



# Recent Results from FASER



UNIVERSITÉ  
DE GENÈVE

*Stefano Zambito*, on behalf of the FASER collaboration

Les Rencontres de Physique de la Vallée d'Aoste, La Thule, 4-3-2024



SIMONS  
FOUNDATION



科研費  
KAKENHI

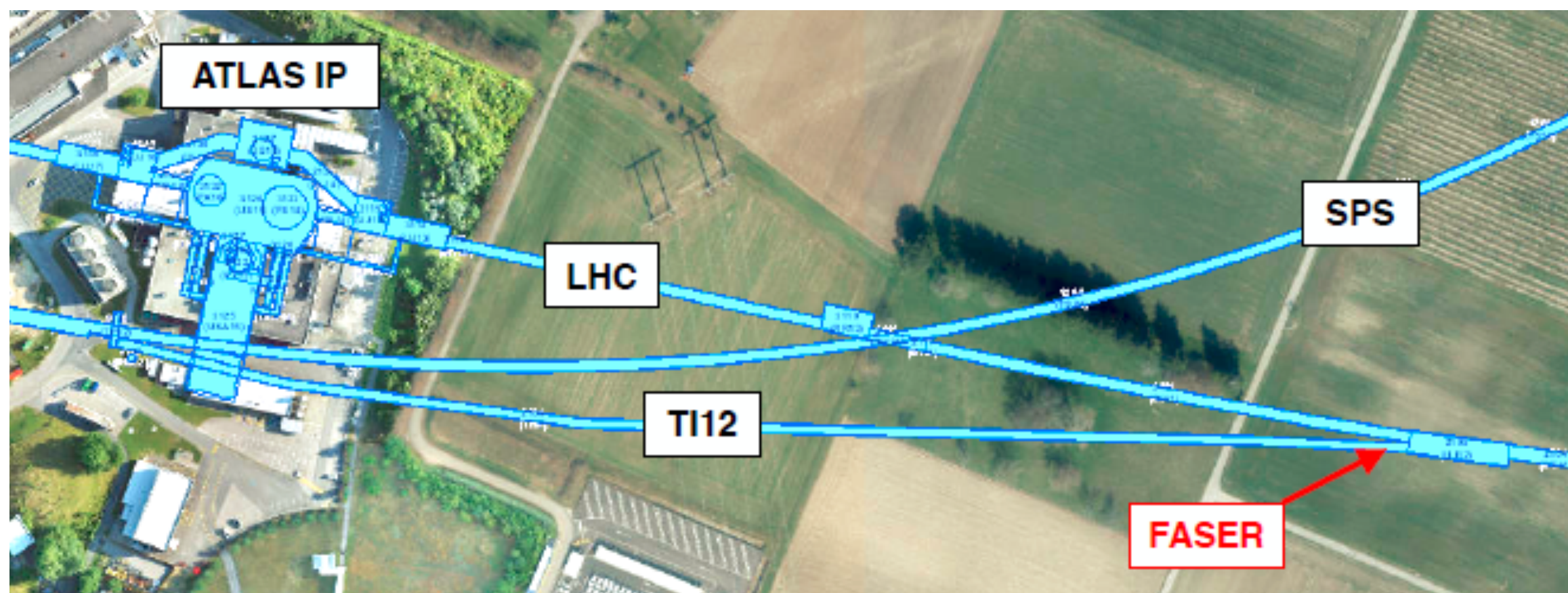
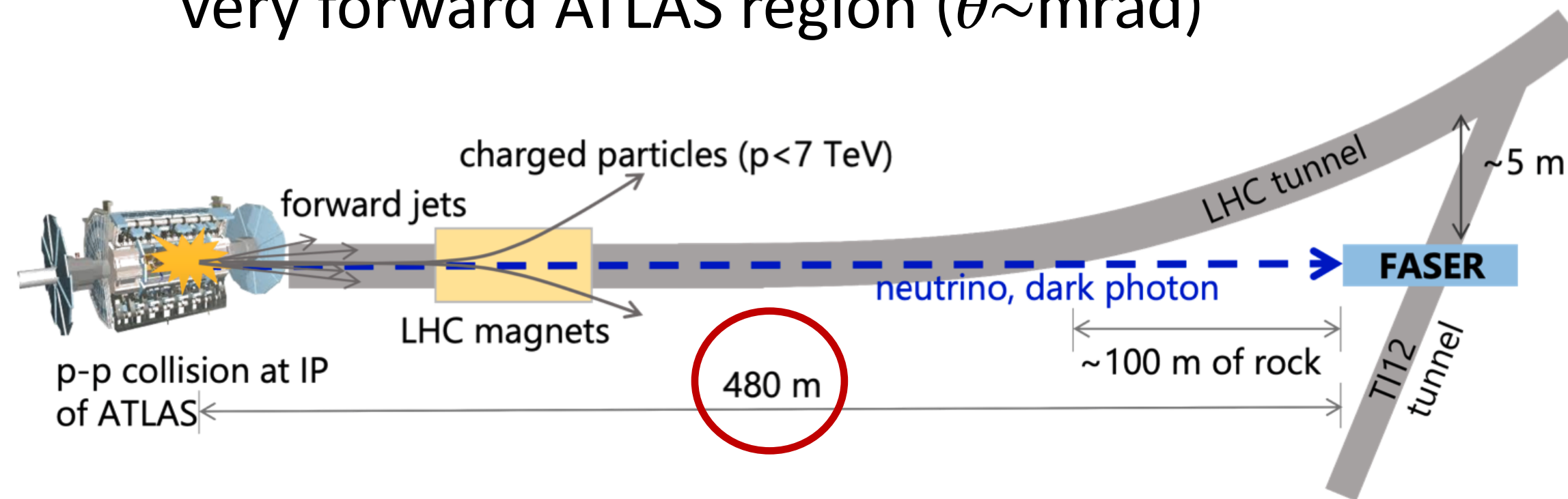
# The ForwArd Search ExpeRiment



## The ForwArd Search ExpeRiment at the LHC

Search for light, weakly interacting (LLP) new particles

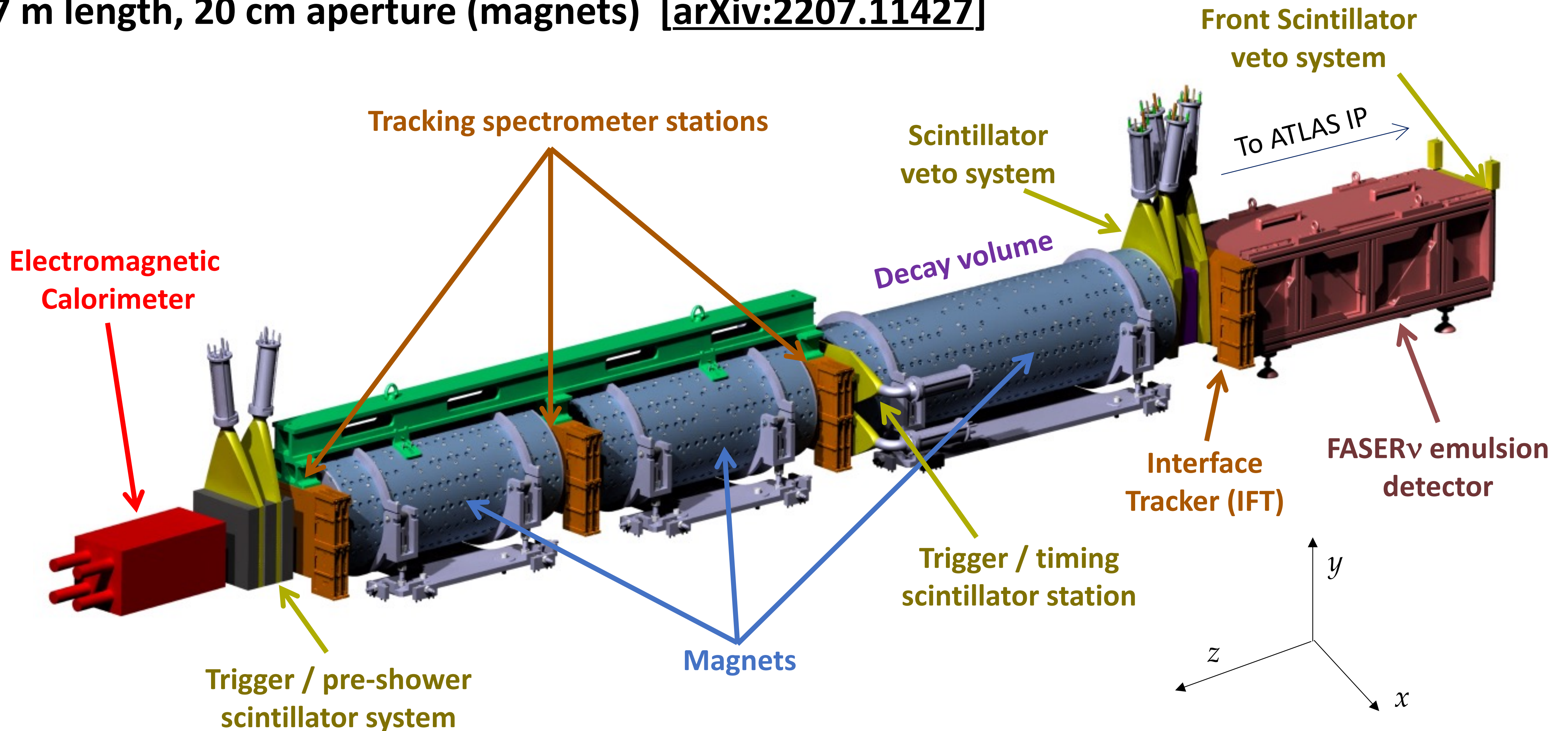
- ↳ stemming from rare meson decays ( $\pi$ ,  $\eta$ ,  $K$ ,  $D$  ...) in very forward ATLAS region ( $\theta \sim \text{mrad}$ )



# The ForwArd Search ExpeRiment



$\approx 7$  m length, 20 cm aperture (magnets) [arXiv:2207.11427]

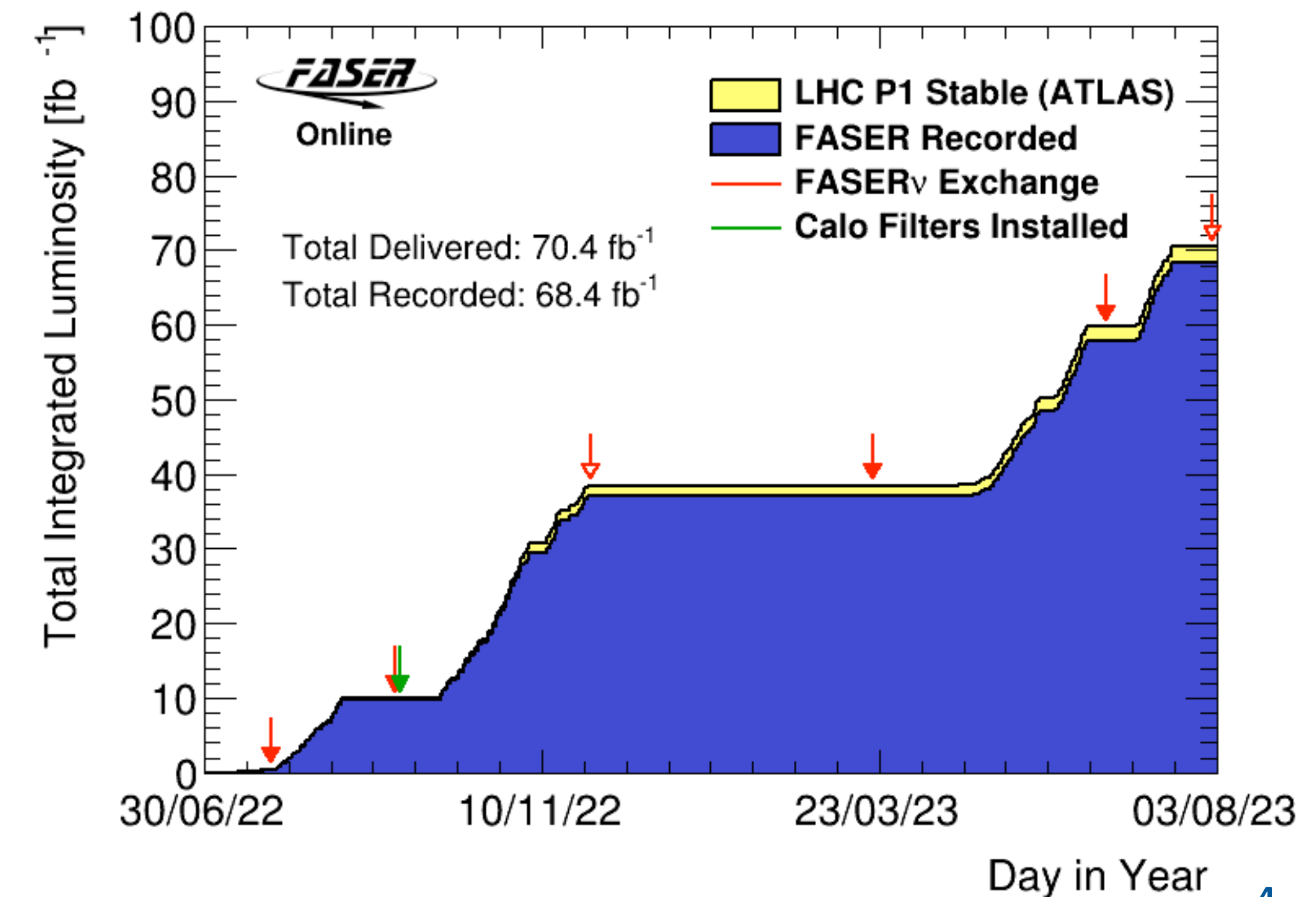
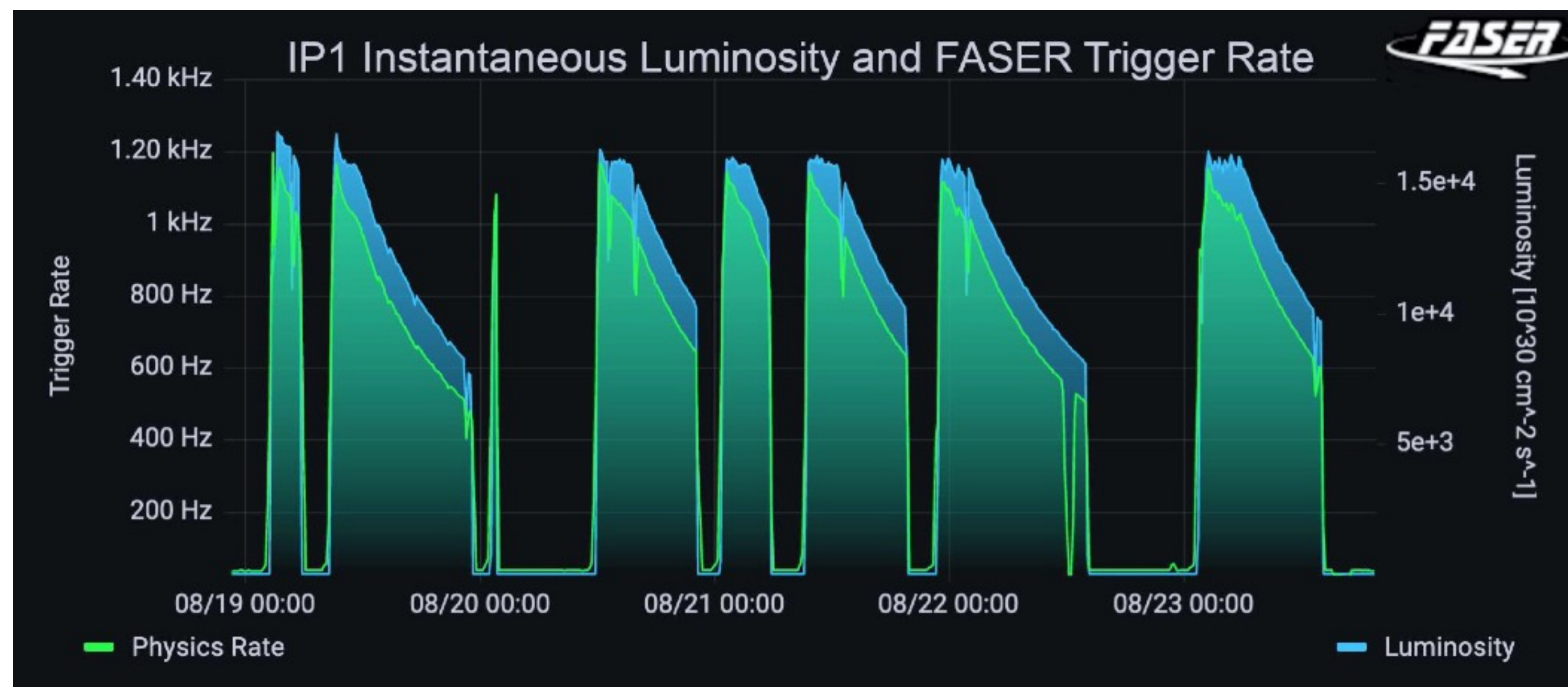


# Detector Operation and Data Taking



## Data taking started in July 2022: experiment successfully operated since then

- ▶ Lightweight operational model (no control room), largely automatic data taking at up to 1.3 kHz
- ▶ Excellent detector performance and 98% data taking efficiency achieved
- ▶ Neutrino emulsions boxes exchanged four times thus far
- ▶ 35 fb<sup>-1</sup> collected in 2022 and 33 fb<sup>-1</sup> in 2023

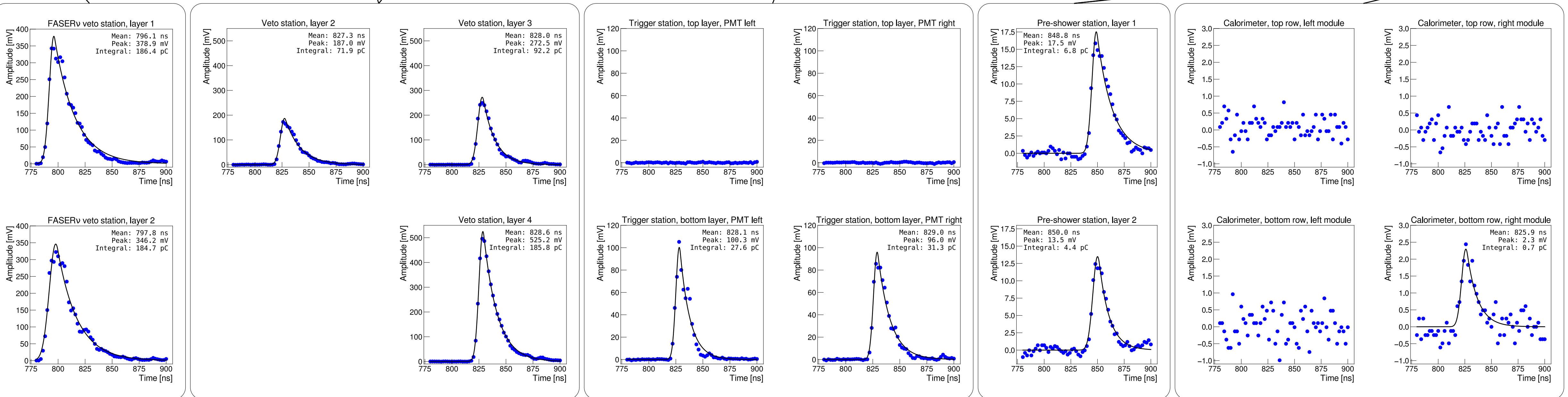
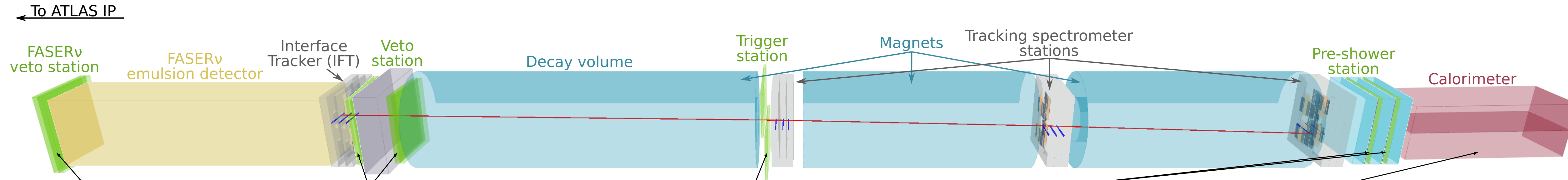


# Detector Operation and Data Taking



Run 8336  
Event 1477982  
2022-08-23 01:46:15

## Example of 1.3 TeV muon from collision event with 6.8 TeV stable beams



**Waveforms: Veto stations**

**Trigger stations**

**Preshower**

**Calorimeter**

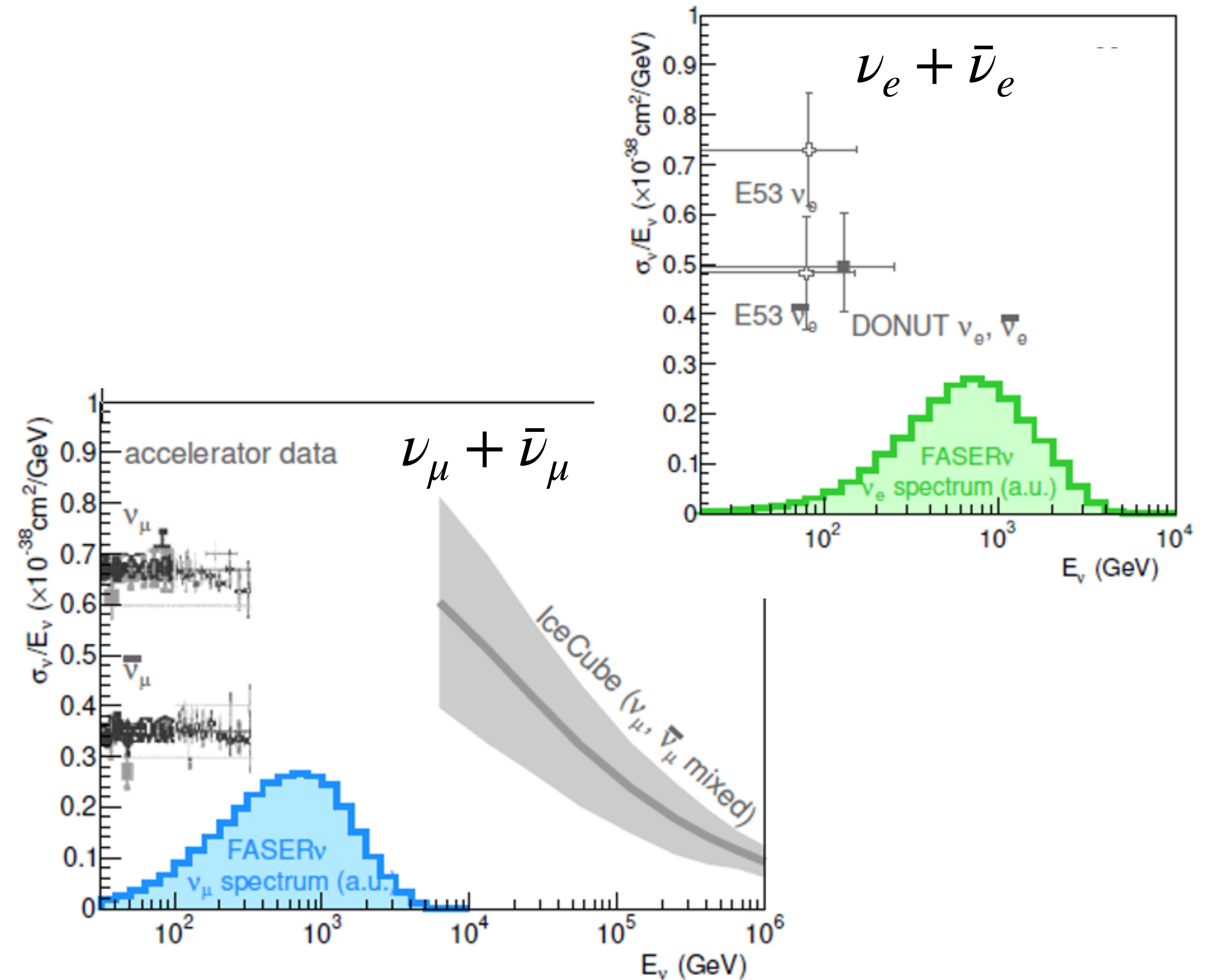
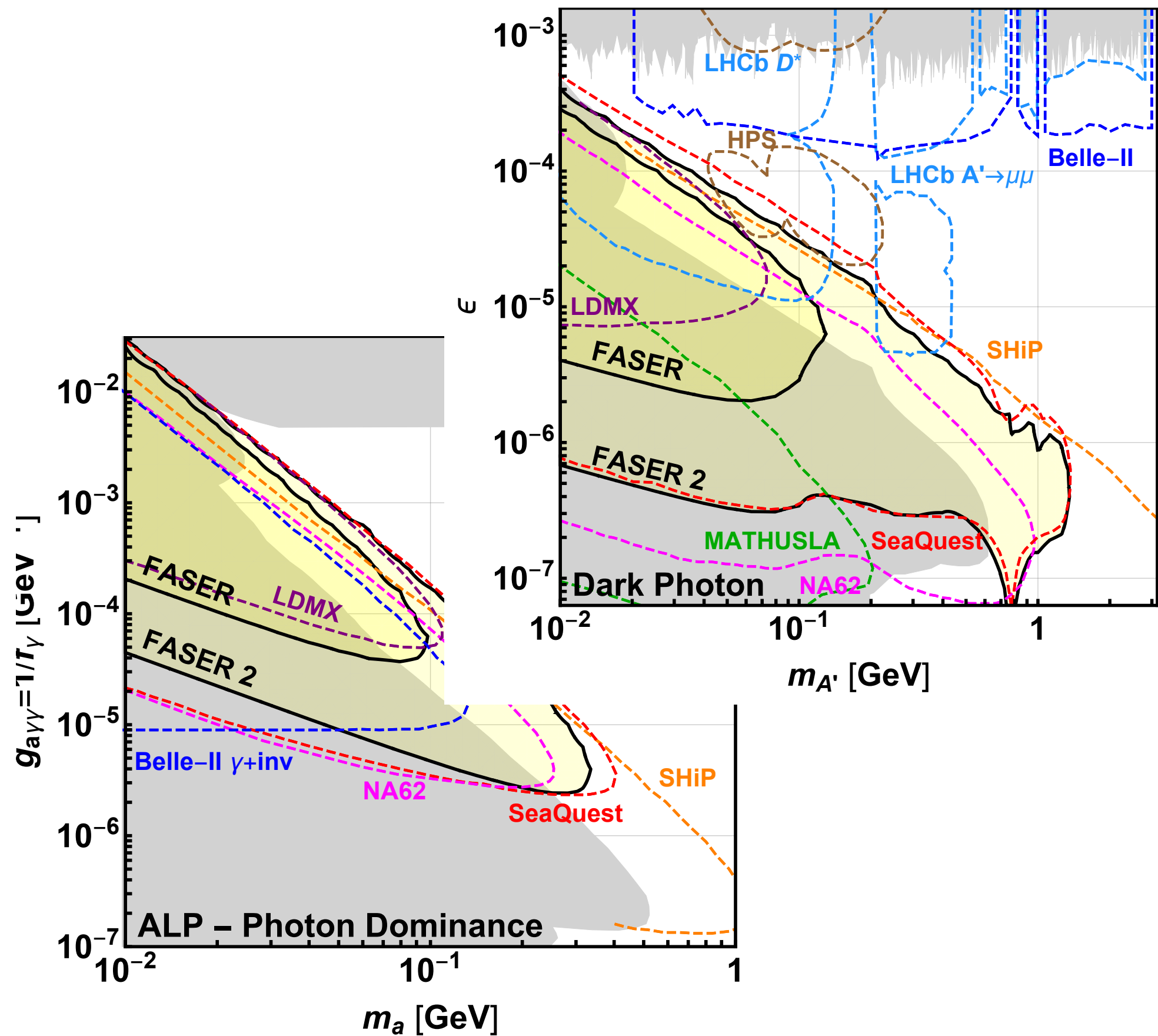
# Physics Opportunities with FASER

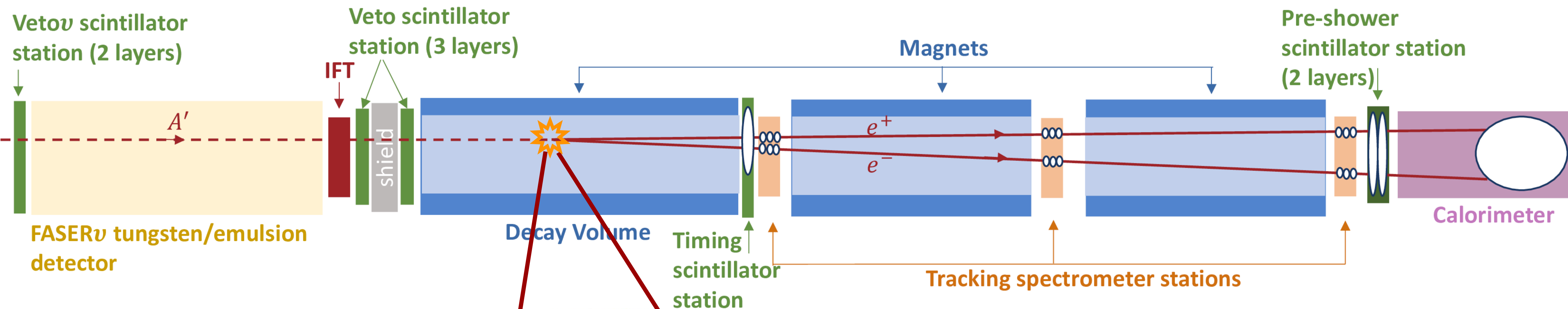


## FASER chases after feebly interacting particles

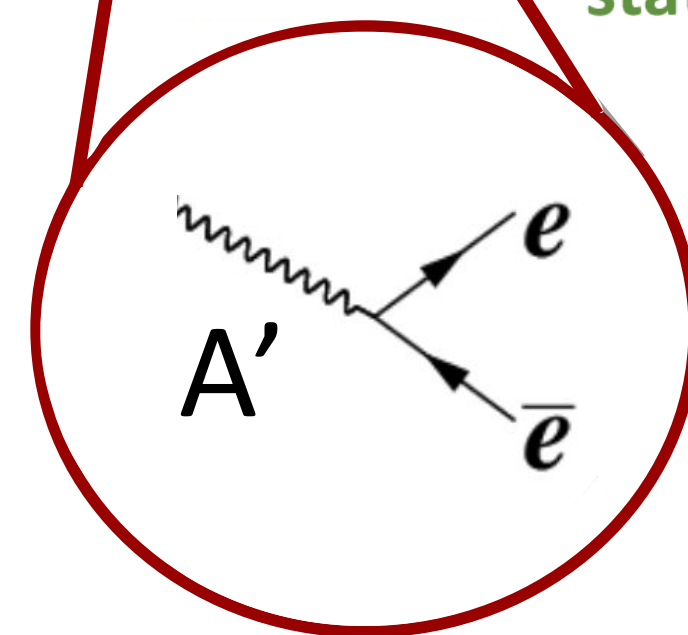
**new particles** [arXiv:1811.12522]: dark photon, ALPs...

**collider neutrinos** [arXiv:1908.02310]





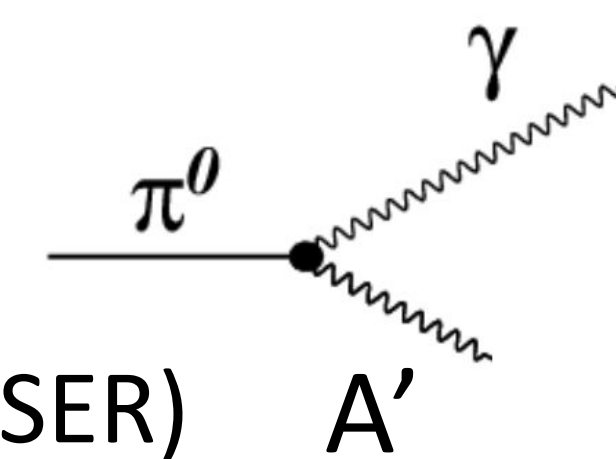
**Dark photon:**  
 hypothetical gauge boson from *hidden sector* mixing with SM photon



$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f A'^\mu \bar{f} \gamma_\mu f$$

⇒ At LHC, mainly from rare light meson decays;  $O(100\text{m})$  decay length for model of interest

⇒ Almost exclusively decaying to  $e^+e^-$  pairs for  $1 \text{ MeV} < m_{A'} < 211 \text{ MeV}$  (region accessible to FASER)



# Search for **Dark Photons**: Backgrounds



## Veto inefficiency

- ⇒ Measured layer-by-layer using muon tracks
- ⇒ Completely negligible:  $10^{-12}$  expected out of  $10^8$  muons

## Non-collision background

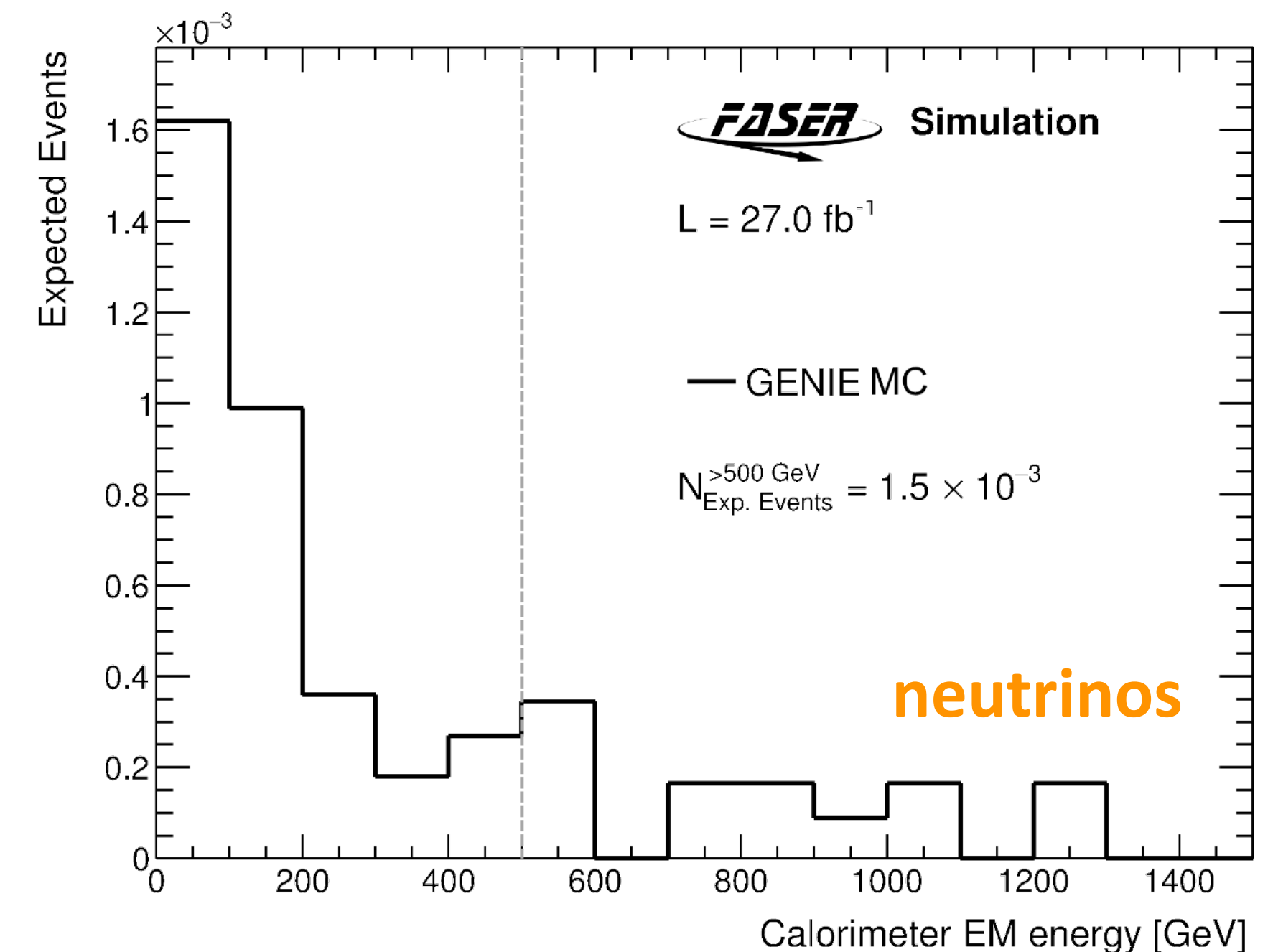
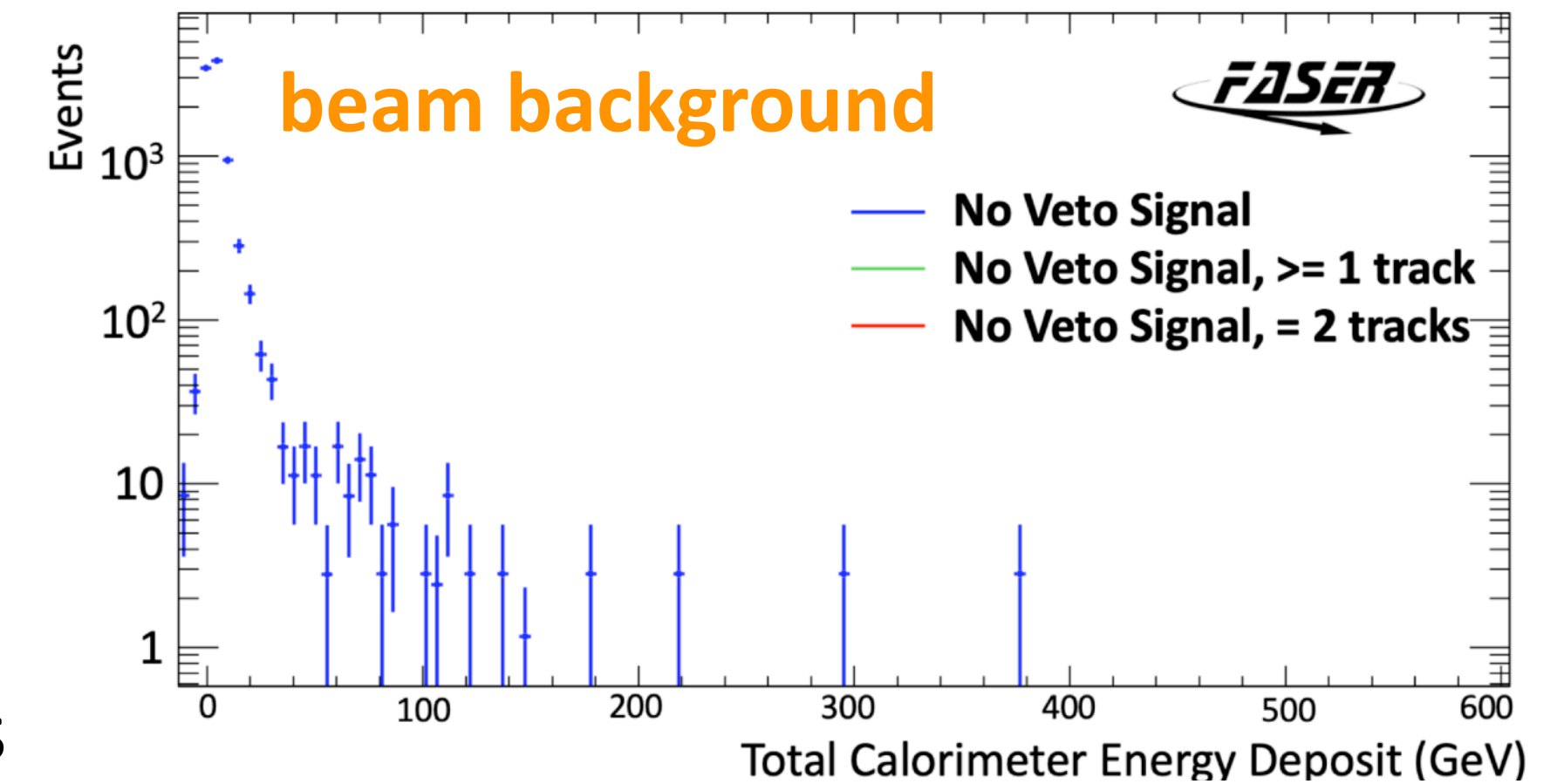
- ⇒ Cosmics if no beam + beam debris from non-colliding bunches
- ⇒ No events seen with  $\geq 1$  track or  $E_{\text{calo}} > 500$  GeV

## Neutral hadrons

- ⇒ Estimated from low-E events with 2-3 tracks + different veto
- ⇒ Suppressed by veto &  $E_{\text{calo}} > 500$  GeV:  $(2.2 \pm 3.1) \times 10^{-4}$  events

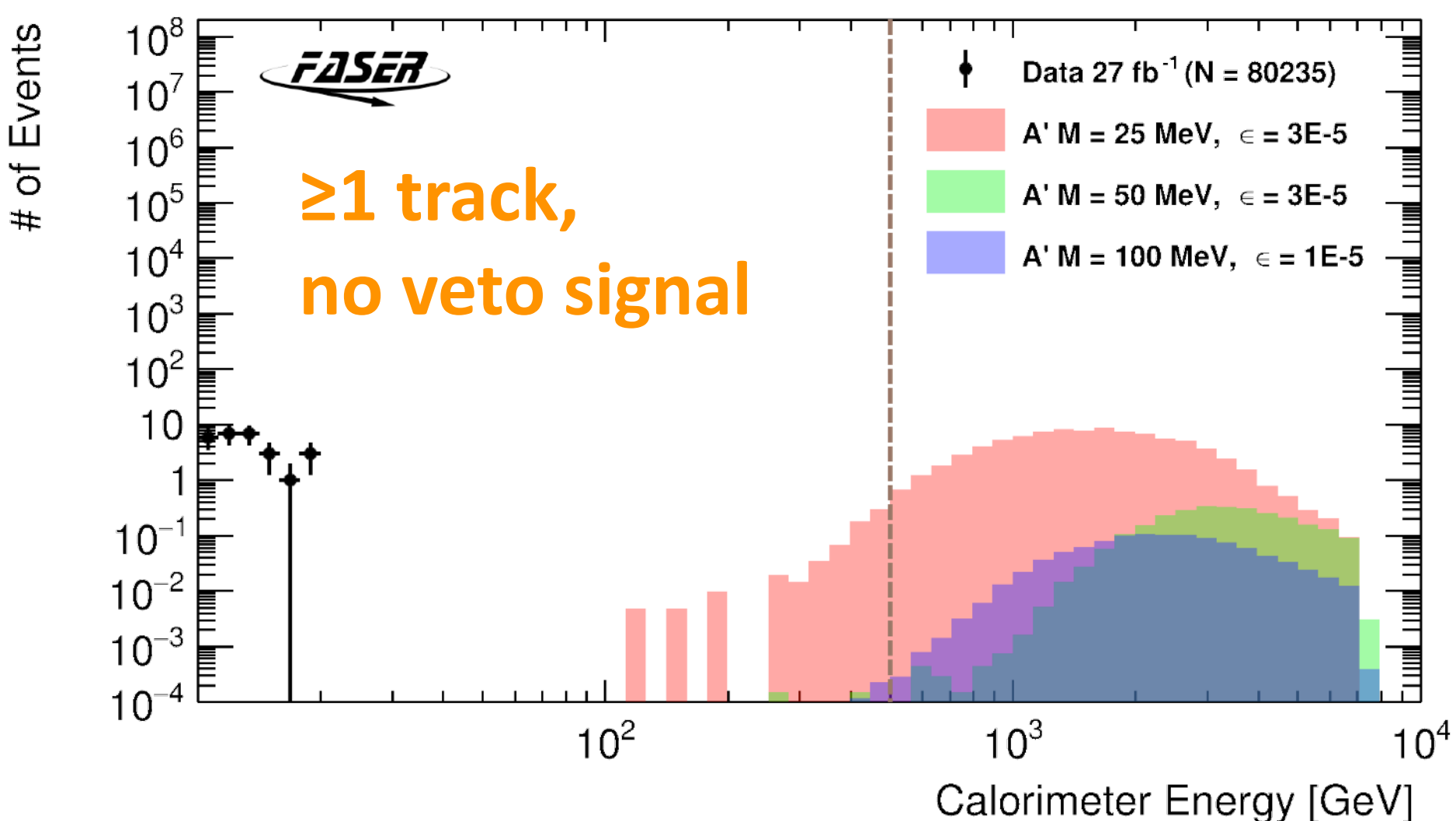
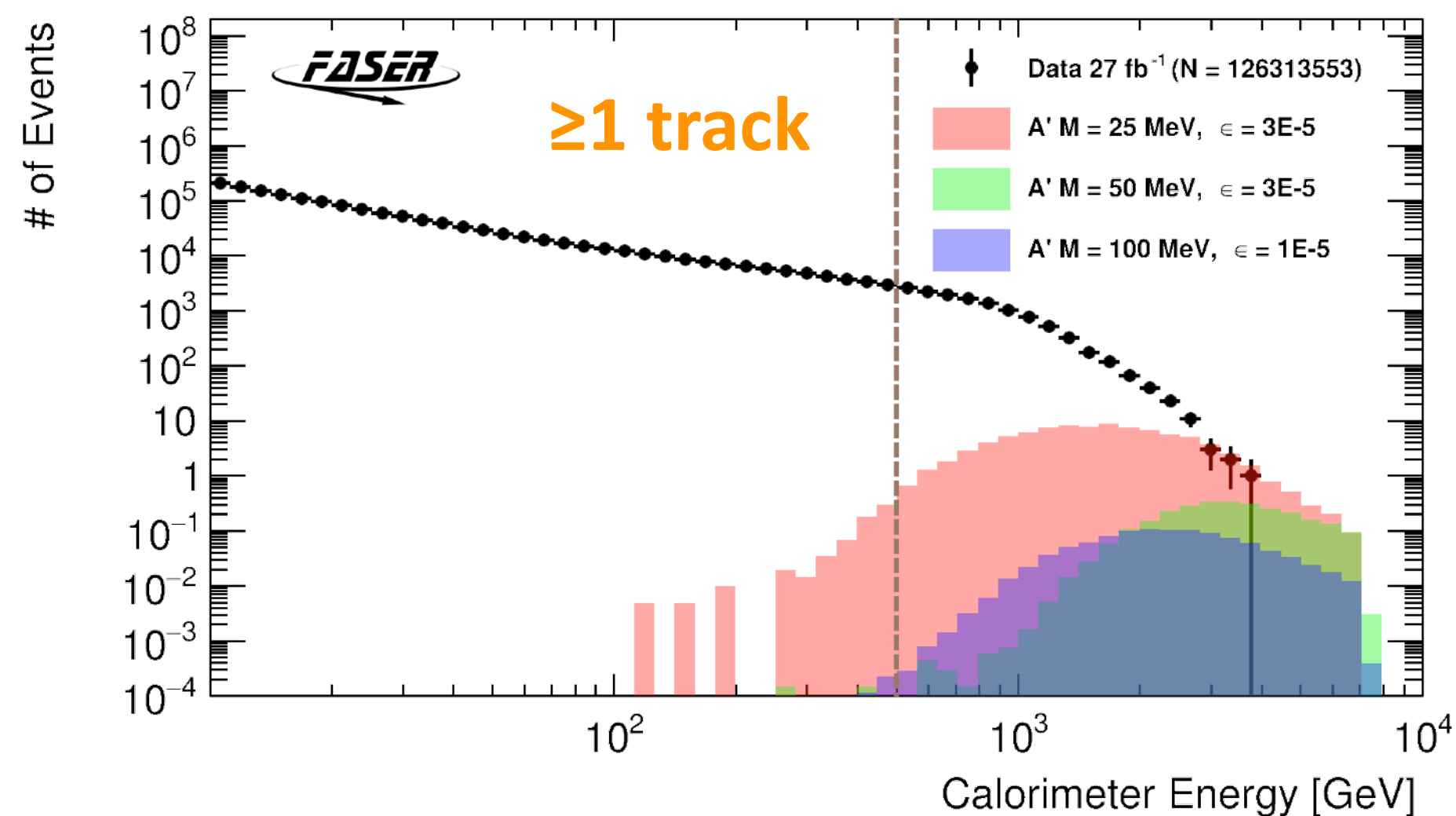
## Neutrino interactions

- ⇒ "Dominant" background: estimated from Genie MC
- ⇒ Suppressed by  $E_{\text{calo}} > 500$  GeV:  $(1.8 \pm 2.4) \times 10^{-3}$  events



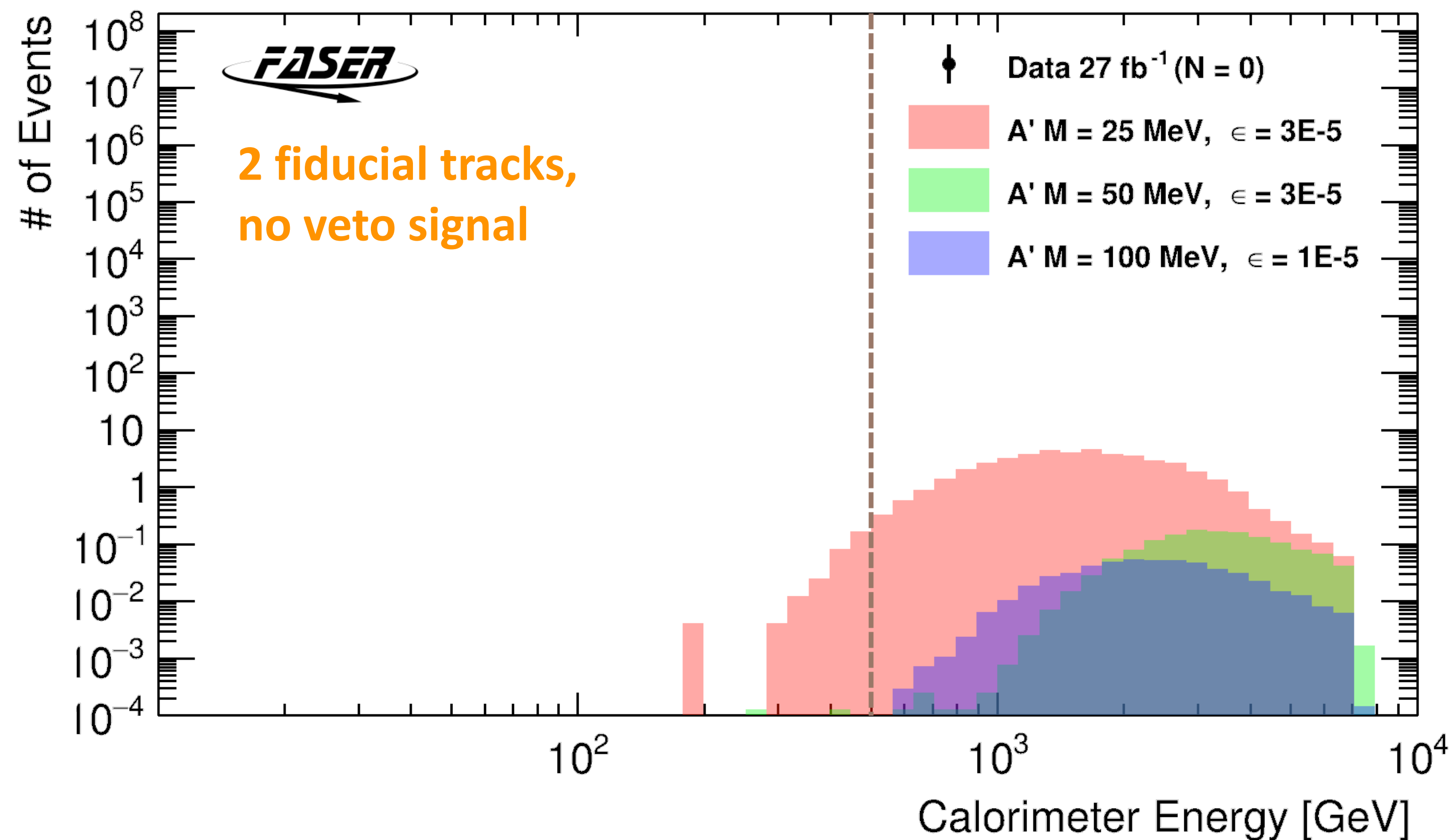


# Search for Dark Photons: Signal Region



## No observed data events in signal region:

- ⇒ Event time consistent with collision bunch at IP1
- ⇒ No signal in veto scintillators, two good >20 GeV tracks
- ⇒ Signal in downstream scintillators,  $E_{\text{calorimeter}} > 500$  GeV



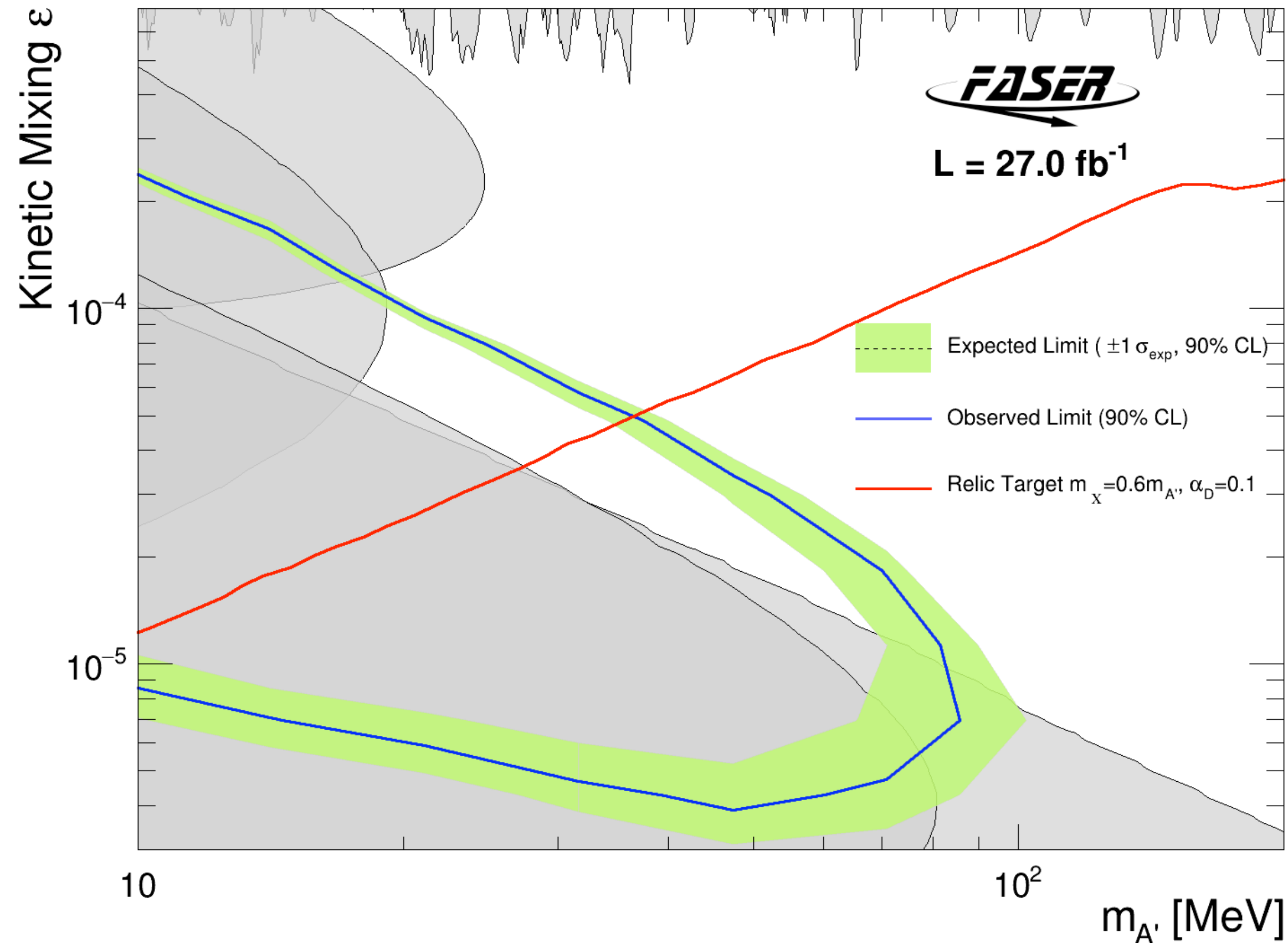
# Search for Dark Photons: Exclusion Limits



## Dark photon: benchmark model

90% CL exclusions:

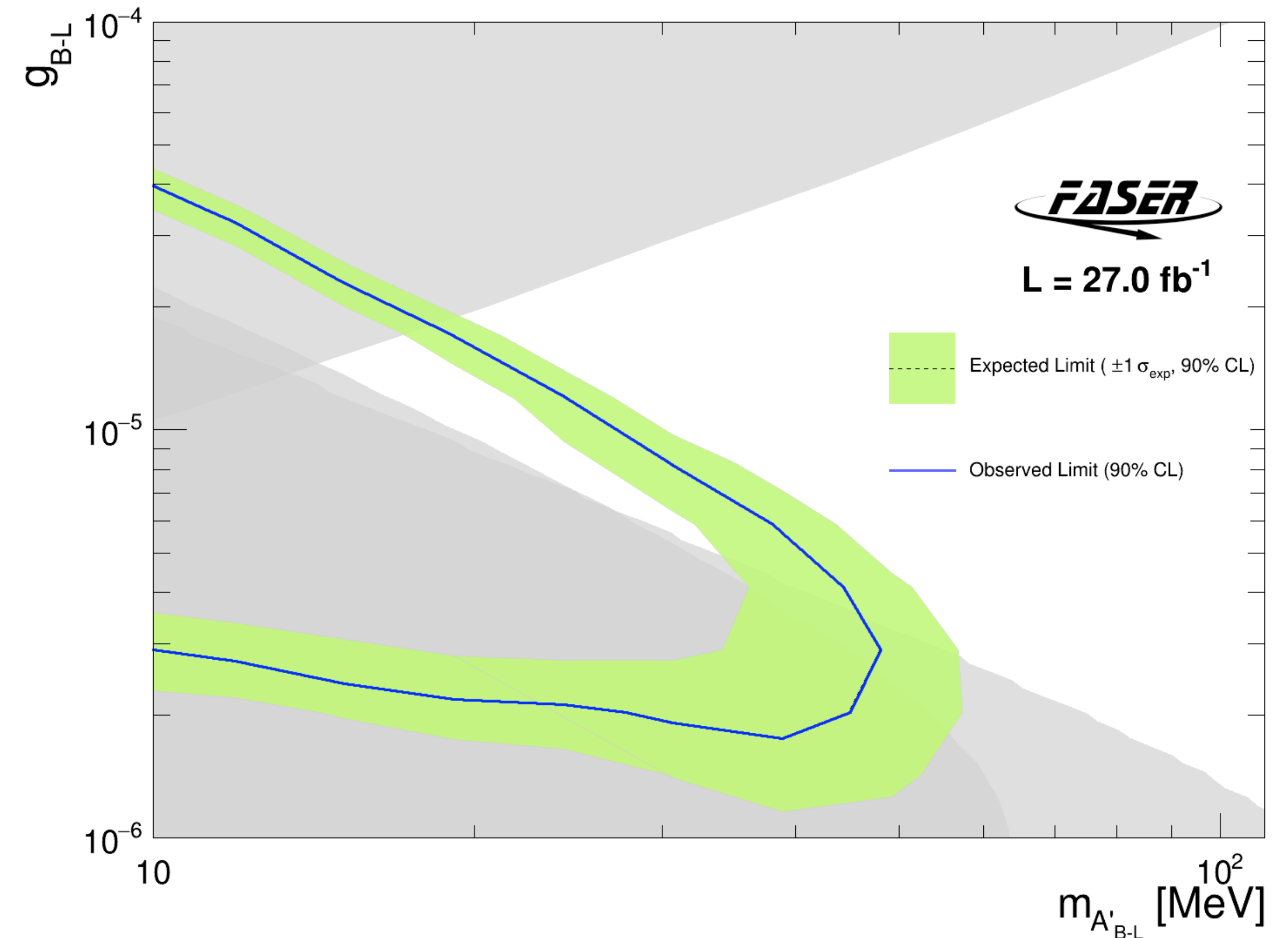
$\epsilon \sim 4 \times 10^{-6} - 2 \times 10^{-4}$  and  $m_{A'} \sim 10 \text{ MeV} - 80 \text{ MeV}$



## Reinterpretation: B-L gauge boson

90% CL exclusions:

$g_{B-L} \sim 3 \times 10^{-6} - 4 \times 10^{-5}$  and  $m_{A'} \sim 10 \text{ MeV} - 50 \text{ MeV}$



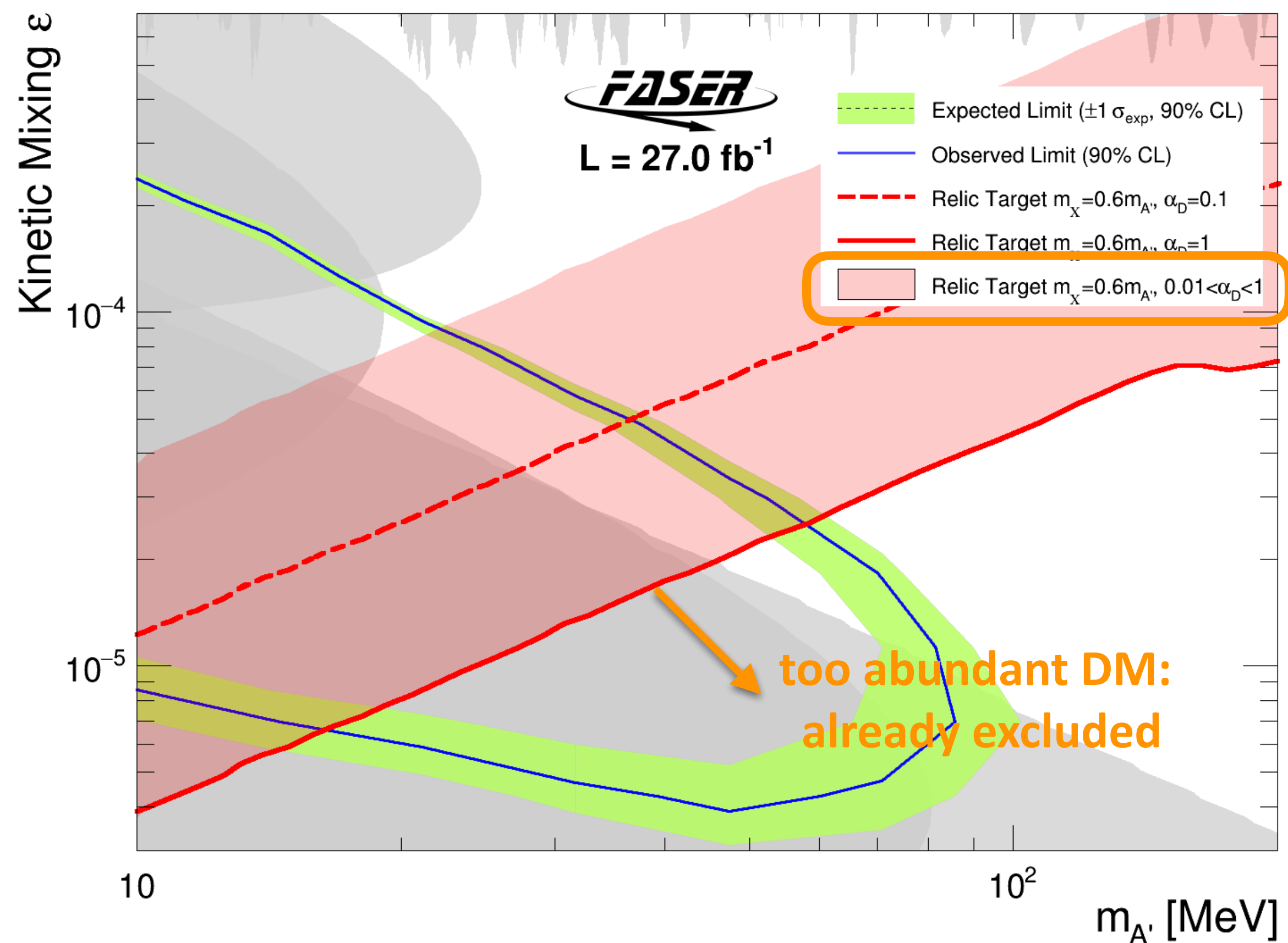
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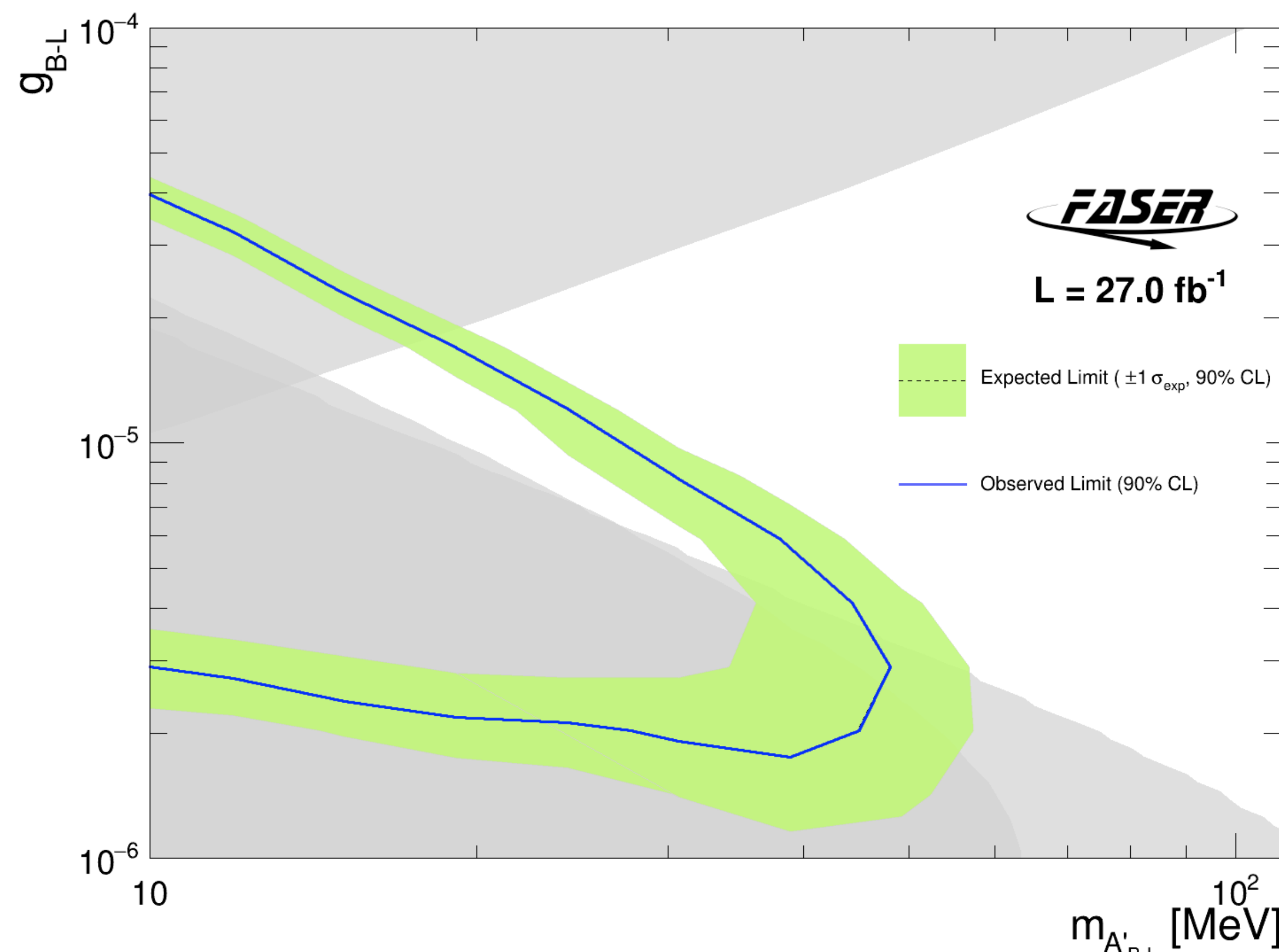
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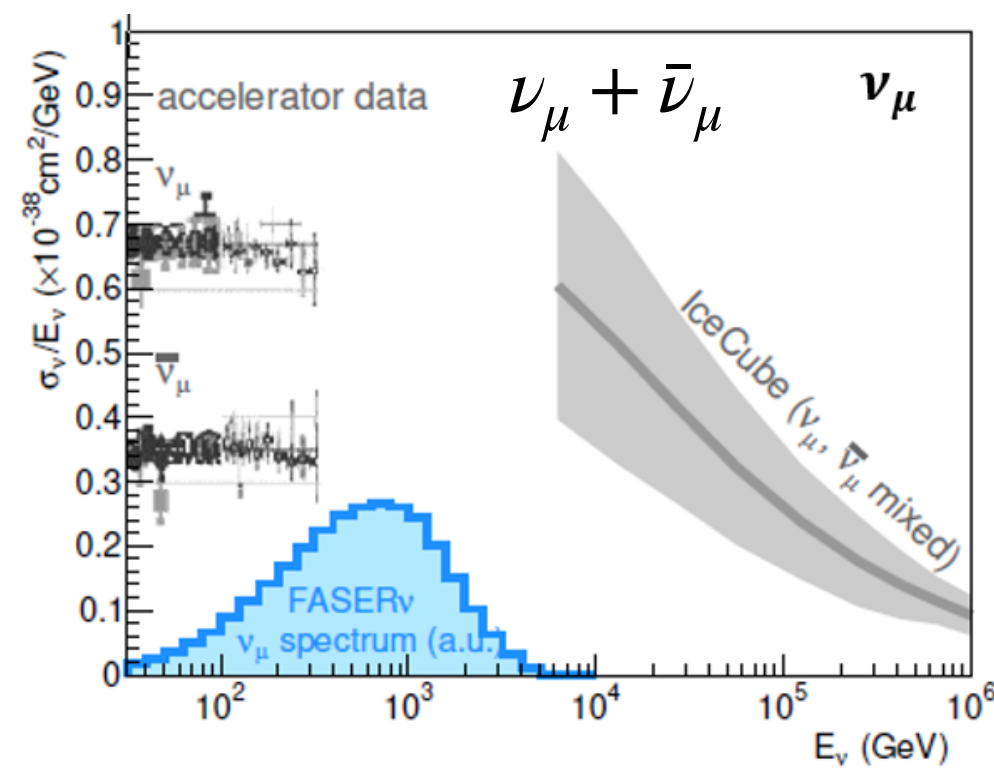
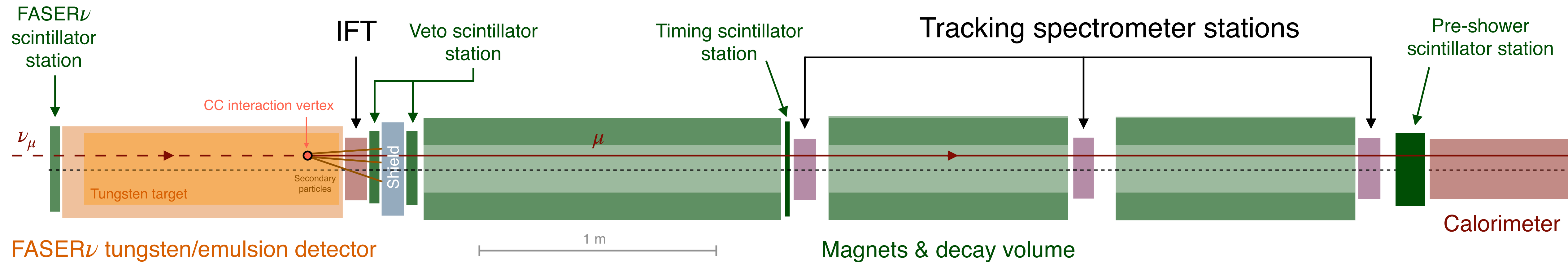


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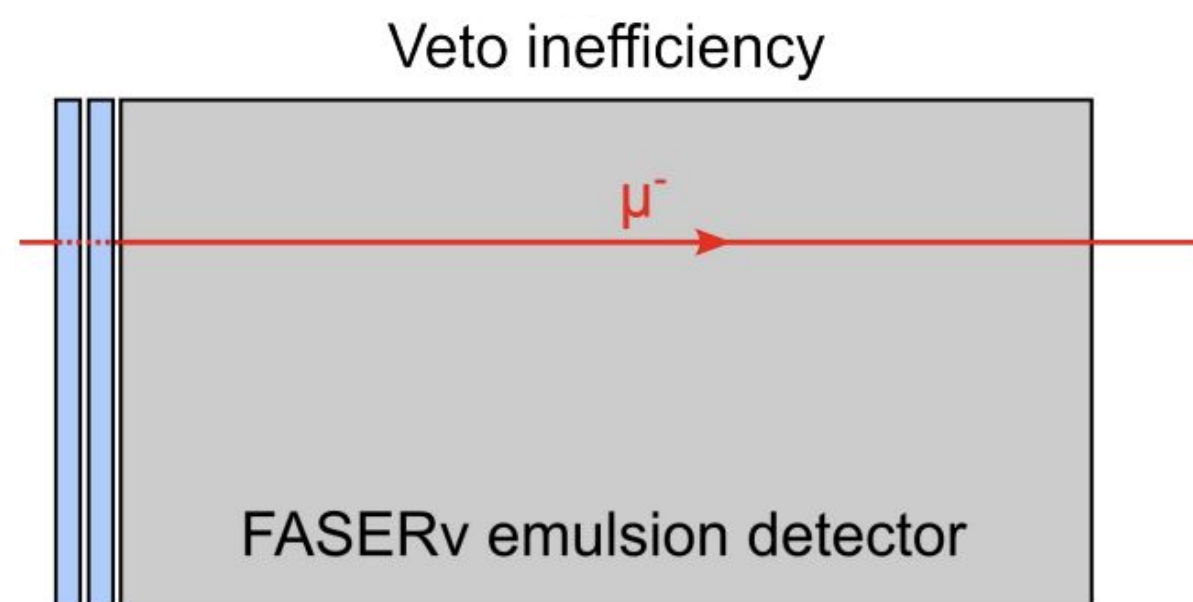
**Collider neutrinos:** never observed before, filling existing energy gap between reactor/beam-dump and astrophysical sources

Neutrino **DIS** insightful tool to probe nuclear PDFs in unconstrained momentum fraction regions

- ⇒ At LHC, abundant production of neutrinos from forward hadron decays
- ⇒ Strategy: no signal in FASERν veto, track in spectrometer, MIP-like signal in downstream scintillator

## Veto inefficiency

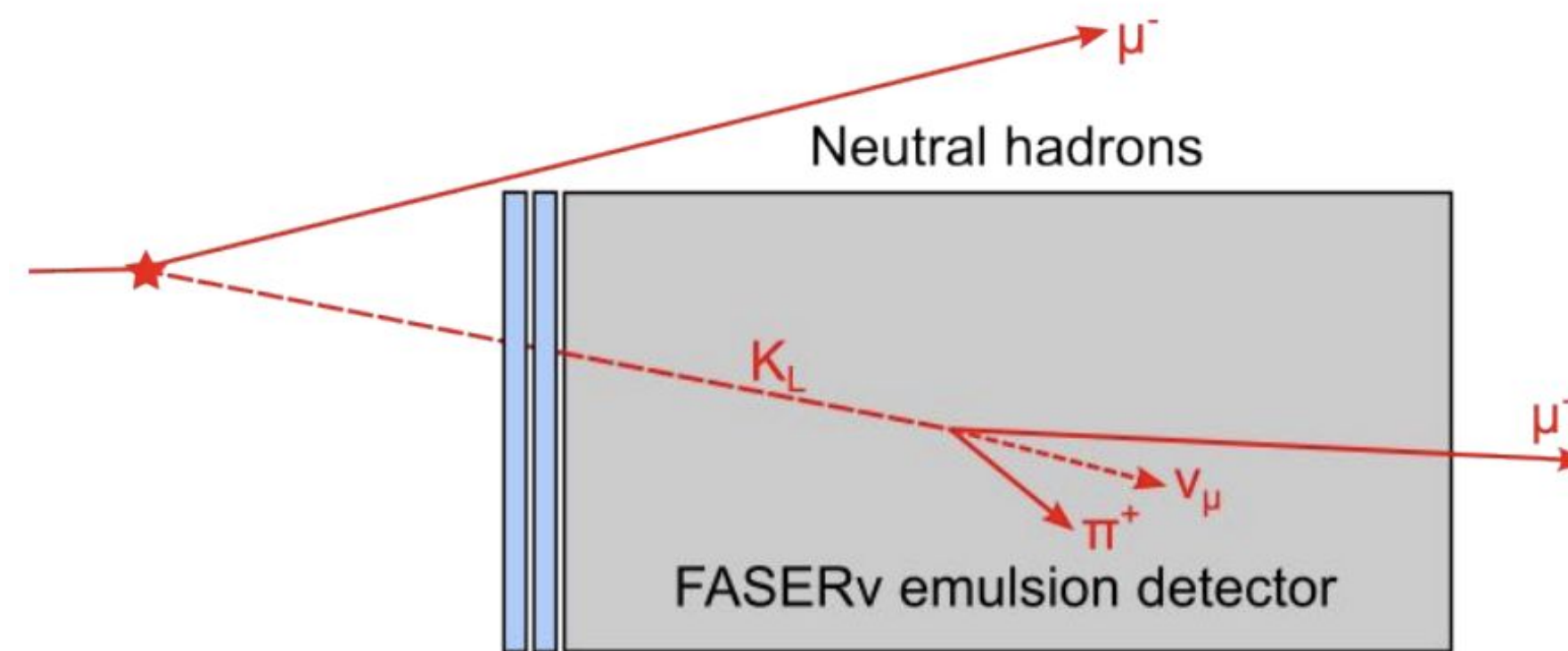
Estimated by comparing hit differences in first and second scintillator planes directly in collision data



Negligible:  
inefficiency  $\approx 10^{-7}$

## Neutral hadrons

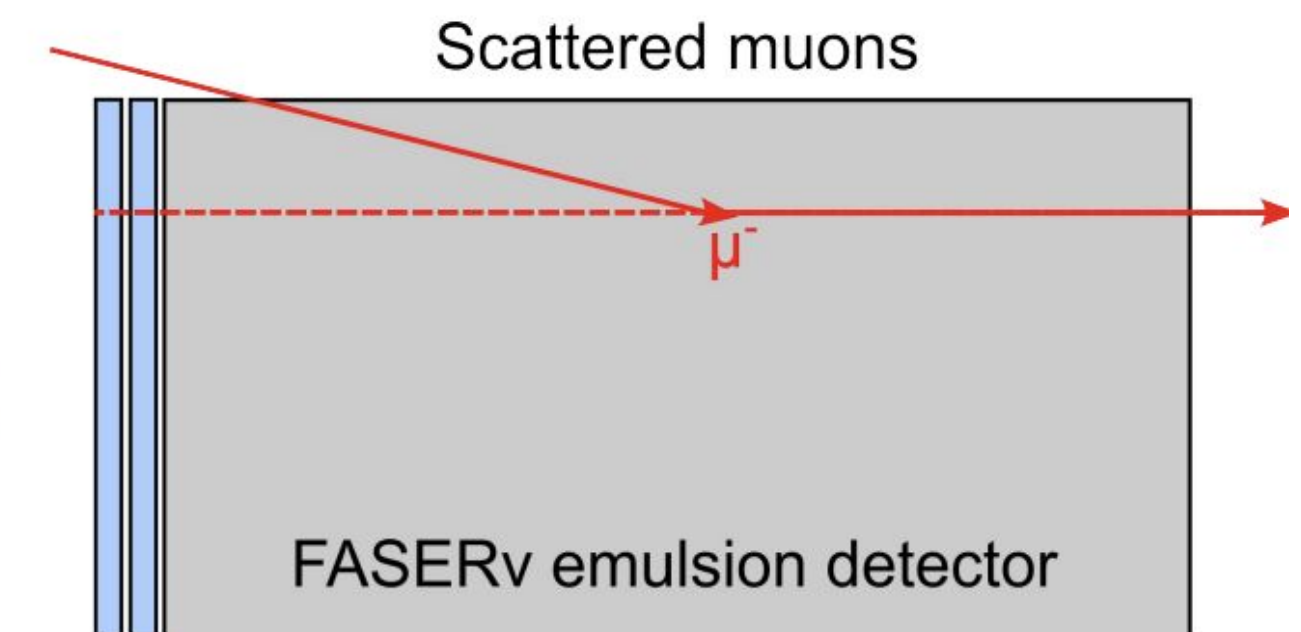
Majority of hadrons absorbed in FASERv tungsten planes.  
Produced muon often hitting veto.  
Estimated with MC



Expectations ( $35.4 \text{ fb}^{-1}$ ):  
 **$0.11 \pm 0.06$  events**

## Scattered muons

Estimated in dedicated control region of events with single track segment at large radius



Expectations ( $35.4 \text{ fb}^{-1}$ ):  
 **$0.08 \pm 1.83$  events**

**153 events observed with  $16\sigma$  significance**

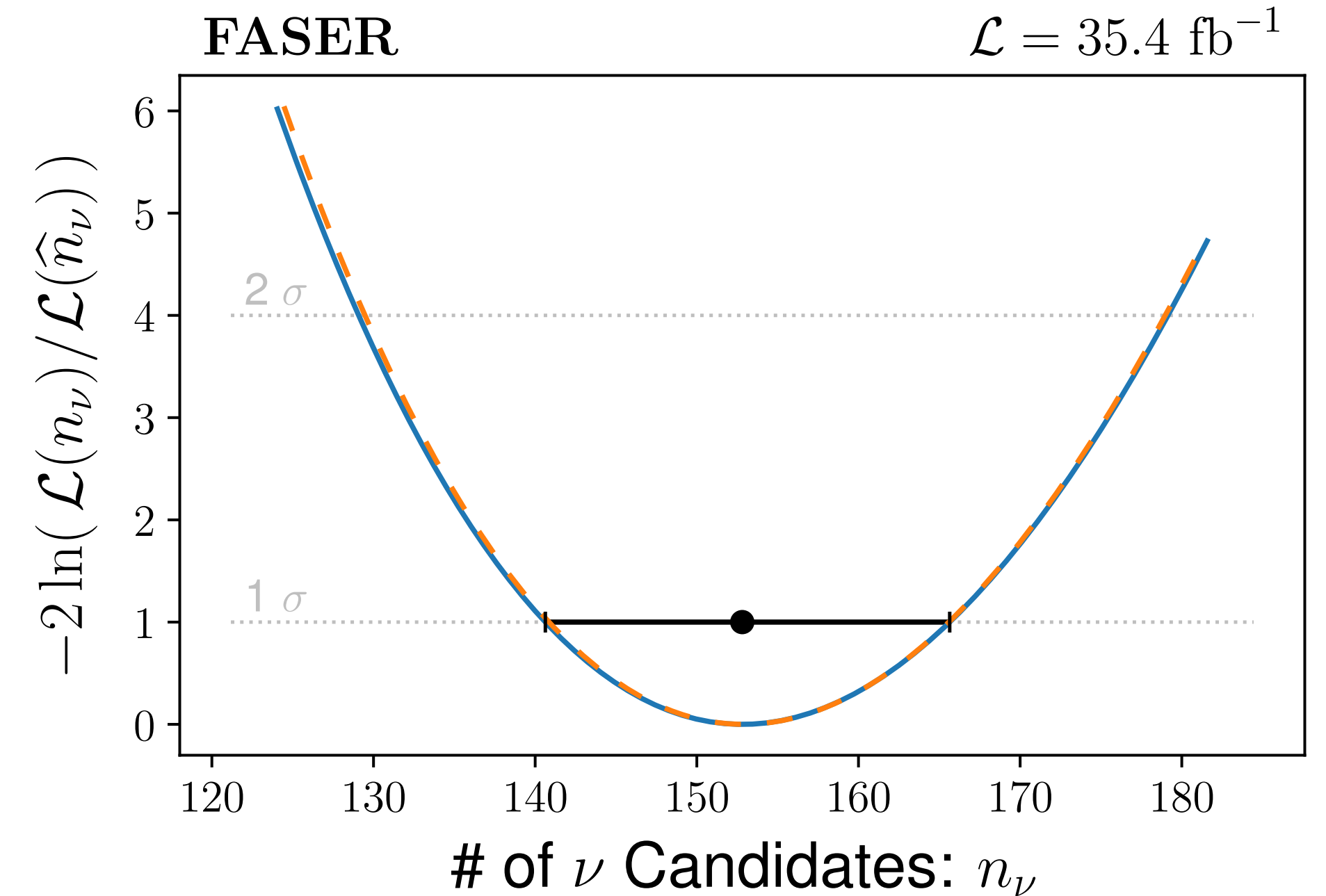
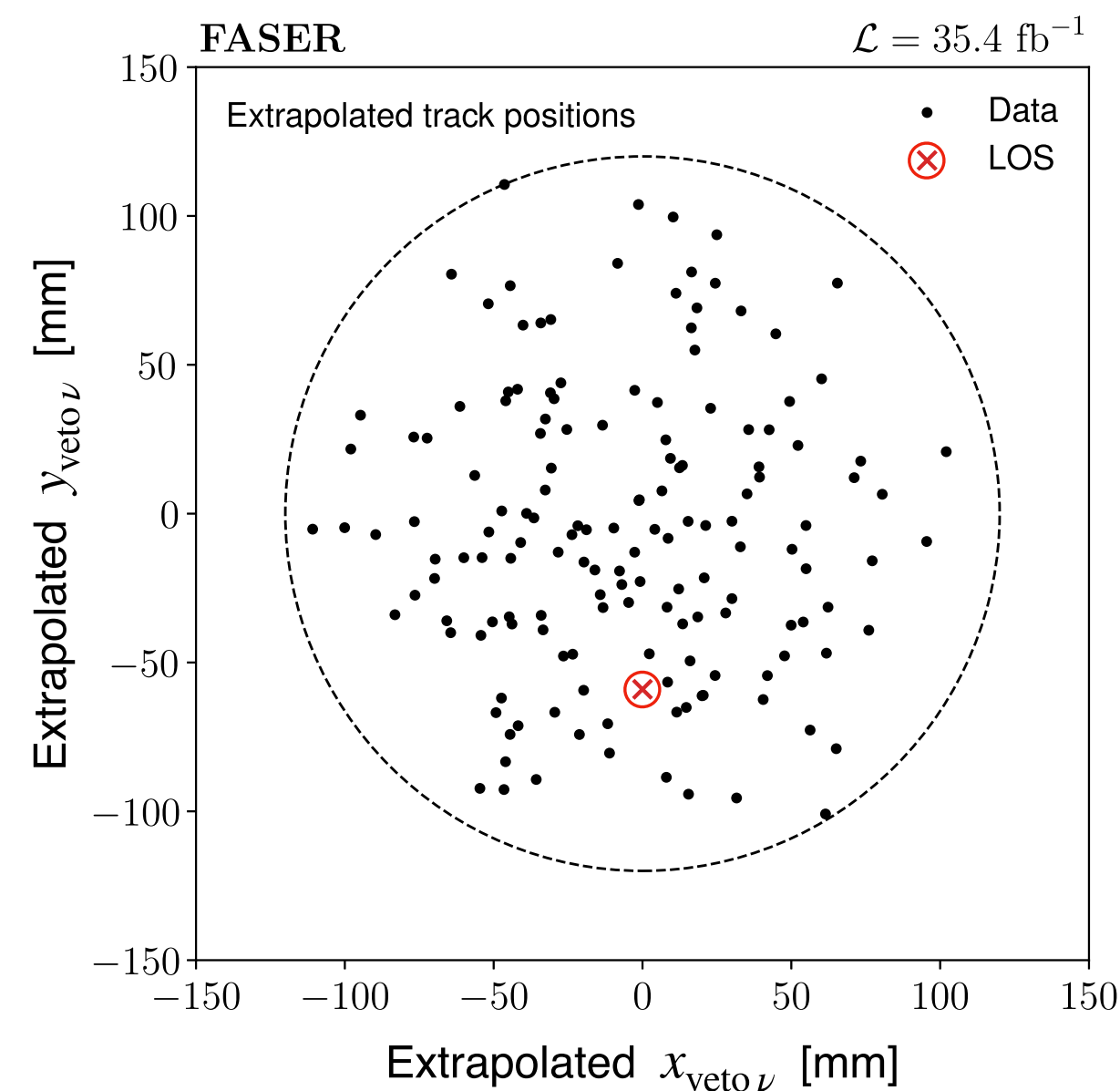
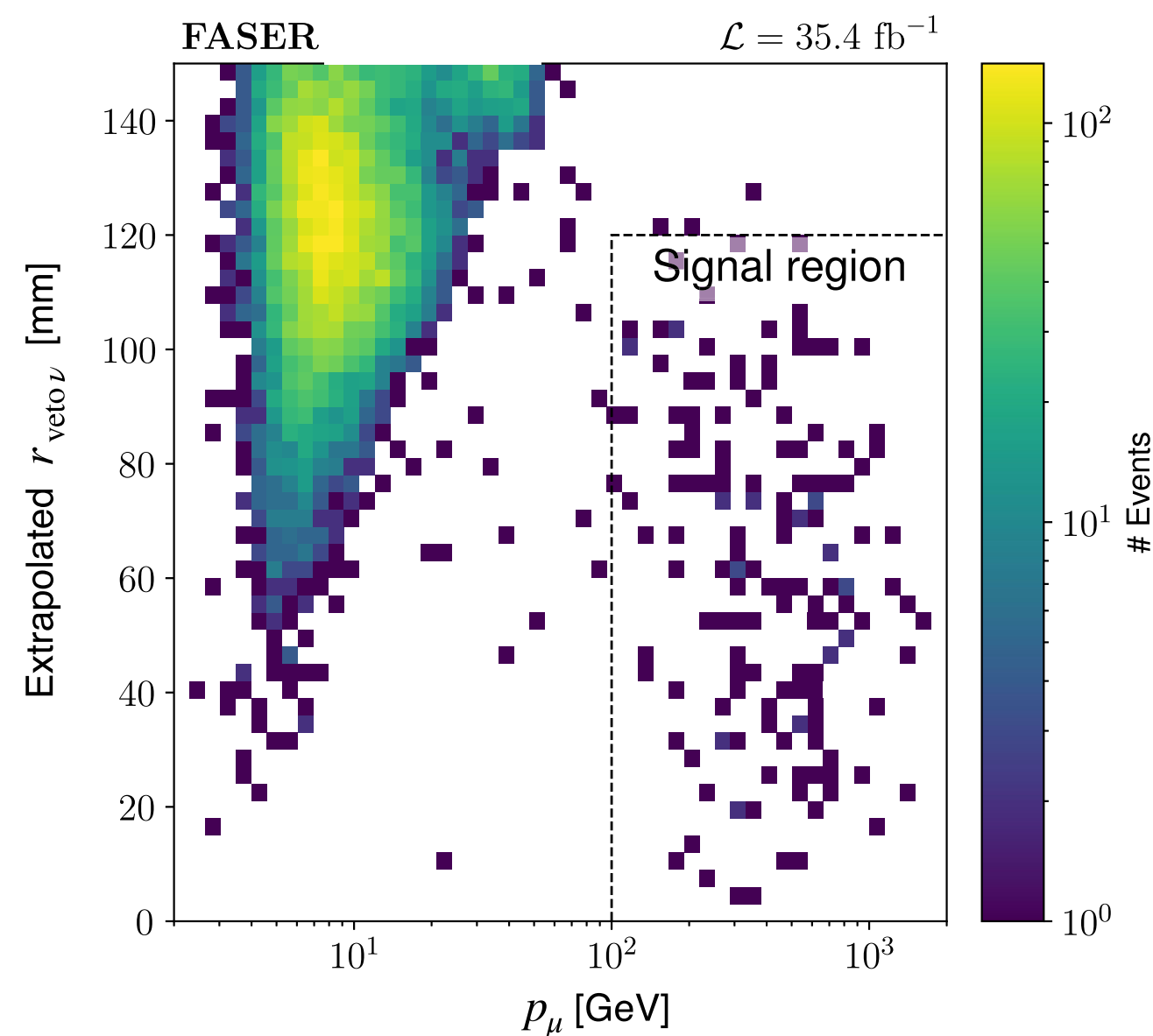
Expected signal:  $151 \pm 41^{(*)}$  events

(\*)  $\approx 30\%$  systematic from uncertainty in neutrino flux driven by DPMJET / SIBYLL difference

Run3 (4): MC expectations for 250 fb<sup>-1</sup> (680 fb<sup>-1</sup>)

| Generators    |               | FASER $\nu$ at Run 3  |                           |                             | FASER $\nu$ at Run 4   |                           |                             |
|---------------|---------------|-----------------------|---------------------------|-----------------------------|------------------------|---------------------------|-----------------------------|
| light hadrons | charm hadrons | $\nu_e + \bar{\nu}_e$ | $\nu_\mu + \bar{\nu}_\mu$ | $\nu_\tau + \bar{\nu}_\tau$ | $\nu_e + \bar{\nu}_e$  | $\nu_\mu + \bar{\nu}_\mu$ | $\nu_\tau + \bar{\nu}_\tau$ |
| EPOS-LHC      | -             | 1149                  | 7996                      | -                           | 3382                   | 23054                     | -                           |
| SIBYLL 2.3d   | -             | 1126                  | 7261                      | -                           | 3404                   | 21532                     | -                           |
| QGSJET 2.04   | -             | 1181                  | 8126                      | -                           | 3379                   | 22501                     | -                           |
| PYTHIAforward | -             | 1008                  | 7418                      | -                           | 2925                   | 20508                     | -                           |
| -             | POWHEG Max    | 1405                  | 1373                      | 76                          | 4264                   | 4068                      | 255                         |
| -             | POWHEG        | 527                   | 511                       | 28                          | 1537                   | 1499                      | 91                          |
| -             | POWHEG Min    | 294                   | 284                       | 16                          | 853                    | 826                       | 51                          |
| Combination   |               | $1675^{+911}_{-372}$  | $8507^{+992}_{-962}$      | $28^{+48}_{-12}$            | $4919^{+2748}_{-1141}$ | $24553^{+2568}_{-3219}$   | $91^{+163}_{-41}$           |

arXiv:2402.13318



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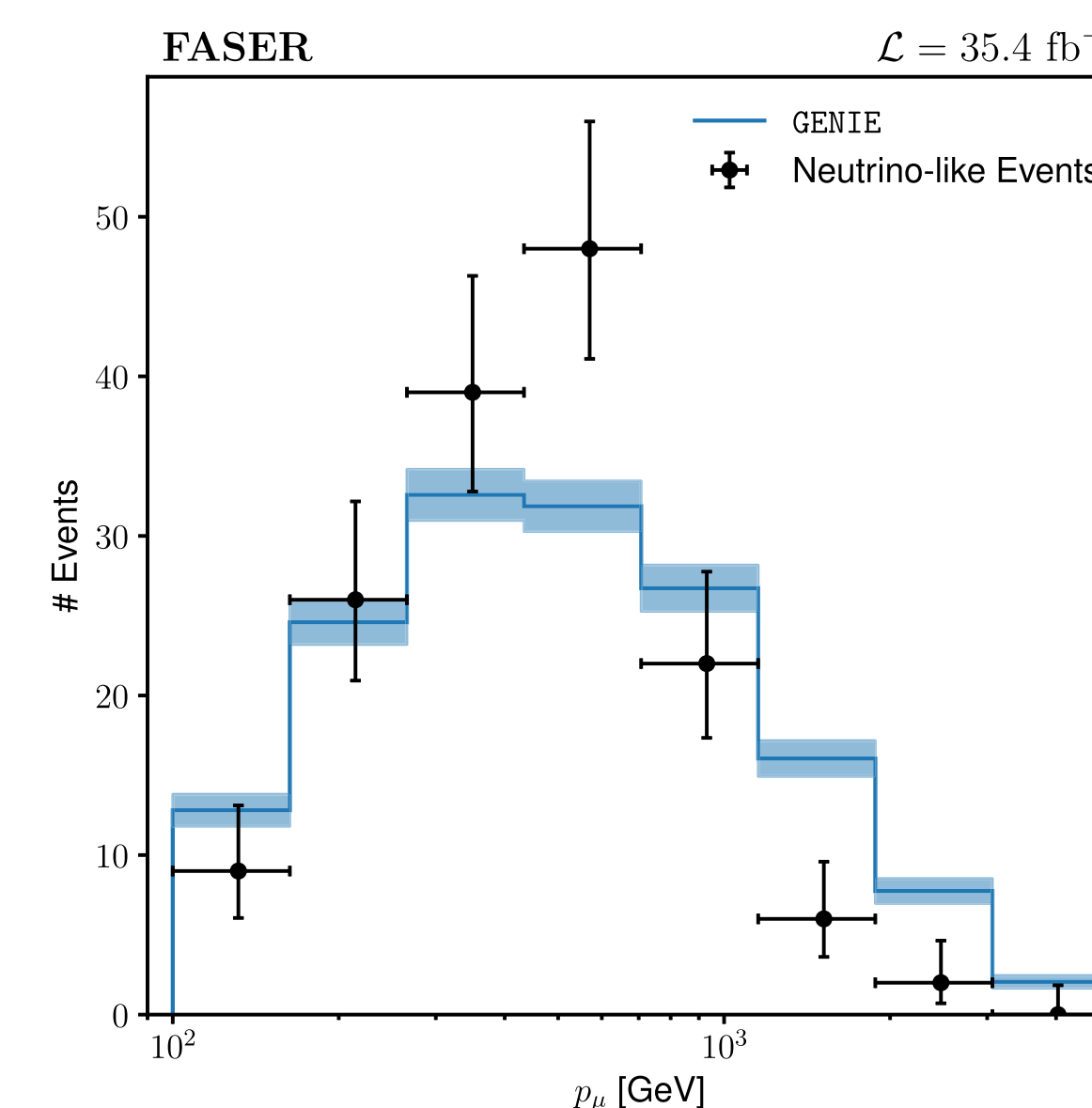
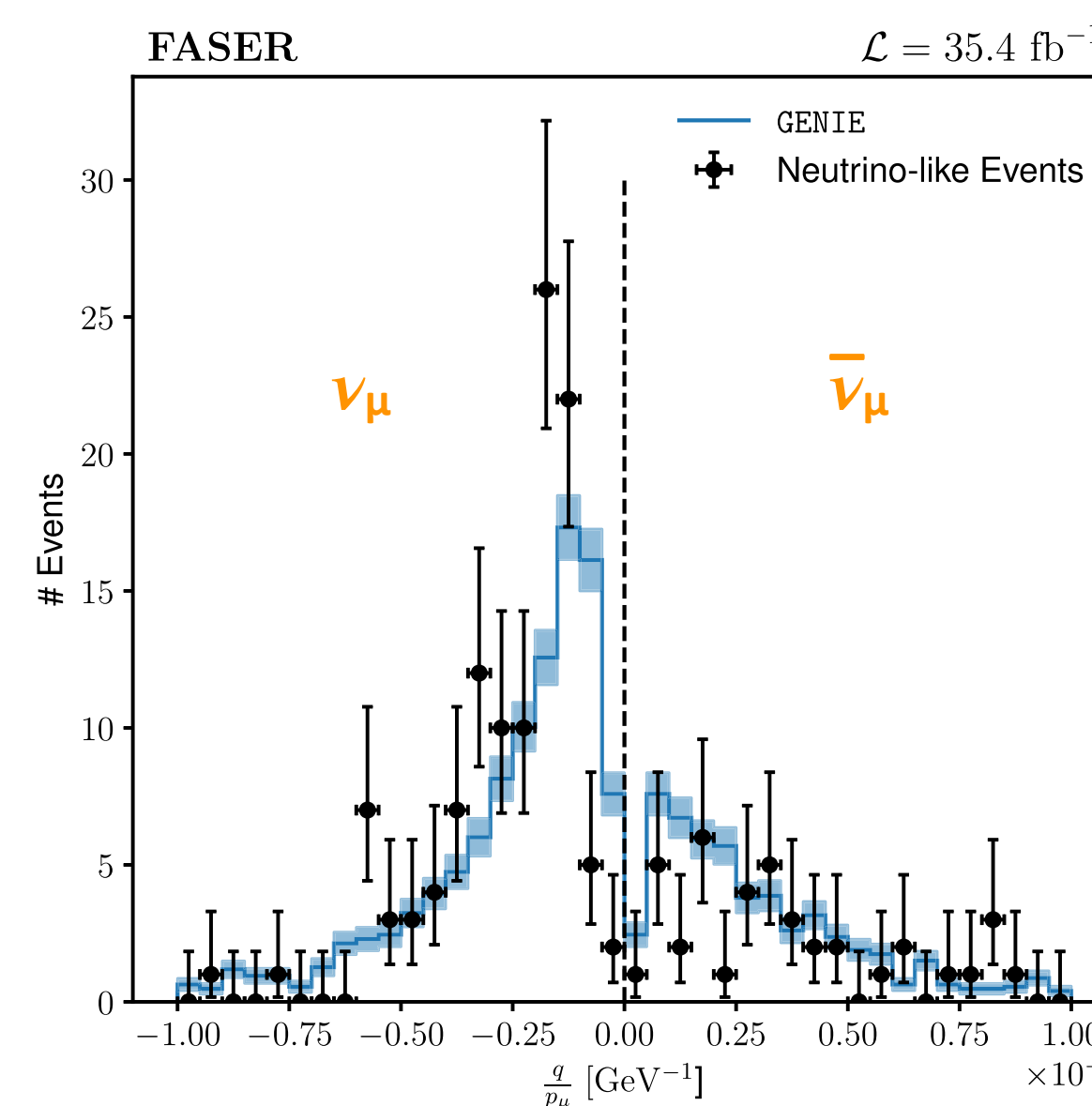
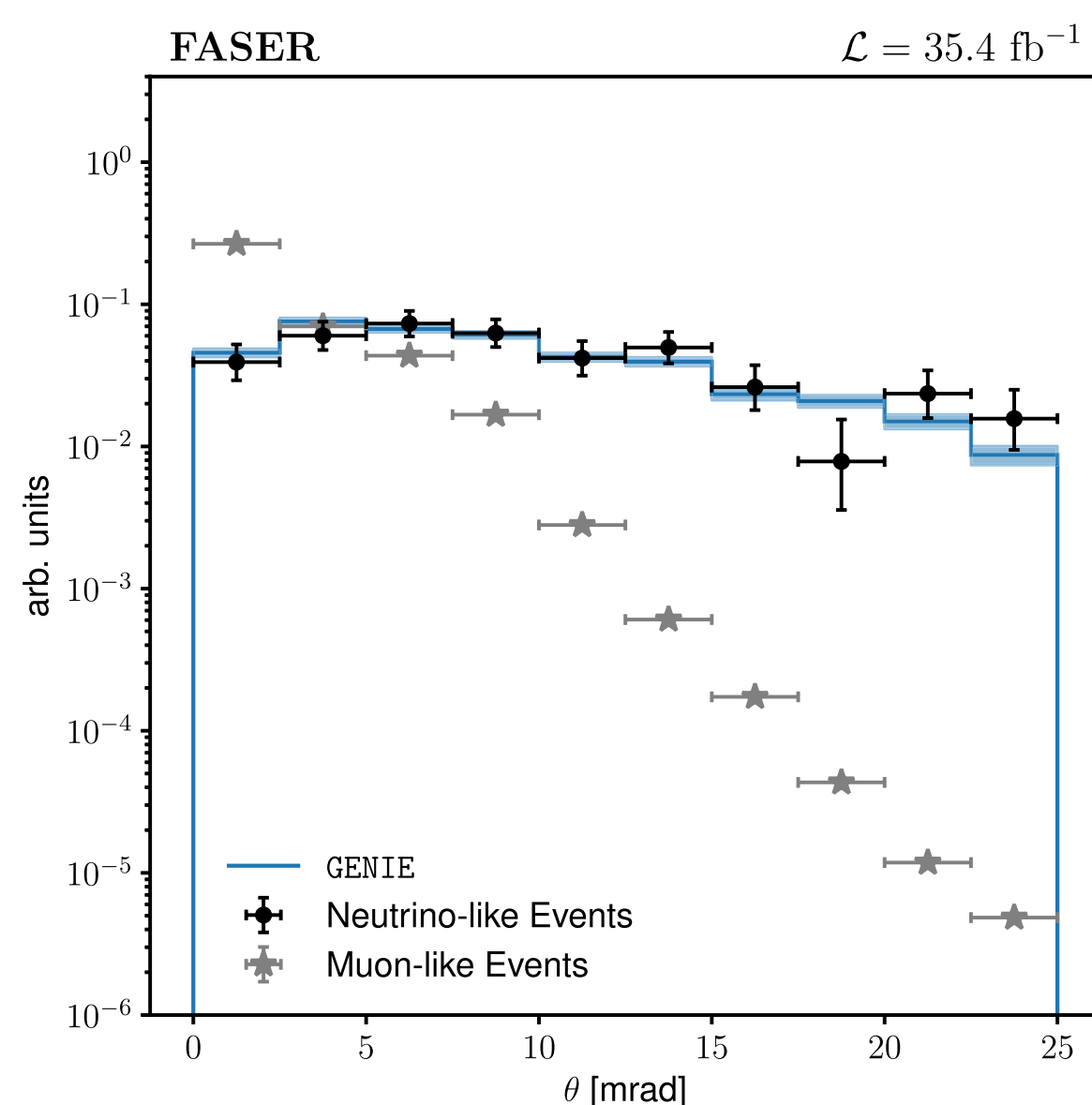
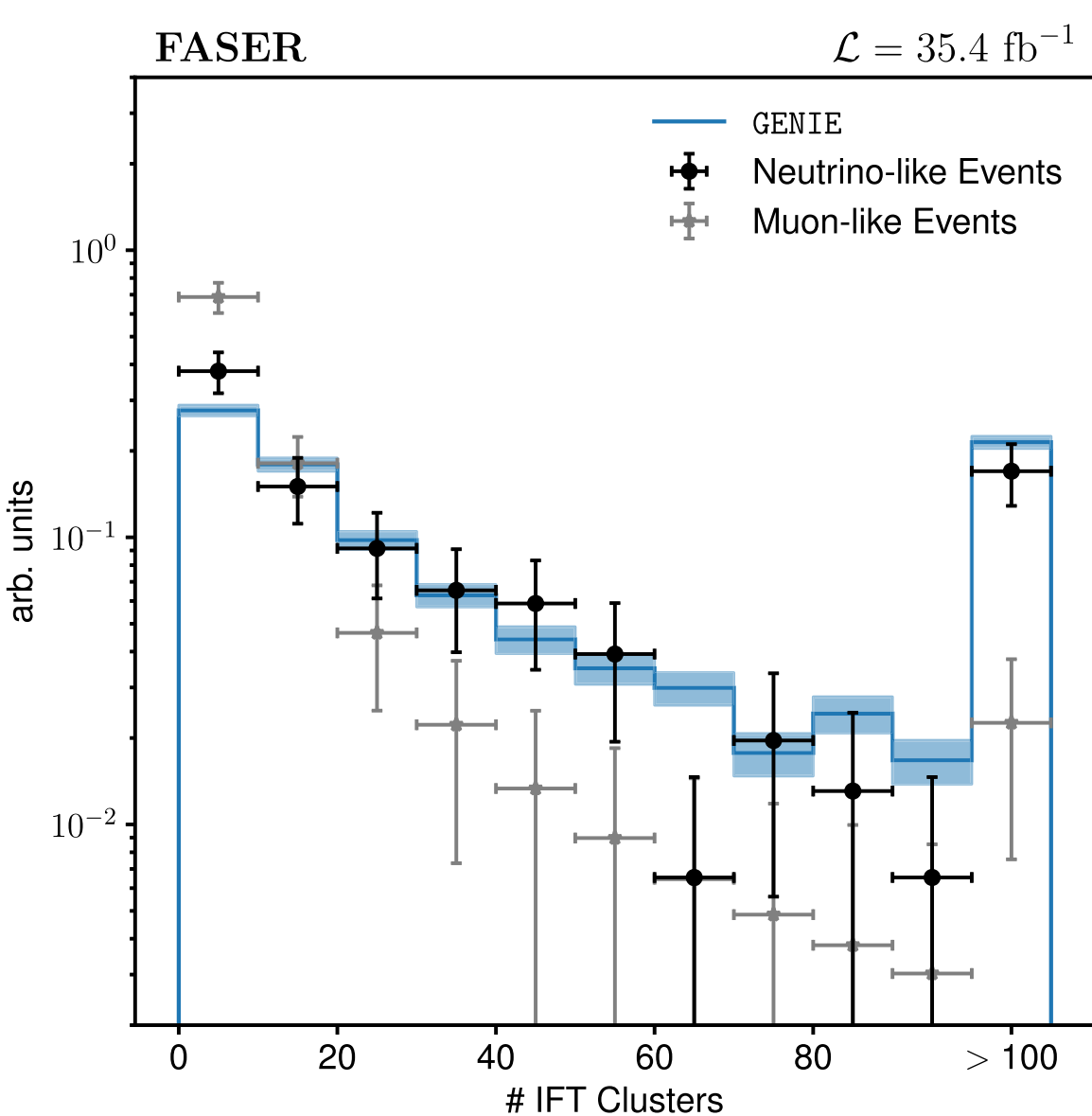
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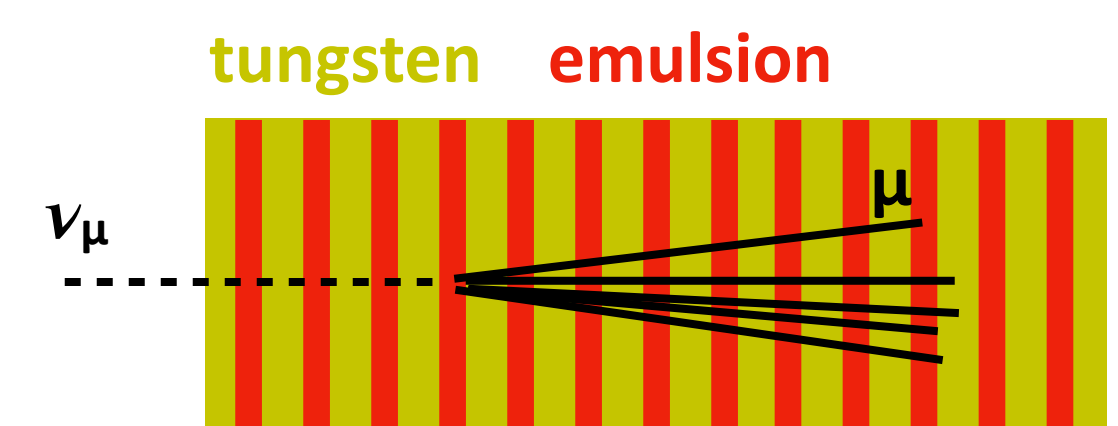
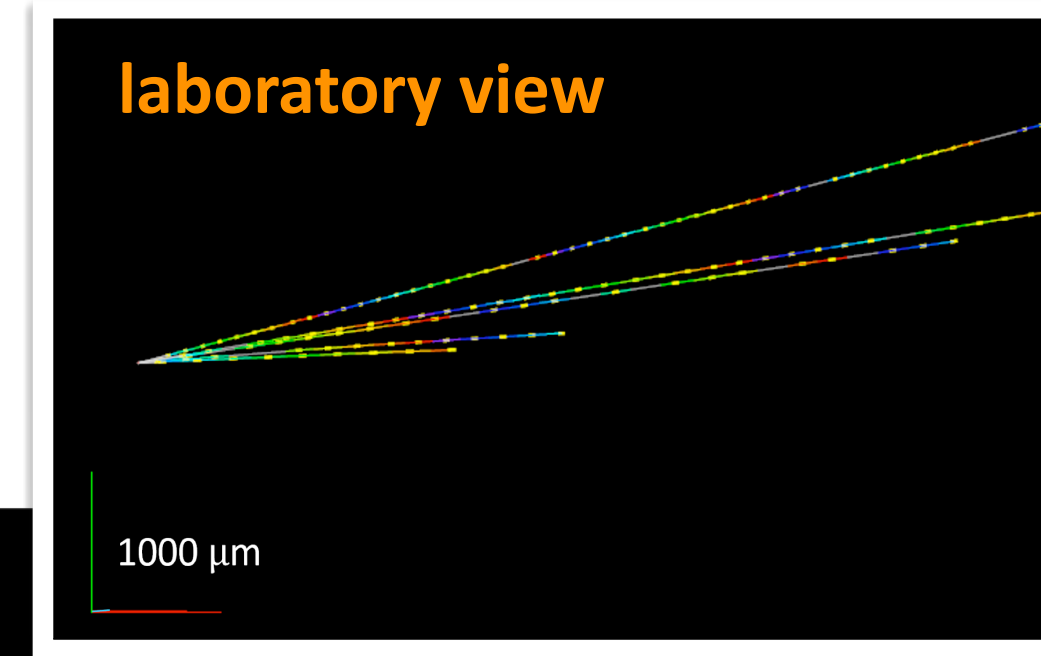
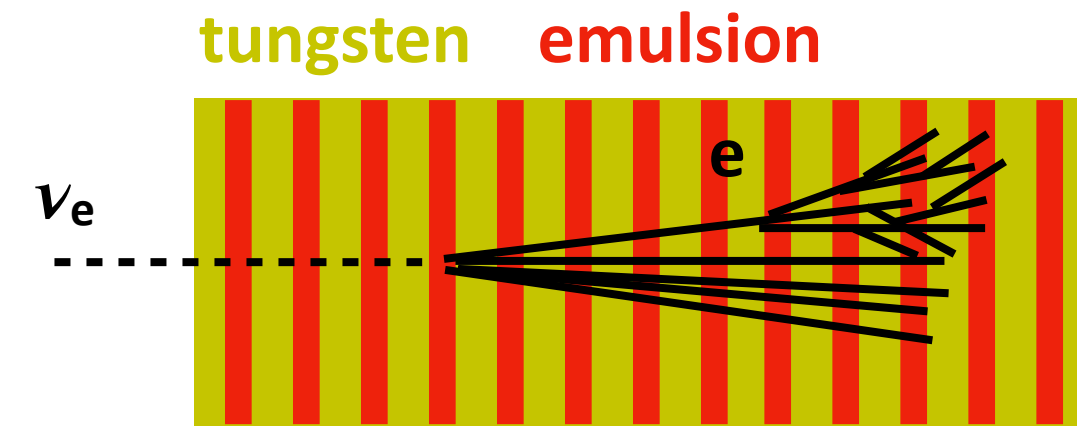
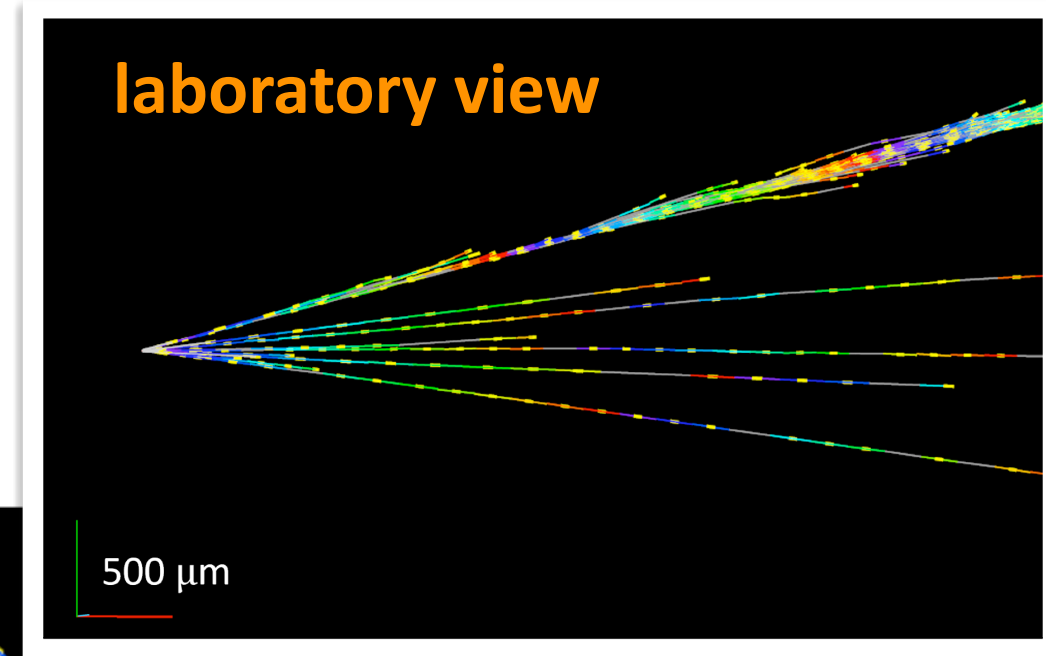
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GENIE histograms do not include experimental systematics

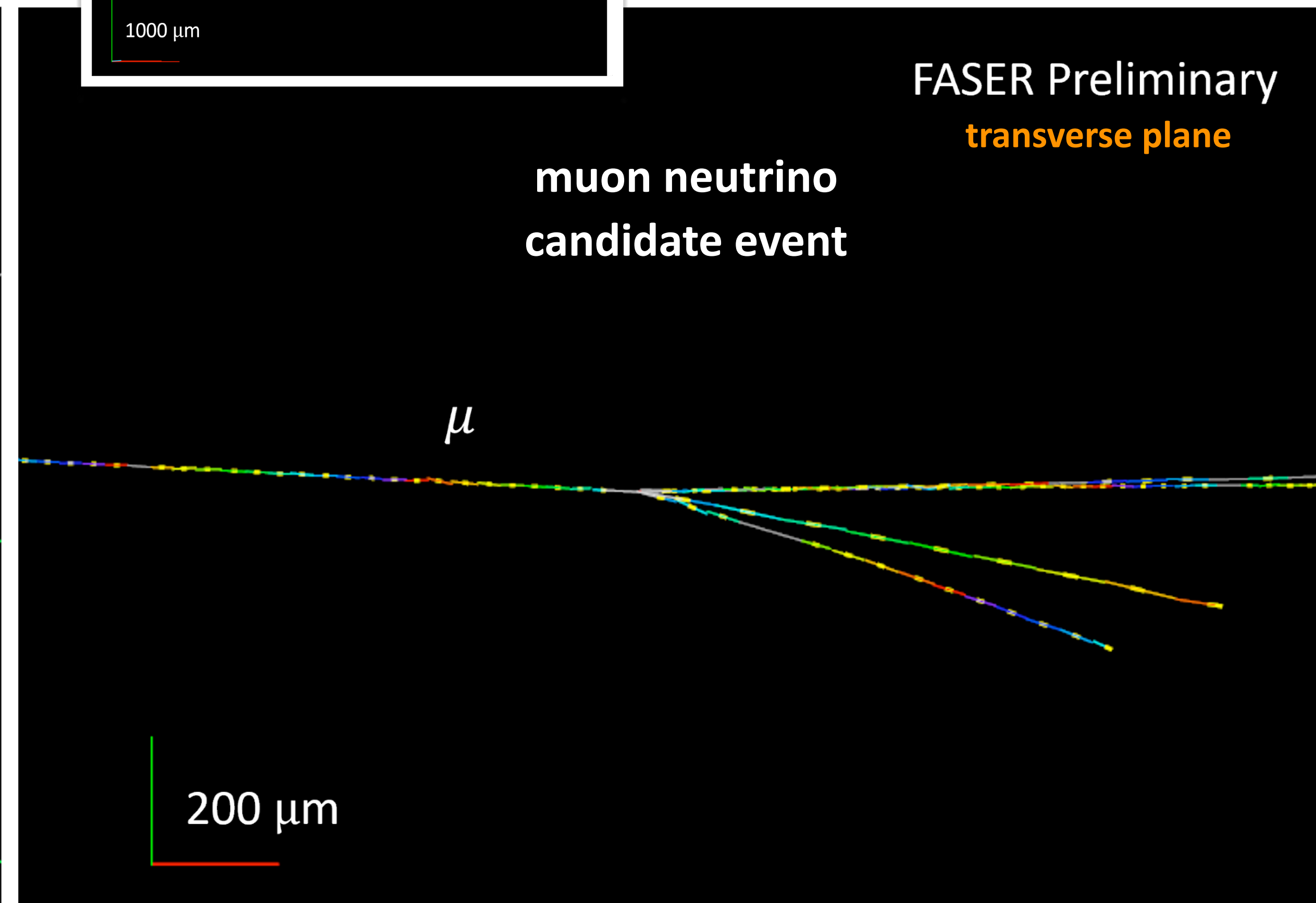
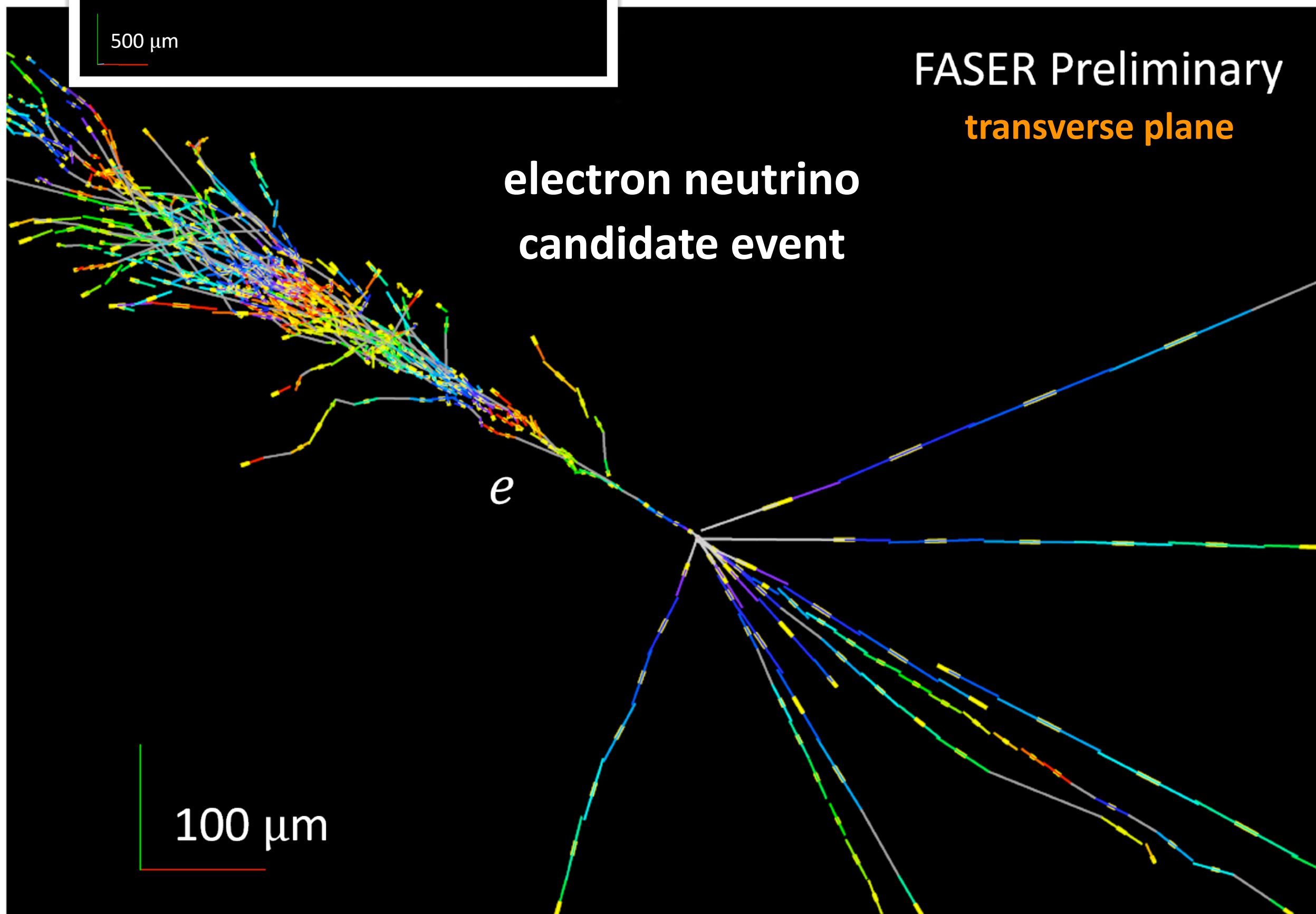


FASER Preliminary  
transverse plane

electron neutrino  
candidate event

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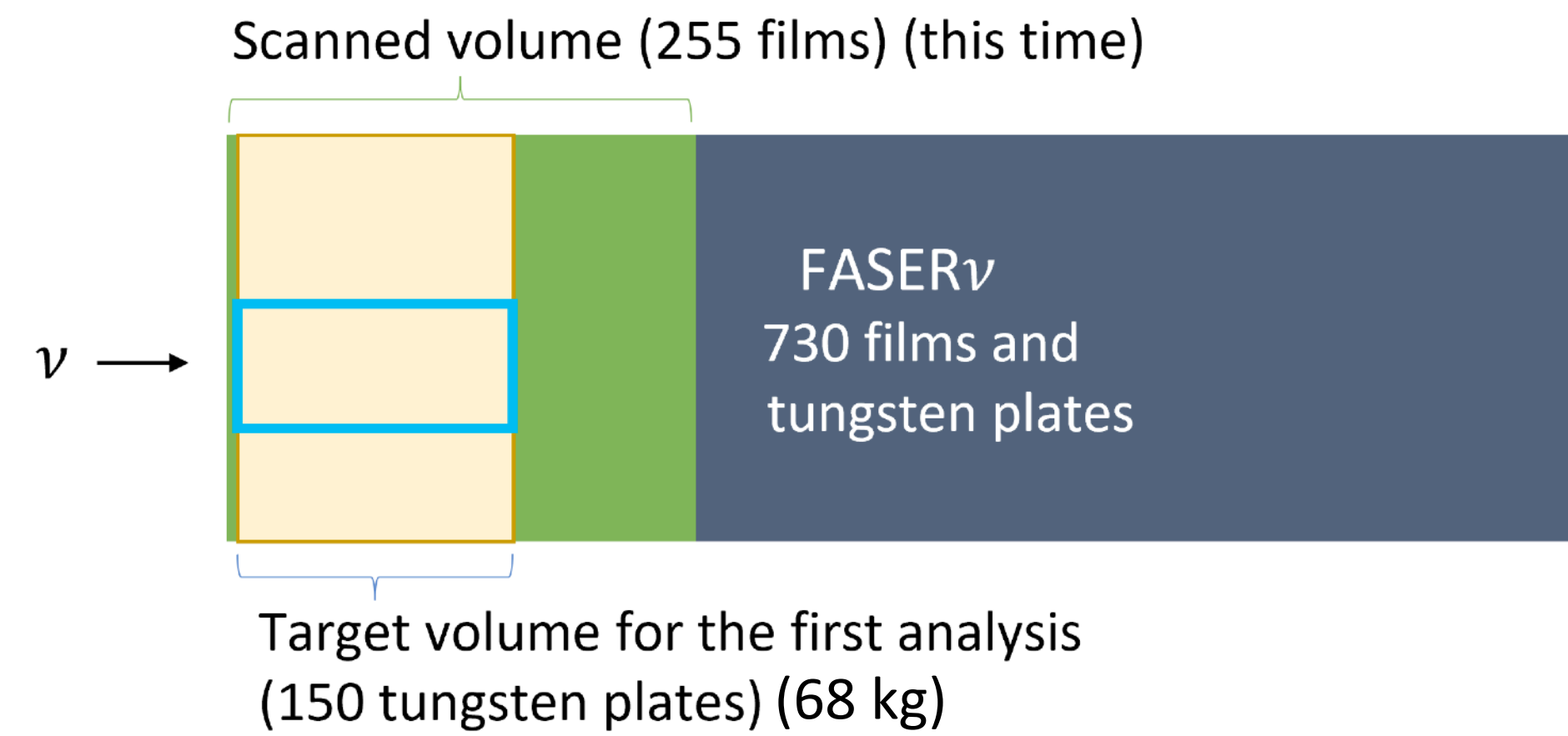
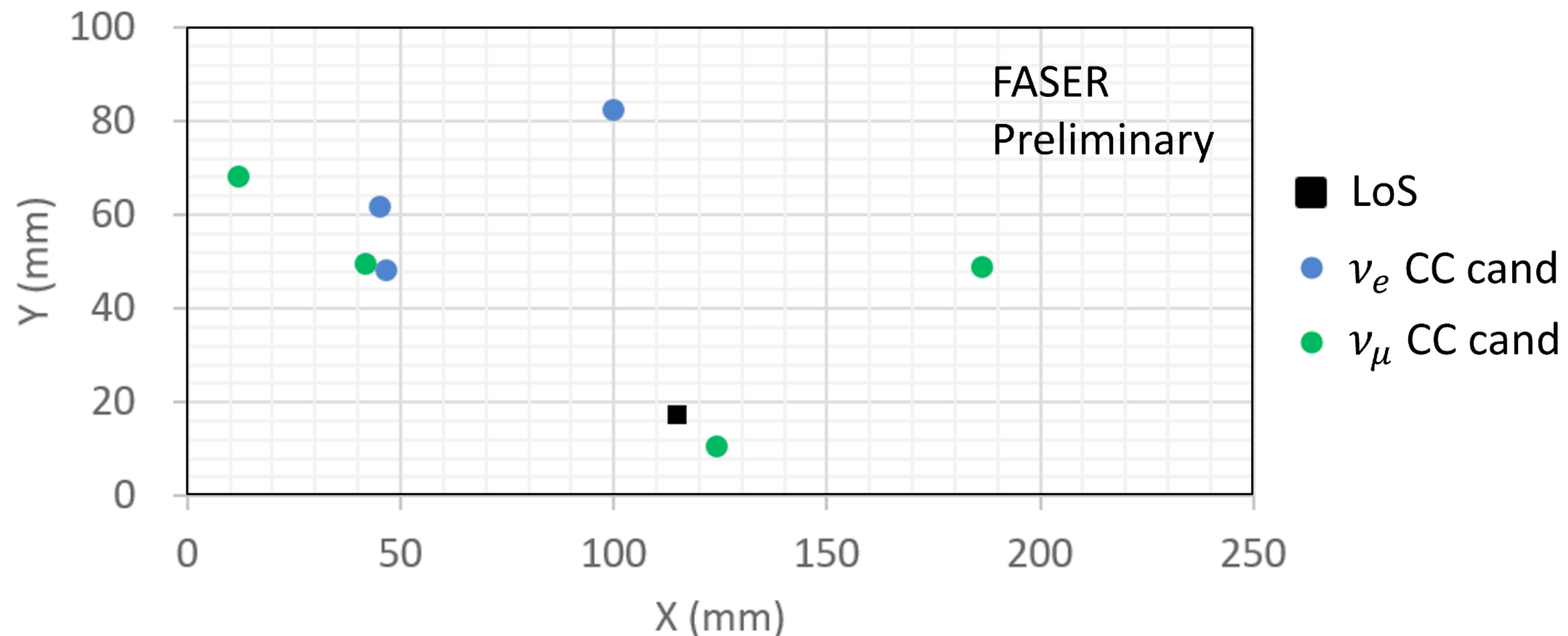
muon neutrino  
candidate event





## Analysed 150 of 730 emulsion layers for 9.5 fb<sup>-1</sup> of data

- ⇒ Target mass analysed: 68 kg out of 1.1 tonnes
  - ↳ Develop emulsion before analysis: long workflow
- ⇒ For CC, select vertices with  $\geq 5$  tracks
  - ↳ electrons: short track, electromagnetic shower
  - ↳ muons: long track and no secondary particles
- ⇒ Enforce large angle between lepton and CC remnants



Expected 3.0-8.6  $\nu_\mu$  CC events  
**Observed 4  $\nu_\mu$  vertices: 2.5 $\sigma$  sign.**

Expected 0.6-5.2  $\nu_e$  CC events  
**Observed 3  $\nu_e$  vertices: 5 $\sigma$  sign.**  
*first observation of collider  $\nu_e$ !*

# Future Plans?

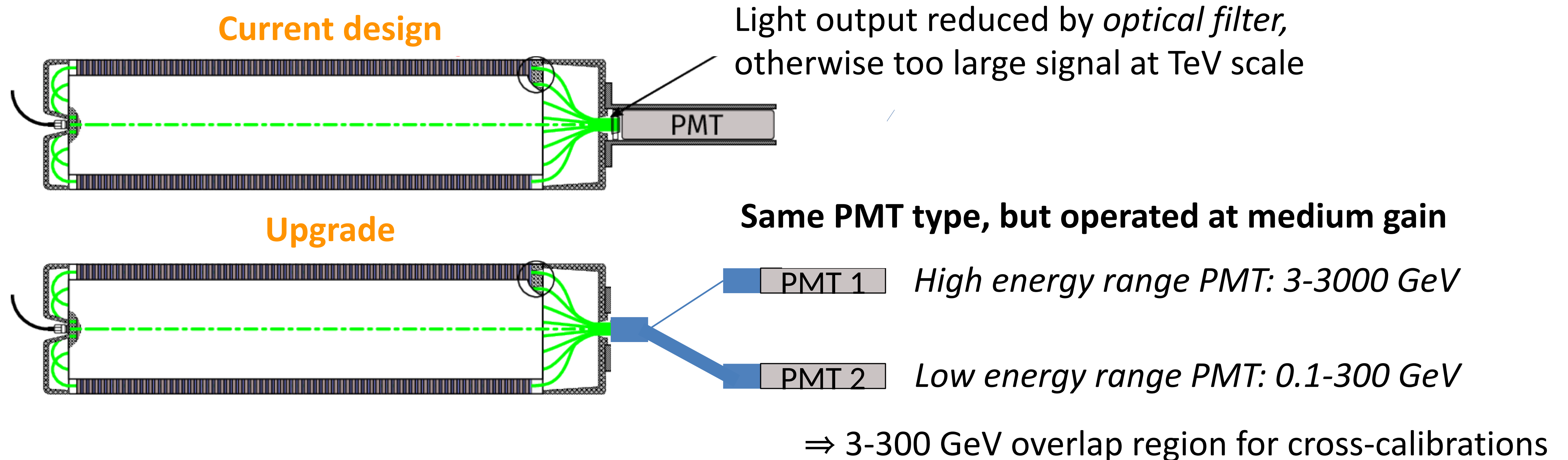


# Near Future: **Upgraded Calorimeter** Readout Scheme



## Upgrading the calorimeter readout scheme to improve *range* and *energy scale*

- ⇒ Currently relying on single PMT, and optical filter to reduce light output by factor 10
  - ↳ *Calibrations: MIP data (high PMT gain) extrapolated to low gain with LED-determined gain ratio*
- ⇒ Upgrade: use two separate PMTs to cover low E (high gain) and high E (low gain) at same time

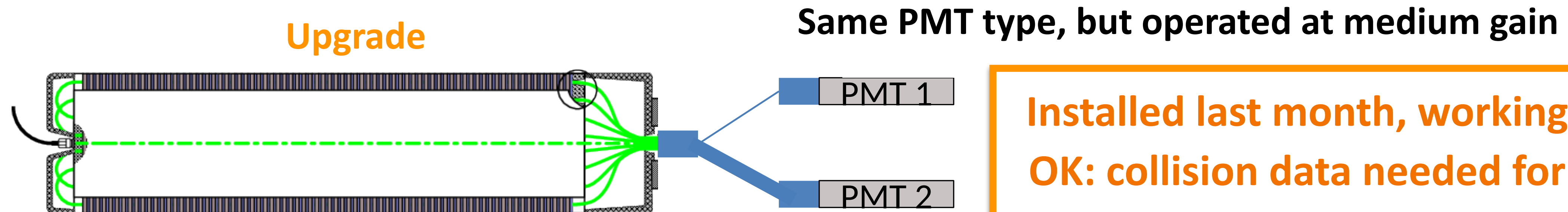
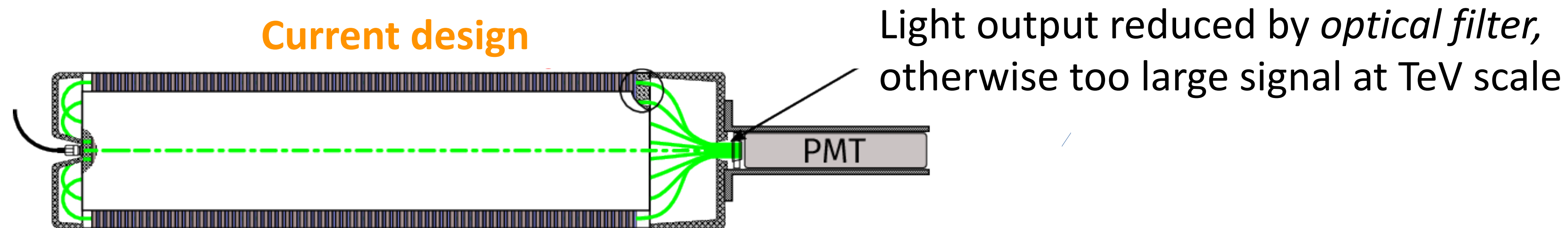


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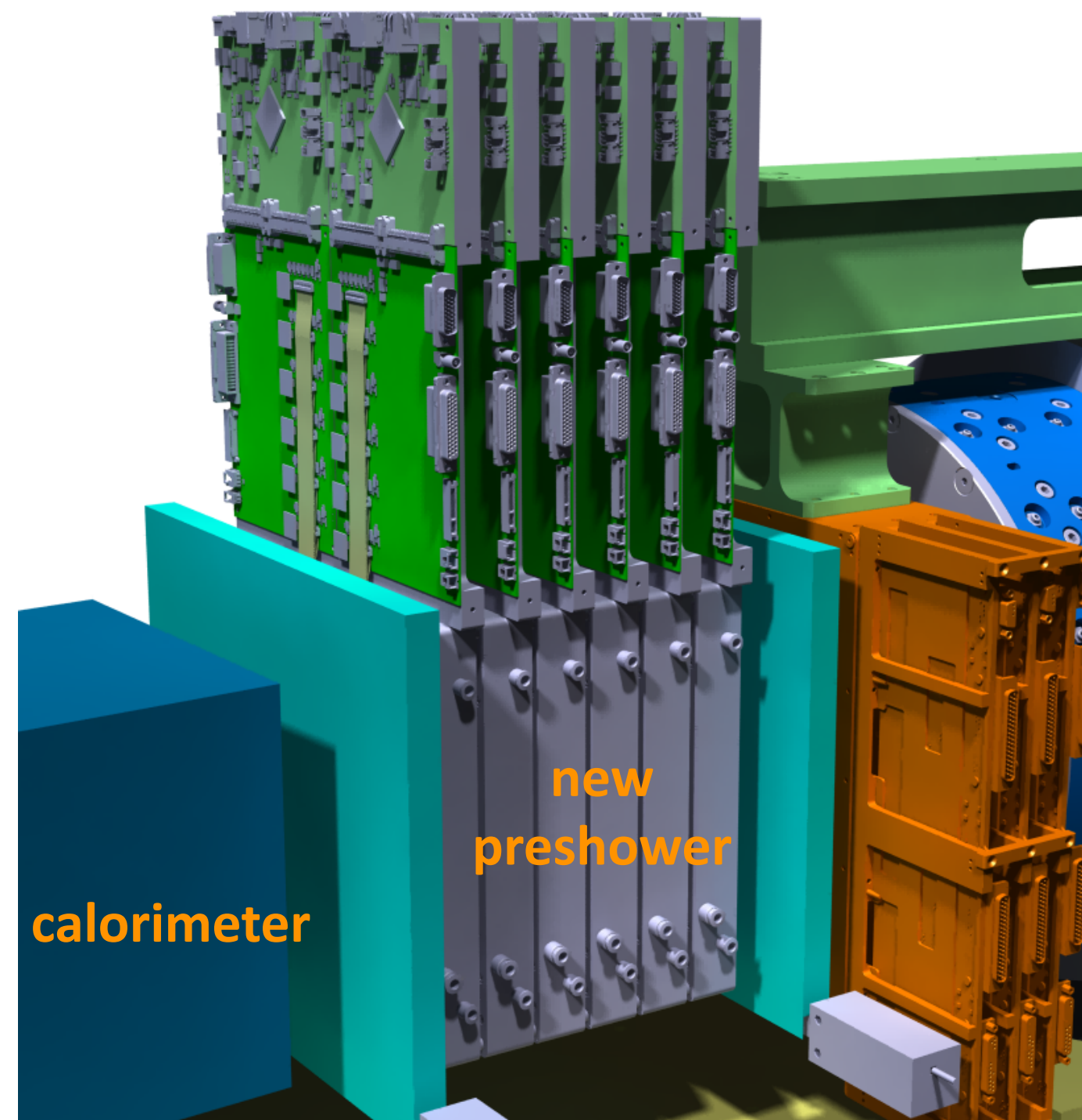
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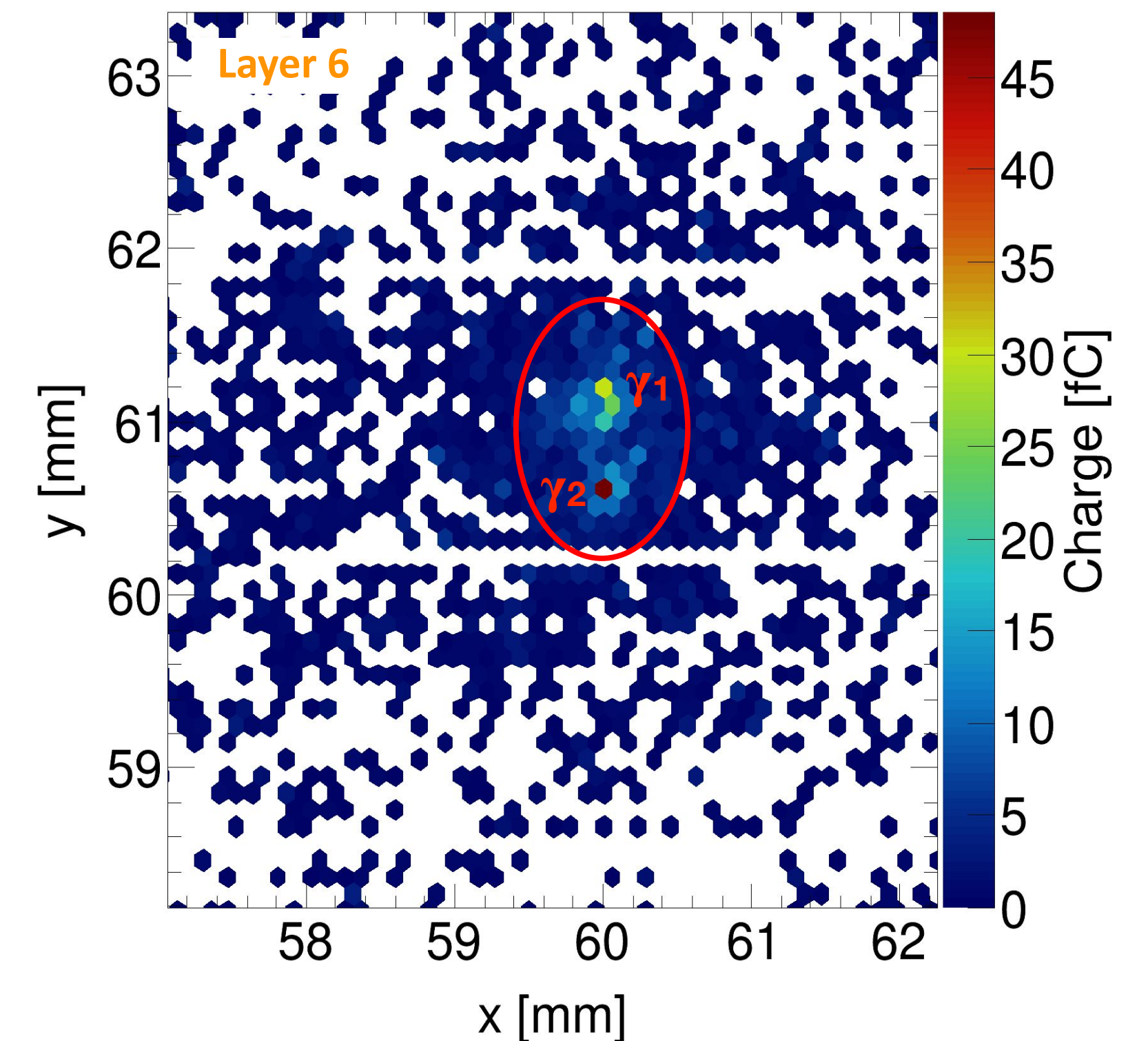
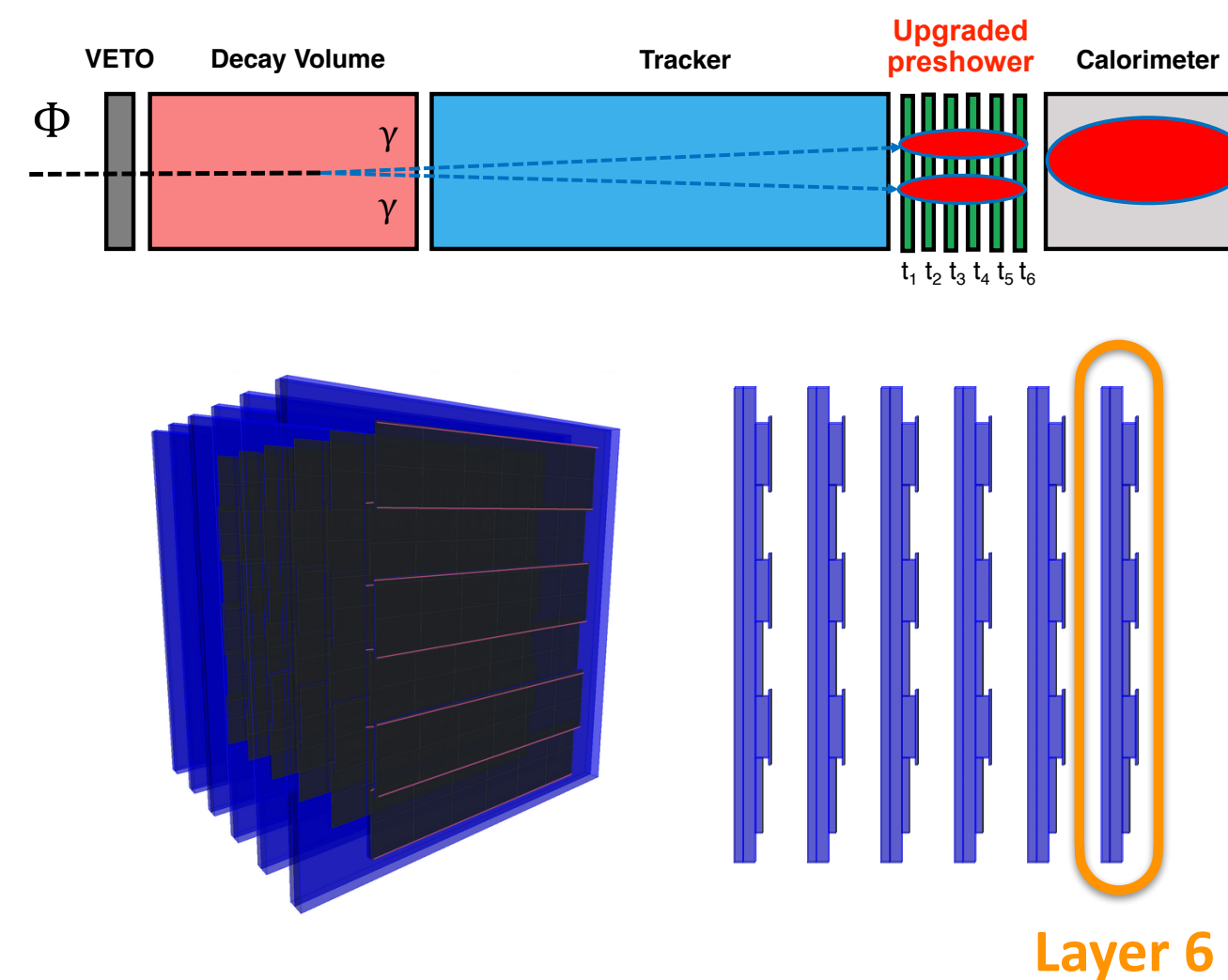
**Installed last month, working OK: collision data needed for final commissioning**

## New preshower detector to enable multi- $\gamma$ tagging and increase ALP searches' reach

- ⇒ Six planes of tungsten ( $6 X_0$  in total) and monolithic SiGe pixelated sensors with  $\sim 100 \mu\text{m}$  pitch
- ⇒ High dynamic range for charge measurement to capture electromagnetic showers' development
- ⇒ Project on schedule for installation during 2024 EYETS, to take data in 2025 and Run 4



Simulating two photons:  
 $E_\gamma = 1 \text{ TeV}$ ,  $\Delta R_\gamma = 0.5 \text{ mm}$

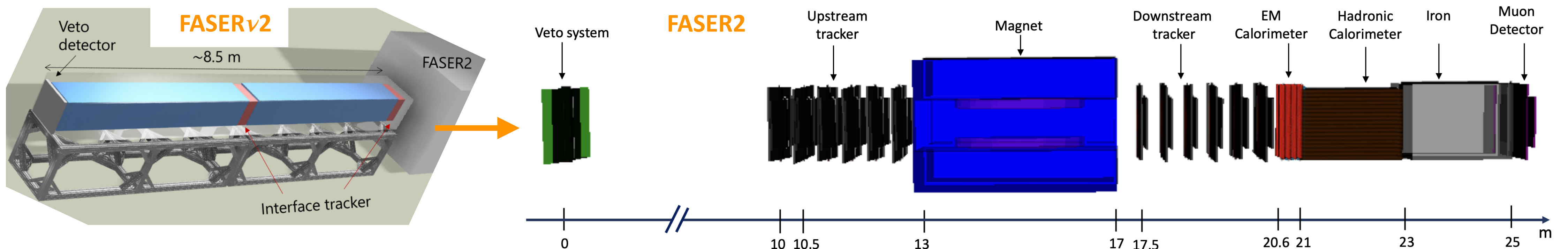
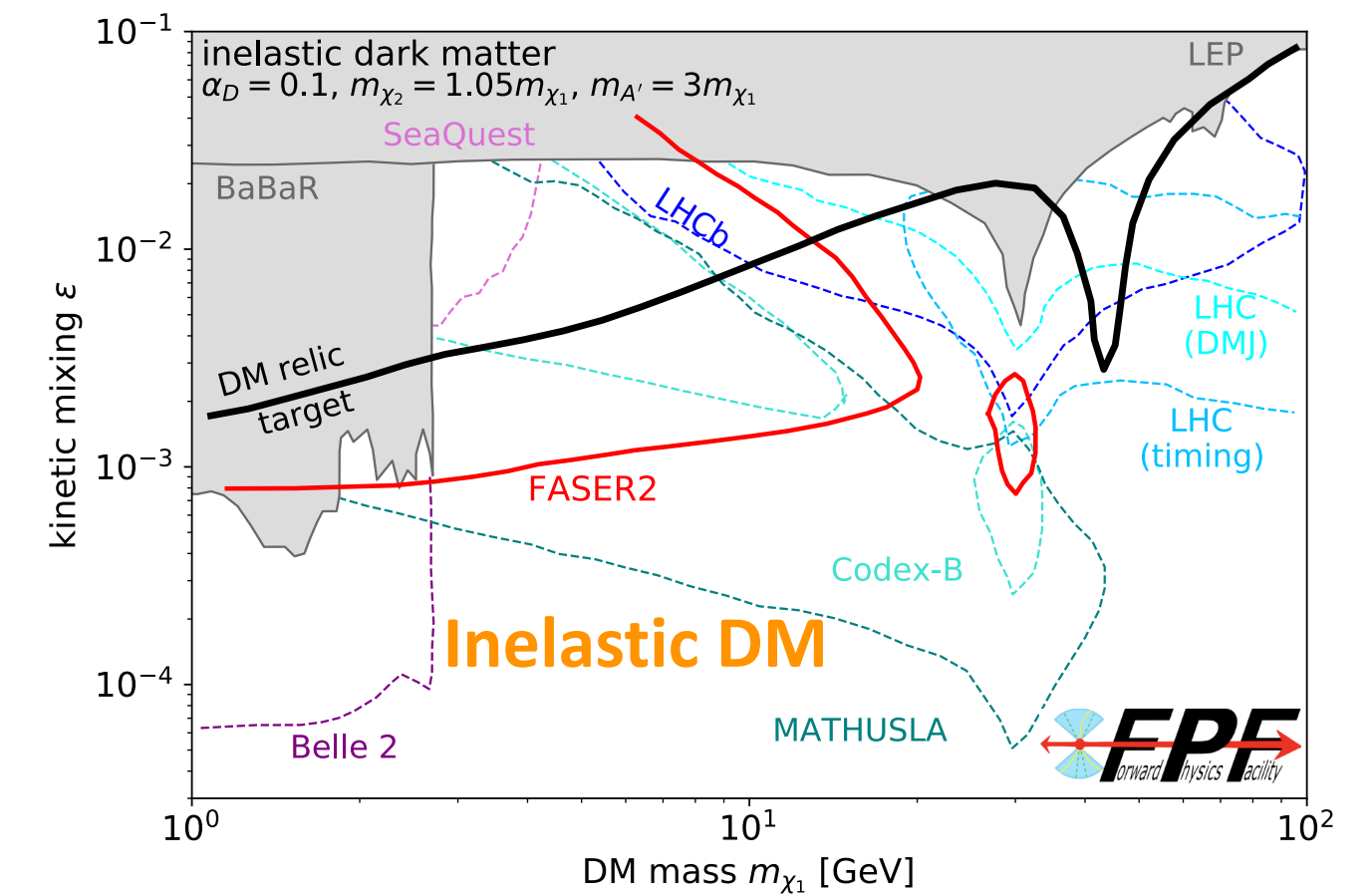
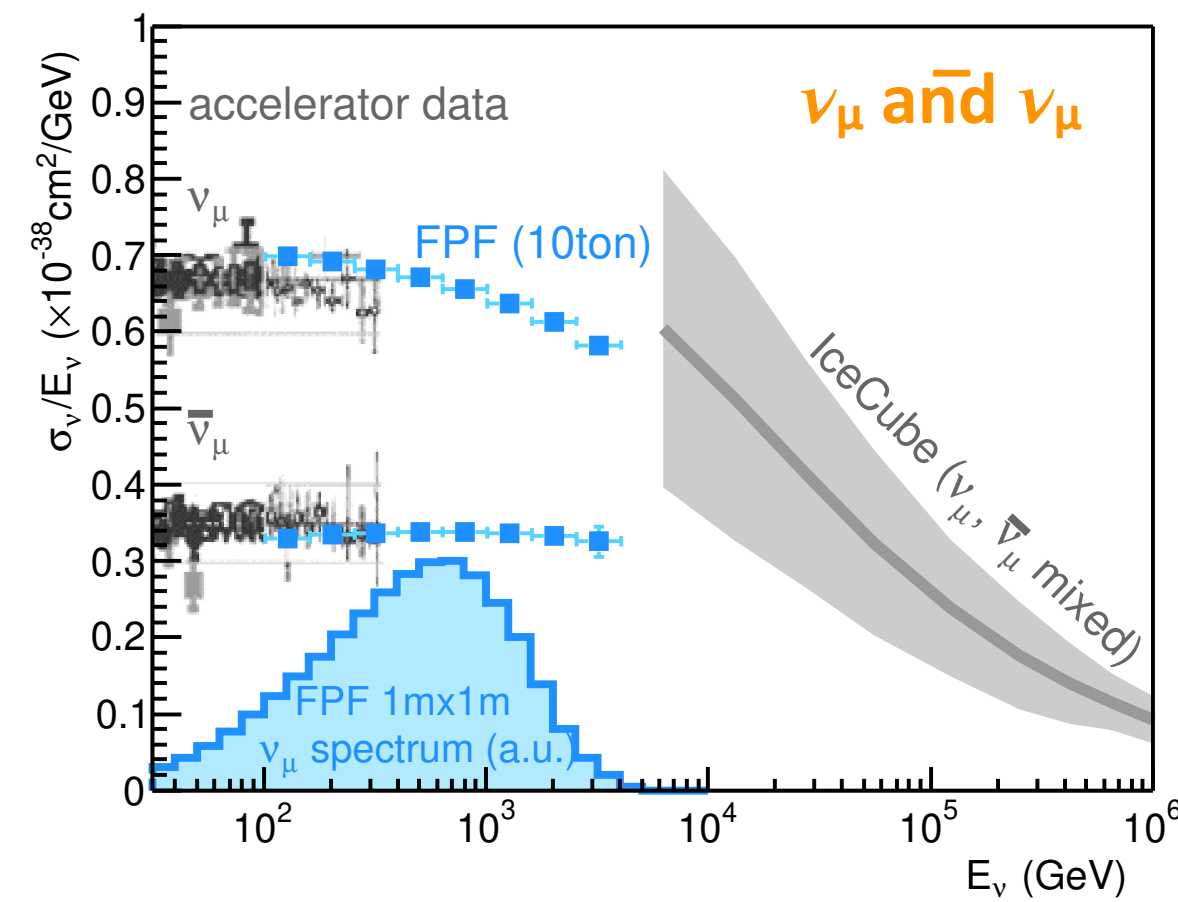
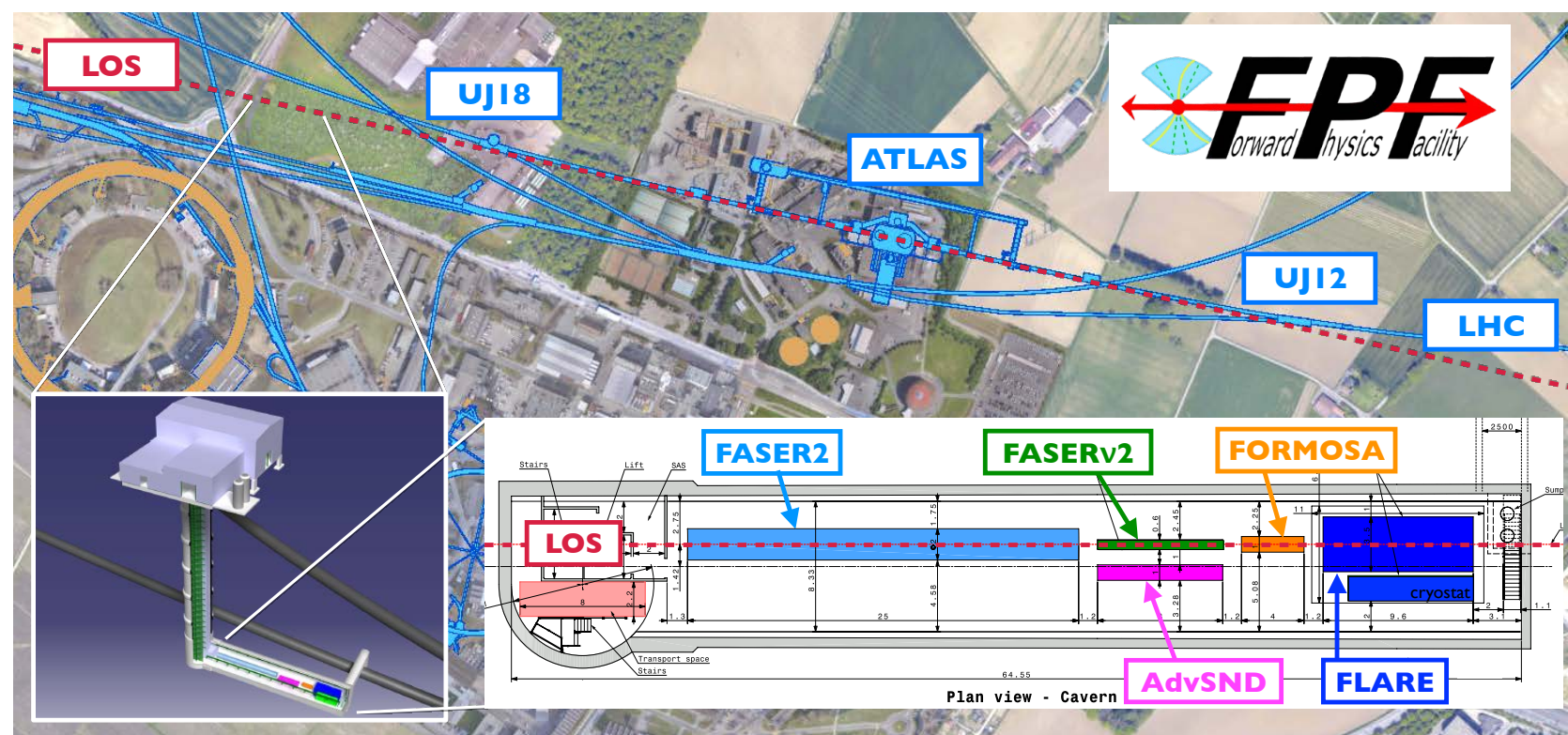


# Proposal [Link]: Forward Physics Facility at the LHC



## FASER 2 upgrade proposed in the context of a broader Forward Physics Facility (FPF)

- ⇒ 65 m long and 9 m wide cavern, 617-682 m west of ATLAS IP, on beam collision axis
- ⇒ FASER $\nu$ 2: x20 increase in target mass - FASER2:  $\pi^0$  angular acceptance increasing from 0.6% to 10%



## **FASER taking data smoothly in LHC Run3, and recently approved for Run 4 operation**

- => Searched for dark photons in events with two electrons**
  - ↳ Extended existing exclusions to low mass and low kinetic mixing
- => Observed  $\approx 150$  collider neutrino interactions in spectrometer**
  - ↳ First direct observation of neutrinos and  $\nu_e$  CC interactions at collider
  - ↳ Only a small fraction of already-collected data analysed thus far...
- => Further empowering FASER's capabilities with calorimeter and preshower upgrades**
  - ↳ Expanding physics reach for multi-photon final states (e.g. ALPs)

**... Several more years of exciting physics ahead of us!**