High Energy Neutrino Studies in the forward direction with the *FASER* experiment at the LHC

FASER: ForwArd Search ExpeRiment at the LHC

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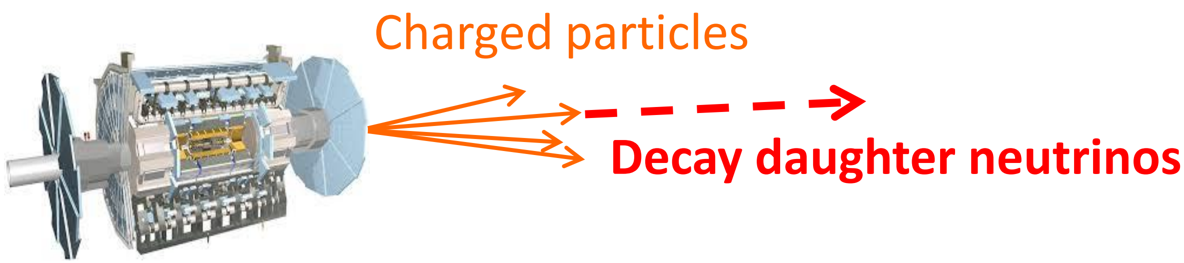
for the FASER Collaboration

9th July 2024

Supported by

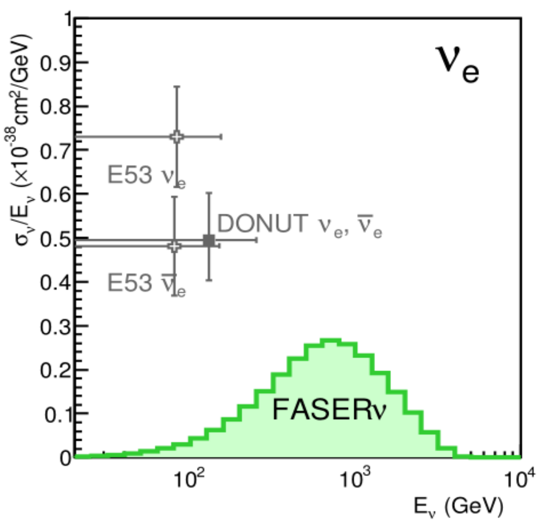
Motivation

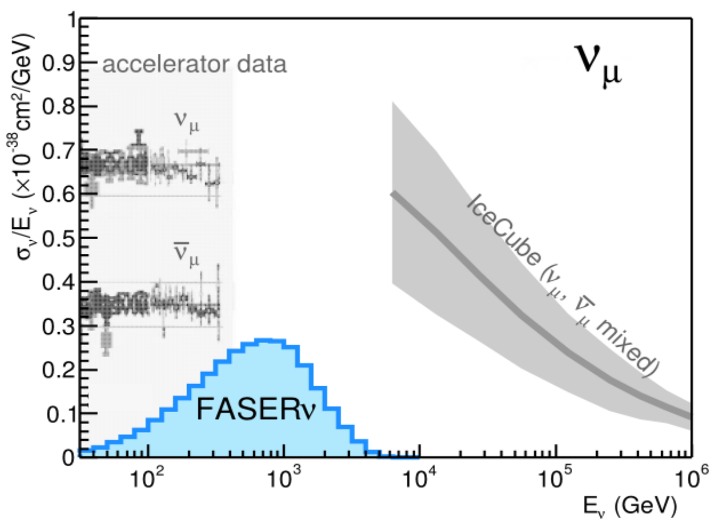


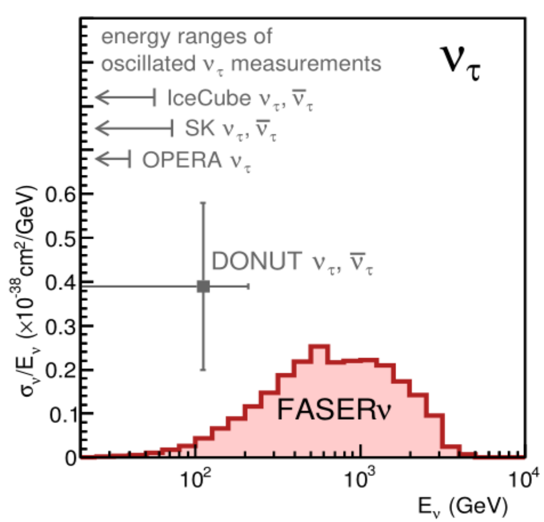
- LHC collision products in forward direction can be high energy neutrino source.
- Also study K/π/Charm production ratio (@$\sqrt{s}$ =14TeV) can be studied by their decay daughter, ie. Neutrino.
- No data on the neutrino interactions at Eν in several 100 GeV to several TeV.
- **Measuring neutrino cross section of 3 types of neutrinos at unexplored energy.**

- **Lepton Universality check, especially tau neutrino interactions and others, possible anomaly indication by B mesons.**

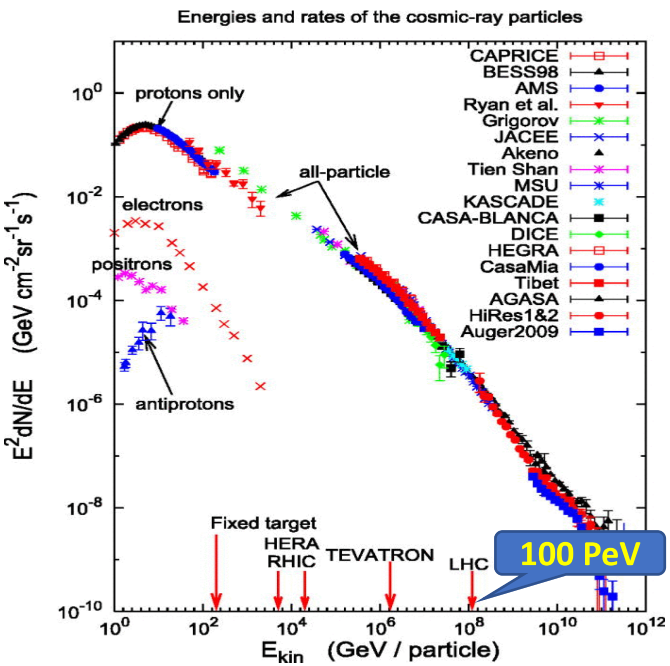
$$R(D) = \frac{\mathcal{B}(B \to \tau \nu_\tau D)}{\mathcal{B}(B \to \mu \nu_\mu D)}$$





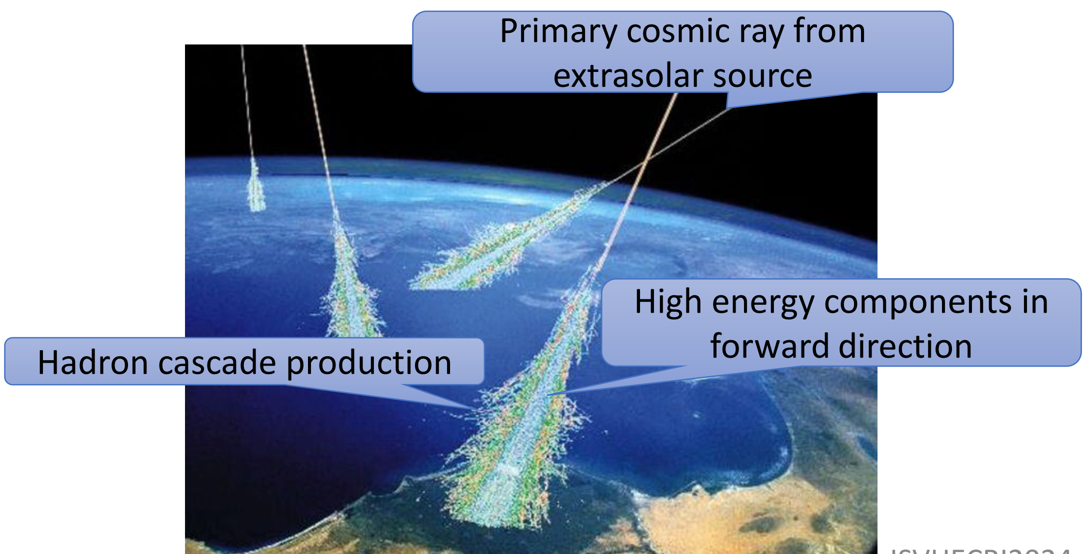


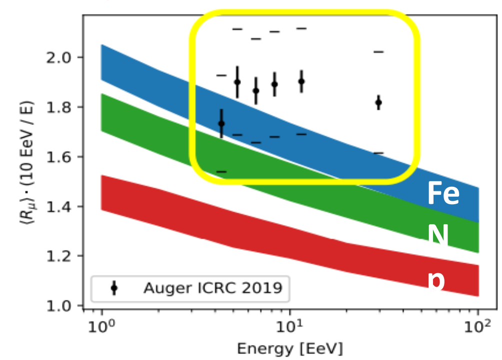
Energy scale and feedback to cosmic ray study



- Fixed target experiments (NA61, NA65)
  - Limited in energy, $\sqrt{s}$~30 GeV at the CERN SPS
- Collider experiments
  - $\sqrt{s} = 14$ TeV at the LHC, equivalent to 100 PeV proton interaction in fixed target mode
  - Transverse detectors (ATLAS/CMS/LHCb) is limited in angular acceptance
  - Forward detectors
    - LHCf: neutral particles (γ, π^0, n)
    - FASERν: neutrinos → π, K, D

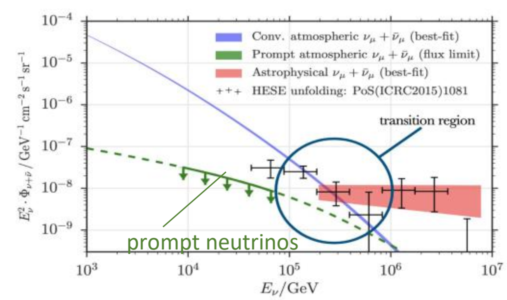
➢ Input/Feedback to Atmospheric Leptons
Key: "Forward particle production with flavor sensitivity"





Muon excess

π/K



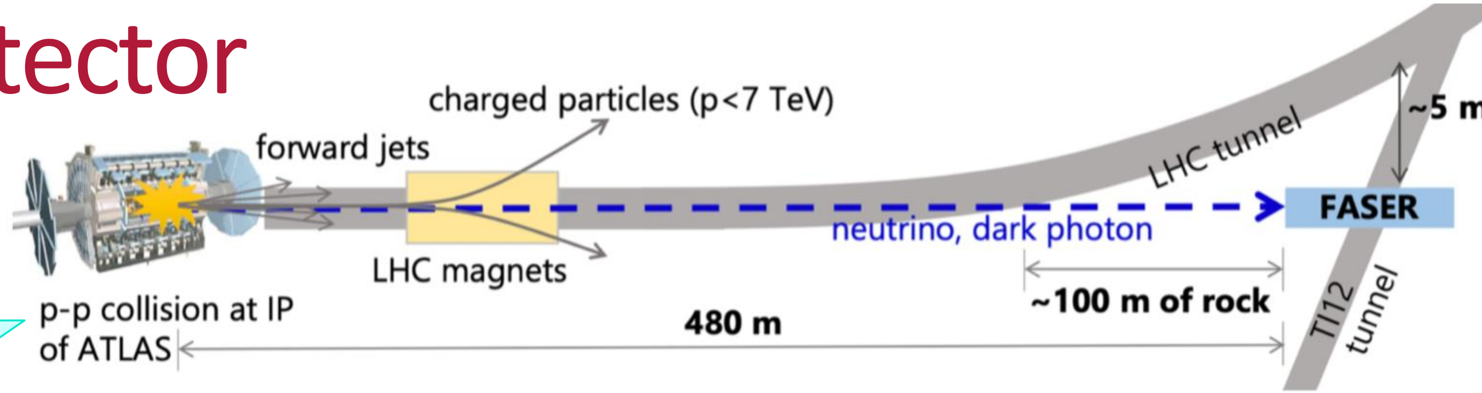
Prompt neutrinos

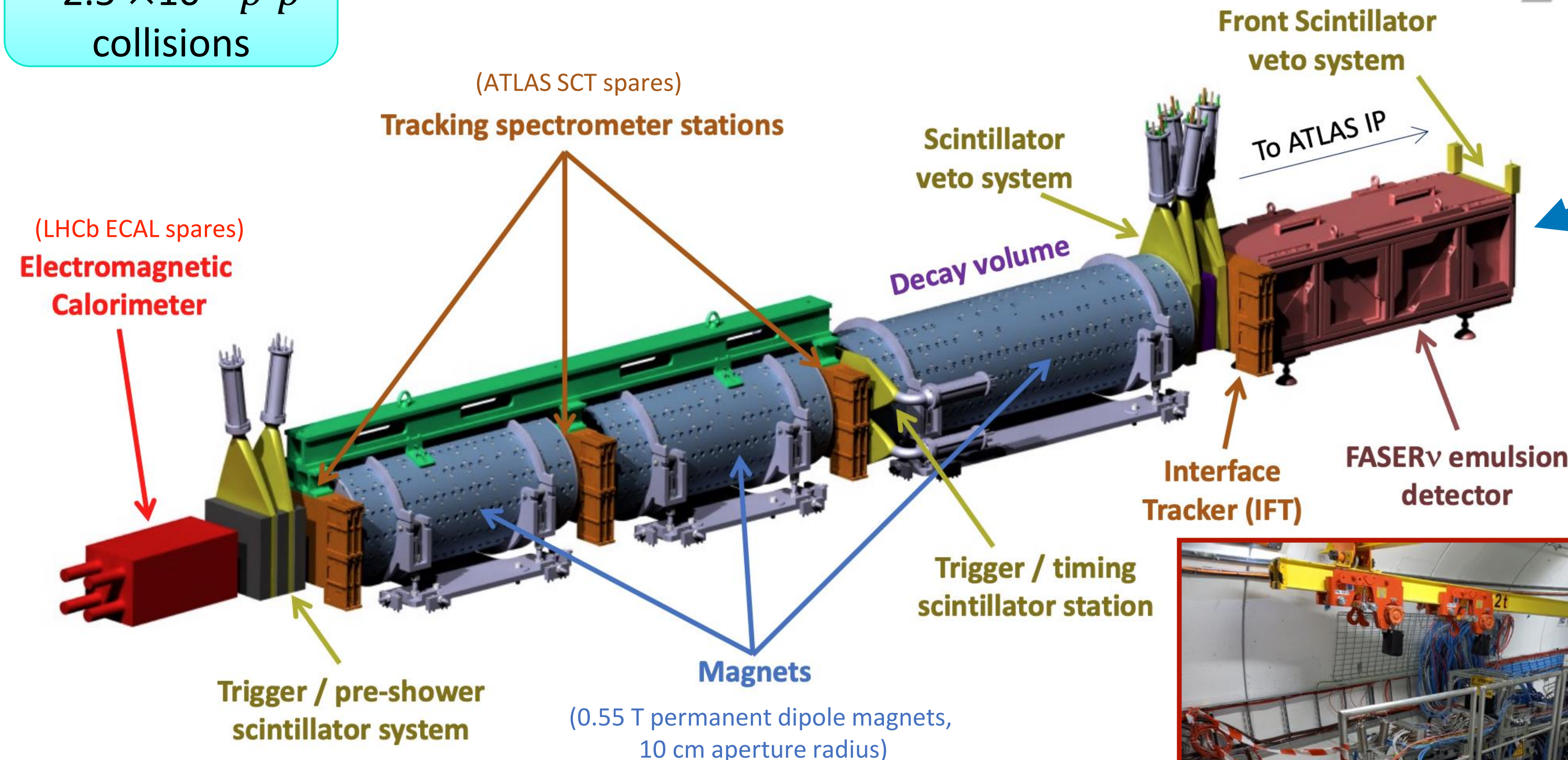
IceCube Collaboration, Astrophys. J. 833 (2016)

Charm

FASER Detector

250 fb^{-1}
~2.5 ×10^{16} p-p collisions



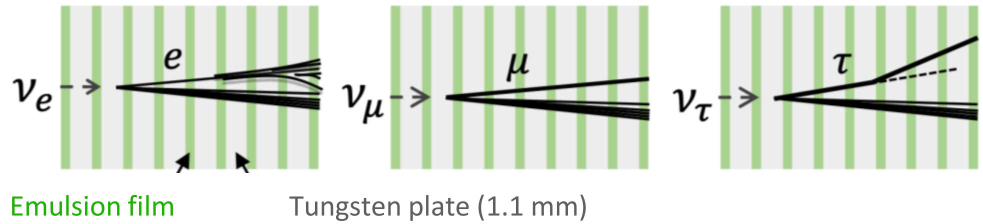


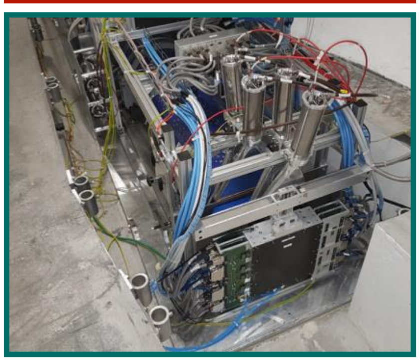
Length: ~7 m

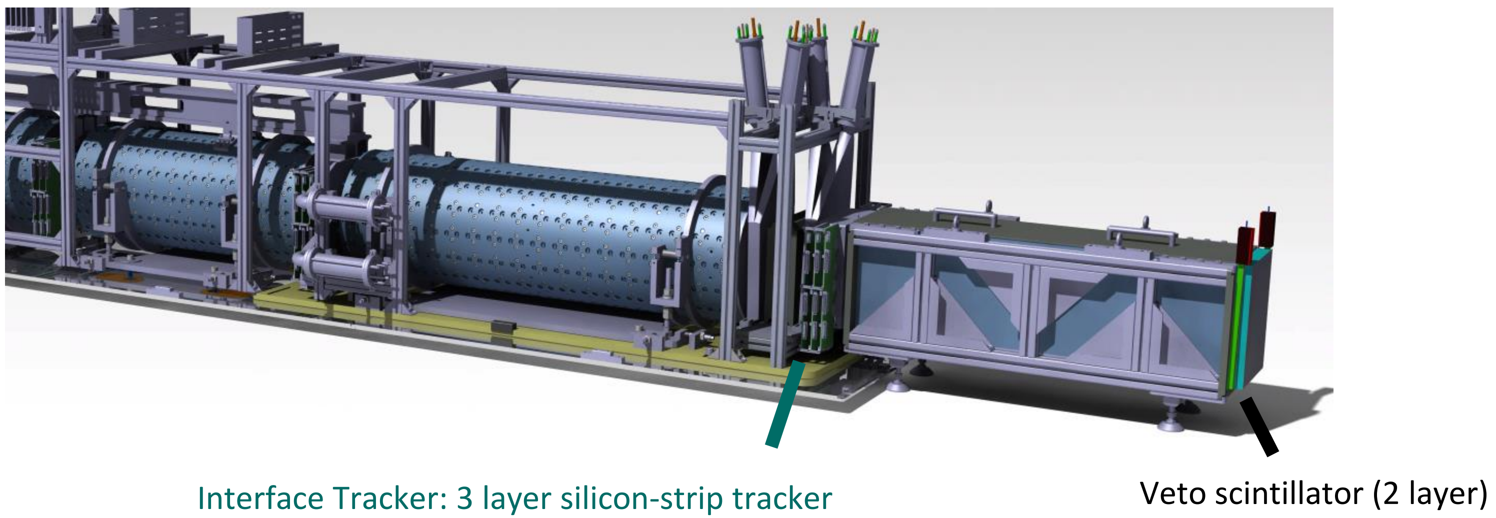
FASERν Neutrino Detector

- Emulsion-based detector
  - 730 × [tungsten (1.1 mm thickness) + emulsion film]
  - 250 mm × 300 mm, 1 m long, 1.1 tons (220 X_0)
  - Install (exchange) emulsions 3 times a year

- ν flavor identified with topological/kinematical info.

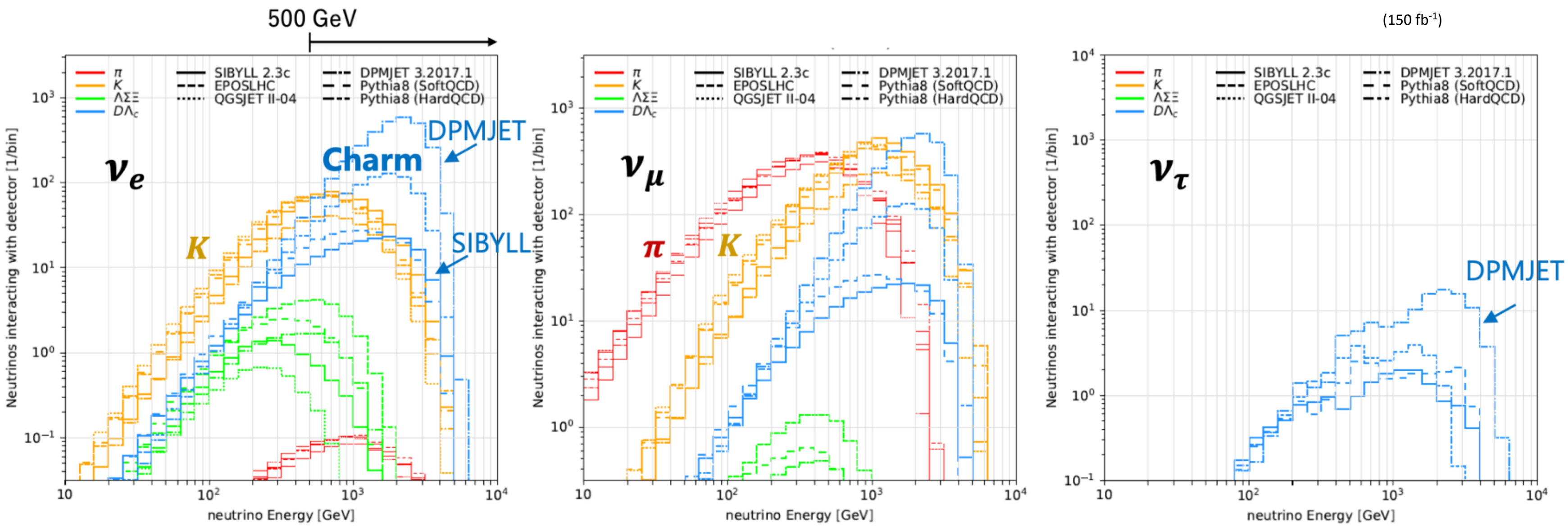






- Global reconstruction with FASER spectrometer
- Muon charge identification (ν_μ)

FASERν Expected Number of Interactions

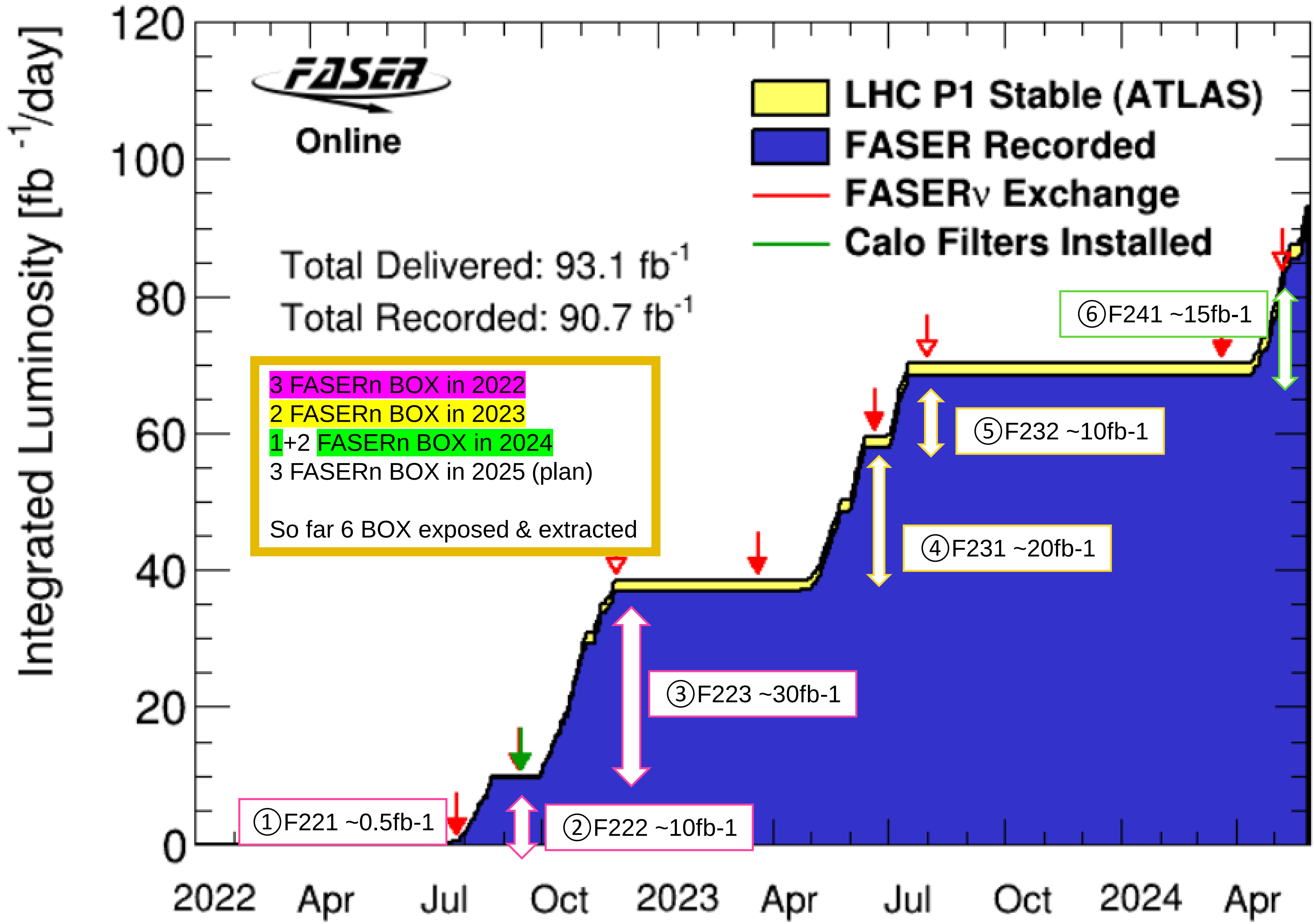


Expected CC interaction events (250 fb^{-1}) (arXiv :2402.13318)

Generators		FASERν at Run 3		
light hadrons	charm hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–
SIBYLL 2.3d	–	1126	7261	–
QGSJET 2.04	–	1181	8126	–
PYTHIAforward	–	1008	7418	–
–	POWHEG Max	1405	1373	76
–	POWHEG	527	511	28
–	POWHEG Min	294	284	16
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}

- **Neutrino's mother is different neutrino flavor by flavor**
- So with **3 neutrino flavors energy distribution can provide information of mother π, K, Charm production information**
- Discrepancy between generators for charm production
- **~10,000 ν** interactions expected in LHC Run 3 (2022-2025)

FASERν exchange during LHC Run3

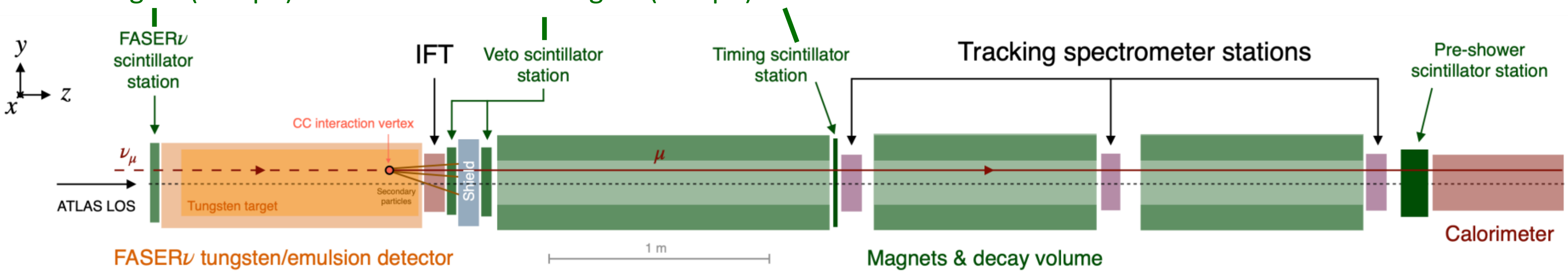


“Electronic” Neutrino Search

(Phys. Rev. Lett. 131, 031801)

- Collision event with good data quality (35.4 fb^{-1}) in 2022 run

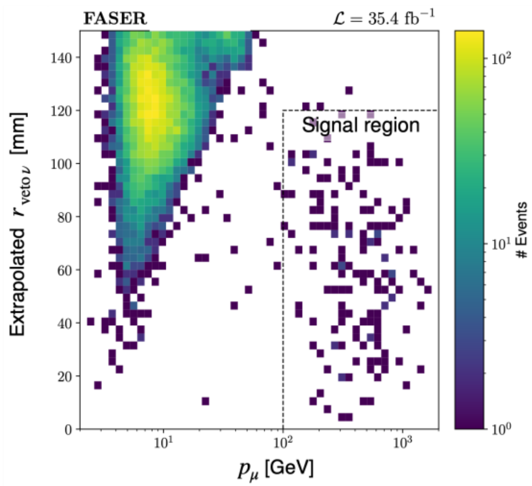
- No signal (<40 pC)
- Signal (>40 pC)

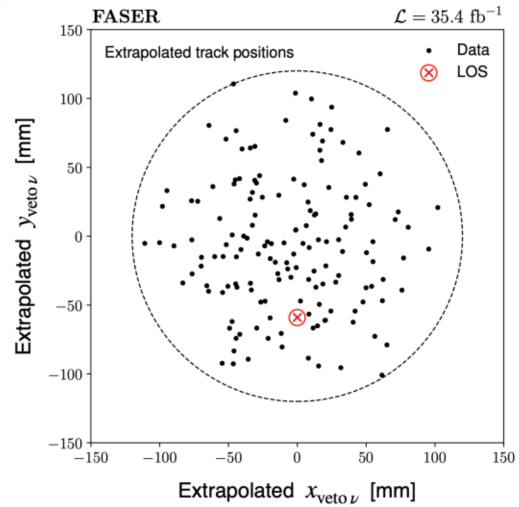


- Timing and pre-shower consistent with ≥ 1MIP
- Exactly 1 good fiducial (r < 95 mm) track
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto

- Expect 151 ± 41 events from GENIE simulation
  - Uncertainty from DPMJET vs. SIBYLL
  - No experimental errors

Results





Category	Events
Signal	153
n_{10}	4
n_{01}	6
n_2	64014695

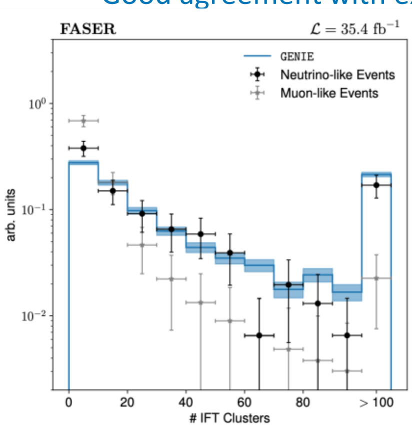
n_0: A neutrino enriched category from events that pass all event selection steps.

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

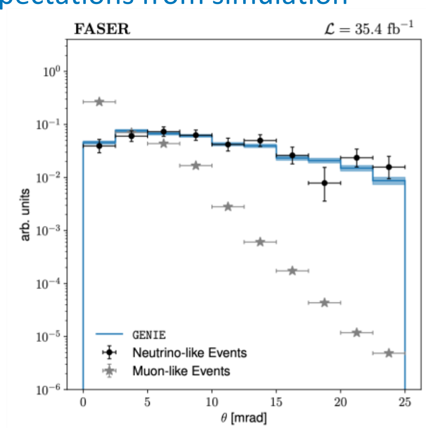
n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

n_2: Events for which both layers observe more than 40 pC of charge.

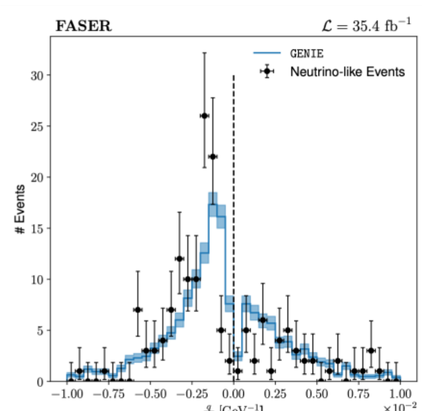
- Observed 153^{+13}_{-12} events (151 ± 41 events expected), background=0.08±1.83
- Signal significance of 16σ
- First directory observation of collider neutrinos
- Except systematic uncertainty on signal efficiency, which will be in next paper.
- Most events at high momentum (E_μ > 200 GeV)
- Observed both νμ and anti- νμ_events
- Good agreement with expectations from simulation



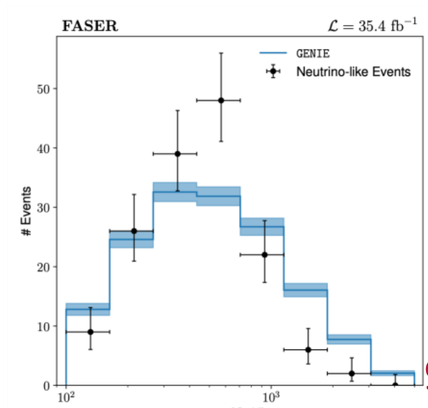
High occupancy in IFT



Large μ polar angle



More ν_μ than $\overline{\nu_\mu}$



High μ momentum

FASERν Emulsion Detector

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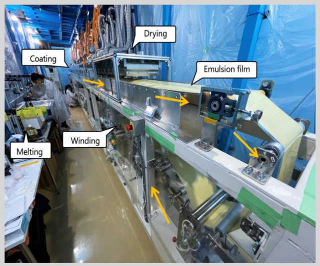
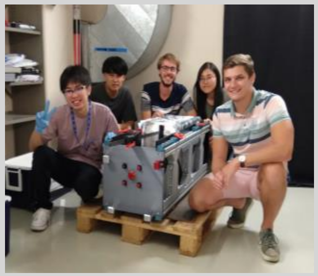


Film production →

CERN

Assembly → Exposure → Disassembling → Development →



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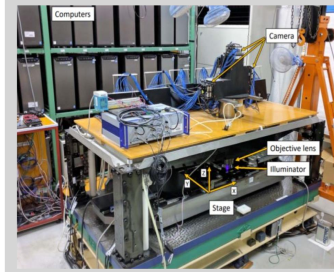
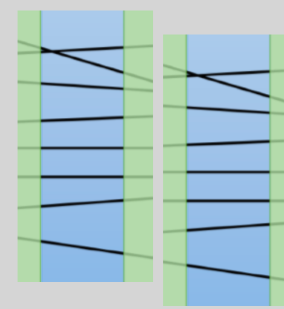


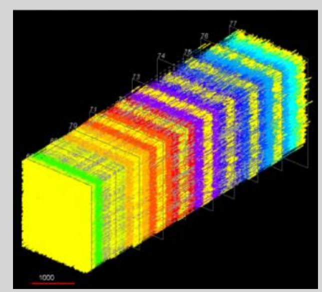
Readout

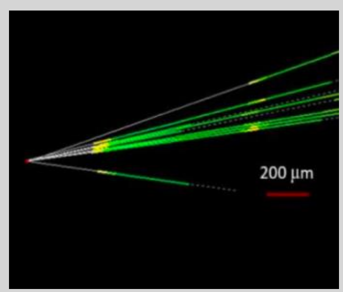
↓

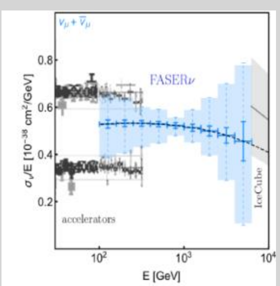
Offline analysis

Alignment → Track reconstruction → Vertex reconstruction → Kinematical analysis, Lepton ID, etc → Physics analysis

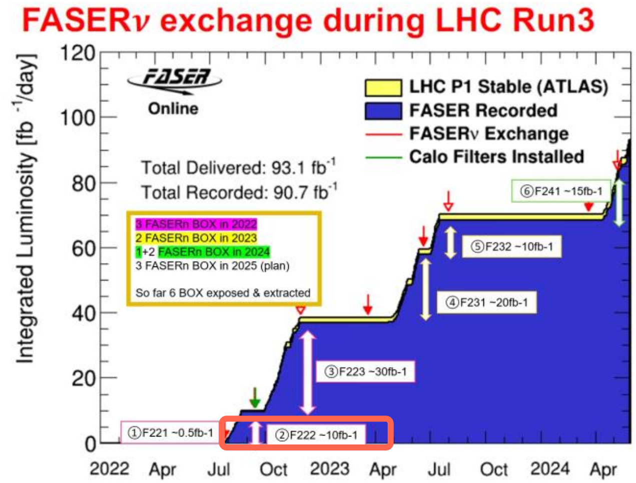








The first analysis result from FASERν



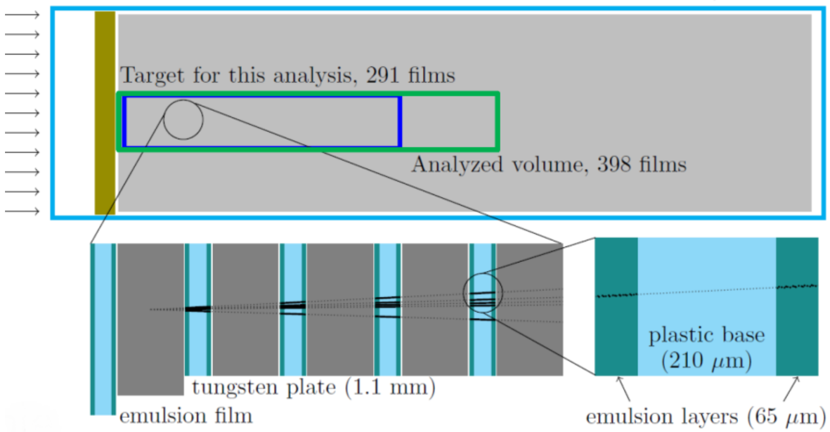
- Analyzed sample

  2nd module (9.5 fb-1) of 2022.

  A fiducial volume 128.6 kg

- "Zero" background by high purity selection

High purity selection	
Vertex reconstruct	Ntrack≥5 Ntrack(tanθ<=0.1) ≥4
Charged lepton	P >200 GeV/c & tanθ>0.005
Ange between charged lepton and Hadron axis	ϕ>90°



- Result

4 νe CC candidate events → First observation of ne CC interactions at the LHC !

→ First cross section in the TeV energy region !

8 νμ CC candidate events

	Expected background	Expected signal	Observed	Significance
νe CC	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	**4**	**5.2 σ**
νμ CC	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4	**8**	**5.7 σ**

Energy estimation

➢ muon like particle case

Penetrating more than 100 tungsten plates.

- Position residual due to Multiple Coulomb Scattering are measured with 0.3 um special resolution.

dP/ P ~ 30% at 200 GeV

< 50% for higher momentum

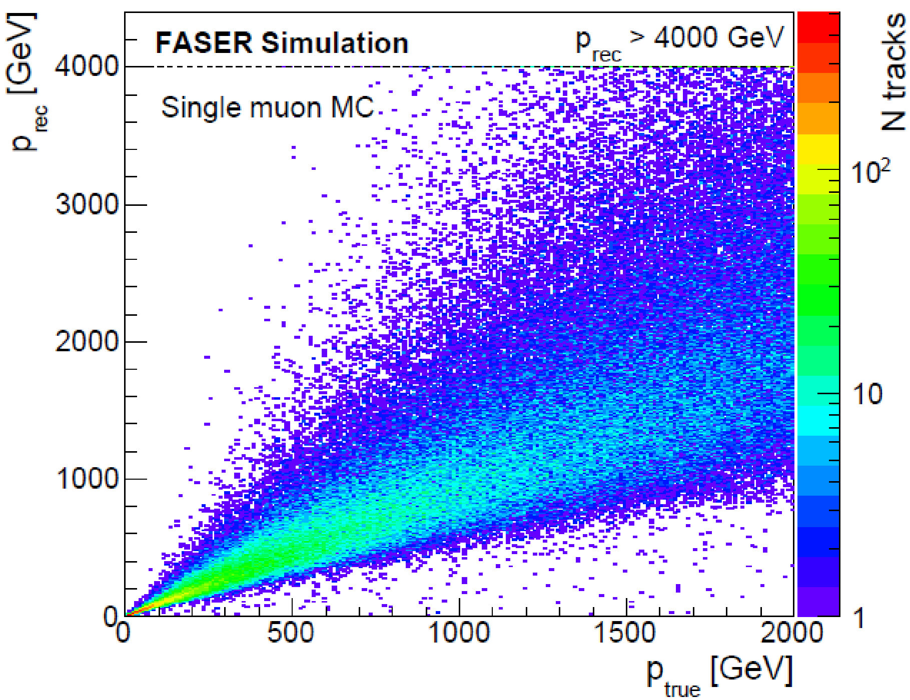
➢ electron like particle case

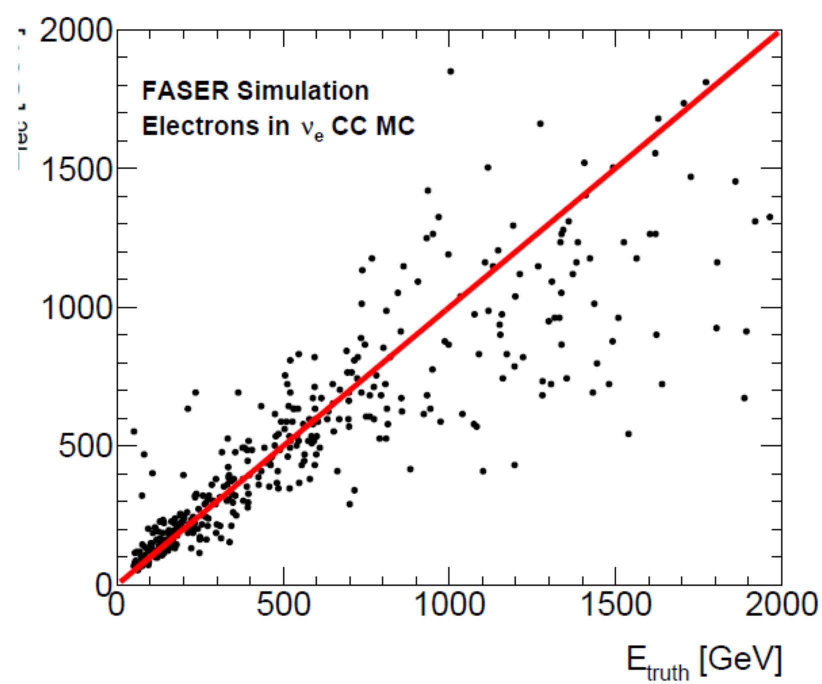
Making an electro magnetic shower.

- Counting track segments in emulsion at electro magnetic Shower maxim (+-3 films) Then convert to electron energy.

dE/E ~25% at 200 GeV.

25-40% for higher energy

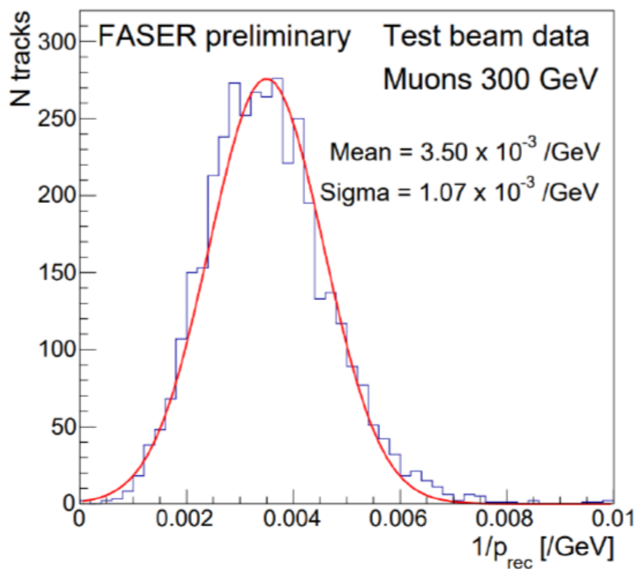


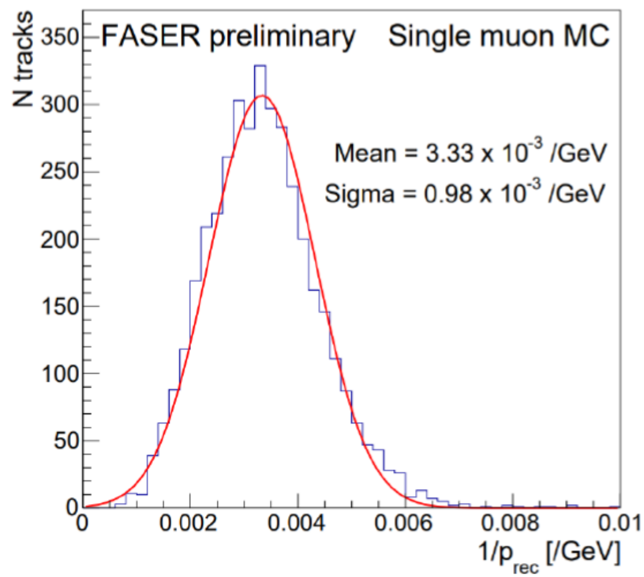


Momentum measurement Validation

In 2023, test beam performed.
300 GeV muon beam are exposed with same ECC structure with the FASERν box.
The momentum were evaluated with the same way as performed in RUN3 data.

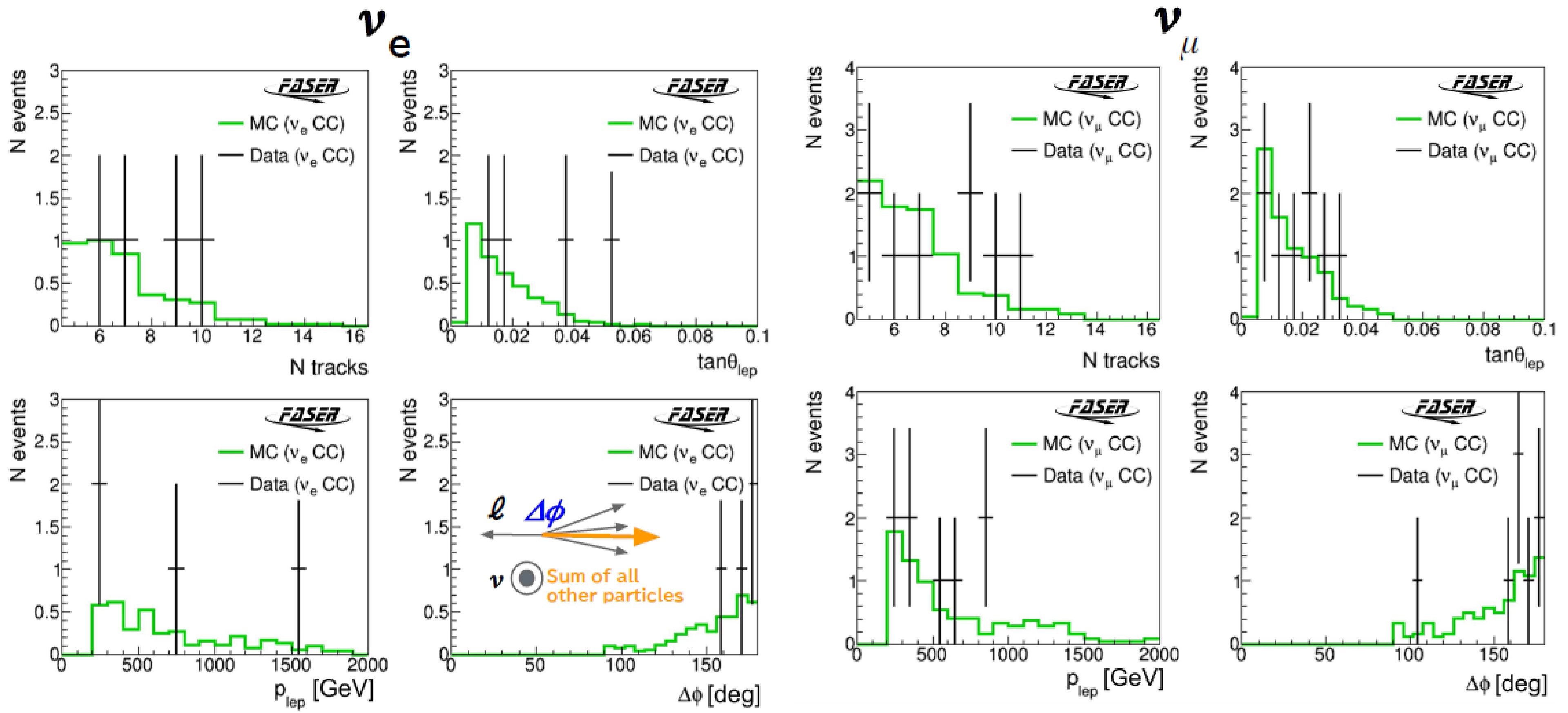
- The momentum value for 300 GeV muon beams is estimated as 286 GeV from the average in inverse momentum.
- The width from the inverse momentum, the momentum measurement resolution shows dP/P ~ 30% as expected from Monte Carlo simulation.



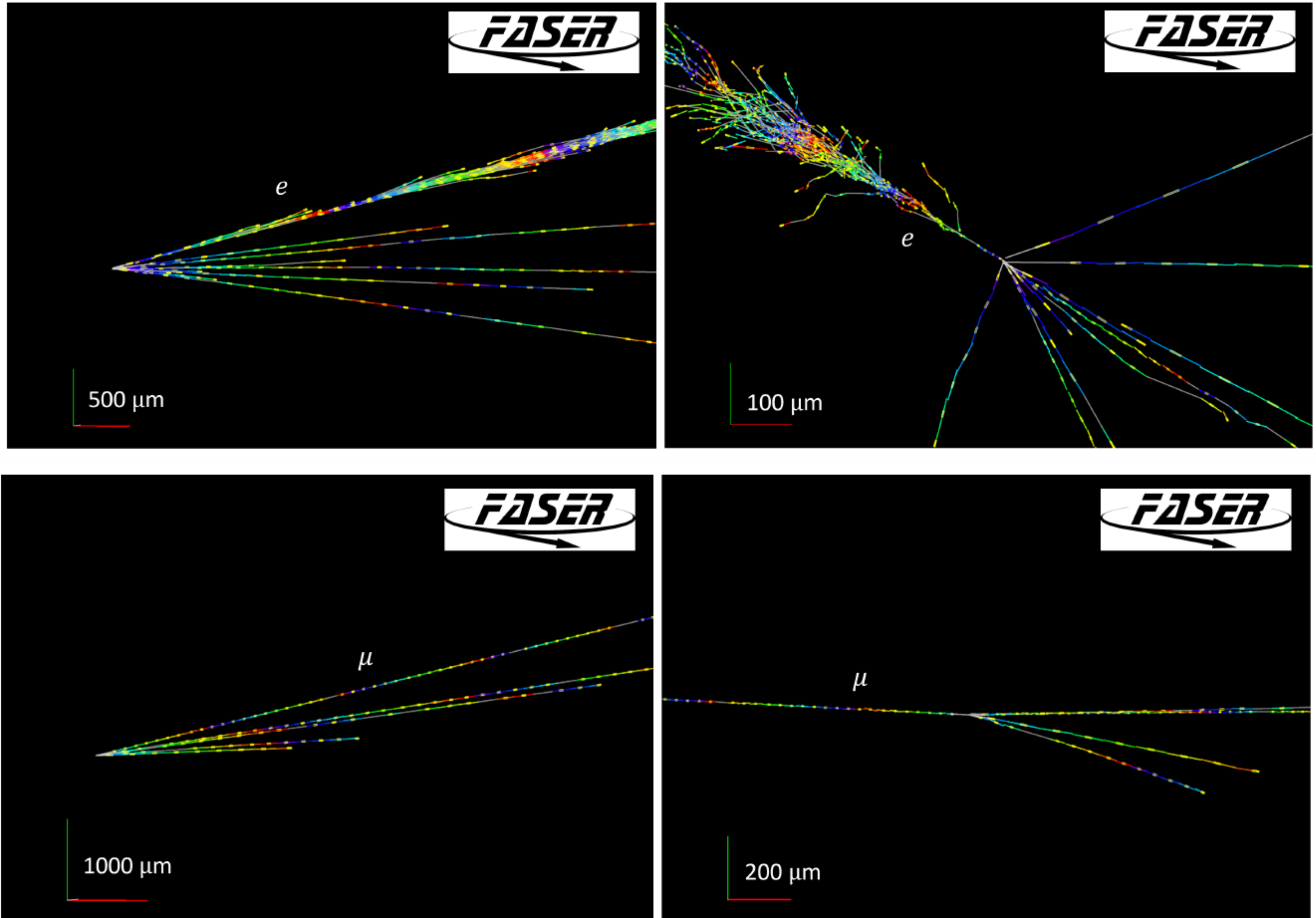


Observed events features

- Key 4 variables used for the selection are shown.
- Statistics is not much but consistent with expectation



Event display of candidate event



First cross section measurement at TeV energy region

- arXiv:2403.1250 (will be appear PRL in a few days)

First cross section measurement at TeV energy region

Using 9.5 fb^{-1} and 128.6 kg target

$\sigma(\nu e + N)/E = 1.2^{-0.8}_{-0.7} \times 10^{-38}$ cm^2/GeV

$\sigma(\nu\mu + N)/E = 0.5 \pm 0.2 \times 10^{-38}$ cm^2/GeV

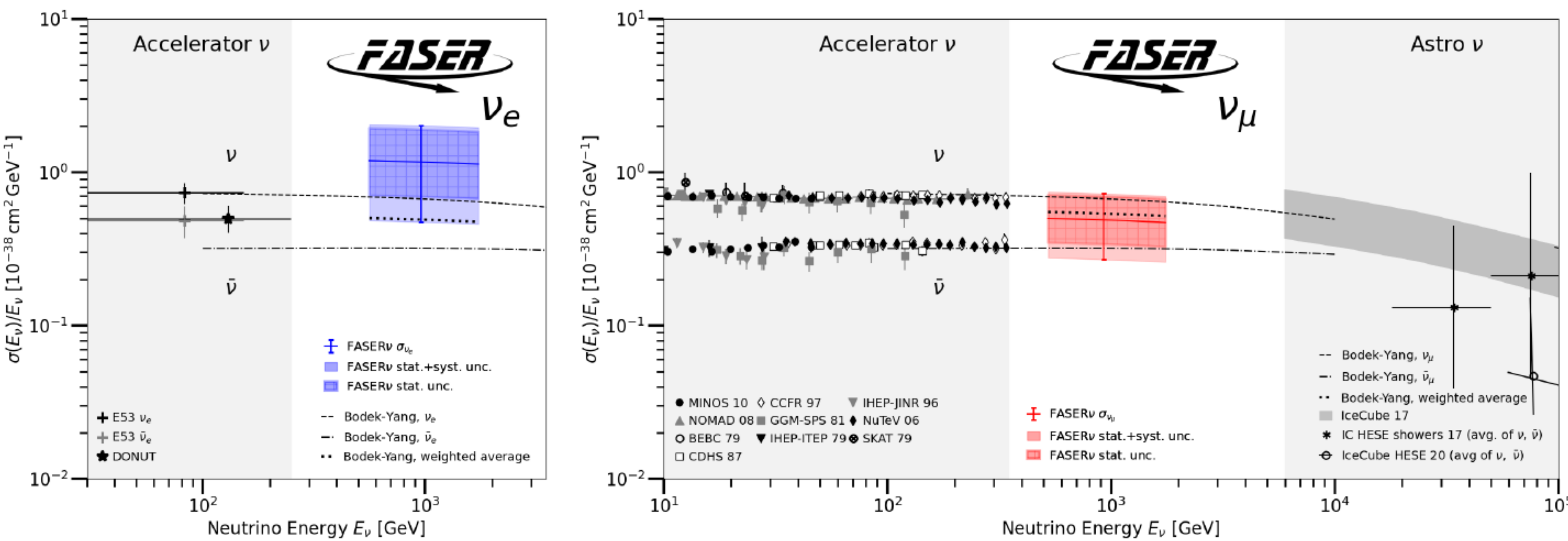
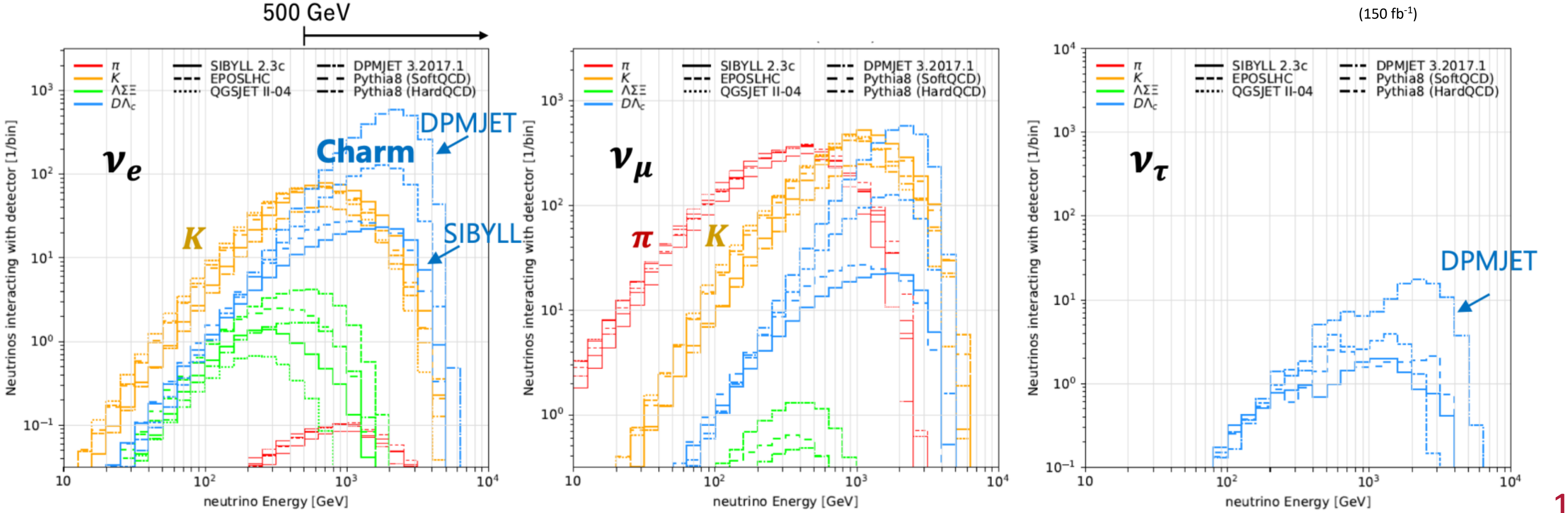


Figure 13: The measured cross section per nucleon for ν_e (left) and ν_μ (right). The dashed contours labelled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, as implemented in GENIE.

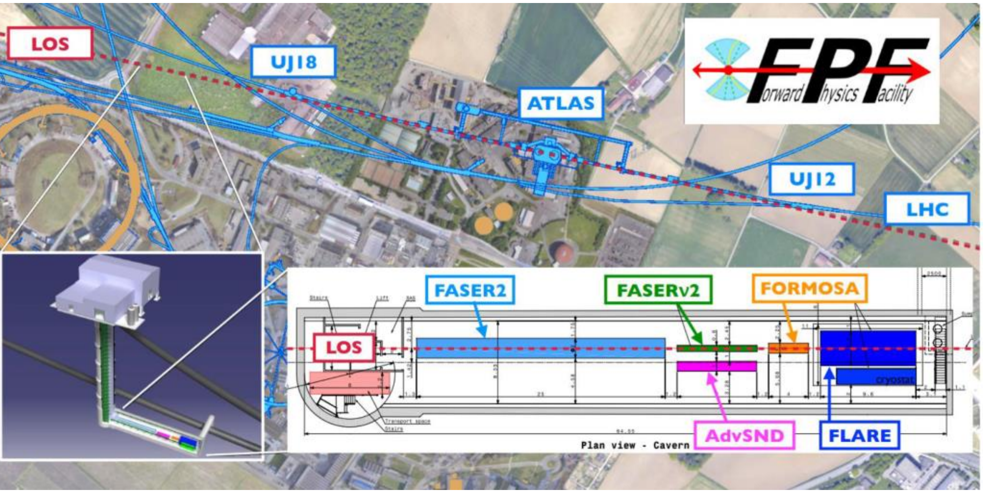
Prospect

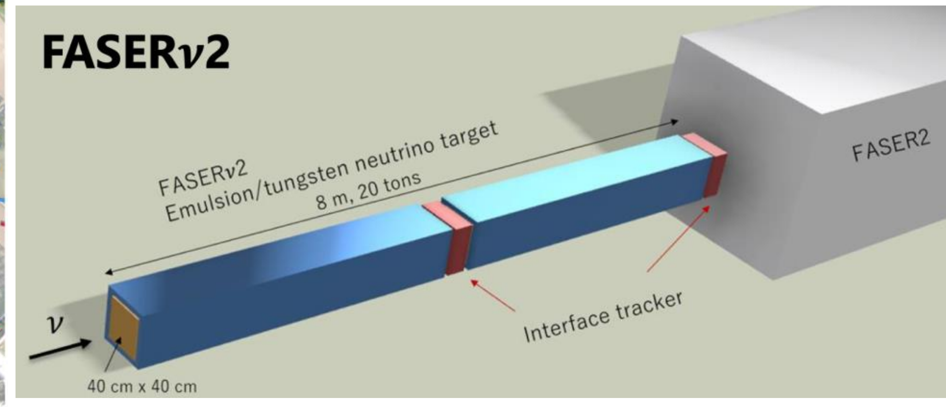
- Here ne and nm cross section were reported using 1.7 % of accumulated data so far.
- We will collect data at the end of LHC-RUN3 (up to 2025)
- In total about 10,000 CC neutrino interactions will be detected.

- Tau neutrino cross section will be measured.
- All 3 neutrino flavors, Neutrino nucleon interaction cross section will be measured.
  → **Lepton universality check.**
- We can extract information on forward meson production rate (Charm/K/π) at LHC collision point, since the origin of mesons for each neutrino flavor is different.
- Charm production rate in CC interaction by 3 neutrino flavors, → Again, **Lepton universality check**



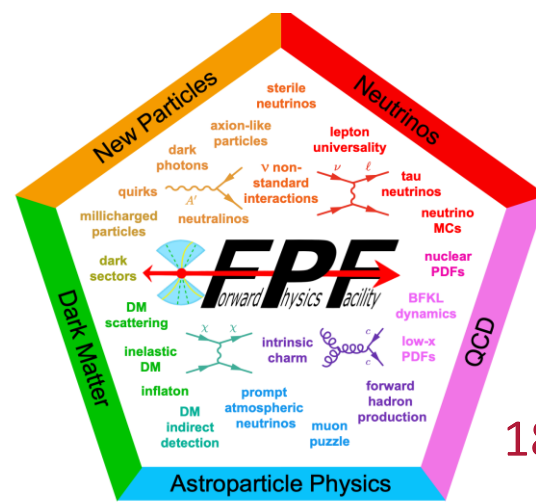
After RUN3 : Forward Physics Facility





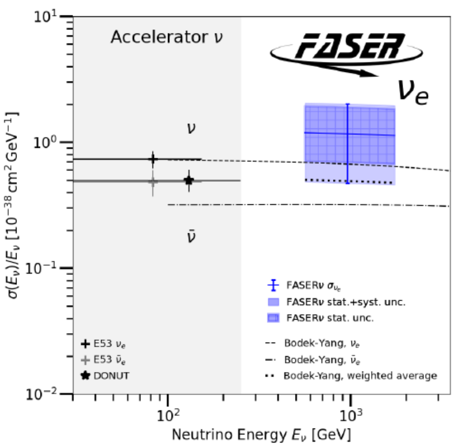
- FASERν2 as part of the proposed **Forward Physics Facility (FPF) at HL-LHC** arXiv::2203.05090
  - target mass: 20 tons
- Studying possibility of installing a dedicated sweeper magnet to reduce muon background
  - Emulsion detector replacement: Once per a year
- Expected tau neutrino interactions:
  ~2300 (SIBYLL) / ~20000 (DPMJET)
- Many interesting QCD topics as well as neutrino and BSM physics

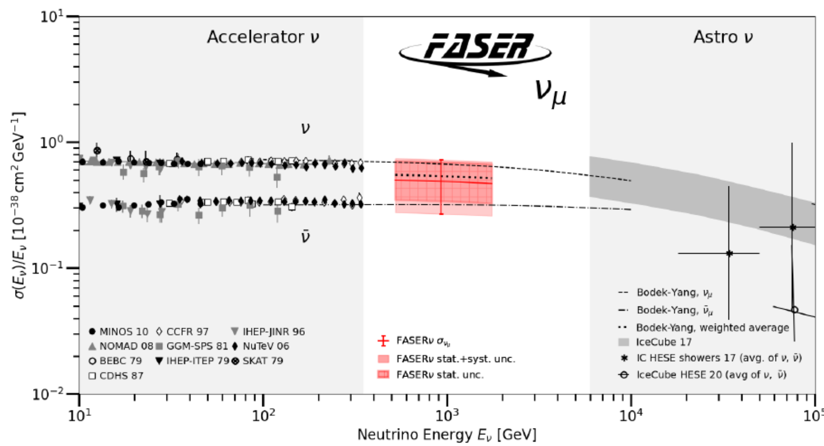
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754



Summary

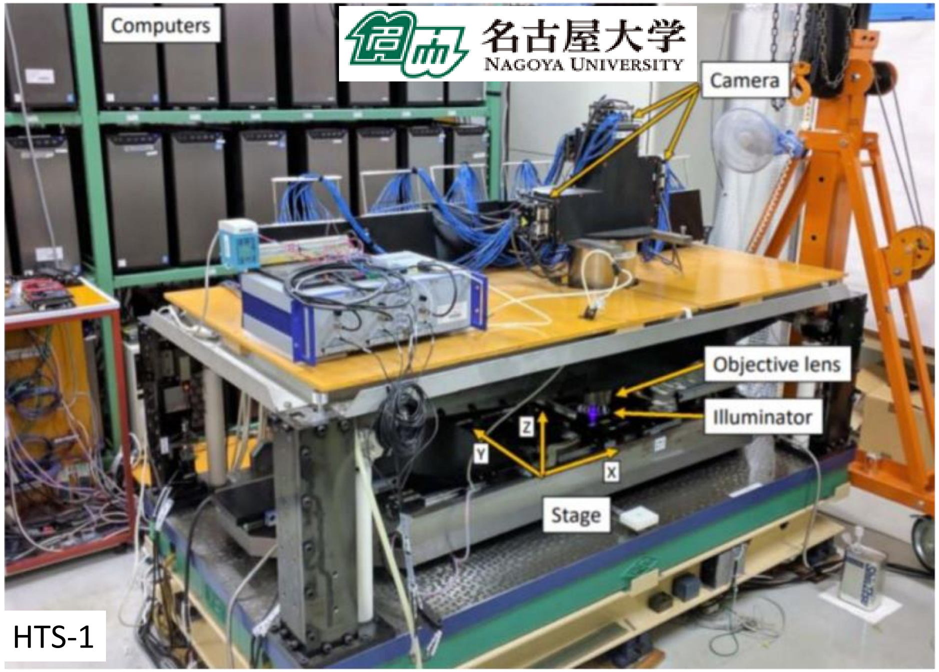
- FASERν is a project to analyze high energy **neutrinos coming from LHC collision products**.
- Study neutrino interactions at the **unexplored energy region by each neutrino species**.
- FASERν studies three flavor neutrinos at the high energy frontier
  - ~10,000ν interactions expected in LHC Run 3 (2022-2025, 250 fb^{-1})
- Observed 153 ν_μ CC interactions with FASER (signal significance of 16σ)
  - First direct observation of collider neutrinos
- **First measurement of neutrino-nucleon cross section at TeV energy region !**
  - **8 νμ CC candidates in ECC →** $\sigma(\nu_\mu + N)/E = 0.5 \pm 0.2 \times 10^{-38}\ cm^2/GeV$
  - **4 νe CC candidates in ECC →** $\sigma(\nu_e + N)/E = 1.2^{-0.8}_{-0.7} \times 10^{-38}\ cm^2/GeV$
  - Tau neutrino observation and cross section measurement will come soon.
  - **All 3 neutrino flavors cross section will be reported by same detector , FASERν !**

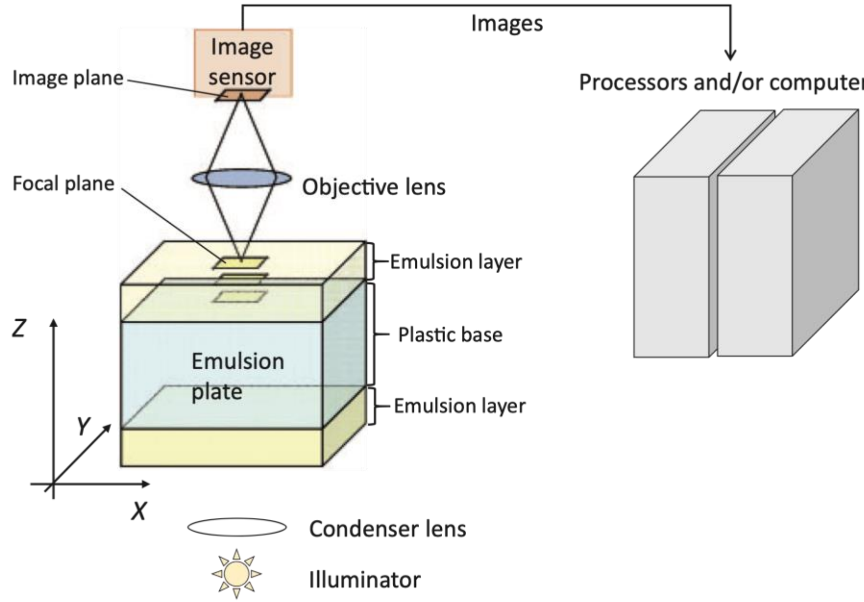




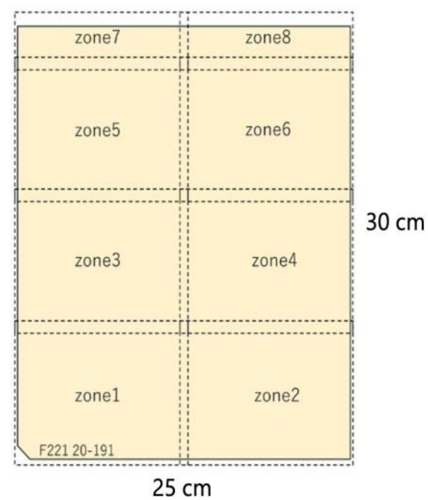
BACK UP

High speed Readout from films : HTS



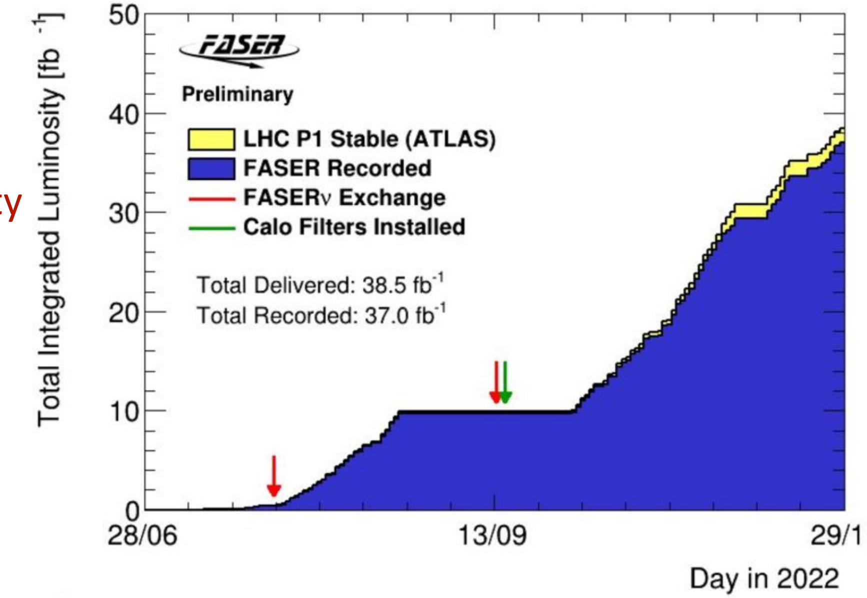


- Transport films to Japan after development
- Readout by Hyper Track Selector-1 (HTS-1)
  - Field of view: 5.1 mm × 5.1 mm
  - 60-80 minutes per a film(25 x 30 cm^2)

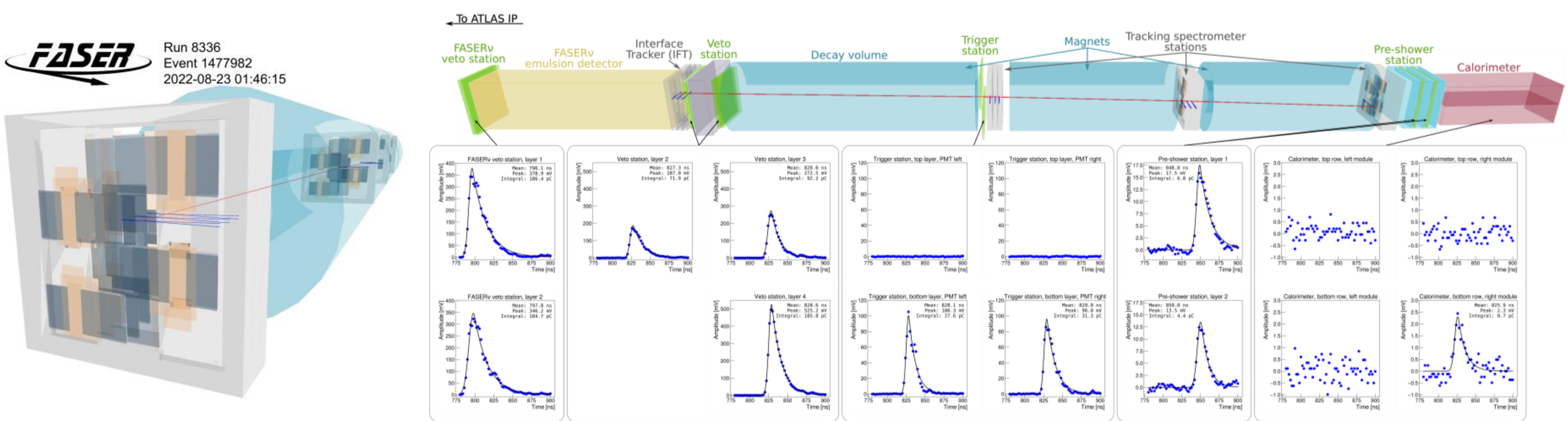


FASER Operations

- Successfully operated throughout 2022
    - FASER recorded 96% of delivered luminosity
- FASER operating very well in 2023 data taking with >30fb-1 of data recorded so far



Muon leaving track passing through full detector

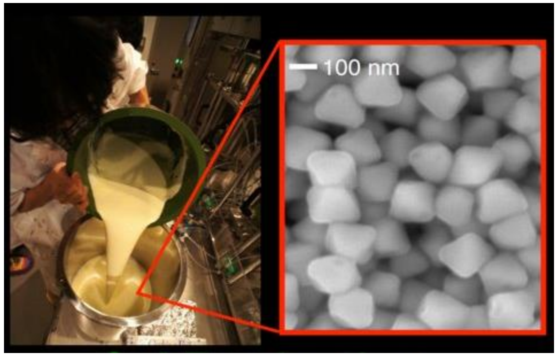


consistent with MIP

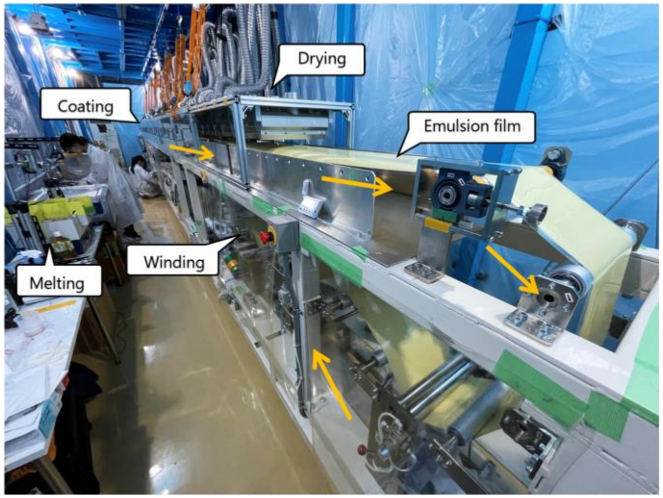
Film Production

名古屋大学
NAGOYA UNIVERSITY

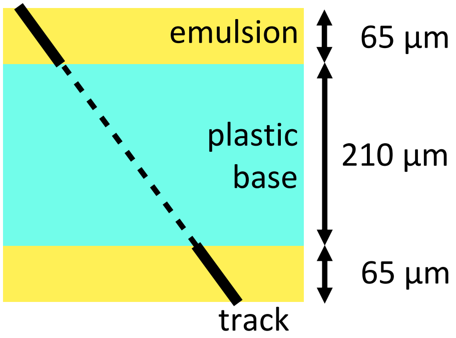
Nuclear Emulsion Gel production



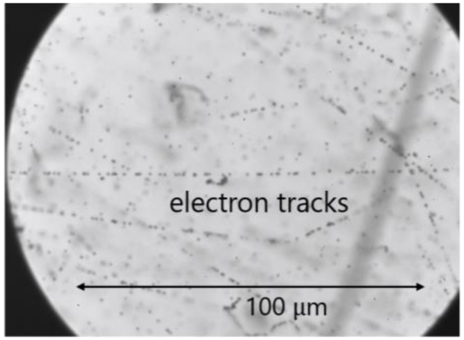
Nuclear Emulsion film coating system



Double sided emulsion coating



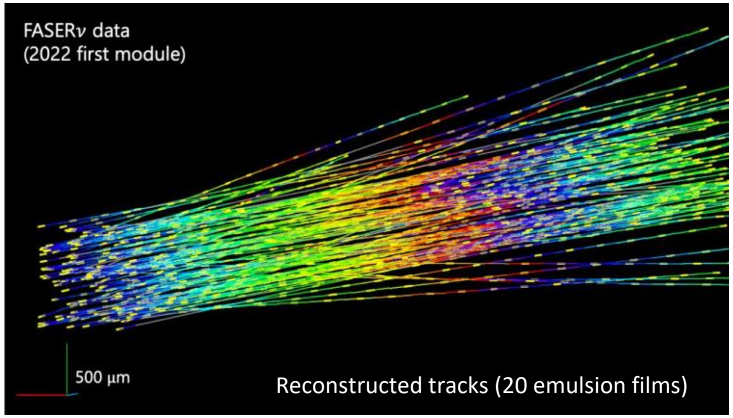
Microscopic view

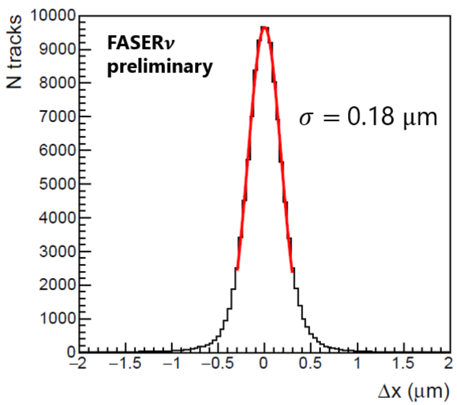


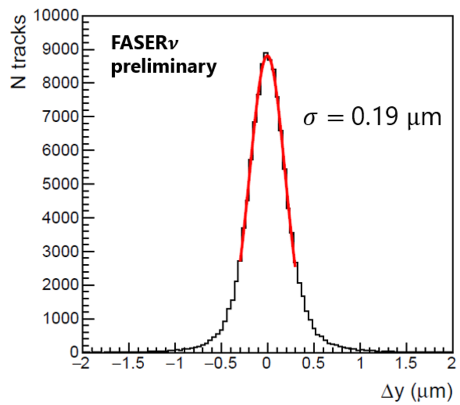
- 200 nm diameter silver halide crystals dispersed in gelatin
- Very good spatial and angular resolution
  → Needed for short lived particle detection , tau , charms ..
- Produced gel and film at Nagoya University
- Total area of 730 films: ~55 m^2 per replacement

FASERν Performances

- Dataset: most downstream 10 emulsion films of the 1st FASERν module
  - From March to July 2022, integrated luminosity: 0.5 fb^{-1}



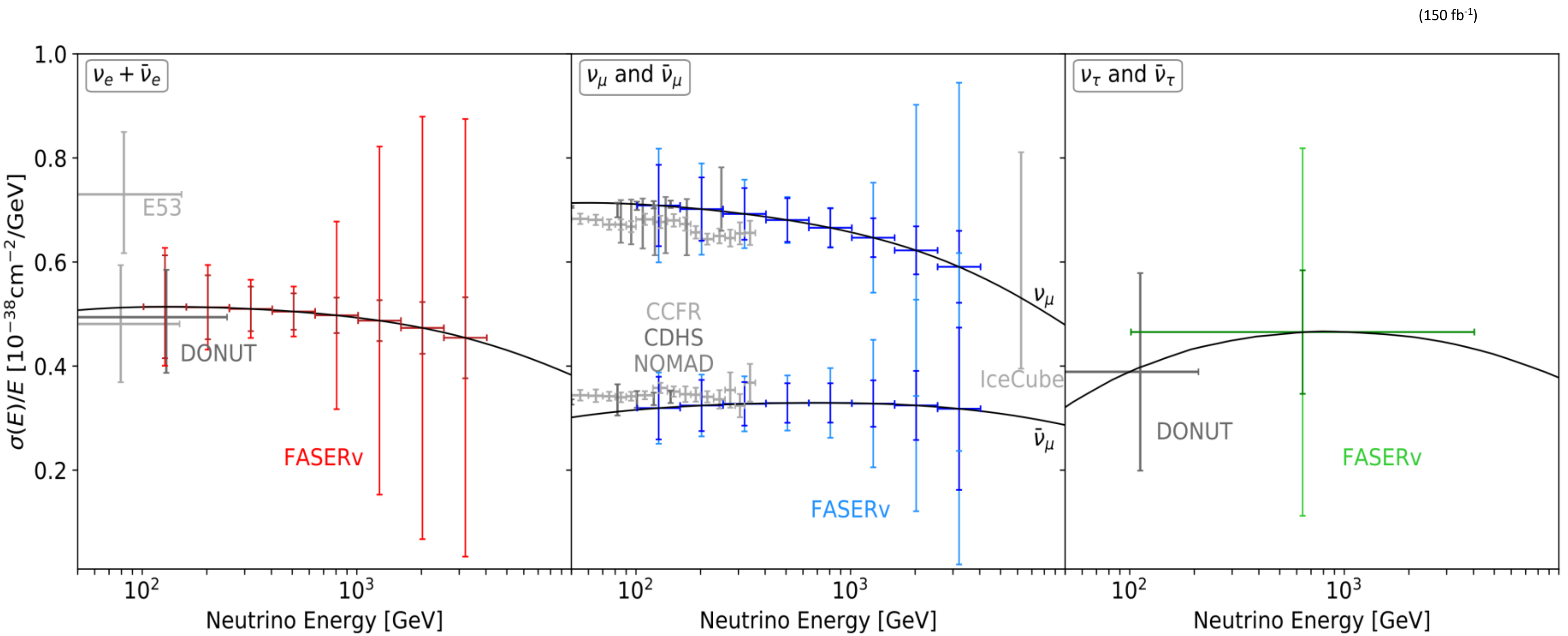




Position deviation between hits and the straight-line fits to the reconstructed tracks

- Observed ~0.2 μm position accuracy with dedicated alignment
  → use for high momentum muon tracks

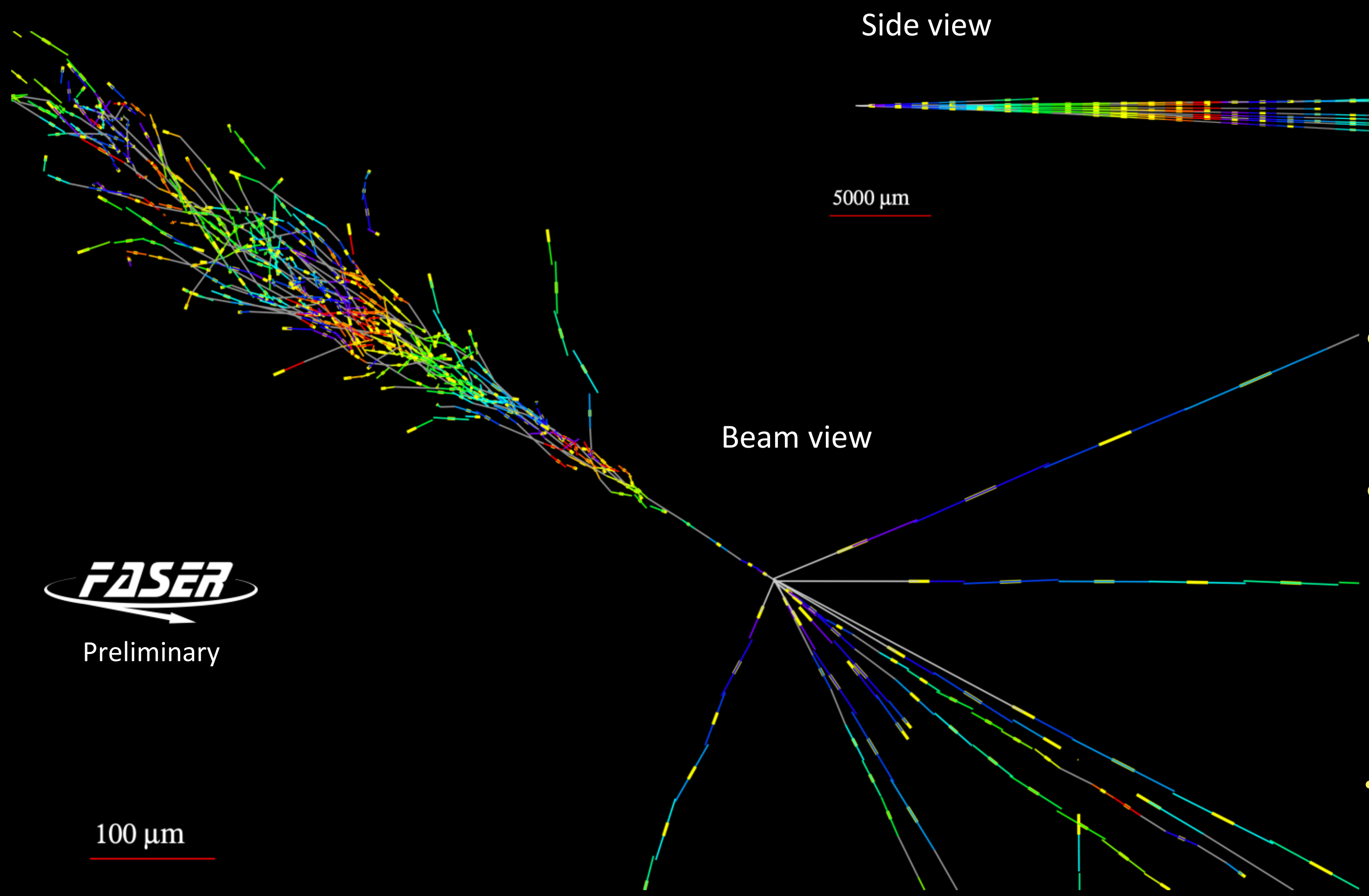
FASERν Cross-Section Sensitivity



(inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate)

- Three flavors neutrino cross-section measurements for unexplored energy ranges
- Neutrino energy reconstruction with resolution of 30% expected from simulation studies

Observation of ν_e Candidate with FASERν ECC

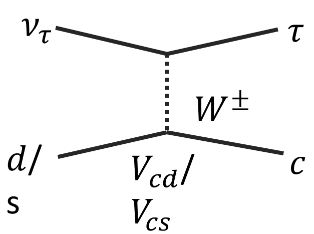


- Vertex with 11 tracks
  - 615 µm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max at $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

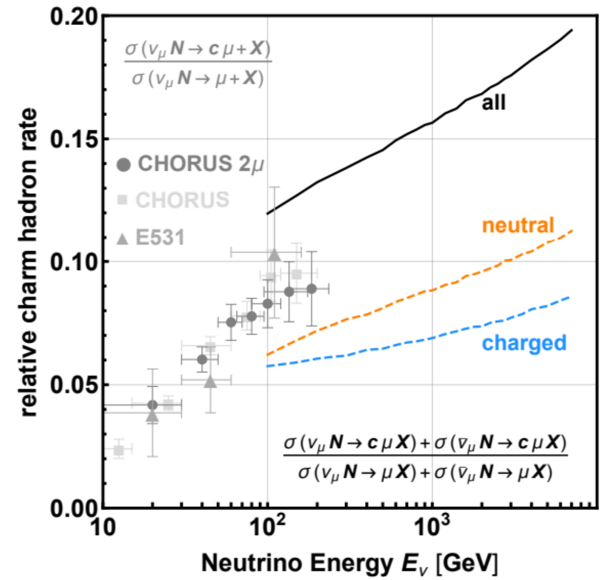
Physics studies in the LHC Run 3 (2):

Heavy-flavor-associated channels

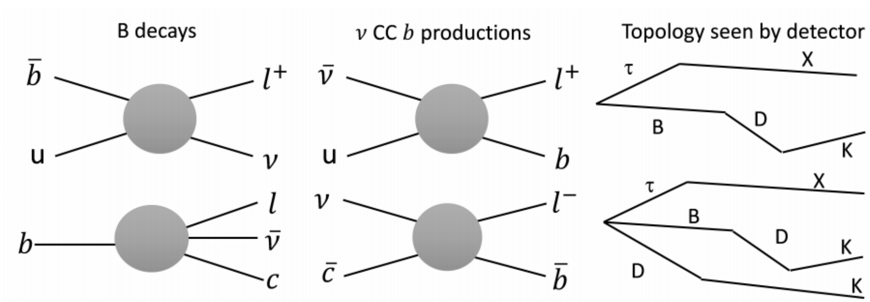
- Measure charm production channels
  - Large rate ~ 15% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.



$$\frac{\sigma(\nu_\ell N \to \ell X_c + X)}{\sigma(\nu_\ell N \to \ell + X)} \quad \ell = e, \mu, \tau$$



- Search for Beauty production channels
  - Expected SM events (ν_μ CC b production) are $\mathcal{O}(0.1)$ events due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$



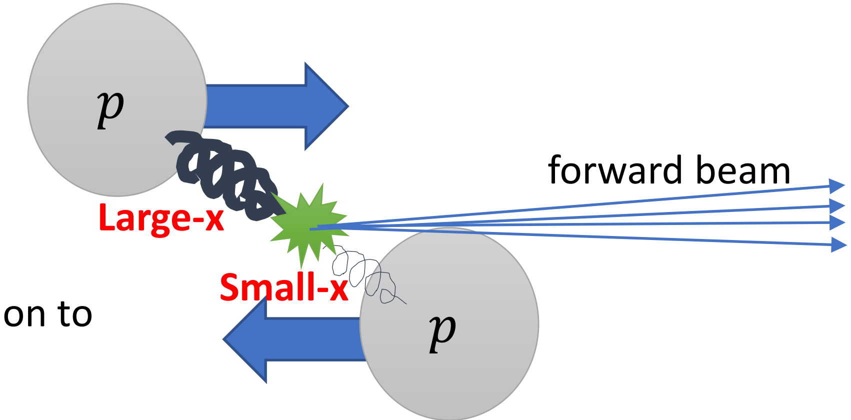
$\bar{\nu}N \to \ell\bar{B}X$

$\nu N \to \ell BDX$

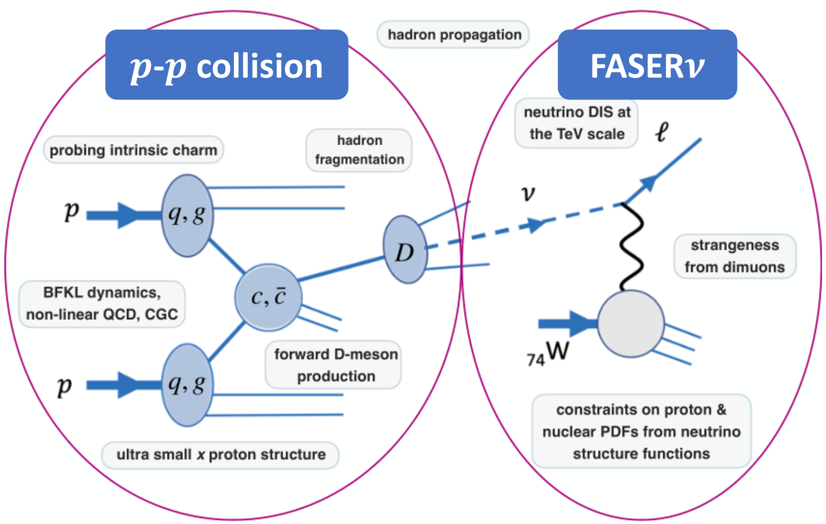
Eur. Phys. J. C (2020) **80**: 61

Physics studies in the LHC Run 3 (3):

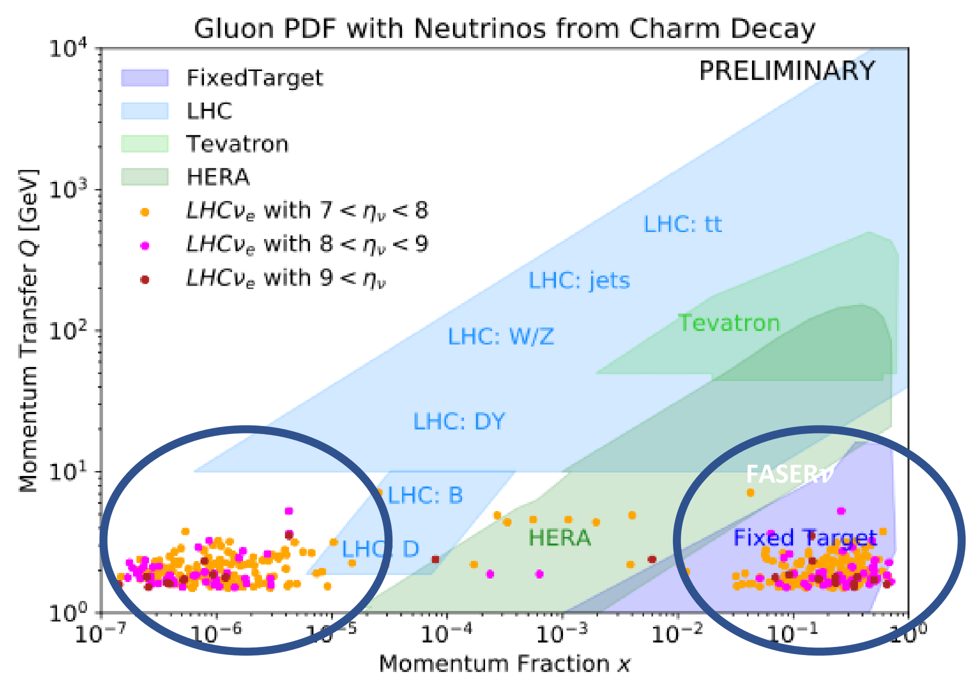
Further insights on QCD



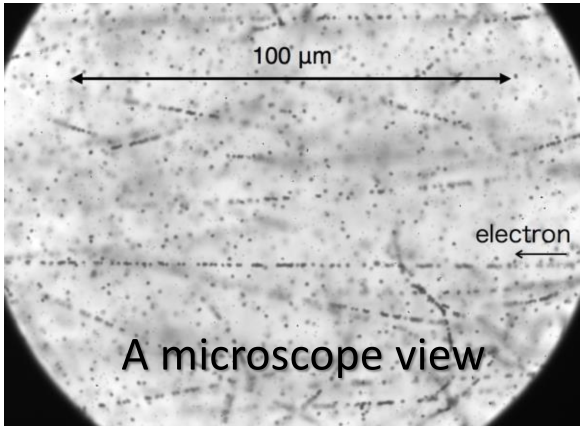
- Asymmetric gluon-gluon interaction, **small-x × large-x**
- **Neutrinos from charm decay** could allow to test transition to small-x factorization, probe intrinsic charm
- Deep understanding of neutrinos from charm decays (**prompt neutrinos)** is important for astrophysical neutrino observations



2203.05090



Status of pre-analysis



1. Feasibility test

Background track density acceptable for emulsion detector ?

Concern: Emulsion accumulate all charged particle tracks before its chemical -development.
More than $10^6/cm^2$ make emulsion detector analysis difficult.
Is track density in situ acceptable for analyzing neutrino interaction by emulsion detector ?

2. Pilot neutrino detector run in 2018

Demonstrating neutrino interaction detection at realistic background track density.
FASER detector was not yet ready .
→ Test with small size **Emulsion detector alone**.

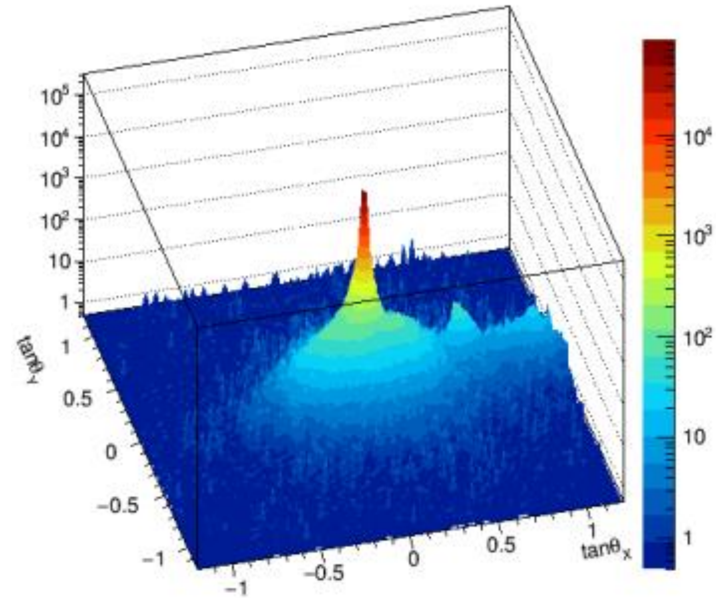
1. Feasibility test
back ground track flux at the site

- *In-situ* measurements in 2018

No problem with emulsion analysis

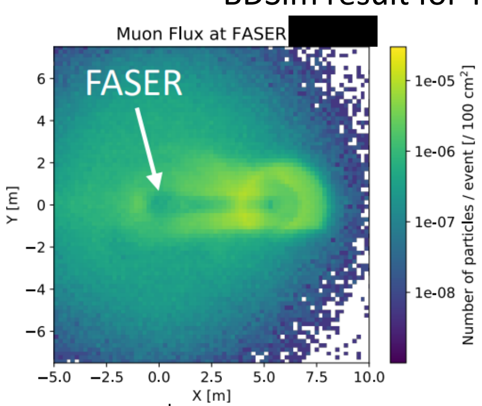
	Flux in main peak [fb/cm^2]
TI18 data	$1.7 \pm 0.1 \times 10^4$
TI12 data	$1.9 \pm 0.2 \times 10^4$
FLUKA MC	2.5×10^4

(uncertainty 50%)

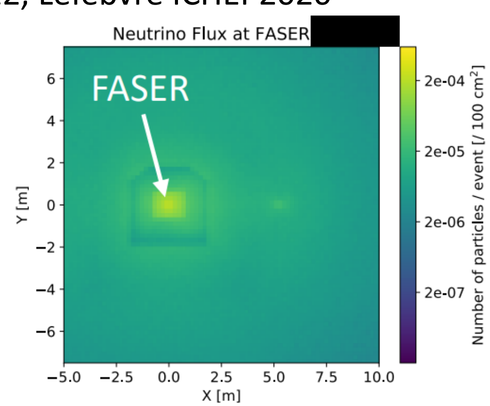


Observed angular distribution of background tracks

BDSim result for TI12, Lefebvre ICHEP2020

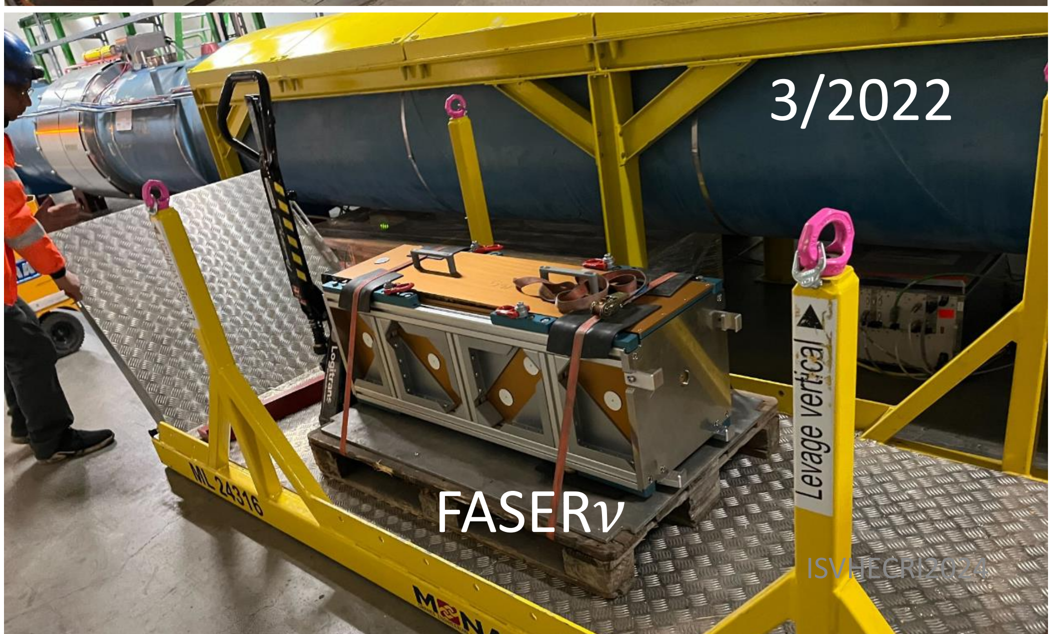


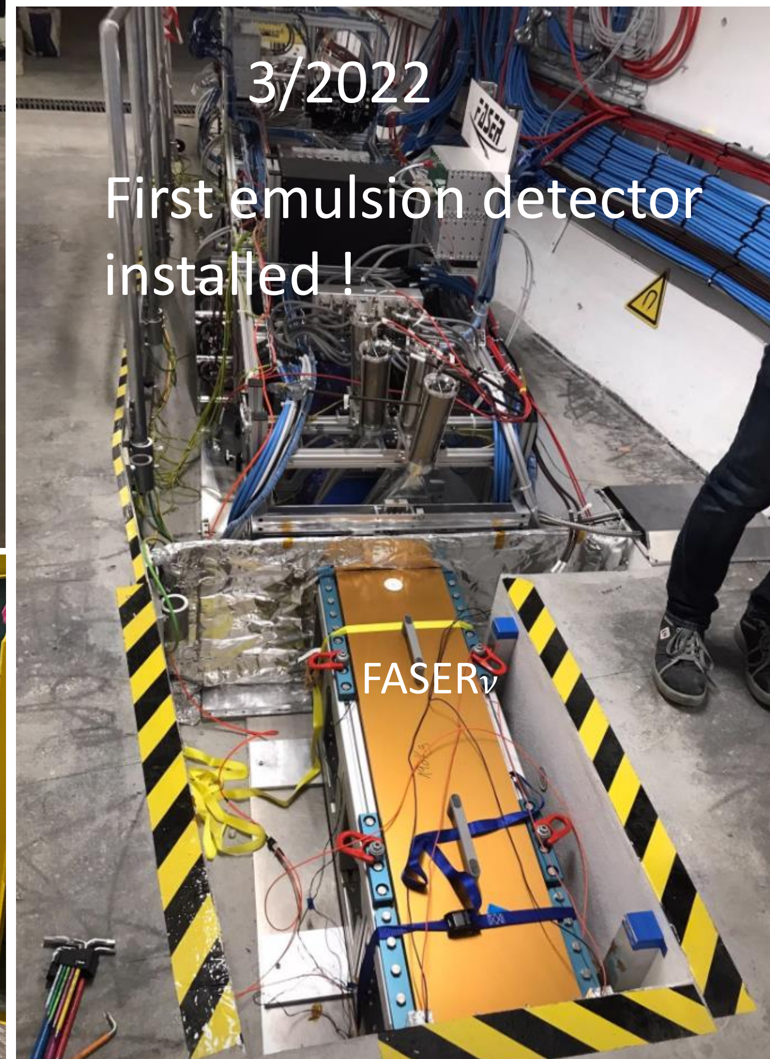
$\mu^\pm$



ν

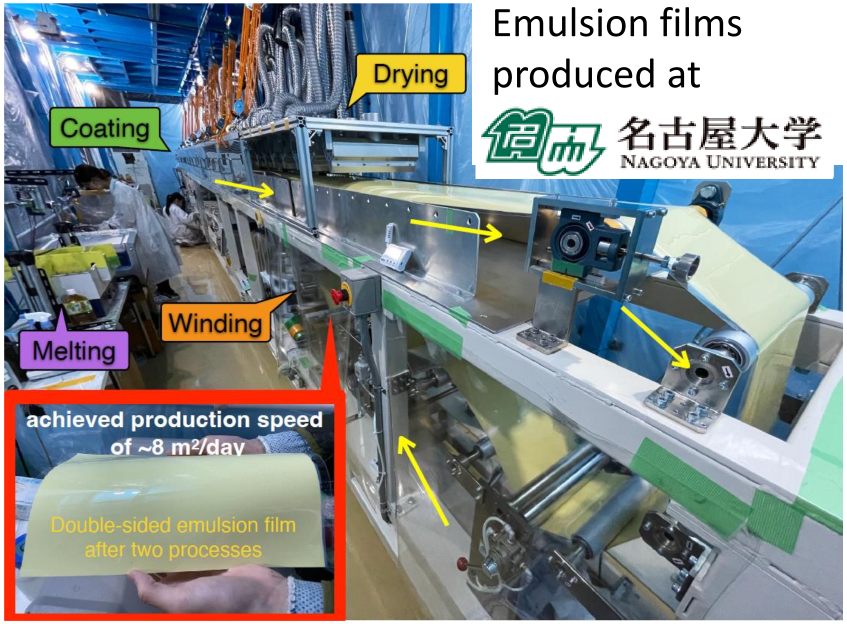
Preparation for Run 3 at site



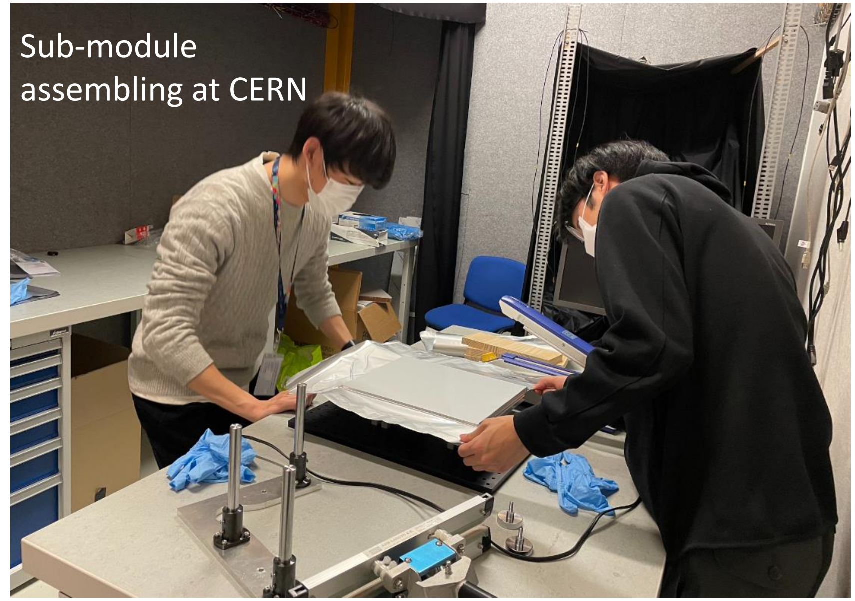


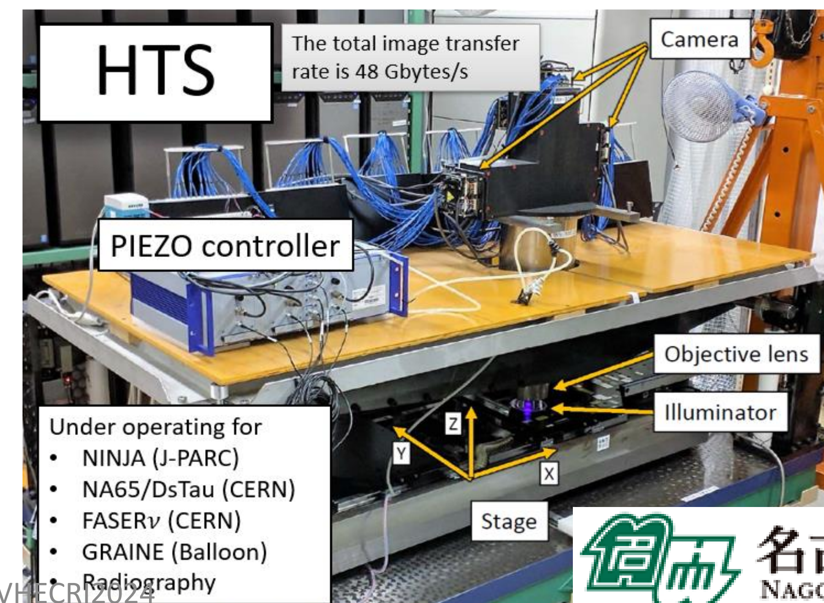
ν

Preparation for Run 3: FASERν detector



Emulsion films produced at 名古屋大学 NAGOYA UNIVERSITY

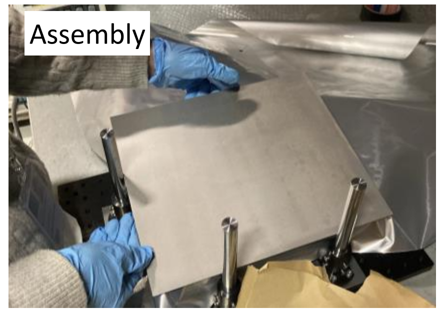


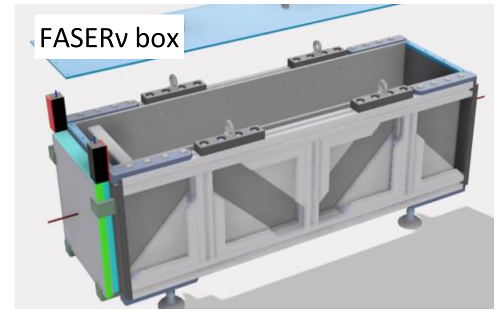


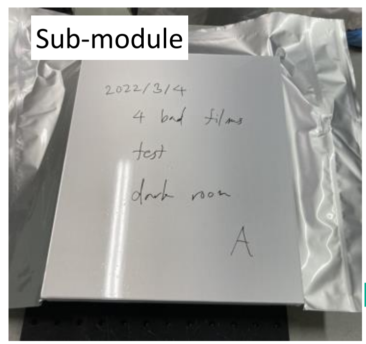
名古屋大学 NAGOYA UNIVERSITY

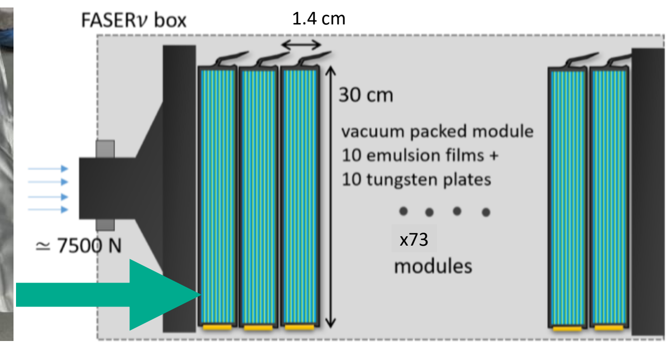
Module Assembly

33



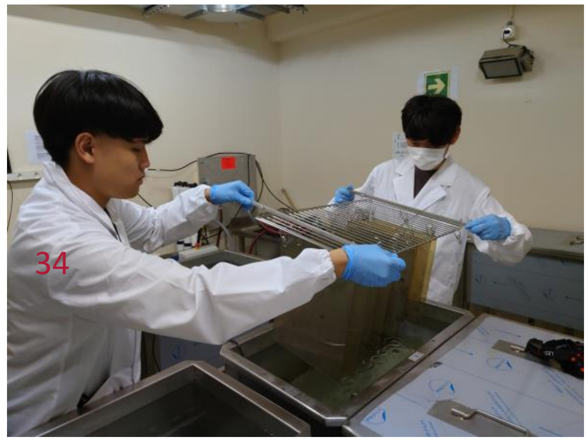


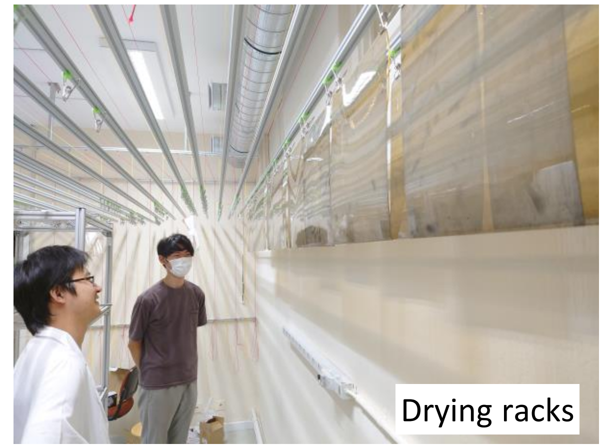




- Sub-module: vacuum-packed 10 films + 10 tungsten plates
- ~14 days to complete 73 packs
- Apply external force (equivalent to 1 bar) to the sub-modules in the FASERν box

Film Development

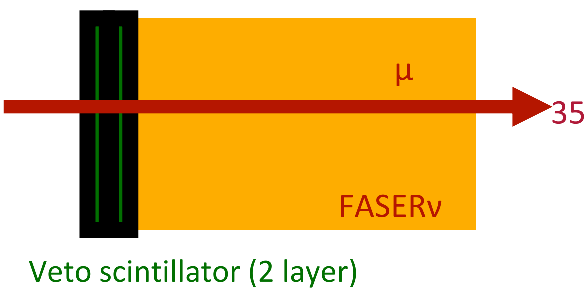




- Installed new development chains and drying racks at the renovated CERN darkroom facility
  - Sharing the facility with other emulsion experiments: NA65/DsTau, SND@LHC, etc
- 10-12 days to complete 730 films

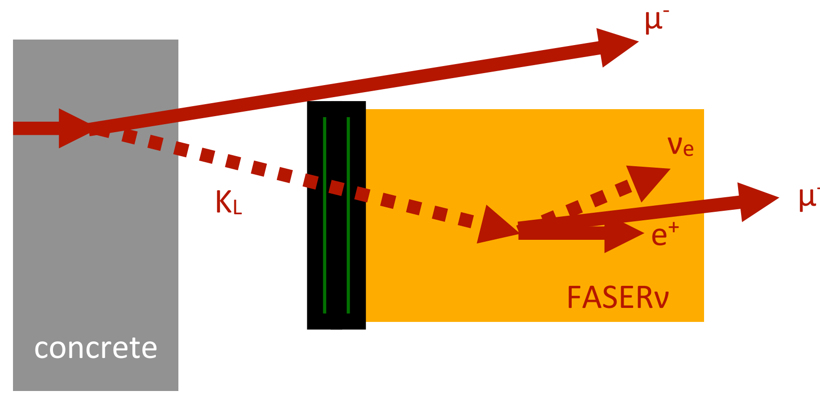
Background Estimation (1)

Veto inefficiency



- Estimated from events with just one veto scintillator firing
- Negligible background expected due to very high veto efficiency

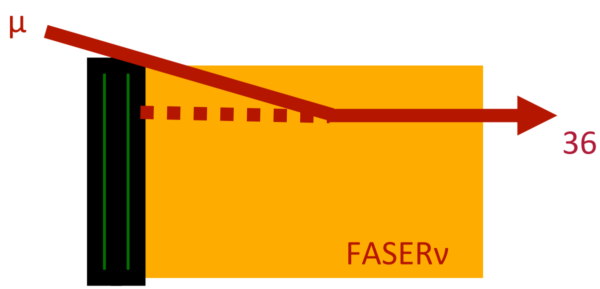
Neutral hadrons

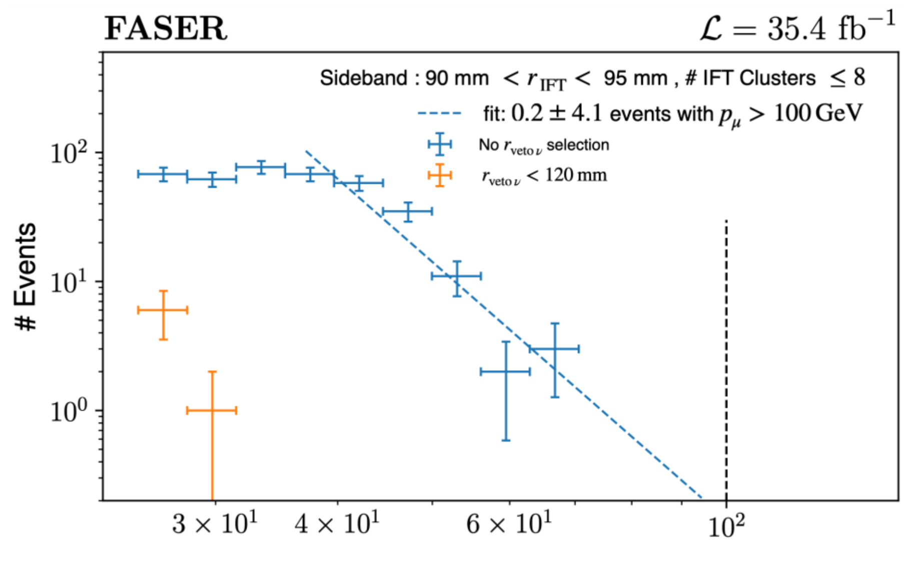


- Expect ~300 neutral hadrons with E>100 GeV
- Most are absorbed in tungsten
- Estimated from 2-step MC simulations
- Estimate 0.11±0.06 events

Background Estimation (2)

Scattered muons (geometric BG)





- Estimated from sideband

  -Fit to extrapolate to higher momentum

- Calculate scaling factor using MC simulations to extrapolate to signal region
- Estimate 0.08±1.83 events (uncertainty from varying selection)

FASER

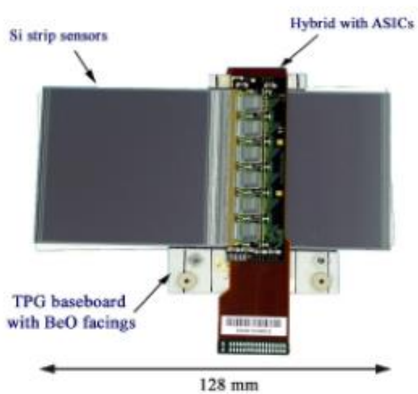
FASER INSTITUTIONS

77 collaborators, 21 institutions, 9 countries

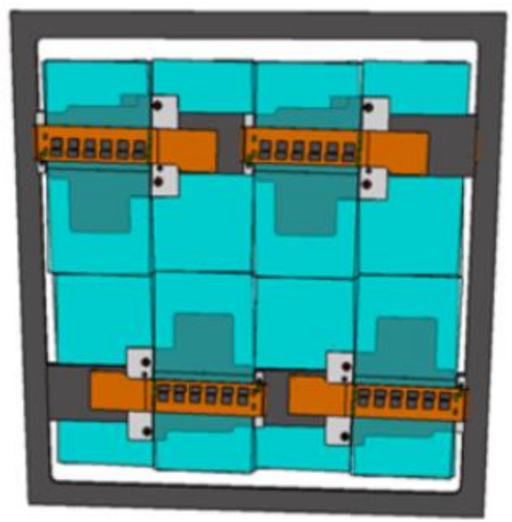
CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大學 Tsinghua University
SLAC NATIONAL ACCELERATOR LABORATORY
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
US UNIVERSITY OF SUSSEX
JINR

Tracking device of FASER

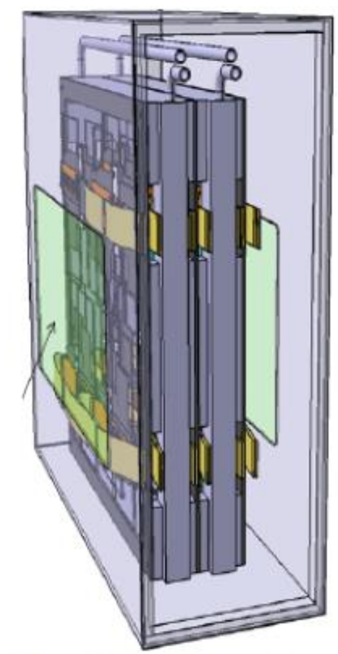
- Thee tracking station and a interface tracker to FASERnu.
- Each containing 3 layers of double sided silicon micro-strip detectors
- Spare ATLAS SCT modules, 80um strip pitch, 40mrad stereo angle.
- SCT modules a 24cm x 24cm tracking layers by 8 SCT modules.



SCT module



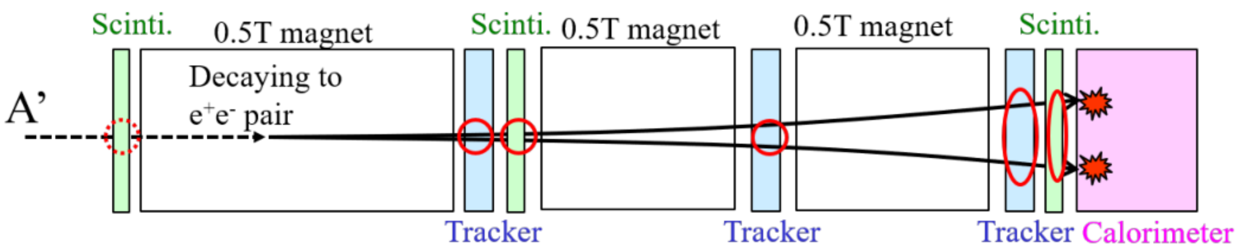
Tracking layer



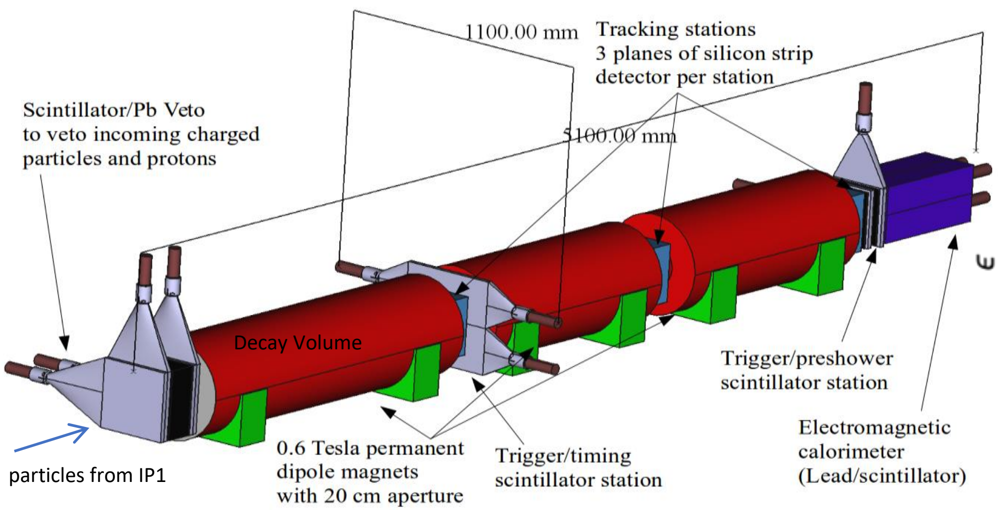
Tracking station

FASER detector & sensitivity

- Dark photon: Photon in dark sector, and it has mass
- Signal: Dark photon decay into e^+e^- pair



Detector schematic (original one without FASERnu)



Sensitivity for dark photon search in Run 3