Recent results on LHC neutrinos from the FASER experiment

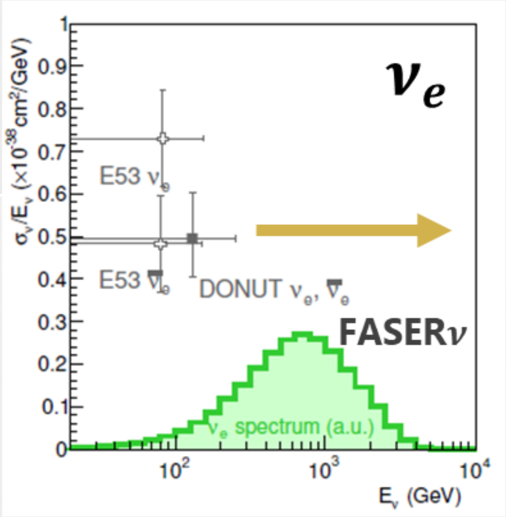
Tomoko Ariga (Kyushu University) on behalf of the FASER Collaboration

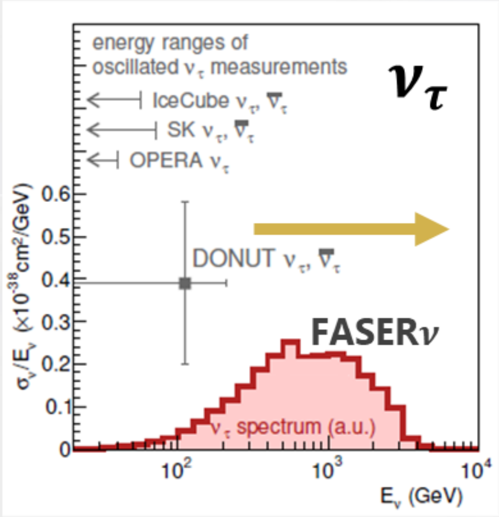
九州大学
KYUSHU UNIVERSITY

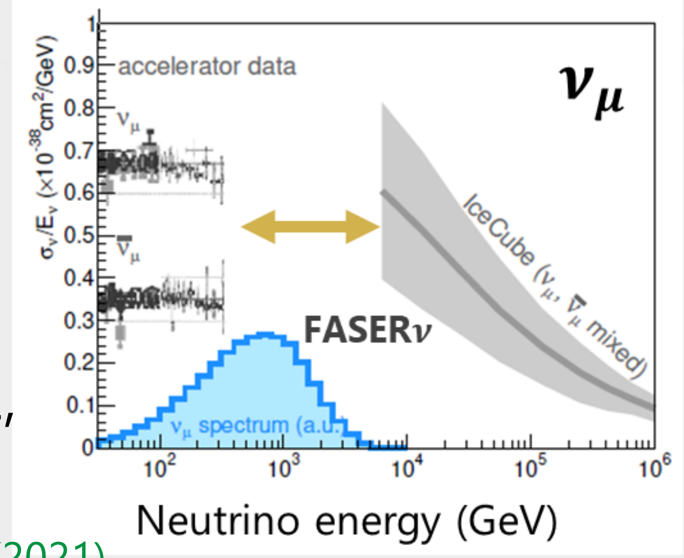
FASER is supported by:
HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION
CERN
erc
科研費 KAKENHI
NSF
Swiss National Science Foundation

Neutrinos at the LHC

FASER measures highest-energy man-made neutrinos

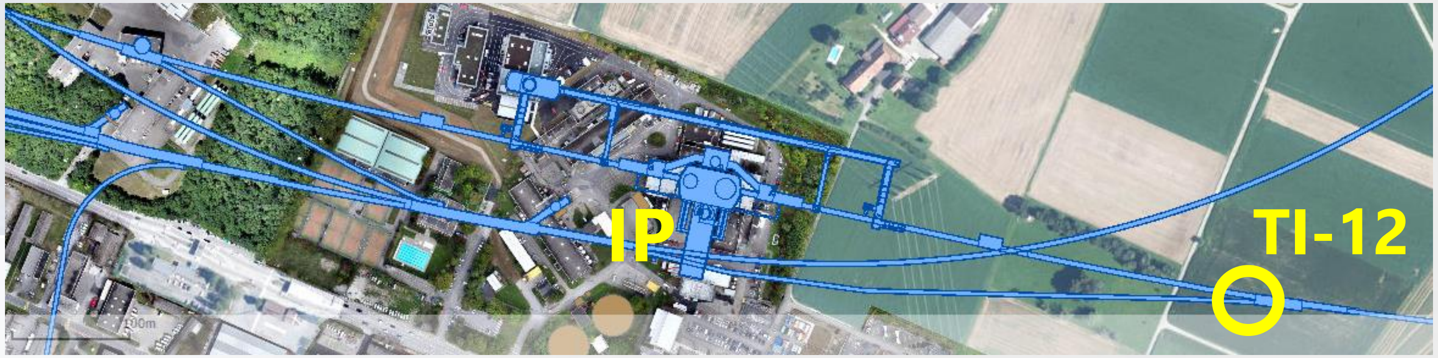


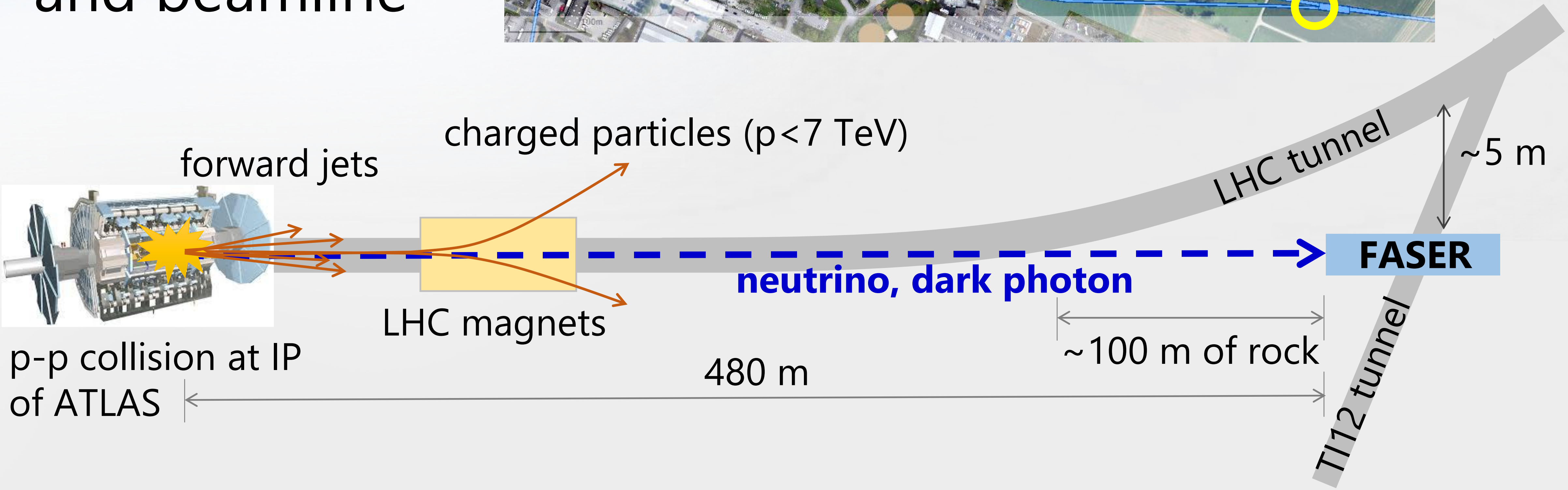




- Large production of neutrinos at the LHC
  - High energy frontier of man-made neutrinos
- It was considered in the past, e.g.,
  - A. De Rujula and R. Ruckl, “Neutrino and muon physics in the collider mode of future accelerators”, 1984
- But no neutrinos had ever been directly detected at a collider.
- In 2018, the FASER collaboration was formed and began investigating far-forward locations near ATLAS, TI-18 and TI-12, to directly detect and study collider neutrinos.
  - First neutrino interaction candidates at the LHC Phys. Rev. D 104, L091101 (2021)
  - First direct observation (of ν_μ CC interactions) Phys. Rev. Lett. 131, 031801 (2023)

Location and beamline



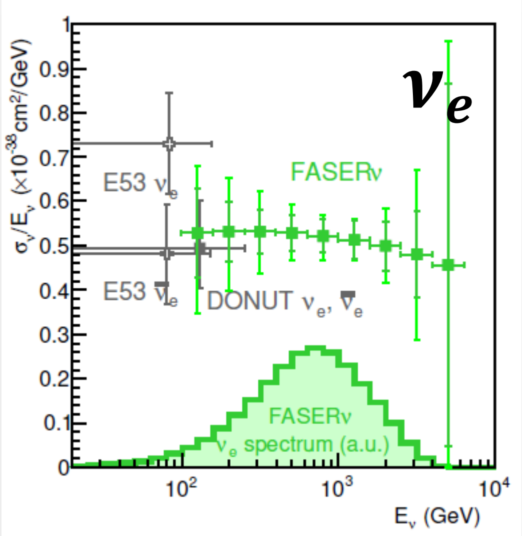


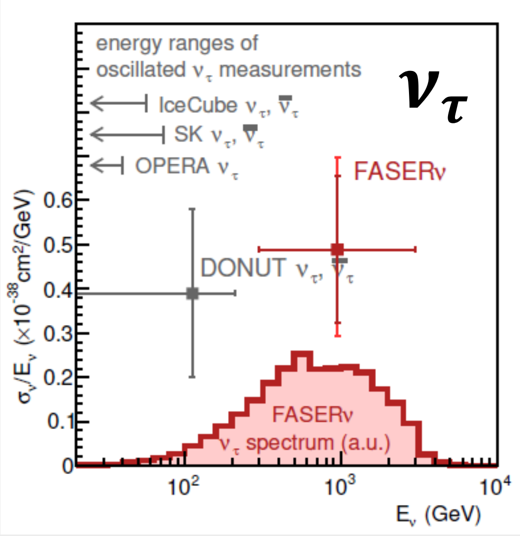
- Because the neutrinos have ~TeV energies, we can detect many with just a 1-ton detector.
- The transverse spread of TeV neutrinos from pion decay is only ~10 cm after propagating 480 m. The detector is aligned with the line of sight (LoS) which maximizes the rate and energy of neutrinos of all flavors.
- 100 m rock implies that the only background to neutrinos from ATLAS are muon-induced events.

FASERν physics potential

(1) Study high-energy neutrino interactions

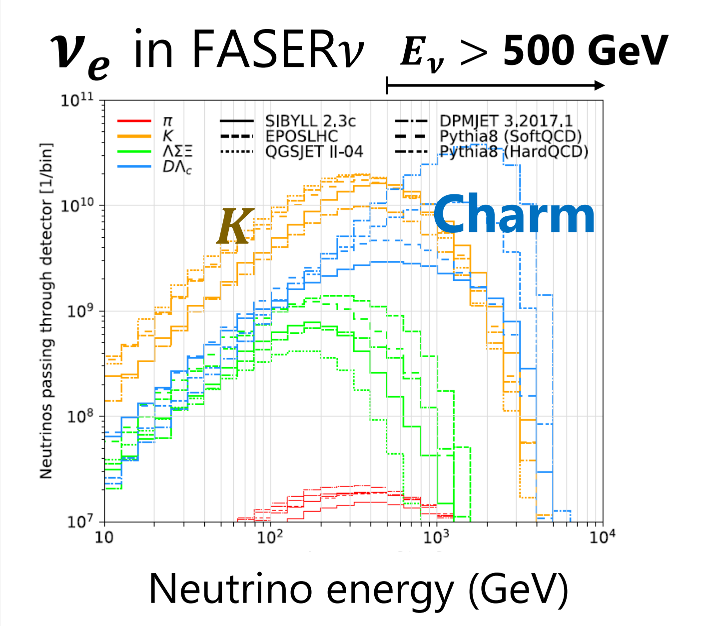
- **Cross sections of different flavors** at TeV energies: FASER probes unexplored energy range.
- Neutrino CC interactions with charm production ($\nu s \rightarrow lc$)
- Nuclear PDFs





(2) Use neutrinos as probe of **forward hadron production**

- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles.

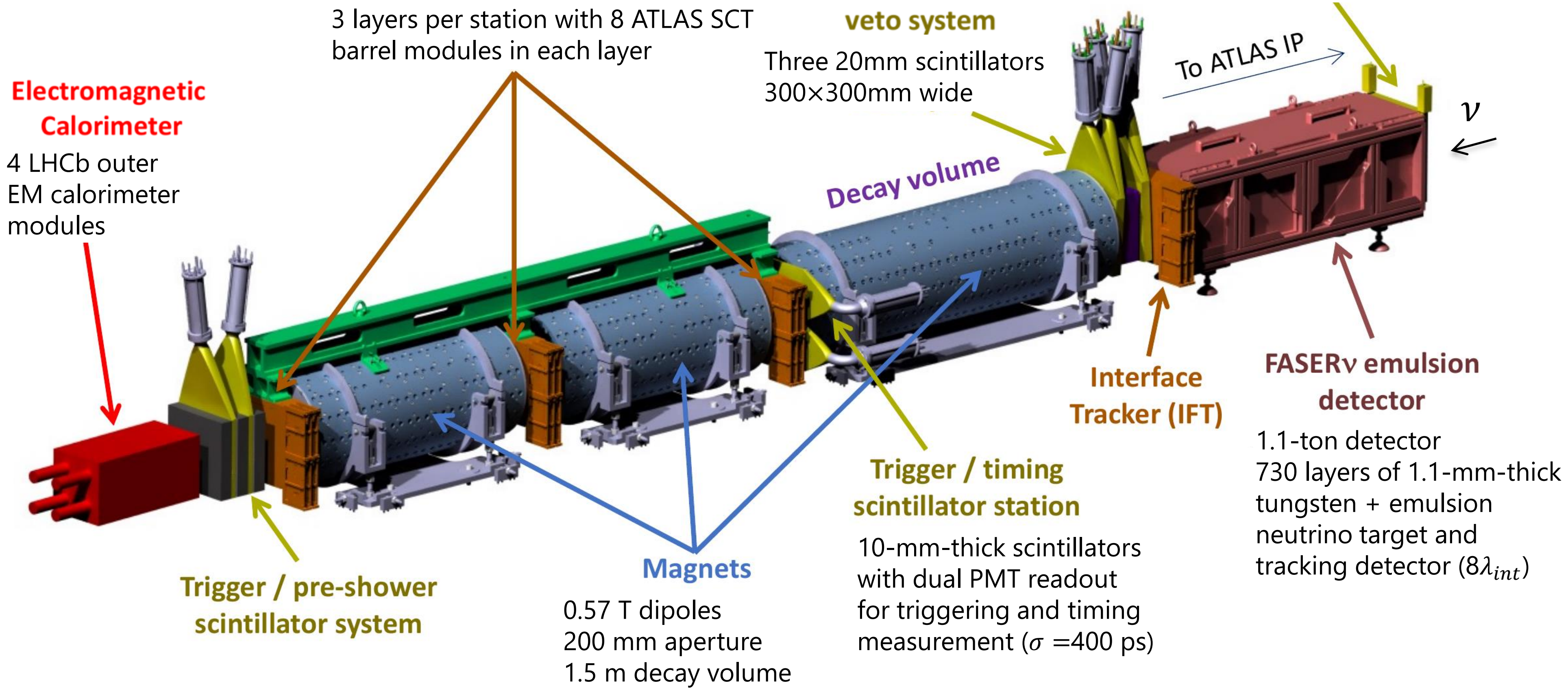


Neutrinos from charm decay is relevant for neutrino telescopes (such as IceCube) for understanding the prompt atmospheric neutrino production (currently very poorly constrained).

- First data on forward charm, hyperon, and kaon
- FASERν's measurements provide novel input to QCD (low-x PDFs, intrinsic charm, saturation) and astroparticle physics (prompt atmospheric neutrinos, cosmic ray muon puzzle)

The FASER detector

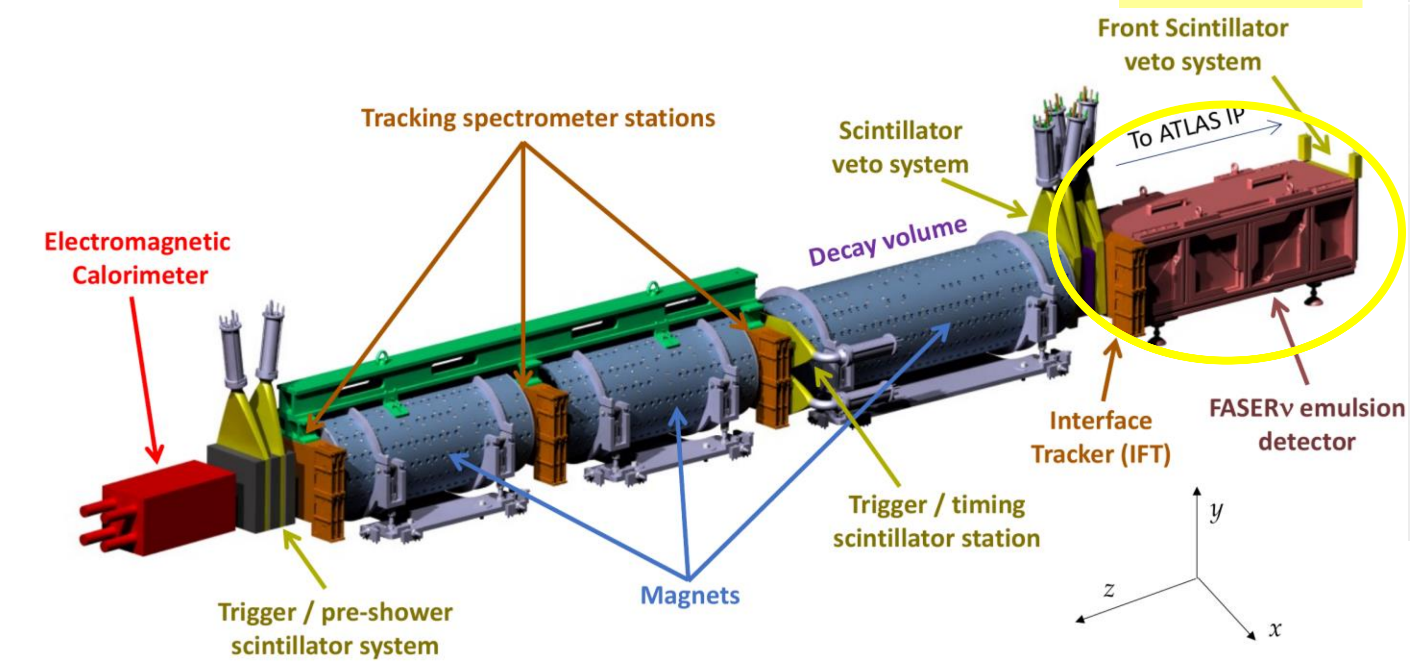
"The FASER Detector", arXiv:2207.11427

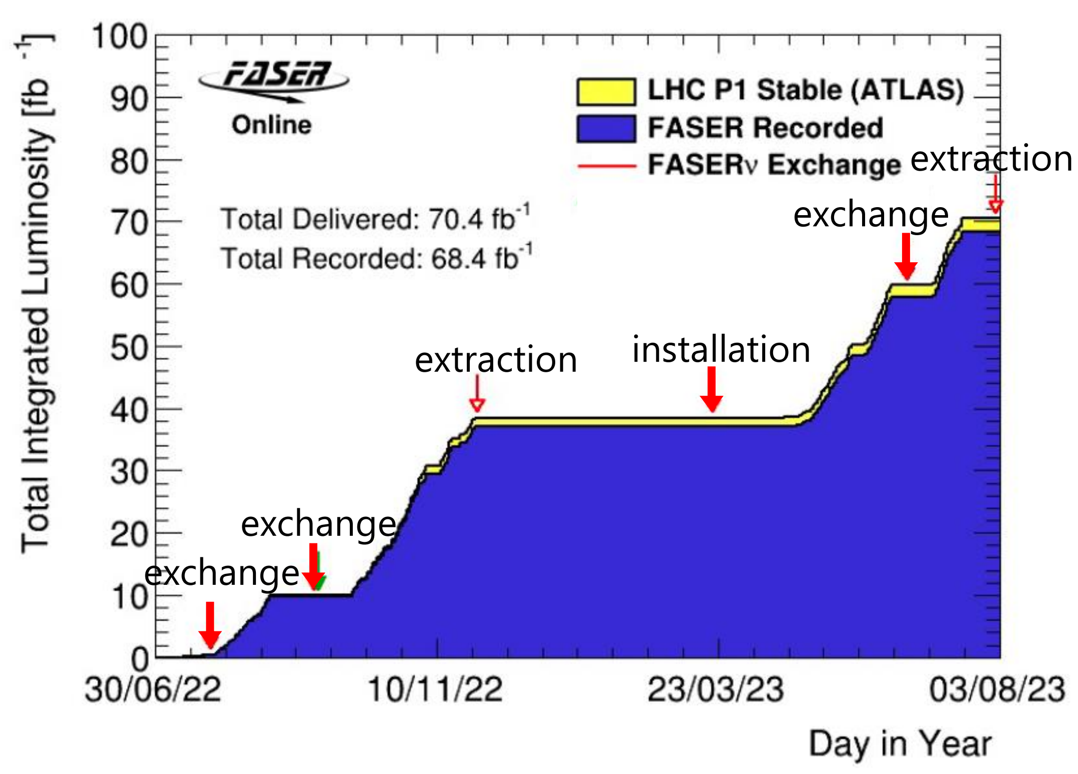


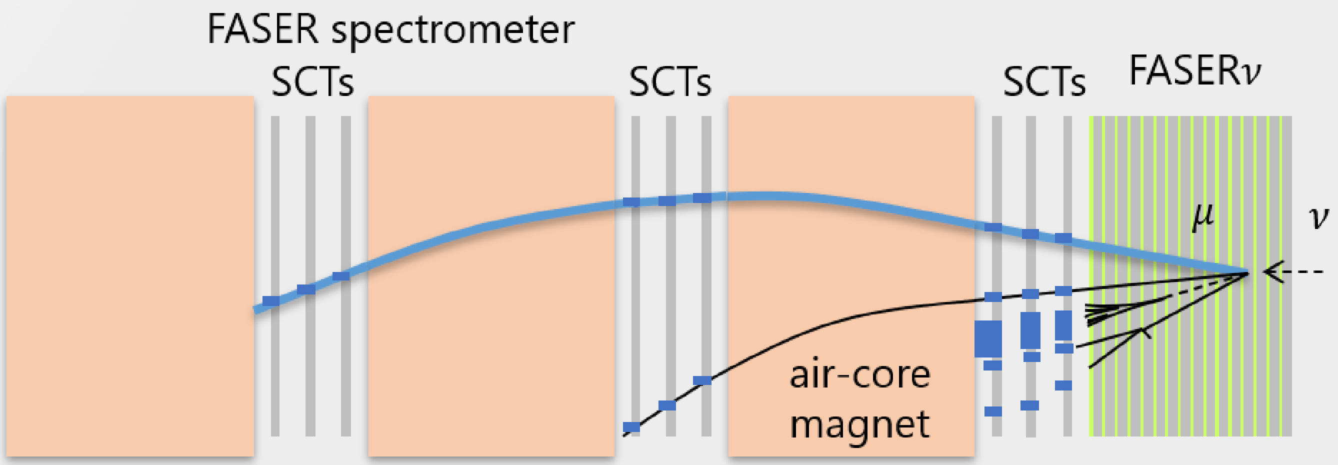
Recent dark photon result

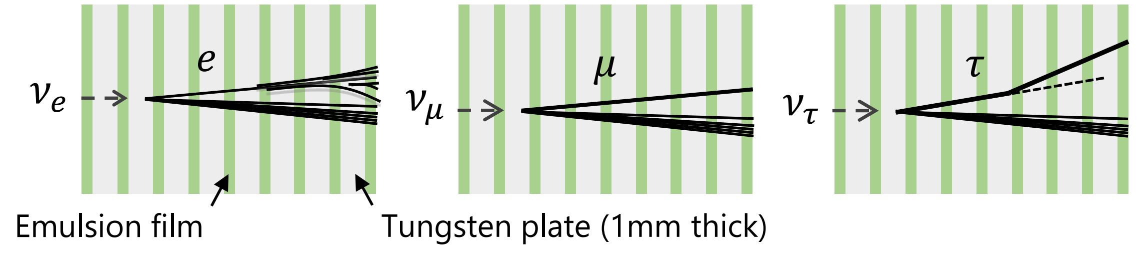
"Search for Dark Photons with the FASER detector at the LHC", arXiv:2308.05587

The FASERν detector









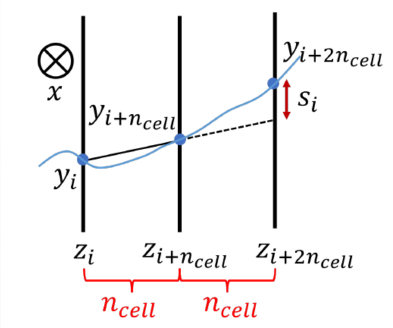
Emulsion/tungsten detector

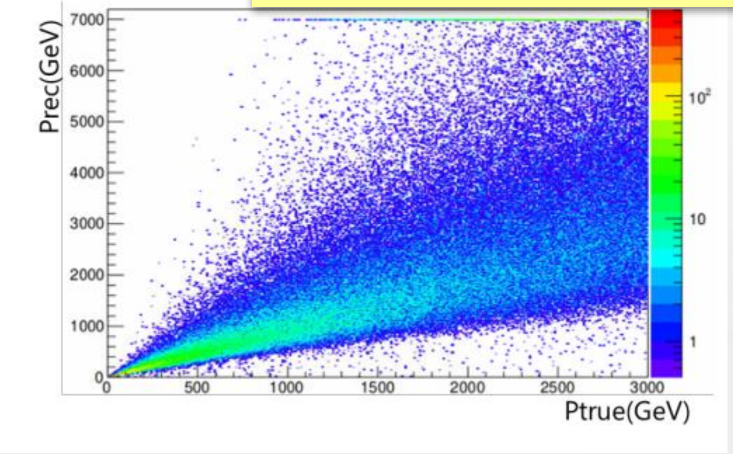
- 730 1.1-mm-thick tungsten plates, interleaved with emulsion films
- Vacuum-packed sub-modules with 10 layers
- 25×30 cm^2, 1.1 m long, 1.1 tons

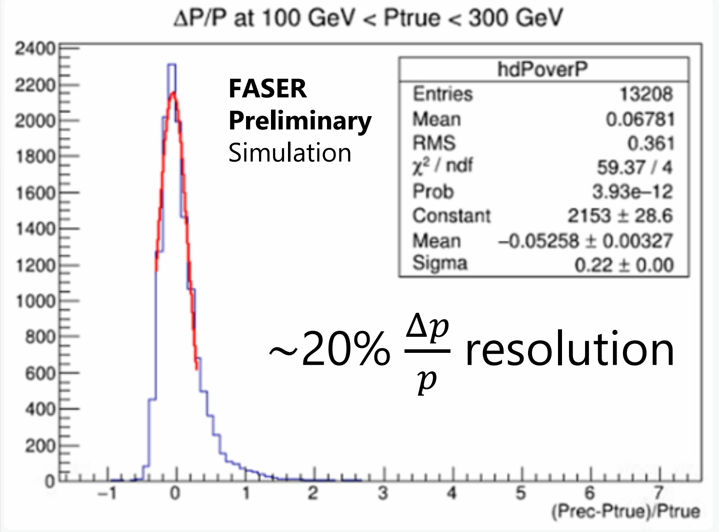
FASERν detector performance

Momentum measurement

A1-P-12, Haruhi Fujimori



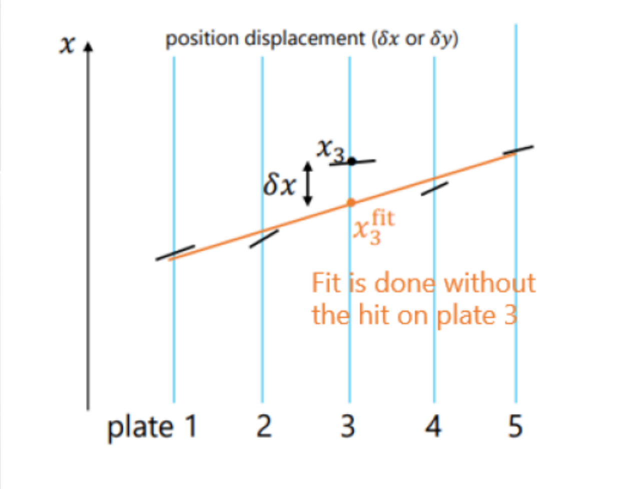


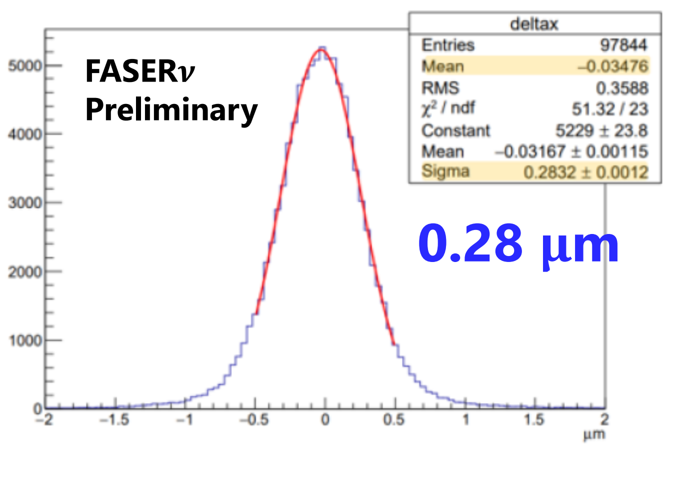


~20% $\frac{\Delta p}{p}$ resolution

Momentum measurement performance is validated in the data using split tracks, confirming the MC results.

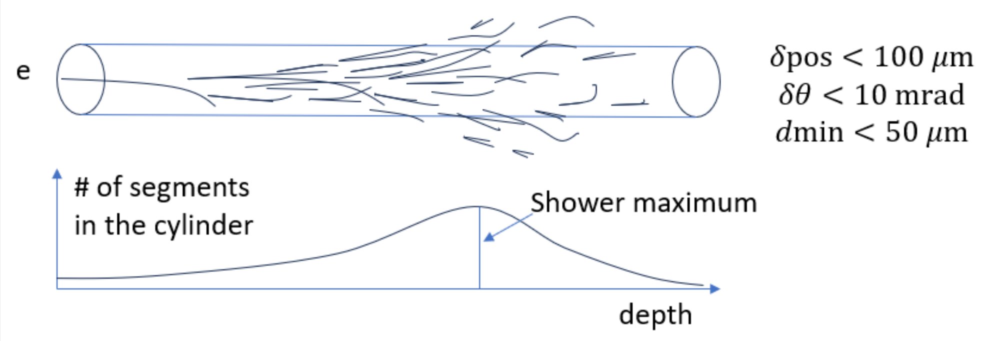
Position resolutions (after ~100 plates reconstruction)

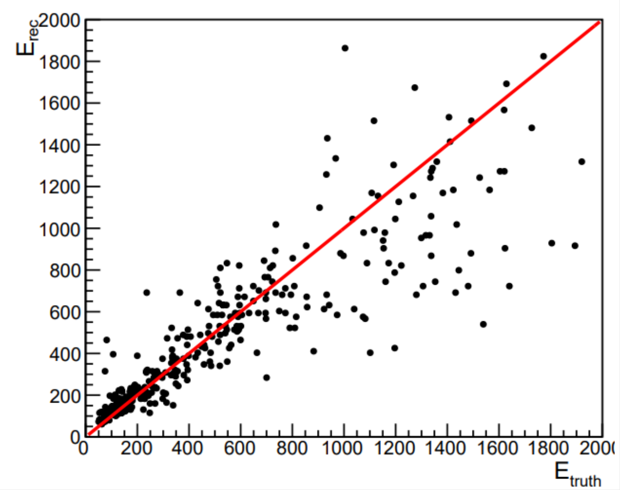




Electron energy measurement

Number of segments (sum 7 films around shower maximum) are used to estimate electron energy. ~25% $\frac{\Delta E}{E}$ resolution



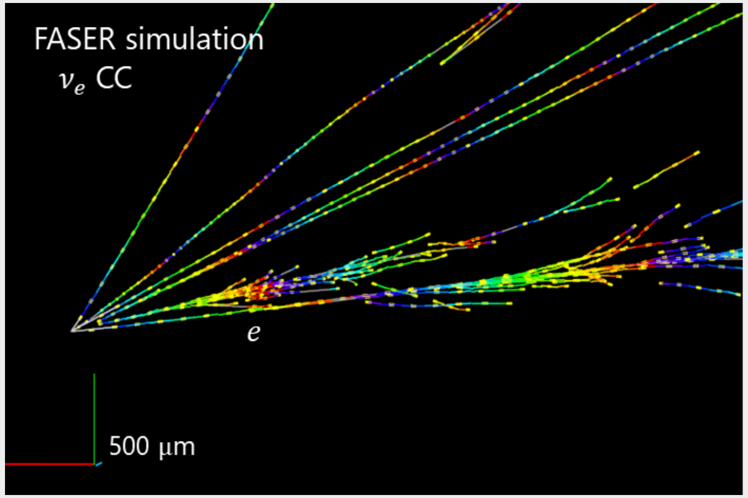


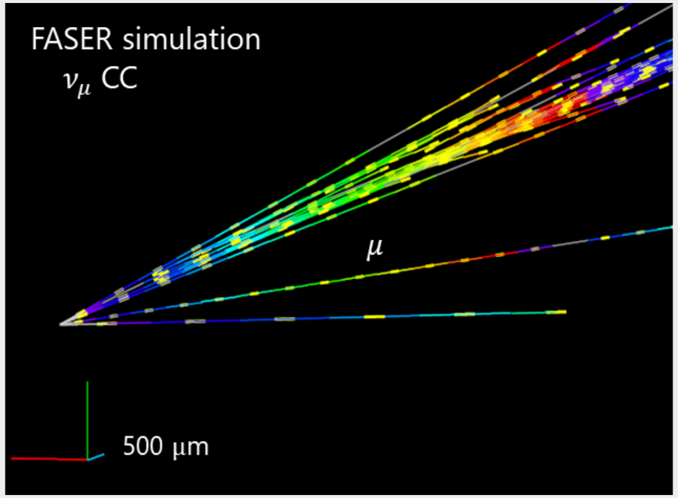
Expected neutrino event rates

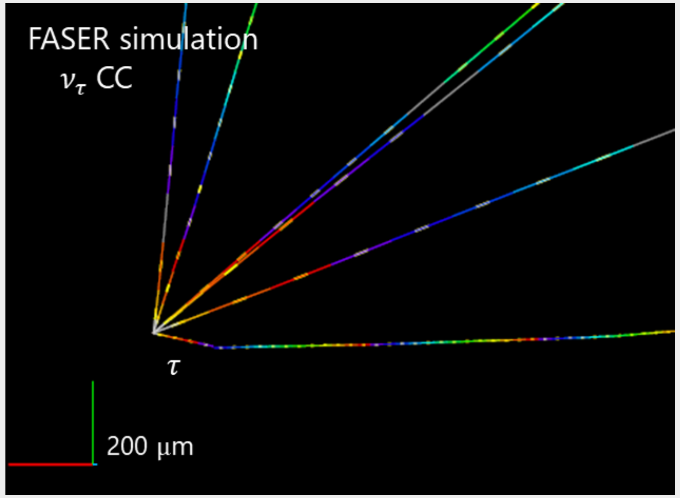
Based on
F. Kling and L. J. Nevay,
"Forward Neutrino Fluxes at the LHC",
Phys. Rev. D 104, 113008

Expected number of CC interactions (250 fb^{-1})

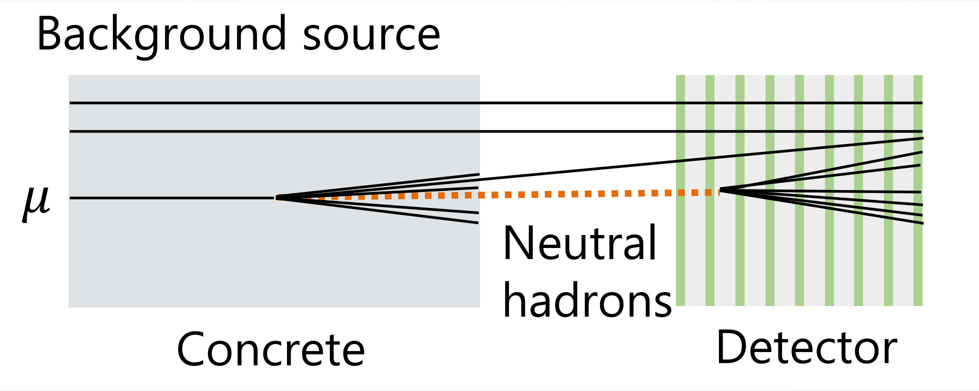
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$



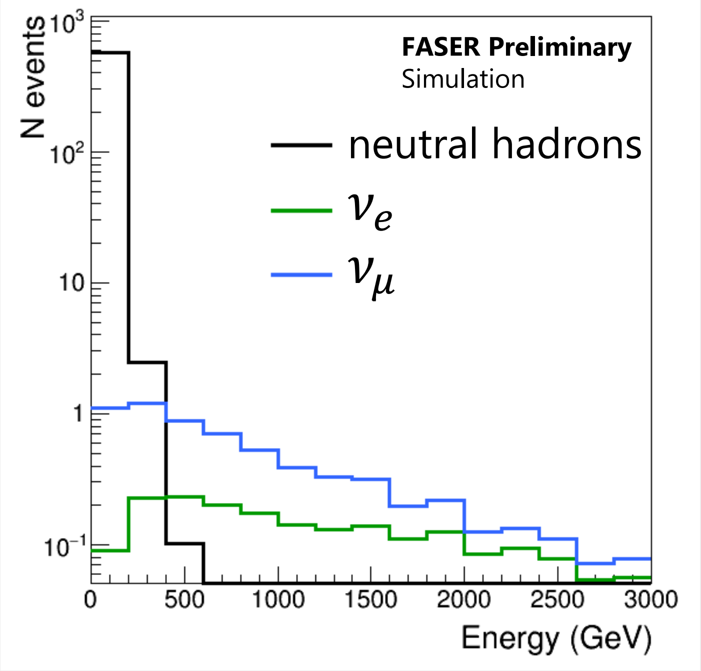




Main background source



- There is a flux of 0.5 Hz/cm^2 of high energy muons traversing FASER from IP1 at the highest luminosity.
- The muons rarely produce neutral hadrons in the upstream concrete and inside the detector, which can mimic neutrino interaction vertices.
- Most of the produced neutral hadrons are low energy.



	Interaction rates of neutral hadrons with $\mathrm{E_h}$ >200 GeV in 150 tungsten plates per incident muons
K_S	2.1×10^{-5}
K_L	2.5×10^{-4}
n	2.0×10^{-4}
Λ	2.3×10^{-4}
$\bar{\Lambda}$	3.1×10^{-5}

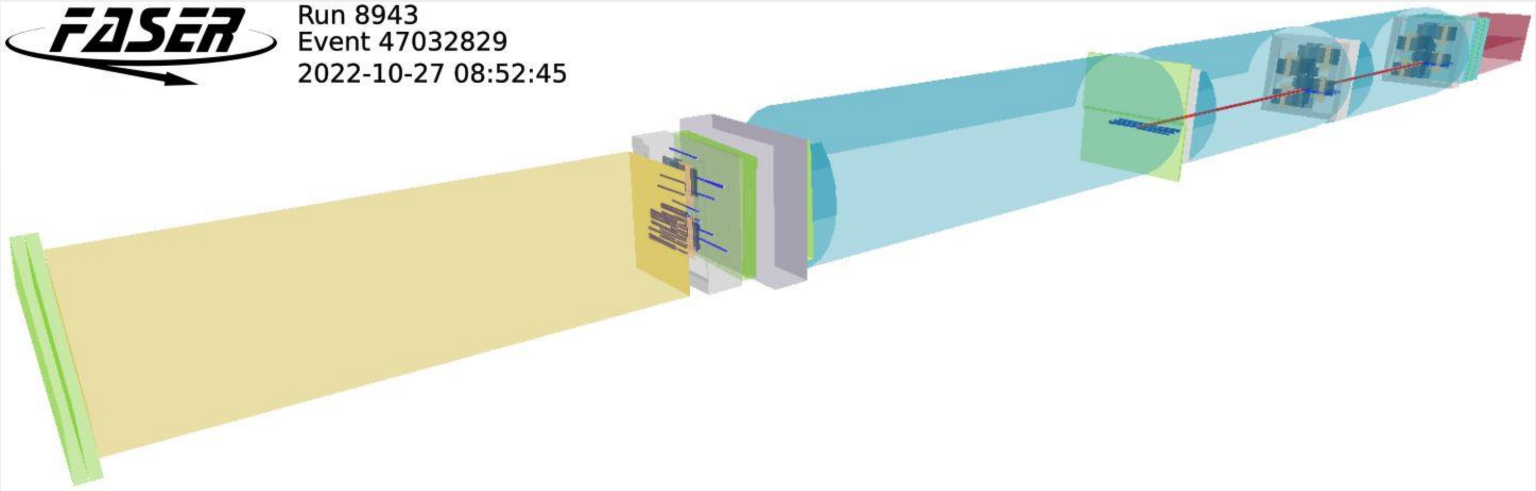
First direct observation of ν_μ interactions at the LHC

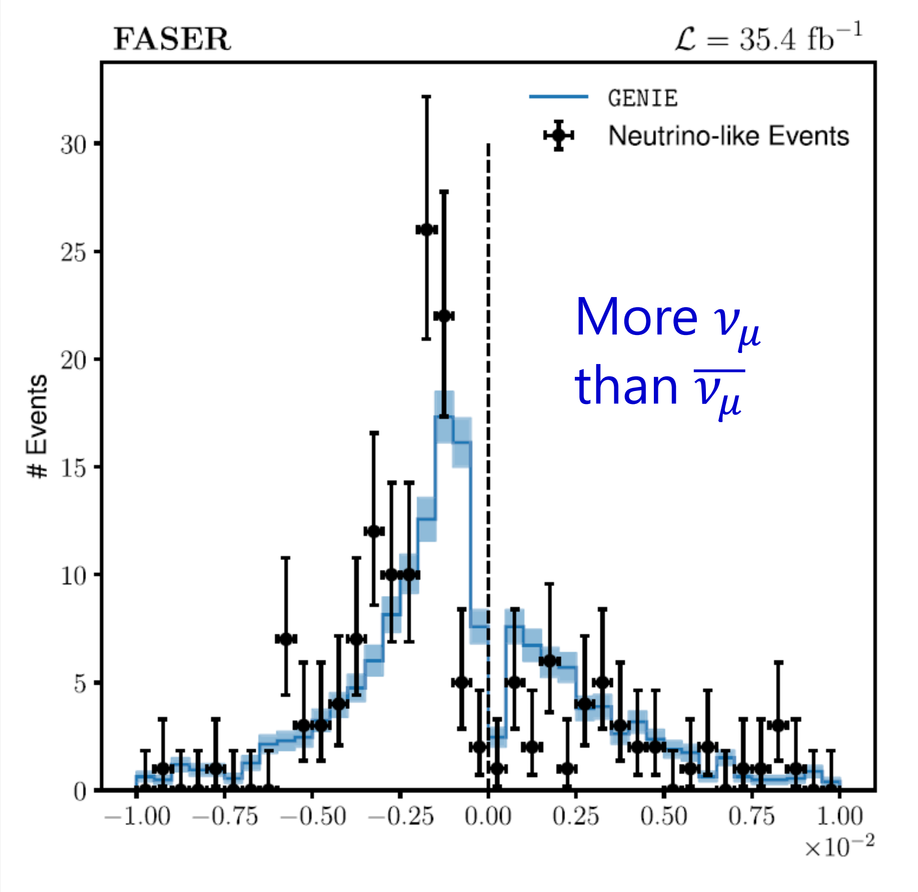
by the FASER electronic detectors

Phys. Rev. Lett. 131, 031801 (2023)

Unblinded results:
153 events in the signal region
(significance of 16σ)

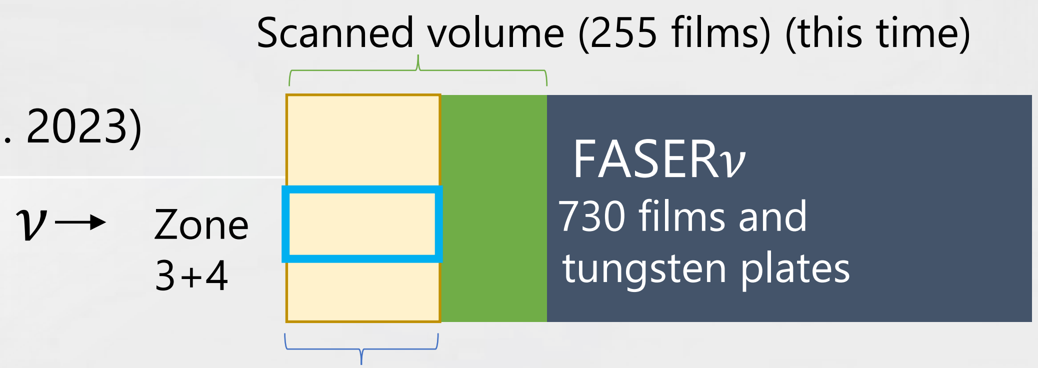
First direct observation of ν_μ interactions at the LHC
using FASERν as a target





q/p_μ (GeV[-1])

Results from FASERν (CONF note Aug. 2023)



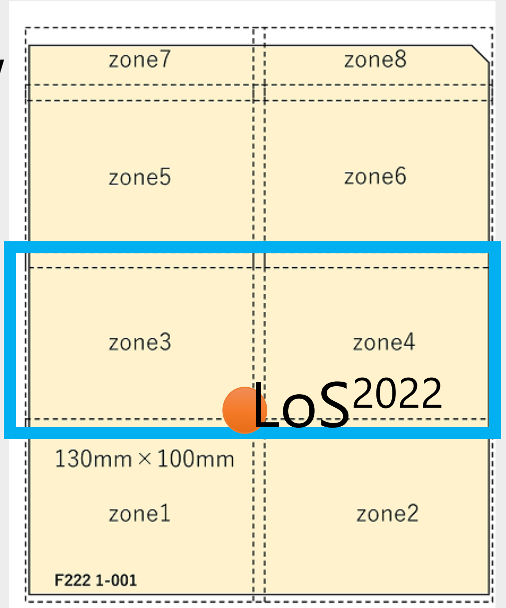
Target volume for the first analysis (150 tungsten plates)

Target mass (zone 3+4)
$\simeq$ 9 cm x 24 cm x 0.1087 cm x 150 x 19.3 g/cm^3
= 68.0 kg

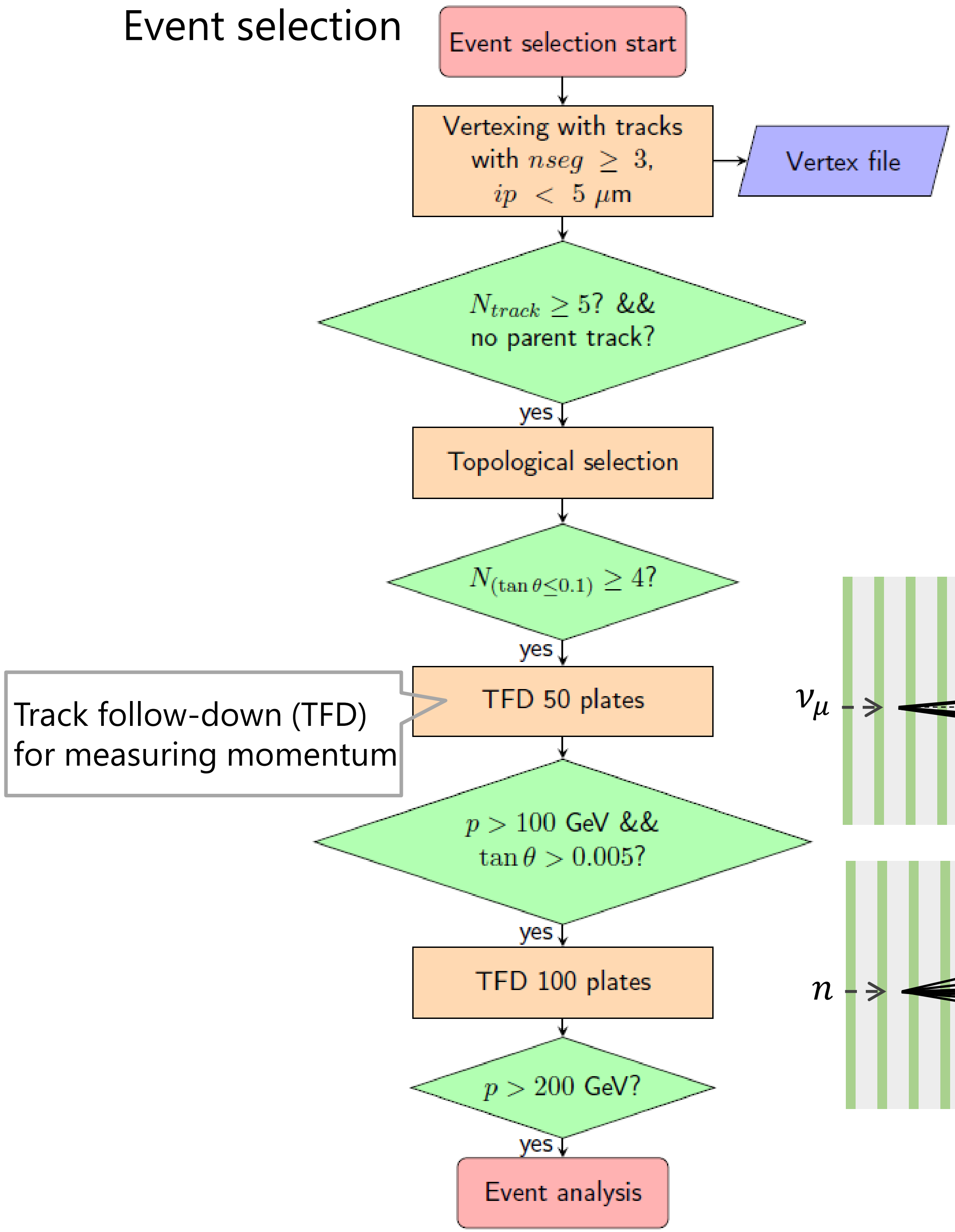
- **Strategy of the analysis**
  - Analyzing 250/730 films of the 2022 2nd module
    - 150 films for vertex reconstruction and 100 films for momentum/energy measurements
  - Detecting **ν_e and ν_μ CC interaction candidates** with a high-energy selection (p_{lep}>200 GeV) towards cross section measurements (and flux constraints)
  - (Due to the lack of charge measurement, we measure the sum of $\nu_e + \overline{\nu_e}$ and the sum of $\nu_\mu + \overline{\nu_\mu}$.)

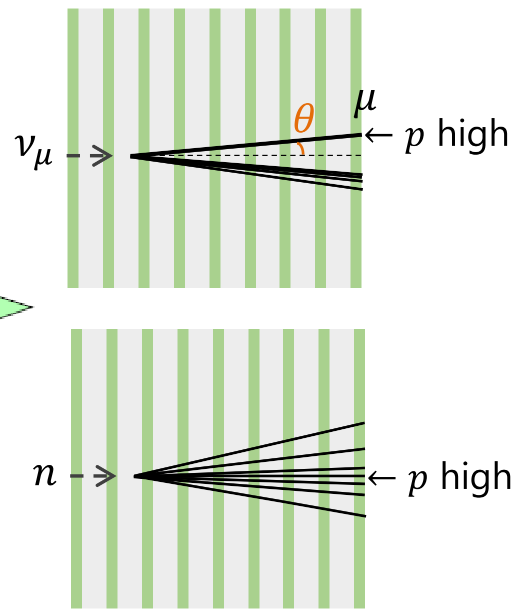
module name	installed period	load	integrated luminosity per module (fb^{-1})
2022 1st module (F221)	Mar 15 - Jul 26	30%	0.4705
2022 2nd module (F222)	Jul 26 - Sep 13	100%	9.523
2022 3rd module (F223)	Sep 13 - Nov 29	100%	28.9082

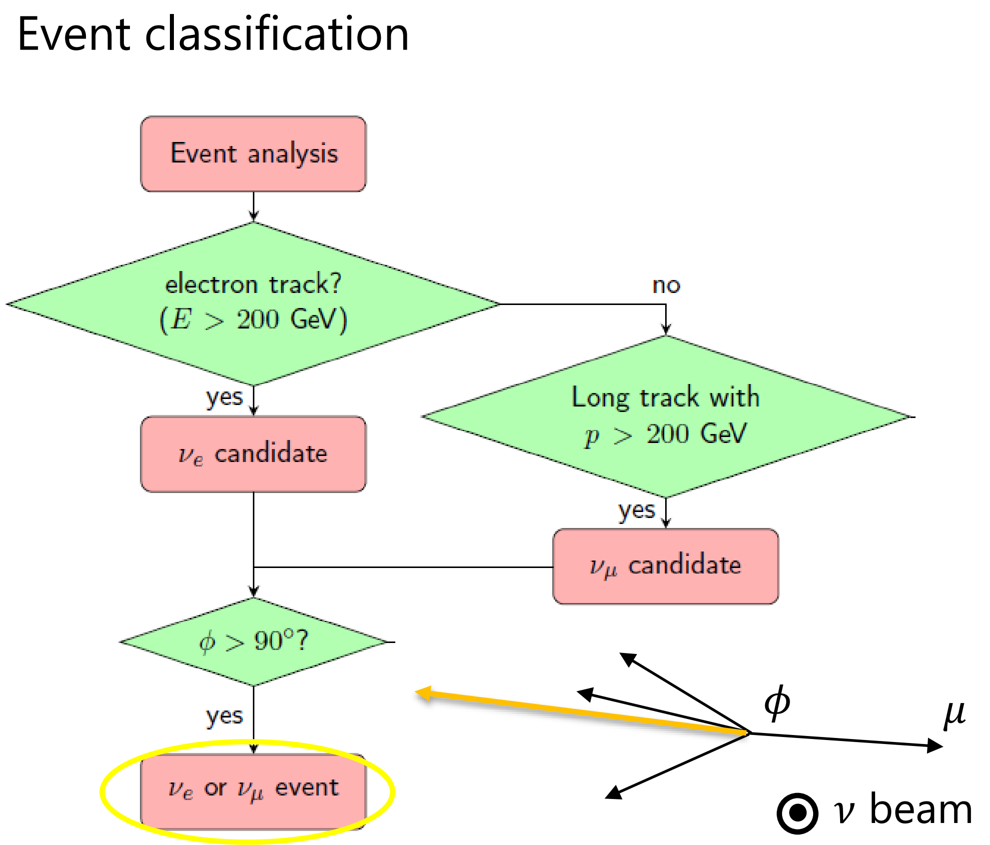
Top view



Event selection procedure







Background study using the data

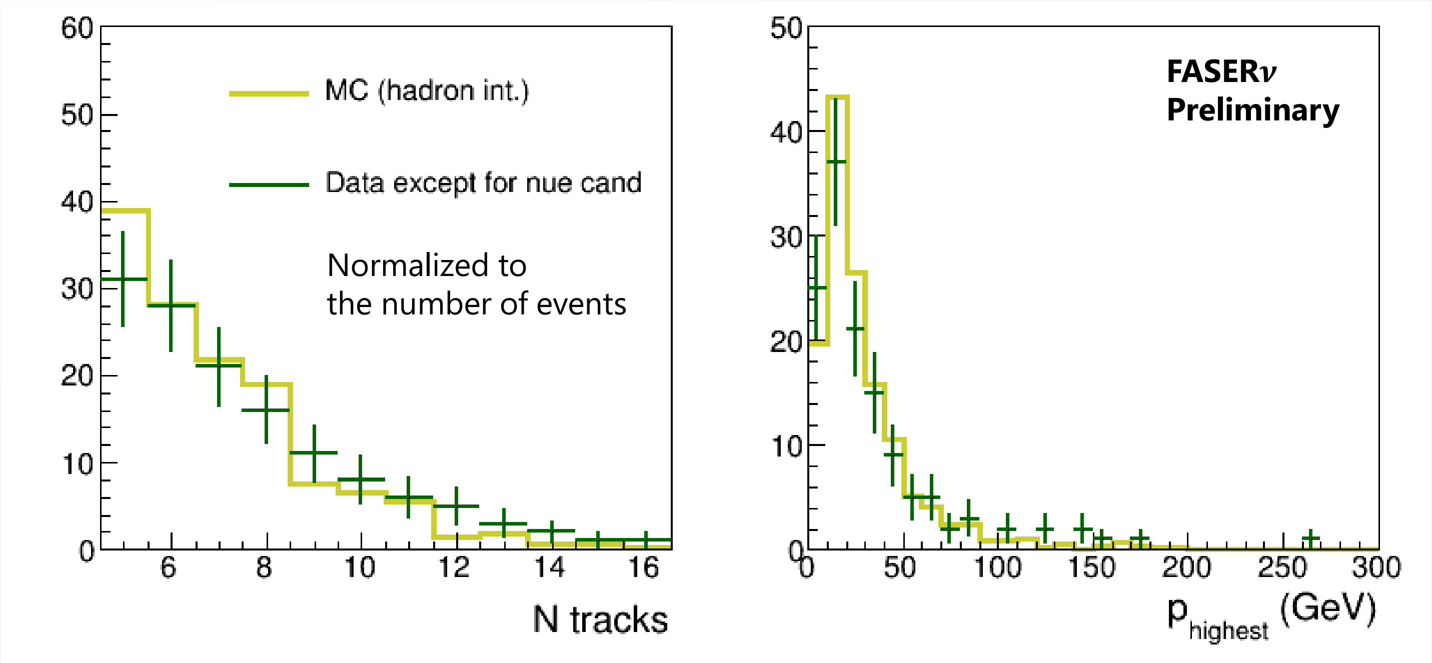
Detected vertices **before the high-energy selection** are dominated by neutral hadron interactions.

Expectation from simulation ⇔ **Data**

216 vertices

- $K_S, K_L, n, nbar, \Lambda, \Lambda bar$ interactions

133 vertices (140 vertices − 7 ν CC candidates)

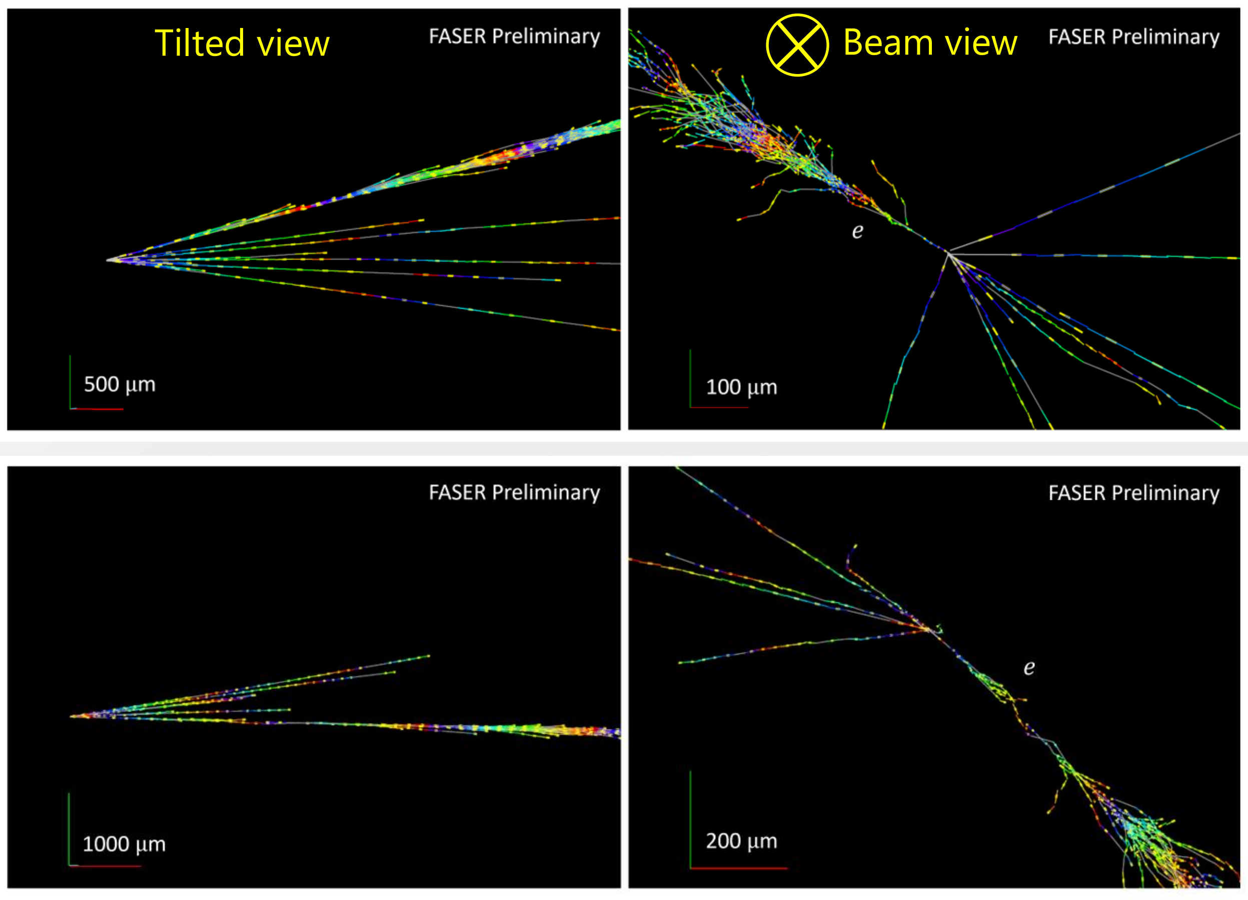


- The event rate agrees with the expectation within 50% uncertainty.
- No significant difference in the shape of the distributions.

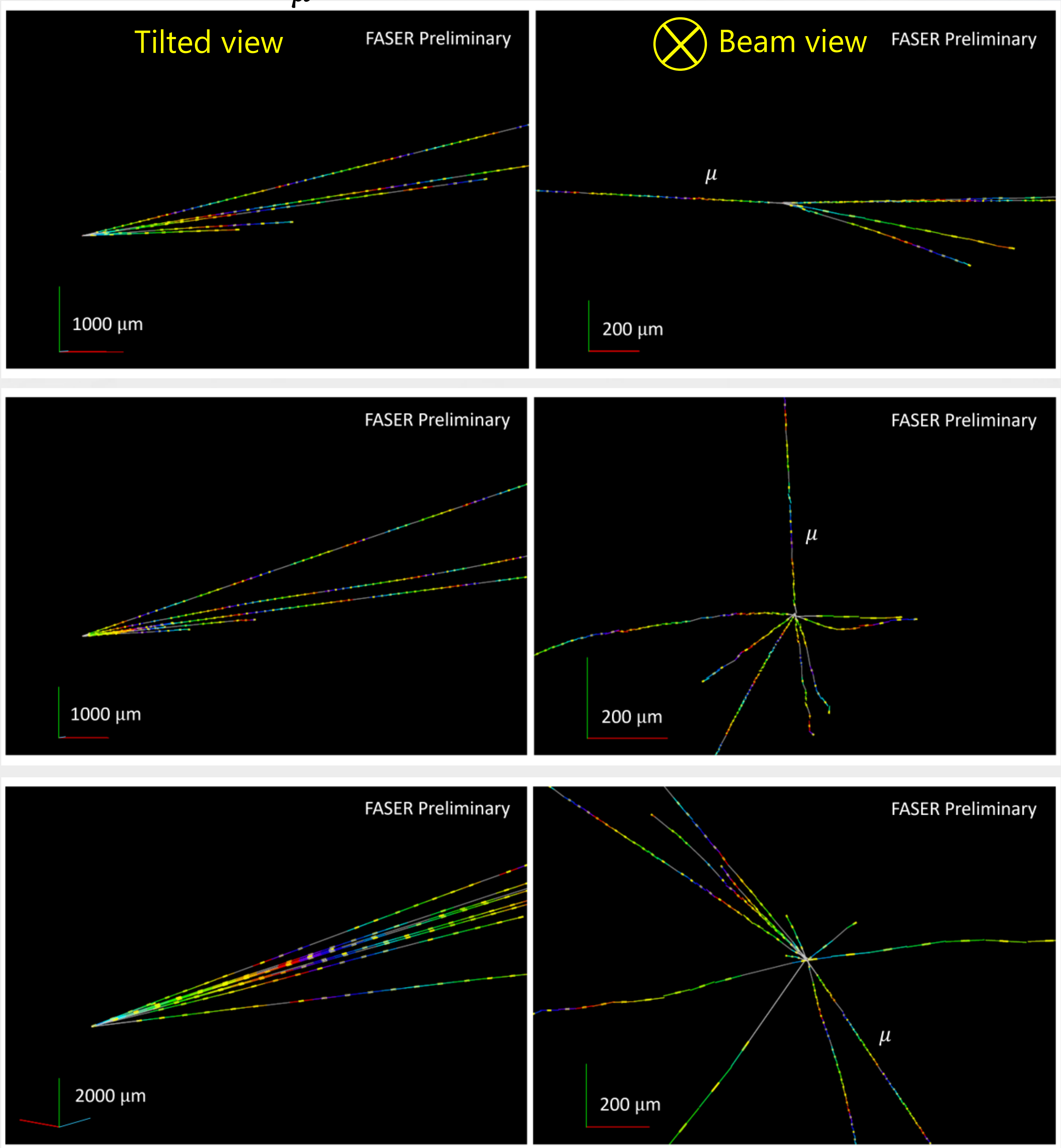
→ validating the background simulation at low energy

ν CC candidate events

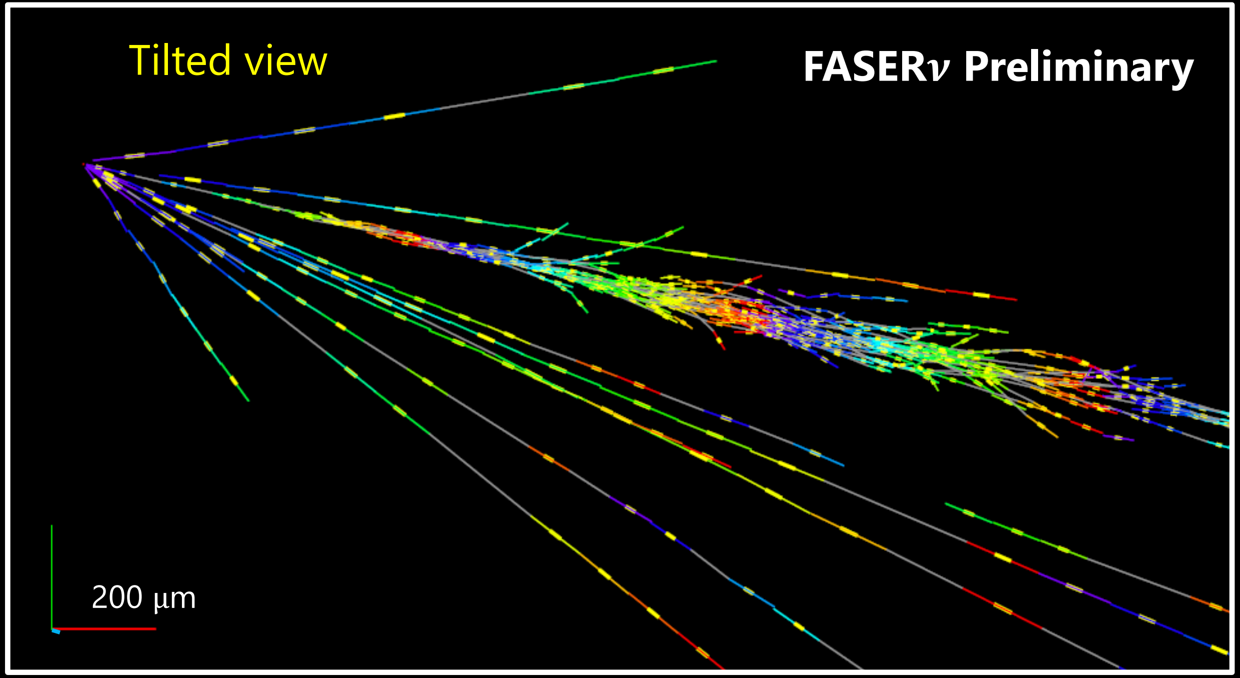
Two of the ν_e CC candidates

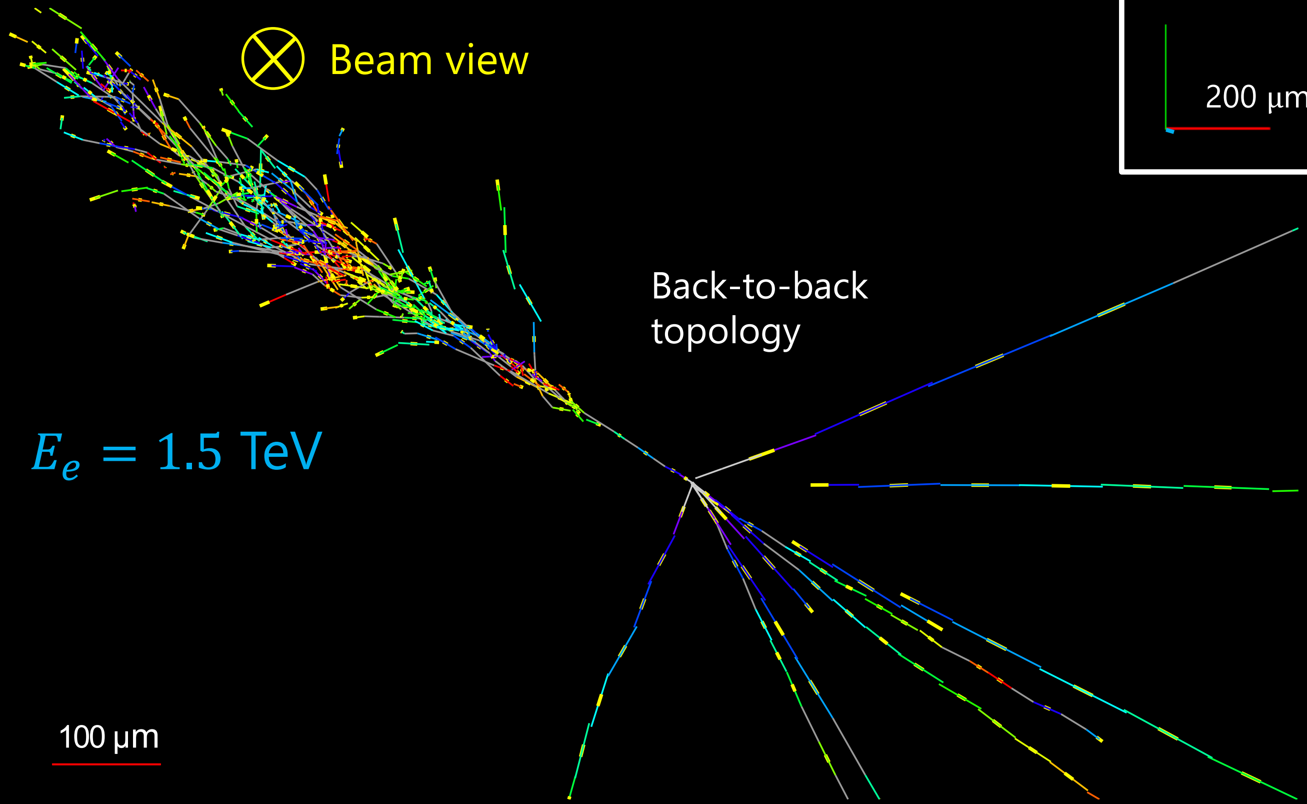


Three of the ν_μ CC candidates



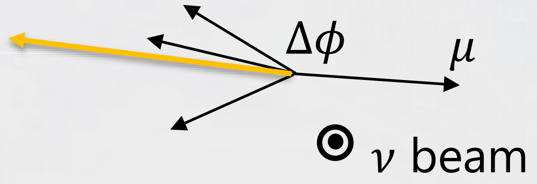
One of the ν_e CC candidates





- 11 tracks at the vertex, 615 μm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- 175° between e-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

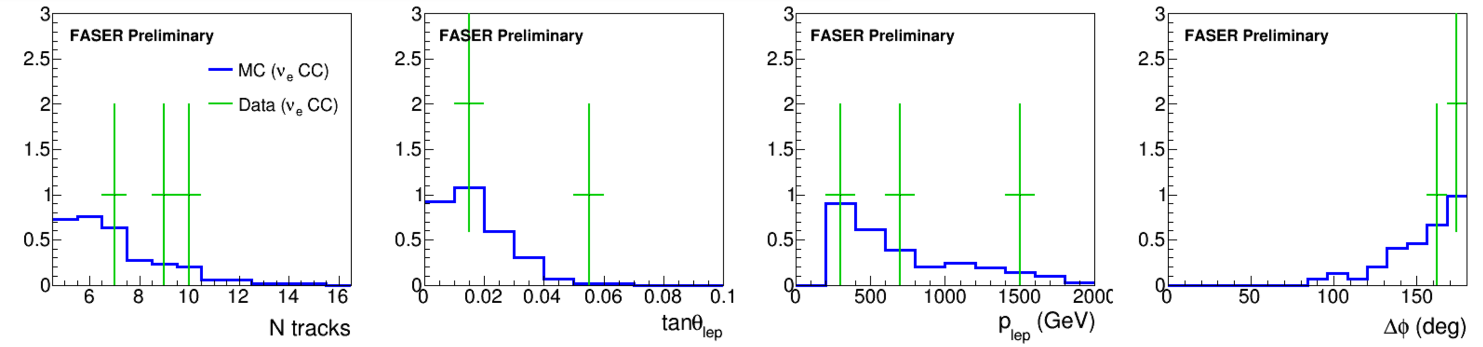
Properties of the detected ν_e and ν_μ CC candidates



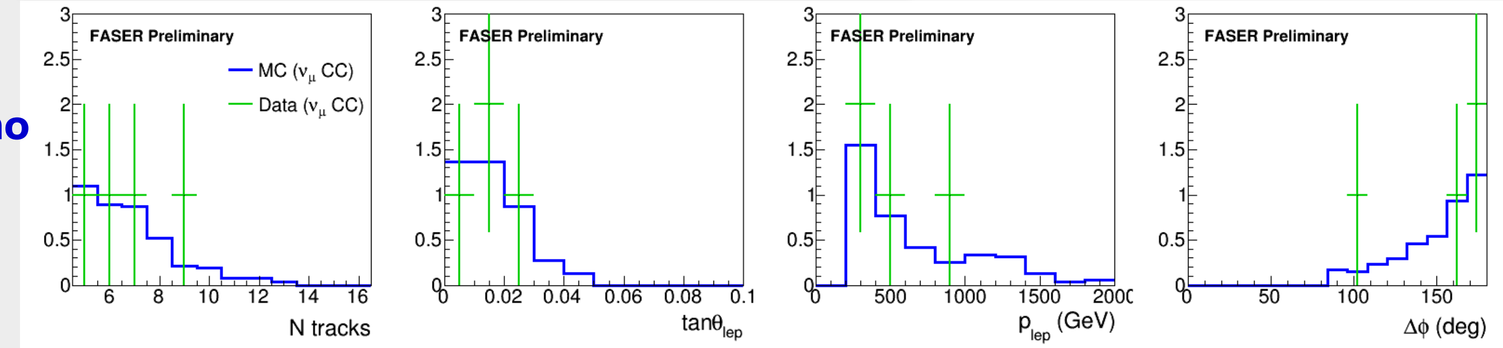
	Expected background		Expected signal	Observed
	Hadron int.	ν NC int.		
ν_e CC	0.002 $\pm$0.002(stat) $\pm$0.002(syst)	-	$1.2^{+4.0}_{-0.6}$	3
ν_μ CC	0.32 $\pm$0.15(stat) $\pm$0.16(syst)	0.19 $\pm$0.15	$4.4^{+4.2}_{-1.4}$	4

- ν_e: $p = 1.6 \times 10^{-7}$ (5.1σ)
  - **First direct observation of electron-neutrino CC interactions at the LHC**
- ν_μ: $p = 5.2 \times 10^{-3}$ (2.5σ)
  - The performance of ν_μ detection will be improved in future analysis using a longer range for μ ID.

Vertex information of the ν_e CC candidates

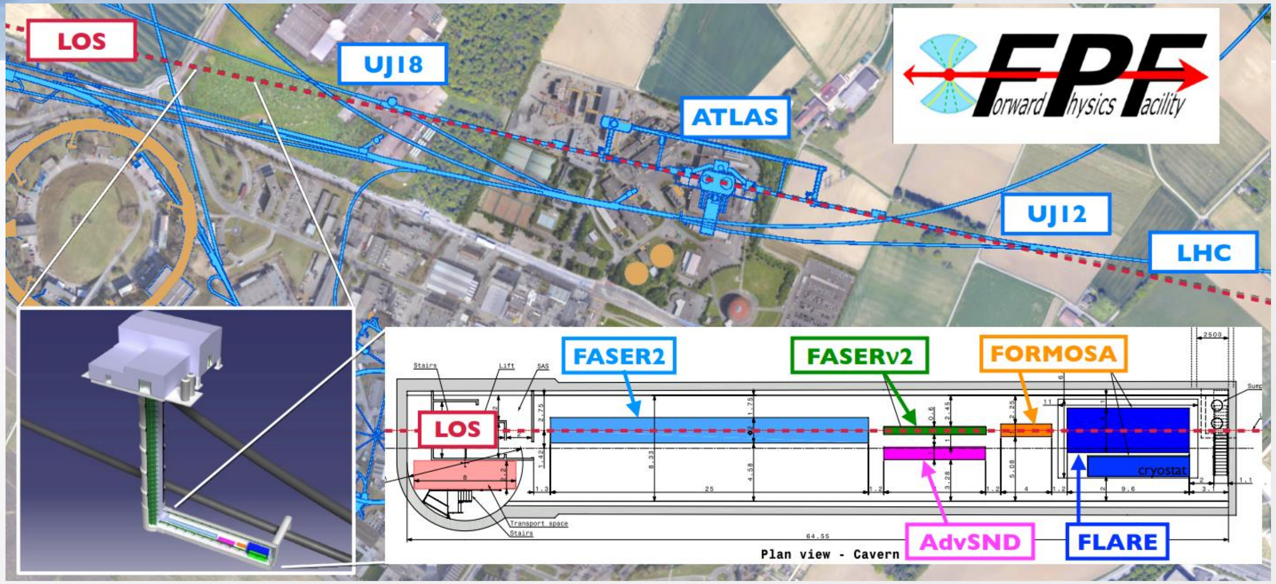


Vertex information of the ν_μ CC candidates

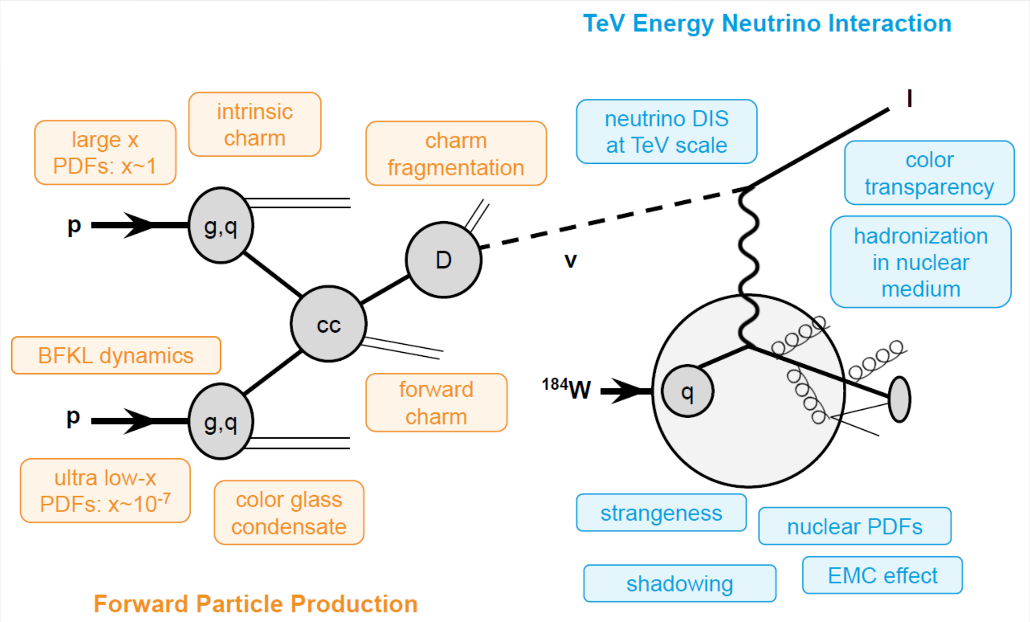


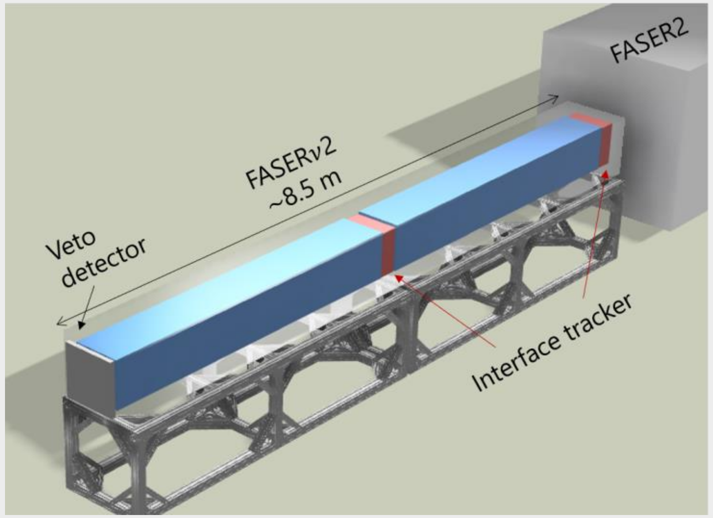
The Forward Physics Facility (FPF) and FASERν2

- "The Forward Physics Facility: Sites, Experiments, and Physics Potential" (short paper), Phys. Rept. 968 (2022) 1-50, arxiv:2109.10905
- "The Forward Physics Facility at the High-Luminosity LHC" (long "White" paper), J. Phys. G 50 (2023) 3, 030501, arxiv:2203.05090



- FPF for the HL-LHC is a proposed facility that could house a suite of experiments to enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.
- FASERν2 is designed to carry out precision tau-neutrino measurements and heavy flavor physics studies
  - Expected to be ~20 tons
  - Should detect $\sim 10^6\ \nu_\mu + \overline{\nu_\mu}$, $\sim 10^5\ \nu_e + \overline{\nu_e}$, and $\sim 10^4\ \nu_\tau + \overline{\nu_\tau}$ CC interactions





Summary

- FASER is successfully taking data in LHC Run 3.
- First observation of muon-neutrino CC interactions at the LHC by the FASER electronic detectors was reported and published.

- Recent results on LHC neutrinos from the FASERν detector, distinguishing ν_e CC and ν_μ CC interaction candidates, are presented.
  - **First observation of electron-neutrino CC interactions at the LHC** at the highest energy ever observed
  - This result confirms emulsion detector can deliver physics measurements in the challenging environment of the LHC.
  - CONF note: https://cds.cern.ch/record/2868284

- The result presented here used 6% of the target mass and 1/7 of the luminosity collected so far. - We already have more than 100x more neutrinos in our collected data and expect to collect 3x more data during LHC run 3.
- **More measurements to come.**
  - ~70 tau neutrino interactions at high energy, maybe first detection of anti-tau neutrino, cross section and flux measurements in an unprobed energy window, new measurements that will sharpen IceCube measurements, clarify cosmic ray muon puzzle, …

Acknowledgements

- FASER is supported by:

HEISING-SIMONS FOUNDATION · SIMONS FOUNDATION · CERN · erc · 科研費 KAKENHI · NSF · Swiss National Science Foundation

- We also thank:
  - LHC for the excellent performance
  - ATLAS Collaboration for providing luminosity information
  - ATLAS SCT Collaboration for spare tracker modules
  - ATLAS for the use of their ATHENA software framework
  - LHCb Collaboration for spare ECAL modules
  - CERN FLUKA team for the background simulation
  - CERN PBC and technical infrastructure groups for the excellent support

Backup

Expected neutrino event rates

Based on
F. Kling and L. J. Nevay,
"Forward Neutrino Fluxes at the LHC",
Phys. Rev. D 104, 113008

Expected number of CC interactions (250 fb^{-1})

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	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	Pythia8 (Hard)	2521	9841	57	445	1871	19.2
QGSJET	Pythia8 (Soft)	1616	8918	26.8	308	1691	12
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}	408^{+248}_{-185}	1651^{+220}_{-333}	$18.8^{+12}_{-6.6}$
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$	325^{+118}_{-101}	1626^{+243}_{-308}	$14.6^{+4.5}_{-2.5}$