FASER experiment at the LHC and its connection to the cosmic-ray muon puzzle

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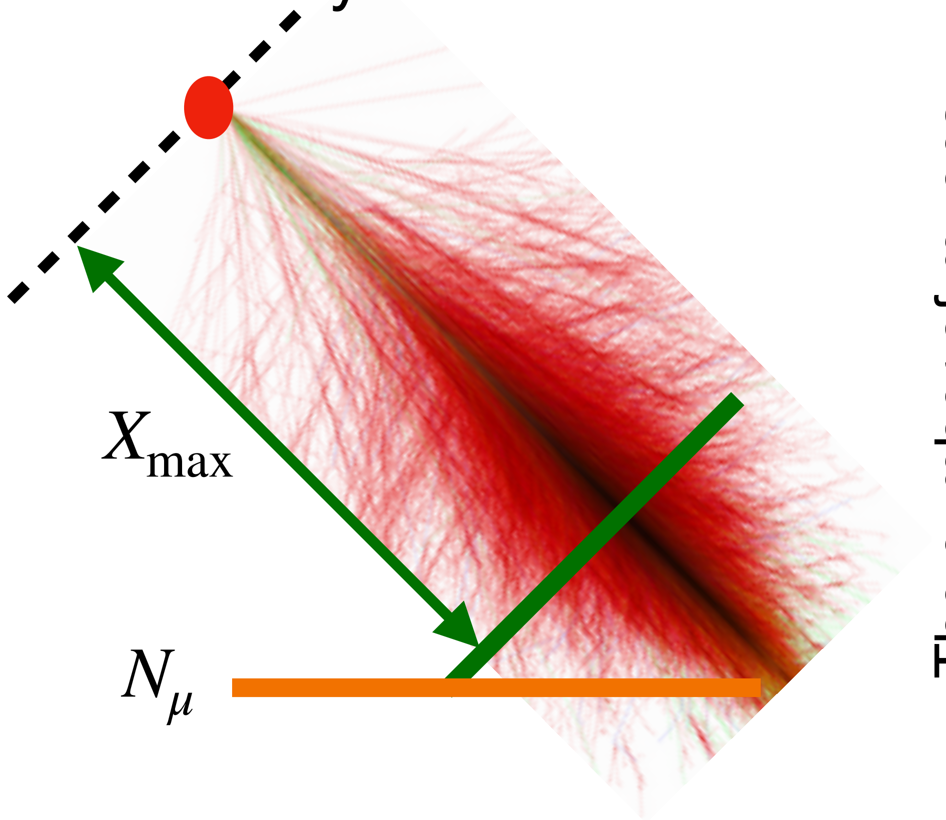
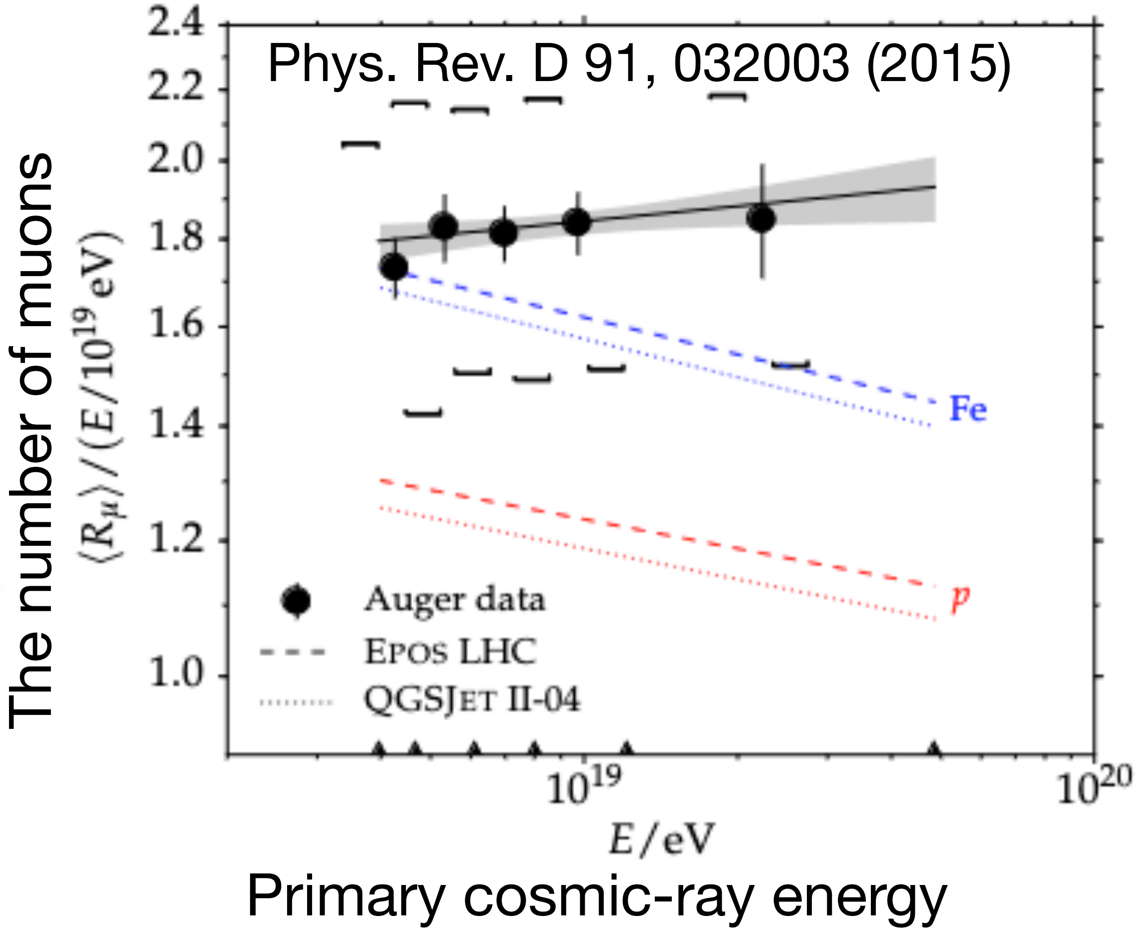
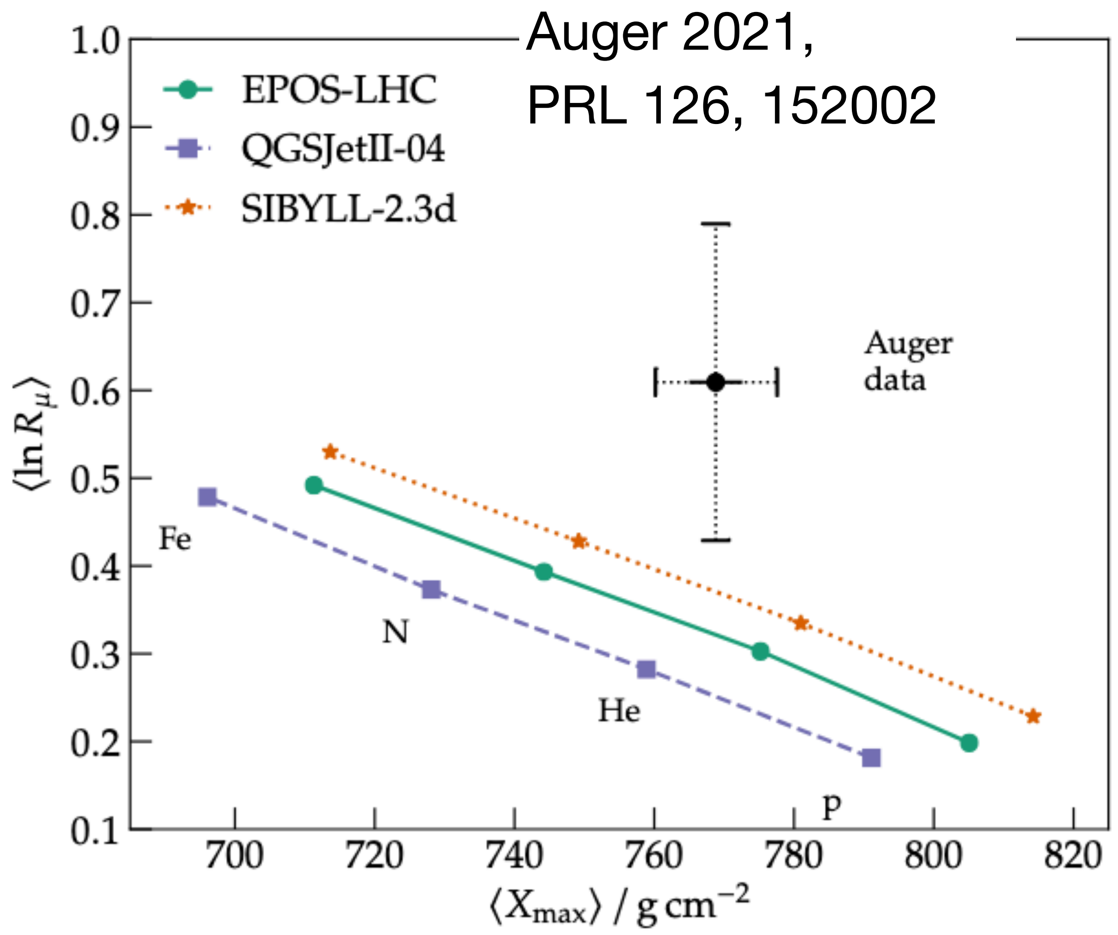
Ultra-high-energy cosmic rays and the muon puzzle

Ultra-high energy cosmic-ray $> 10^{18}$ eV

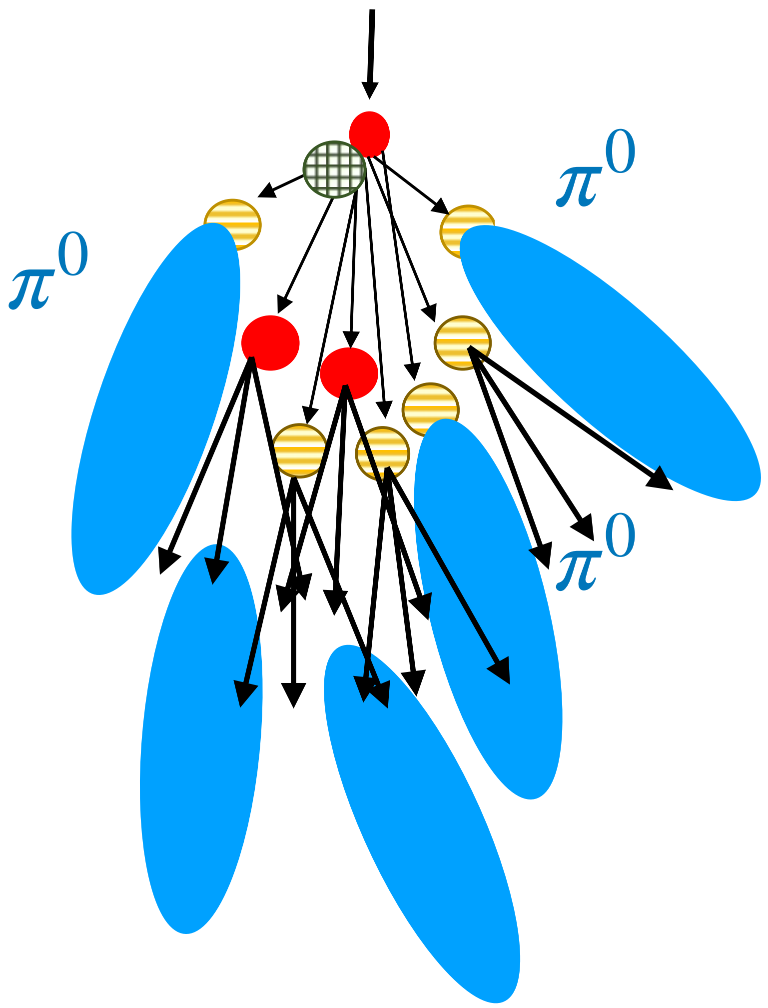






The number of muons measured by the Pierre Auger experiment shows a much larger value than the simulation (muon puzzle)

Ultra-high-energy cosmic rays and the muon puzzle



π^0 -> electromagnetic shower
Other hadrons -> hadronic shower (produces μ)

- Scenarios to solve this issue
  - Some mechanism to reduce π^0 productions?
  - Less π^0, more Kaons
  - Less π^0, more ρ^0
  - Less π^0, more baryons
  - …
- How can we confirm or reject these scenarios experimentally?
  - Measure hadronic interactions at colliders!
  - But which interaction should we measure?

Which particles in which interactions should we measure?

In an air shower induced by 10^{19} eV($= 10^{10}$ GeV) proton,
We have a huge number of particles from $\mathcal{O}(1)$ to $\mathcal{O}(10^{10})$ GeV

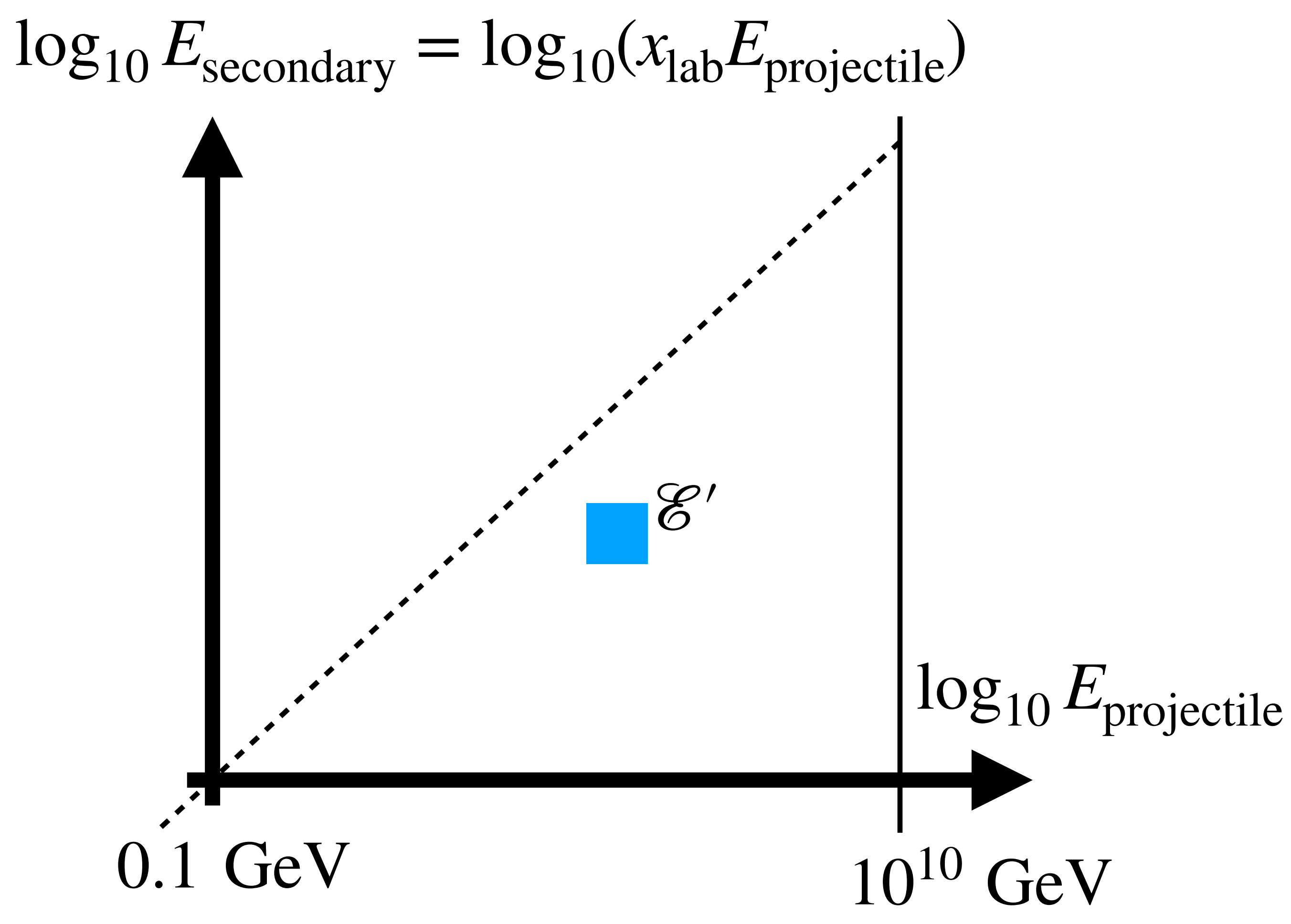
Simulation study:
(K.O., Anatoli Fedynitch, Hiroaki Menjo, in prep.)

Focus on a simple scenario of the strangeness enhancement

Reduce pions ($\pi^{\pm}$, π^0) by a factor (1-f_{enhance}) and increases kaons ($K^{\pm}$, K^0) simultaneously, without changing total pion/kaon productions

Check how the number of muons N_μ changes when we modify a small area of interactions

Calculate $\mathcal{D} = \frac{1}{N_\mu}\frac{\partial N_\mu}{\partial f_{\text{enhance}}}(x_{\text{lab}}, E_{\text{projectile}})$



Important interactions — forward π K productions

Simulation study:

(K.O., Anatoli Fedynitch, Hiroaki Menjo, in prep.)

Results (contour)

Top 25%, 50%, 80% cumulative value of

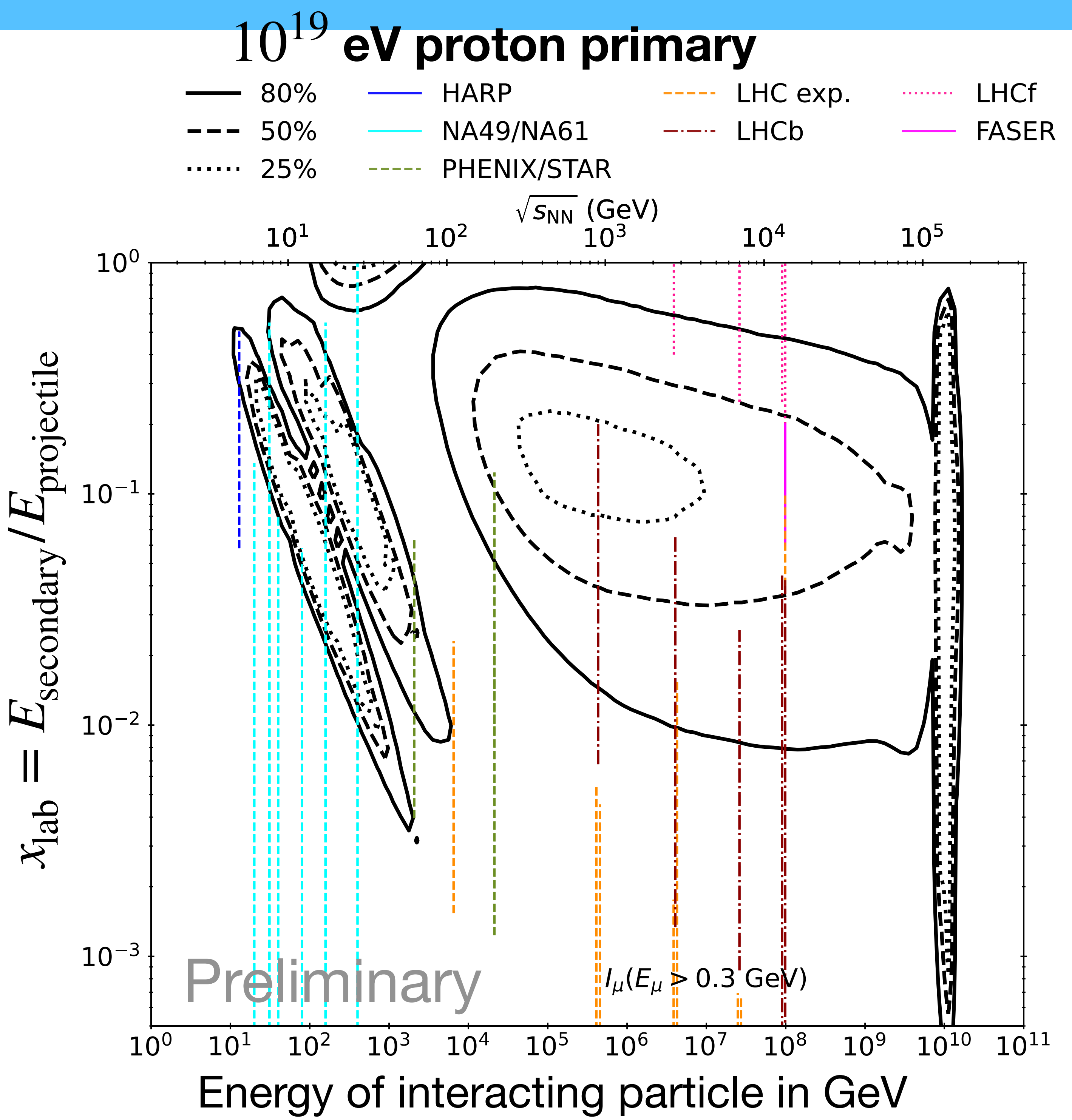
$$\mathscr{D} = \frac{1}{N_\mu}\frac{\partial N_\mu}{\partial f_{\text{enhance}}}(x_{\text{lab}}, E_{\text{projectile}})$$

Inside area $\mathscr{E}_A$ closed by the solid line contour,

$$\int_{\mathscr{E}_A} p\mathrm{d}\mathscr{E}' = 0.80, \text{ where } p = \frac{\mathscr{D}(\mathscr{E}')}{\int \mathscr{D}\mathrm{d}\mathscr{E}}$$

Two regions are important for the number of muons

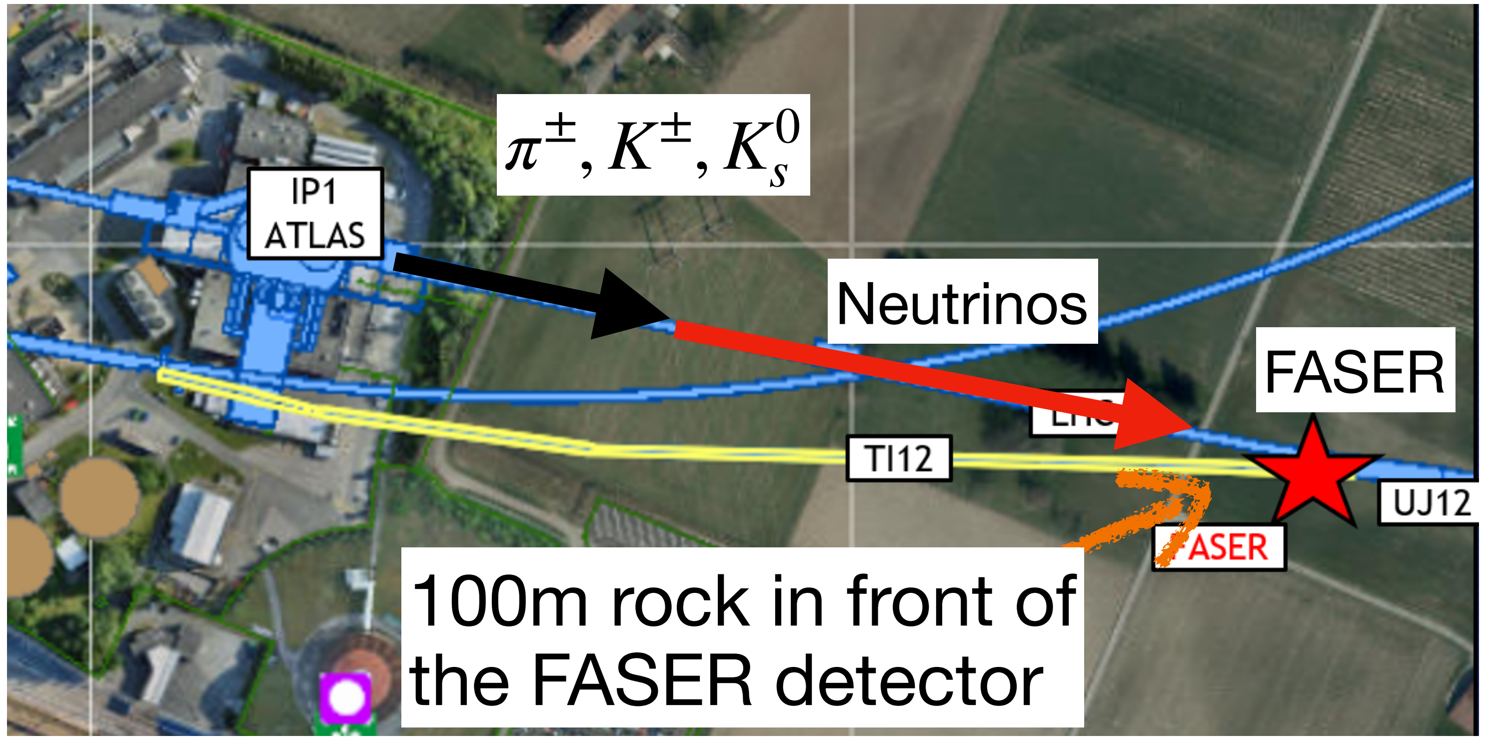
- (a) by the primary cosmic ray
- (b) by the secondary projectile particles with energy 10^4 GeV $< E_{\text{beam}} < 10^{-2} \times E_{\text{primary}}$ and $0.01 < x_{\text{lab}} < 0.5$
    - <u>**Covered by FASER experiment**</u>



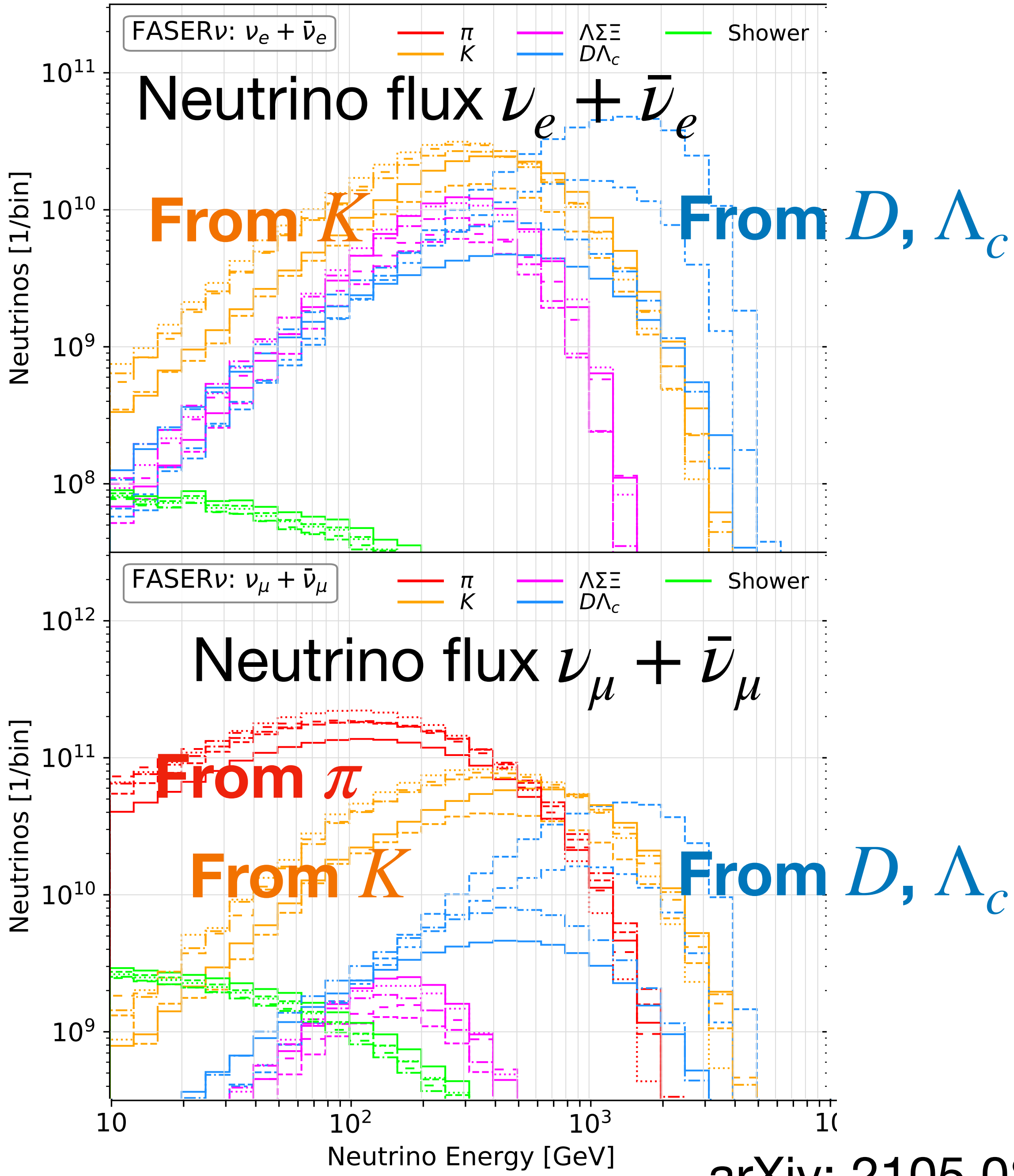
K.O., Anatoli Fedynitch, Hiroaki Menjo in prep.

The FowArd Search ExpeRiment (FASER)

An experiment at LHC for Neutrino measurements & Long-lived particle search

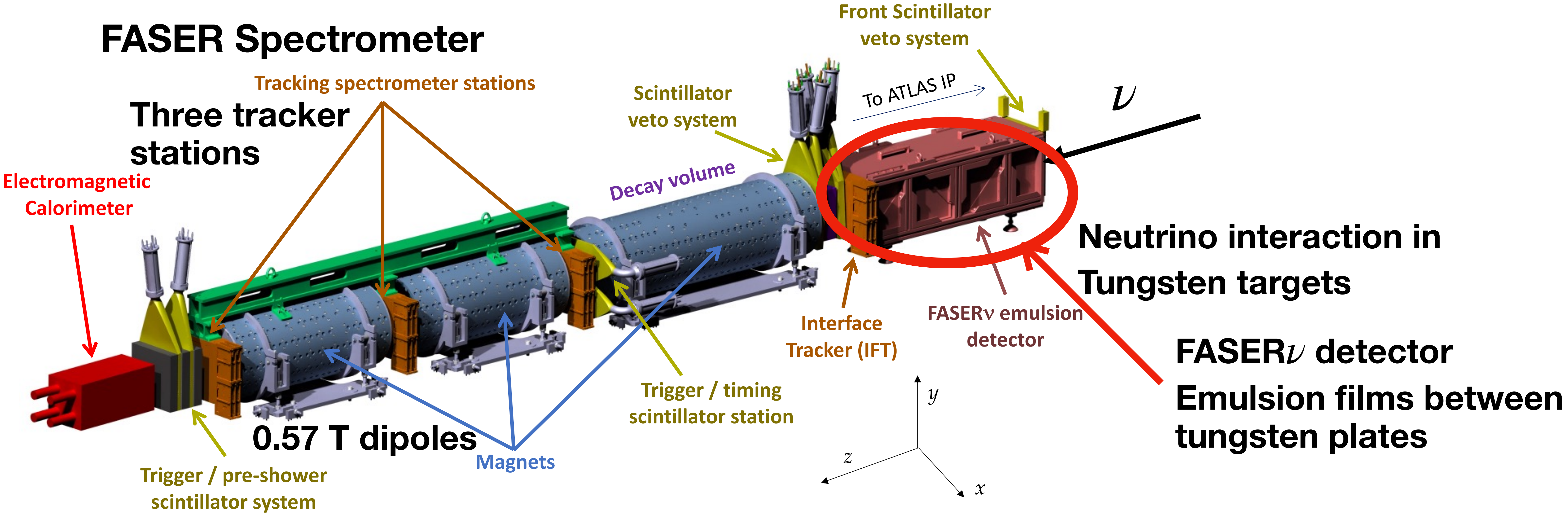


Physics
- Light long-lived particle search
- Neutrino-nucleon interaction in the detector
- **<u>Hadron production studies using neutrino</u>**



arXiv: 2105.08270

The FASER detector & neutrino results



First detection of neutrinos at collider (PRL 131 031801, 2023, FASER spectrometer)

First detection of $\overset{(-)}{\nu}_e$ **at collider** (PRL 133 021802, 2024, FASERν emulsion detector)

ν_μ **and** $\bar{\nu}_\mu$ **measurements with energy** (arXiv 2412.03186, FASER spectrometer)

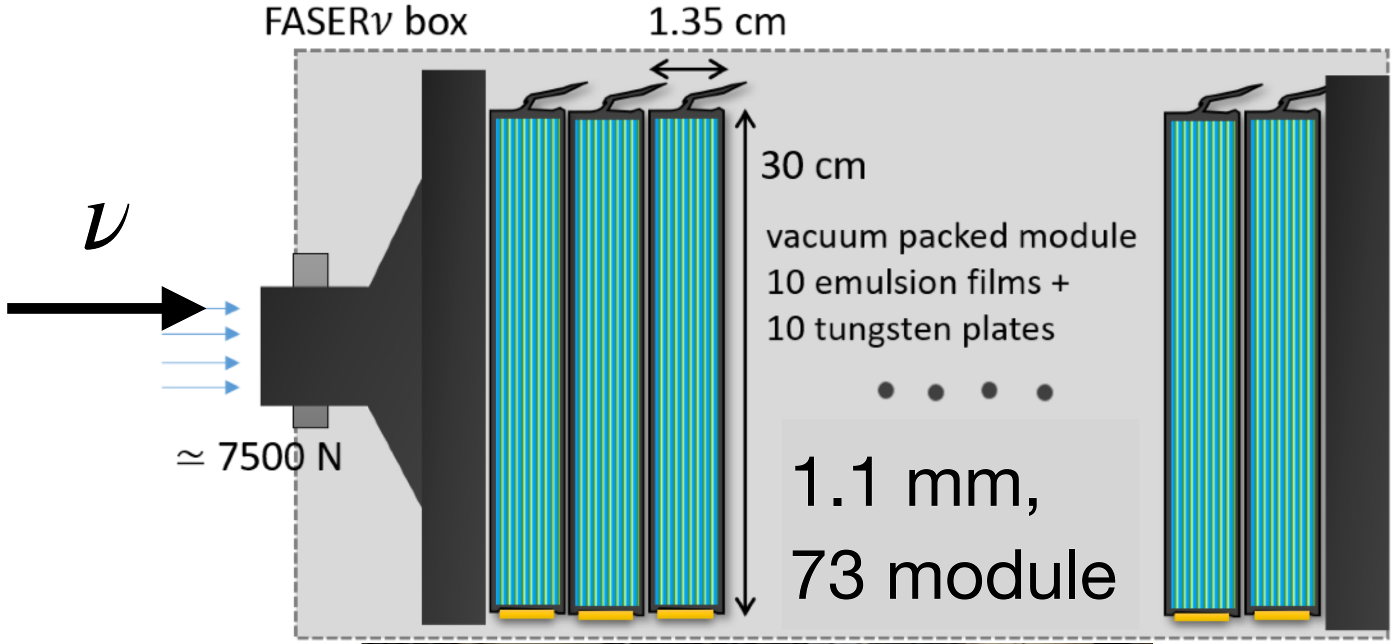
The FASERν detector

FASERν detector

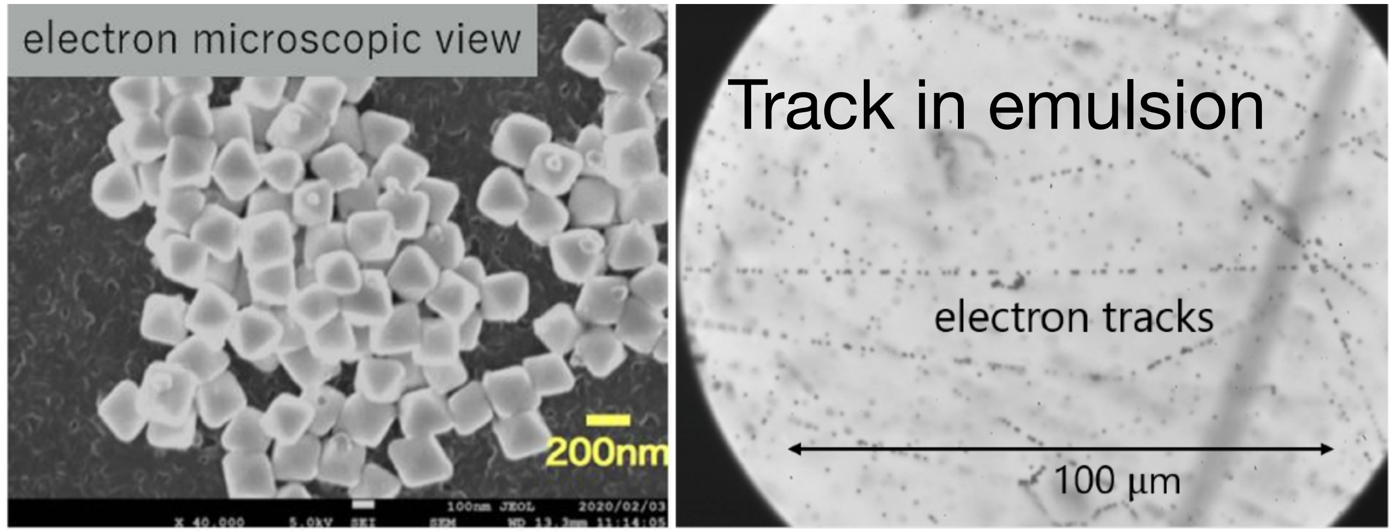
Emulsion films between tungsten plates

1.1 mm tungsten plates x 730: target

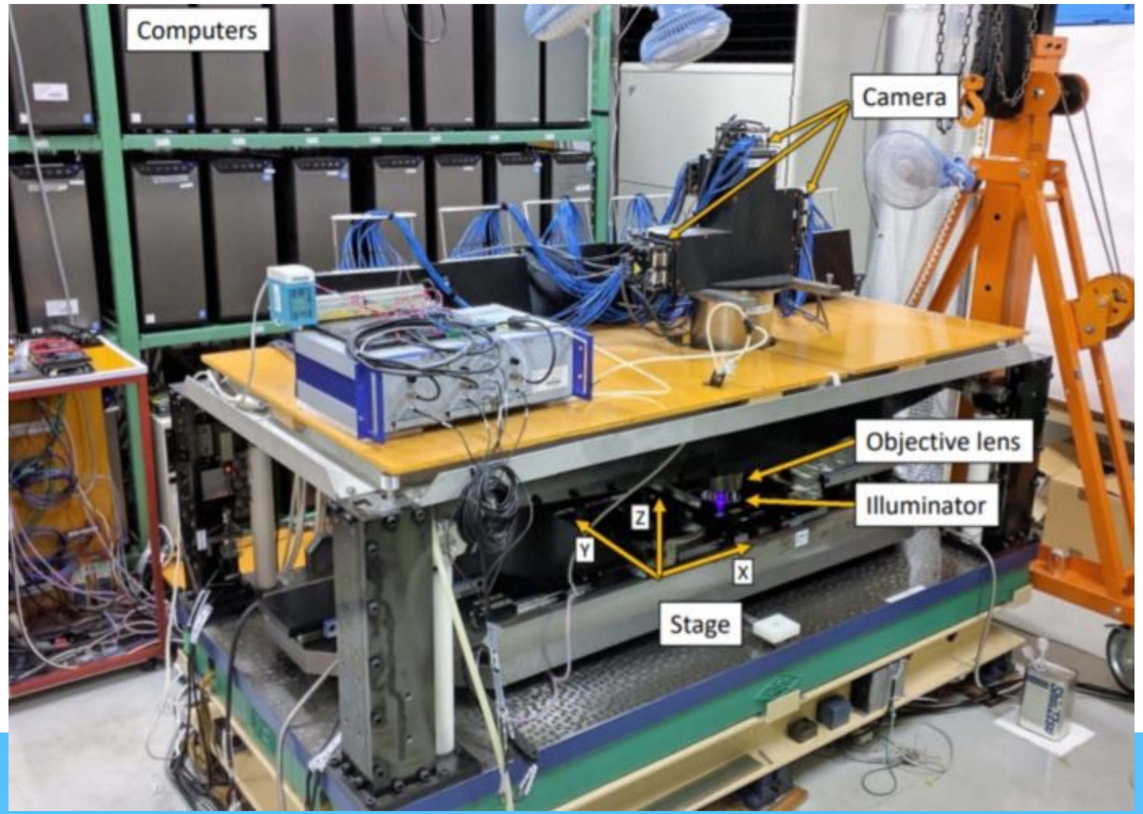
Emulsion film x 730: to measure tracks



Emulsion films (25cm x 30cm)



Microscope in Nagoya Univ.

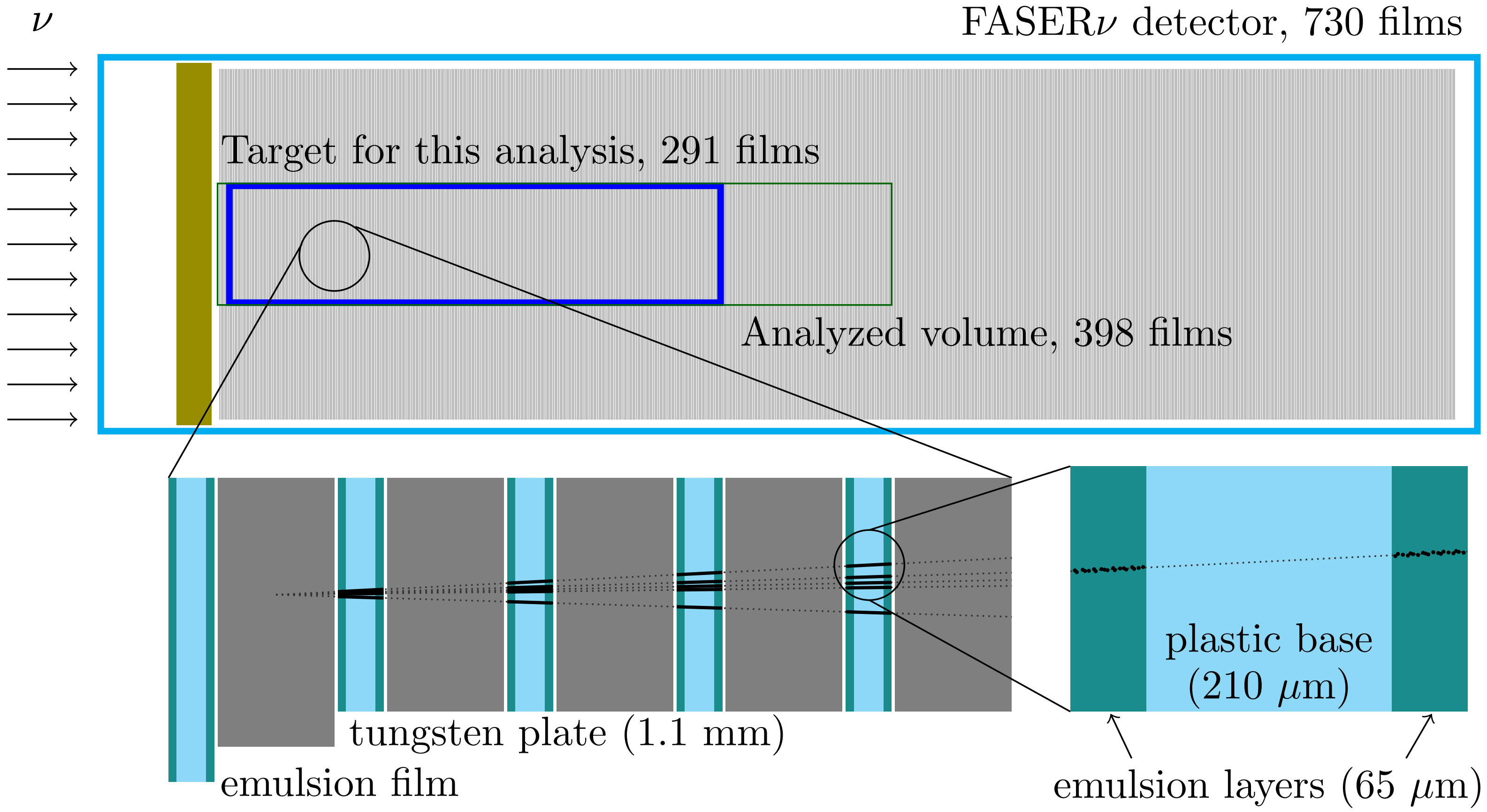


Event selection

FASER Collaboration
PRL 133 021802, 2024

2nd module of 2022,

Installed from July 26th to September 1, 9.5 fb^{-1}

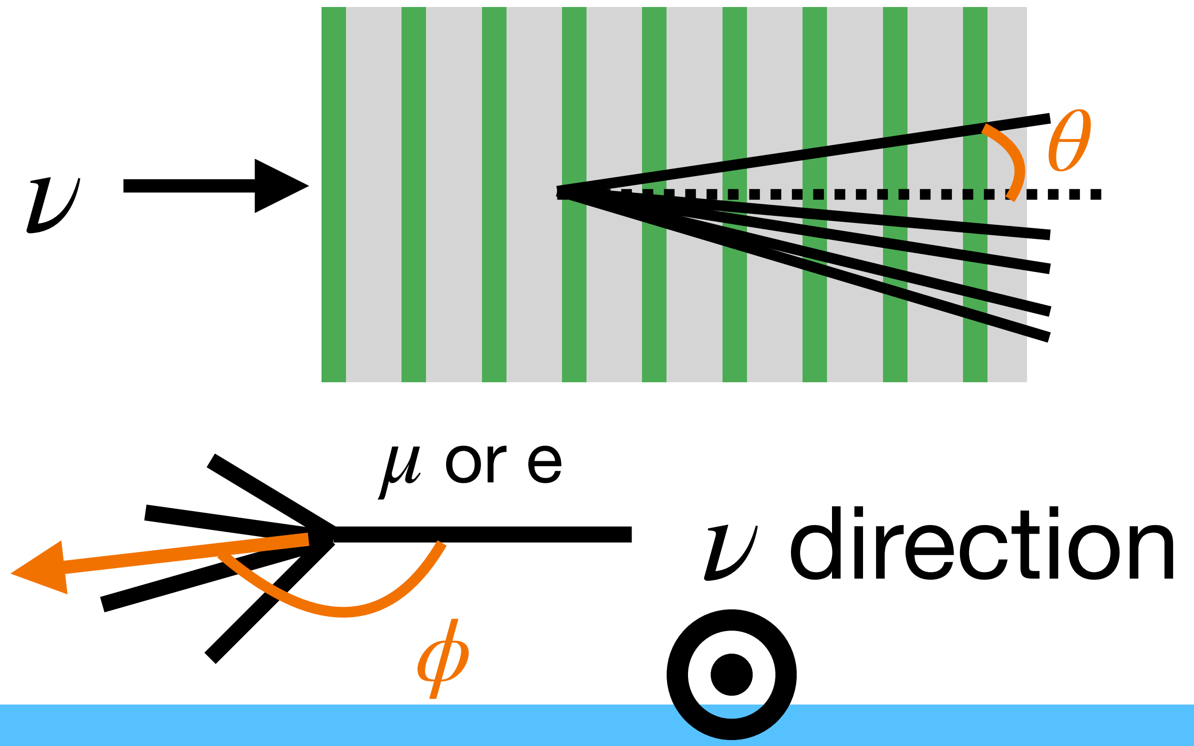


Main background: neutral hadrons

- lower energy
- Well removed by applying a track or a EM shower more than 200GeV

Event selections

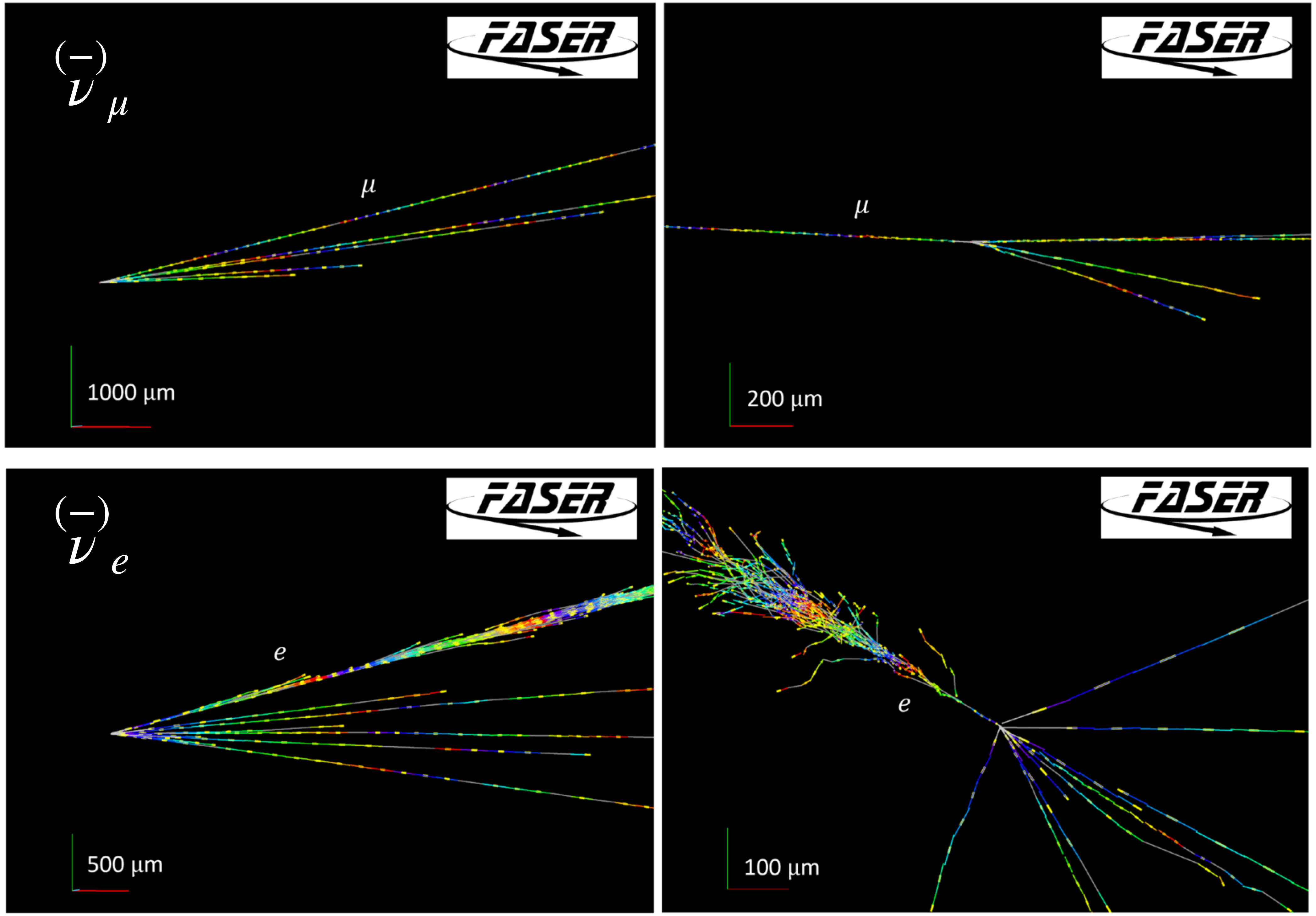
- 5 or more tracks attached to a vertex
- No charged parent track
- 4 or more tracks with $\tan_\theta < 0.1$
- $\tan\theta > 0.005$ for muon or EM shower
- An EM shower or a track of more than 200 GeV
- $\phi > 90^\circ$



First $\overset{(-)}{\nu}_e$ detection by the FASERν module

FASER Collaboration
PRL 133 021802, 2024

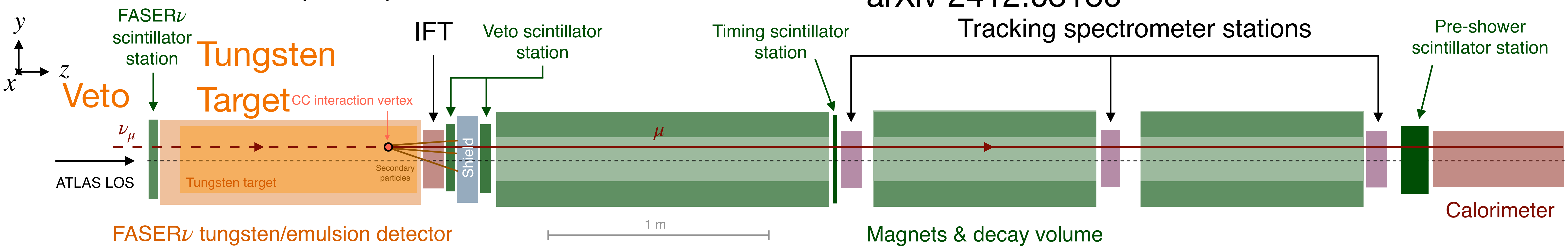
- $\overset{(-)}{\nu}_e$ candidates: 4 events
- $\overset{(-)}{\nu}_\mu$ candidates: 8 events
- Background estimations
  - ν_e: $0.025^{+0.015}_{-0.010}$
  - ν_μ: $0.22^{+0.09}_{-0.07}$
- significance
  - ν_e: 5.2 σ
  - ν_μ: 5.7 σ
- This is only 1.5 % of data taken with the FASERν emulsion detector so far
  - More results will follow soon!



Analysis using the FASER spectrometer

Detection of $\nu_\mu + \bar{\nu}_\mu$

FASER Collaboration,
arXiv 2412.03186



Event selections

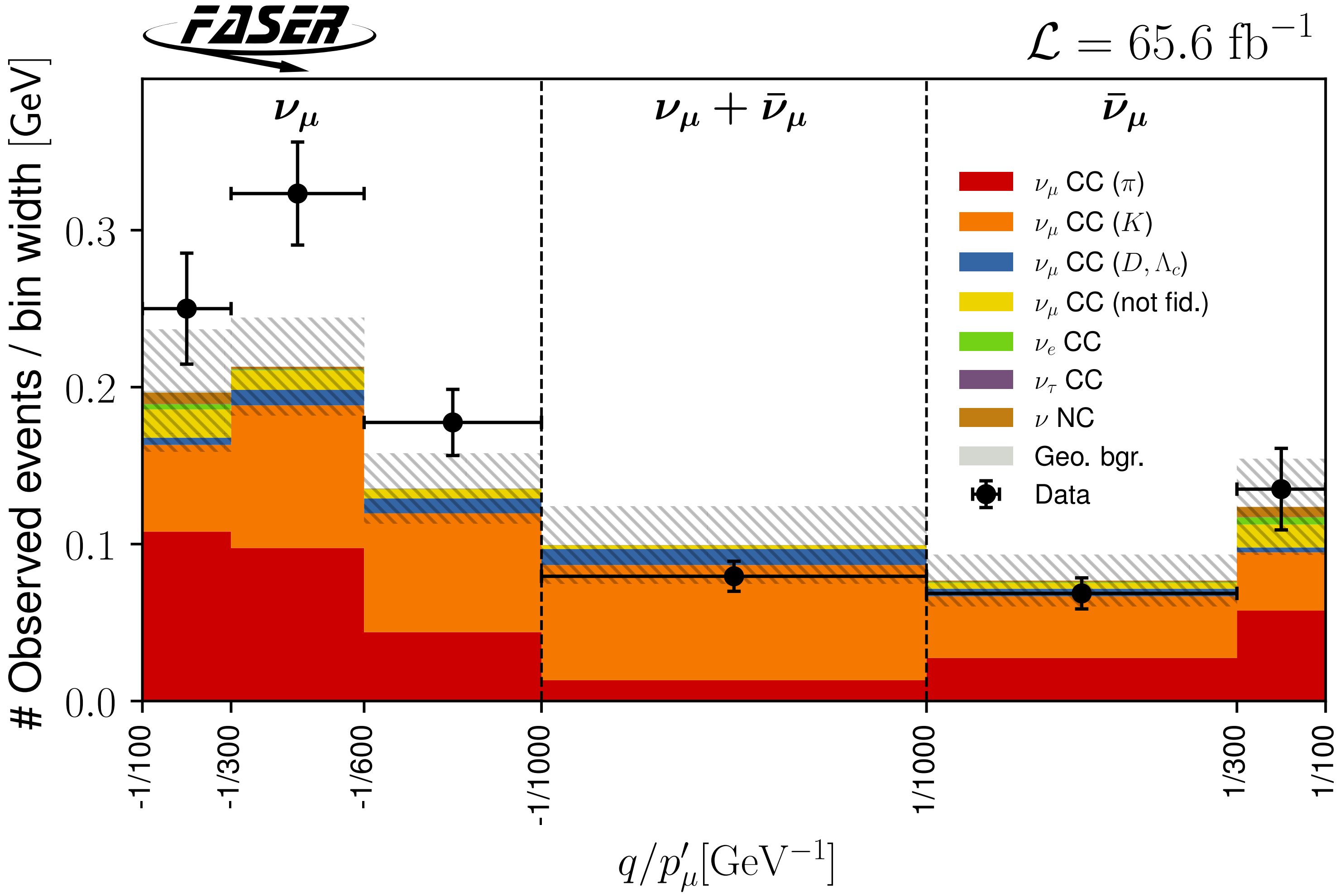
Signals track with > 100 GeV

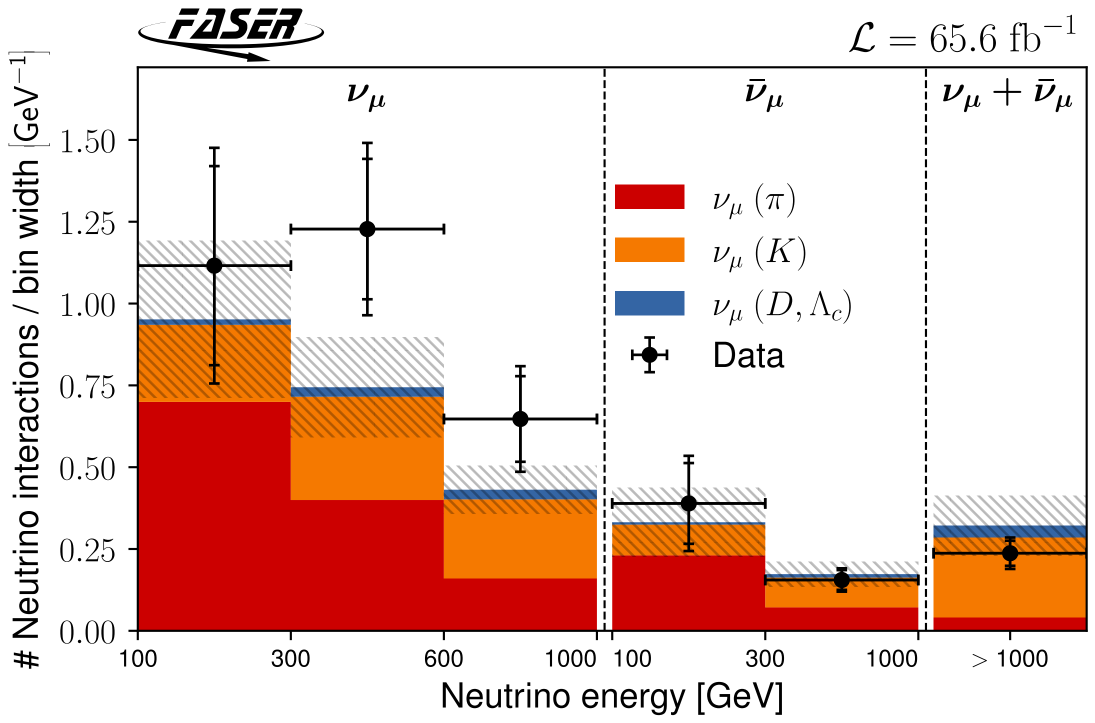
- Collision event with good data quality (65.6 fb-1)
- Triggered by any scintillator downstream of the veto scintillators
- No signal in two front veto scintillators(<30 pC)
- The time difference of the scintillators before and after the tungsten target
- At least 14 hits in the silicon tracker across at least seven layers (for selecting good track)
- At least one track passes through all three tracking stations with >100 GeV
- Track in fiducial tracking volume, <95 mm
- Track extrapolate to <120 mm in front veto scintillator
- Angle less than 25 mrad with respect to the detector axis

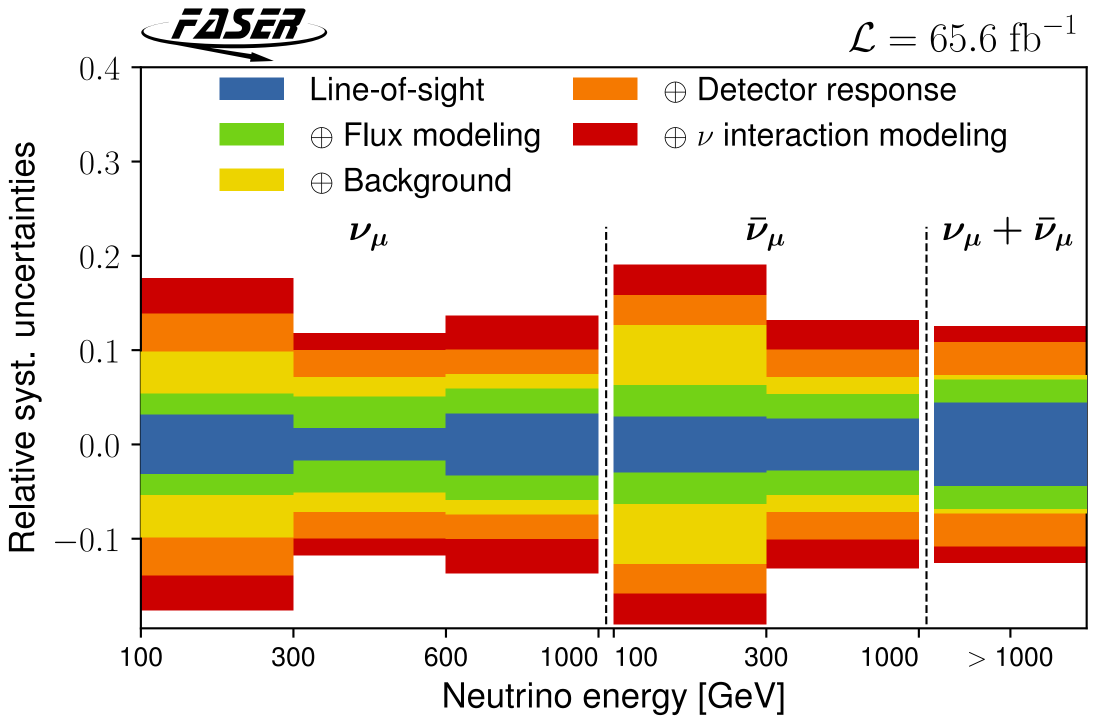
Number of neutrino interactions

363 neutrino candidates are detected.

$$n_{\nu,\mathrm{obs}} = 338.1 \pm 19.0\ (\mathrm{stat})\ \ \pm 8.8\ (\mathrm{syst})$$



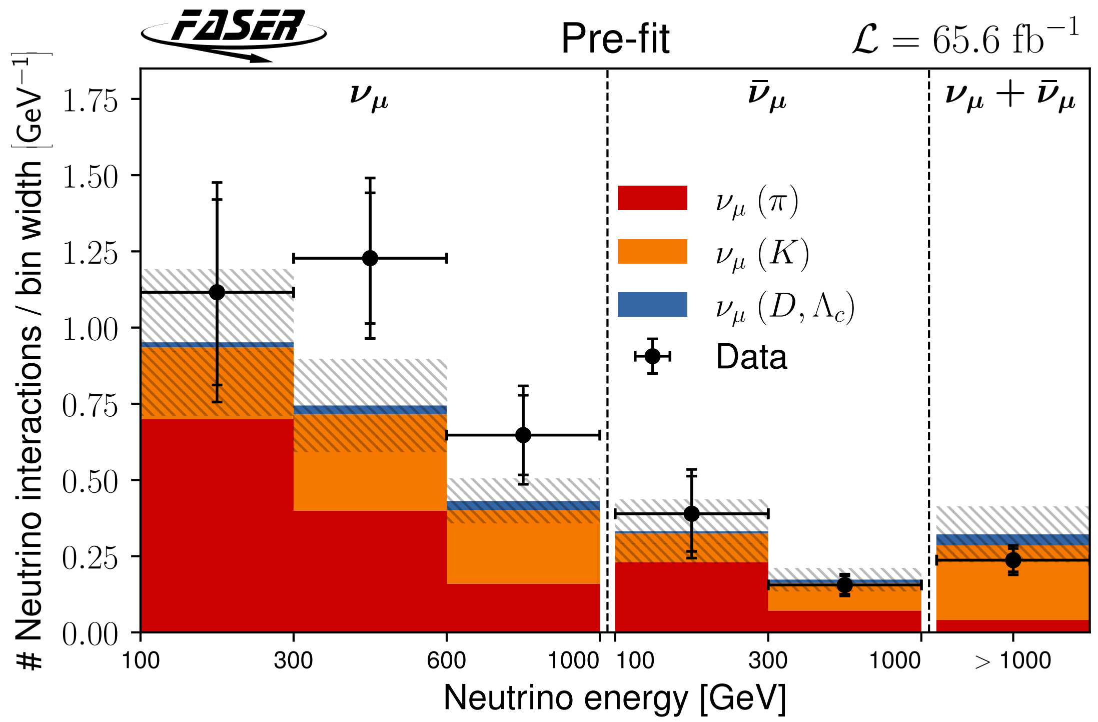


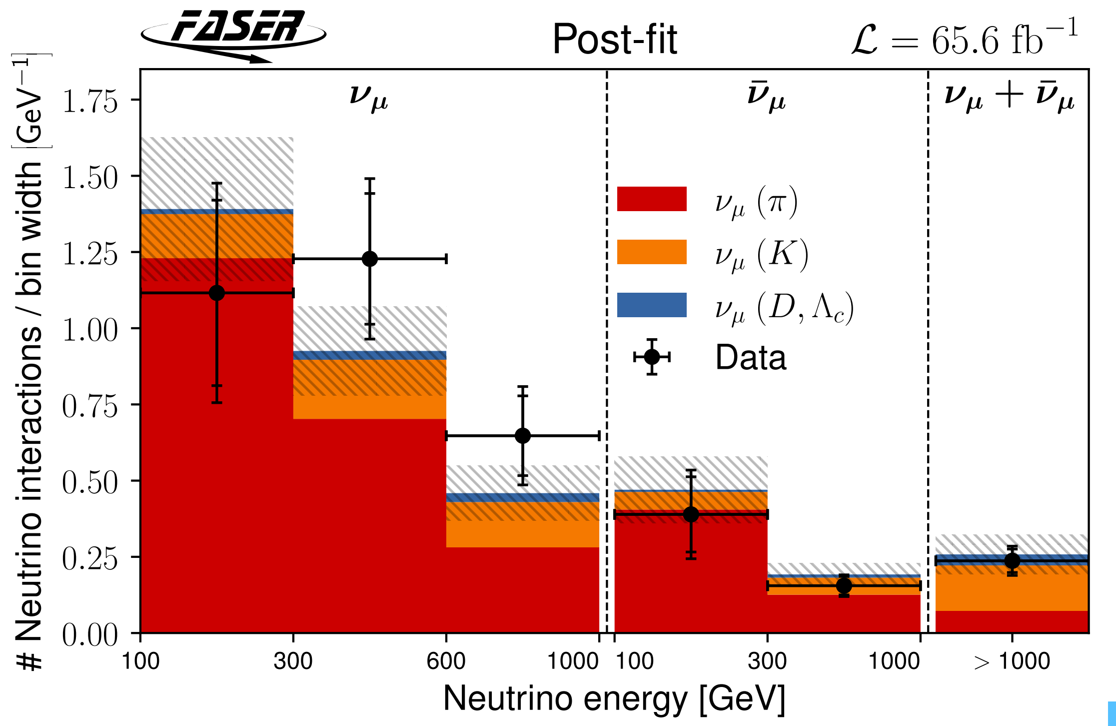


Background from muon scattering: 0.3 ± 0.6 events

The majority of backgrounds are ν_μ CC events in non-fiducial regions and ν NC events

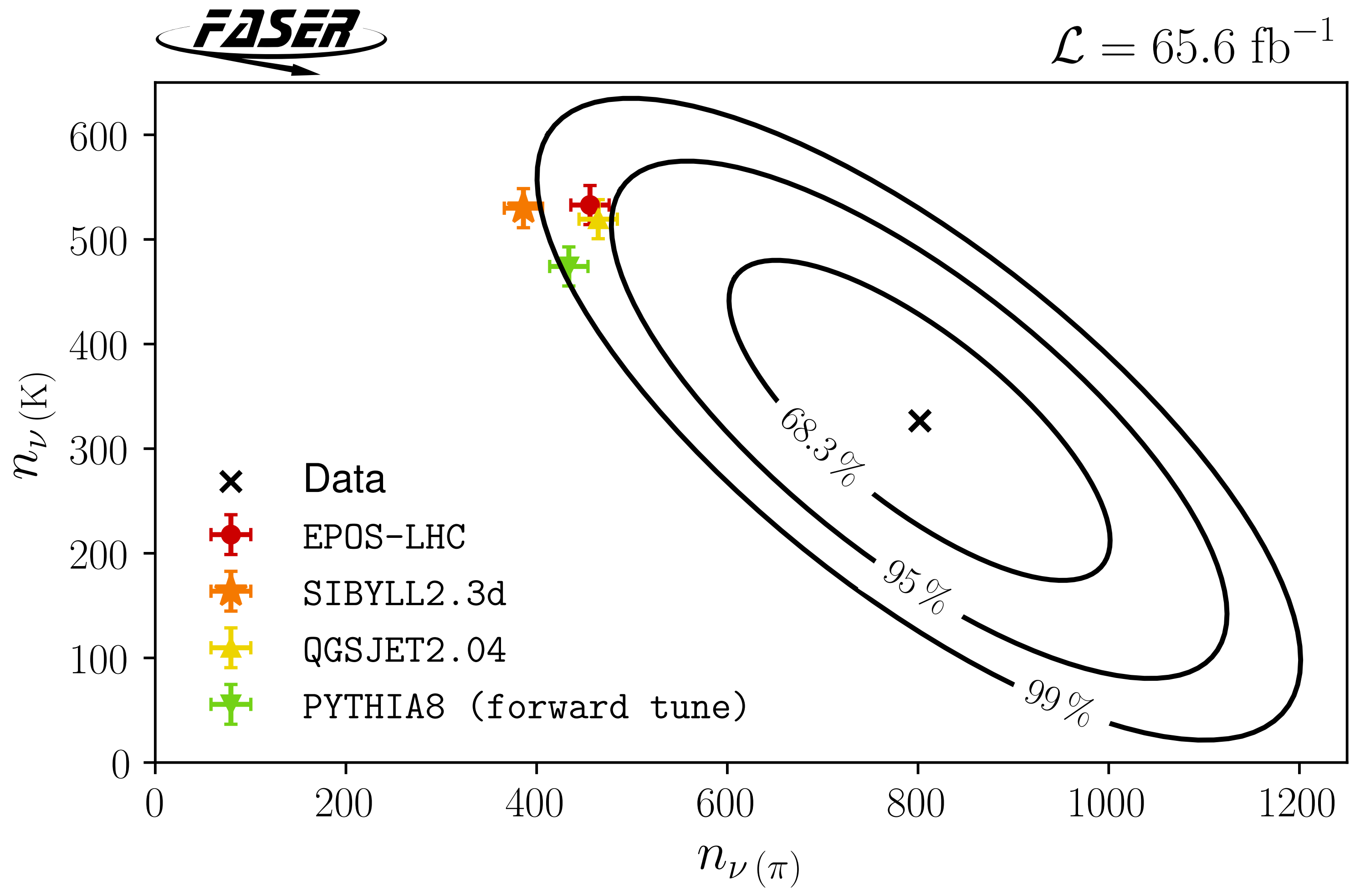
Fit with normalization factors for π and K





Template fit of measured neutrinos

Normalization for π and K for free parameters



We are starting to validate the hadron productions

Summary

- The FASER experiment is an experiment located at 480m from the ATLAS interaction point at LHC aiming to search for long-lived particles and neutrinos.
- Neutrinos measured by FASER are a proxy of hadron productions from p-p collisions.
- For the muon puzzle of ultra-high-energy cosmic rays, pions and kaons with 1%- 50% of beam energy are important, and FASER covers this well.
- In the past two years, we have reported three neutrino analyses: one using the FASER emulsion-based detector and the other using the FASER spectrometer.
- Four $\overset{(-)}{\nu}_e$ and eight $\overset{(-)}{\nu}_\mu$ candidates are reported using the FASERν detector, corresponding to >5 σ. This is the first $\overset{(-)}{\nu}_e$ measurements using a collider.
- 362 neutrino candidates are detected by the latest analysis using 65.5fb^{-1} of data by the FASER spectrometer.
- ν_μ and $\bar{\nu}_\mu$ are measured with energy separately. These results are compared with hadronic interaction models, starting the validation of hadronic interactions using the collider neutrino.
- We have measured 190 fb^{-1} so far. More results will follow soon!!

Back ups

Which particles in which interactions should we measure?

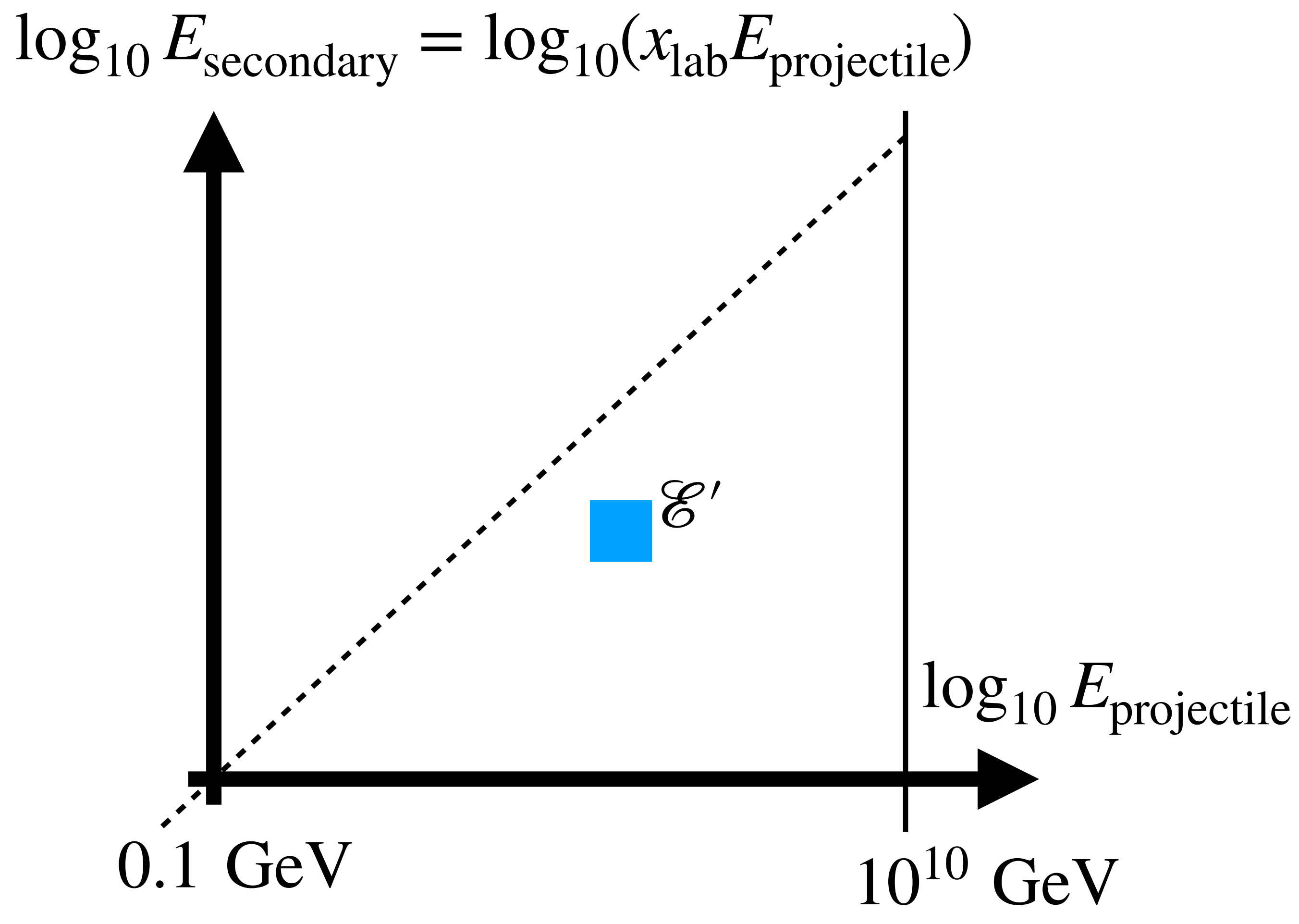
In an air shower induced by 10^{19} eV($= 10^{10}$ GeV) proton,
We have a huge number of particles from $\mathcal{O}(0.1)$ to $\mathcal{O}(10^{10})$ GeV
Which particles in which interactions is important?

<u>Simulation study:</u>
(K.O., Anatoli Fedynitch, Hiroaki Menjo, in prep.)

Focus on a simple scenario of the strangeness enhancement
Swap pions($\pi^{\pm}$, π^0) by kaons ($K^{\pm}$, K^0) simultaneously with a fraction of f_{enhance}

Check how the number of muons N_μ changes when we modify a small area of interactions

Calculate $\mathscr{D} = \dfrac{1}{N_\mu}\dfrac{\partial N_\mu}{\partial f_{\mathrm{enhance}}}(x_{\mathrm{lab}}, E_{\mathrm{projectile}})$



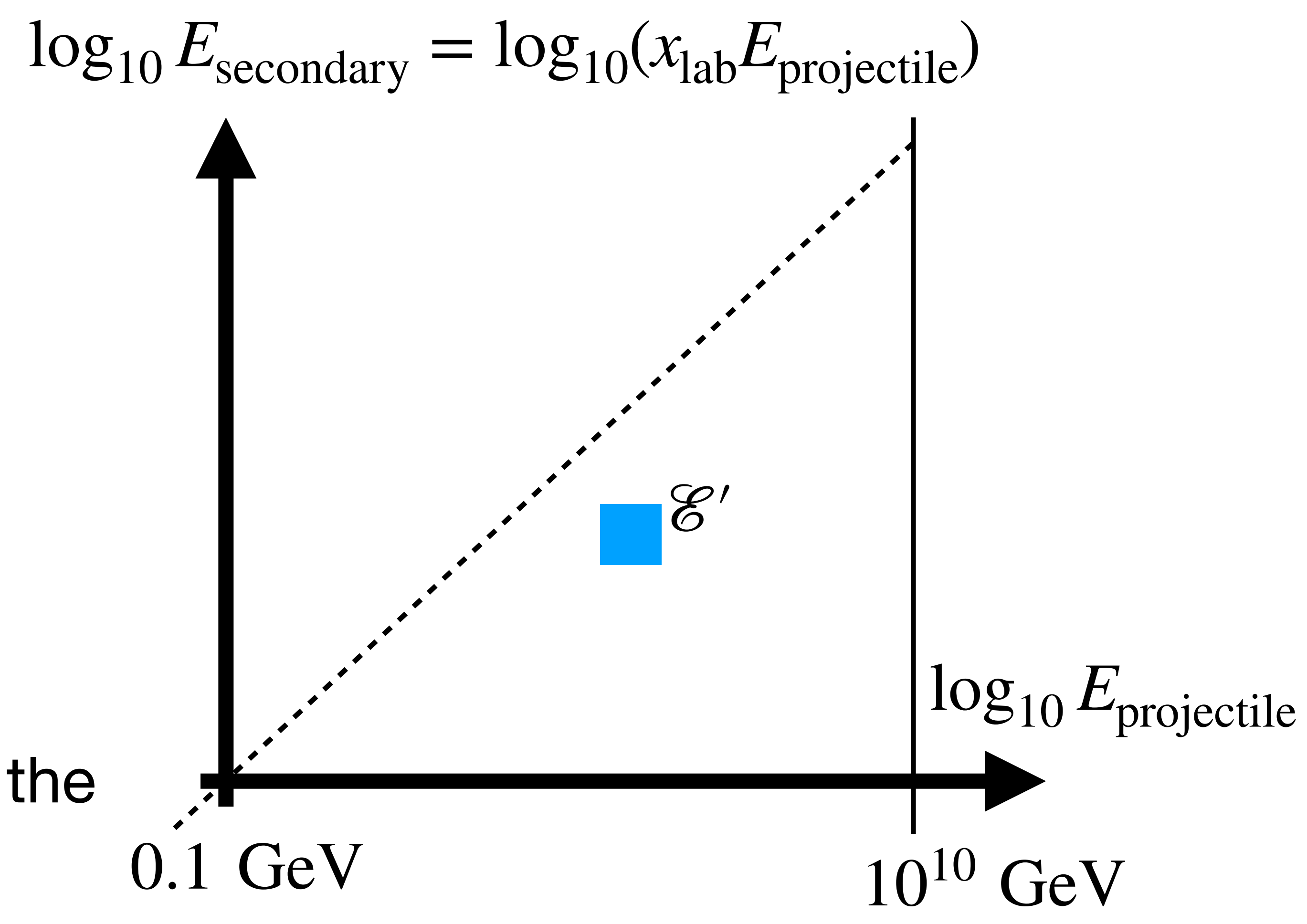
Calculation method of derivative

Simulation set-up

- Simulation package MCEq
- SIBYLL 2.3d for hadronic interaction
- 10 bins per decade
- Calculate N_μ with modification by $f_{\text{enhance}} = 0.005$
  - Swap 0.5% of pions into kaons.

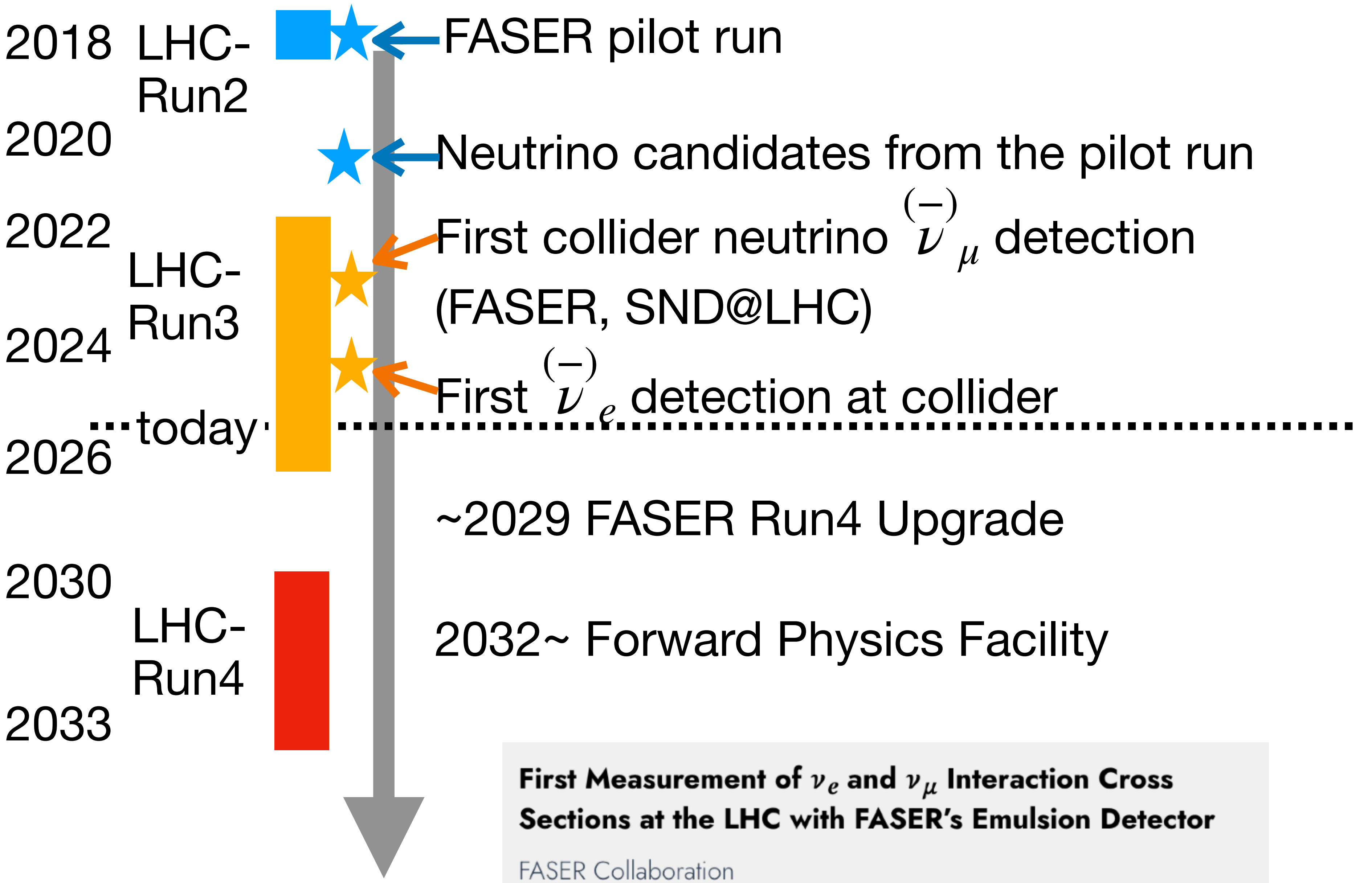
How to calculate effects actually

- Define an area $\mathcal{E}'$ with $E_{\text{projectile}}$ and $E_{\text{secondary}}$
  - Size of a bin: $\log_{10} E = 0.1$
- Swap pions by kaons with a fraction f_{enhance} and calculate the number of muons by MCEq
- Swap (pi+ / pi- / pi0) to (K+ / K- / K0S/L) simultaneously.
  - Swap fraction f_{enhance}
  - $M'_\pi = M_\pi - f_{\text{enhance}} M_\pi + f_{\text{enhance}} M_K$
  - $M'_K = M_K - f_{\text{enhance}} M_K + f_{\text{enhance}} M_\pi$
- Calculate $\mathcal{D}$ at that area and repeat for all phase space



FASER experiment

FORWARD SEARCH EXPERIMENT AT THE LHC



First Measurement of ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector

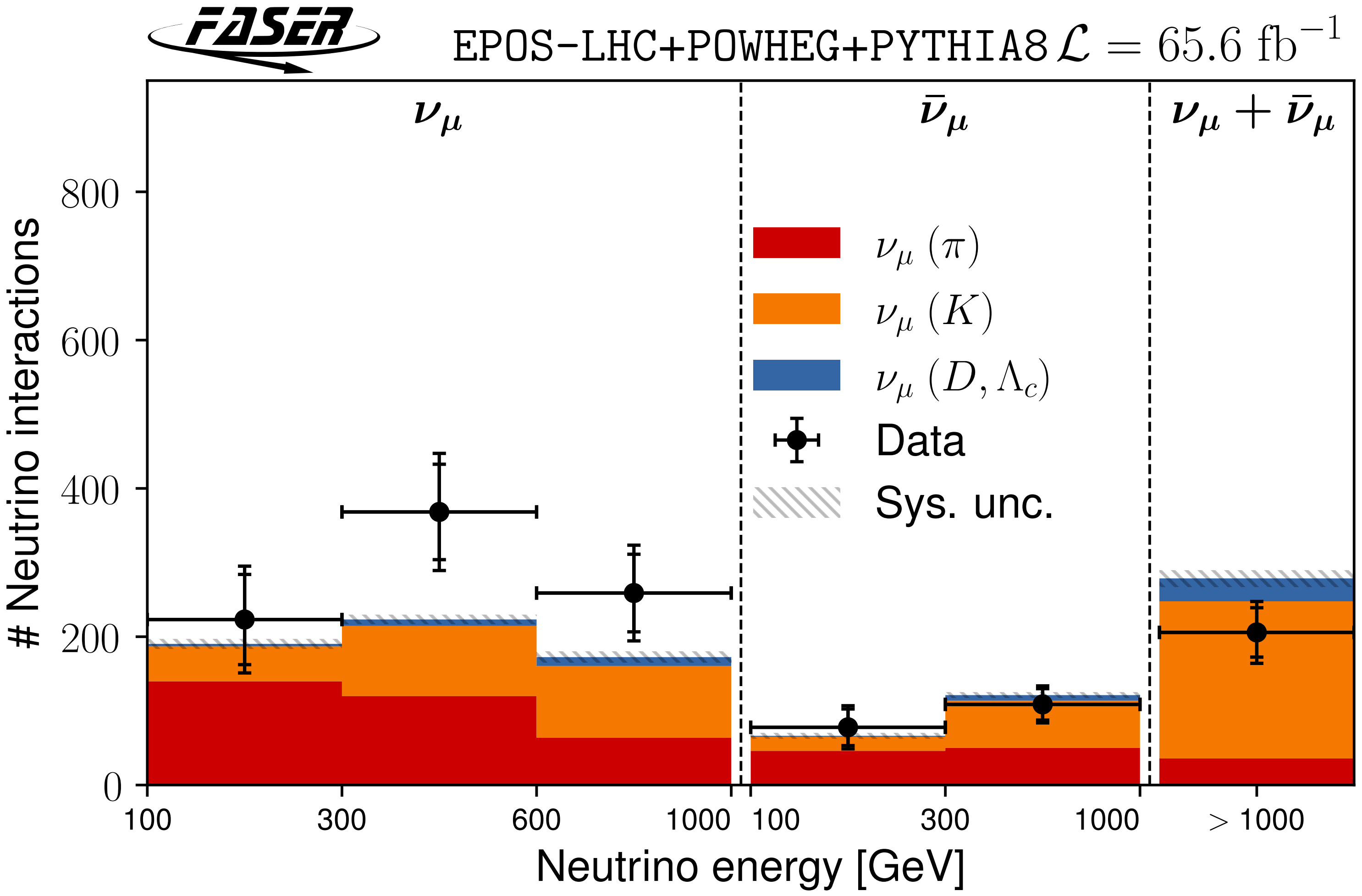
FASER Collaboration

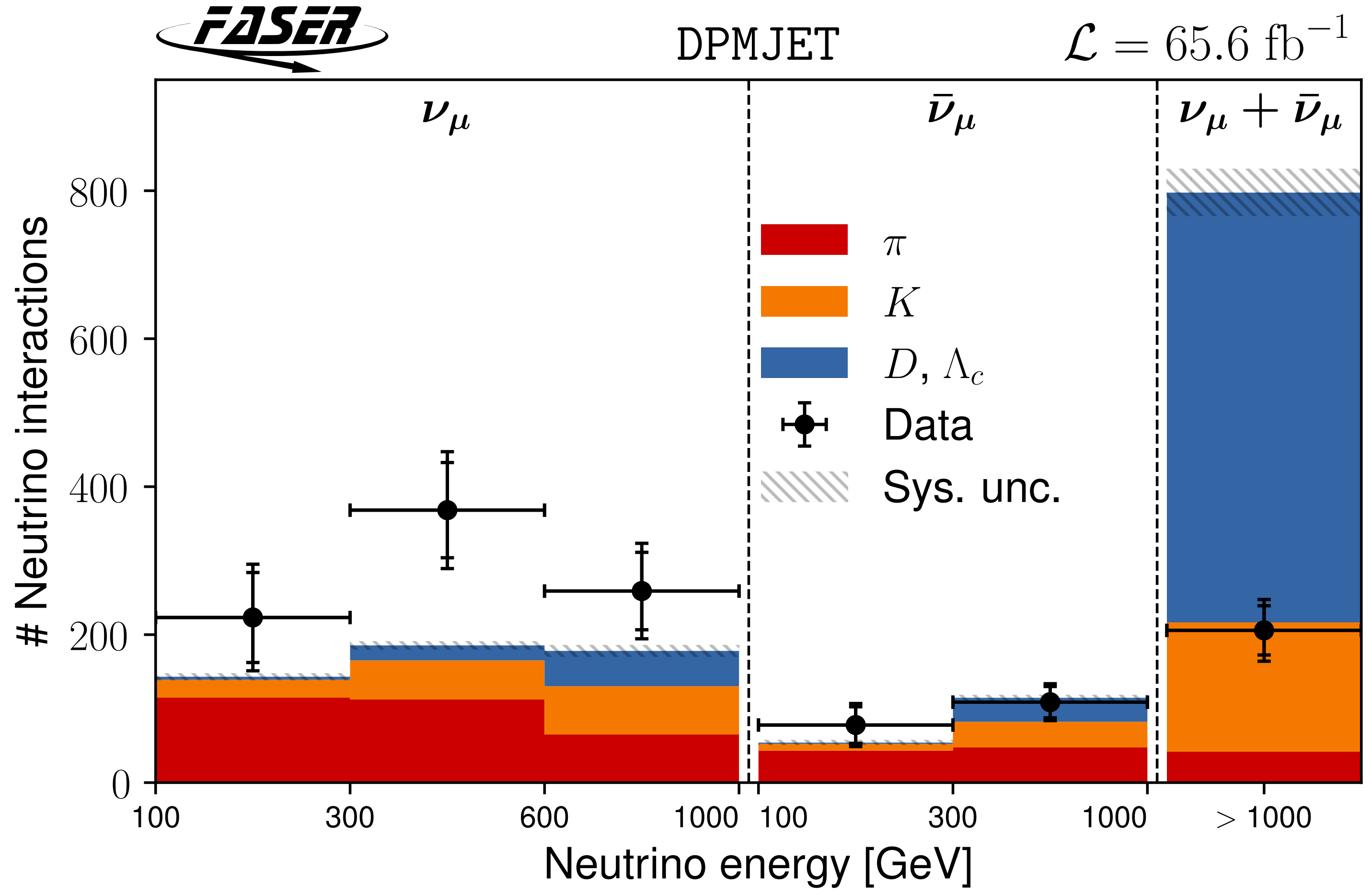
***Physical Review Letters* collection of the year 2024**

Comparison with hadronic interactions

EPOSLHC for π and K productions
POWHEG + PYTHIA8 tune
for charmed hadron productions

DPMJET III-2019





We are starting to validate the hadron productions