High-energy neutrino measurements with FASERν

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On behalf of FASER collaboration

Supported by:

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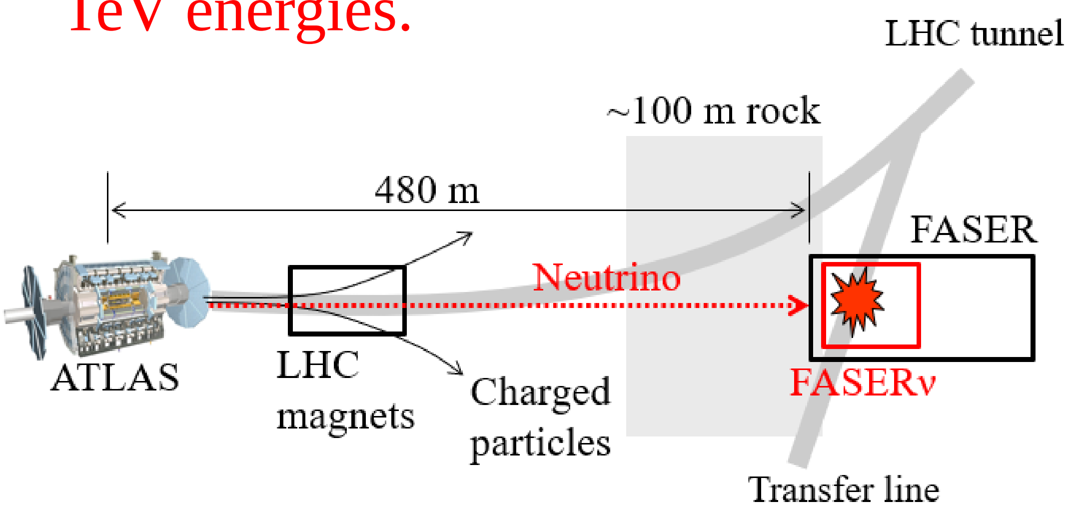
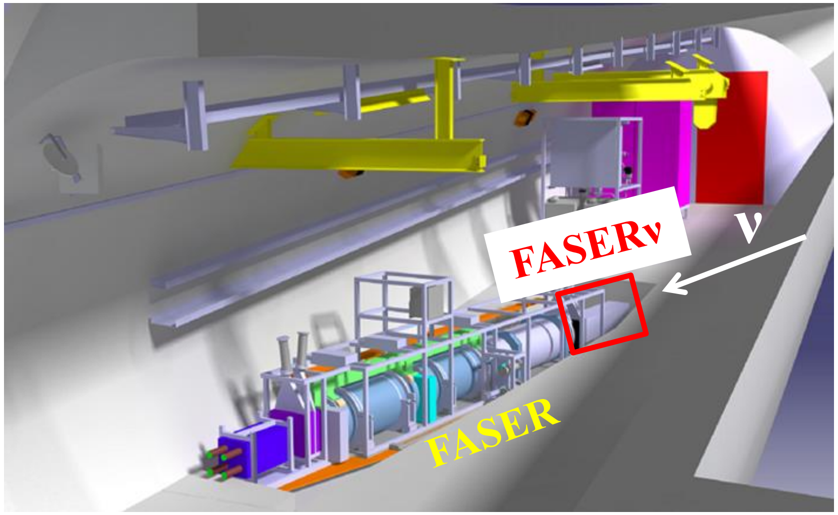
FASERν in FASER

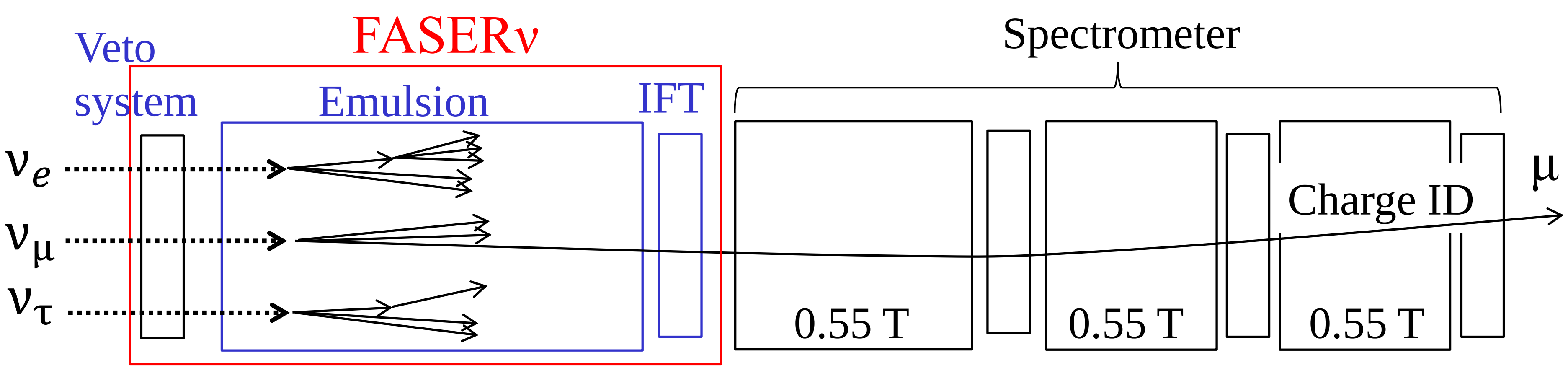
- FASER is a new experiment to search for new long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022.
- The detector is installed 480 m downstream of ATLAS IP (TI12).
- FASERν is a part of FASER detector dedicated for neutrino measurements.
- FASER will be the first experiment to study three-flavor neutrinos at TeV energies.





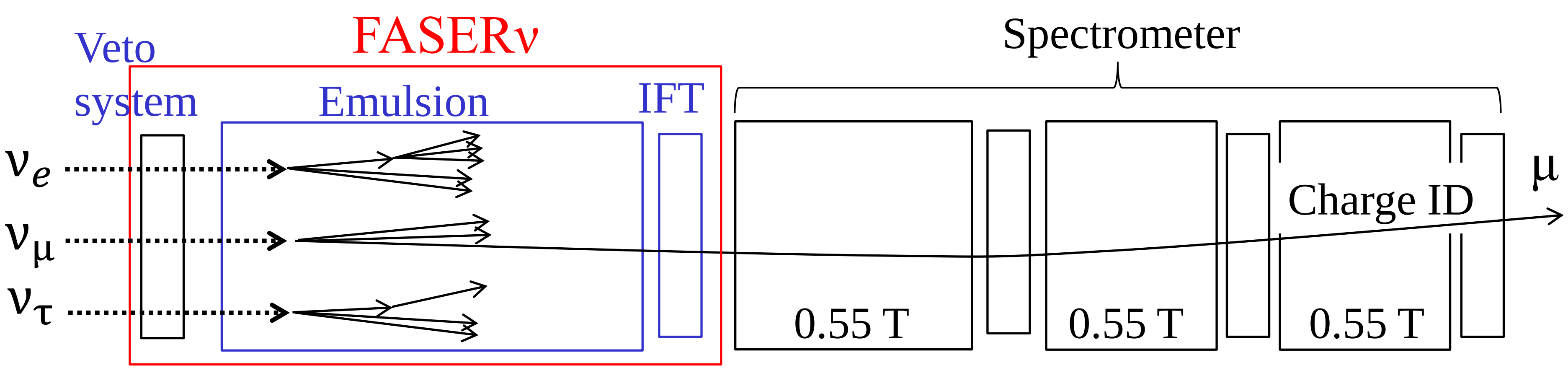
FASERν detector (Emulsion detector)

- 700 layers of an emulsion film and 1.1 mm tungsten plate
  - 25 cm × 30 cm × 1.1 m, 1.1 tons, 220 X_0
- The emulsion films will be replaced every 30-50 fb^{-1} during LHC technical stop.
- Measured particle (muon) flux was ~500 Hz at FASER with 2×10^{34} $cm^{-2}s^{-1}$ in 2018 run which gives an acceptable detector occ. for physics.
- Measured radiation level was low enough for detector performance requirements (<5×10^{7} 1MeV n_{eq}/year).



FASERν detector (IFT & Veto)

- Silicon strip tracker (IFT: InterFace Tracker) is used as the interface for tracking with FASER spectrometer behind it.
  - ➢ Charge identification of muons is possible with three 0.55 T dipole magnets in the spectrometer (3.5 m length in total).
- Veto scintillator system at the most front part of FASERν rejects charged particles coming from the upstream.
  - ➢ Allows matching of the signal muon tracks in IFT and spectrometer.



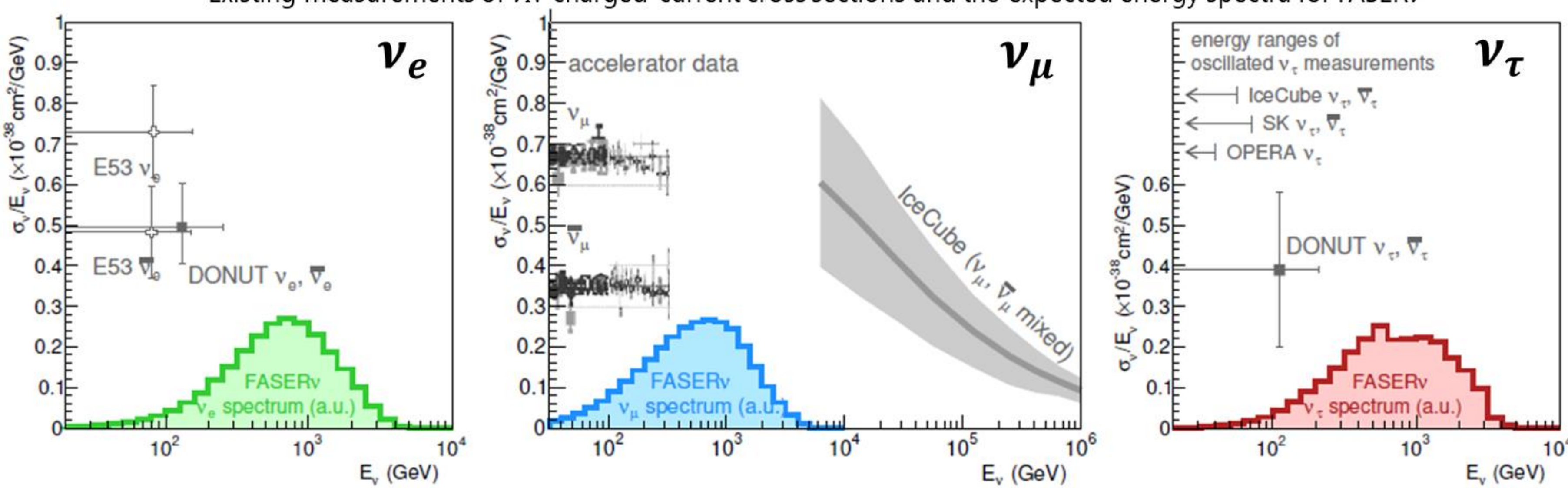
Charged current interaction (1)

- 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 interaction with 150 fb^{-1} @FASERν [PRD 104, 113008 (2021)]

Generators		FASERν		
Light hadrons	Heavy hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
SIBYLL	SIBYLL	901	4783	14.7
DPMJET	DPMJET	3457	7088	97
EPOSLHC	PYTHIA8 (Hard)	1513	5905	34.2
QGSJET	PYTHIA8 (Soft)	970	5351	16.1
Combination (all)		1710^{+1746}_{-809}	5782^{+1306}_{-998}	$40.5^{+56.6}_{-25.8}$
Combination (w/o DPMJET)		1128^{+385}_{-227}	5346^{+558}_{-563}	$21.6^{+12.5}_{-6.9}$

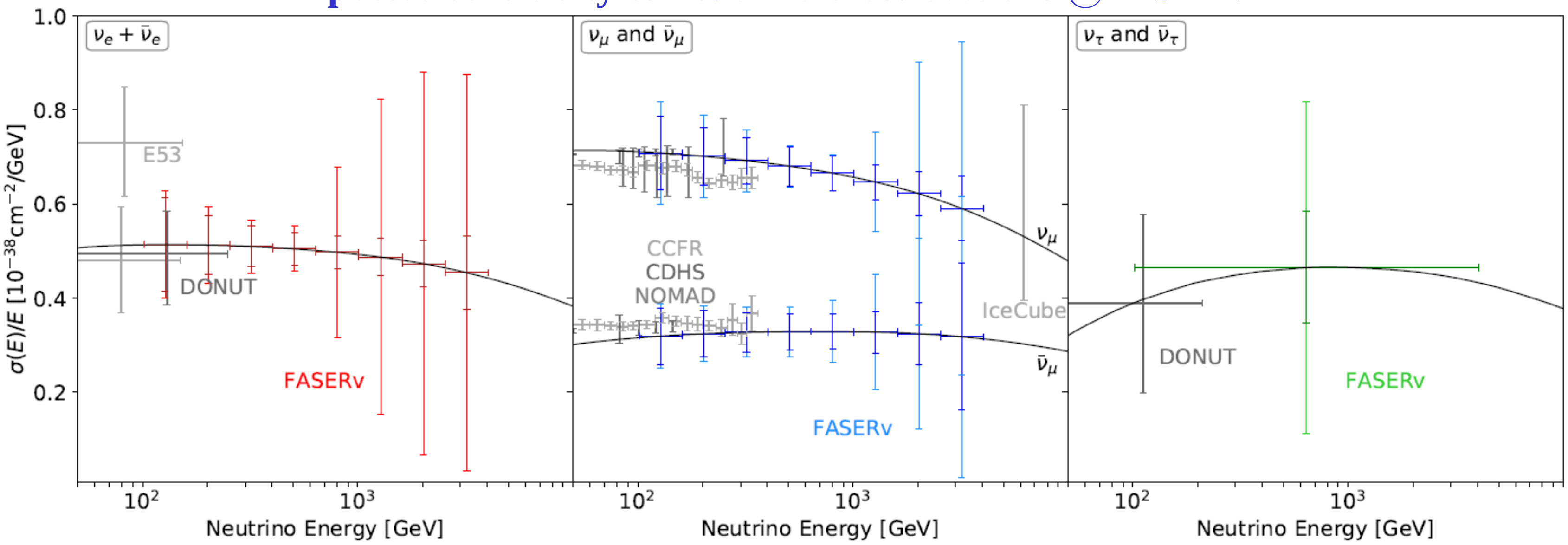
Existing measurements of νN charged-current cross sections and the expected energy spectra for FASERν



Charged current interaction (2)

- CC cross-section will be measured at TeV region, and its consistency with Standard Model (SM) will be studied.
- The anomaly of the third generation coupling will be explored.
  - 4σ deviation from SM is reported in the quark-sector [here].
- The charge measurement in cooperation with spectrometer behind FASERν enables to separate $\nu_\mu/\bar{\nu}_\mu$.

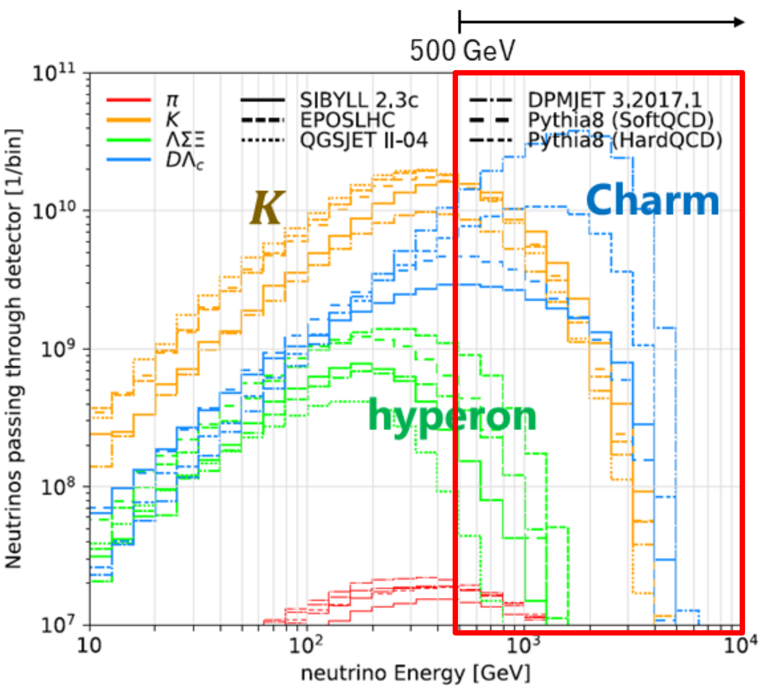
Expected sensitivity to neutrino cross-sections @FASERν



Charged current interaction (3)

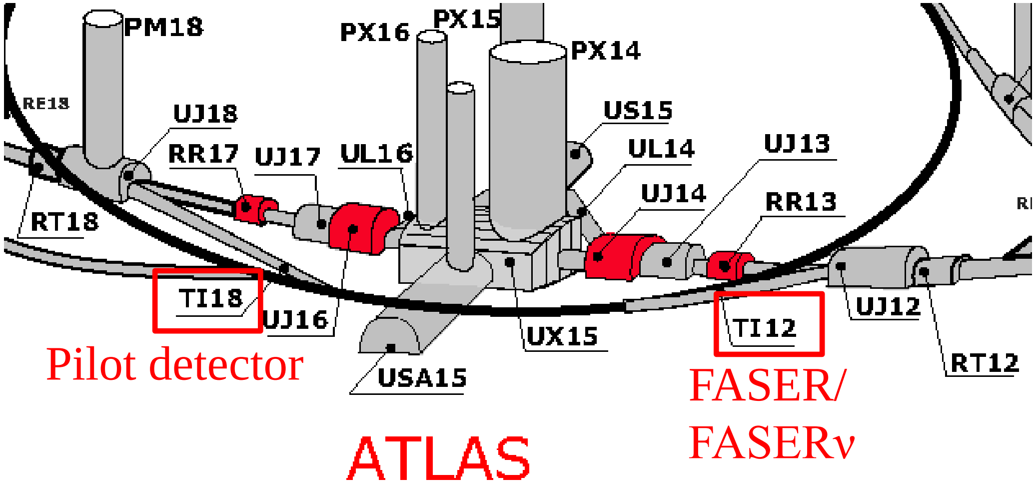
- There are large number of difference between generator predictions, especially for ν_e and ν_τ from large uncertainties in forward charm production.
- The forward charm production can be studied with ν_e above 500 GeV in FASERν.

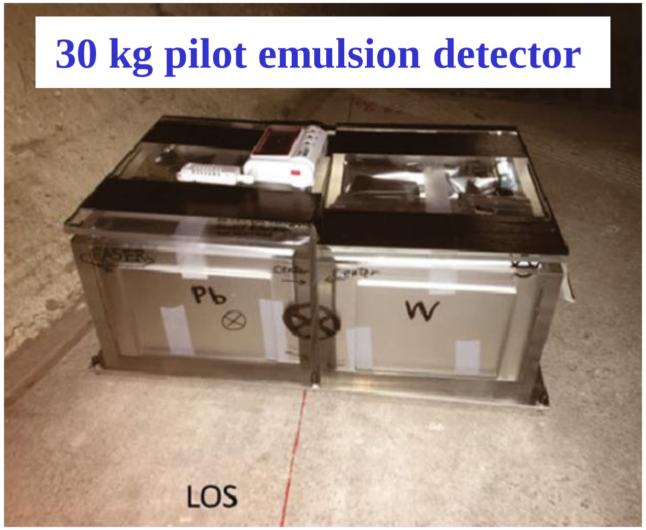
Electron neutrino in FASERν



Pilot data-taking (1)

- The pilot runs took place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018.
  - FASER/FASERν is installed at T12.
  - TI18 is the tunnel at the same distance from ATLAS IP as TI12 but opposite side.
- Neutrino detection was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 fb^{-1} of data (10 kg are used in the analysis).

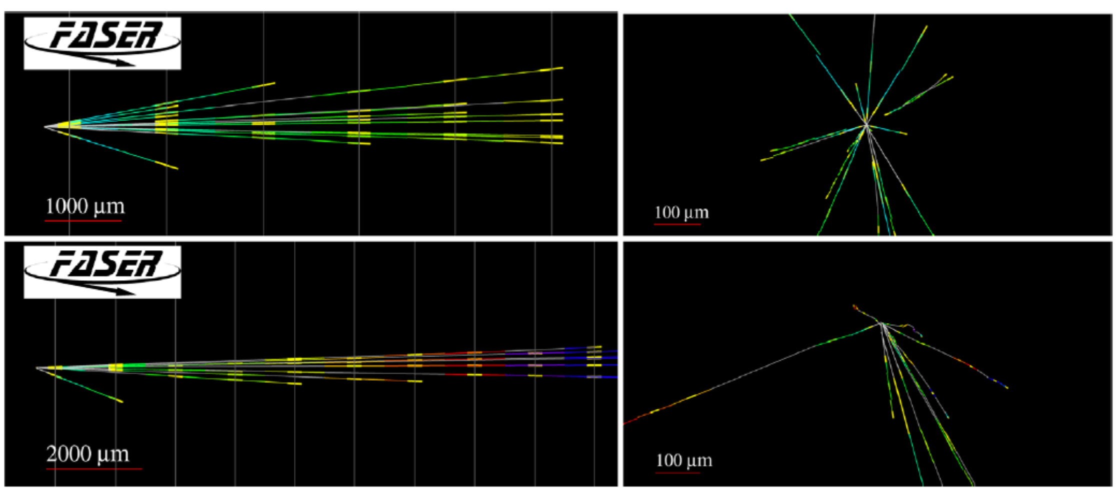




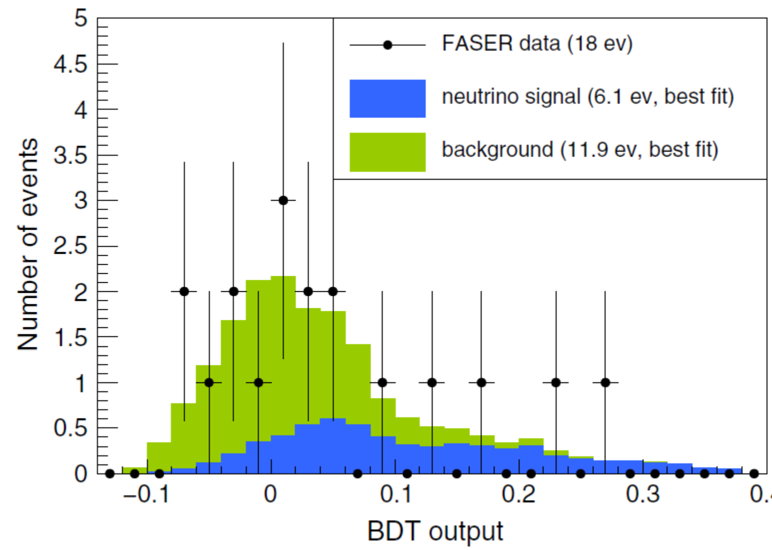
Pilot data-taking (2)

- 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

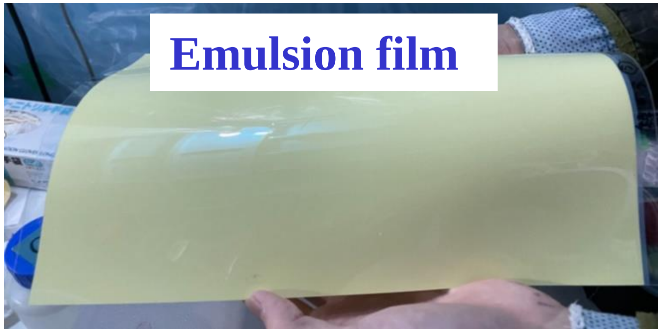


FASERν construction (1)

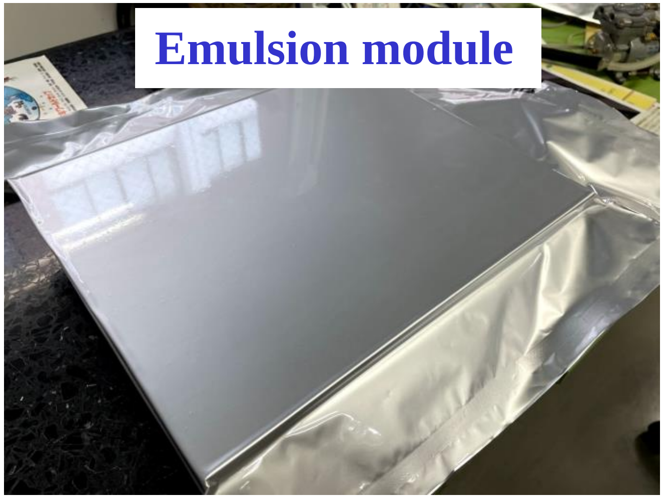
- 268 emulsion films (~20 m^2) corresponding to ~30% of the full loading were produced in Japan for data-taking during commissioning period.
- 10 sets of a tungsten plate and emulsion film were assembled per module and vacuum-packed at CERN.

Film production facility

Emulsion film

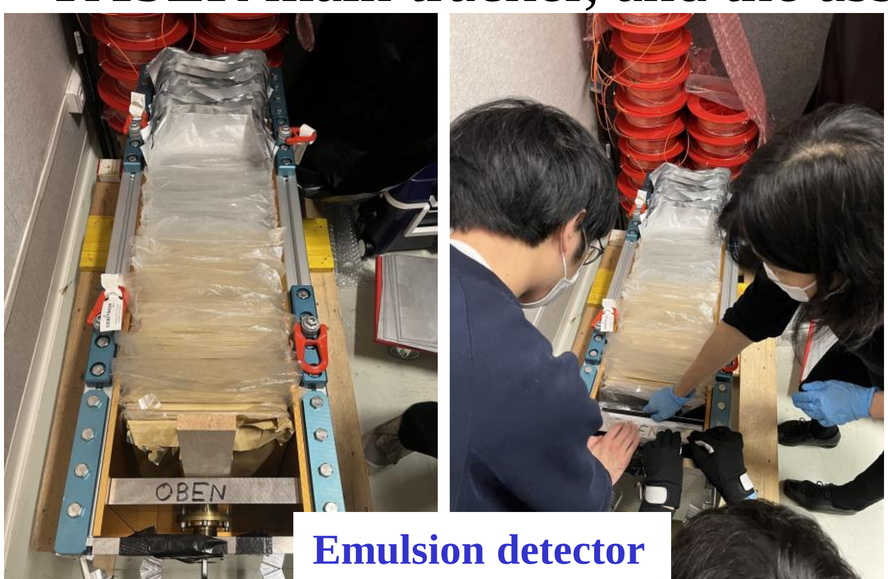


Emulsion module

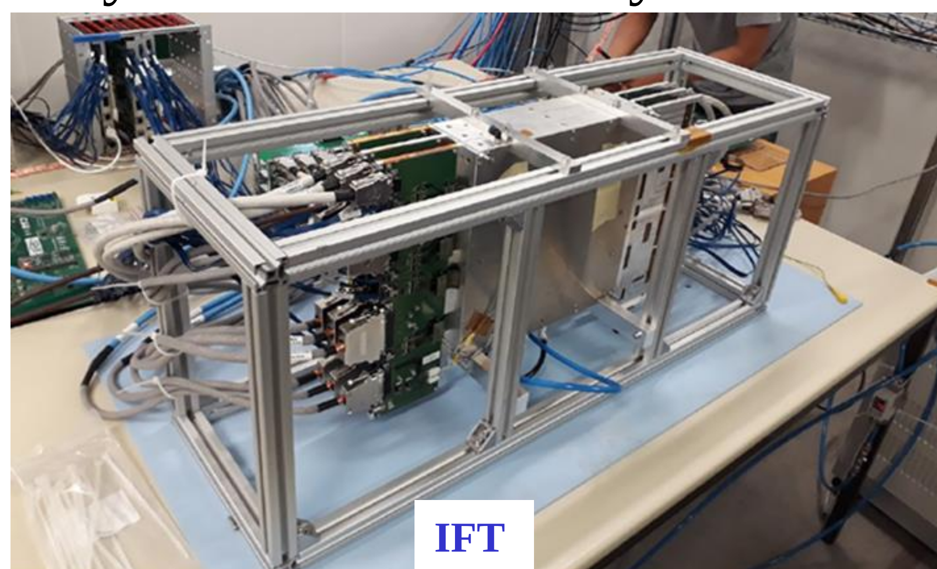


FASERν construction (2)

- The first emulsion detector was prepared in March 2022.
  - 22 emulsion modules were housed in the emulsion box with tungsten plates for the remaining volume.
  - This is ~30% of the full emulsion for commissioning, and it will be replaced with a full detector for the first physics at the end of July.
- IFT was built with spare ATLAS SCT modules with the same design as FASER main tracker, and the assembly was finished in July 2021.



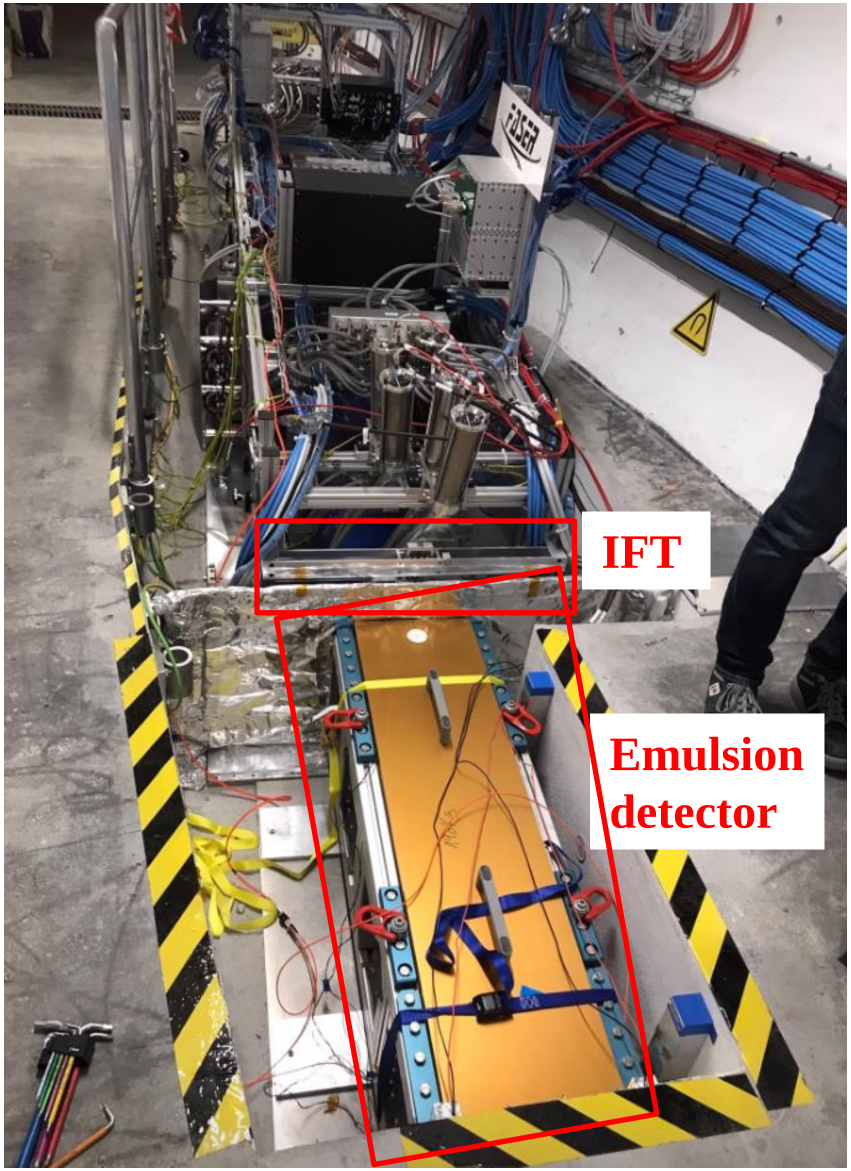
Emulsion detector



IFT

FASERν installation

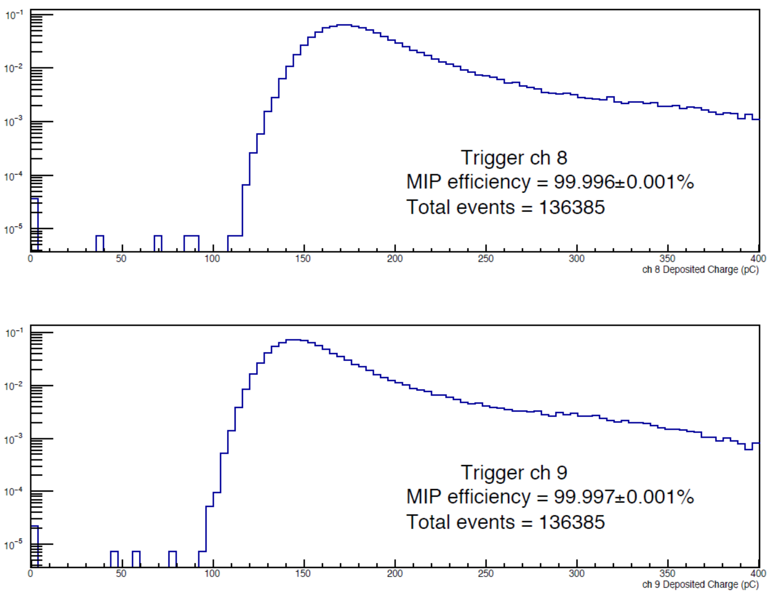
- Most of the FASER main detector was installed in spring 2020.
- IFT was installed in November 2021.
- The first emulsion box was installed in March 2022.
  - Placed on the LOS (Line Of Site) to maximize the flux of all neutrino flavors (the trench dug allows this).
- The physics data-taking will start in July 2022.
- The emulsion films will be replaced 11 times every 30-50 fb^{-1}.

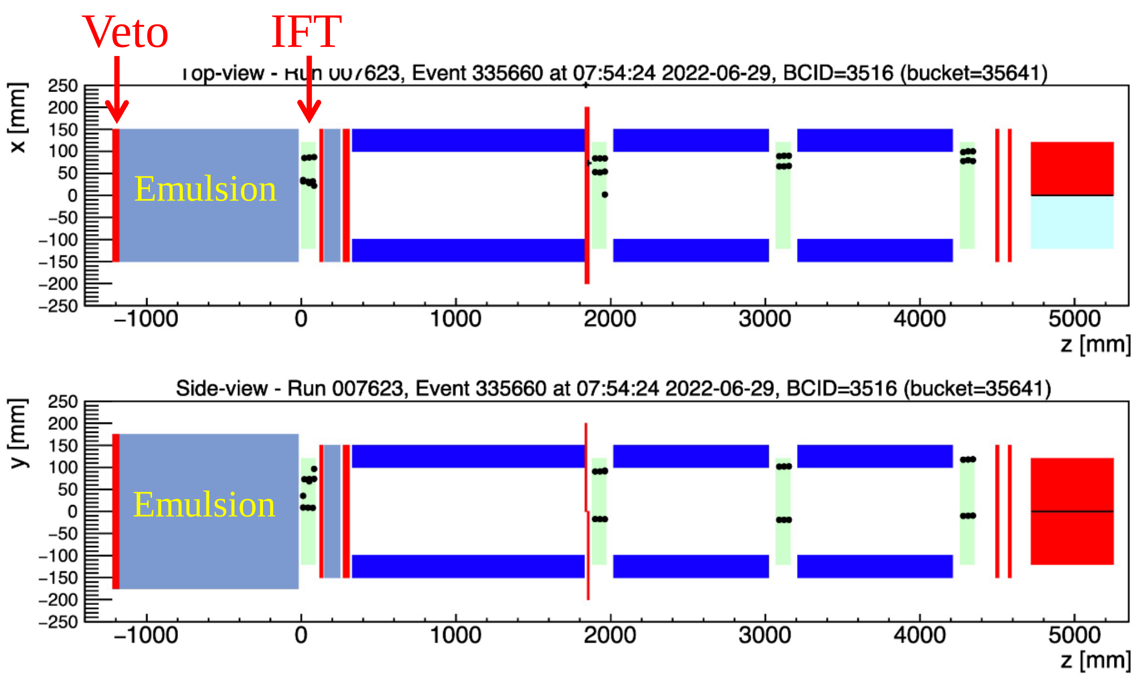


Test beam & commissioning

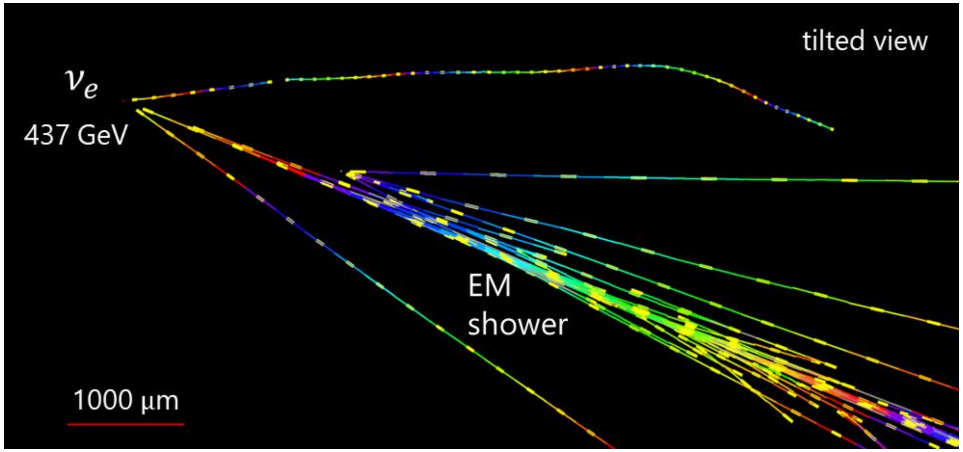
- MIP efficiency of the veto system was measured in testbeam at CERN-SPS H2 beam line, and better performance than the requirement (>99.98%) was obtained.
- The commissioning is ongoing by using cosmic and beam collisions at LHC.

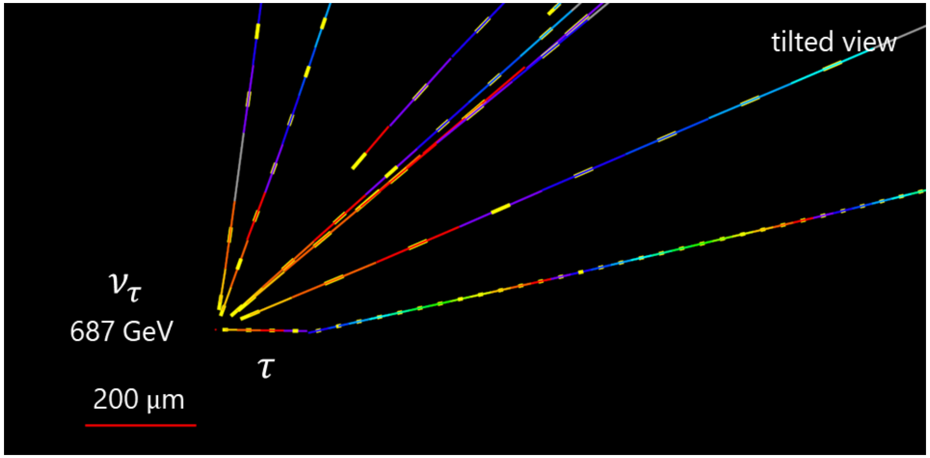
Charge deposit in veto system @Testbeam

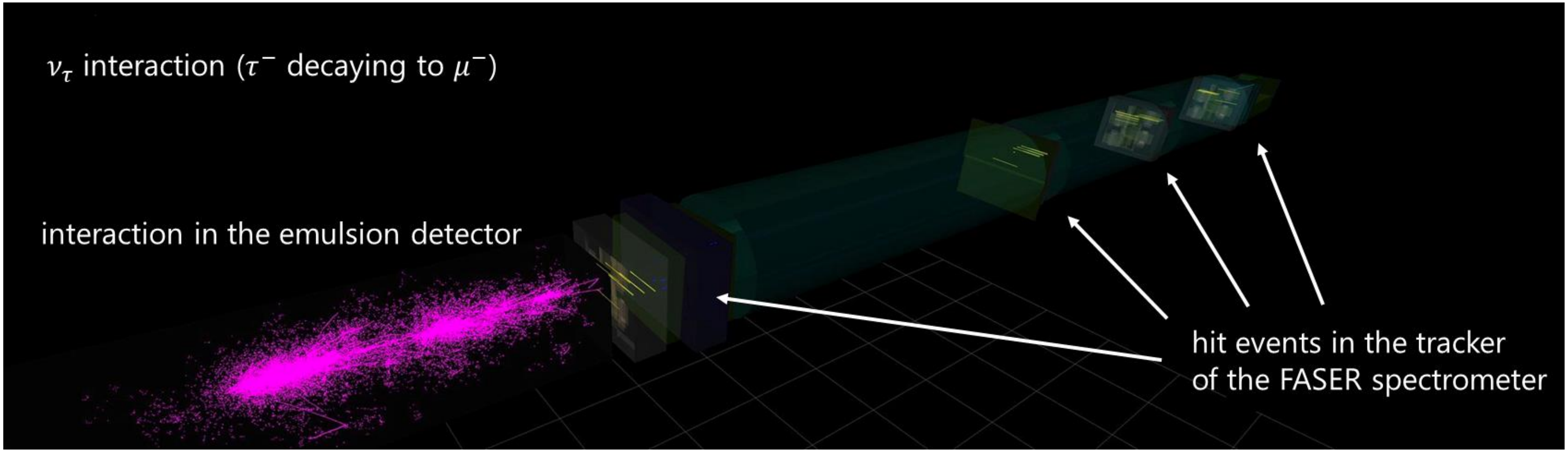




Simulated neutrino events in FASERν







Summary & Conclusions

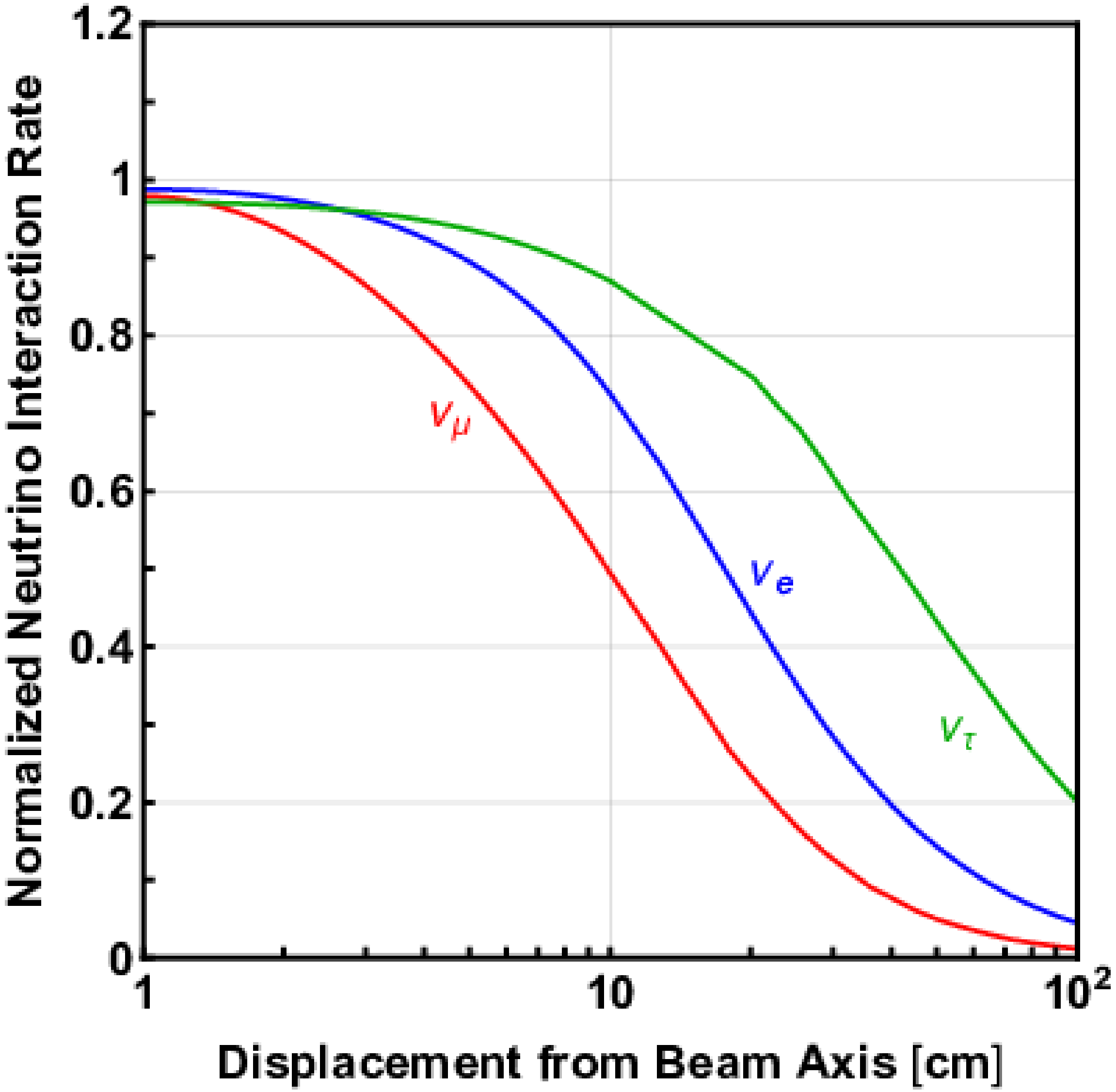
- FASERν is the detector in FASER experiment to measure cross-section of high energy neutrinos with ~1 TeV originated from proton-proton collisions at LHC.
  - First experiment making use of beam collisions as neutrino source.
- FASERν can measure cross-section for all neutrino flavors, thanks to excellent position resolution of the emulsion detector.
- The first candidates of the neutrino interactions at LHC was observed in the pilot data-taking in 2018.
- Both the first emulsion detector and IFT were installed at FASER site.
  - The emulsion films will be replaced every 30-50 fb^{-1}.
- The data-taking will start in July 2022 at LHC Run3.
- A future 10 times larger upgrade of FASERν is being considered as a part of the proposed [Forward Physics Facility].

Backup

Collaboration & Foundation

FASER collaboration consists of 75 collaborators, 22 institutes, and 9 countries.

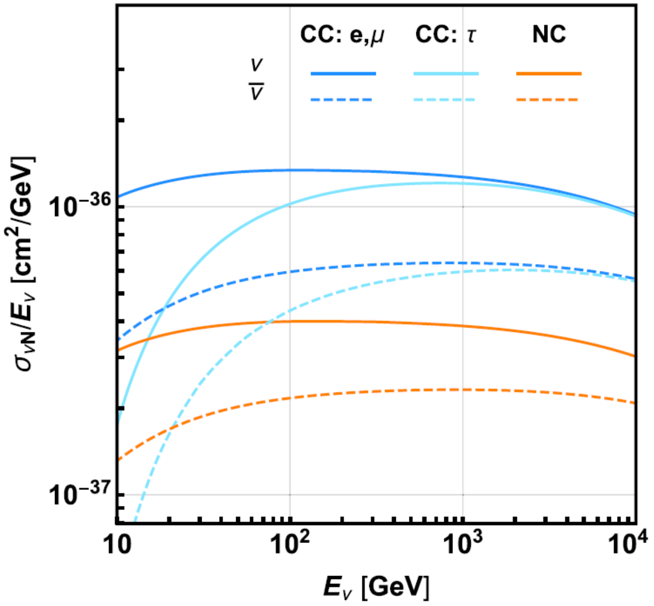
Neutrino flux v.s. distance from LOS

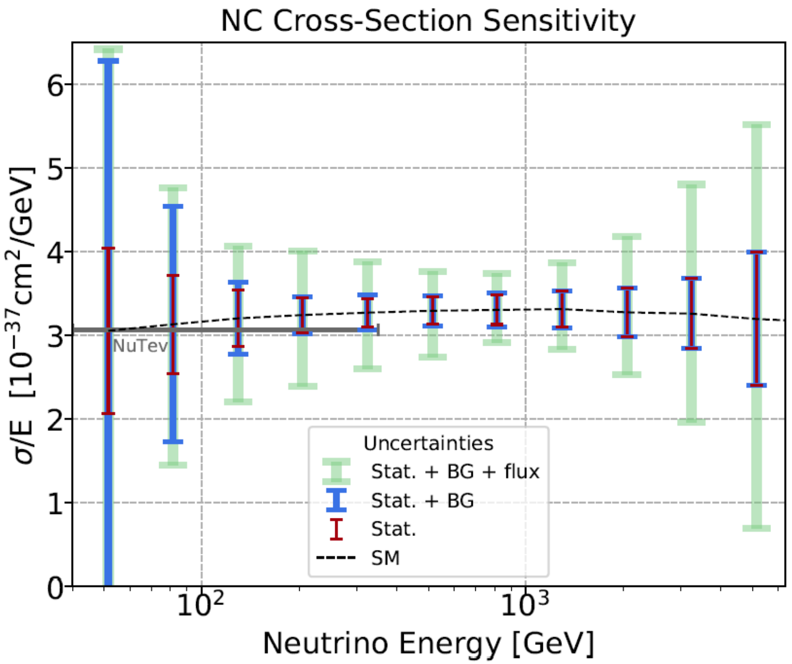


Neutral current interaction

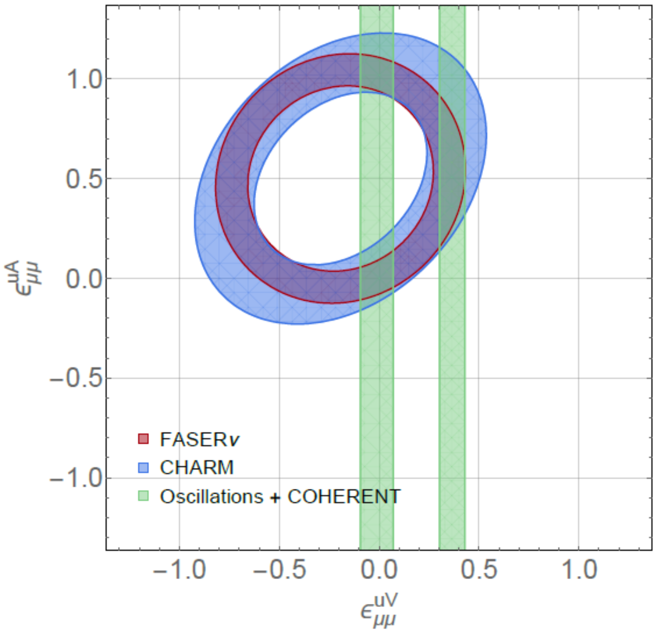
- FASERν also measures cross-section of Neutral Current (NC) neutrino interactions [arXiv: 2012.10500].
- Non-Standard Interaction (NSI) can be explored in conjunction with measurement of CC cross-section.

DIS cross-section of CC/NC interactions





Expected sensitivity to NSI (up-quark)

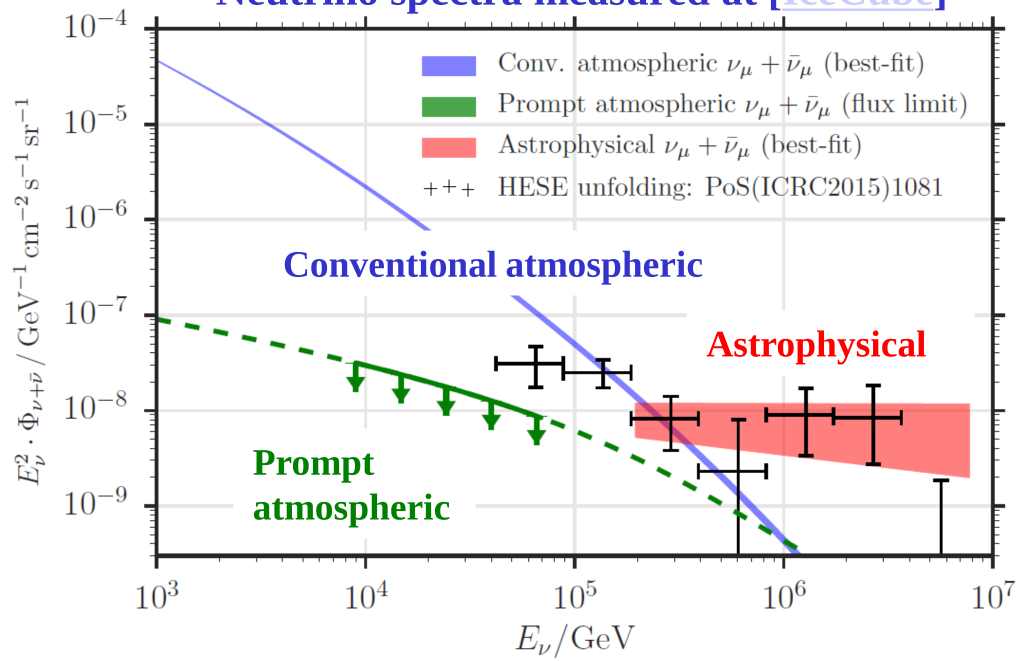


Forward charm production

- 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)).

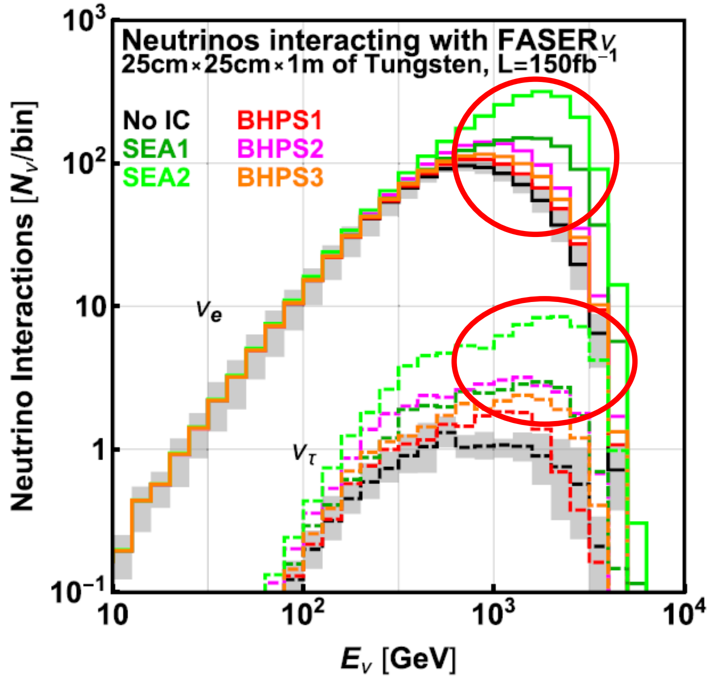
Neutrino spectra measured at [IceCube]

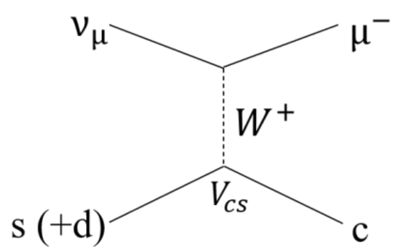


Charm/strange PDF

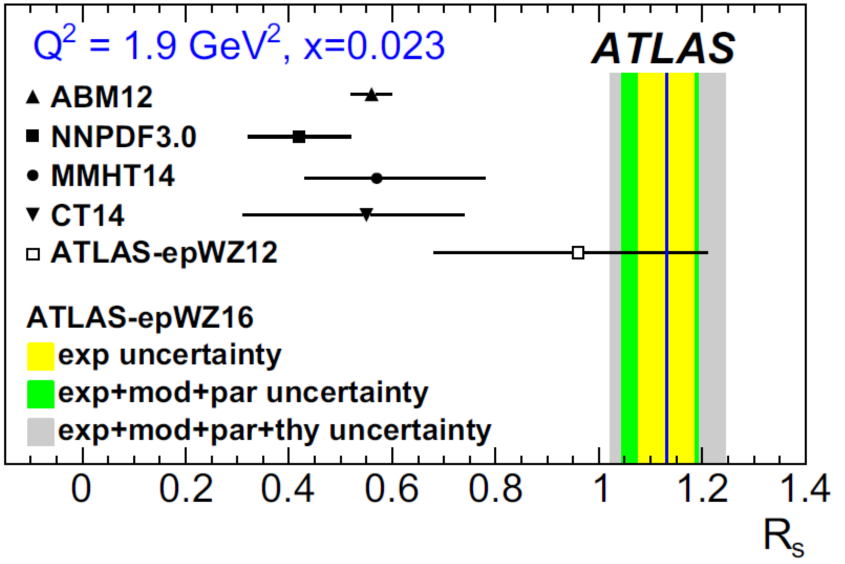
- There is a controversial prediction in which an additional charm component exists in a proton (so-called intrinsic charm).
- It only affects the forward charm production (cg→cg) in pp collisions, to which ν_e/ν_τ energy spectrum in FASERν is sensitive.

Expected energy dist. of ν_e/ν_τ @FASERν





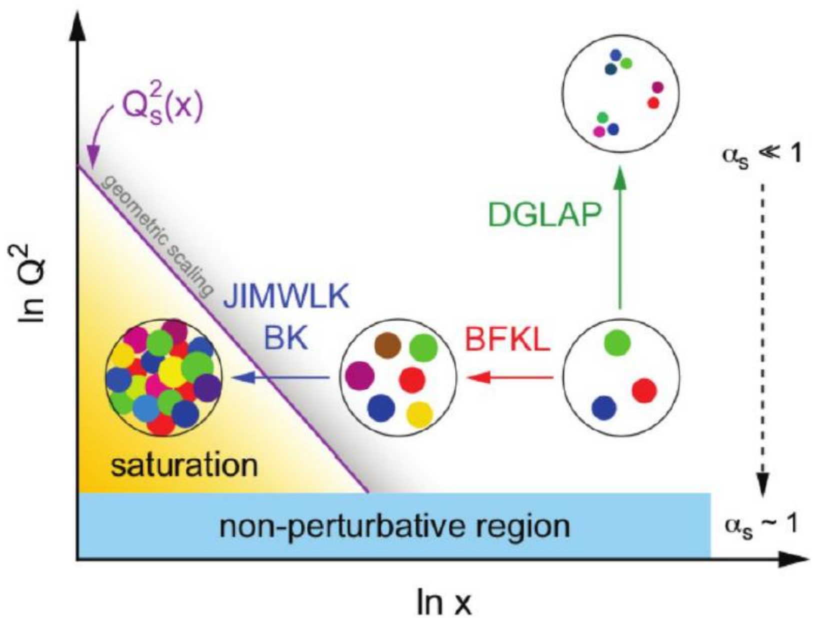
$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ [Eur. Phys. J. C77 (2017) 367]



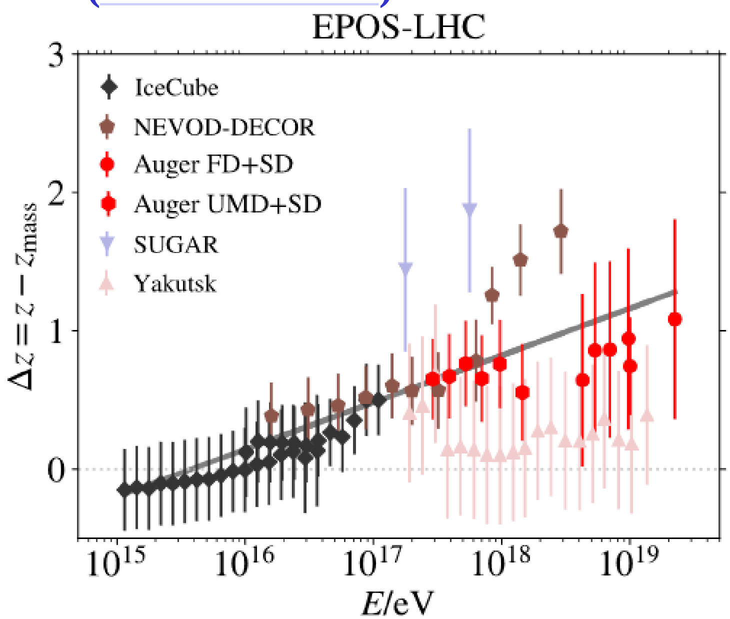
- D meson production in CC ν_μ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and predictions.

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.



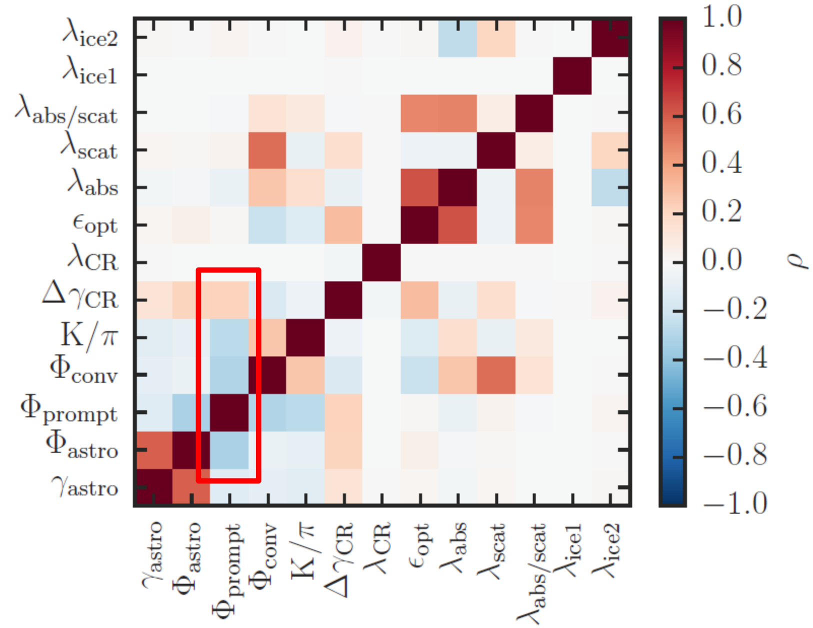
Muon excess from prediction (Snowmass LOI)



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}.

Correlation matrix of nuisance parameters



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

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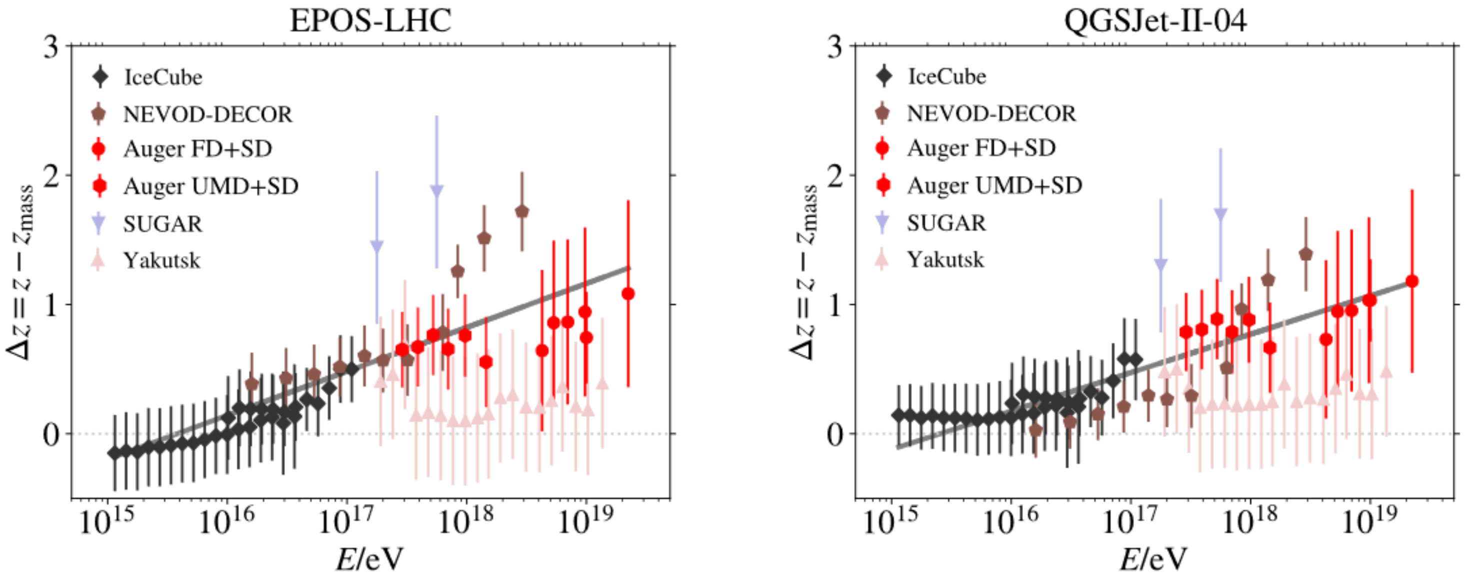
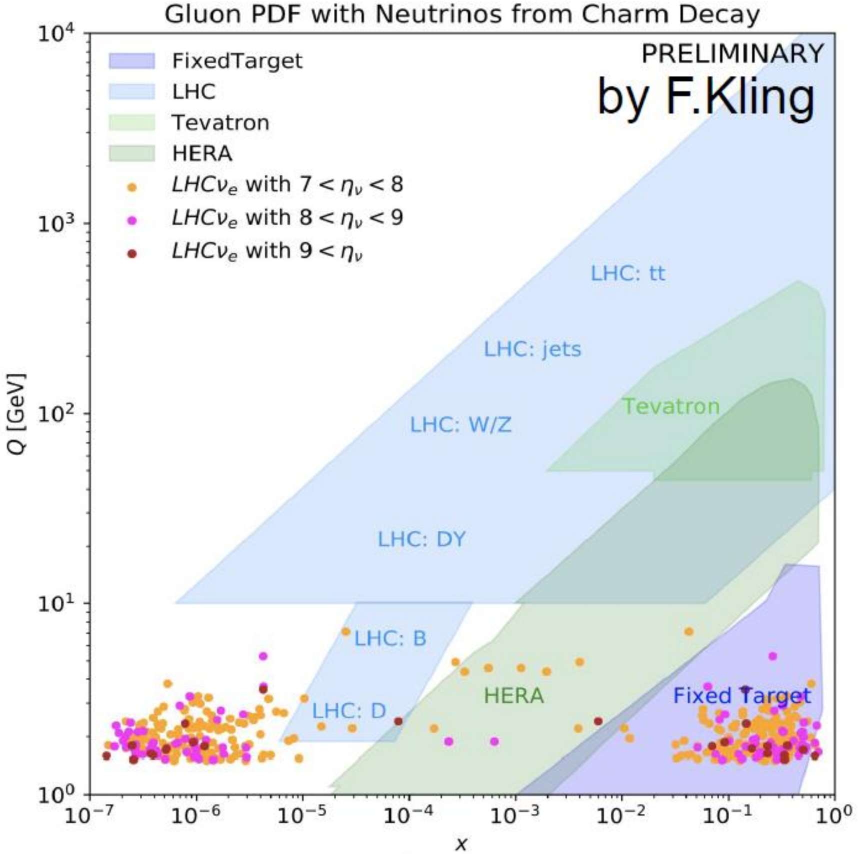
Muon excess in extensive air showers

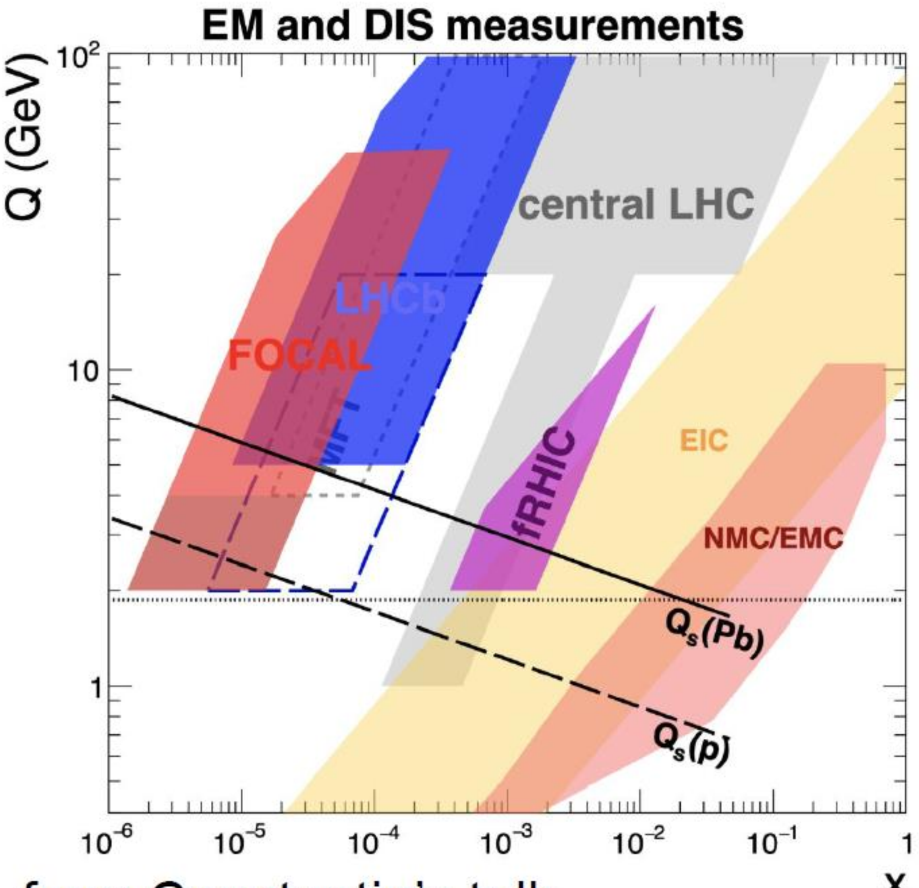
- Excess of muons with respect to the prediction (8σ) are observed in cosmic ray experiments.
- The hadronic interaction models used for the prediction were developed by using results of measurement in LHC and SPS.
- Measurement of muon/neutrino flux at FASER/FASERν will provide feedback to the interaction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

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



Gluon saturation in proton (2)

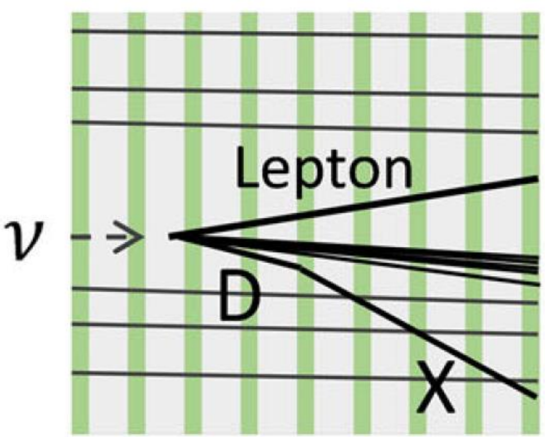




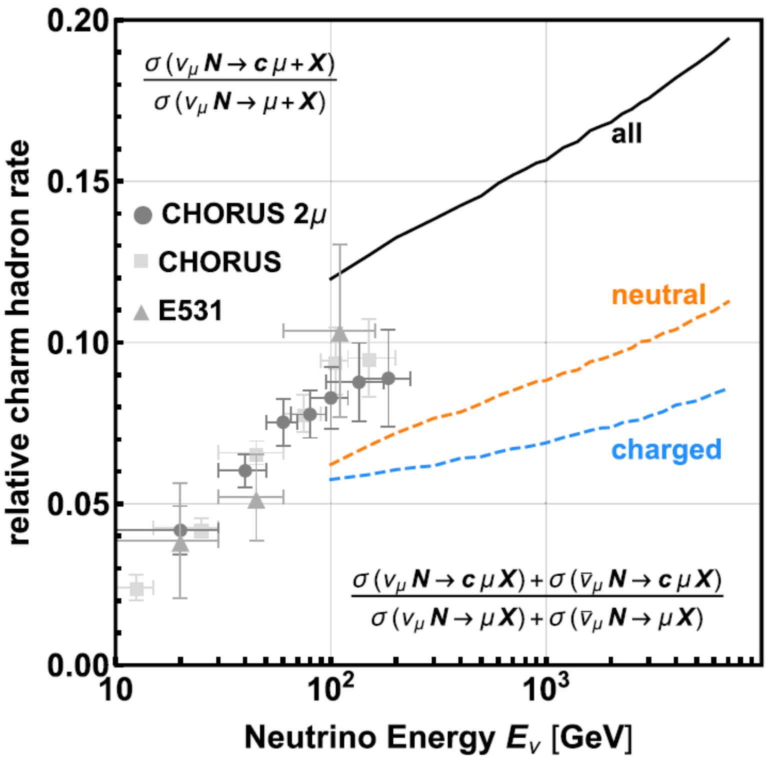
From [F. Kling's presentation]

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

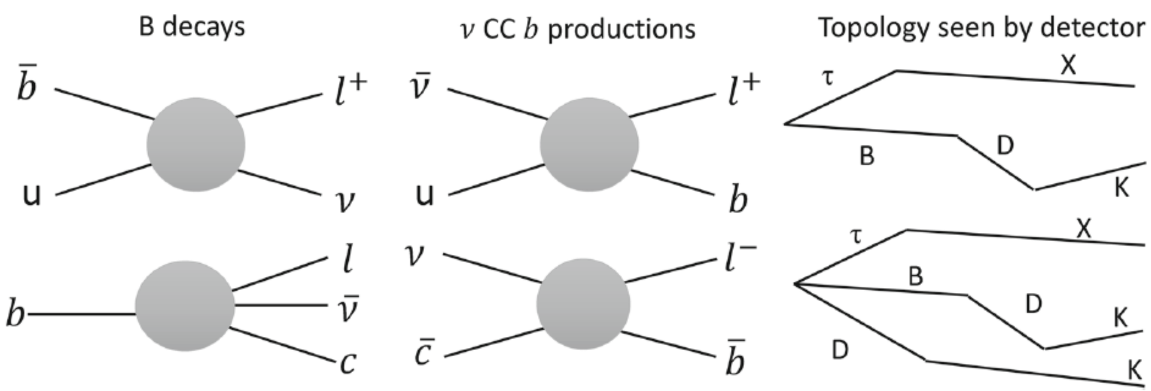


Beauty-associated neutrino events (1)

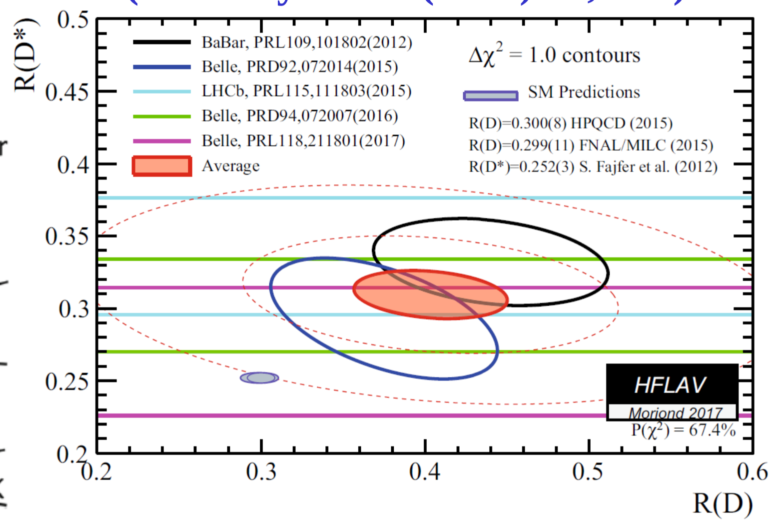
- Results in measurements in of B→D*$\ell\nu$, B→K*$\ell\ell$ and B^+→$K^+\ell\ell$ suggest lepton universality violation.

- 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.

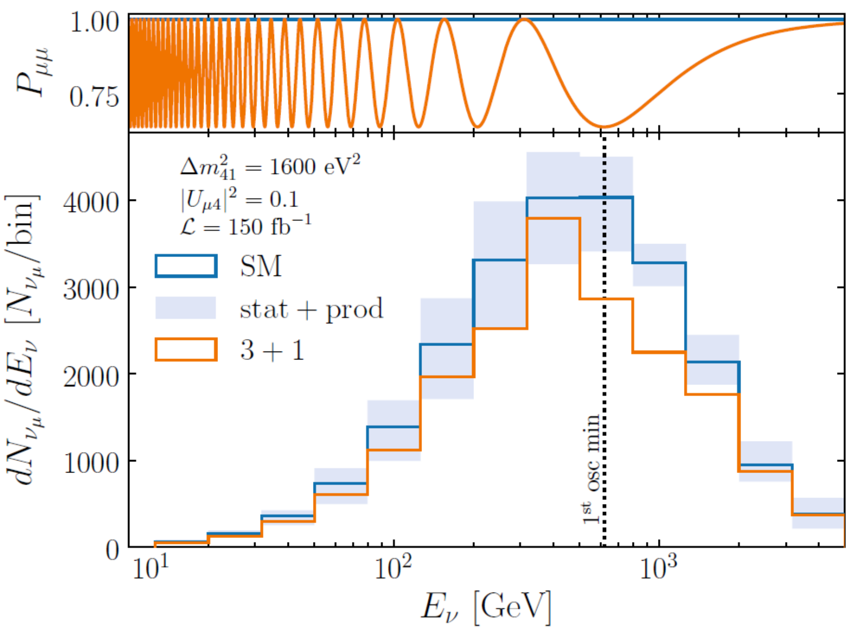
Sterile neutrino oscillation

- 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