First Physics Results

Supported by: HEISING-SIMONS FOUNDATION, CERN, SIMONS FOUNDATION

Deion Fellers (University of Oregon)

on behalf of the FASER collaboration

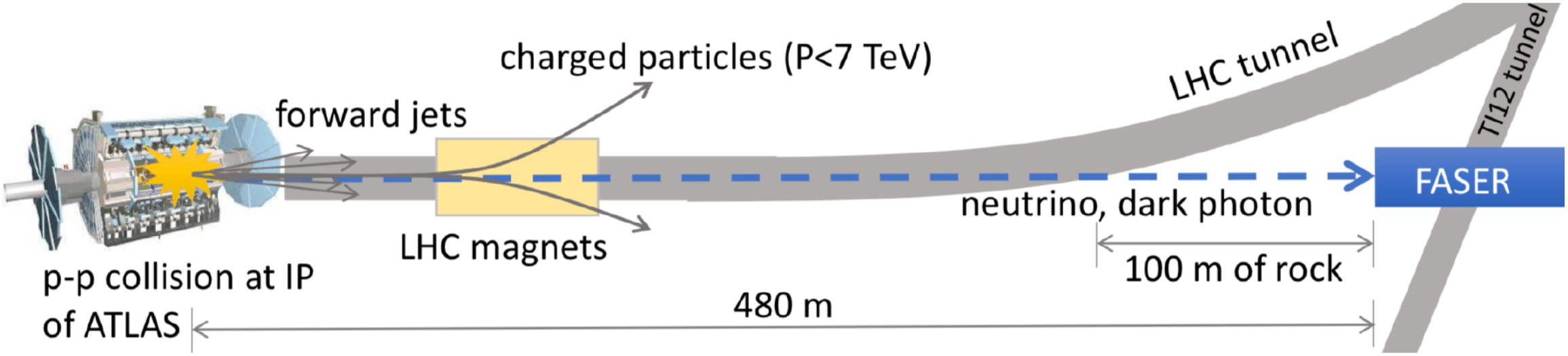
Mitchell Conference

May 16th, 2023

Additional US support from: NSF

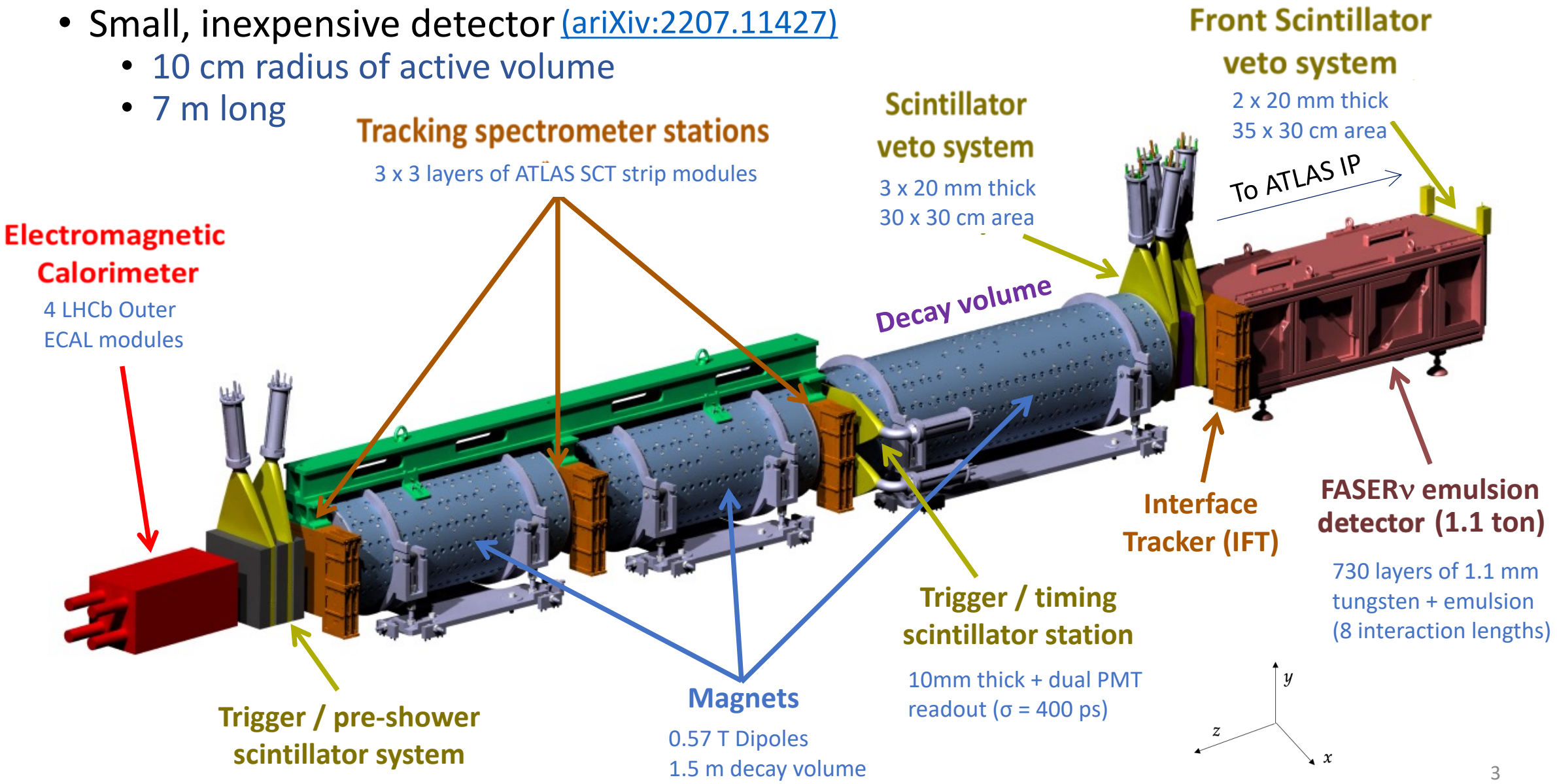
FASER Overview

- FASER is a new experiment at the LHC
  - Built in 2019-2021
- Located along the longitudinal beam axis, 480m from the ATLAS interaction point
  - LHC magnets and 100m of rock stop most particles
  - Sensitive to light and weakly interacting particles
- Our first physics results were announced this past March
  - Probed dark photon phase space that was previously unconstrained
  - First direct observation of collider neutrinos



FASER Detector

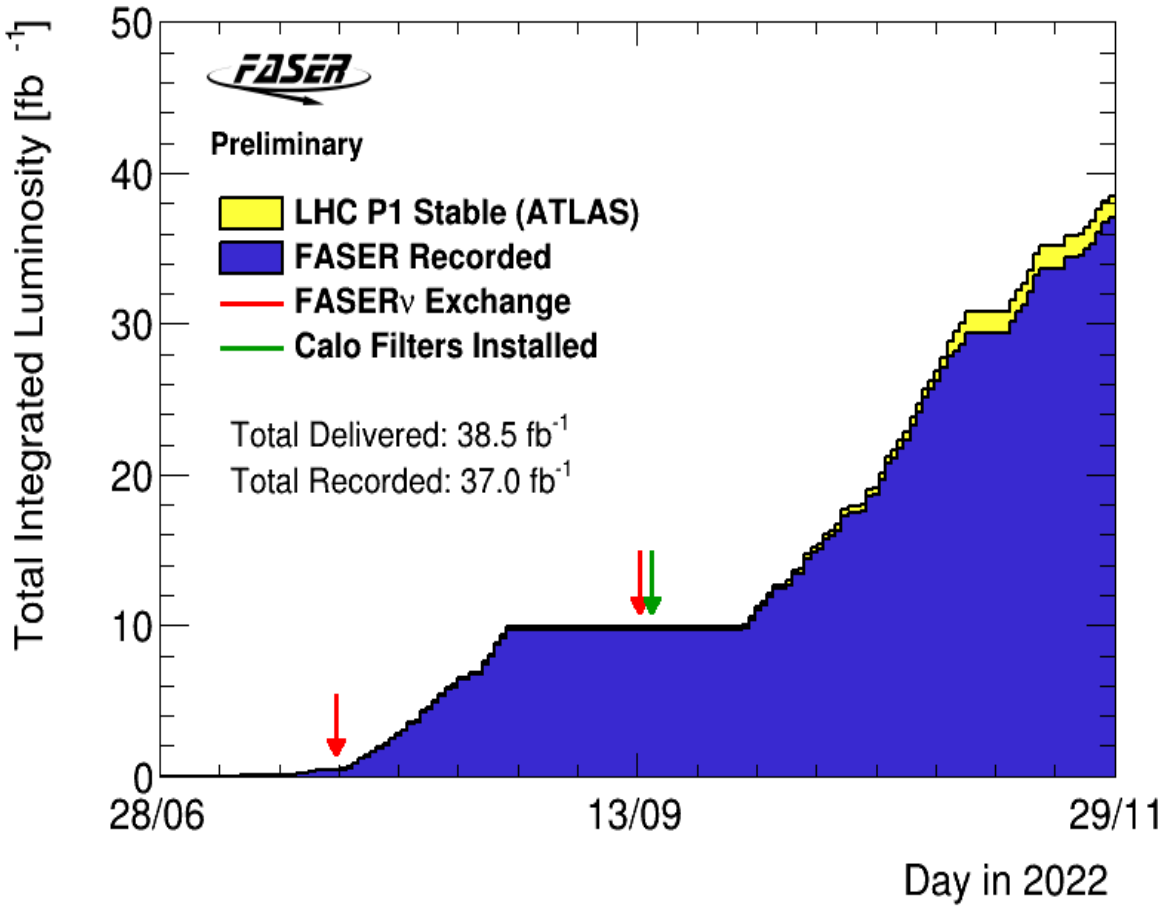
- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius of active volume
  - 7 m long



- Detector installed between March – Nov 2021, ready for LHC run 3

FASER Operations

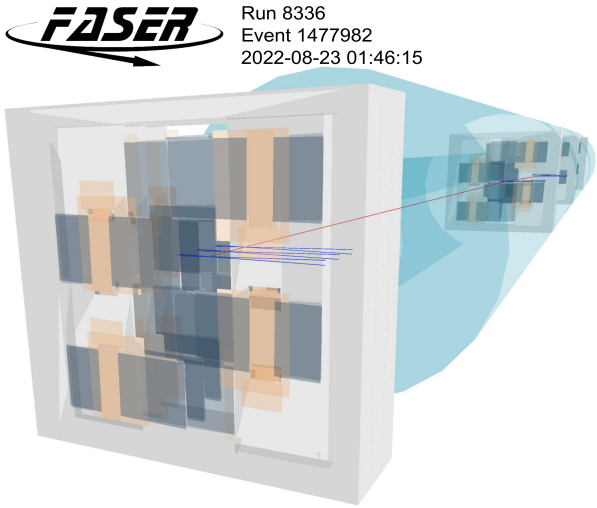
- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered lumi
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after this exchange

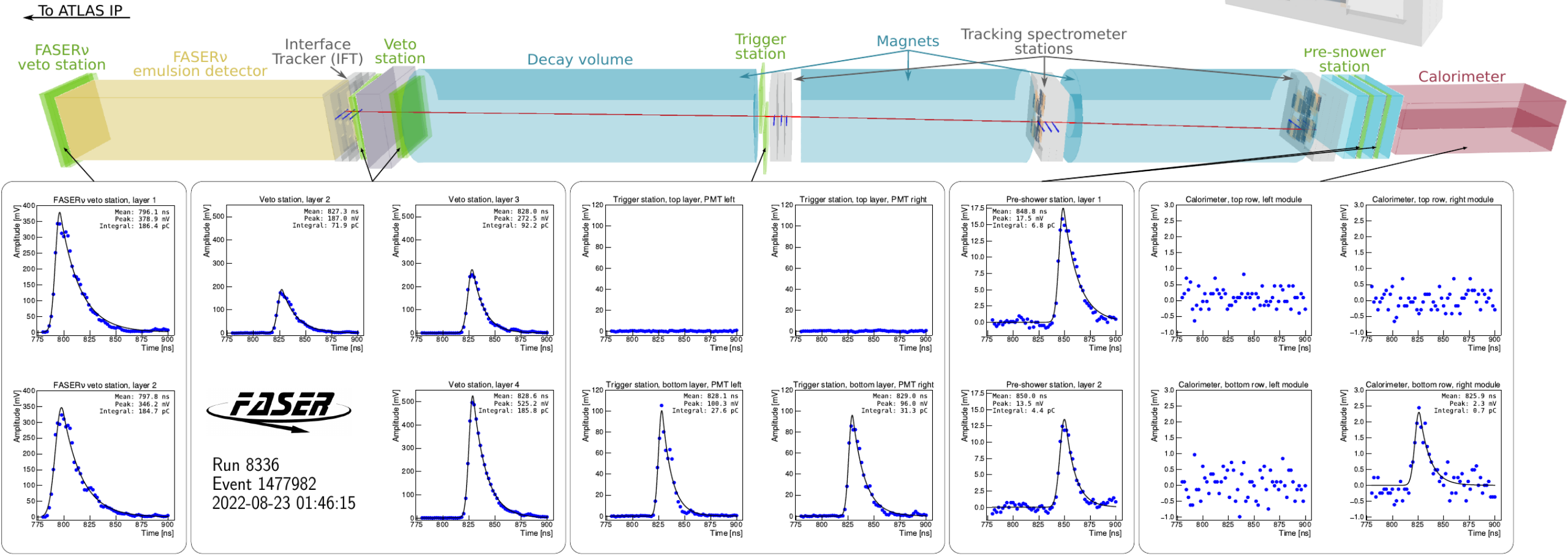


Analyses presented use 27.0 fb^{-1} or 35.4 fb^{-1}

Example Collision Event

- More than 350M single-muon events recorded
  - Example: muon leaving track passing through full detector + scintillator/calorimeter deposits consistent with MIP





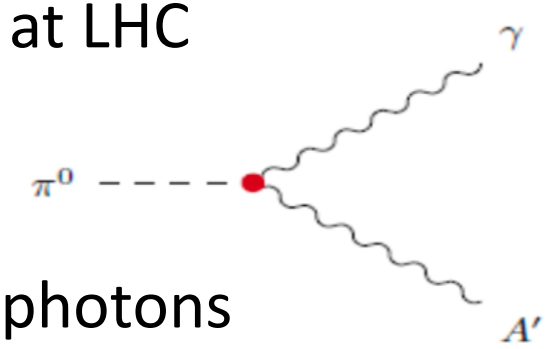
Search for Dark Photons

- Dark photon (A') is a common feature of hidden sector models
  - Weakly coupled to SM via kinetic mixing (ε) with SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

- MeV-scale dark photons are produced mainly in meson decays at LHC

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



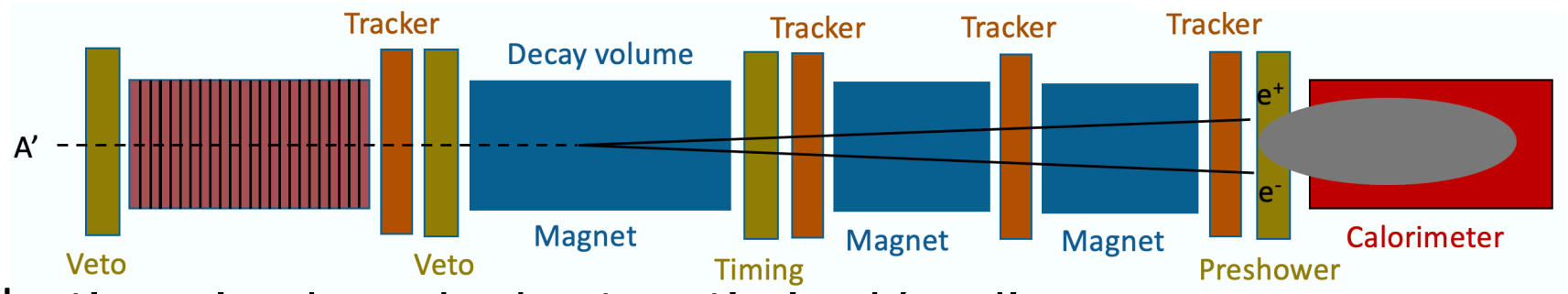
- FASER targets small ε, highly boosted, MeV-scale massive dark photons which have decay lengths ideal for FASER

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

- Will decay 100% to e+e- pair for $1<m_{A'}<211$ MeV

Dark Photon Event Selection

- Signal: $\pi/\eta \rightarrow A'\gamma$, A' travels hundreds of meters through LHC magnets and rock/concrete, then decays $A' \rightarrow e^+e^-$ inside FASER

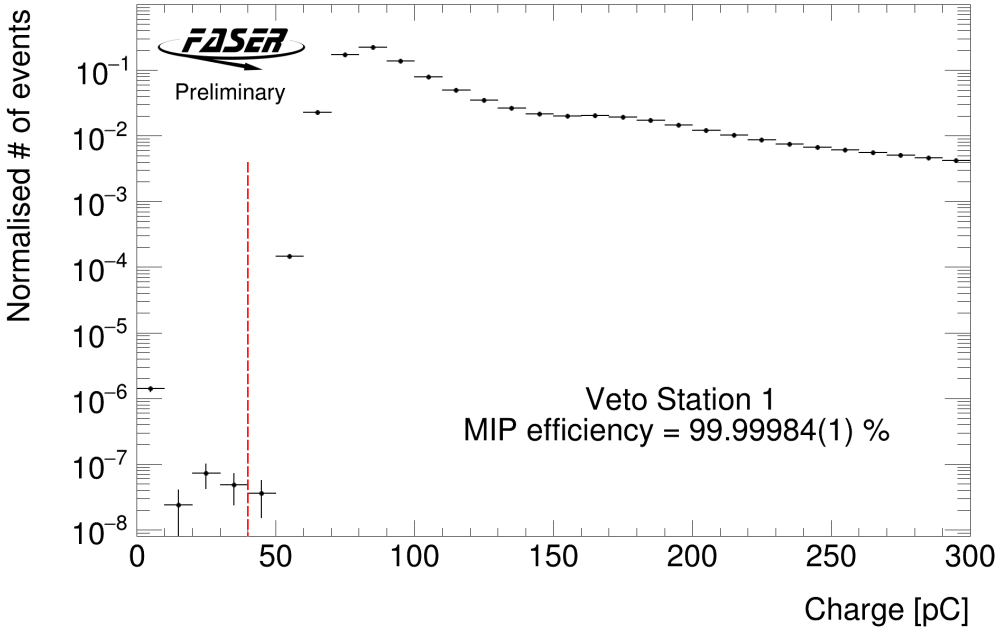


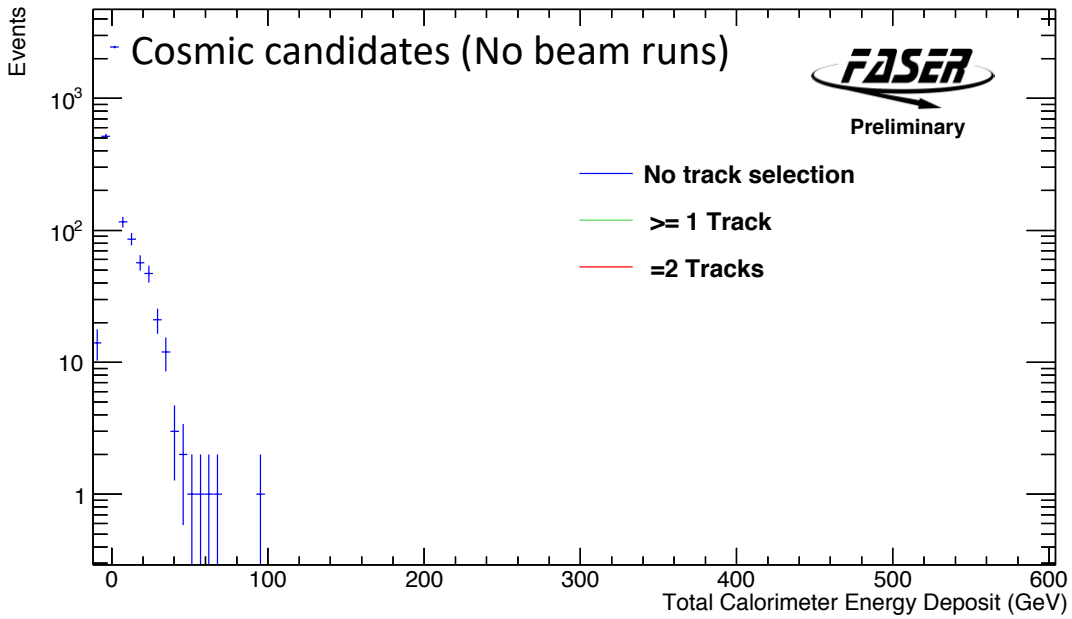
- Event selection: simple and robust, optimized for discovery
  - LHC collision event with good data quality
  - No signal in any of the 5 veto scintillators
  - Timing and preshower scintillators consistent with $\geq$ 2 MIPs
  - Exactly 2 good tracks (p > 20 GeV and r < 95 mm, extrapolating to r < 95 mm at vetos)
  - Calorimeter energy > 500 GeV
- Signal efficiency $\approx$ 40% across parameter space that FASER is sensitive to
- Blinded events with no veto signal and calorimeter energy > 100 GeV

Dark Photon Backgrounds

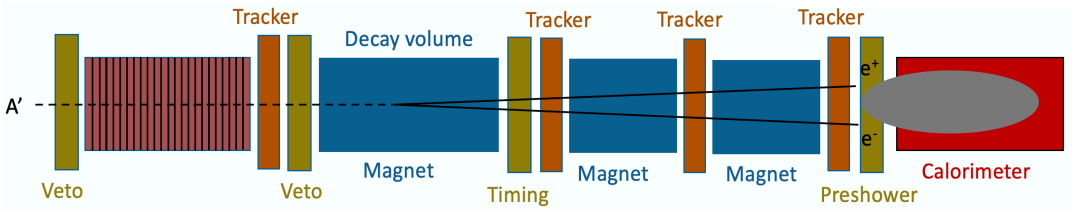
1. Veto inefficiency
   - Measured layer-by-layer via muons with tracks pointing back to vetos
   - Layer efficiency > 99.998%
   - 5 layers reduce exp. 10^8 muons to negligible level (even before cuts)

2. Non-collision backgrounds
   - Cosmics measured with no beam
   - Near-by beam debris measured in non-colliding bunches
   - No events observed with ≥1 track or E(calo) > 500 GeV

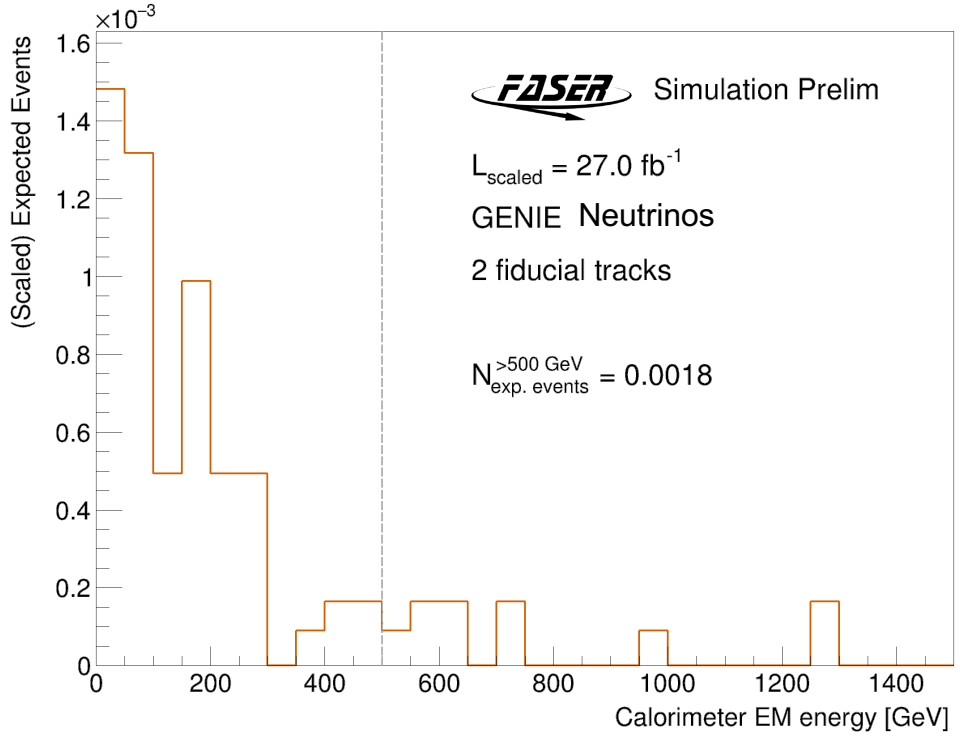




Dark Photon Backgrounds



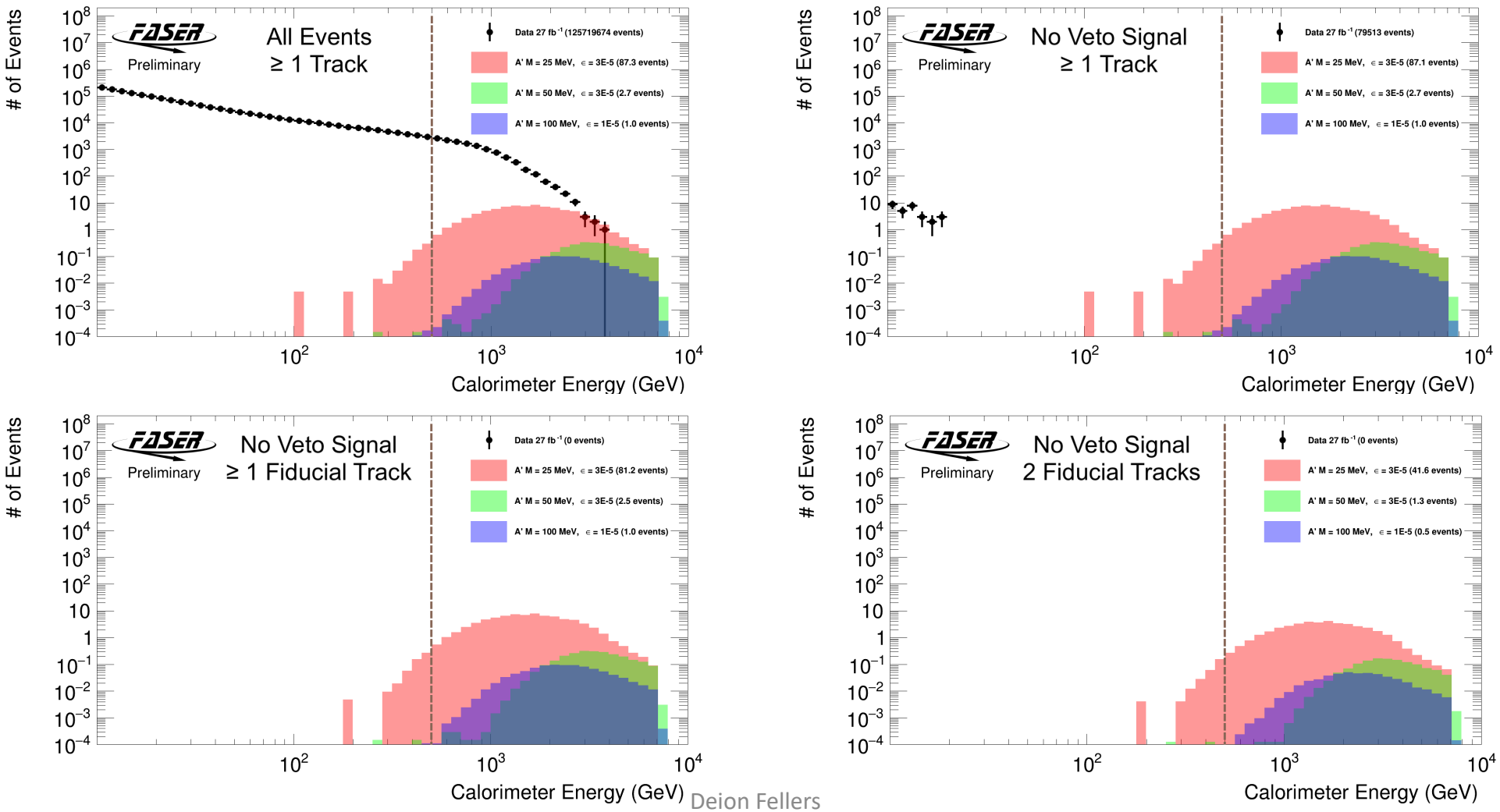
3. Neutrino interactions (main background)
   - Primarily coming from vicinity of timing detector
   - Estimated from GENIE simulation (300 ab^{-1})
     - Uncertainties from neutrino flux & mismodelling
   - Predicted signal-like events in 27 fb^{-1} = $(1.8 \pm 2.4) \times 10^{-3}$
4. Neutral hadrons from upstream muons interacting in rock in front of FASER
   - Heavily suppressed since:
     - Muon nearly always continues after interaction
     - Has to pass through 8 interaction lengths (FASERν tungsten)
     - Decay products must leave E(calo) > 500 GeV
   - Data-driven estimate from lower energy events with 2 or 3 tracks and different veto conditions
   - Predicted signal-like events = $(2.2 \pm 3.1) \times 10^{-4}$



- Total background prediction = $(2.02 \pm 2.4) \times 10^{-3}$ events

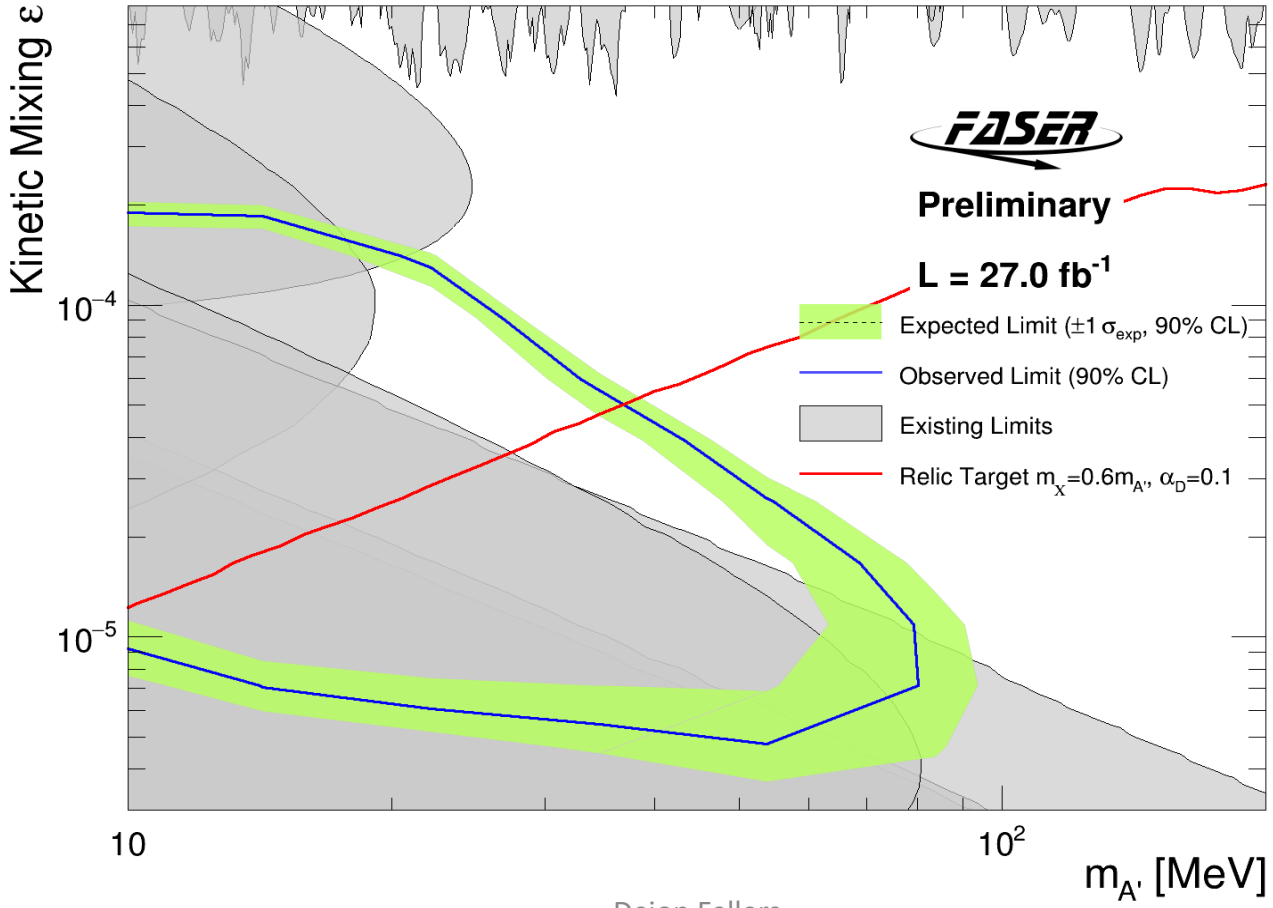
Dark Photon Unblinded Data

- No events seen in unblinded signal region (not even any with ≥1 fiducial track)



Dark Photon Exclusion

- With null-result, FASER sets limits on previously unexplored parameter space
  - Extends exclusion into region motivated by thermal relic dark matter
  - Public conf note: CERN-FASER-CONF-2023-001

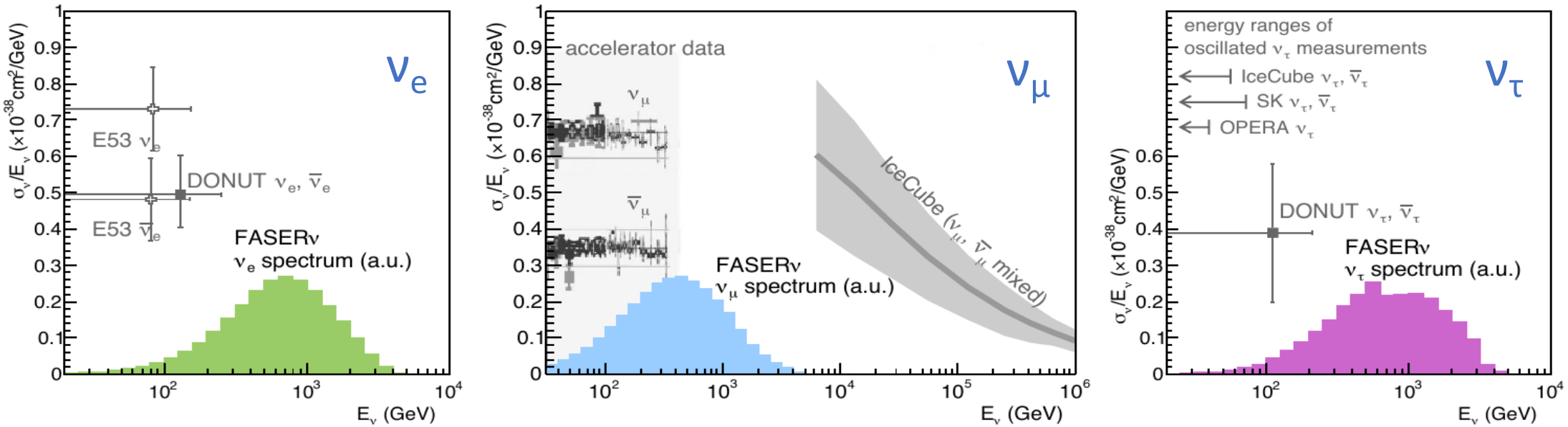


Collider Neutrinos

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → larger interaction cross section
- FASER is sensitive to an exciting neutrino program
  - Collider neutrinos have never been directly observed before
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments

For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERν	~10^{10}	~10^{11}	~10^{8}
# interacting in FASERν	≈200	≈1200	≈4

PRD 104, 113008



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  - Energy

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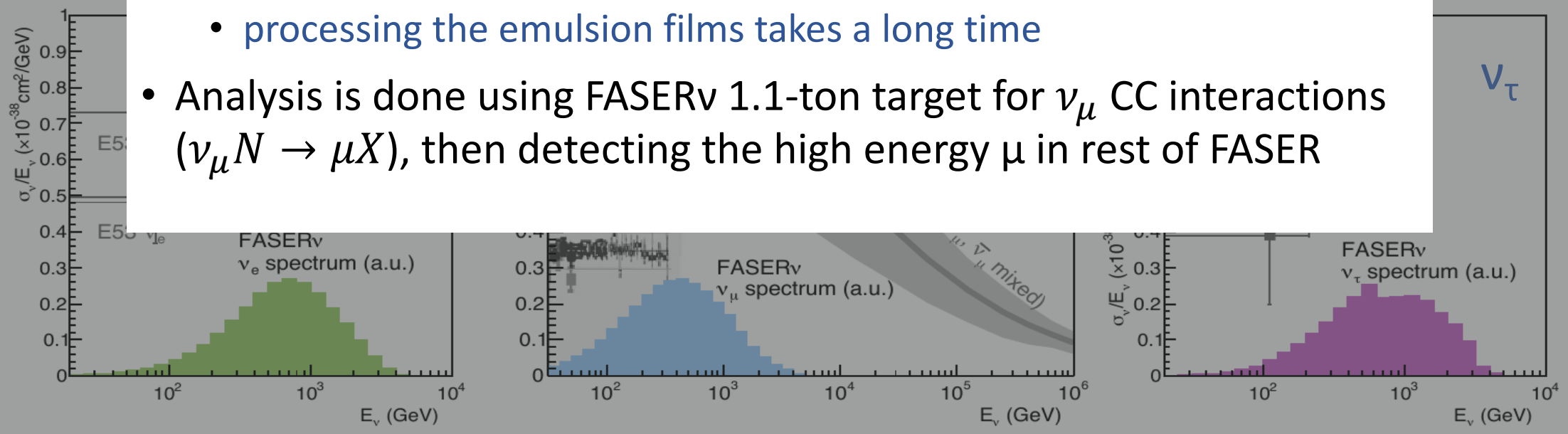
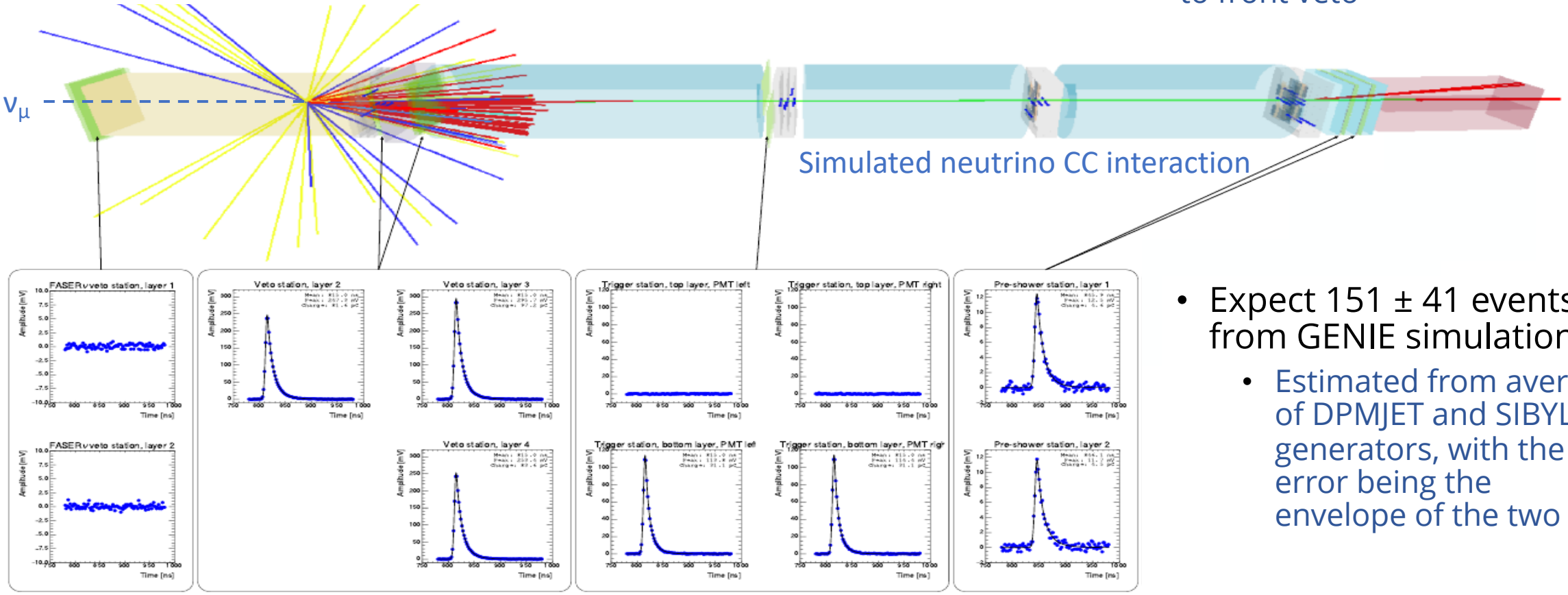
PRD 104, 113008

- Our first ever ν analysis only strives to claim observation
- The FASERν emulsion is not used for this analysis
  - processing the emulsion films takes a long time
- Analysis is done using FASERν 1.1-ton target for ν_μ CC interactions ($\nu_\mu N \rightarrow \mu X$), then detecting the high energy μ in rest of FASER



FASER Neutrino Event Selection

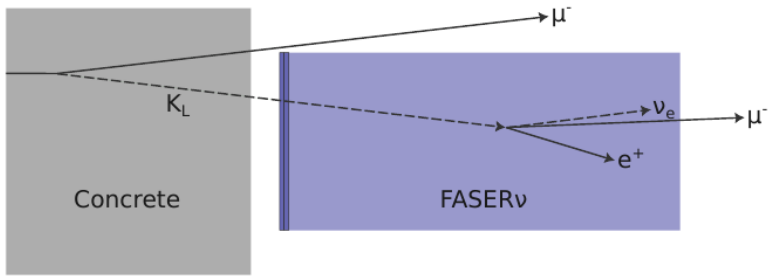
1. LHC collision event and good data quality
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos after FASERν
4. Timing and preshower consistent with ≥1 MIP
5. Exactly 1 good track
   - p > 100 GeV and θ < 25 mrad
   - r < 95 mm in tracking stations
   - r < 120 mm when extrapolating to front veto

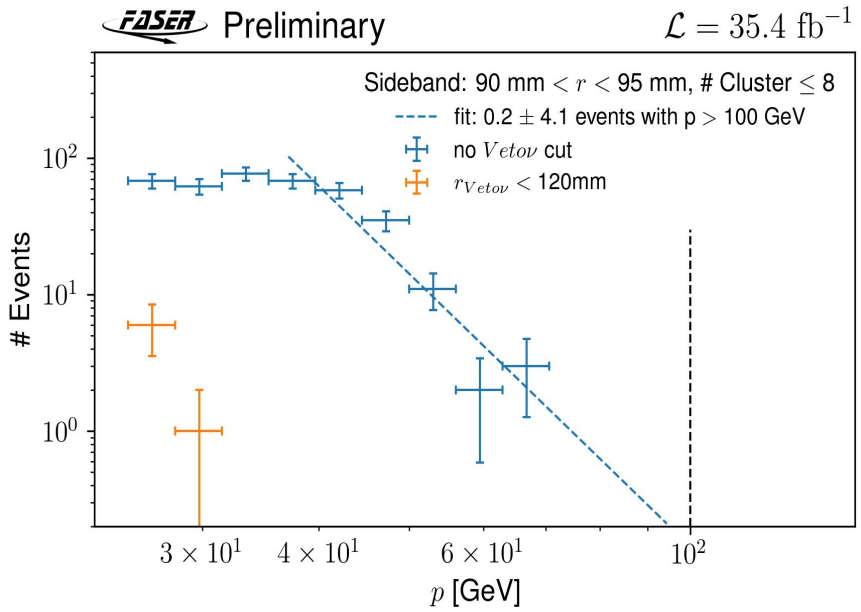


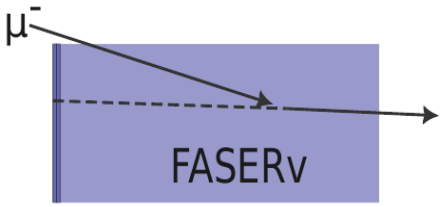
- Expect 151 ± 41 events from GENIE simulation
  - Estimated from average of DPMJET and SIBYLL generators, with the error being the envelope of the two

Neutrino Backgrounds

- Neutral hadrons estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
    - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
    - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events
- Scattered muons estimated from data sideband
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
    - Uncertainty from varying selection
- Veto inefficiency estimated in final likelihood fit
  - Fit events with 0 (SR) and also 1 or 2 front veto layers firing
  - Find negligible background due to very high veto efficiency



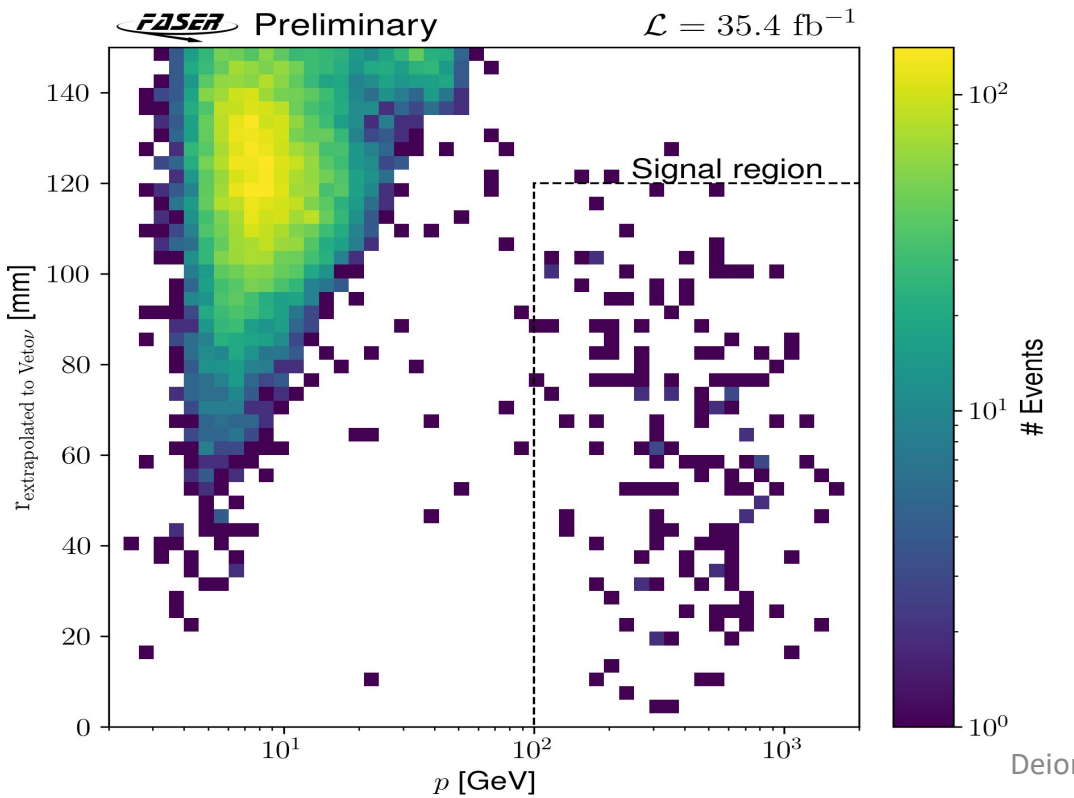


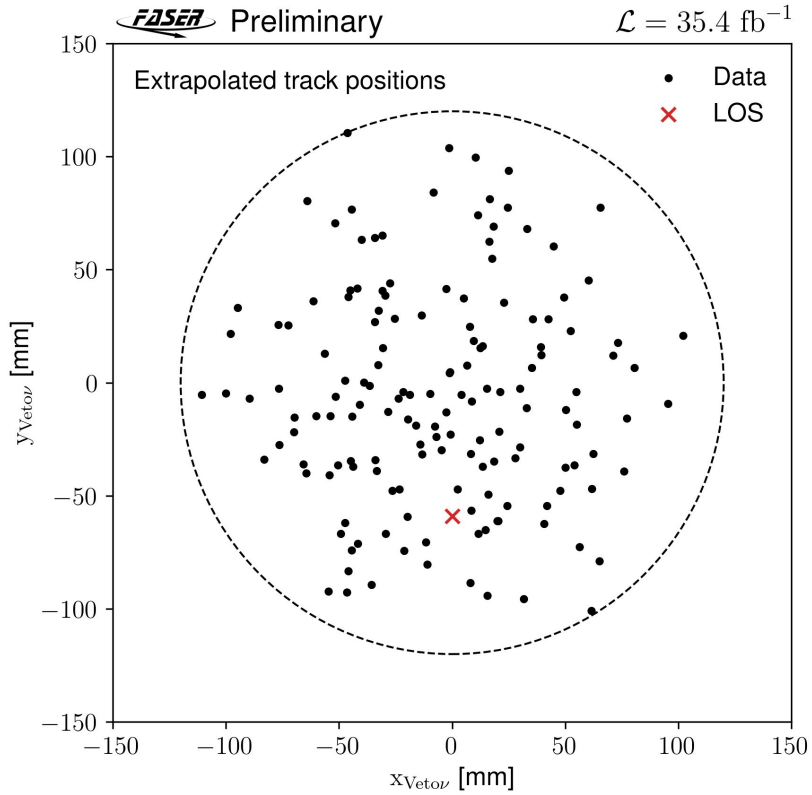


Neutrino Results

- Upon unblinding find 153 events with no veto signal
  - With signal significance of 16σ
  - First direct detection of collider neutrinos!
  - Accepted for publication in PRL: arXiv:2303.14185

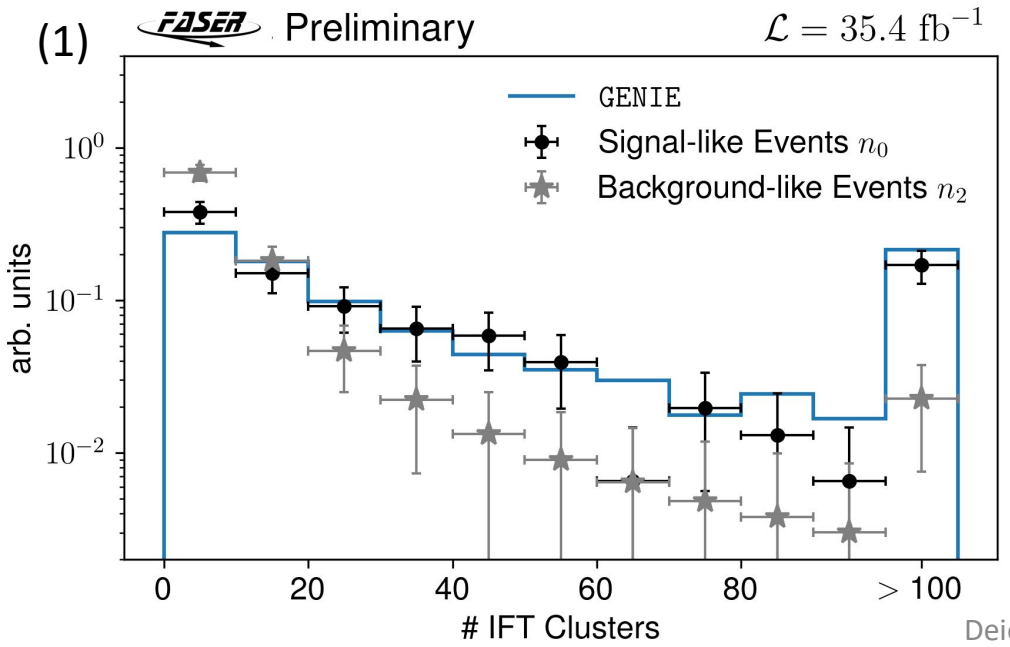
Front Vetos Hit	Events
n_{00}	153
n_{10}	4
n_{01}	6
n_{11}	64014695

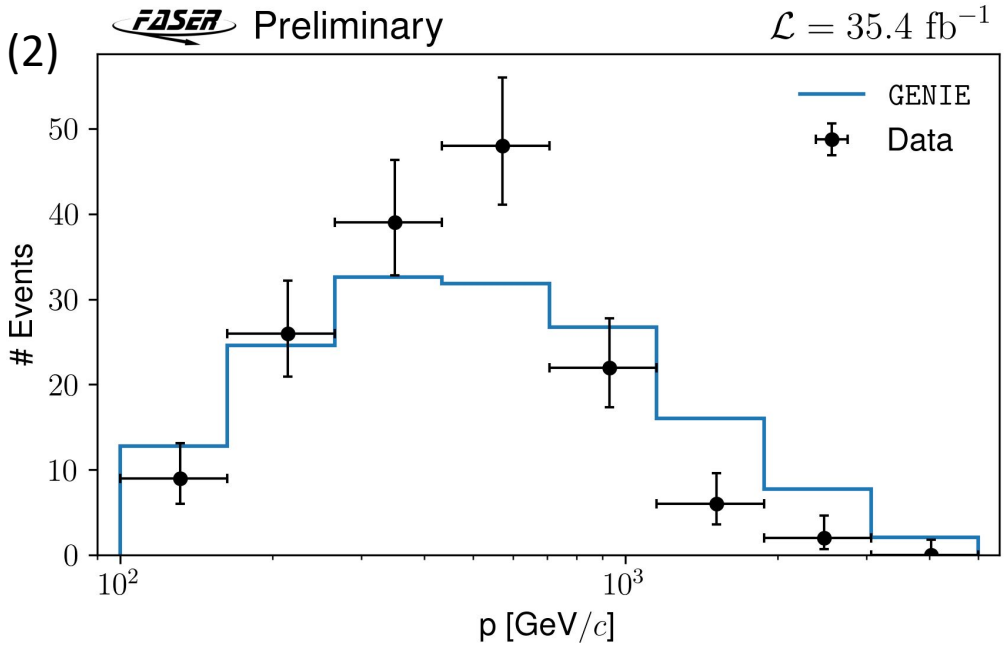


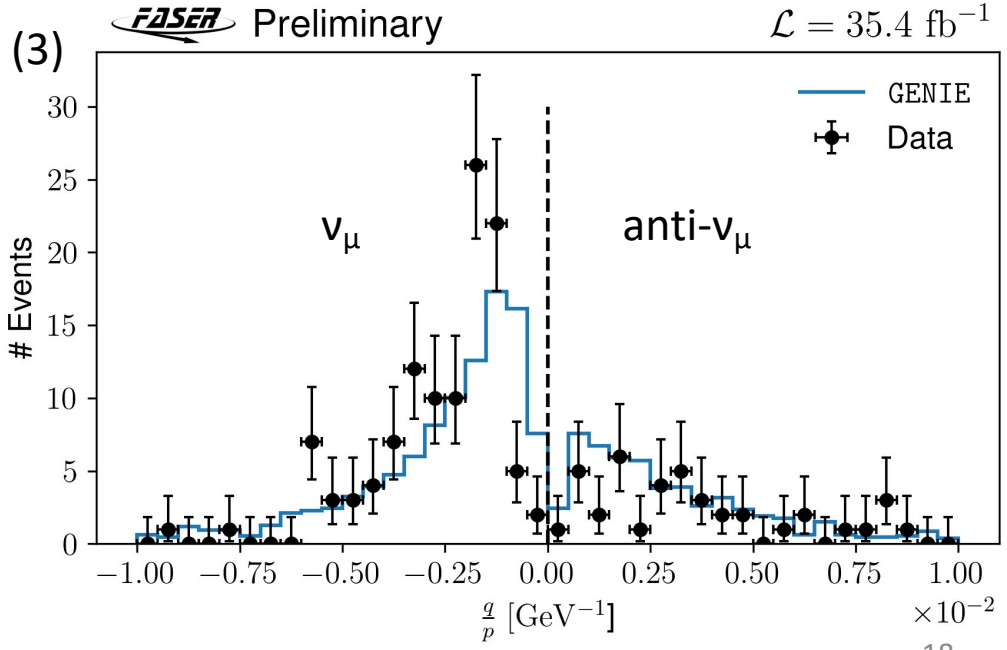


Neutrino Characteristics

- Candidate neutrino events match expectation from signal
  1. High occupancy in front tracker station
  2. Most events have high μ momentum
  3. More ν_μ than anti-ν_μ
  - Note: no experimental uncertainties included in these plots

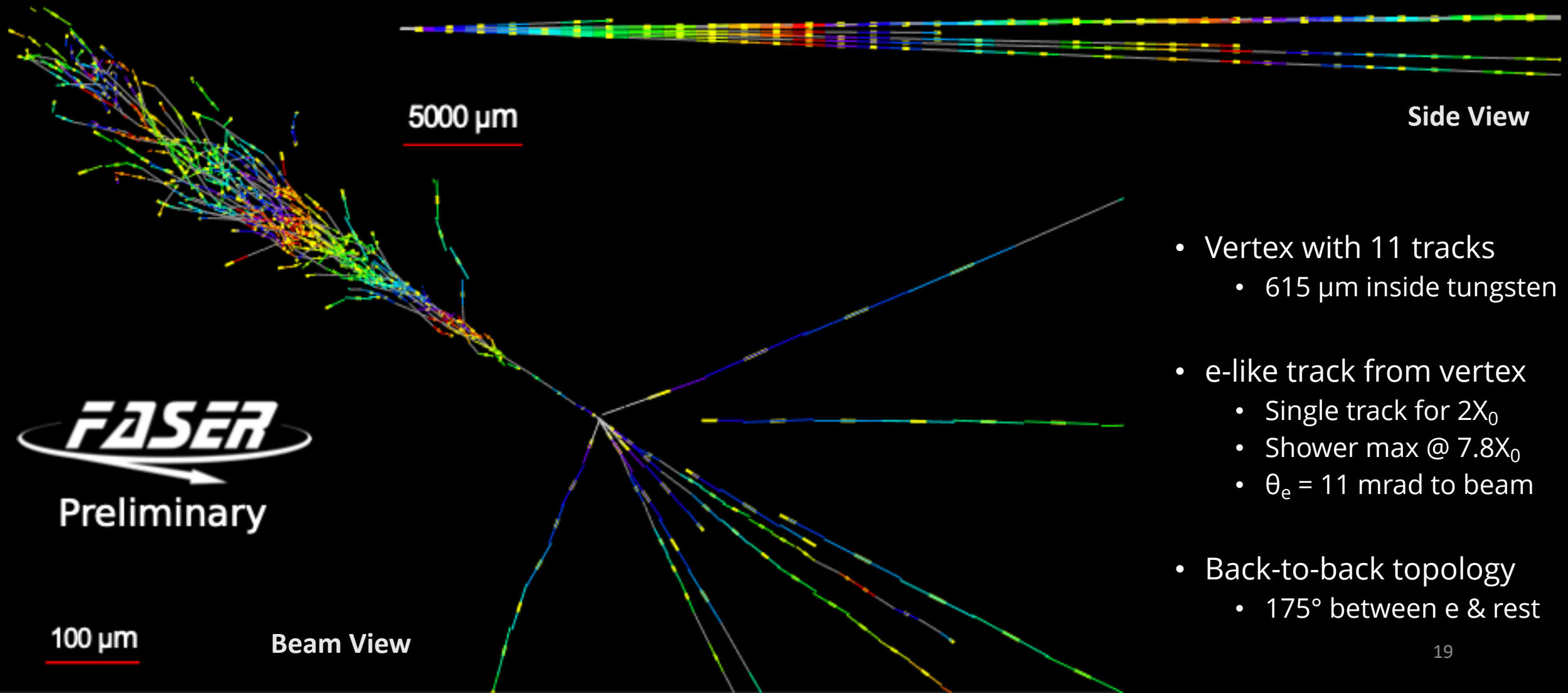






Neutrinos in FASERν

- Analysis of FAESRν emulsion detector underway
  - Have multiple candidates including highly ν_e like CC event



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

Summary

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency
- Excluded A' in region of low mass and kinetic mixing
  - Probes new territory in interesting thermal-relic region
- Reconstructed ~150 ν_μ CC interactions in spectrometer
  - First *direct* detection of collider neutrinos!
- More searches and neutrino measurements to come
  - Including first results from emulsion detector
- Looking forward to up to 10x more LHC run-3 data
  - FASER is operating well for the startup of 2023 LHC running