



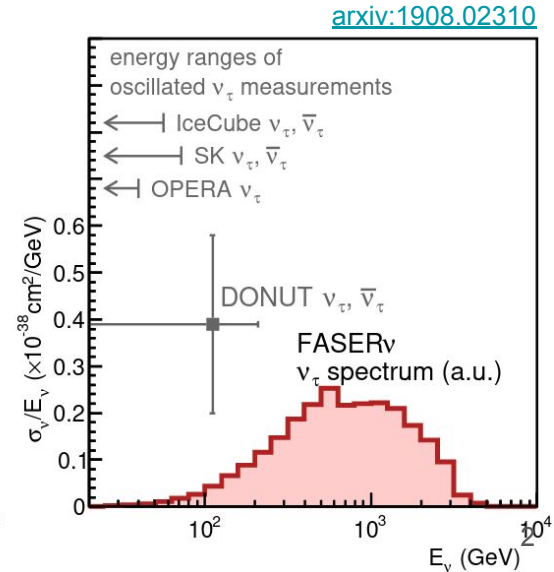
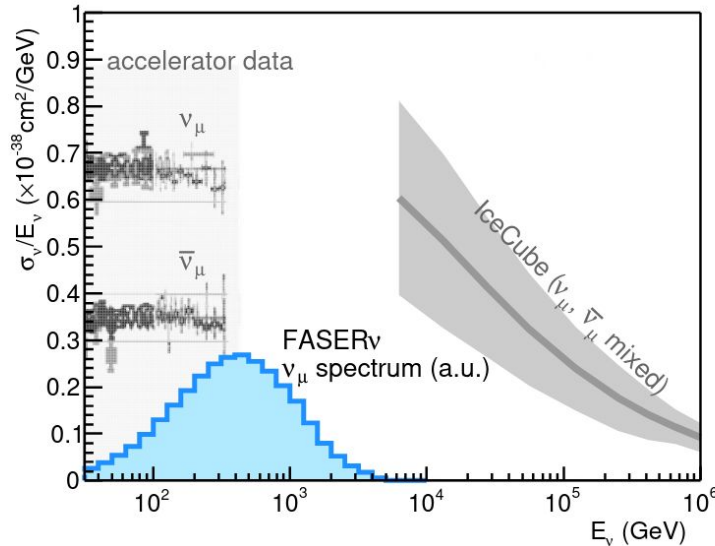
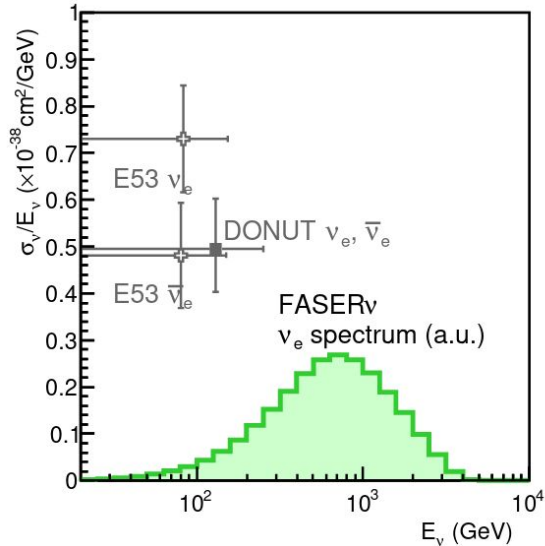
# Search for Collider Neutrinos with FASER

Particle Physics Seminar, 04.05.2023  
Tobias Böckh



# Collider Neutrinos

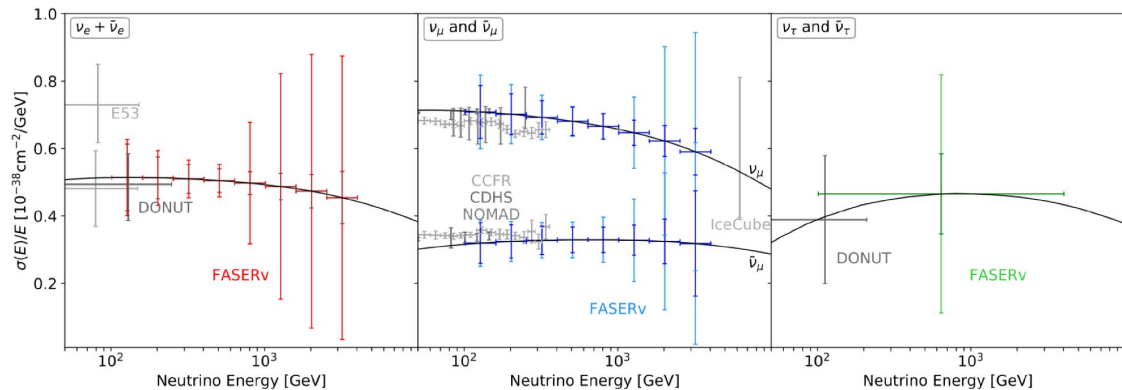
- Observed neutrinos from a variety of sources:  
nuclear reactors, fixed-target experiments, cosmic rays, sun, earth, supernovae, ...
- Neutrinos produced copiously at hadron colliders, but no direct observation yet!
  - Neutrinos interact only weakly
  - Highest energy neutrinos produced in forward direction (parallel to beamline)
- Energy spectrum complementary to existing neutrino experiments



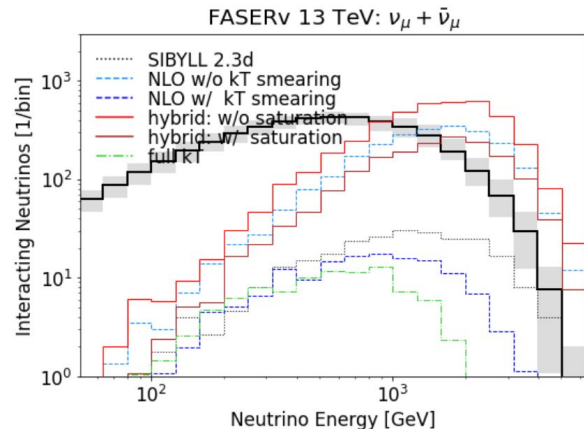
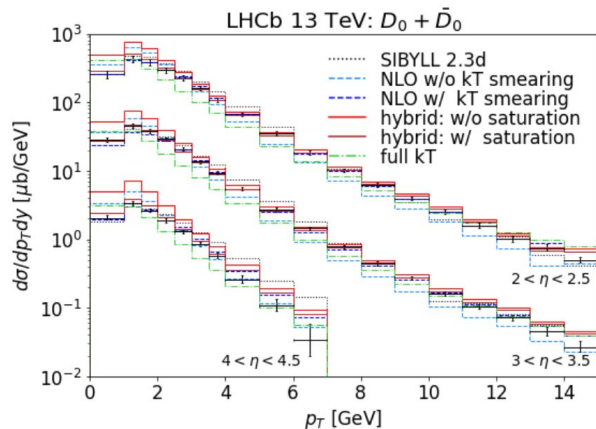
[arxiv:1908.02310](https://arxiv.org/abs/1908.02310)

# Cross Section Measurement

for 35.4 fb <sup>-1</sup>	$\nu_e$	$\nu_\mu$	$\nu_\tau$
Main source	Kaon decay	Pion decay	Charm decay
# Traversing FASER	O(10 <sup>10</sup> )	O(10 <sup>11</sup> )	O(10 <sup>8</sup> )
# Interactions in FASER $\nu$	~200	~1200	~4

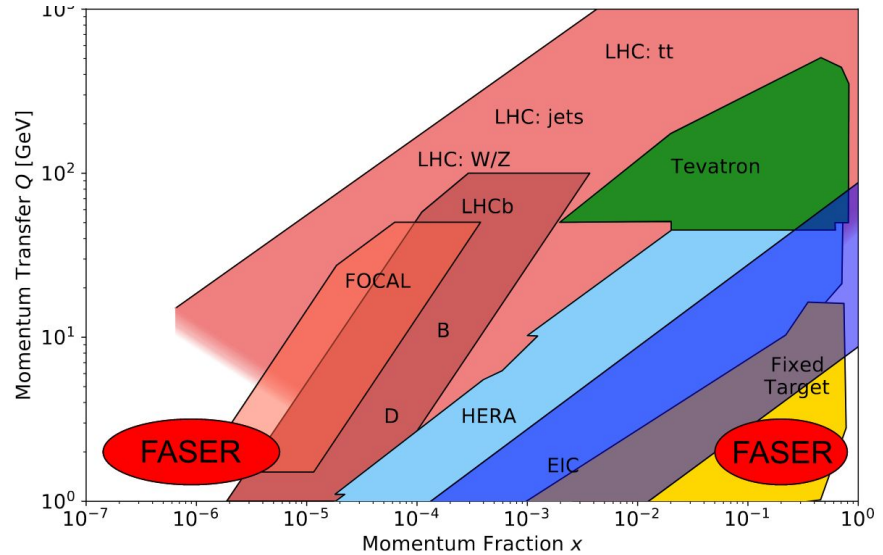
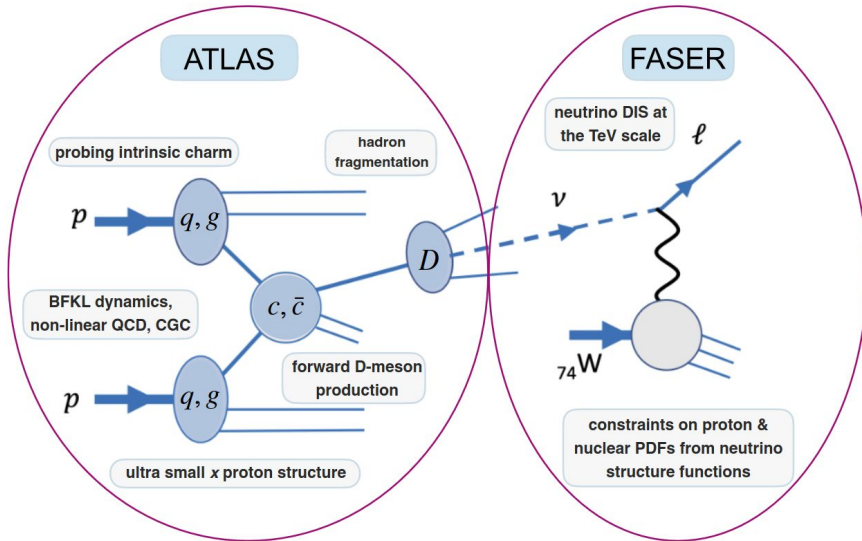
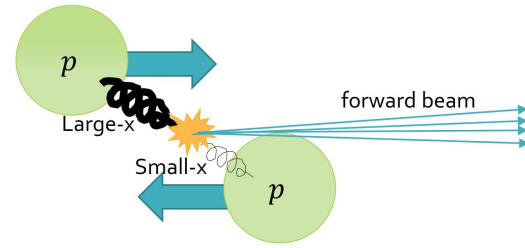


- test Monte Carlo generators and perturbative QCD at large  $\eta$



# QCD Studies

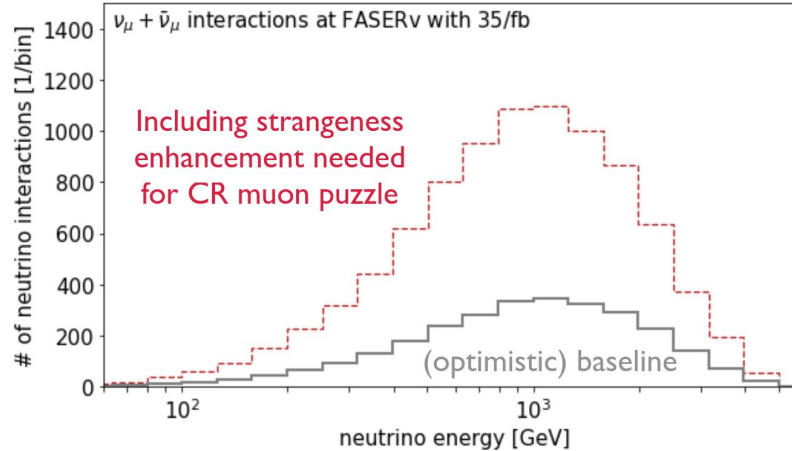
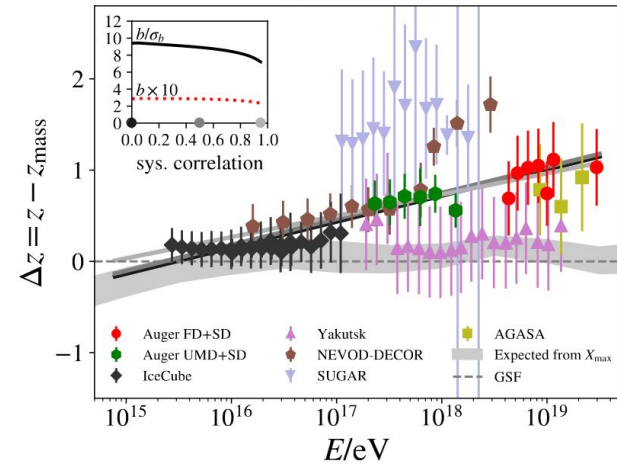
- Measure QCD dynamics at low- $x$  and high- $x$
- Crucial for any future higher-energy proton-proton collider, e.g. FCC
  - standard electroweak processes such as  $W$  and  $Z$  production become dominated by low- $x$  dynamics
- Forward Charm Production at high- $x$ 
  - intrinsic-charm component of proton may dominate for forward  $D$ -meson production



# Cosmic Ray “Muon Puzzle”

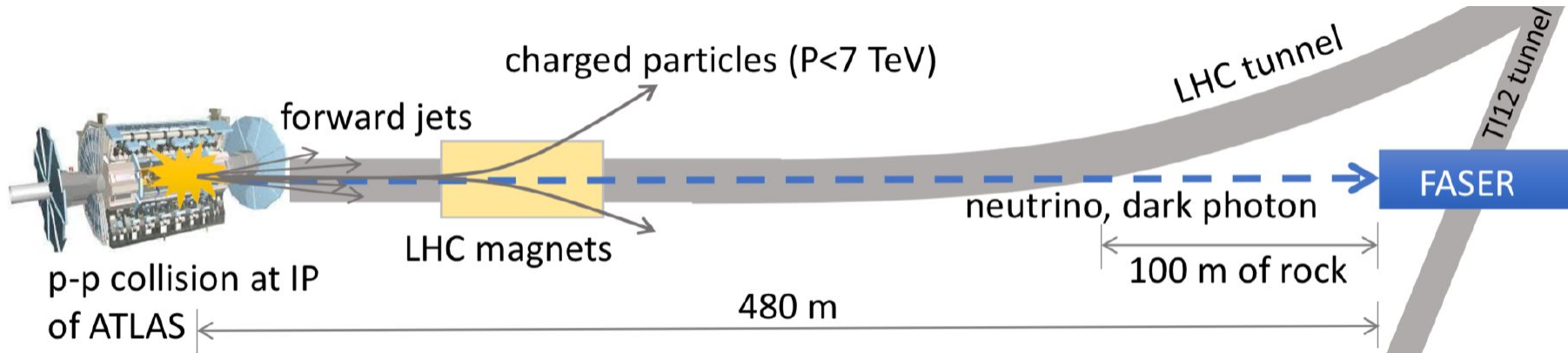
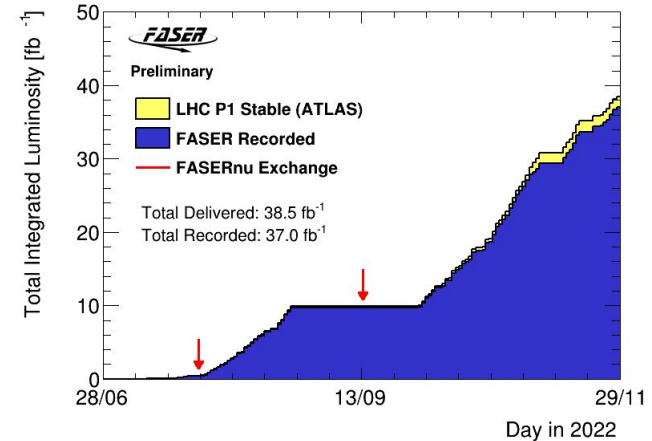
- Excess of muons compared to hadronic interactions models
  - Required to understand the flux composition and origin of the cosmic rays
  - Possible explanation: enhanced forward strangeness production at high energies: expect more Kaons and less Pions
- Huge increase of muon neutrino flux at FASER

EPOS-LHC

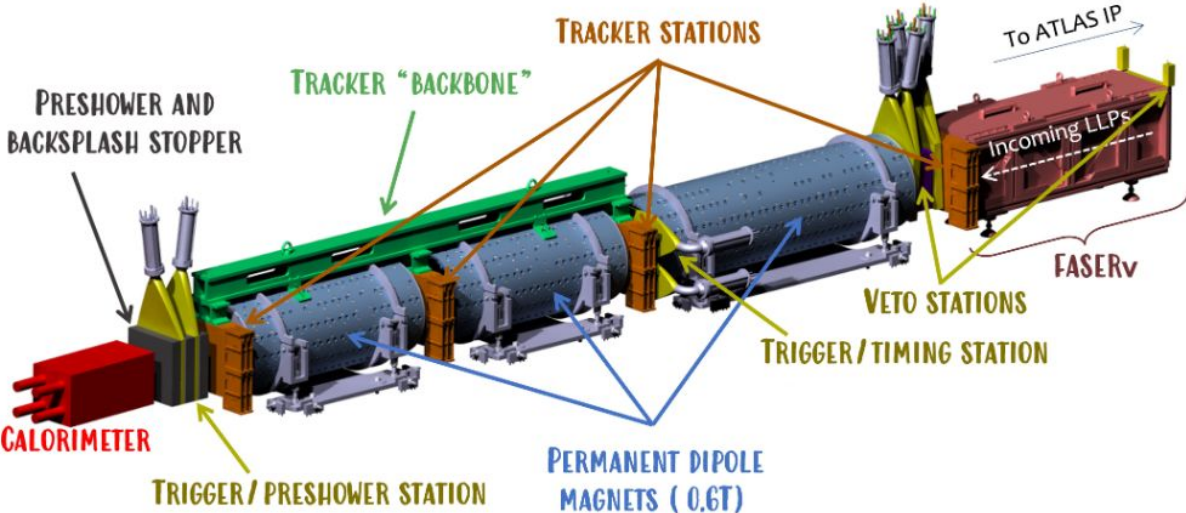


# The ForwArd Search ExpeRiment

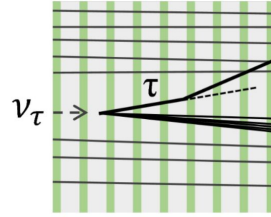
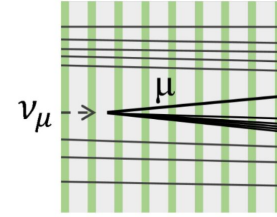
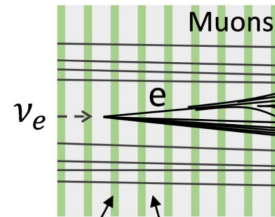
- FASER is new, small experiment at the LHC
  - Constructed and installed in 2019 - 2021
- Located 480 m downstream of ATLAS interaction point
  - Positioned on line-of-sight → cover  $\eta > 9.2$
  - LHC magnets as well 100 m of rock shields most backgrounds
- Targets long-lived particles ( $A'$ , ALPs, ...) and neutrinos
- Successfully operated during all of 2022



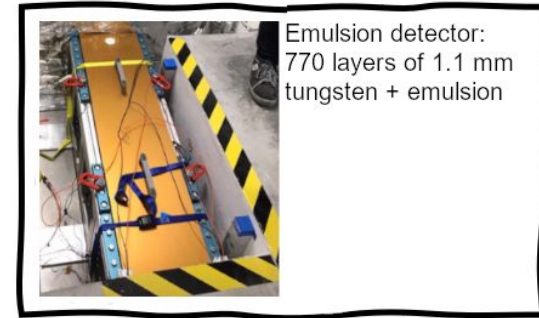
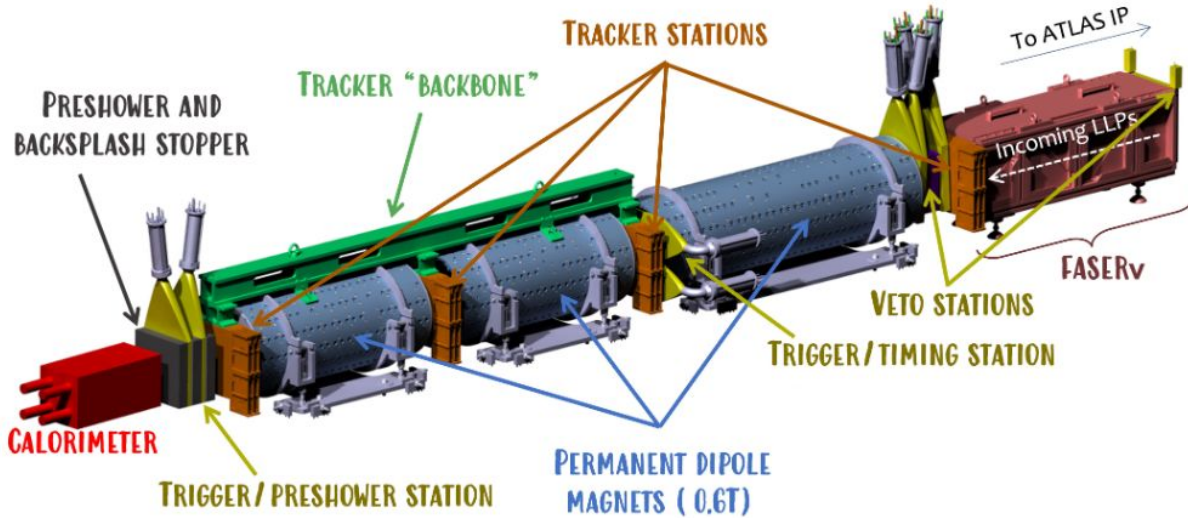
# Detector



# Detector

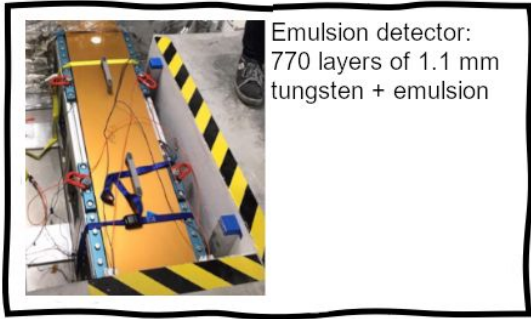
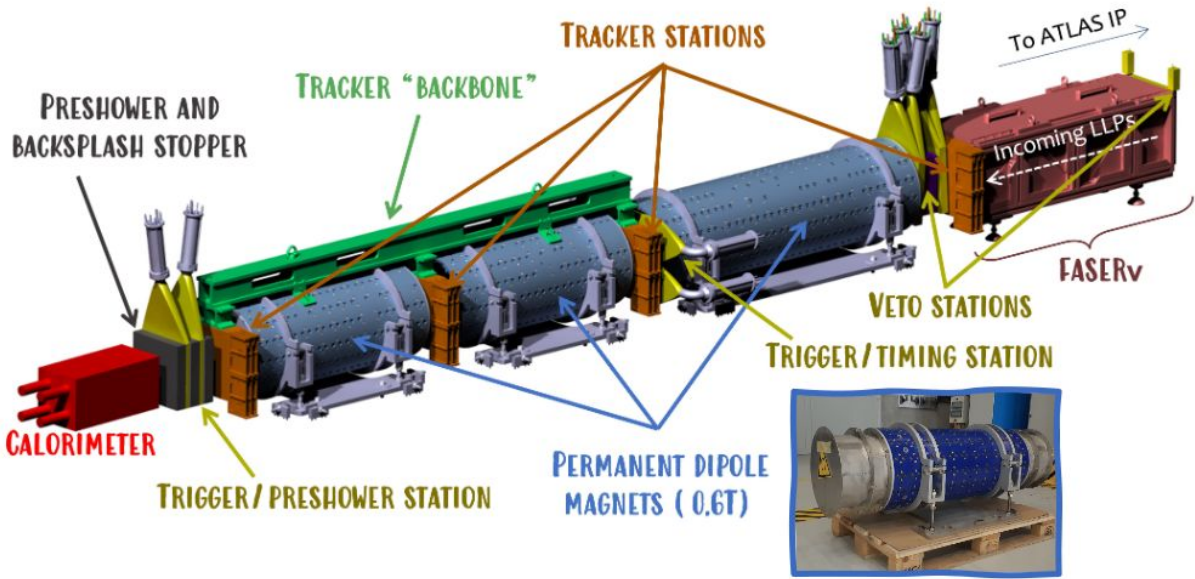


Emulsion film Tungsten plate (1 mm thick)  
(25 cm x 25 cm)

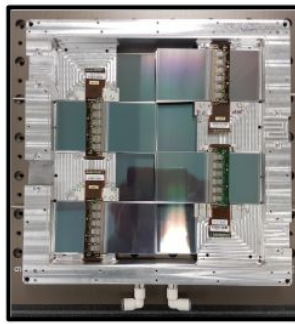




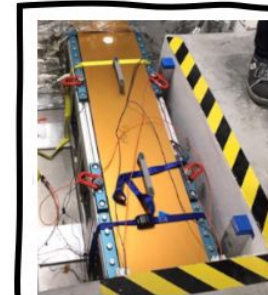
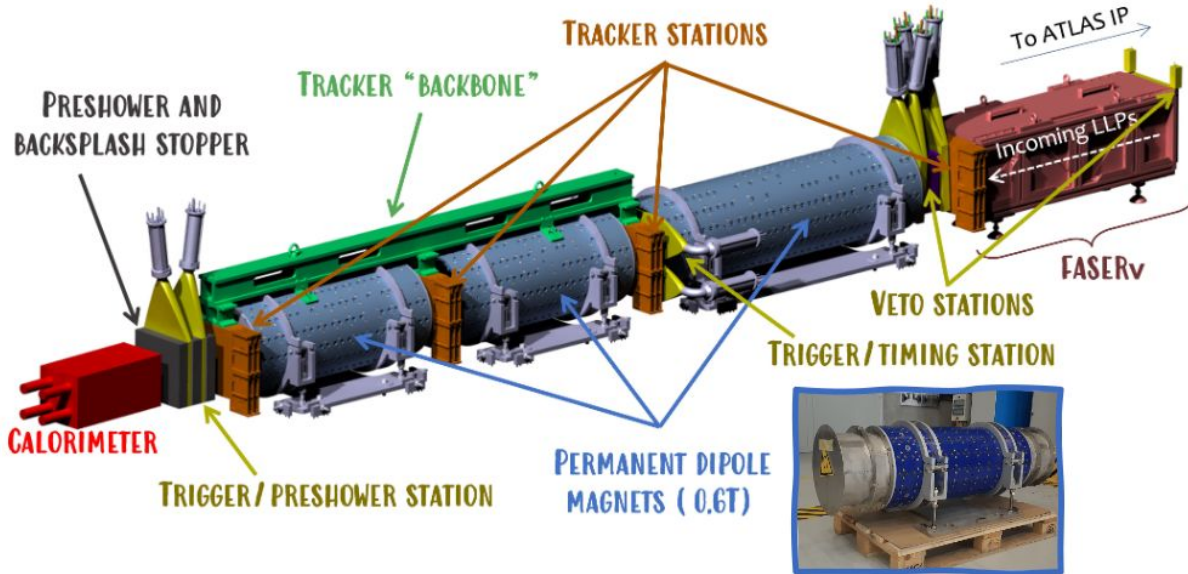
# Detector



# Detector



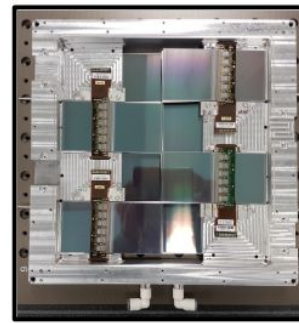
A tracker layer made of ATLAS SCT modules



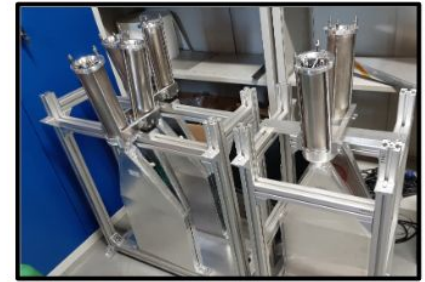
Emulsion detector:  
770 layers of 1.1 mm tungsten + emulsion

# Detector

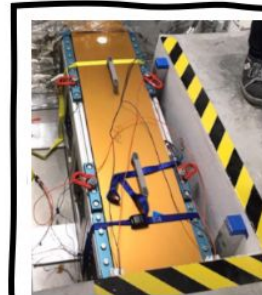
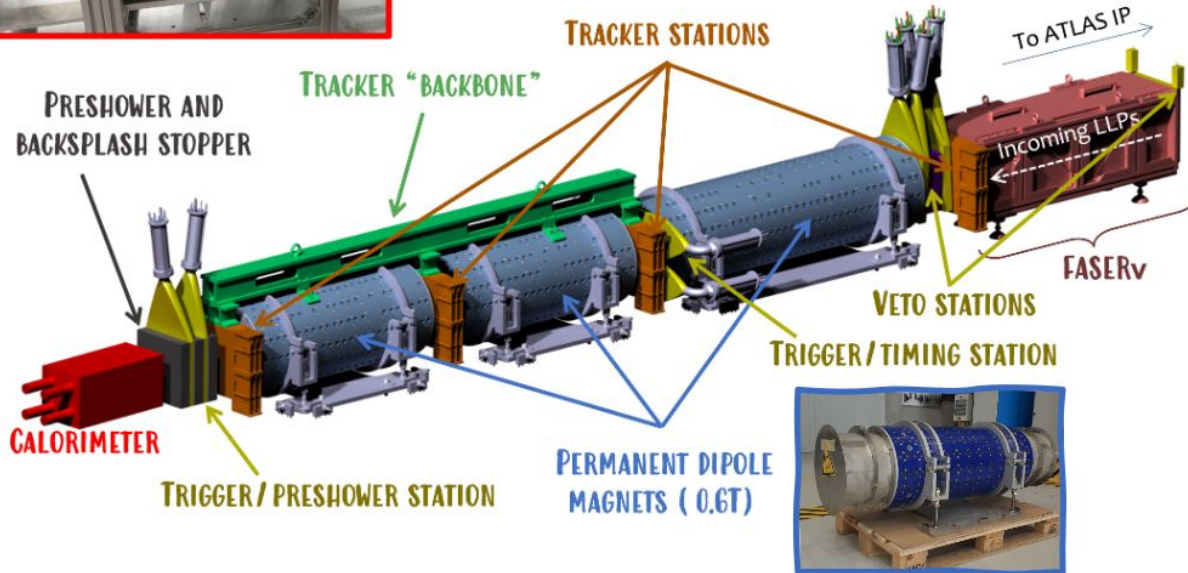
Calorimeter modules (LHCb) mounted in support



A tracker layer made of ATLAS SCT modules



Two stations to veto  $O(10^9)$  muons  
A timing station, resolution  $< 1$  ns  
A preshower station

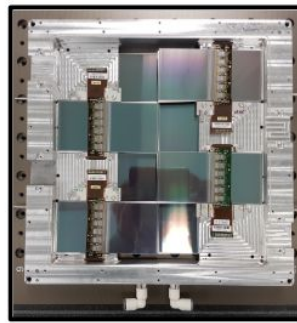


Emulsion detector:  
770 layers of 1.1 mm tungsten + emulsion

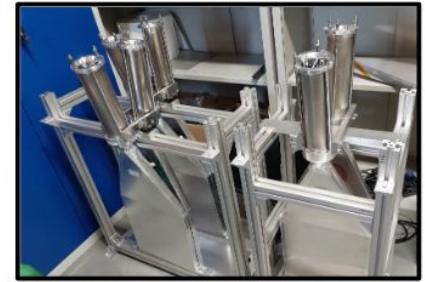
# Detector

[arxiv:2207.11427](https://arxiv.org/abs/2207.11427)

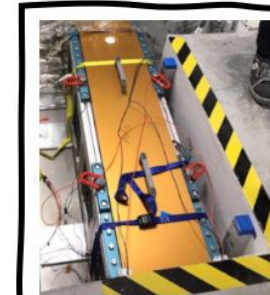
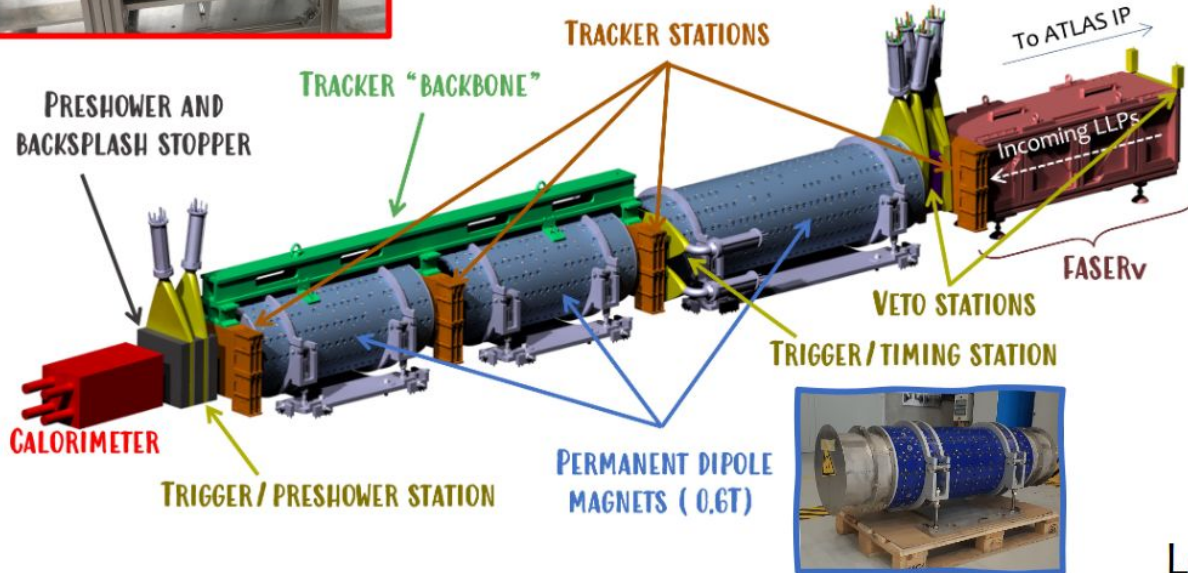
Calorimeter modules (LHCb)  
mounted in support



A tracker layer made of  
ATLAS SCT modules



Two stations to veto  $O(10^9)$  muons  
A timing station, resolution  $< 1$  ns  
A preshower station



Emulsion detector:  
770 layers of 1.1 mm  
tungsten + emulsion



Length: 7 m

Aperture: 20 cm

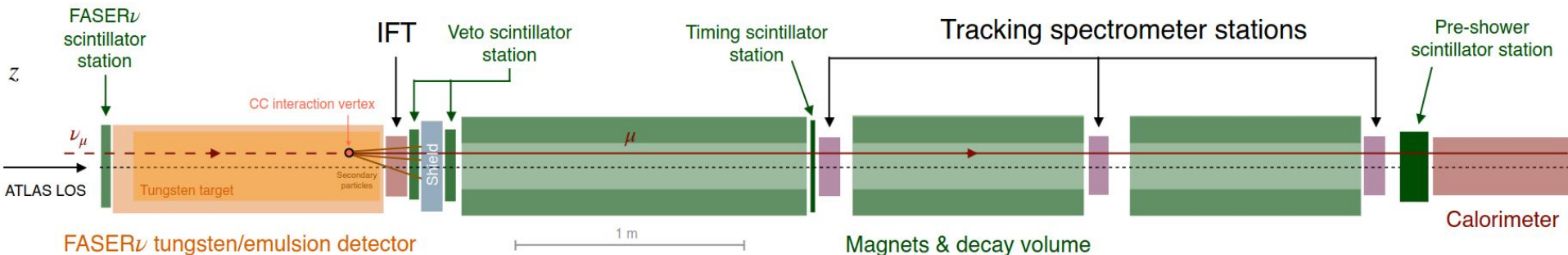
Length of decay volume: 1.5 m



• Detector installed between March – Nov 2021, ready for LHC run 3

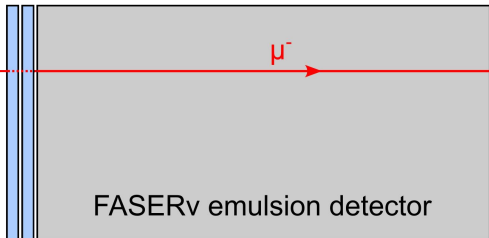
# Neutrino Signature

- Emulsion detector takes time to read out, reconstruct tracks & vertices, analyze data
- Detect CC  $\nu_\mu$  interaction using electronic detectors
  - FASER $\nu$  only used as target
  - Use two layers of front veto station to discard muon background
  - Require signal in other veto stations consistent with muon and good reconstructed track



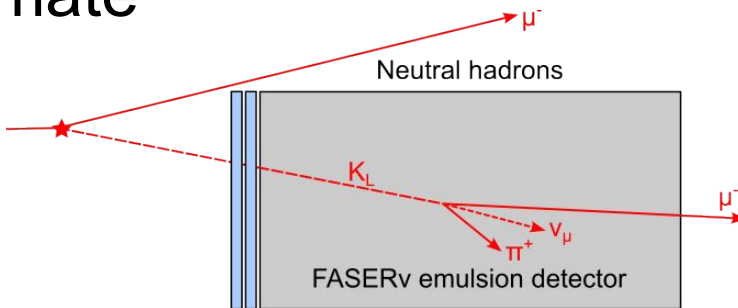
# Background Estimate

Veto inefficiency



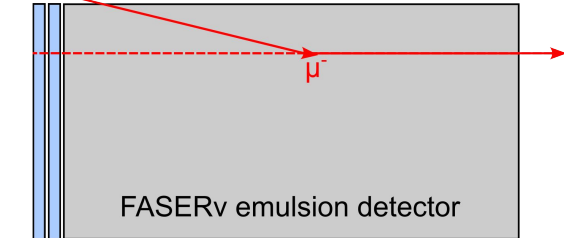
- Estimated from events with just one veto scintillator firing
- Expect  $(3.7 \pm 2.5) \times 10^{-7}$  events

Neutral hadrons

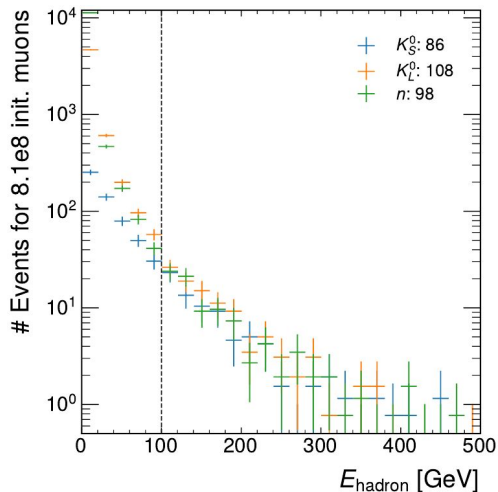


- Expect  $O(300)$  neutral hadrons with  $E > 100$  GeV
- Most neutral hadrons absorbed in tungsten
- Expect about  $0.11 \pm 0.06$  events

Scattered muons

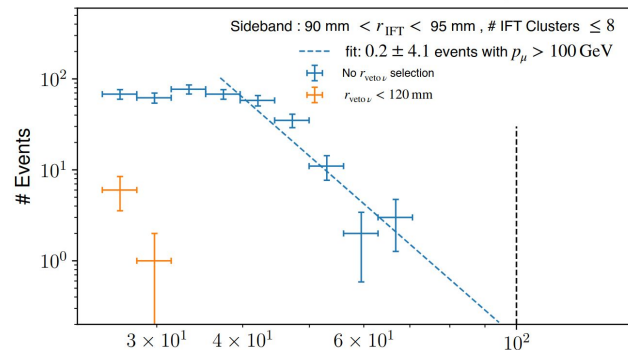


- Estimated from control region ( $90 < r < 95$  mm, # clusters  $\leq 8$ )
- Expect  $0.08 \pm 1.83$  events



FASER

$\mathcal{L} = 35.4 \text{ fb}^{-1}$

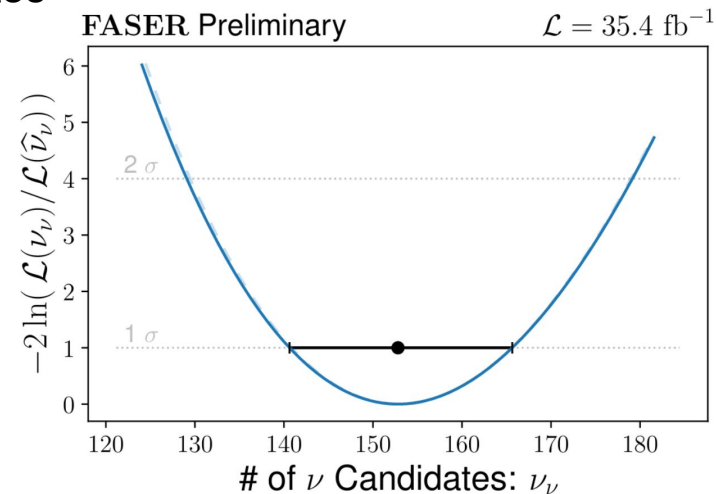


# Neutrino Observation

- Based on simulation expect  $151 \pm 41$  neutrino events
  - no systematic uncertainties from detector response and event selection
- Count number of events with hits in none, one or both front veto layers and Likelihood fit to determine number of signal candidates
- Observe 153 events with no veto signal
- Signal significance of  $16 \sigma$

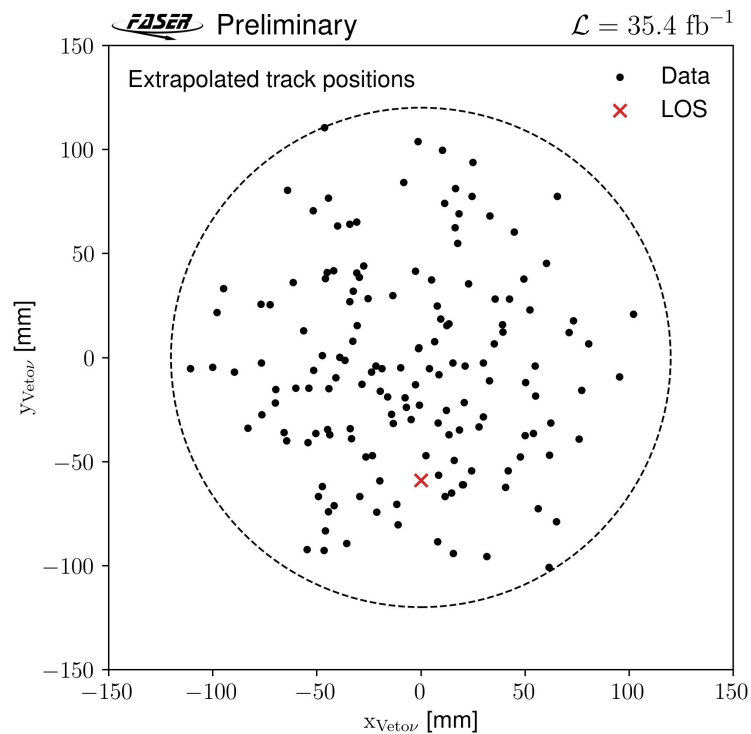
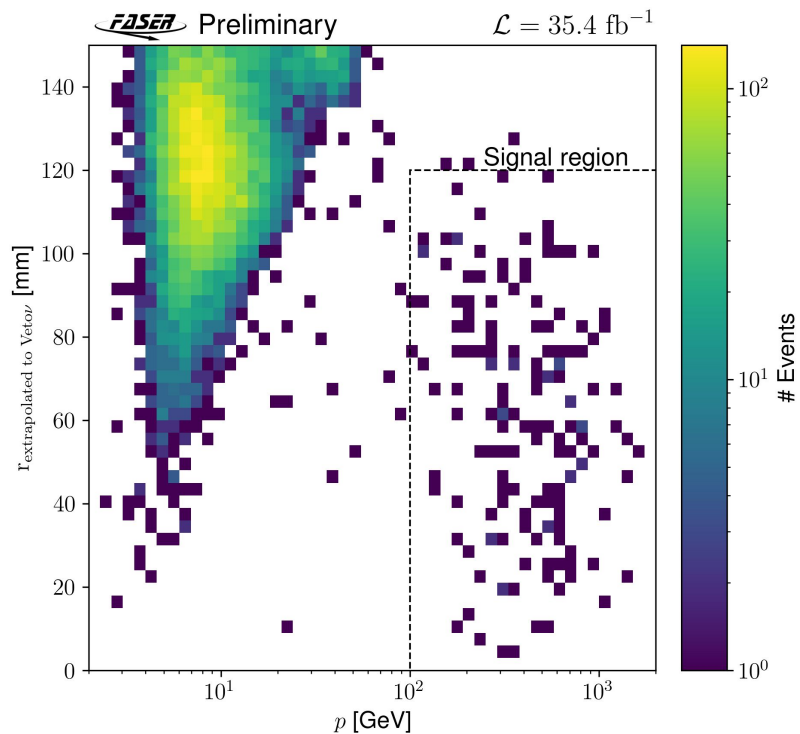
**First direct observation of collider neutrinos!**

Category	Events
$n_0$	153
$n_{10}$	4
$n_{01}$	6
$n_2$	64014695



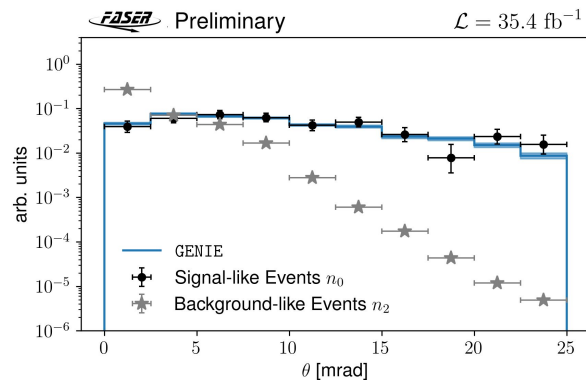
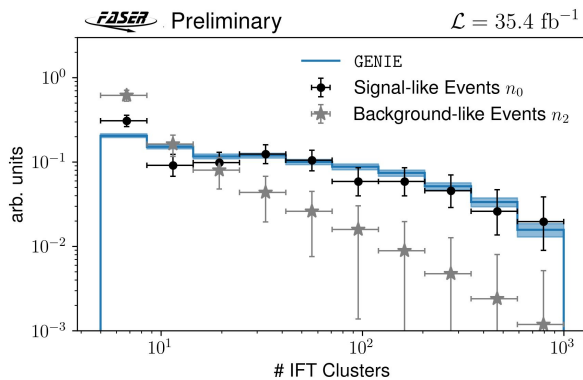
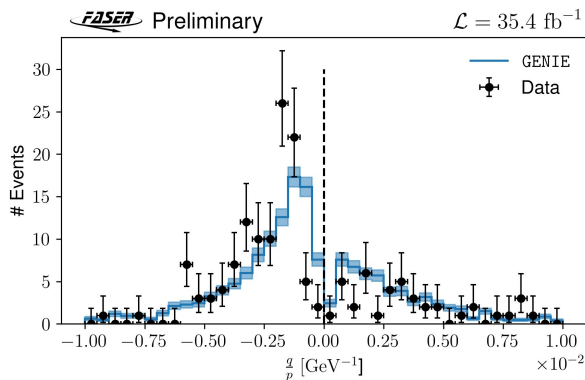


# Neutrino Distributions (1)



# Neutrino Distributions (2)

- More  $\nu_\mu$  than anti- $\nu_\mu$
- Most events at high momentum
- High occupancy in front tracker station
- Large angle  $\theta$



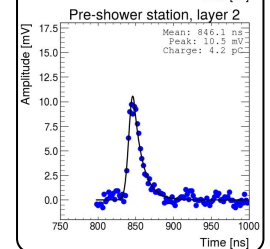
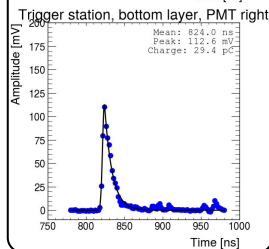
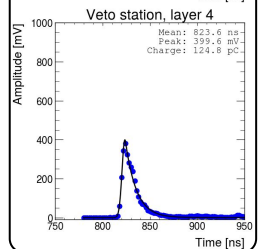
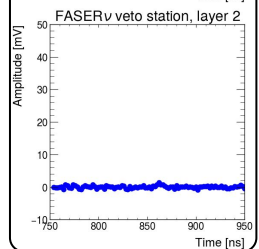
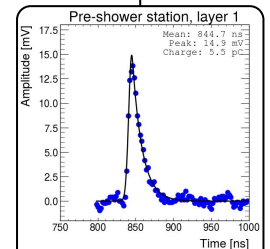
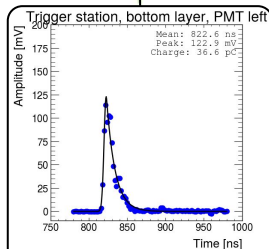
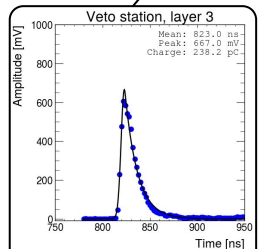
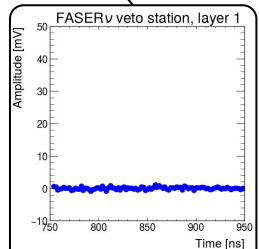
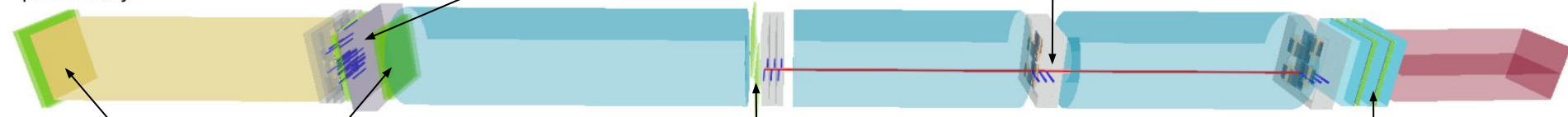
# Event Display

**FASER**  
preliminary

Run 8943  
Event 47032829  
2022-10-27 08:52:45

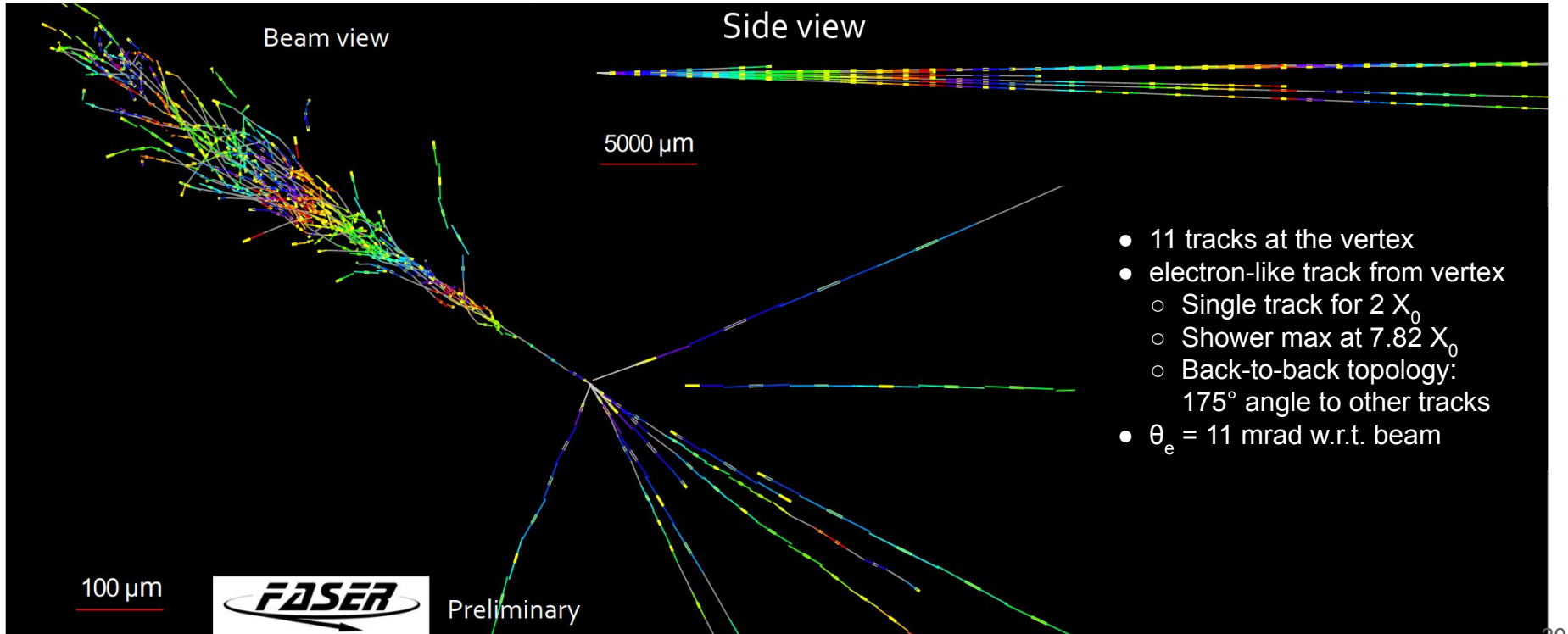
57 IFT Clusters

1 good track with hits in all layers,  
 $p = 843 \text{ GeV}$ ,  $r = 54.6 \text{ mm}$ , charge = -1



# Neutrinos in FASER $\nu$

- Analysis of emulsion detector still ongoing
- Have multiple candidates, including highly  $\nu_e$  like event:



# Summary

- Observed 153  $\nu_{\mu}$  CC interactions
- First direct observation of collider neutrinos!
  - Many neutrinos with large momentum ( $> 200$  GeV)
  - Charge indicates neutrinos and anti-neutrinos
- Plan to measure in neutrino cross section next
- Neutrino candidates from FASER $\nu$  emulsion detector



Run 8943  
Event 2453196  
2022-10-26 20:42:02

