New results on LHC neutrinos from the FASER experiment

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on behalf of the FASER Collaboration

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SIMONS FOUNDATION
CERN
erc
科研費 KAKENHI
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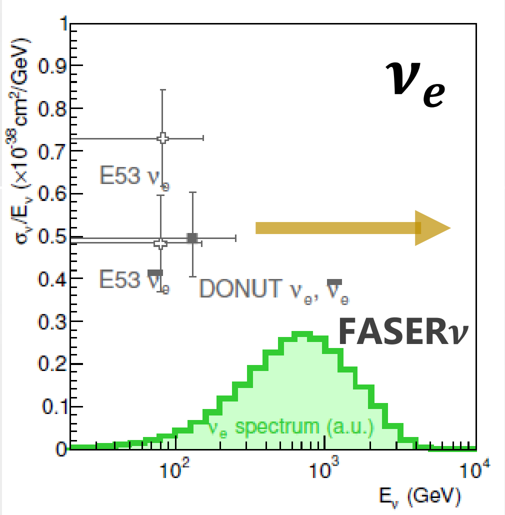
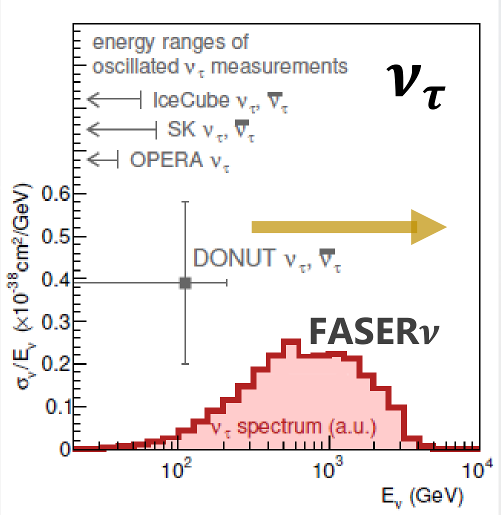
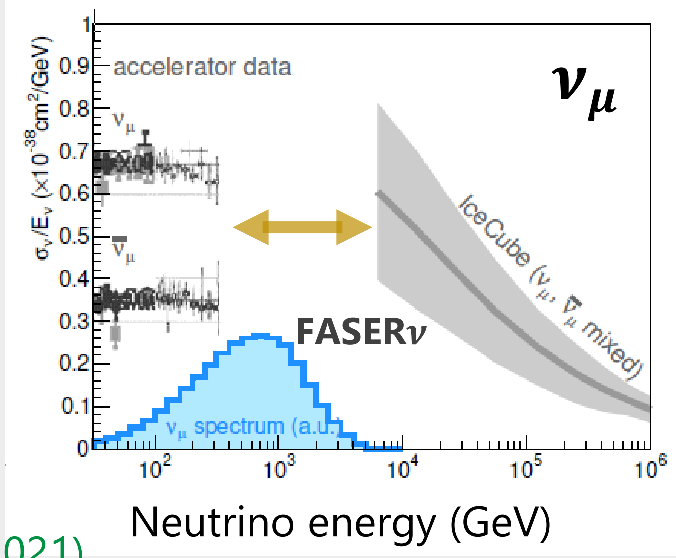
Neutrinos at the LHC

- Large production of neutrinos at the LHC
  - High energy frontier of man-made neutrinos
- There has been a longstanding interest, 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)]

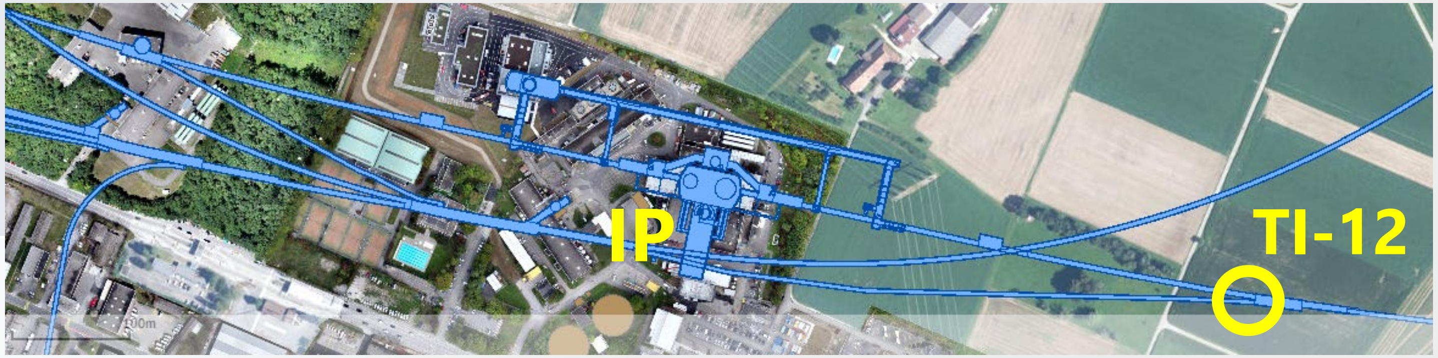
FASER measures highest-energy man-made neutrinos

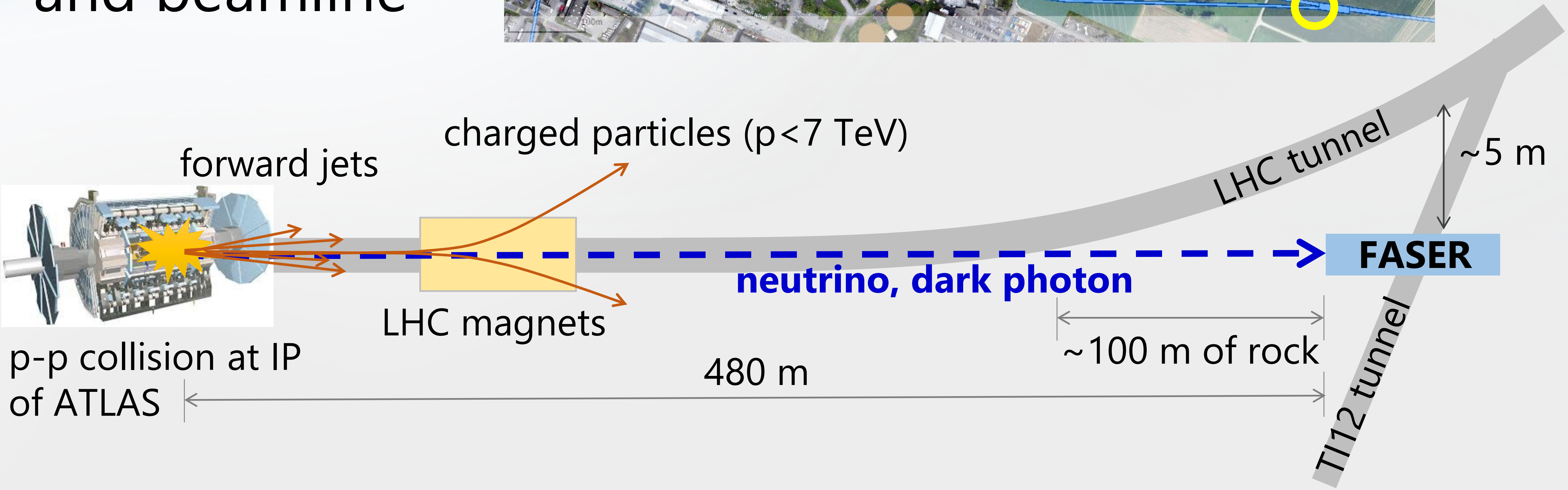






Location and beamline



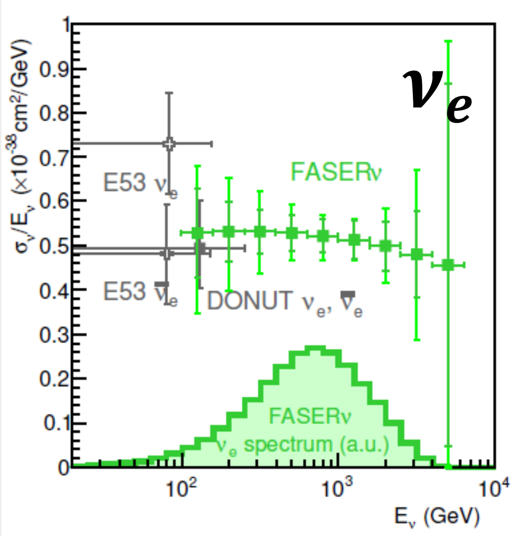


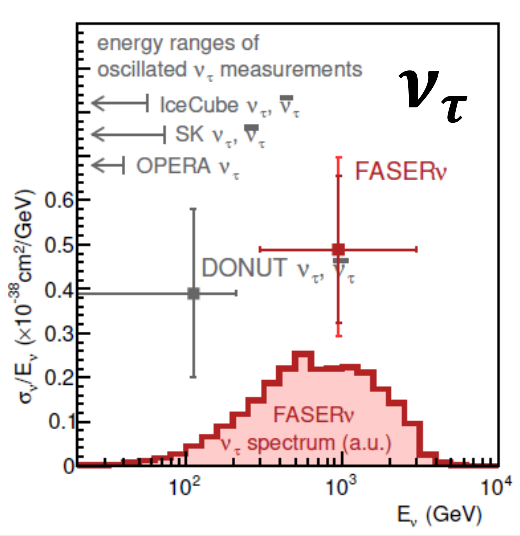
- Because the neutrinos have ~TeV energies, we can detect many with just a 1-ton detector.
- The transverse spread of TeV neutrinos from pion decay is only ~10 cm after propagating 480 m. The detector is aligned with the line of sight (LoS) which maximizes the rate and energy of neutrinos of all flavors.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

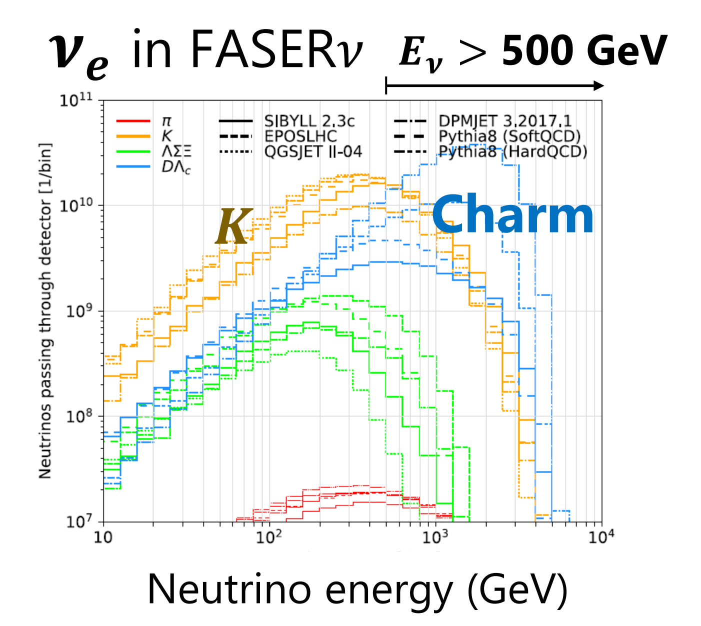




(2) Use neutrinos as probe of **forward hadron production**

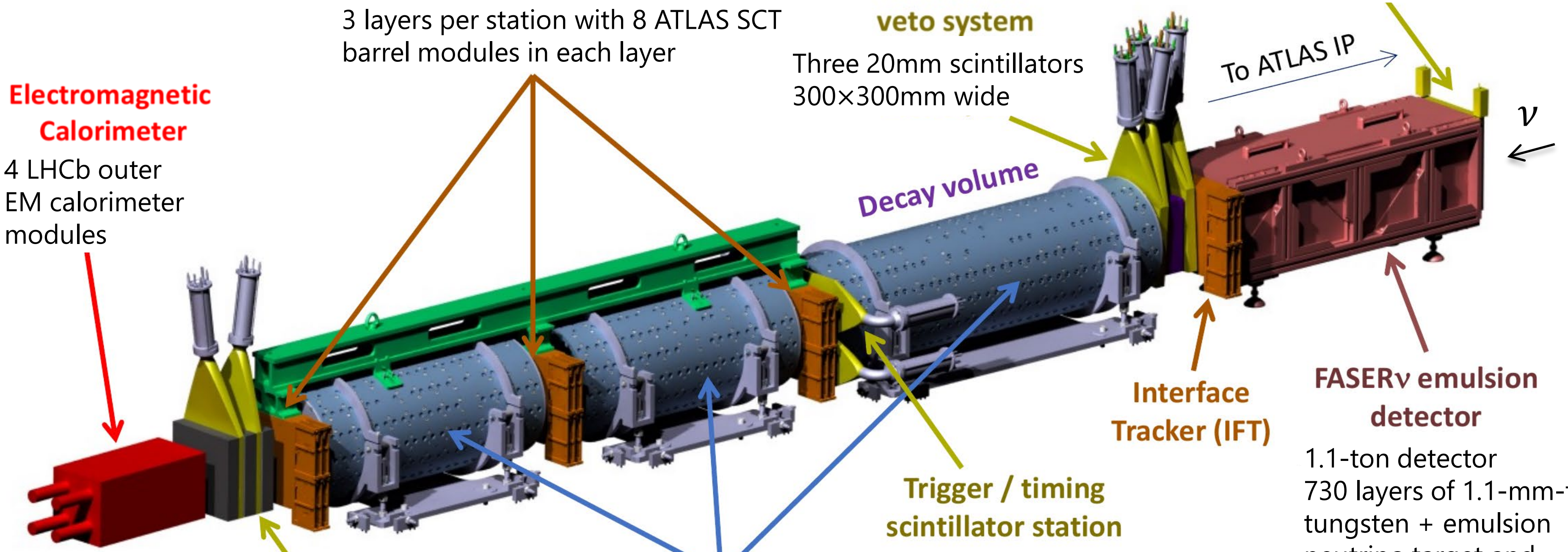
- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles.
- FASERν's measurements provide novel input to QCD (low-x PDFs, intrinsic charm, saturation) and astroparticle physics (prompt atmospheric neutrinos, cosmic ray muon puzzle)
- First data on forward charm, hyperon, and kaon

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

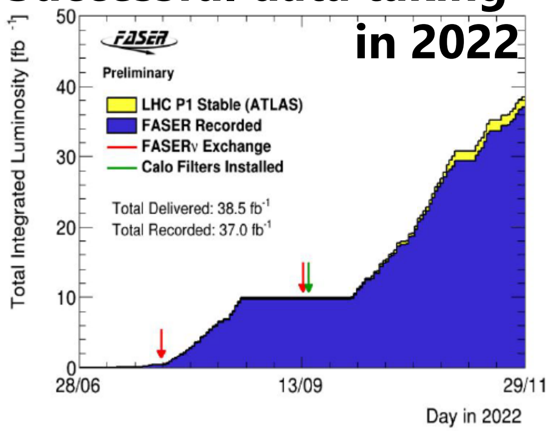


The FASER detector

“The FASER Detector”, arXiv:2207.11427



Successful data taking in 2022

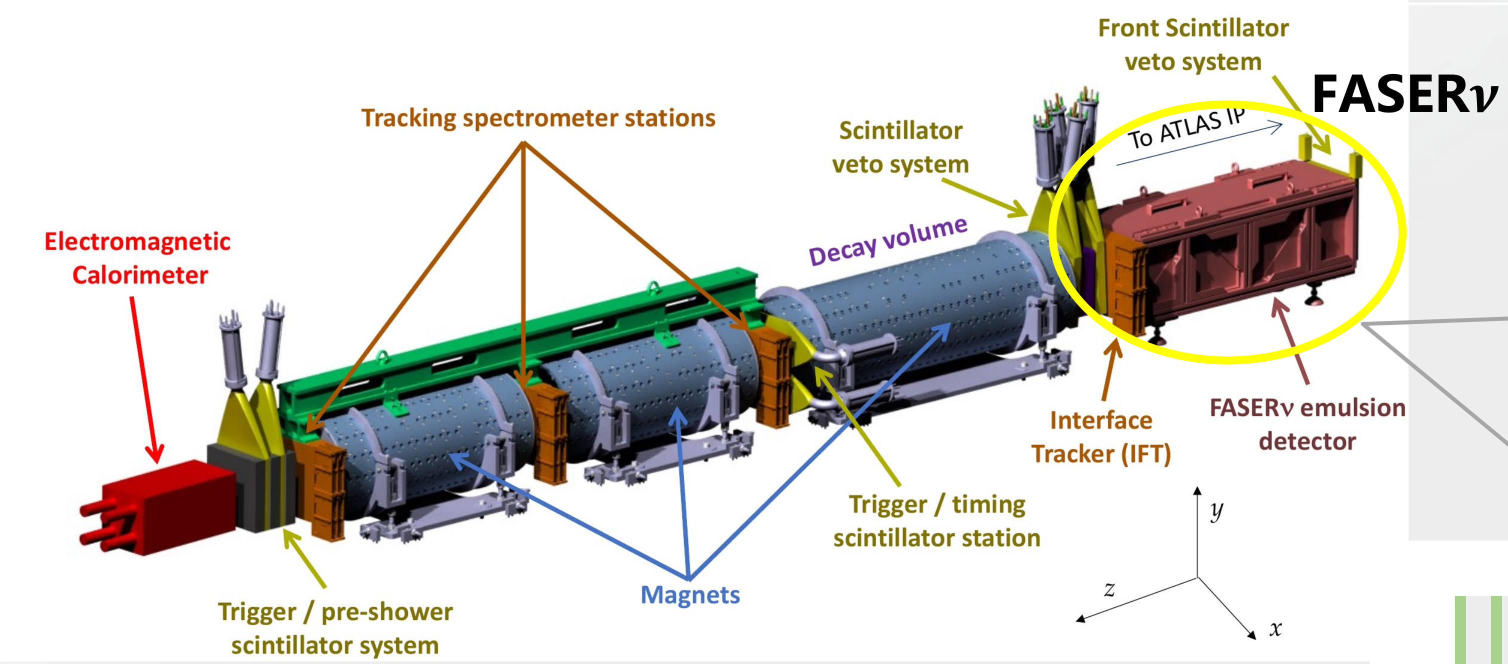


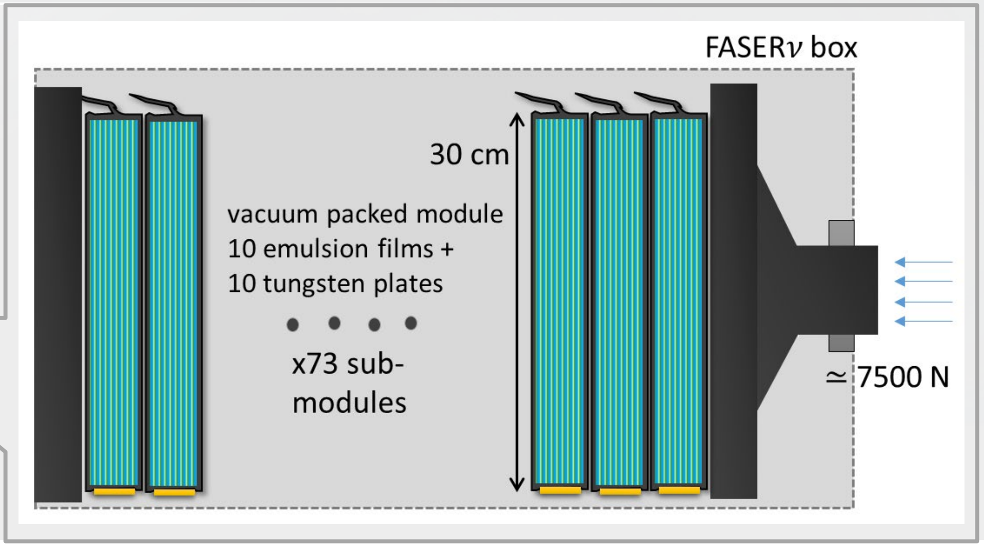
Constraints on unexplored dark photon parameter space

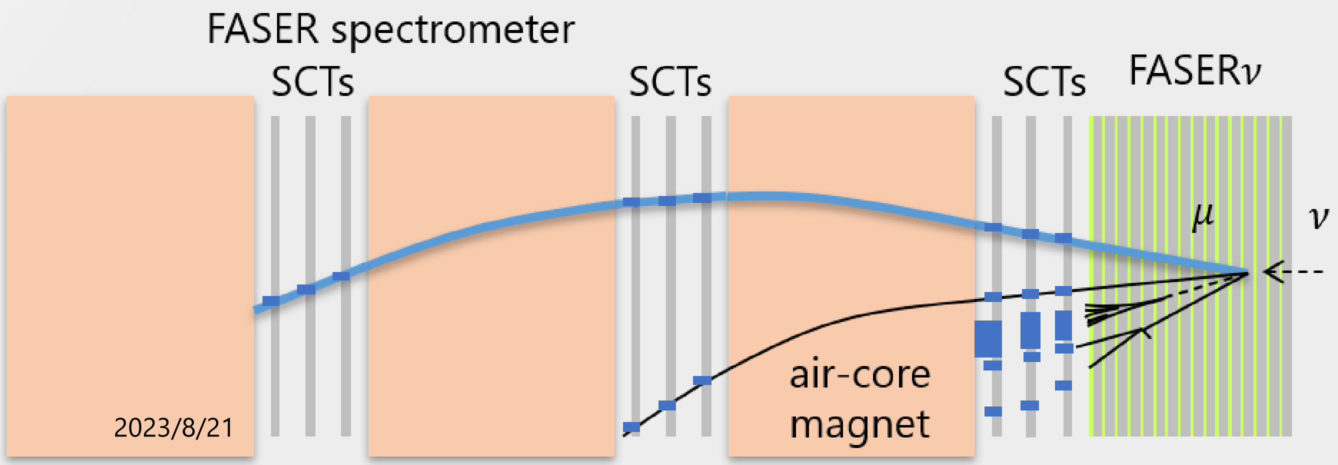
“Search for Dark Photons with the FASER detector at the LHC”, arXiv:2308.05587

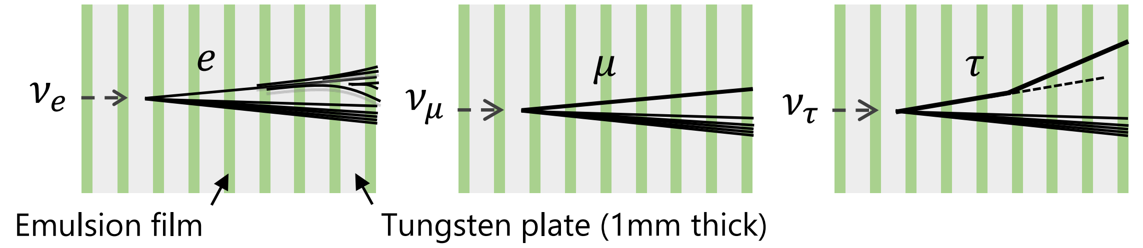
The FASERν detector

See also **Jeremy Atkinson's talk** in WG2 on Aug 25, "Operation and results of the FASERν detector"









Emulsion/tungsten detector

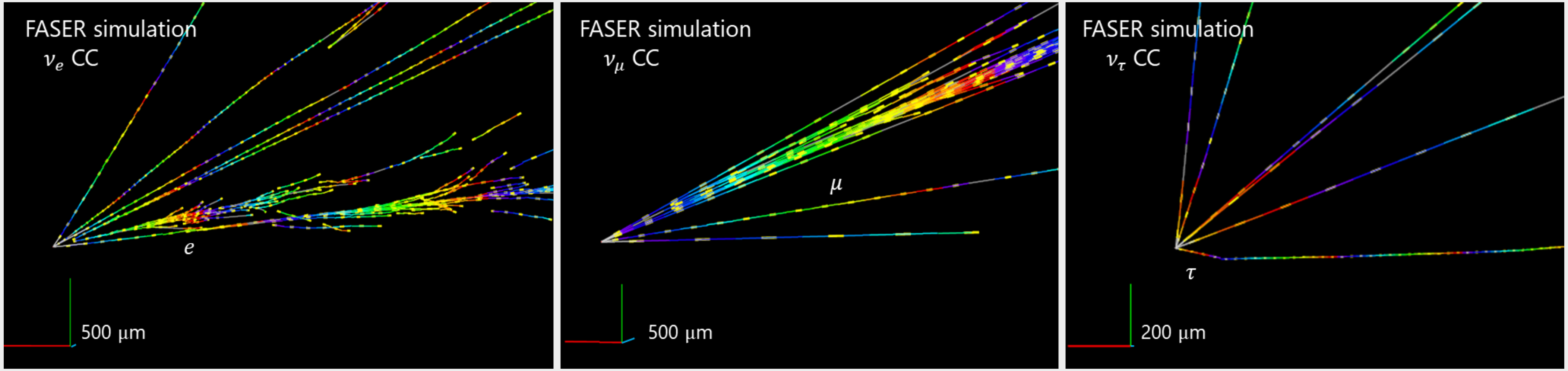
- 730 1.1-mm-thick tungsten plates, interleaved with emulsion films
- 25×30 cm^2, 1.1 m long, 1.1 tons

Expected neutrino event rates

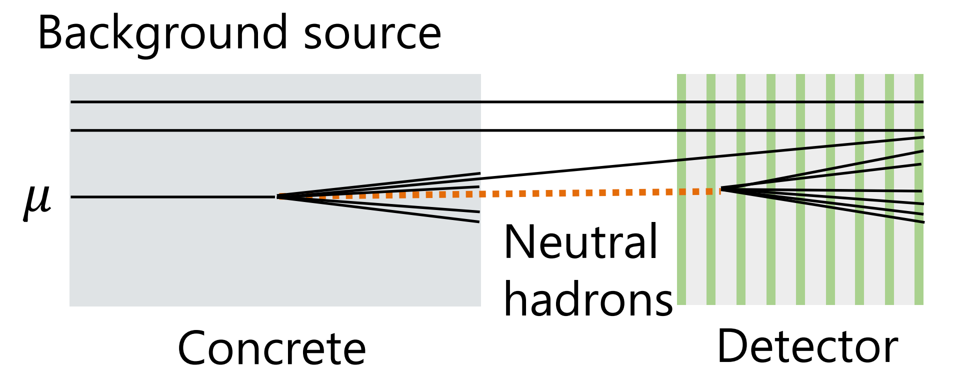
Based on
F. Kling and L. J. Nevay,
"Forward Neutrino Fluxes at the LHC",
Phys. Rev. D 104, 113008

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

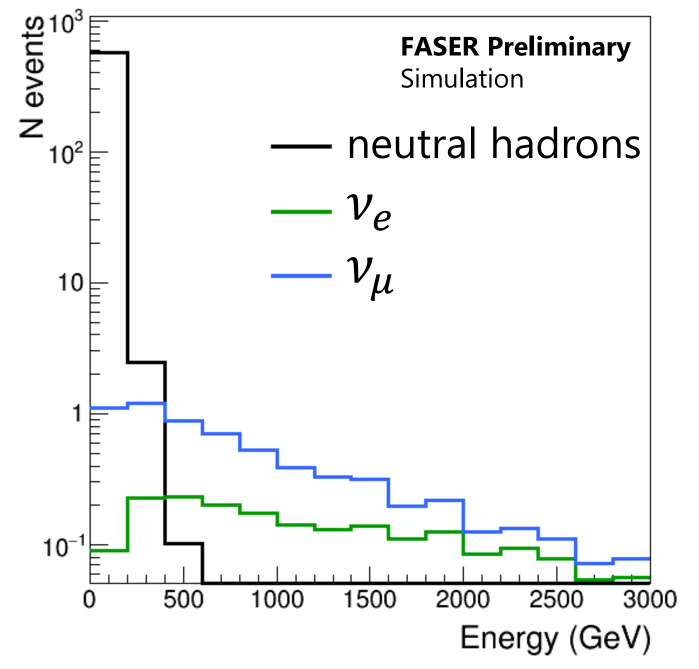
Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	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.



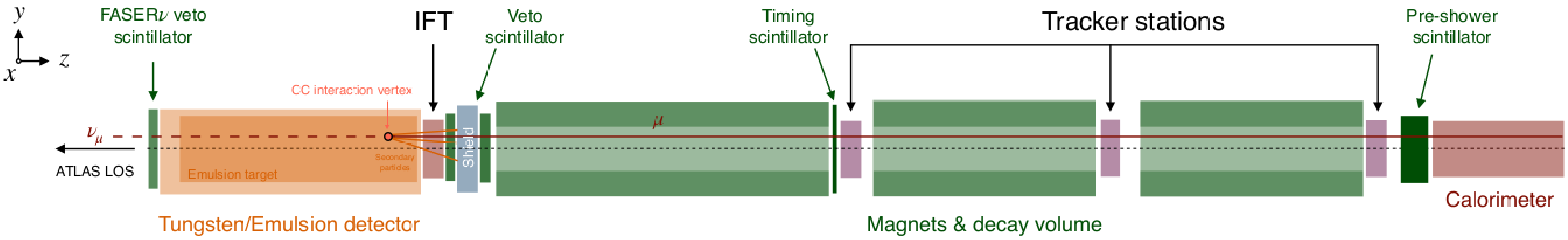
	Interaction rates of neutral hadrons with $\mathrm{E_h}$ >200 GeV in 150 tungsten plates per incident muons
K_S	2.1×10^{-5}
K_L	2.5×10^{-4}
n	2.0×10^{-4}
Λ	2.3×10^{-4}
$\bar{\Lambda}$	3.1×10^{-5}

First direct observation of ν_μ interactions at the LHC

by the FASER electronic detectors

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

- **Event selection**
  - Collision event with good data quality (35.4 fb^{-1})
  - **No signal in two front veto scintillators** (<40 pC~0.5 MIP)
  - Signal in last two veto layers
  - Signal and pre-shower scintillators consistent with ≥1 MIPs
  - Exactly **one good quality spectrometer track with p>100 GeV**
  - Track in fiducial tracking volume, r<95 mm
  - Track extrapolate to r<120 mm in front veto scintillator
  - Track polar angle less than 25 mrad
- Signal expectation
  - 151 ± 41 events
  - Uncertainty from DPMJET vs SIBYLL
- Background estimate
  - Neutral hadrons: 0.11 ± 0.06 events
  - Scattered muons: 0.08 ± 1.83 events
  - Front veto inefficiency: negligible



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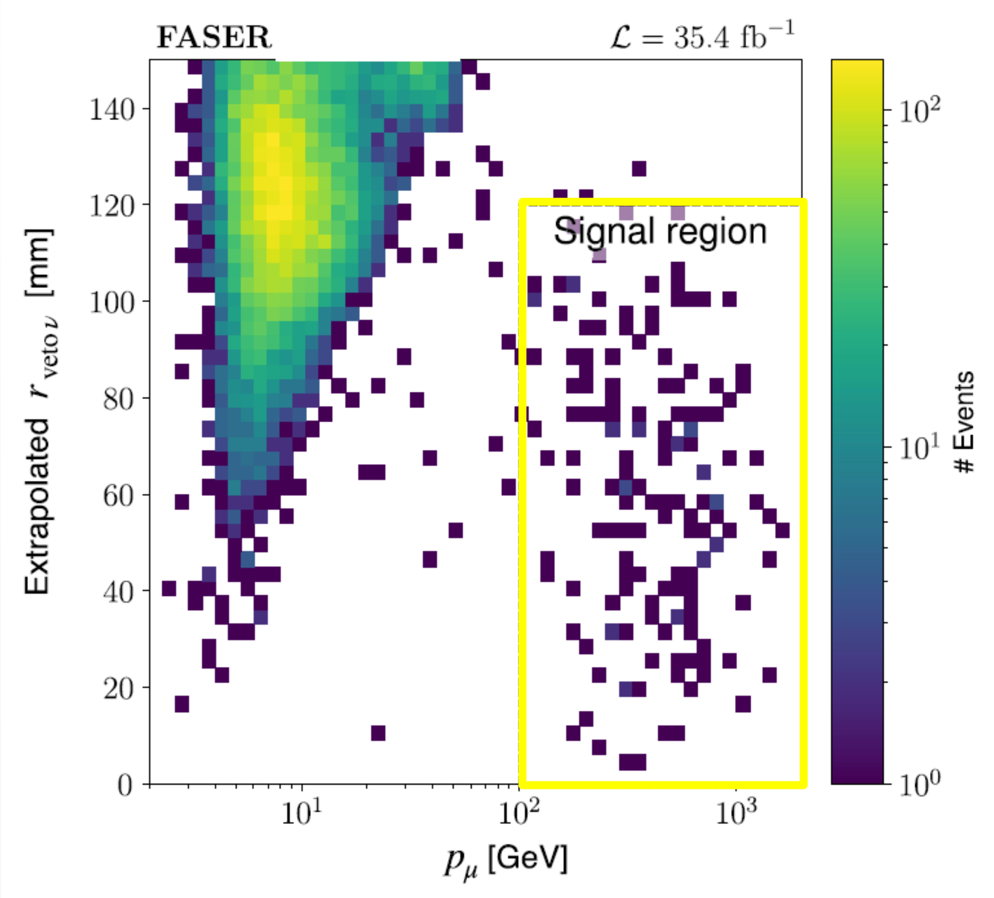
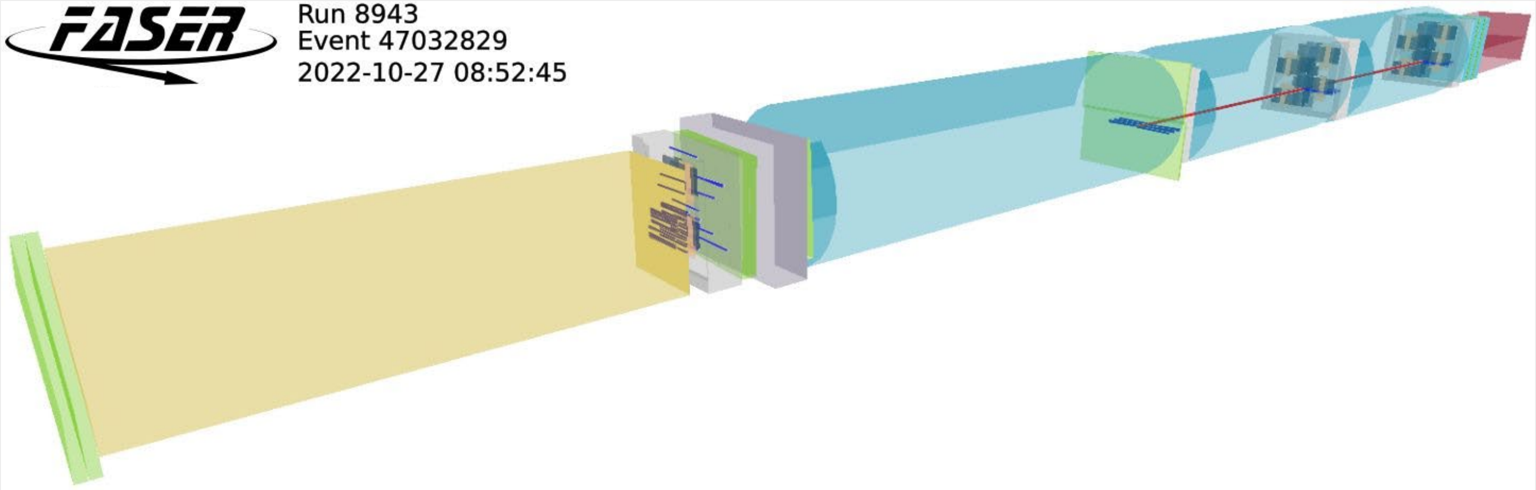


Unblinded results:
153 events in the signal region
(significance of 16σ)

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

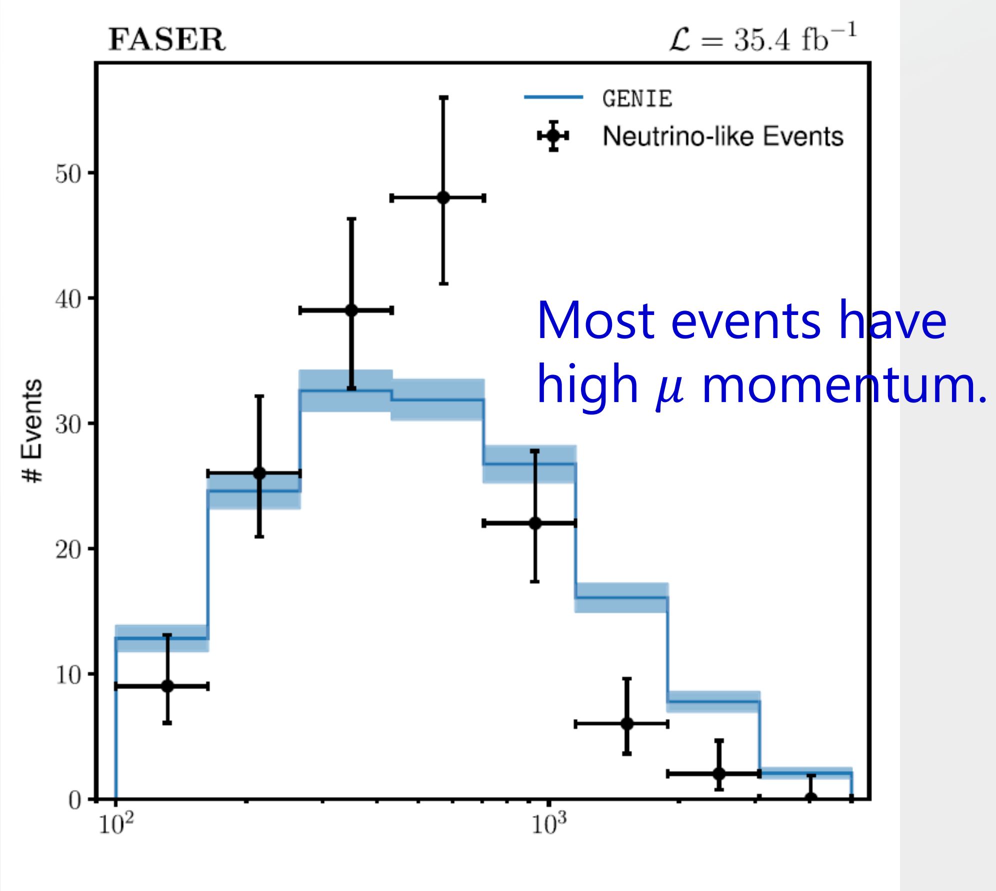


First direct observation of ν_μ interactions at the LHC

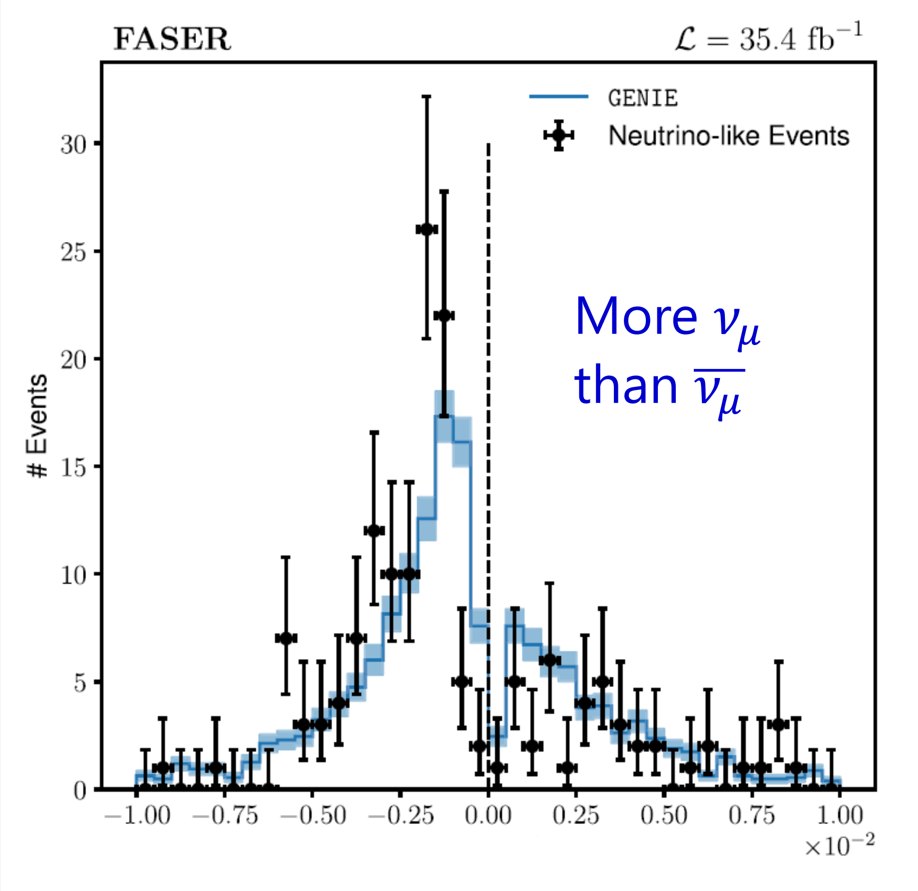
by the FASER electronic detectors

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

- Signal event distributions



Reconstructed momentum p_μ (GeV)



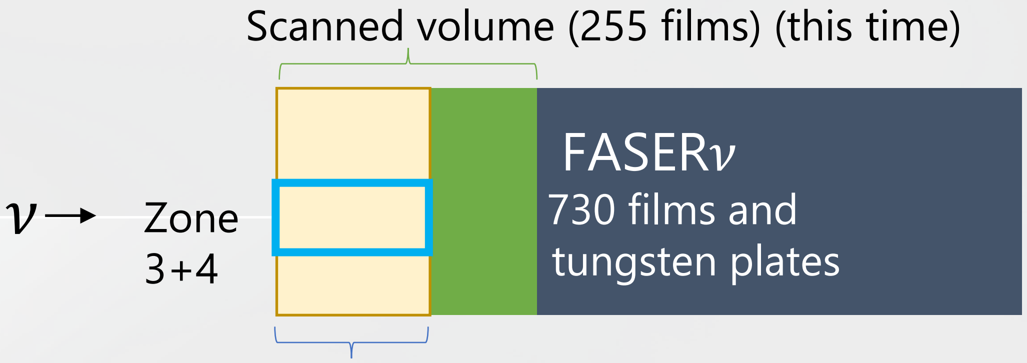
q/p_μ (GeV^{-1})

(No systematic uncertainties are included (e.g., on the efficiencies/resolution in the MC).)

New results
from the FASERν emulsion detector

- **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 $\nu_\mu + \overline{\nu_\mu}$.)

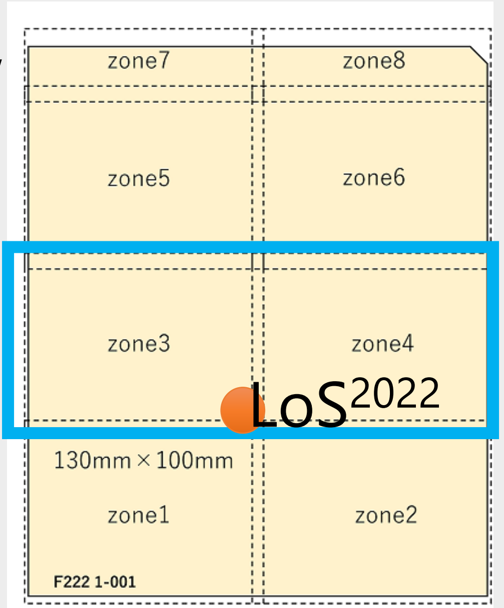
module name	installed period	load	integrated luminosity per module (fb^{-1})
2022 1st module (F221)	Mar 15 - Jul 26	30%	0.4705
2022 2nd module (F222)	Jul 26 - Sep 13	100%	9.523
2022 3rd module (F223)	Sep 13 - Nov 29	100%	28.9082



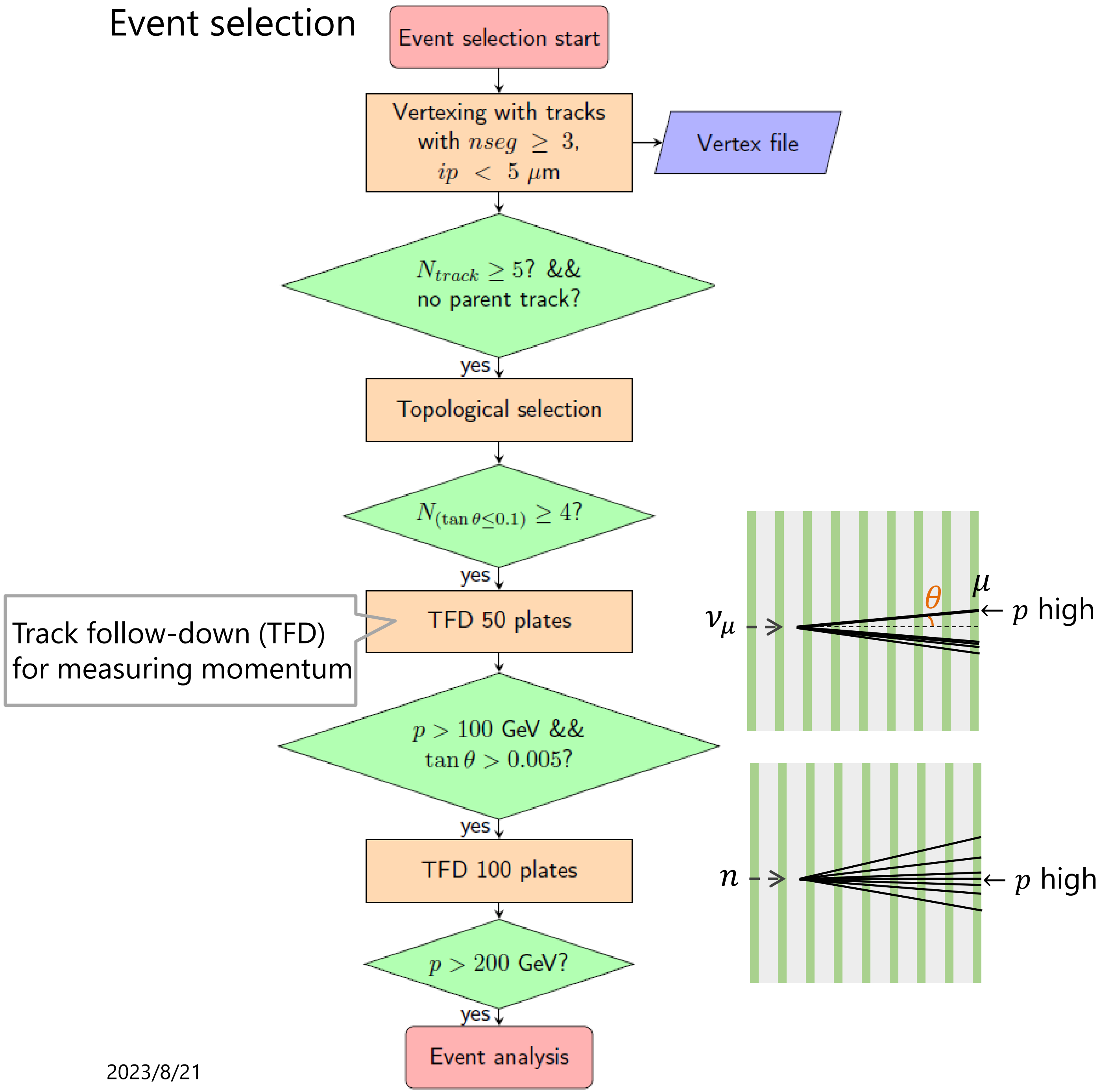
Target volume for the first analysis (150 tungsten plates)

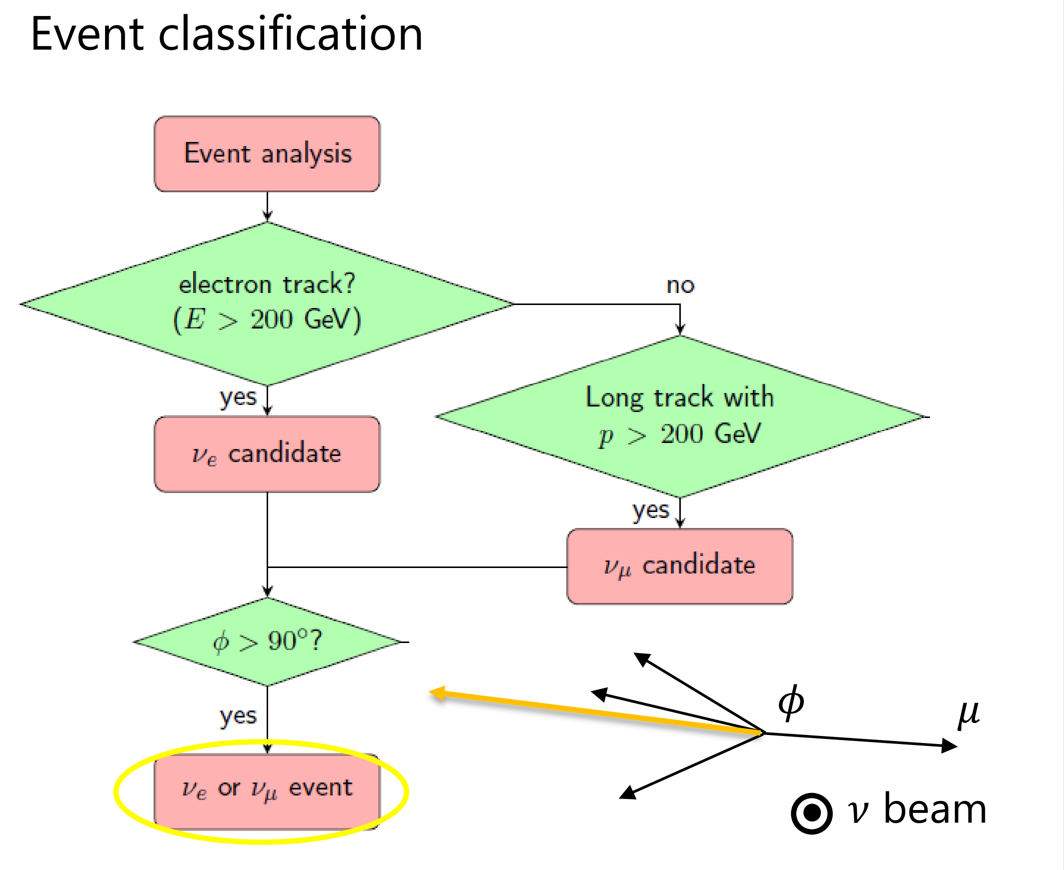
Target mass (zone 3+4)
$\simeq$ 9 cm x 24 cm x 0.1087 cm x 150 x 19.3 g/cm^3
= 68.0 kg

Top view



New results from FASERν: event selection procedure



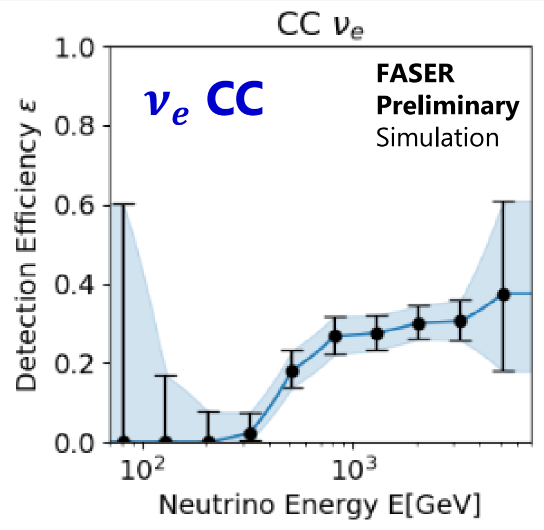


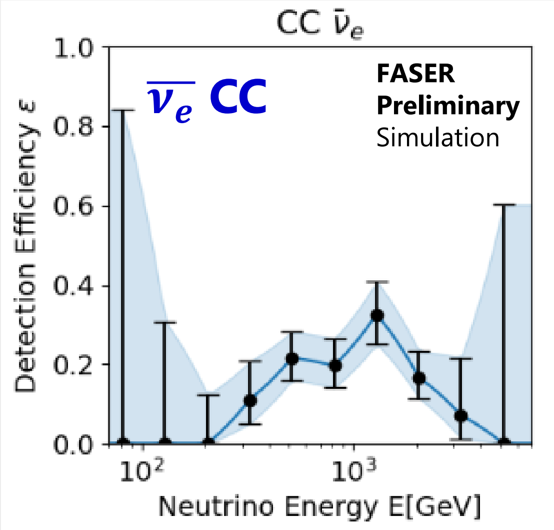
New results from FASERν: efficiencies

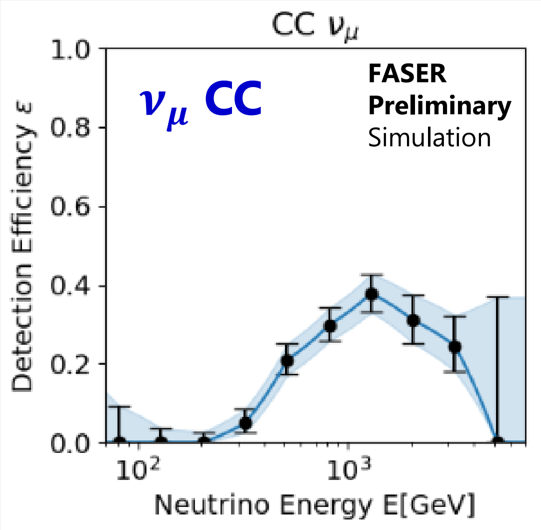
Breakdown of the efficiencies

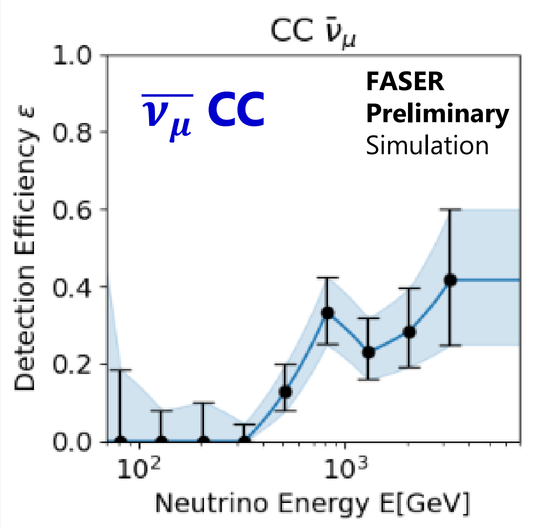
Selection	ν_e CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.516	0.336	0.813	0.803	0.753
E >200 GeV	0.340	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005	0.270	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.226	0.000	0.000	0.000	0.000

Selection	ν_μ CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.446	0.336	0.813	0.803	0.753
p >200 GeV	0.284	0.071	0.028	0.026	0.018
p >200 GeV, tanθ >0.005	0.236	0.051	0.007	0.013	0.007
p >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.192	0.004	0.002	0.006	0.004



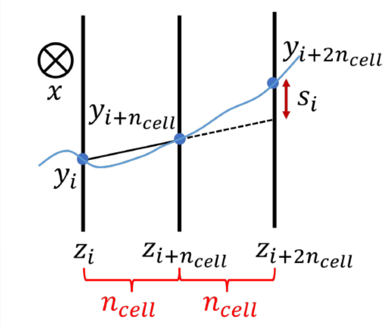


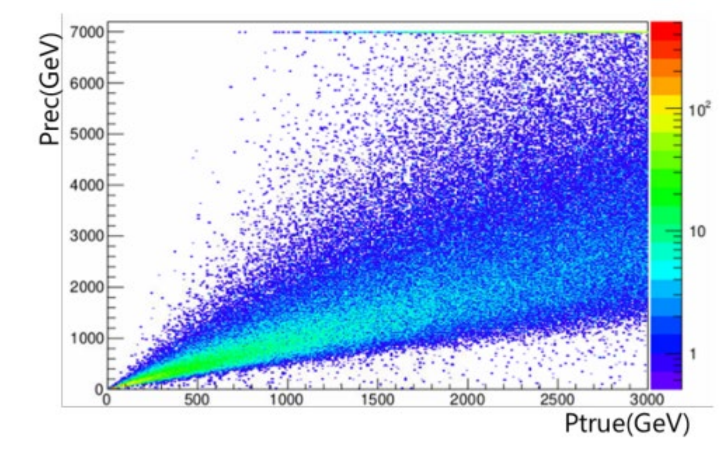


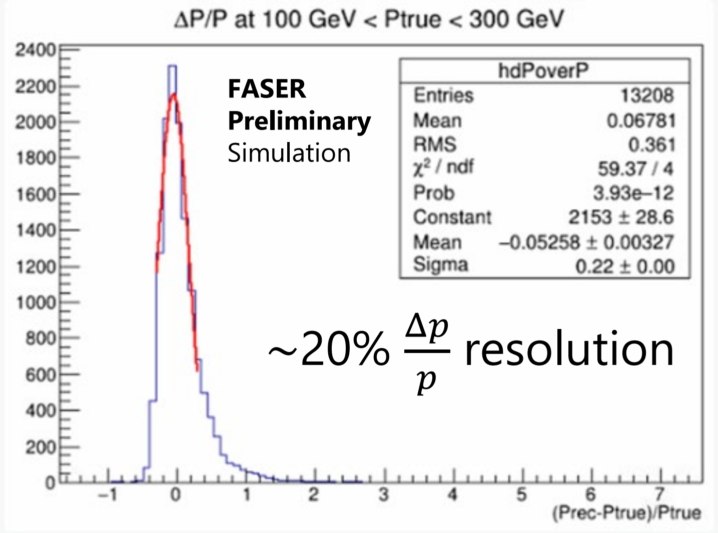


New results from FASERν: detector performance

Momentum measurement

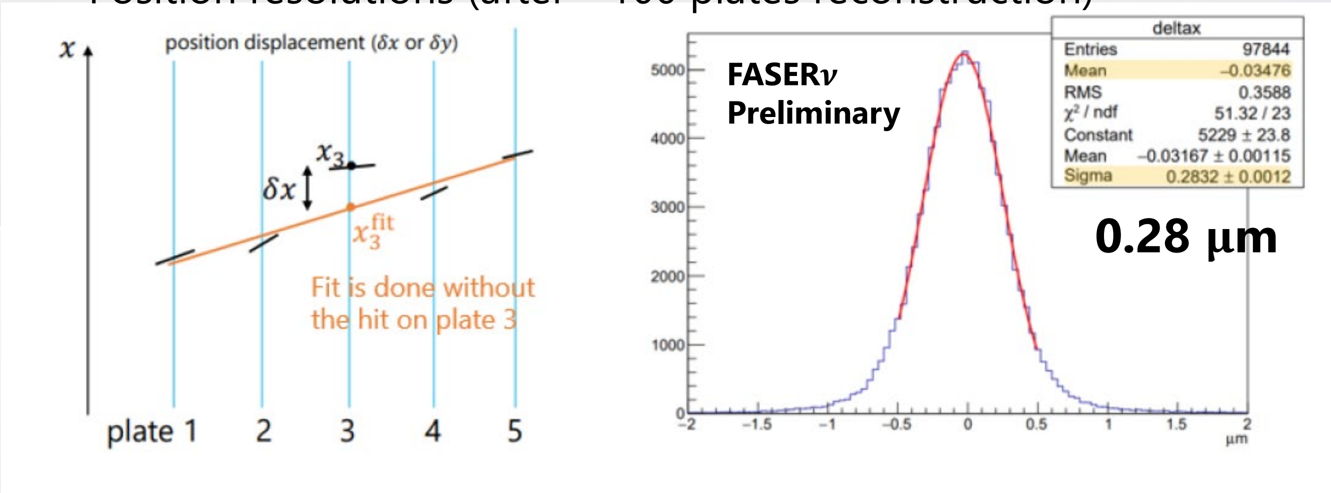






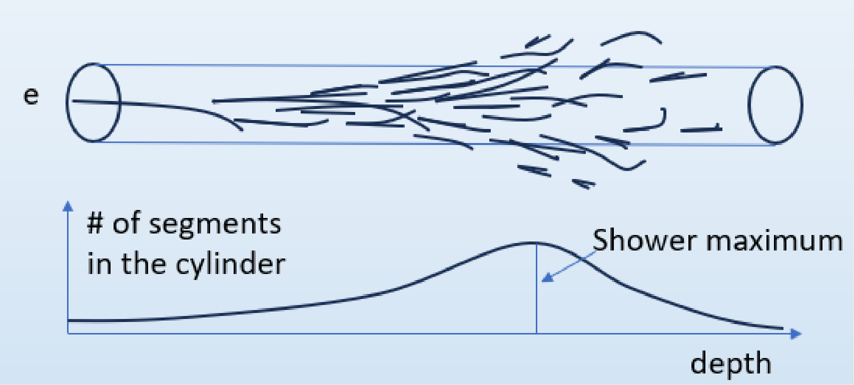
Momentum measurement performance is validated in the data using split tracks, confirming the MC results.

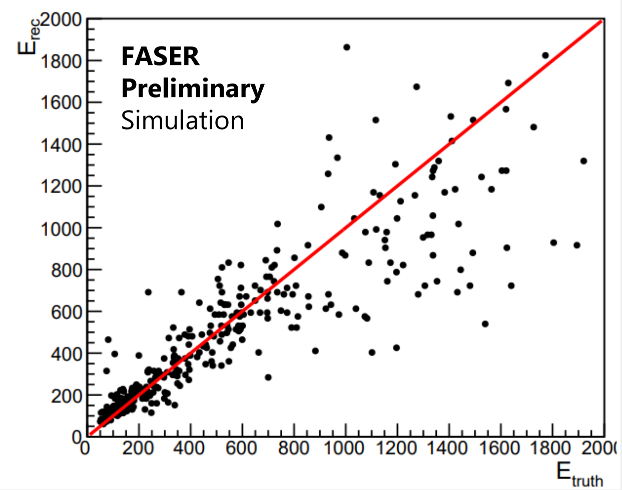
Position resolutions (after ~100 plates reconstruction)



Electron energy measurement

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





New results from FASERν: background study using the data

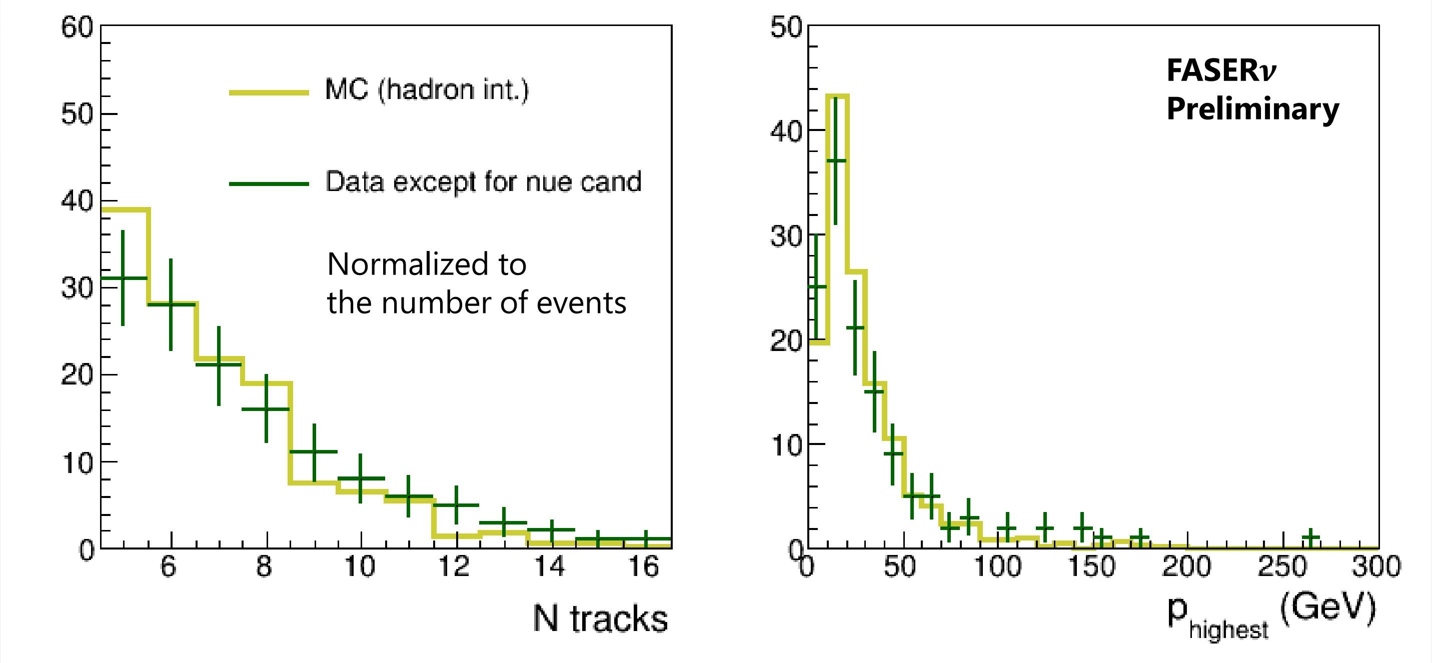
Detected vertices **before the high-energy selection** are dominated by neutral hadron interactions.

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

- For the background estimate after the selection, we used MC samples of individual neutral hadrons (equivalent to 20x the data).
  - ν_μ BG: 6 MC events seen with p>200 GeV
  - ν_e BG: no MC events seen with E_e>200 GeV, and only 1 event with E_e>50GeV

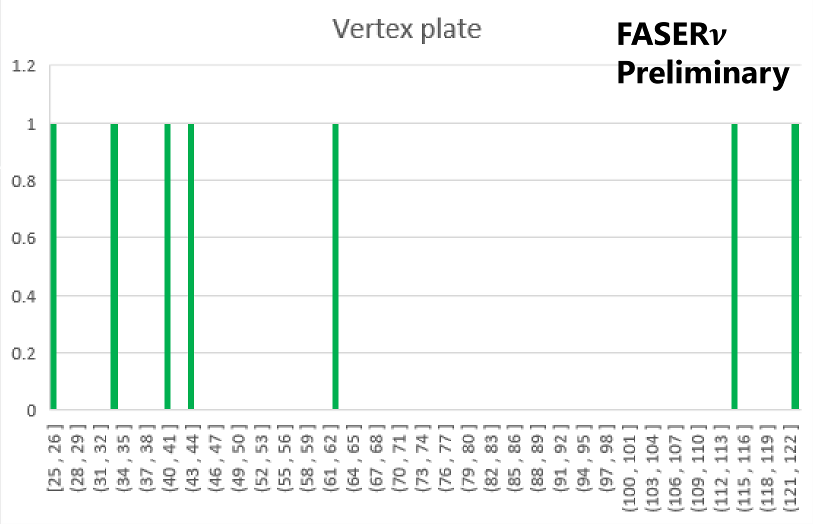
New results from FASERν: results of the selection

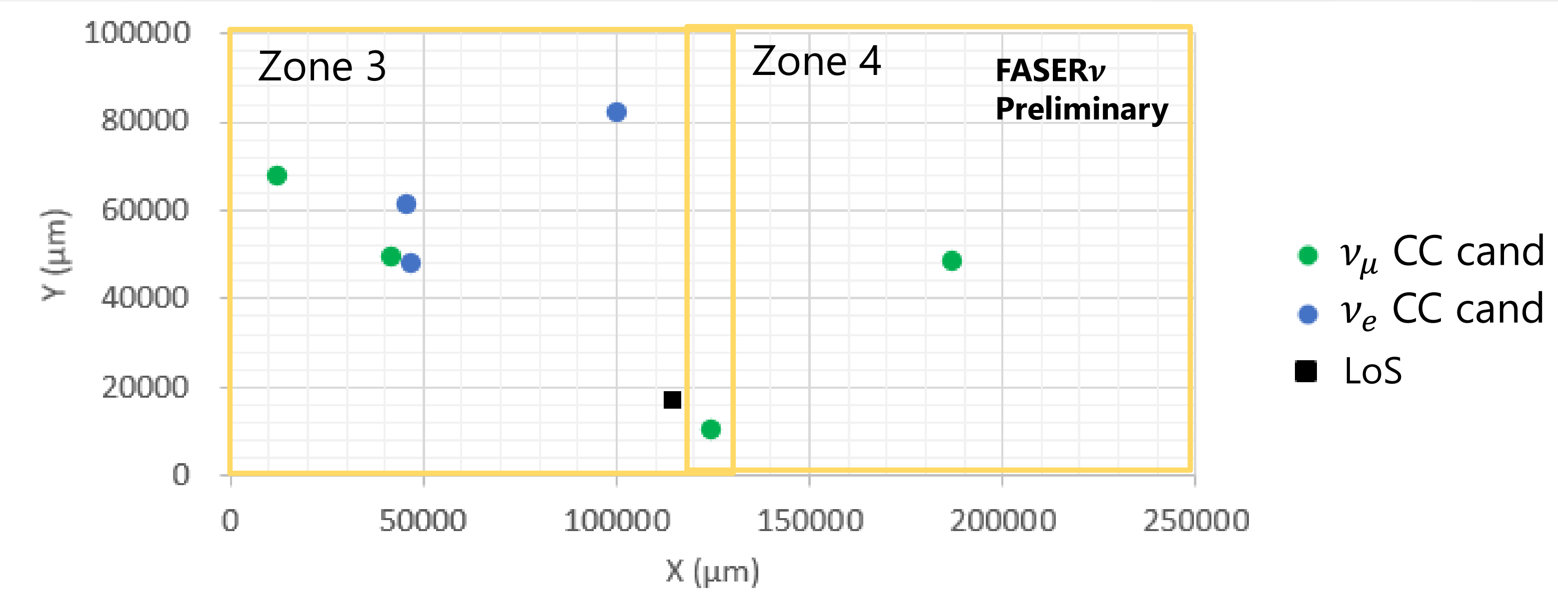
After applying
the high-energy selection

FASERν Preliminary

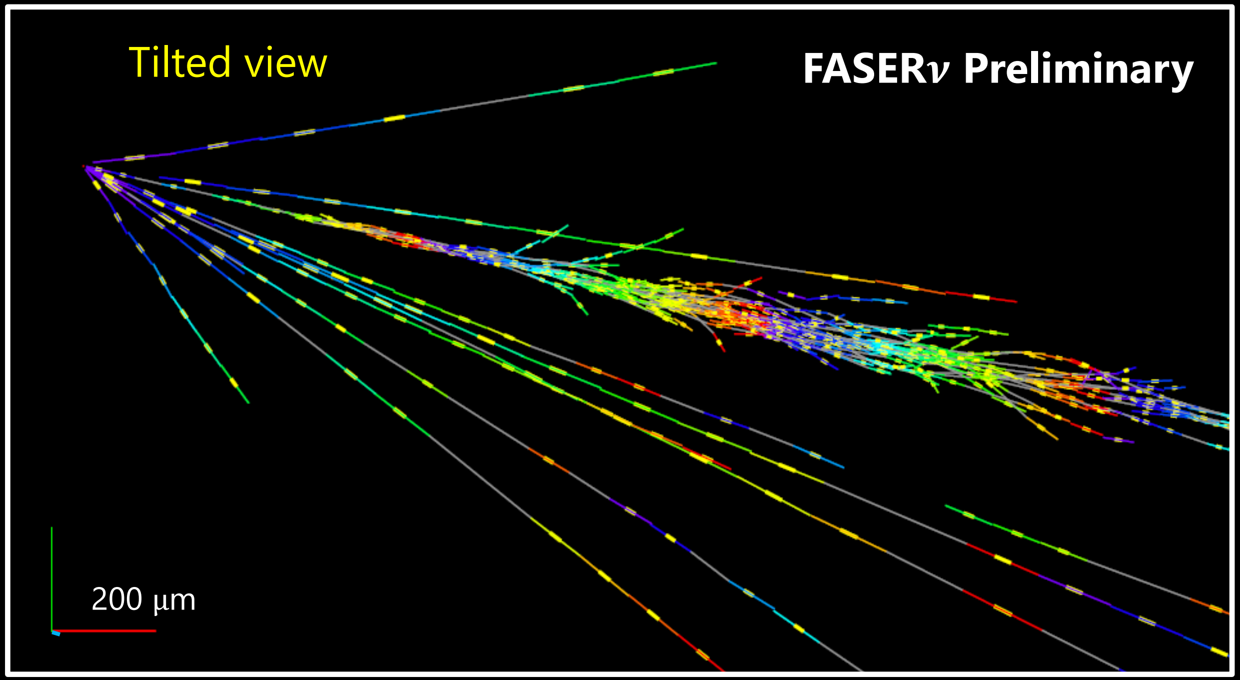
	Data
ν_e **CC**	3
ν_μ **CC**	4

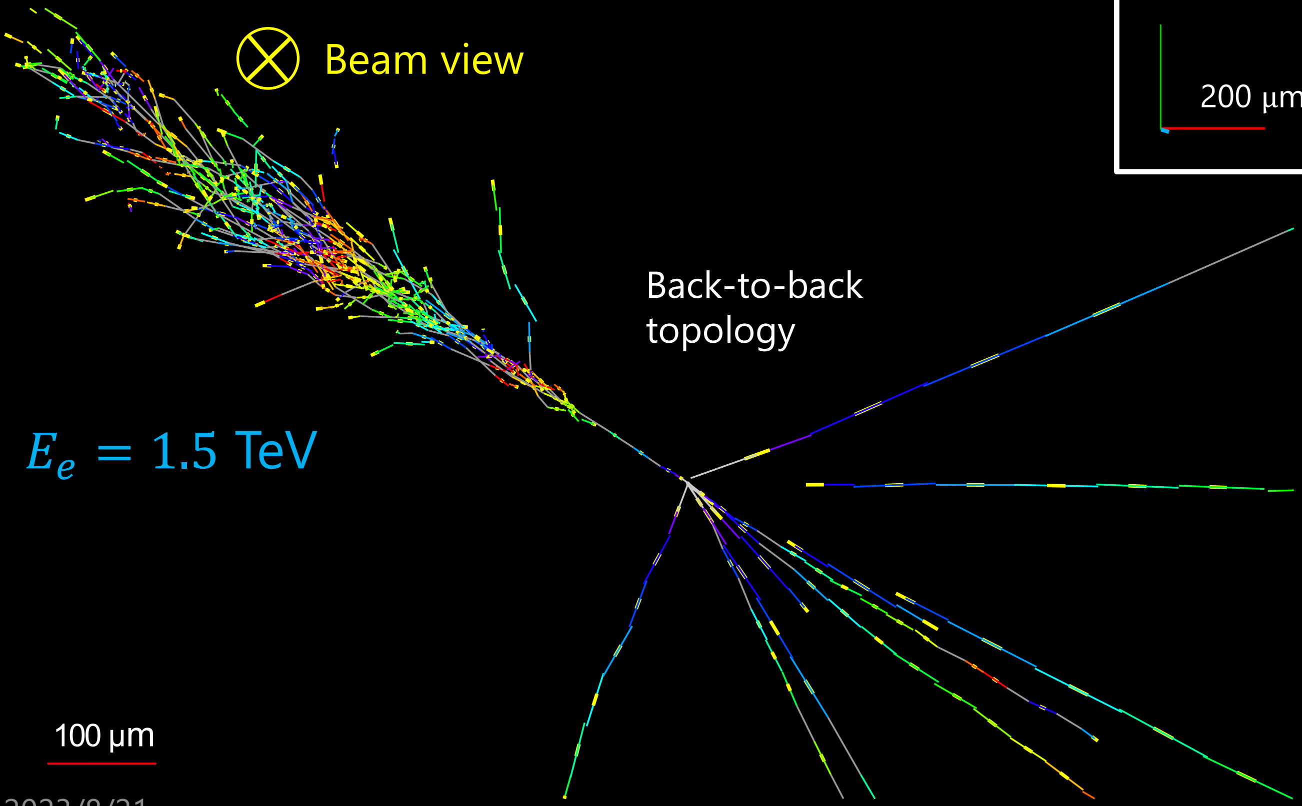
Vertex positions of
the CC interaction candidates





New results from FASERν: one of the ν_e CC candidates



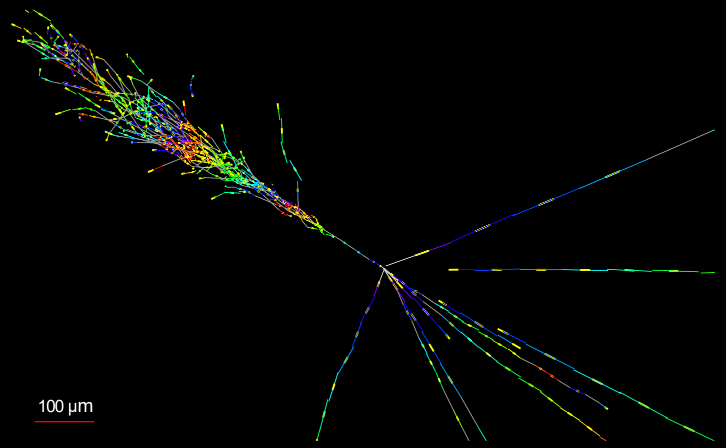


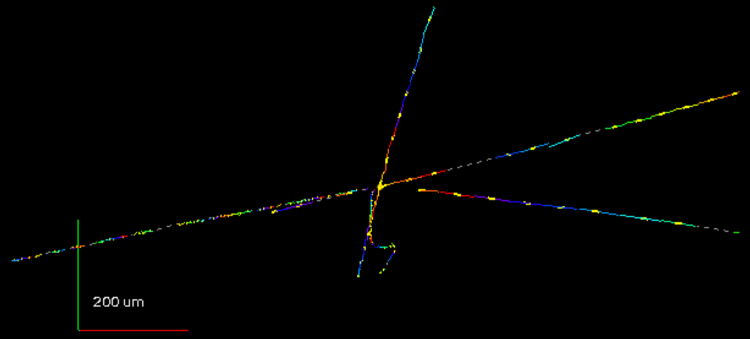
- 11 tracks at the vertex, 615 µm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- 175° between e-like track and others
- θ_e = 11 mrad w.r.t. beam

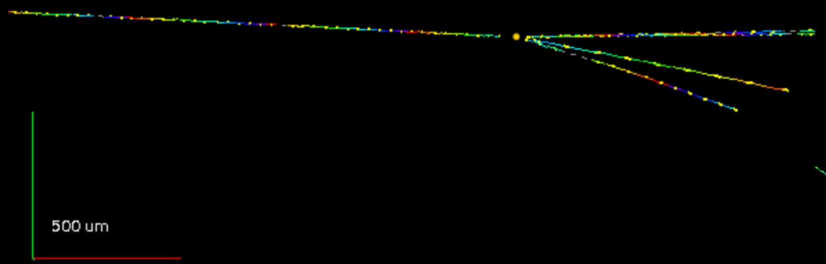
All the ν_e and ν_μ CC candidate events

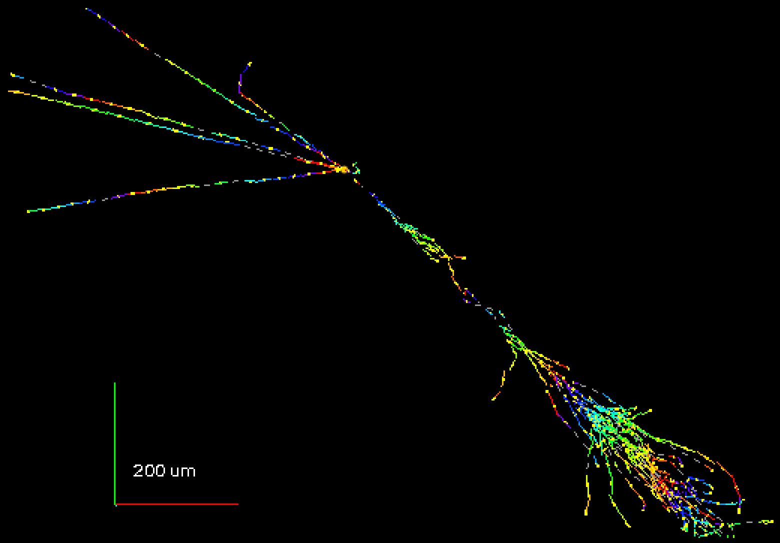
FASERν Preliminary

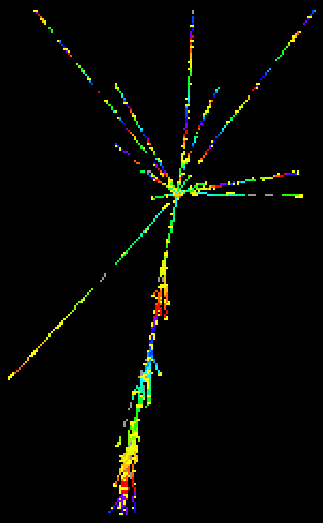
Beam view

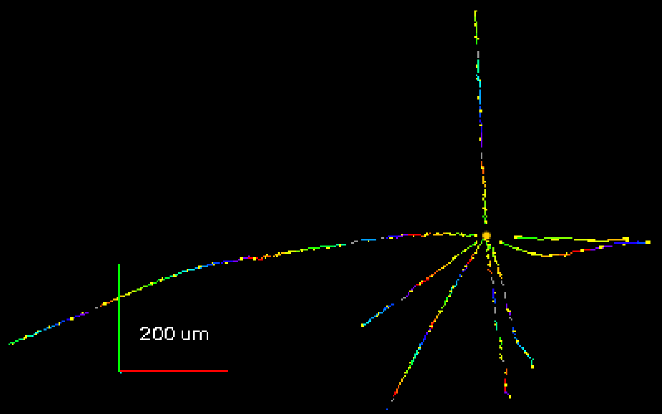


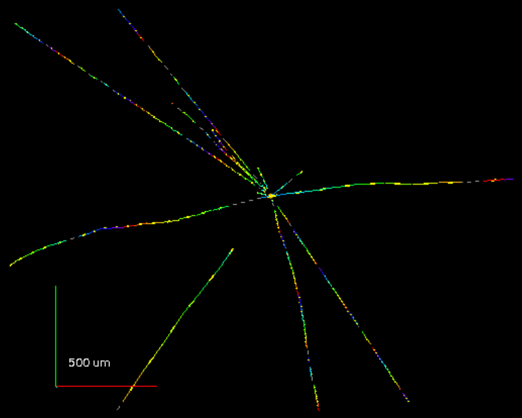




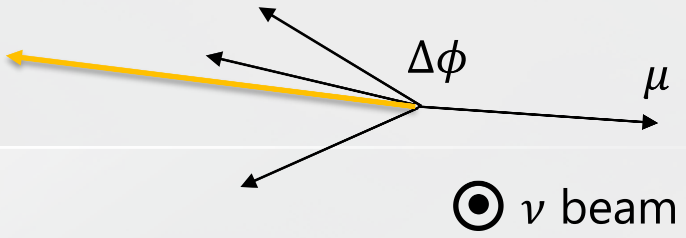




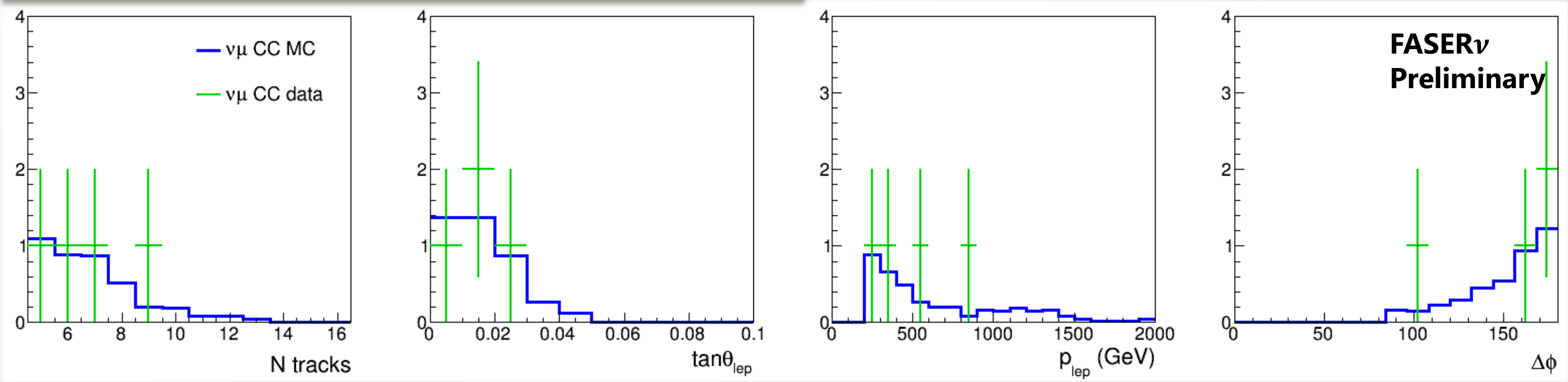




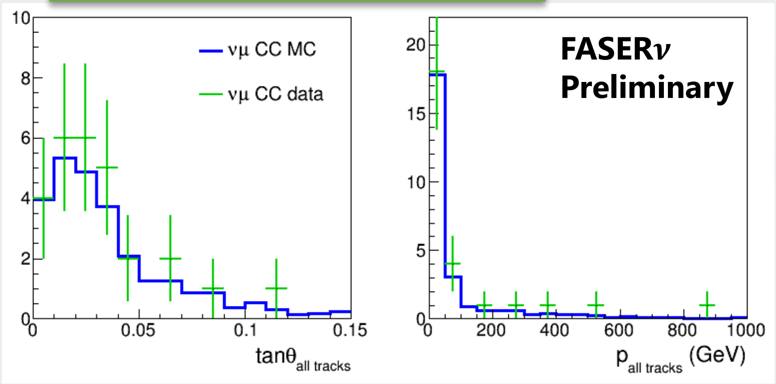
New results from FASERν: data/MC comparisons



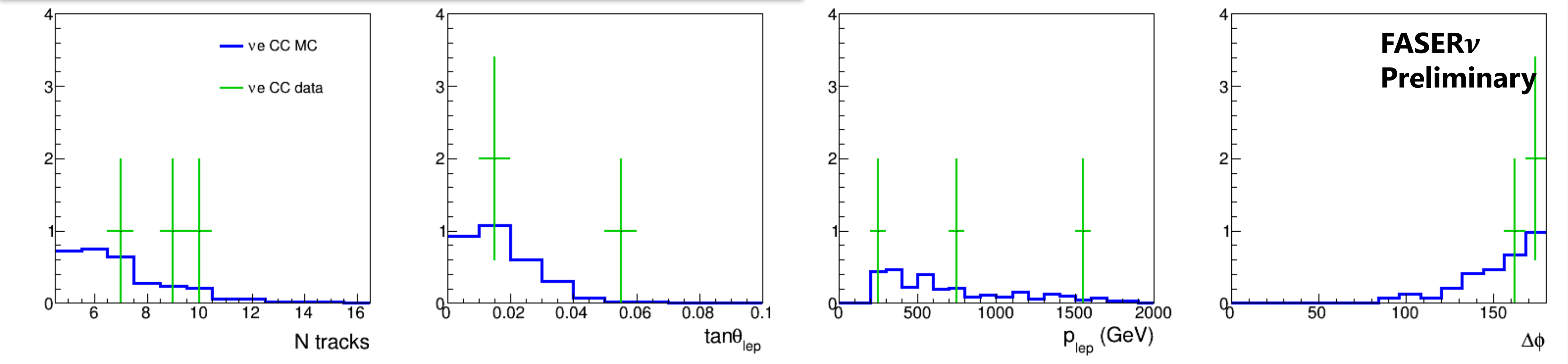
Vertex information of the ν_μ CC candidates



Tracks from the vertices



Vertex information of the ν_e CC candidates



New results from FASERν: statistical significance

FASERν Preliminary

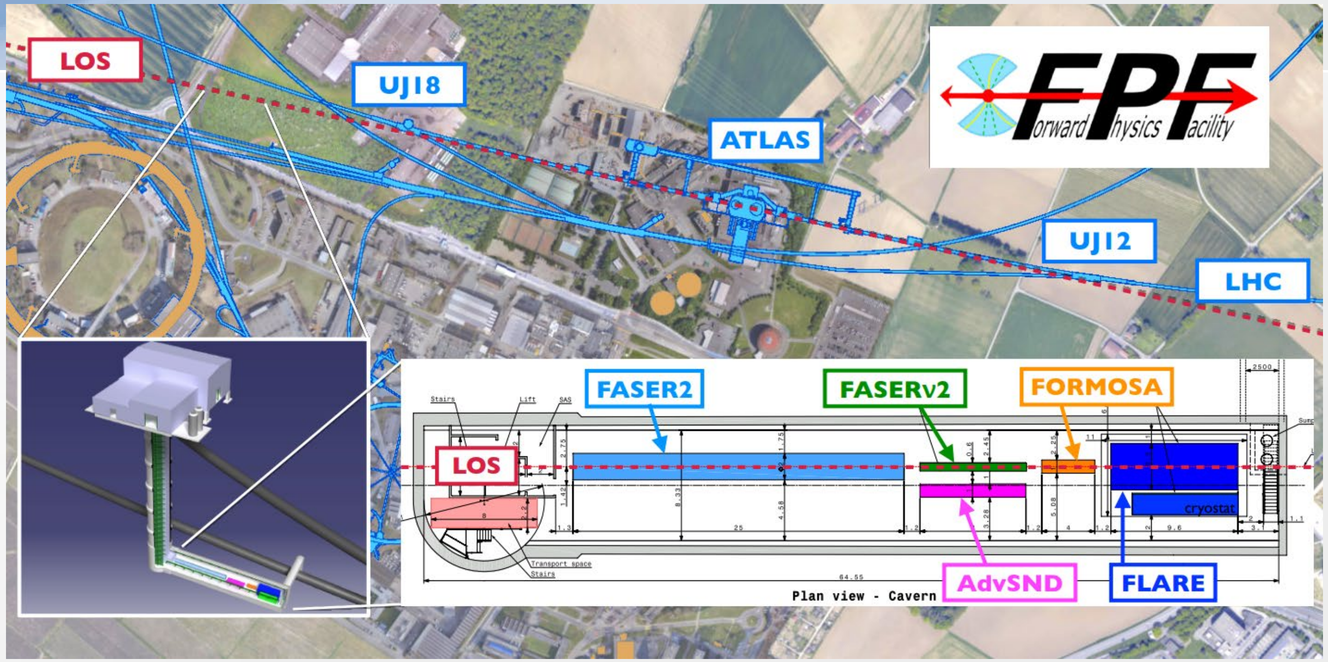
	Expected background		Expected signal	Observed	
	Hadron int.	ν NC int.			
ν_e CC	0.002±0.002	-	$1.2^{+4.0}_{-0.6}$	3	$p = 1.6 \times 10^{-7}$ (5.1σ)
ν_μ CC	0.32±0.16	0.19±0.15	$4.4^{+4.2}_{-1.4}$	4	$p = 5.2 \times 10^{-3}$ (2.5σ)

3 ν_e CC candidate events are observed.
→ Probability to be explained by background is 1.6×10^{-7}, corresponding to 5σ exclusion of the background-only hypothesis.

First direct observation of electron-neutrino CC interactions at the LHC

The performance of ν_μ detection will be improved in future analysis using a longer range for μ ID.

The Forward Physics Facility (FPF) and FASERν2

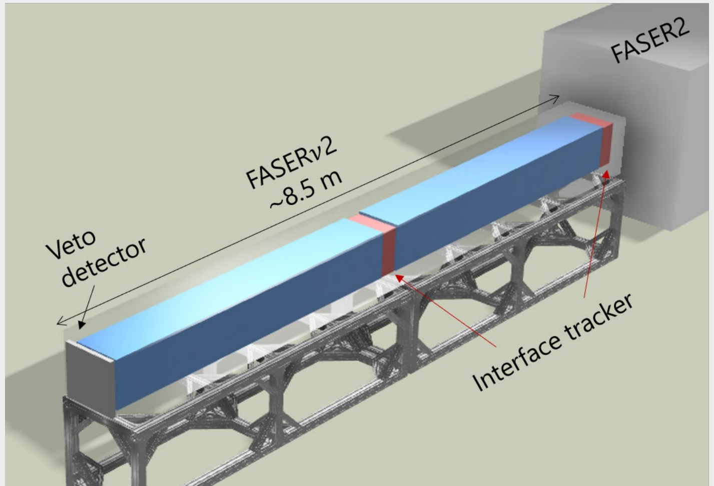


- FPF for the HL-LHC is a proposed facility that could house a suite of experiments to enhance the LHC's physics potential for BSM physics searches, neutrino physics and QCD.
- FASERν2 is designed to carry out precision tau-neutrino measurements and heavy flavor physics studies
  - Expected to be ~20 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

FPF papers

- "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

See also **Jianming Bian's talk** in WG3 on Aug 25, on the Forward Liquid Argon Experiment at the FPF



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.
- New 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.
  - Public note in preparation
- 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 neutrinos at highest energies ever observed, 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})

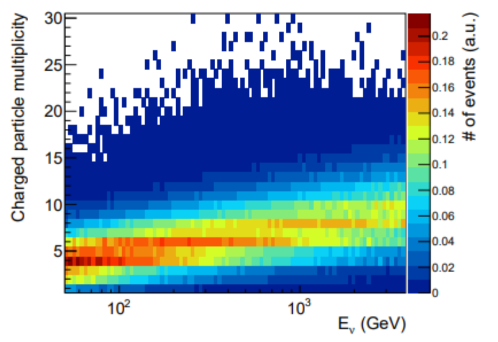
Generators		FASERν			SND@LHC		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5	223	1316	12.6
DPMJET	DPMJET	5761	11813	161	658	1723	31
EPOSLHC	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}	$14.6^{+4.5}_{-2.5}$

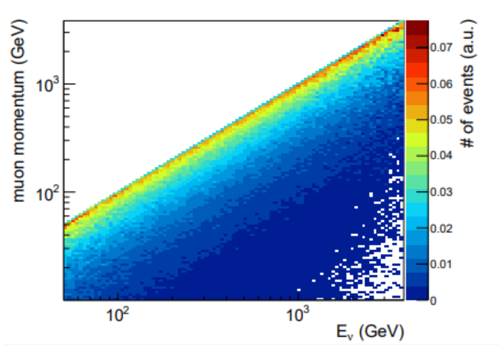
FASERν energy reconstruction

- Neutrino energy will be reconstructed by combining topological and kinematical variables

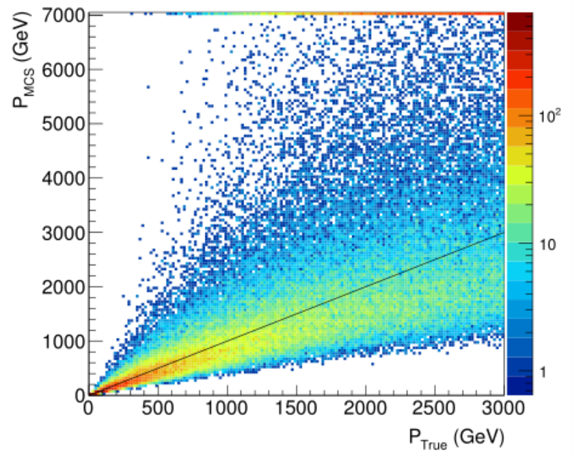
An ANN algorithm was built with
topological variables
- # of charged tracks → E_h
- # of γ showers → E_h
- inverse of lepton angle → E_l
- sum of inverse of hadron track angles → E_h
- inverse of median of all track angles → E_h, E_l

kinematical info (smeared)
- lepton momentum → E_l
- sum of charged hadron momenta → E_h
- sum of energy of γ showers → E_h

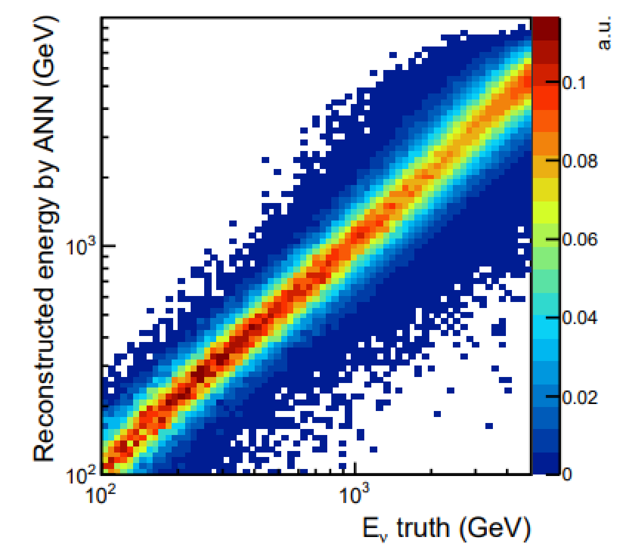




Momentum resolution
(using MCS in the emulsion detector)



$E_\nu - E_{ANN}$



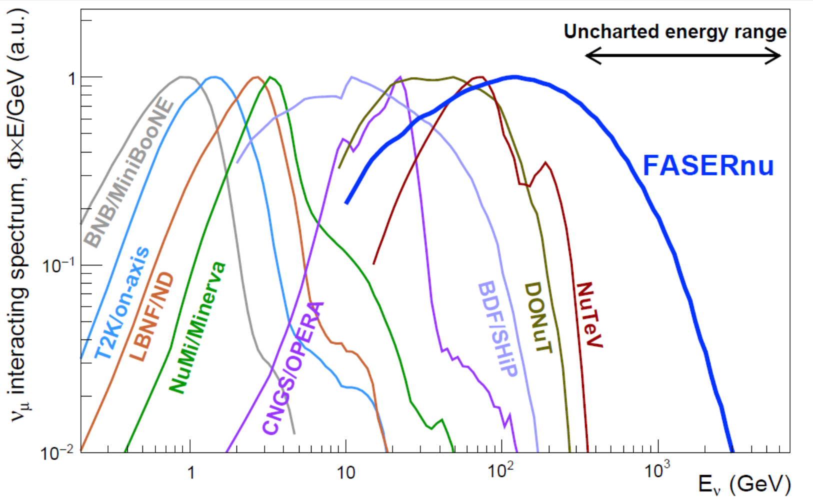
$$\frac{\Delta E_\nu}{E_\nu} \sim 30\%$$

FASERν physics potential (1): high-energy neutrino interactions

- Cross section measurements of **different flavors at TeV energies**
  - where no such measurements currently exist.

Expected number of charged-current interactions in FASERν during LHC Run-3 $\sim 3000\ \nu_e, \sim 10000\ \nu_\mu, \sim 70\ \nu_\tau$ interactions

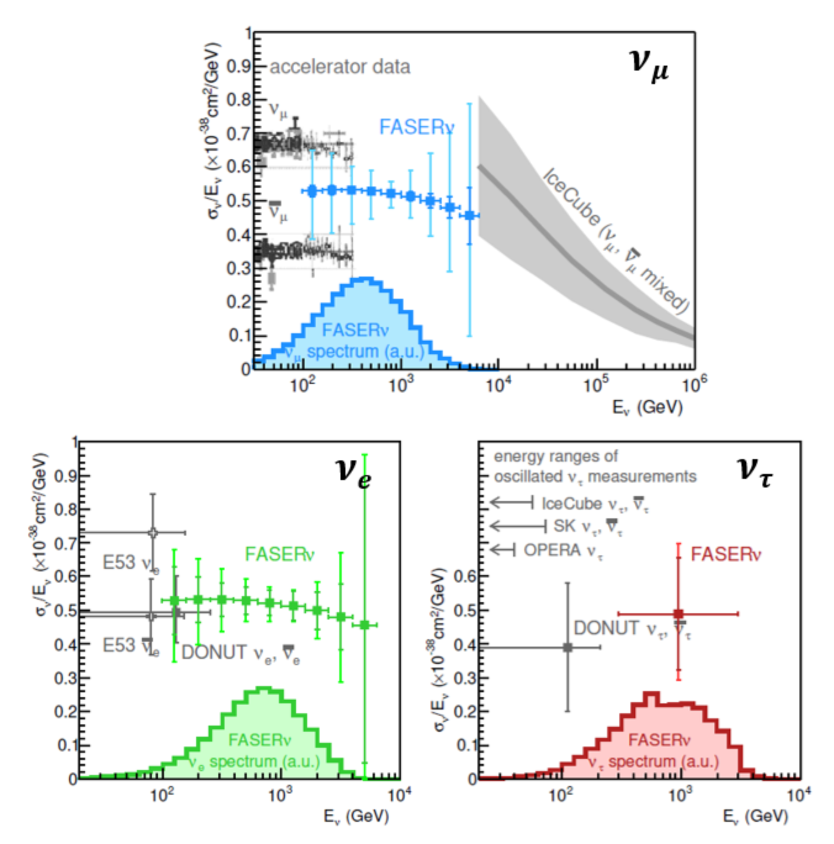
FASER Collaboration,
Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310



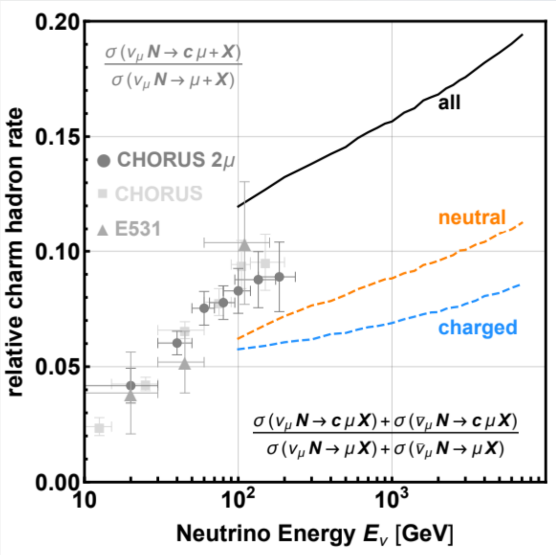
- Measurement of differential distributions
  - can be used to probe PDFs.

- Neutral-current measurements
  - could constrain neutrino non-standard interactions (NSI).

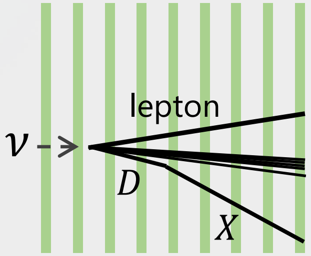
A. Ismail, R.M. Abraham, F. Kling,
Phys. Rev. D 103, 056014 (2021),
arXiv:2012.10500



FASERν physics potential (2): heavy-flavor-associated channels

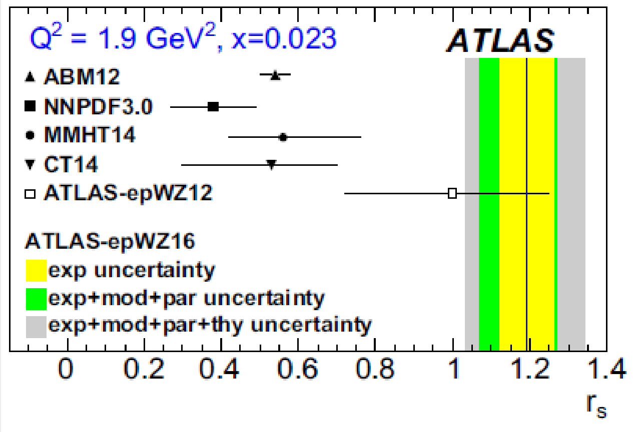


- Neutrino CC interaction with charm production ($\nu s \to lc$)
  - Study the strange quark content → Probe inconsistency between the predictions and the LHC data

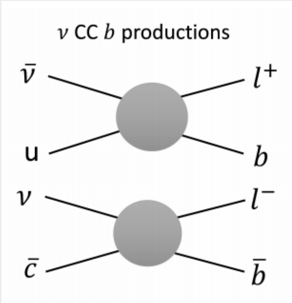


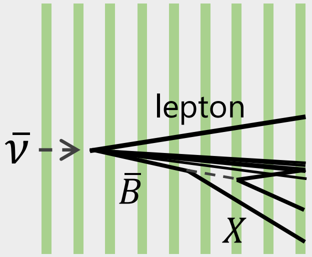
Eur. Phys. J. C77 (2017) 367

$$r_s = \frac{s+\bar{s}}{2\bar{d}}$$



- Neutrino CC interaction with beauty production
  - Has never been detected.

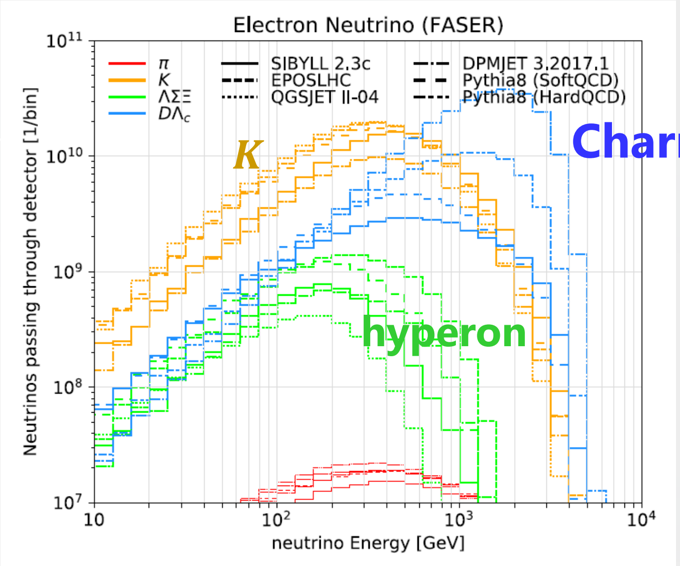


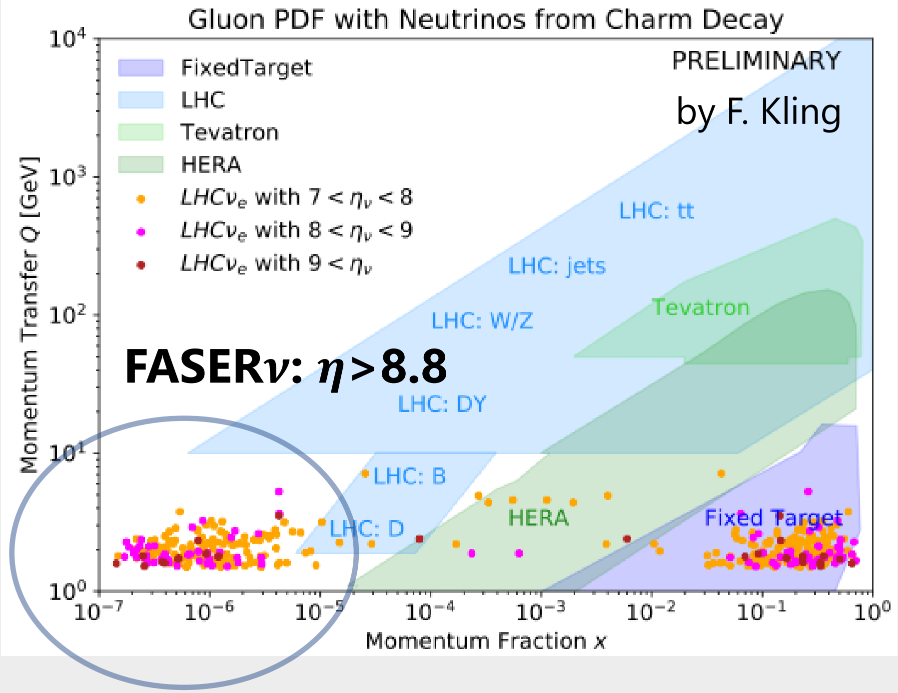


- Tests of lepton universality in the heavy-flavor-associated channels
  - ~100 ν_e CC charm, ~600 ν_μ CC charm, ~2 ν_τ CC charm, and ~0.1 ν_μ CC beauty production expected in FASERν → 100 more statistics in FASERν2

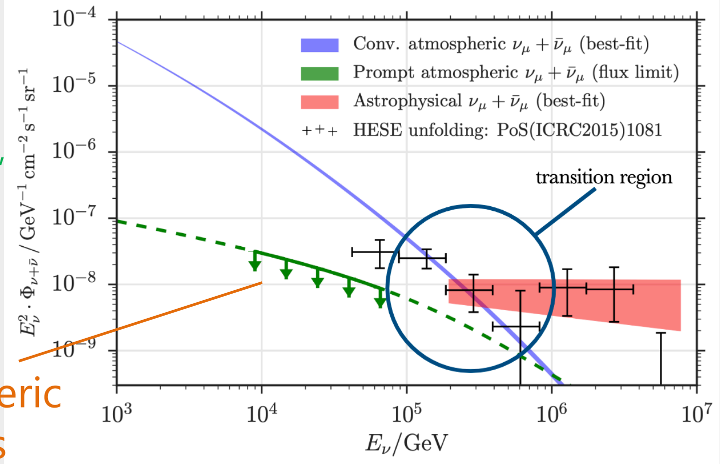
FASERν physics potential (3): forward hadron production

- Neutrinos produced in the forward direction at the LHC originate from decays of hadrons, mainly pions, kaons, and charm particles.
- Forward hadron production is poorly constrained by other LHC experiments. FASER can study it by measuring the neutrino event rate.
- FASERν's measurements provide novel input to **QCD** and **astroparticle physics**
  - Neutrinos from charm decay could allow to test transition to small-x, see effects of gluon saturation, constrain low-x gluon PDF, probe intrinsic charm.
  - Forward charm production is relevant for neutrino telescopes (such as IceCube) for understanding the **prompt atmospheric neutrino** production.
  - Forward hadron production is relevant for muon problem in CR physics (**cosmic ray muon puzzle**): CR experiments reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data.





IceCube Collaboration, Astrophys. J. 833 (2016)



prompt atmospheric neutrinos