FASER

NOW 2024
Neutrino Oscillation Workshop

Recent results from FASER at CERN

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on behalf of the FASER collaboration

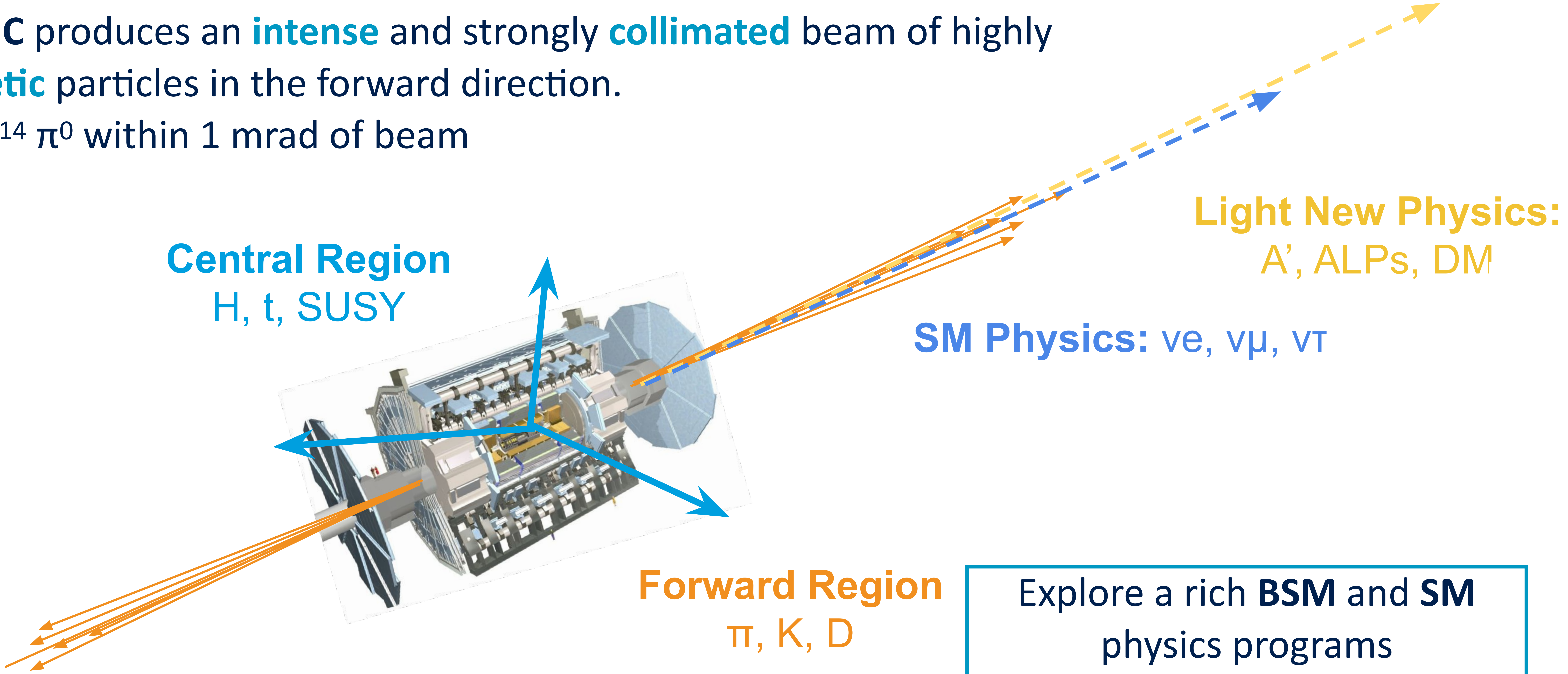
CERN

FASER - New experiment at the LHC Run3

FASER has started operation since July 2022

Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.
e.g. 10^{14} π^0 within 1 mrad of beam



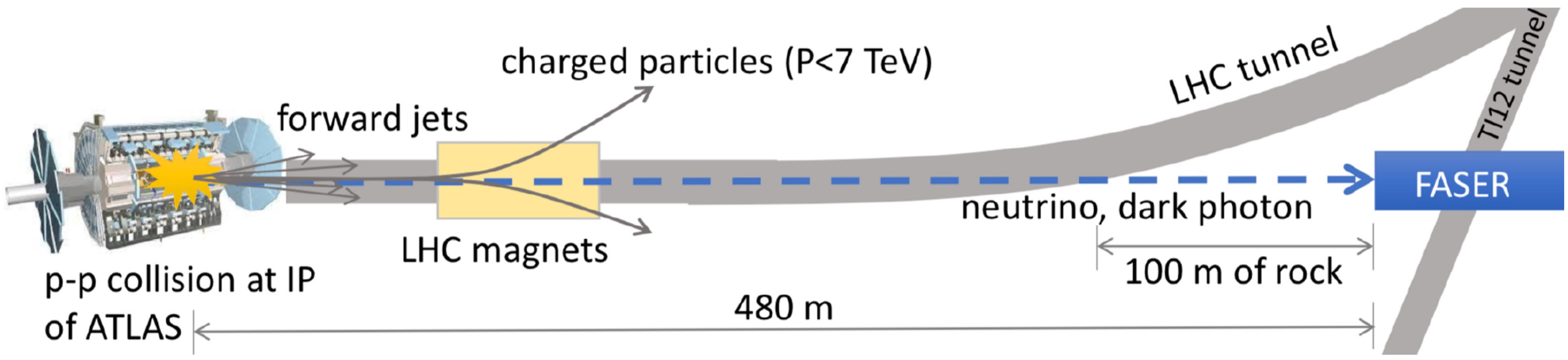
Explore a rich **BSM** and **SM** physics programs
in the far farward region

FASER

- **ForwArd Search ExpeRiment (FASER) at the LHC**
  - Placed **480 m downstream of the ATLAS IP** on the beam axis
  - Started the **operation** from July 2022 (LHC run3)

- **Physics motivation**
  - **New long-lived particle searches** in **MeV-GeV masses**
  - **All flavors of neutrinos** at the **TeV-energy frontier**

- **Favorable location**
  - **Very low background from collision**
    - **Only high-energy muon** at about $1/cm^2/sec$
  - **Low radiation level from the LHC**
    - 4×10^6 1-MeV neutron/cm^2/year



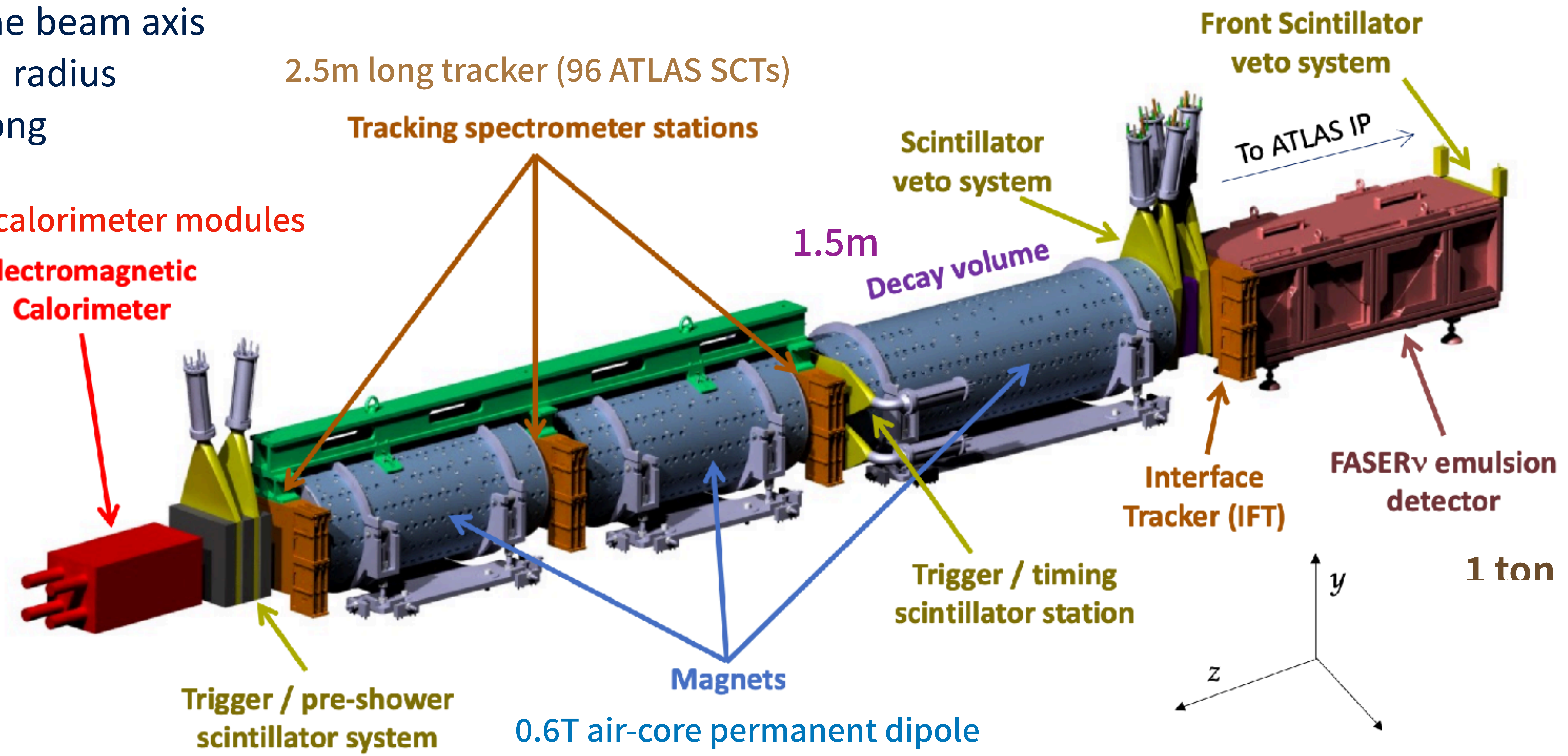
FASER detector

JINST 19 (2024), P05066

On the beam axis
10cm radius
7m long

2.5m long tracker (96 ATLAS SCTs)

4 LHCb calorimeter modules



0.6T air-core permanent dipole

Scintillators for veto, trigger, and preshower (particle ID)

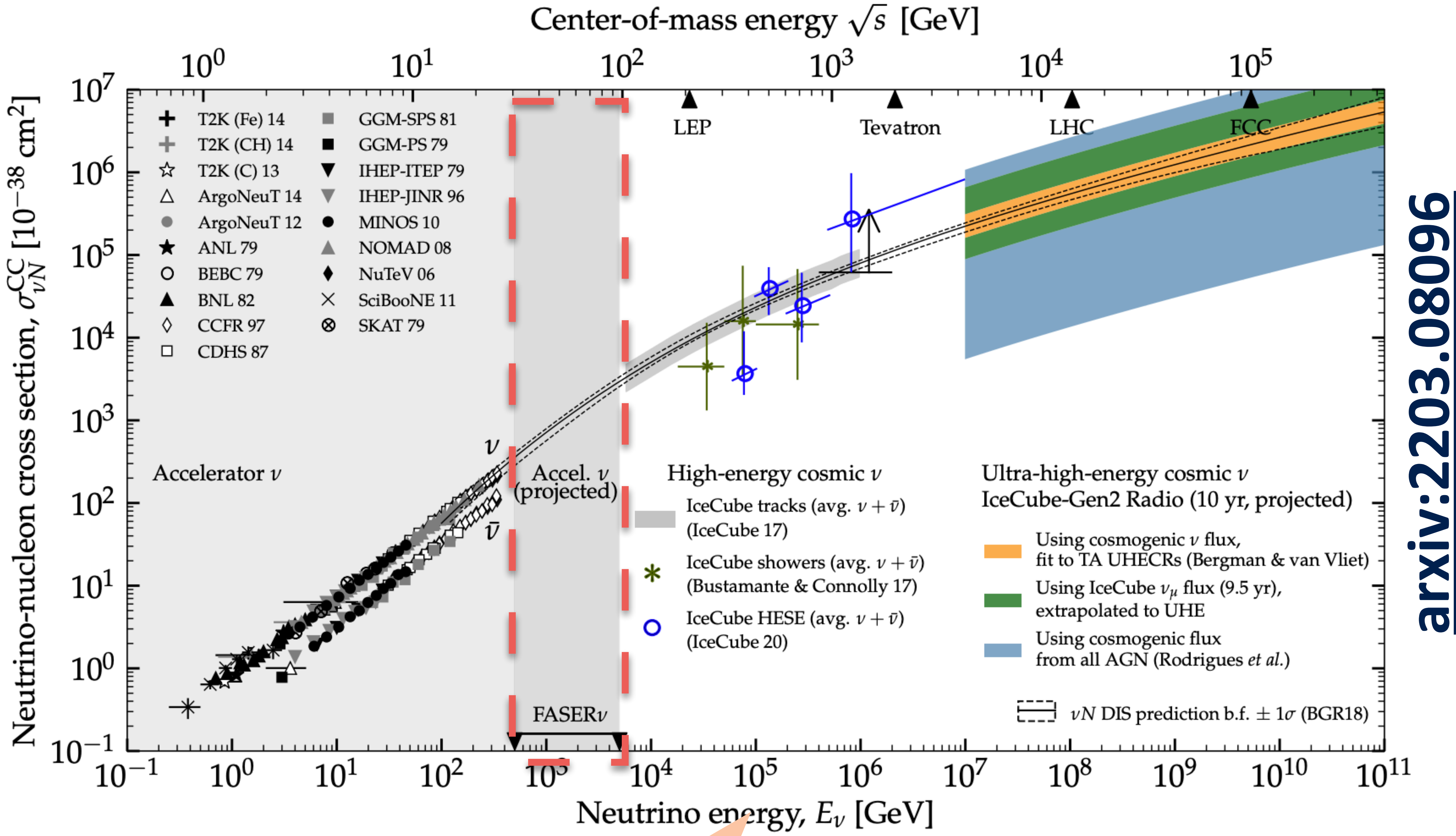
All detector components are successfully installed in T12 in March 2022

Neutrino Physics

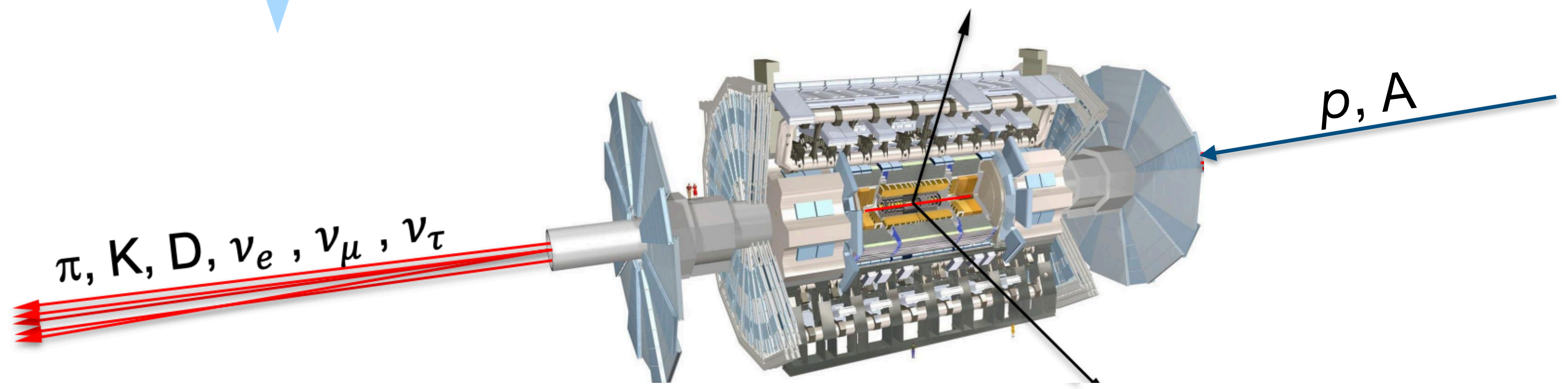
Collider neutrinos w/ FASER

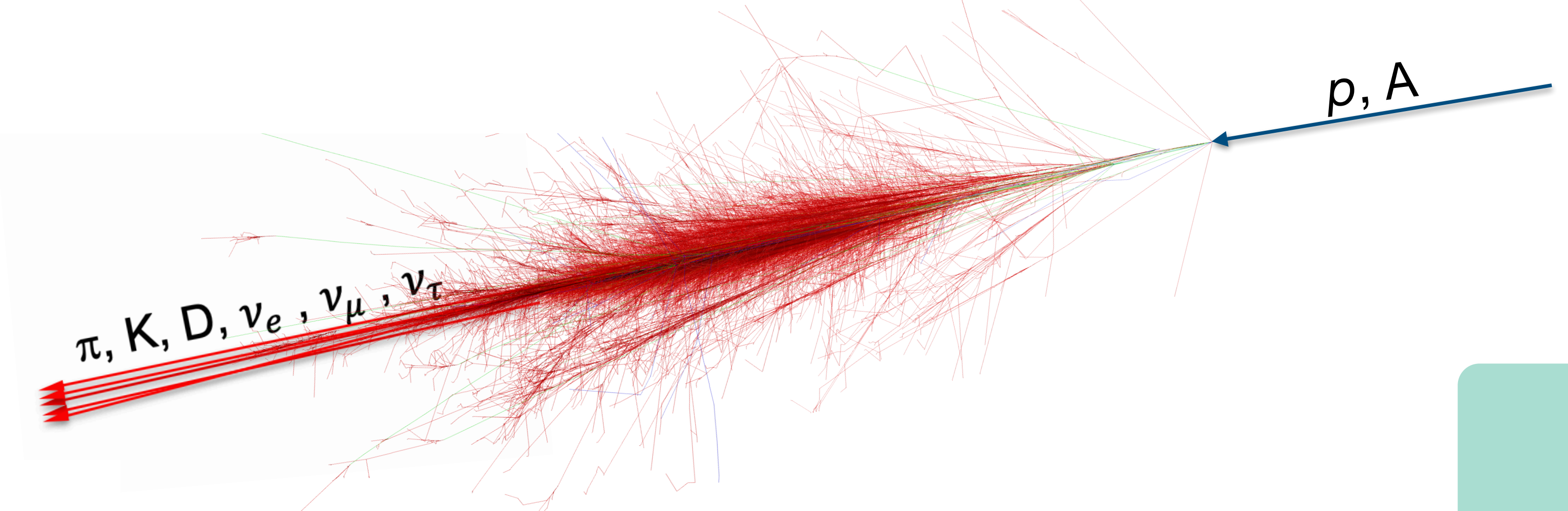
$\sqrt{s}$ = **13.6 TeV ⇄ lab. frame 100 PeV p-p interaction**

Possible to study hadron interaction models of neutrino flux e.g. application into air-showers study like prompt neutrino



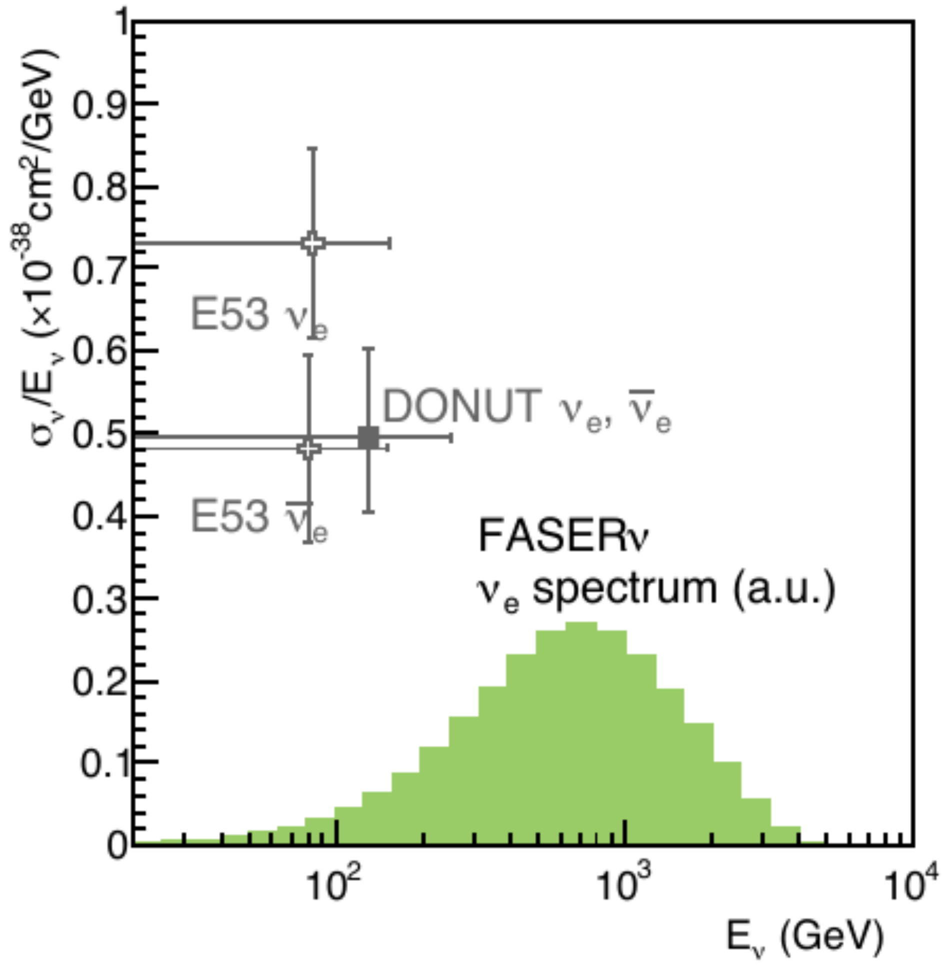
arxiv:2203.08096

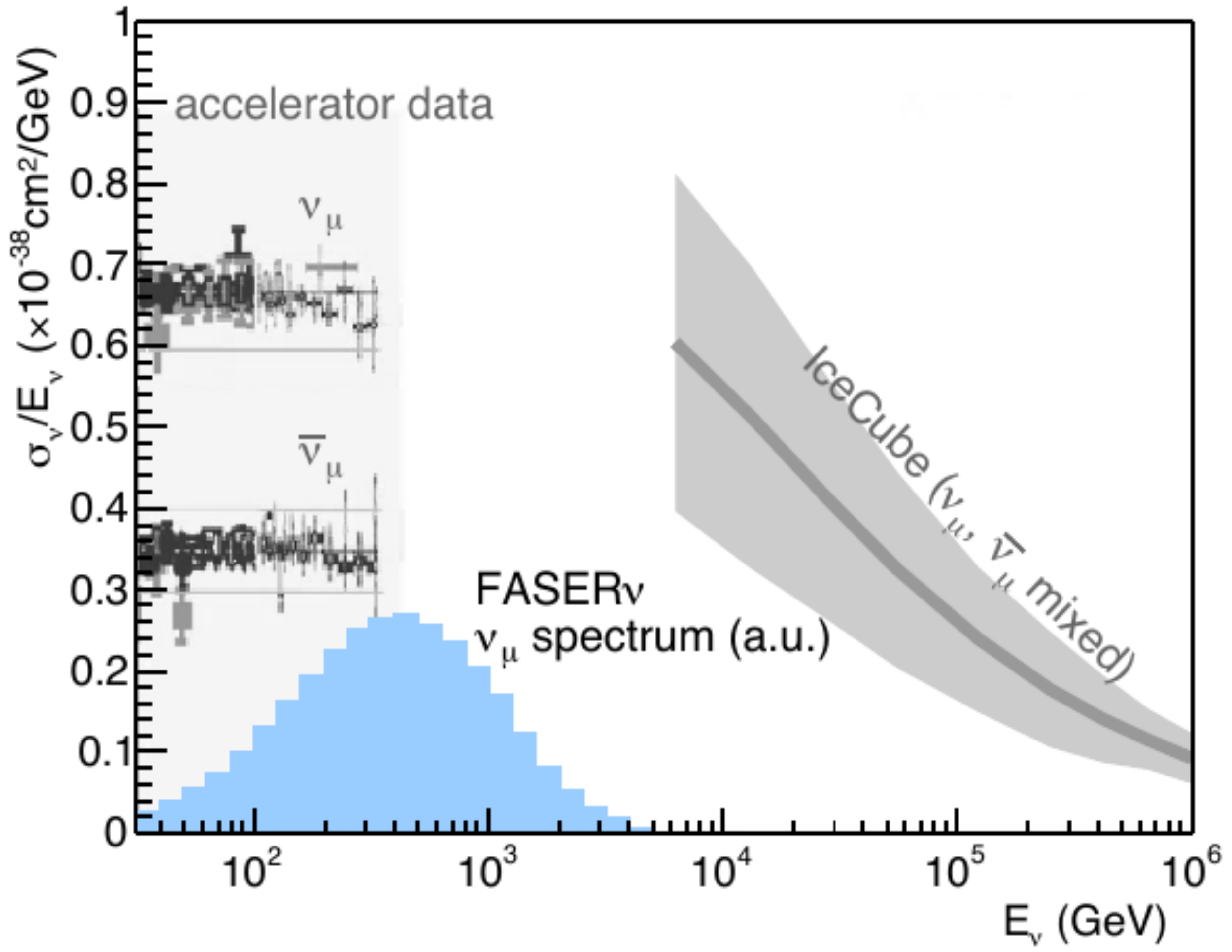




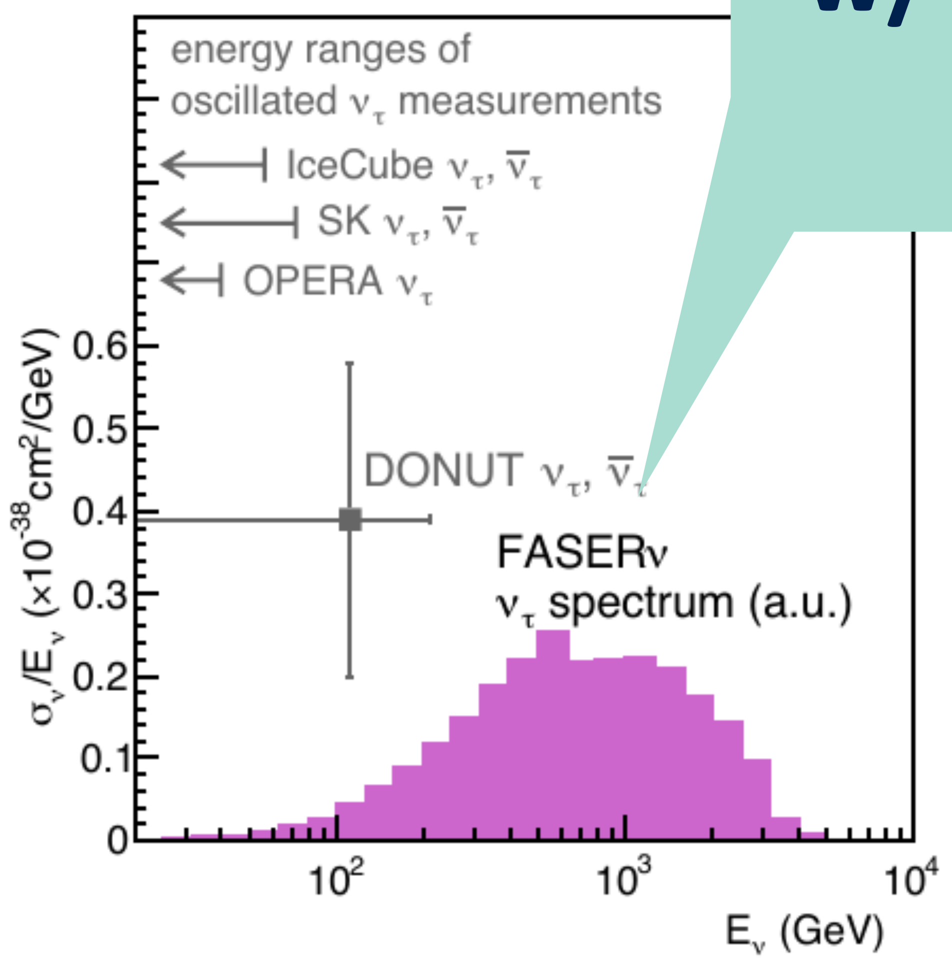
GeV-TeV ν beam

Fill **gaps** between fixed target experiments and cosmic-ray experiments **w/ highest energy human-made TeV neutrinos**





w/ all flavors



Neutrino flux

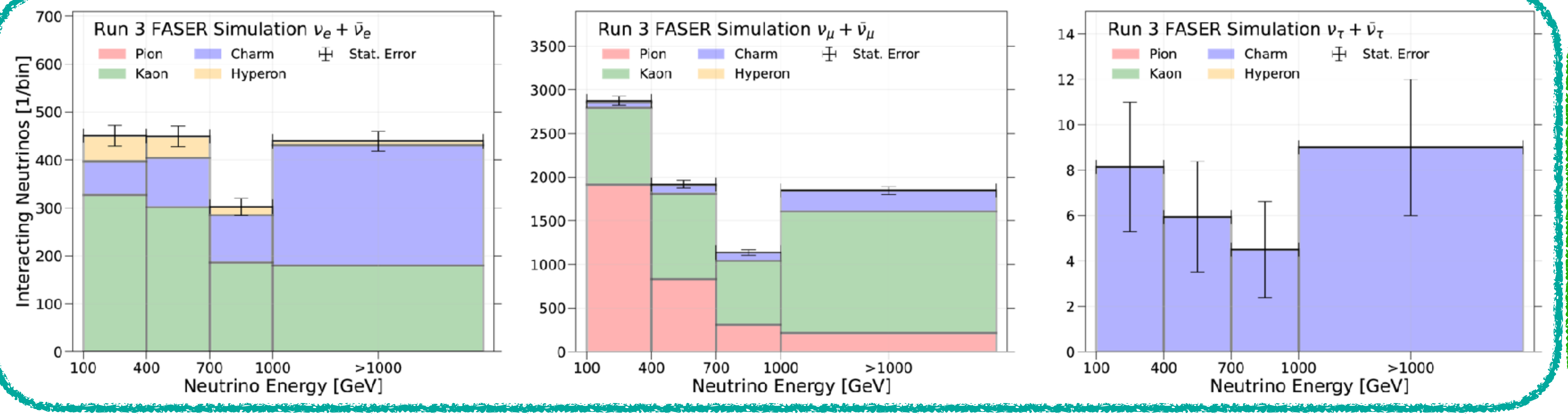
Phys. Rev. D 110, 012009

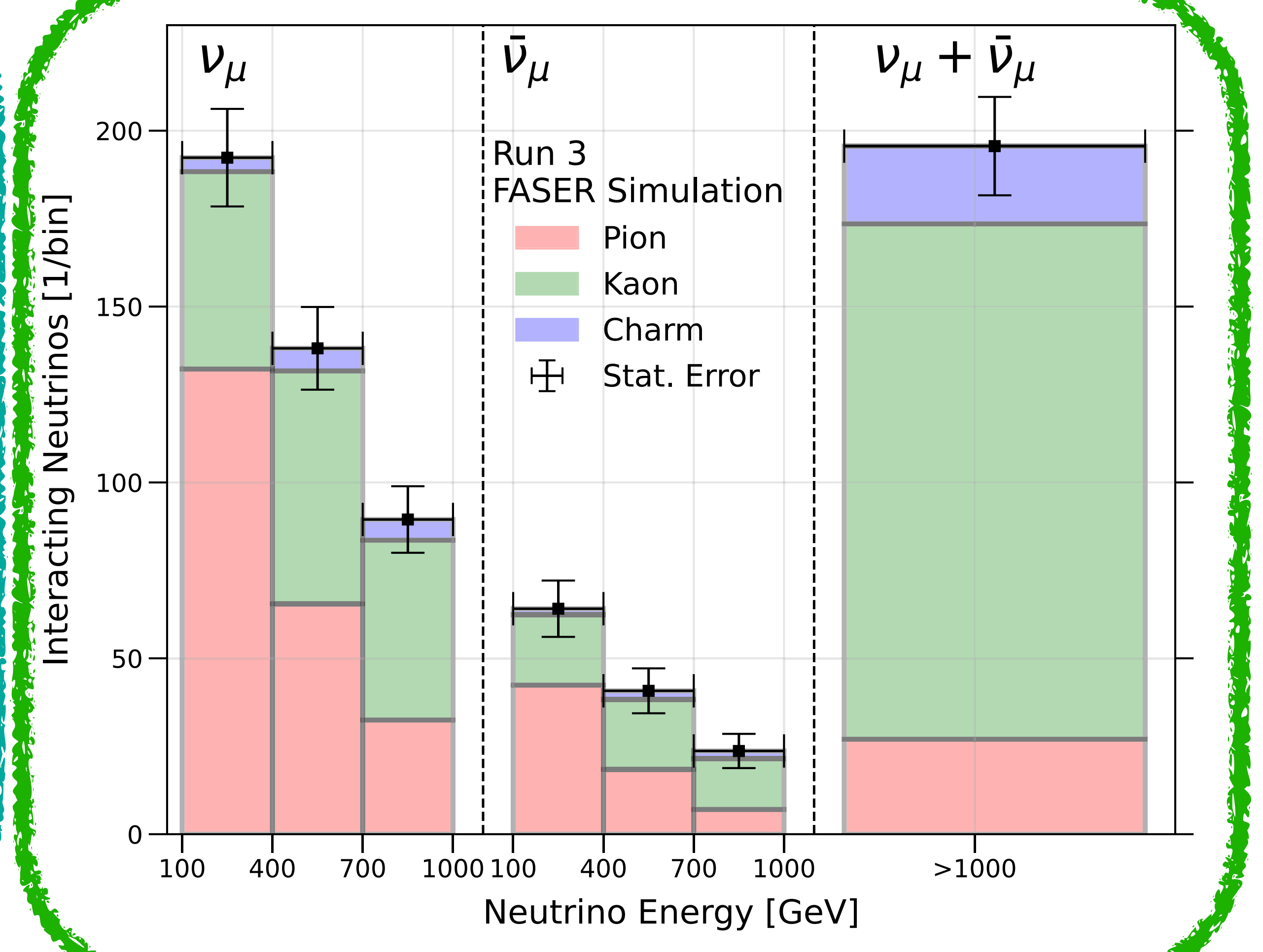
FASERν (Emulsion-based detector)

Sensitive to all 3 flavors

“Electric” detector technique

Charge separation $\nu_\mu/\nu_{\bar{\mu}}$





- **Two strategies for measurements**
  - Emulsion-based detector → all flavor sensitive
  - “Electric” detector technique → $\nu/\bar{\nu}$ separation
- $\sim$10,000 neutrinos should be collected

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

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^{+18}_{-12}

Neutrino flux

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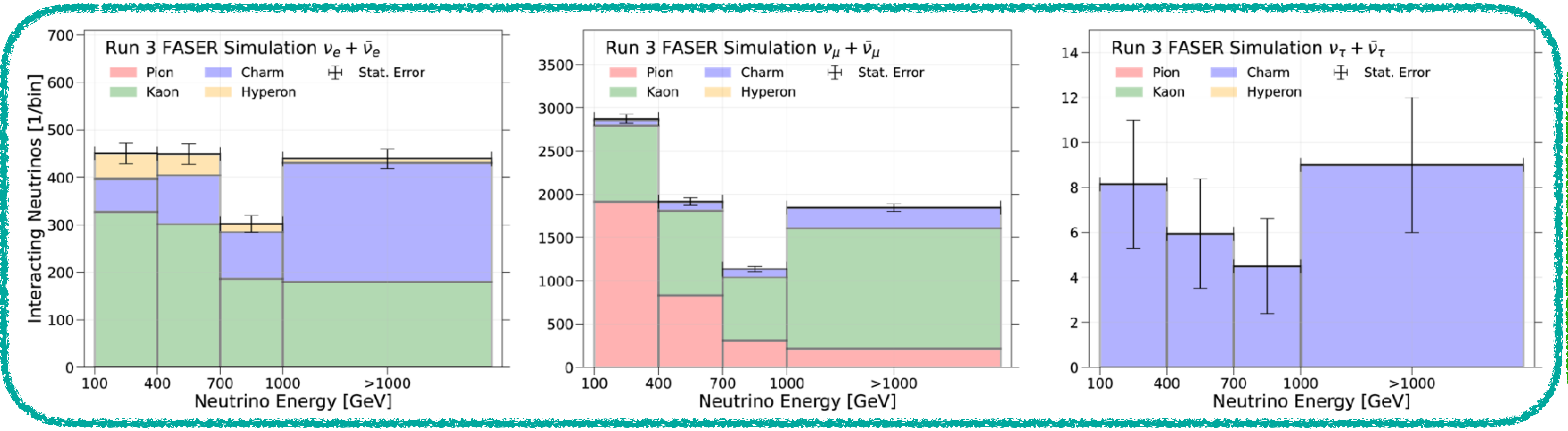
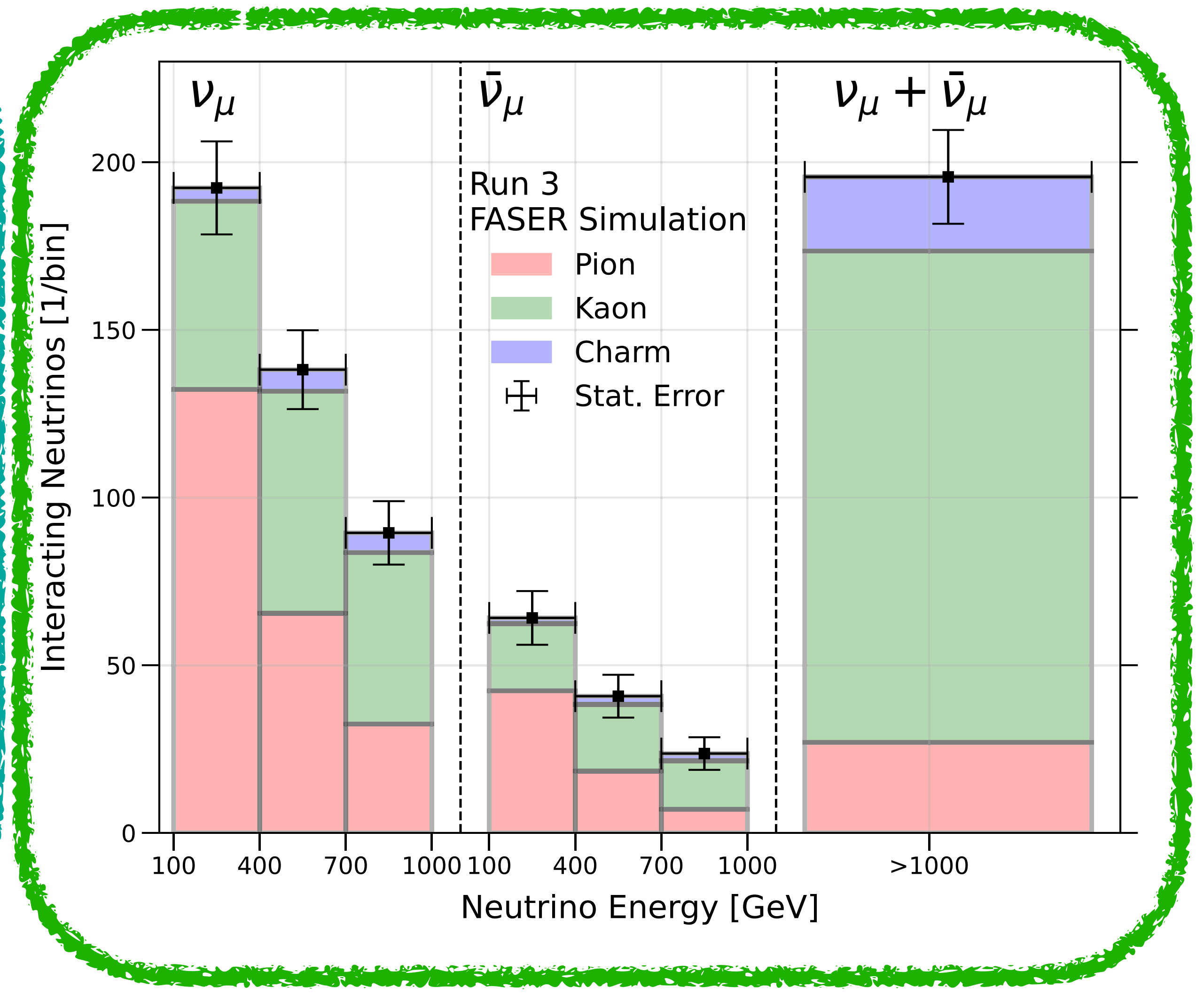
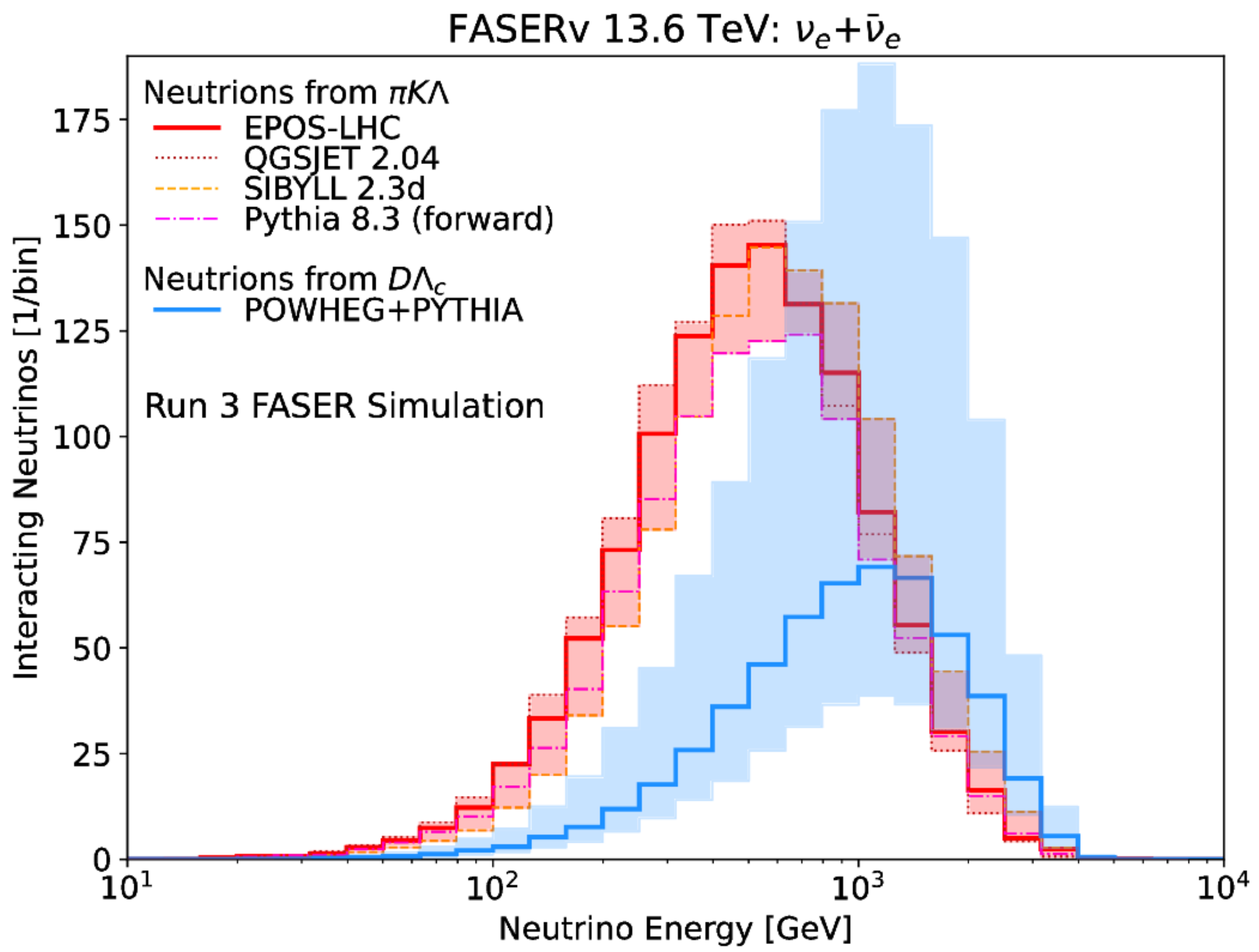
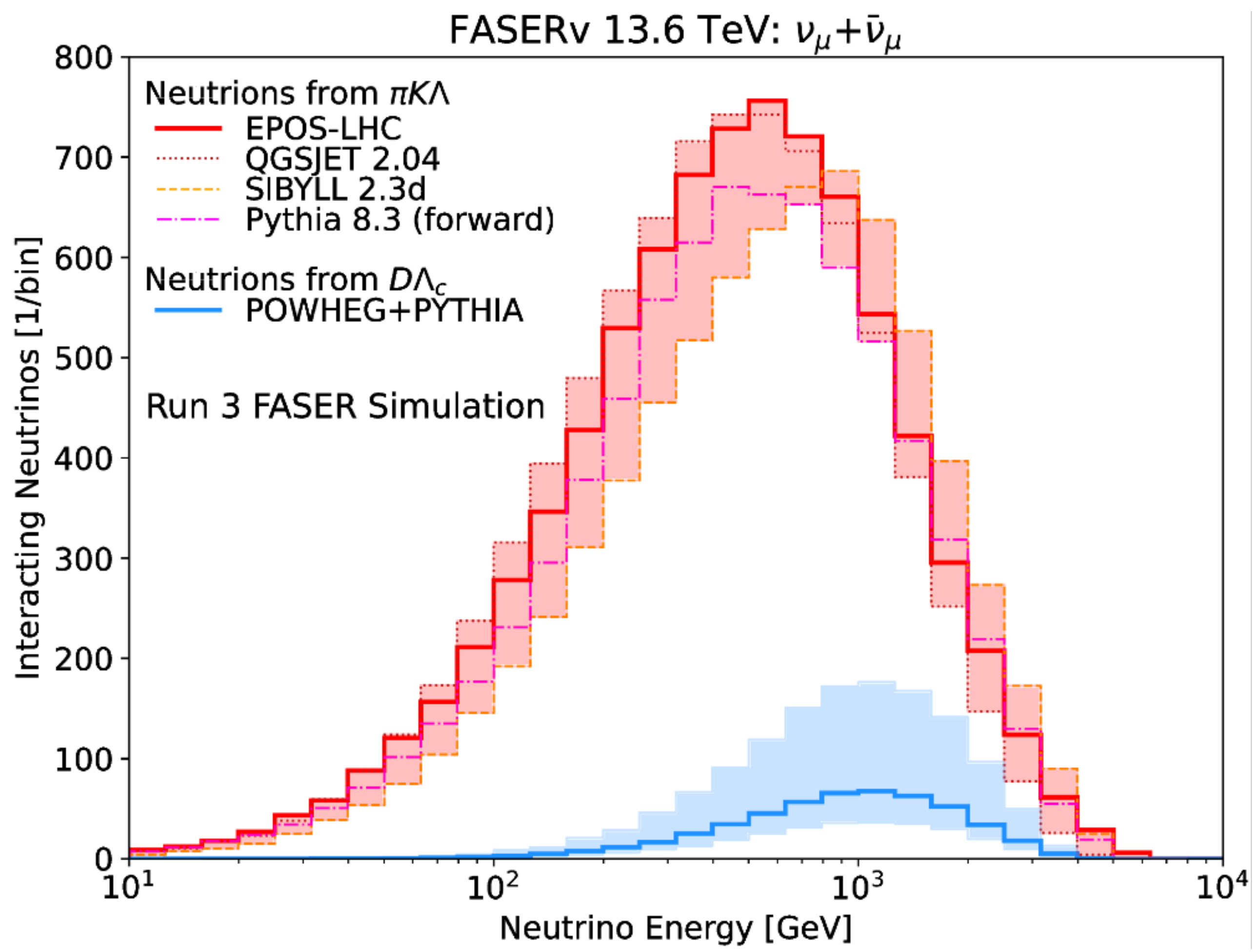




- **Flux uncertainties**
  - about 10-15% from light hadrons
  - 50-100% from **charm**

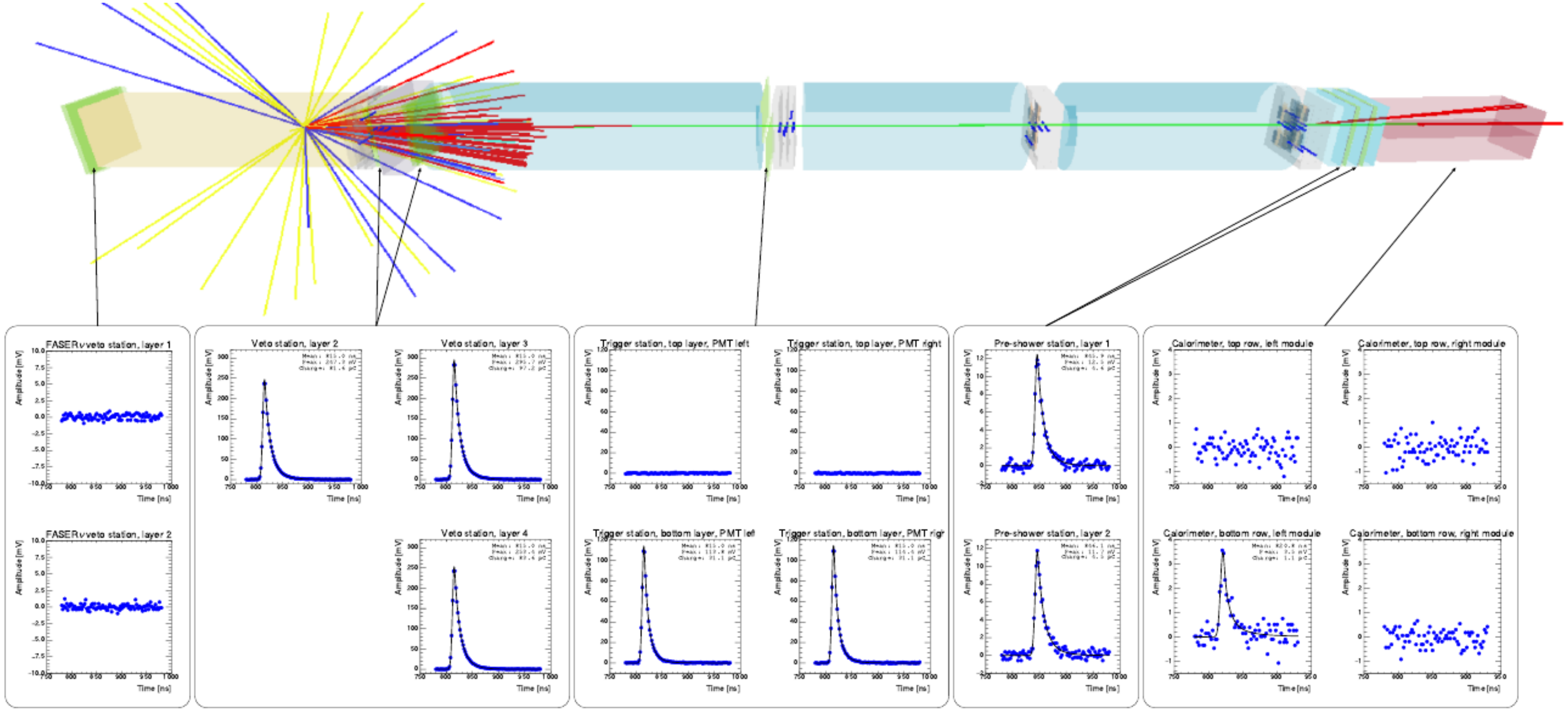




Observing Neutrino Candidates in FASER spectrometer

- Try to make a first observation of neutrinos using trackers and veto system
- Signal: **no signal in two front veto** and **one high momentum track** in the rest of detector

1. Good collision events
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos
4. Timing and preshower consistent with ≥1 MIP
5. Exactly **1 good fiducial** (r < 95 mm) track
   - p_T>100 GeV and θ<25 mrad
   - Extrapolating to r<120 mm in front veto



Expect **151 ± 41 signals** from **GENIE simulation**

- Uncertainty from DPMJET vs SIBYLL
- No experimental errors

Background

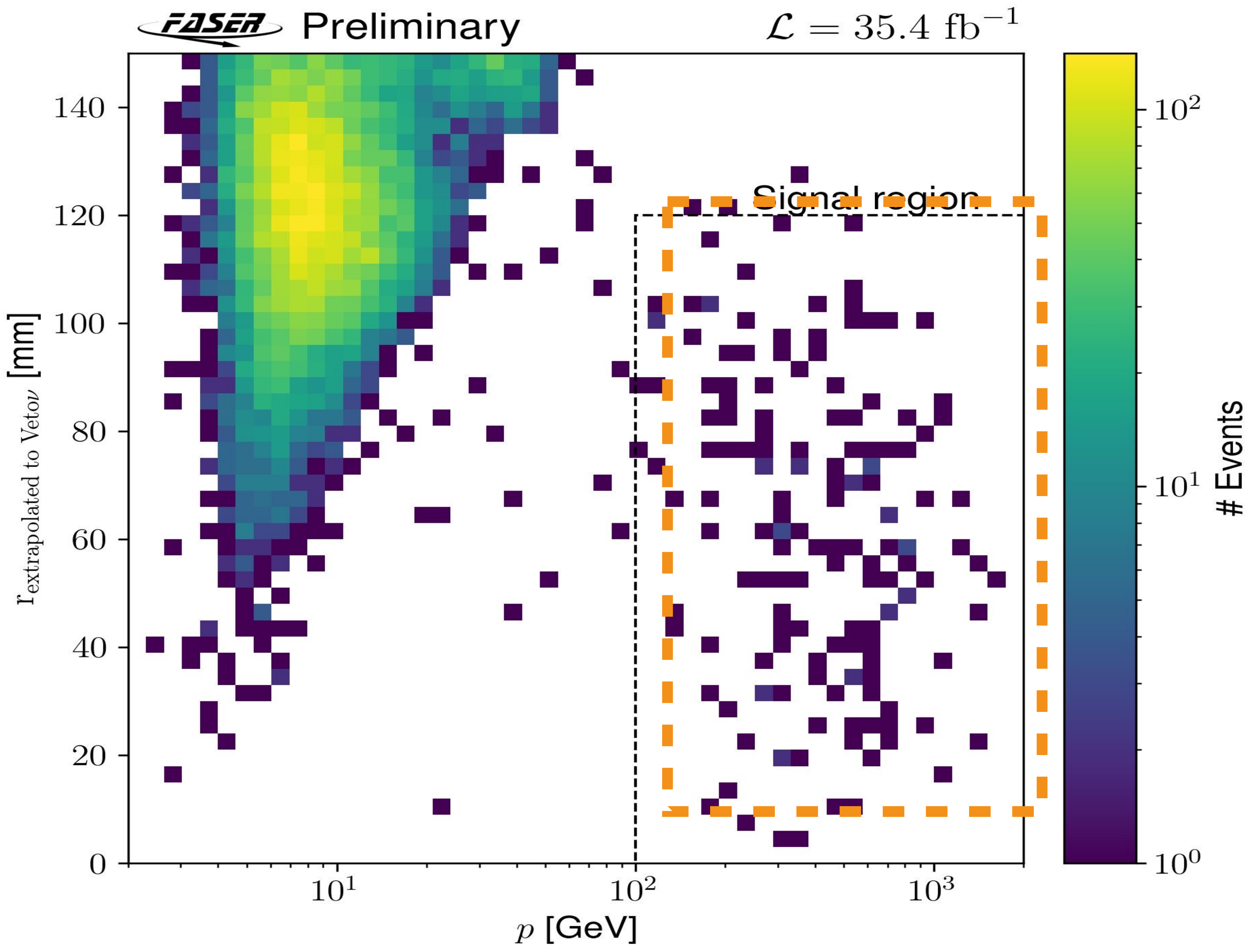
- Veto inefficiency: negligible
- Neutral hadrons: **0.11±0.06** events (MC)
- Scattered large-angle muons: **0.08±1.83** events (sideband)

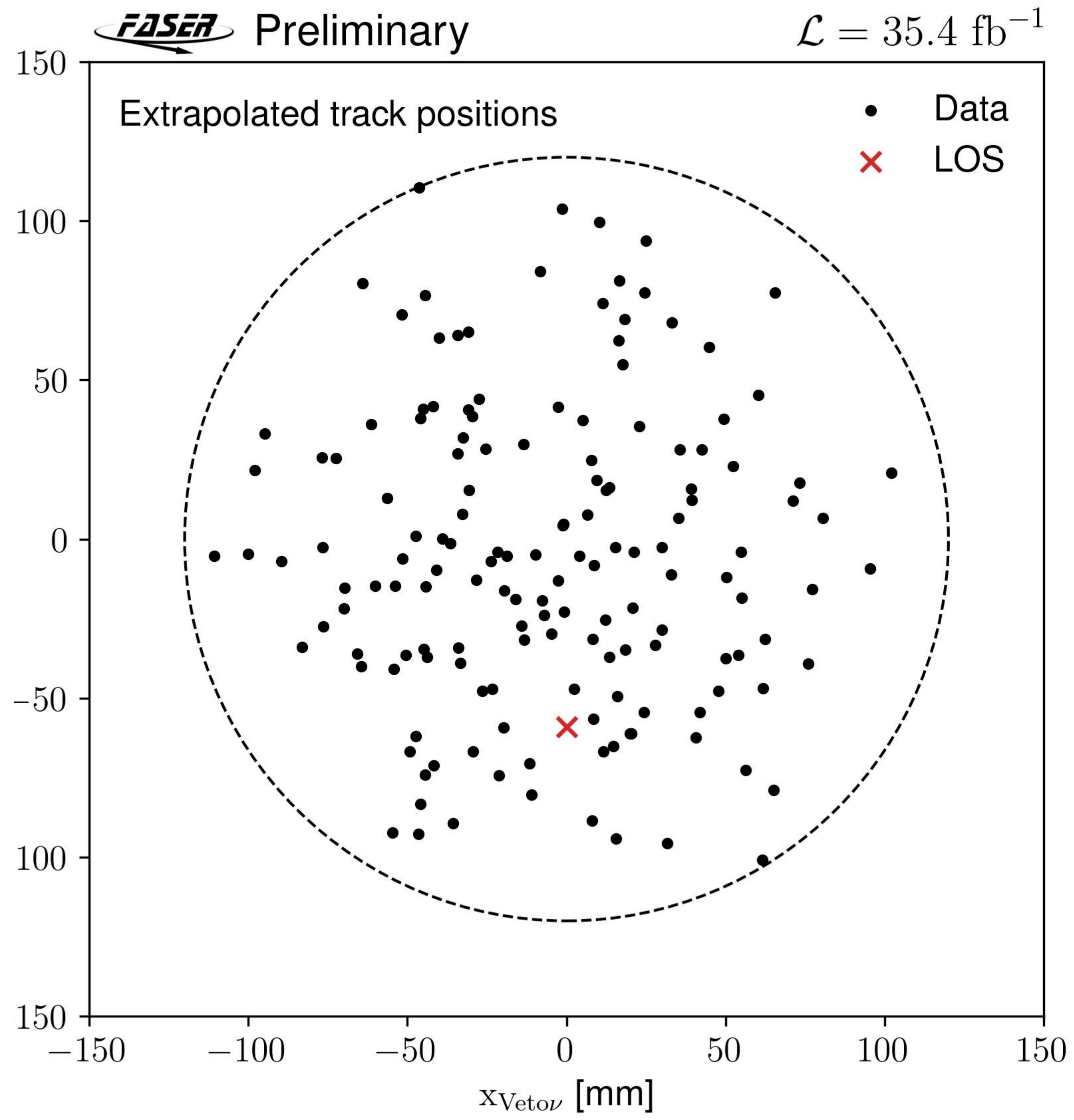
First detection of collider neutrino

Phys. Rev. Lett. 131, 031801 (2024)

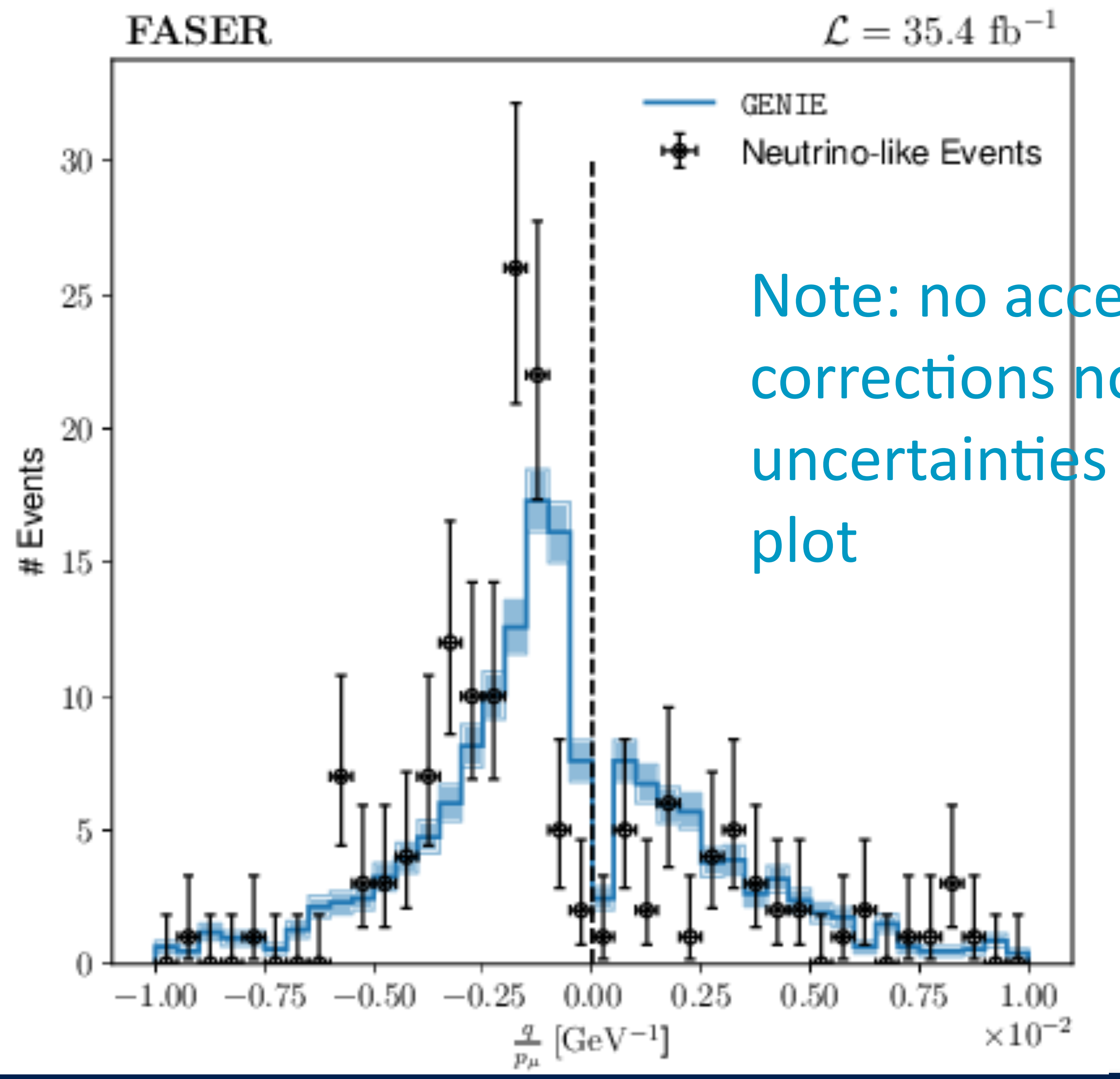
- Upon unblinding find **153 events** with no veto signal
  - Just 10 events with one veto signal
- **First direct detection of collider neutrinos!**
  - **With signal significance of 16σ**
- Candidate neutrino events match expectation from signal
  - see both neutrinos and anti-neutrinos with about the expected

Candidate	Events
ν enriched Events (Passed all event selection)	153, (151±41, MC)
Events (1 veto signal at the first layer)	4
Events (1 veto signal at the second layer)	6
Events (Veto signals for both layers)	64014695





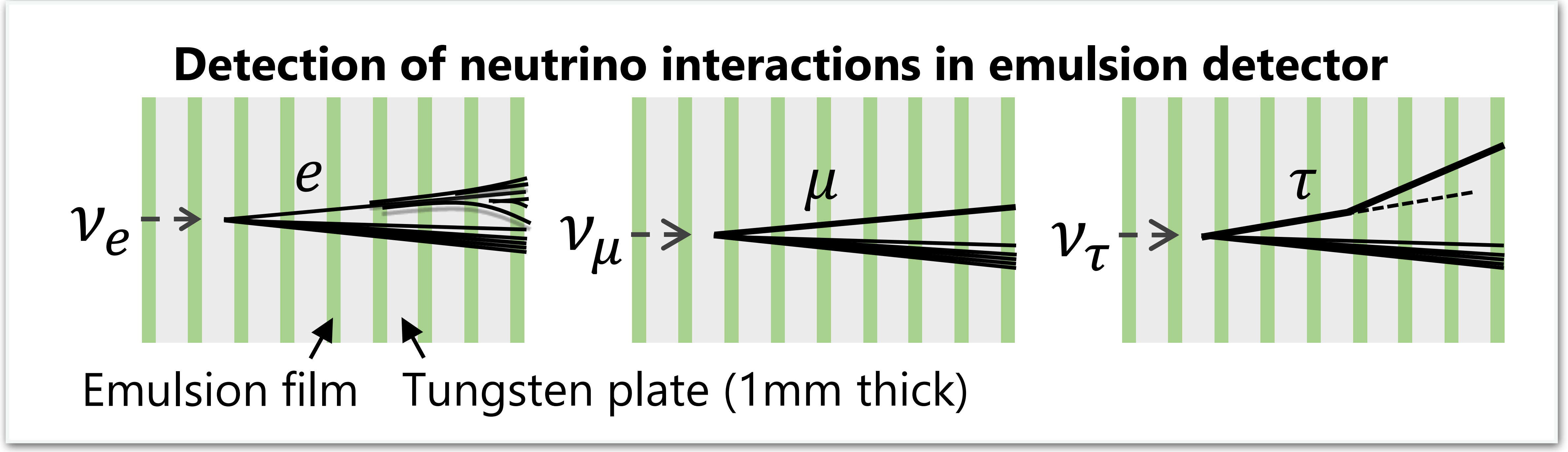
Track momentum distribution



Note: no acceptance corrections nor any uncertainties in the plot

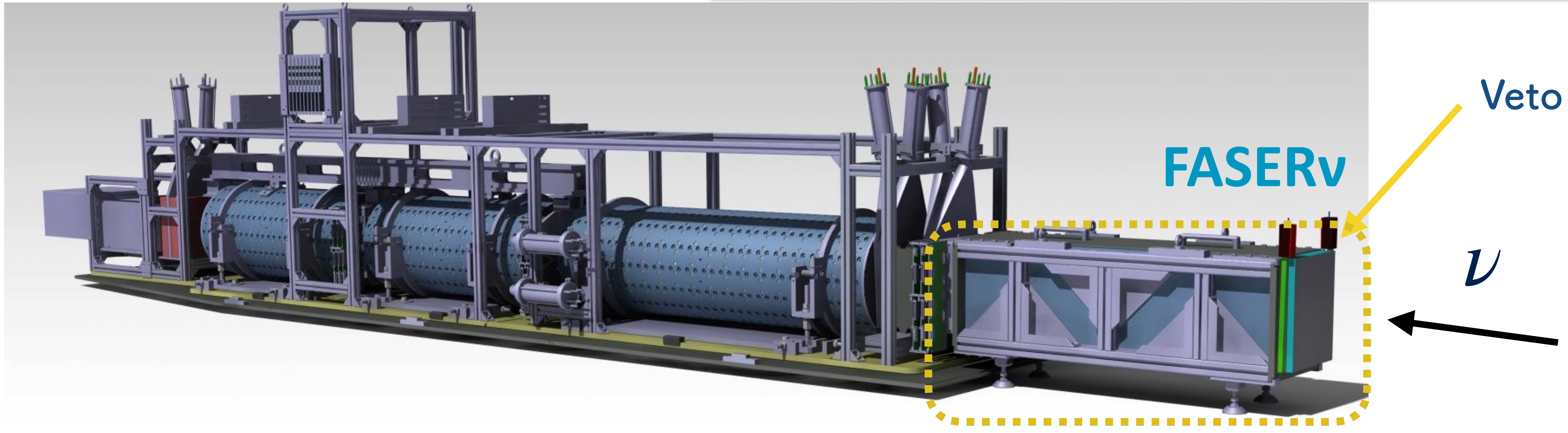
FASERν Emulsion detector

flavor tagging with topological/kinematical informations



Emulsion/tungsten detector

- 730 x [tungsten plates(1.1 mm thickness) + emulsion films, 25×30 cm^2, 1 m long, 1.1t (220 X_0)
- **Emulsion films will be replaced every 30-50 fb^{-1}**
  - (3 times per year)



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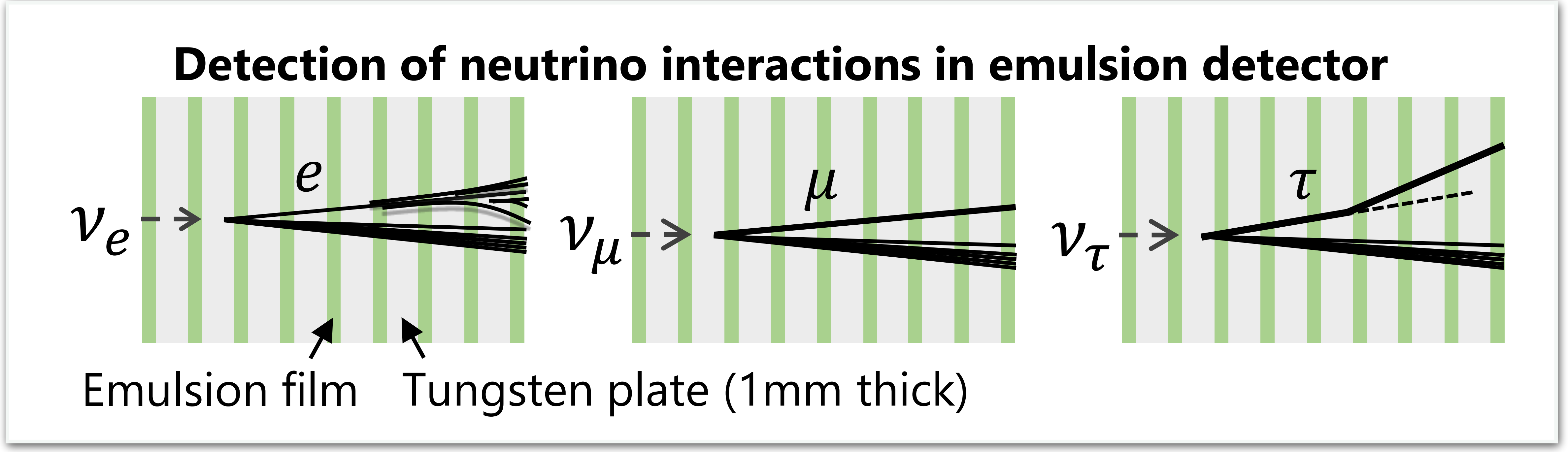

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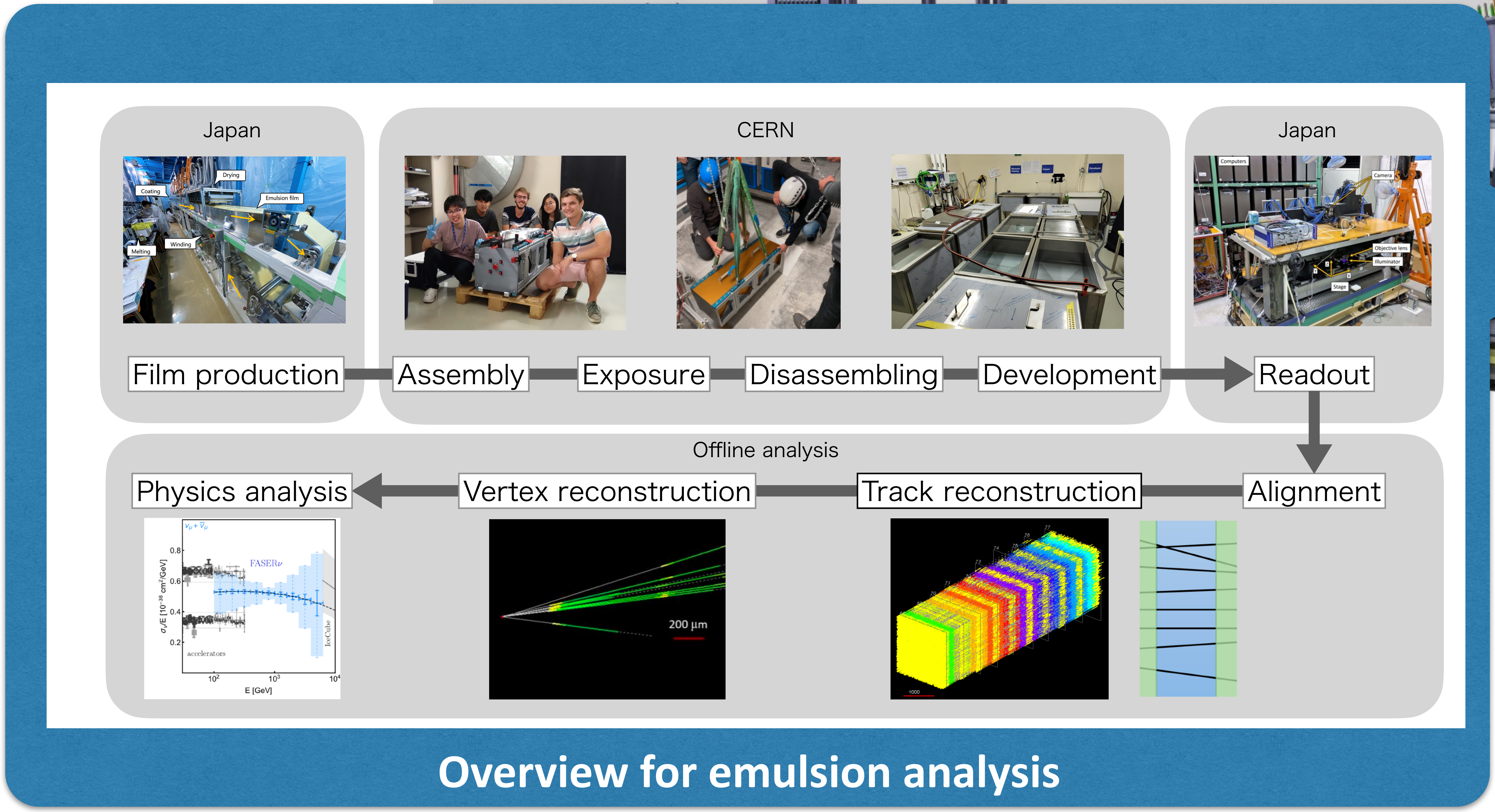

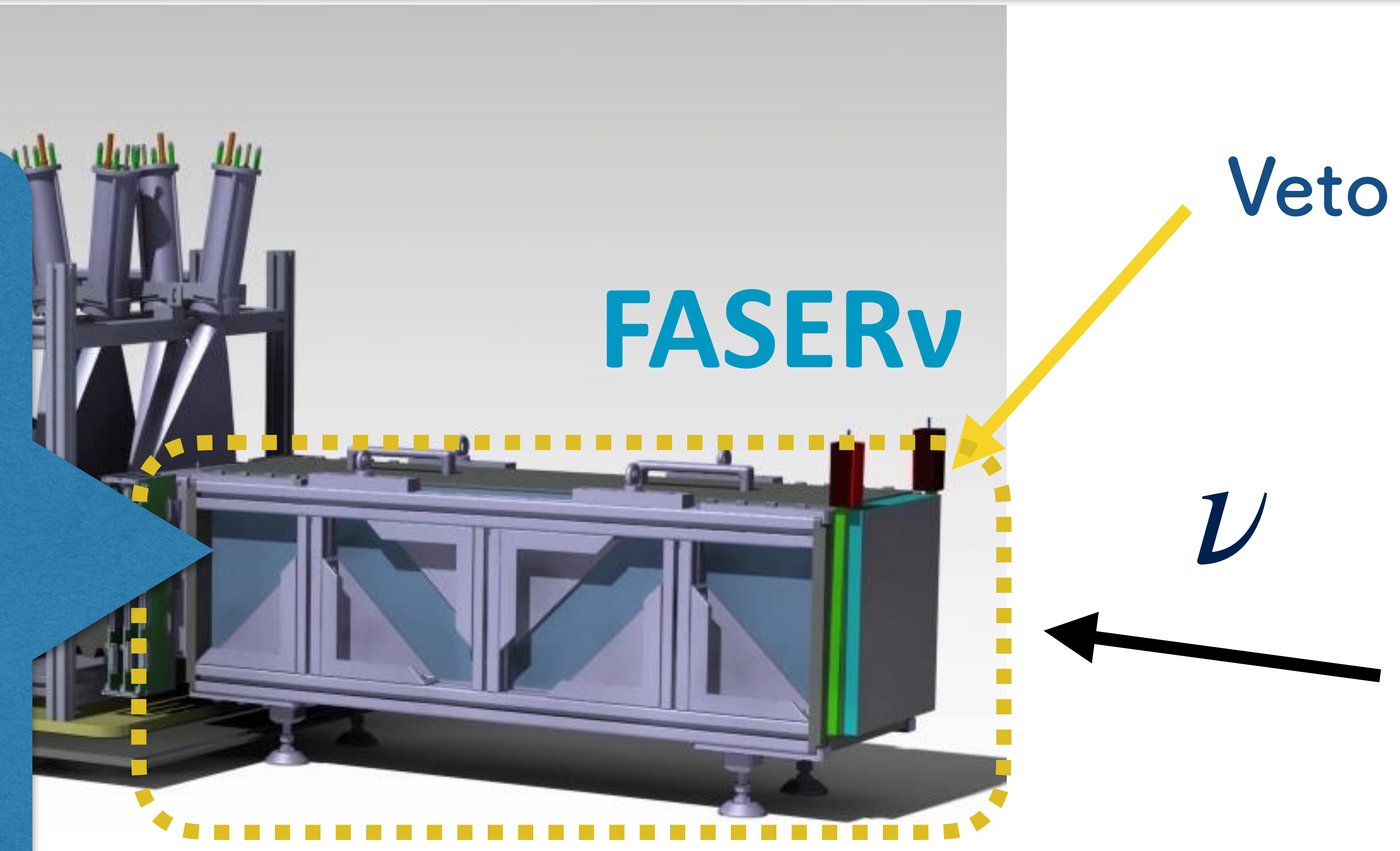

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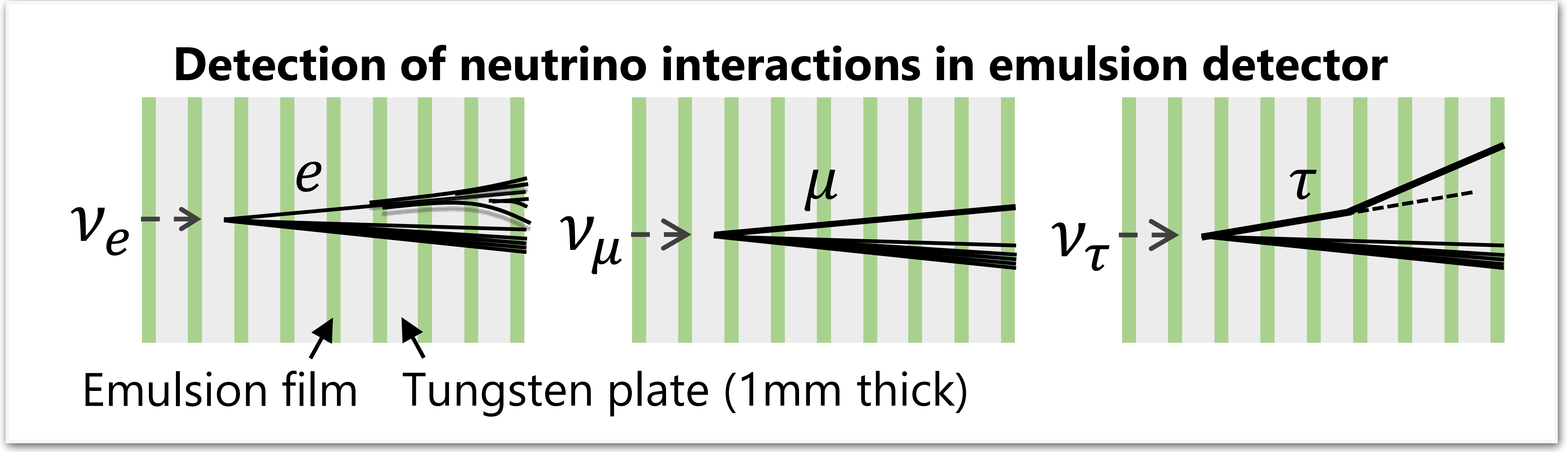

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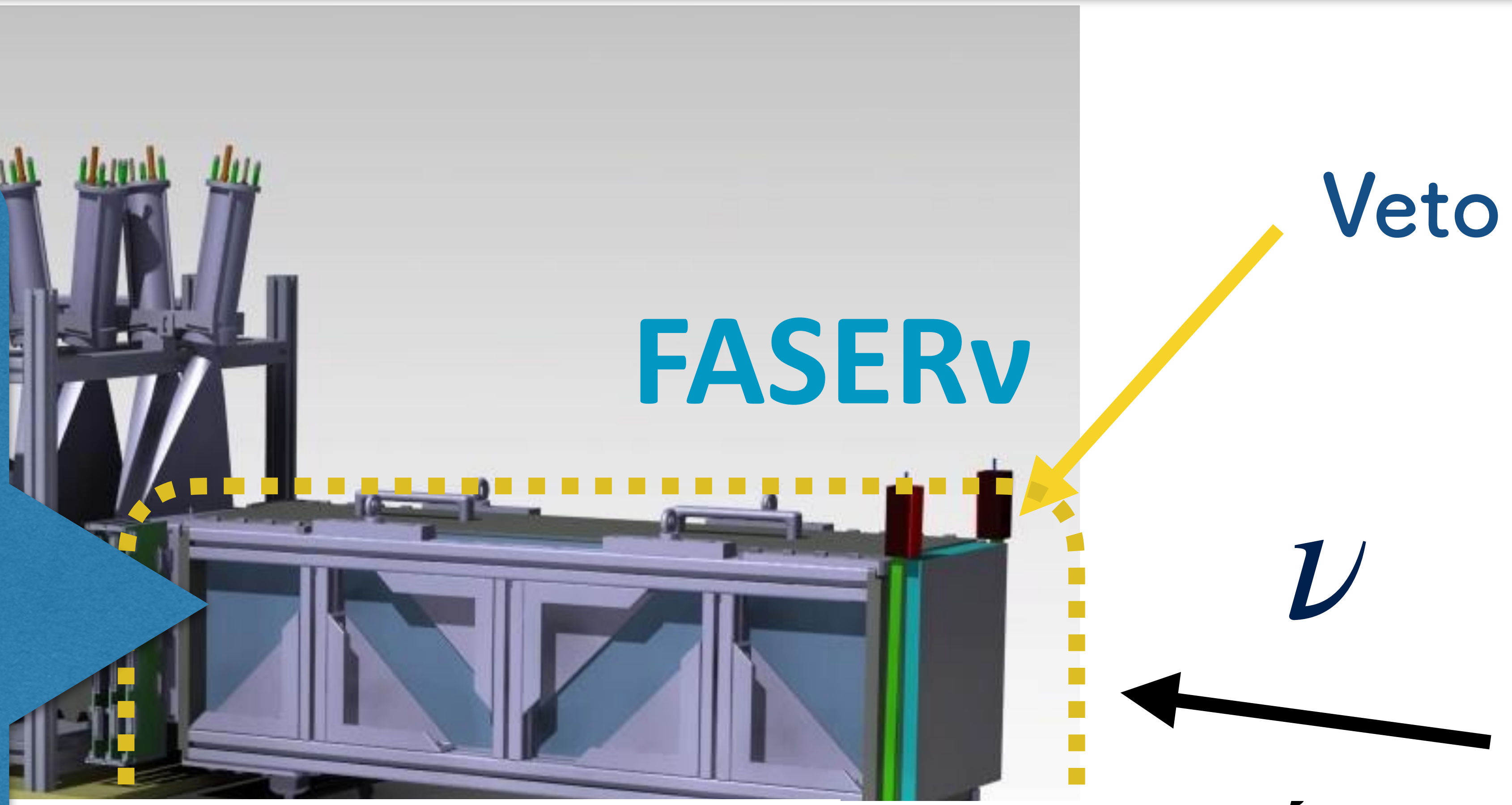
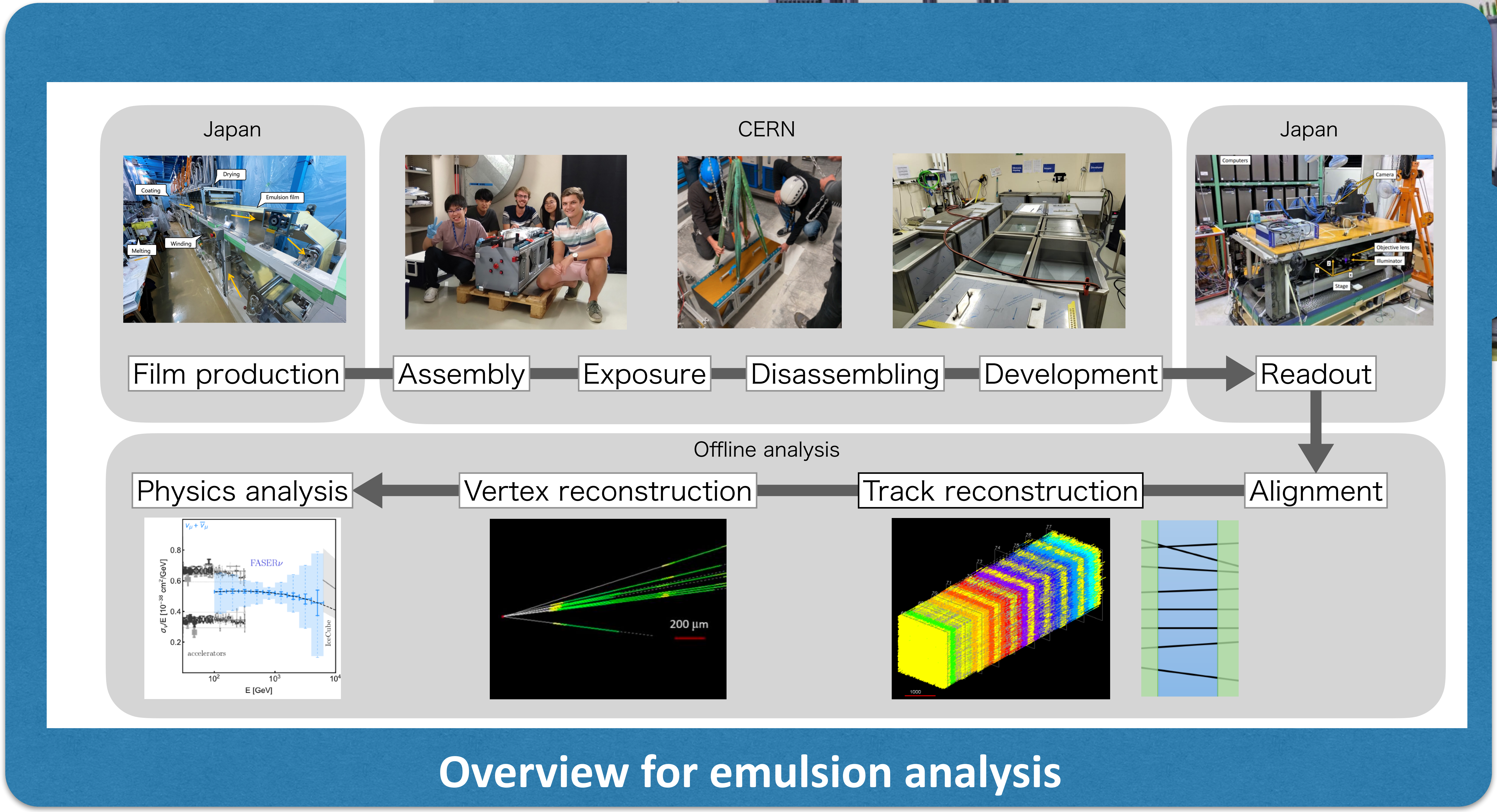
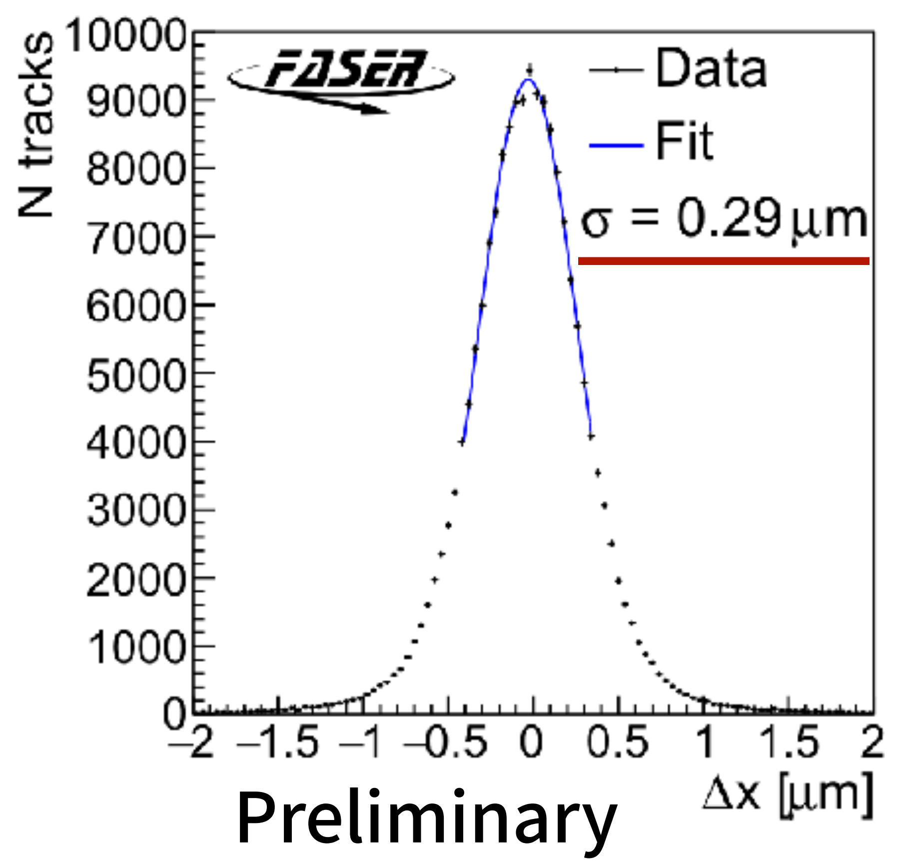
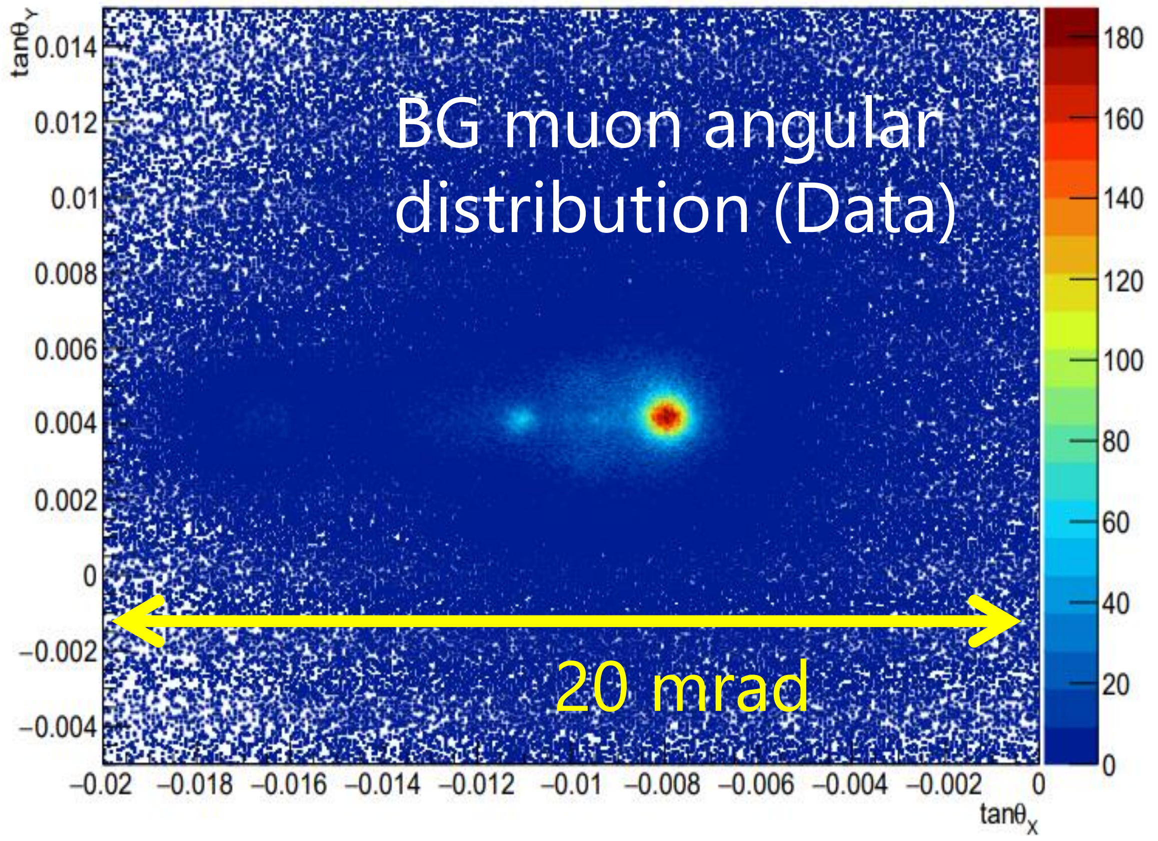




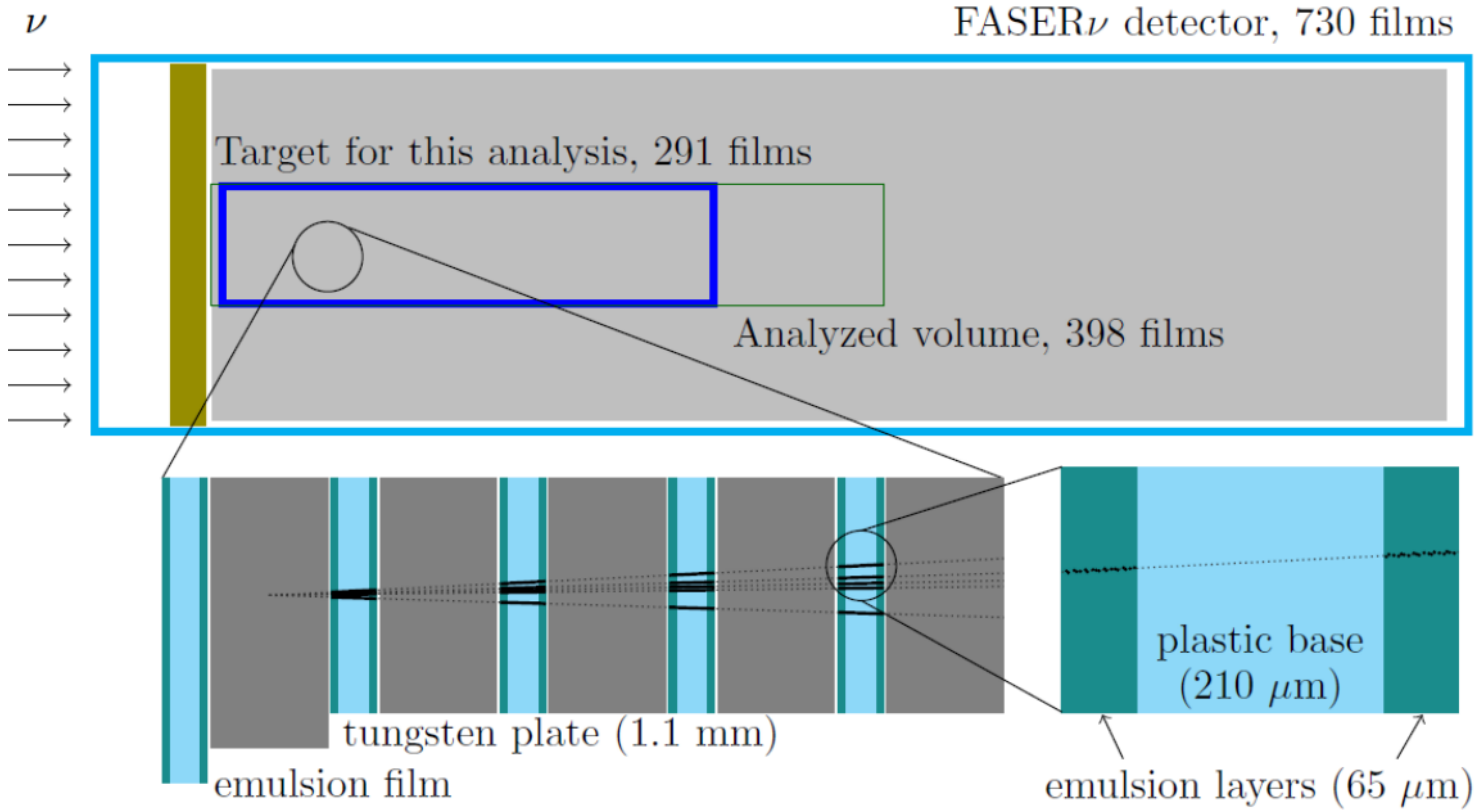




FASERν Analysis toward ν_e and ν_μ detections

Data set:

- 2022 second module→9.5 fb^{-1};
  - Target mass: 128.6 kg;
  - ~ 1.7% of data collected to date.



Selection criteria:

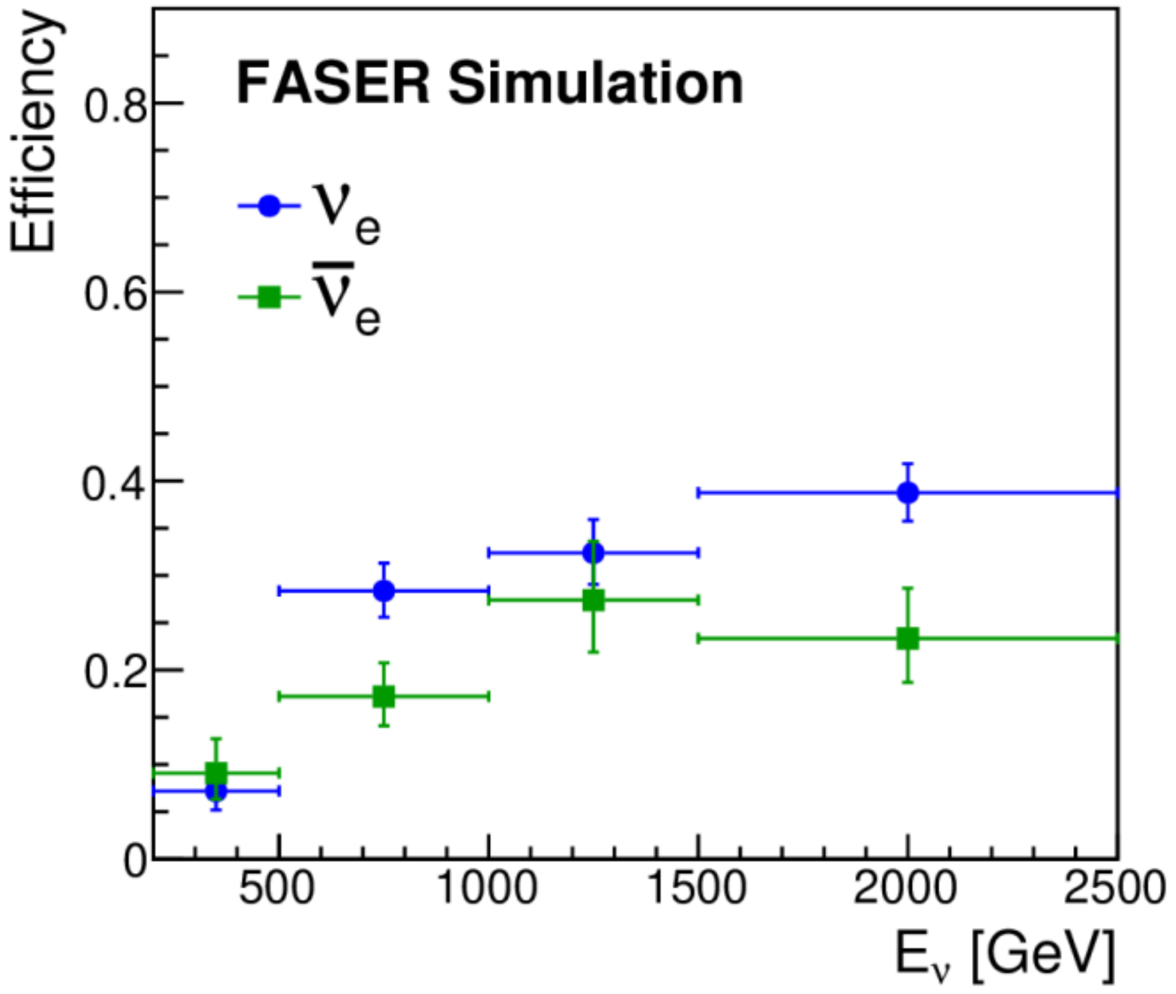
Vertex reconstruction:

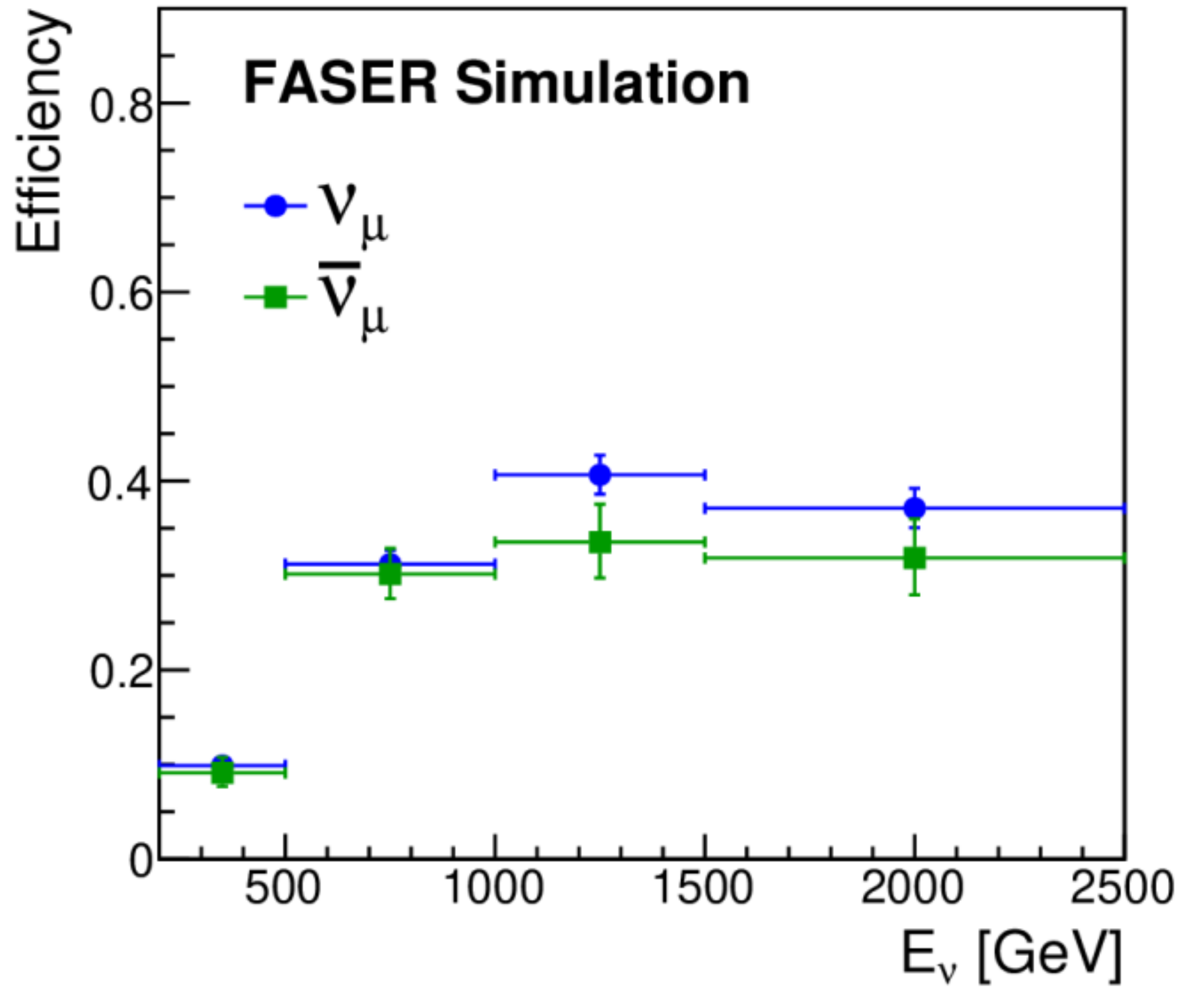
- $N_{track} \geq 5$
- $N_{track}(\tan\theta \leq 0.1) \geq 4$

Lepton requirements:

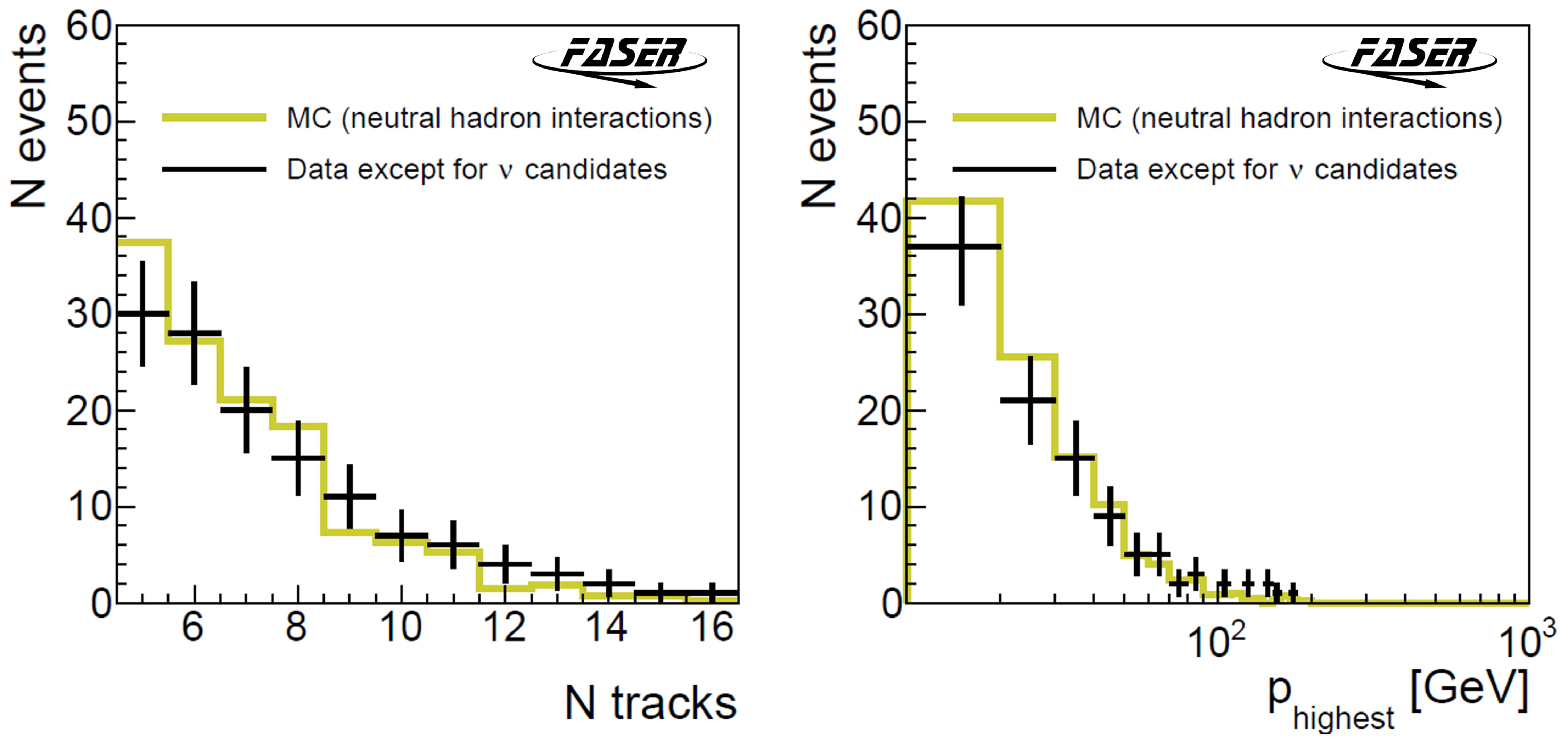
- E_e or p_μ >200GeV
- $\tan\theta_e$ or $\tan\theta_\mu > 0.005$

Back-to-back topology: $\Delta\phi > 90°$



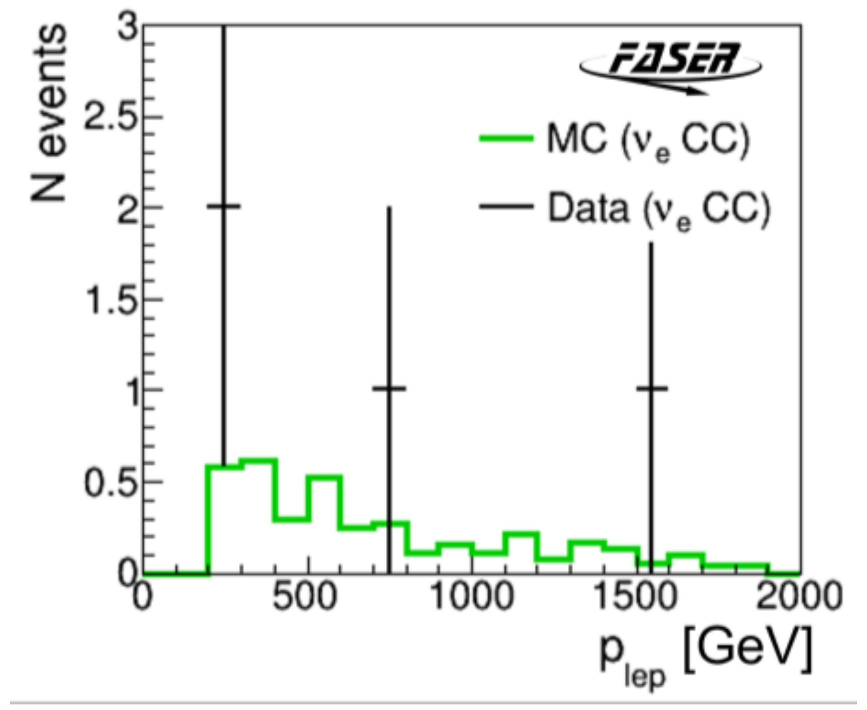


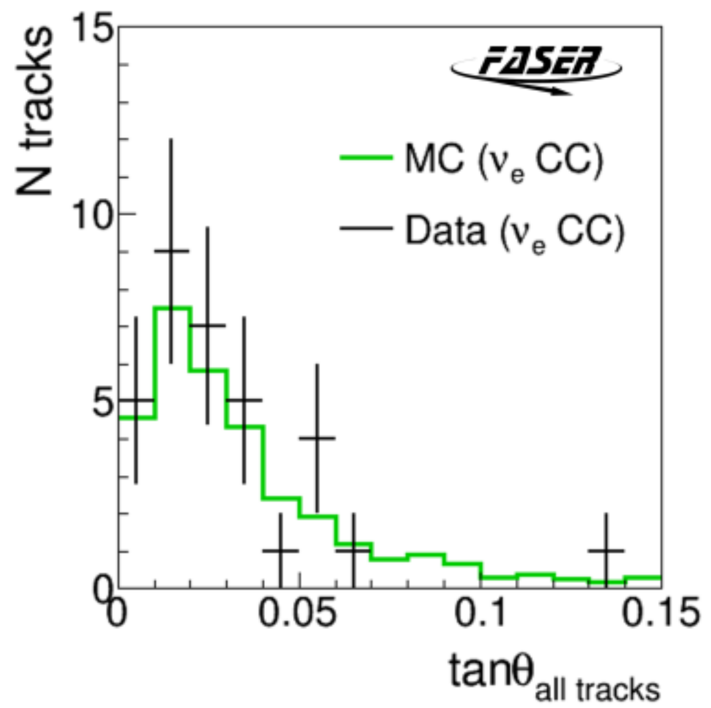
Background model

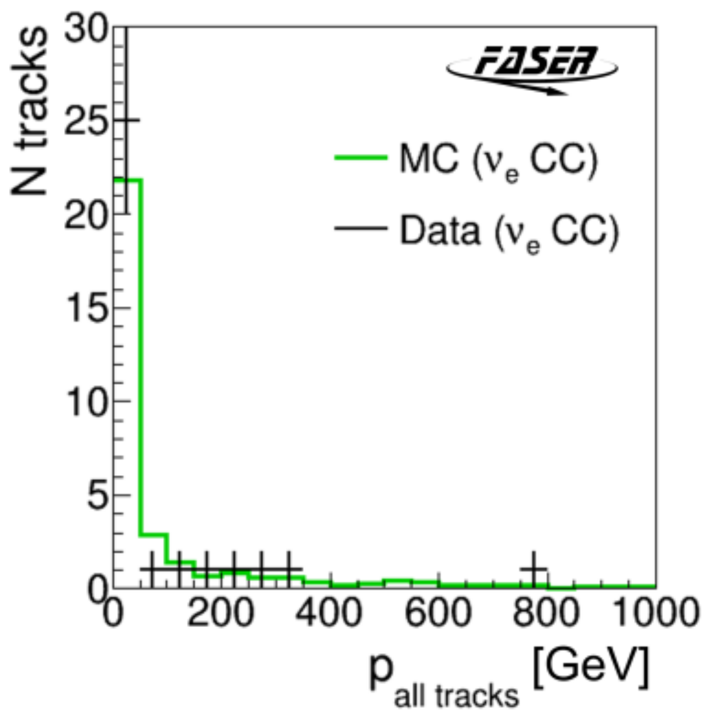


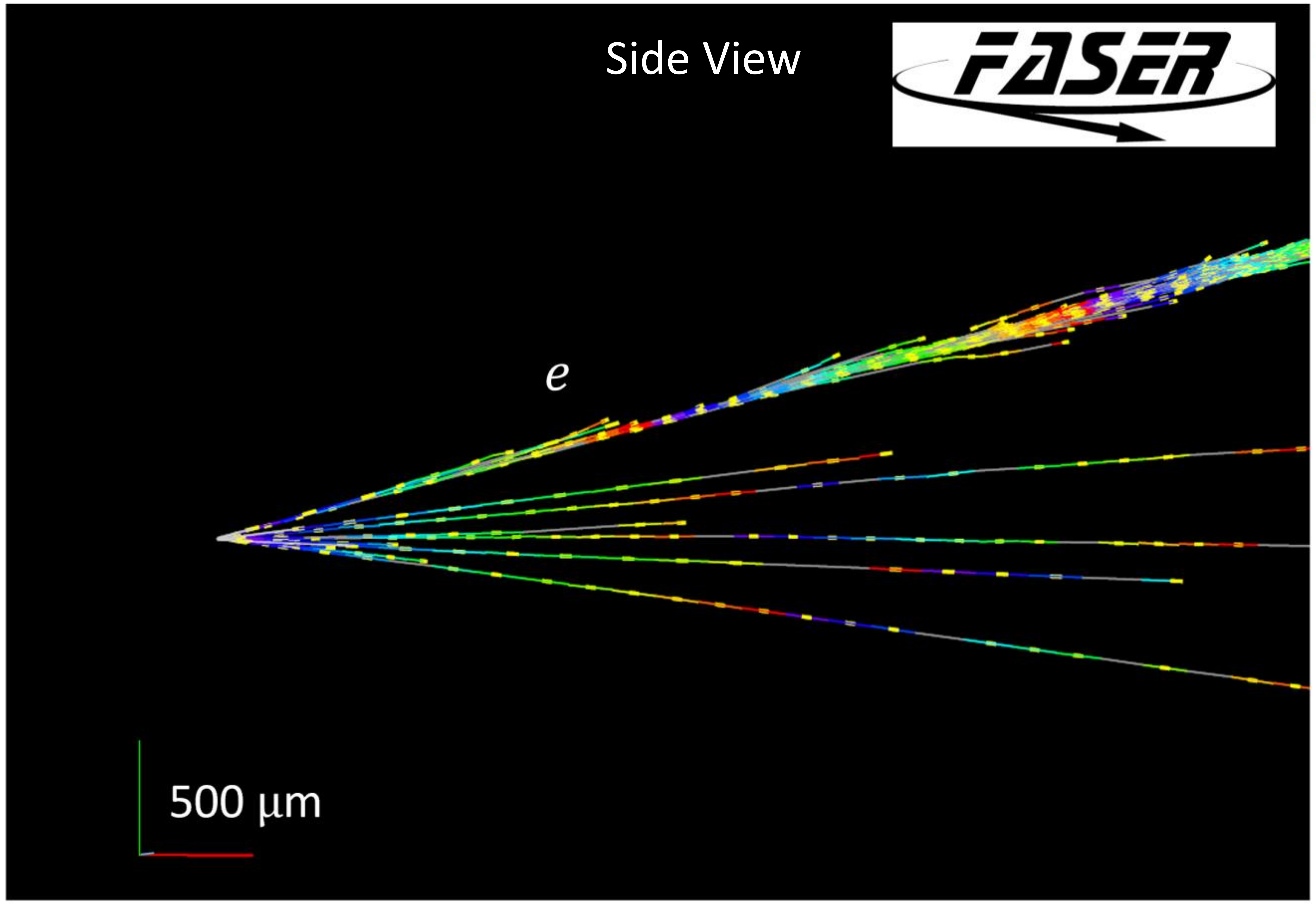
ν_e events

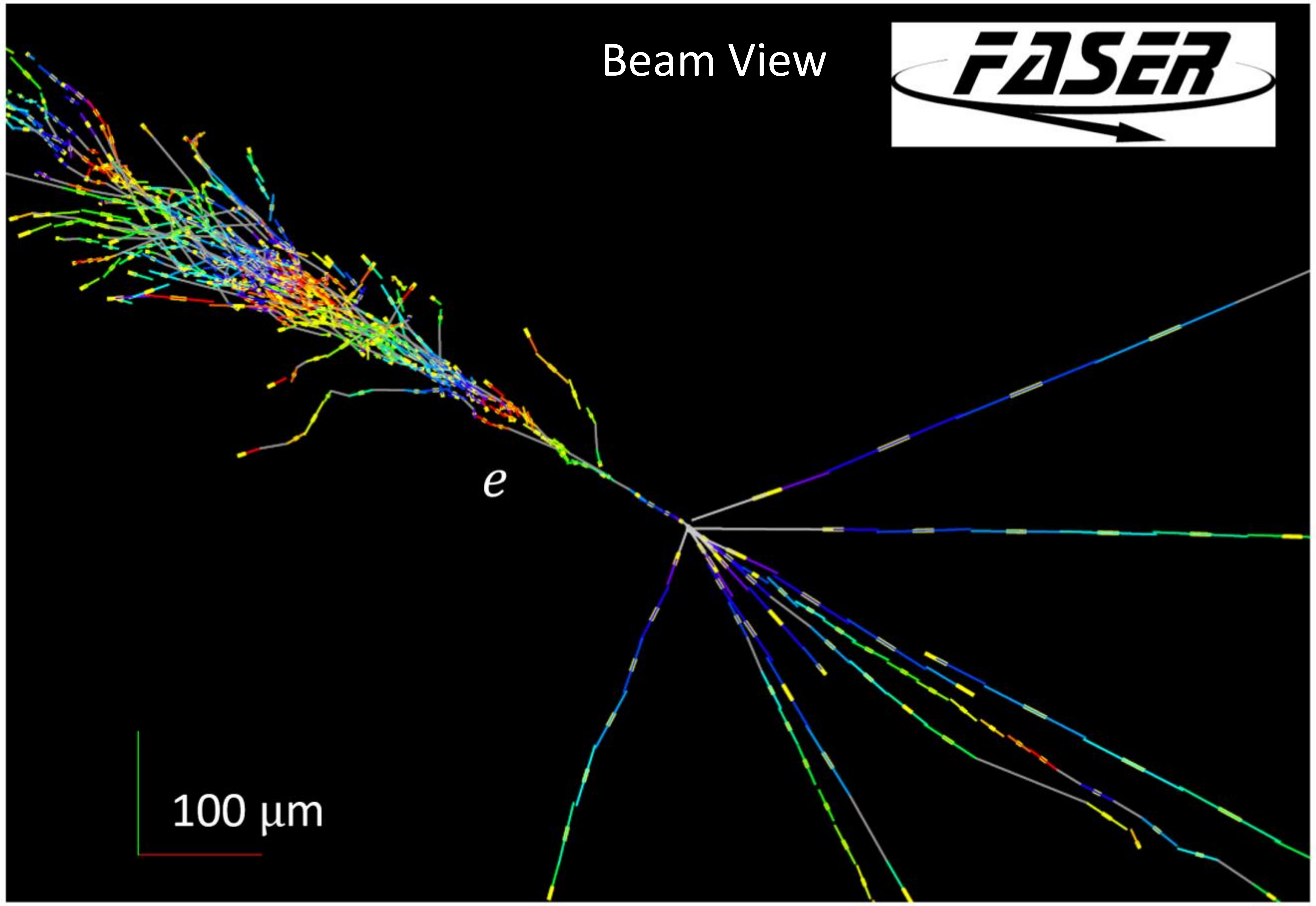
- E_e = 1.5 TeV, highest ν_e measured
- MC normalized to number of observed events.





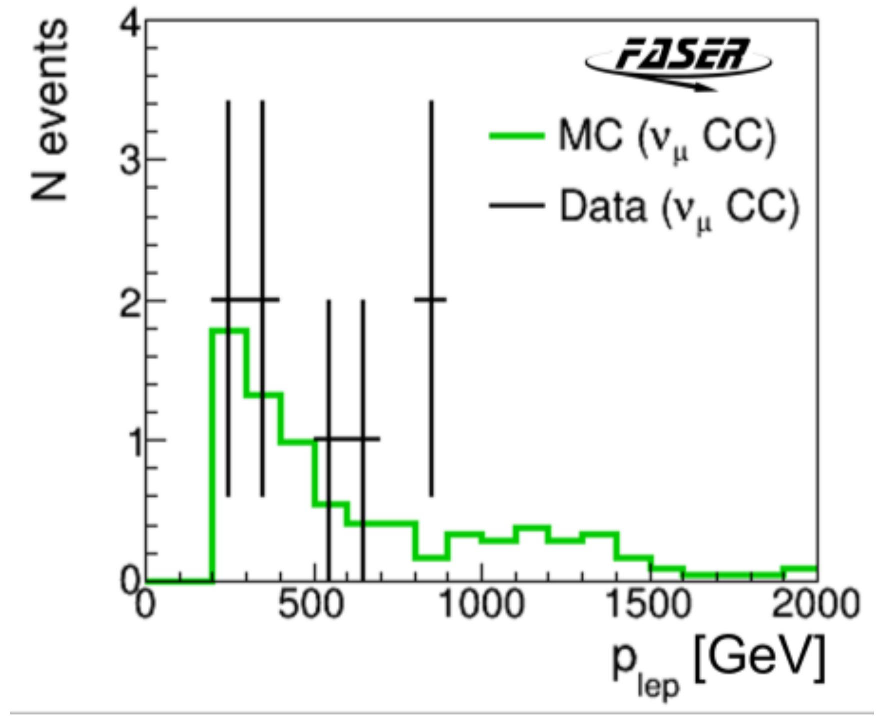


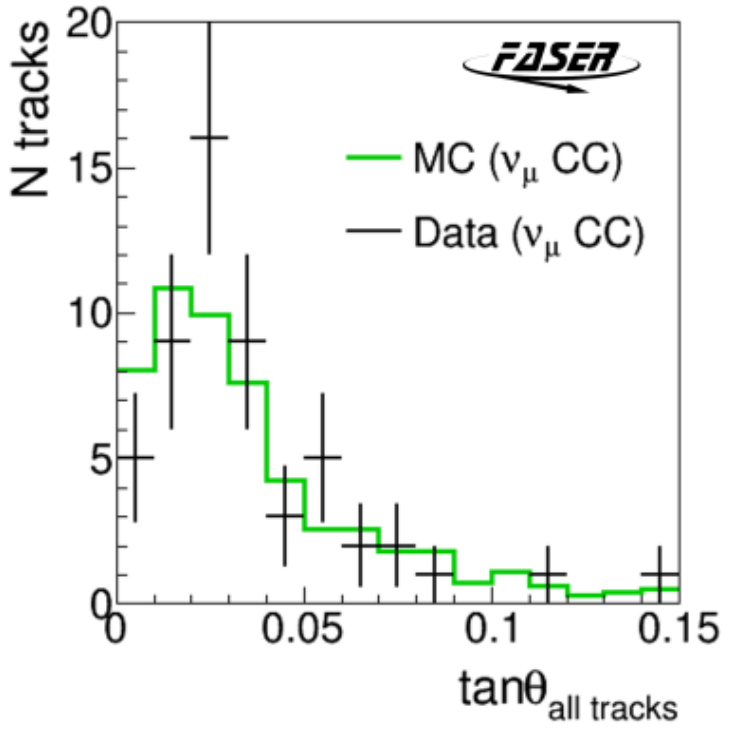


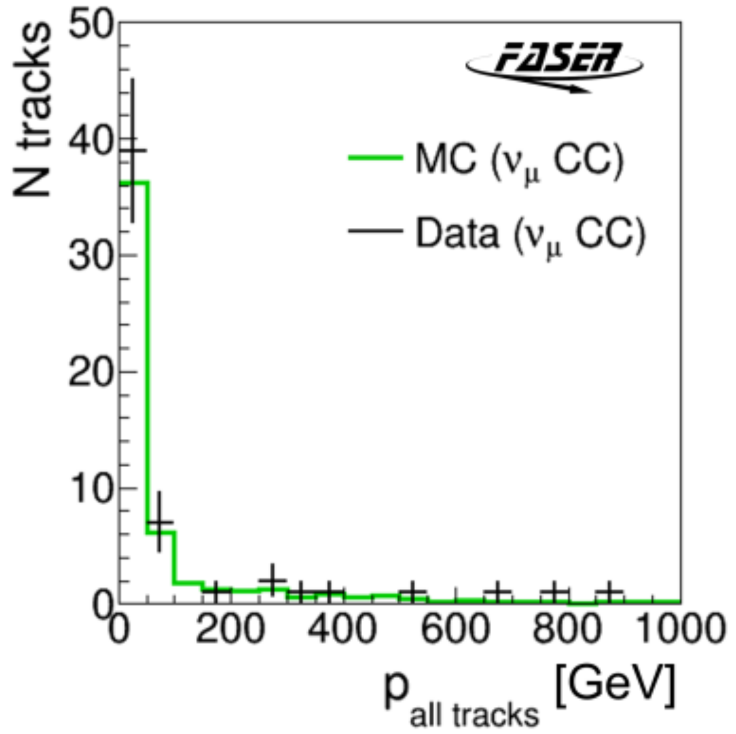


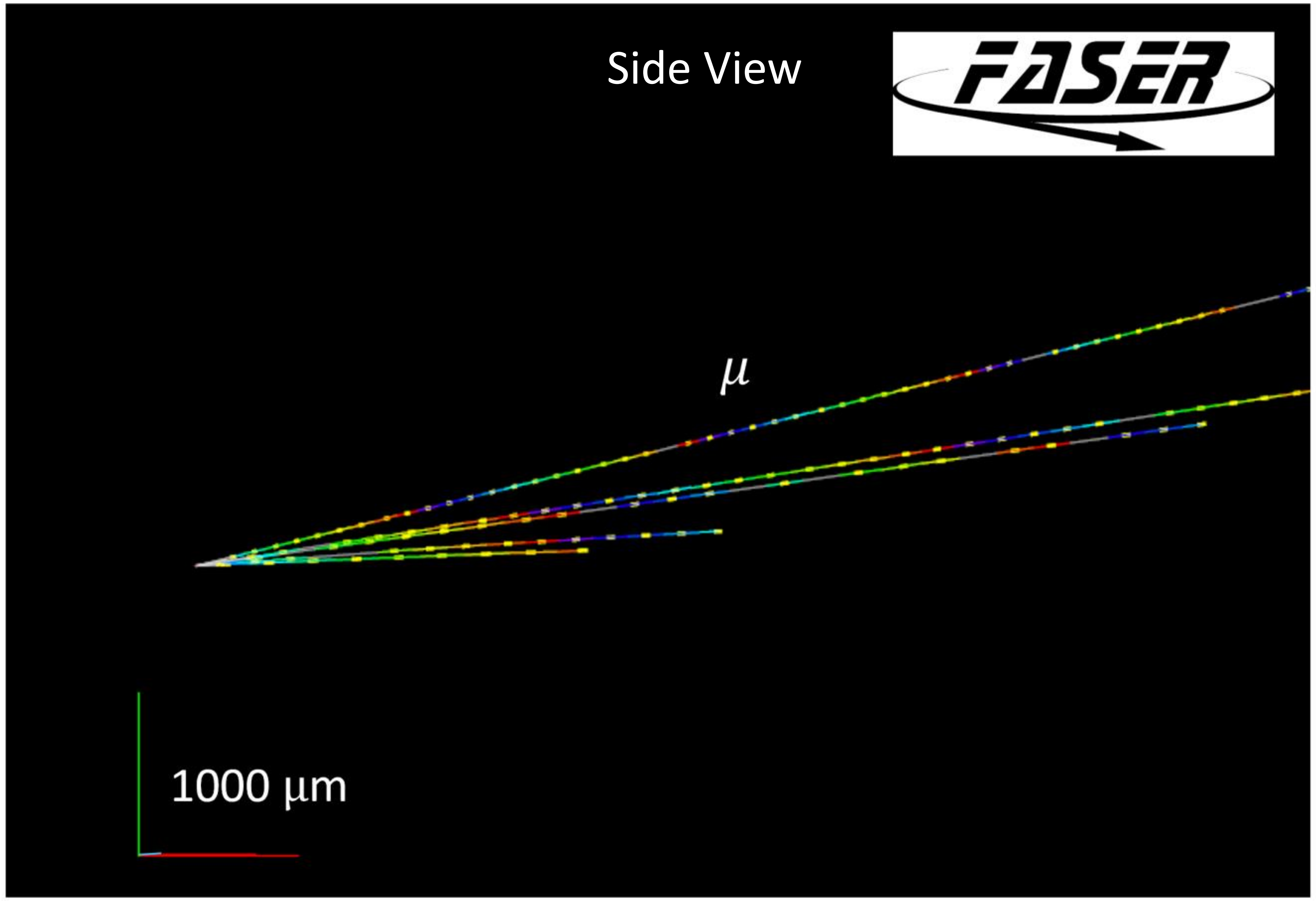
ν_μ events

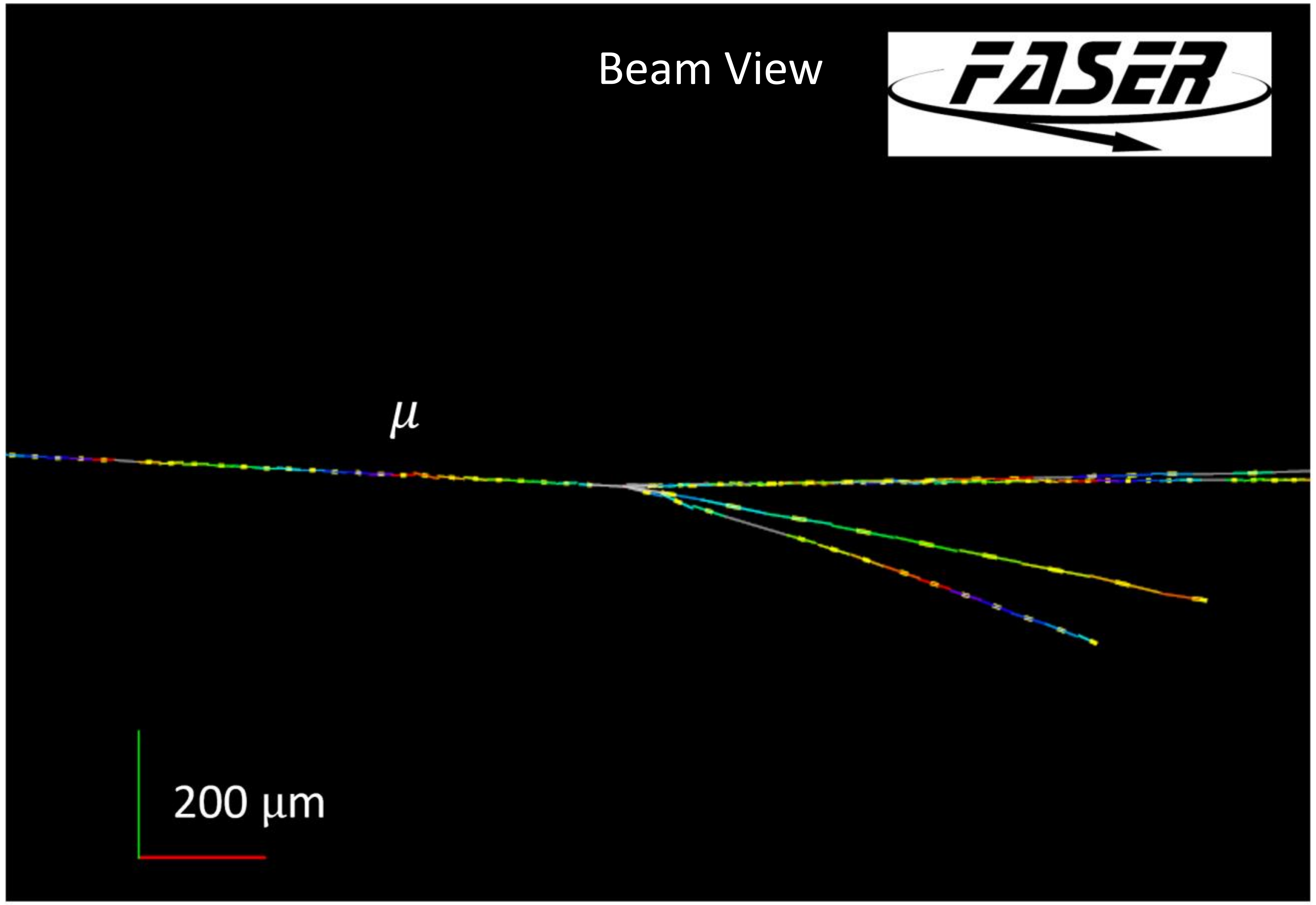
- p_μ = 360 GeV.
- MC normalized to number of observed events.









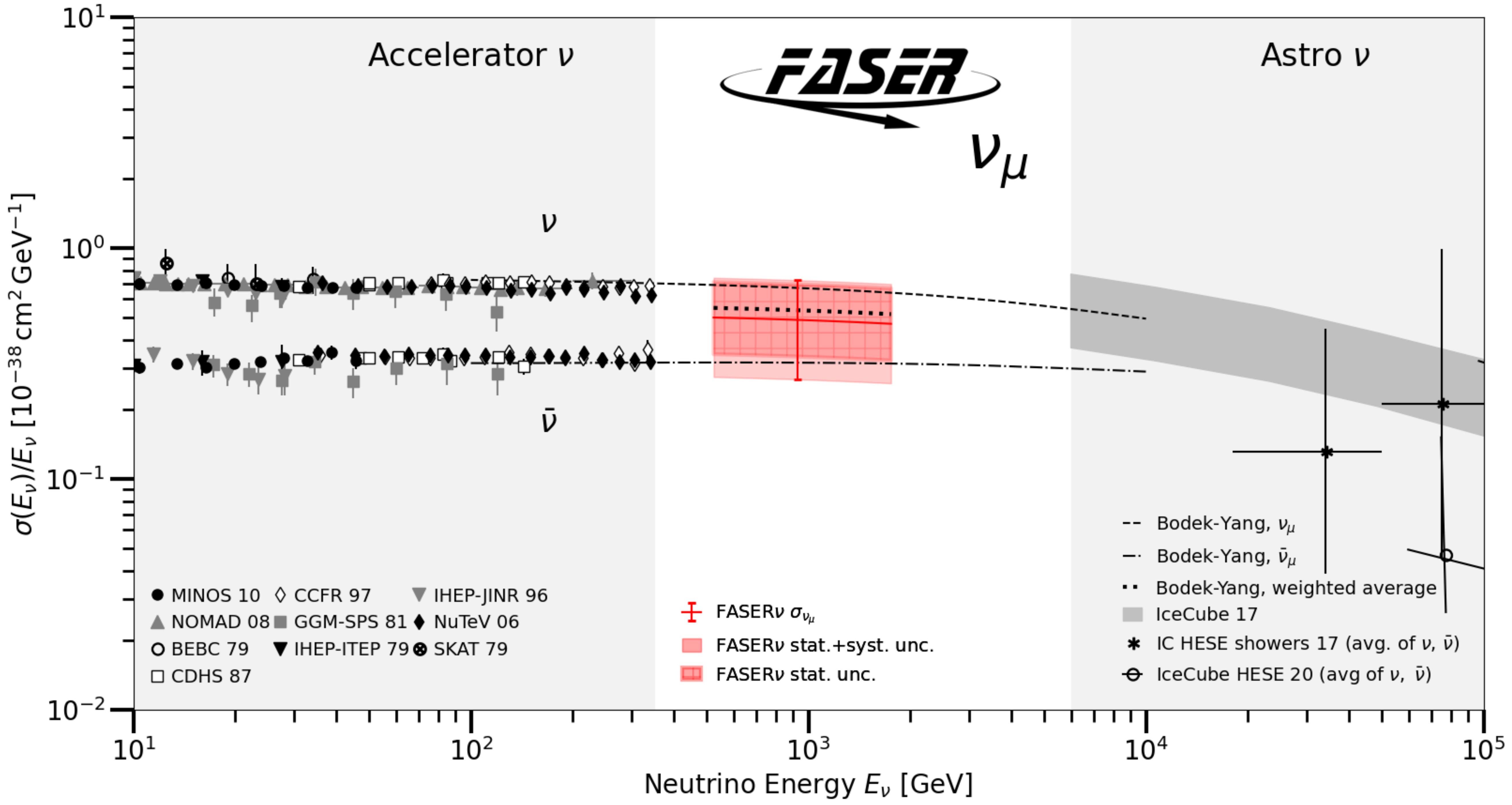


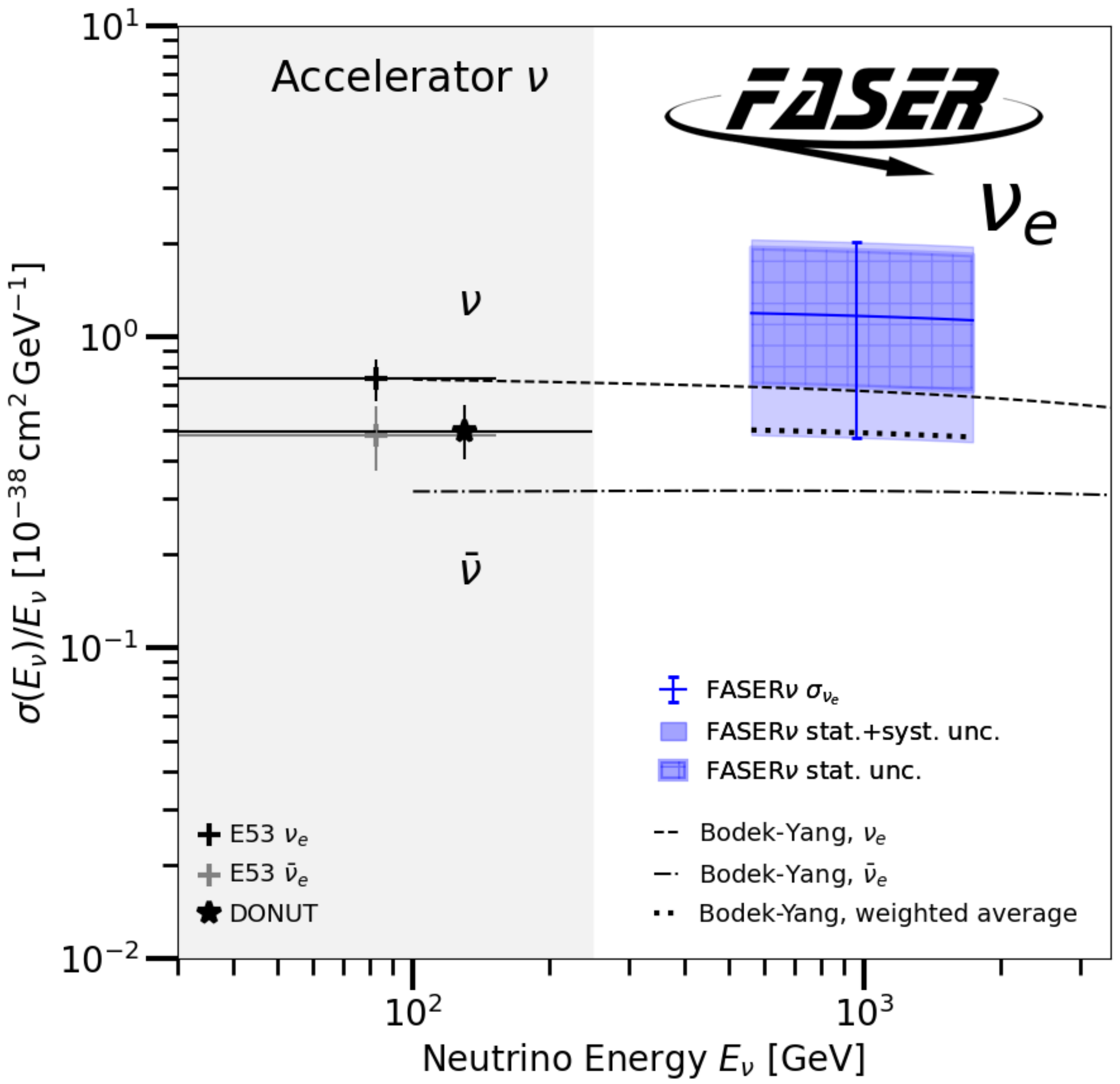
Phys. Rev. Lett. 133, 021802 (2024)

Results from FASERν: ν_μ and ν_e events!

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

- First observation of ν_e at the LHC!
- First neutrino cross-section measurement in the TeV range!
- Large uncertainty from neutrino flux

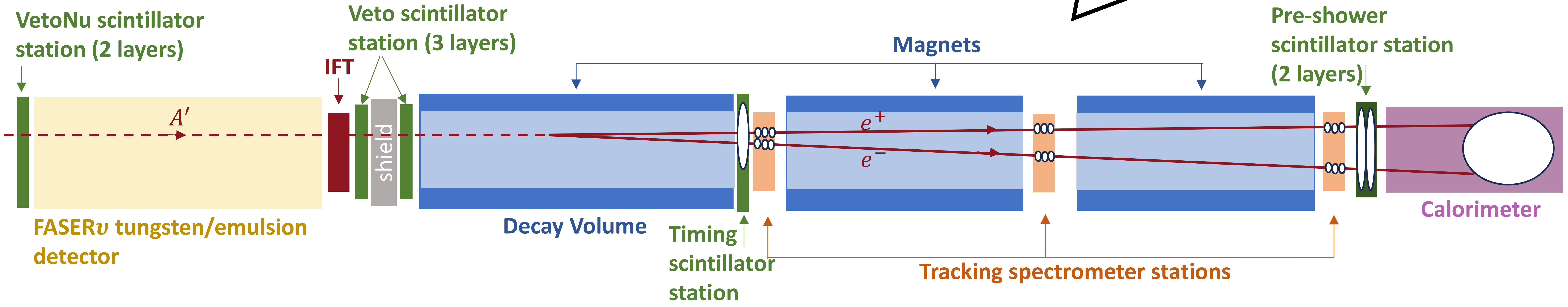




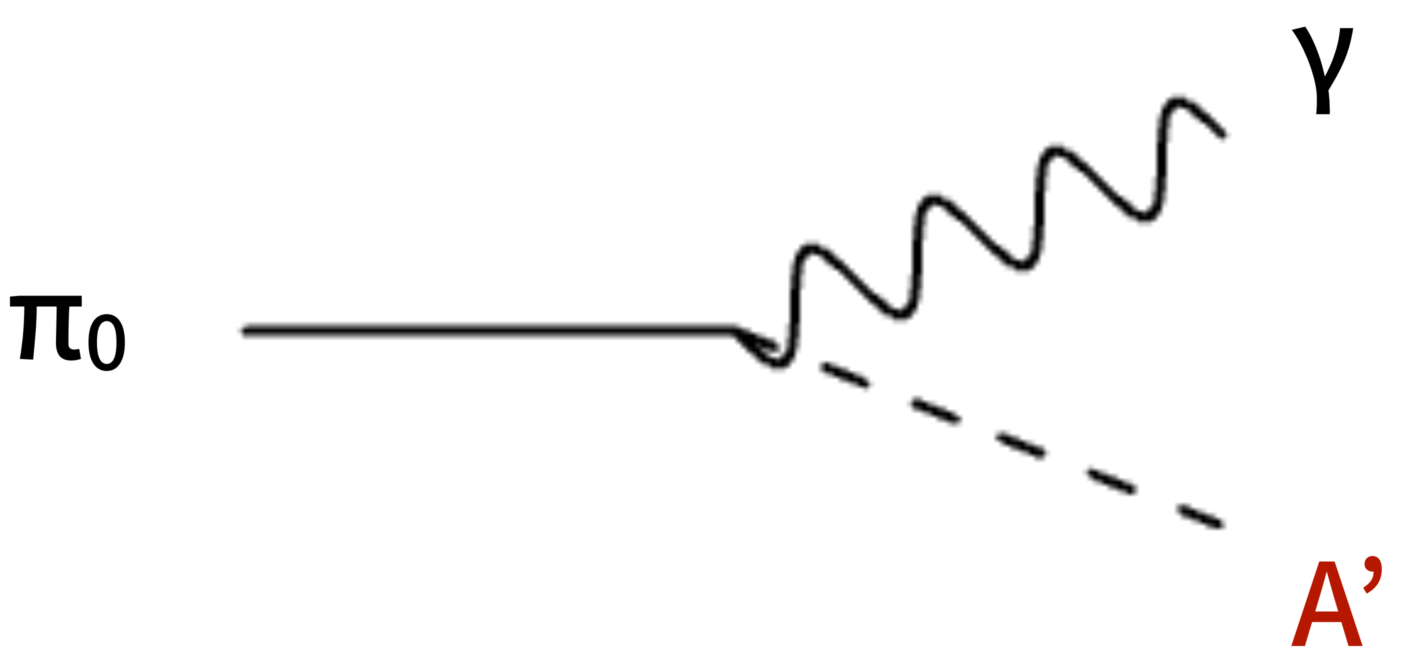
Beyond the Standard Model

Dark Photon Searches

Analysis was **blinded for E>100 GeV** events **without any veto signals**



- Used 27.0 fb^{-1} obtained in 2022
- Electron-positron pair in a decay volume



- Dark Photon(A’): U(1) gauge-boson, hidden sector particles
- Dominant source is neutral pion decay

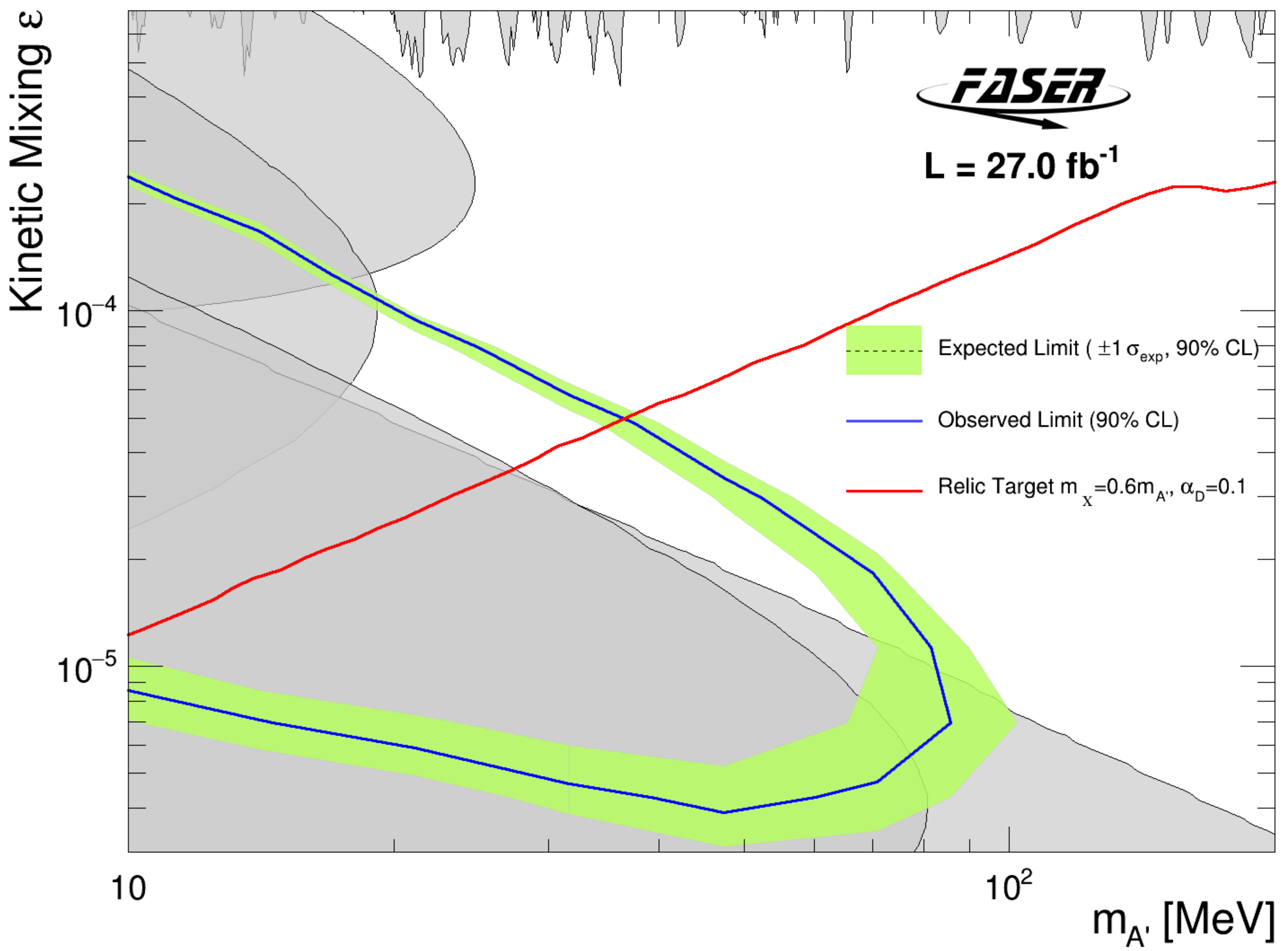
- **Signal criteria**
  - Exactly **two good quality tracks** with **p>20 GeV** inside fiducial volume (r<95mm)
  - **No signal** in any of **veto** scintillators (<40 pC ~ 0.5 MIP)
  - Timing and preshower scintillators consistent with ≥2 MIPs
  - Calorimeter **E > 500 GeV**

- **Background :** $(2.3 \pm 2.3) \times 10^{-3}$ events
  - Veto inefficiency, neutral hadrons, large-angle muons, neutrinos, non-collision evens

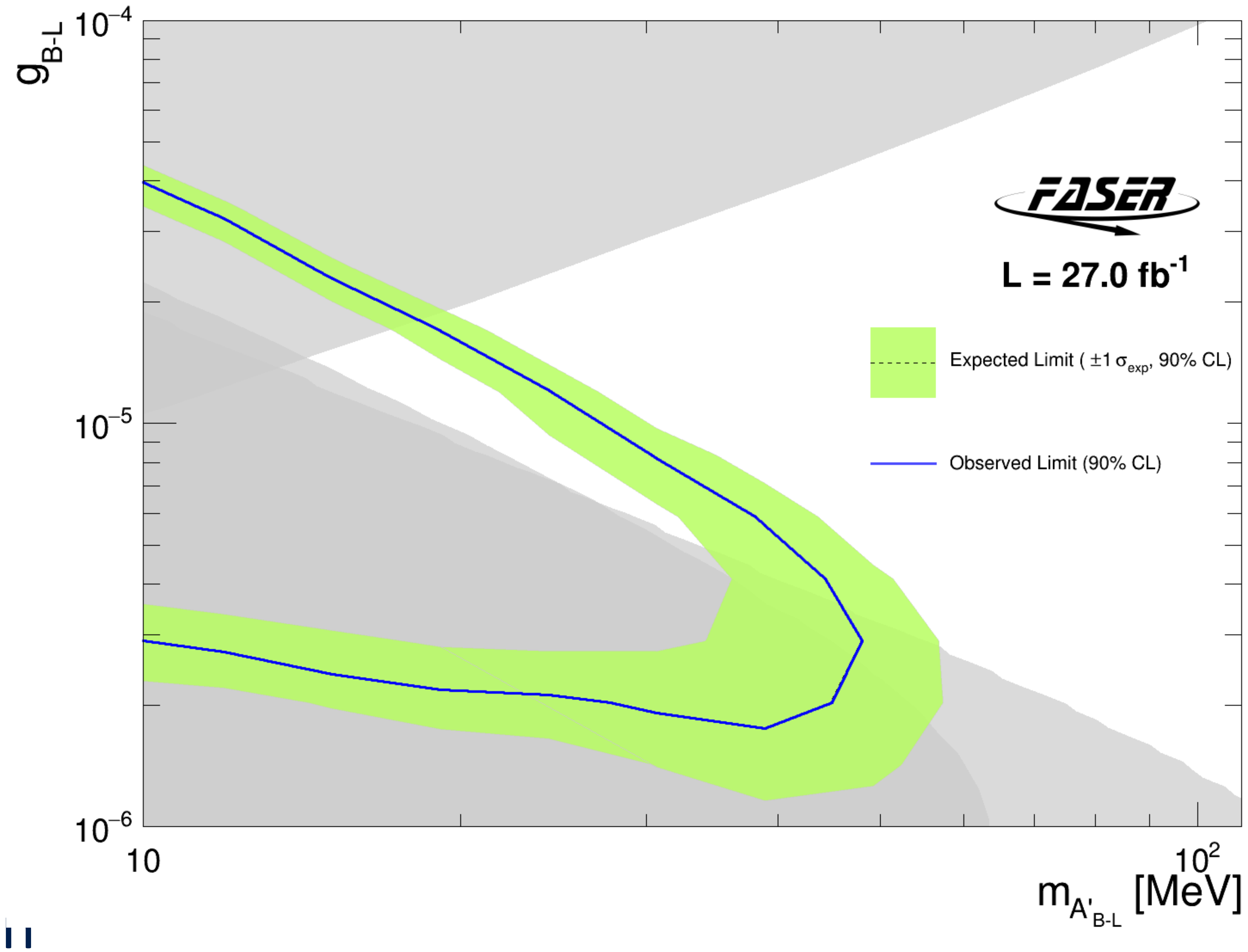
Results

Phys. Lett. B 848 (2024), 138378

Dark photon



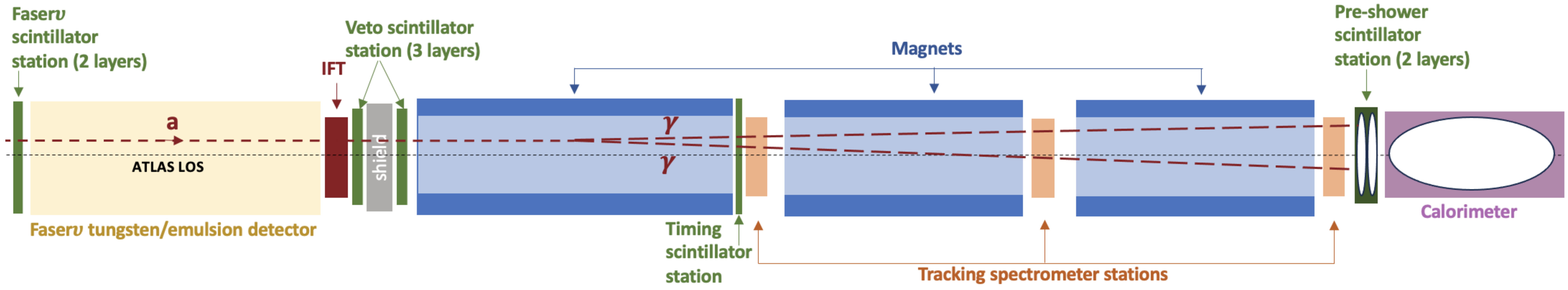
U(1)$_{B-L}$ gauge boson

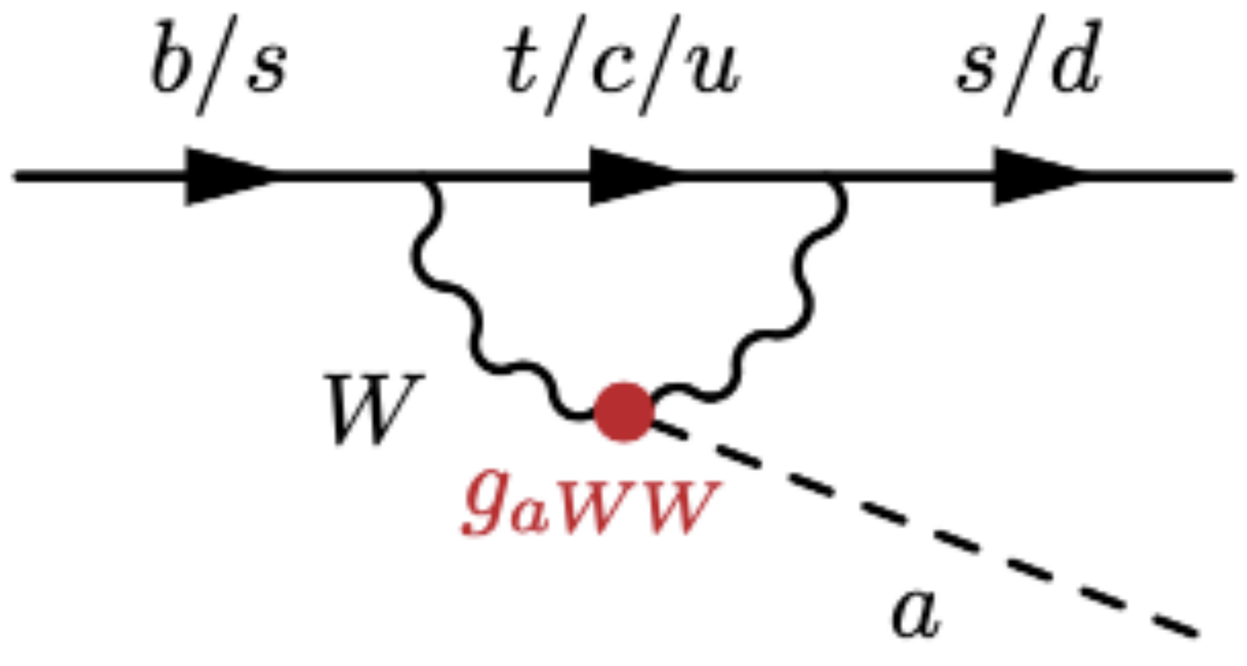


- **No events seen** in unblinded signal region
- Based on this null results, FASER sets limits in previously **unexplored parameter space**!
  - Probing region **interesting from thermal relic target**
- Also, constrained massive gauge boson from U(1)$_{B-L}$ model

Axion Like Particles

Conf note: CERN-FASER-CONF-2024-001





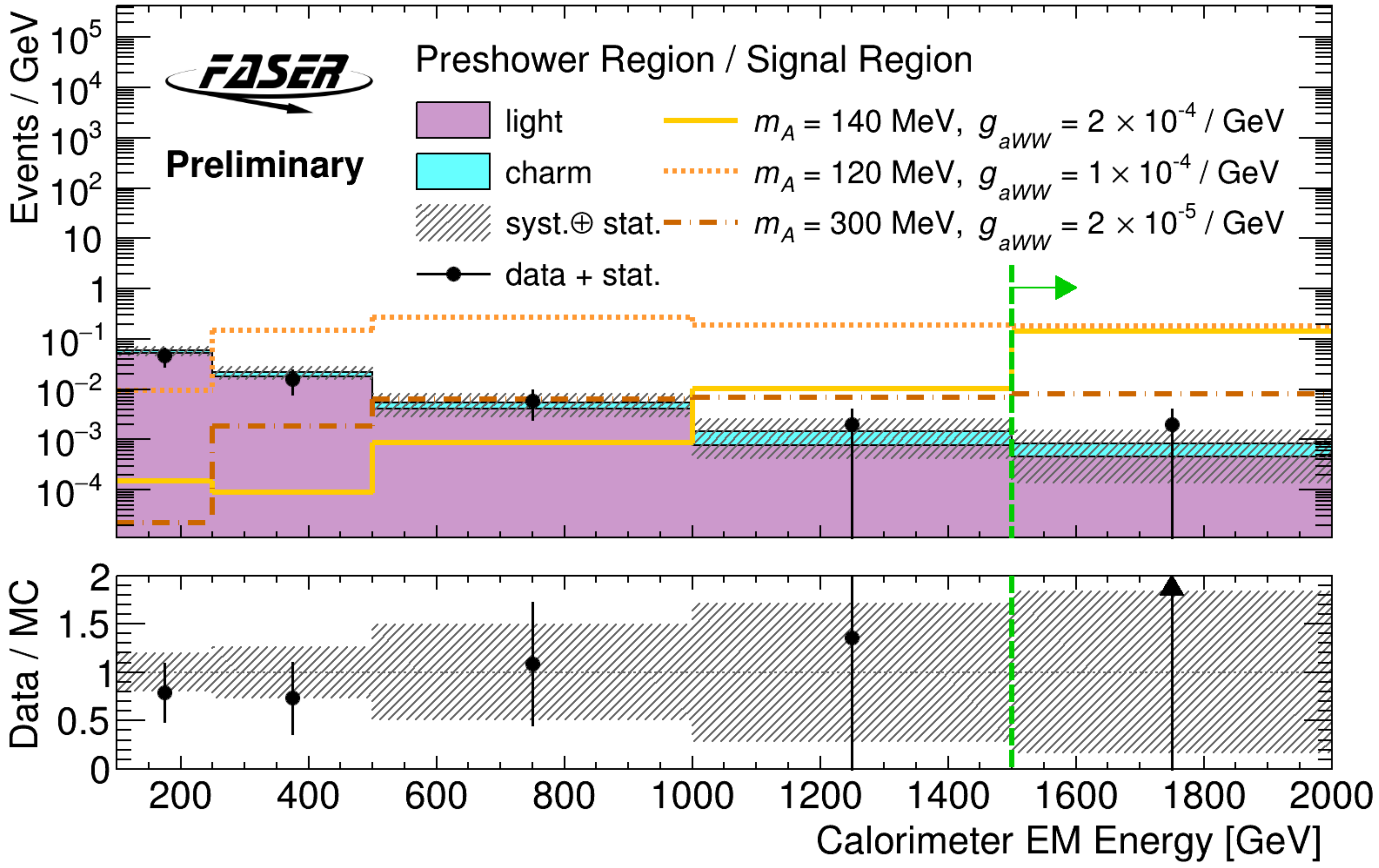
- Used 57.7 fb^{-1} obtained in 2022 and 2023
- Very collimated energetic photon pair produced
  - A high energy deposit in the EM calorimeter

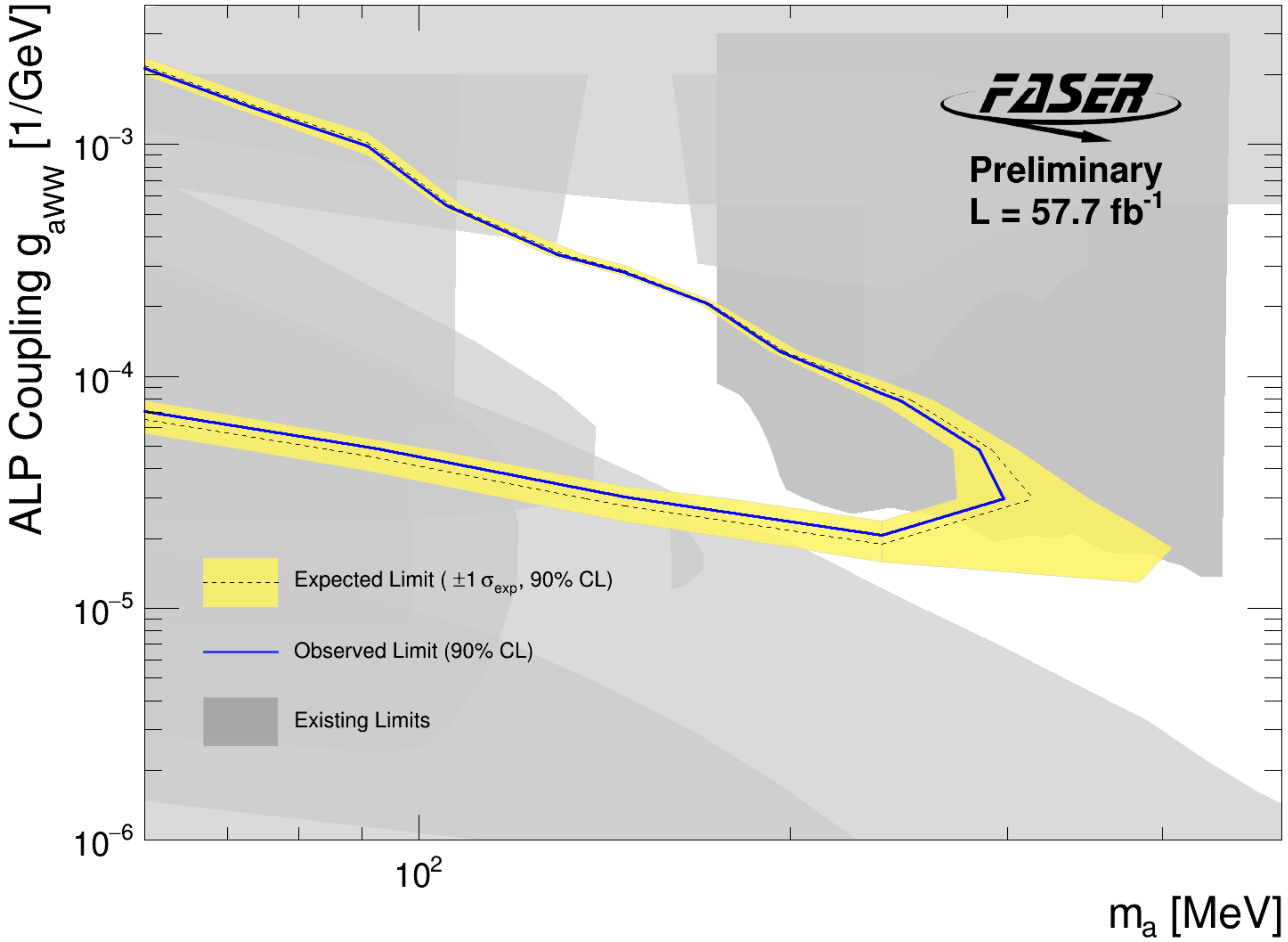
- **Signal criteria**
  - No signal in all 5 veto scintillators
  - EM shower (> 1.5 TeV) in calorimeter
  - Good timing along with LHC collision

- **Background negligible**
  - Neutral hadrons, large-angle muons, non-collision / cosmics

- FASER is sensitive to ALPs coupling to SU(2)$_L$ gauge bosons
- Dominant source is b(s)-flavoured hadrons decay

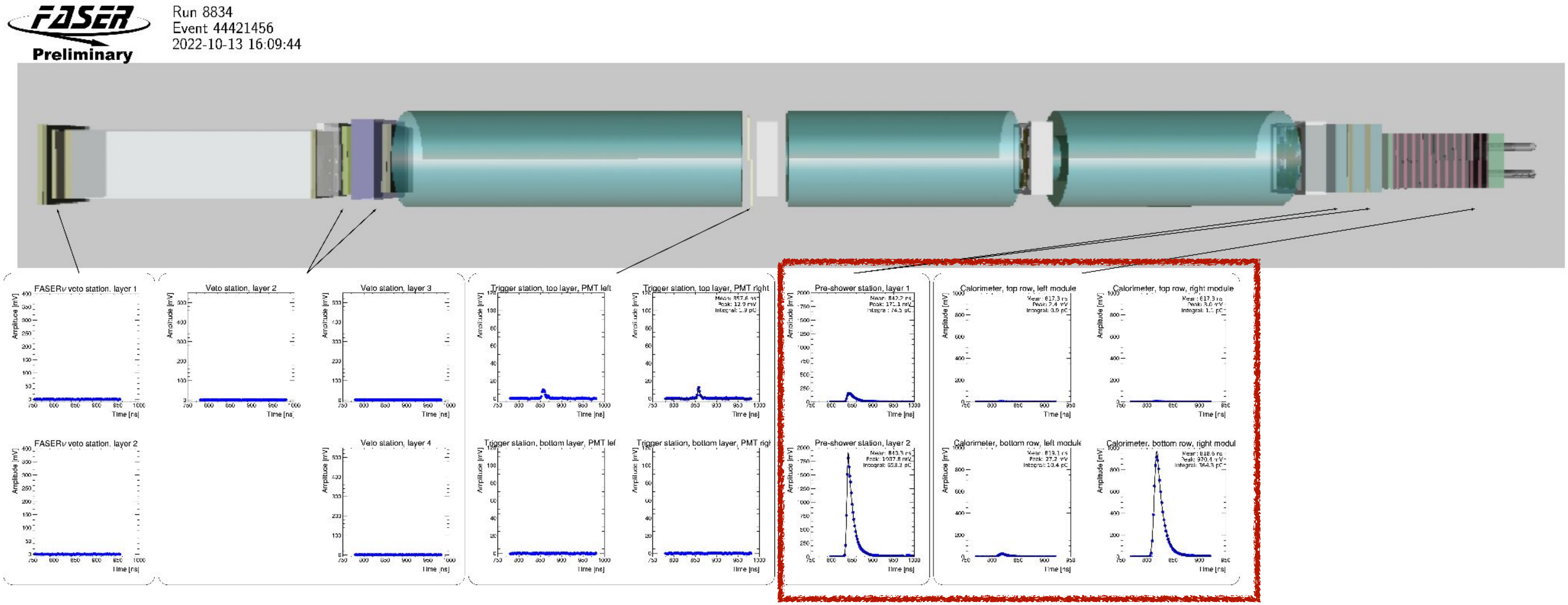
Results





- **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
- Observed **1 event** after unbinding
- Probing new parameter space of ALPs Model

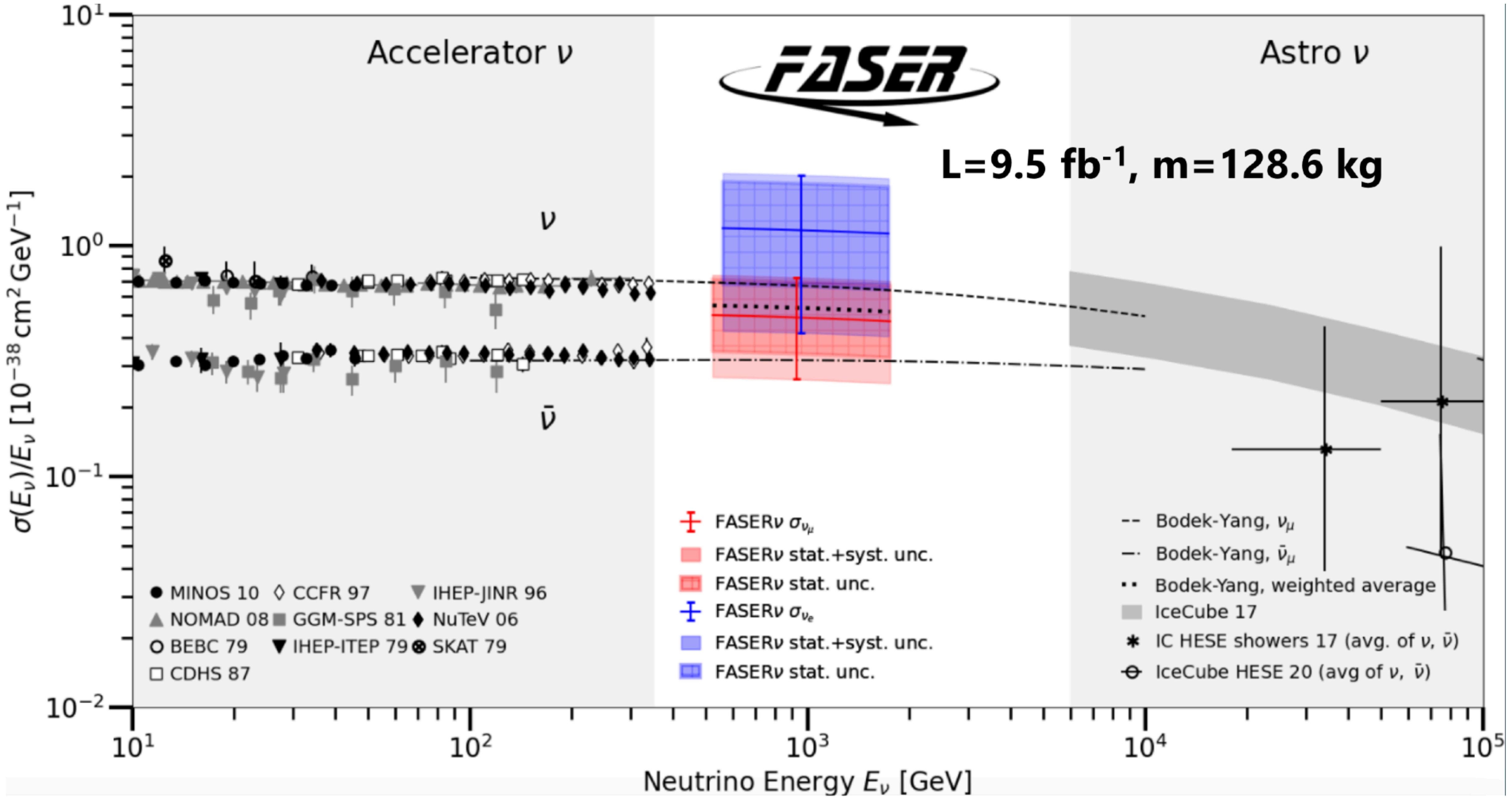
Event Display of "ALPtrino"

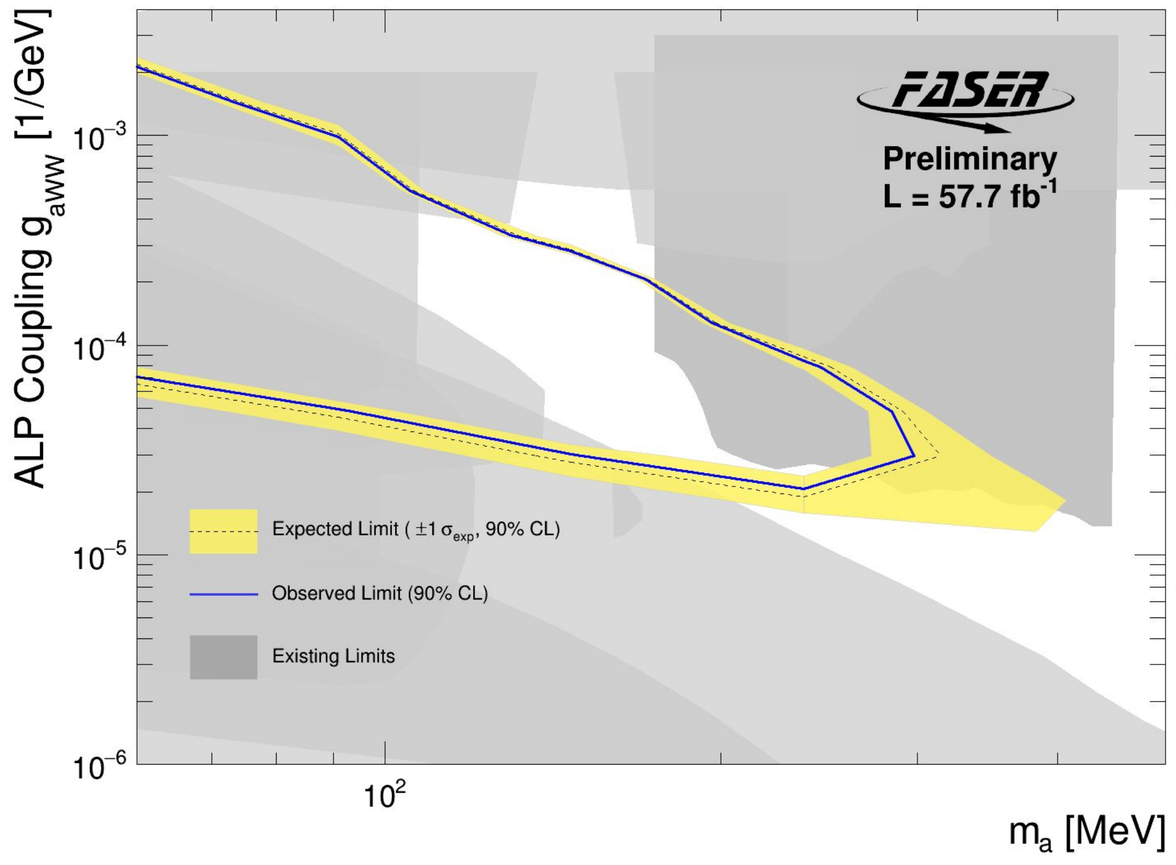


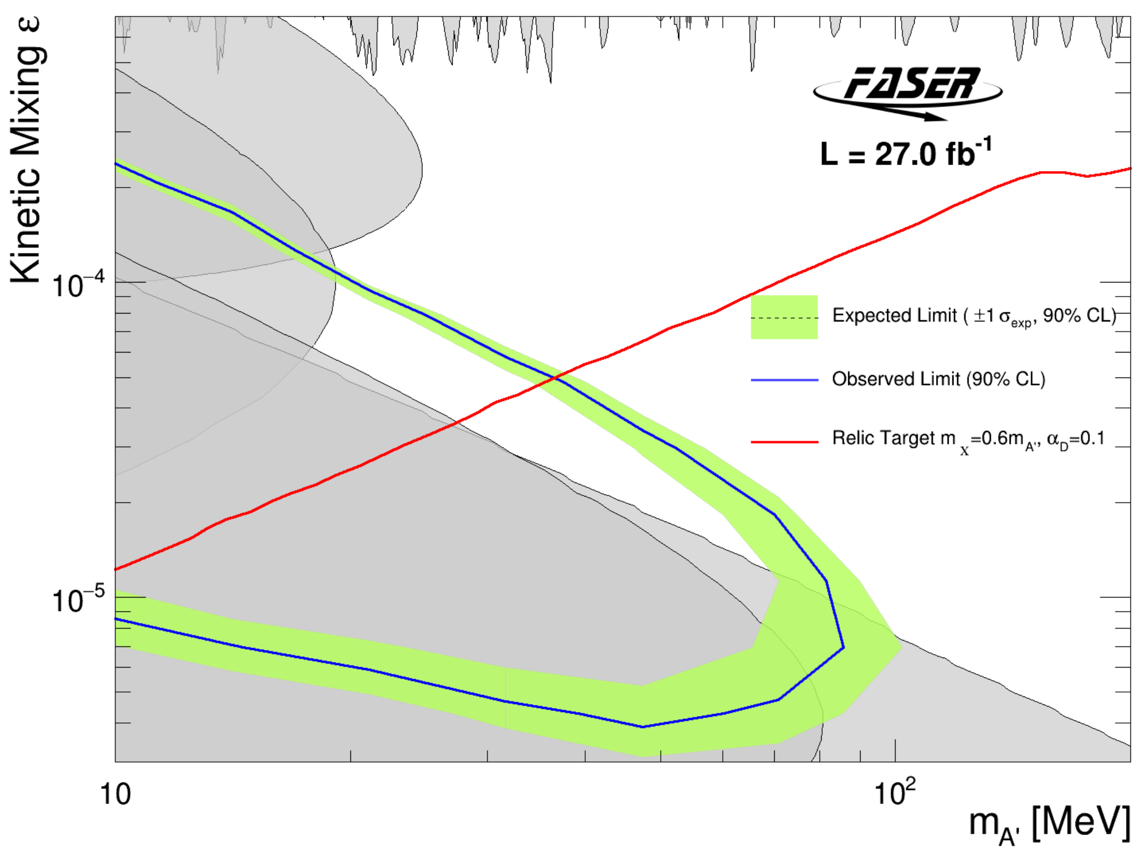
- This event has a calorimeter energy of 1.6 TeV
  - Shows Pre-shower deposits constant with an EM shower
- Even consistent with both being an ALP signal event or a ν_e background event

Summary

- LHC-FASER is taking data in Run3 of LHC operation, ~70 fb^{-1} collected
- Providing timely physics results
  - First ν_e, ν_μ cross sections (with 2 % of data)
  - ALPs limits
  - Dark photon limits







Prospects

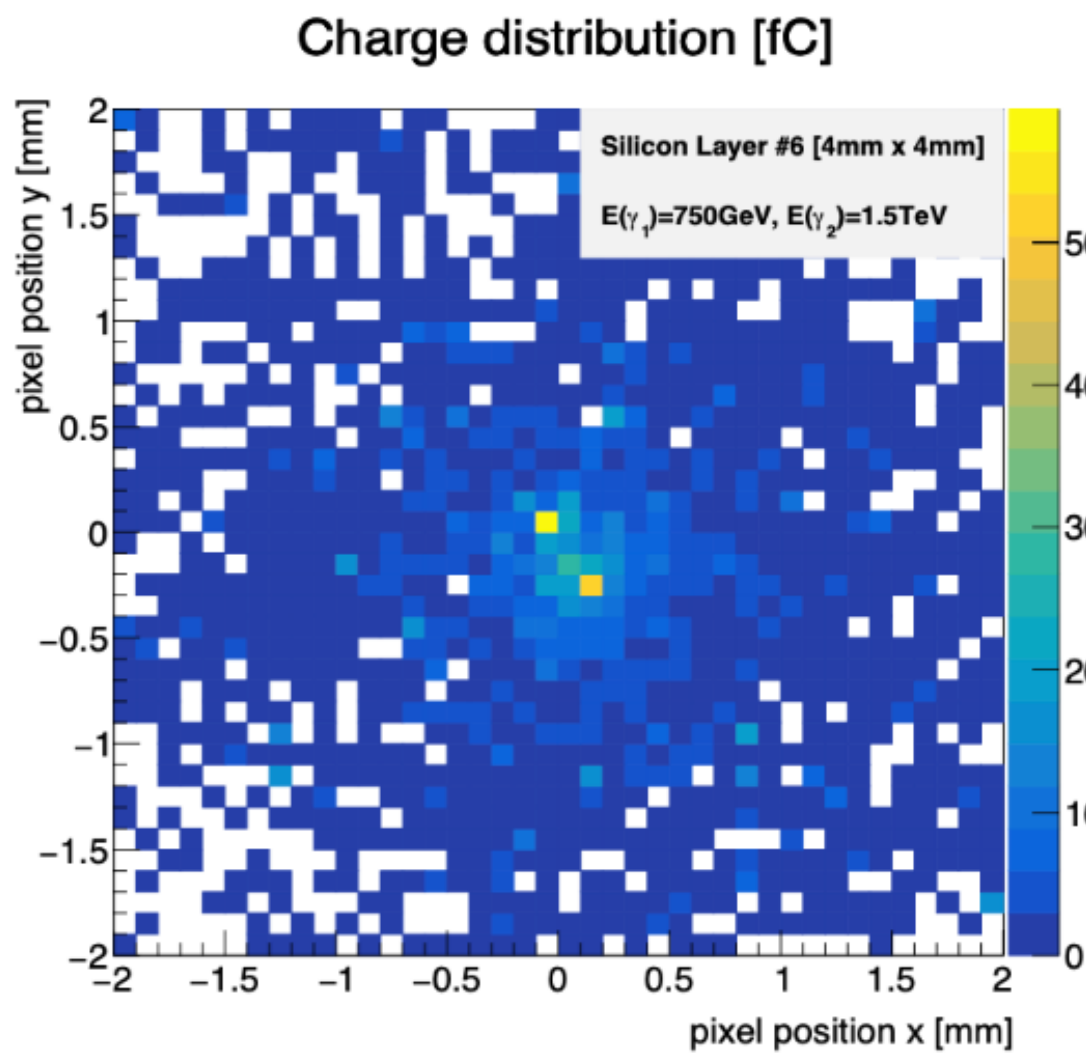
- Additional 180 fb^{-1} to be collected in 2024. 2025
- Pre-shower detector upgrade in 2025 to enhance ALPs sensitivity
- FASER in Run4 approved
- Discussing extended physics programs in Forward Physics Facility (2031-) in HL-LHC era

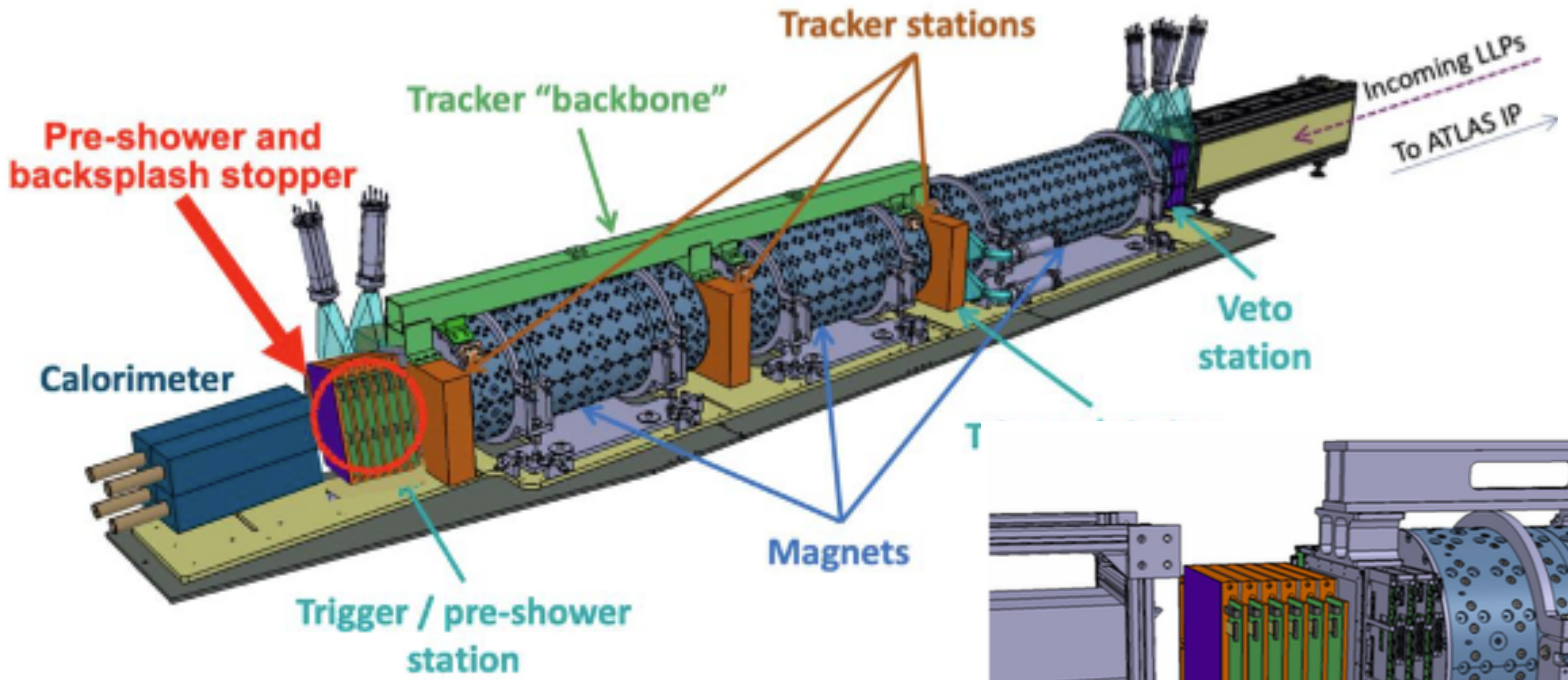
Acknowledgement

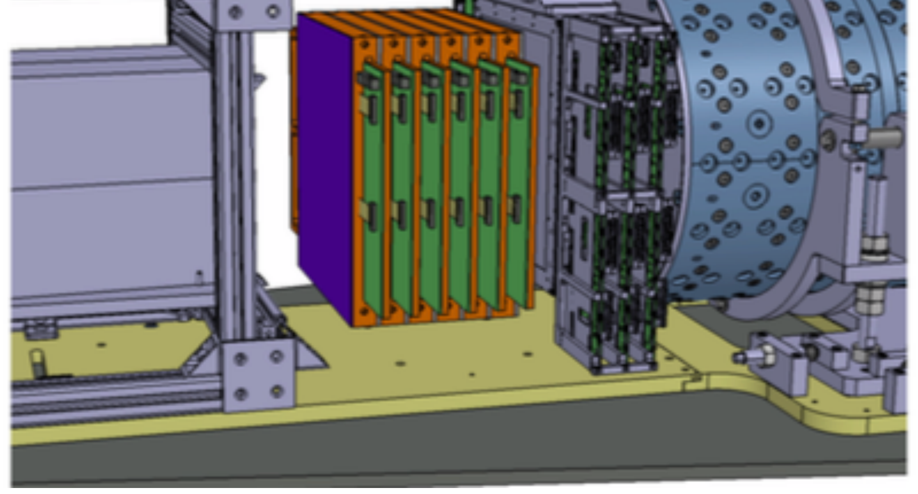
Future upgrade plan for ALPs

- **Upgrade to enable 2-γ physics**
  - enable to measure Axion Like Particles and long live particles decaying into two photons
  - current preshower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs
    - hexagonal pixels of 65 µm side

200 µm between two photons
Distinguishable

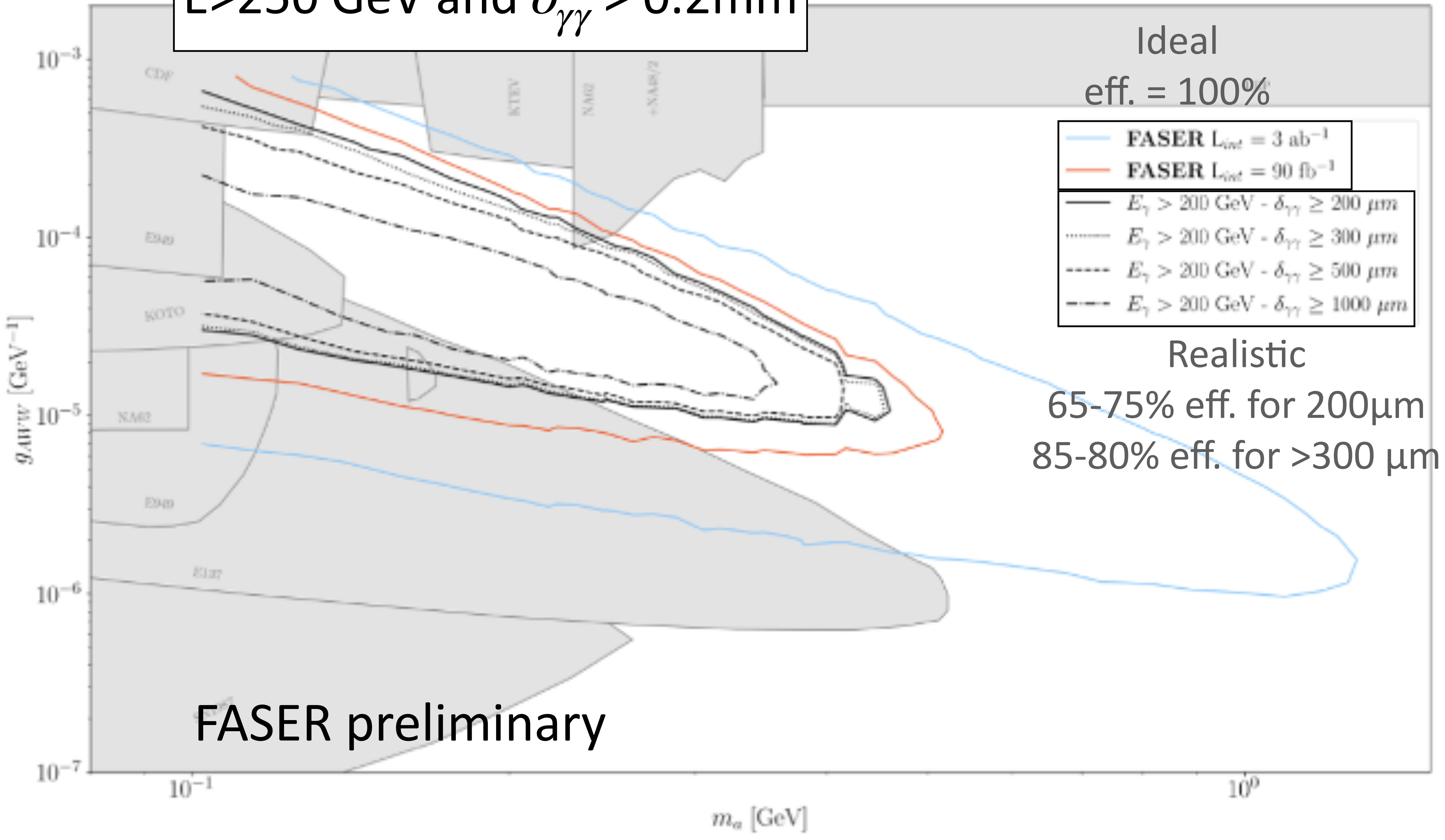






Planned to be ready for 2024 data taking

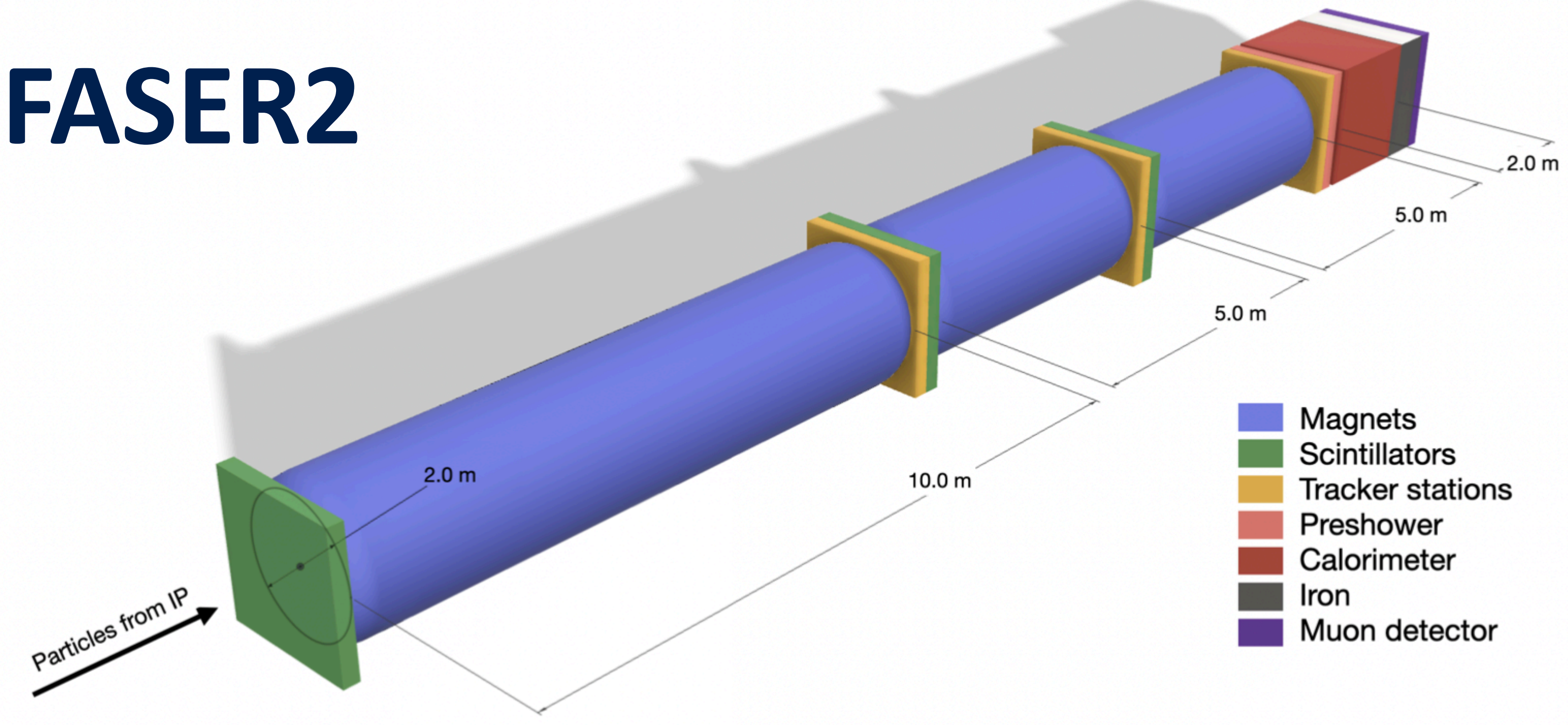
2-photon pairs with
E>250 GeV and $\delta_{\gamma\gamma}$ > 0.2mm

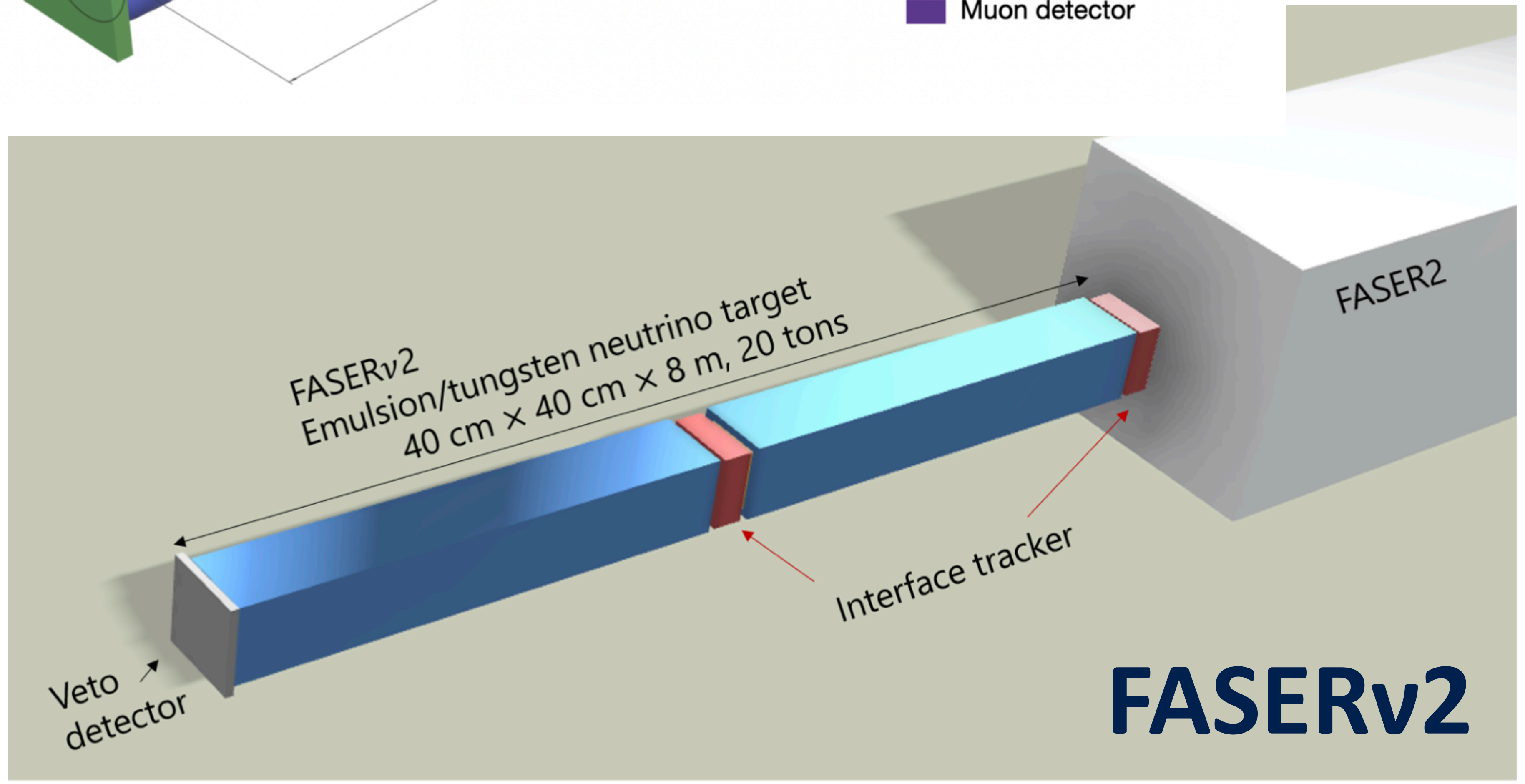


The Forward Physics Facility

In LHC HL-era, it is expected to increase statistics **(×20 Run3, 3000 fb^{-1}) in HL-LHC era**

FASER2





e.g. Expected Neutrino Flux

	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754