Detecting and studying three-flavor neutrinos with FASER at LHC

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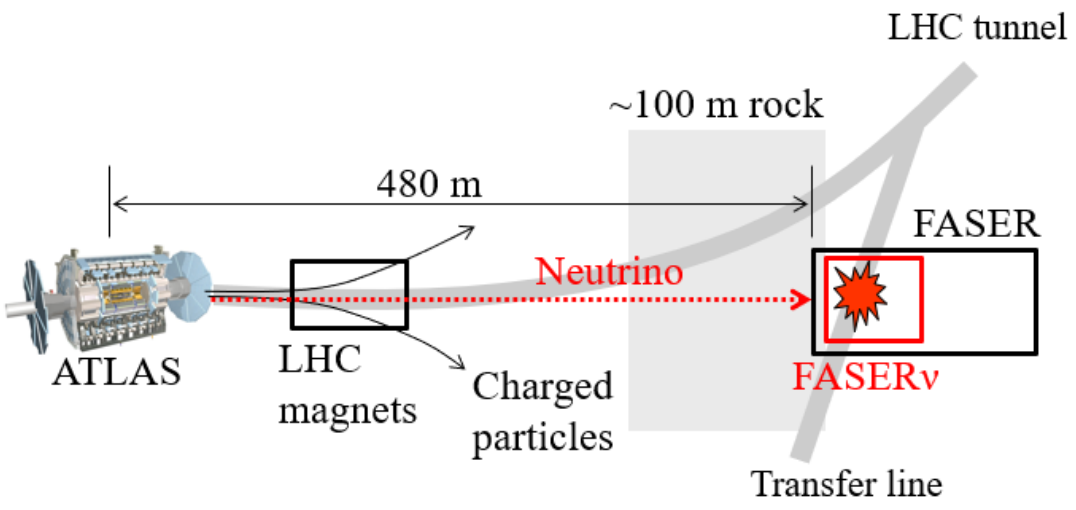
On behalf of FASER collaboration

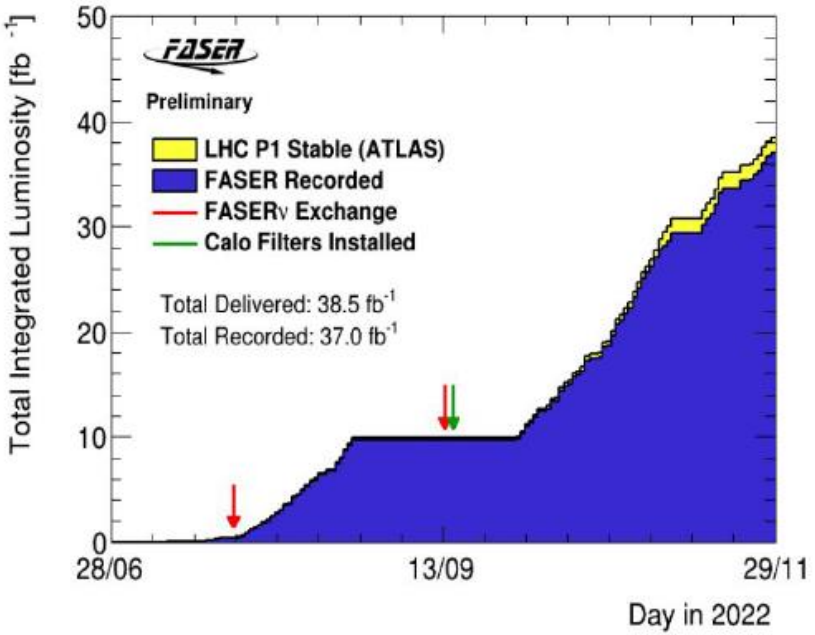
Supported by:

FASER

- FASER is an experiment to search for new long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022.
- The detector is installed 480 m downstream of ATLAS IP (TI12).
- FASER utilizes high cross-section of pp interactions at forward region.
- FASER is the first experiment to study three-flavor neutrinos at TeV energies.

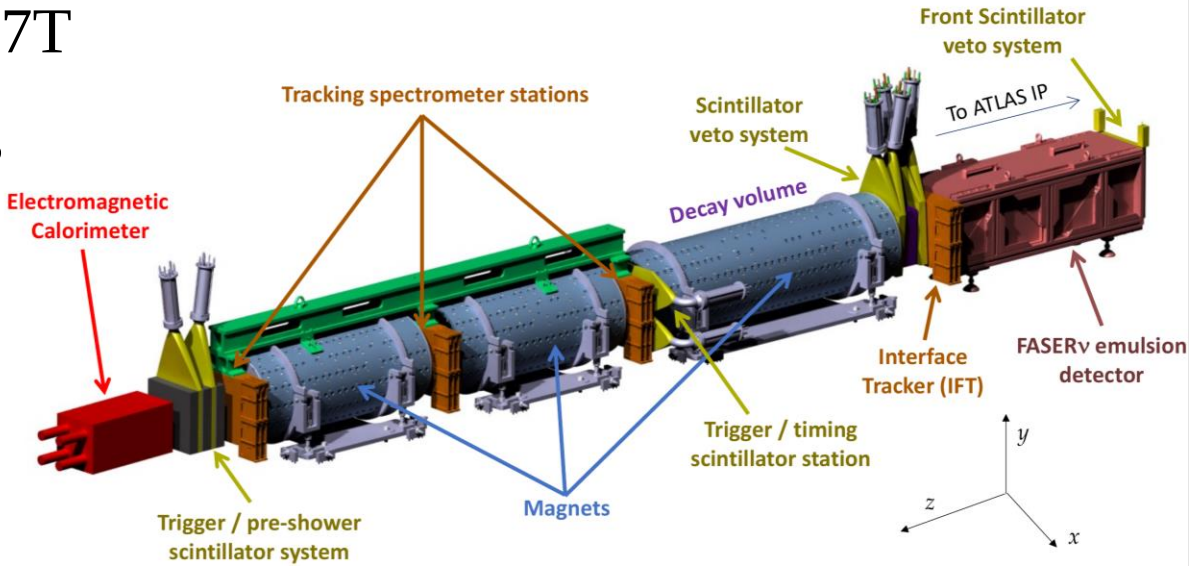


Integrated luminosity in 2022 (FASER)



FASER detector

- FASERν (neutrino detector)
  - Scintillator veto
  - 730 layers of an emulsion film and 1.1 mm tungsten plate (1.1 t, 220 X_0)
  - Silicon tracker station (IFT: Inter Face Tracker)
- Scintillator veto/trigger
- Decay volume with 1.5m/0.57T
- Spectrometer with 2m/0.57T
  - 3 silicon tracker stations
- EM calorimeter



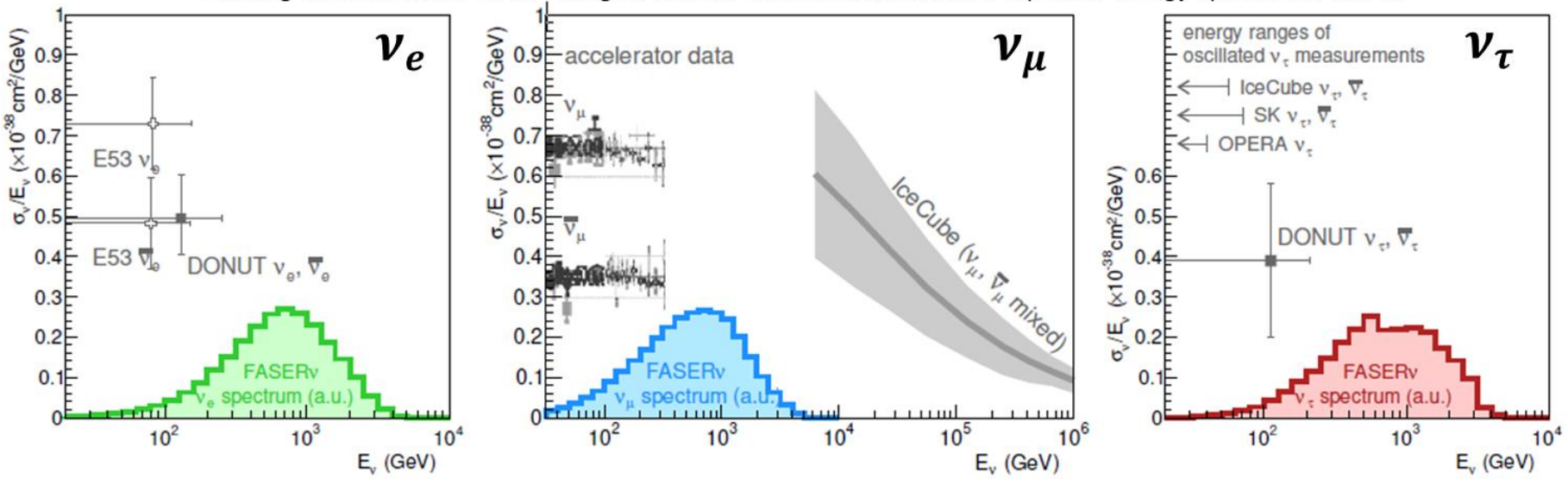
Charged current interactions at FASERν

- FASERν will measure neutrino cross-sections at TeV region which is uncovered by existing experiments.
- All neutrino flavors in Charged Current (CC) interactions can be identified including τ-neutrino, thanks to excellent position resolution of the emulsion detector.

Expected # of CC int. with 250 fb^{-1} @FASERν

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}	$36^{+20.8}_{-11.5}$

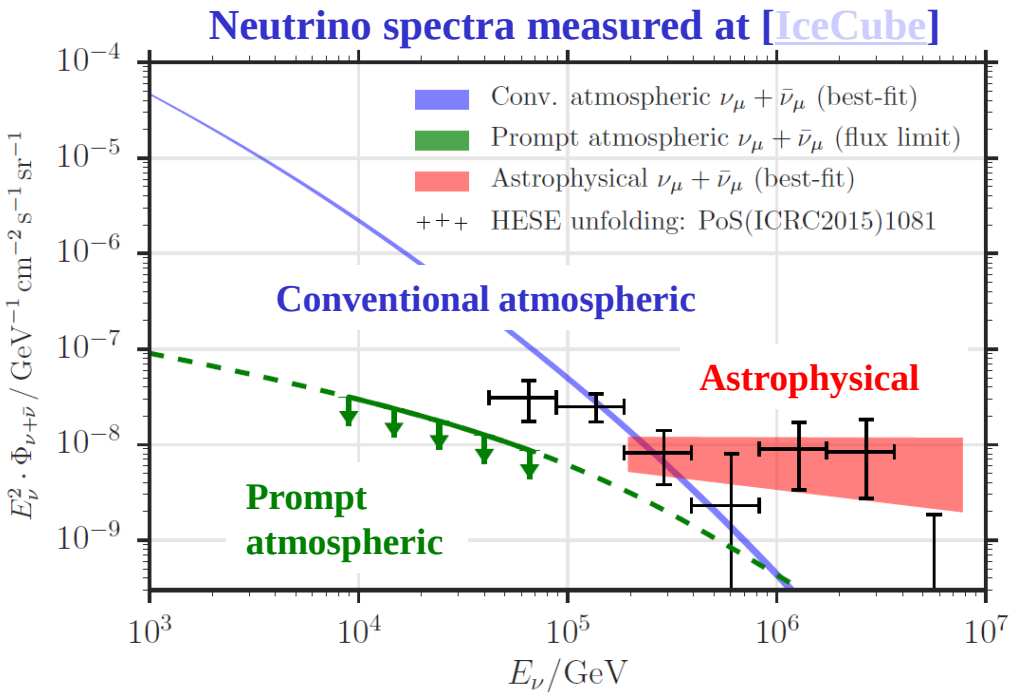
Existing measurements of νN charged-current cross sections and the expected energy spectra for FASERν



Forward charm production at LHC

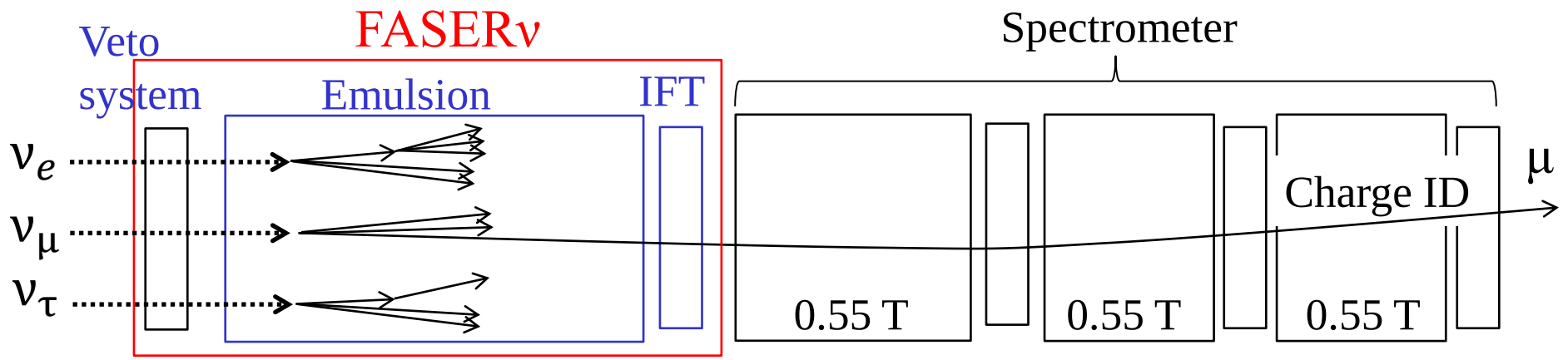
- Atmospheric neutrinos from charm decays (prompt neutrino) could be an important background for astrophysics neutrino observations.
  - Only upper limit was given by IceCube.
- gg→cc is the leading order for cham production in perturbative QCD.
- Proton-proton collision at LHC corresponds to ~100 PeV proton interaction with fixed target.

Measurement of production cross-section of heavy mesons at LHC can provide constraint on the prompt flux (current syst. error is O(1)).



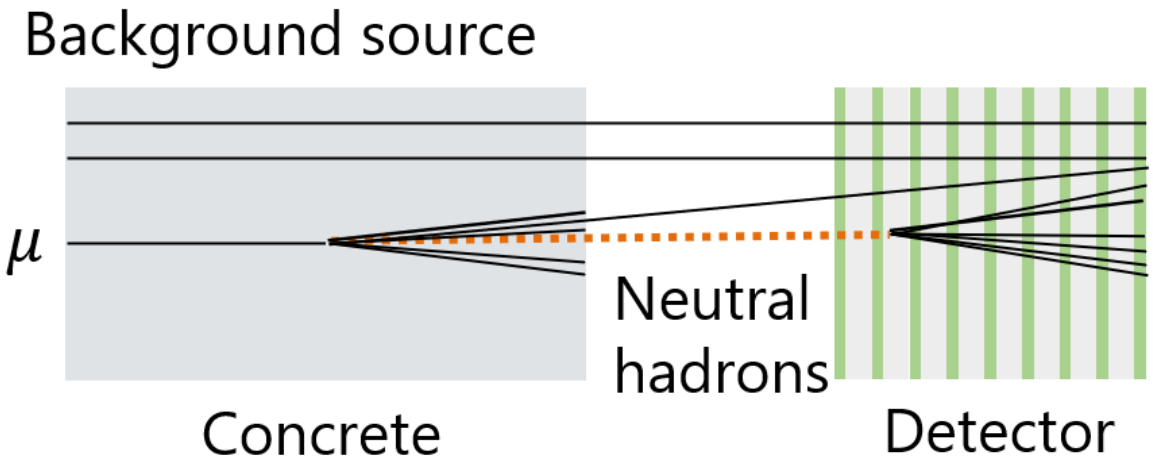
Neutrino detection at FASER

- Tungsten plates in the emulsion detector work as the neutrino target.
  - A total of 1.1 tons (220 X_0)
- 3 neutrino flavors can be identified by using event topologies in the emulsion detector.
  - The emulsion films will be replaced every 30-50 fb^{-1}.
- ν_μ and $\bar{\nu}_\mu$ can be identified separately with the spectrometer that was used for the first observation of ν_μ produced at LHC.

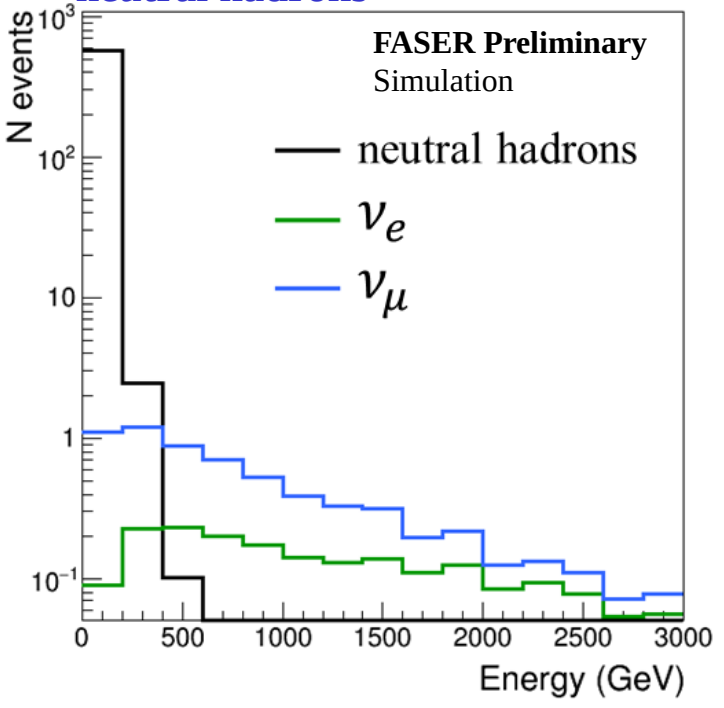


Backgrounds in neutrino measurement

- High energy muons coming from the pp interactions traverse FASER detector with a flux of 0.5 Hz/cm^2.
- The muons rarely produce neutral hadrons in the upstream concrete and inside the detector, that can mimic neutrino interaction vertices.
- Most of the produced neutral hadrons are low energy and can be eliminated with momentum/energy cut.

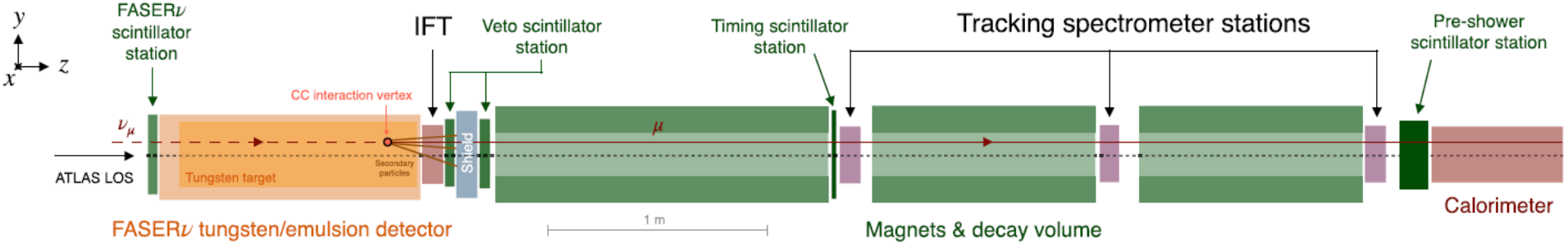


Energy distributions of ν_e/ν_μ and neutral hadrons



ν_μ detection with electric detector (1)

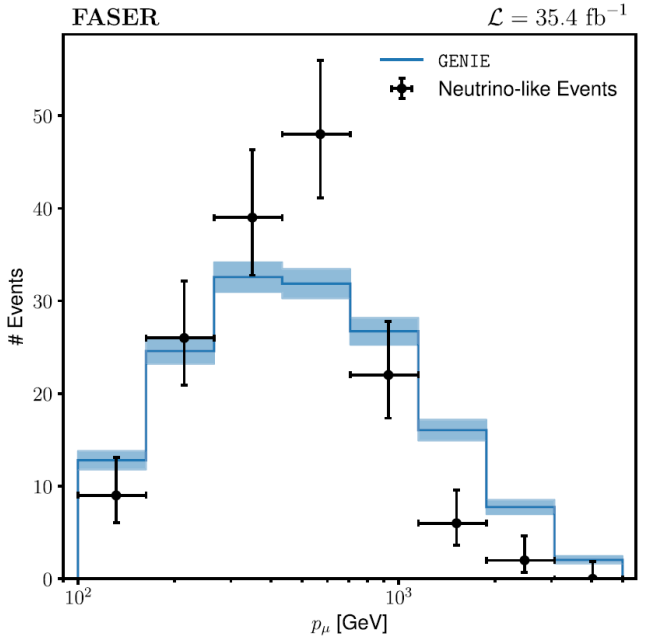
- The first detection of collider neutrinos was performed with the electric detectors in FASER by using data taken in 2022 (35.4 ± 0.8) fb^{-1}.
- All events triggered by any of the scintillators downstream of FASERν are used.
  - FASERν scintillator station eliminates charged particles coming from the upstream.
  - Signal is required to veto scintillator after Pb wall and calorimeter.
- The tracker detects muons created in ν_μ CC interactions with the tungsten plates in the emulsion detector.

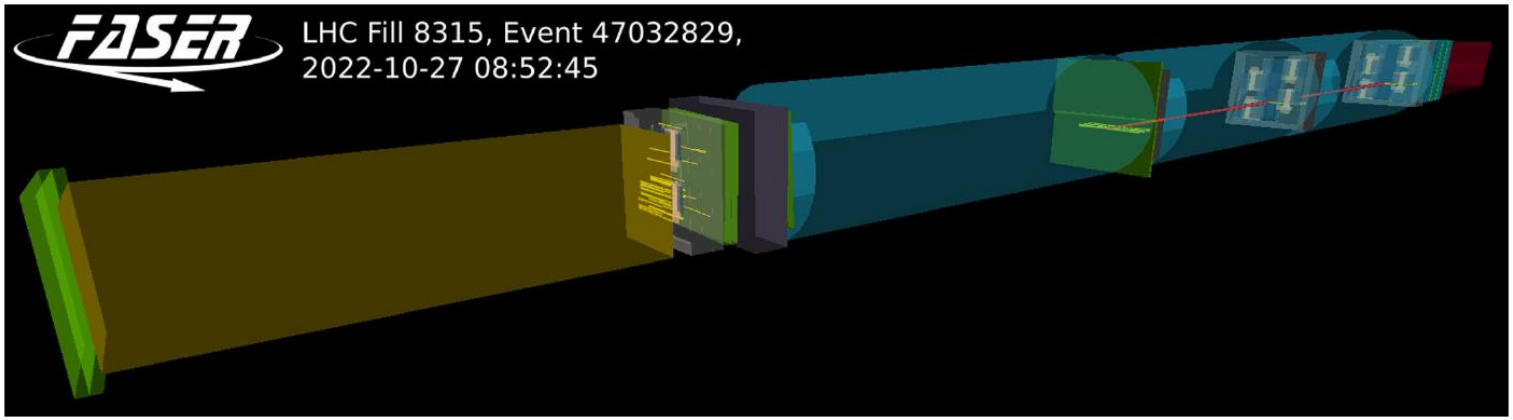


ν_μ detection with electric detector (2)

- $n_\nu = 153^{+12}_{-13}(\text{stat})^{+2}_{-2}(\text{bkg})$
- Expected BG: 0.11 ± 0.06 for neutral hadron, 0.08 ± 1.83 for geometrical BG.
- Significance is 16σ over BG only hypothesis
- The results were published in [PRL 131, 031801 (2023)].

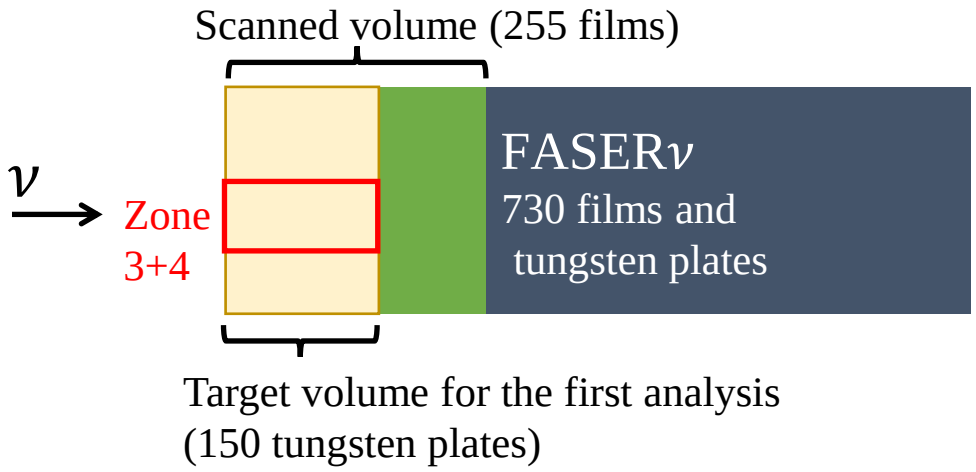
Muon momentum distribution in the signal region

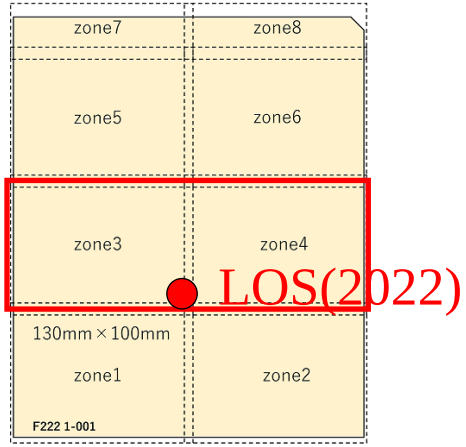




$\nu_{e/\mu}$ measurement with FASERν (1)

- 250 out of 730 films of 2022 2nd module in FASERν were analyzed.
  - Corresponding to 9.5 fb^{-1} taken during July 26th to September 13th.
  - 150 films for the vertex reconstruction and 100 films for momentum/energy measurements.
- The ν_e and ν_μ CC interaction candidates are identified with a high-energy selection (p_ℓ > 200 GeV).
- The sum of $\nu_e/\bar{\nu}_e$ and that of $\nu_\mu/\bar{\nu}_\mu$ are measured.





$\nu_{e/\mu}$ measurement with FASERν (2)

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

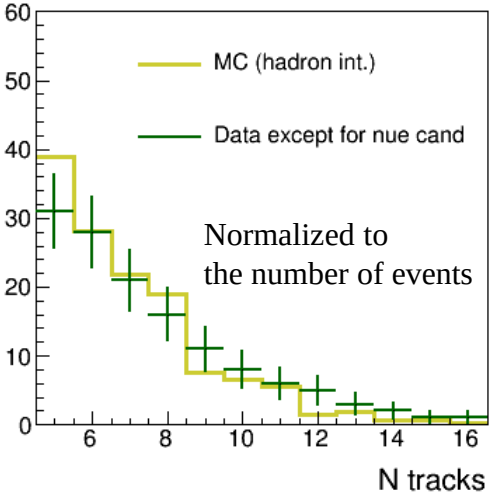
MC exp.: 216 vertices
$K_{s/L}$, $n/\bar{n}$, $\Lambda/\bar{\Lambda}$ interactions

⇔

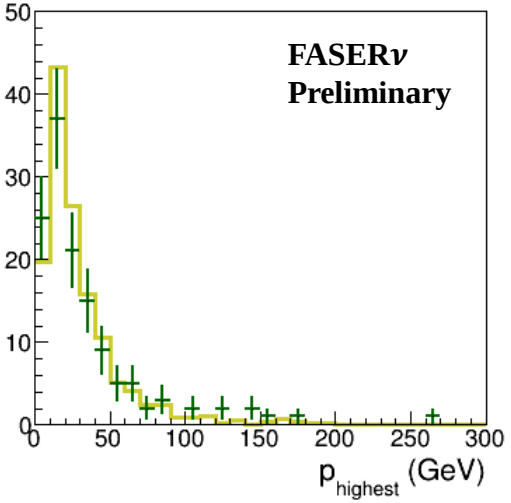
Data: 133 vertices
140 vertices -7 ν CC candidates

- The event rate agrees with the expectation within 50% uncertainty.
- No significant difference in the shape of the distributions.
- MC samples of individual neutral hadrons are used for BG estimation (equivalent to 20 times of the data).
  - 6 ν_μ BG (p > 200 GeV)
  - 0 ν_e BG (E_e > 200 GeV)

# of tracks



Highest momentum of tracks



$\nu_{e/\mu}$ measurement with FASERν (3)

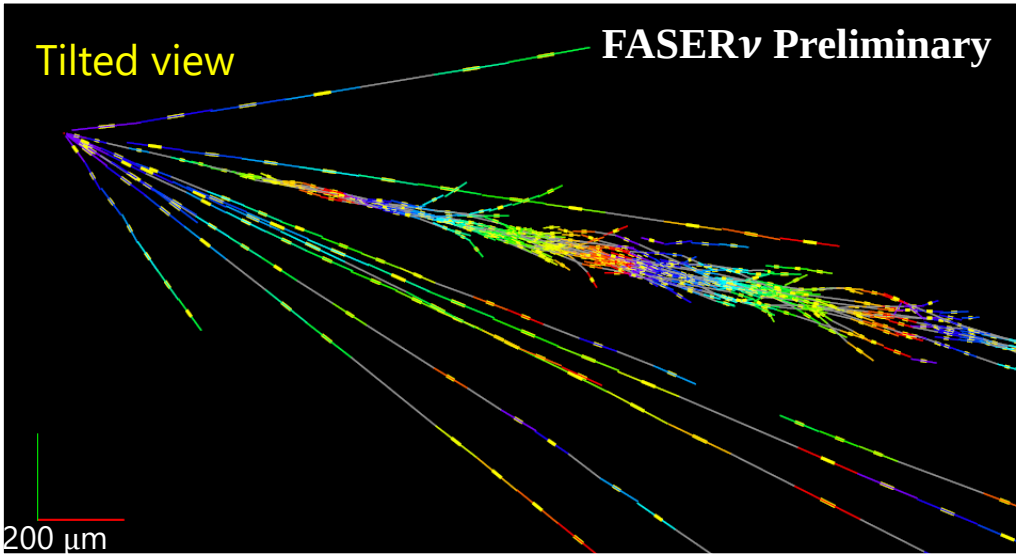
FASERν Preliminary

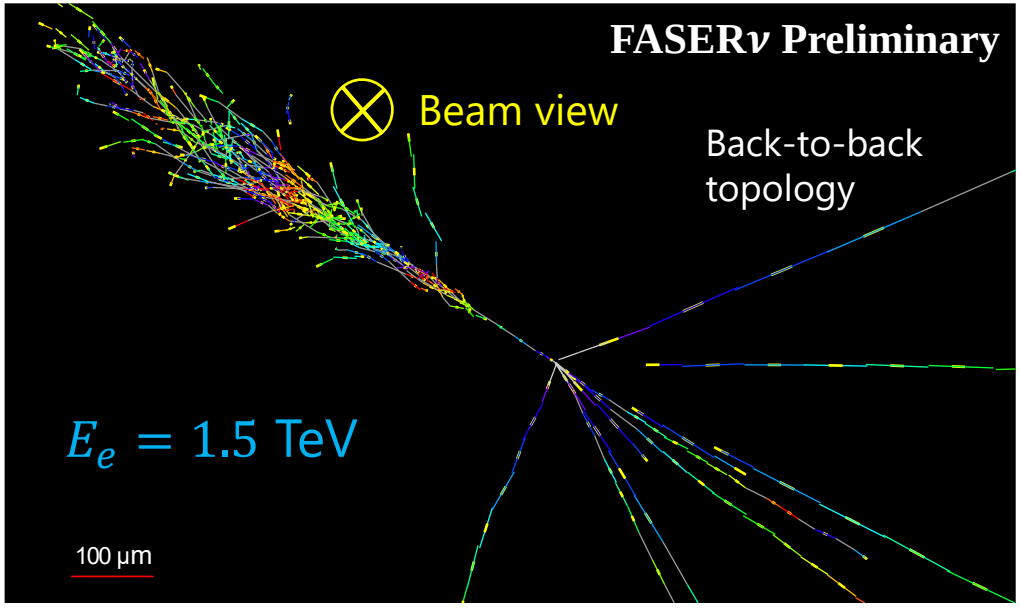
	Expected background		Expected signal	**Observed**	
	Hadron int.	ν NC int.			
ν_e CC	0.002±0.002	-	$1.2\,^{+4.0}_{-0.6}$	3	$p = 1.6 \times 10^{-7}$ (5.1σ)
ν_μ CC	0.32±0.16	0.19±0.15	$4.4\,^{+4.2}_{-1.4}$	4	$p = 5.2 \times 10^{-3}$ (2.5σ)

- The first direct observation of electron-neutrino CC interactions at a beam collider.
- The performance of detection will be improved in future analysis using a longer range for μ ID.

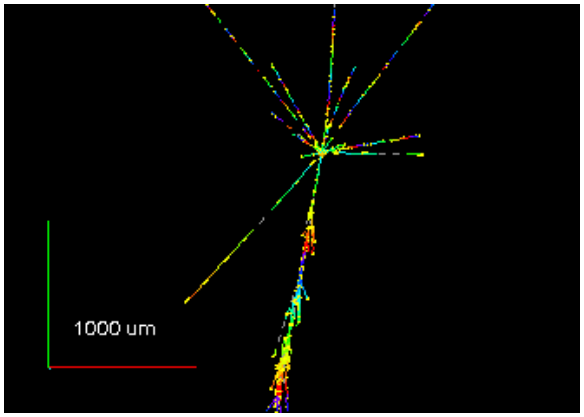
$\nu_{e/\mu}$ measurement with FASERν (4)

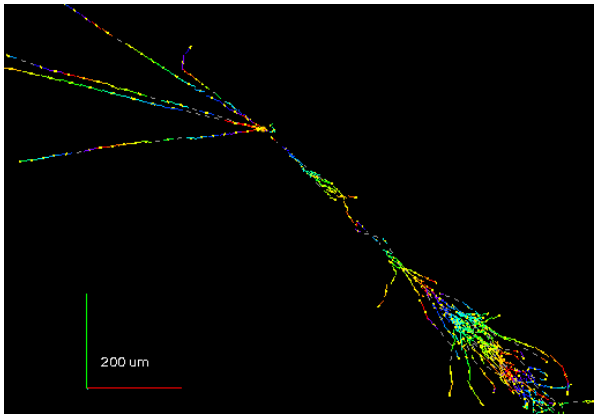
- 11 tracks at the vertex, 615 μm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- 175° between e-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

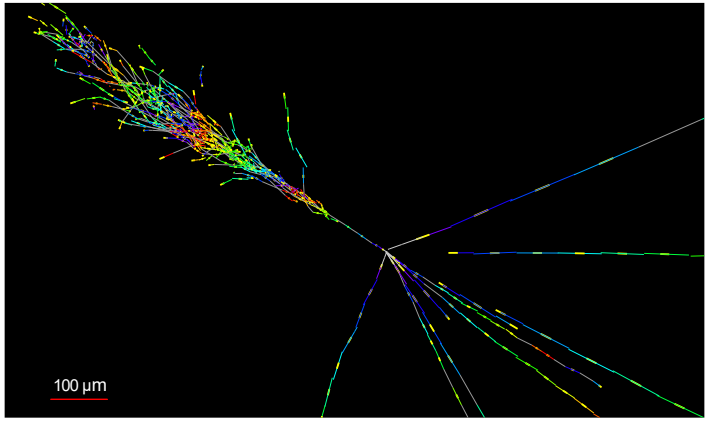




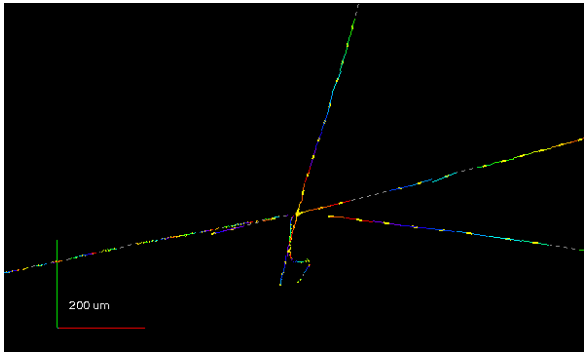
$\nu_{e/\mu}$ measurement with FASERν (5)

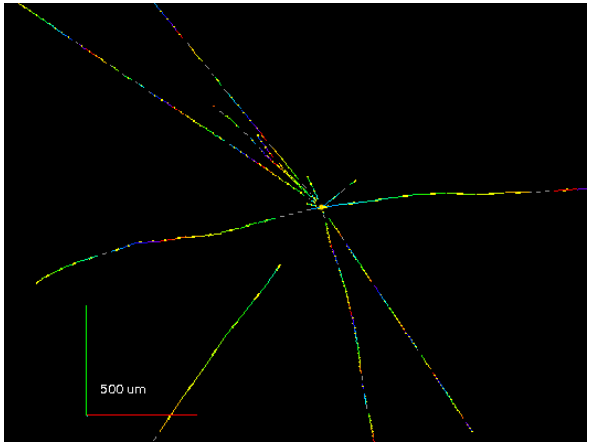


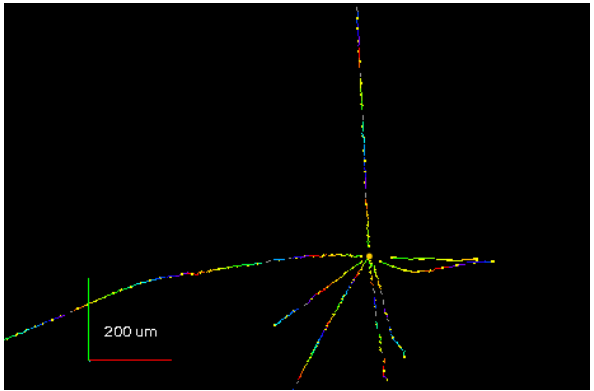


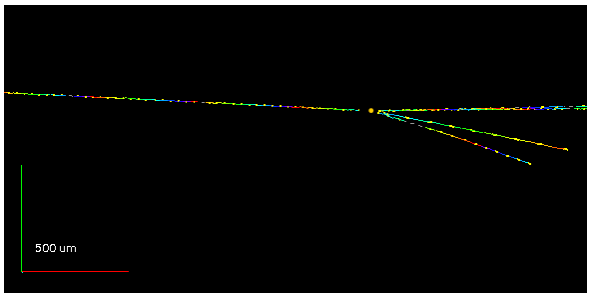


FASERν Preliminary









⊗ **Beam view**

Summary & Conclusions

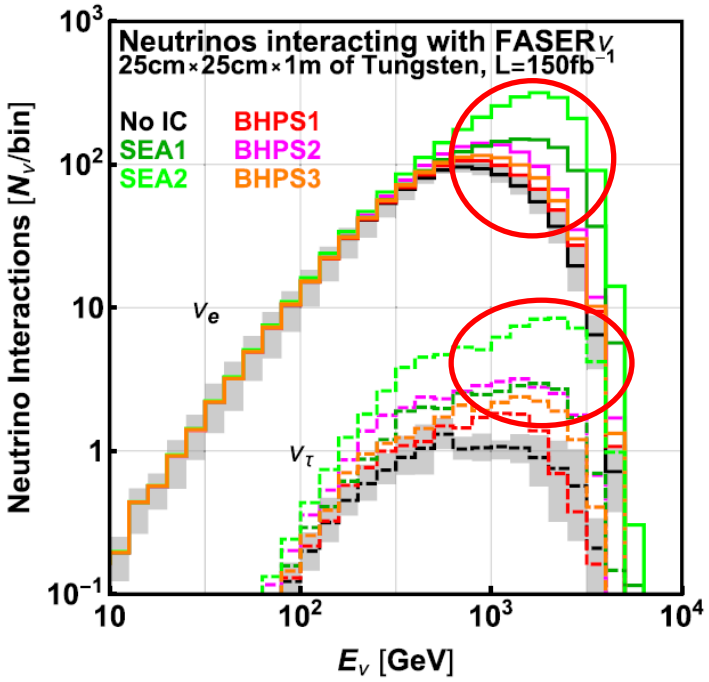
- FASER is an experiment to search for new long-lived particles and measure cross-sections of neutrinos, starting data-taking in 2022.
- FASER was succeeded in the first observation of neutrinos (ν_μ) that are produced at a collider experiment by using active electric detectors.
- The analysis was performed for data stored in a part of FASERν, that were taken in 2022 (9.5 fb^{-1}).
- FASERν achieved the first observation of electron-neutrino CC interactions at the LHC at the highest energy ever observed by accelerator-based experiments.
- The cross-section of three neutrino flavors will be measured with additional data, improving the analysis method.
- Upgrade of FASER main detector and FASERν is being discussed as a part of the proposed [Forward Physics Facility].

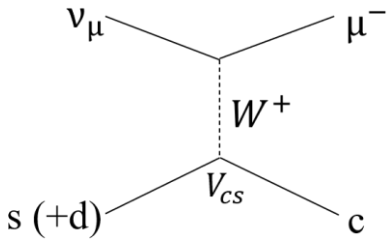
Backup

Charm/strange PDF

- There is a controversial prediction in which an additional charm component exists in a proton (so-called intrinsic charm).
- It only affects the forward charm production (cg→cg) in pp collisions, to which ν_e/ν_τ energy spectrum in FASERν is sensitive.

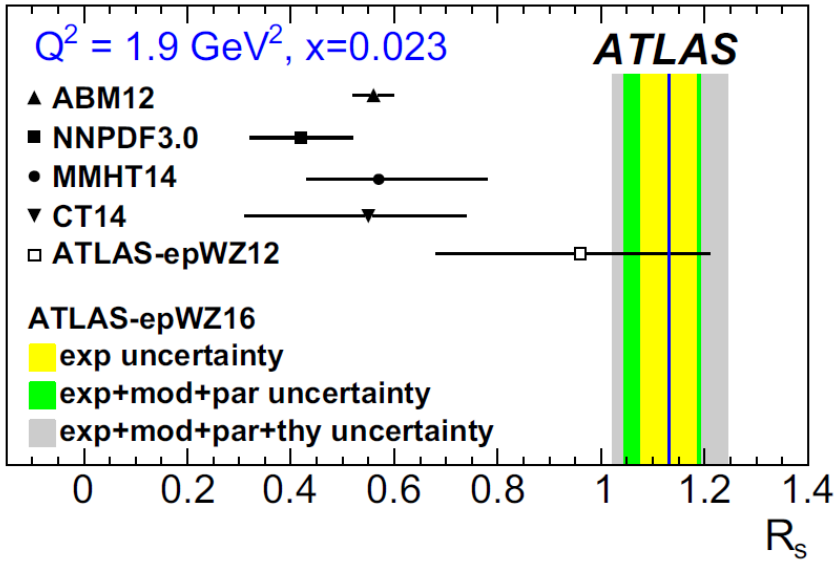
Expected energy dist. of ν_e/ν_τ @FASERν





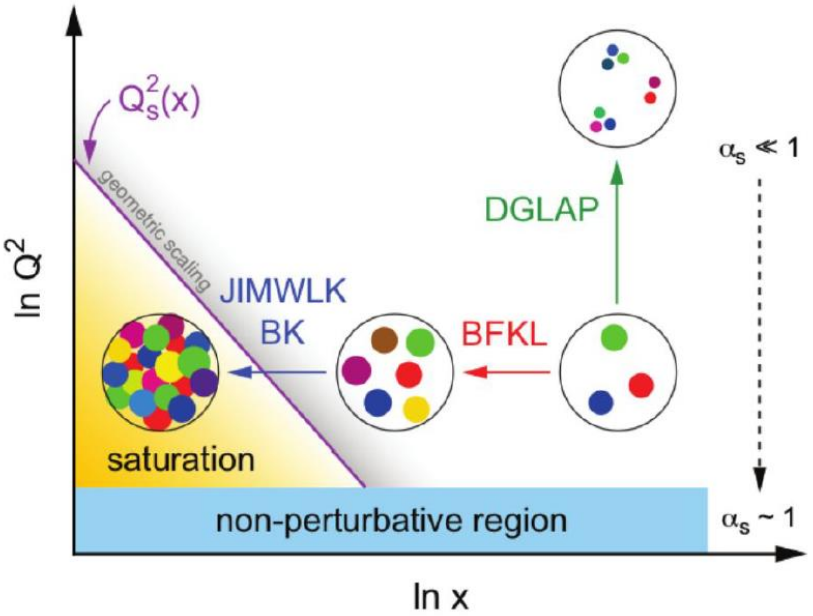
- D meson production in CC ν_μ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and predictions.

$R_s = \frac{s+\bar{s}}{u+\bar{d}}$ [Eur. Phys. J. C77 (2017) 367]

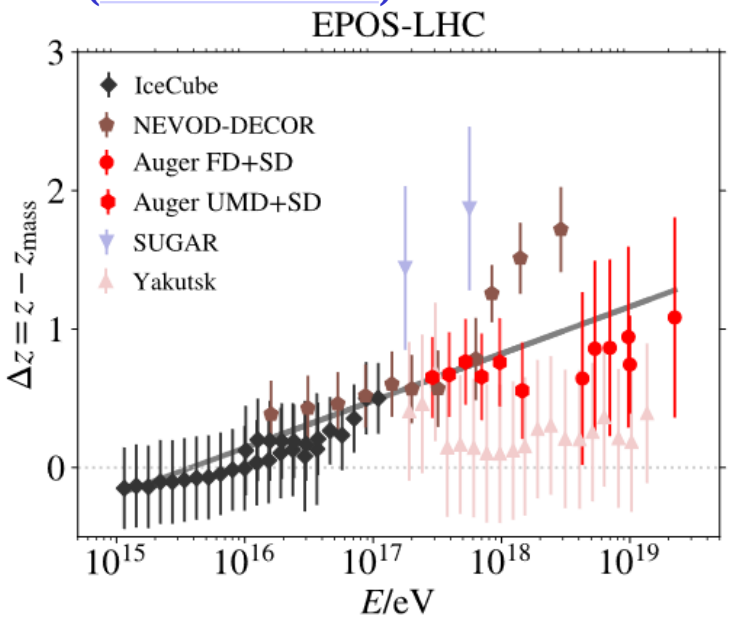


Theoretical interest in QCD

- FASERν can explore charm production (gg→cc) at Q ~ 2 GeV with x ~ 10^{-7}, where gluon saturation by color glass condensation appears.
- Measurement of muon/neutrino flux and energy spectrum constrains production of primary hadrons (mainly pions and kaons).
  - The results can be used to validate/improve cosmic ray MC, especially to understand muon excess.



Muon excess from prediction (Snowmass LOI)

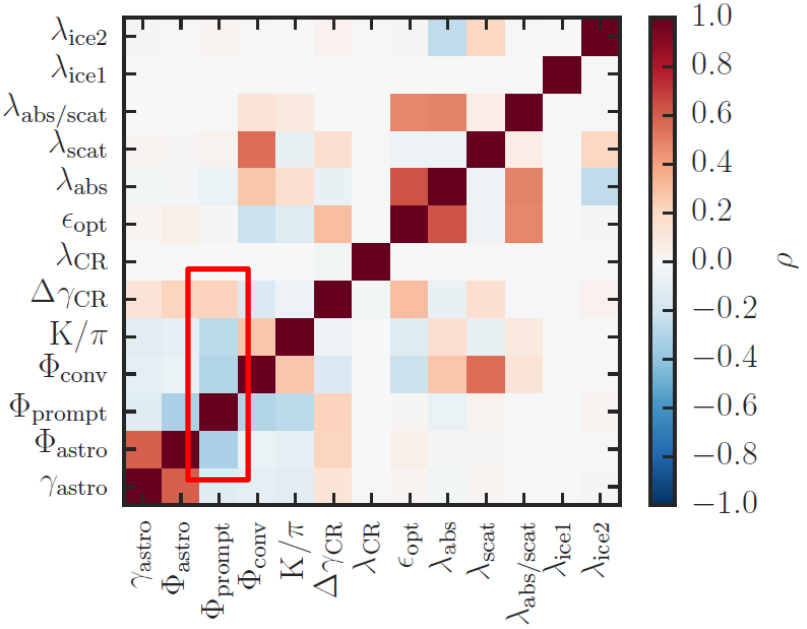


Astrophysics neutrino & prompt flux at IceCube

- Uncertainty on conventional atmospheric neutrino flux (Φ_{conv}) is ~30% and absorbs any uncertainty which influences the global flux norm..
- The cosmic ray spectrum parameterized as $\Delta\gamma_{CR}$ also affects the expectation of Φ_{conv} and prompt flux (Φ_{prompt}).
- Φ_{prompt} is a free parameter in the fitting and currently zero consistent.
- Astrophysical parameters (Φ_{astoro}, γ_{astro}) are found to be almost independent from Φ_{prompt}.

Parameter	Best-Fit	68% C.L.
Φ_{astro}	0.90	$0.62 - 1.20$
γ_{astro}	2.13	$2.00 - 2.26$
Φ_{prompt}	0.00	$0.00 - 0.19$

Correlation matrix of nuisance parameters



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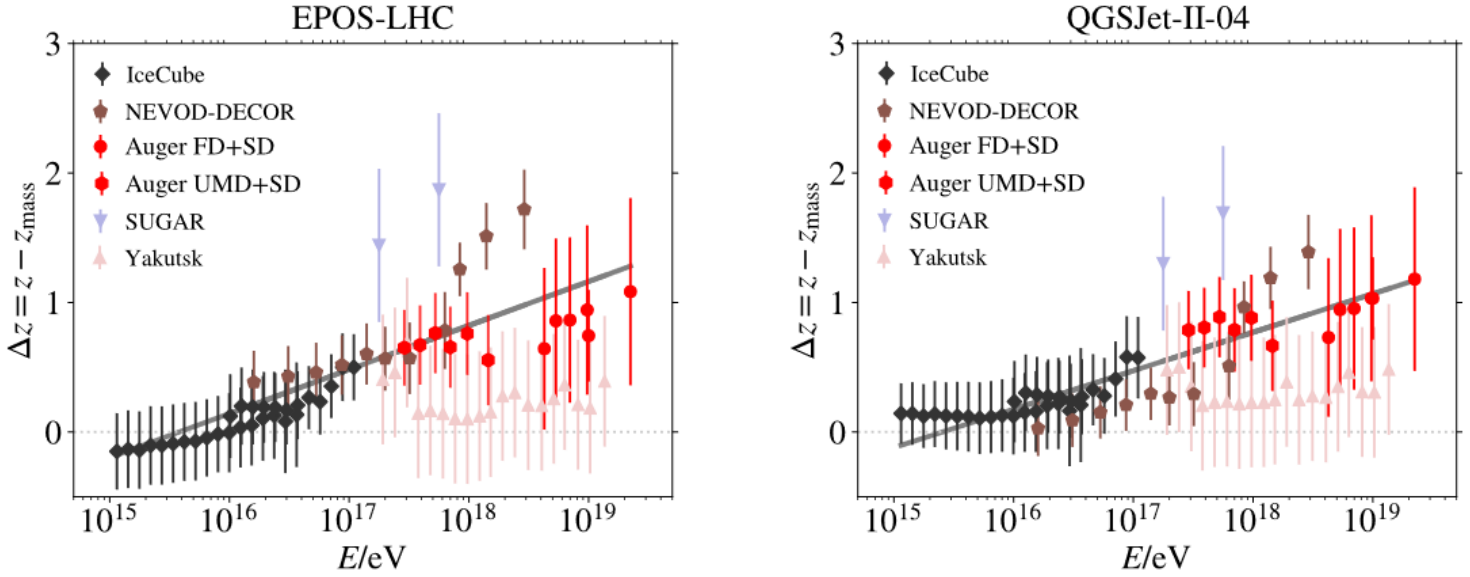
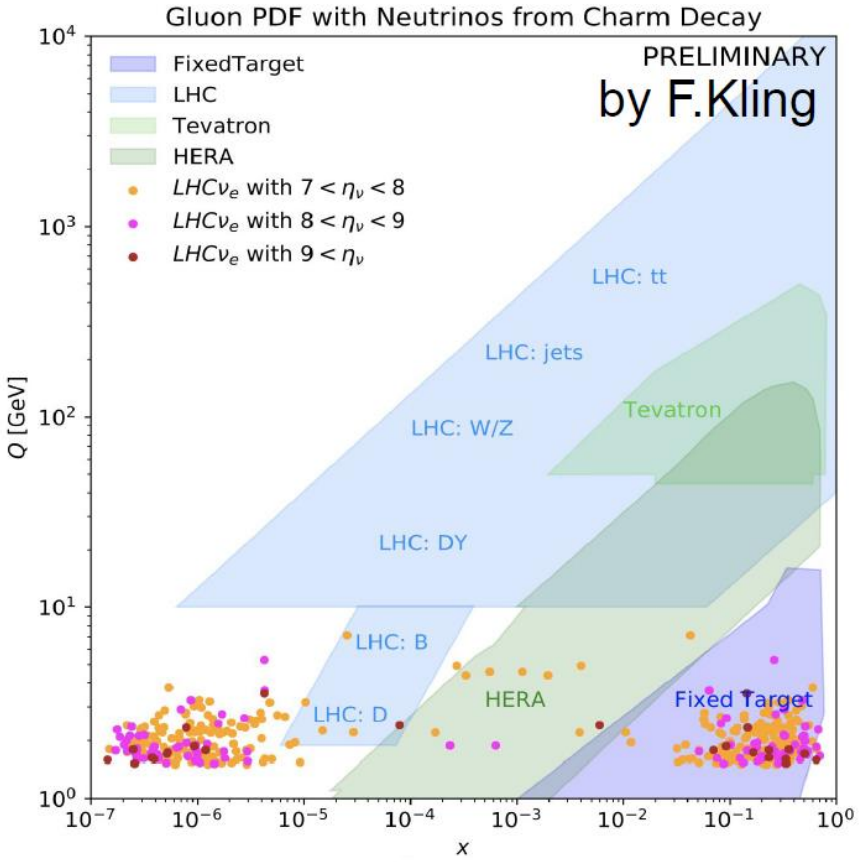
Muon excess in extensive air showers

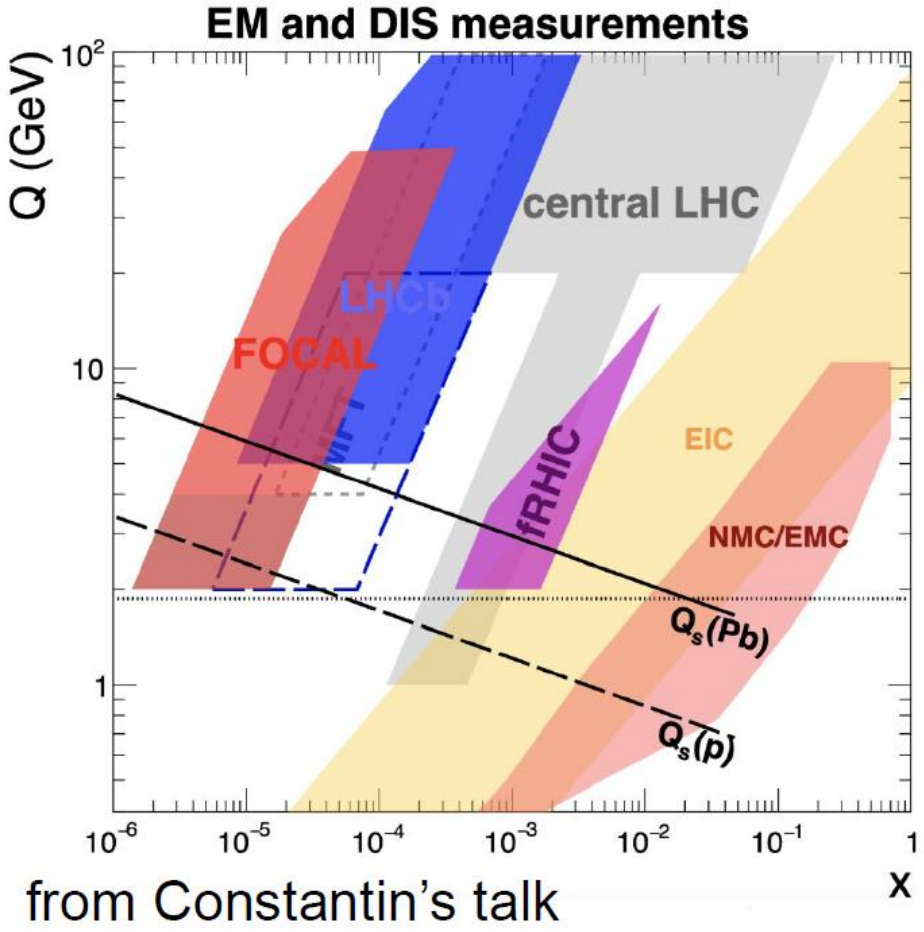
- Excess of muons with respect to the prediction (8σ) are observed in cosmic ray experiments.
- The hadronic interaction models used for the prediction were developed by using results of measurement in LHC and SPS.
- Measurement of muon/neutrino flux at FASER/FASERν will provide feedback to the interaction model.

Excess of muons from the predictions (EPOS-LHC and QGSJet-II-04) [Snowmass LOI]



Gluon saturation in proton (2)

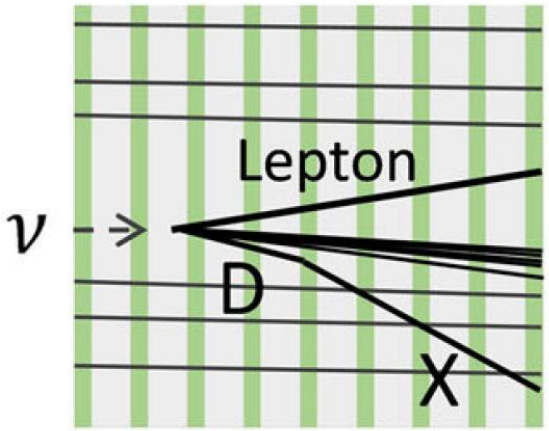




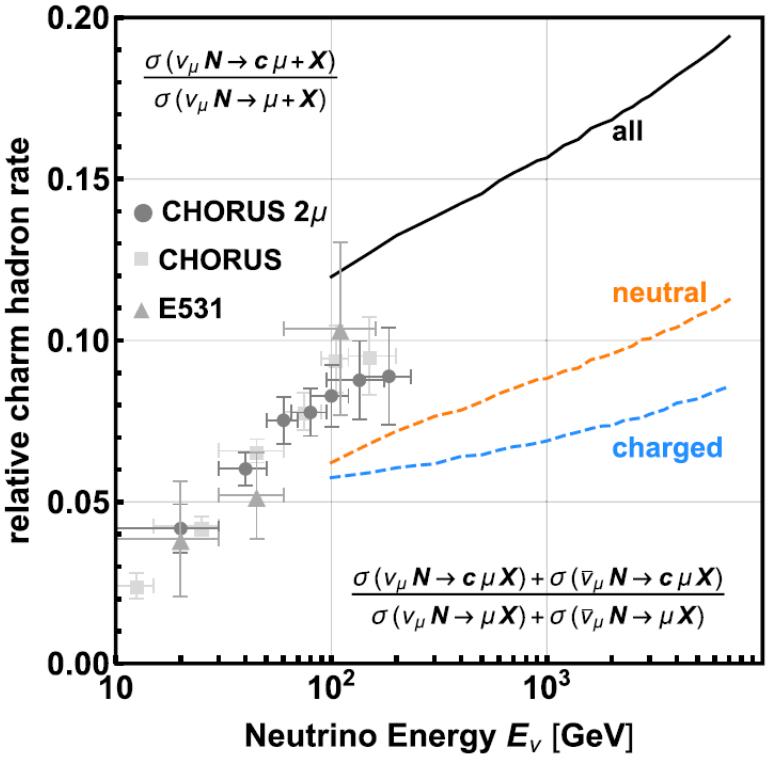
From F. Kling's presentation

Cham-associated neutrino events

- FASERν can measure neutrino interactions associated with D-mesons in the final states.
- 10-20% of neutrino interaction at FASERν is accompanied with D-mesons.
- The emulsion detector can identify D-mesons, measuring tracks and their decay products.



Fraction of neutrino events associated with D-meson @FASERν



Beauty-associated neutrino events (1)

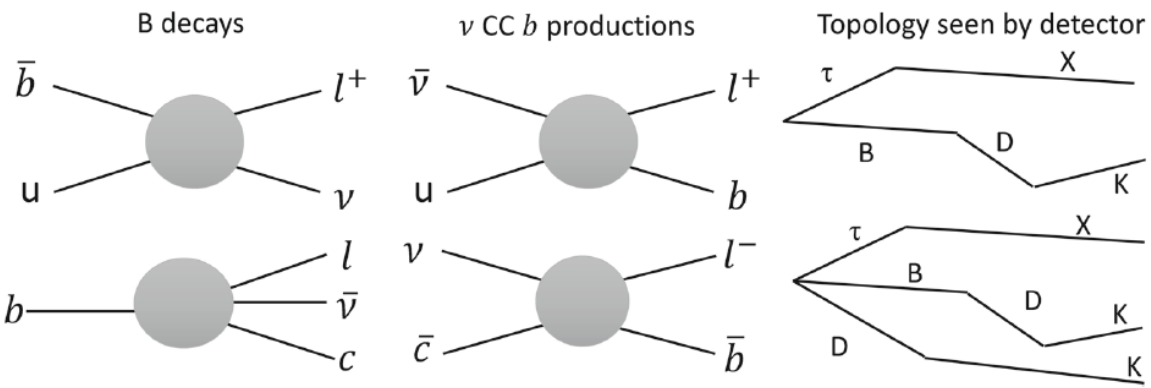
- Results in measurements in of B→D*ℓν, B→K*ℓℓ and B^+→K^+ℓℓ suggest lepton universality violation.

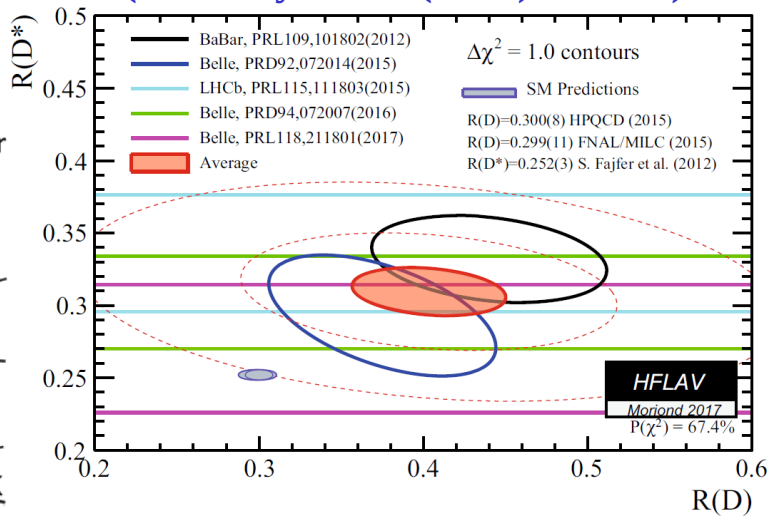
- The neutrino interactions in FASERν are the same as them, exchanging the internal/external lines in Feynman diagrams.

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

R(D) v.s. R(D*)
(Eur. Phys. J. C (2017) 77, 895)





Beauty-associated neutrino events (2)

- Since cross-section of these processes are suppressed by a factor of $O(V_{ub}^2) \sim 10^{-5}$, beauty-associated neutrino events cannot be observed at FASERν in Run3 in SM.
  - Expected number of the events: O(0.1)
- But, the observation means discovery of new physics.
- In addition, lepton universality violation in the third generation can be investigated with sensitivity to ν_τ.

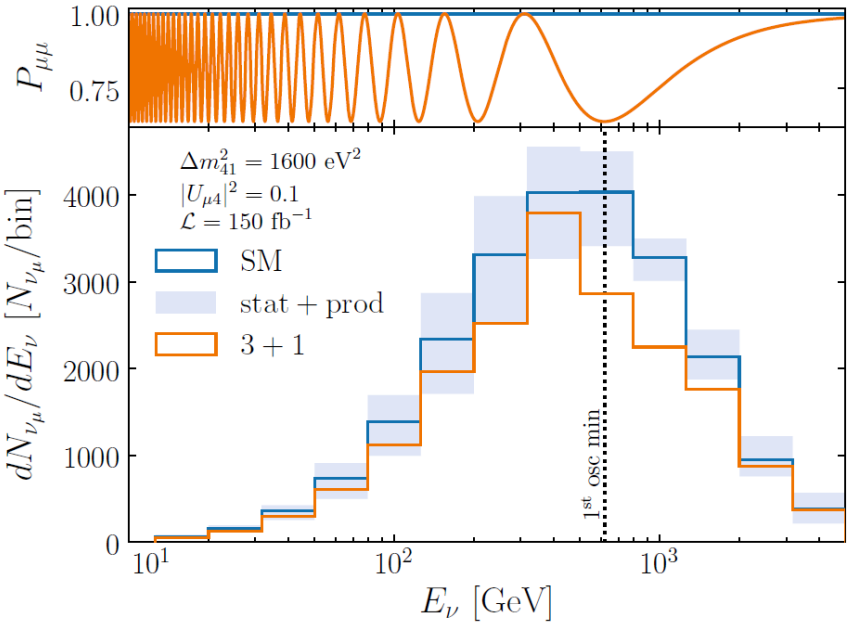
Sterile neutrino oscillation

- SM excludes possibility of neutrino oscillation in FASER condition.

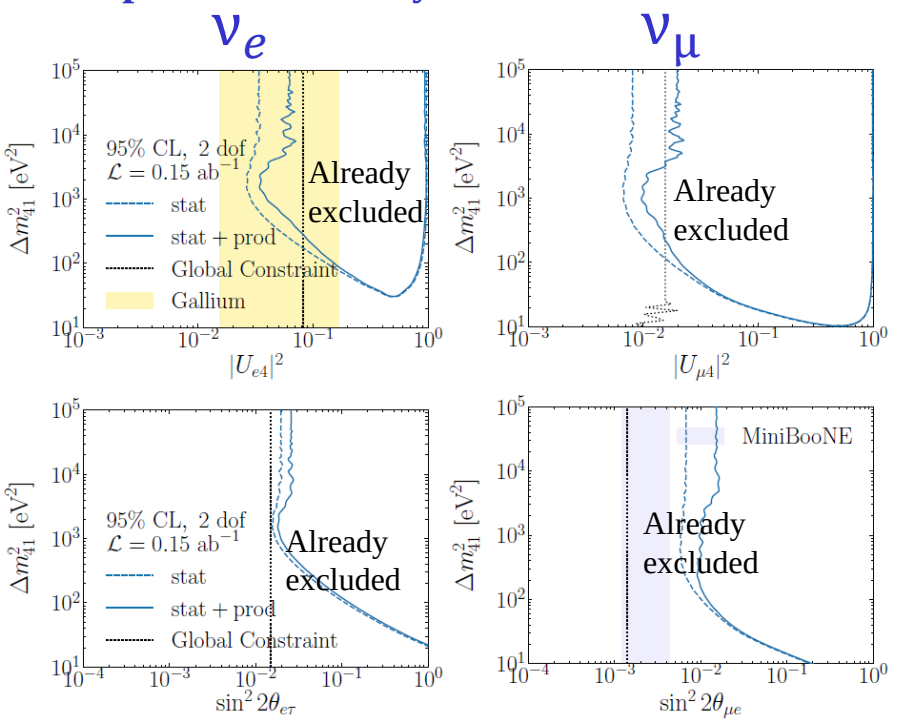
⇨ If appearance or disappearance events are observed, it indicates existence of sterile neutrino.

- For ν_e, FASERν has sensitivity to 2.7σ discovery region with Gallium detector [arXiv:1006.3244].

Neutrino energy dist. with sterile neutrino

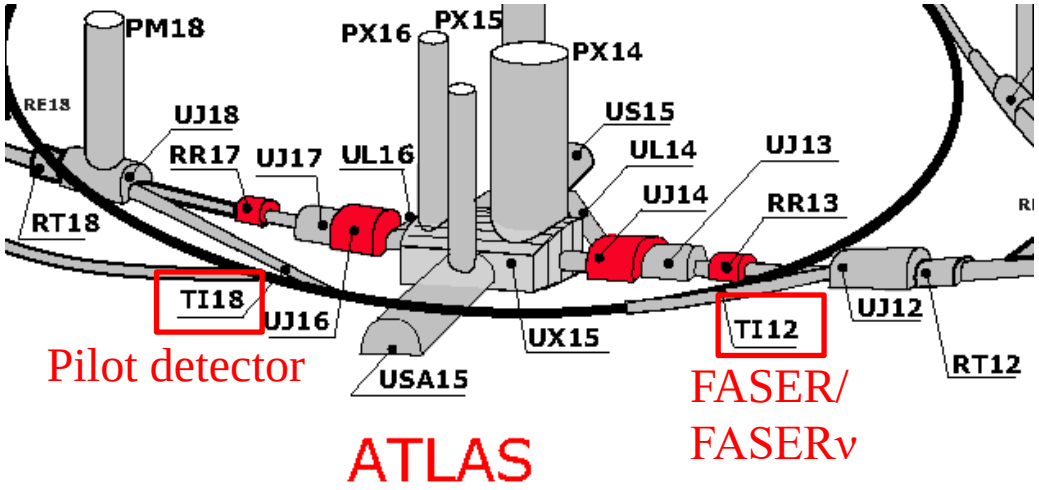


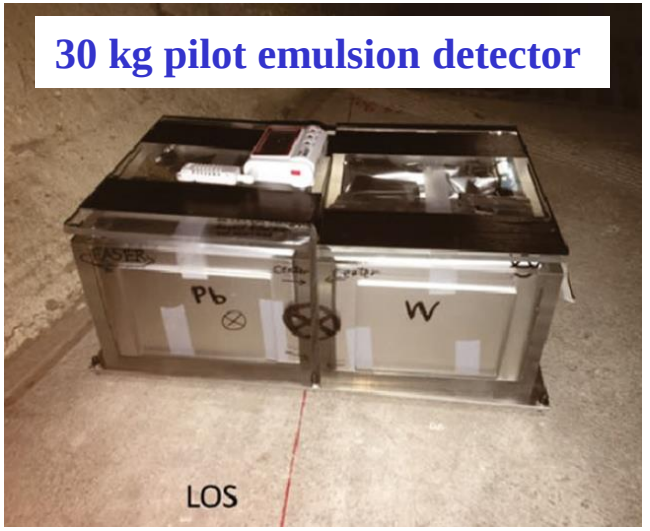
Expected sensitivity to neutrino oscillation



First neutrino candidates from LHC (1)

- The pilot runs took place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018.
  - TI18 is the tunnel at the same distance from ATLAS IP as TI12 (FASER site) but opposite side.
- Neutrino detection was performed with a 30 kg emulsion detector, collecting 12.5 fb^{-1} of data (10 kg are used in the analysis).

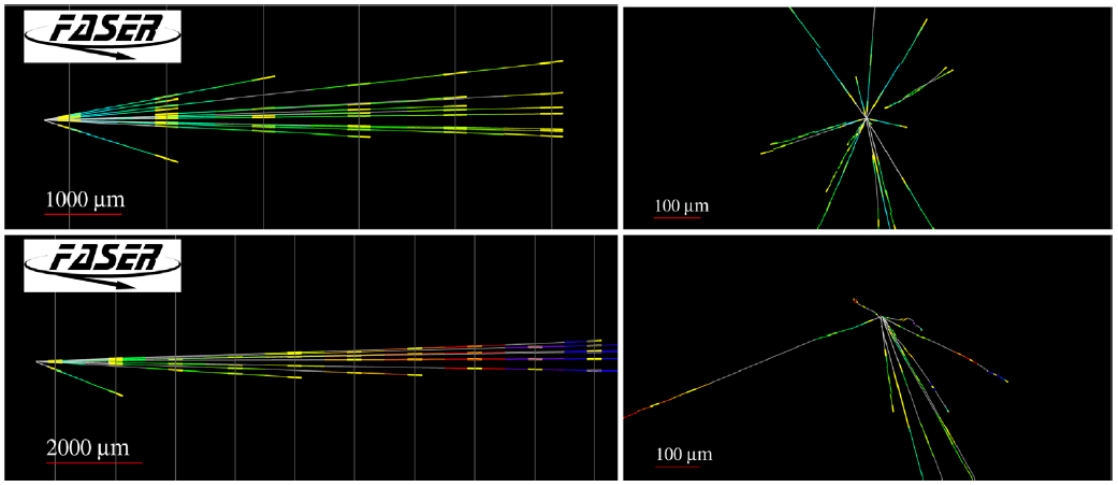




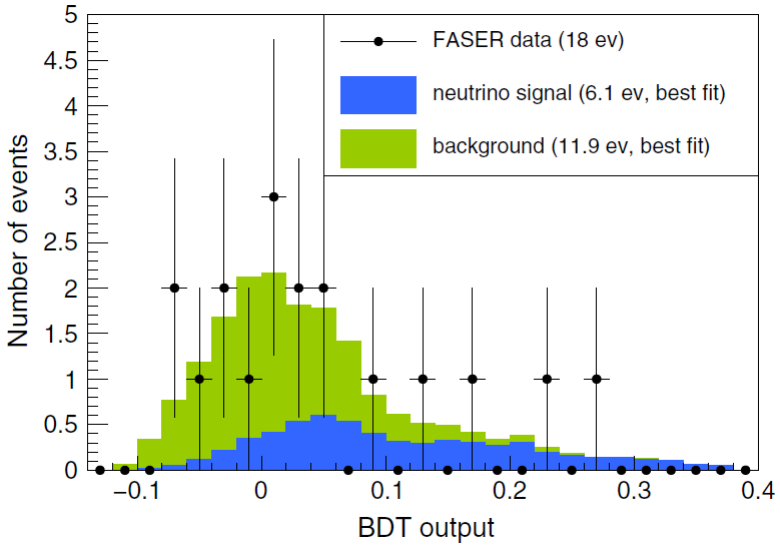
First neutrino candidates from LHC (2)

- 18 candidates of the neutral vertex were detected.
- They are the first candidates of the neutrino interactions at a collider.
- 2.7σ excess of neutrino-like signal above muon-induced background is measured with a multivariate analysis.
- The results were published in [PRD 104, L091101 (2021)].

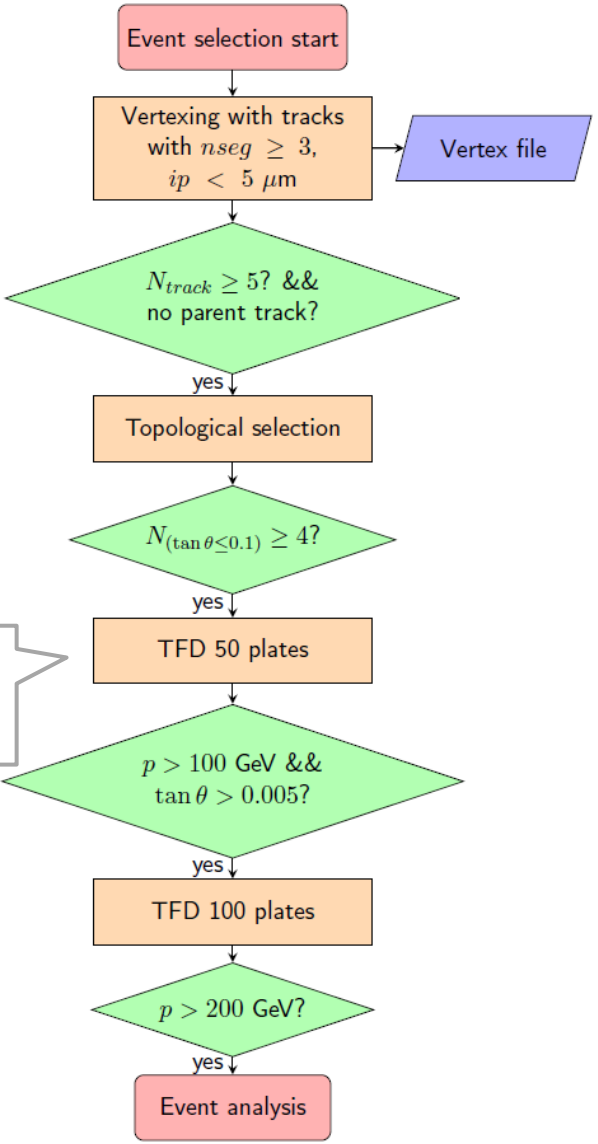
Neutrino event candidates



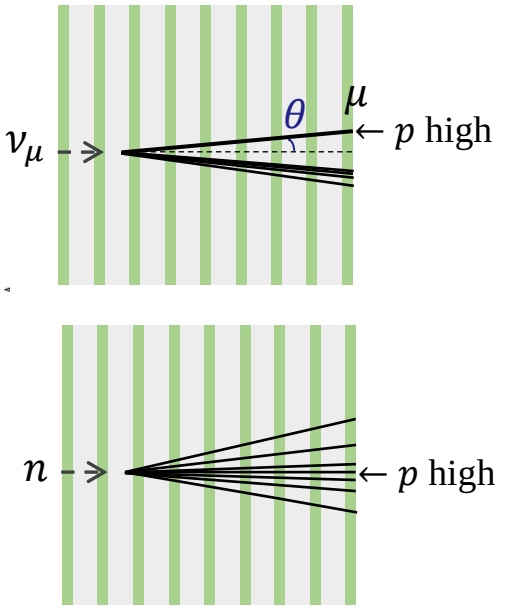
BDT outputs of observed neutral vertices



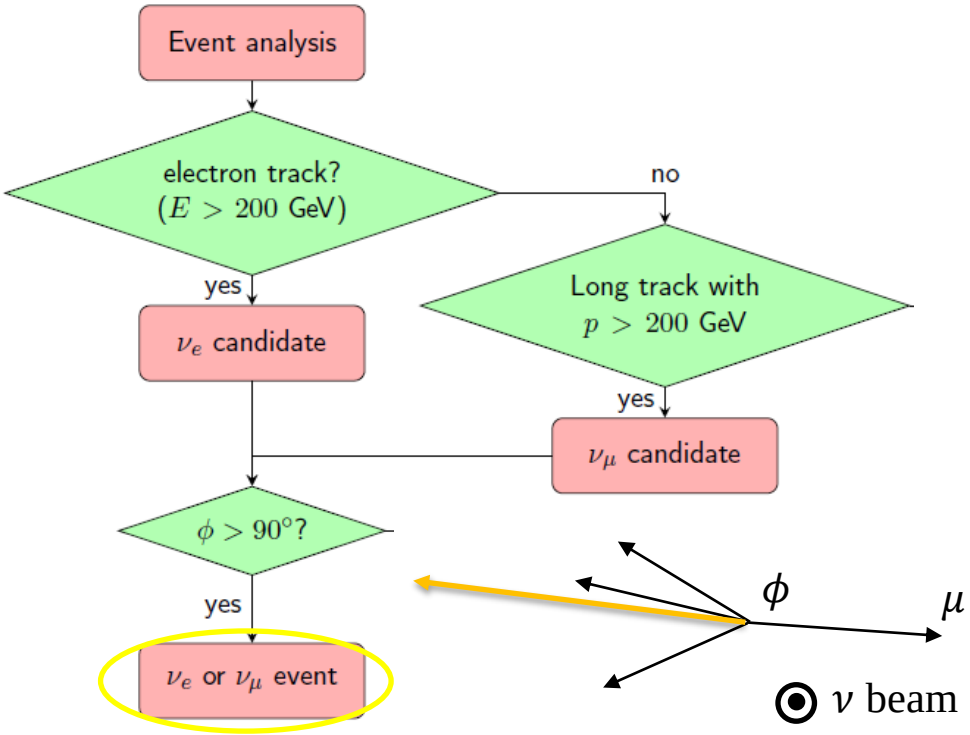
FASERν performance (selection)



Track follow-down (TFD) for measuring momentum

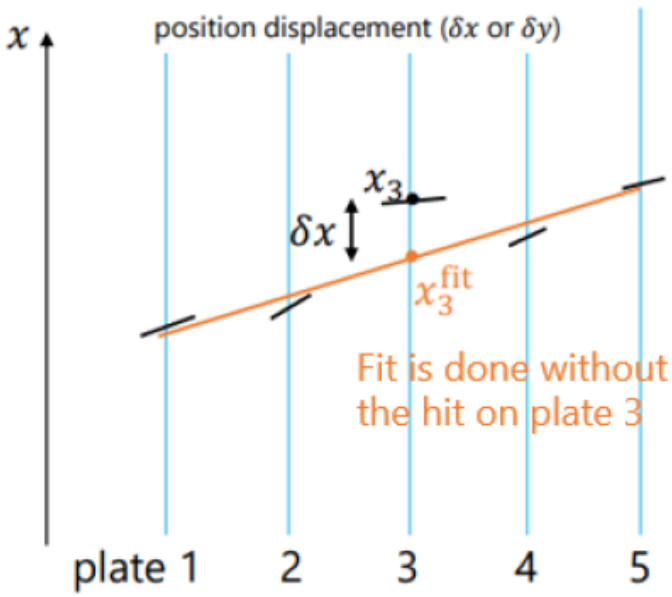


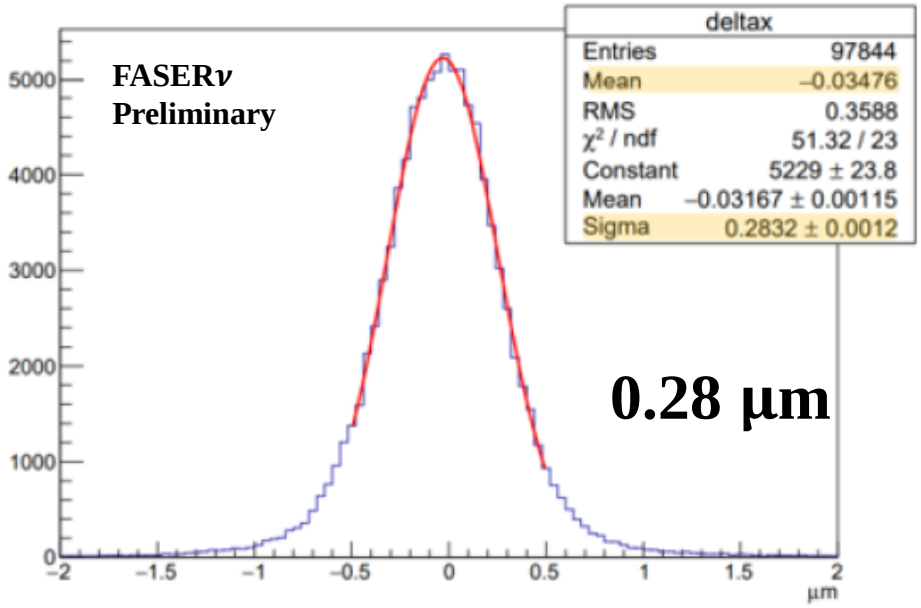
FASERν performance (classification)



FASERν performance (hit position)

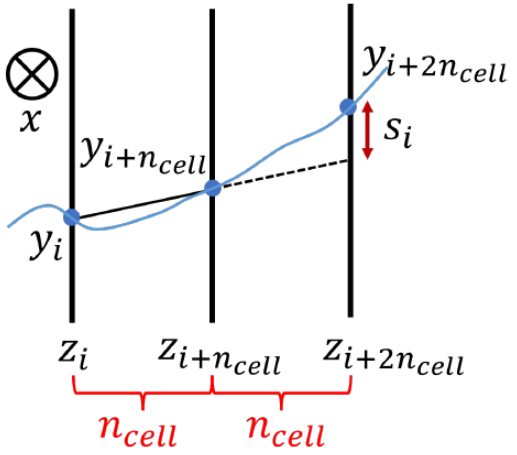
Position resolutions (after ~100 plates reconstruction)

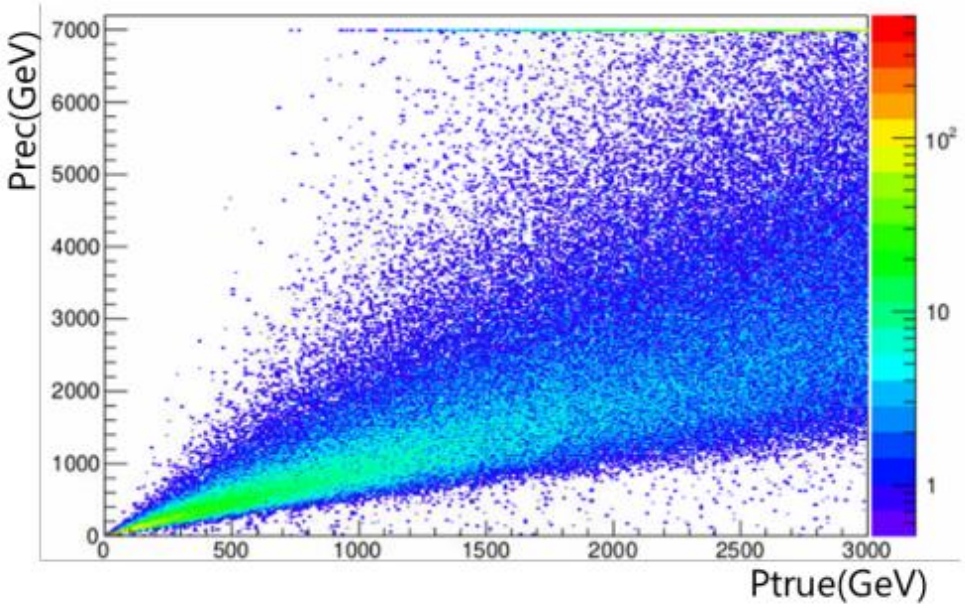


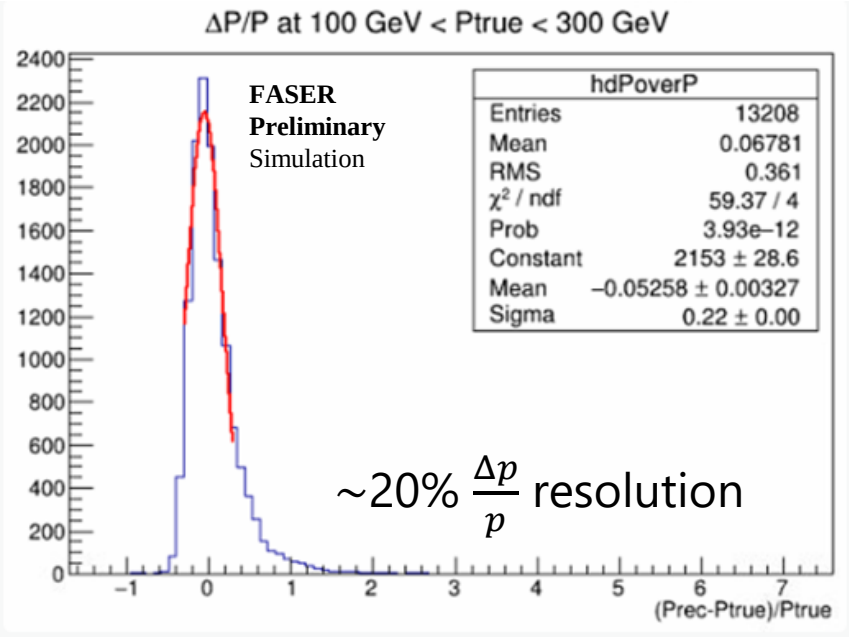


FASERν performance (momentum)

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

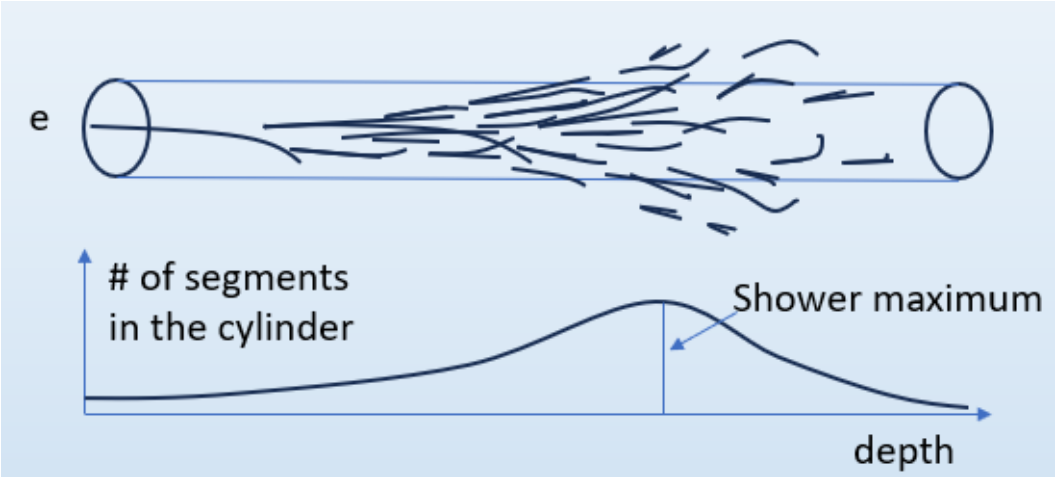


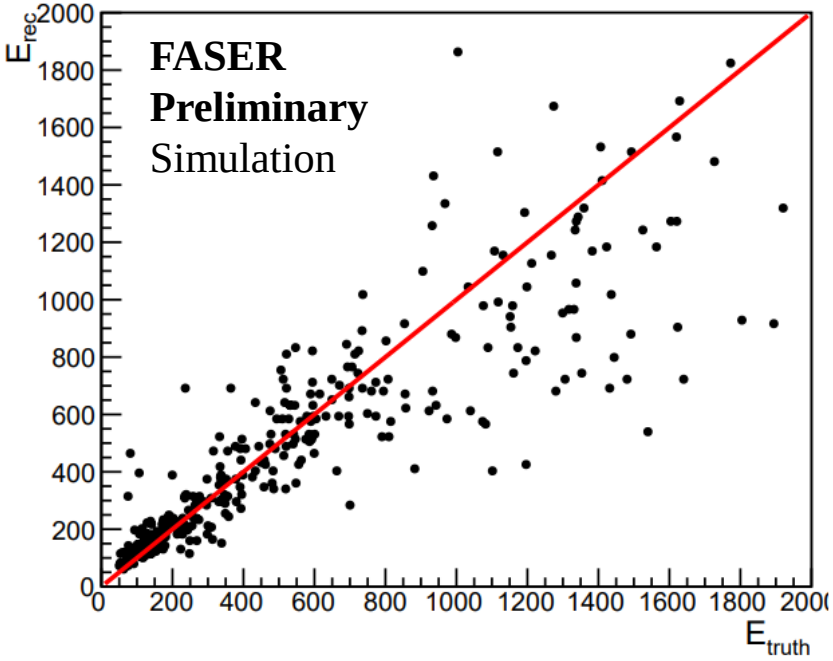




FASERν performance (energy)

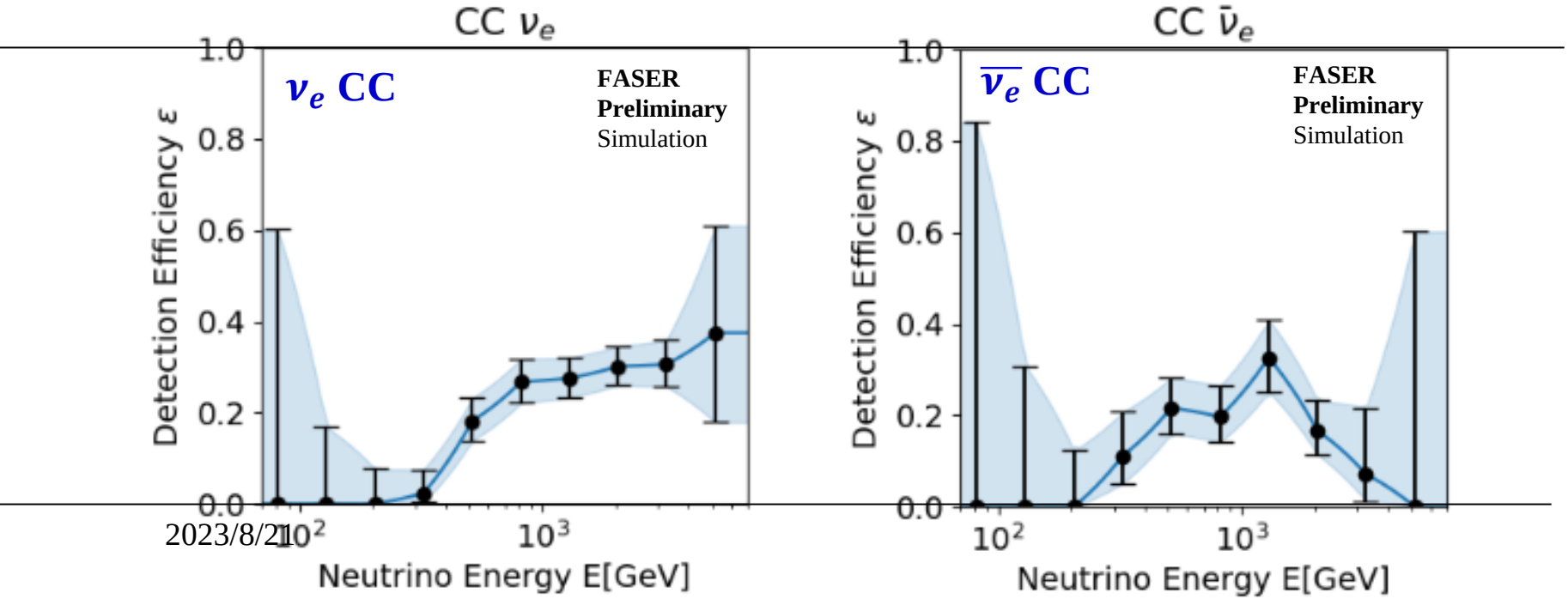
Number of segments (sum 7 films around shower maximum) are used to estimate electron energy. ~25% $\frac{\Delta E}{E}$ resolution





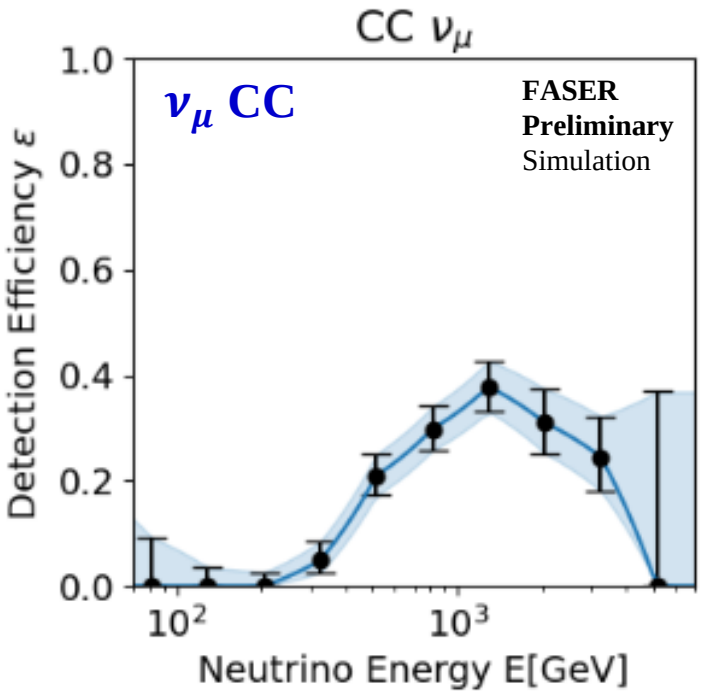
FASERν performance (efficiency ν_e)

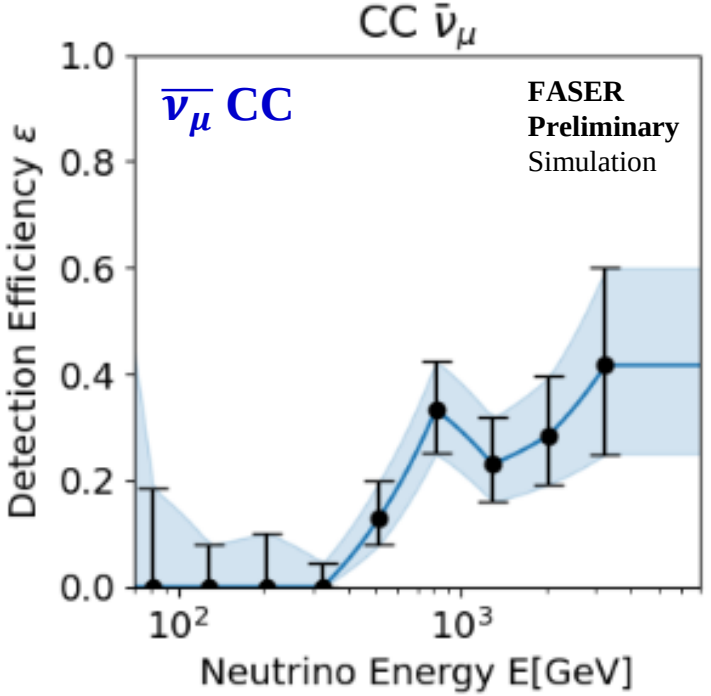
Selection	ν_e CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.516	0.336	0.813	0.803	0.753
E >200 GeV	0.340	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005	0.270	0.001	0.000	0.000	0.000
E >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.226	0.000	0.000	0.000	0.000



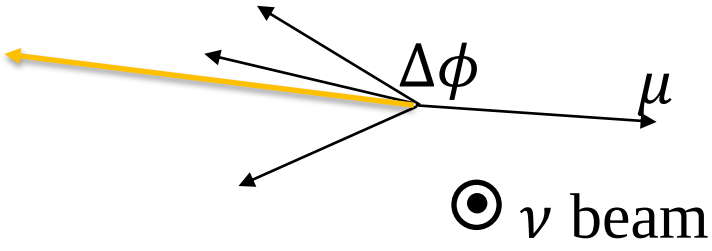
FASERν performance (efficiency ν_μ)

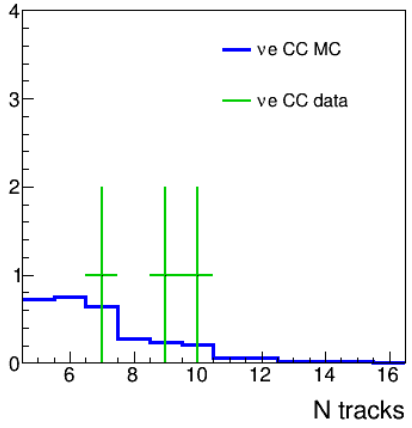
Selection	ν_μ CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction	0.446	0.336	0.813	0.803	0.753
p >200 GeV	0.284	0.071	0.028	0.026	0.018
p >200 GeV, tanθ >0.005	0.236	0.051	0.007	0.013	0.007
p >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.192	0.004	0.002	0.006	0.004

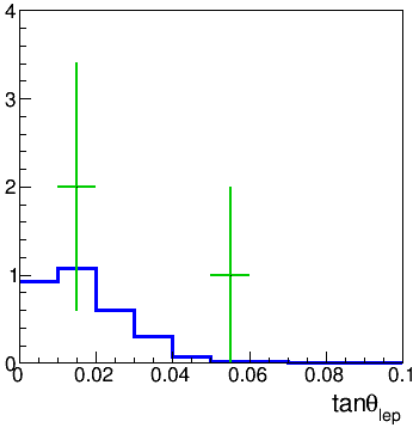


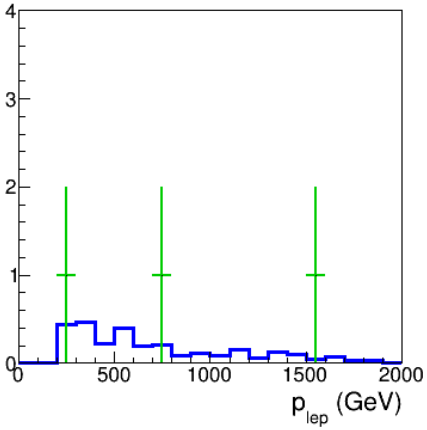


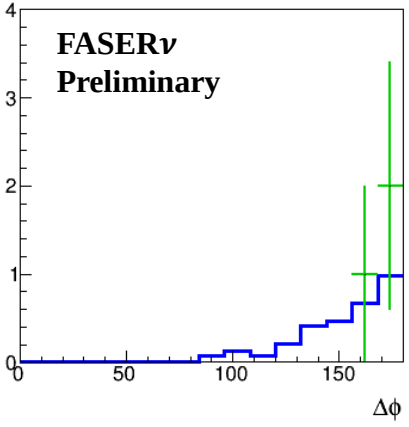
ν_e candidates



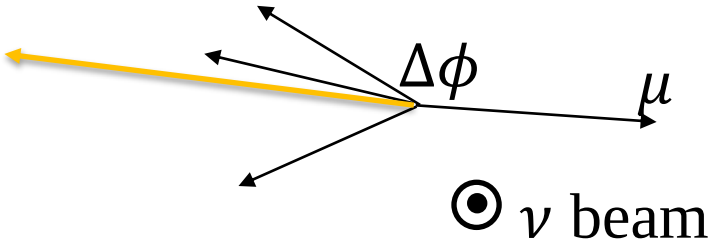


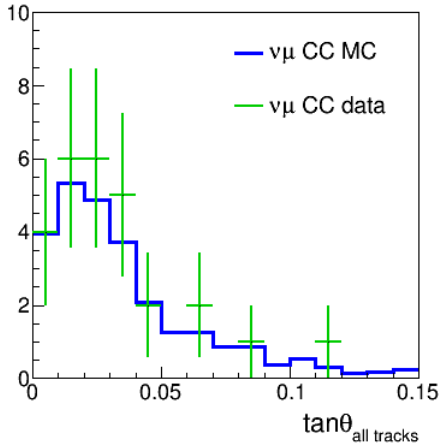


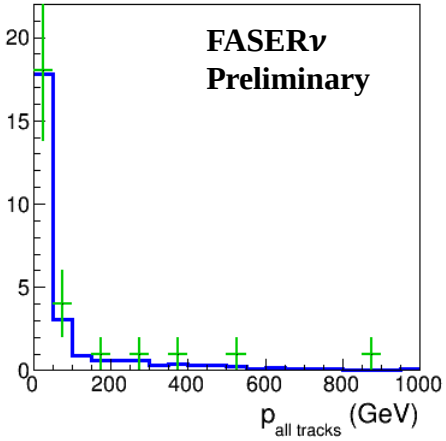


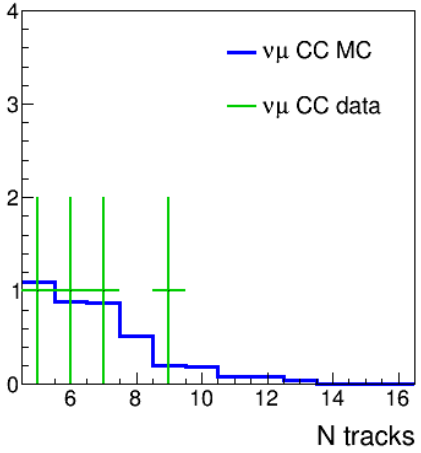


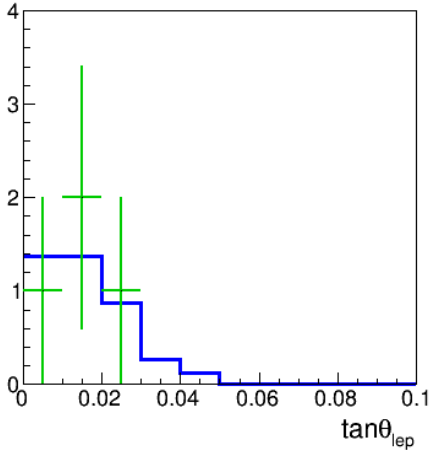
ν_μ candidates

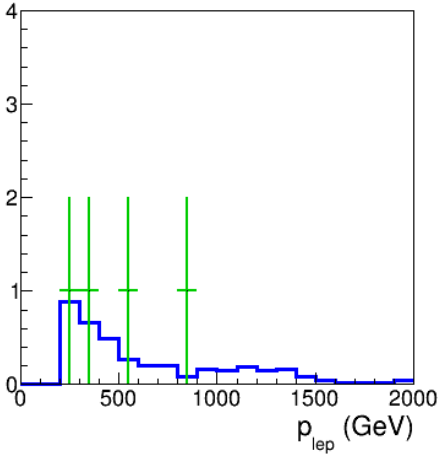


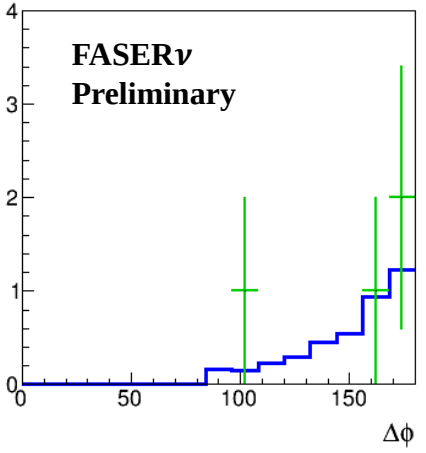












Acknowledgements

- FASER is supported by:

- 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