# Measuring cross-sections of high-energy neutrinos with FASERν at the LHC

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On behalf of FASER collaboration

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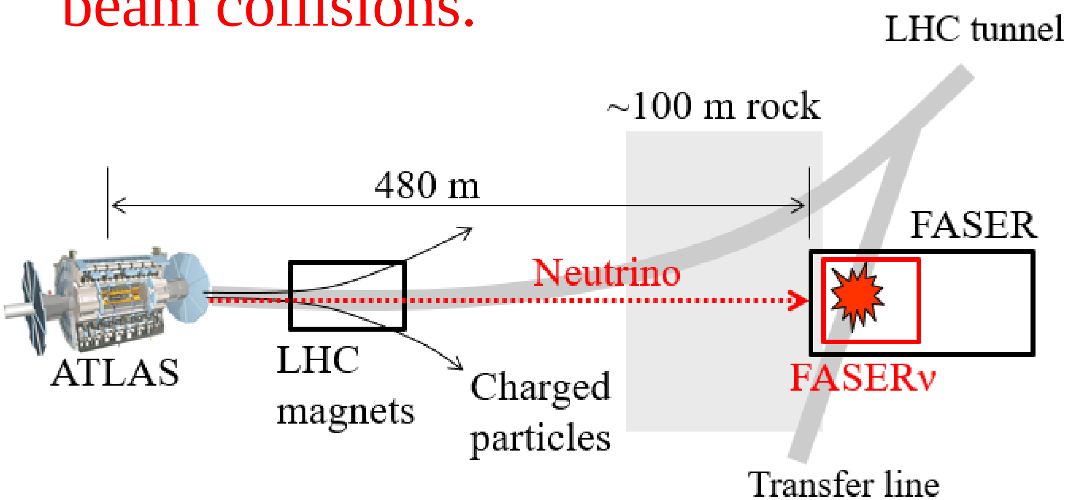
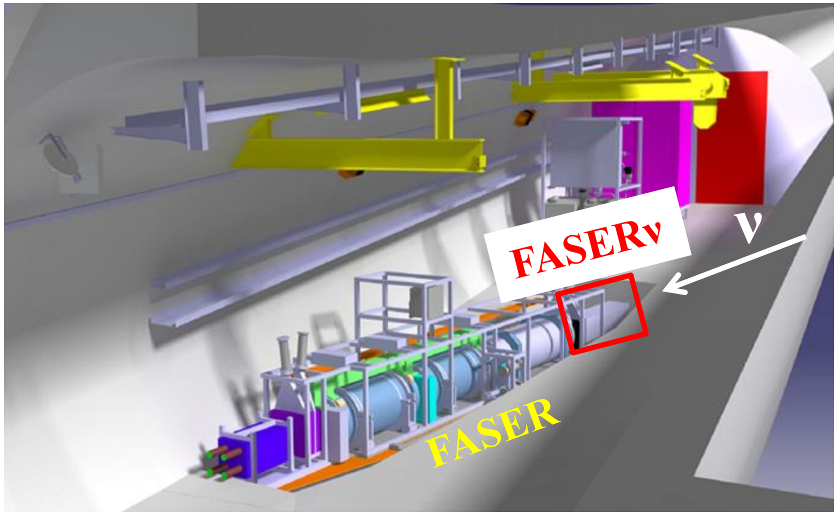
# FASERν in FASER

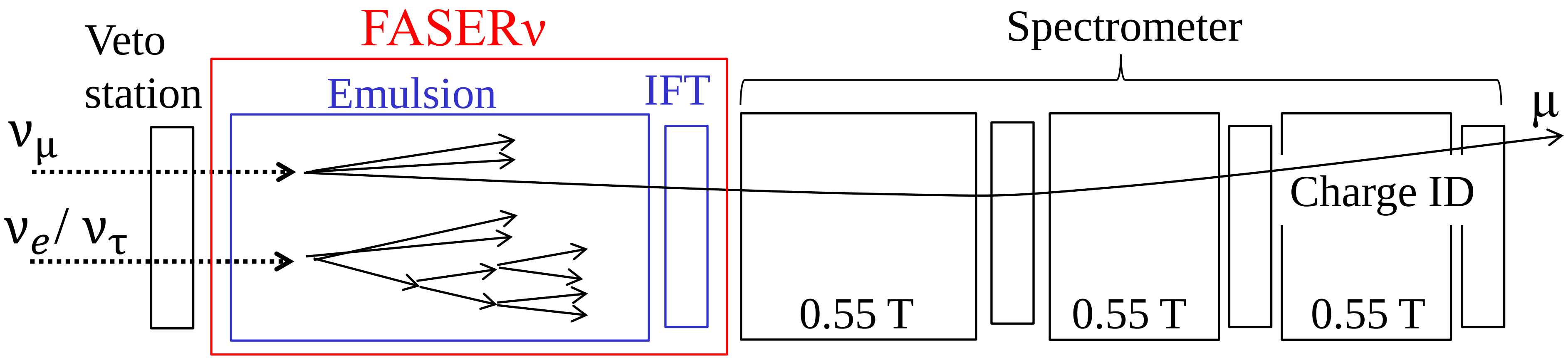
- FASER is a new experiment to search for new long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022.
- The detector will be installed 480 m downstream of ATLAS IP (TI12).
- FASERν is a part of FASER detector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



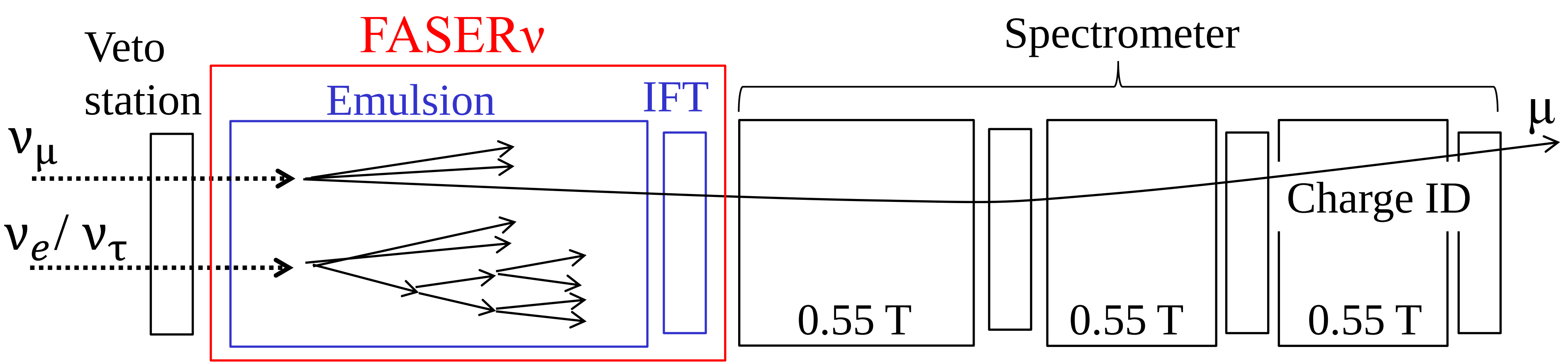
# FASERν detector (Emulsion detector)

- 770 layers of an emulsion film and 1mm 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 $2 \times 10^{34}$ $cm^{-2}s^{-1}$ in 2018 run which gives an acceptable detector occ. for physics.
- Measured radiation level low enough for detector performance requirements (<$5 \times 10^{7}$ 1MeV $n_{eq}$/year).



# FASERν detector (IFT & Veto)

- Silicon strip tracker (IFT: InterFace Tracker) will be 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 station in front of FASERν rejects charged particles coming from upstream of FASERν.
  - Allows matching of the signal muon tracks in IFT and spectrometer.



# Charged current interaction (1)

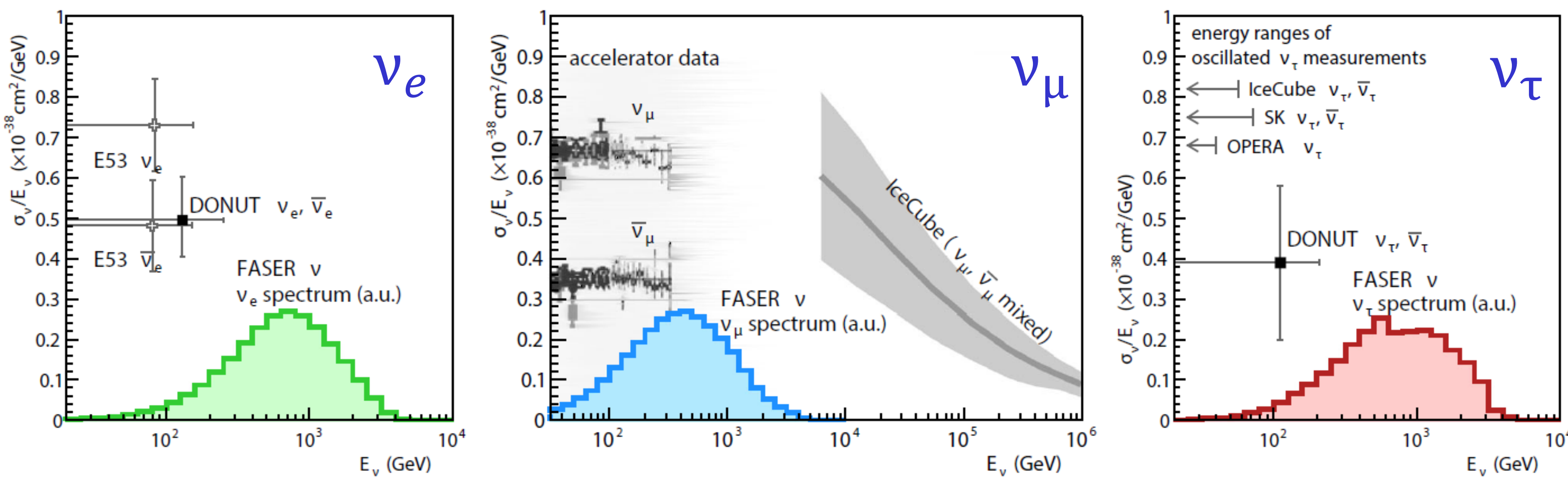
- FASERν will measure neutrino cross-sections at TeV region which is uncovered by existing experiments.
- All neutrino flavors in Charged Current (CC) interactions can be identified, thanks to excellent position resolution of the emulsion detector.

**Differences between the generators** checked with the same propagation model (RIVET-module)

| | DPMJET | SIBYLL | Pythia8 |
|---|---|---|---|
| $\nu_e$ , $\bar{\nu}_e$ | 3390 , 1024 | 800 , 452 | 826 , 477 |
| $\nu_\mu$ , $\bar{\nu}_\mu$ | 8270, 2391 | 6571 , 1653 | 7120 , 2178 |
| $\nu_\tau$ , $\bar{\nu}_\tau$ | 111 , 43 | 16 , 6 | 22 , 11 |

With 150 $fb^{-1}$

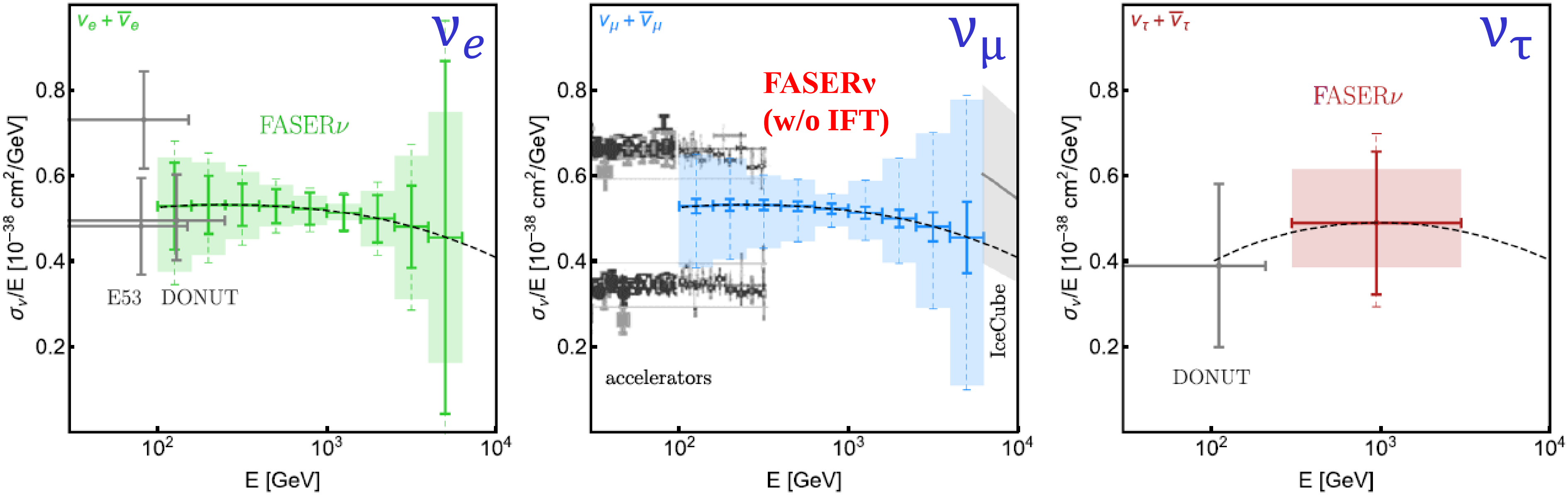
**Neutrino energy distributions @FASERν**



# Charged current interaction (2)

- CC cross-sections at TeV region will be measured for all neutrino flavors.
  - Lepton flavor universality in neutrino sector can be investigated.
- The charge measurement in cooperation with spectrometer behind FASERν enables to separate $\nu_\mu/\bar{\nu}_\mu$.

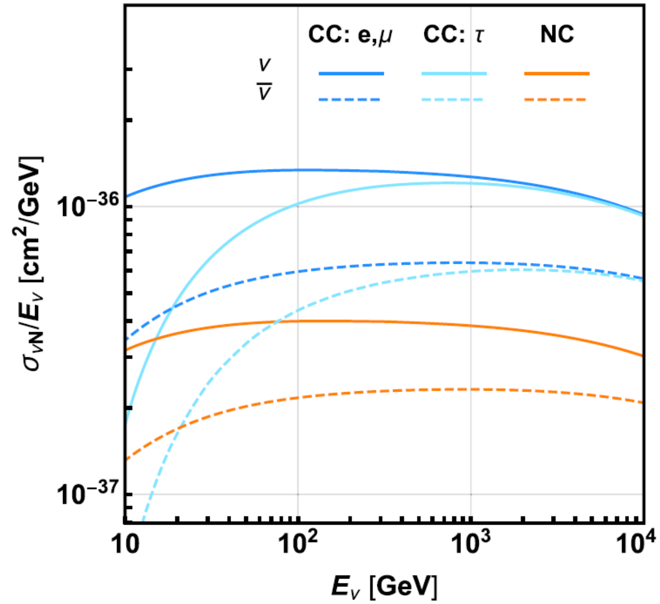
**Expected sensitivity to neutrino cross-sections @FASERν**

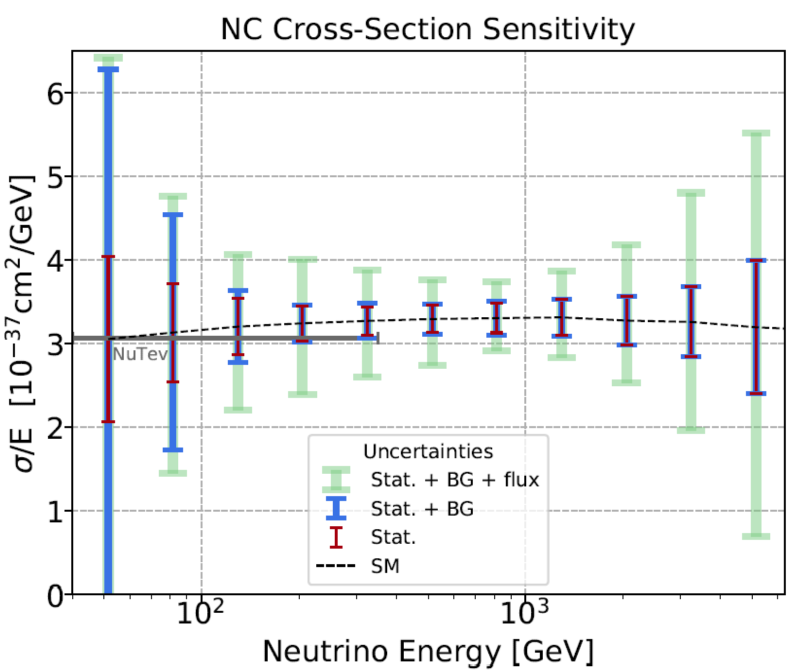


# Neutral current interaction

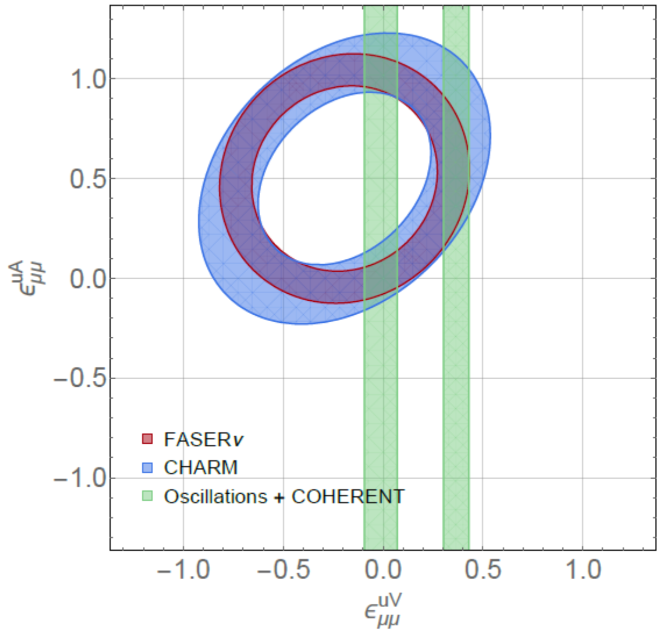
- FASERν also measures cross-section of Neutral Current (NC) neutrino interactions [arXiv: 2012.10500].
- Non-Standard Interaction (NSI) can be explored in conjunction with measurement of CC cross-section.

**DIS cross-section of CC/NC interactions**




**Expected sensitivity to NSI (up-quark)**

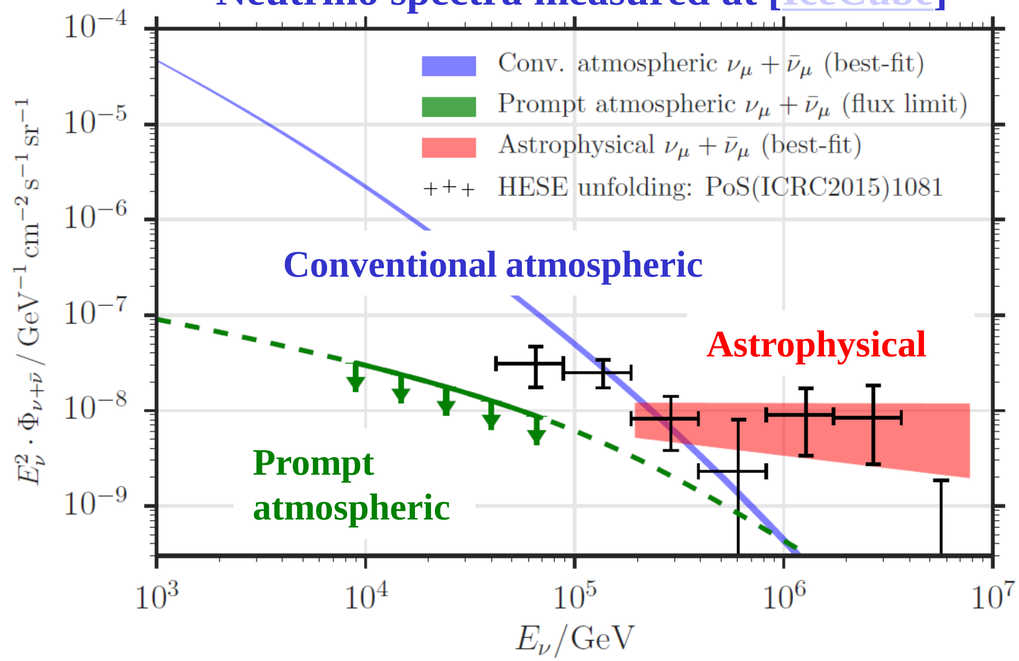


# Forward charm production

- 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.

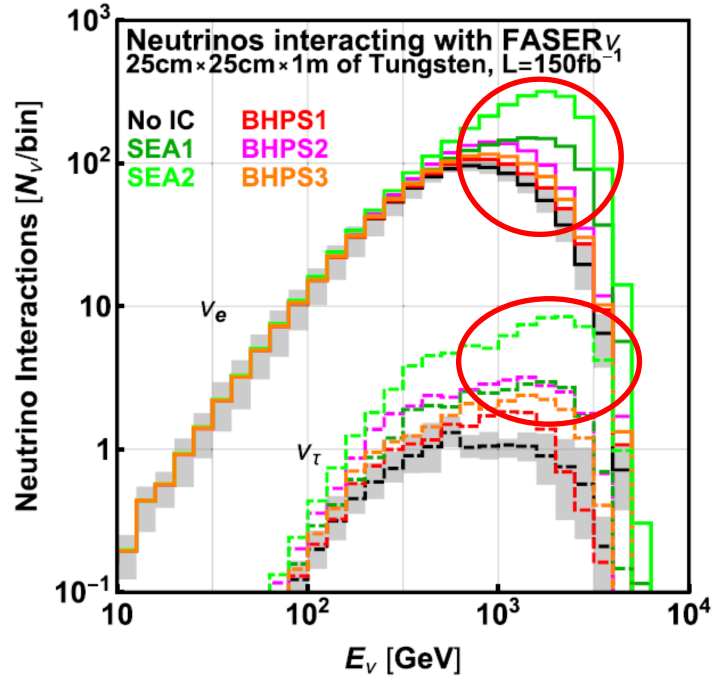
Measurement of production cross-section of heavy mesons at LHC can provide constraint on the prompt flux (current syst. error is O(1)).

**Neutrino spectra measured at [IceCube]**



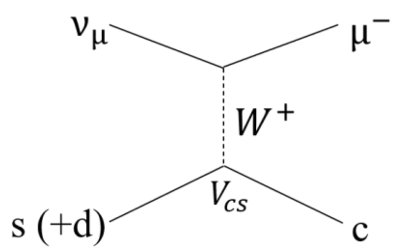
# Charm/strange PDF

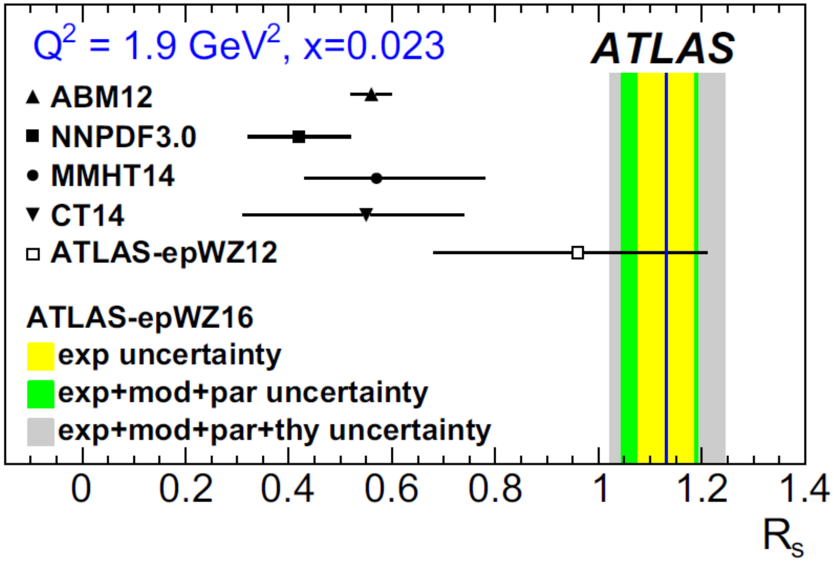
**Expected energy dist. of $\nu_e/\nu_\tau$ @FASERν**




- 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 $\nu_e/\nu_\tau$ energy spectrum in FASERν is sensitive.

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

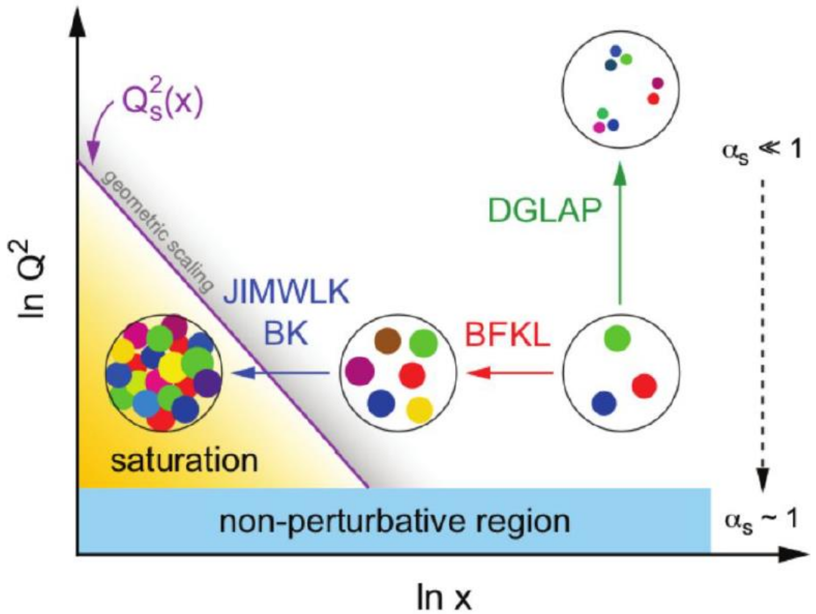


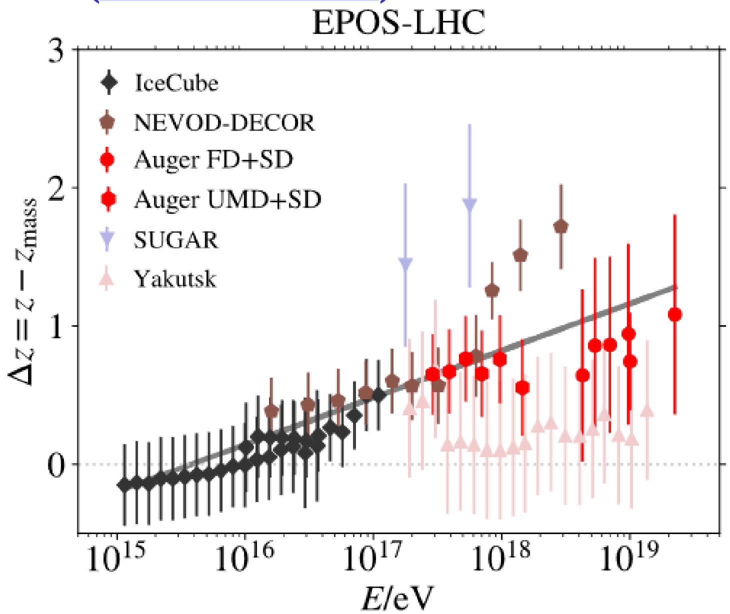

- D meson production in CC $\nu_\mu$ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and predictions.

# 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.

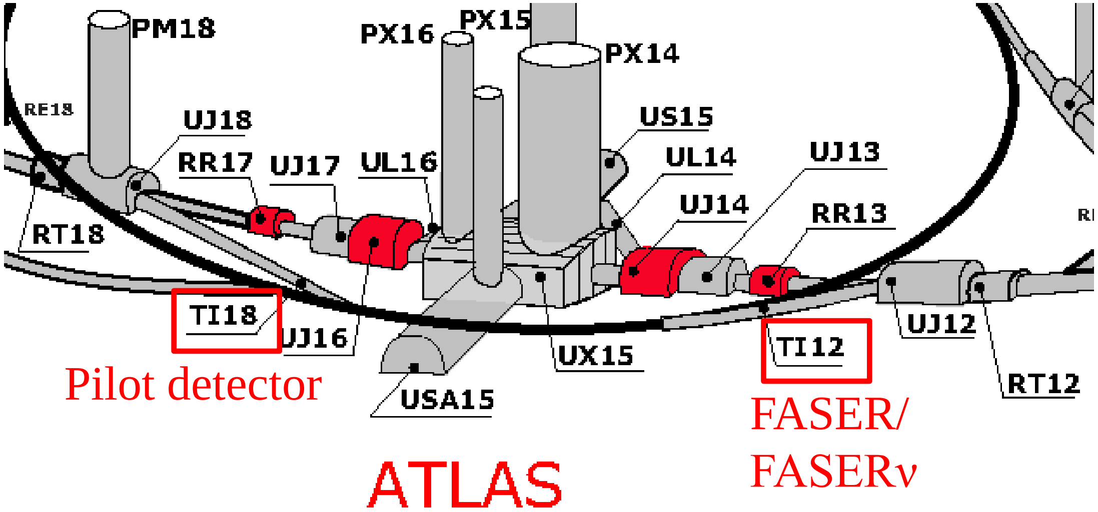


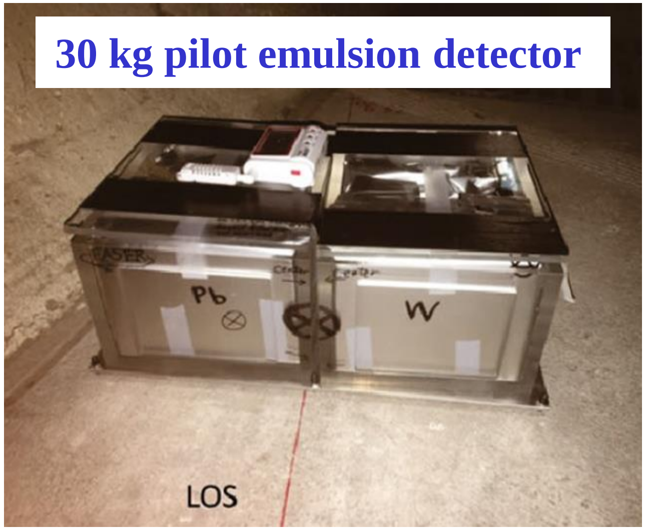

**Muon excess from prediction (Snowmass LOI)**



# Pilot data-taking (1)

- The pilot runs were taken place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018.
  - ➢ FASER/FASERν will be installed at T12.
  - ➢ TI18 is the tunnel at the same distance from ATLAS IP as TI12 but opposite side.
- The neutrino detection was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 $fb^{-1}$ of data.

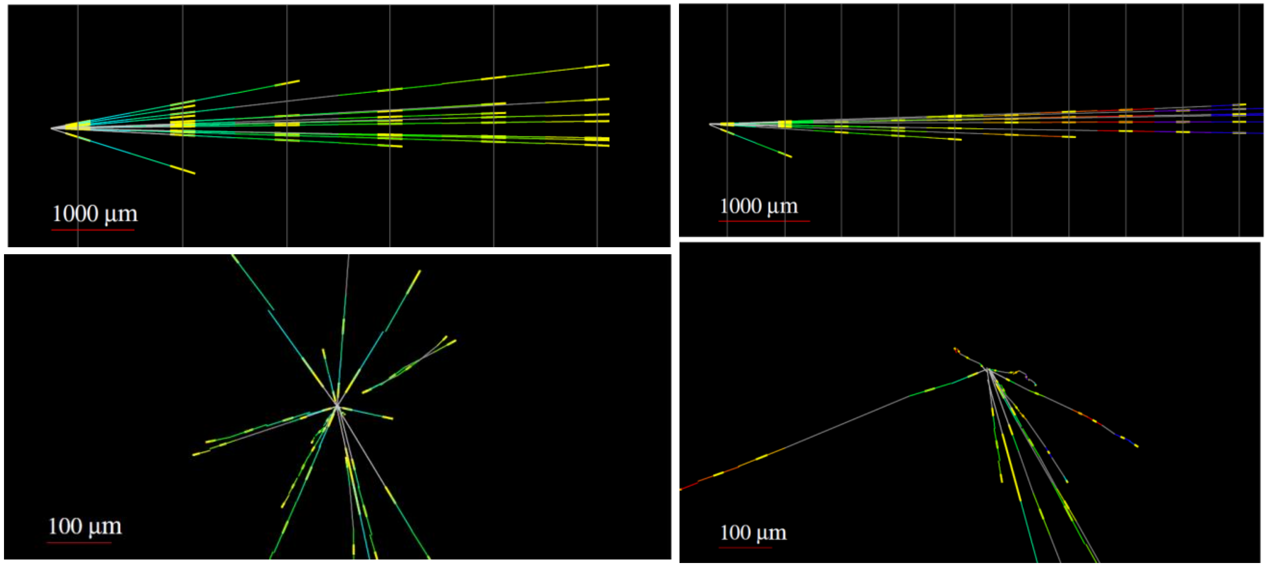


# Pilot data-taking (2)

- The data analysis is ongoing for the first observation of neutrinos originated from proton-proton collisions at LHC.
- 18 candidates of the neutral vertex were detected.
  - Selection criteria: # track >= 5 for tanθ < 0.1, <= 4 for tanθ > 0.1
- The multivariate analysis is ongoing for the signal extraction.
- The journal paper is under preparation.

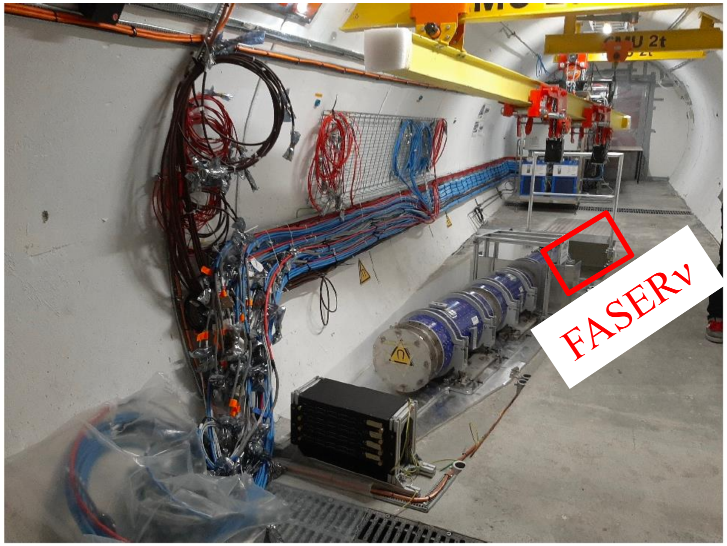
**Neutrino event candidates**



# Detector construction/installation (1)

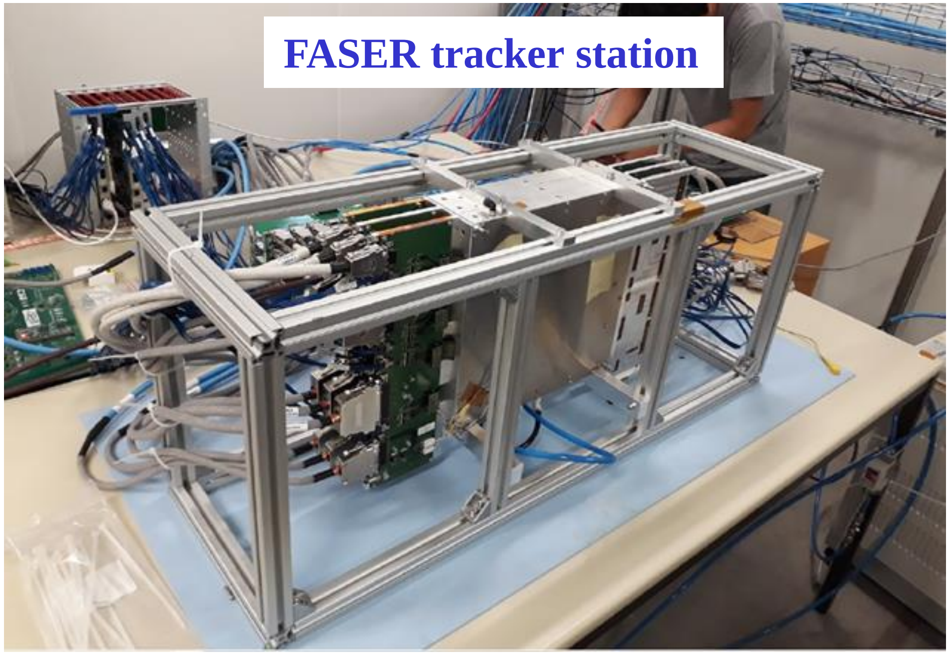
- Detector installation is ongoing and all components except for FASERν will be installed until March 2021
  - Installation of FASERν will start in October 2021.
- FASERν will be placed on the LOS (Line Of Site) to maximize the flux of all neutrino flavors (the trench dug allows this).
- Handling infrastructure has been installed to transport detector in/out of the trench and over the LHC machine.

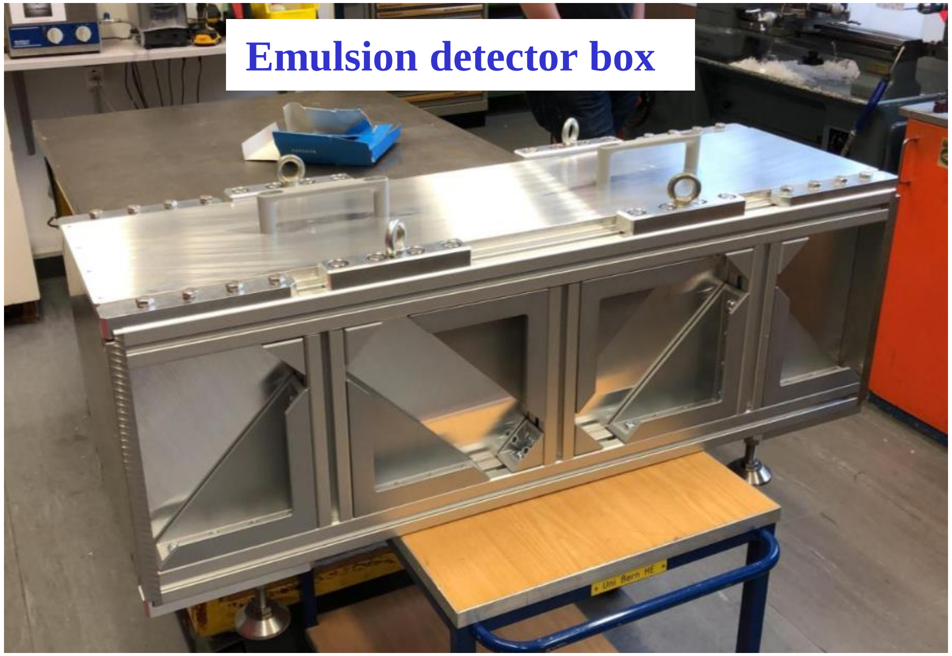

**Commissioning on ground w/o FASERν**



# Detector construction/installation (2)

- Assembly of IFT will start on April and will be installed into FASER in October 2021.
  - The same design as the tracker station in the spectrometer will be adopted for IFT.
- Production of the emulsion films will be done in second half of 2021.



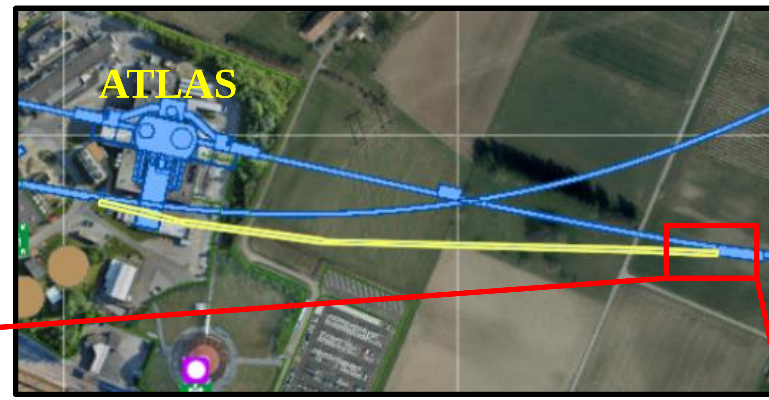
# Detector upgrade for HL-LHC

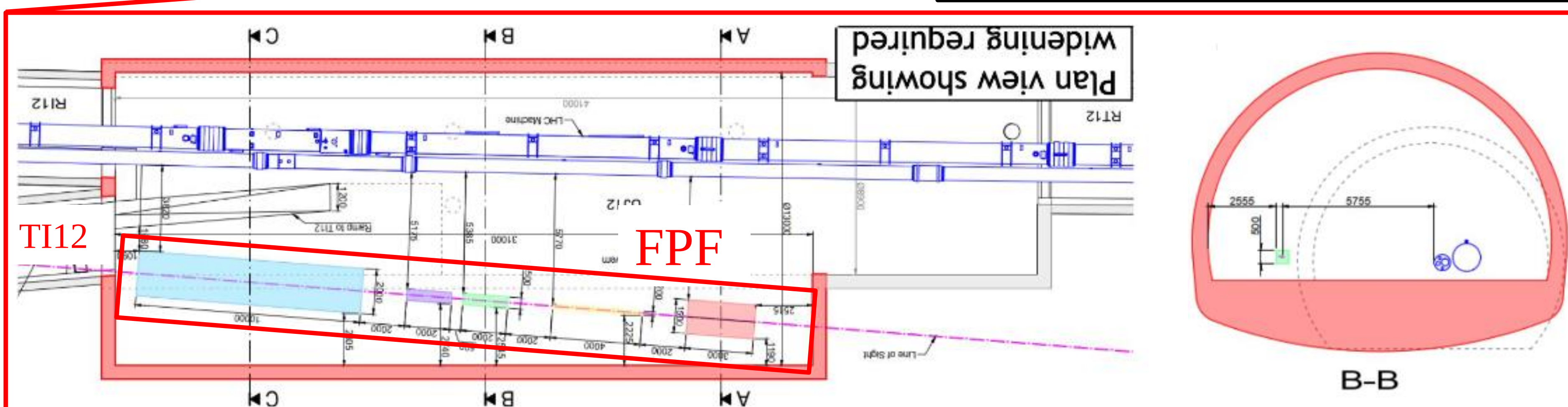
- Detector upgrade (FASERν2) is being discussed to secure much larger target mass at HL-LHC in the context of [Forward Physics Facility].

- 10 times bigger target mass and 20 times larger integrated luminosity

→ 200-fold increase in neutrino event rate

- Snowmass LOI was submitted: [Physics], [Detector]



# Collaboration & Foundation

FASER collaboration consists of 8 countries, 18 institutes and 65 members.

## Foundation

- FASER: Heising-Simons, Simons Foundations
- FASERν: Heising-Simons Foundation, ERC, JSPS and the Mitsubishi Foundation
- CERN for infrastructure costs

# Summary & Conclusions

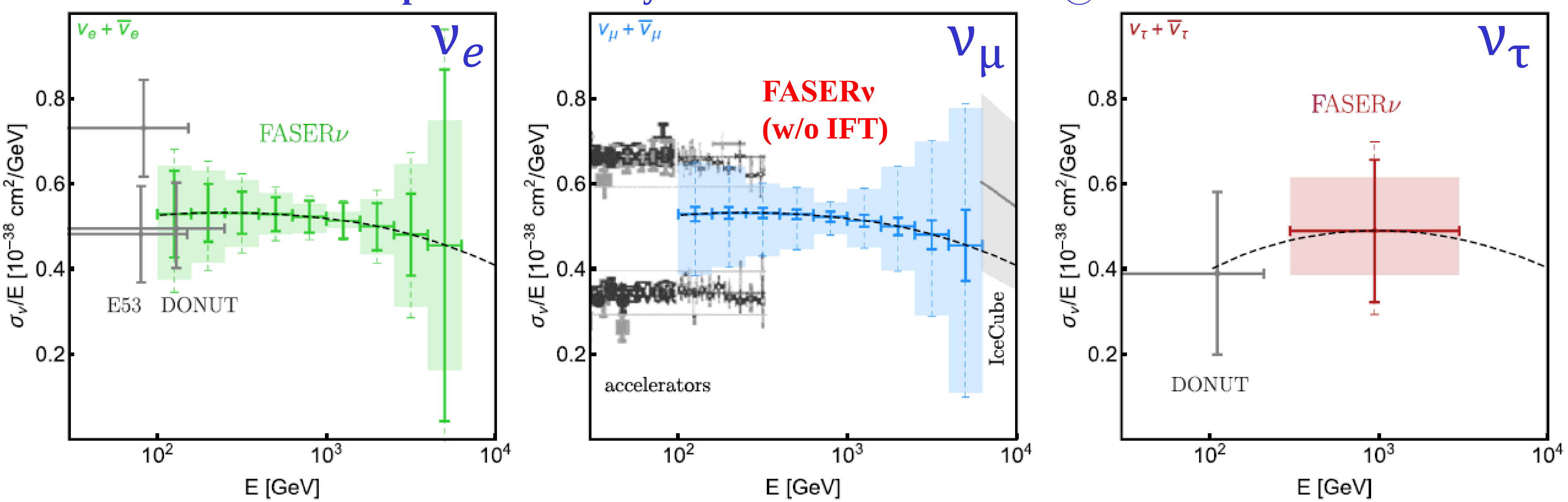
- FASERν is the detector in FASER experiment to measure cross-section of high energy neutrinos with ~1 TeV originated from proton-proton collisions at LHC.
  - First experiment making use of beam collisions as neutrino source.
- FASERν can measure cross-section for all neutrino flavors, thanks to excellent position resolution of the emulsion detector.
- FASERν is sensitive to charm/strange PDF in a proton as well as production of primary hadrons.
- Assembly of IFT start in April 2021 and the emulsion detector is also being prepared, aiming data-taking at LHC Run3 in 2022.
- The detector upgrade towards HL-LHC era (FASERν2) is under discussion with a prospect to increasing neutrino statistics by 1-2 order of magnitude.

# Backup

# Systematic error on neutrino flux

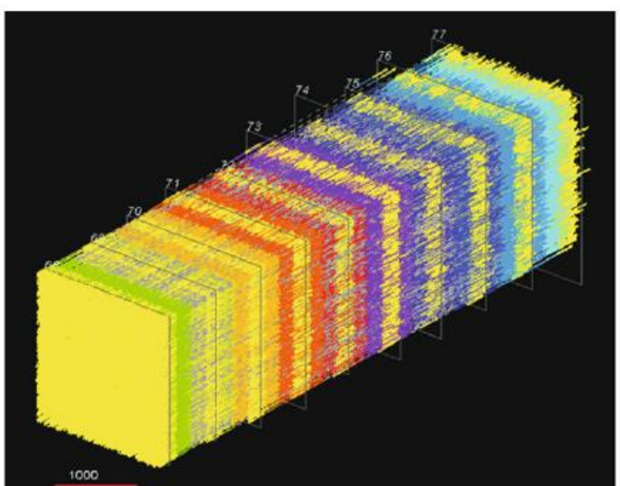
- The error bars correspond to the statistical error.
- The range of flux estimates with different MC generators are assigned as systematic error with shaded area.
  - ➢ The error on neutrino flux is being evaluated.

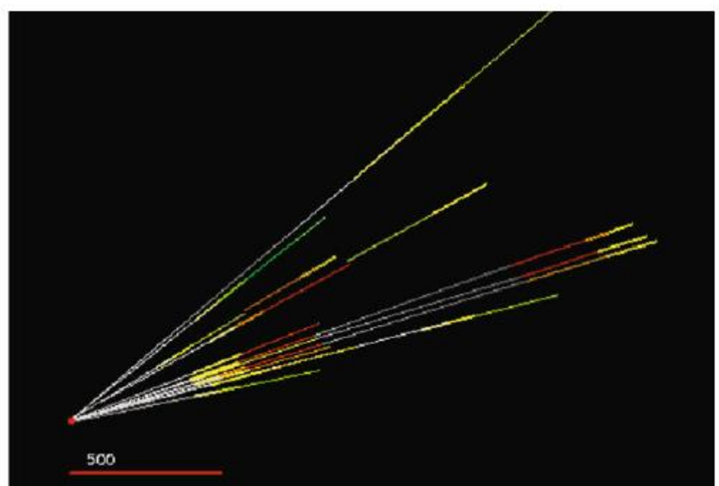
**Expected sensitivity to neutrino cross-sections @FASERν**



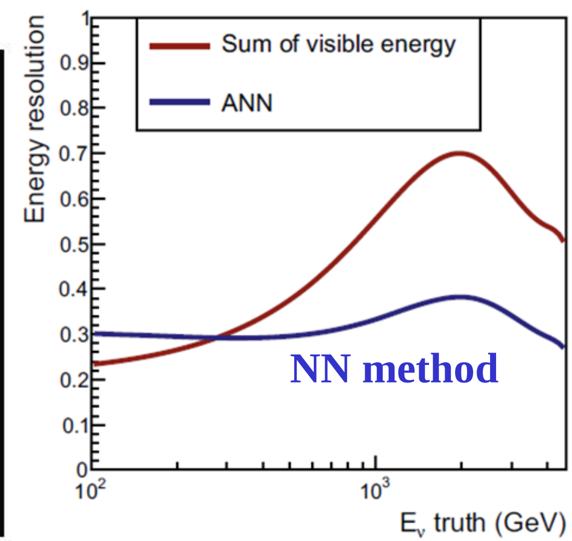
# Neutrino detection with emulsion

- The emulsion detector accumulates all tracks for certain data-taking period, and the tracks are reconstructed by scanning the films afterwards.
- The position resolution of ~1 μm can be achieved but timing information is not available.
- About 30% of energy resolution can be realized in measurement with neural network method.






**Expected energy resolution**



# Energy measurement with ANN algorithm

The following variables are used as input for artificial neural network algorithm to evaluate energy resolution with the emulsion films.

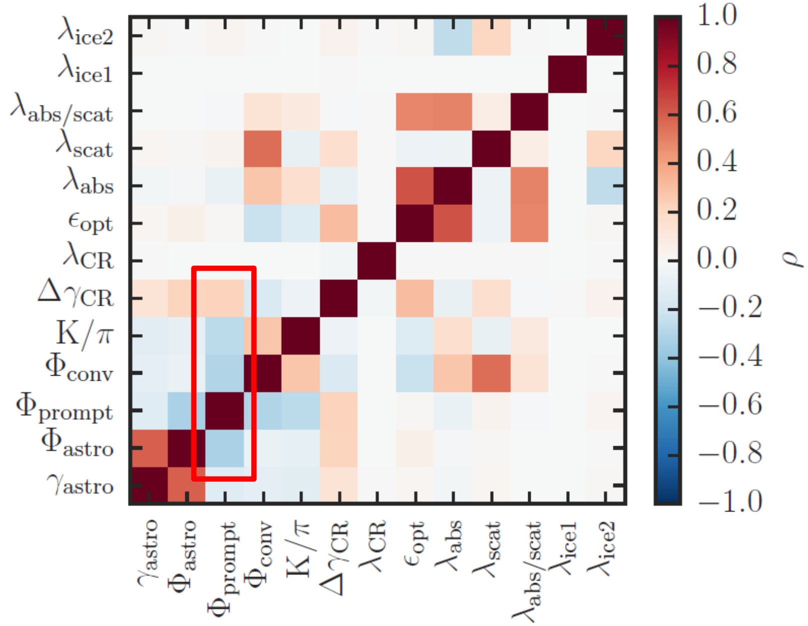
| Topological variables | | Related to |
|---|---|---|
| $n_{\mathrm{tr}}$ | Multiplicity of charged tracks at the neutrino interaction vertex with momentum $p_{\mathrm{tr}} > 0.3$ GeV and angle $\tan\theta_{\mathrm{tr}} < 0.3$ | $E_{\mathrm{had}}$ |
| $n_\gamma$ | Photon multiplicity | $E_{\mathrm{had}}$ |
| $\lvert 1/\theta_\ell \rvert$ | Inverse of lepton angle with respect to neutrino direction | $E_\ell$ |
| $\sum \lvert 1/\theta_{\mathrm{had}} \rvert$ | Sum of inverse of hadron track angles | $E_{\mathrm{had}}$ |
| $1/\theta_{\mathrm{median}}$ | Inverse of the median of the track angles of all charged particles | $E_{\mathrm{had}}, E_\ell$ |
| Track momentum via MCS | | |
| $p_\ell^{\mathrm{MCS}}$ | Estimated lepton momentum from MCS | $E_\ell$ |
| $\sum p_{\mathrm{had}}^{\mathrm{MCS}}$ | Sum of estimated charged hadron momenta from MCS | $E_{\mathrm{had}}$ |
| Energy in showers | | |
| $\sum E_\gamma$ | Sum of energy in photon showers | $E_{\mathrm{had}}$ |

# Astrophysics neutrino & prompt flux at IceCube

- Uncertainty on conventional atmospheric neutrino flux ($\Phi_{conv}$) 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 $\Phi_{conv}$ and prompt flux ($\Phi_{prompt}$).
- $\Phi_{prompt}$ is a free parameter in the fitting and currently zero consistent.
- Astrophysical parameters ($\Phi_{astoro}$, $\gamma_{astro}$) are found to be almost independent from $\Phi_{prompt}$.

| Parameter | Best-Fit | 68% C.L. |
|---|---|---|
| $\Phi_{astro}$ | 0.90 | 0.62 – 1.20 |
| $\gamma_{astro}$ | 2.13 | 2.00 – 2.26 |
| $\Phi_{prompt}$ | 0.00 | 0.00 – 0.19 |

**Correlation matrix of nuisance parameters**

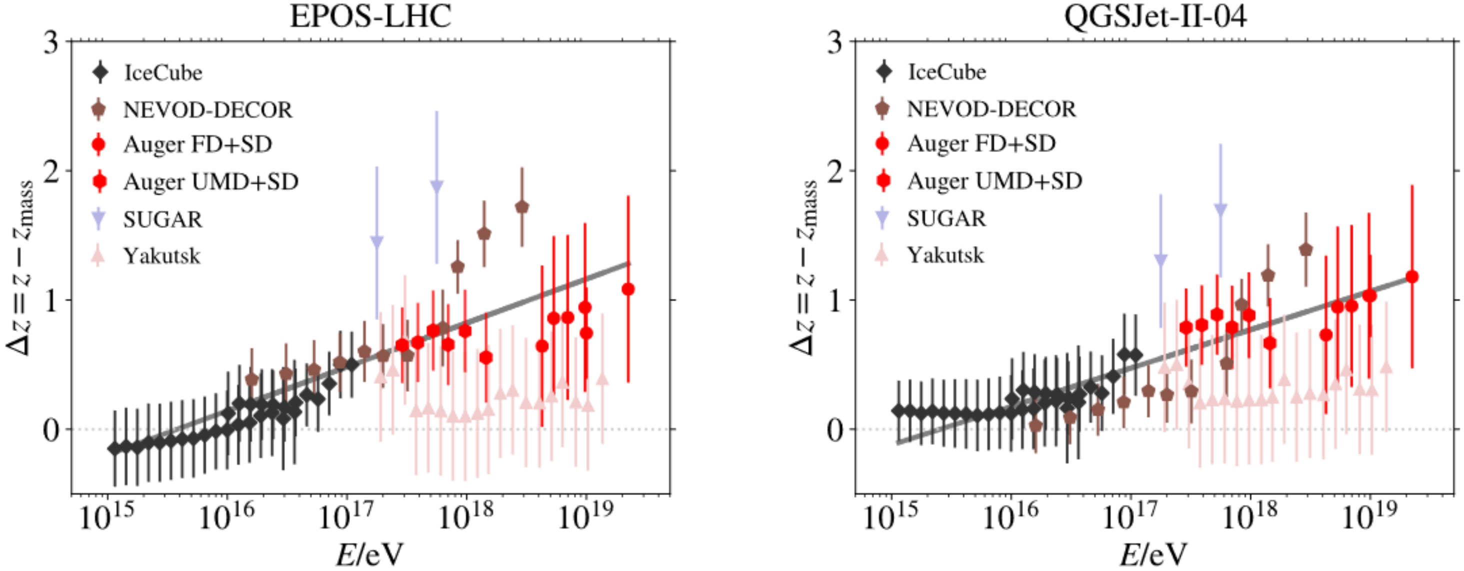



Astrophys. J. 833 (2016) 3

# 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.

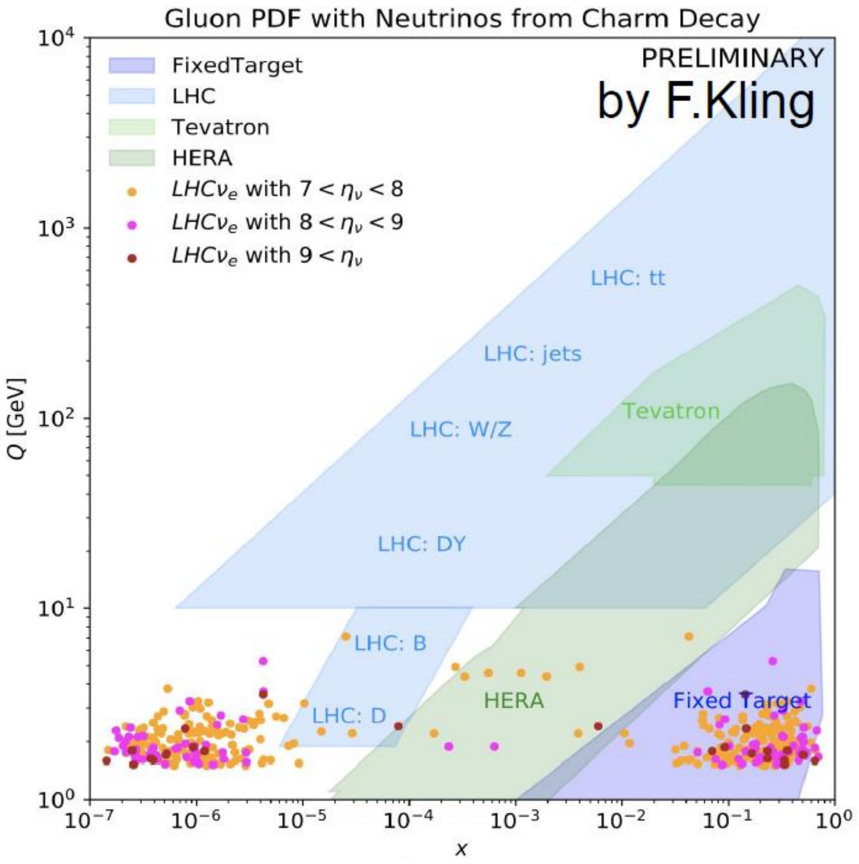
**Excess of muons from the predictions (EPOS-LHC and QGSJet-II-04) [Snowmass LOI]**

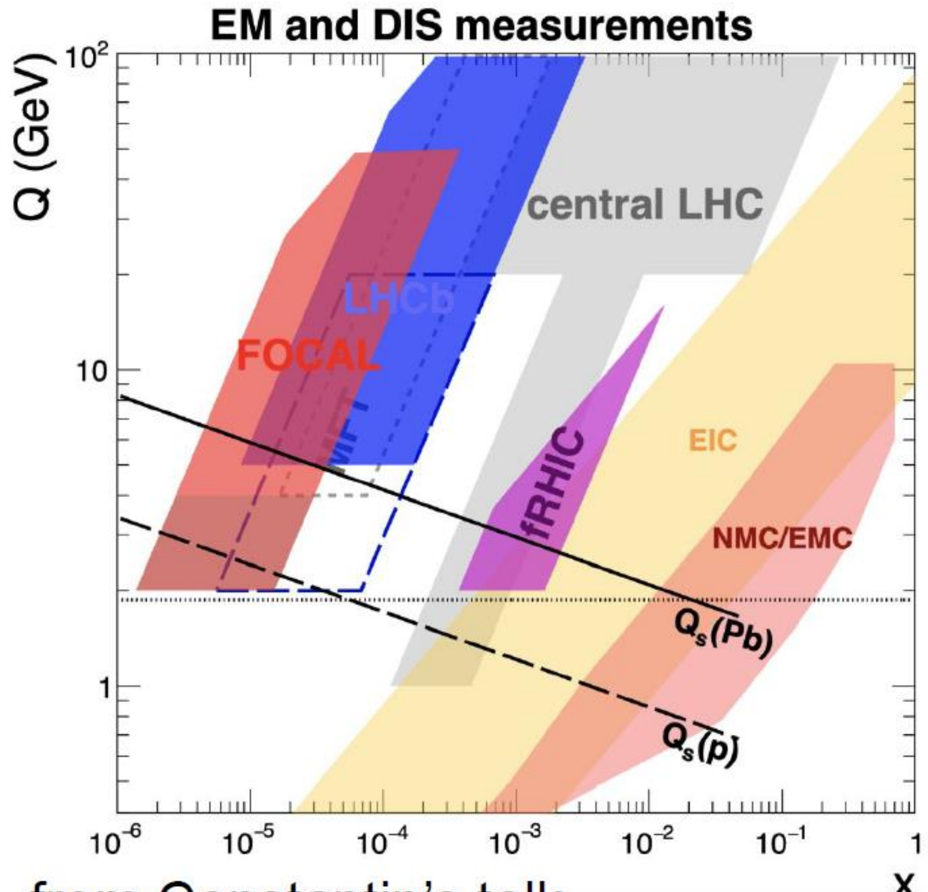


# Gluon saturation in proton (1)

- The parton PDF for ($x > 10^{-3}$, $Q > 2$ GeV) can be described by DGLAP equation.
- The gluon saturation for proton is expected to start at ($x \sim 10^{-6}$, $Q \sim 2$ GeV).
  - $Q < 1$ GeV is region where QCD cannot be described perturbatively.
- The charm production in pp collisions at LHC ($gg \rightarrow cc$) realizes ($x \sim 10^{-7}$, $Q \sim 2$ GeV).
- PDF with gluon saturation is used for perturbative calculation of the charm production in $gg \rightarrow cc$ at FASER, therefore, FASERν can be sensitive to the gluon saturation effects.

# Gluon saturation in proton (2)

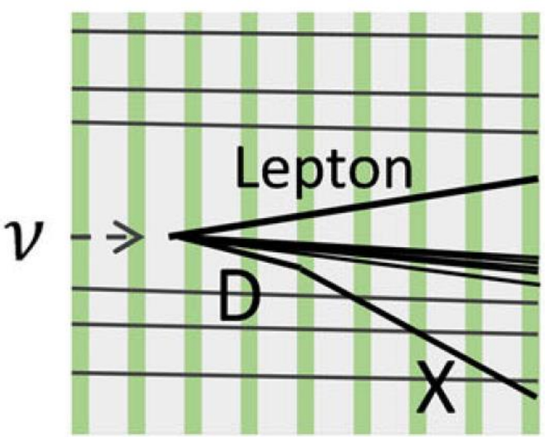


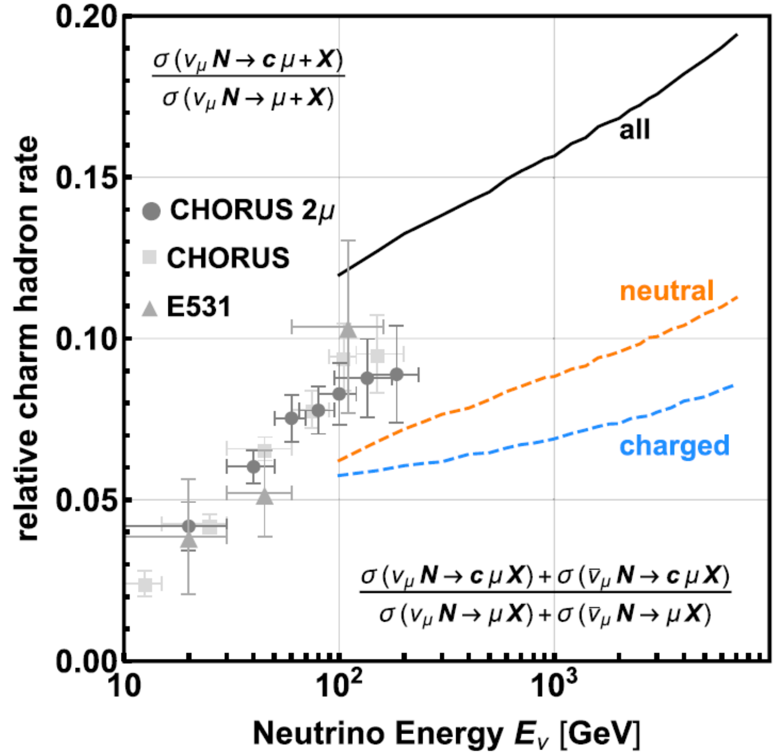

From [F. Kling's presentation]

# 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**



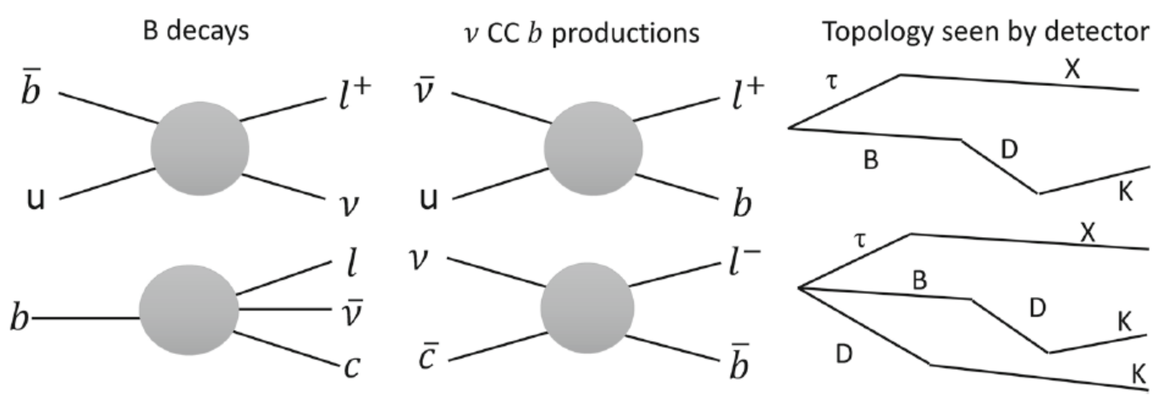
# Beauty-associated neutrino events (1)

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

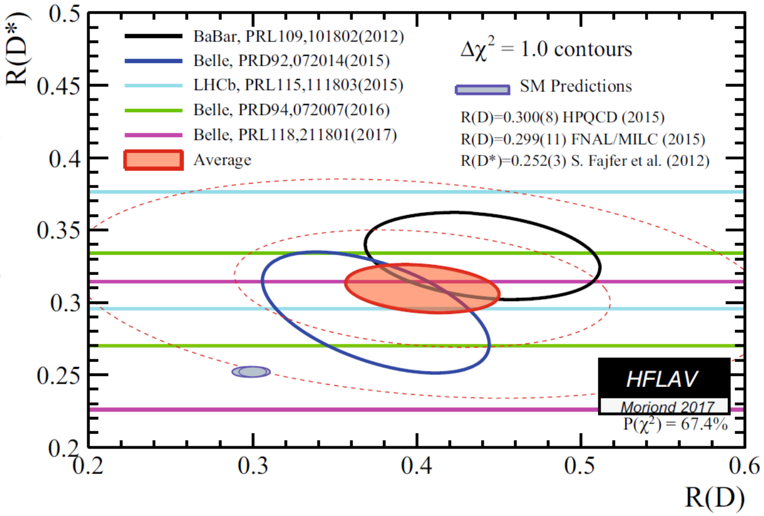
- The neutrino interactions in FASERν are the same as them, exchanging the internal/external lines in Feynman diagrams.

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

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




**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 $\nu_\tau$.

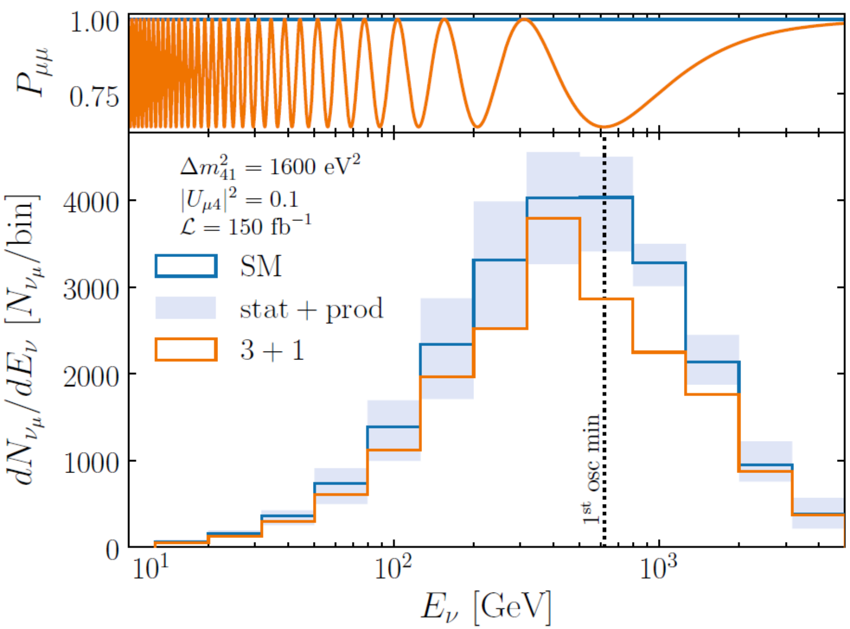
# Sterile neutrino oscillation

- SM excludes possibility of neutrino oscillation in FASER condition.

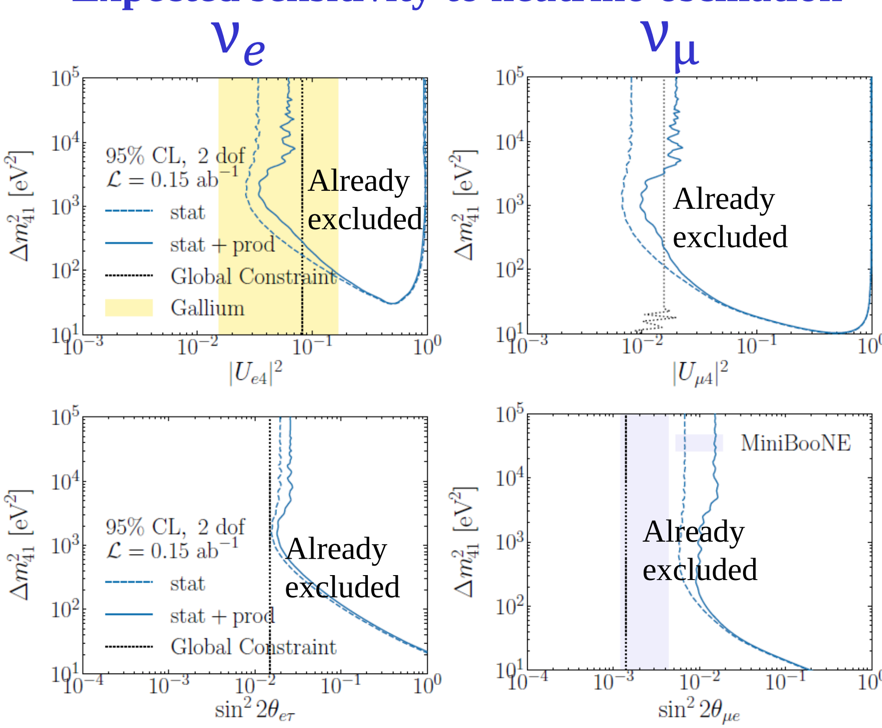
⇨ If appearance or disappearance events are observed, it indicates existence of sterile neutrino.

- For $\nu_e$, FASER$\nu$ has sensitivity to 2.7σ discovery region with Gallium detector [arXiv:1006.3244].

**Neutrino energy dist. with sterile neutrino**




**Expected sensitivity to neutrino oscillation**



# Support from Foundations & Grants


- Heising-Simons Foundation Grant Nos. 2018-1135, 2019-1179, 2020-1840
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- ERC
- Mitsubishi Foundation
- Joint research program of the Institute of Materials and Systems for Sustainability
- CERN for infrastructure costs