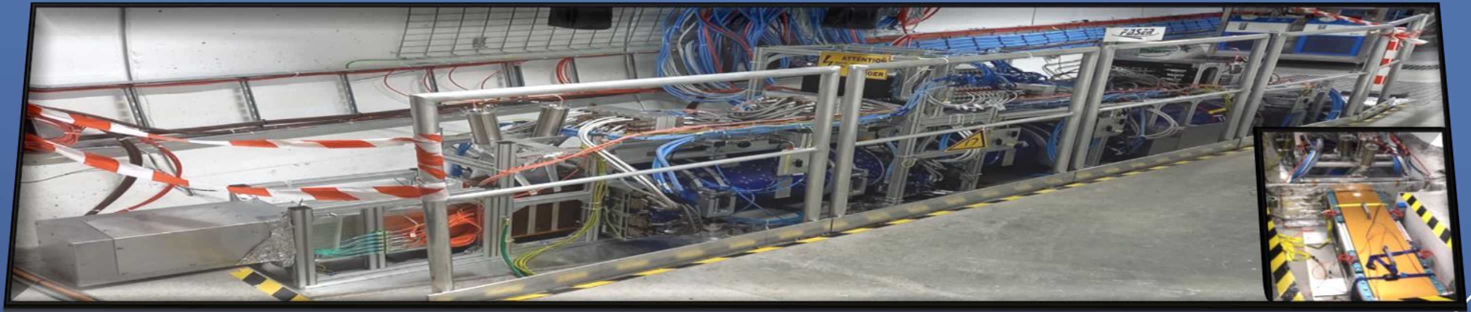
FASER

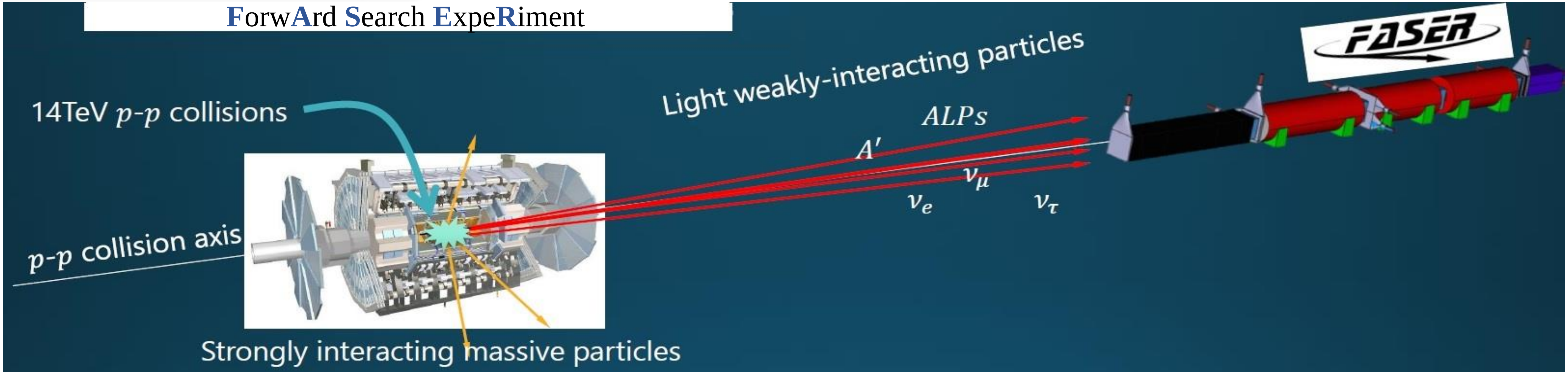


# Recent results from the FASER experiment at the LHC

*Elena FIRU*
*Institute of Space Science - subsidiary of INFLPR*
*on behalf of the FASER collaboration*

CERN
HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION
ISS
NSF
erc
Swiss National Science Foundation
科研費 KAKENHI

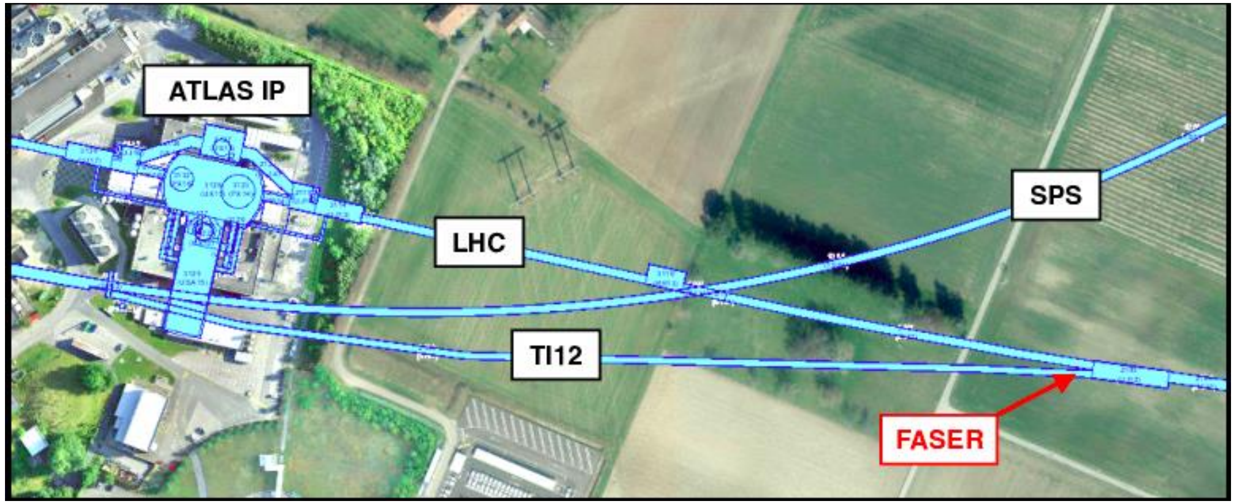
# FASER physics goals



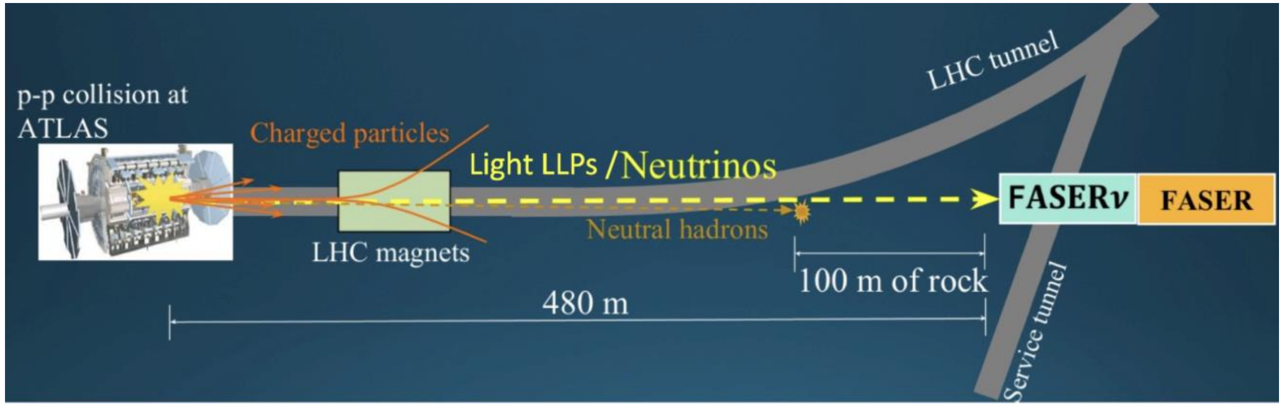

- **Experiment designed to search for:**
  - light, weakly interacting particles produced in the far-forward region of proton-proton collisions at the ATLAS interaction point (IP):
  - long-lived BSM particles (dark photons (A’), axion-like-particles (ALPs))
  - 3-flavor neutrinos in unexplored TeV energies

# FASER experiment

- **ForwArd Search ExpeRiment** - faser.web.cern.ch
  - relatively new experiment at the LHC
  - small detector designed to search for new physics in the very forward region
  - complementary to existing LHC experiments
  - built between 2019 and 2021
  - 101 members, 27 institutes, 11 countries




- **Located 480 m from ATLAS** p-p interaction point
  - aligned with ATLAS collision axis line-of-sight (LOS)
  - $\simeq$ 7 m length, 20 cm aperture (magnets)
  - FASER$\nu$ has a transverse size of 25 x 30 cm$^2$
  - shielded by 100 m of rock



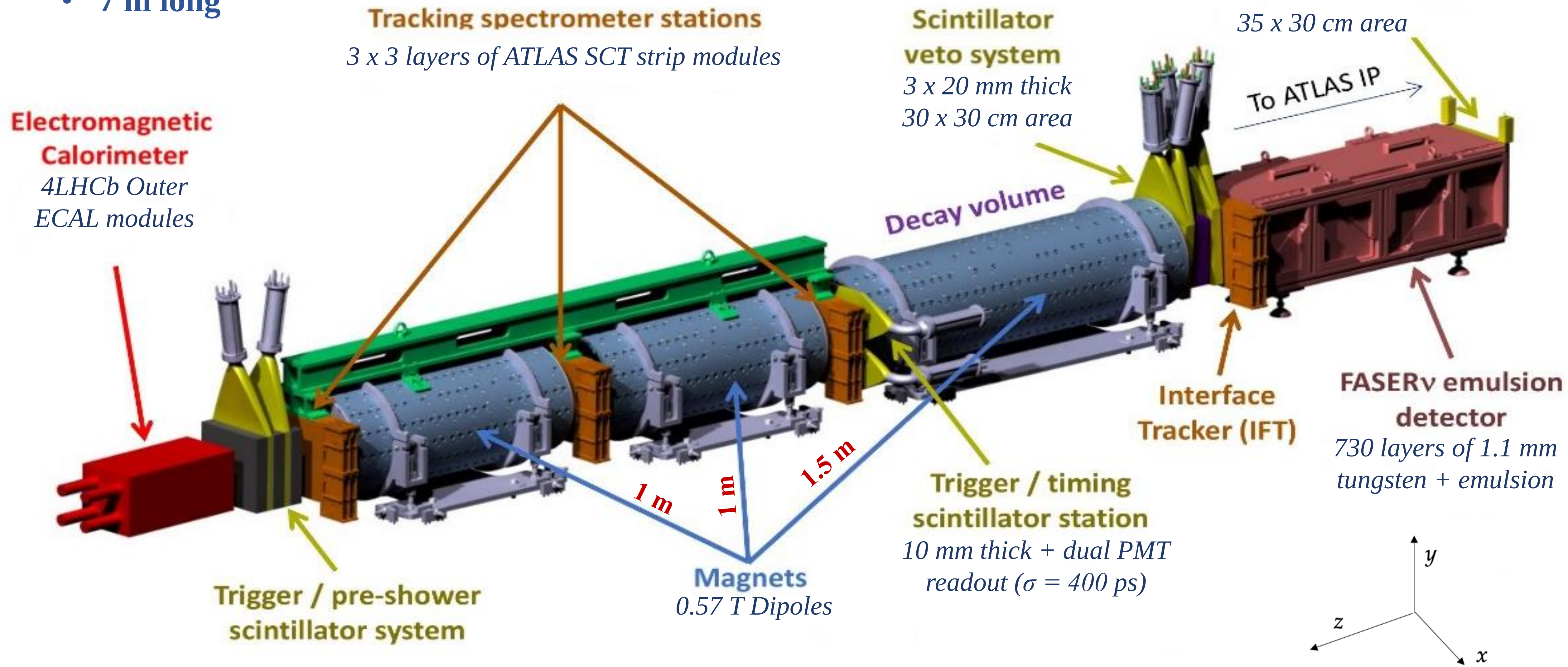

- **Physics data taking** since LHC Run 3 start

# FASER experiment

# FASER detector

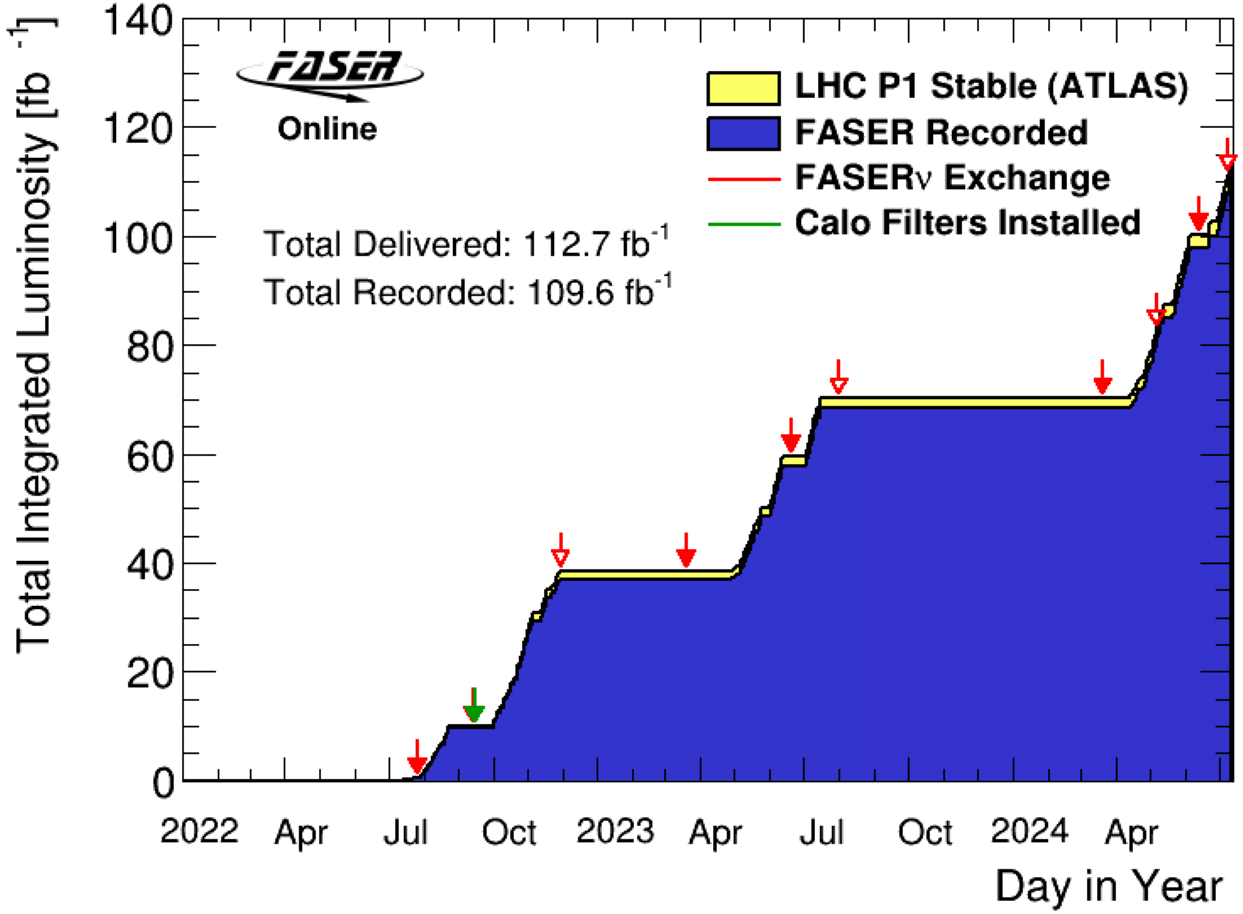
[JINST 19 (2024) P05066]

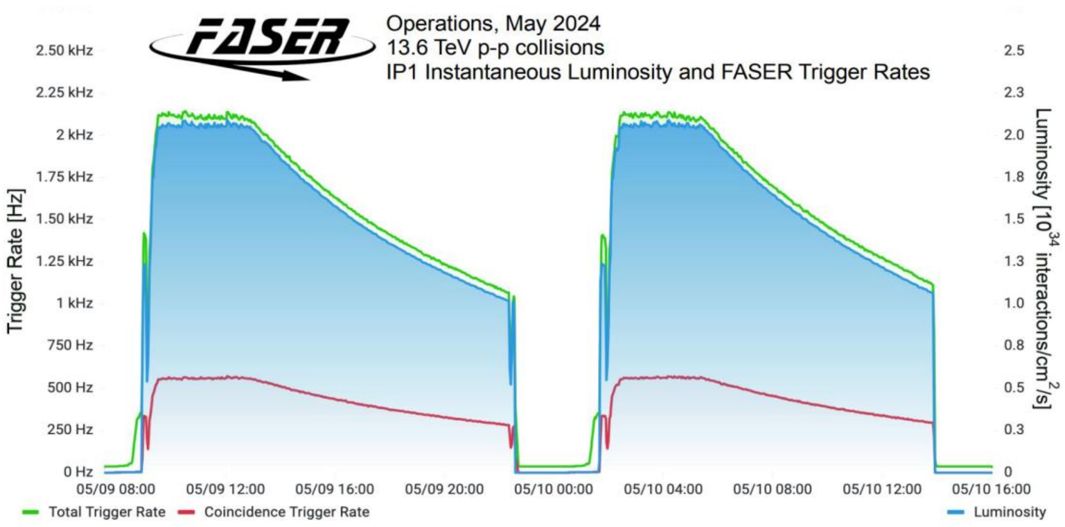
- **Small inexpensive detector**
  - **10 cm radius of active volume**
  - **7 m long**



# FASER data taking

- Start of data taking in July 2022
- Integrated luminosity collected:
  - 35 $fb^{-1}$ in 2022
  - 33 $fb^{-1}$ in 2023
  - so far 803 $fb^{-1}$ in 2024
- Exchanges of FASERν emulsion boxes 6 times so far (every 15 $fb^{-1}$ to keep occupancy at manageable level)
- Excellent detector performance
- Recorded 97.4% of delivered luminosity:
  - limited by deadtime (<3%)
  - luminosity information provided by ATLAS




- 2022: 3 FASERν modules
- 2023: 2 FASERν modules
- 2024: 3 FASERν modules

# FASER experiment latest results

FASER Publications

## Publications:

- Neutrino Rate Predictions for FASER - Phys. Rev. D 110, 012009
- First Measurement of the $\nu_e$ and $\nu_\mu$ Interaction Cross Sections at the LHC with FASER's Emulsion Detector - Phys. Rev. Lett. 133, 021802
- Search for Dark Photons with the FASER Detector at the LHC - Physics Letters B, Volume 848, 138378
- First Direct Observation of Collider Neutrinos with FASER at the LHC - Phys. Rev. Lett. 131, 031801

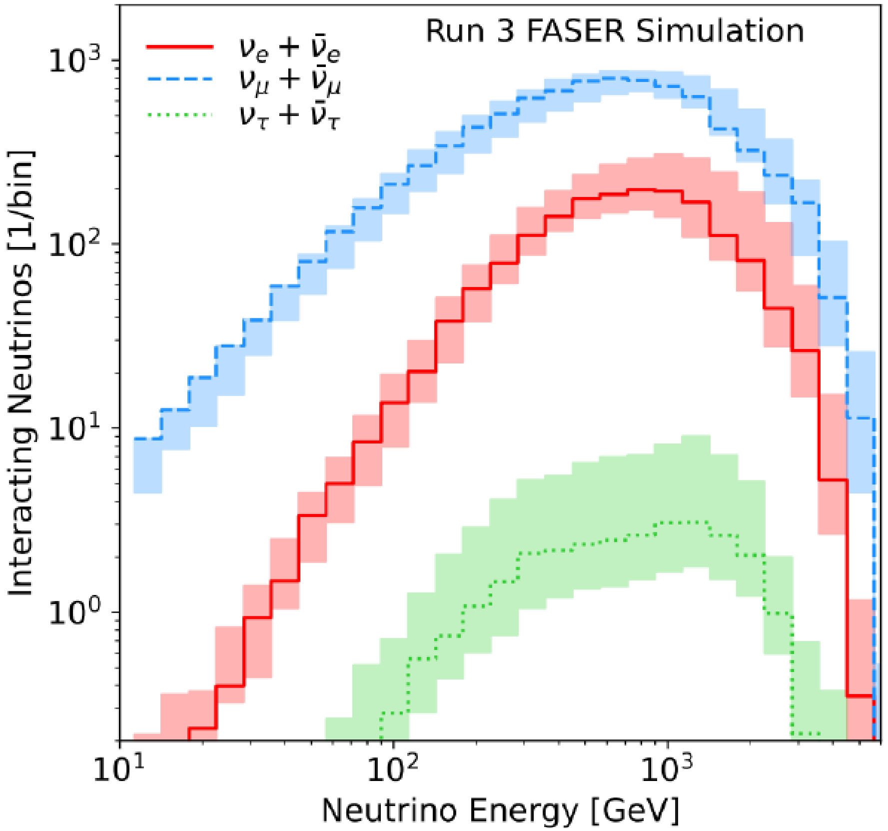
## Preliminary Results:

- Search for Axion-like Particles in Photonic Final States with the FASER Detector at the LHC – CERN-FASER-CONF-2024-001

# Collider neutrinos in FASER

Phys. Rev. D 110, 012009

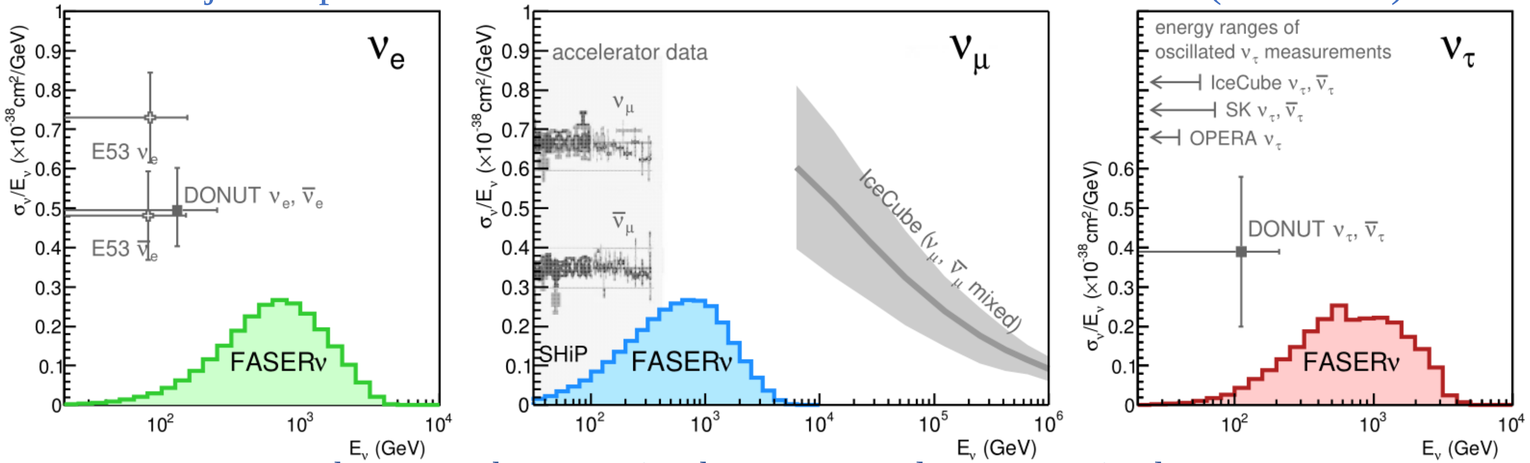
- ***> 10 000 neutrinos** expected to interact in FASER throughout LHC Run3 (2022 – 2025)*
- 3 - flavor cross-section measurement at unexplored TeV energy
- uncertainty on neutrino flux different from neutrinos from light flavor hadrons (~15% uncertainty) and heavy flavor hadrons (up to 100% uncertainty).
- can measure forward charm production
- high statistics allows to study neutrino induced heavy quark (charm) production
- BG for long - live (LLP) searches




The energy spectra of neutrinos in FASERν at LHC Run 3 *(shaded bands are the uncertainties due to the flux and do not include cross section uncertainties)*

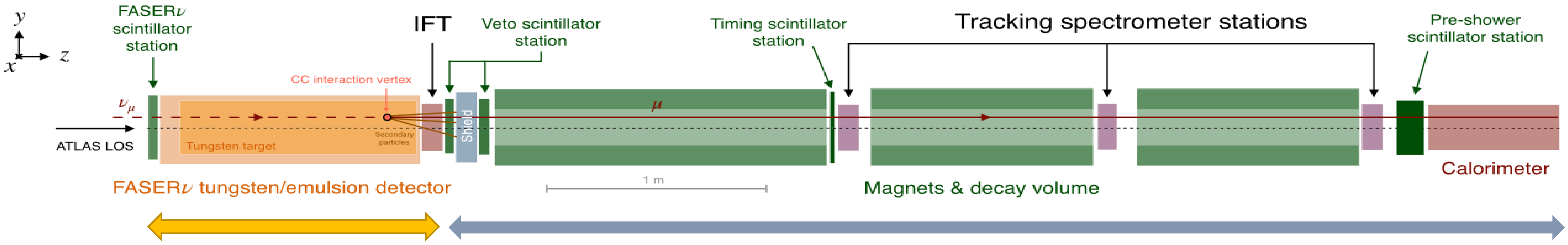
| FASERν at Run 3 | $\nu_e + \bar{\nu}_e$ | $\nu_\mu + \overline{\nu\mu}$ | $\nu_\tau + \bar{\nu}_\tau$ |
|---|---|---|---|
| Dominant production process | kaon/ charm decay | pion/ charm decay | charm decay |
| Expected CC interactions in FASER*ν* (RUN 3) | 1675 | 8507 | 28 |

Projected precision of FASERν measurement at 14-TeV LHC (~150 fb-1)




- have a peak at energies that are currently unconstrained

# Neutrino measurements with FASER




***FASERν emulsion films***

***Electronic components of FASER***

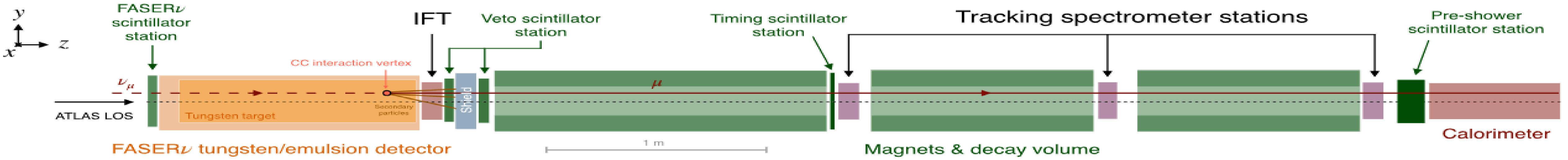
- Emulsion/tungsten neutrino detector
- Sensitive to all neutrino flavors
  - *in particular, tau neutrino is interesting*
- High spatial and angular resolution
- Analysis take time due to scanning and processing of emulsion films

- FASERnu as target (1.1 t) - using electronic components to detect muon from charged current interaction
- Can separate neutrino and anti-neutrino
- Fast analysis of data possible
- Only sensitive to muon neutrinos

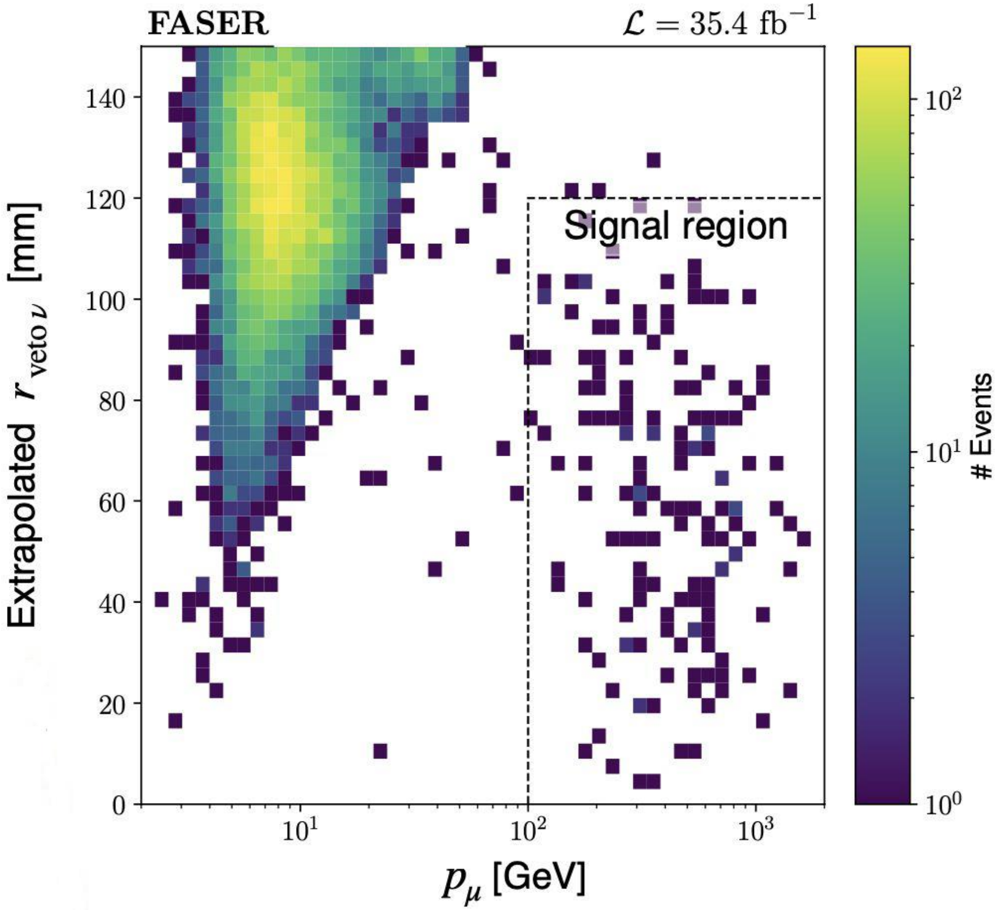
# First direct observation of collider neutrinos

Phys. Rev. Lett. 131, 031801

Schematic side view of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion-tungsten target

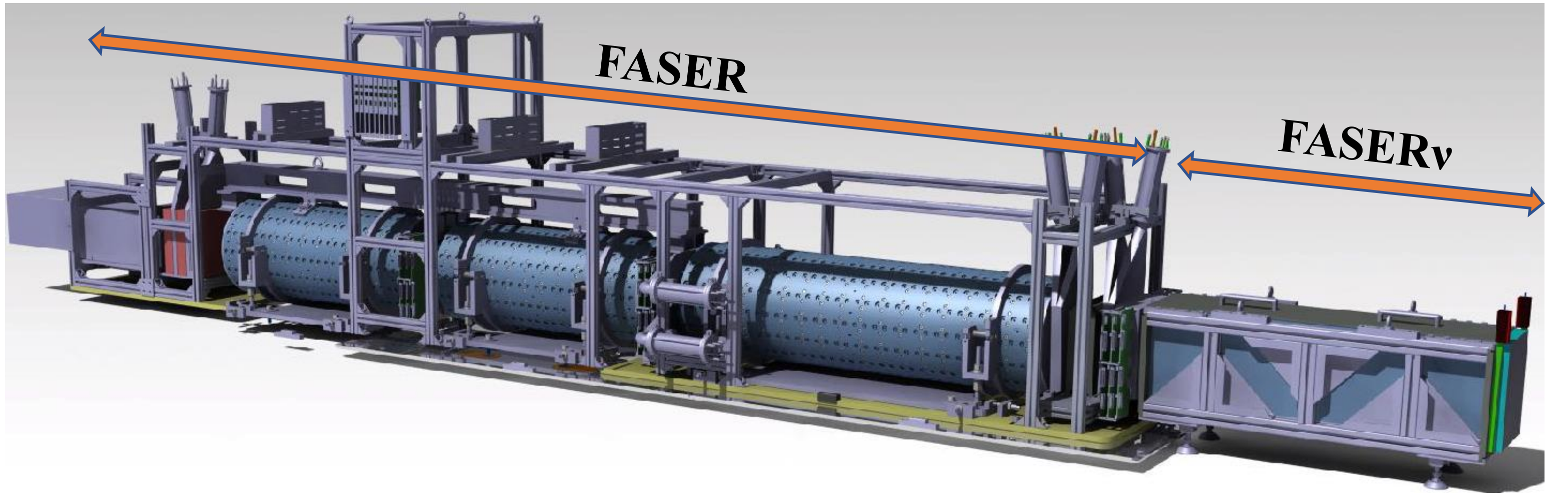


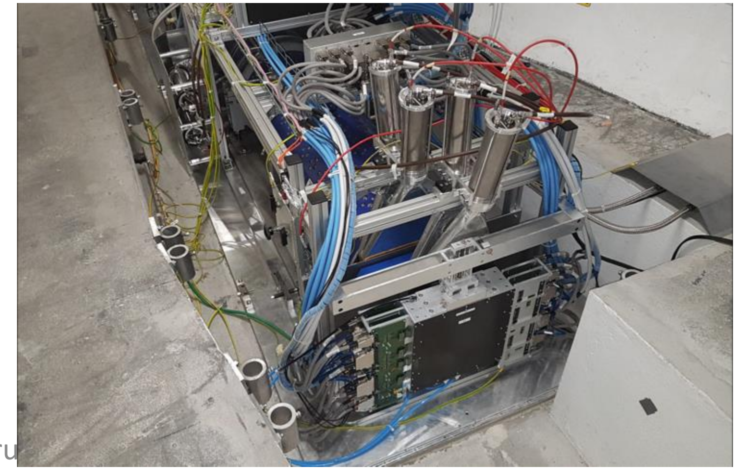

- **Strategy**
  - search for charged current $\nu_\mu$ events through muon appearance
  - use only electronic detector
- **Selection criteria**
  - 1 good track (r < 95 mm)
    - p > 100 GeV
    - θ < 25 mrad
  - front veto not activated
- **Background**
  - neutral hadrons - 0.11±0.06 events from MC
  - large-angle muons - 0.08±1.83 events from data
- **Results**
  - 153 $\nu_\mu$ observed (151 ± 41 events expected)
  - signal significance 16 σ
  - first direct observation of collider neutrinos

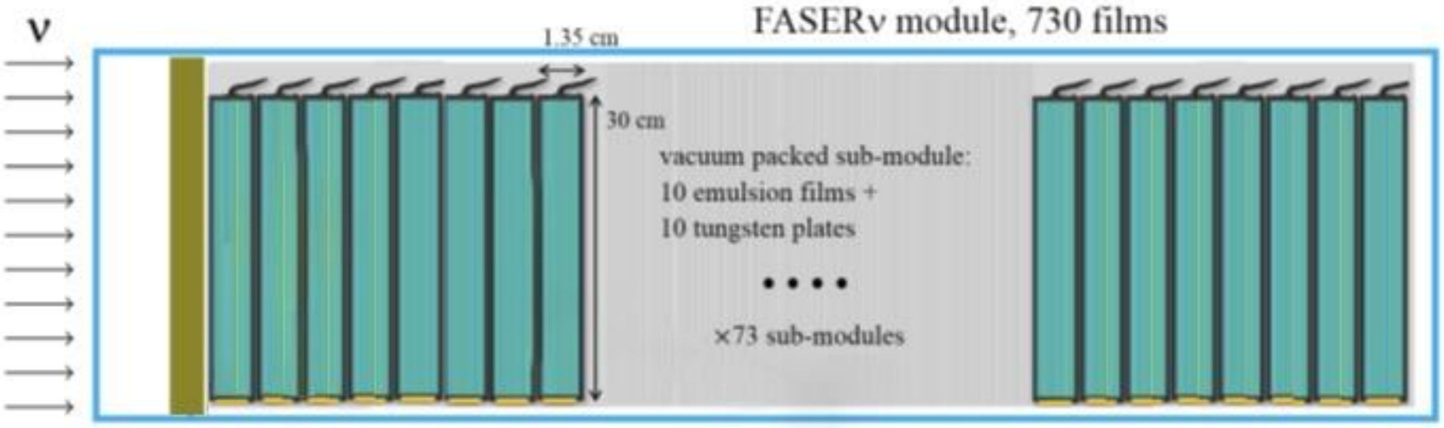


# FASERν emulsion detector

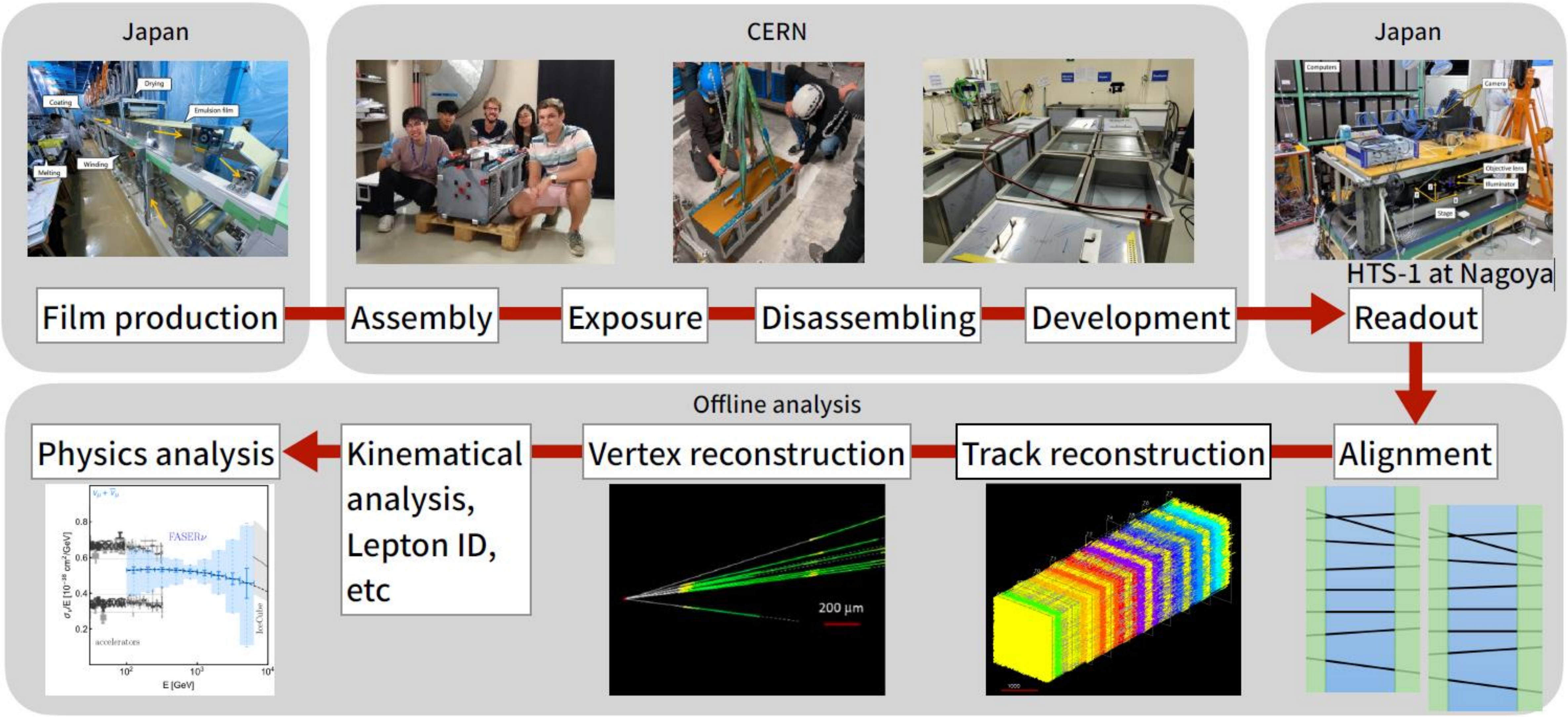
- 730 emulsion films interrelated with 1.1 mm thick tungsten plates
- 25 cm × 30 cm, 1 m long, 1.1 tons ($8\lambda_{int}$, $220X_0$)
- Track resolution in emulsion is 0.3 μm
- 3 detectors per years (install - exchange)





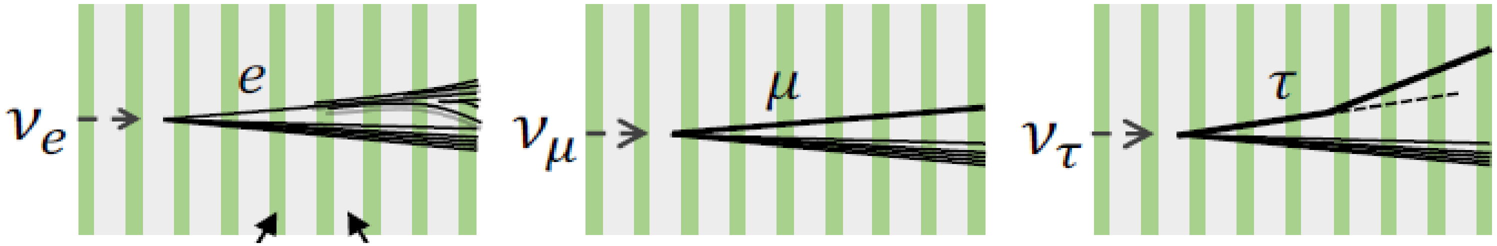
# FASERν emulsion detector

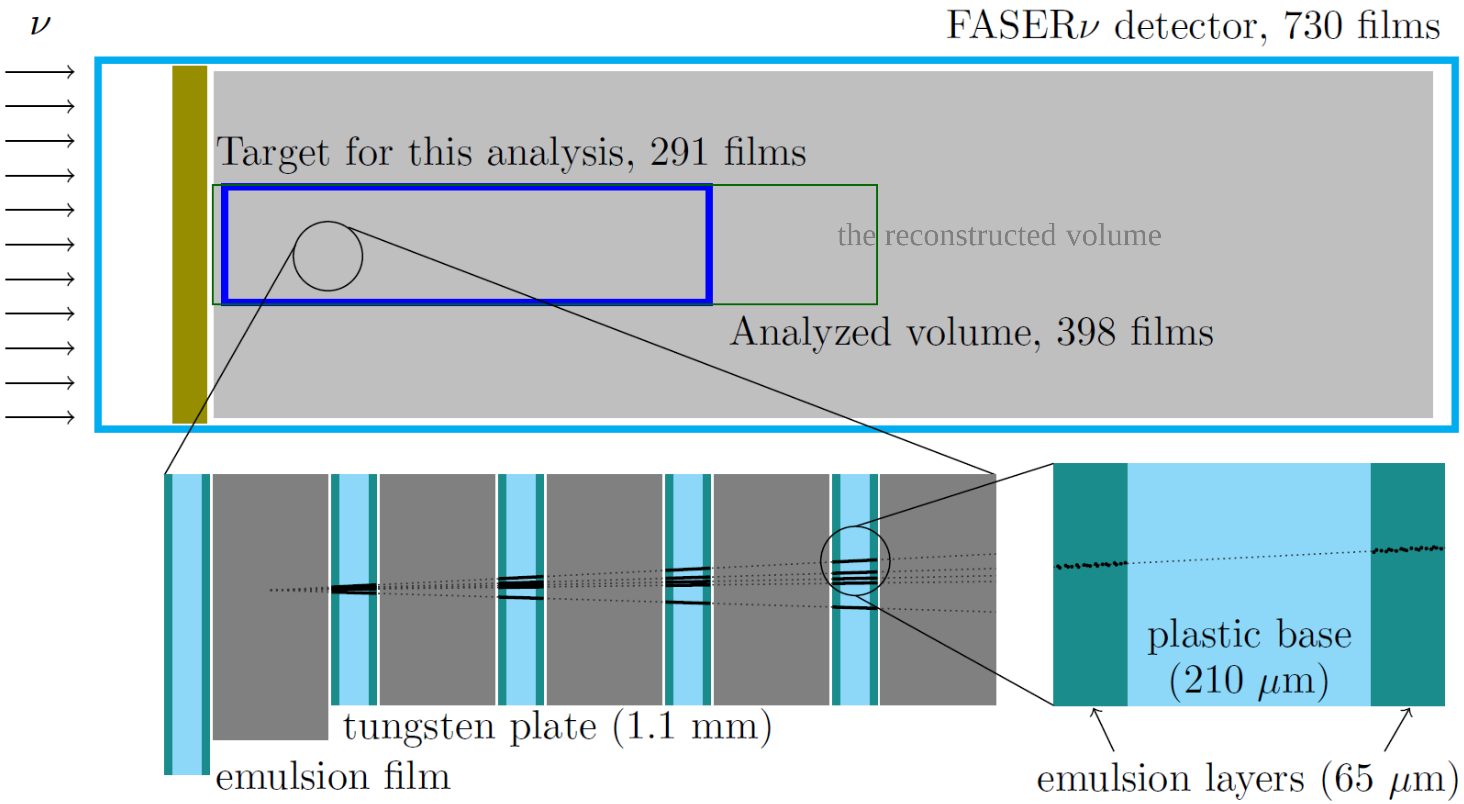


# FASERν data analysis

- **Data set analyzed:**
  - using 2nd module from 2022 (9.5 $fb^{-1}$)
  - target mass analyzed - 128.6 kg
  - 1.7% of data collected

*ν flavor tagging with topological information*



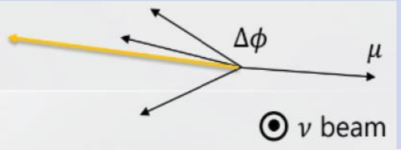





- neutrino interactions are searched inside the fiducial volume defined by the blue box.

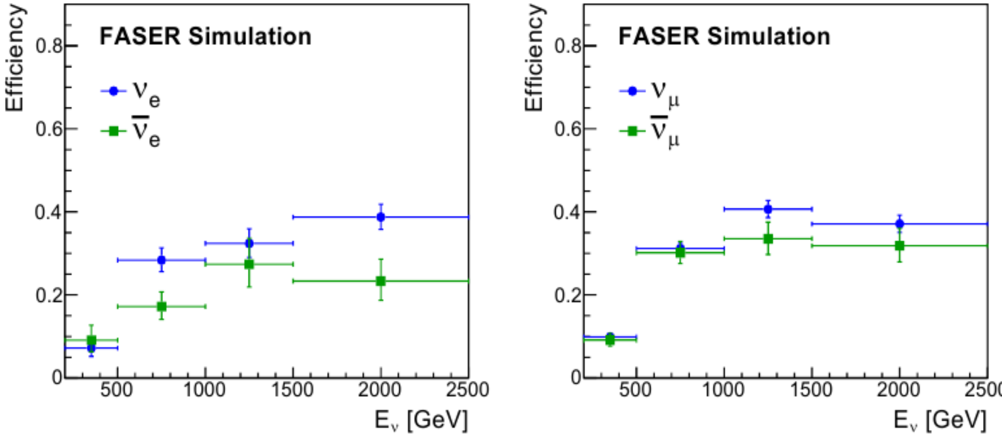
# First detection of $\nu_e$ and $\nu_\mu$ with FASER$\nu$ emulsion detector

Phys. Rev. Lett. 133, 021802

| Selection criteria | |
|---|---|
| Vertex reconstruction | $N_{track} \geq 5$ |
| | $N_{track}$ ($\tan\theta \leq 0.1$) $\geq 3$ (suppress the neutral-hadron background) |
| Lepton requirements | $E_e$ or $p_\mu > 200$ GeV |
| | $\tan\theta_e$ or $\tan\theta_\mu > 0.005$ |
| Back to back topology | $\Delta\phi > 90°$  |

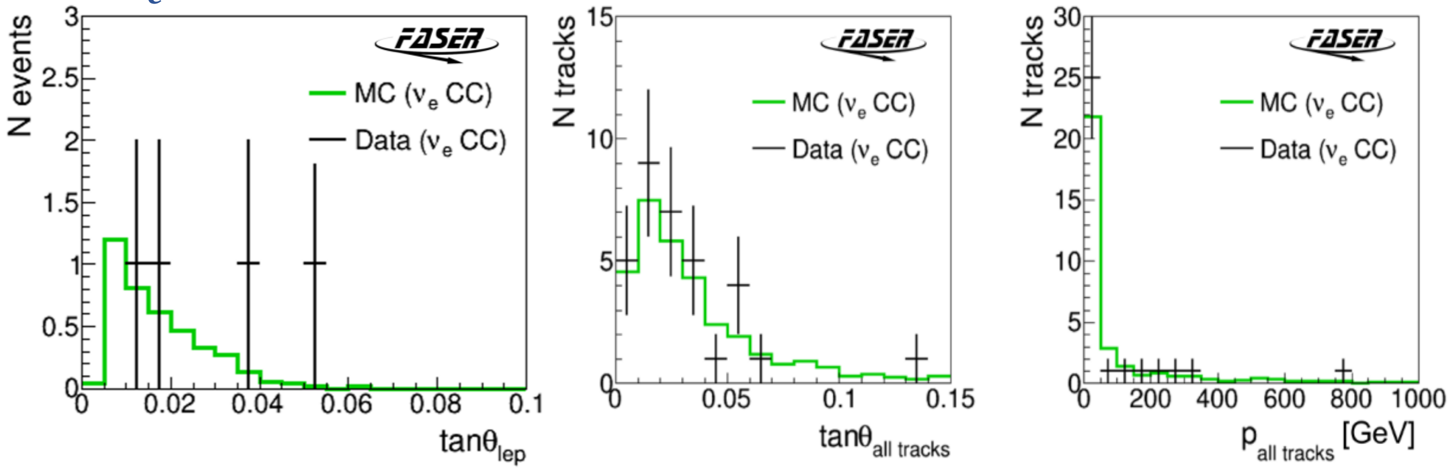


- the efficiency of $\bar{\nu}$ events that pass the vertex selection is slightly lower than ν events



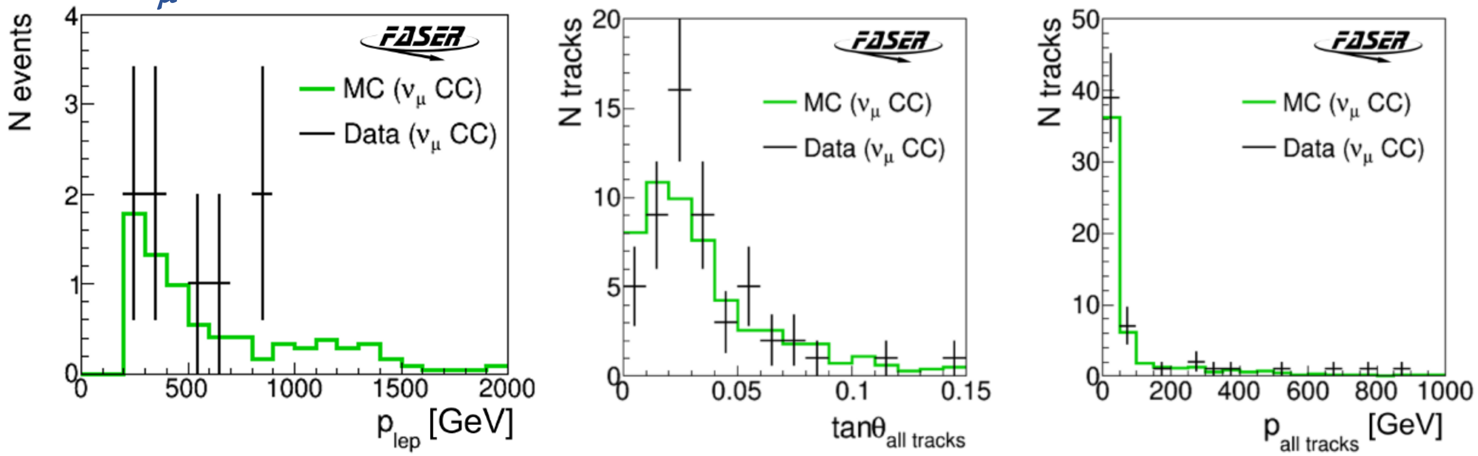

- $E_e$ – from counting track segments at EM shower maximum (resolution: ~25% at 200 GeV) - associated high-energy EM shower
- $p_\mu$ – from track spread due to multiple Coulomb scattering (resolution: ~30% at 200 GeV/c, validated with test beam)

$\nu_e$




*MC normalized to number of observed events*

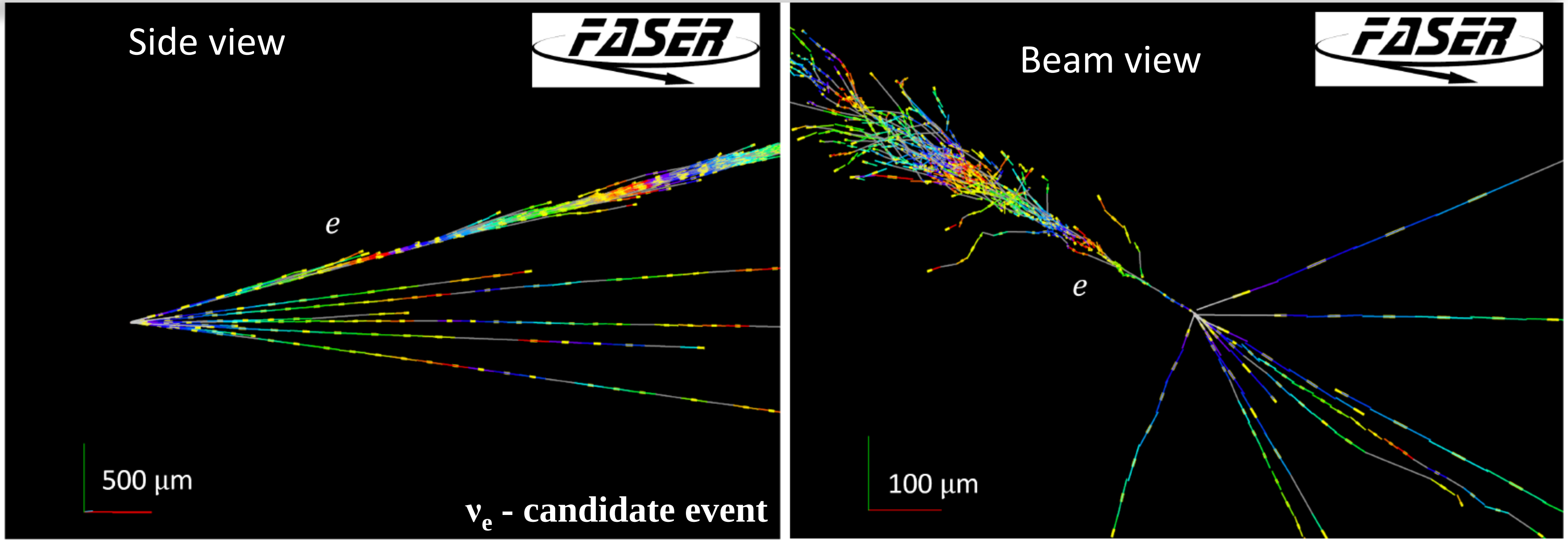
$\nu_\mu$

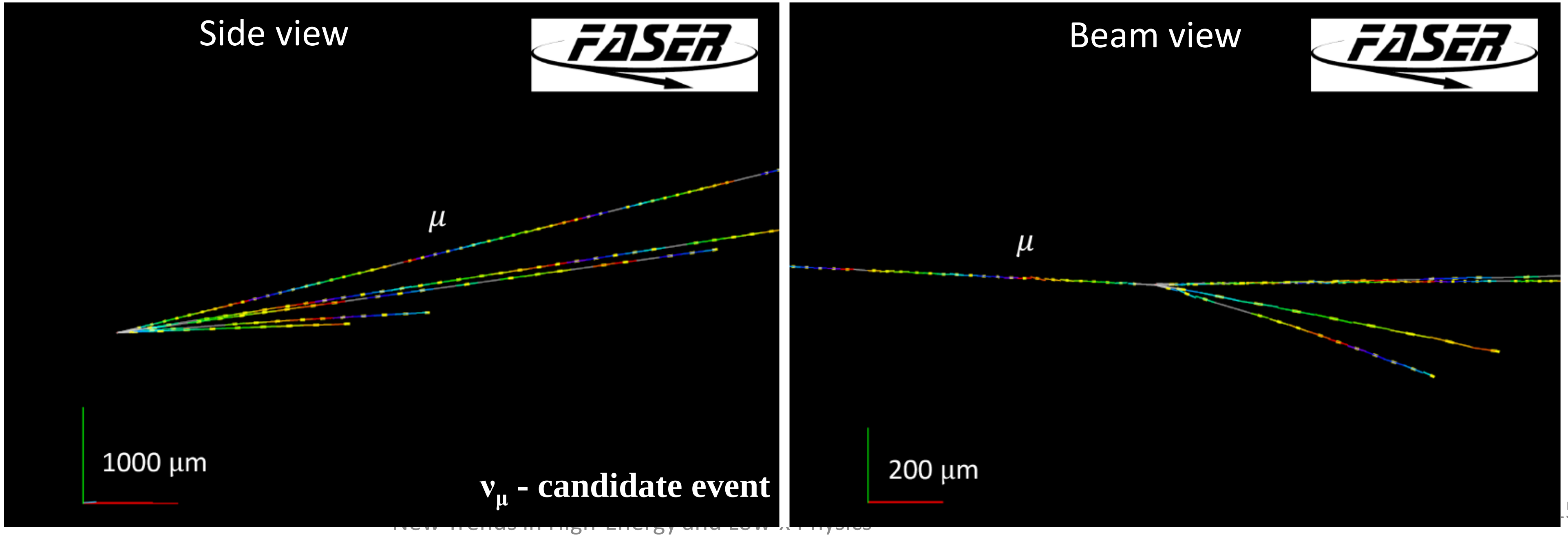



- kinematics of observed ν interactions are in good agreement with MC
- ν interactions at TeV range

# First detection of $\nu_e$ and $\nu_\mu$ with FASER$\nu$ emulsion detector

Phys. Rev. Lett. 133, 021802



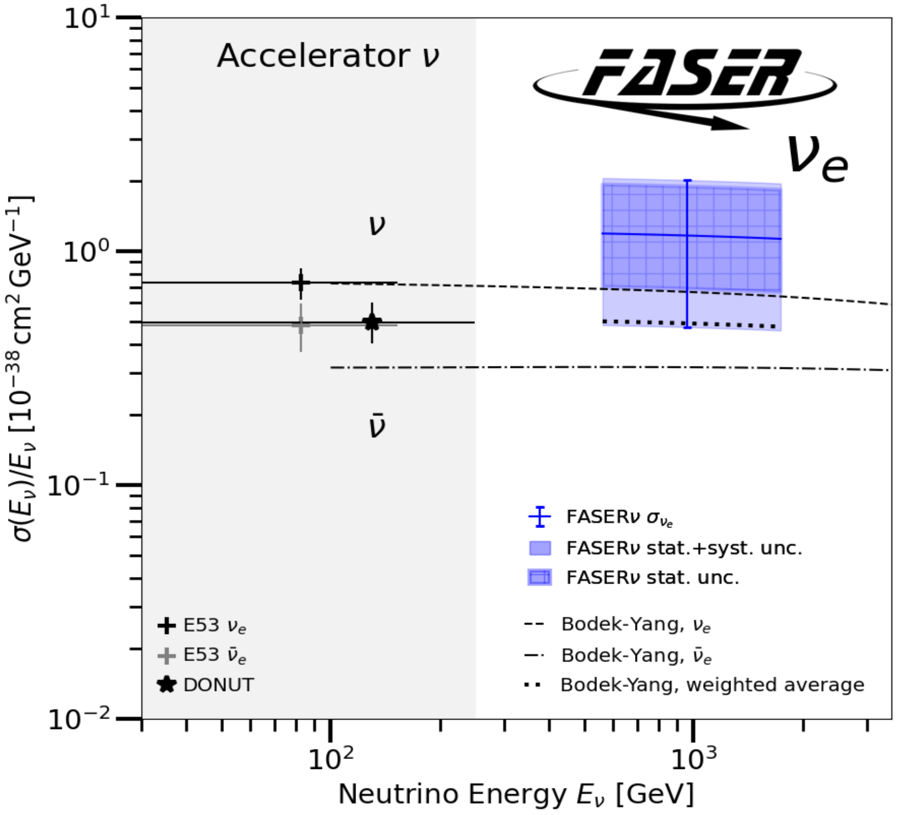



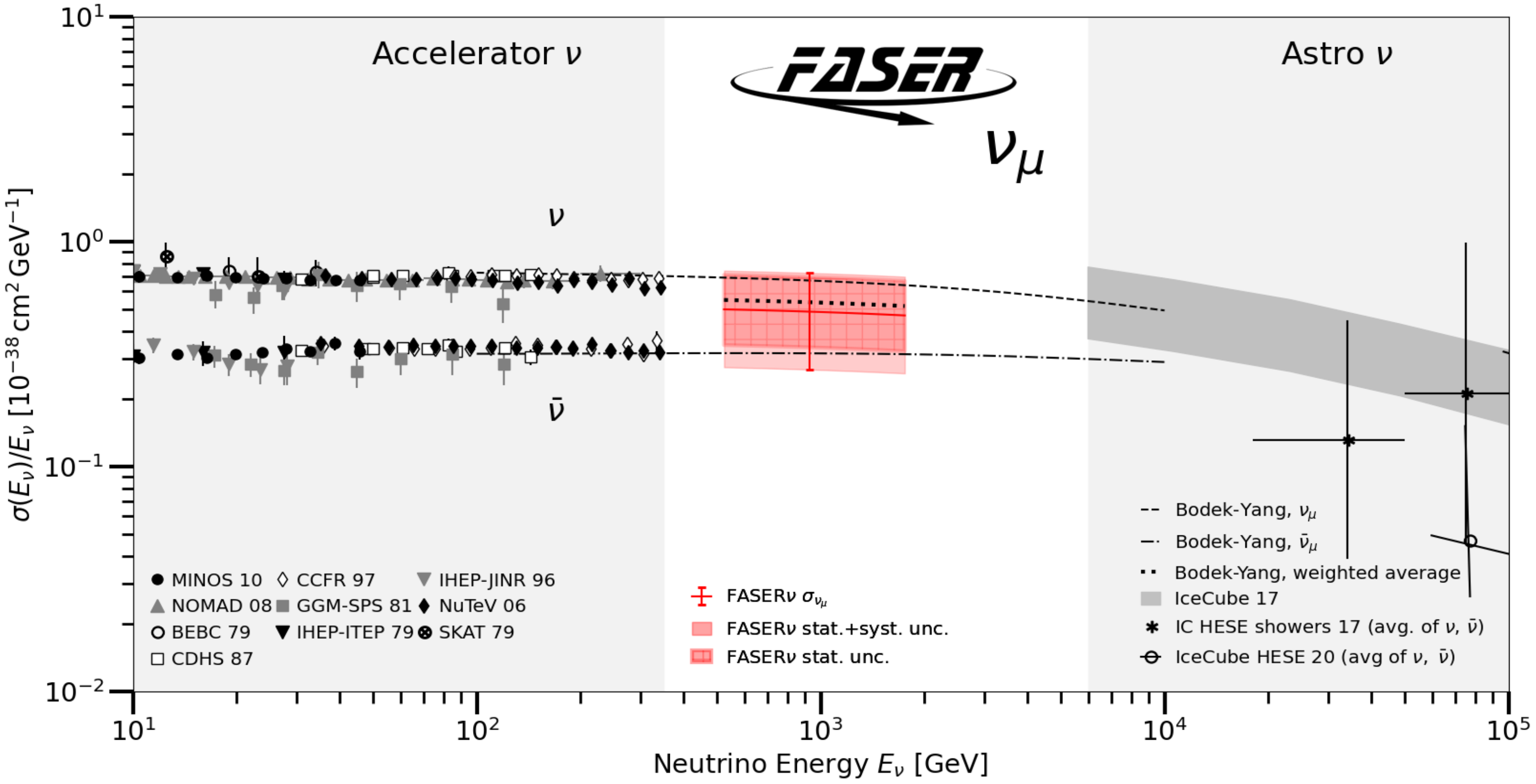
# $\nu_e$ and $\nu_\mu$ cross section measurements at TeV energies

Phys. Rev. Lett. 133, 021802

- **First observation of $\nu_e$ at the LHC**
- **First neutrino cross section measurement in the TeV range**
- Large uncertainty from neutrino flux

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

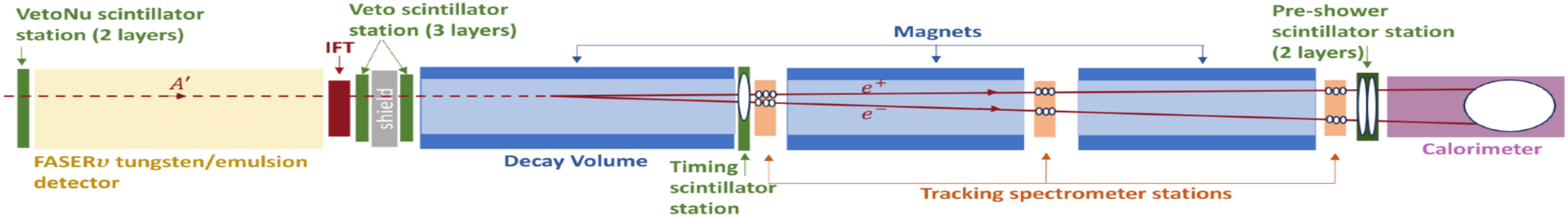


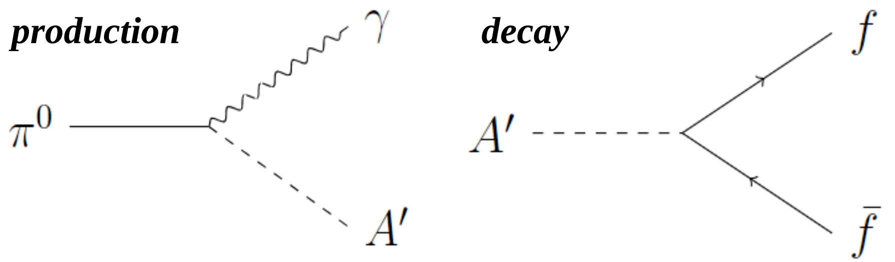



# Search for Dark Photons

Physics Letters B, volume 848, 138378

- **Long-lived dark photon produced in decays of forward mesons - decay into electron pairs in the detector**




**Dark Photons (A’): U(1) gauge boson**

- signature: $e^+e^-$ pair appears from ‘nothing’
- must decay in 1.5 m decay volume

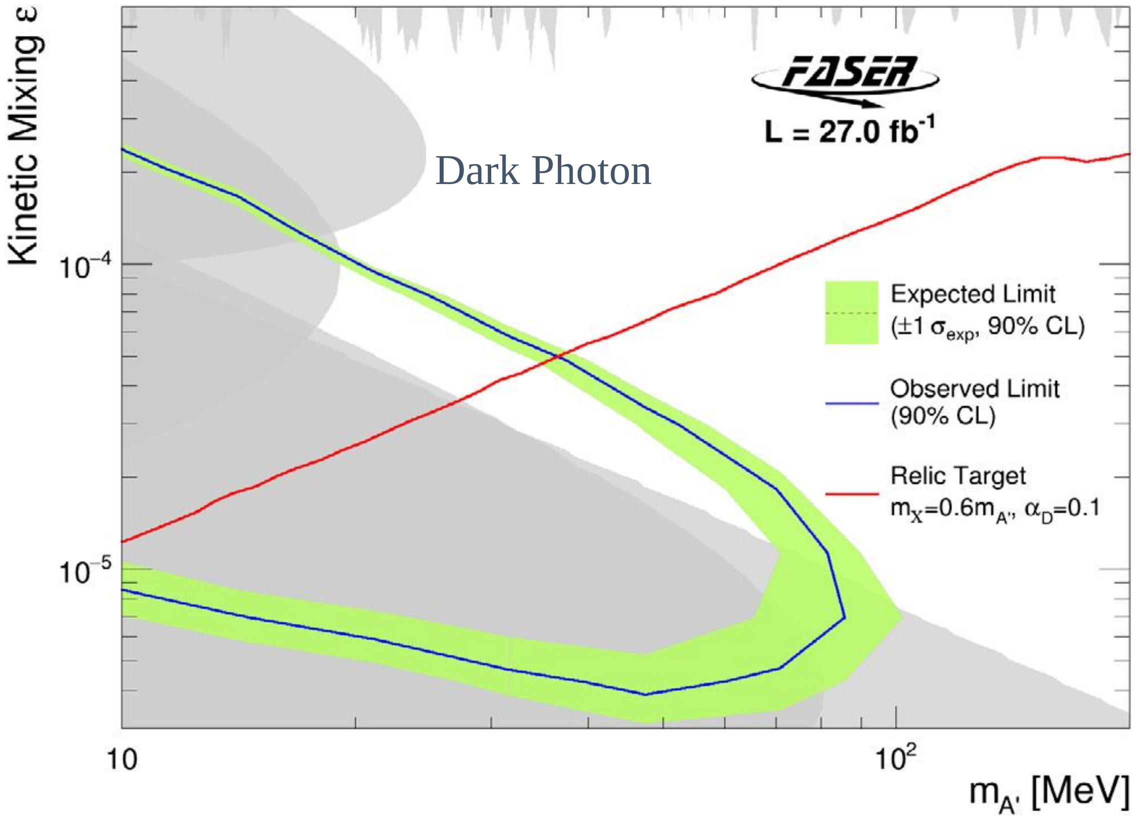
- **Selection**
  - 2 opposite-sign tracks
  - 500 GeV in calorimeter
  - no signal in all 5 veto scintillator counters
  - something in downstream scintillators
  - negligible backgrounds: $(2.3 \pm 2.3)$ X $10^{-3}$ events

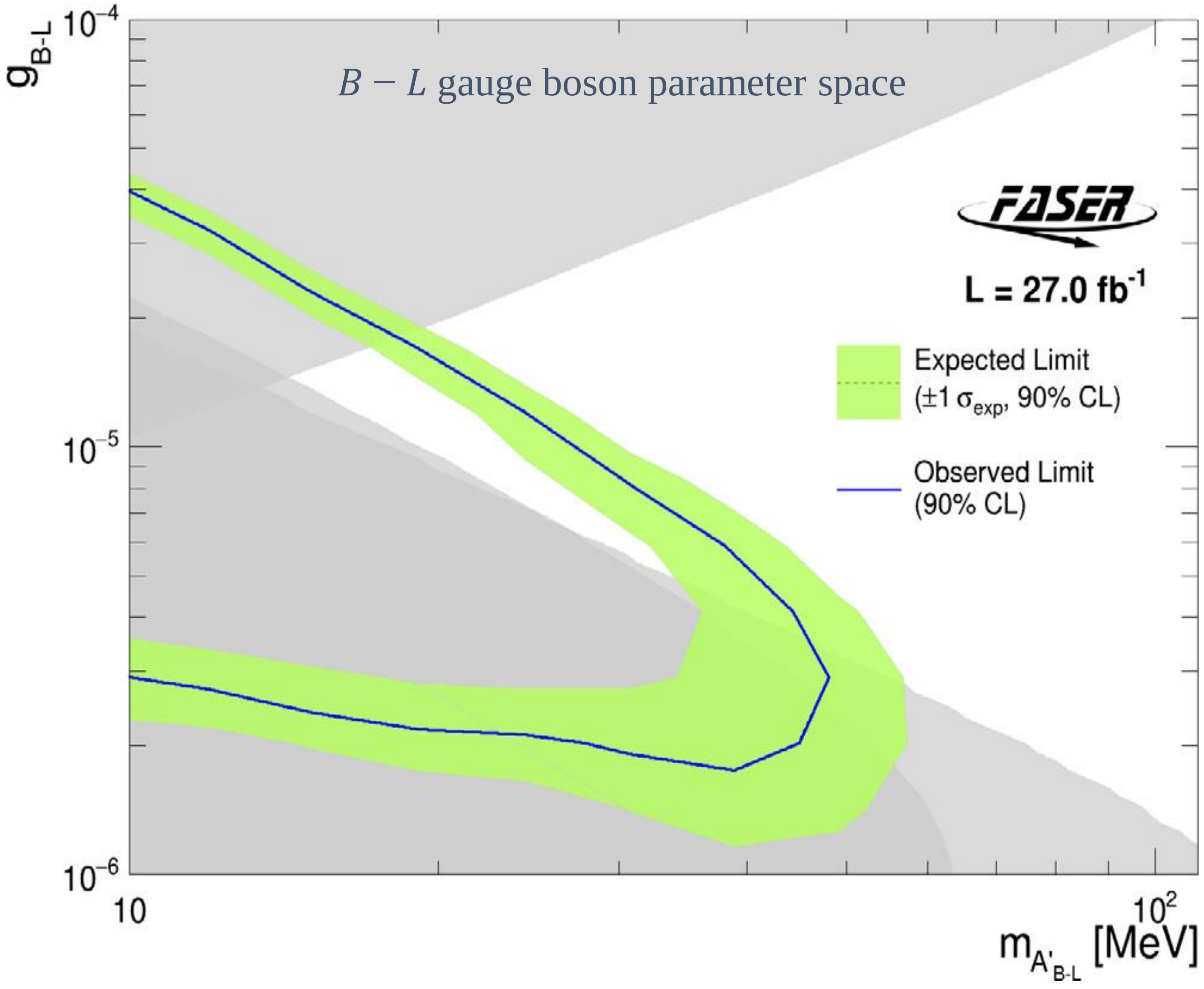
    - *veto inefficiency, neutral hadrons, large-angle, muons, neutrinos, non-collision evens*

# Search for Dark Photons

[Physics Letters B, Volume 848, 138378]

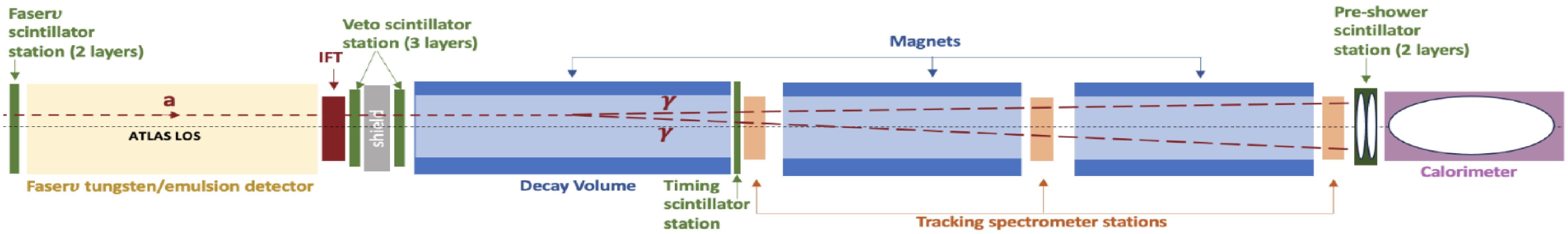
- **Results**
  - 27 $fb^{-1}$ collected in 2022
  - no events observed/with in expected background of $(2.3 \pm 2.3) \times 10^{-3}$ events
  - new limits on unexplored parameter space
  - probes new parameter space in a region motivated by the dark matter relic density

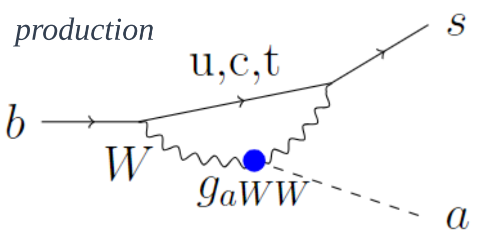


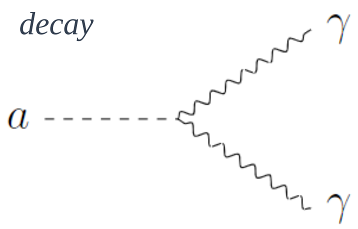




-- region of parameter space that yields the correct dark matter relic density

-- region excluded by previous experiments



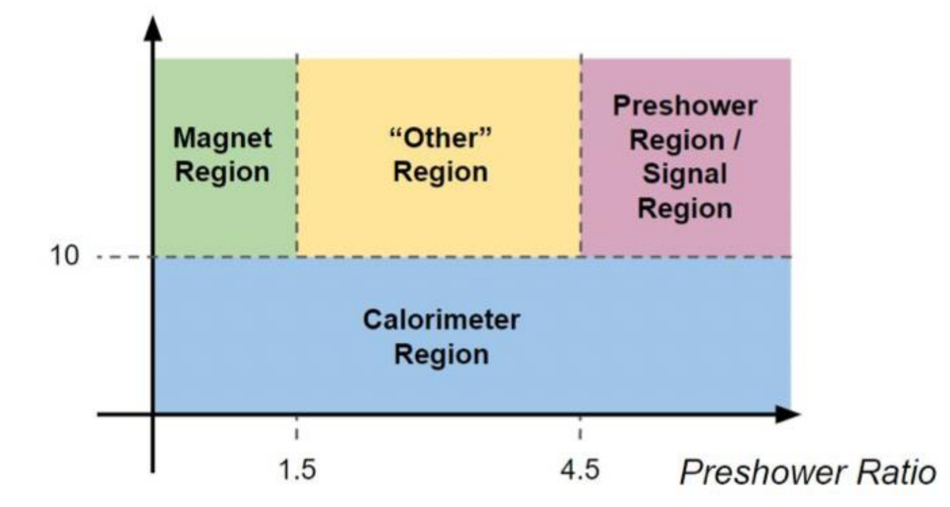

- Sensitive to axion-like particles (ALPs) coupling to SU(2)L gauge bosons
- Mainly produced in B meson decays in our sensitivity range
- Signal: a → γγ appearing from 'nothing' with ~TeV of energy
- Can decay anywhere in FASER decay-volume/spectrometer volume
- **57.7 fb$^{-1}$ collected in 2022 and 2023**

# Axion-like Particles (ALPs) search

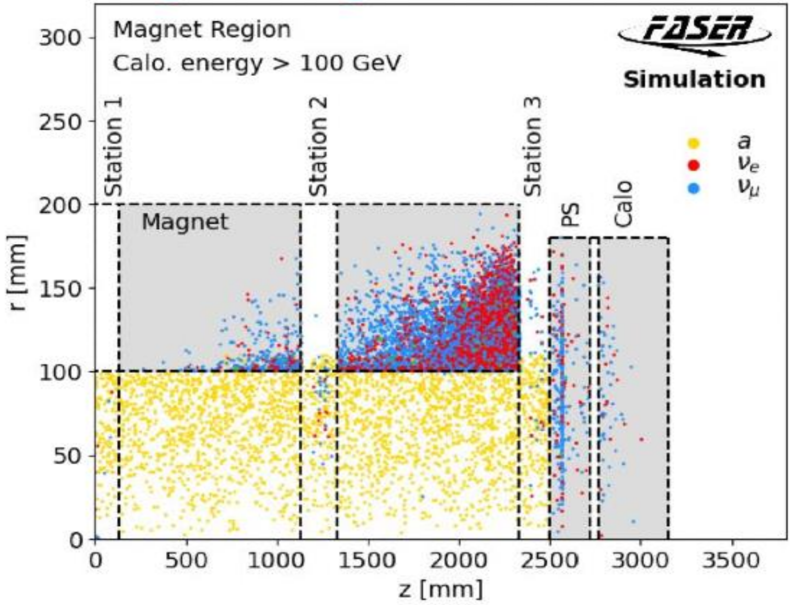


- **Selection**
  - No signal is expected in all 5 veto scintillators
  - evidence of EM shower in pre-shower
  - >1.5 TeV in calorimeter
  - requires events triggering the calorimeter

*regions used for analysis*




*Simulated interaction of decay position of $a, \nu_e, \nu_\mu$ in control sample*



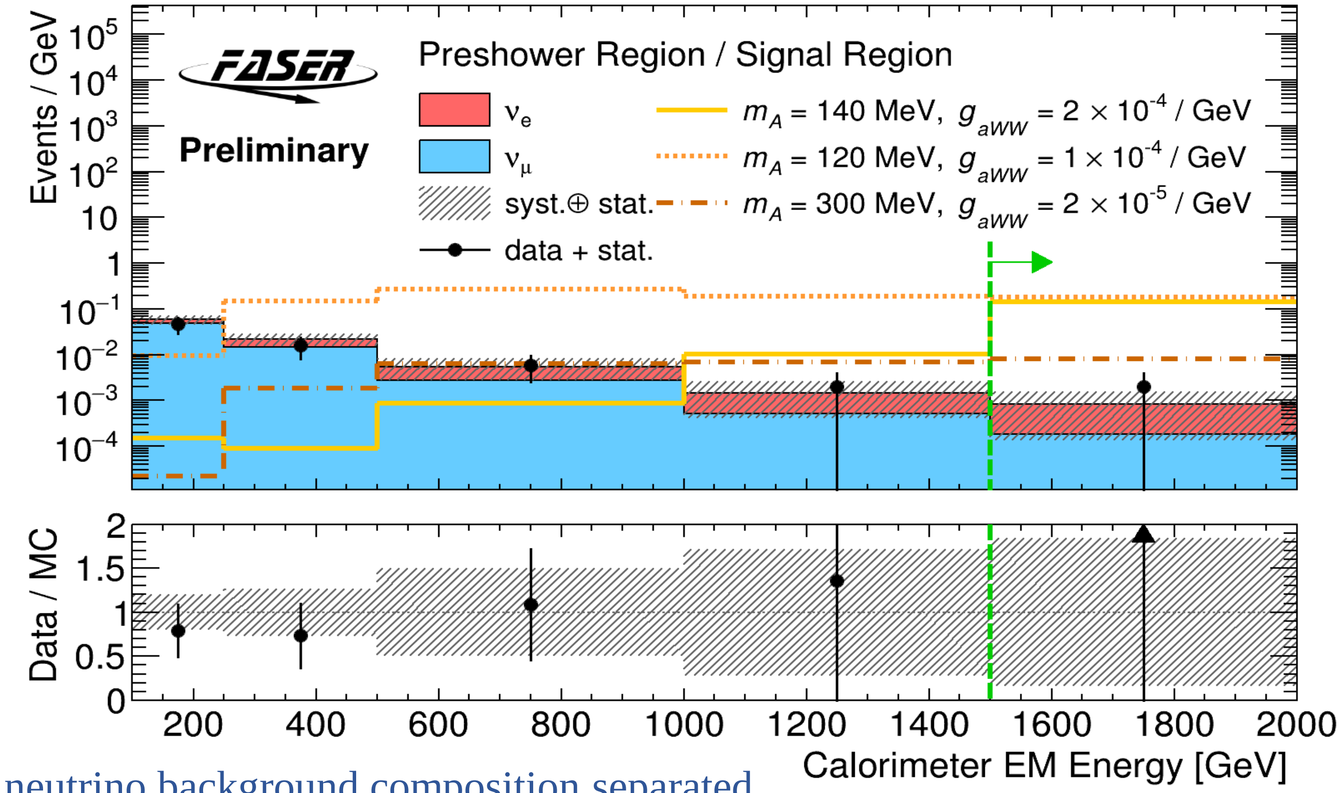

- **Background**
  - Dominant
    - neutrino interactions (simulated to be 0.4 ± 0.4 events)
  - Negligible
    - neutral hadrons
    - large-angle muons
    - non-collision / cosmics

- *Data control regions and simulation used in blinded analysis to evaluate backgrounds*

# Axion-like Particles (ALPs) search - results

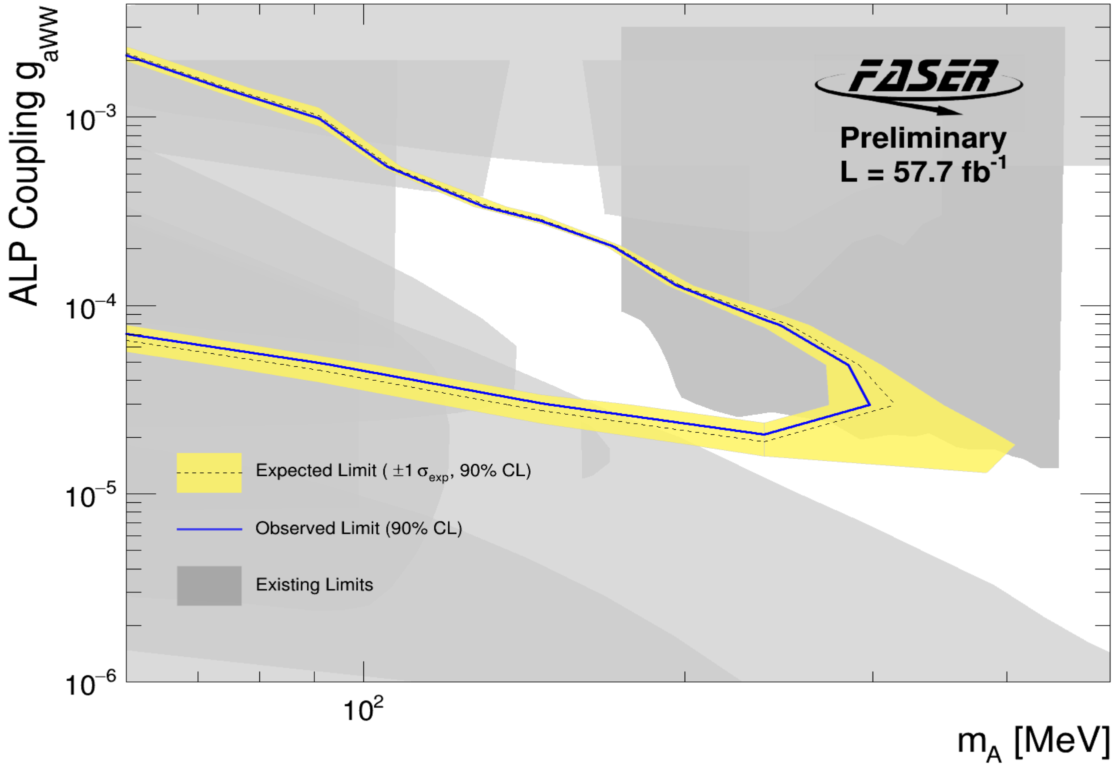
CERN-FASER-CONF-2024-001

- Main background: neutrinos produced upstream of FASER through light/charm hadron decays
  - evaluated with MC simulations and validated in different detector regions
  - expecting 0.42 ± 0.38 from ν CC interactions in pre-shower station
- 1 observed event after unblinding
- Probing new parameter space of this ALPs Model




neutrino background composition separated according to neutrino production mechanism

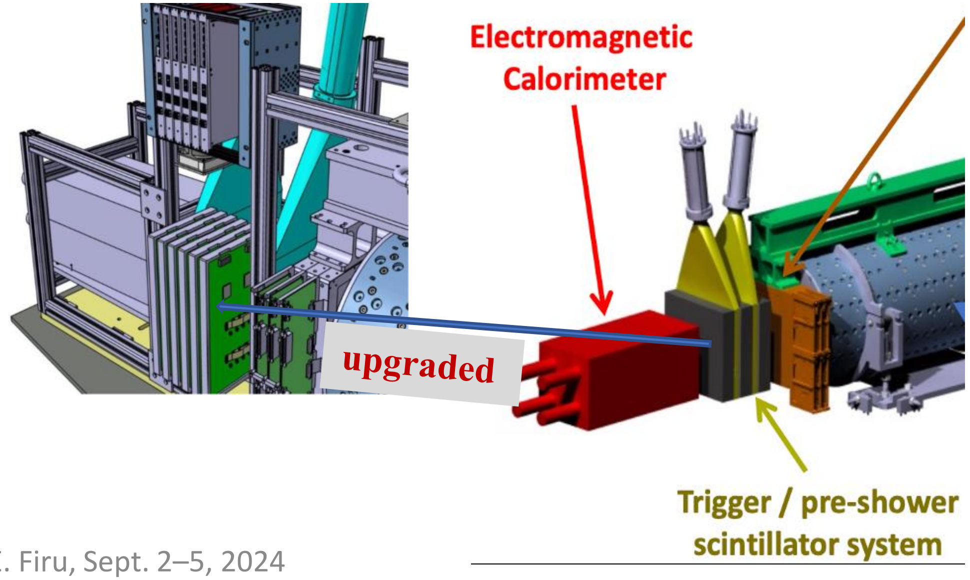
interpretation of the signal region yield as ALP

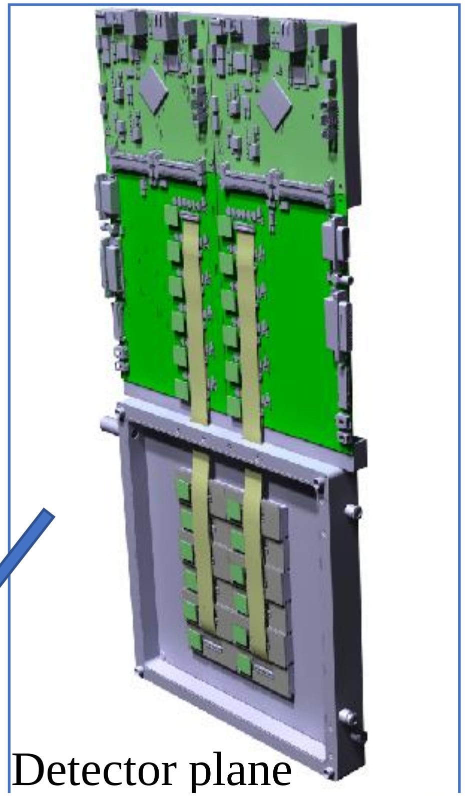


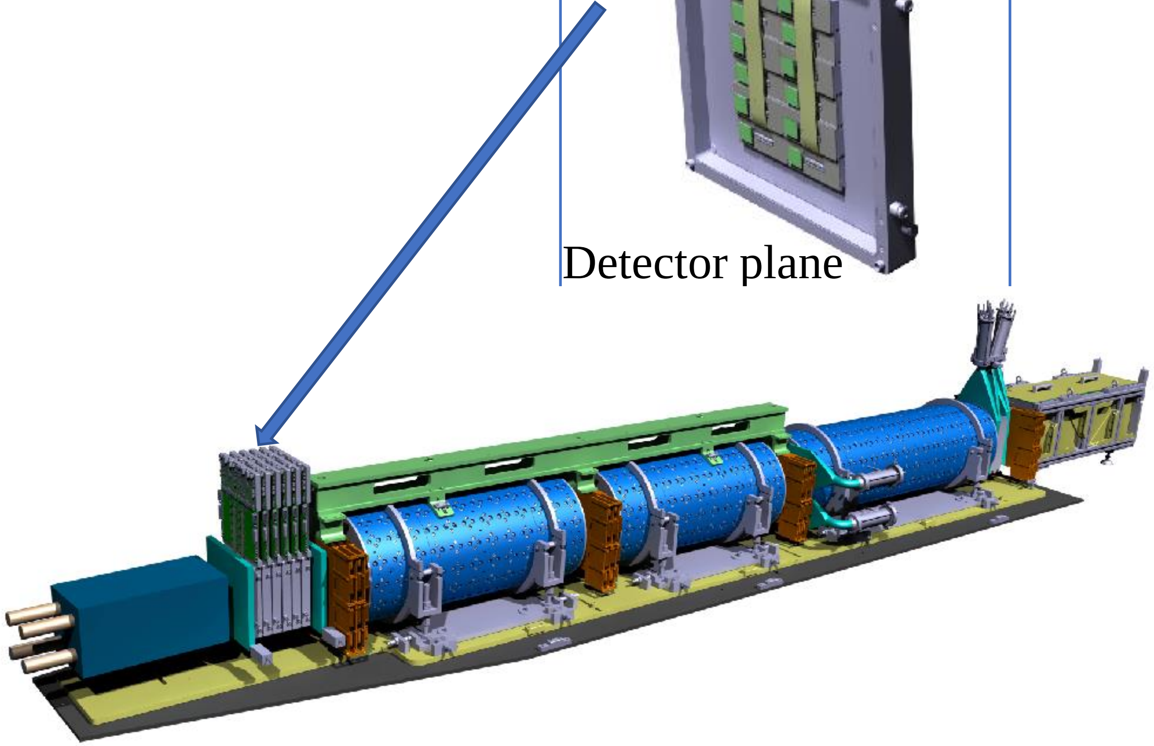
# Prospects - New Pre-shower Calorimeter

CERN-LHCC-2022-006; LHCC-P-023

- Resolve di-photon events by upgraded pre-shower calorimeter with high X-Y granularity
  - improve ν BG suppression in the search for ALPs
- 6 detector planes + 2 scintillators
  - each plane: tungsten absorber + monolithic SiGe pixel sensors
- FASER approved to run during HL-LHC Run4
  - will record large dataset with upgraded FASER
- Installation before 2025
  - data taking during last year of LHC Run 3 and HL-LHC



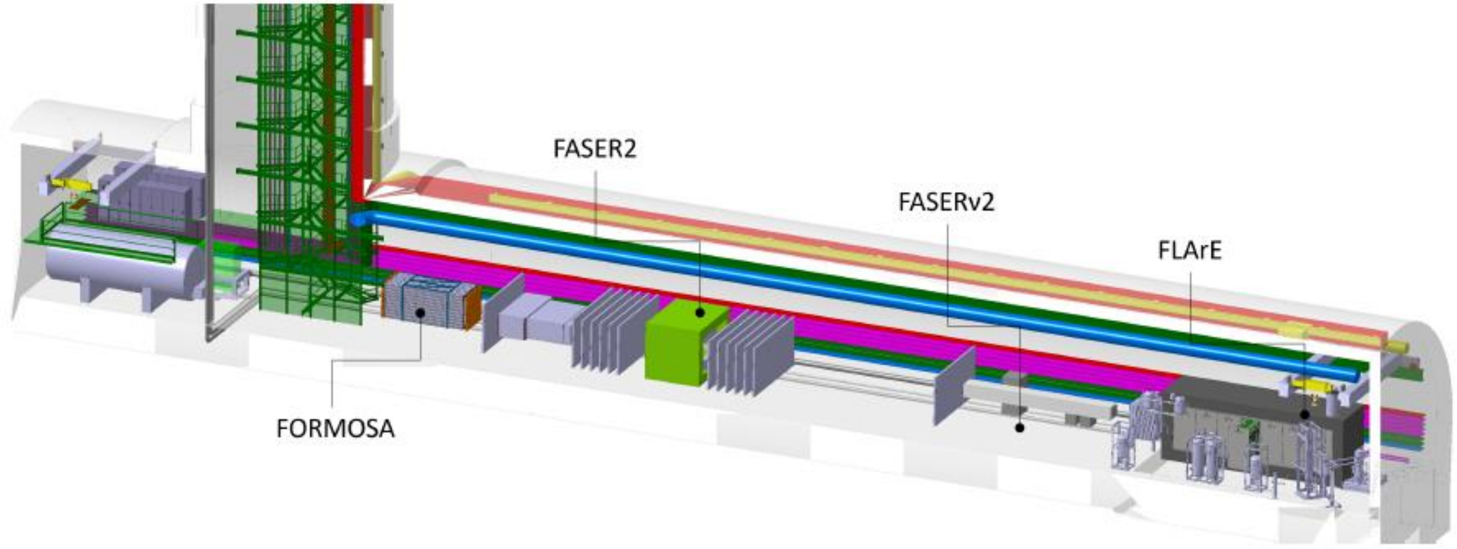



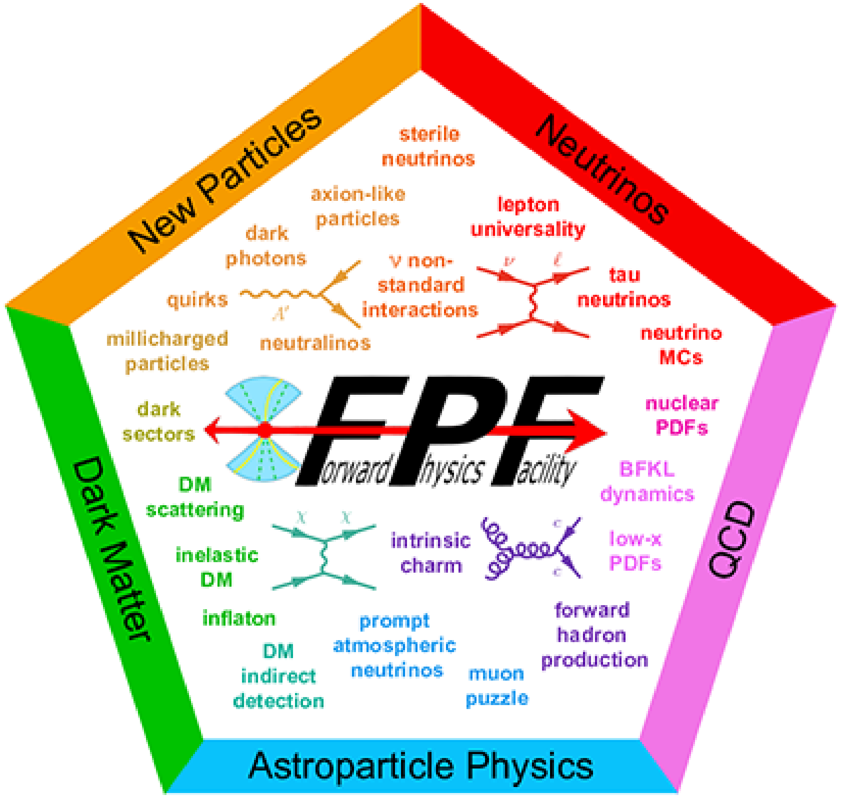
# Prospects - Forward Physics Facility (FPF)

FPF publication

- FPF is a proposal to create a new facility 650 m away on the LOS for HL-LHC era
- At the moment 4 proposed experiments to be situated in the FPF
- Broad physics case covering BSM searches, QCD studies, neutrino physics
  - essential input to realizing the full potential of the HL-LHC
- Provides opportunities for interdisciplinary studies
  - understanding hadron production related to cosmic-ray experiments

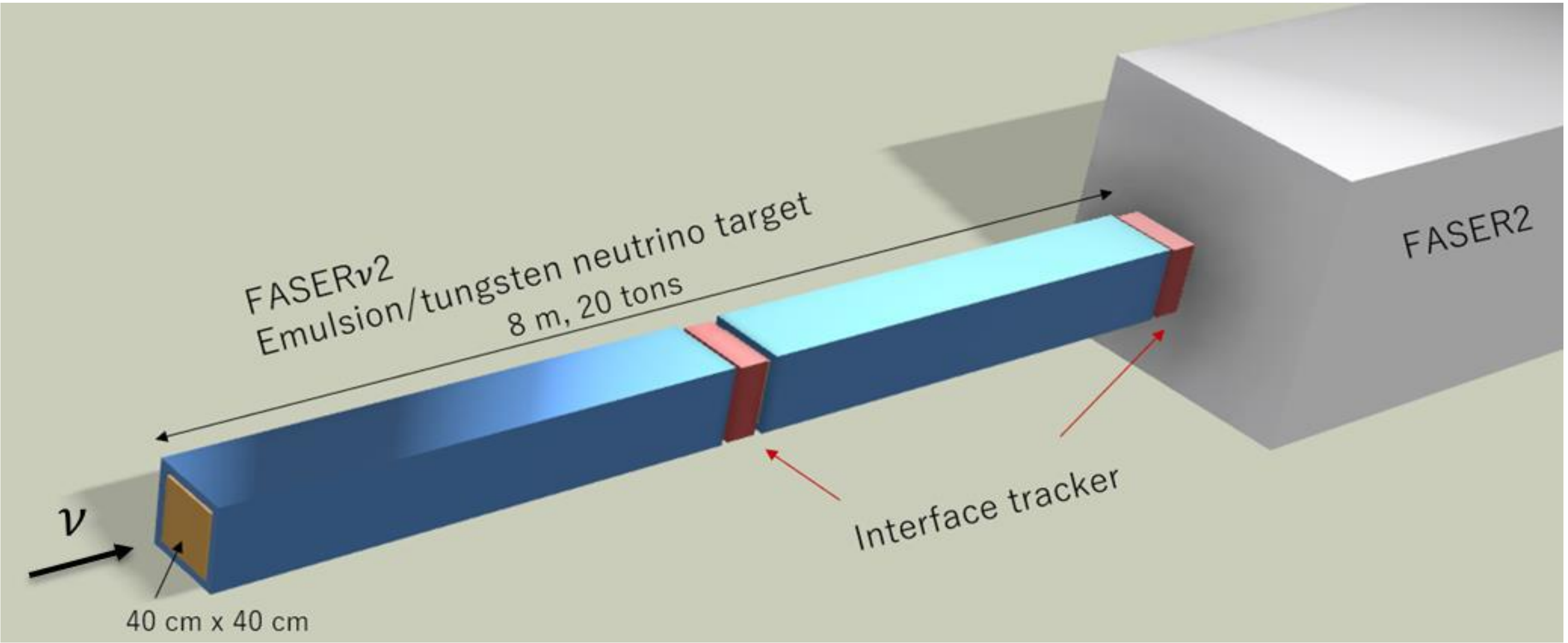


Baseline layout of detectors in the FPF cavern.



# Prospects - FASERν2

- 20 tons target mass emulsion neutrino detector
- Study the possibility of installing a dedicated sweeper magnet to reduce muon background
- Once per a year - emulsion detector replacement
- O(10K) tau neutrino interactions expected
- First detection of Anti-tau neutrino



# Summary & Outlook

- **Summary**
  - FASER is a small experiment but with good potential of discovery for new physics
  - Continuing to operate successfully in Run 3 of LHC approximately 140 $fb^{-1}$ collected
  - Physics results
    - first $\nu_e$ , $\nu_\mu$ interaction cross sections at TeV energies with FASERν using the 2022 data
    - first results on Axion-Like Particles at FASER
    - dark photon limits
- **Perspectives**
  - Additional 180 $fb^{-1}$ will be collected in 2024, 2025
  - To increase ALPs sensitivity, pre-shower detector will be upgraded in 2025
  - Approved to operate in Run 4
  - New project (***Forward Physics Facility (FPF)***) - discussions to build a new experimental cavern in the HL-LHC era to improved physics programme

# FASER collaboration meeting #6

THANK YOU!

# BACKUP SLIDE

# FASER collaboration

## FASER COLLABORATION

101 collaborators, 27 institutions, 11 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
CHIBA UNIVERSITY
UNIVERSITY OF OREGON
DESY.
INFN
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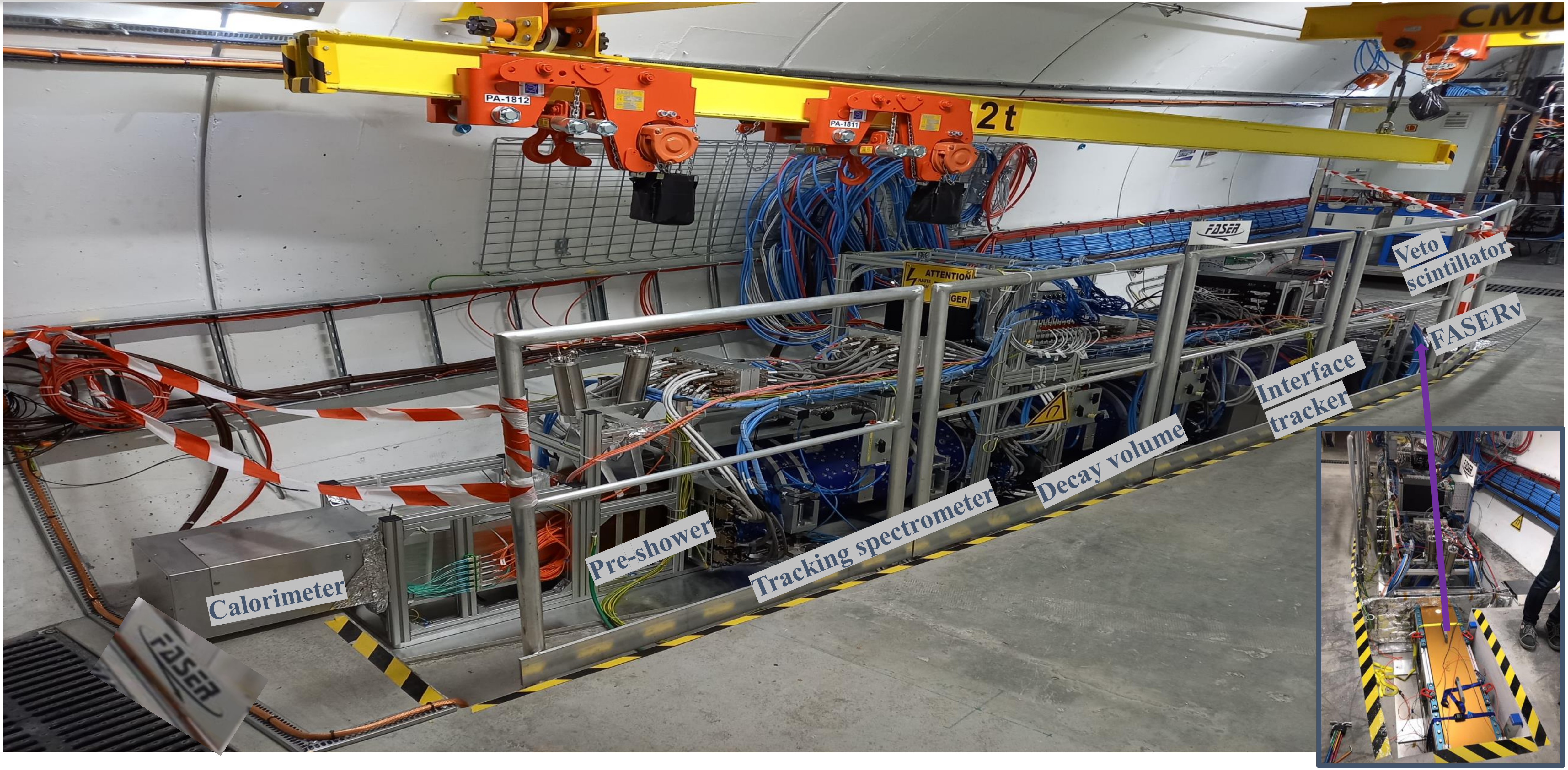
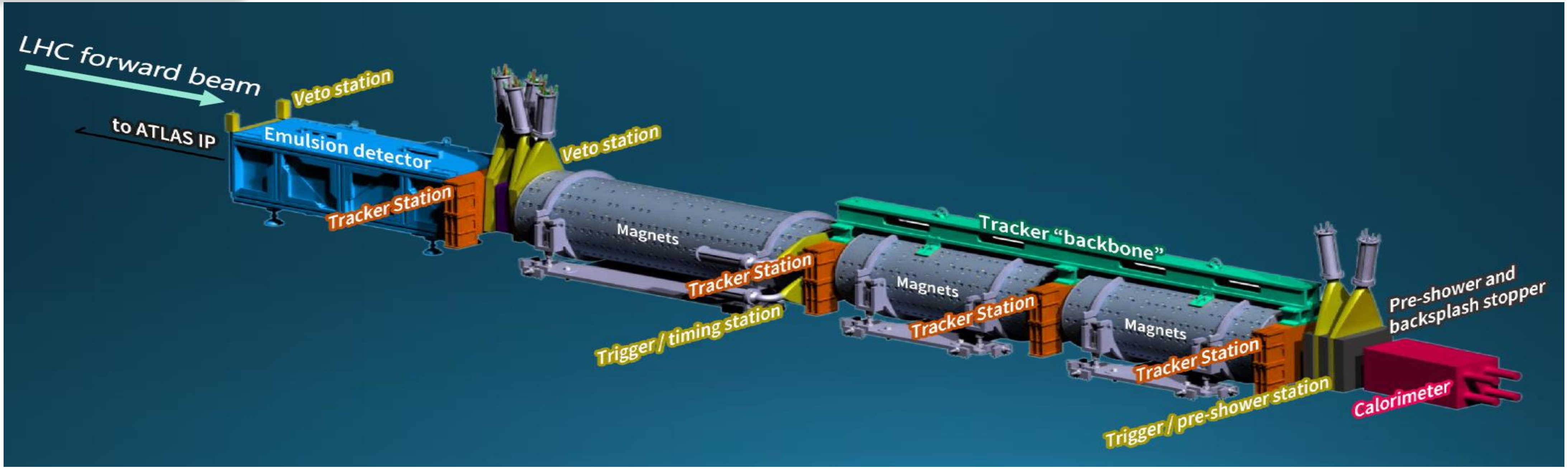
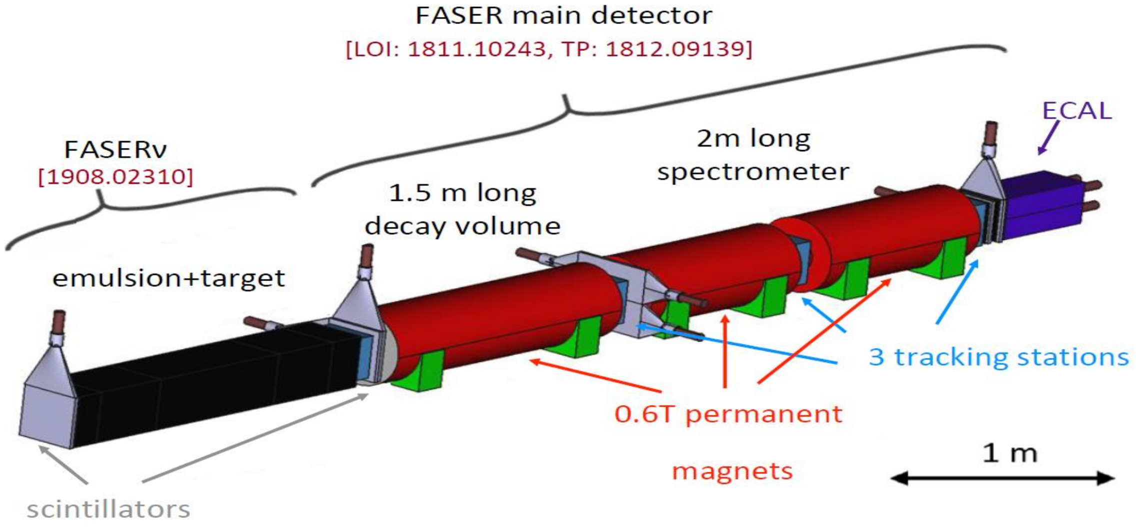
# The FASER detector



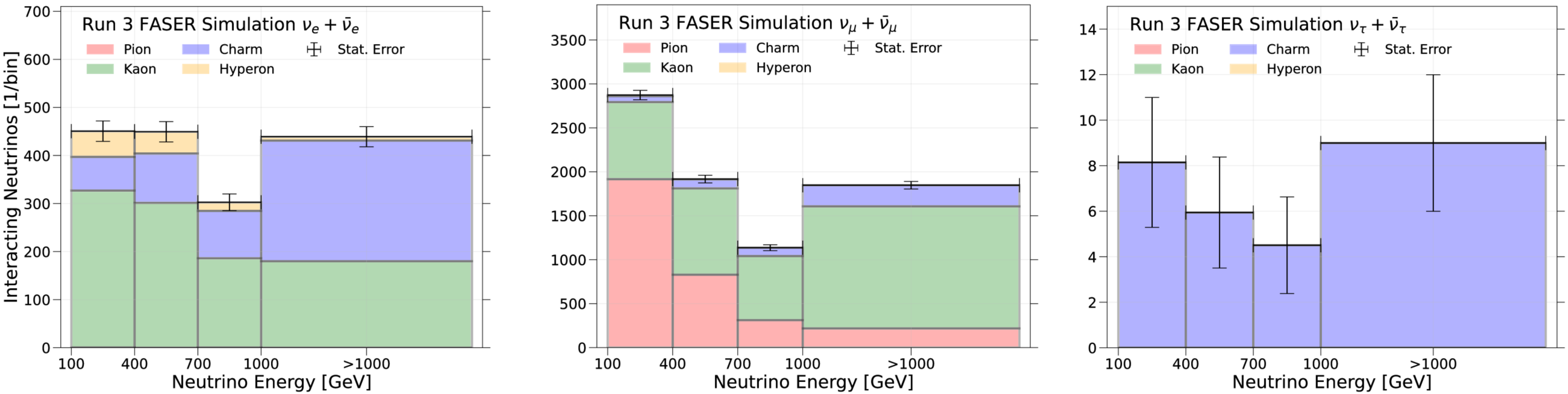
# FASER detector



# FASERν expected number of interactions

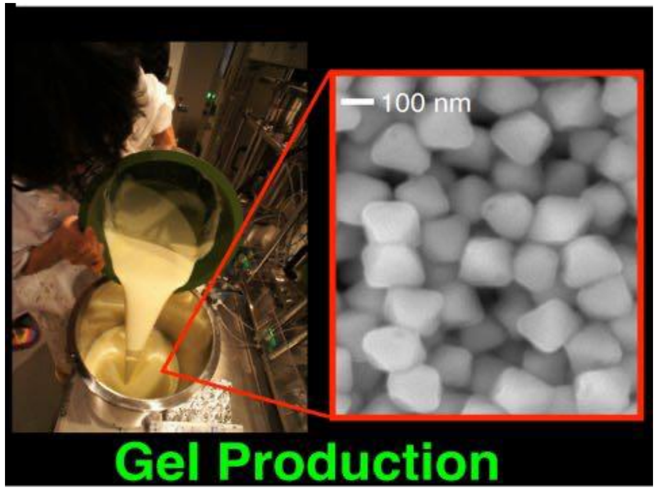
***FASERν (Emulsion-based detector) - sensitive to all 3 flavors***

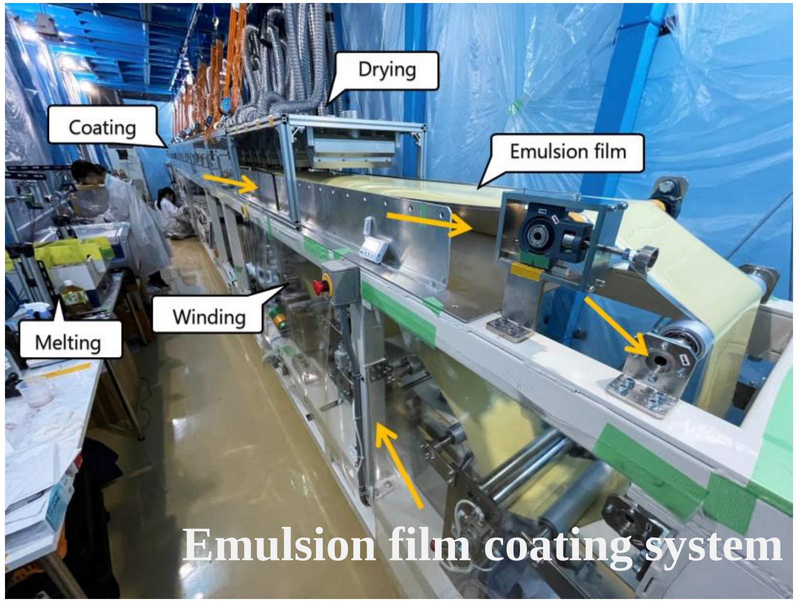



- Energy spectra for electron (left), muon (center), and tau (left) neutrinos interacting in FASERν at LHC Run 3 with a total integrated luminosity of 250 $fb^{-1}$

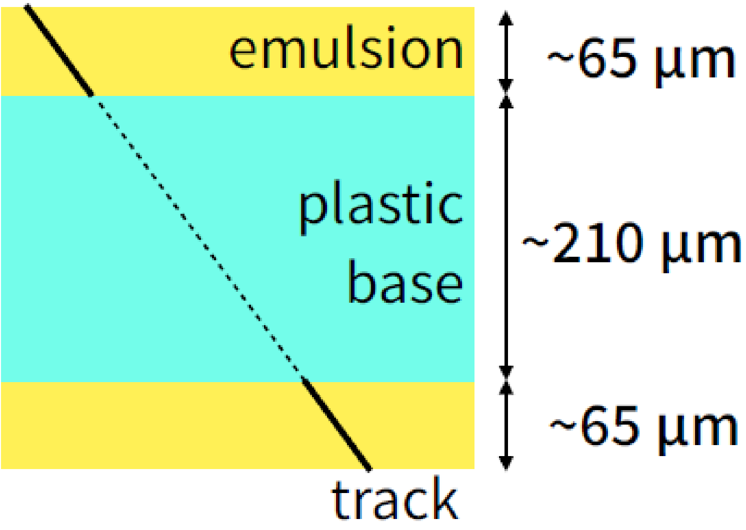
# Emulsion detector

- *Gel and film production at Nagoya University*

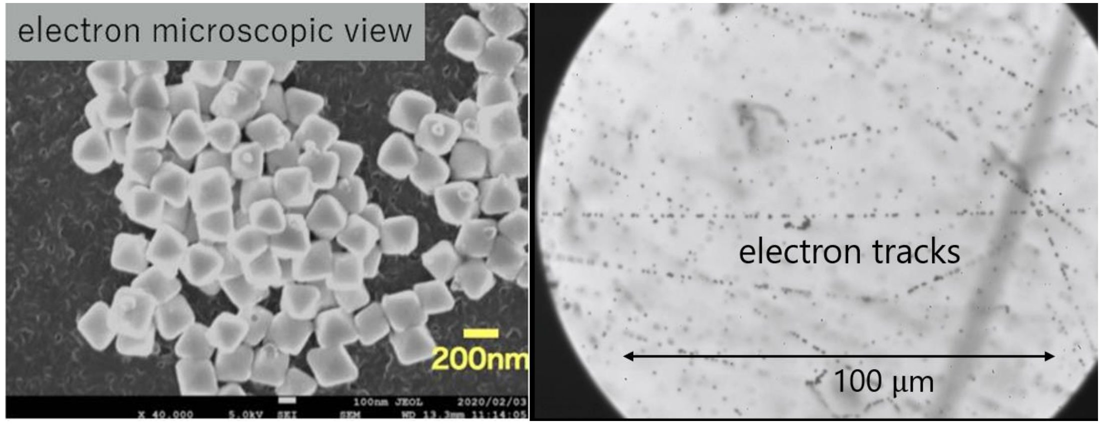



*Double sided emulsion coating*




*Microscopic view*

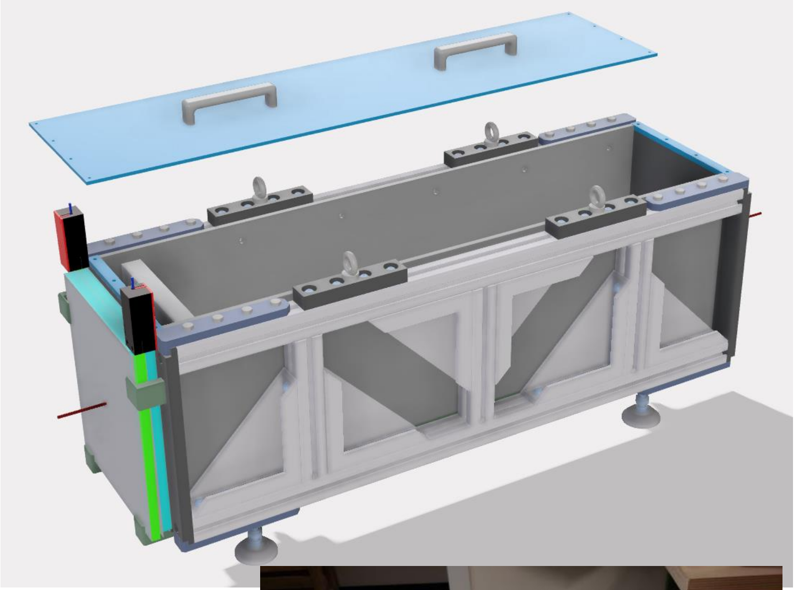



- 200 nm diameter silver halide crystals dispersed in gelatin
- ≈ 100 nm position resolution can be achieved

# FASERν module assembly

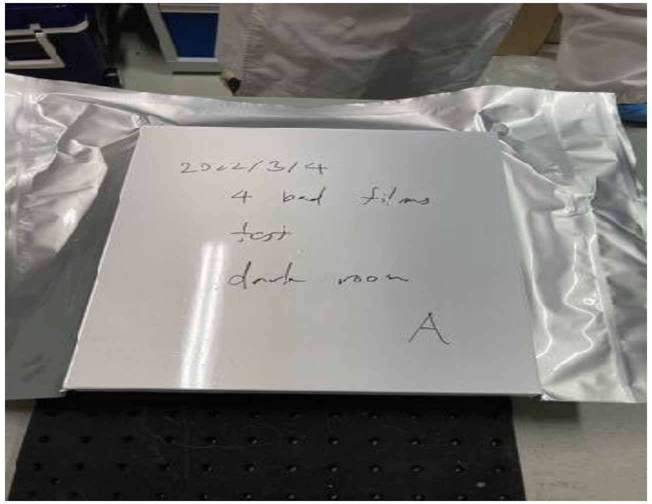

Assembly

FASERν box



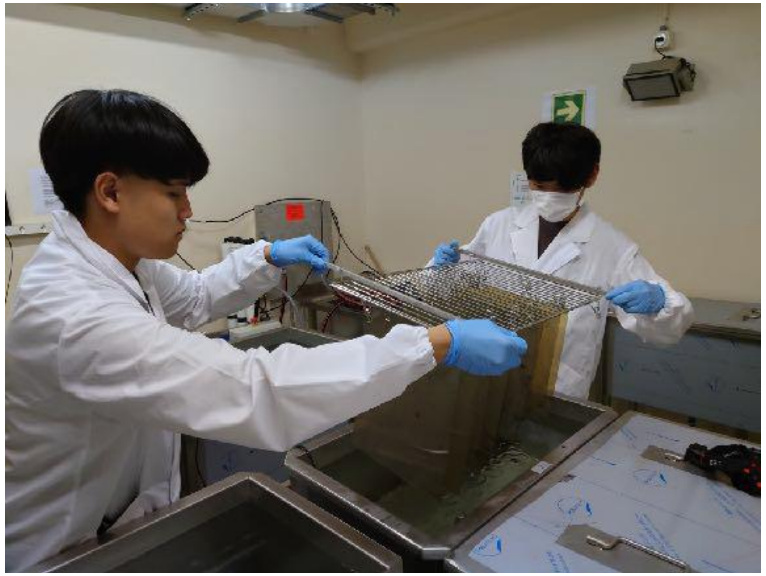
- Sub-module: 10 films + 10 tungsten plates
- Vacuum-pack to keep alignment for several months
- 10-12 days to complete 73 packs
- Apply external force (equivalent to 1 bar) to the sub-modules in the FASERν box

Sub-module




# FASERν development of emulsion films

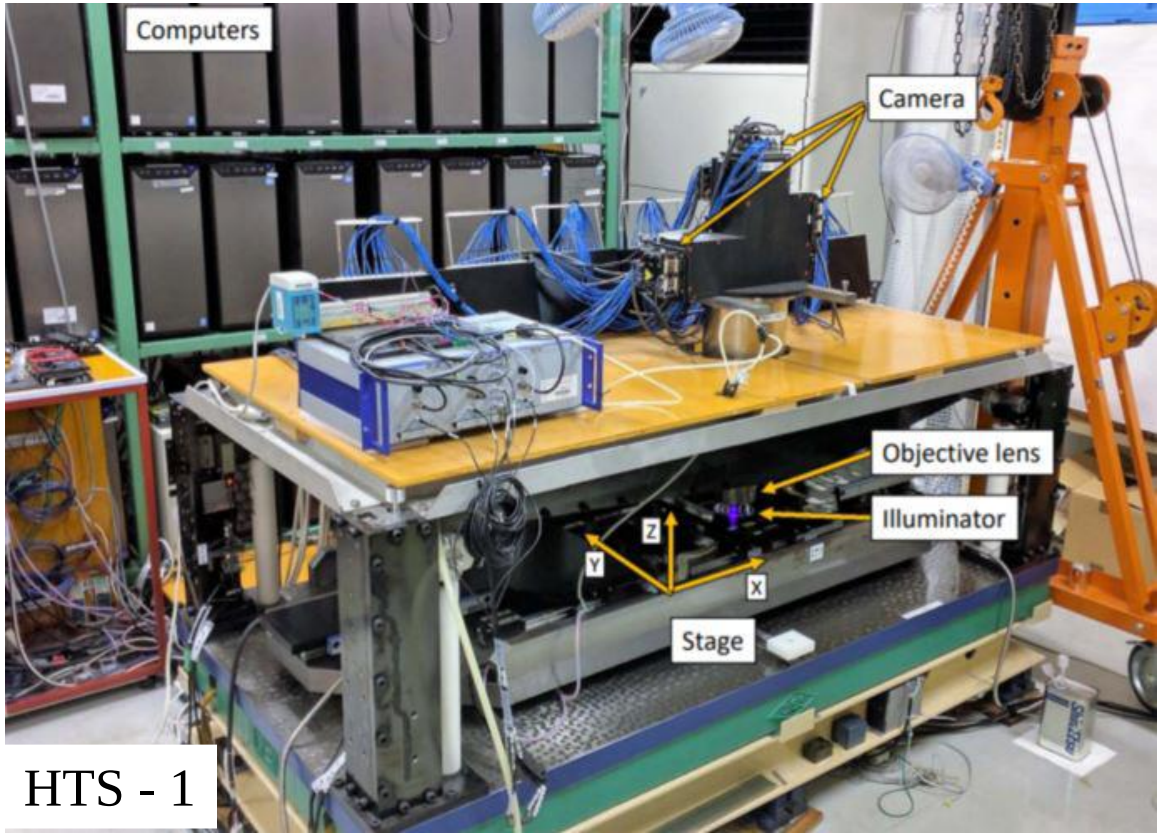
Development chains

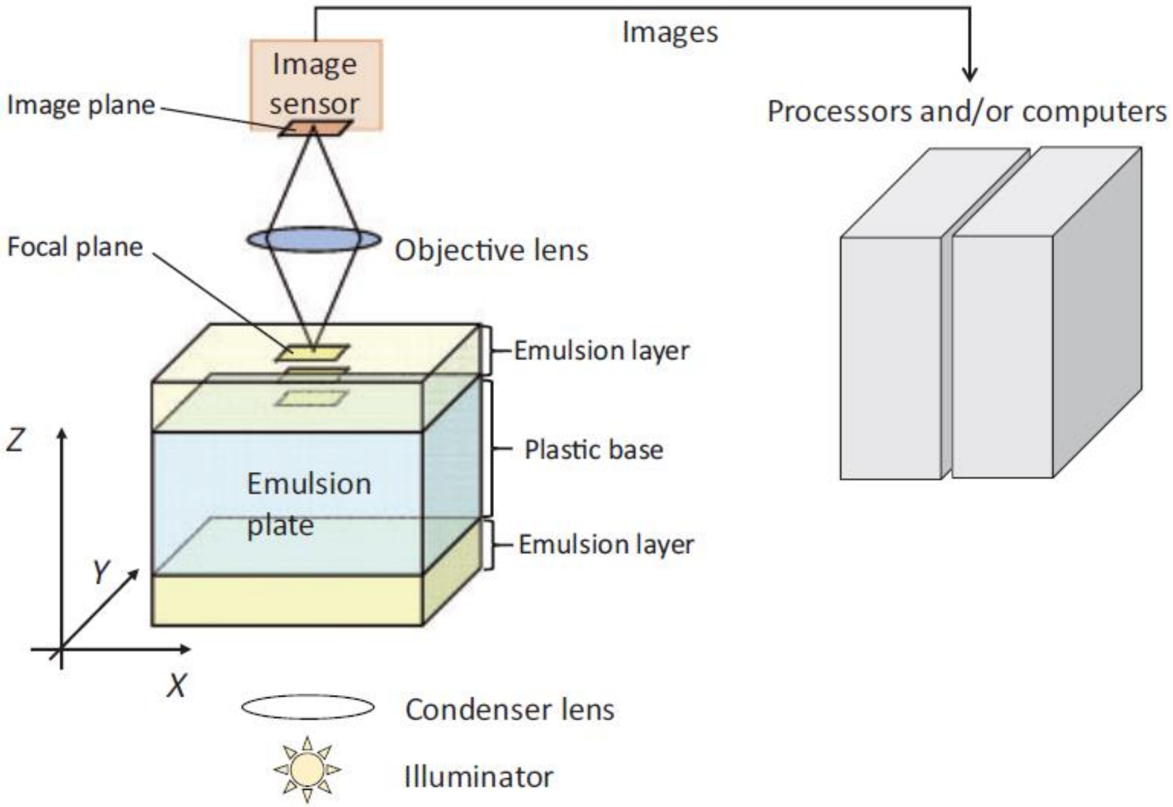


- Installed new development chains and drying racks at the renovated CERN darkroom facility
- Sharing the facility with other emulsion experiments: DsTau (NA65), SND@LHC, etc.
- 10-12 days to complete 730 films


Drying system

# FASERν readout system

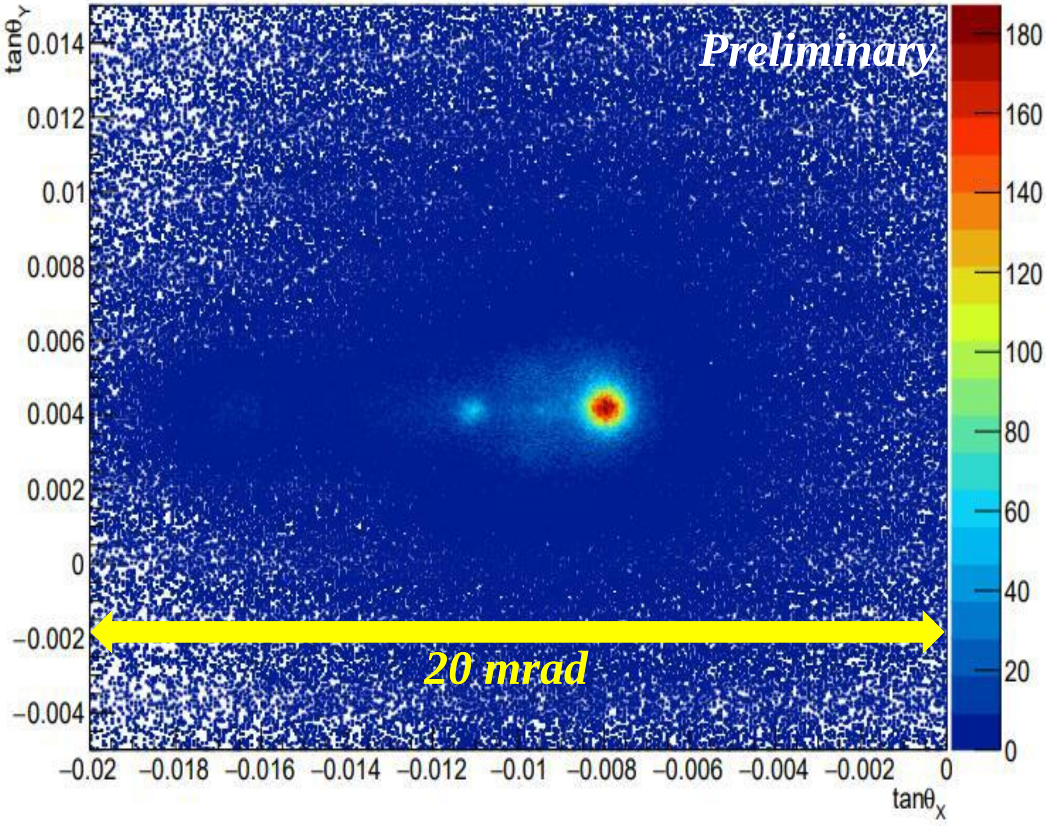


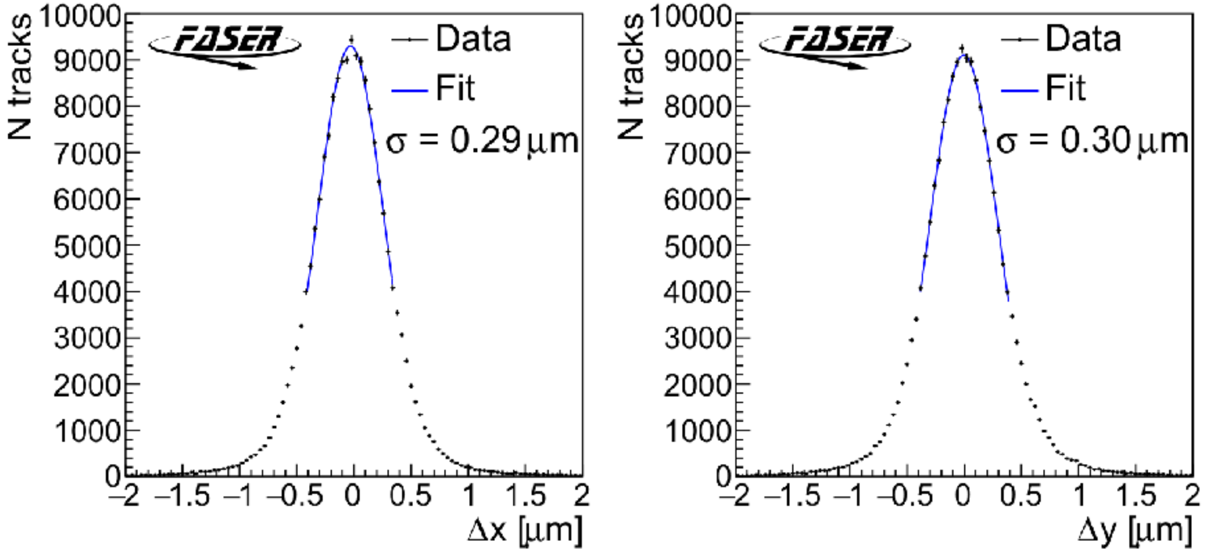

- After development films are transport University of Nagoya, Japan
- Readout by Hyper Track Selector-1 (HTS-1)
  - field of view: 5.1 mm × 5.1 mm
  - 60 – 80 minutes per film

# FASERν detector performance

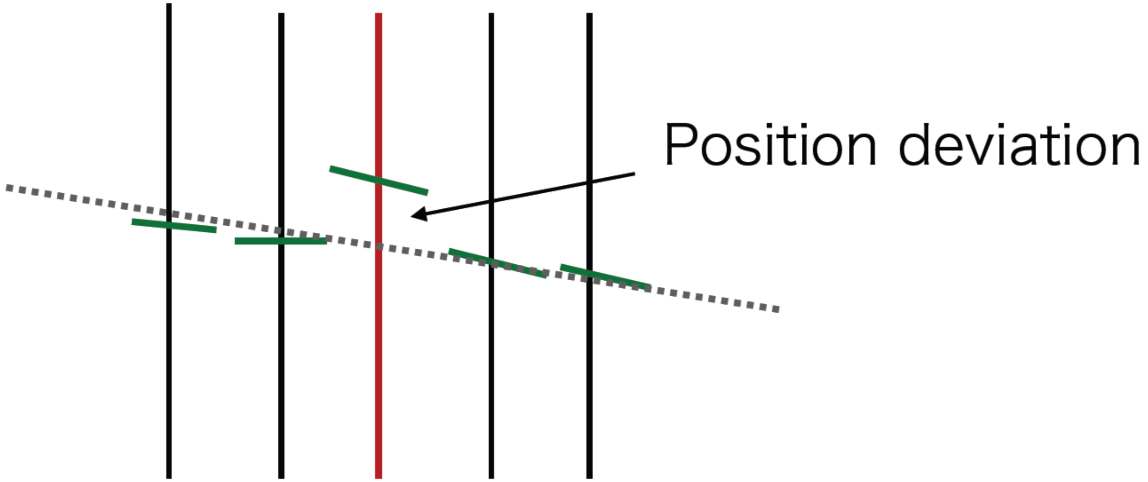
**BG muon angular distribution (Data)**



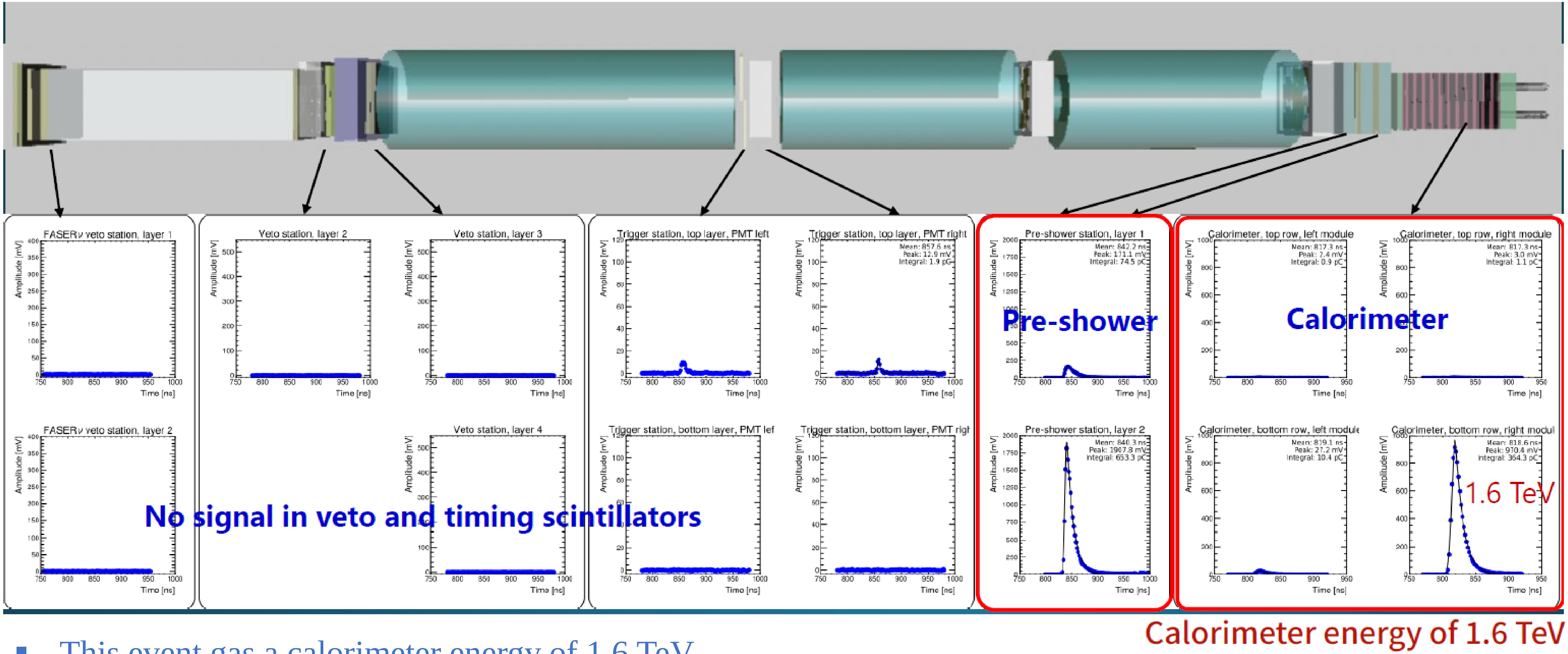

*Angular spread of muon peaks ~**0.4 mrad***




***~ 300 nm** position resolution*



# Event display of 1 selected event: “ALPtrino” event




- This event gas a calorimeter energy of 1.6 TeV
- Shows Pre-shower deposits constant with an EM shower

# Dark Photon

- Dark matter from MeV-GeV can be thermal relics
- Dark photon(A'): U(1) gauge boson, hidden sector particle

Produced in very rare meson decays:

$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- Mass $m_{A'}$
- Kinetic mixing: ε (couplings to SM fermions )

Travels long distances through matter without interacting, decays to e+e- (μ+μ-)

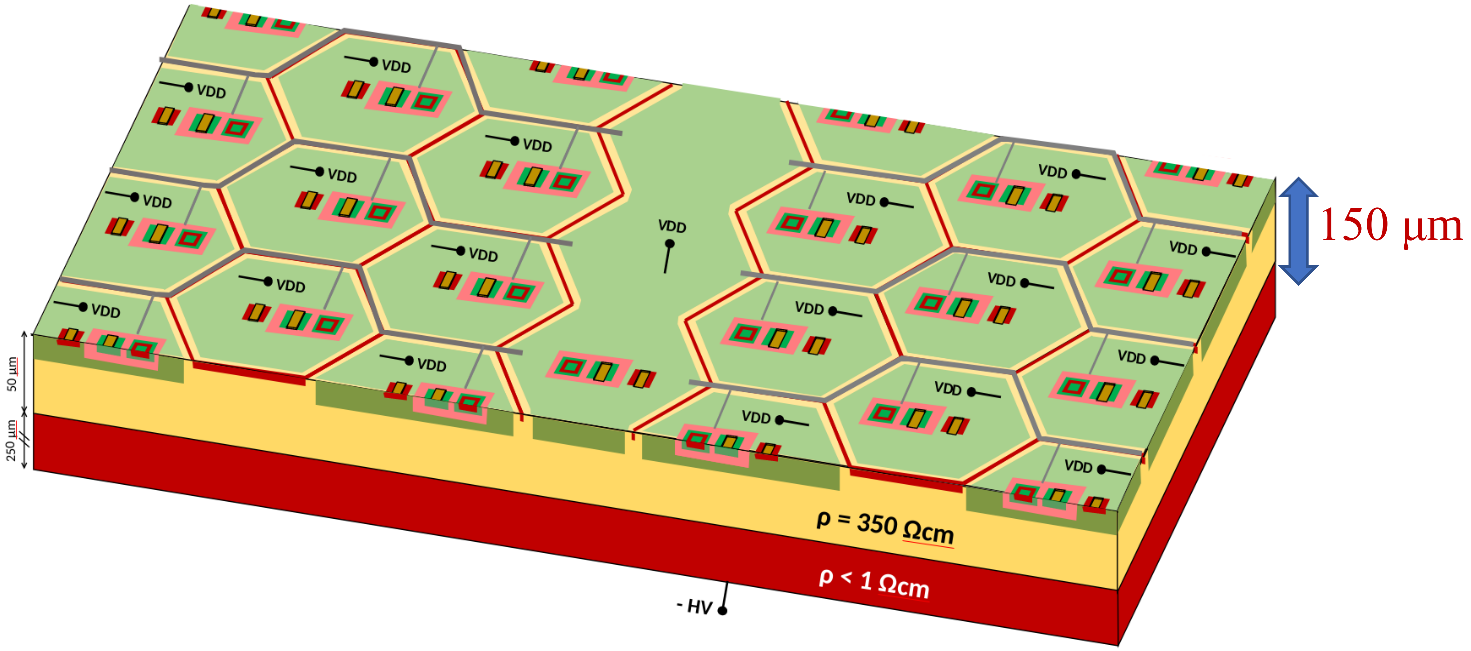
$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2 \qquad (E_{A'} \gg m_{A'} \gg m_e)$$

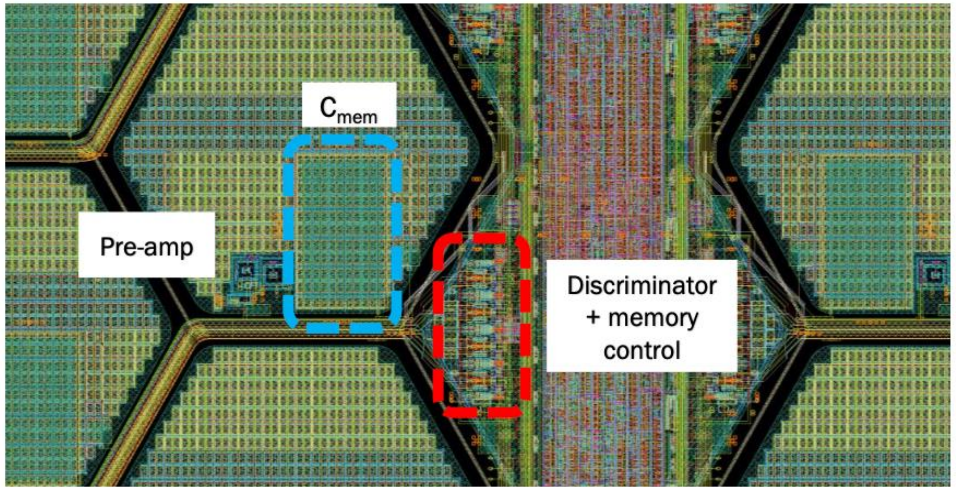
TeV energy at the LHC: **huge boost, decay lengths of ~100 m possible**

Very large number of dark photons are produced. **LHC can be a dark photon factory**

# New Pre-shower Calorimeter

- **Monolithic pixel sensors: 130 nm SiGe BiCMOS technology**




| Main specifications | |
|---|---|
| Pixel size | 65 μm side (hexagonal) |
| Pixel dynamic range | 0.5 ± 65 fC |
| Cluster size | ≈ 1000 pixels |
| Readout time | < 200 μs |
| Power consumption | < 150 mW/cm$^2$ |
| Time resolution | < 300 ps |

- High dynamic range for charge measurement (0.5 to 65 fC)
- Ultra fast readout with no digital memory on chip (minimize dead area)
- Local analog memories to store the charge in pixel.