Neutrinos at the LHC

Scattering and Neutrino Detector at the LHC

43rd International Symposium on Physics in Collision

NCSR "Demokritos", Athens, Greece

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LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Cristóvão Vilela

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

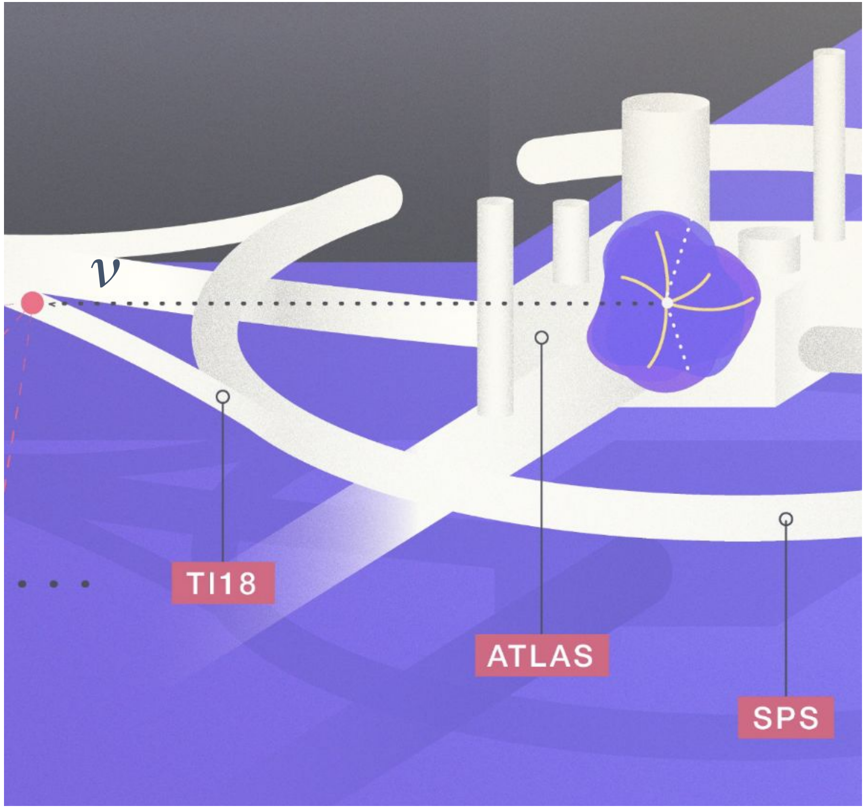
Neutrinos at the Large Hadron Collider

- 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.
  - Also to search for new particles.
    Phys.Lett.B 153 (1985) 183

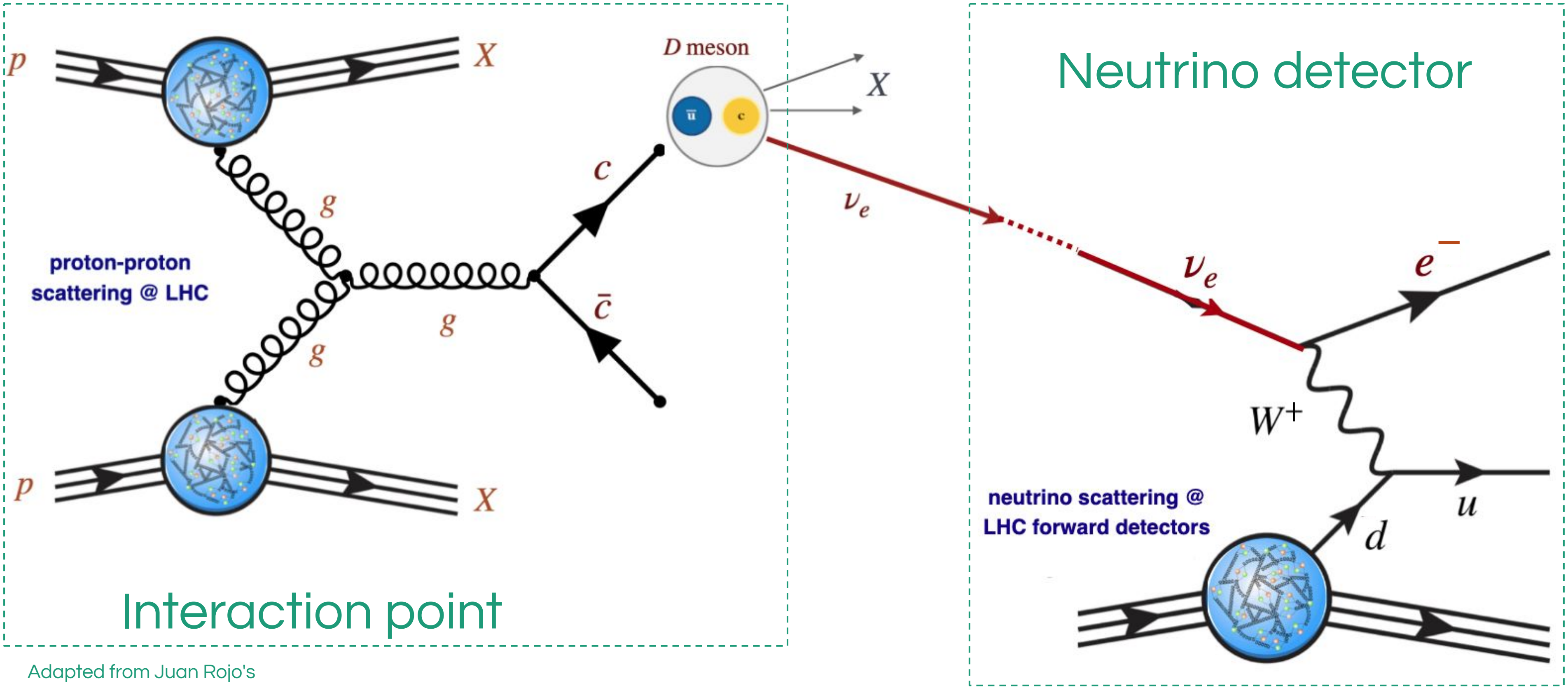
- **Large flux** of neutrinos in the forward region.
- Very **high neutrino energy** ($\sigma_\nu \propto E_\nu$).

⇒ 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 **FASERν**

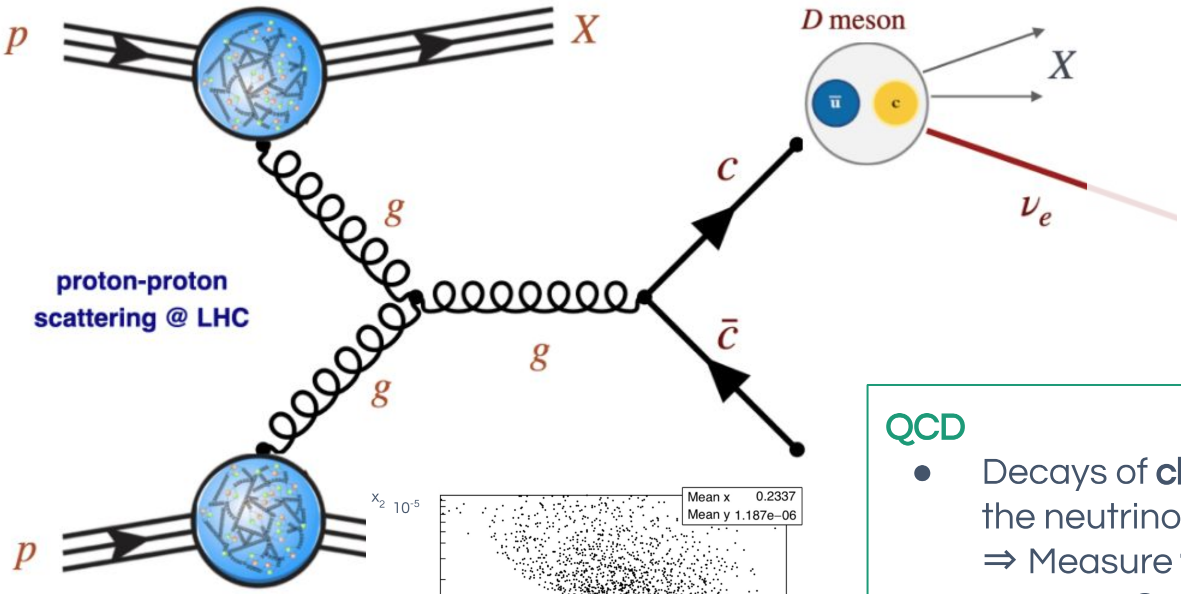


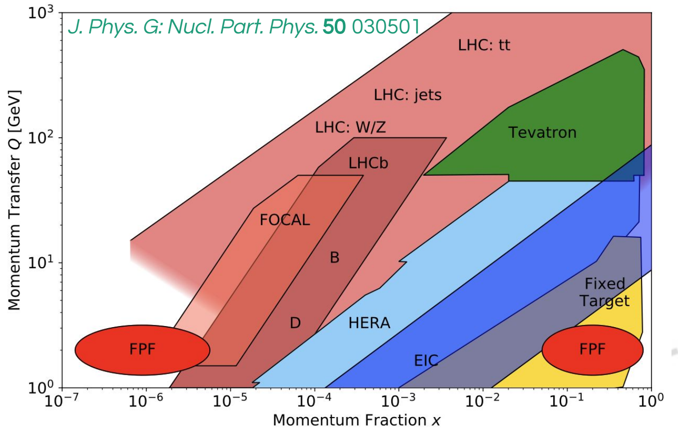
Hadron collider neutrino physics

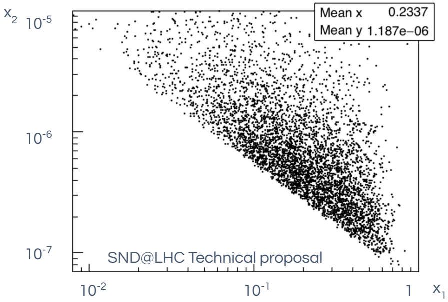


Adapted from Juan Rojo's
CERN TH seminar

Quantum chromodynamics







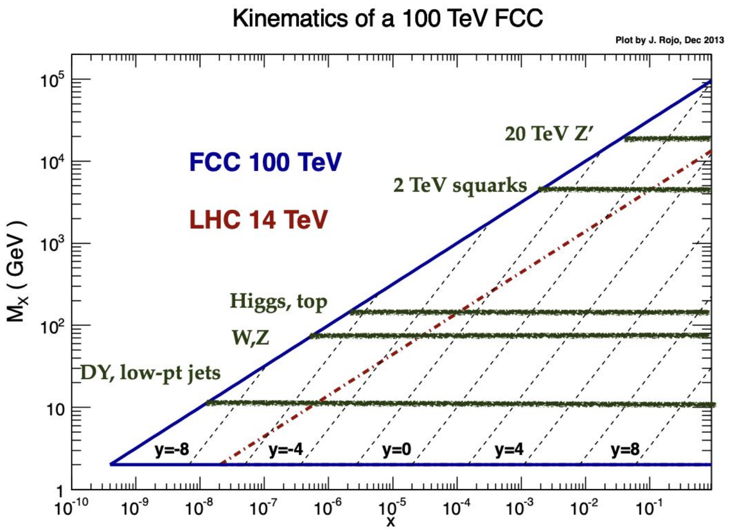
QCD

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

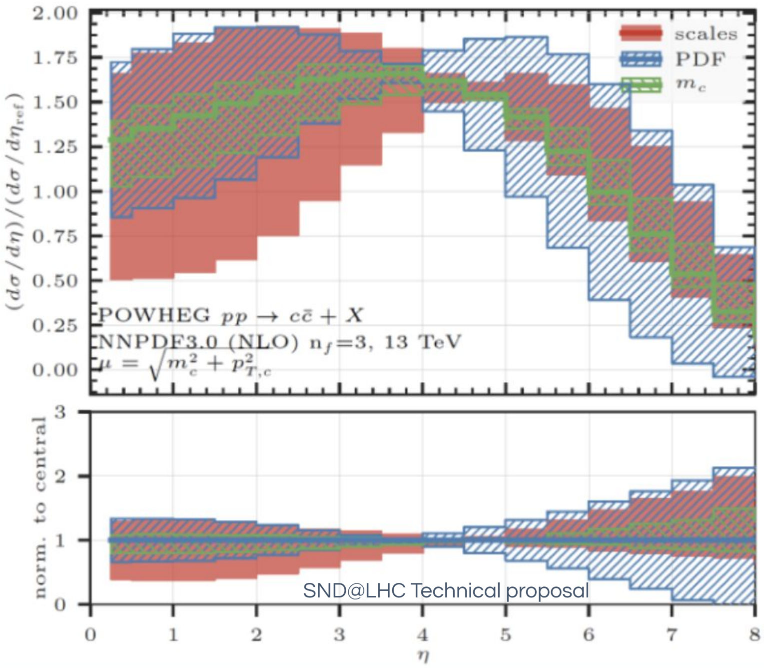
Adapted from Juan Rojo's CERN TH seminar

Implications for FCC-pp

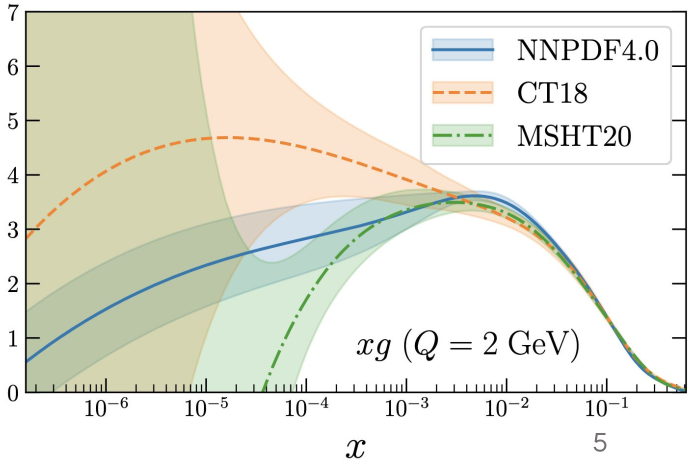
- Much of the ***FCC-pp*** physics will be produced at very ***small x.***
  - Even electroweak and Higgs measurements will be



J. Rojo CERN-TH Colloquium 11/2023



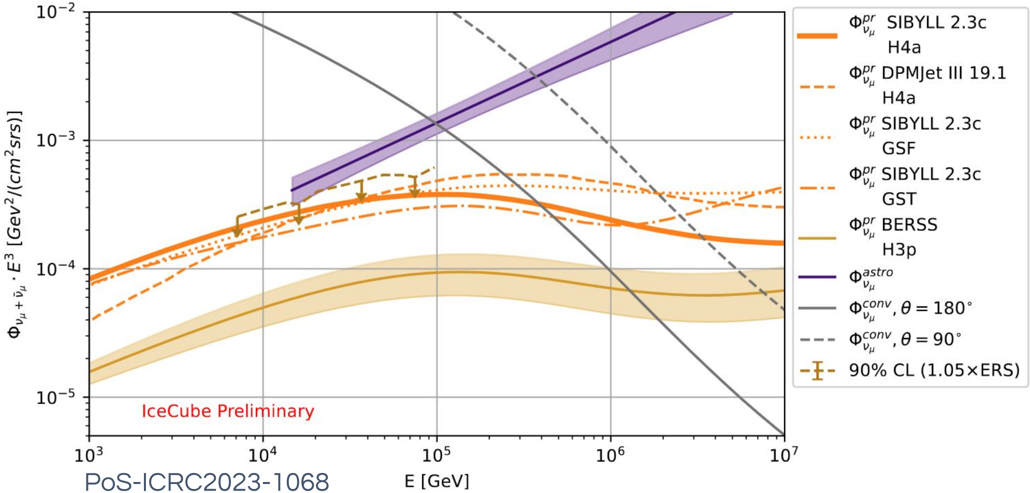
SND@LHC Technical proposal



Implications for astroparticle physics

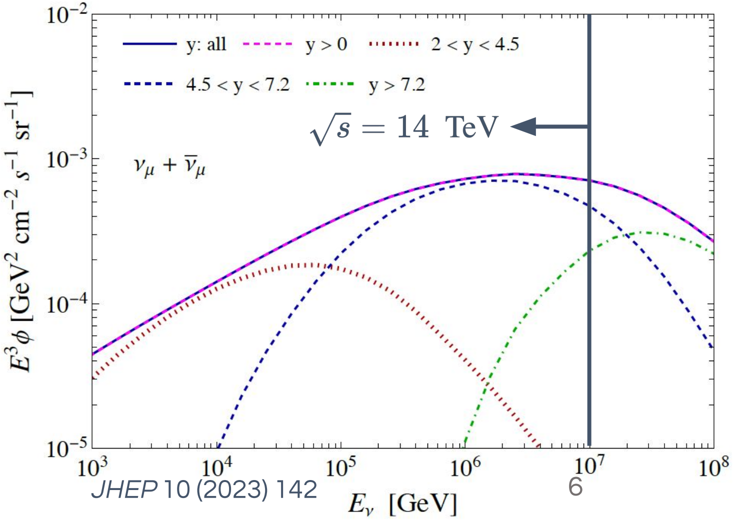
- The ***prompt*** flux of atmospheric neutrinos, originating from charm decays, is not known.
  - This is an important component in the ***transition region*** between ***atmospheric*** and ***astrophysical*** neutrino flux.
- LHC neutrinos originating from ***charm*** hadrons with rapidities > ~ 7 correspond to atmospheric neutrino energies up to **10^7 GeV**, in the ***transition region*** .

Current IceCube limits on the prompt neutrino flux, along with model predictions.



PoS-ICRC2023-1068

Prompt flux of atmospheric neutrinos broken down by charm hadron rapidity in the pp collision frame.



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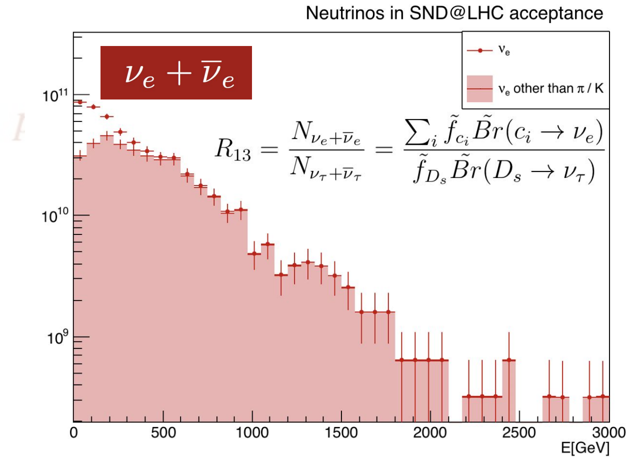
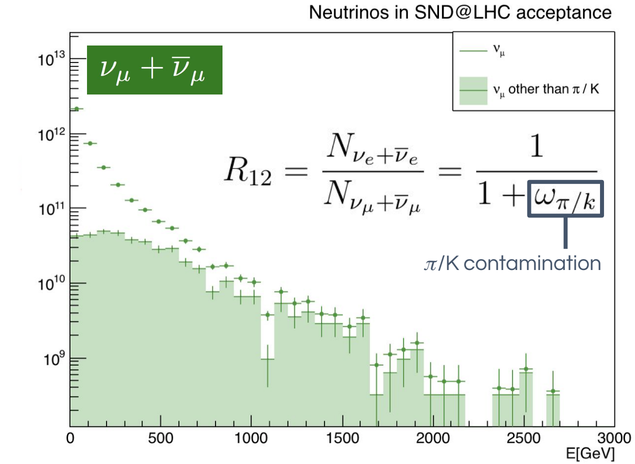
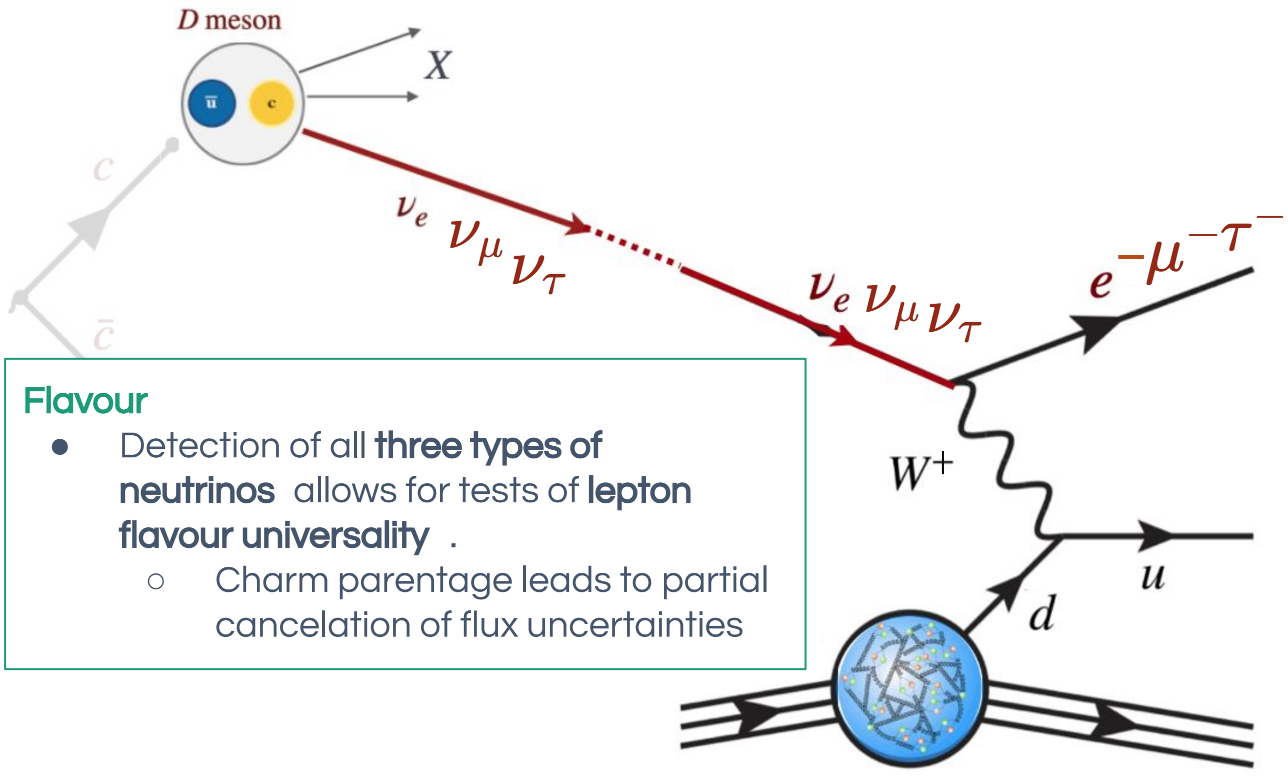
Lepton flavour universality



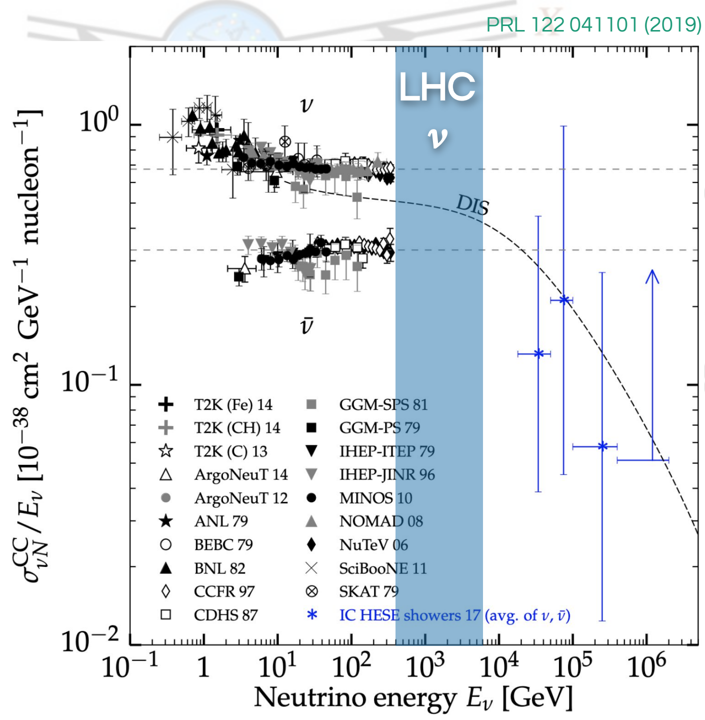




Flavour

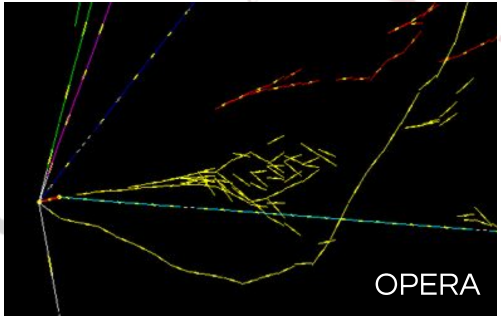
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**.
  - Charm parentage leads to partial cancelation of flux uncertainties

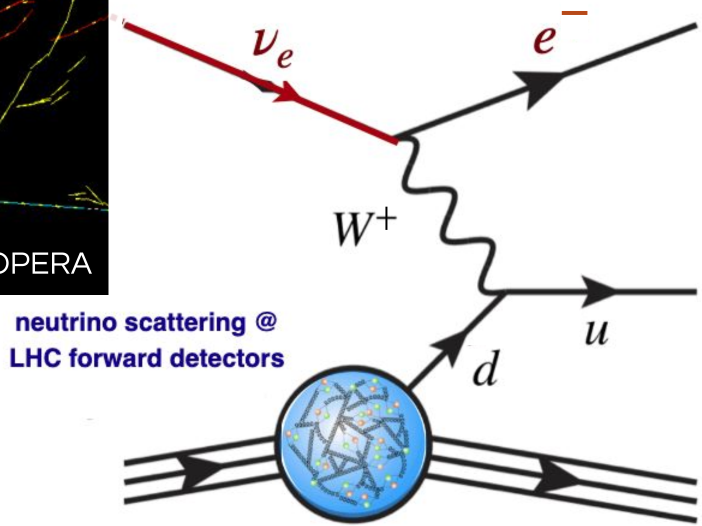
Neutrino interactions



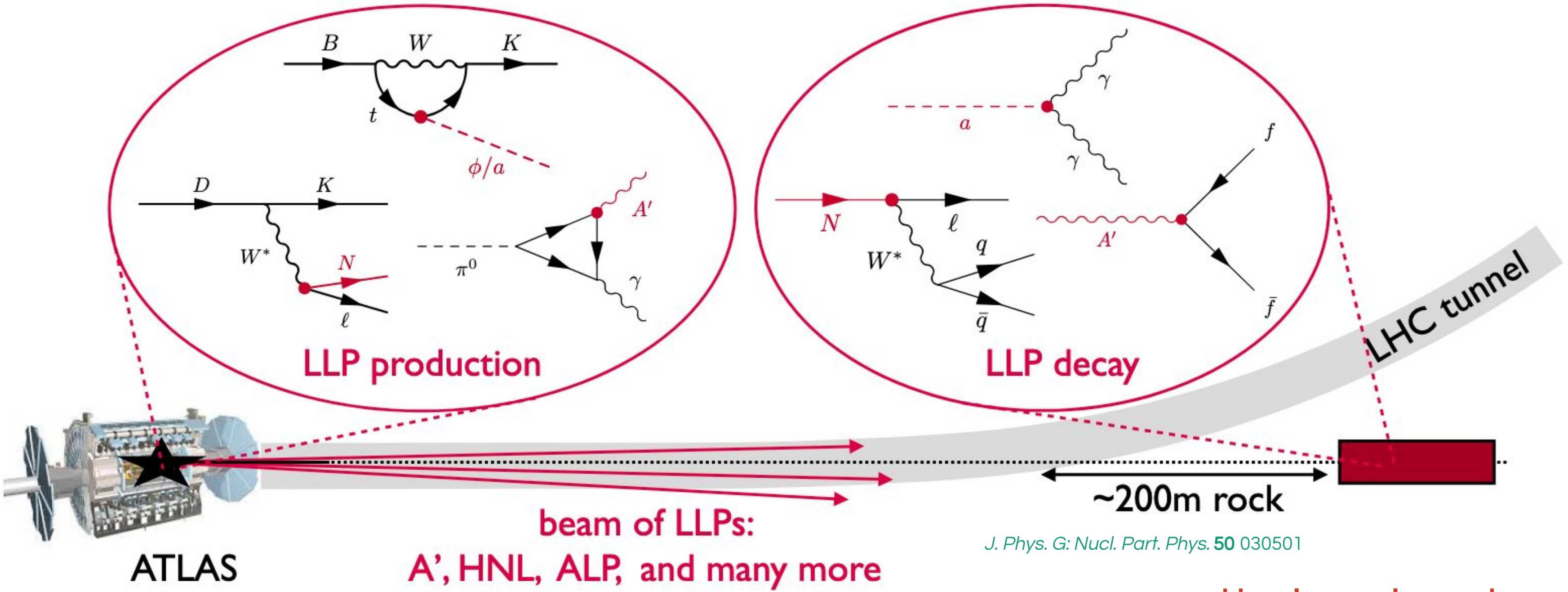
Neutrino interactions

- Measure **ν interactions** in unexplored ~TeV energy range.
- Large yield of ν_τ will likely double existing data.
    - About 20 events observed by DONuT and OPERA.
- Opportunity to discover the $\overline{\nu_\tau}$!





Beyond the Standard Model



J. Phys. G: Nucl. Part. Phys. **50** 030501

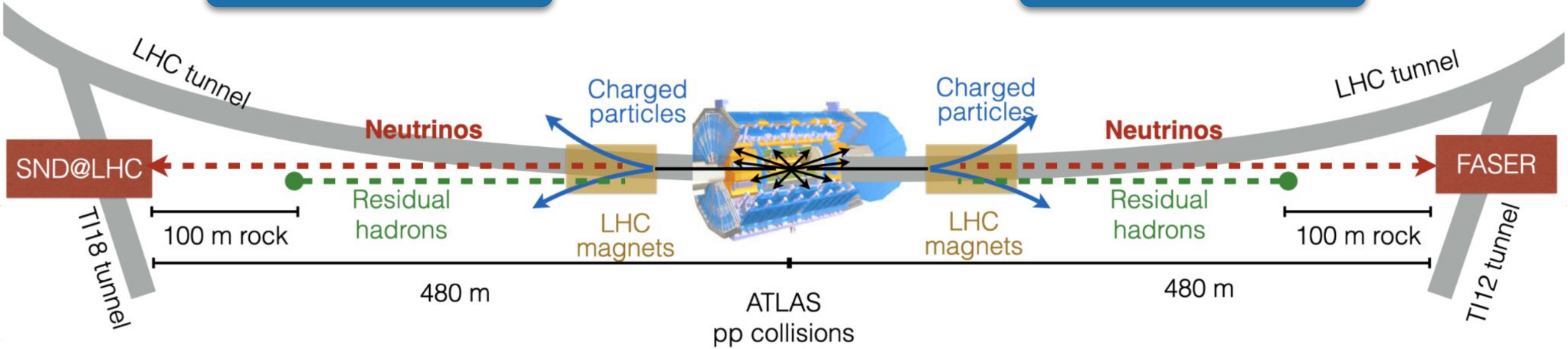
+ scattering signatures

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

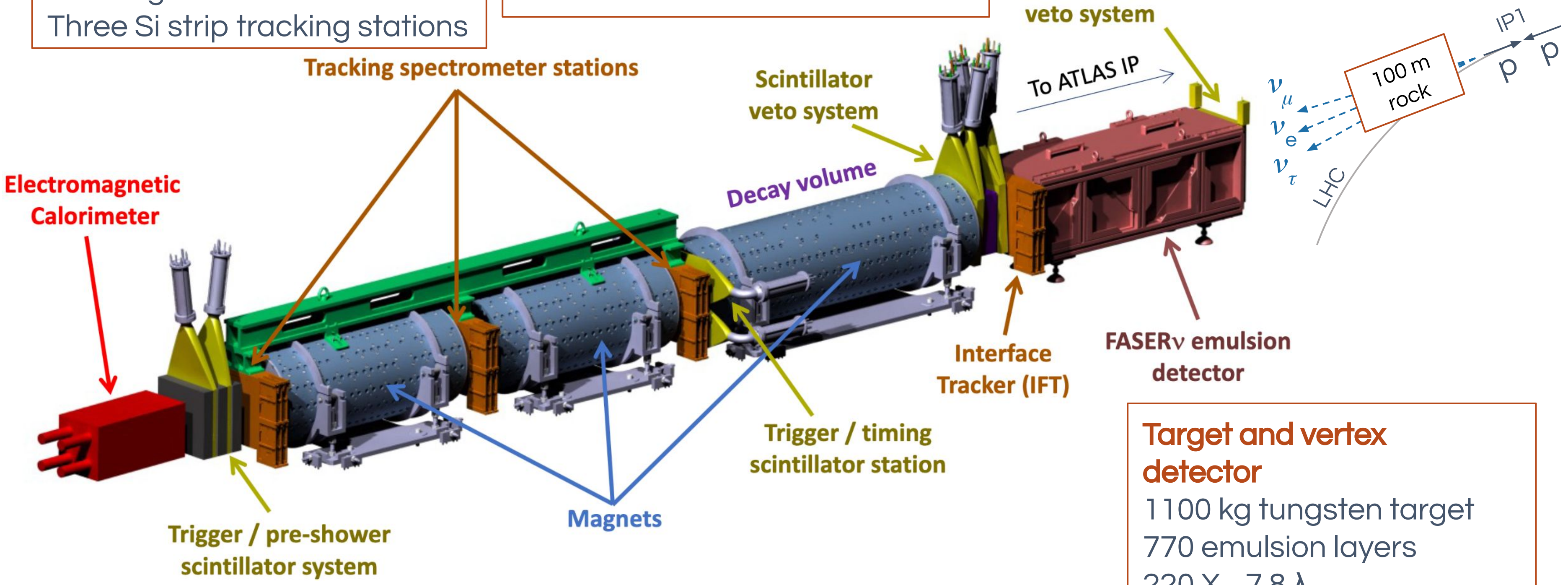


ForwArd Search ExpeRiment

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: η > 9.2



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

JINST 19 (2024) P05066

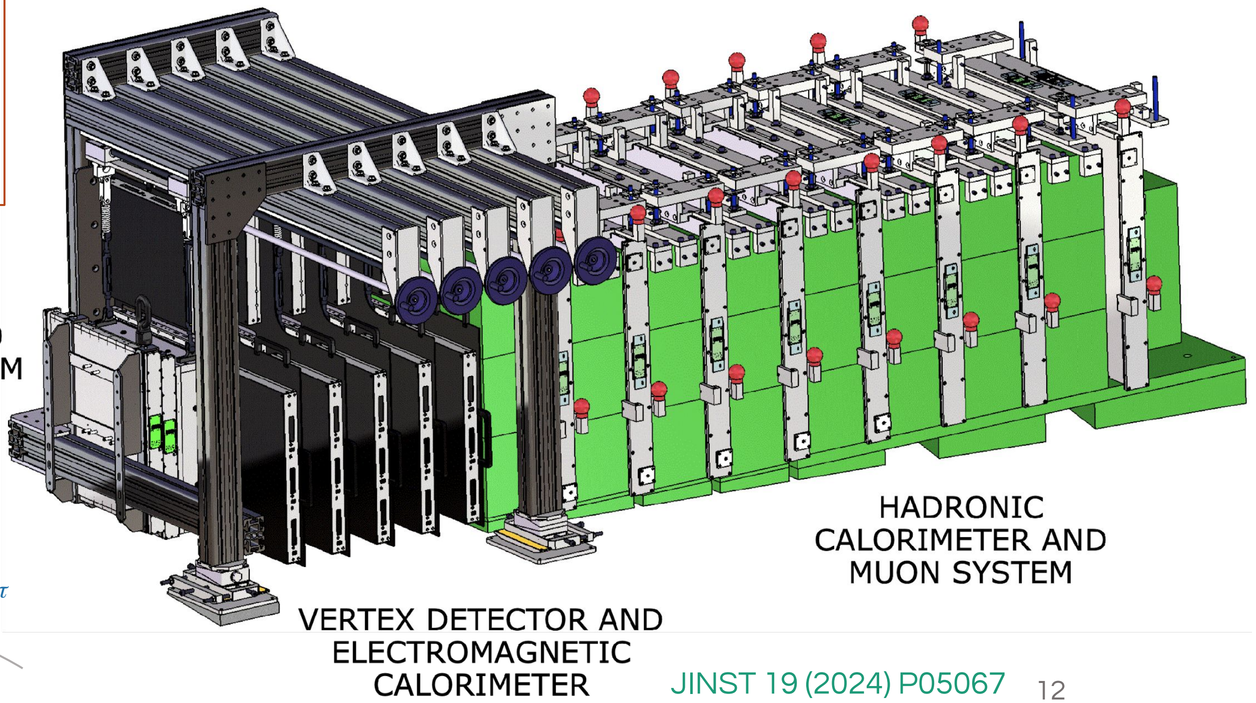
Scattering and Neutrino Detector at the LHC

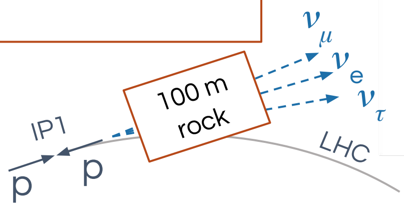
Veto system
2 (2022 – 2023) / 3 (2024 -) 1 cm thick scintillator planes.

Off-axis : $7.2 < \eta < 8.4$
Enhances the flux with charm origin.

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}





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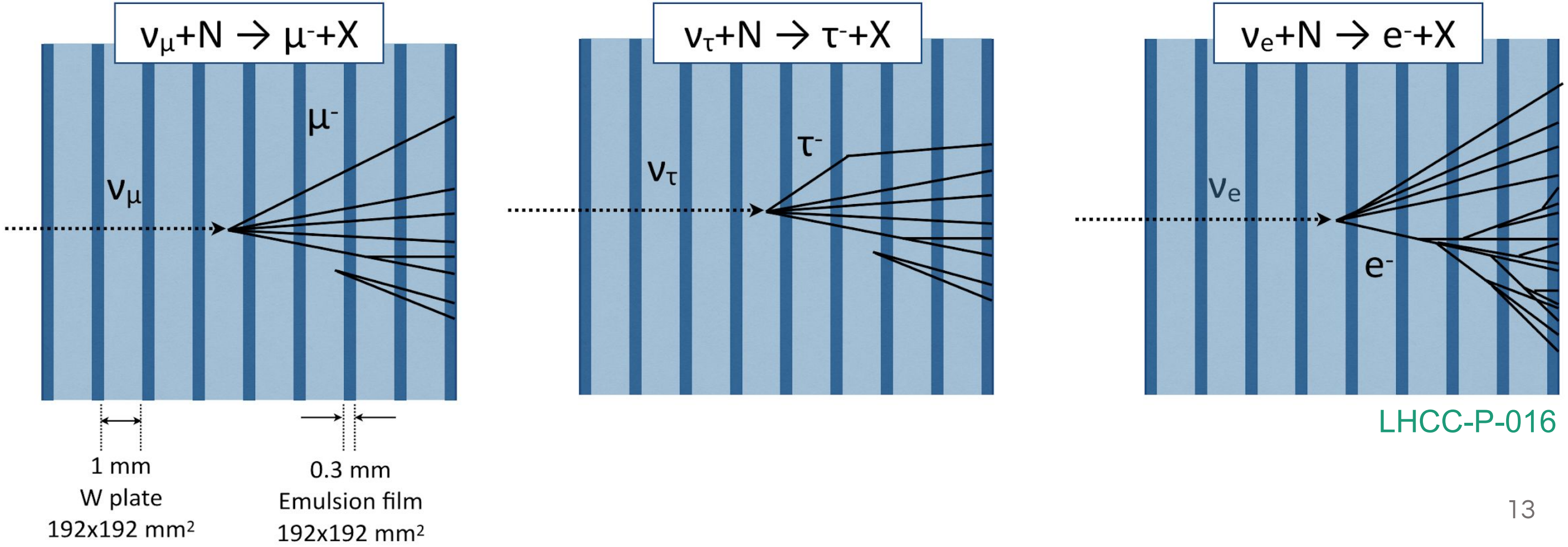
Neutrino identification with emulsions

- **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**.

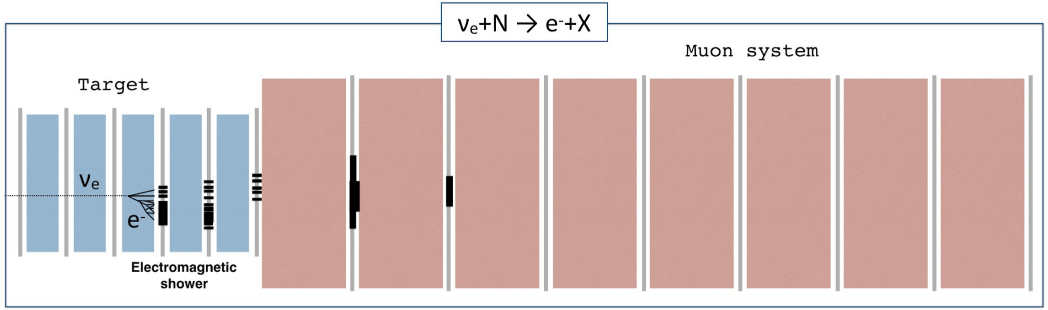


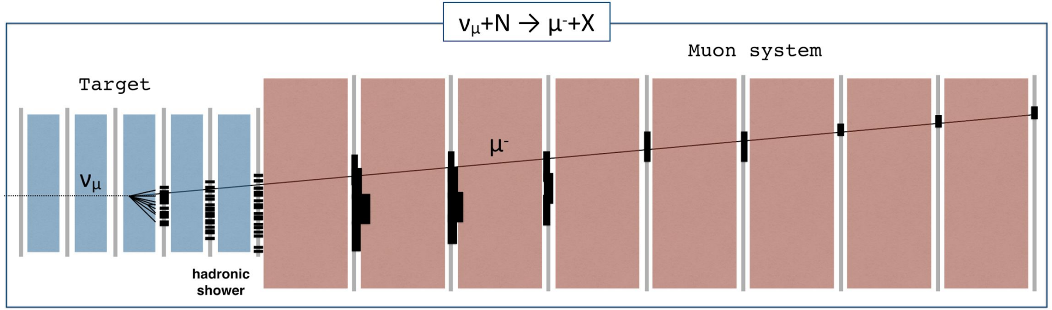
LHCC-P-016

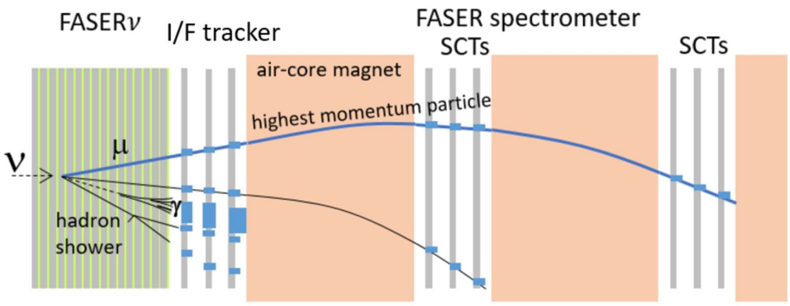
Neutrino event reconstruction strategies

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

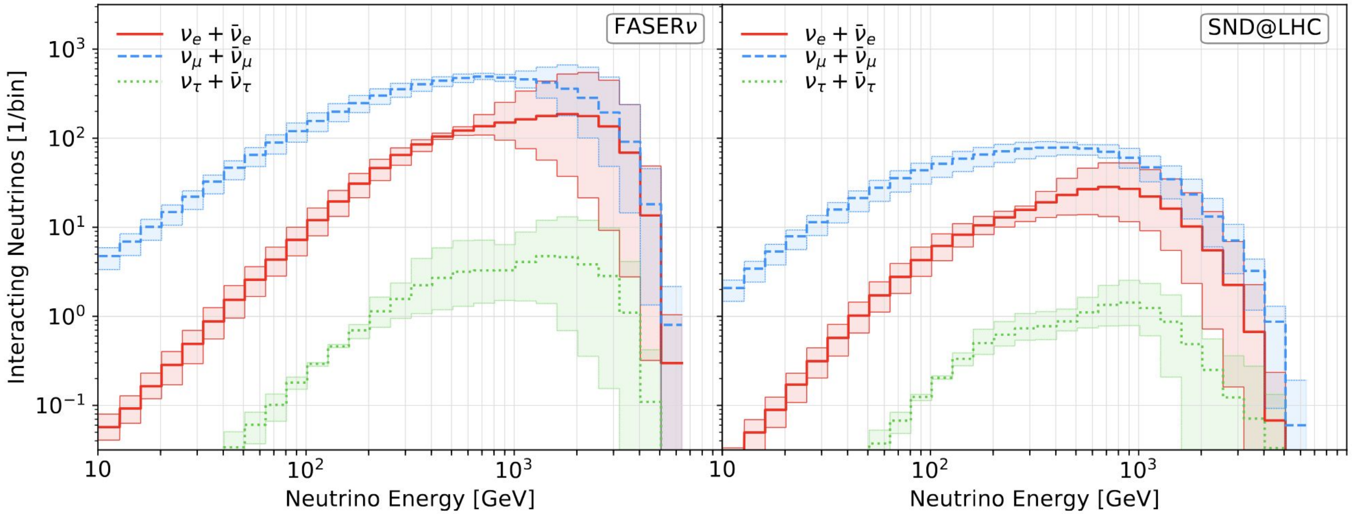
- Use **interface tracker** to **match** electronic detector events to emulsion detector vertices.
- Measure **track momenta** with **spectrometer**.
- **Muon tagging** based on absence of hadronic interactions in the tungsten and track momentum.

Neutrino rate predictions

Phys. Rev. D 104, 113008

- Uncertainty on ν_μ flux at the order of 10 – 20%.
- Larger uncertainties for other flavours.
- Models validated with forward data, e.g., LHCf.
- Very active development.

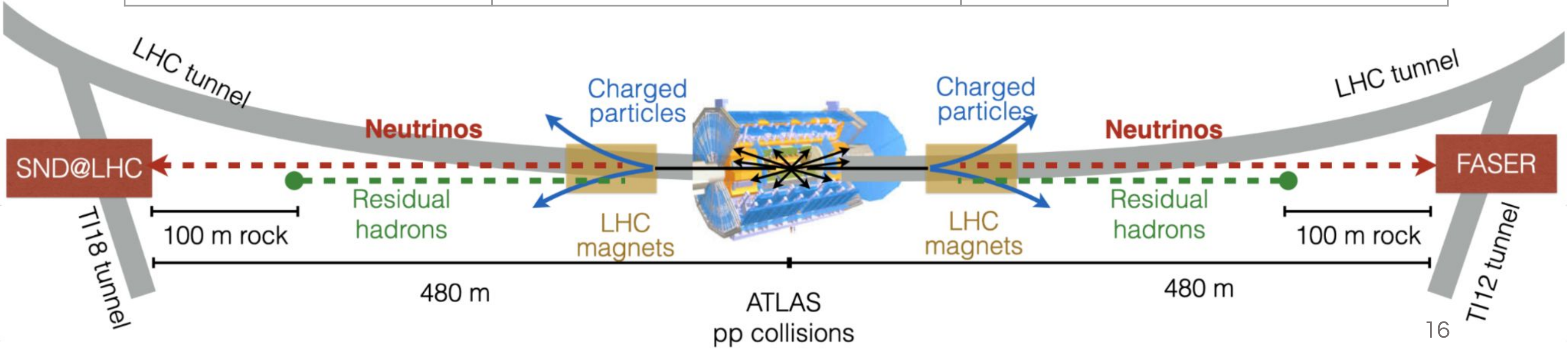
Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7	134	790	7.6
DPMJET	DPMJET	3457	7088	97	395	1034	18.6
EPOSLHC	Pythia8 (Hard)	1513	5905	34.2	267	1123	11.5
QGSJET	Pythia8 (Soft)	970	5351	16.1	185	1015	7.2
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$	245^{+149}_{-111}	991^{+132}_{-200}	$11.3^{+7.3}_{-4.0}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$	195^{+71}_{-61}	976^{+146}_{-185}	$8.8^{+2.7}_{-1.5}$



For 150 fb^{-1}

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**

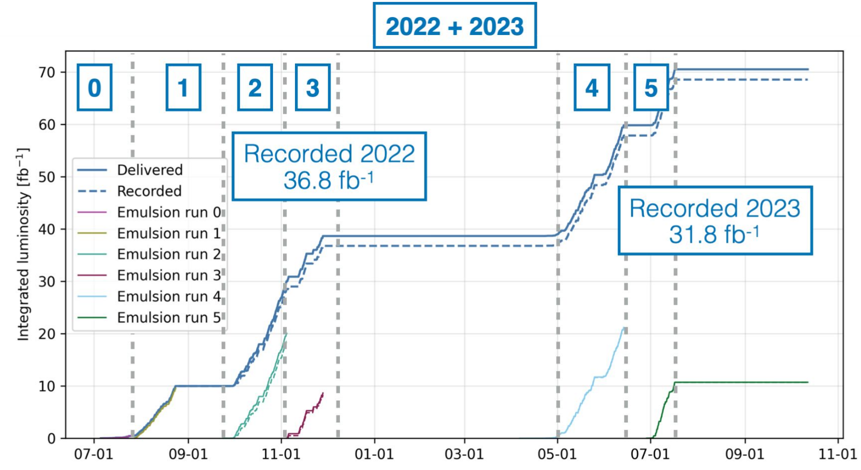


LHC

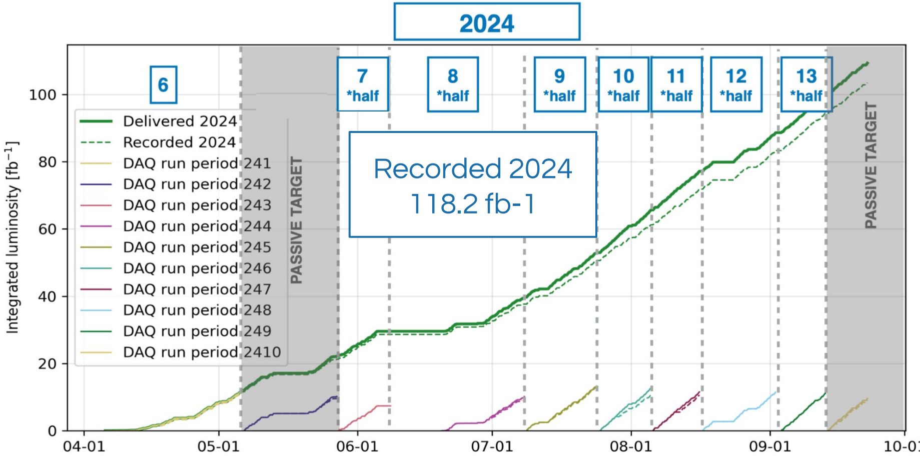
Scattering and Neutrino Detector
at the LHC

SND@LHC Data

- **68.6 fb $^{-1}$** of proton-proton collisions recorded by the electronic detectors in **2022-2023**
  - 97% detector uptime
  - Five emulsion target replacements
    - Keep track density < $4x10^5$ tracks/cm^2
    - Limit the exposure to 20 fb^{-1}

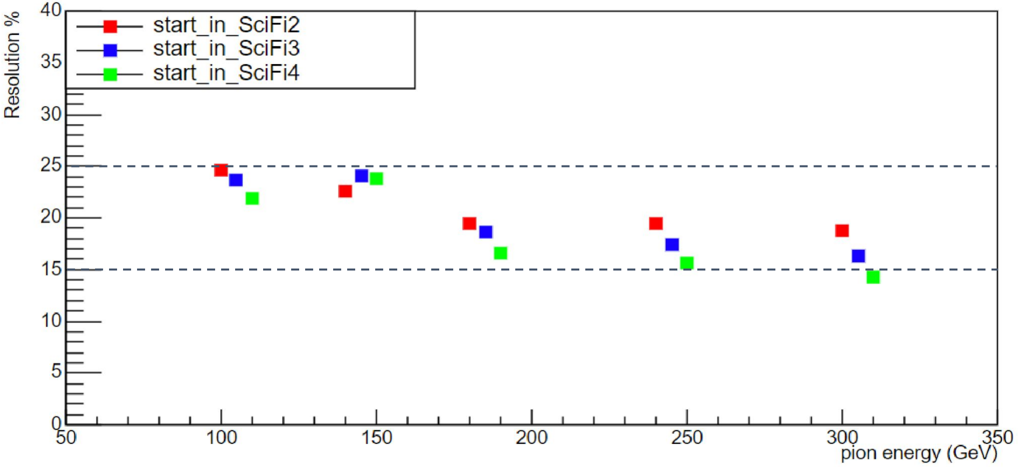


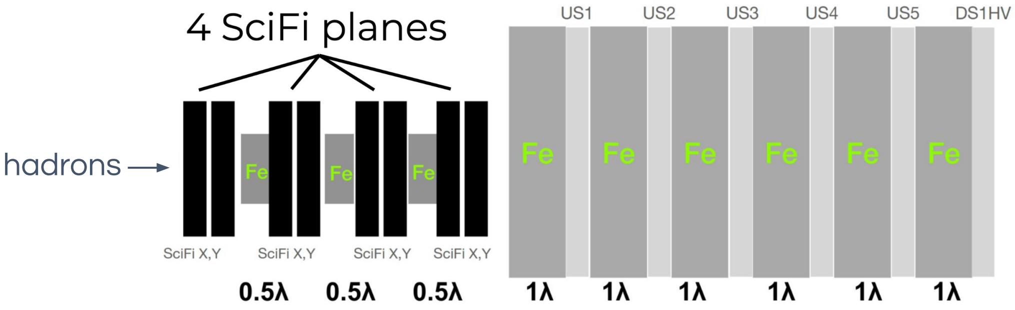
- Unexpected increase in the muon flux in **2024**
  - New strategy for the emulsion target replacement:
    - Instrument only the lower half target with emulsions.
    - Exposure limited to 12 fb^{-1}
    - Keep 65% of events .
  - **118.2 fb $^{-1}$** of proton-proton collisions recorded by the electronic detectors in 2024.
  - Nine emulsion target replacements performed, two periods with passive target.



Hadron calorimeter test beam

- Very successful hadron test beam data taking campaign in August 2023.
- Exact replica of the hadron calorimeter.
- Downsized mockup of the target.
  - Narrow beam spot.
- Calibrated calorimeter response.
  - Confirmed expected performance.
- **New**: electron test beam campaign ended last week!

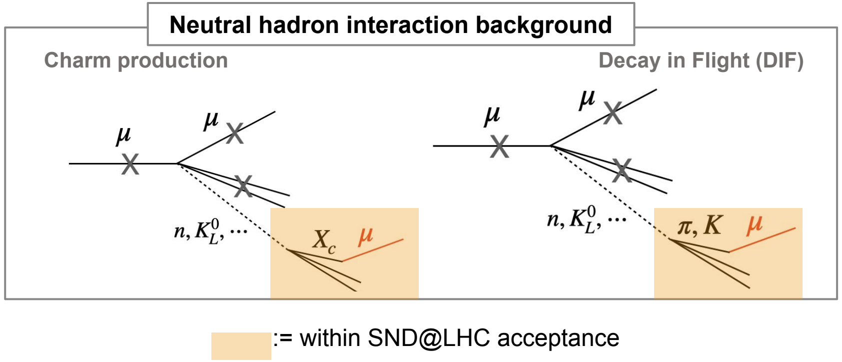


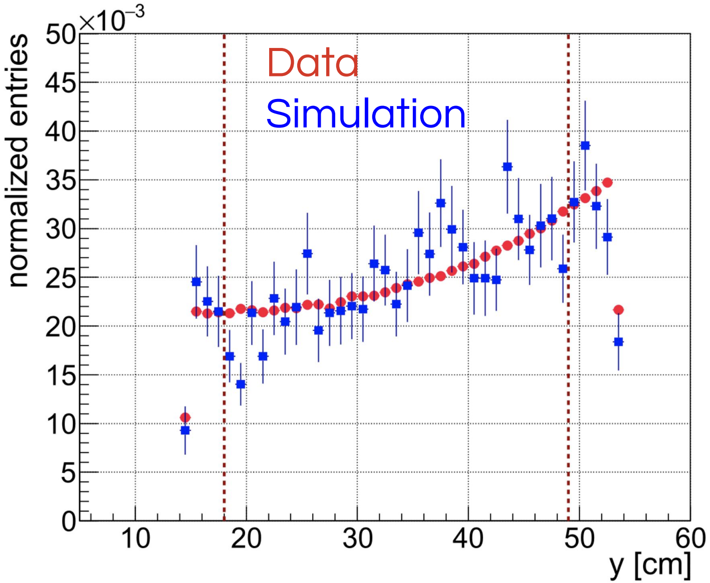


Muon flux measurement

Eur. Phys. J. C (2024) **84**: 90

- Backgrounds to neutrino signals in SND@LHC are mainly due to muon interactions in the tunnel walls.
- Precise measurements of the muon flux allow for validating and constraining our background model.





System	Muon flux [10^4 fb/cm^2] same fiducial area
SciFi	$2.06 \pm 0.01\,(\text{stat.}) \pm 0.12\,(\text{sys.})$
DS	$2.02 \pm 0.01\,(\text{stat.}) \pm 0.08\,(\text{sys.})$

- Measurements with the SciFi tracker, downstream muon system and emulsion detectors give consistent results.

Search for ν_μ events in SND@LHC

2023

Phys. Rev. Lett. 131, 031802

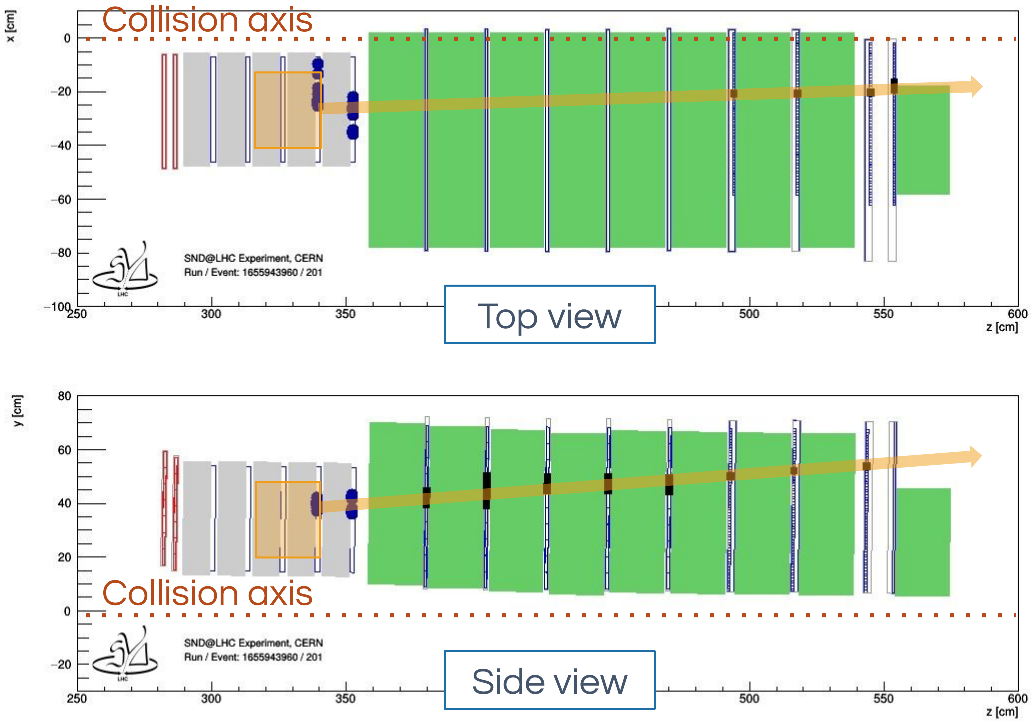
Fiducial volume

- Neutral vertex 3rd 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

2023

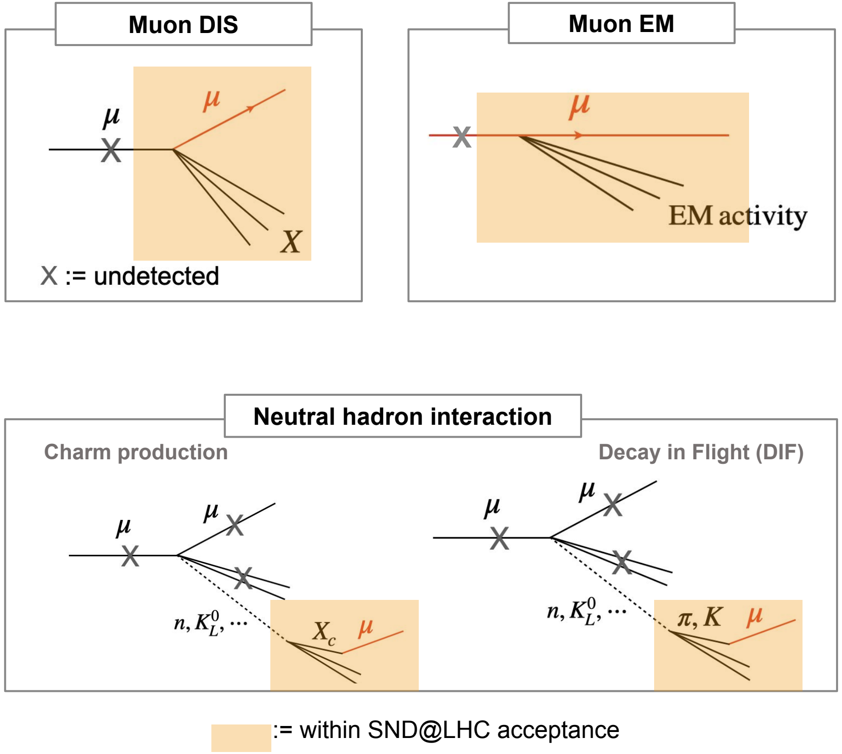
Phys. Rev. Lett. 131, 031802

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.

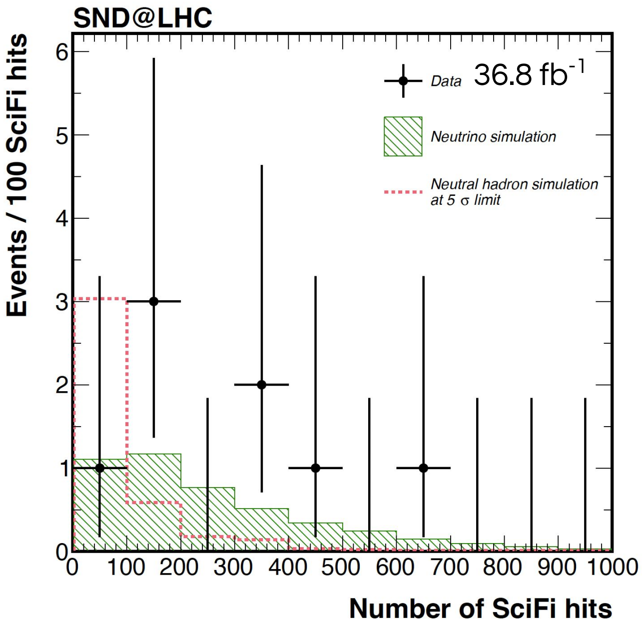


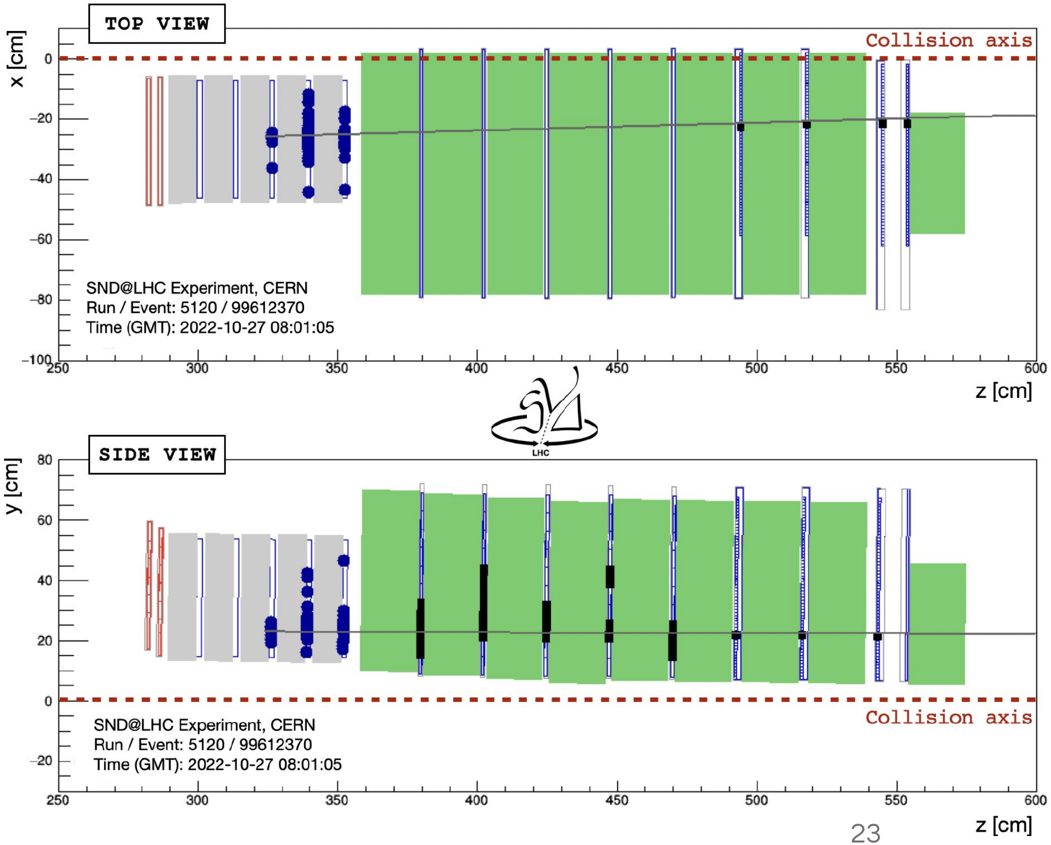
SND@LHC neutrino observation

2023

Phys. Rev. Lett. 131, 031802

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





Muon neutrino analysis update

2024

New this year
Updated analysis with 2023 data and extended fiducial volume.

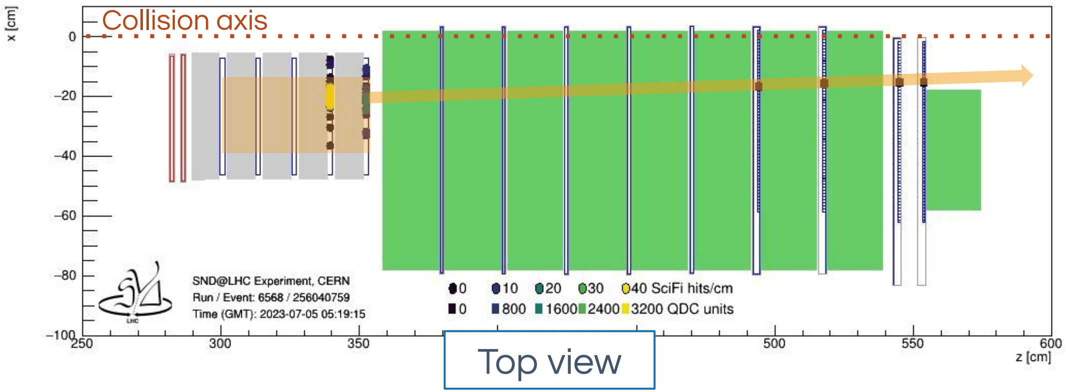
Event selection

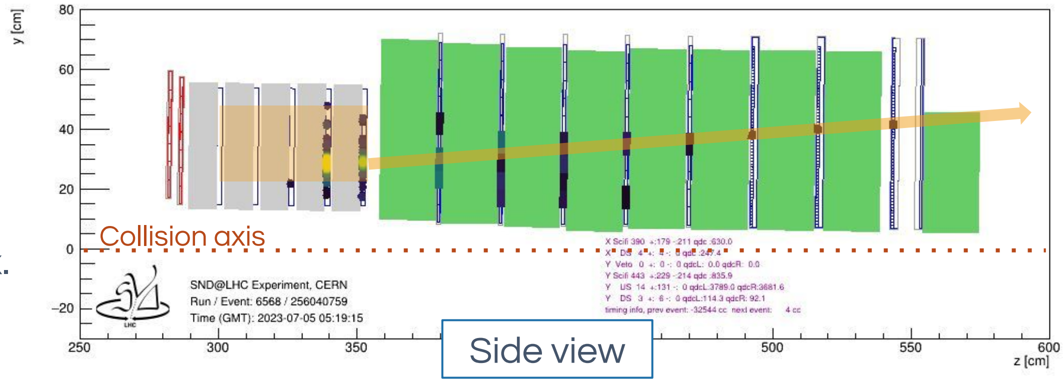
Fiducial volume

- Reject events in first wall.
  - Previously used only walls 3 and 4.
- Reject side-entering backgrounds.
- Signal acceptance: 18%
  - Up from 7.5%.

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 35%





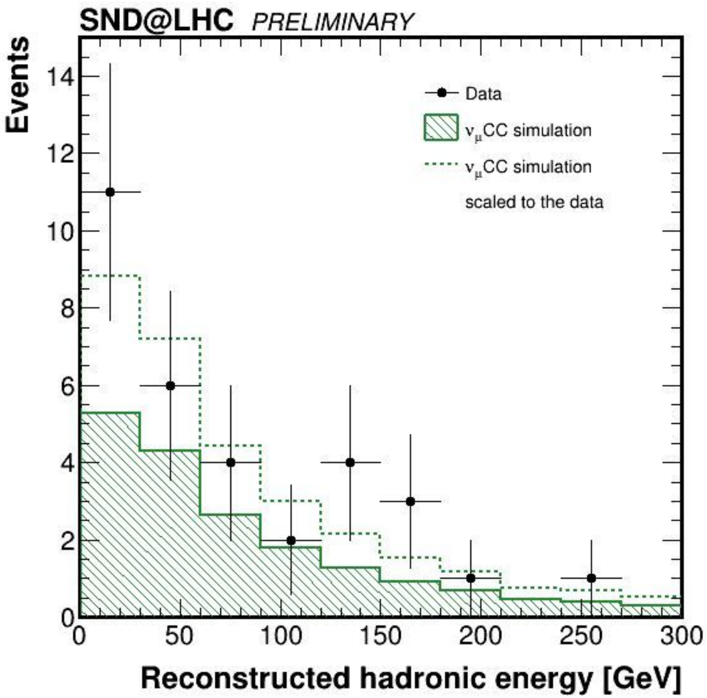
Updated muon neutrino results

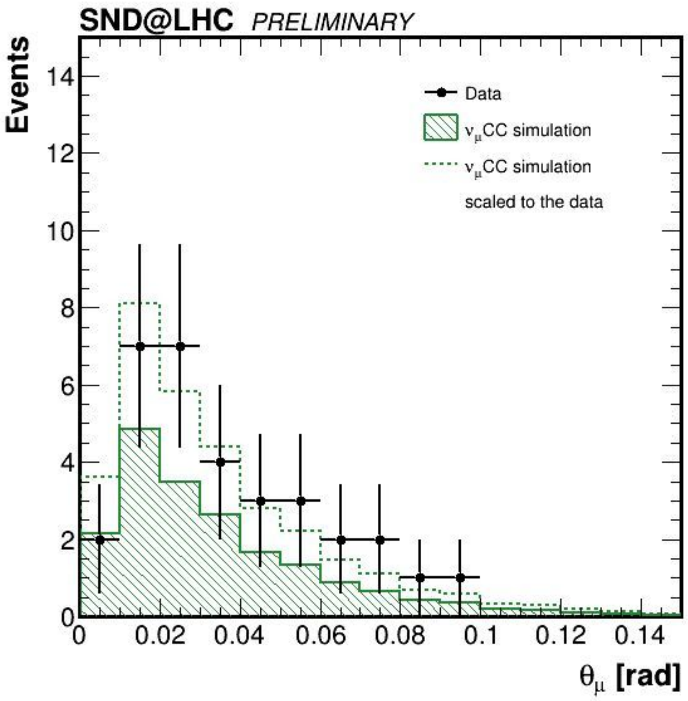
2024

Number of events expected in 68.6 fb^{-1}

- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

Number of events observed: 32





Search for shower-like (0μ) neutrino events

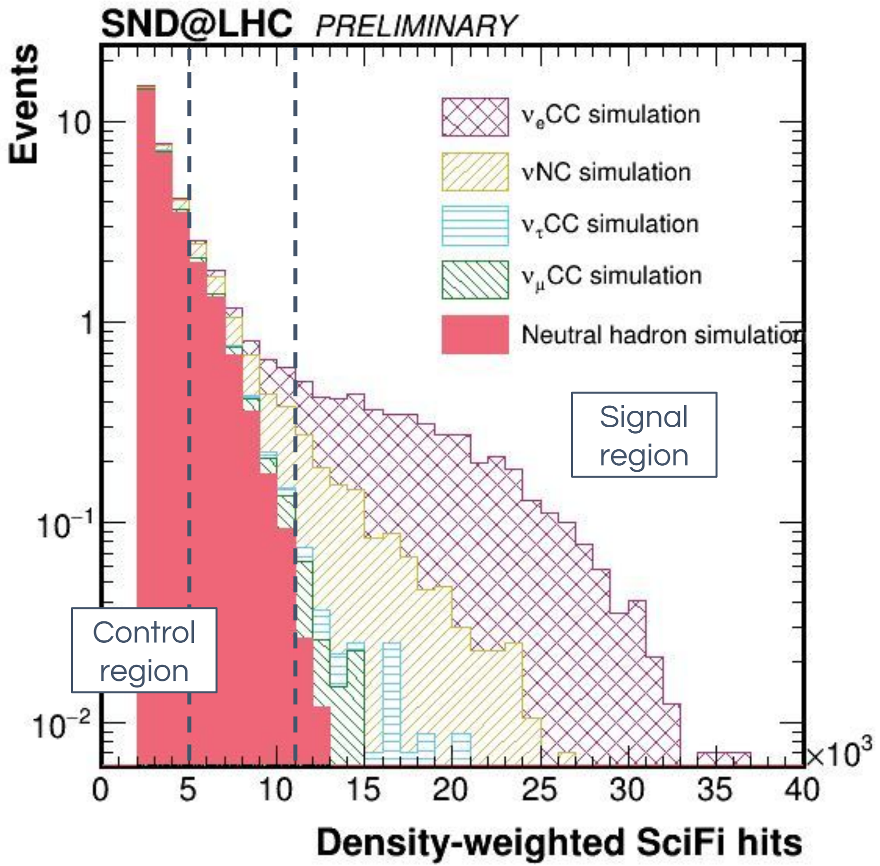
Signal: ν_eCC and NC interactions

Fiducial volume

- No hits in the veto detector.
- Reject side-entering backgrounds.
- Signal acceptance: 12%

0μ neutrino event identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- No hits in last two muon system planes.
  - No reconstructable muon.
- Density-weighted number of hits in most active station > 11x10^3.
  - Optimized for maximum expected significance
- Signal selection efficiency: 42%



Observation of 0μ events in SND@LHC

Neutral hadron background

- Define background-dominated control region.
- Scale the background prediction to the number of observed events in the control region.
    - Observed neutral hadron background is ⅓ of the predicted value.
- Events **expected in signal region : 0.01**

Neutrino background

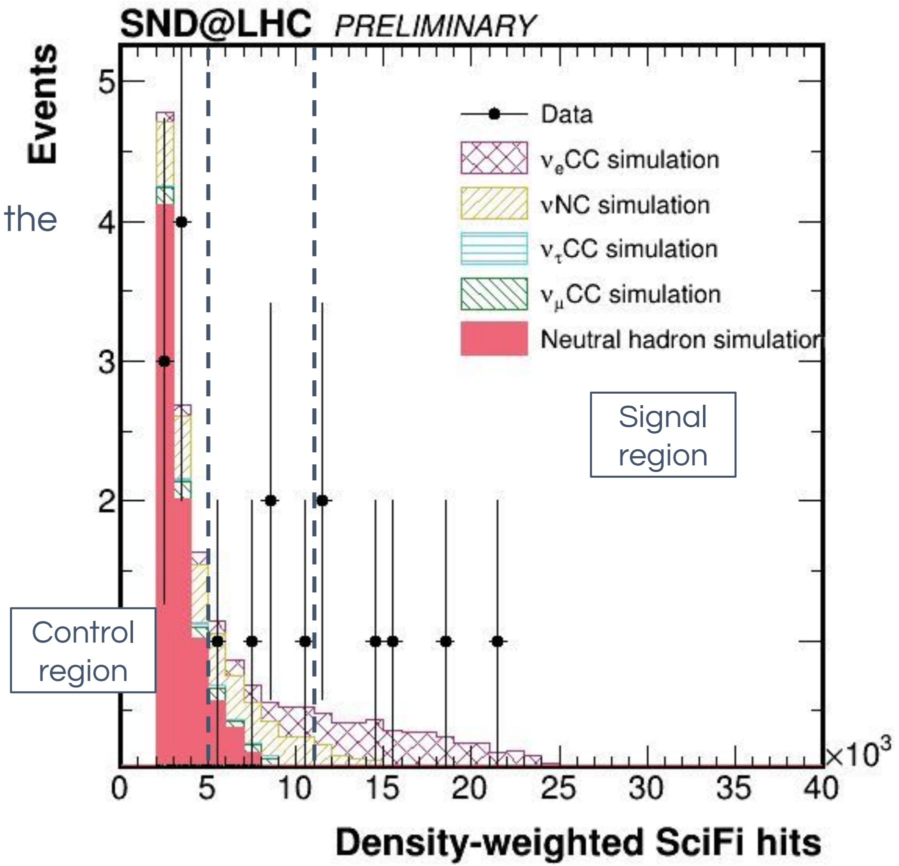
- Muon neutrino CC interactions are the dominant background, with **0.12** expected events.
- Tau neutrino CC1μ interactions expected: 0.002

0μ observation significance

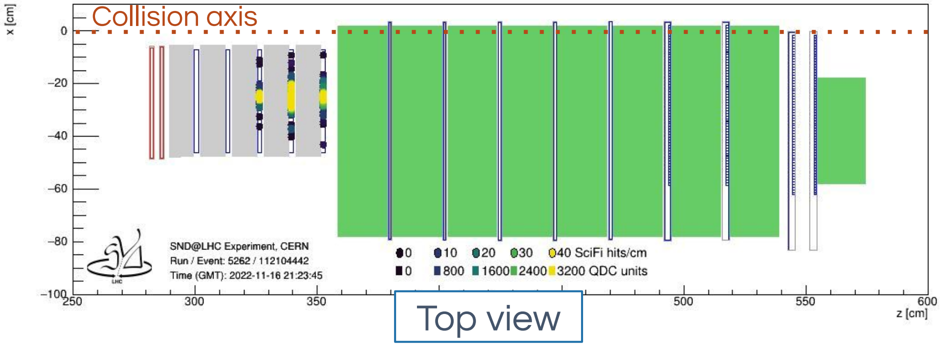
- **Total expected background: 0.13 ± 0.11 events**
- **Expected signal: 4.7 events**
- **Expected significance: 4.9 σ**

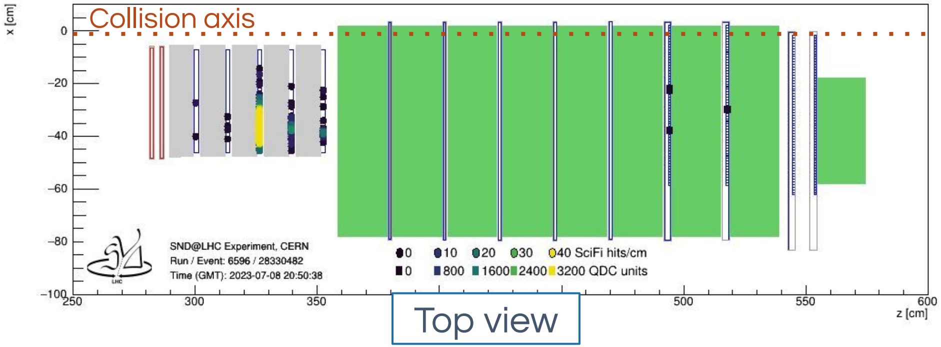
Number of events observed: 6
Observation significance: 5.8 σ

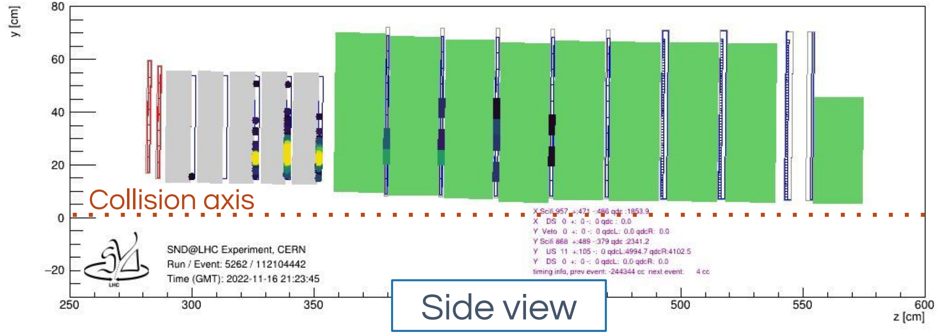
Paper in preparation

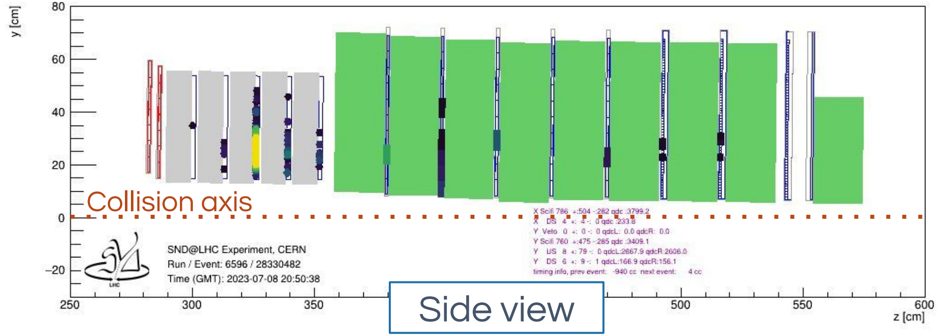


0μ neutrino candidates









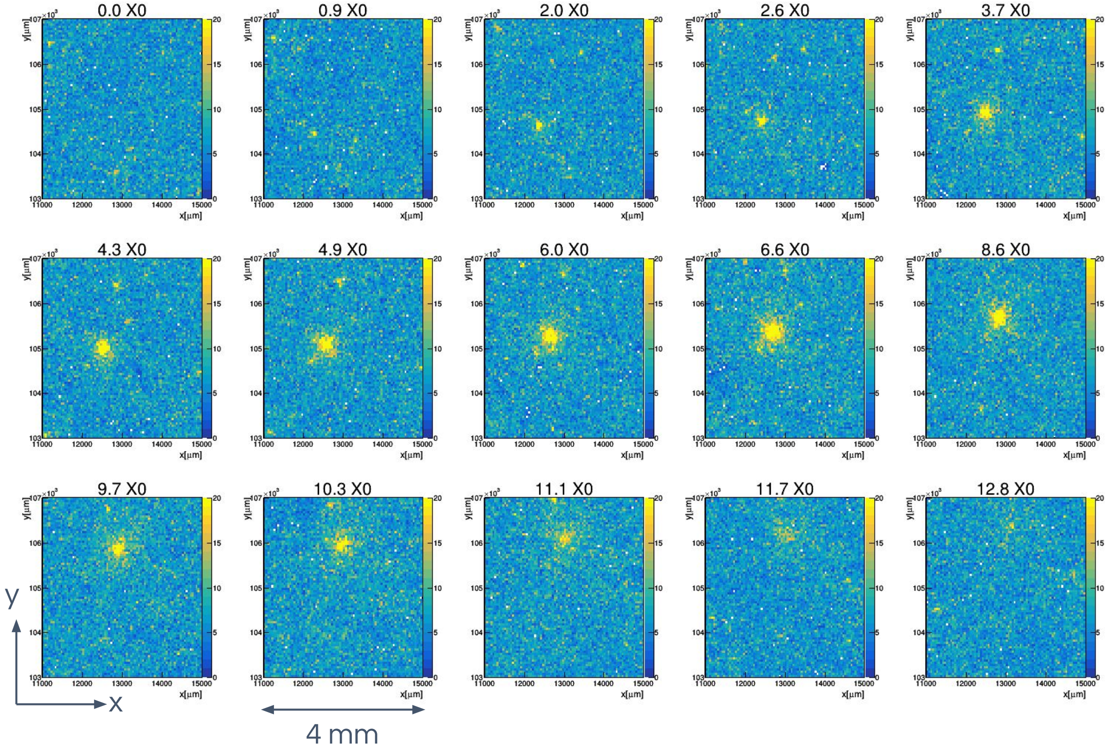
Search for ν_eCC interactions in the emulsion data

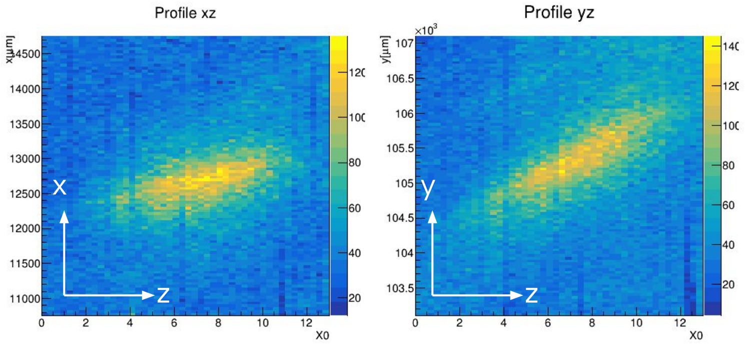
Strategy

- Identify regions of high track density in the emulsions.
- Consistent with the expectation of electromagnetic shower development.
- Search for neutral vertices associated to identified showers.

Status

- Electromagnetic shower patterns identified.
- Vertex association ongoing.





Detector upgrades in 2024

Veto detector upgrade

- Installed a 3rd plane veto plane in the detector.
  - Additional redundancy to mitigate the impact of detector inefficiency.
- Floor was excavated so that veto system could be lowered.
  - Better coverage of the target.
- This upgrade will allow for a significant increase of the fiducial volume used in neutrino data analyses.

New muon telescope

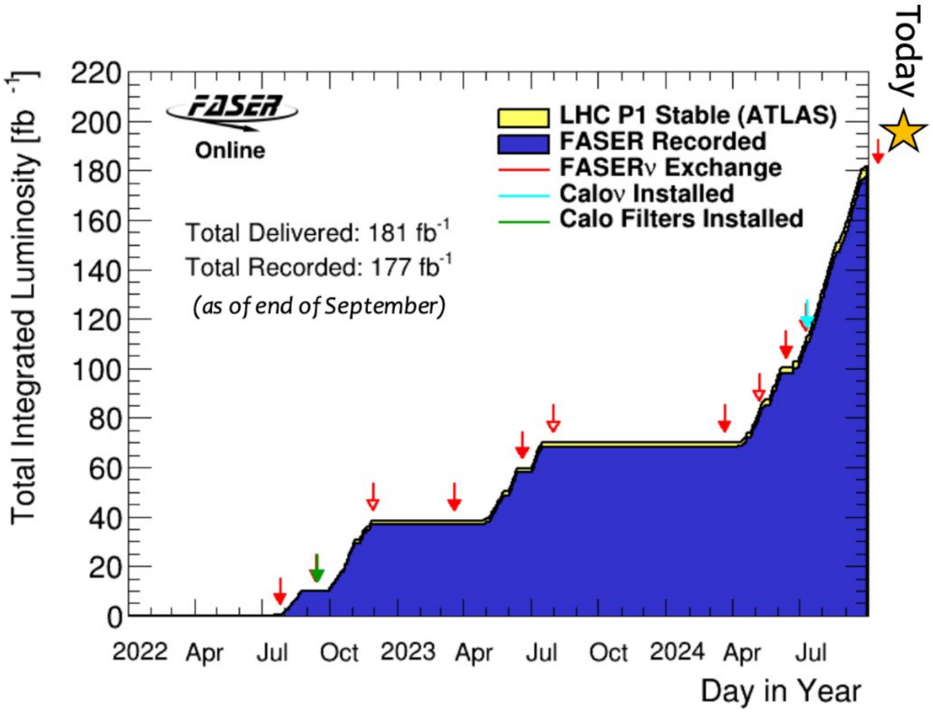
- Technology demonstrator: sealed resistive-plate chambers.
- Will allow for measuring the muon flux outside of the SND@LHC acceptance.
  - Further validation of the background model.

FASER

Anna Sfyrla
LHC seminar 15/10/24

FASER Data

- Recorded 98% of delivered lumi
- Dead-time of < 3 %
- Tiny data loss due to specific operational issues
- **Two-shifter operational model**
  - One run manager / week
  - One monitoring shifter / week
  - No control room - all **remote,** counting on **automated** alarms & mattermost



Results use various chuncks of data depending on availability / conditions

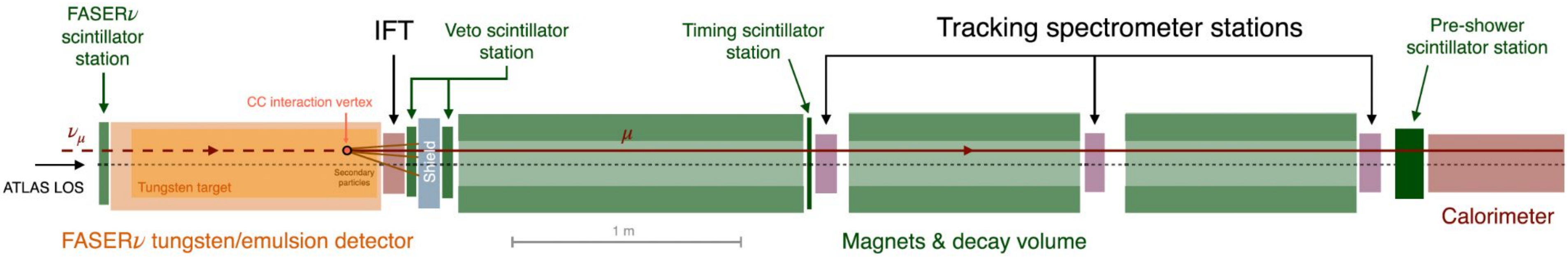
Search for ν_μ events in FASER

2023

Phys. Rev. Lett. 131, 031801

- 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

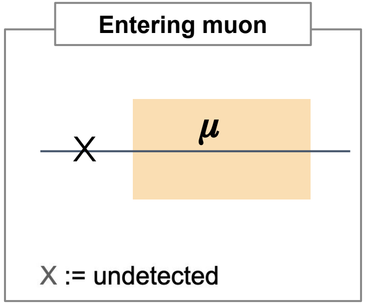
Number of ν_μ CC events expected in 35.4 fb^{-1} after cuts: 151 ± 41

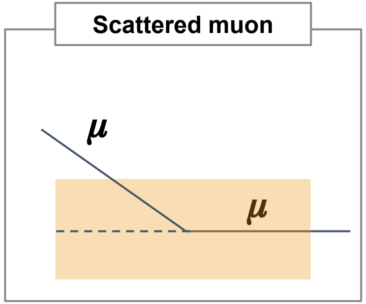


FASER backgrounds

2023

Phys. Rev. Lett. 131, 031801





Entering muons

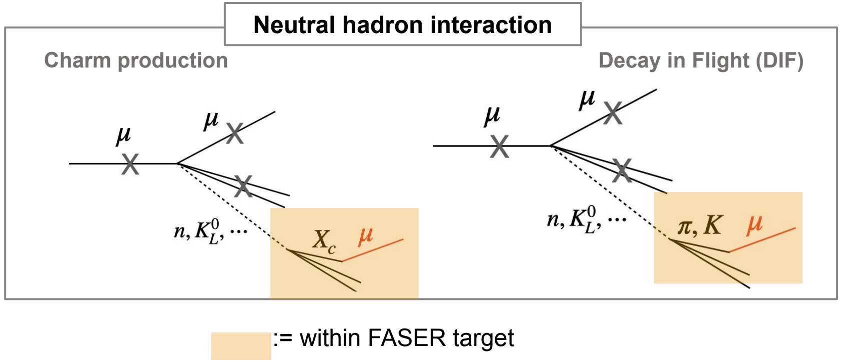
- Incoming muon track missed due to detector inefficiency.
- Expect (3.7 ± 2.5) x 10^{-7} events.
    - Estimated from events with only one scintillator plane firing.

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 ± 0.06** events.

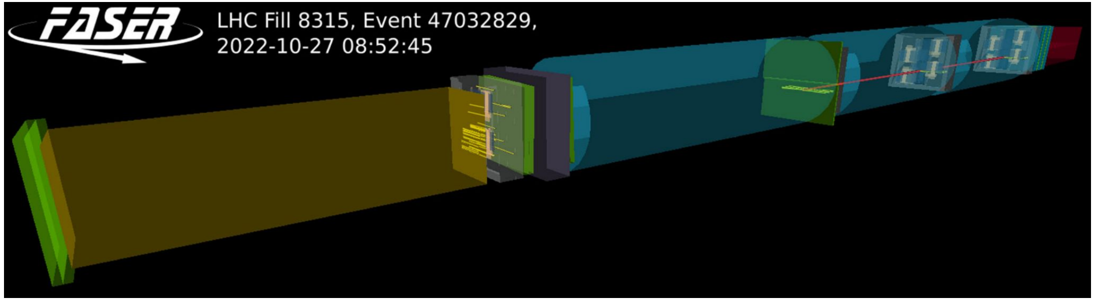


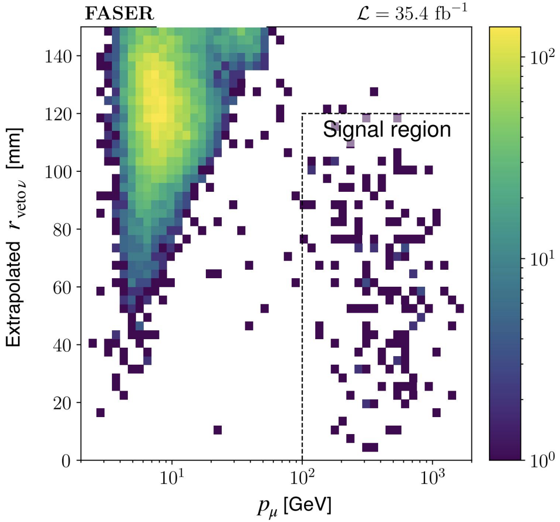
FASER neutrino observation

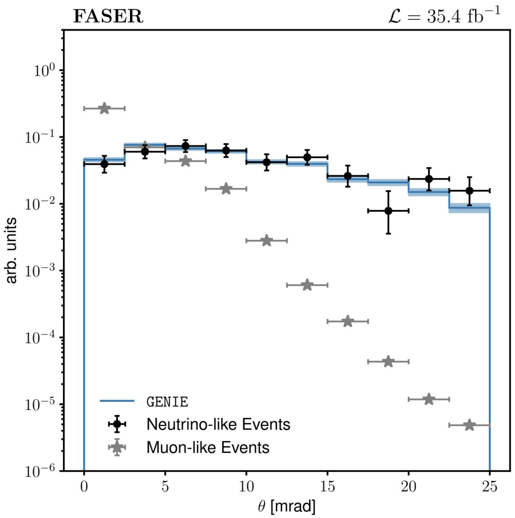
2023

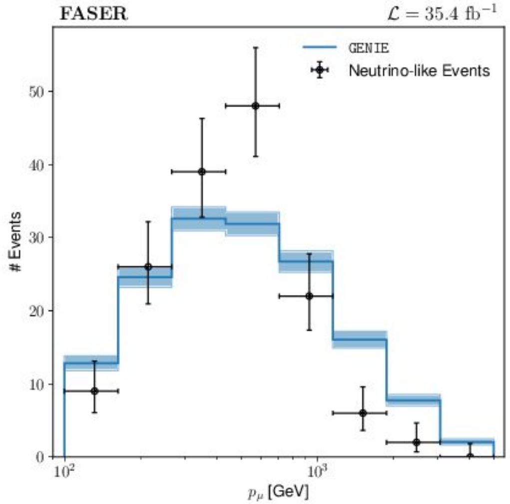
Phys. Rev. Lett. 131, 031801

Observed 153 neutrino event candidates with a statistical significance >> 5 σ





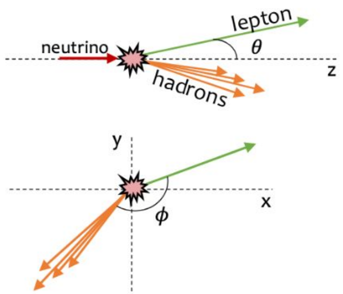




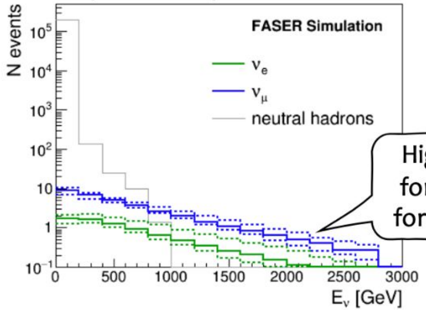
Also reported by FASER: limits on **dark photons** and **axion-like particles**.

Search for neutrinos in FASERν

High purity selection
Vertex reconstruction ($N_{track} \geq 5$, $N_{track}(\tan\theta \leq 0.1) \geq 4$)
E_e or p_μ >200 GeV
$\tan\theta_e$ or $\tan\theta_\mu$ >0.005
ϕ>90°



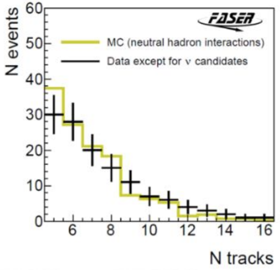
Expected spectra

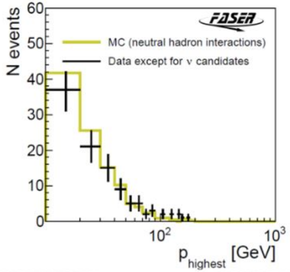


Higher energy for signal than for background

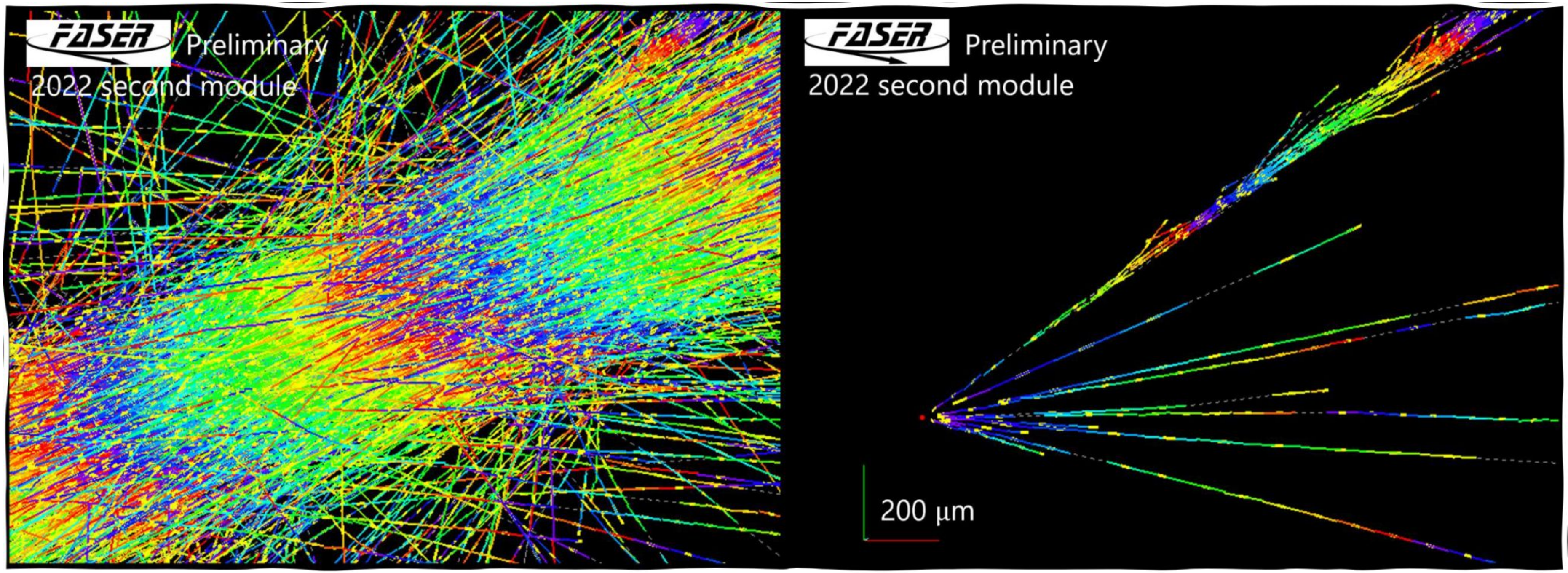
Main background: neutral hadrons interacting with detector. Also some NC interactions for ν_μ.
Estimate from simulation and validate it using lower energy vertices

	Expected background	Expected signal
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4





Electron neutrino event selection



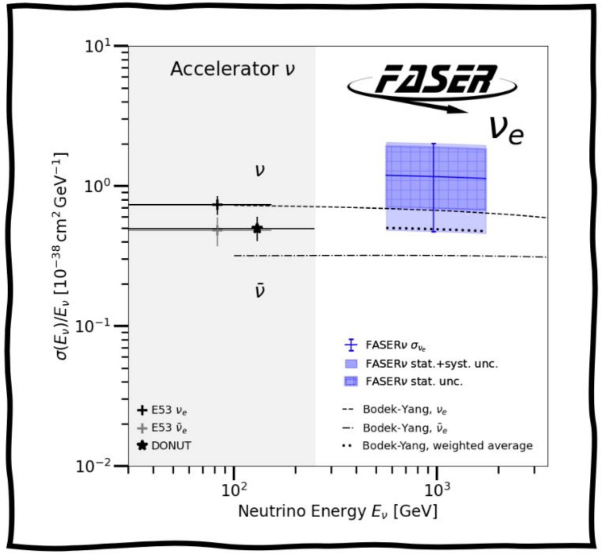
~2.4 x 10^4 tracks / cm^2 / fb^{-1}
10 fb^{-1} integrated

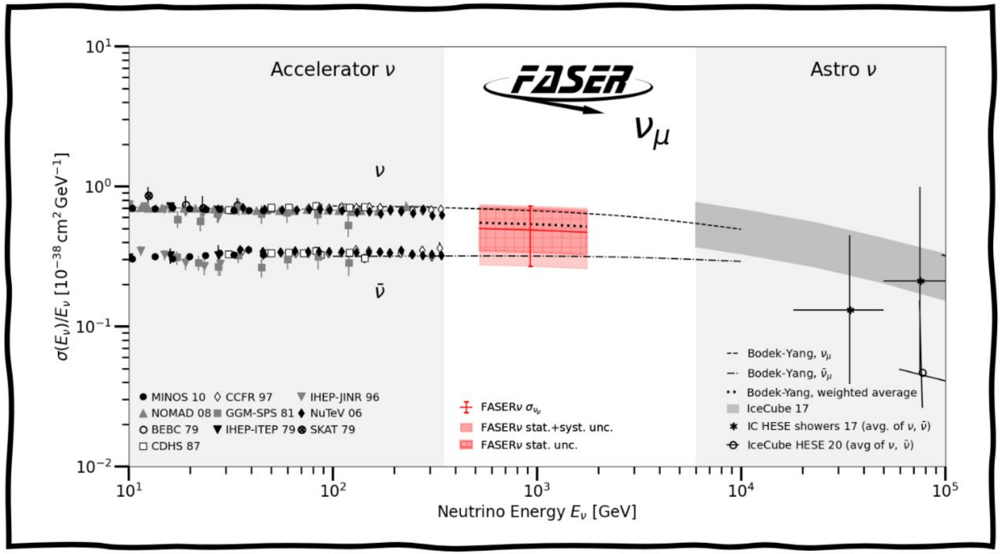
FASERν results

Phys. Rev. Lett. 133, 021802

Anna Sfyrla
LHC seminar 15/10/24

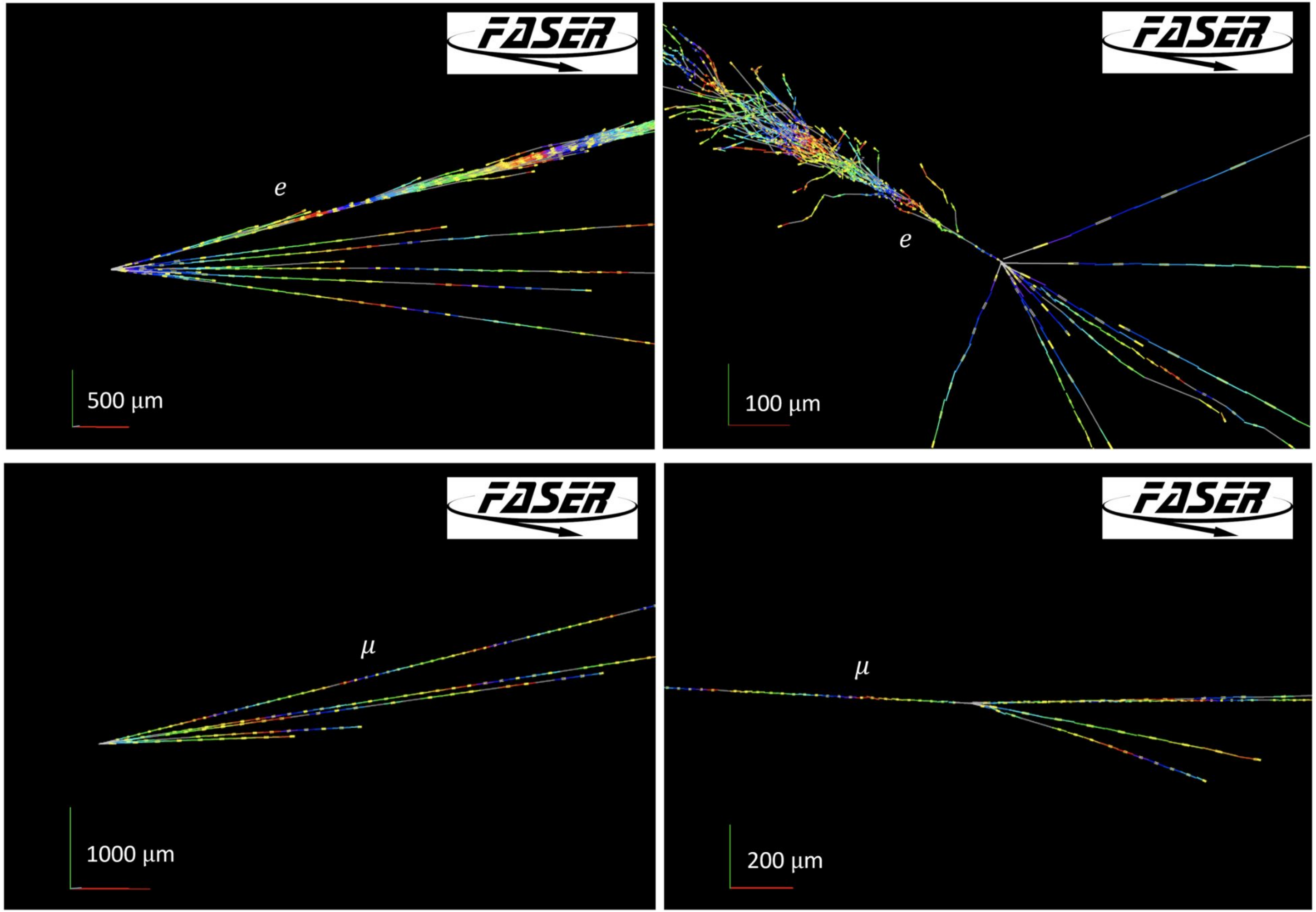
	Expected background	Expected signal	Observed	Significance
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	4	5.2σ
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	8	5.7σ





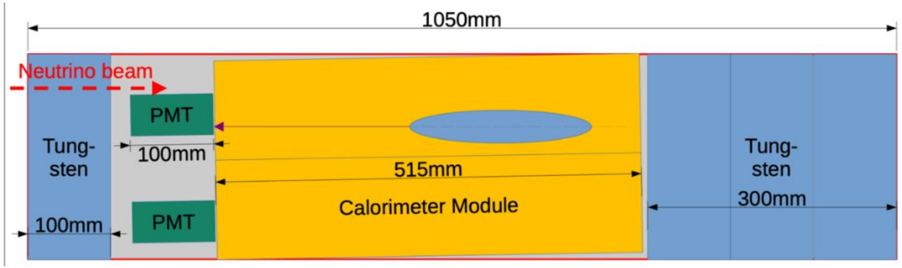
Electron neutrino candidate

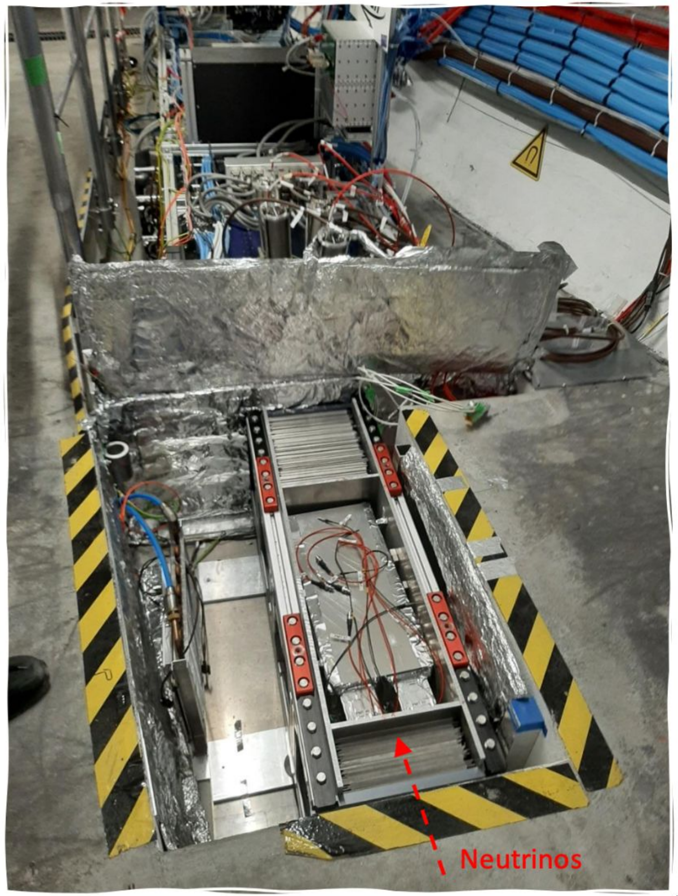
Muon neutrino candidate



CaloNu

- Increased muon background in 2024 made it impractical to install FASERν emulsion for most of the year
- In order to try to keep ***some*** sensitivity to electron neutrinos decided to install spare calorimeter modules in FASERν box for period when emulsion not installed
- Can potentially allow for electronic detector neutrino physics
- Detector replaced by FASERν box for last part of 2024 data-taking



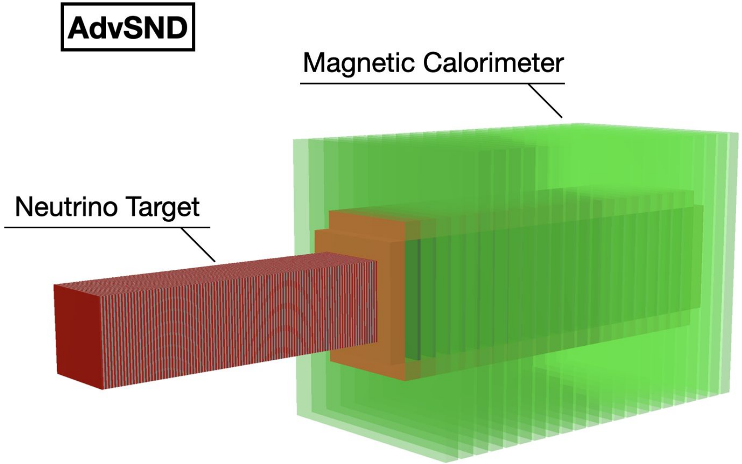


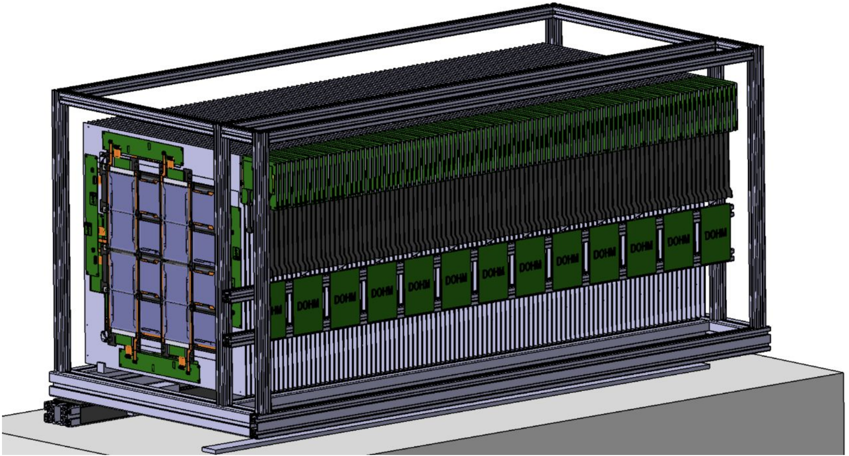
Beyond Run 3

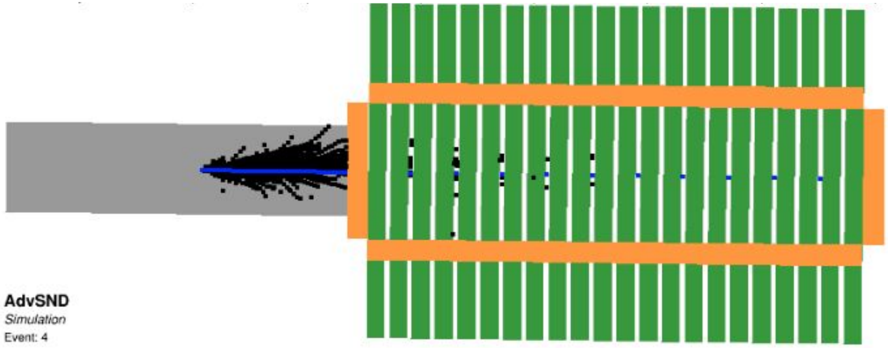
SND@LHC Run 4 upgrade: AdvSND

CERN-LHCC-2024-007 CERN-LHCC-2024-014

- Silicon strip detector.
- Neutrino target:
  - Finer sampling, tungsten.
- Calorimeter / muon detector:
  - Coarser sampling, magnetized iron.
- Synergy with detector development for the SHiP experiment.
  - Approved this year: NA67.

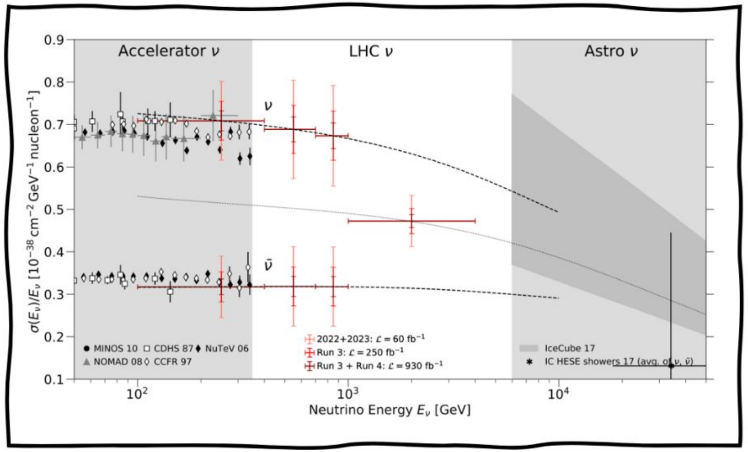




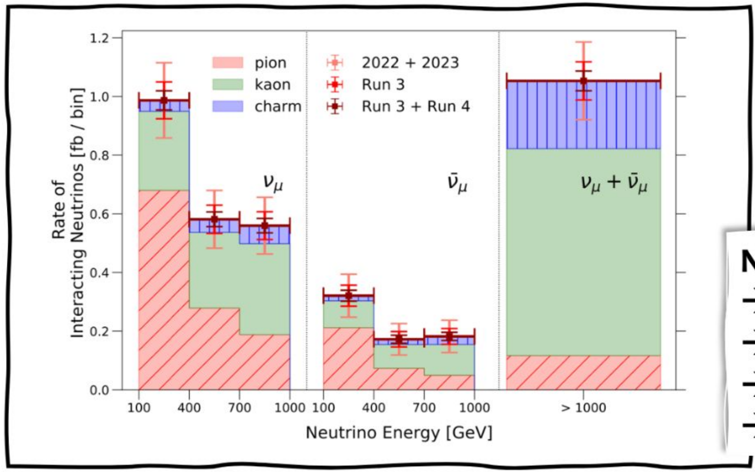


FASERν in Run 4

- High muon rate due to higher luminosity might lead to too frequent FASERν replacements
  - *No concrete FASERν plans yet for Run 4*
- **Still: interesting neutrino physics expected with electronic detector**
- Explorations for minimal detector additions ongoing



CERN-LHCC-2023-009



Neutrino flux measurement

→ Indirect constraints to forward production of hadrons
→ Probes QCD in novel kinematic regimes
→ Broad implications even in astroparticle physics
→ ***Still limited stats in Run 4 FASER***

Dedicated Forward Physics Facility proposed to host future far forward experiments at the LHC.

Summary

- **Neutrinos** produced in **proton-proton collisions** have been observed for the first time!
  - Neutrino measurements 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** needed to deal with high rates.