observed 153 neutrino event candidates with a statistical significance of 16 σ

More details in Ke Li's talk on Tuesday's BSM session.



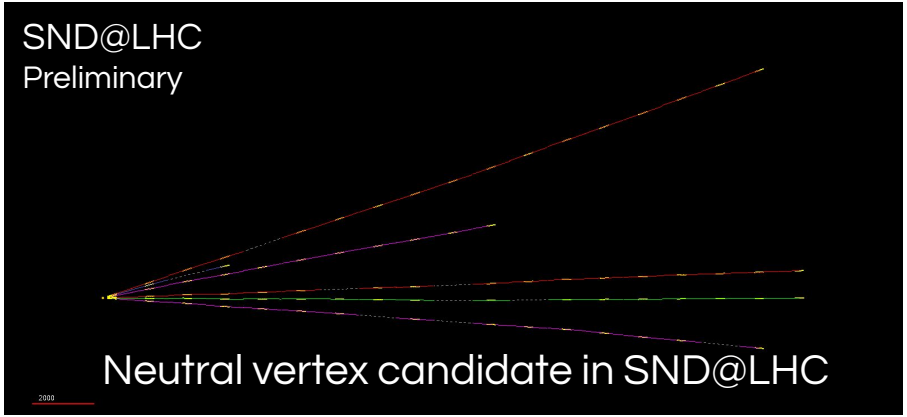


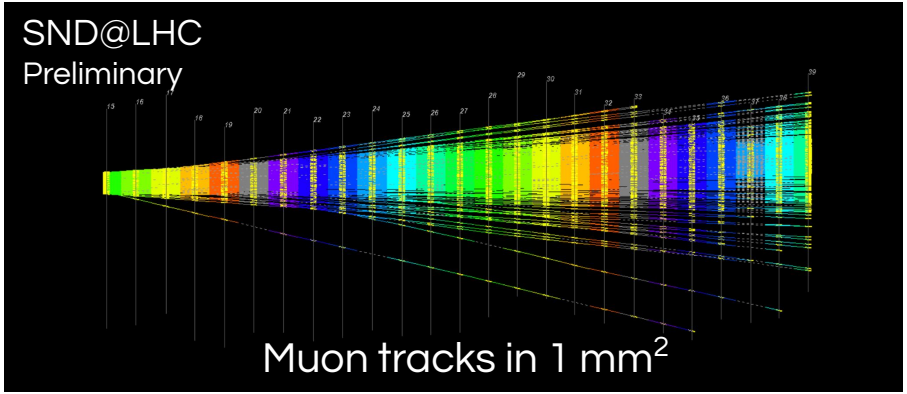


FASER has also reported its first limits on dark photons.
CERN-FASER-CONF-2023-001

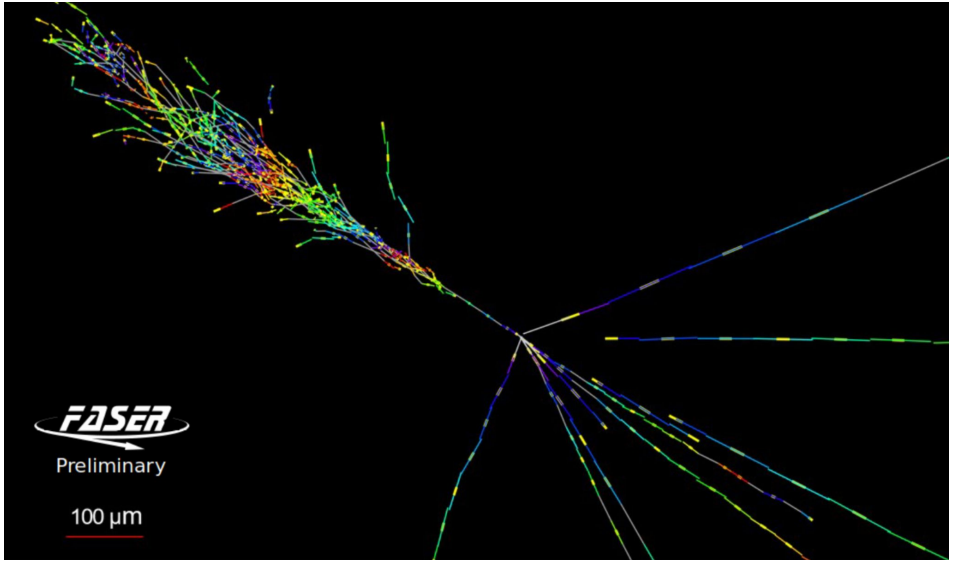
Emulsion detector analyses

Analysis of emulsion detector data is ongoing in both collaborations.





10^5 tracks/cm^2 in 10 fb^{-1} exposure

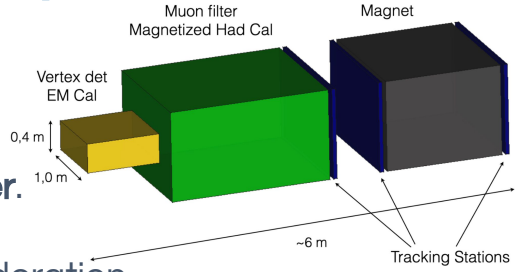


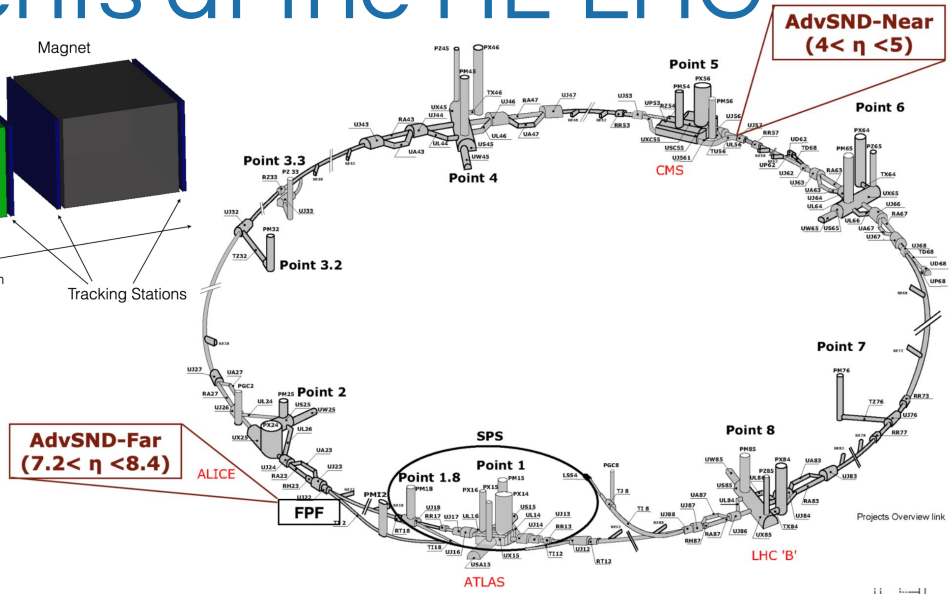
Electron neutrino candidate in FASER

Neutrino experiments at the HL-LHC

SND@LHC upgrade: AdvSND

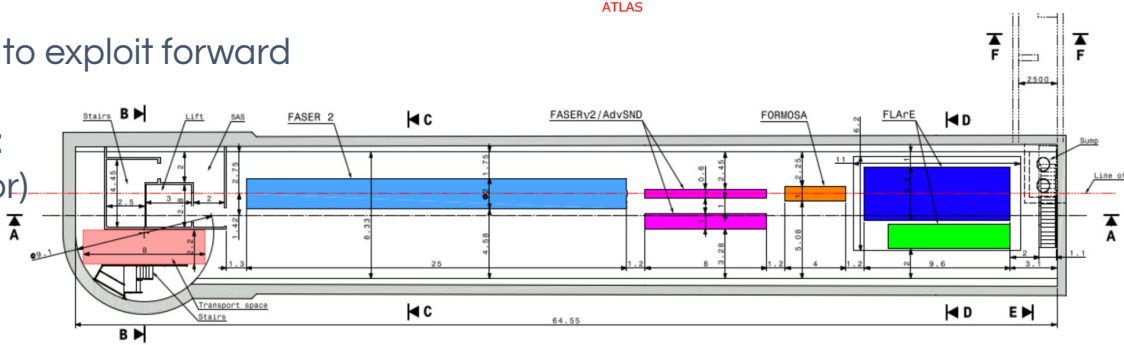
- Iron-core **muon spectrometer**.
- Electronic **vertex detector**.
  - Si options under consideration.
- **Near detector** at lower η to constrain systematic uncertainties and **far detector** in the same η range as the current detector.





Forward Physics Facility

- Dedicated experimental area proposed to exploit forward physics at HL-LHC.
- Several proposed neutrino experiments:
  - **FASERv2** (emulsion vertex detector)
  - FLArE (LArTPC)
  - AdvSND-Far



Summary

- **Neutrinos** produced in **proton-proton collisions** have been detected for the first time!
  - Highly significant observations of muon neutrinos by two complementary experiments: **FASER** and **SND@LHC**.
- This marks the start of an exciting new era of **neutrino** measurements at the **LHC**.
  - Rich physics program spanning **neutrino interactions**, **QCD**, **flavour** and **BSM** searches.
- Neutrino and forward physics programme proposed for the **HL-LHC**:
  - **Detector upgrades** to deal with high rates and reduce systematic uncertainties.
  - Dedicated **Forward Physics Facility**.