The FASER Experiment: First Physics Results

34th Rencontres de Blois 14th – 19th May 2023

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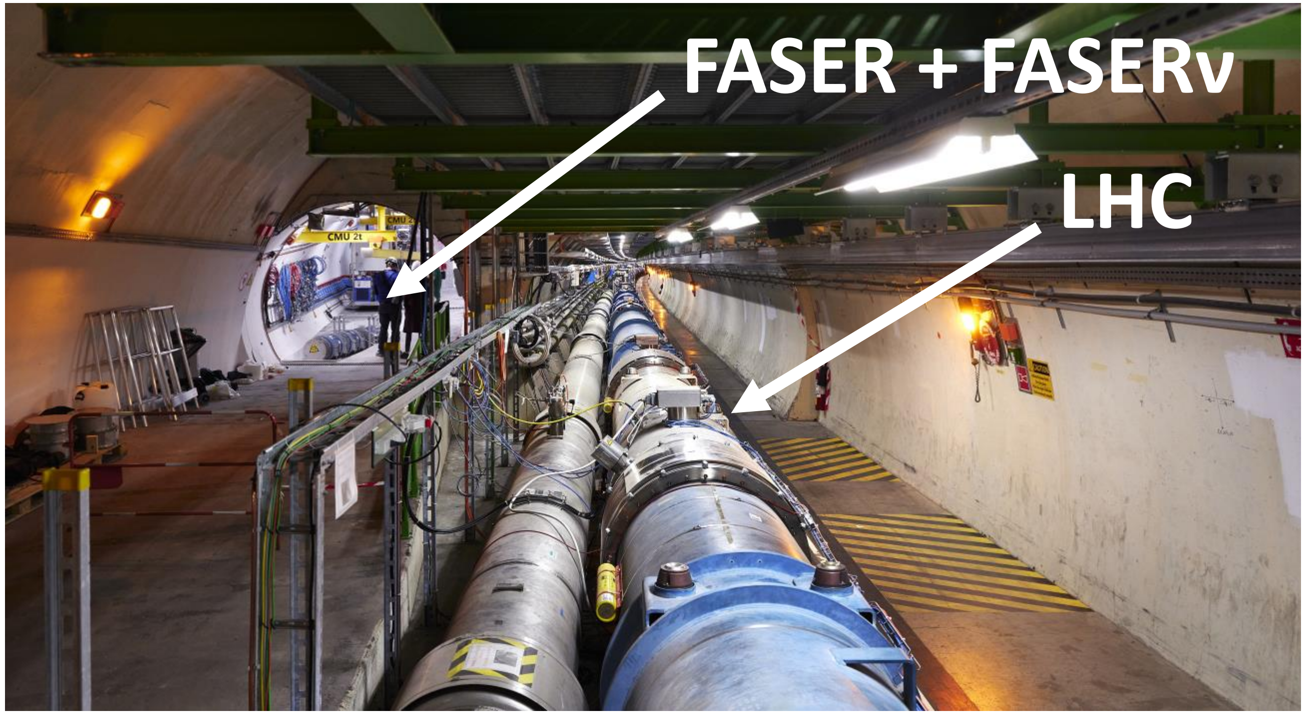
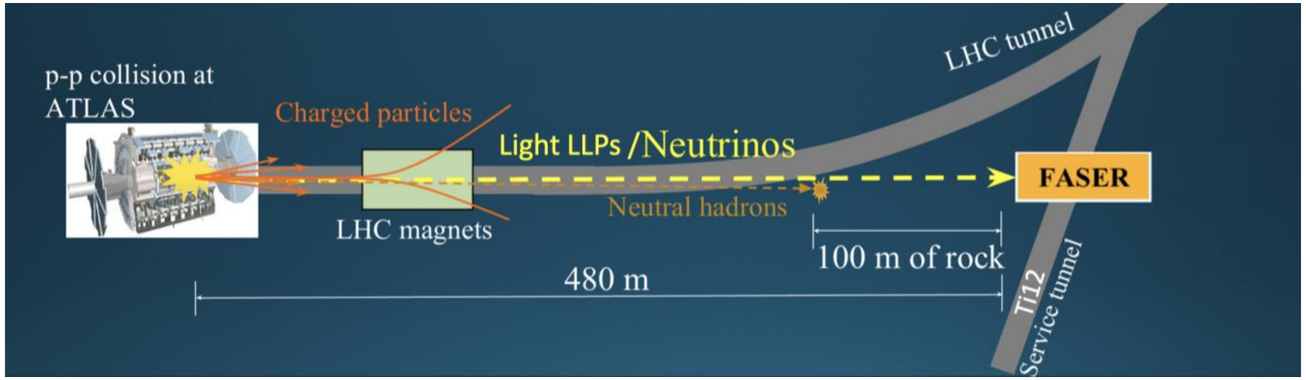
Introduction: The FASER Experiment

FASER is a new, small experiment designed to search for new long-lived particles (LLPs), and to study high energy neutrinos, produced at the ATLAS Interaction Point.

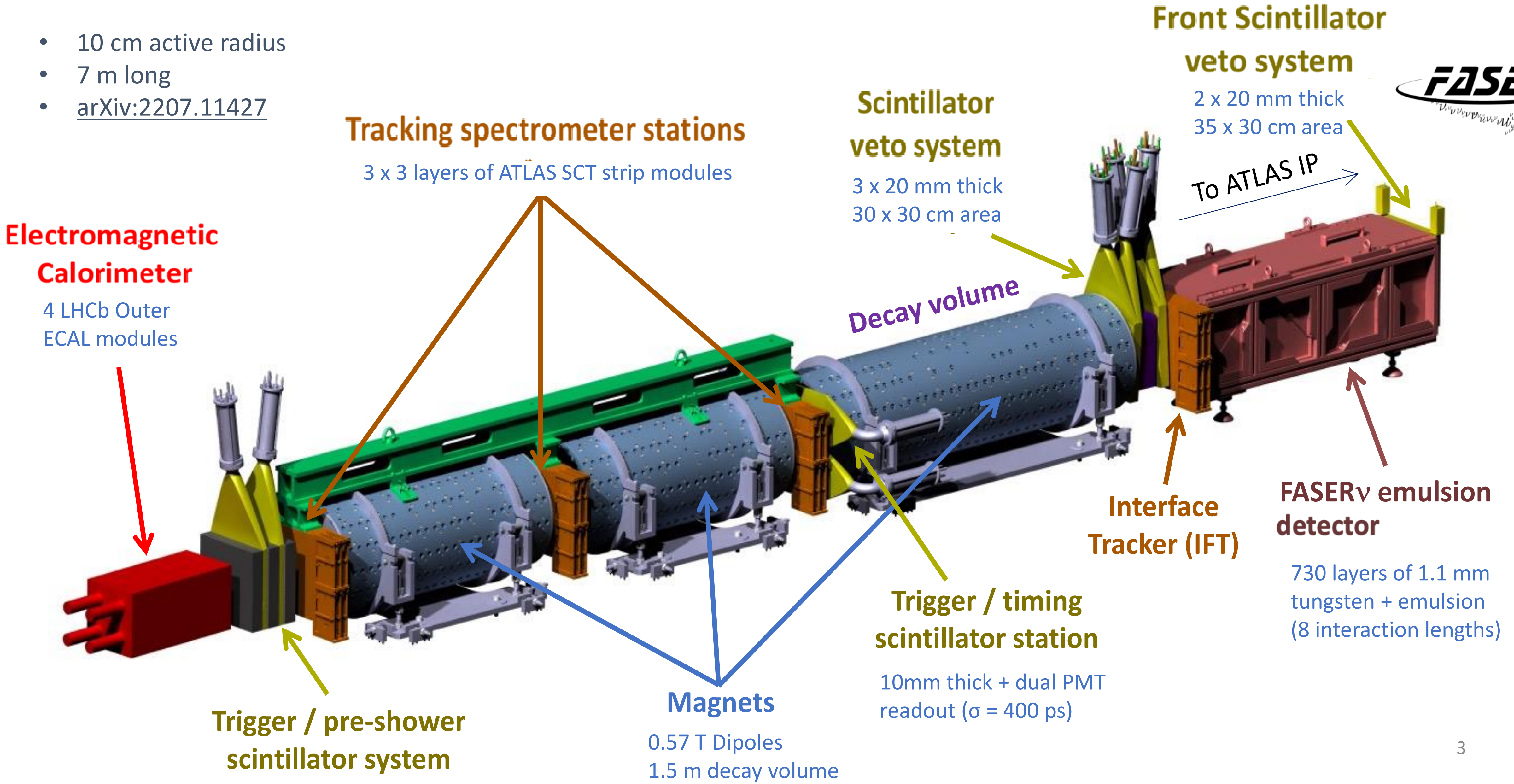
- Exploits large LHC collision rate with highly collimated forward production of light particles
- In addition to neutrinos, FASER targets new long-lived BSM particles including dark photons and ALPs
- Located 480m downstream of ATLAS, shielded with 100m of rock and concrete





The FASER Detector

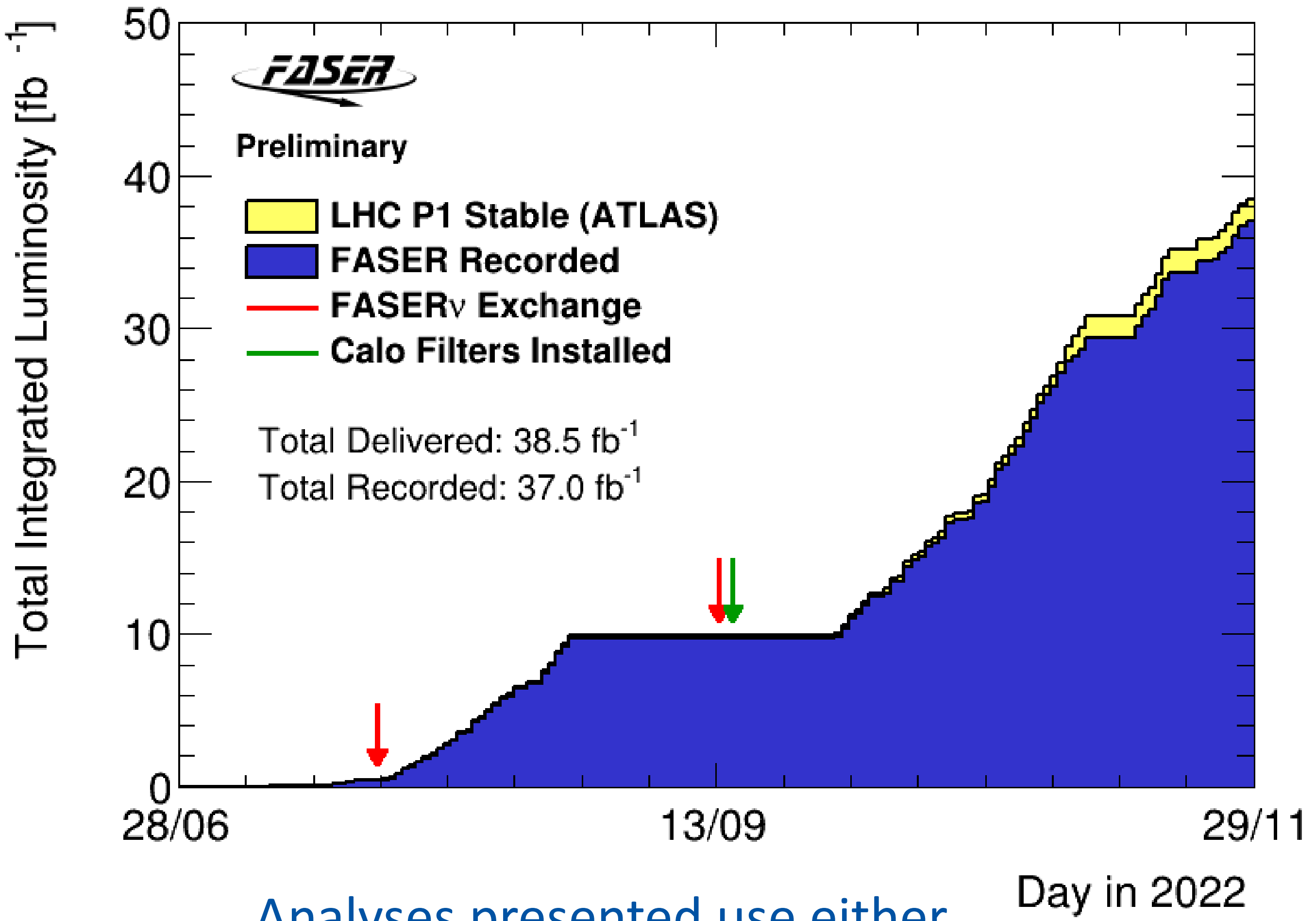
- 10 cm active radius
- 7 m long
- arXiv:2207.11427



Detector installation between March – Nov 2021, ready for LHC Run 3

FASER Operations

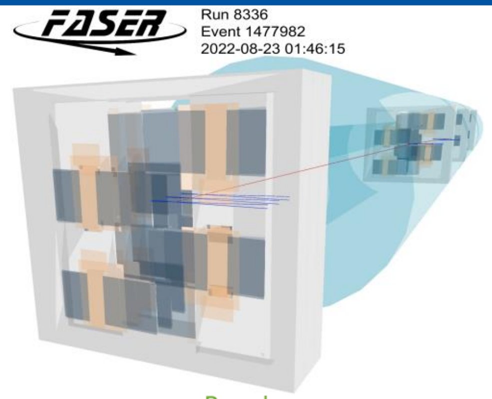
- Successful operation throughout 2022
  - Continuous and largely automatic data taking
  - Up to 1.3 kHz trigger rate
- Recorded 96.1% of delivered luminosity
  - DAQ deadtime 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - To manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low energy (< 300 GeV) before second exchange
  - High energy (up to 3 TeV) after this exchange

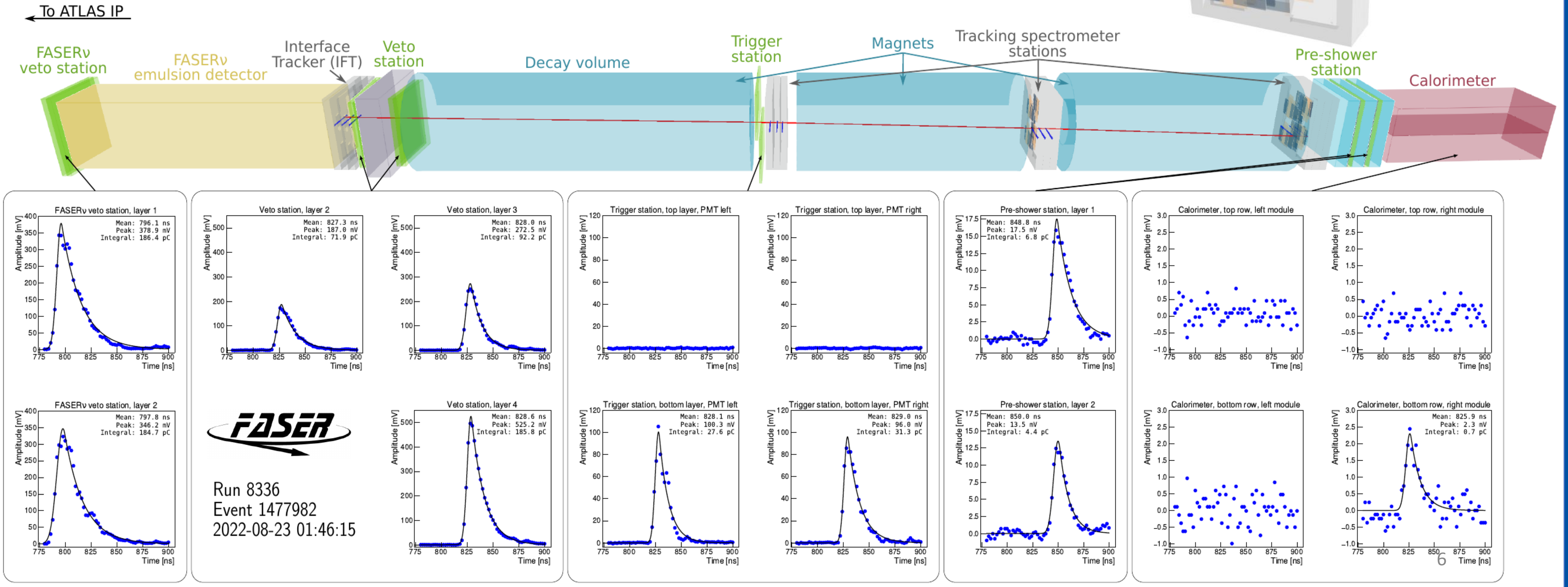


Analyses presented use either $35.4\ fb^{-1}$ or $27.0\ fb^{-1}$

FASER Operations: Example Collision Event

- All detector components are working very well
  - More than 350 million single-muon events recorded
  - Example: muon leaving track through full detector



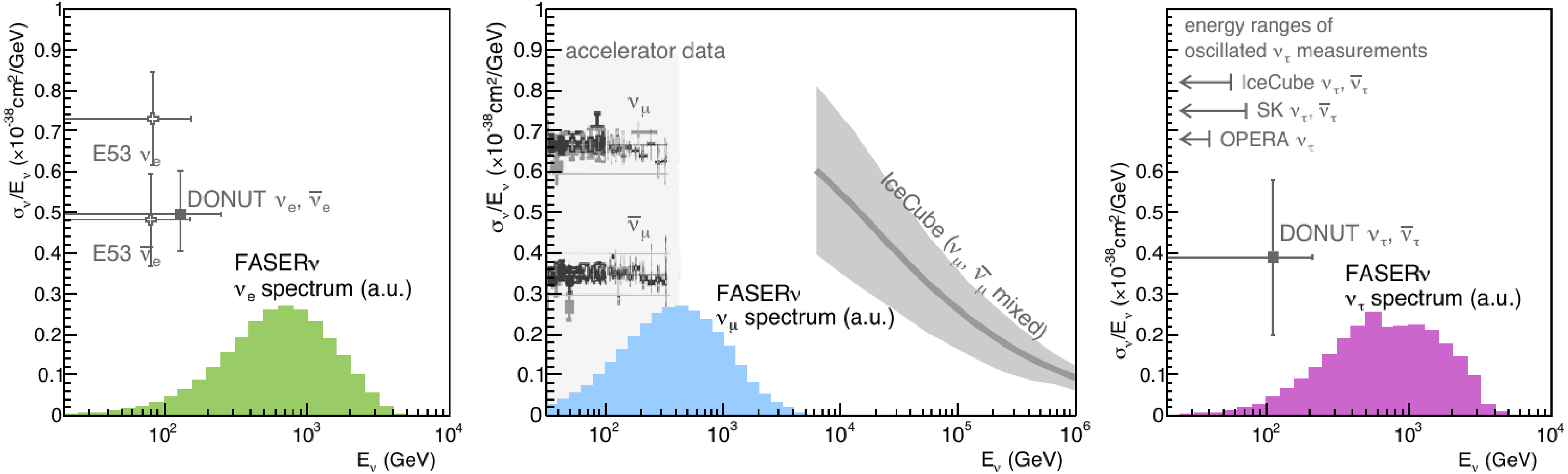


Electronic Neutrino Analysis

- Neutrinos are produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale), relatively high interaction cross section
- Extends FASER physics program into SM measurements
  - 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

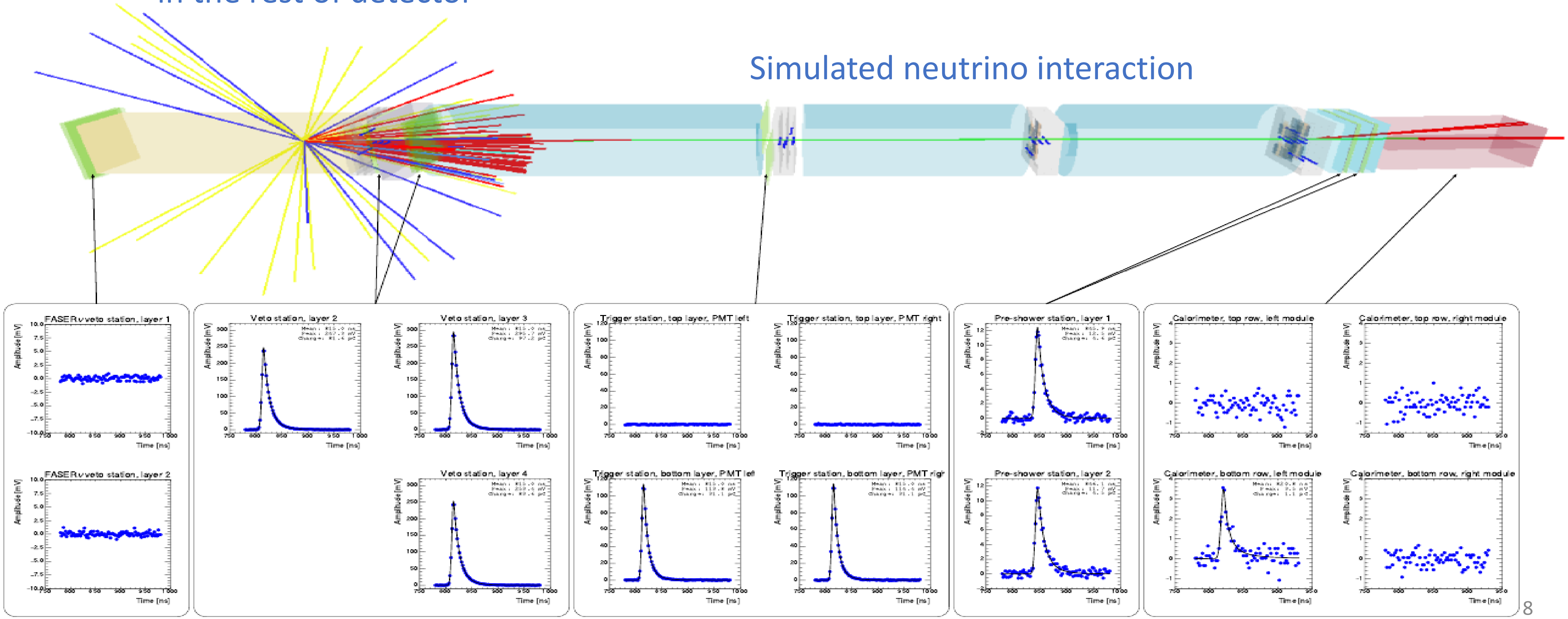
PRD 104, 113008



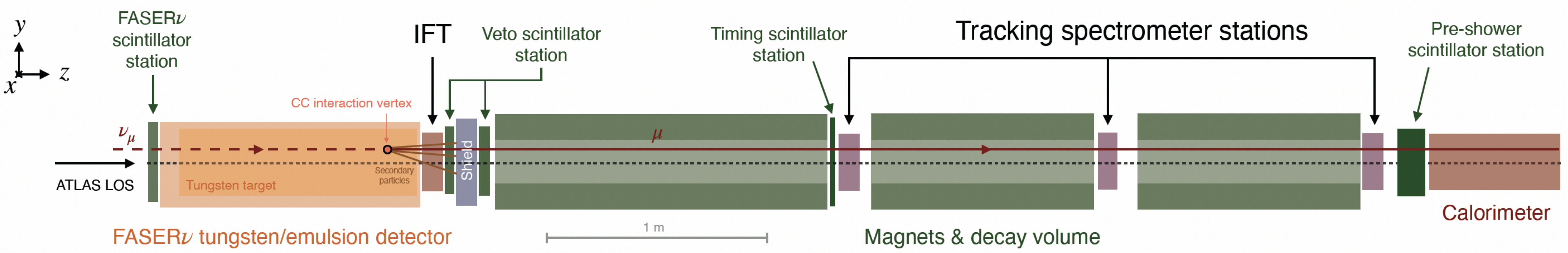
Study at colliders originally proposed by Rújula and Rückl in 1984!

Observing Neutrino Candidates in FASER

- Possible to make a first observation of neutrinos
  - Using just spectrometer and veto systems
  - Search for charged-current ν_μ events with no signal in two front vetos and one high momentum track in the rest of detector



Neutrino Analysis: Event Selection



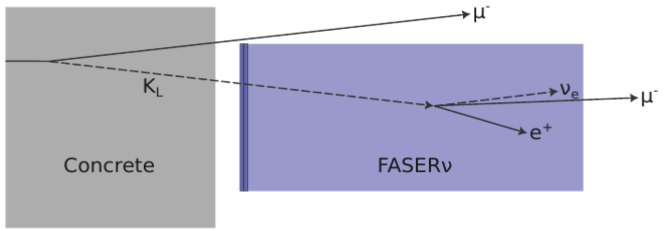
Can detect CC ν_μ using just spectrometer and veto systems!

Expected event yield from simulation:

- Forward hadron production modelled with DPMJET or SIBYLL generator
- Neutrino interaction simulated with GENIE
- Expect 151 ± 41 events (average between DPMJET/SIBYLL with error from difference)
- No experimental errors included
- Current aim is not to measure cross section

- Collision event with good data quality
  - Runs during good physics data periods, 35.4 fb-1
- No signal (< 40 pC) in 2 front vetos
- Signal (> 40 pC) in other 3 vetos
- Exactly 1 good fiducial track (r < 95 mm) track
  - p > 100 GeV, theta < 25 mrad
  - Extrapolating to r < 120 mm in front veto
- Timing and preshower consistent with ≥ 1 MIP

Neutrino Analysis: Background Estimate

1)


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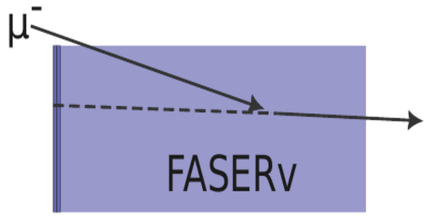

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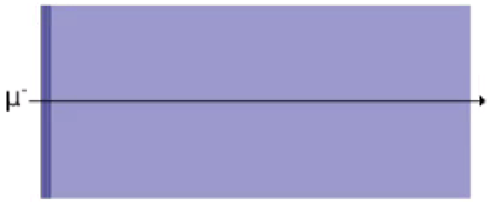
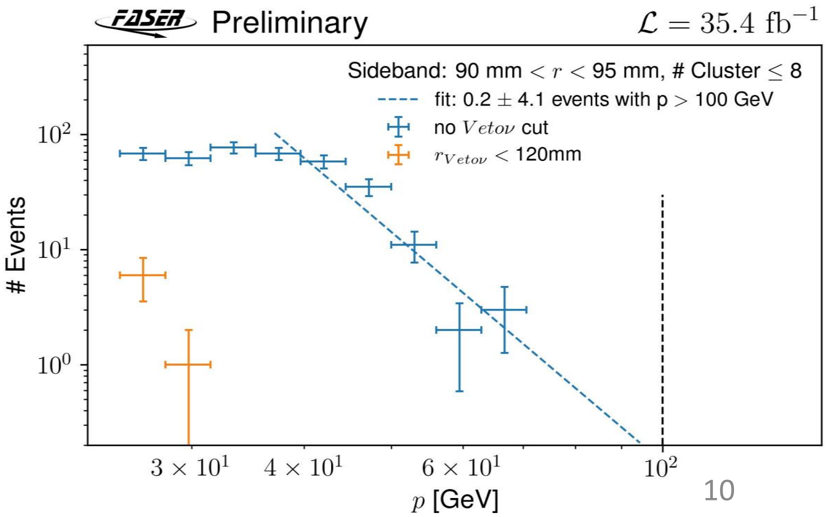


1. Neutral hadrons estimated from 2-step simulation
   - Expect O(300) neutral hadrons with E>100 GeV reaching FASERν
     - Most accompanied by muon, but conservatively assume it misses veto system
   - Most neutral hadrons absorbed in tungsten without producing high-momentum track
   - Expect 0.11 ± 0.06 events

2. Scattered muons estimated from control regions of events with single track segment in front tracker station at large radius (90 < r < 95 mm)
   - Expect: 0.08 ± 1.83 events

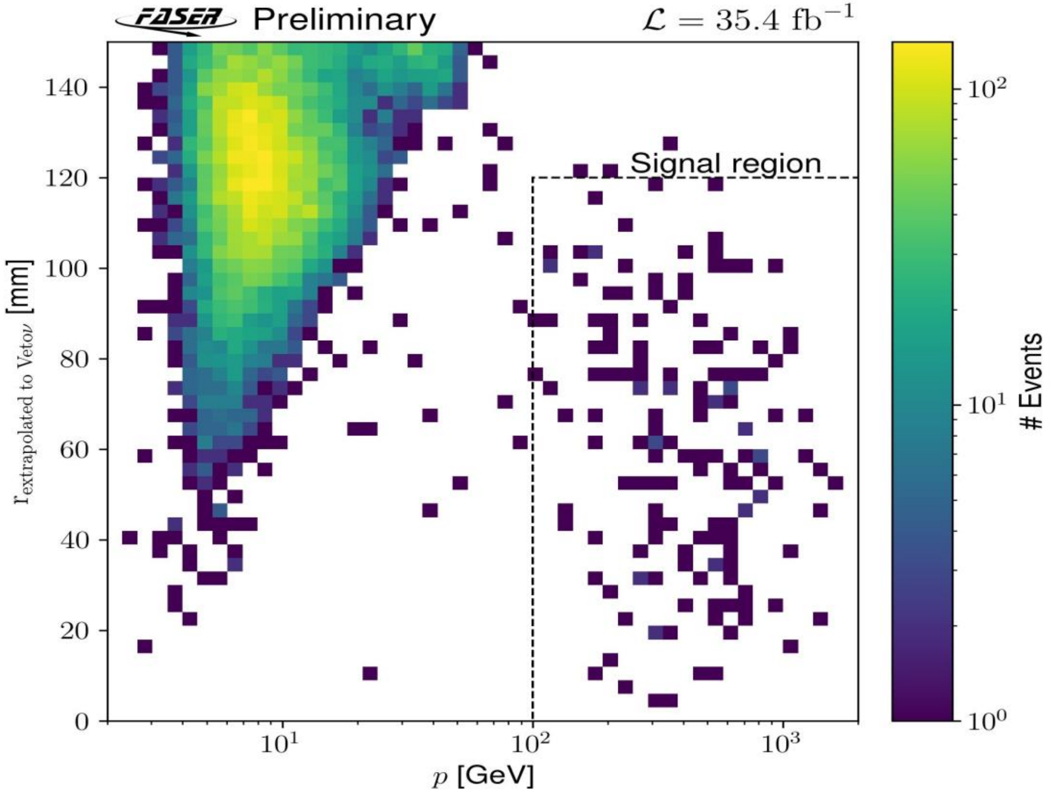


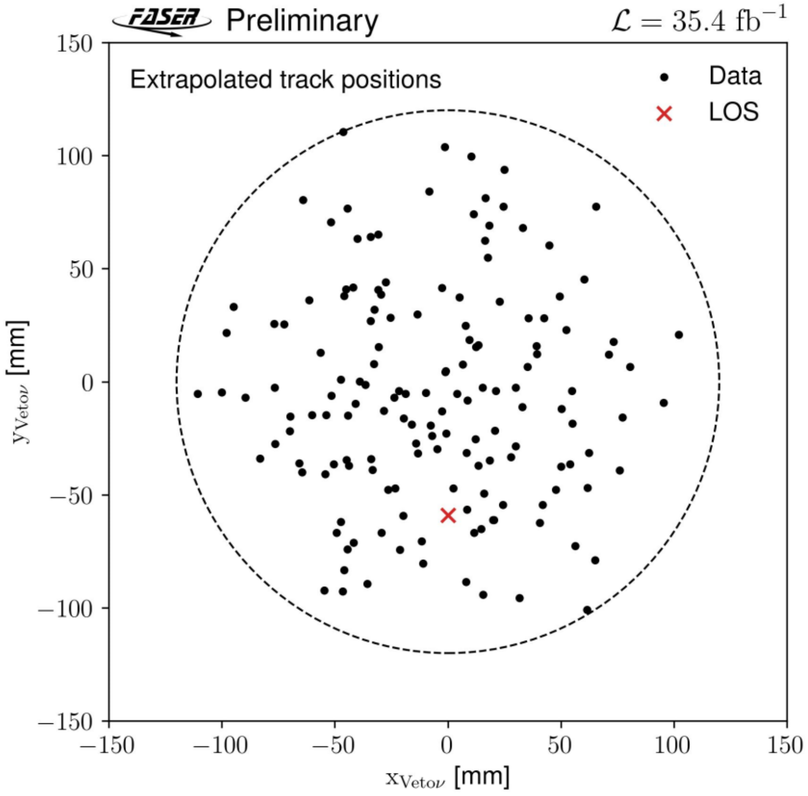
3. Veto inefficiency estimated from events with just one veto scintillator firing
   - Veto efficiencies fitted in final fit of events with 0, 1 or 2 veto layers firing
   - Negligible background due to very high veto efficiency

Neutrino Analysis: Results

- **Unblinded results show 153 events in our signal region!**
  - 10 events have one veto signal
- This is the first *direct* detection of collider neutrinos!
  - Signal significance of 16σ, to appear in PRL: arXiv:2303.14185

Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

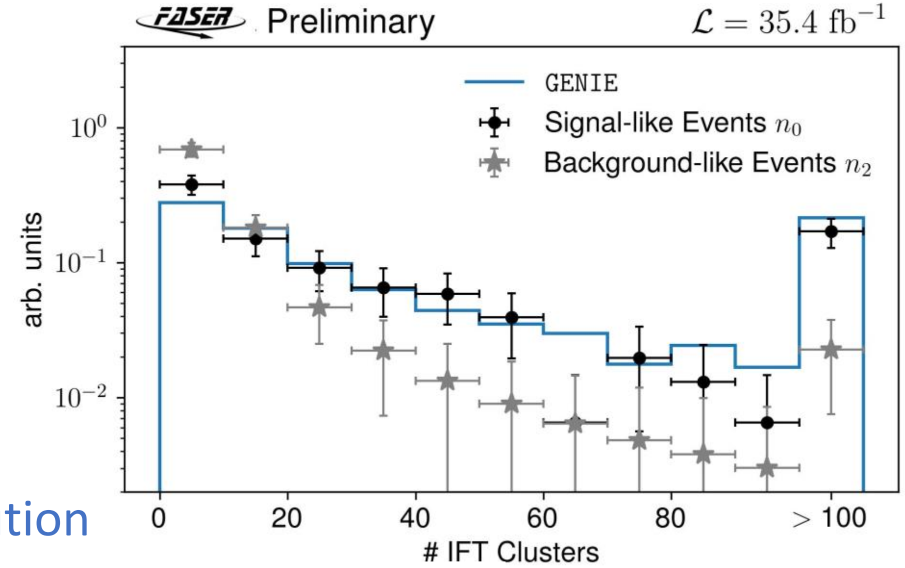




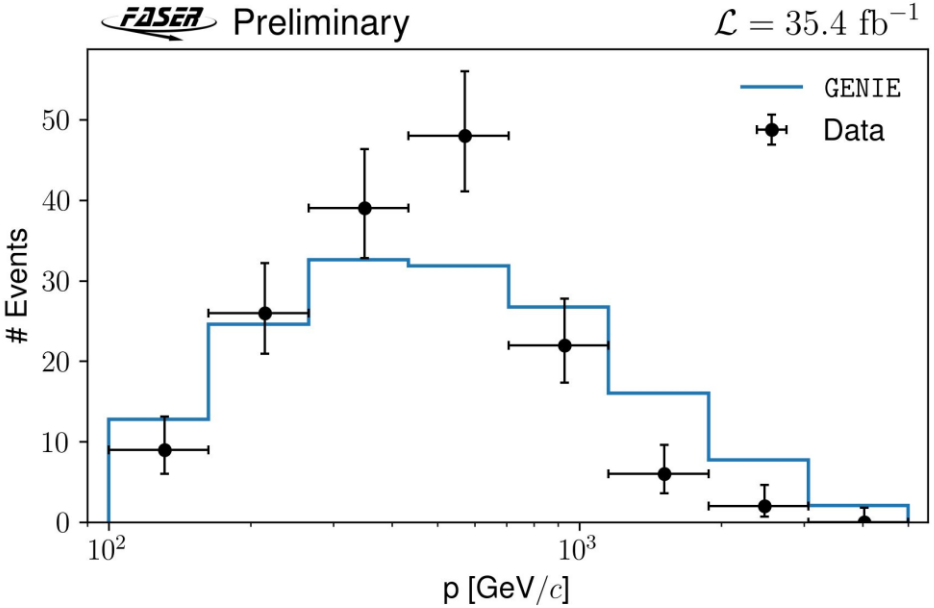
Neutrino Distributions

- Neutrino events match expectations from simulations
  - High occupancy in front track station
  - More ν_μ than anti- ν_μ
  - Most events at high momentum

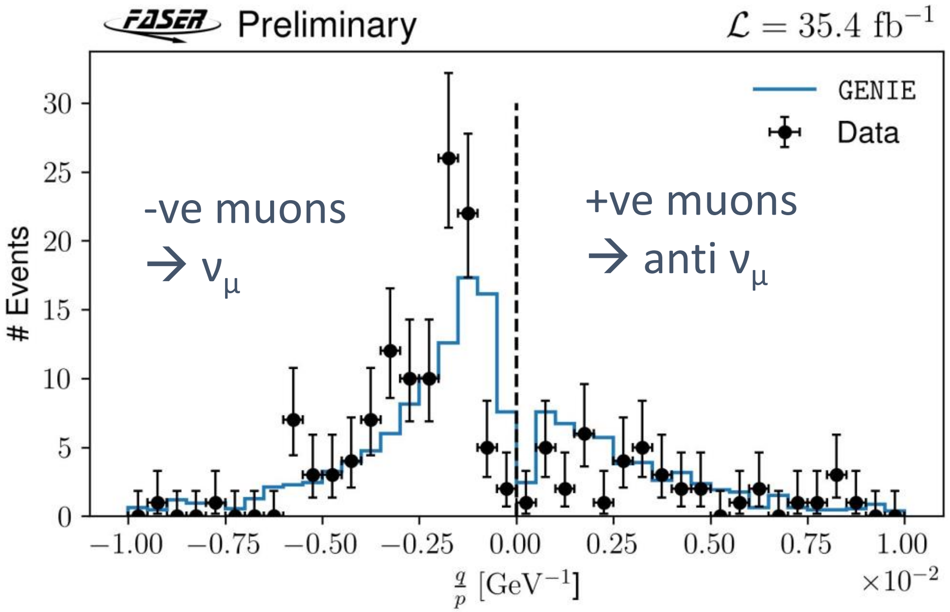
Clusters in front tracker station



Track momentum distribution



Track q/p distribution

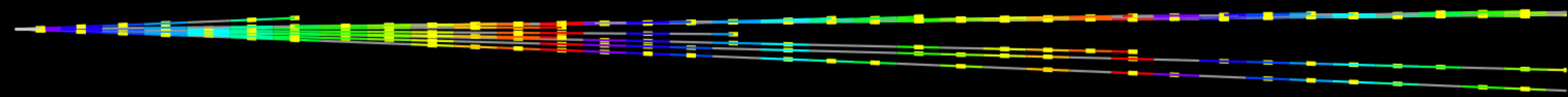


Note: Plots are not acceptance-corrected and do not show systematic uncertainties

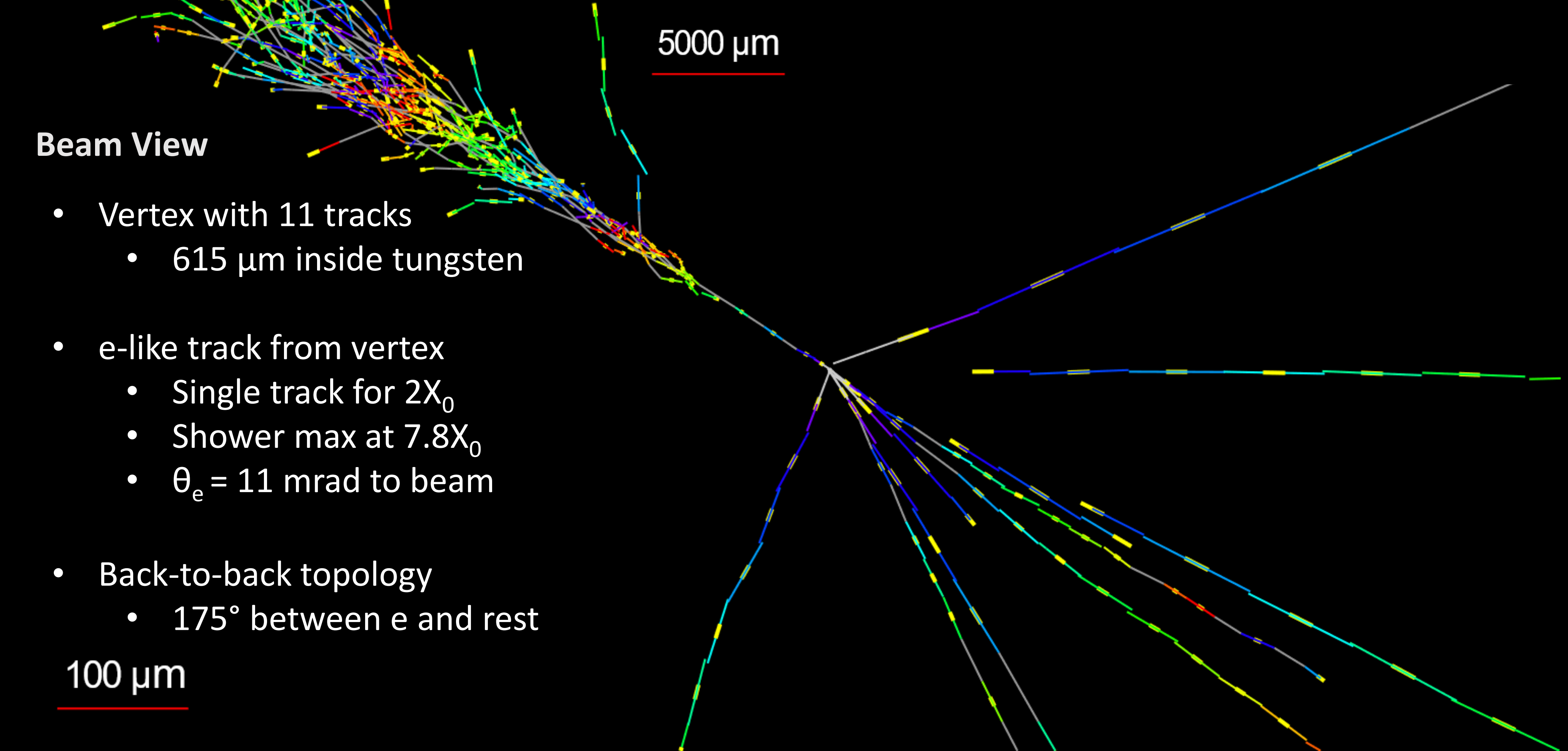
Neutrinos in FASERν

- Analysis of FASERν emulsion detector is underway
  - Multiple candidates, including highly ν_e like CC event

Side View



Beam View



- 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 and rest

100 µm

Dark Photon Search

- The dark photon is a common feature of hidden sector models
  - Weakly coupling to SM via kinetic mixing (ε) with SM γ

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

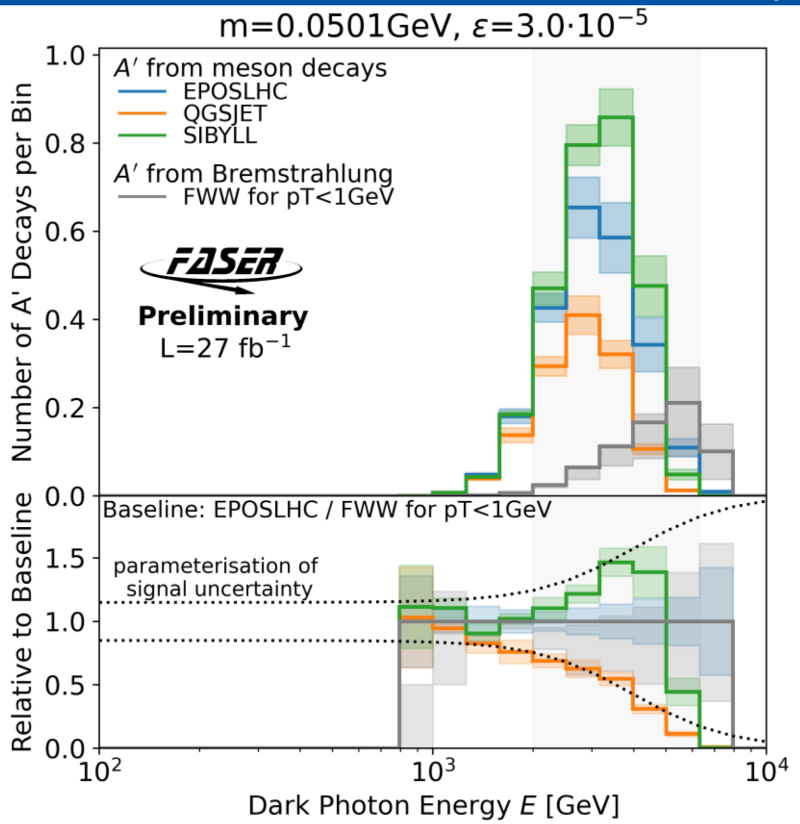
- MeV A's produced mainly in meson decays at the LHC

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

- FASER targets small ε -> long A' decay length
  - $m_{A'} < 2\, m_{\mu}$, A' decays 100% to e^+e^- pairs

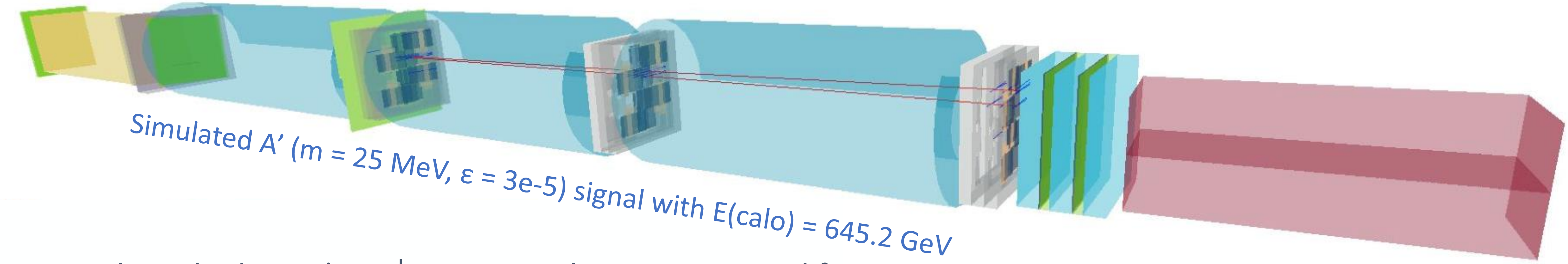
$$L = c\beta\tau\gamma \approx (80\text{ m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100\text{ MeV}}{m_{A'}}\right]^2$$

- A' -> e^+e^- simulated with FORESEE arXiv:2105.07077
  - π^0 and η via EPOS-LHC generator
  - Subdominant dark brem. via FWW



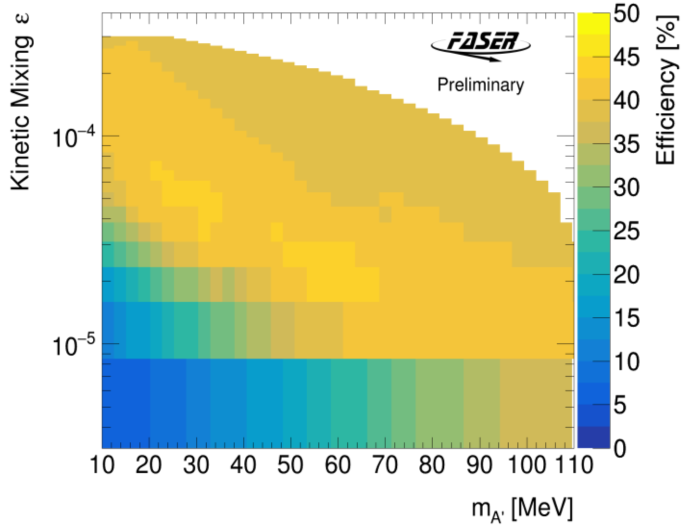
- Dominant uncertainty from forward hadron production (generator uncertainty)
  - Difference to QGSJET/SIBYLL
  - Parameterised based on A' energy

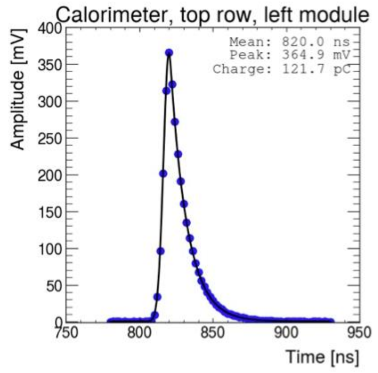
Dark Photon Analysis: Event Selection



- Simple and robust A' -> e^+e^- event selection optimised for discovery
  - Blind events with no veto signal and calo E > 100 GeV
  - Efficiency ~40% across sensitive region

- Collision event with good data quality
- No signal (< 40 pC) in any veto scintillator
- Exactly 2 good fiducial tracks
  - p > 20 GeV and r < 95 mm
  - Extrapolating to r < 95 mm at vetos
- Timing and pre-shower consistent with at least 2 MIPs
- Calo E > 500 GeV

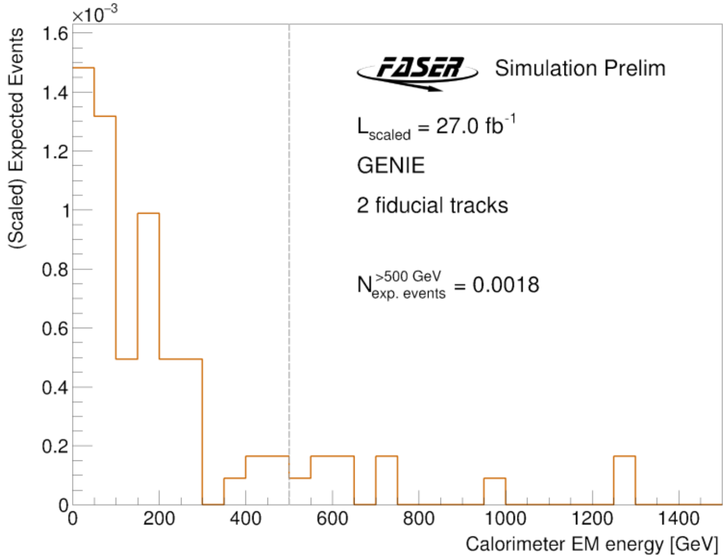




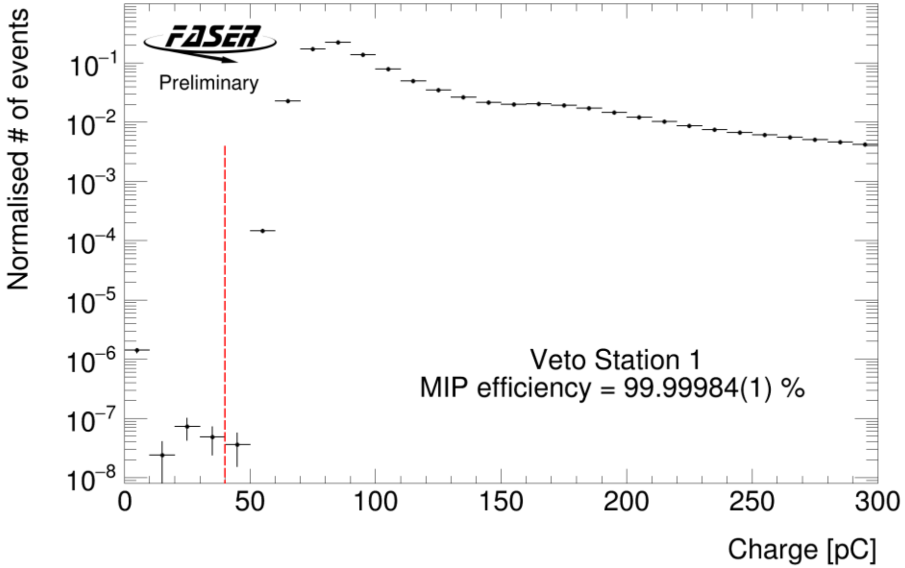
Dark Photon Analysis: Background Estimates

- Largest background: neutrino interactions estimated from simulation
  - Mainly from trigger/timing scintillator
  - Estimated using GENIE simulation (300 ab^{-1}) – uncertainties from neutrino flux and mismodelling

$$N = (1.8 \pm 2.4) \times 10^{-3}$$



- Veto inefficiency
  - Veto layer efficiency > 99.998%
  - Measured layer-by-layer using muon tracks in spectrometer that point back to vetos
  - 5 scintillator layers reduce expected 10^8 background muons to negligible level

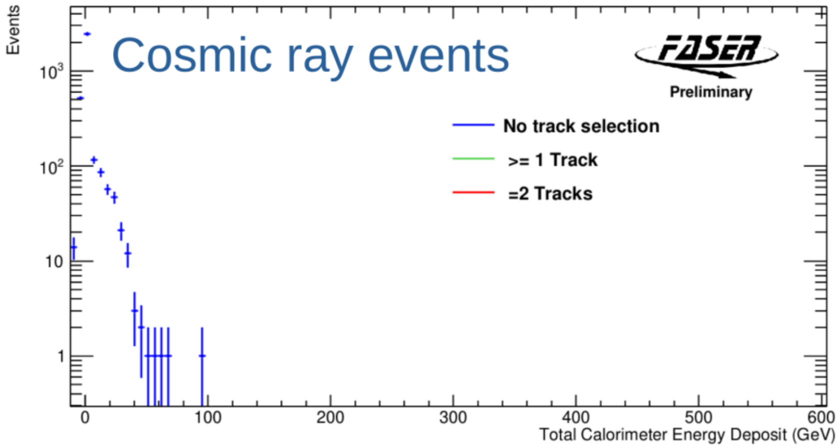


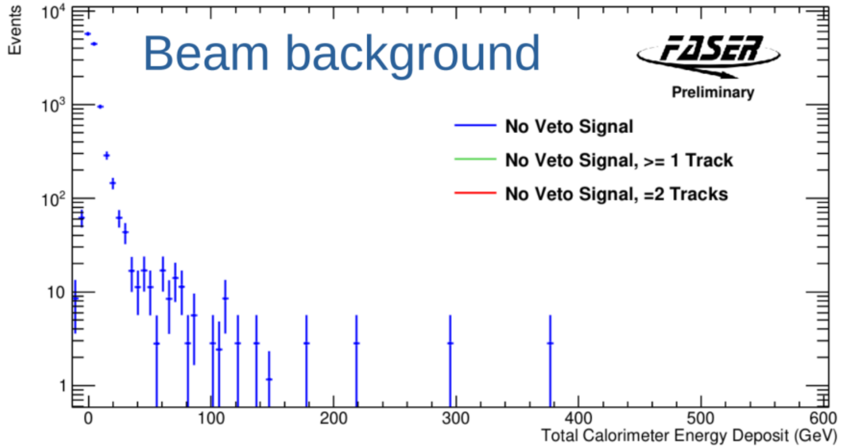
Dark Photon Analysis: Background Estimates

- Neutral hadrons (eg K_s) from upstream muon interacting in rock before FASER
  - Heavily suppressed since:
    - Muon nearly always continues after interacting
    - Must pass through the 8 interaction lengths of FASERν
    - Decay products must have calo E > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

$N = (2.2 \pm 3.1) \times 10^{-4}$

- Non-collision background: cosmics and nearby beam debris
  - Studied in runs without beams and in non-colliding bunches
  - No events observed with ≥ 1 track or calo E > 500 GeV



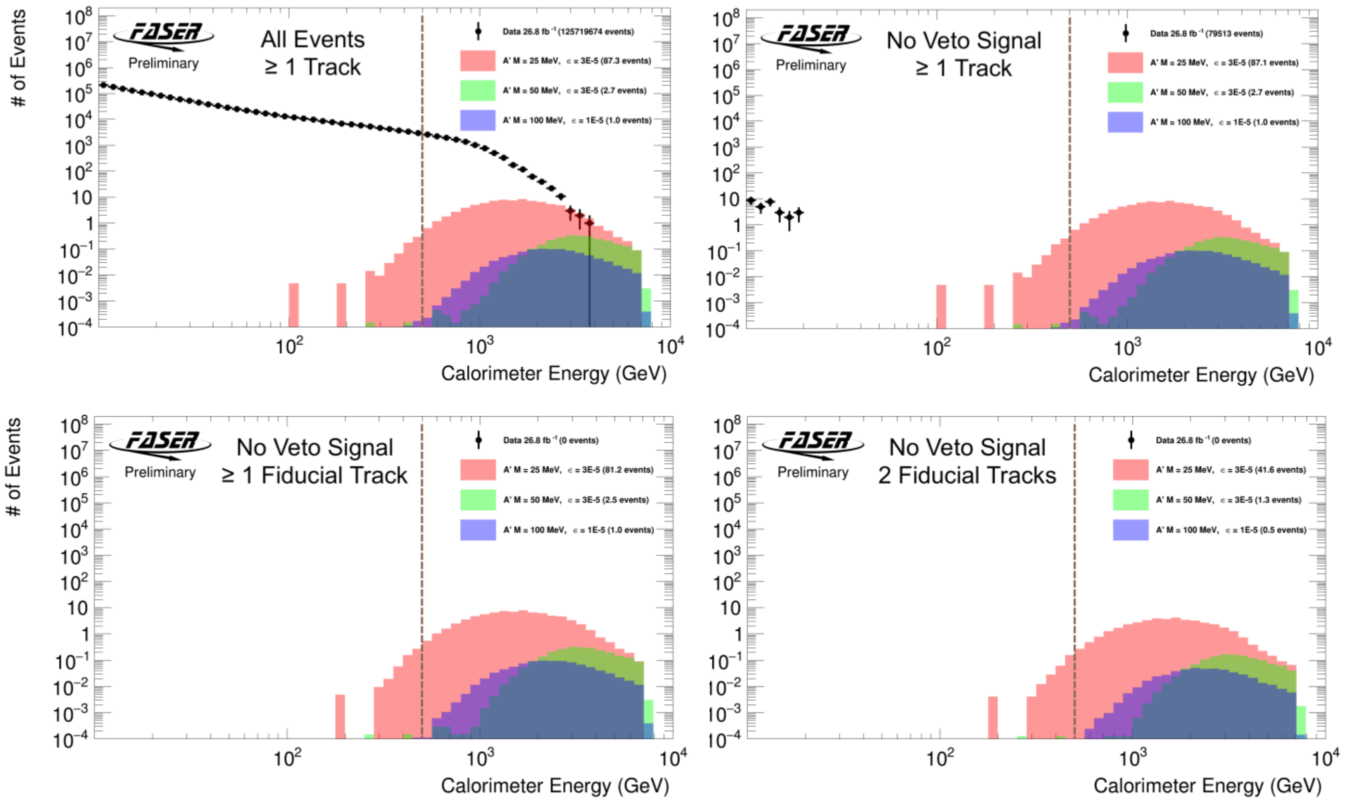


Total background prediction:

$N = (2.02 \pm 2.4) \times 10^{-3}$

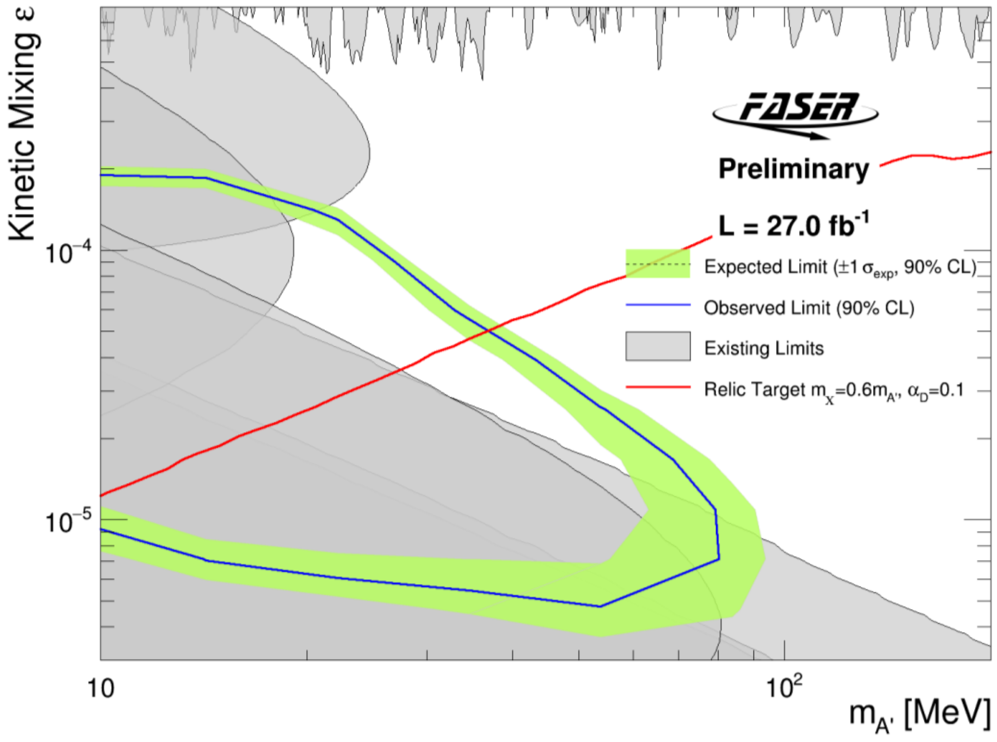
Dark Photon Analysis: Results

- No events in unblinded signal region
  - Not even with ≥ 1 fiducial tracks



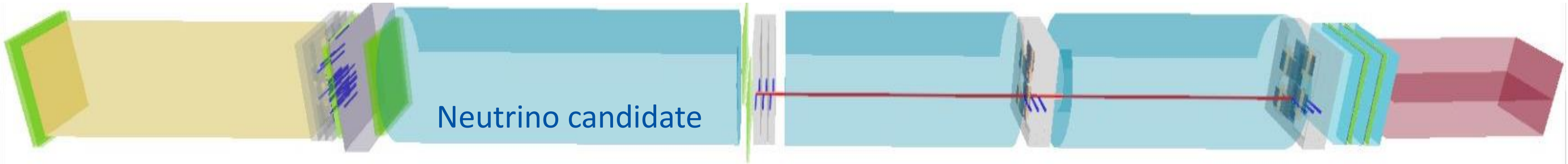
- Public conf note:

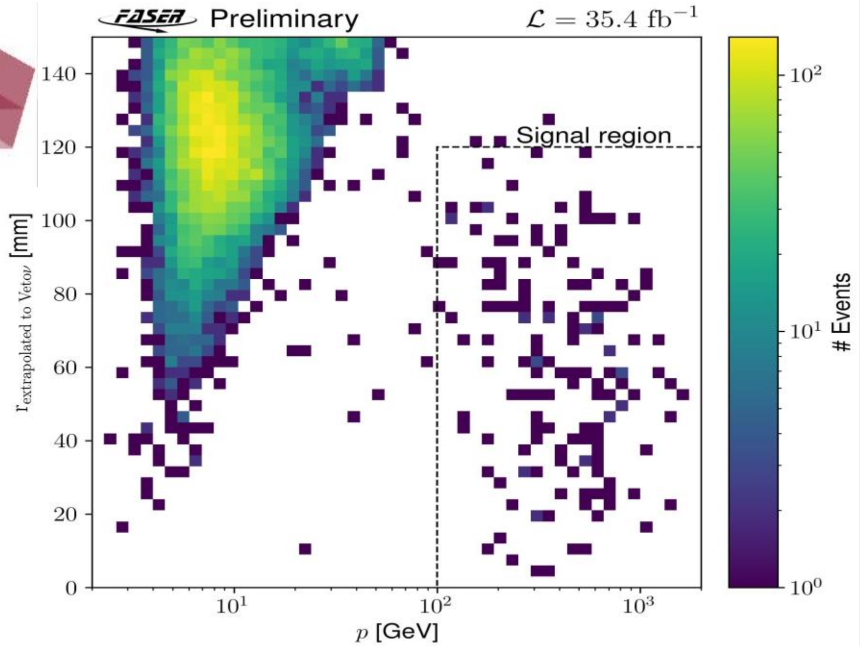
  [CERN-FASER-CONF-2023-001]



- Based on this null result, FASER is able to set limits in previously unexplored parameter space!
  - Extends exclusion into region motivated by dark matter
  - Taking into account NA62 preliminary result

Summary





Operations

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency
  - Operating well for the start-up of 2023 LHC running

Electronic Neutrino Analysis

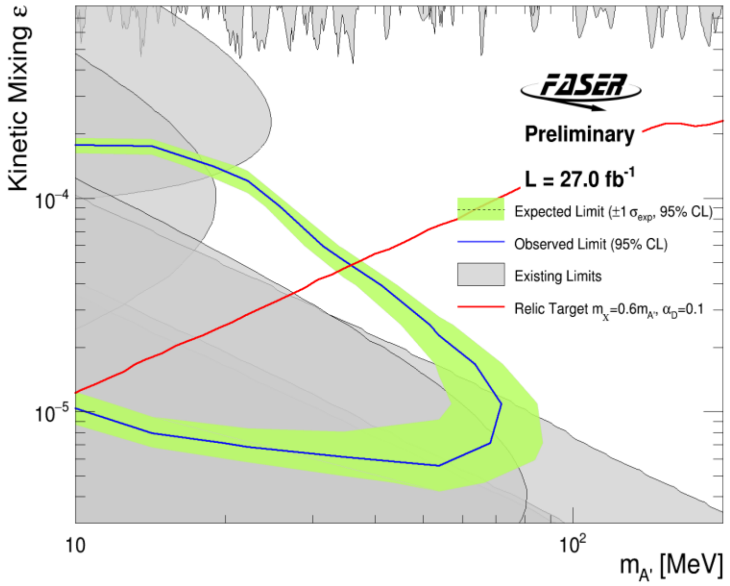
- Reconstructed ~150 ν_μ CC interactions in spectrometer
  - First *direct* detection of collider neutrinos!
  - Opens new window for high energy neutrino studies

Dark Photon Analysis

- Excluded A' in region of low mass and kinetic mixing
  - Probes new territory in interesting thermal relic region

Longer term

- For HL-LHC, larger versions of FASER and FASERν with significant gains in physics sensitivity are being studied in the context of the Forward Physics Facility: https://arxiv.org/abs/2203.05090



Acknowledgements

- FASER is supported by:

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CERN
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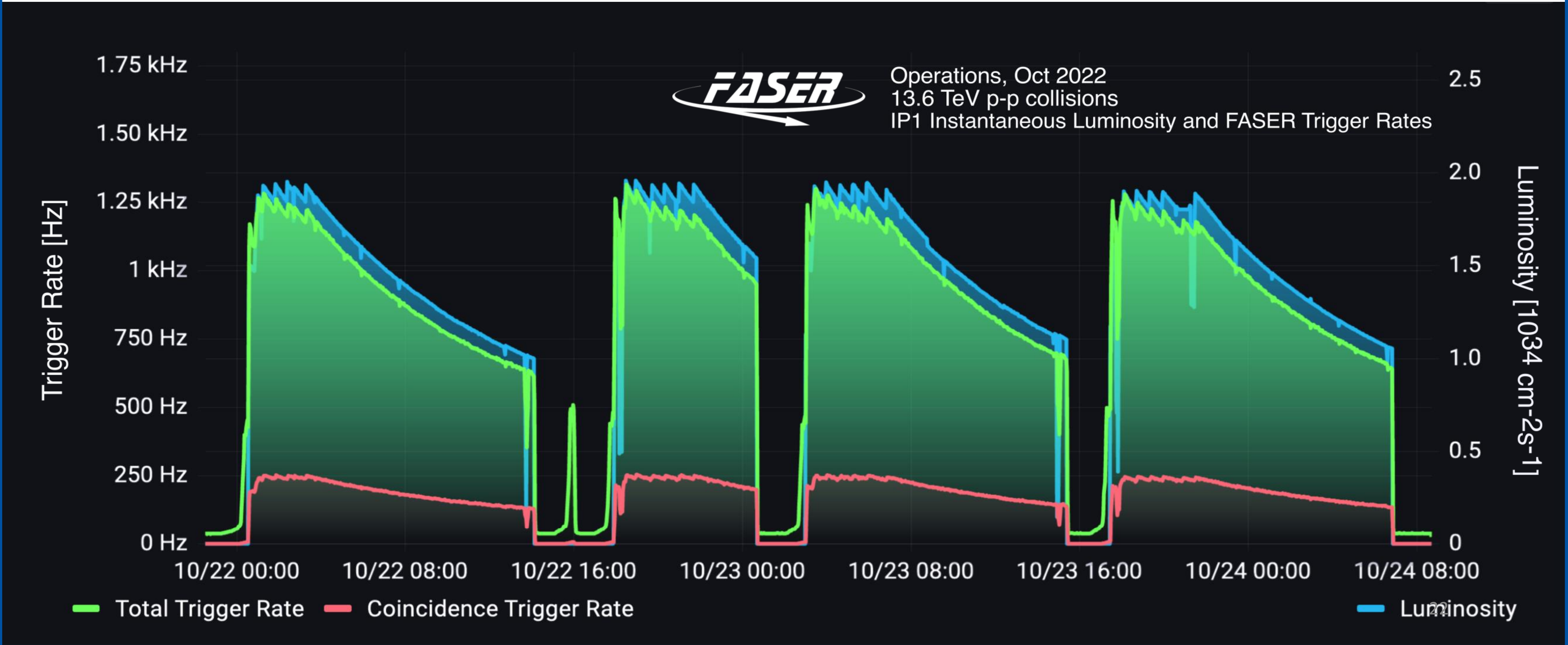
科研費 KAKENHI

- Additional thanks to:
  - LHC for the excellent performance in 2022
  - ATLAS for providing luminosity information
  - ATLAS for use of ATHENA s/w framework
  - ATLAS SCT for spare tracker modules
  - LHCb for spare ECAL modules
  - CERN FLUKA team for background sim
  - CERN PBC and technical infrastructure groups for excellent support during design construction and installation

Backup Slides

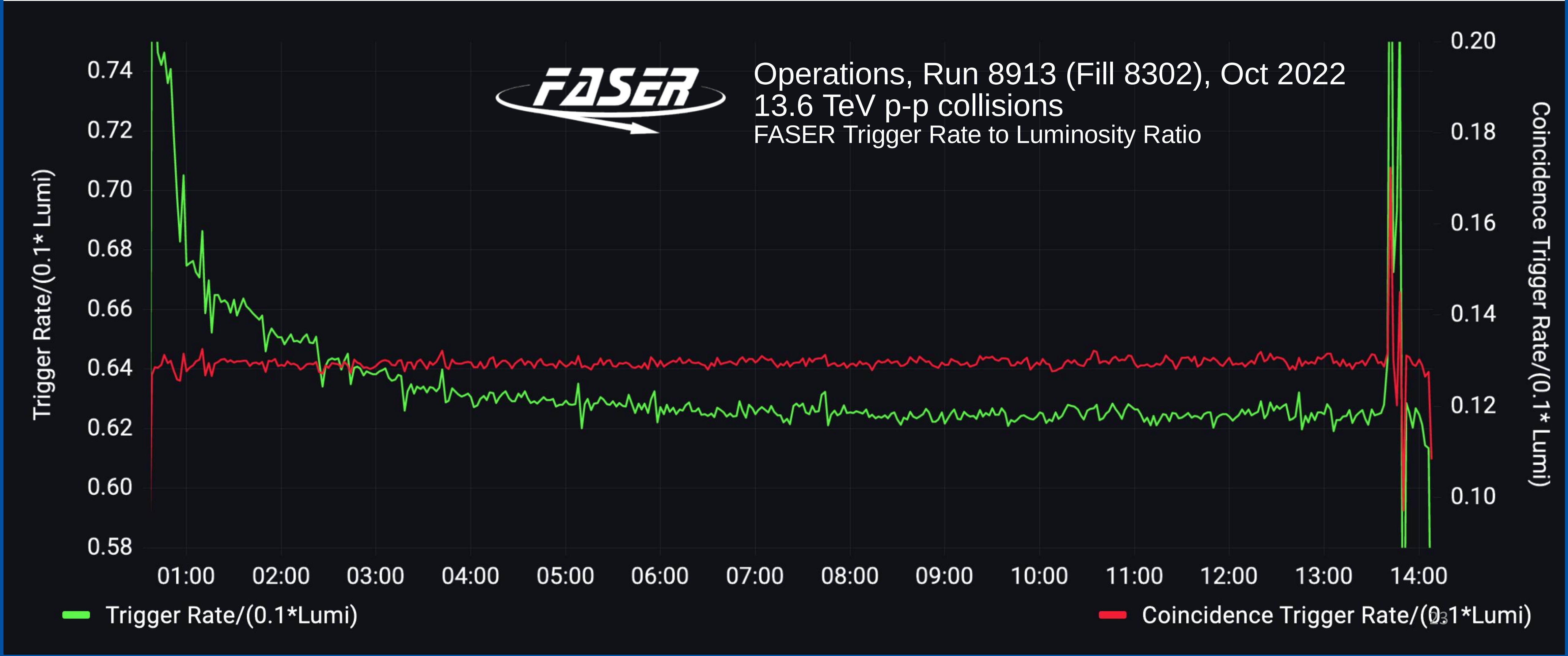
Detector Performance: Trigger + DAQ

- DAQ running smoothly up to 1.3 kHz with deadtime only 1.3%
  - Only two stops in data-taking due to DAQ failures



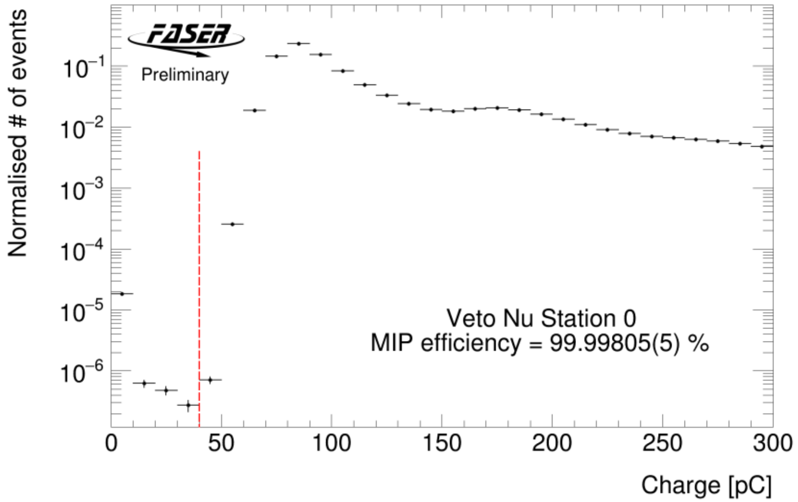
Detector Performance: Trigger + DAQ (2)

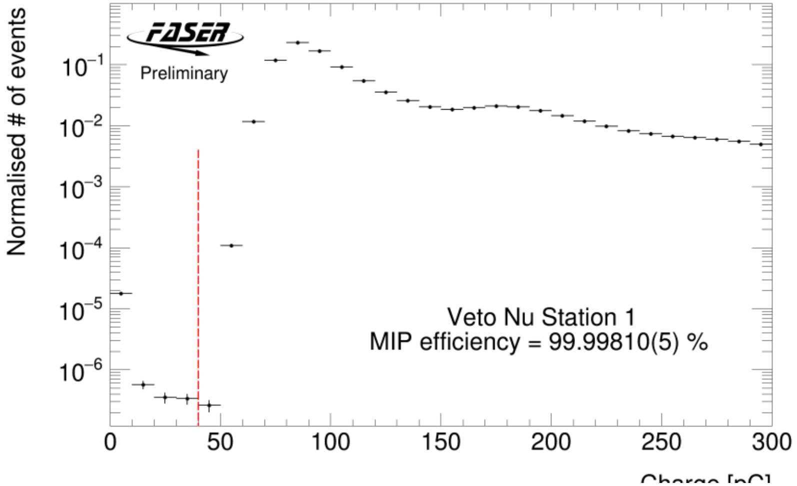
- Total trigger rate falls off faster than luminosity profile during run
  - But coincidence trigger rate flat wrt lumi

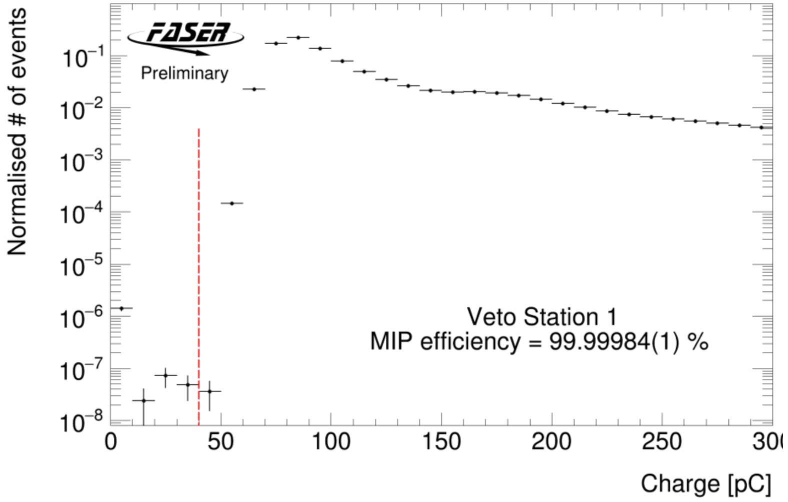


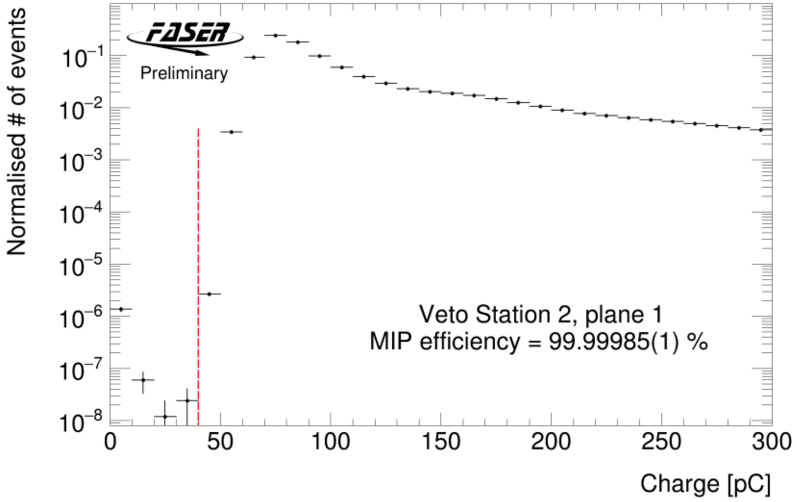
Detector Performance: Veto Scintillators

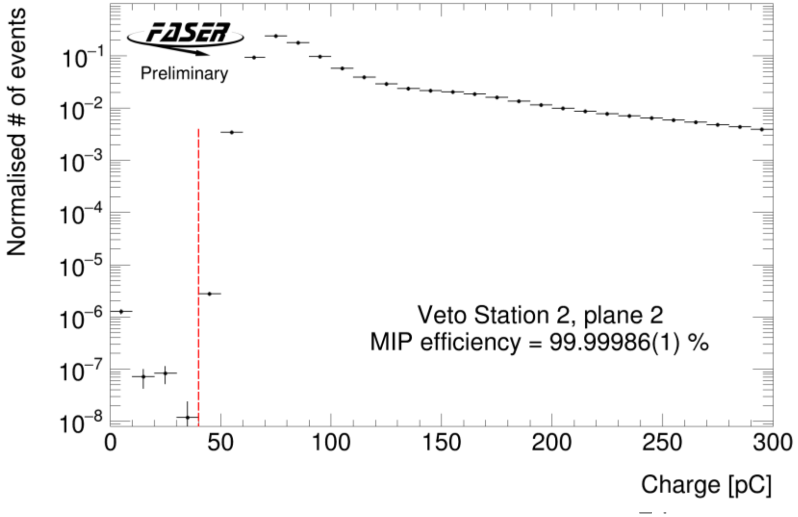
- Veto efficiency measured extrapolating tracks triggered by timing scint. to corresponding layer
  - No requirement on other scintillator layers
  - Layer efficiencies found to be uncorrelated
  - All layers found to have inefficiencies < 2 x 10^{-5}





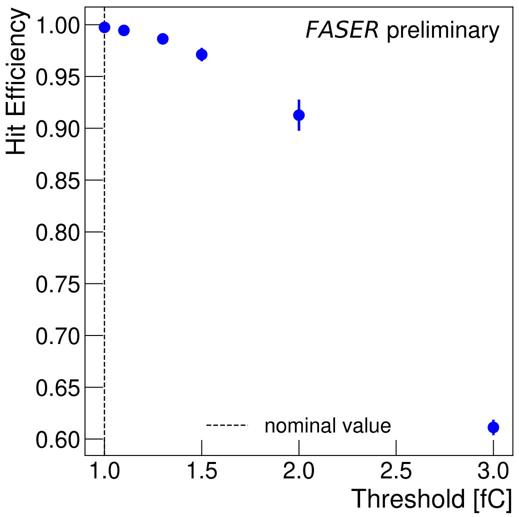


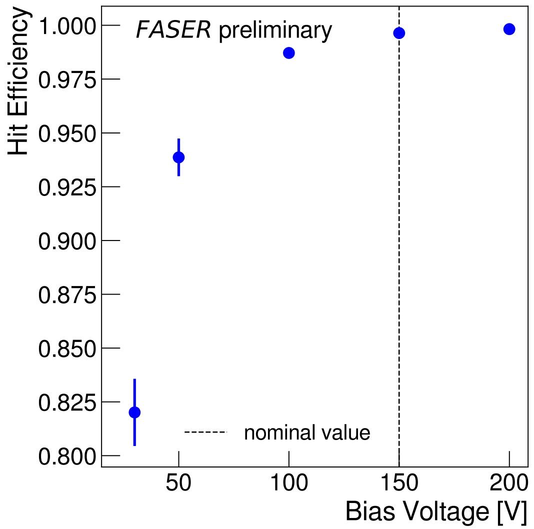




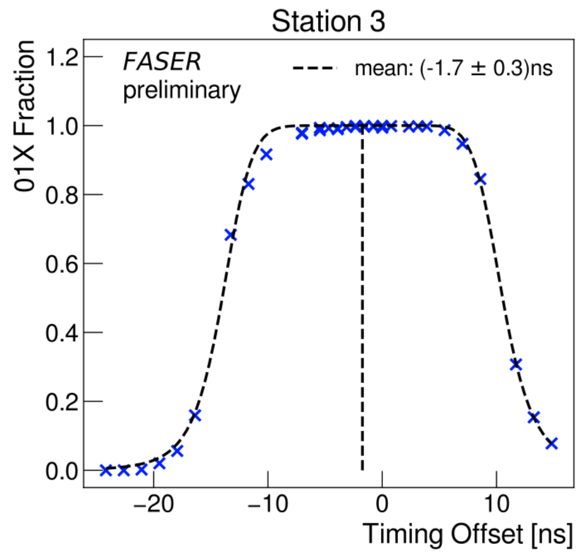
Detector Performance: Tracker

- Hit efficiency 99.64% @ 150 V bias and 1 fC threshold

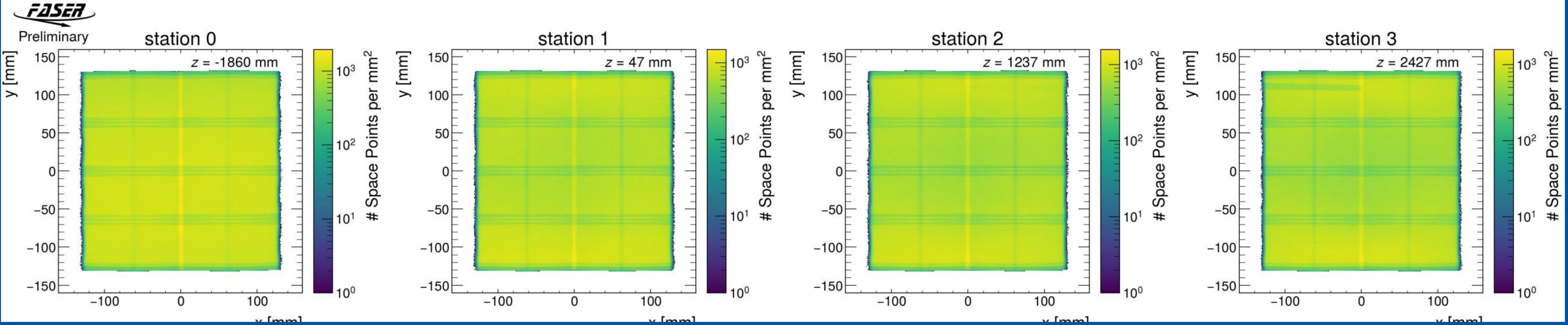




- Tracker fully timed in wrt LHC clock

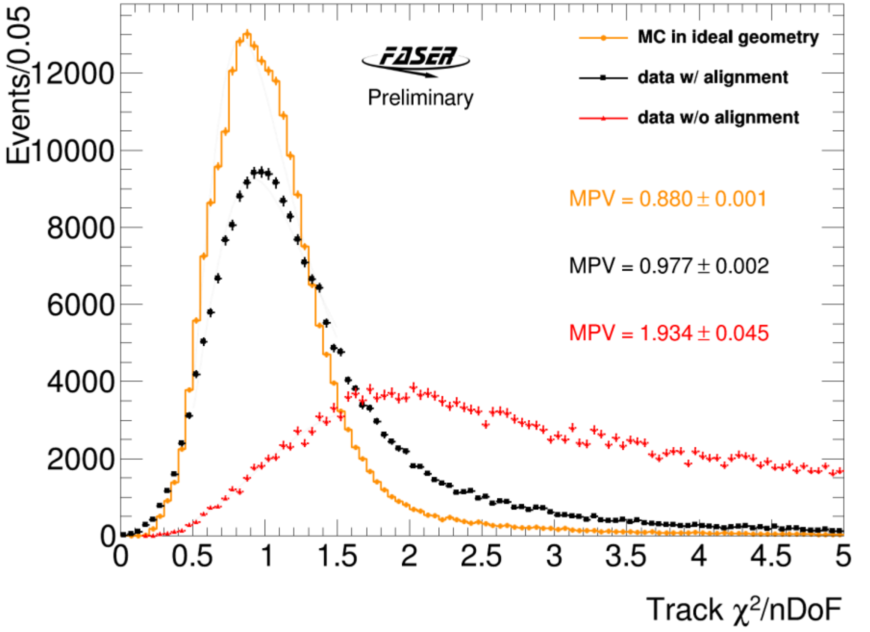


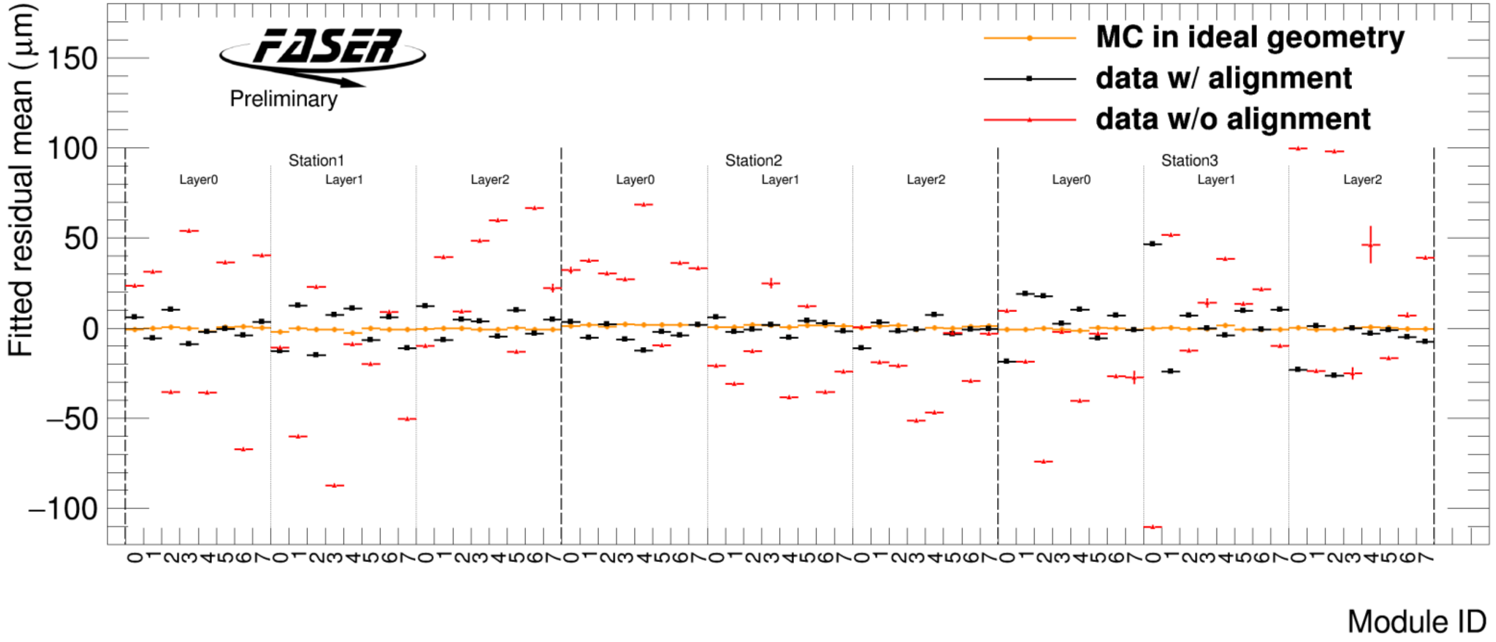
- <0.5% dead/noisy strips (inefficiency at edges expected)

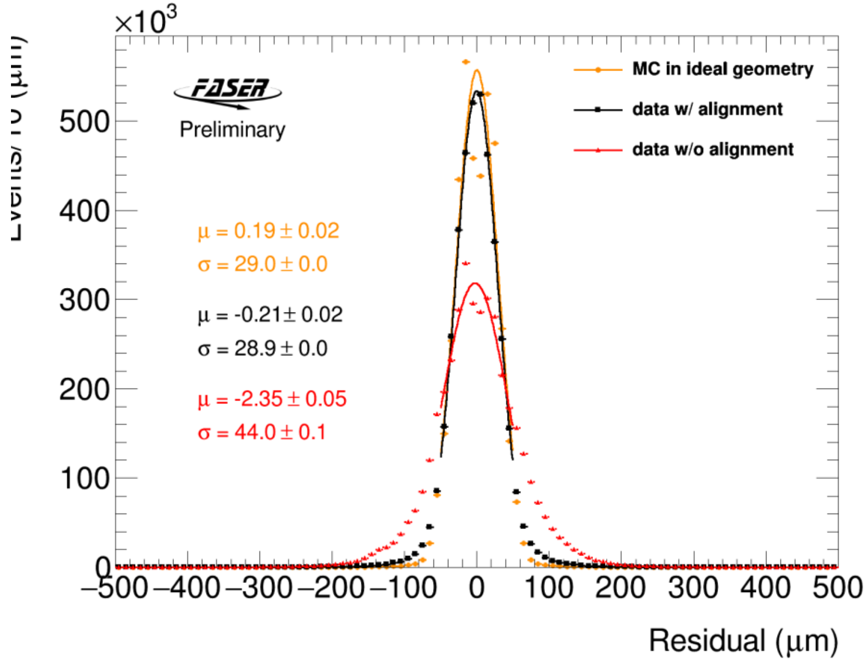


Detector Performance: Alignment

- Tracker aligned using iterative local χ^2 method
  - Validated using simulation with misalignment
- Currently only aligning two most sensitive parameters
  - Vertical shift and in-plane rotation
- Aligned residuals close to ideal geometry simulation

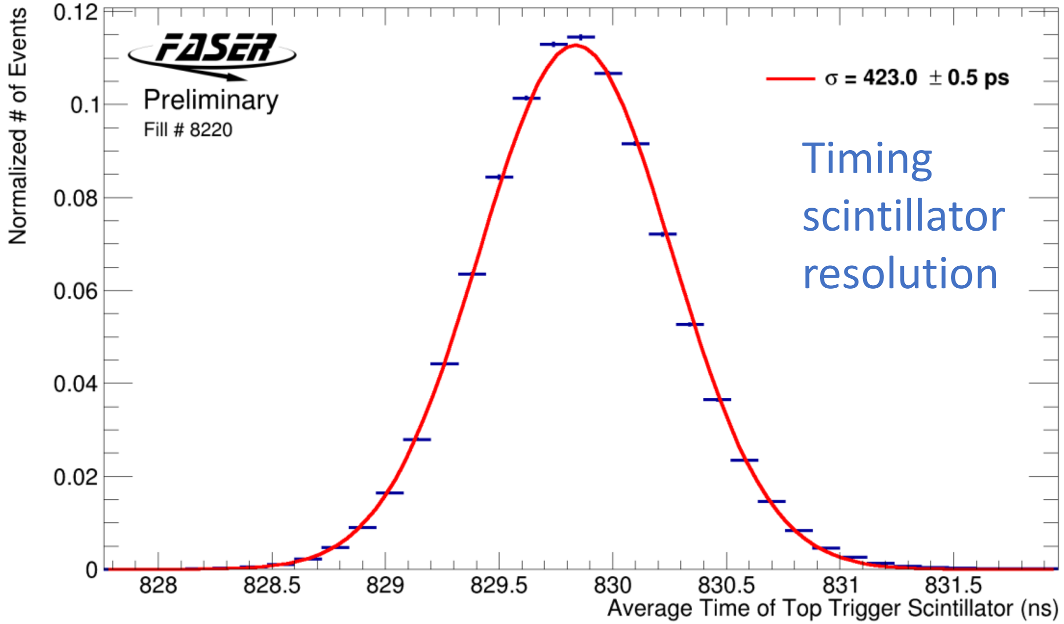




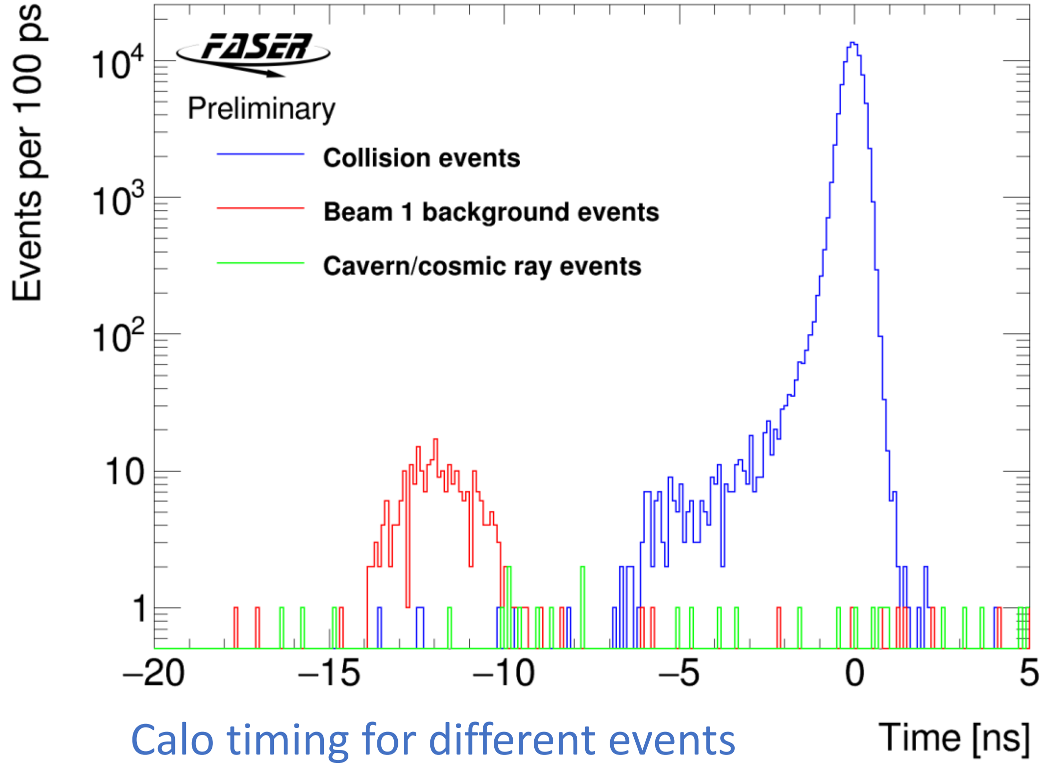


Detector Perf.: Timing and Calo

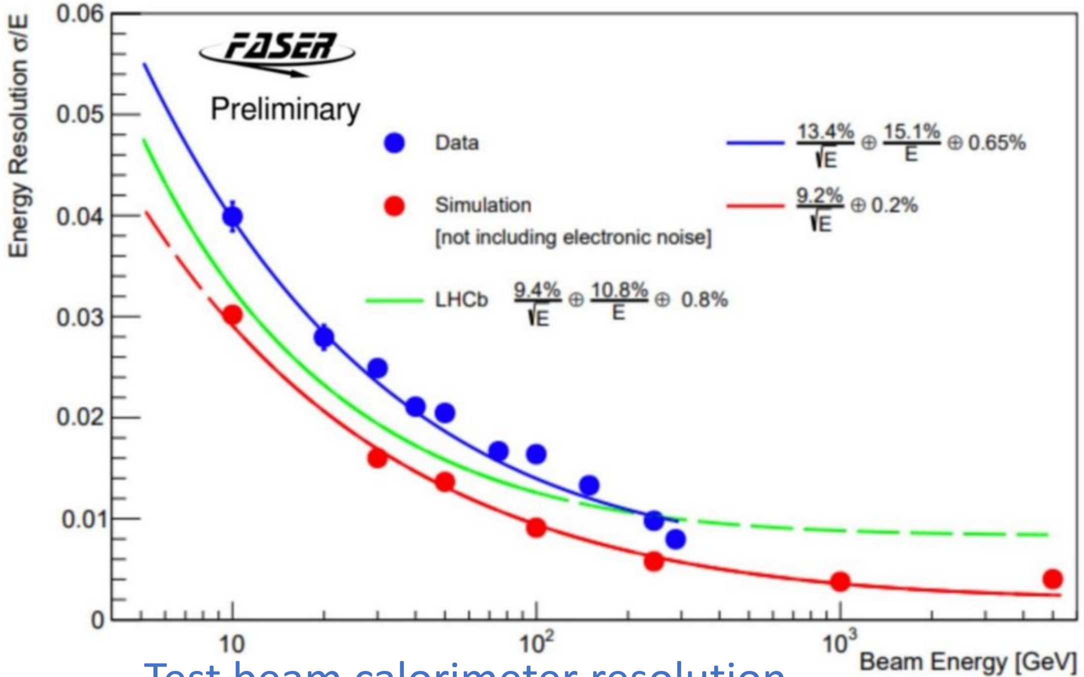
- Calorimeter resolution measured in test beam
  - Better than 1% at high energy
- Precision timing of both scintillator and calorimeter
  - Not used in current analyses



Timing scintillator resolution



Calo timing for different events

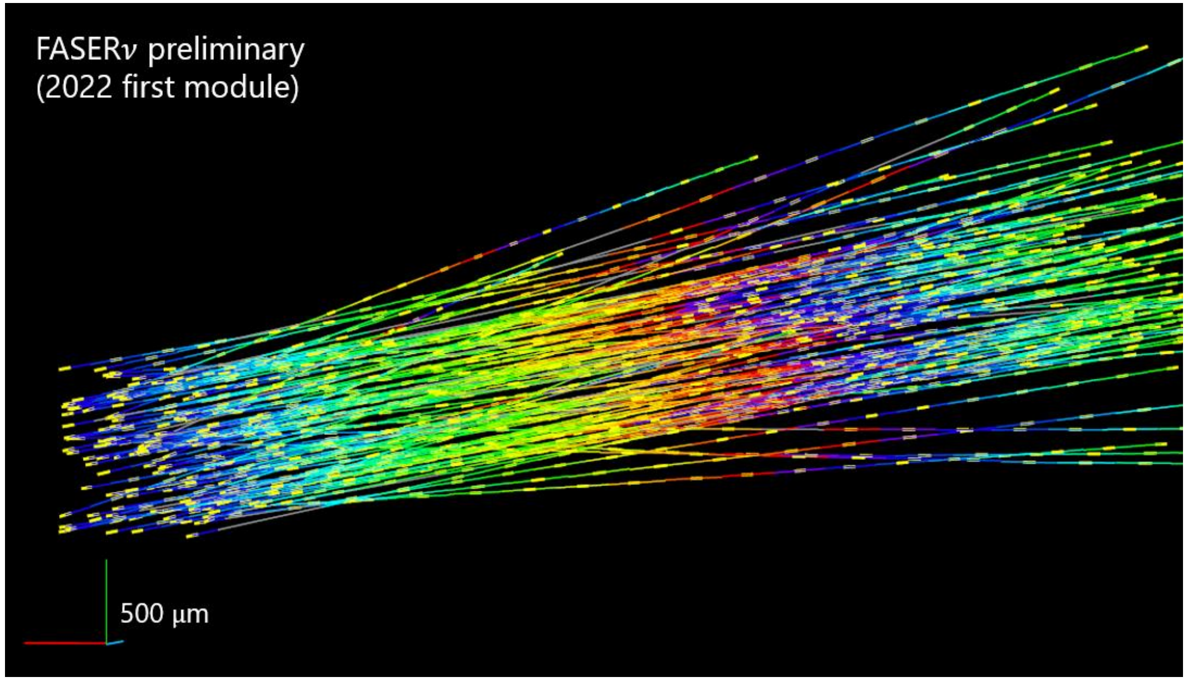


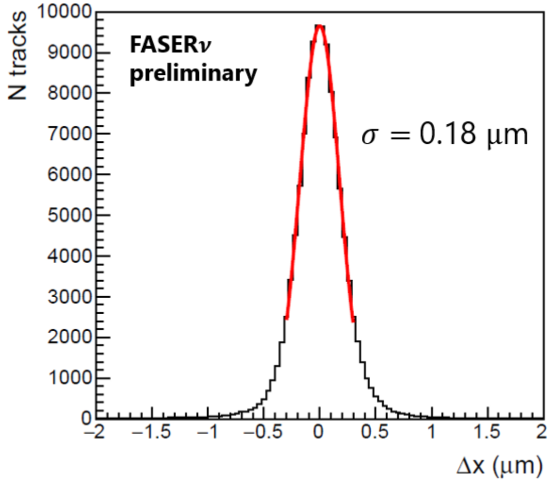
Test beam calorimeter resolution

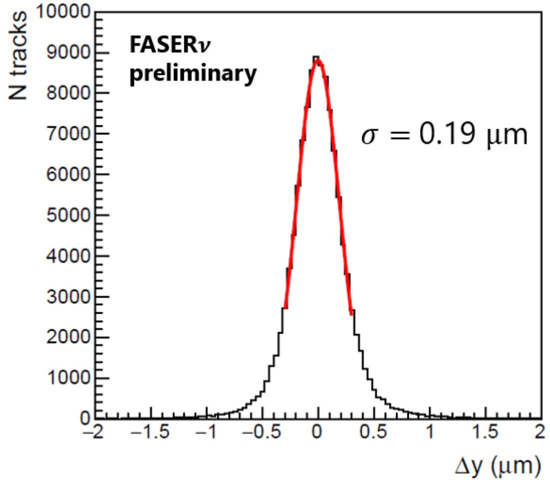
Detector Performance: Emulsion

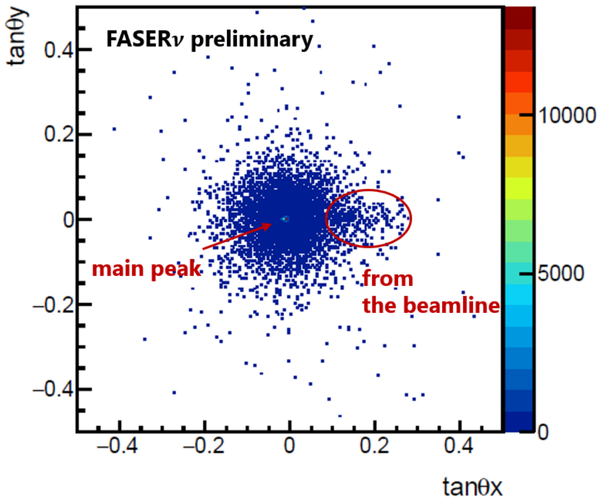
- Track multiplicity and angular distribution measured in initial partial FASERν emulsion
  - Consistent with FLUKA simulation

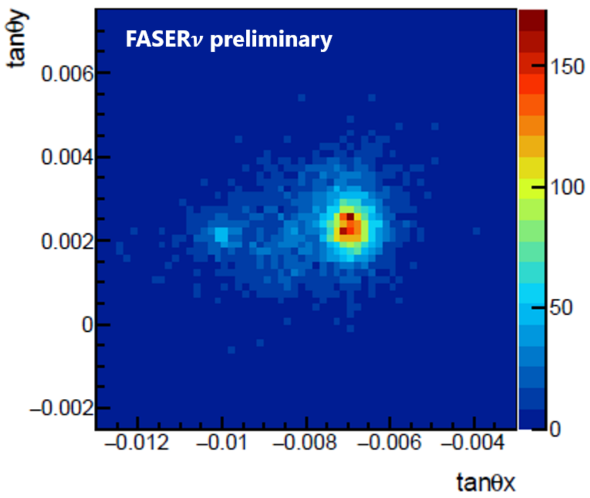
- Excellent hit resol (0.2 μm) after layer alignment



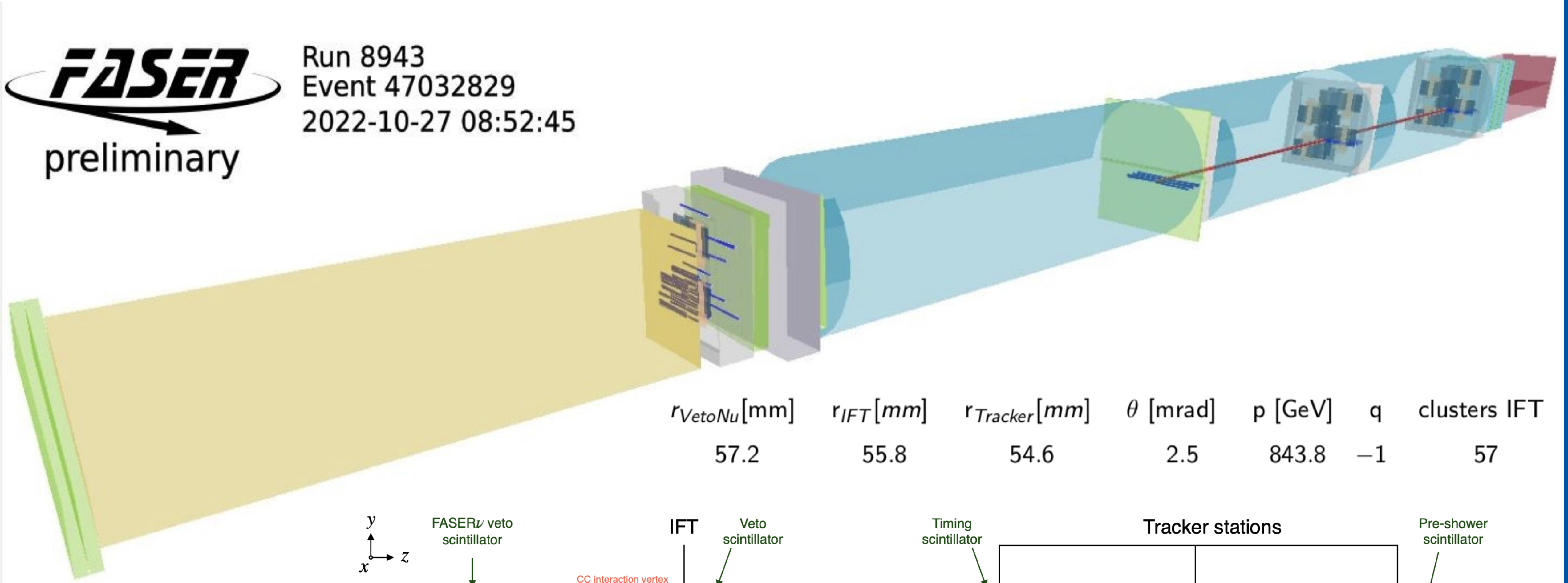








Neutrinos: Event Display



r_{VetoNu}[mm]	$r_{IFT}[mm]$	$r_{Tracker}[mm]$	θ [mrad]	p [GeV]	q	clusters IFT
57.2	55.8	54.6	2.5	843.8	−1	57

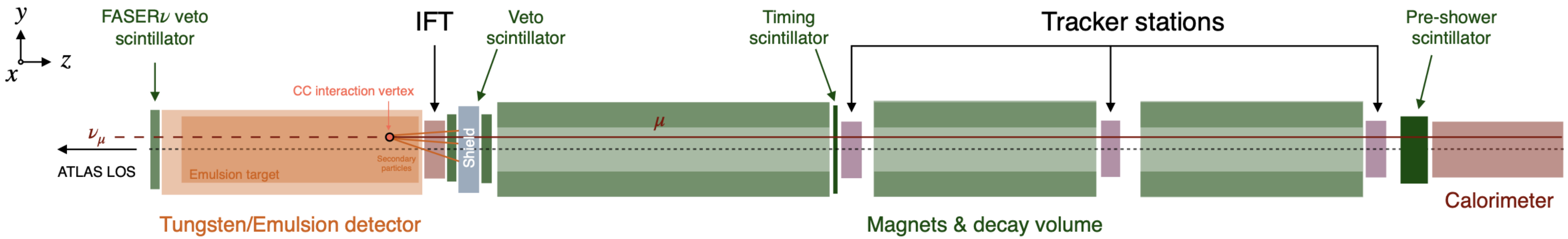
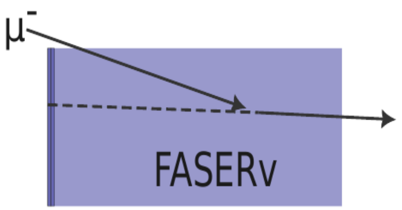
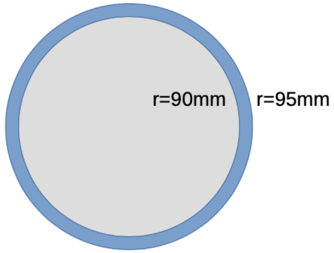


FIG. 1. Illustration of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion target.

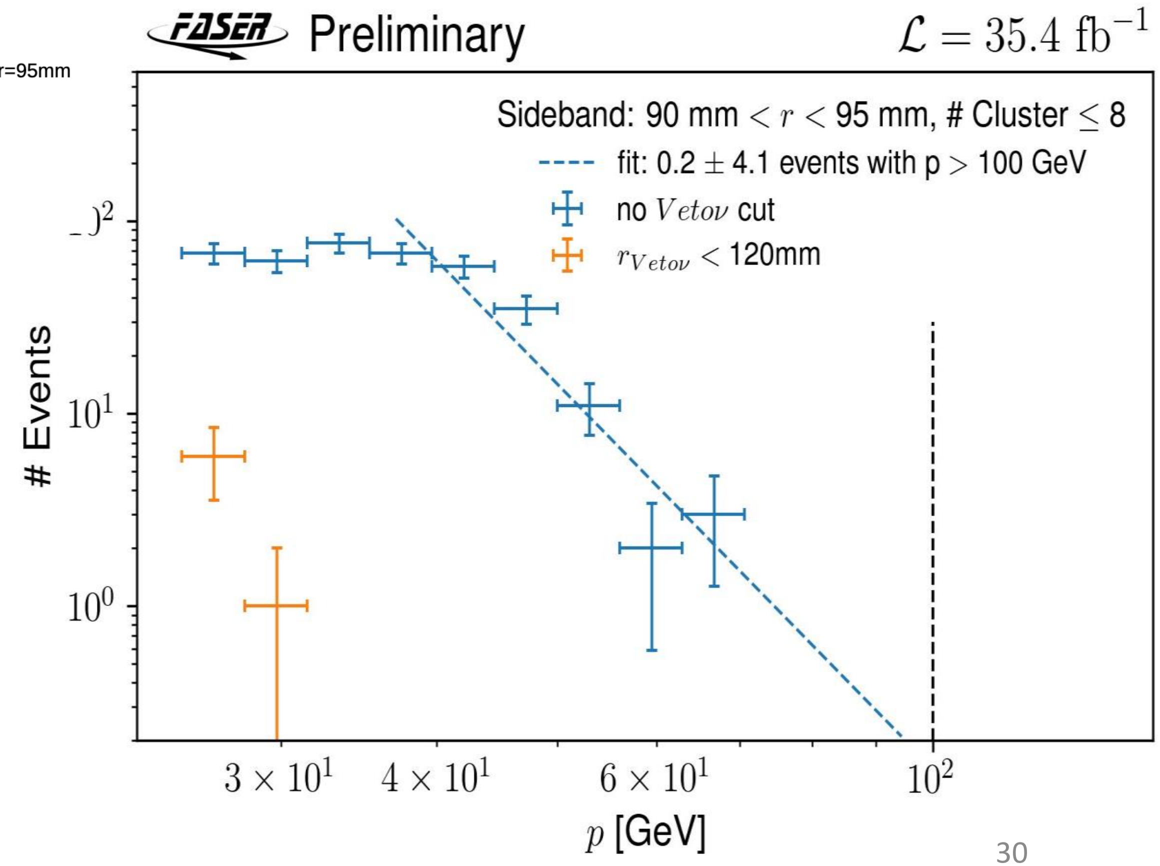
Neutrinos: Geometric Background



- Measure geometric background by counting # events in SB and scale to SR
- SB defined to enhance muons missing FASERν veto that still give a track in the spectrometer
  - Single IFT segment in 90 < r < 95 mm anulus
  - Loosened momentum requirement
  - No FASERν veto radius requirement
  - Negligible neutrino background



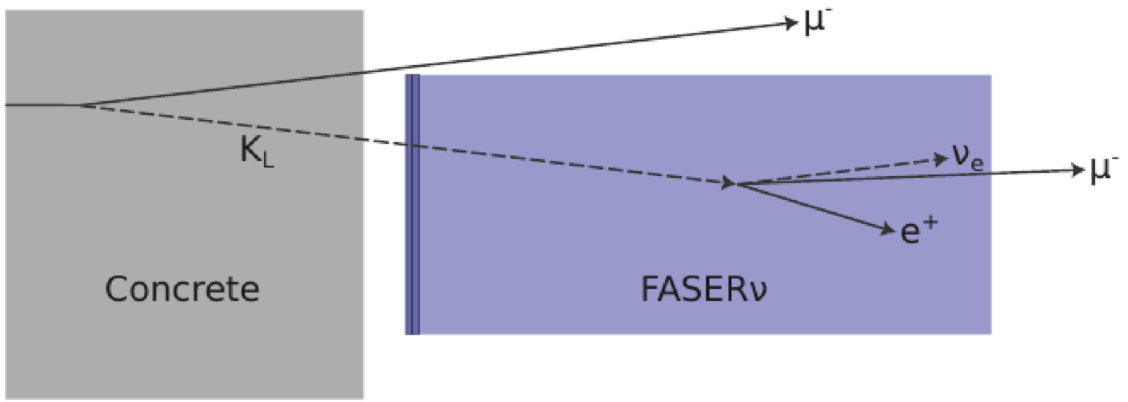
- Fit mom. to extrapolate to p > 100 GeV
- Scale to rate of events with r_{VetoNu} < 120 mm
  - 0 events so use 5.9 events as 3σ upper limit
- Scale from anulus to full acceptance
  - Using large angle muon simulation
- Expect 0.08 ± 1.83 events



Neutrinos: Neutral Hadron Background

- Simulated 10^9 μ^+ and μ^- events
  - Start from FLUKA Spectra
  - G4 propagation through last 8 m of rock
  - Number of hadrons with $p > 100$ GeV reaching FASER ≈ 300.

- Estimate fraction of these passing event selection
  - Simulate kaons (Ks/Kl) and neutrons with $p > 100$ GeV following expected spectra
  - Most are absorbed in tungsten with no high-momentum track → only small fraction pass



- Scale neutral hadrons produced by muons reaching FASER by fraction passing selection
  - Predicts N = 0.11 ± 0.06 events

Neutrinos: fit

- Fit to events with 0, 1 or 2 front veto hits
  - Splitting those were 1 hit is in 1st/2nd layer
- Construct likelihood as product of Poissions
  - With additional 3 Gaussian constraints for Neutral hadron background, Geometric

$$\mathcal{L} = \prod_{i}^{4} \mathcal{P}(n_i | \nu_i) \cdot \prod_{j}^{3} \mathcal{G}_j$$

obs exp

Inefficiencies:
6 / 9 x 10^{-8}

1 - p1 = 99.999994(3)%
1 - p2 = 99.999991(4)%

- Determine number in each category
  - Along with inefficiencies of 2 forward vetos, which are found to be close to expected vals.

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.

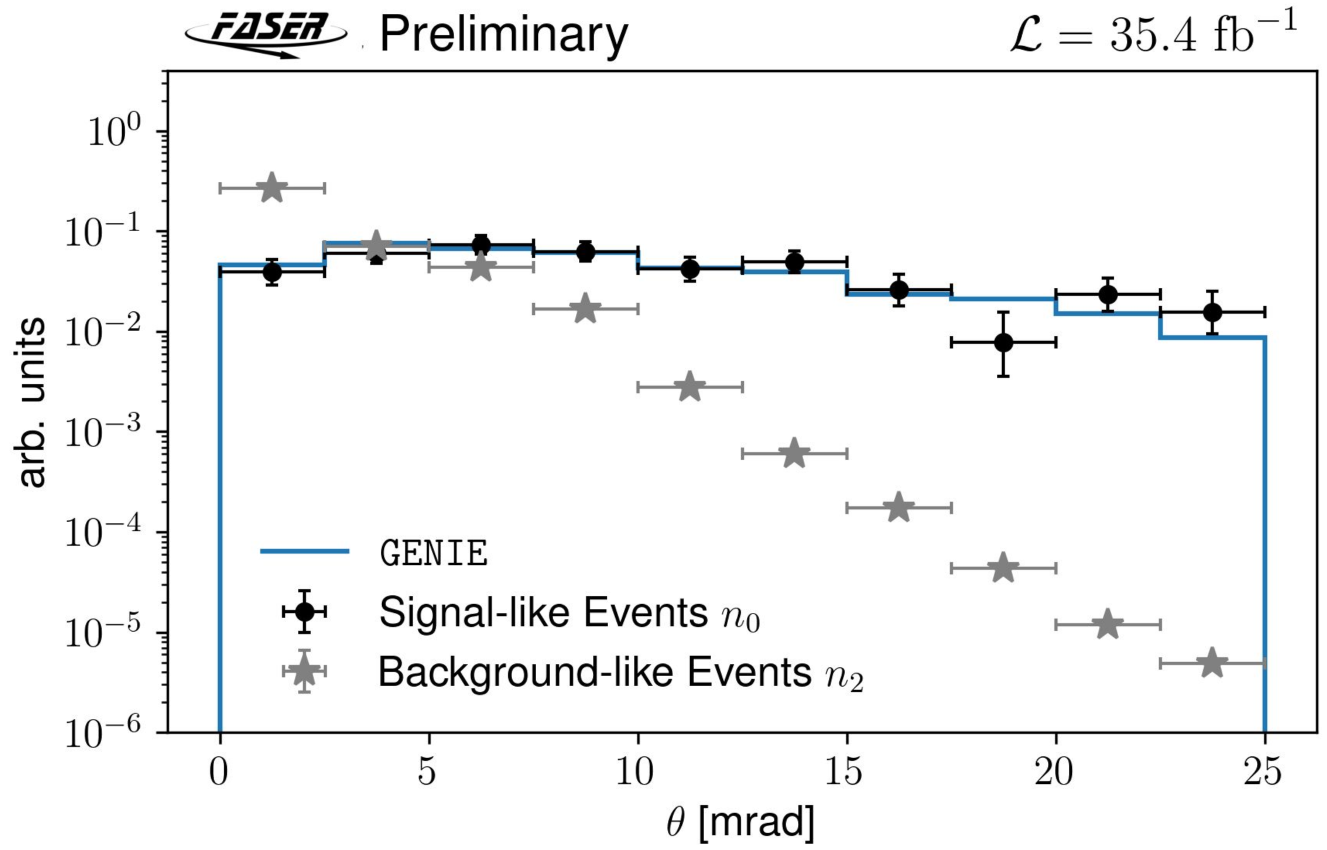
n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

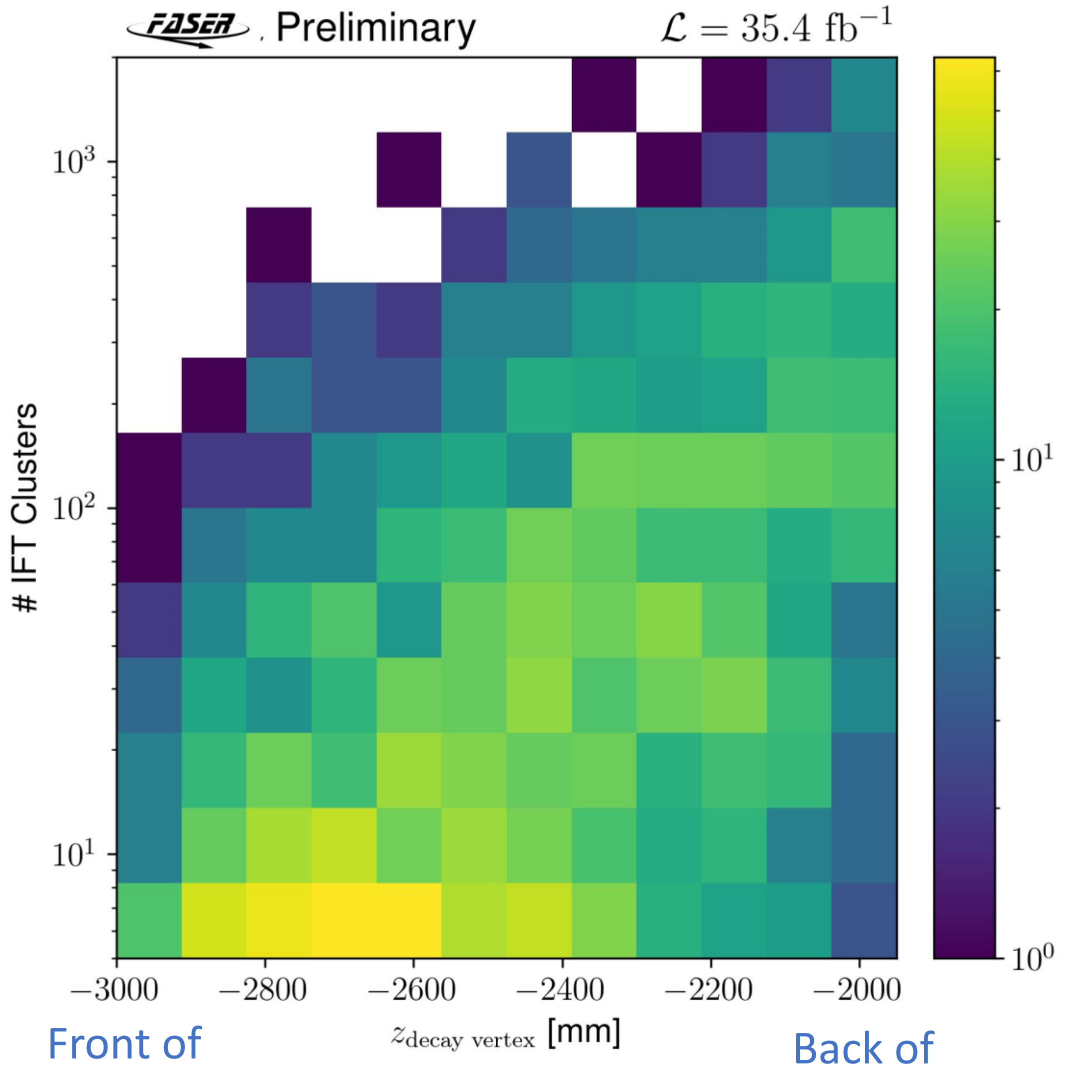
n_2: Events for which both layers observe more than 40 pC of charge.

Category	Events	Expectation
n_0	153	$\nu_\nu + \nu_b \cdot p_1 \cdot p_2 + \nu_{\text{had}} + \nu_{\text{geo}} \cdot \eta_{\text{geo}}$
n_{10}	4	$\nu_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$\nu_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$\nu_b \cdot (1 - p_1) \cdot (1 - p_2)$

Neutrinos: Additional Distributions

- Number of clusters in IFT depends on interaction point
  - Further forward interactions have less clusters
- Neutrino tracks have larger angular range
  - Compared to n_2 background events



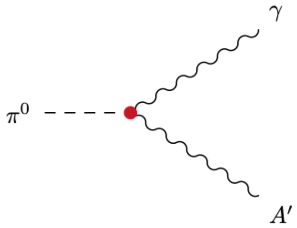


Front of emulsion

Back of emulsion

Dark Photon Search

- Several new physics models propose a hidden sector
  - With a mediator acting as a portal to the SM
- One of best motivated is extra U(1) symmetry
  - Gives rise to additional vector field: dark photon (A'), weakly coupling to SM via kinetic mixing (ε) with SM γ
- MeV A's produced mainly in meson decays at LHC



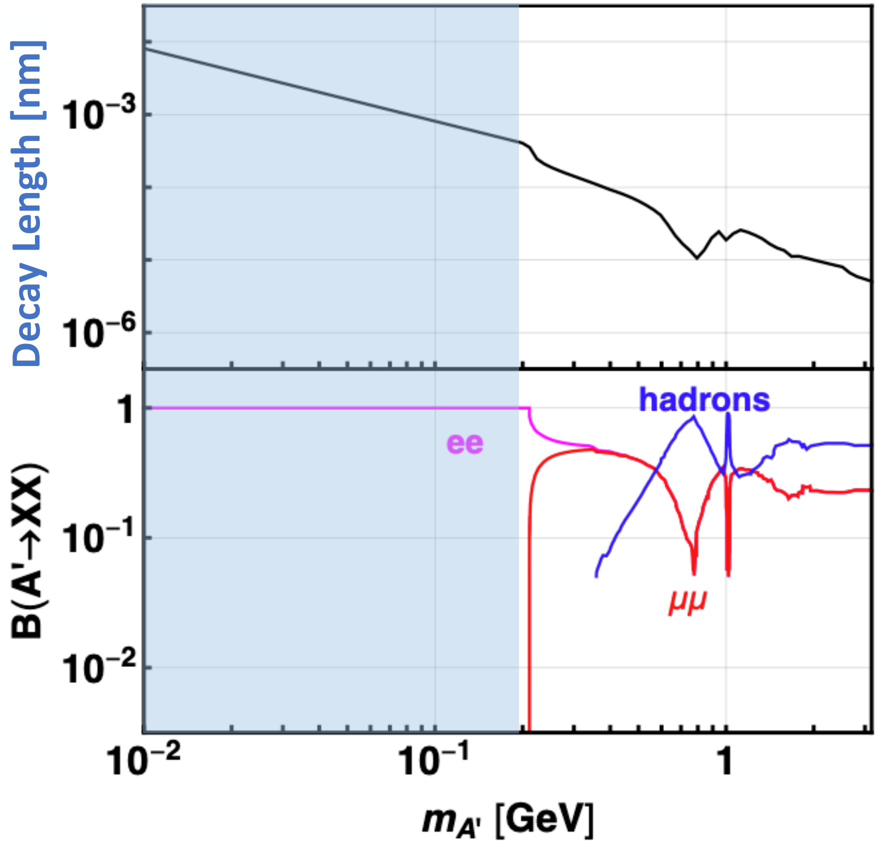
$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- FASER targets small ε, where A' has long decay length

$$\bar{d} = c\,\frac{1}{\Gamma_{A'}}\,\gamma_{A'}\beta_{A'} \approx (80\text{ m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right]$$

  - Below $2m_\mu$ A' has 100% decay to e^+e^- pair

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

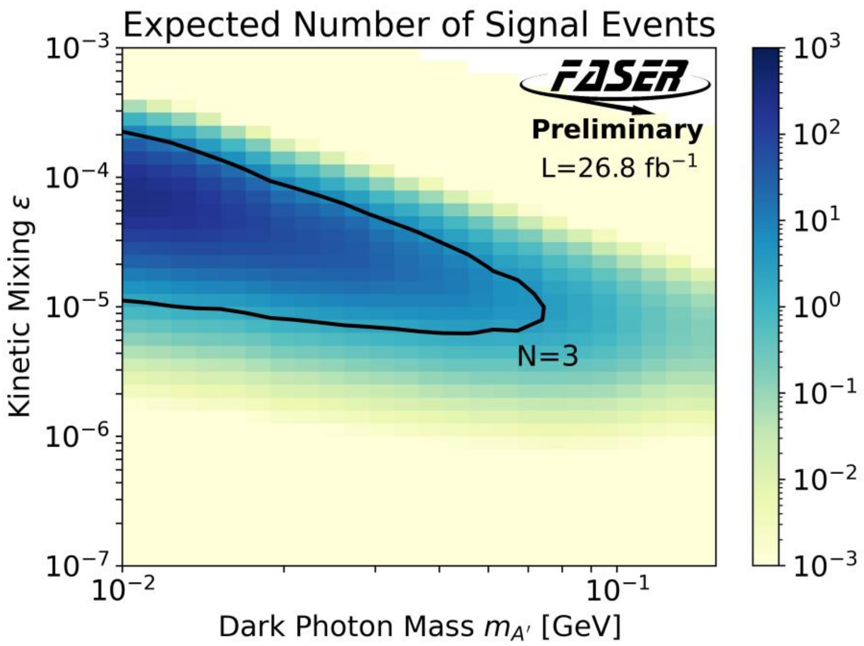


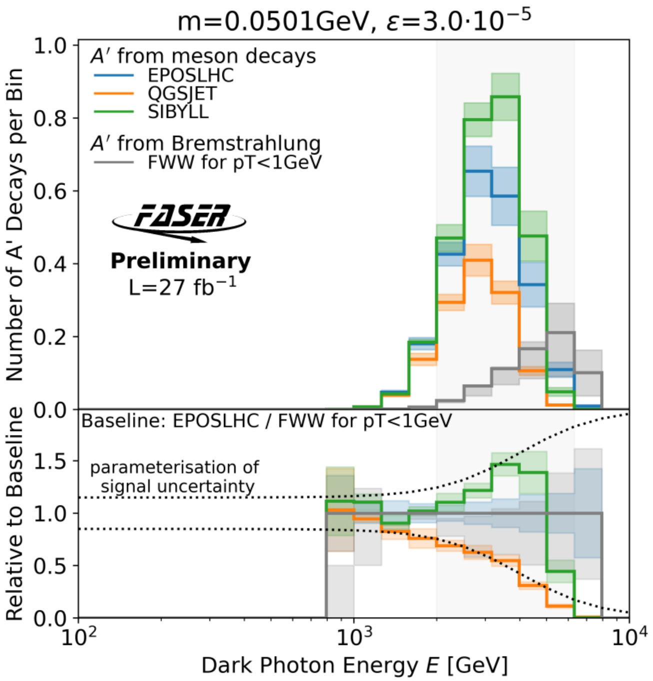
Dark Photon Signal

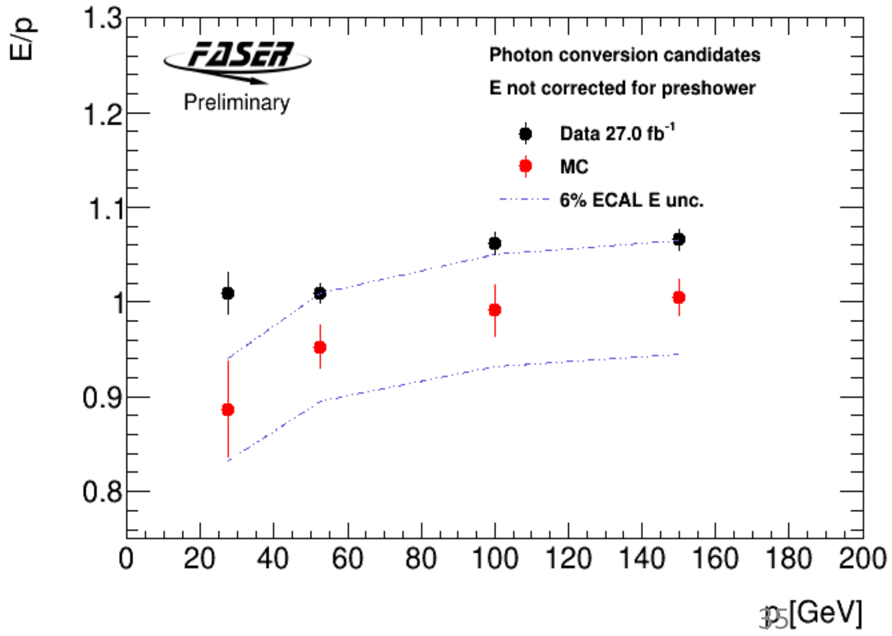
- A′ → e^+e^- decays in FASER volume simulated with FORESEE
  - π^0 and η via EPOS-LHC generator
  - Subdominant dark bremstrahlung via FWW
- Generator uncertainty from difference to QGSJET/SIBYLL
  - Parameterised based on A′ energy

$$\frac{\Delta N}{N} = \frac{0.15 + (E_{A'}/4\ \mathrm{TeV})^3}{1 + (E_{A'}/4\ \mathrm{TeV})^3}$$

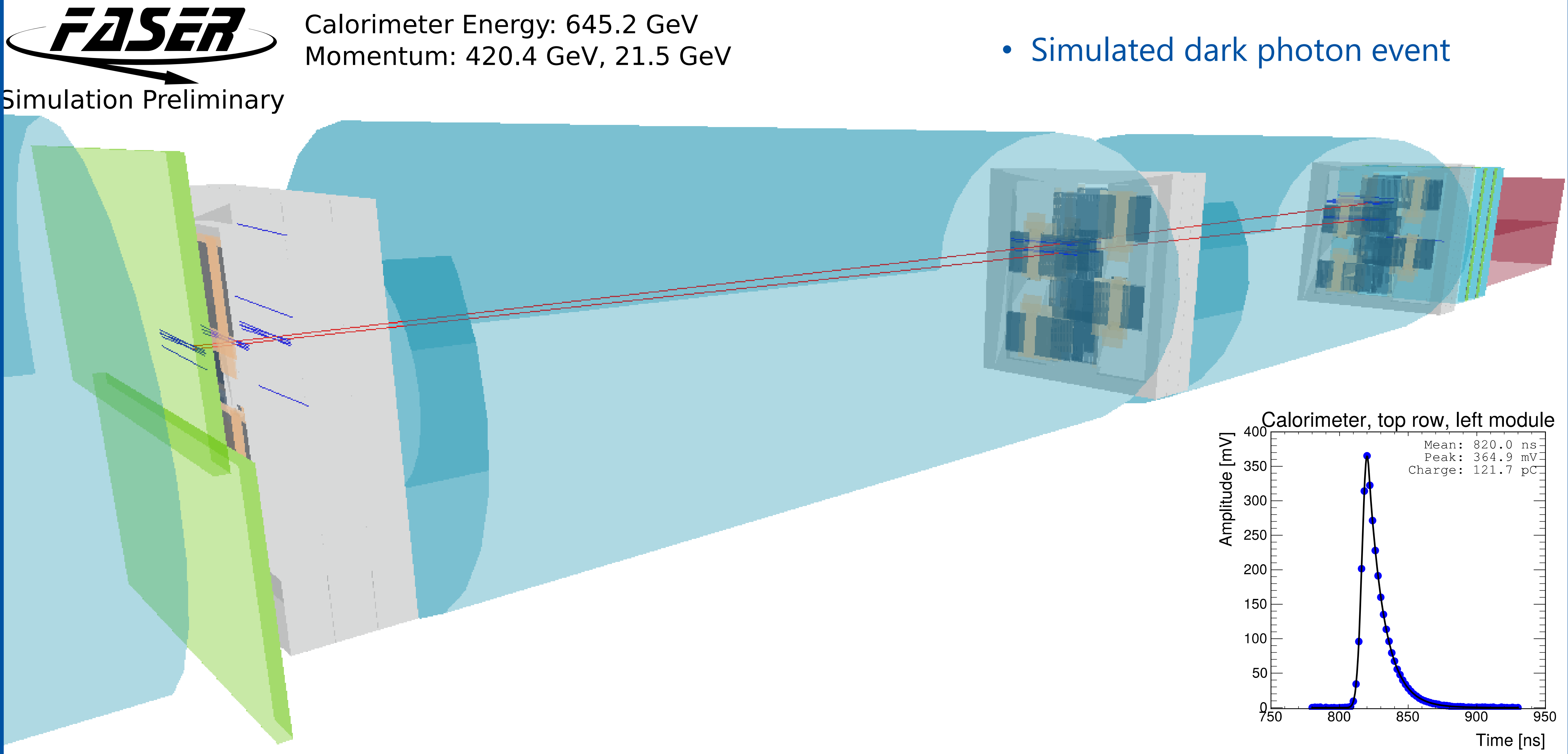
- Experimental uncertainties
  - Tracking efficiency
    - 15% for close-by tracks
    - Estimated from overlay
  - Calo E scale
    - 6% at 500 GeV
    - Cross-checked with E/p
  - Momentum scale/resol.
    - 5% each
    - Negligible effect







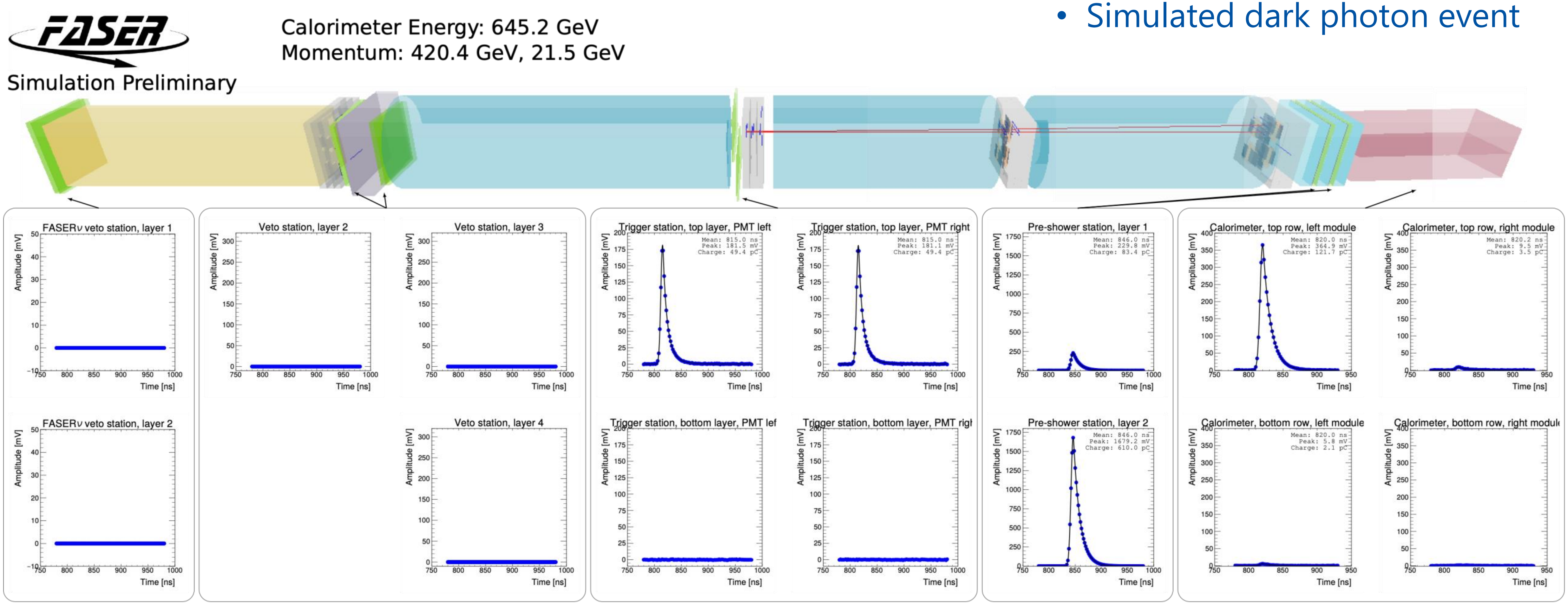
Dark Photon: Event Display (1)



- Simulated dark photon event

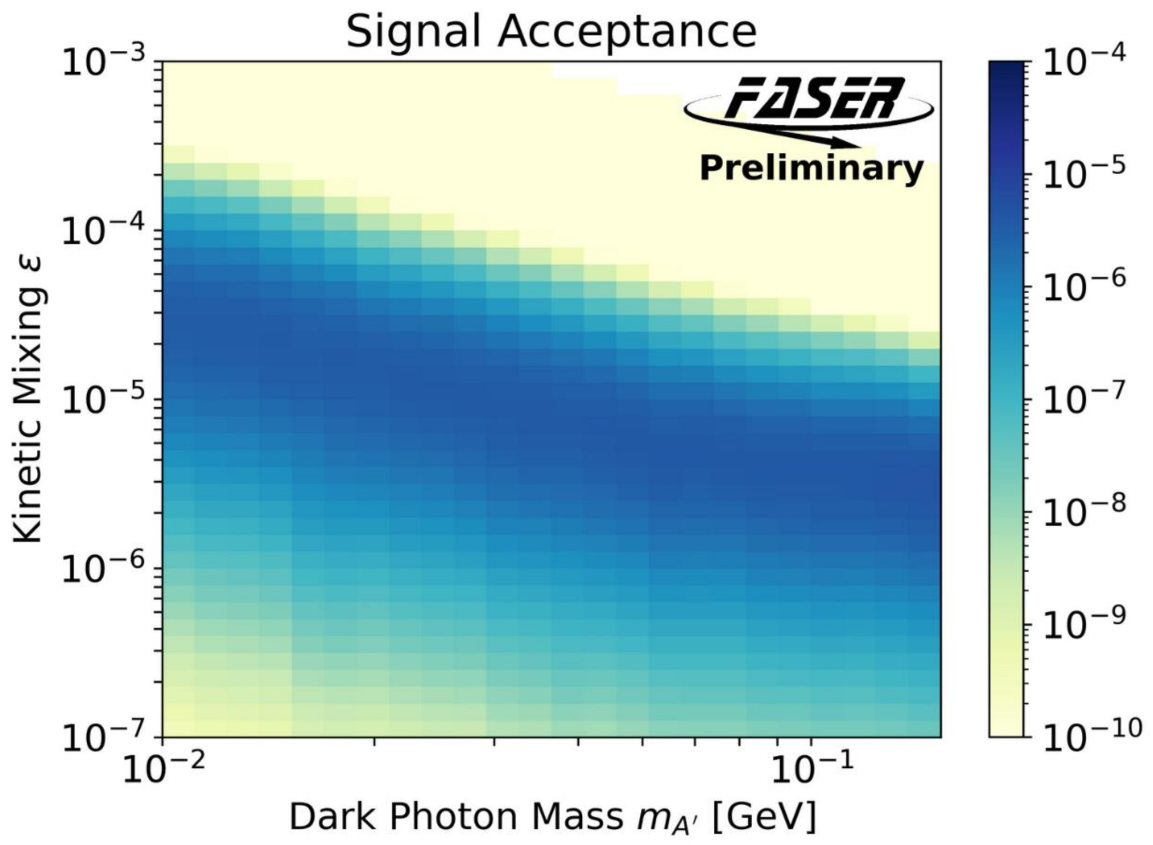
Dark Photon: Event Display (2)

- Simulated dark photon event



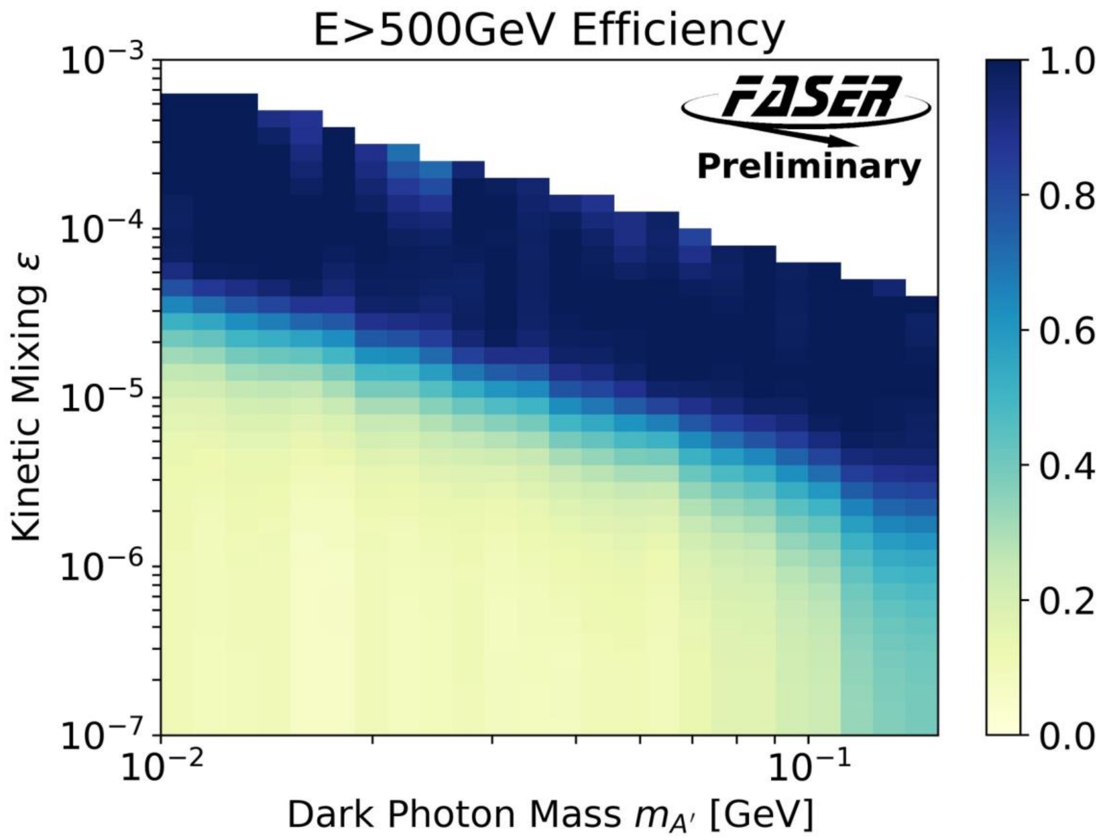
Dark Photon: Signal Acceptance x Efficiency

- Signal acceptance for A' produced in IP1
  - And decaying in FASER decay volume



- Note: FASER solid angle coverage only ~10^{-8}

- Efficiency of calorimeter E > 500 GeV
  - For A' decaying in FASER decay volume

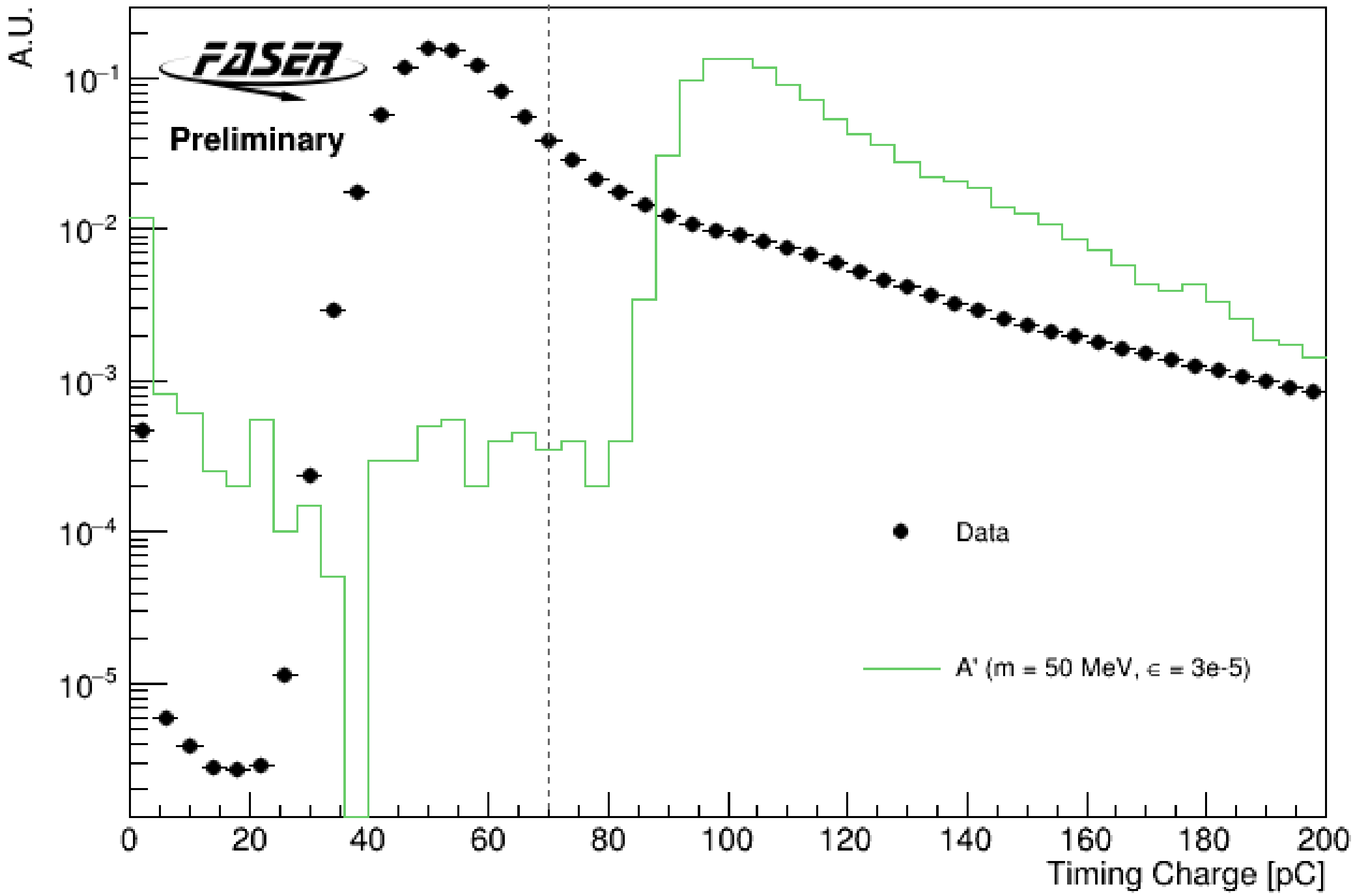


Efficiency of other selections ~40%

Dark Photon: Timing Scintillator Selection

Timing cut of 70 pC is ~100% efficiency for signal

- Supresses a large fraction of data, which are predominantly single-track events



Dark Photon: Cut Flow

Efficiency of analysis selection for data and example signal

Note the data was preselected to have ≥ 1 track (no quality cuts) in the event

Overall signal efficiency ≈ 40 %

While reducing background to 0

Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\text{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good tracks	0	0.000%	44.5	46.6%
Track radius < 95 mm	0	0.000%	40.4	42.3%
Calo energy > 500 GeV	0	0.000%	39.7	41.6%

Dark Photon: Neutral Hadron Background

- Select 3-track events where muon produces two other particles
  - A minority of these are neutral hadrons (Ks) + continuing muon (assumed to have highest momentum)
- Look at number of 3 track events with 100 < Ecalo < 500 GeV
  - Compared to number of 2 track events (muon missed) that don't pass the veto with Ecalo < 100 GeV
- Use this to estimate # events with Ecalo > 500 GeV where muon is not seen
  - Assuming E spectrum of neutral hadron is same whether muon is seen or not
- However, most of these are γ conversions in veto material that would fail event selection
  - Removed by E/p < 0.5 for two-track system (i.e. without muon)
  - But this biases Ecalo → use simulated two-track p_Z to estimate events with Ecalo > 100 or 500 GeV
- From 3-track events in data strong evidence that most Ks decay in FASERv and fire veto
  - Hence scale the neutral hardon events with Ecal > 500 GeV by fraction of 3-track events decaying after veto → $(2.2 \pm 3.1) \times 10^{-4}$

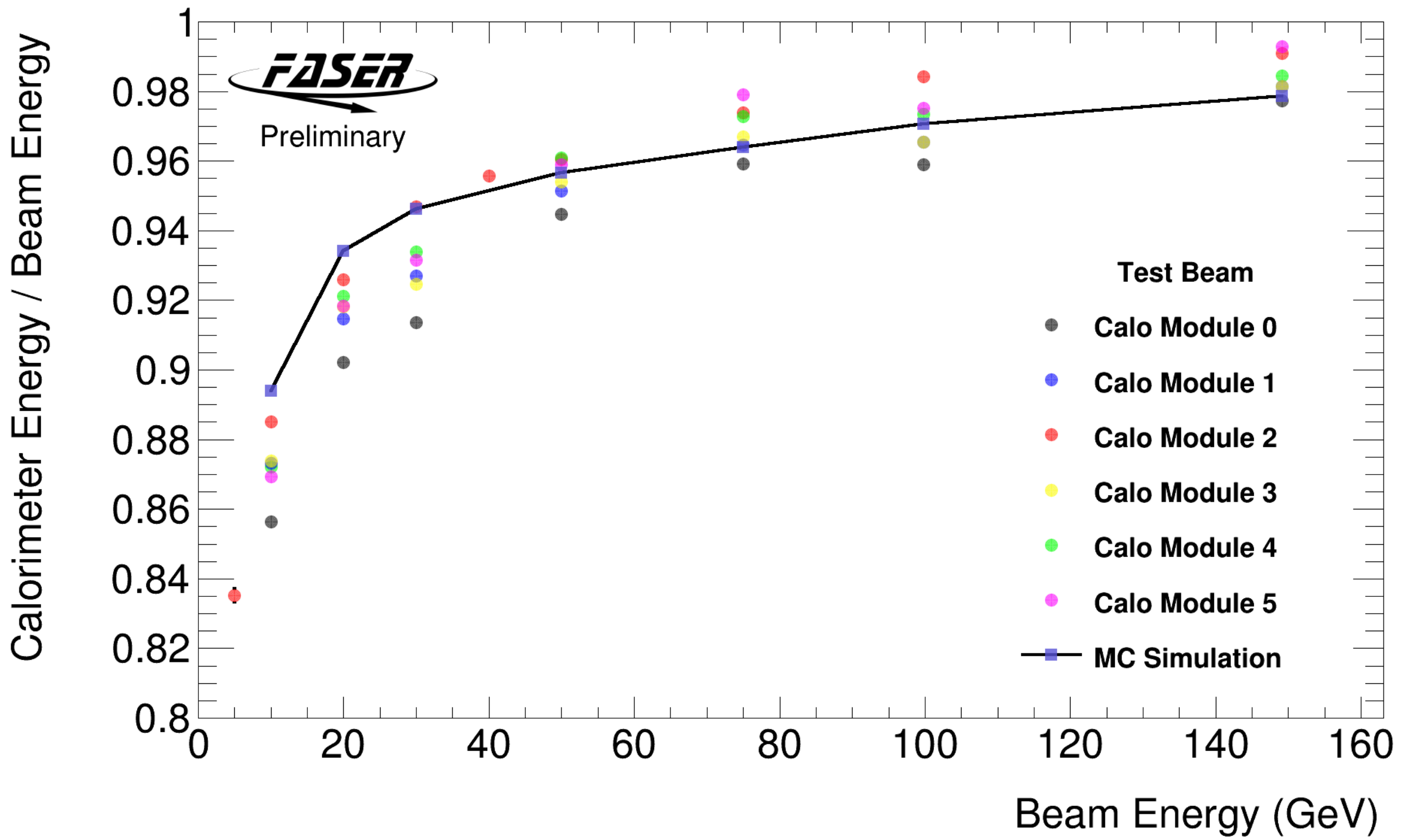
Dark Photon: Systematic Uncertainties Summary

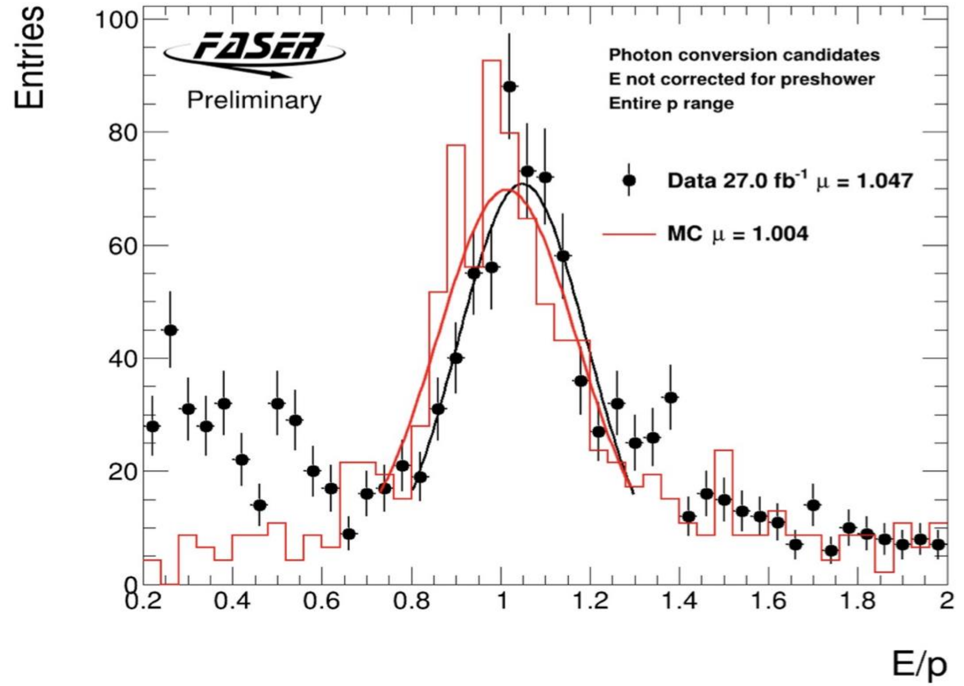
- Complete list of systematic uncertainties and their impact on the signal yield
  - Numbers in parenthesis are the effect on signal in previous unexcluded FASER reach

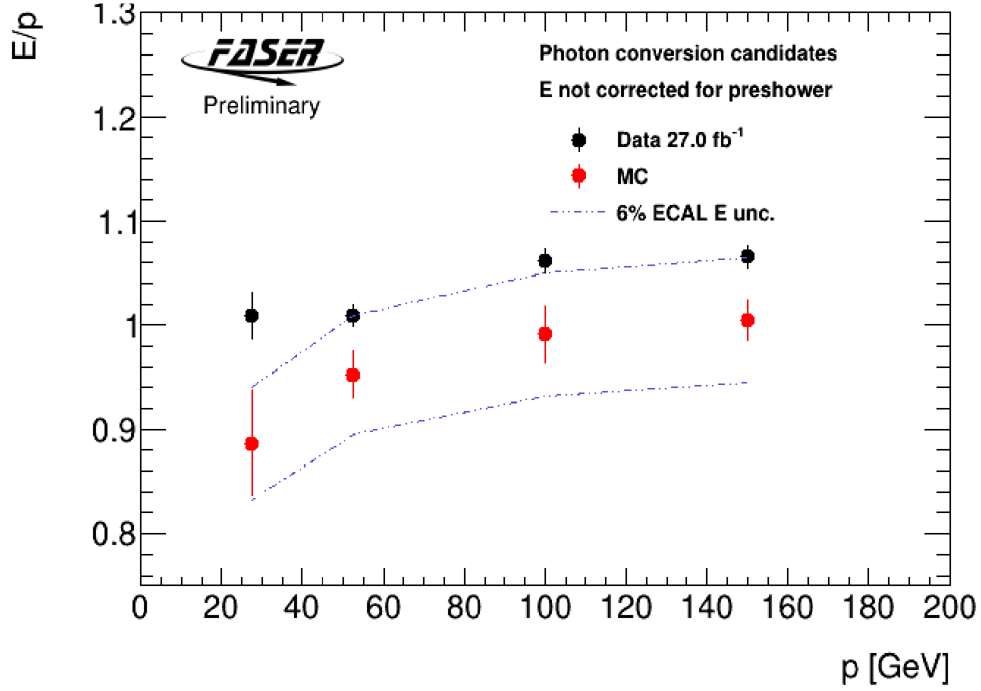
Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	$< 0.5\%$
Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	15%	15%
Calorimetry		
Calo E scale	6%	0-8% ($< 1\%$)

Dark Photon: Calo Energy Scale

- Calorimeter energy scale and uncertainty evaluated based on test beam data and in-situ MIP calibration
  - Validated using conversion events (μ with e^+e^- pair)
  - E/p in data and MC agrees within 6%

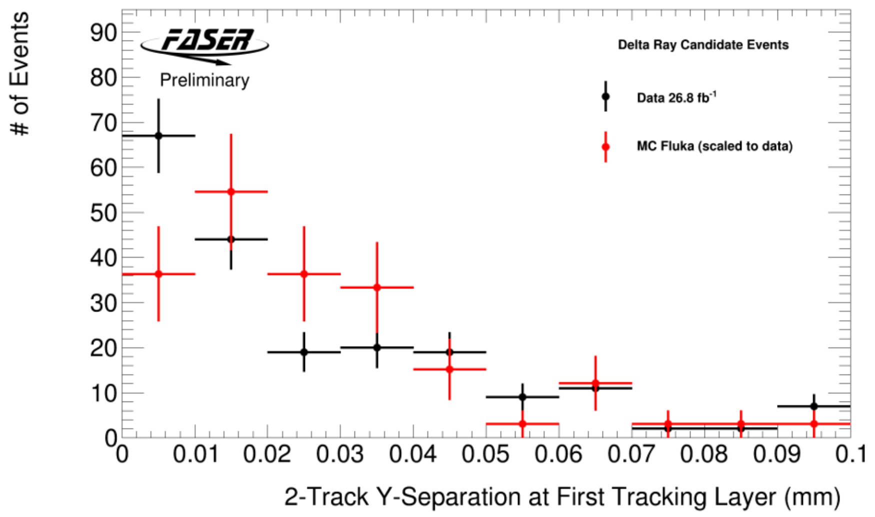






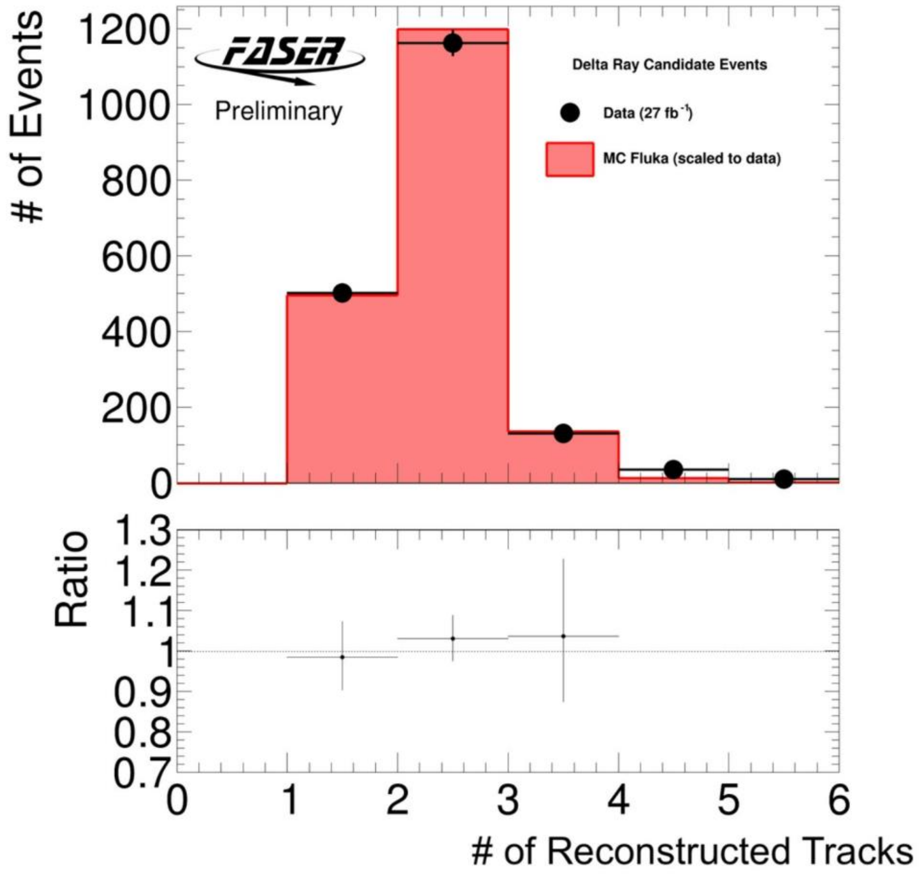
Dark Photon: Tracking Systematics

- Single track efficiency studies in muons events with track segments found in each station
  - 98.4% in data with data/MC agreement at 1.5% level
- Tracking efficiency lower for two close by tracks (~60%) → studied in two ways:
  - Overlaying hits from 2 single track events in either data or MC and measuring efficiency to find 2 tracks
    - Correct MC by ~15% difference and conservatively apply full correction as a MC systematic
  - Conversions and delta-ray events where require 1 less track than needed (i.e. 3 or 2 respectively)
    - With additional track segments + preshower/calo signals consistent with additional EM signal



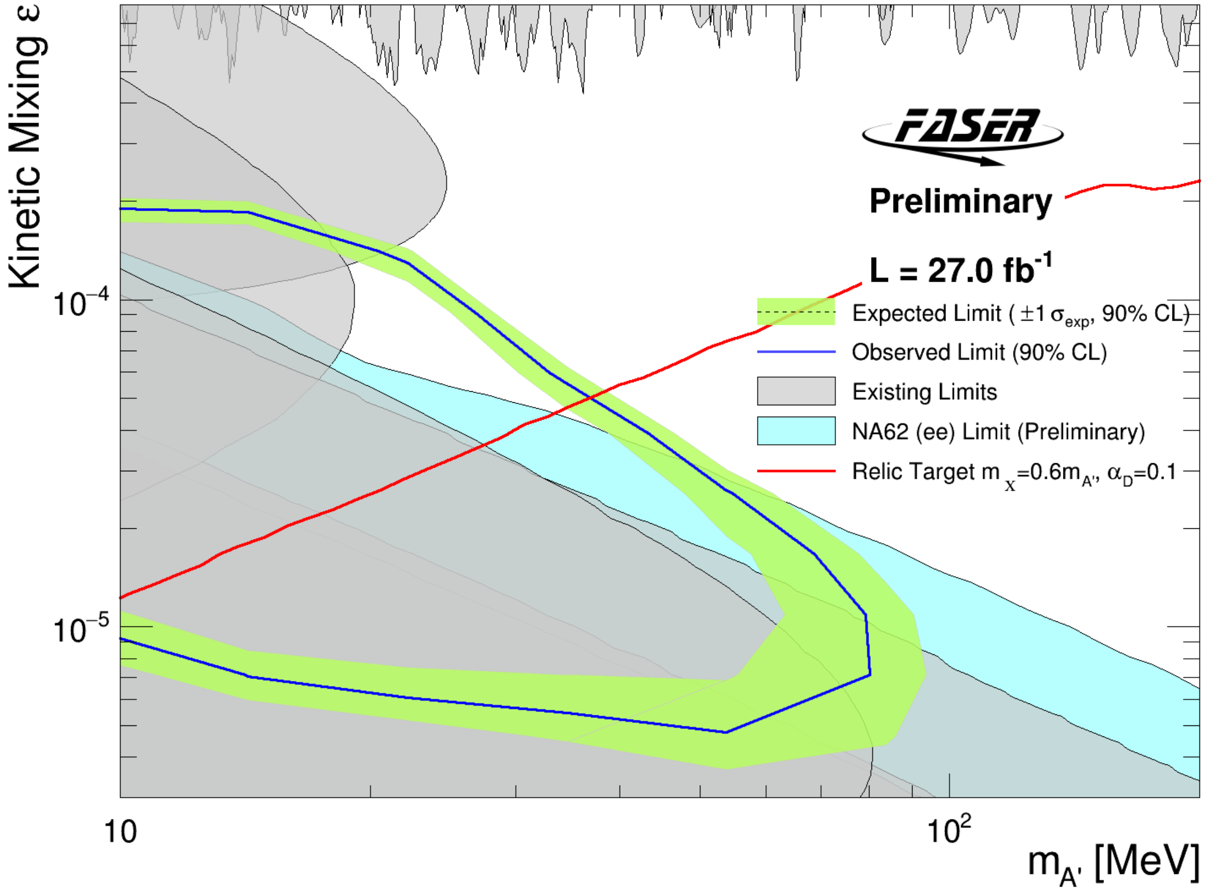
Two-track separation in delta-ray like events

Tracks in delta-ray like events

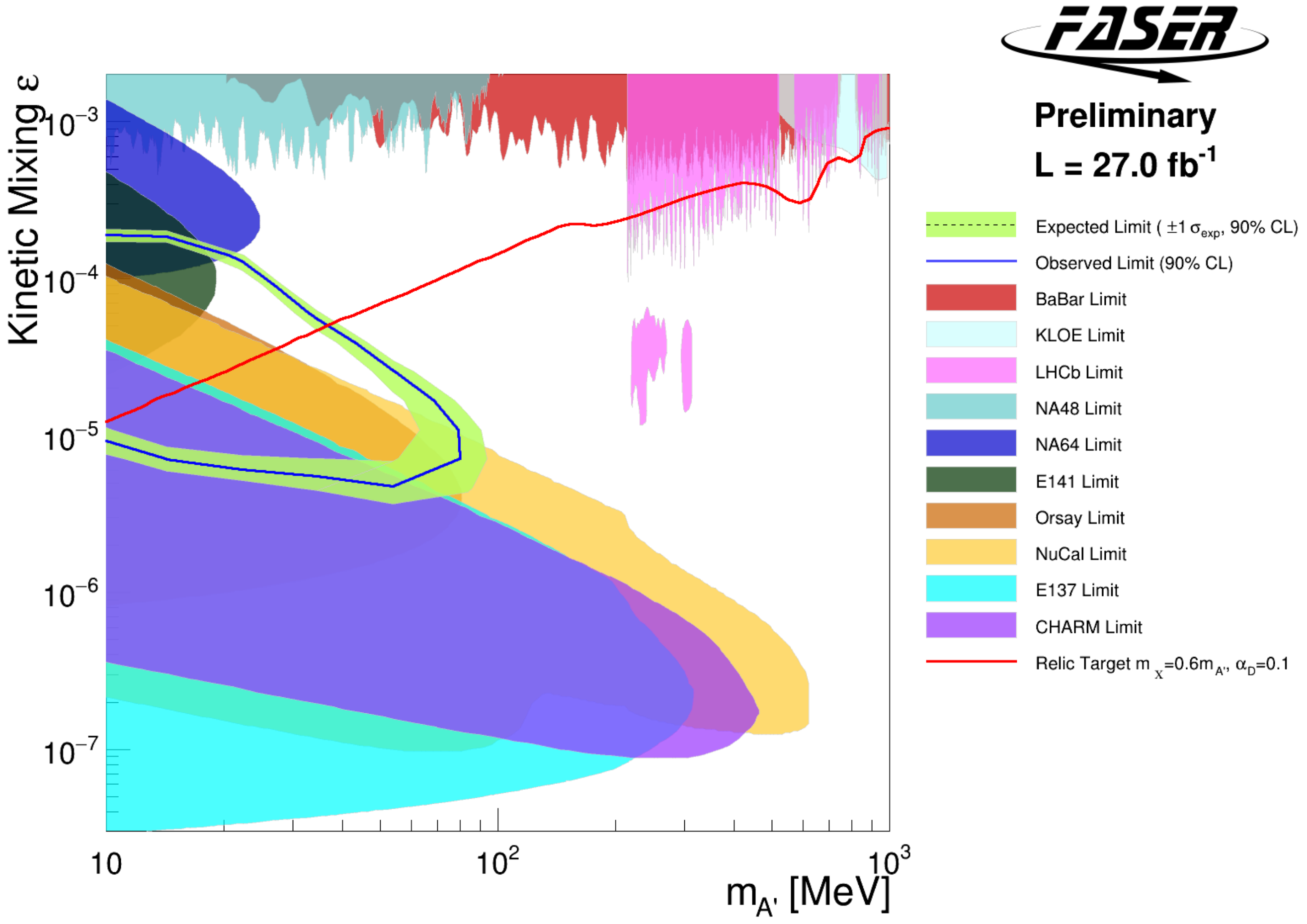


Dark Photon: Additional Limits

- Limits including recent prelim NA62 results
  - Partially overlaps with FASER exclusion



- Alternative limit plot showing individual previous limits available from DarkCast



Note FASER limits very similar at 95% CL and 90% CL

FASER Collaboration

- 87 members across 24 institutes from 10 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
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CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX
Nikhef
DESY.
JINR
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

FASER Publications

- The FASER Detector: arXiv:2207.11427
- The FASER W-Si High Precision Preshower Technical Proposal: CERN Document Server
- The tracking detector of the FASER experiment: NIM 166825 (2022)
- The trigger and data acquisition system of the FASER experiment: JINST 16 P12028 (2021)
- First neutrino interaction candidates at the LHC: PRD 104 L091101 (2021)
- Technical Proposal of FASERν neutrino detector: arXiv:2001.03073
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC: EPJC 80 61 (2020)
- Input to the European Strategy for Particle Physics Update: arXiv:1901.04468
- FASER's Physics Reach for Long-Lived: PRD 99 090511 (2019)
- Letter of Intent: arXiv:1812.09139
- Technical Proposal: arXiv:1811.10243