FASER

ForwArd Search ExpeRiment

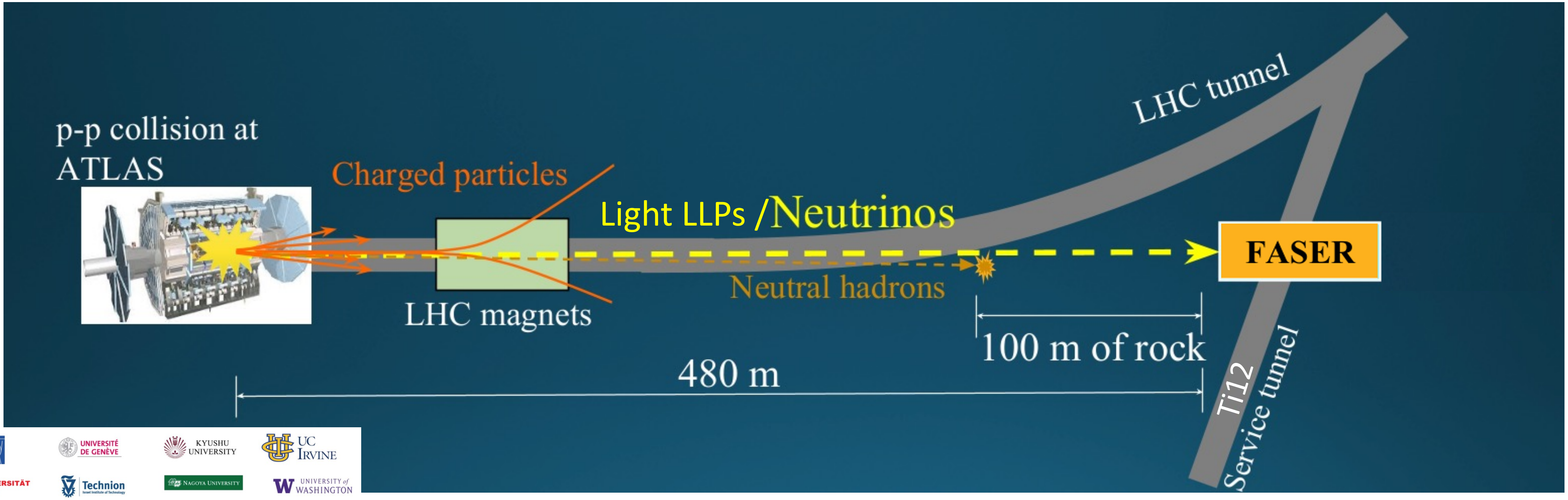
Monica D’Onofrio, Carl Gwilliam, Lottie Cavanagh

18th May 2023

Liverpool HEP Annual meeting

FASER Experiment and Collaboration

- New LHC run-3 experiment located 480 m downstream of ATLAS in Ti12 side service tunnel
  - Exploiting large LHC collision rate + forward-peaked light hadron production
  - Combination of LHC magnets and 100 m of rock shield most background



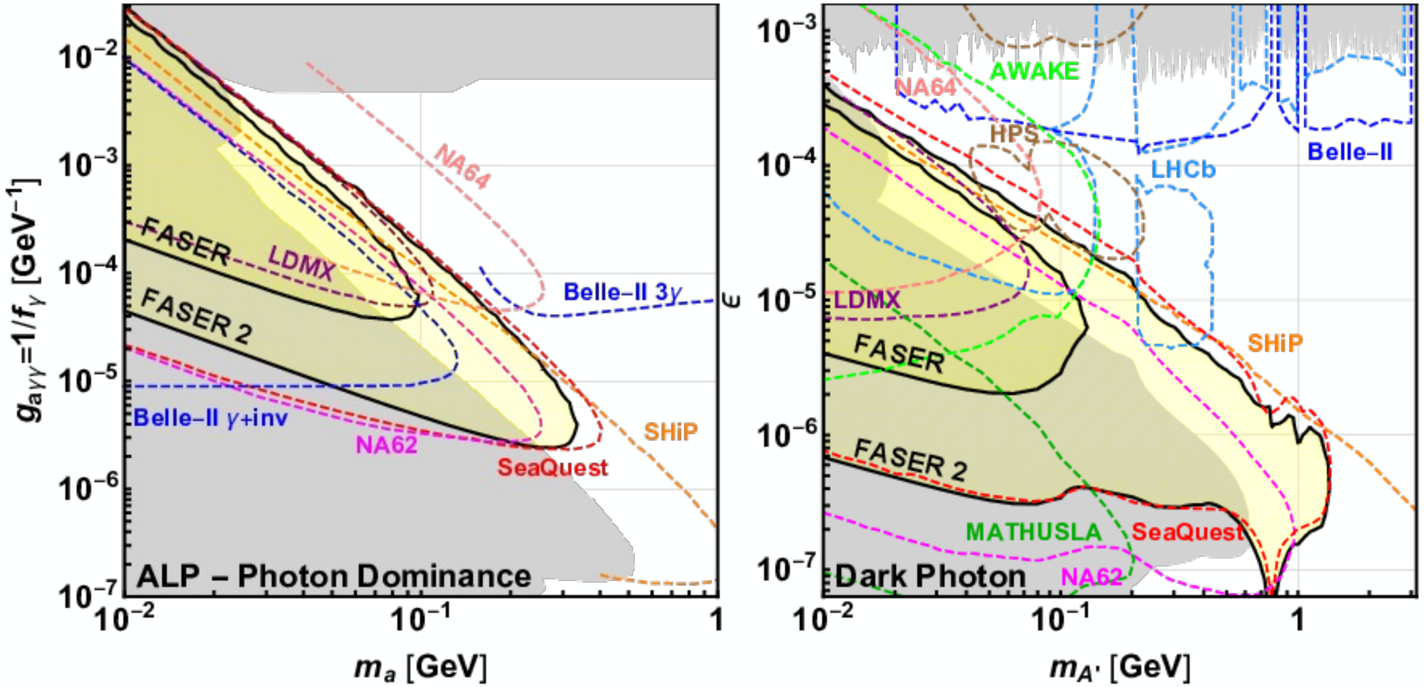
- 87 members from 24 institutes across 10 countries
  - 4 UK: Liverpool, Manchester, SUSSEX and RHUL

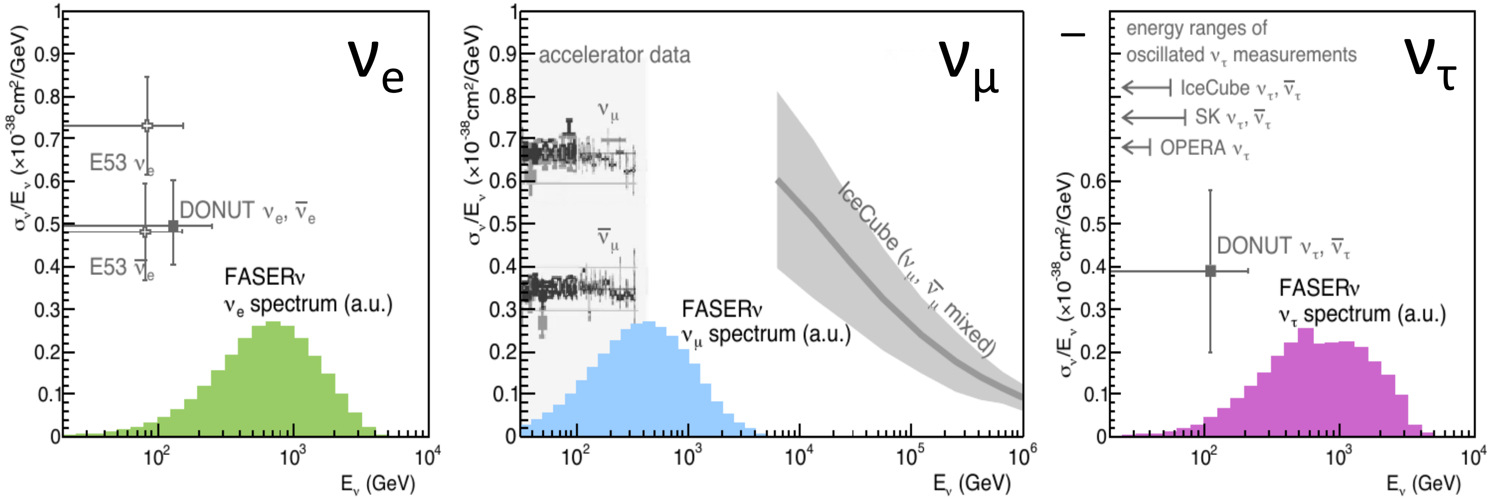
Physics Motivation

- Designed to search for light, weakly interacting particles from ATLAS IP

pp → LLP, LLP travels ~480m, LLP → ee, γγ, μμ, …

- Probes large range of BSM models that predict long-lived particles
  - Dark photons, ALPS, HNL, B-L, …
- Complementary to ATLAS/non-collider
  - Sensitivity to unique parameter space

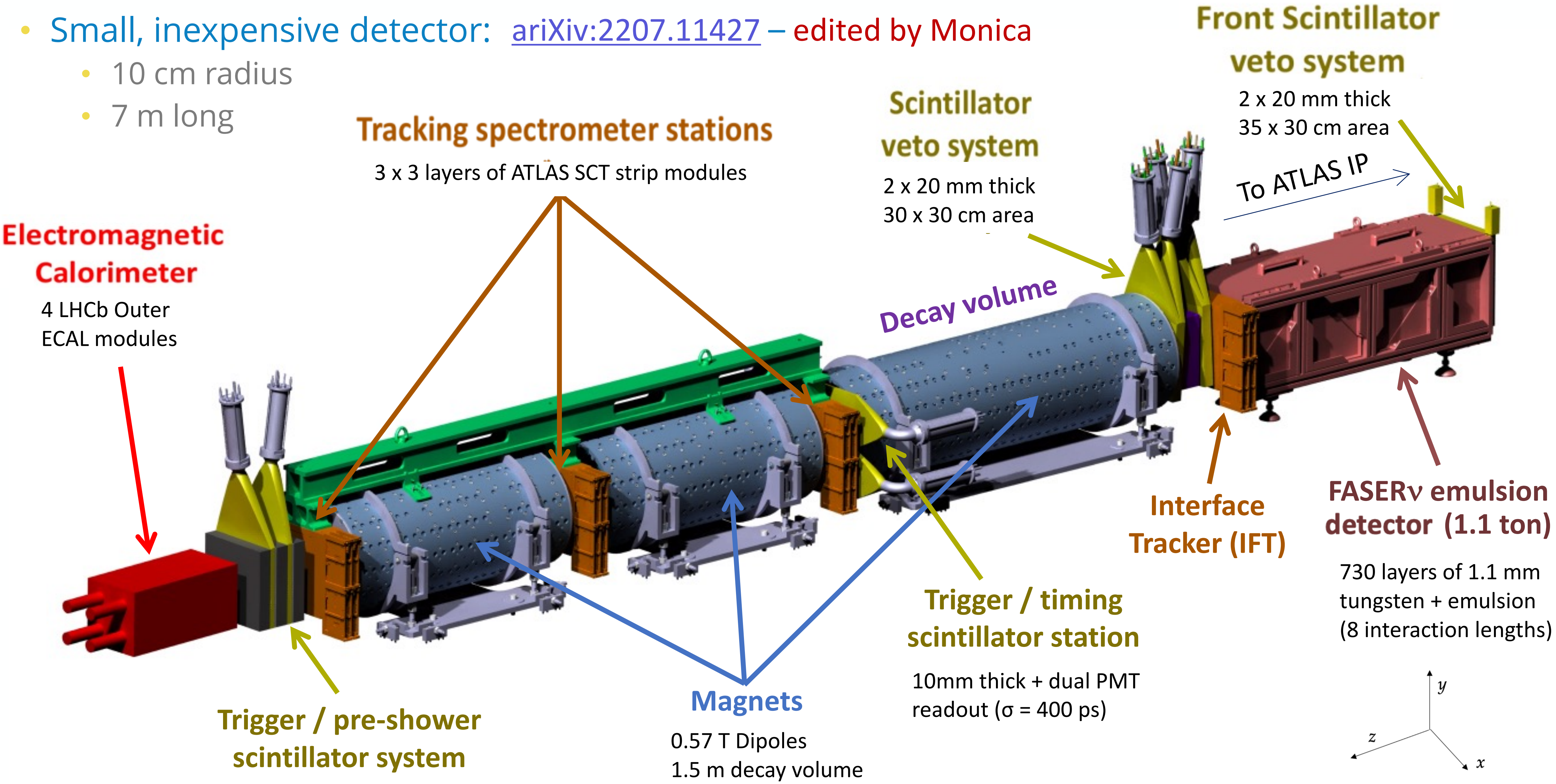




- FASERν adds neutrino program
  - First observation of collider νs
- Cross-section measurement in E range from ~ 100 GeV to ~1 TeV
  - Highest E man-made neutrinos
  - Unconstrained phase space region

FASER Detector

- Small, inexpensive detector: [ariXiv:2207.11427]() – edited by Monica
  - 10 cm radius
  - 7 m long



FASER Operations

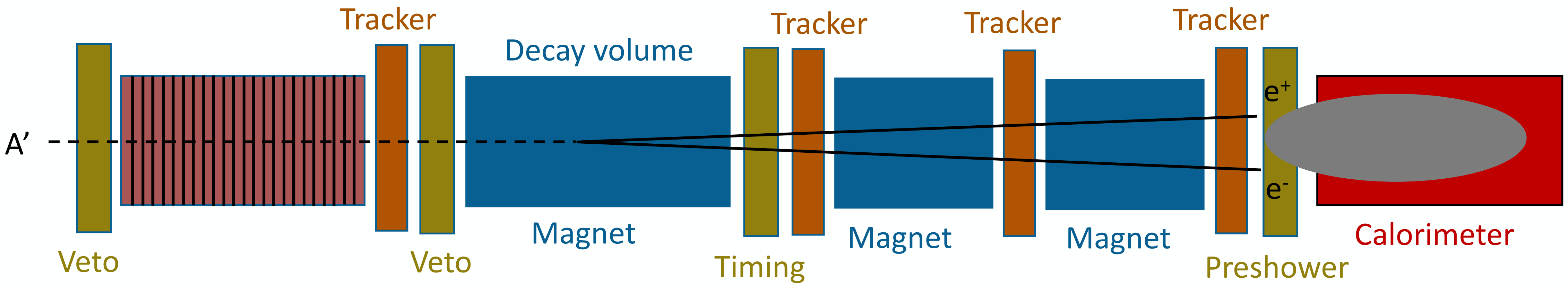
- Successfully operated throughout 2022
- All detector components performing excellently
- Recorded 96.1% of delivered lumi with 1.3% DAQ dead-time

Dark Photon (A') Analysis

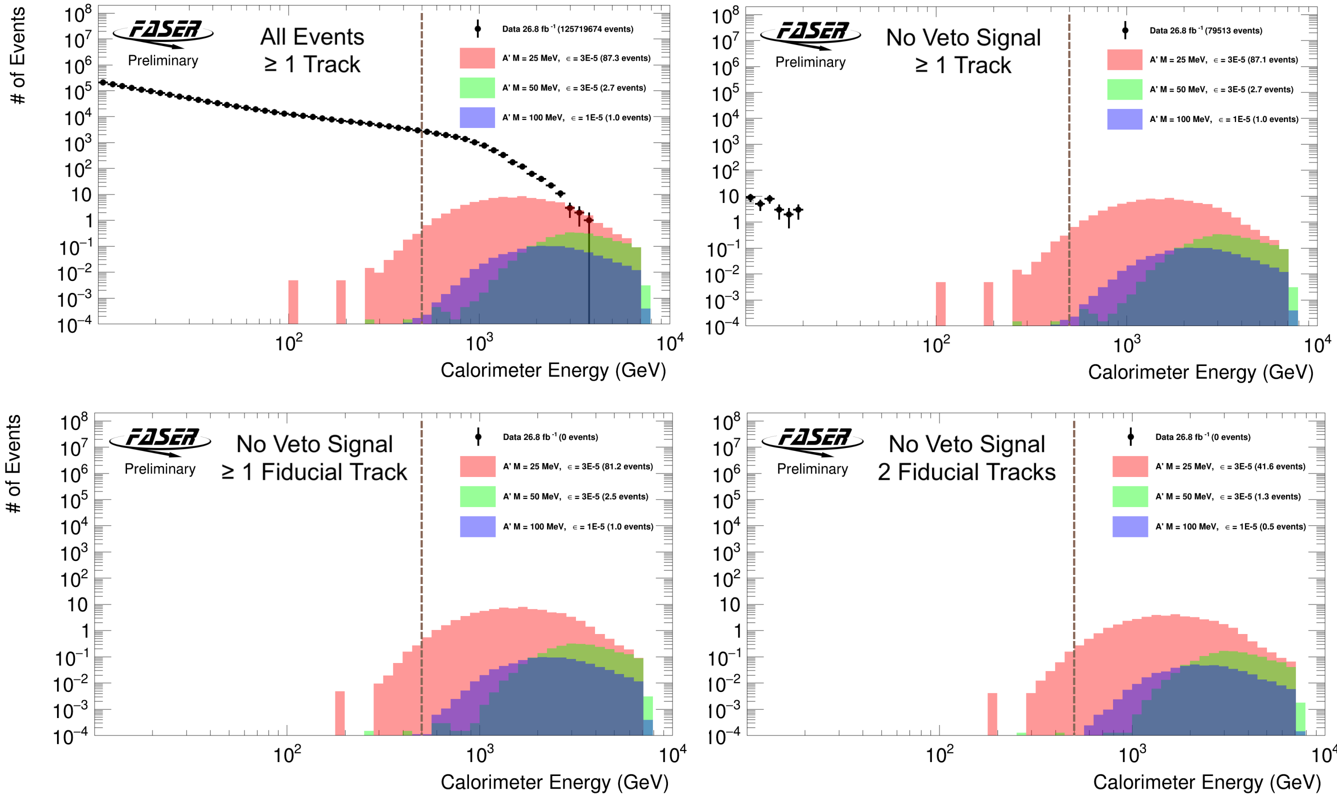
- Simple and robust A' → e^+e^- selection, optimised for discovery
  - Signal efficiency of ~40% across phase-space region sensitive to
  - Expected background, dominated by neutrino interactions, is (2.02 ± 2.4) x 10^{-3}

Leading Liverpool involvement from end-to-end.
- Carl PC and A' analysis contact
- See Lottie's talk for more details

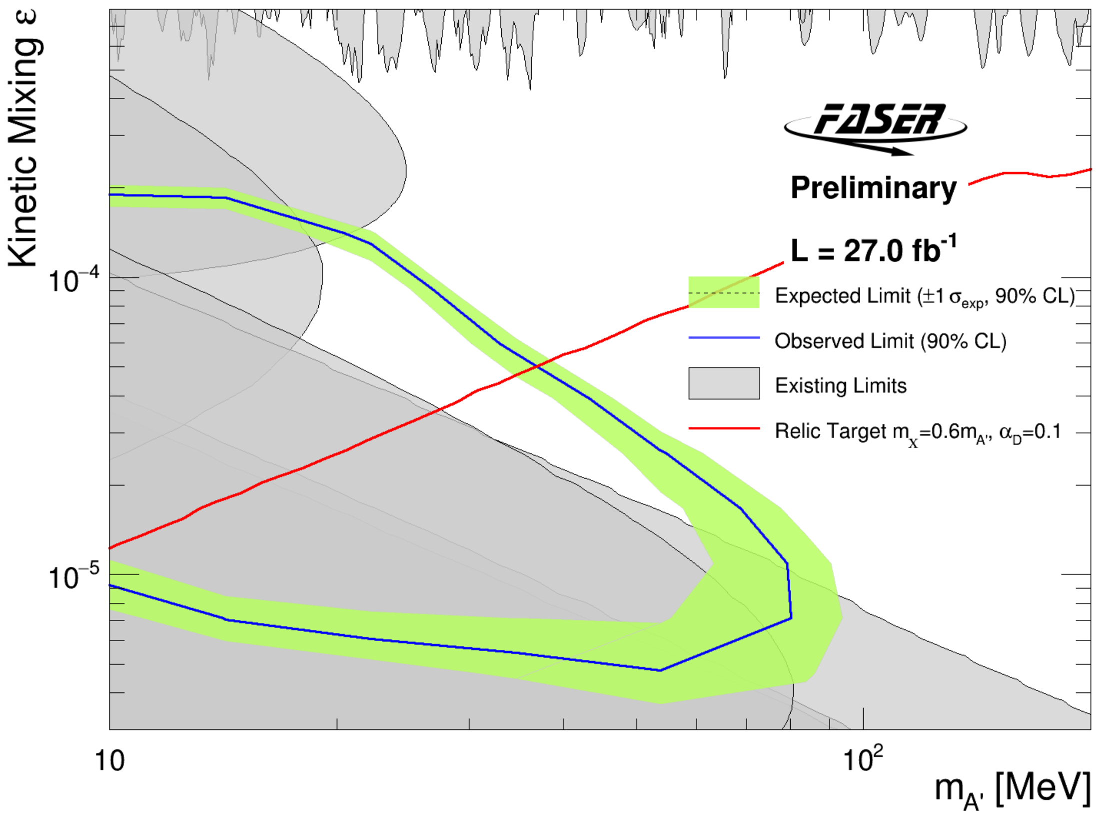
1. Collision event with good data quality
2. No signal (< 40 pC) in any veto scintillator
3. Exactly 2 good fiducial tracks
   - p > 20 GeV and r < 95 mm
   - Extrapolating to r < 95 mm at vetos
4. Timing and preshower consistent with ≥2 MIPs
5. Calo E > 500 GeV



Dark Photon Results



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

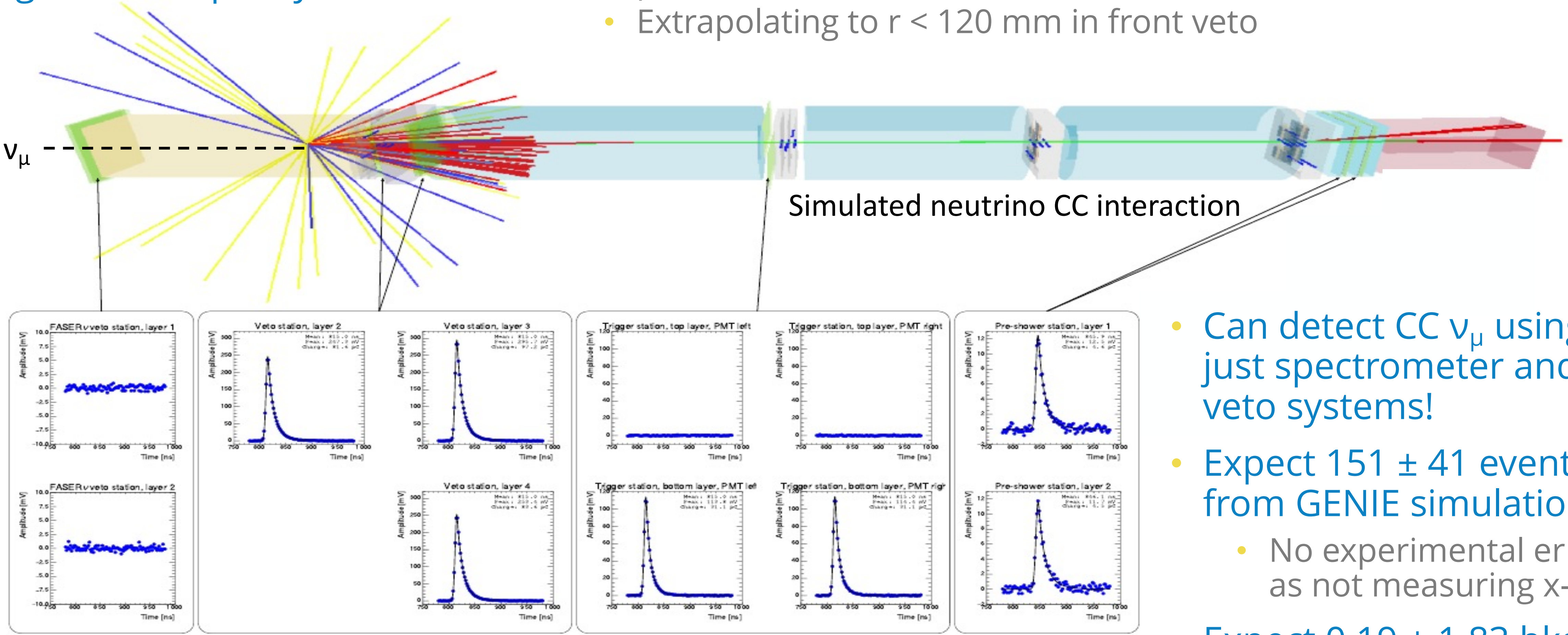


- Based on this null results, FASER sets limits in previously unexplored parameter space!
  - Probing region interesting from thermal relic target

CERN-FASER-CONF-2023-001

Neutrino Analysis

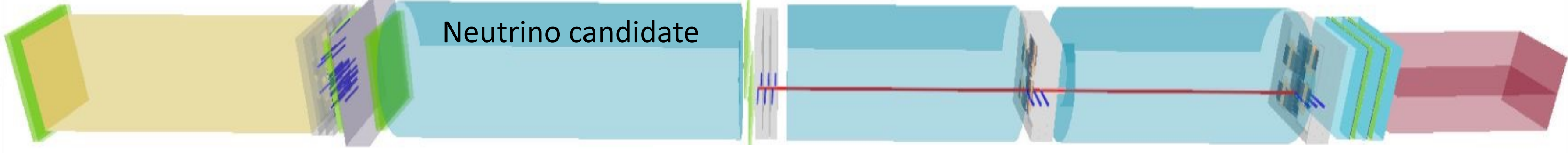
1. Collision event with good data quality
4. Exactly 1 good fiducial (r < 95 mm) track
   - p > 100 GeV and θ < 25 mrad
   - Extrapolating to r < 120 mm in front veto



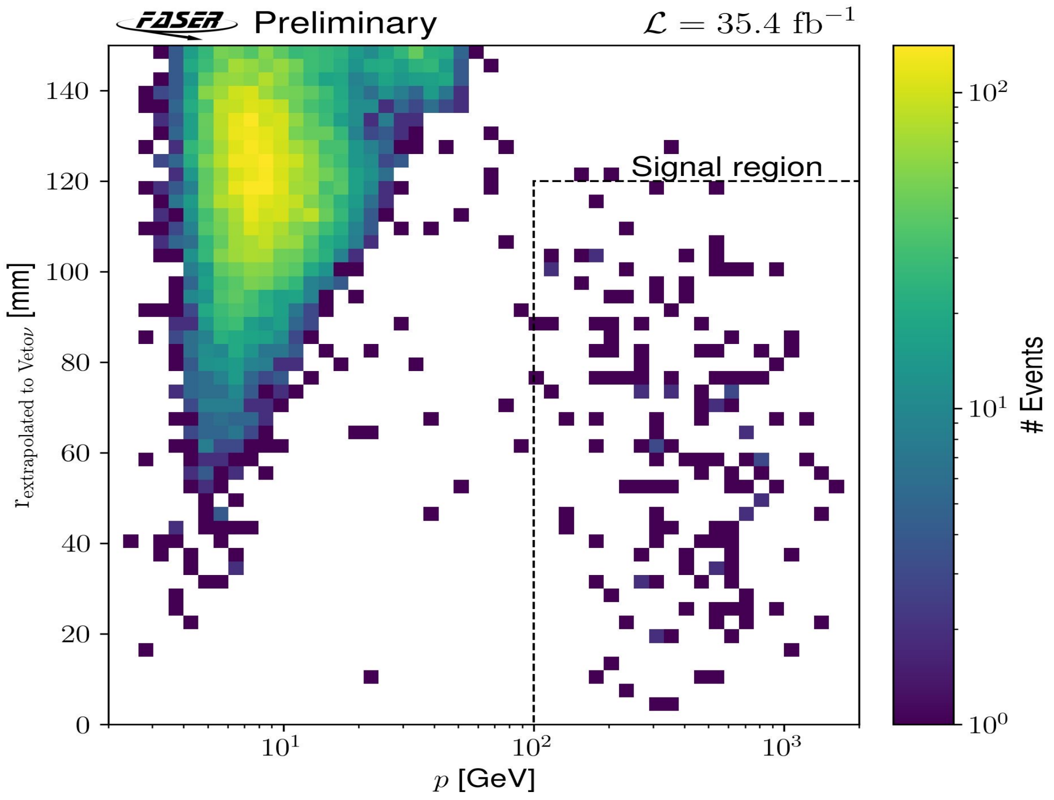
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos
5. Timing and preshower consistent with ≥1 MIP

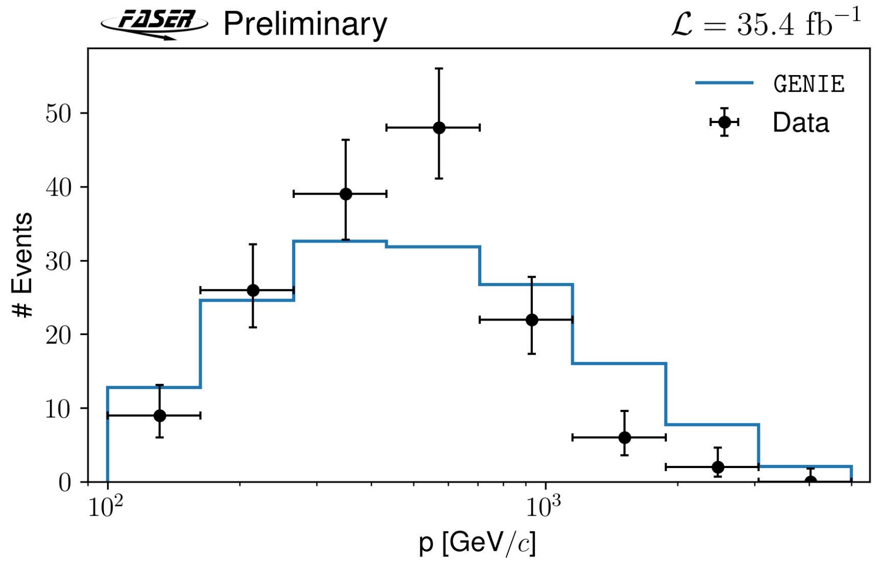
- Can detect CC ν_μ using just spectrometer and veto systems!
- Expect 151 ± 41 events from GENIE simulation
  - No experimental errors as not measuring x-sect
- Expect 0.19 ± 1.83 bkg
  - Mainly neutral hadrons

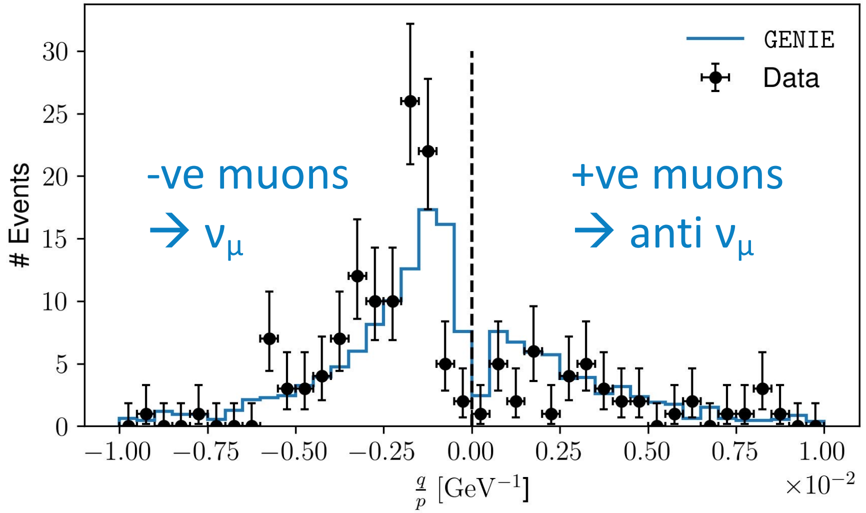
Neutrino Results



- 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
  - Accepted by PRL arXiv:2303.14185



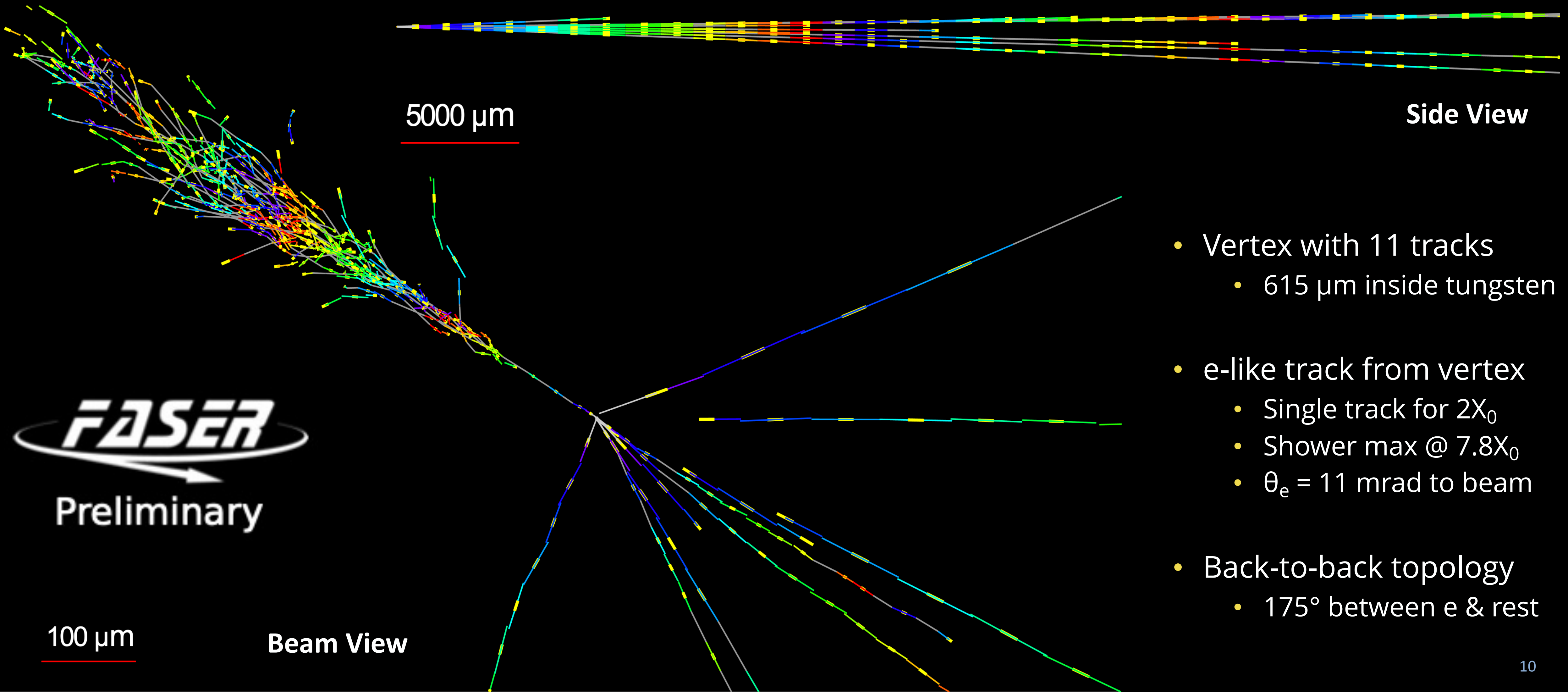




- See both ν_μ and anti-ν_μ (with more ν_μ)
  - Momentum of μ extends to high values

Neutrinos in FASERν

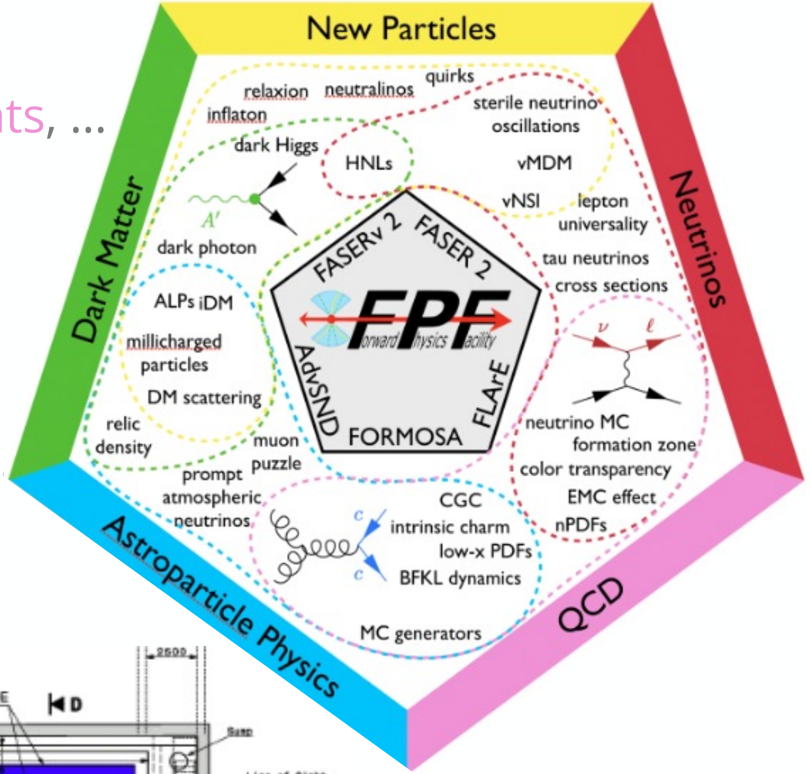
- Analysis of FAESRν emulsion detector underway
  - Have multiple candidates including highly ν_e-like CC event

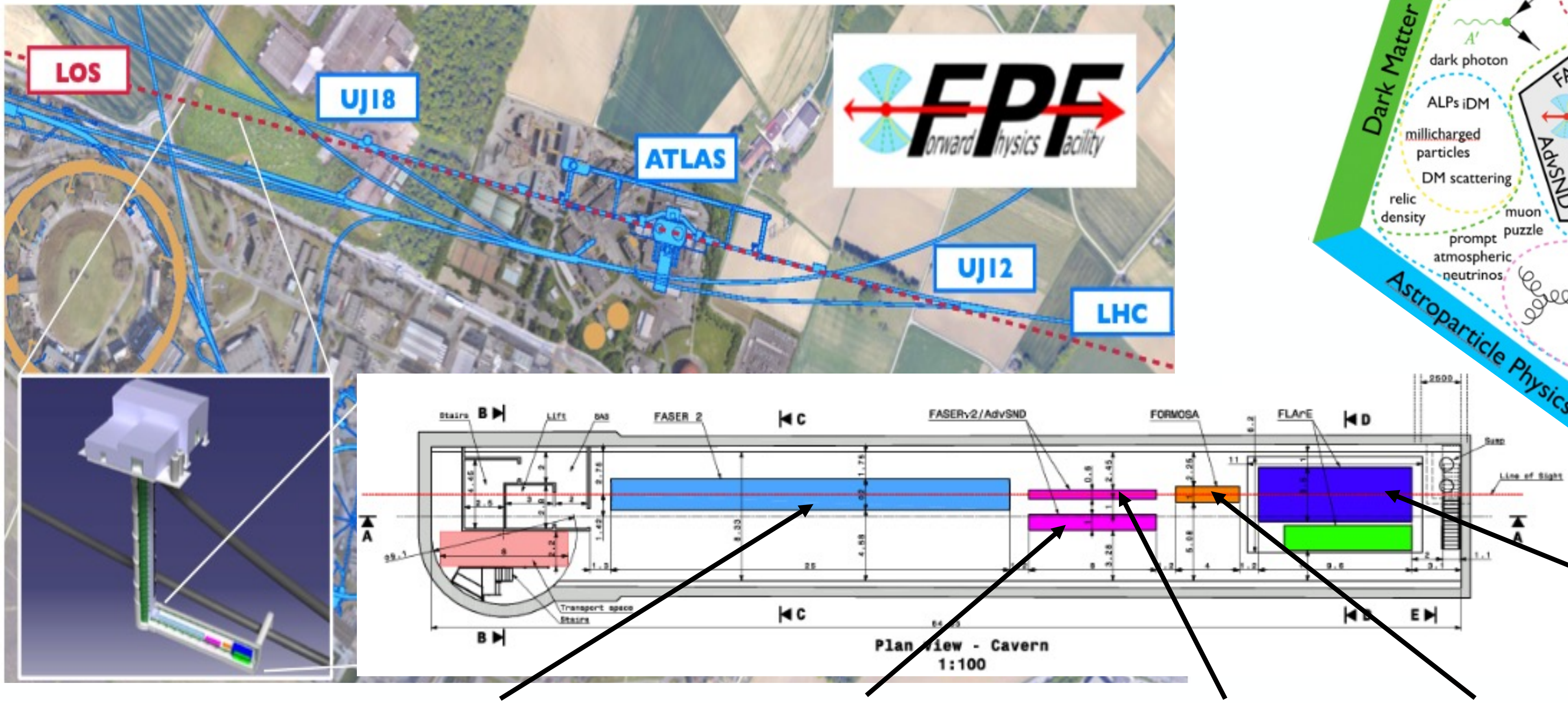


- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Forward Physics Facility (FPF)

- Proposed new dedicated forward physics facility at HL-LHC
  - Broad- physics program: BSM searches, ν physics, QCD measurements, ...





FLArE: LAr-based neutrino detector

[FPF White Paper]

FASER2: spectrometer for BSM LLP searches

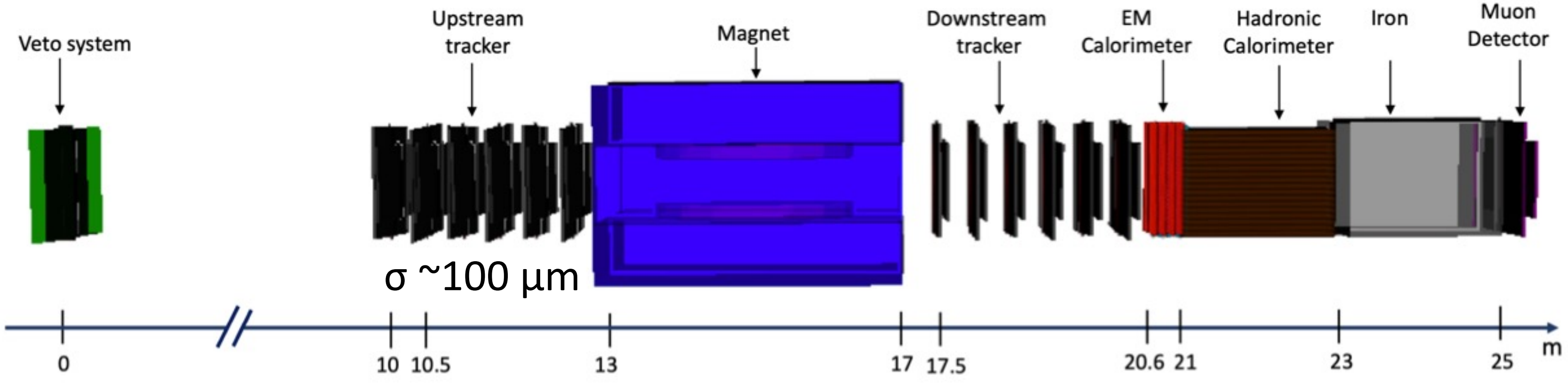
AdvSND: electronic neutrino detector

FASERν2: emulsion neutrino detector

FORMOSA: Plastic scintillator for BSM

FASER(ν)2

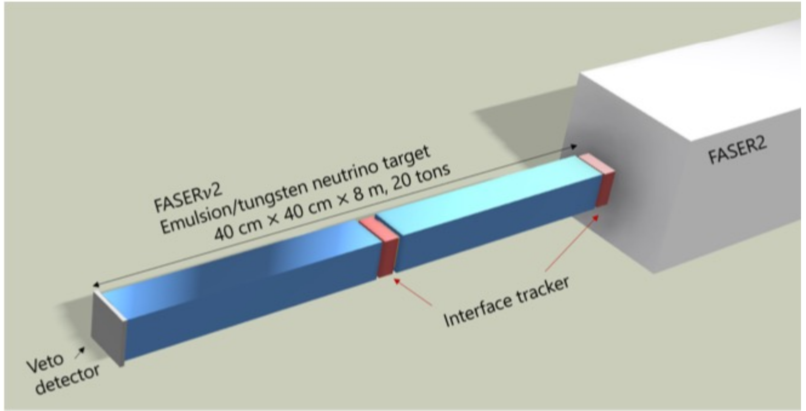
- On-axis spectrometer with 4 Tm superconducting magnet
  - Longer: increased target and decay volume (L =1.5 m → 10 m)
  - Wider: increased sensitivity to HF production (R = 0.1m → 1 x 3 m)

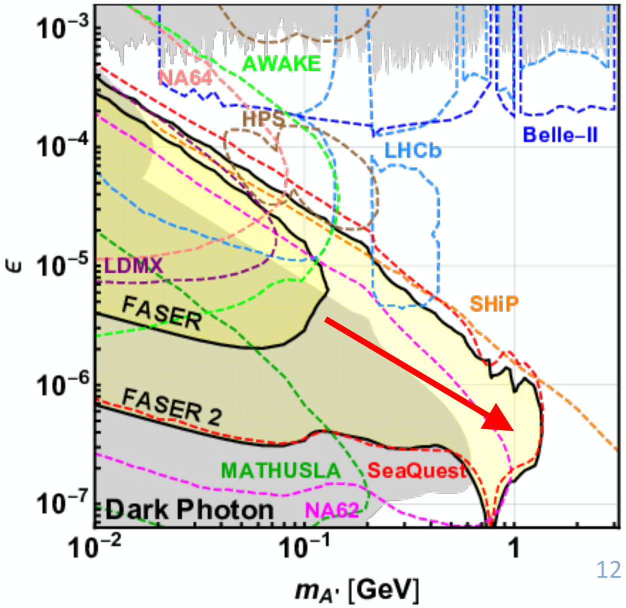


- Wider LLP physics program
  - Probing up to higher mass

Benchmark Model	FASER	FASER 2
Dark Photons	✓	✓
$B-L$ Gauge Bosons	✓	✓
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	✓
Dark Higgs Bosons with hSS	—	✓
HNLs with e	—	✓
HNLs with μ	—	✓
HNLs with τ	✓	✓
ALPs with Photon	✓	✓
ALPs with Fermion	—	✓
ALPs with Gluon	✓	✓
Dark Pseudoscalars	—	✓

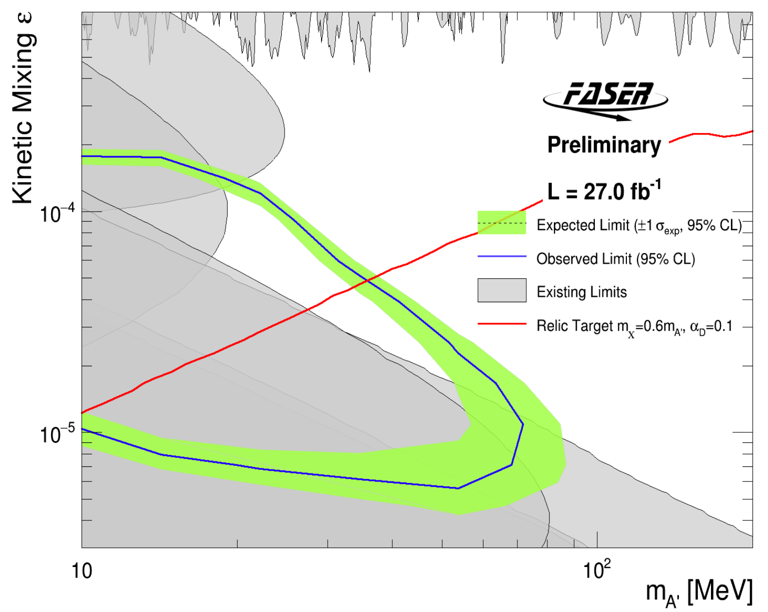
- Tracker: LHCb-like SciFi detector
  - Potential higher resolution silicon detector for 1st layer / central region
- Calorimeter: IDEA-like dual-readout
- Neutrino: 20x larger W + emulsion
  - ~50 nm intrinsic position resolution

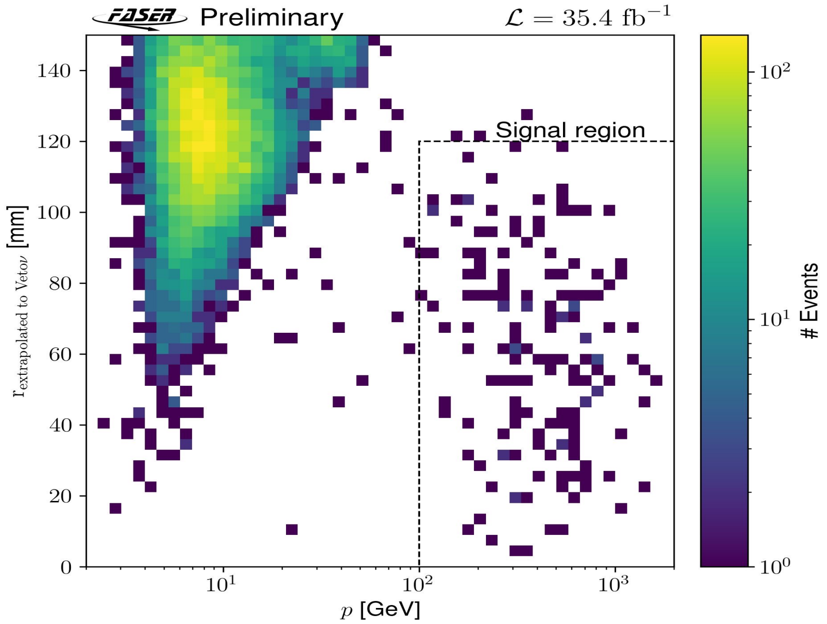




Summary + Outlook

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector & 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
  - Opens new window for high-energy ν study
- Liverpool played a major role across many areas
  - From data-taking & software development to final analysis
- More searches and neutrino measurements to come
  - Including first results from emulsion detector
  - Looking forward to up to 10x more LHC run-3 data
- Proposal for dedicated HL-LHC forward physics facility
  - Liverpool potentially interested in development of tracker
  - Discussing with other UK institutes towards SoI to STFC

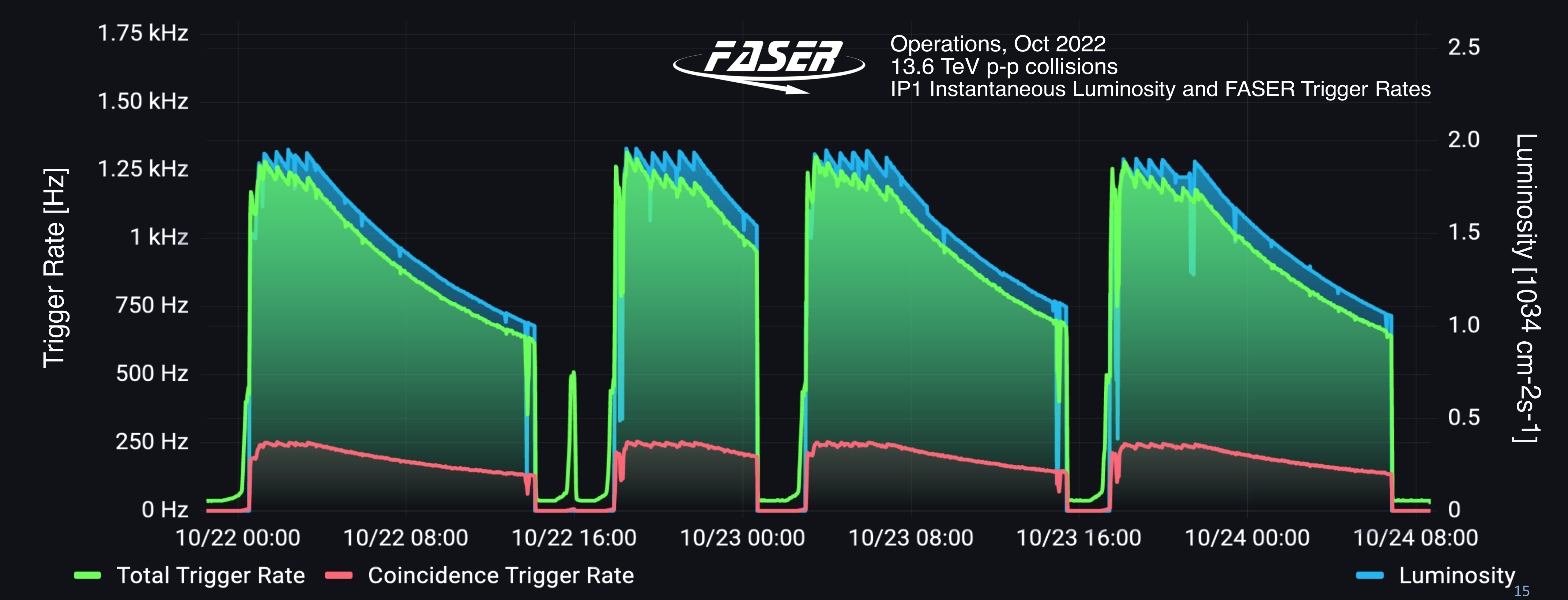




Backup Slides

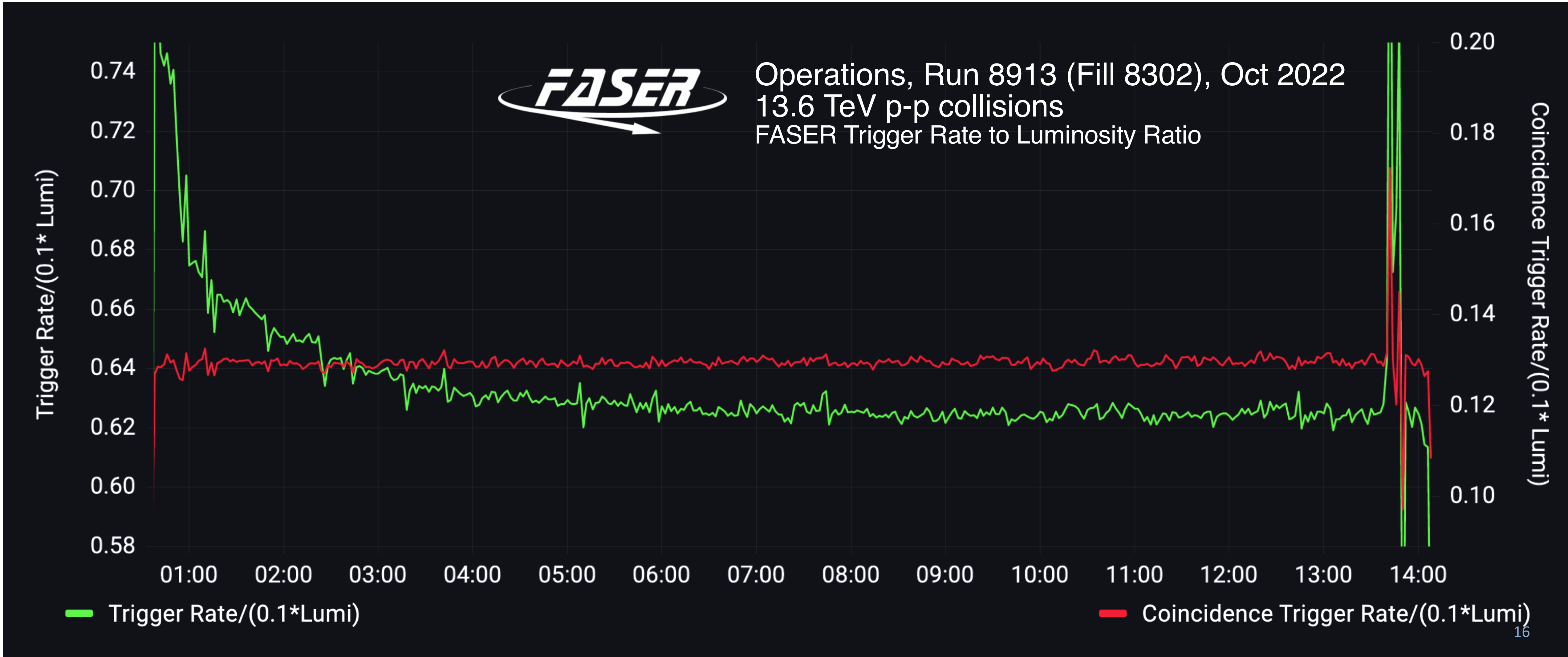
Detector Performance: Trigger + DAQ

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



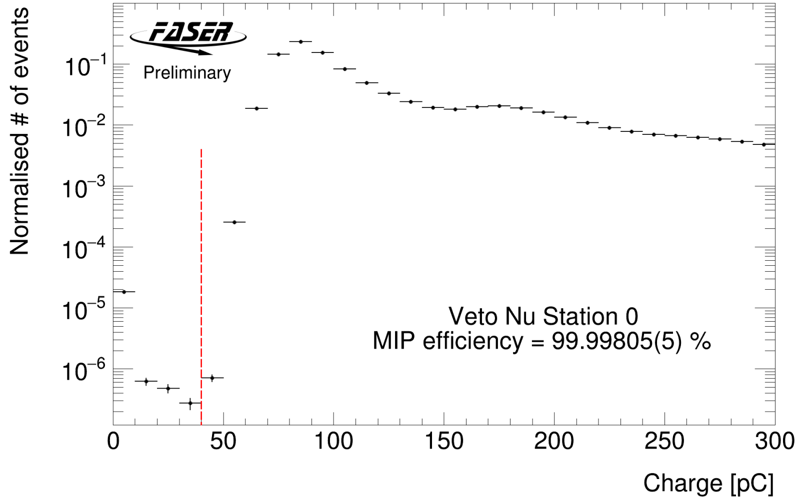
Detector Performance: Trigger + DAQ (2)

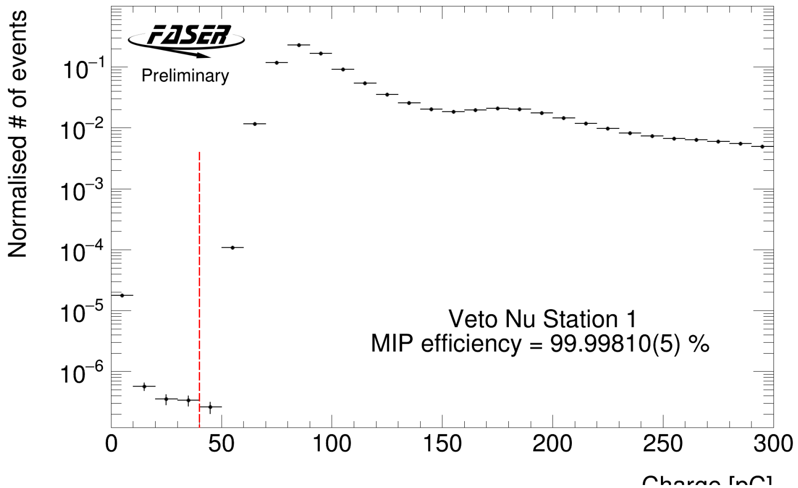
- Total trigger rate falls off faster than luminosity profile during run
  - But coincidence trigger rate flat wrt lumi

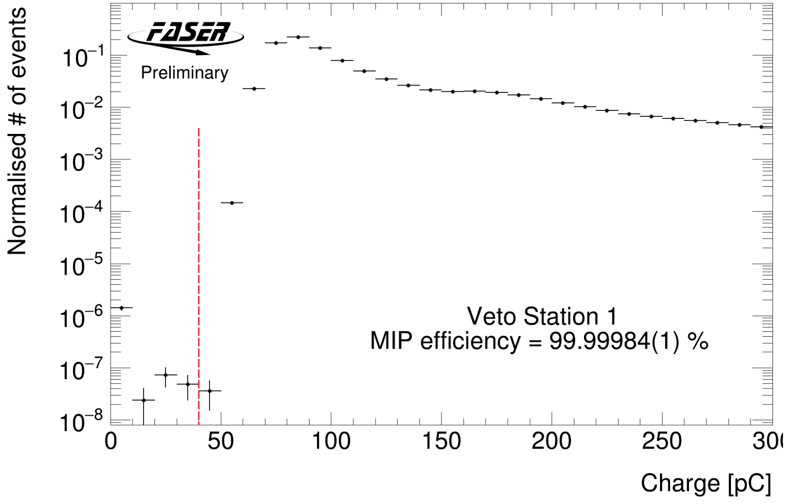


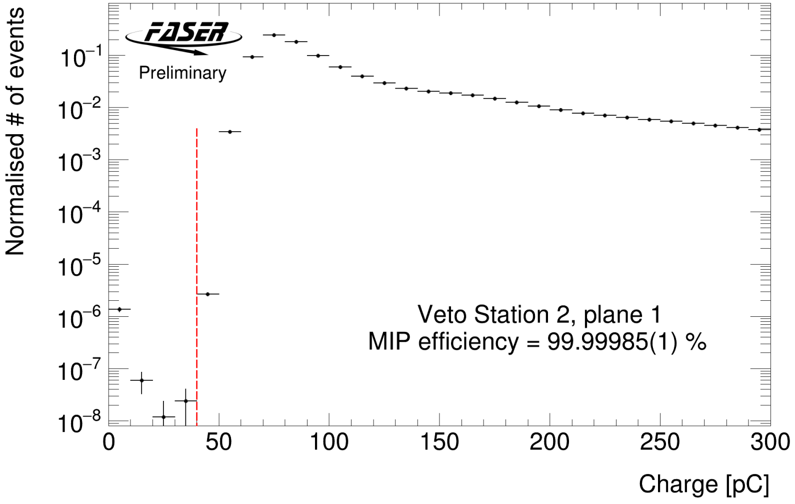
Detector Performance: Veto Scintillators

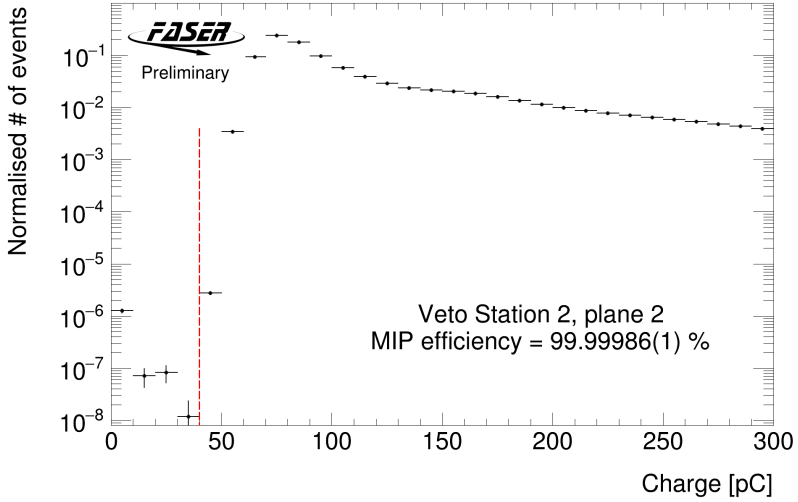
- Veto efficiency measured extrapolating tracks triggered by timing scint. to corresponding layer
  - No requirement on other scintillator layers
  - Layer efficiencies found to be uncorrelated
  - All layers found to have inefficiencies < 2 x 10^{-5}





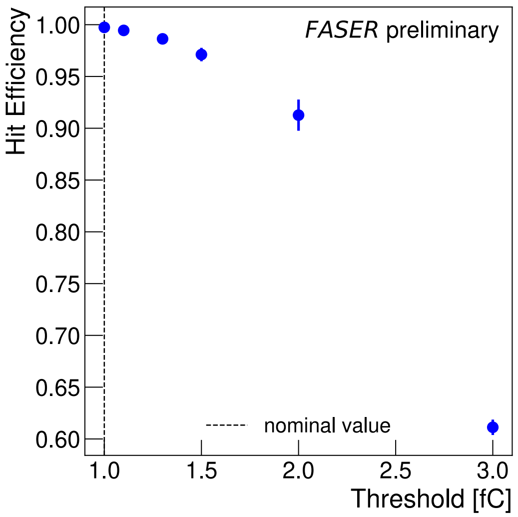


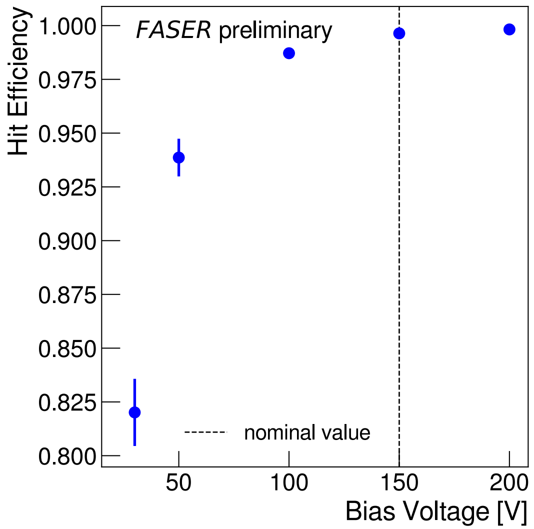




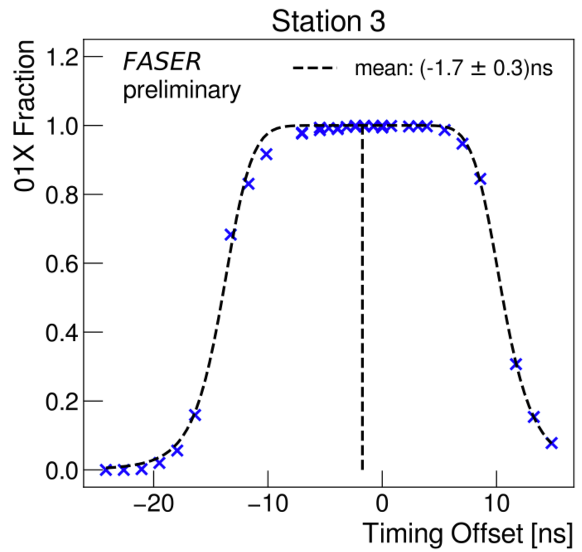
Detector Performance: Tracker

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

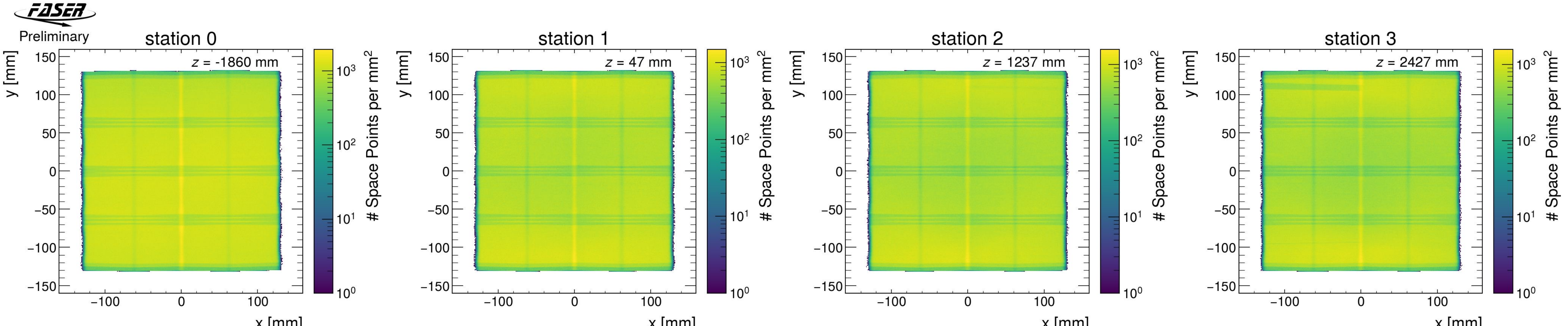




- Tracker fully timed in wrt LHC clock

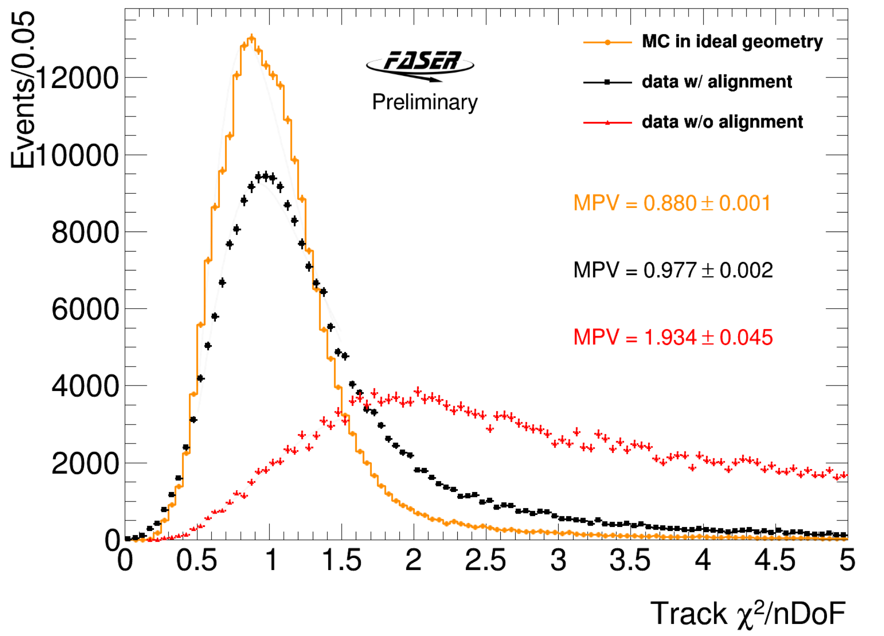


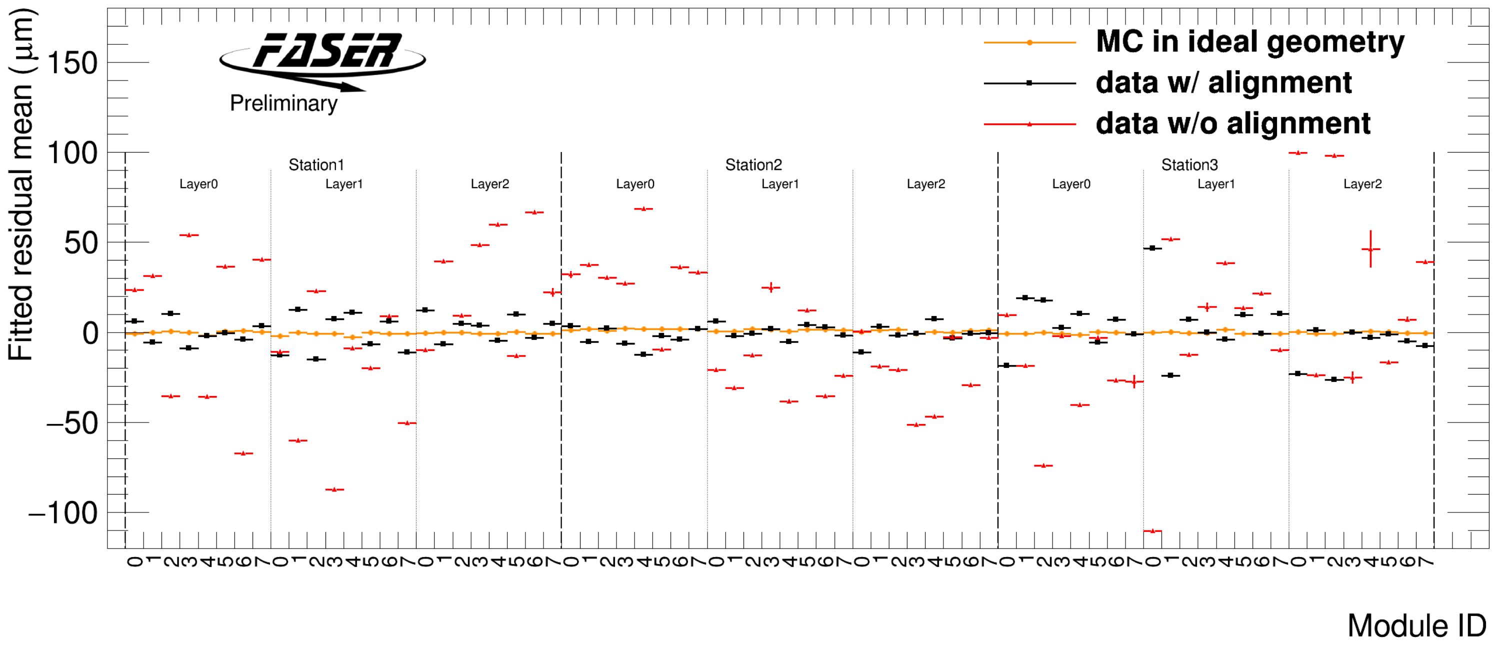
- <0.5% dead/noisy strips (inefficiency at edges expected)

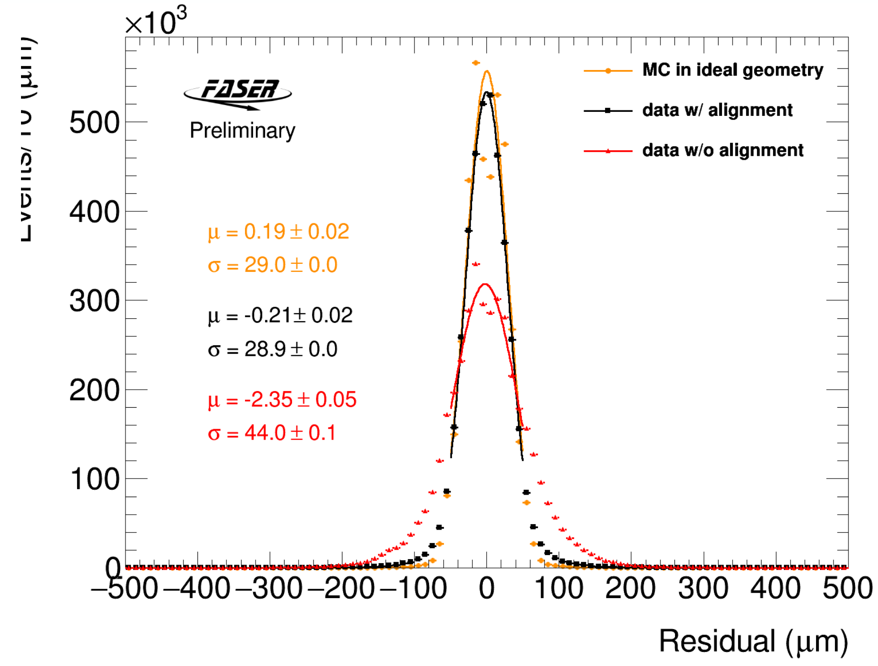


Detector Performance: Alignment

- 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

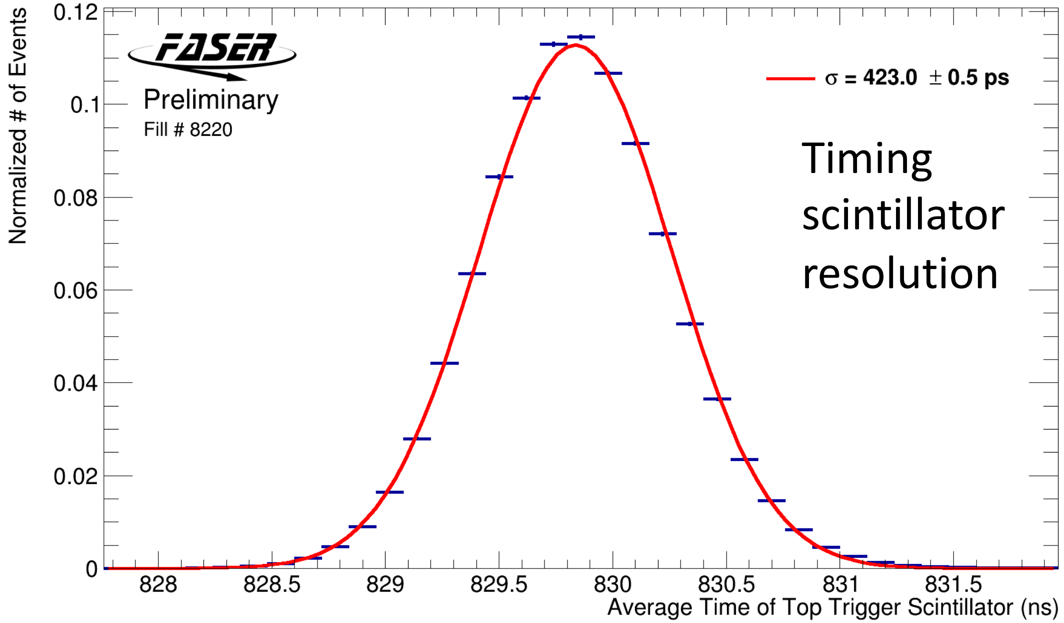


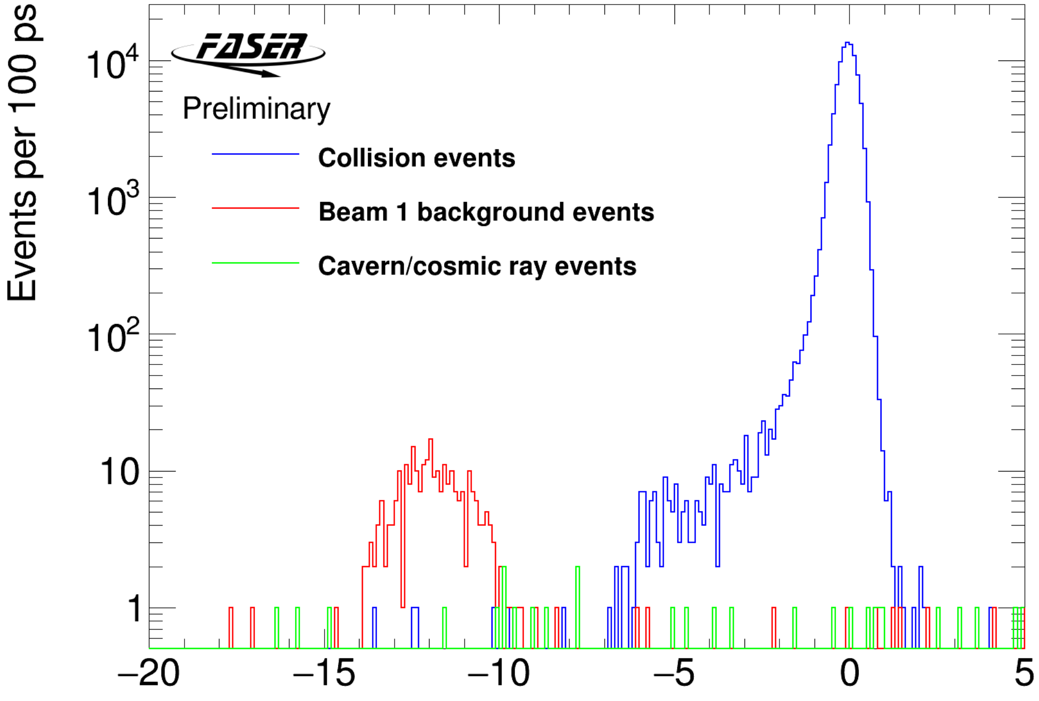




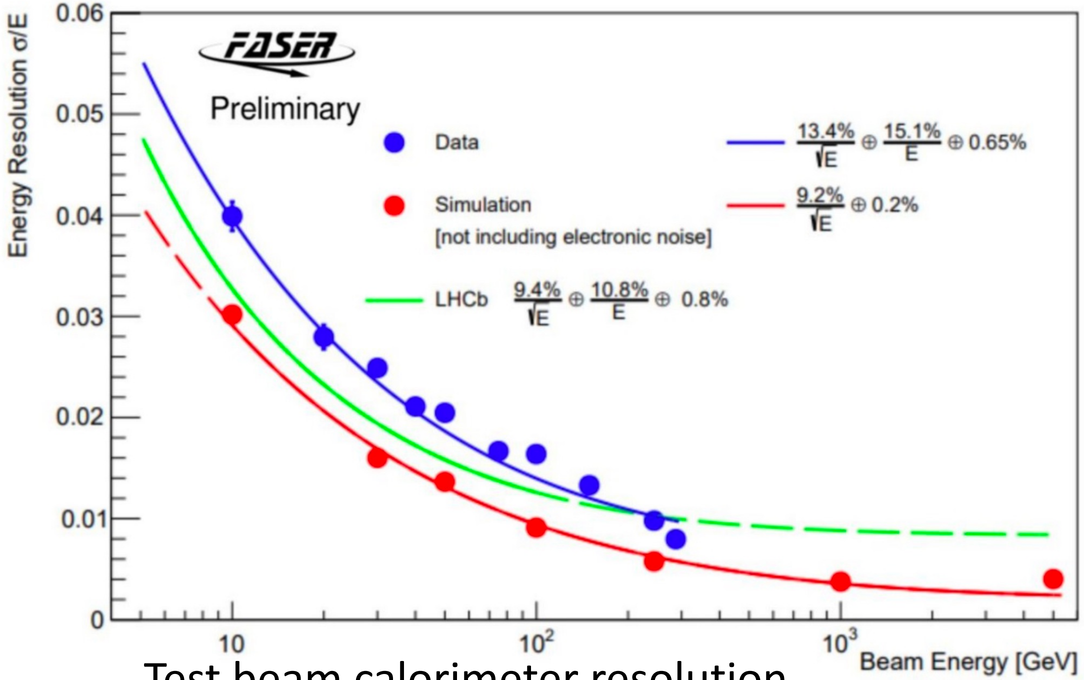
Detector Perf.: Timing and Calo

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





Calo timing for different events

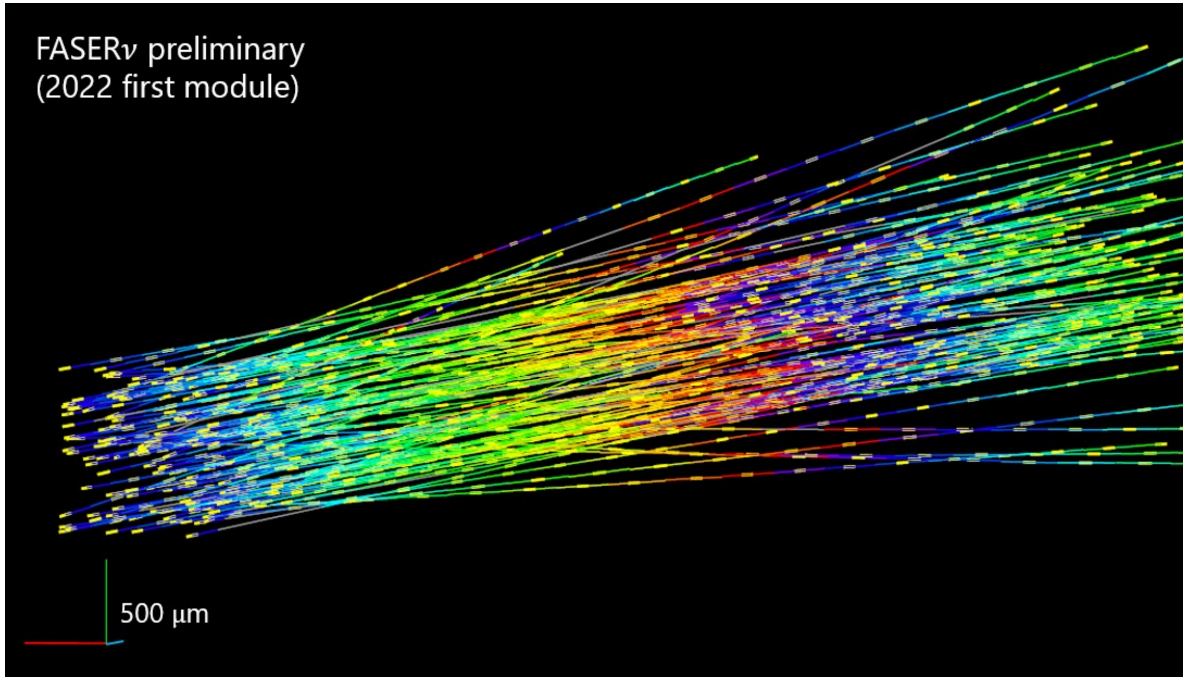


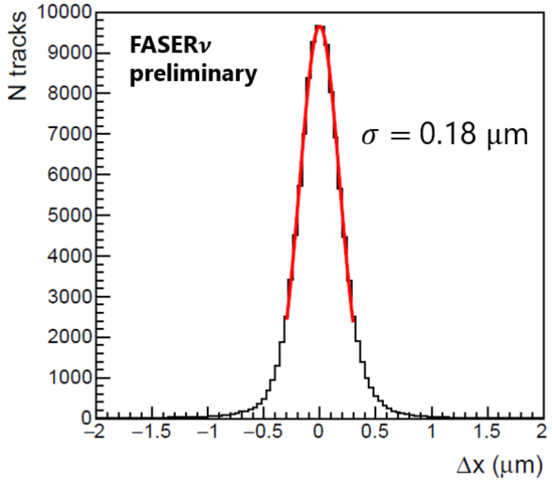
Test beam calorimeter resolution

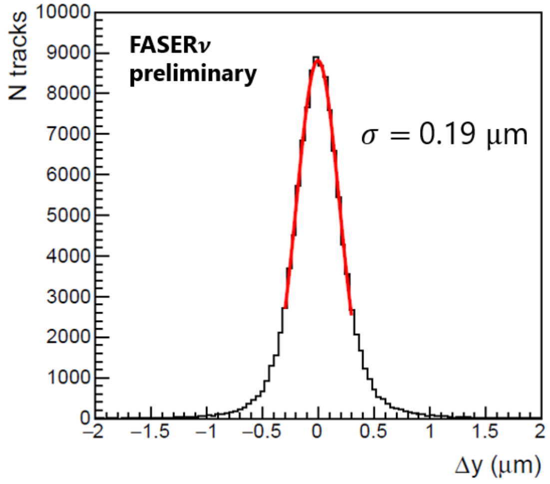
Detector Performance: Emulsion

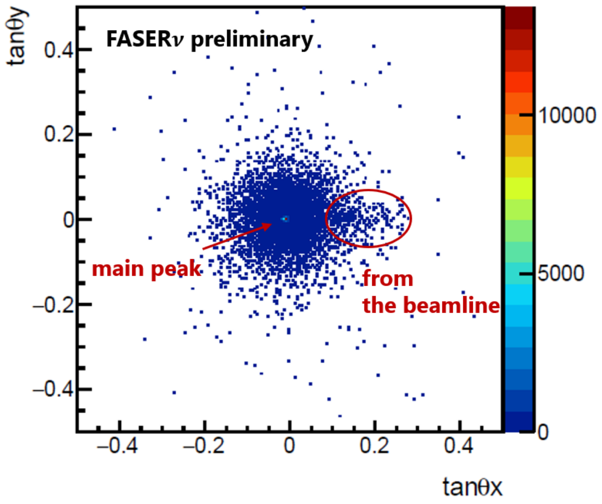
- Track multiplicity and angular distribution measured in initial partial FASERν emulsion
  - Consistent with FLUKA simulation

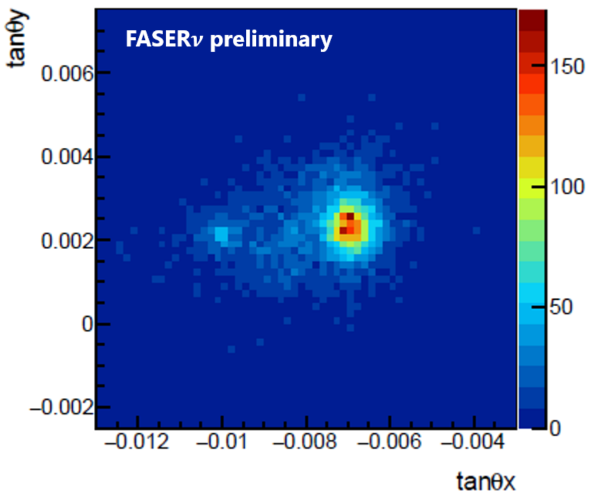
- Excellent hit resol (0.2 μm) after layer alignment





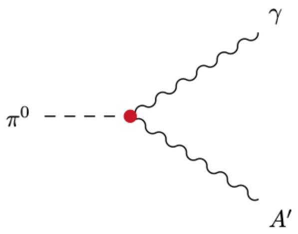






Dark Photon Search

- 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



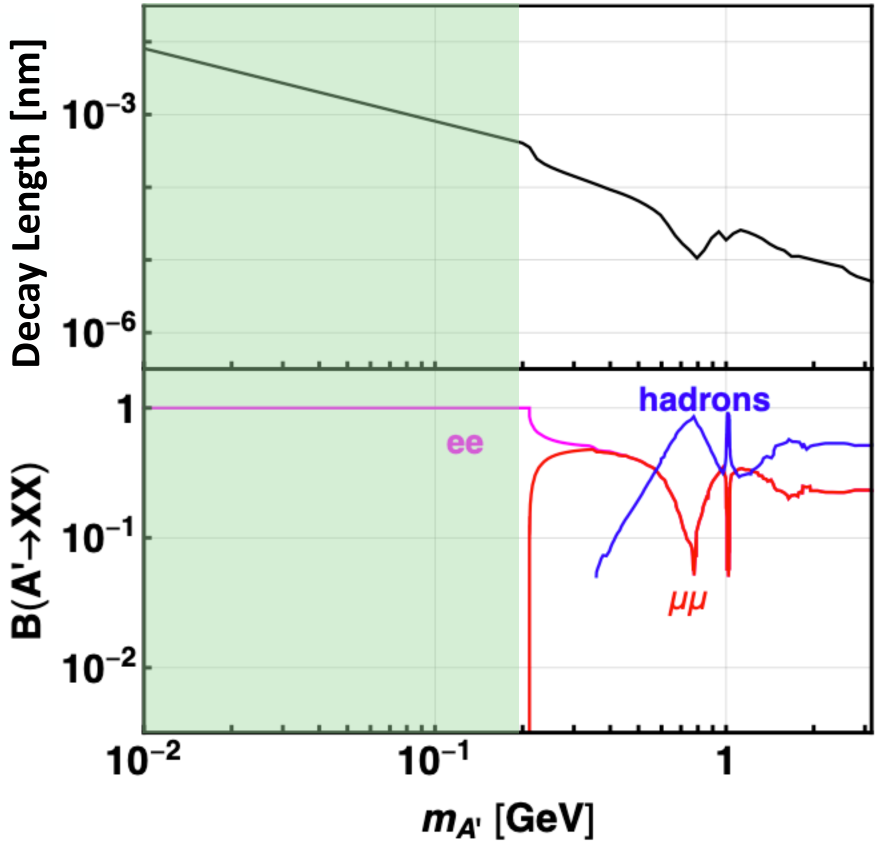
$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- 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

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

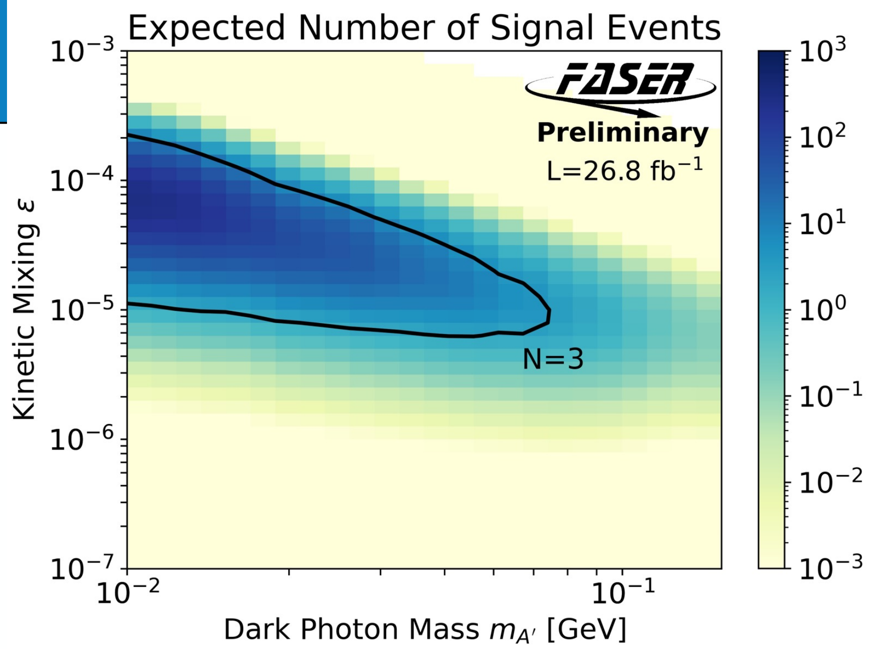


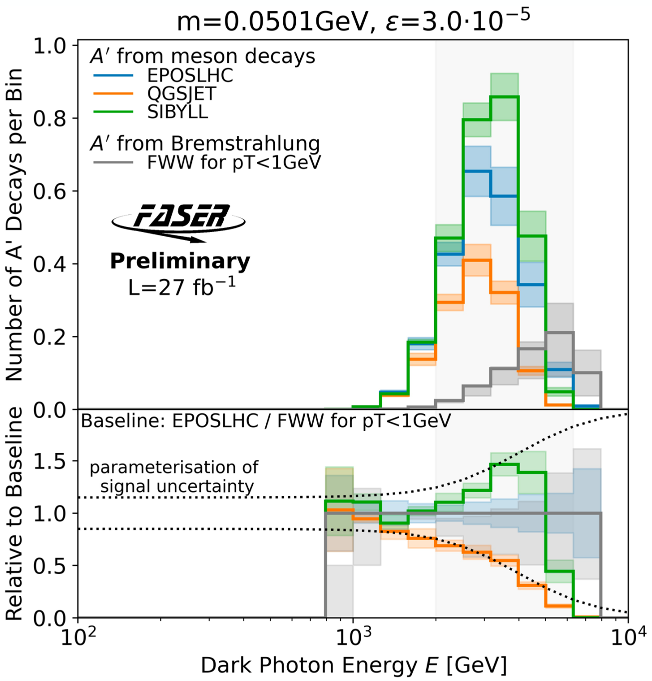
Dark Photon Signal

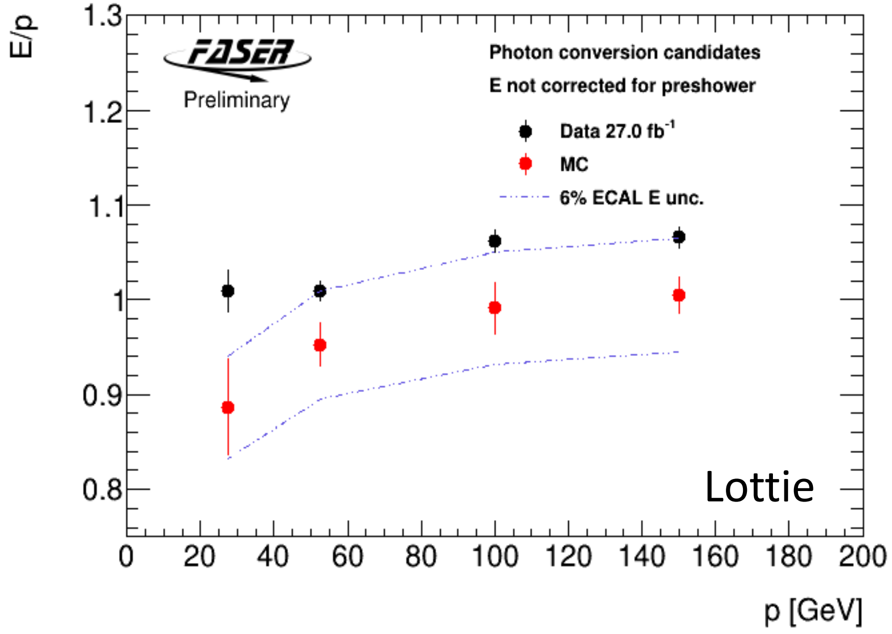
- A′ → e^+e^- decays in FASER volume simulated with FORESEE
  - π^0 and η via EPOS-LHC generator
  - Subdominant dark bremstrahlung via FWW
- Generator uncertainty from difference to QGSJET/SIBYLL
  - Parameterised based on A′ energy

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

- 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





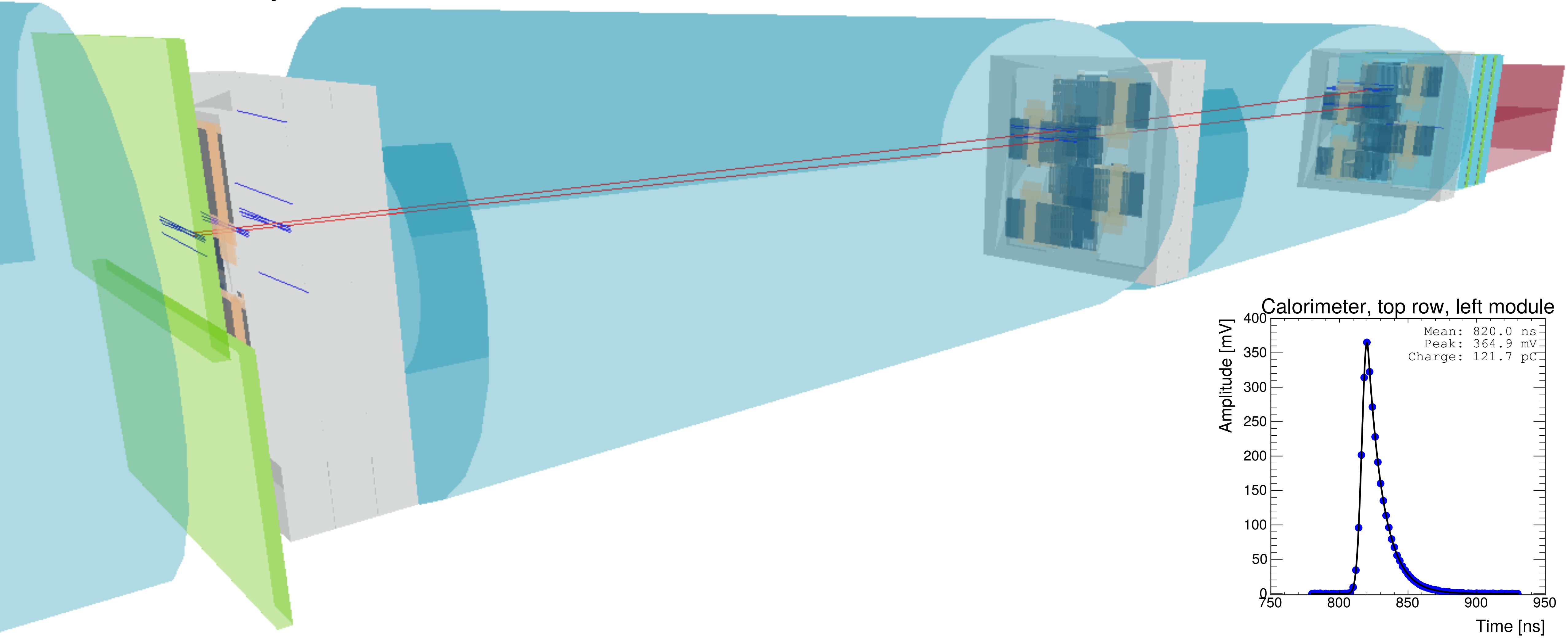


Dark Photon: Event Display (1)

Simulation Preliminary

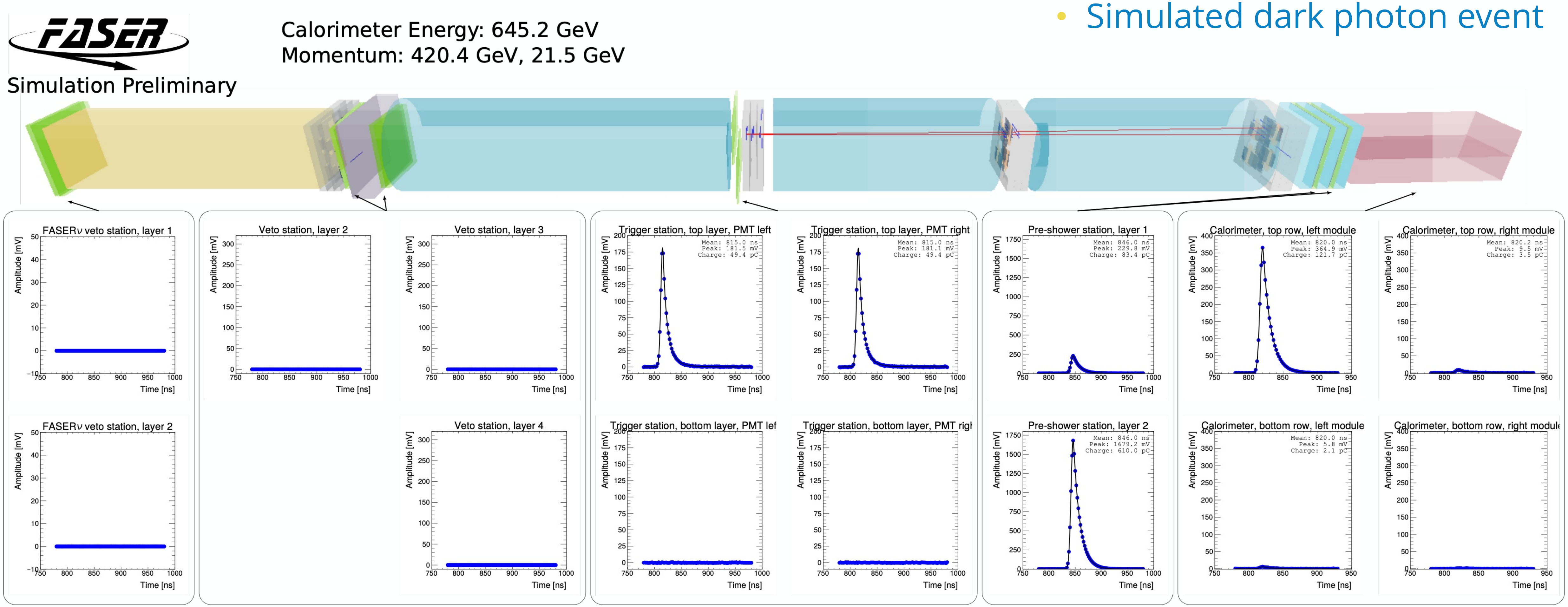
Calorimeter Energy: 645.2 GeV
Momentum: 420.4 GeV, 21.5 GeV

- Simulated dark photon event



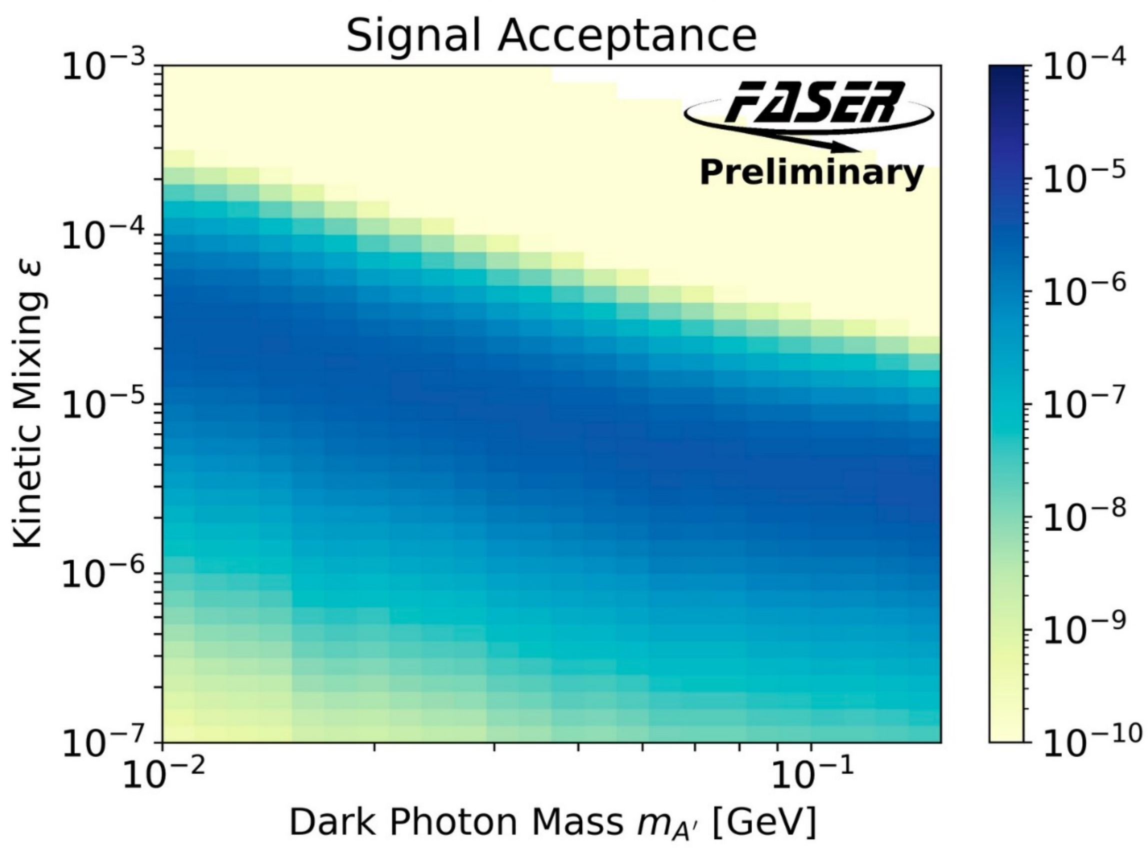
Dark Photon: Event Display (2)

- Simulated dark photon event



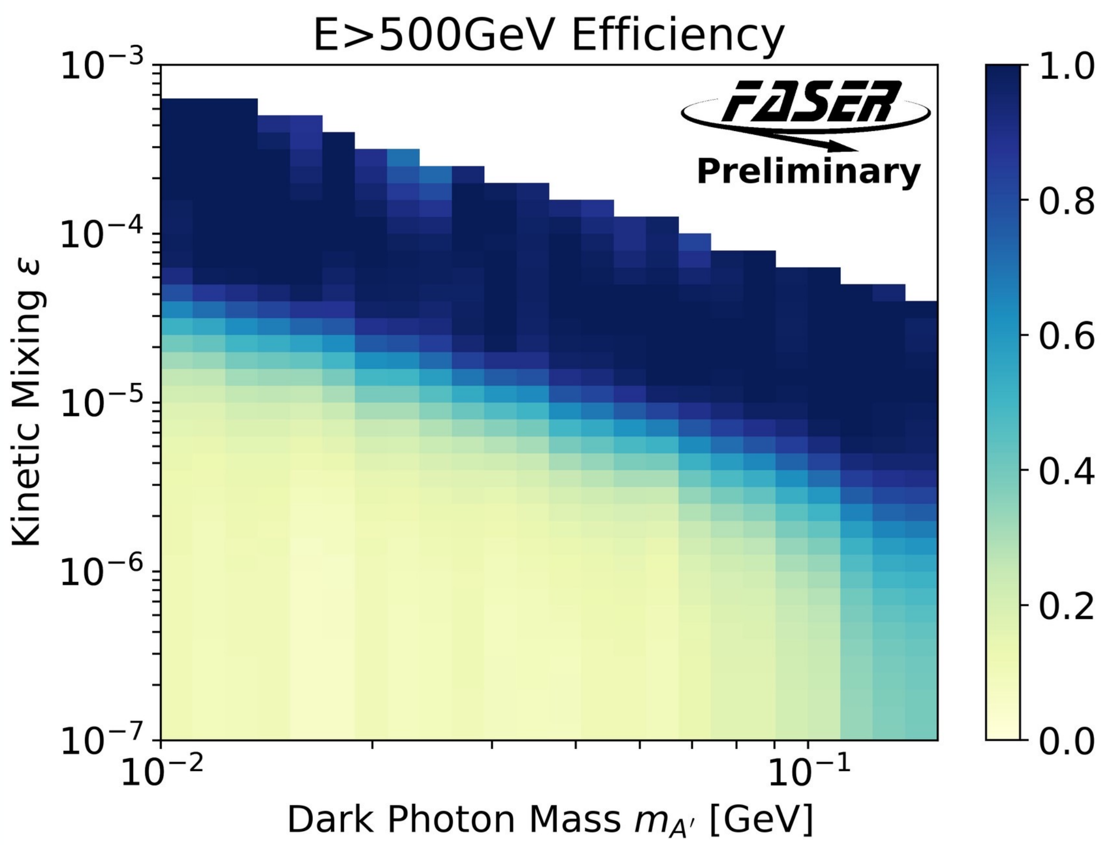
Dark Photon: Signal Acceptance x Efficiency

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



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

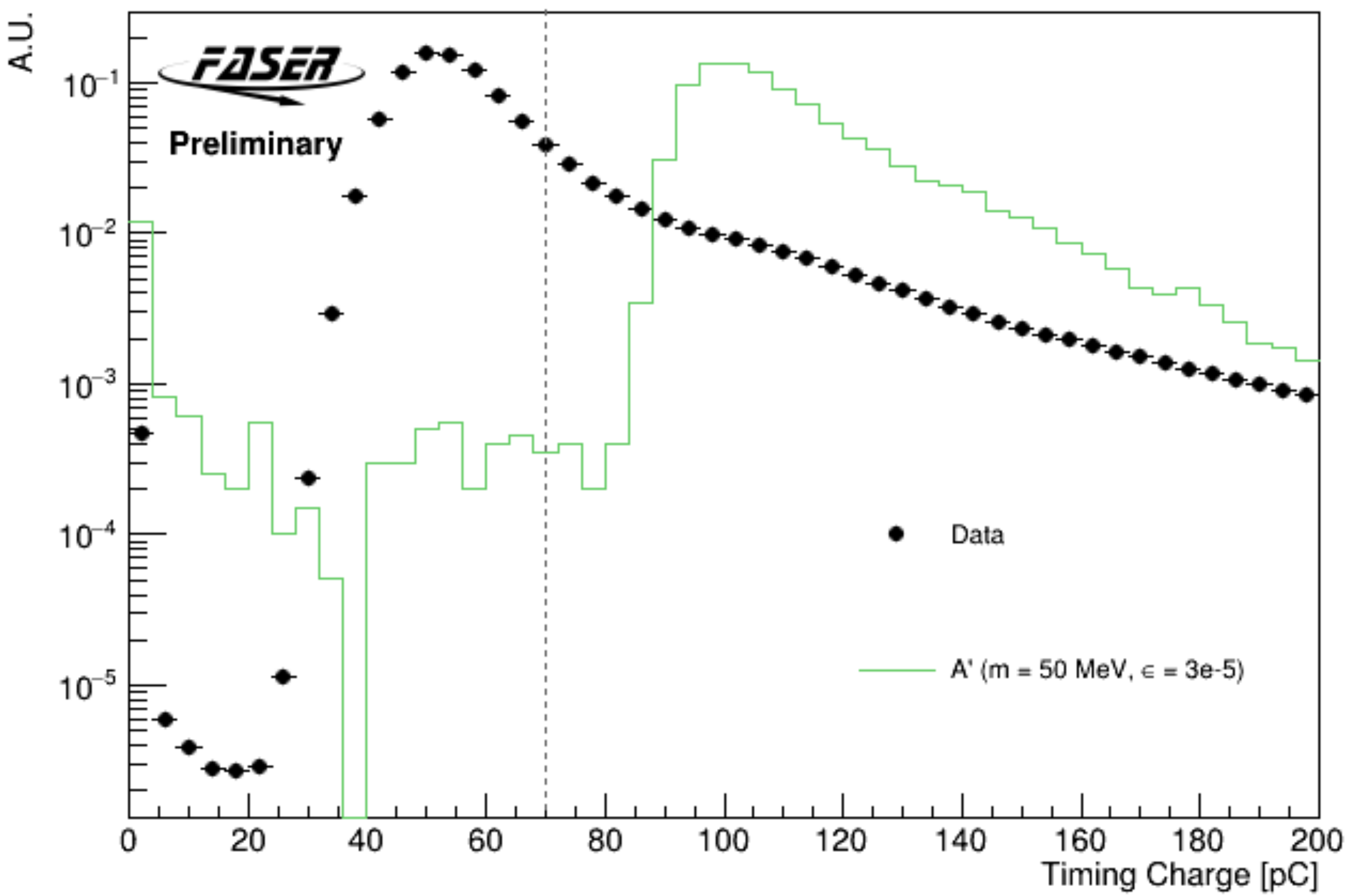
- Efficiency of calorimeter E > 500 GeV
  - For A′ decaying in FASER decay volume



- 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

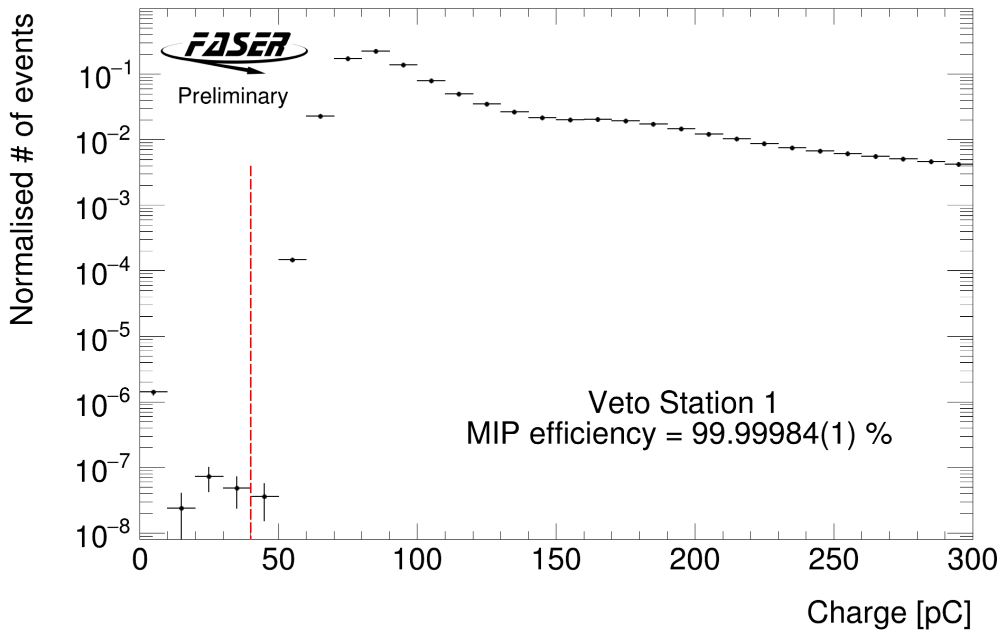
- Efficiency of analysis selection for data and example signal
  - Note the data was preselected to have ≥ 1 track (no quality cuts) in the event

- Overall signal efficiency ≈ 40 %
  - While reducing background to 0

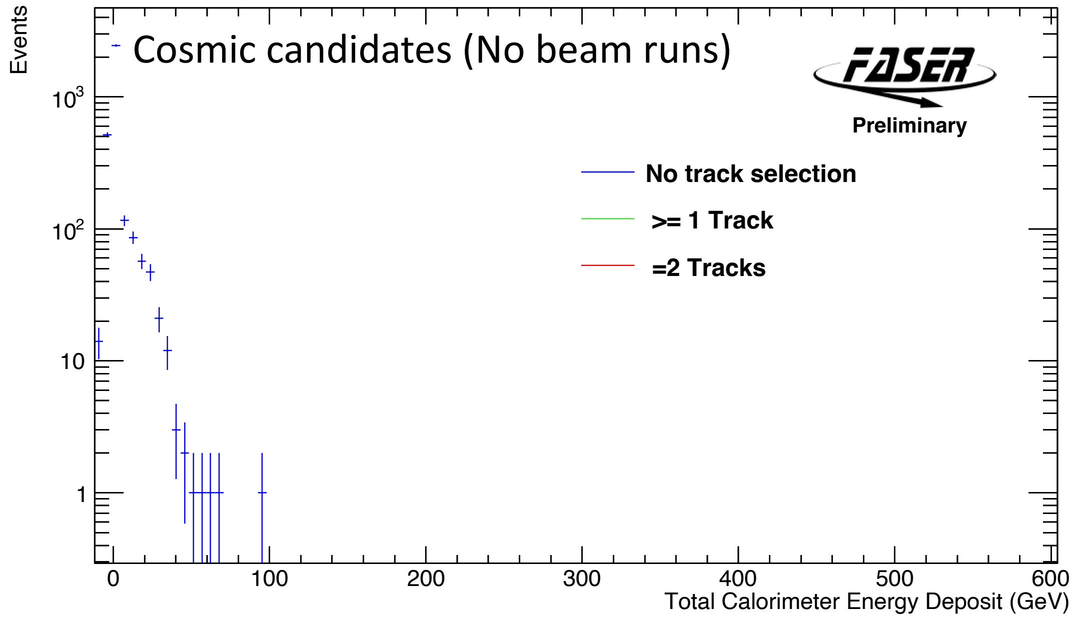
Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\mathrm{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good 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 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)



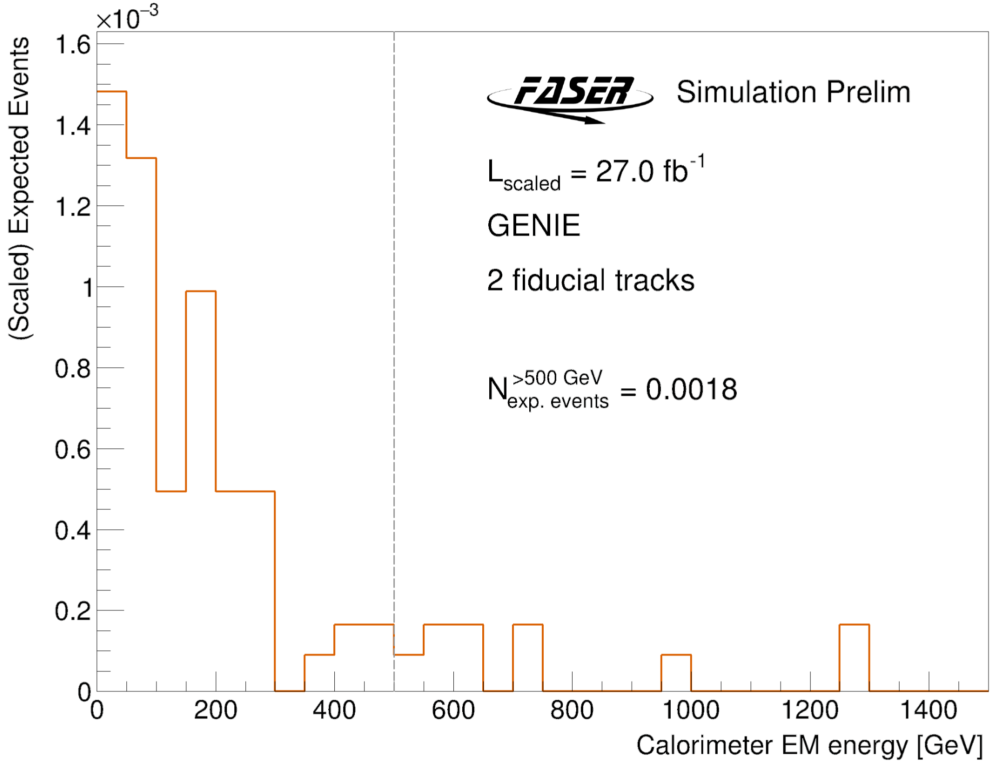
- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually



Dark Photon Backgrounds (2)

- Main background is from neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab^{-1})
    - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

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



- Neutral hadrons (e.g. K_S) 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)
    - Decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

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

- Total background prediction

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

Dark Photon: Neutral Hadron Background Details

- 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 FASERν and fire veto
  - Hence scale the neutral hardon events with Ecal > 500 GeV by fraction of 3-track events decaying after veto → $(2.2 \pm 3.1) \times 10^{-4}$

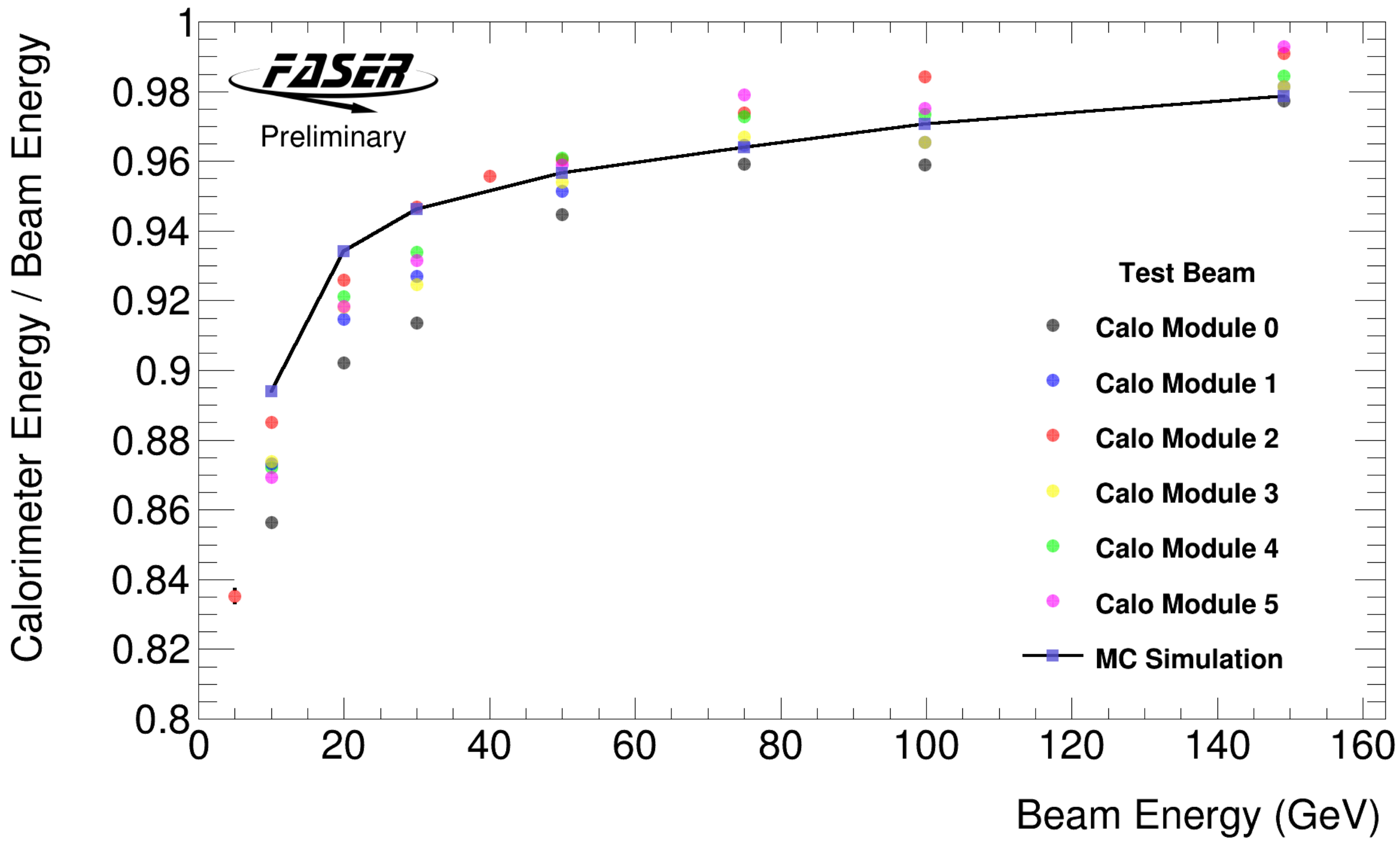
Dark Photon: Systematic Uncertainties Summary

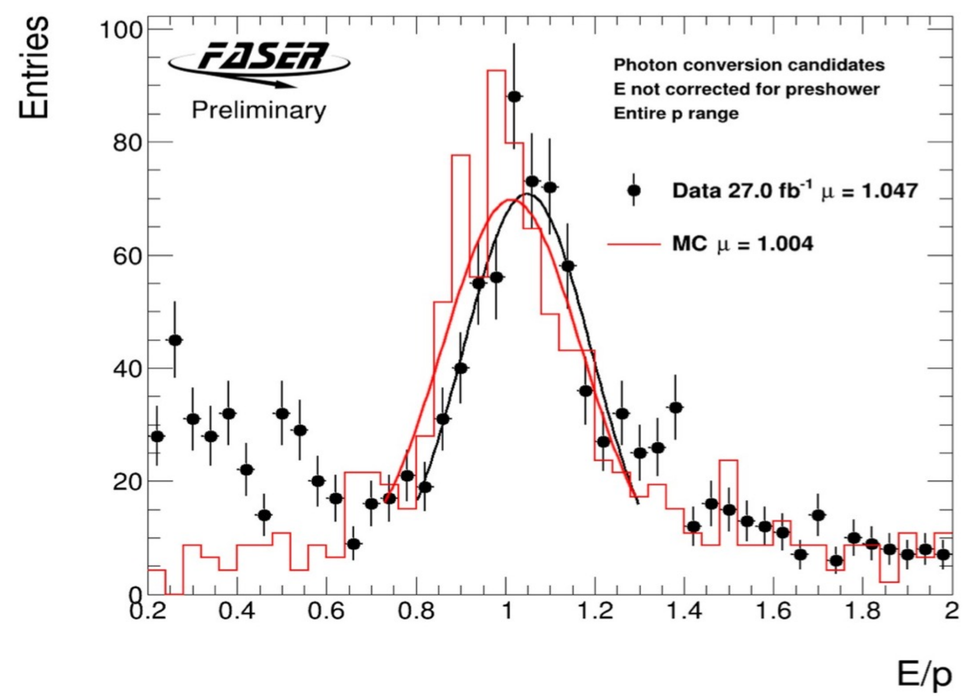
- Complete list of systematic uncertainties and their impact on the signal yield
  - Numbers in parenthesis are the effect on signal in previous unexcluded FASER reach

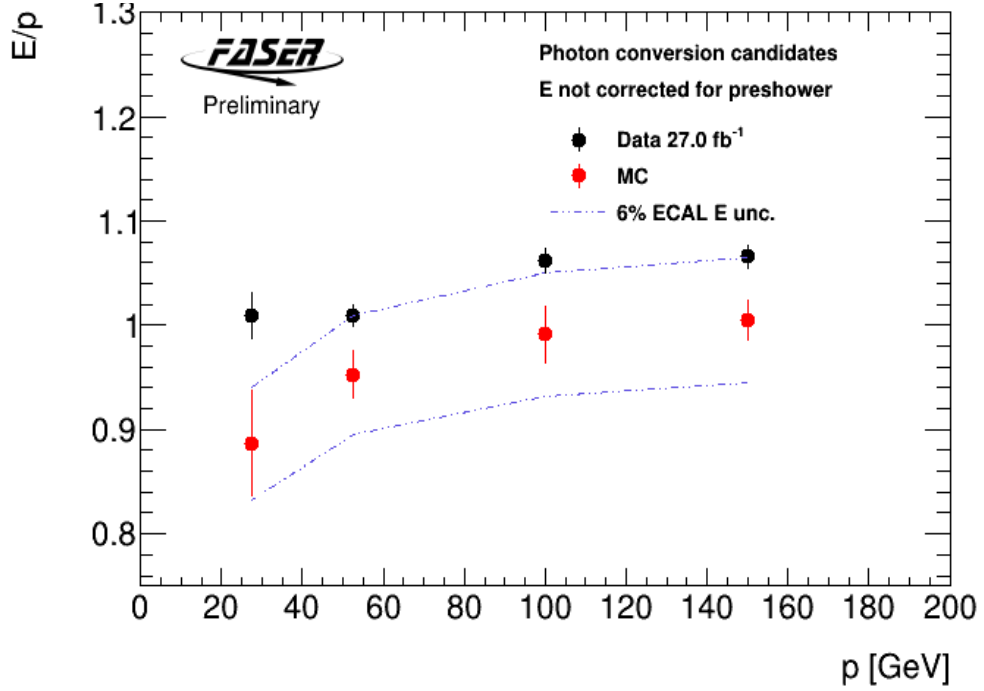
Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	$< 0.5\%$
Momentum Resolution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



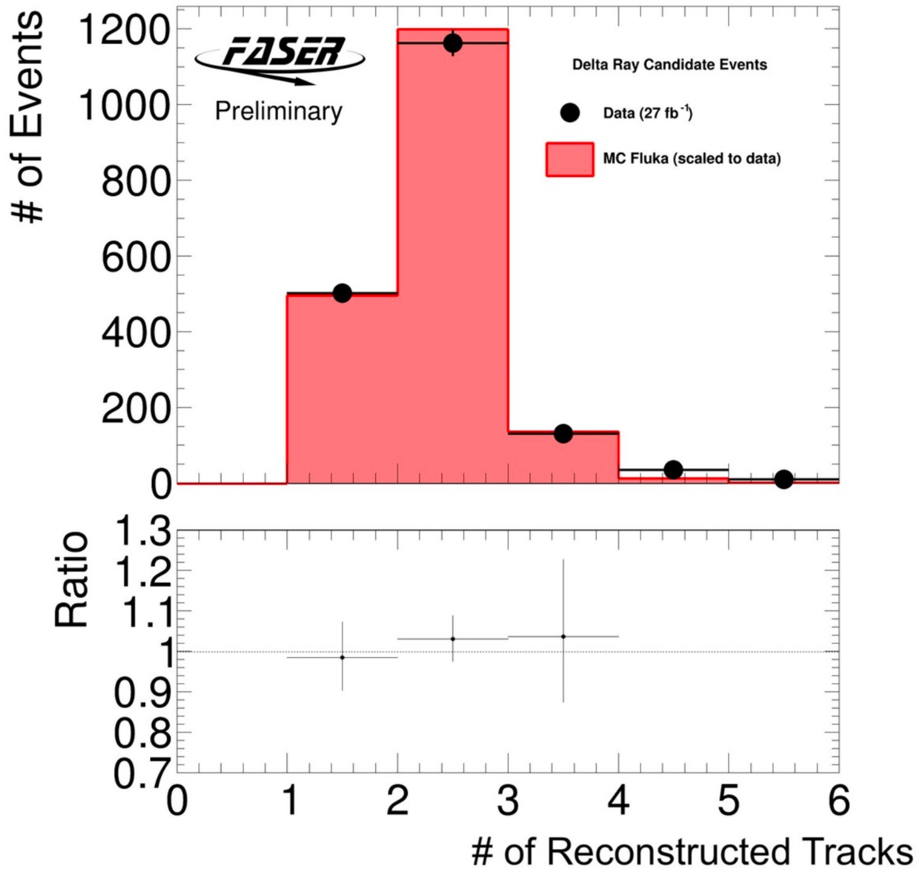


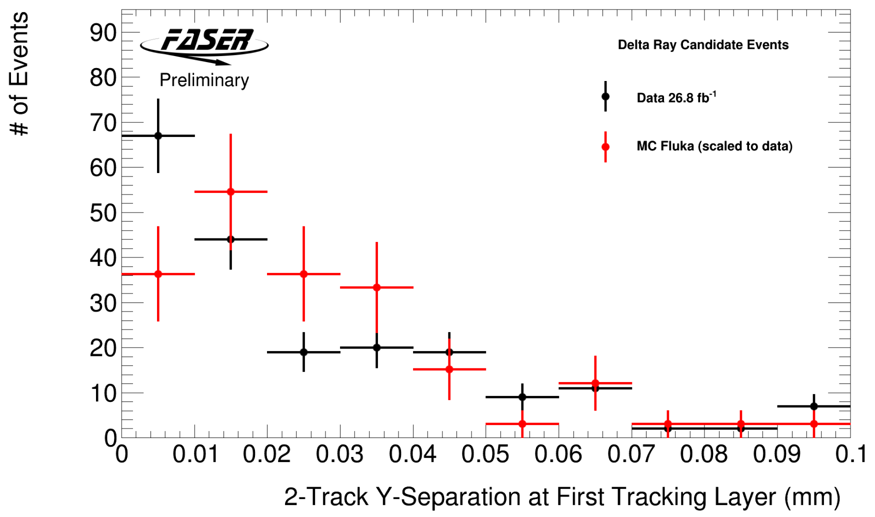


Dark Photon: Tracking Systematics

- 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:
  1. 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
  2. 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

Tracks in delta-ray like events



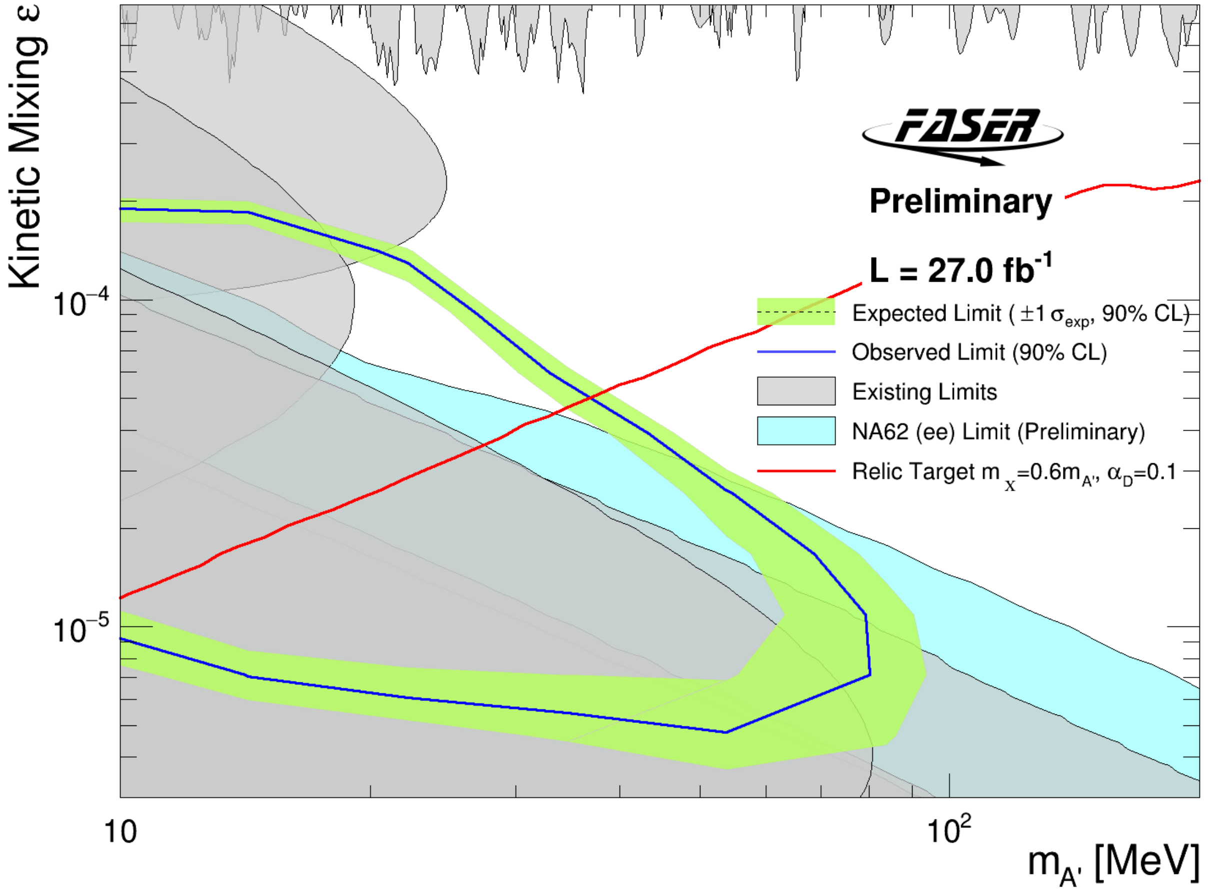


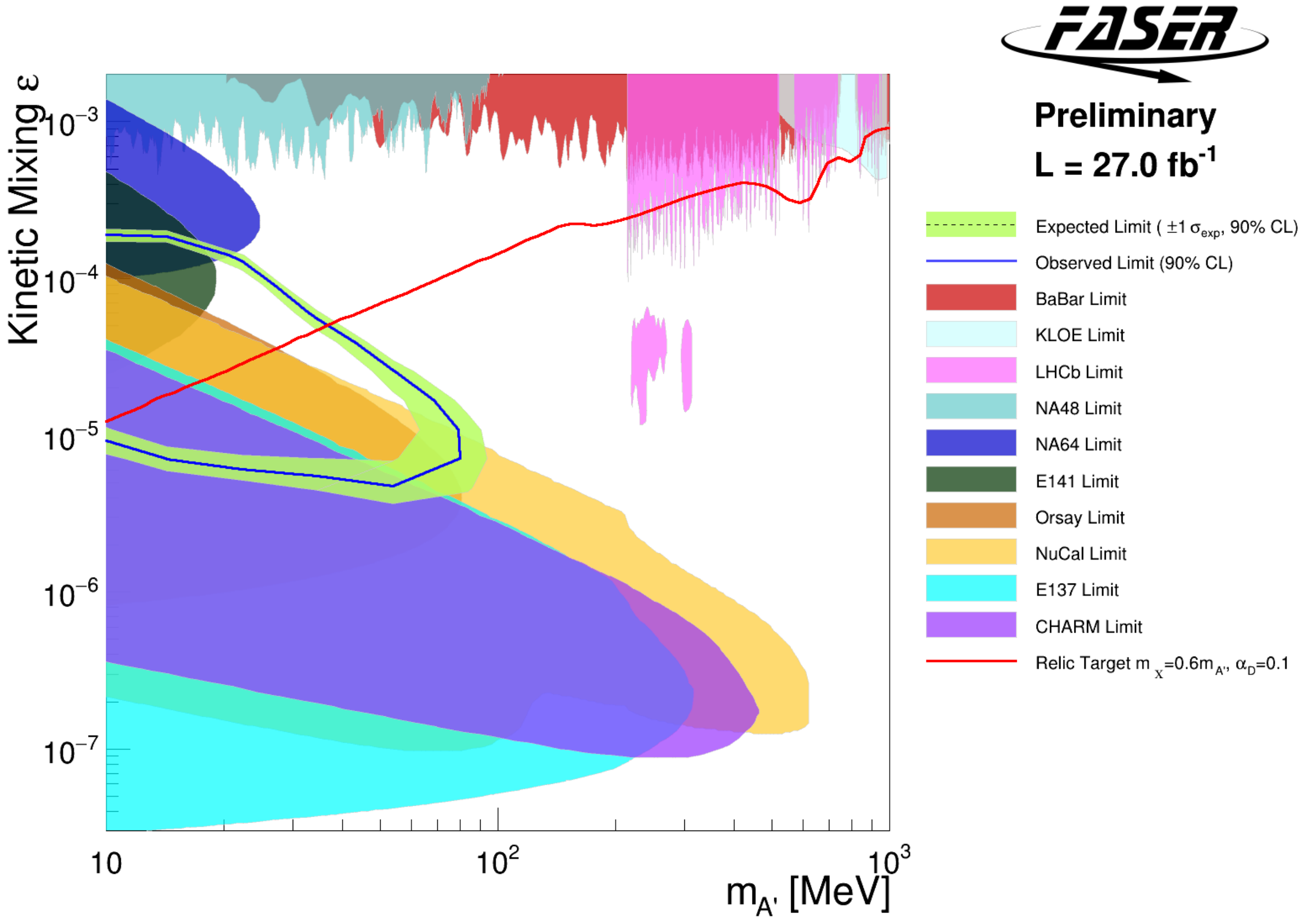
Two-track separation in delta-ray like events

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





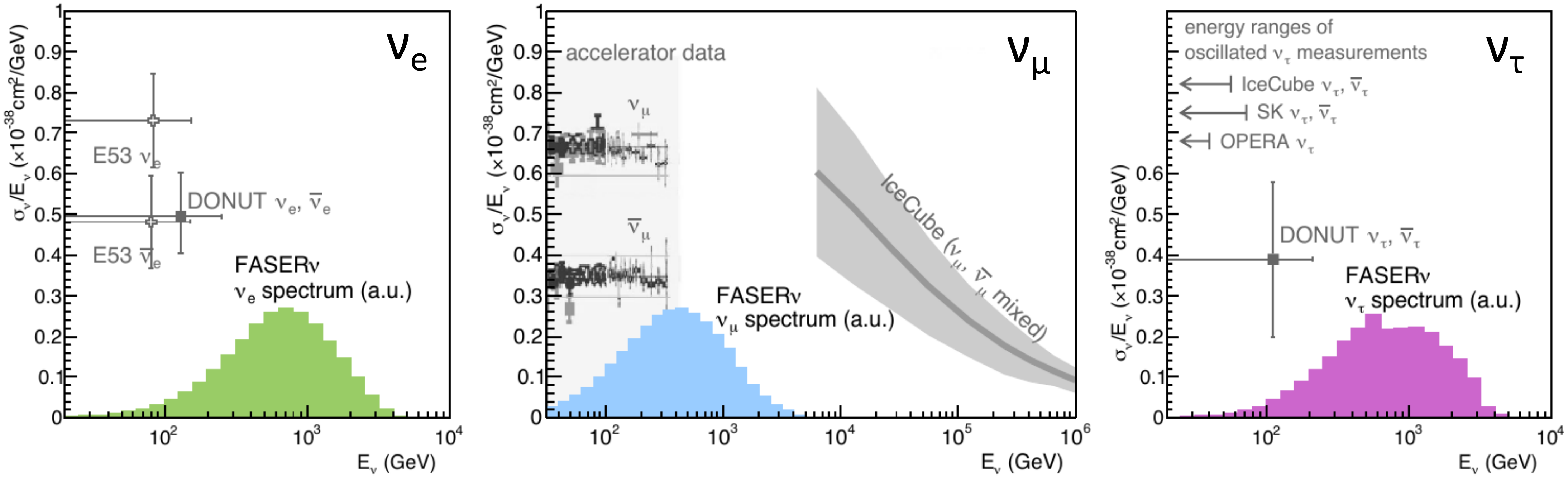
- Note FASER limits very similar at 95% CL and 90% CL

Collider Neutrinos

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → 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

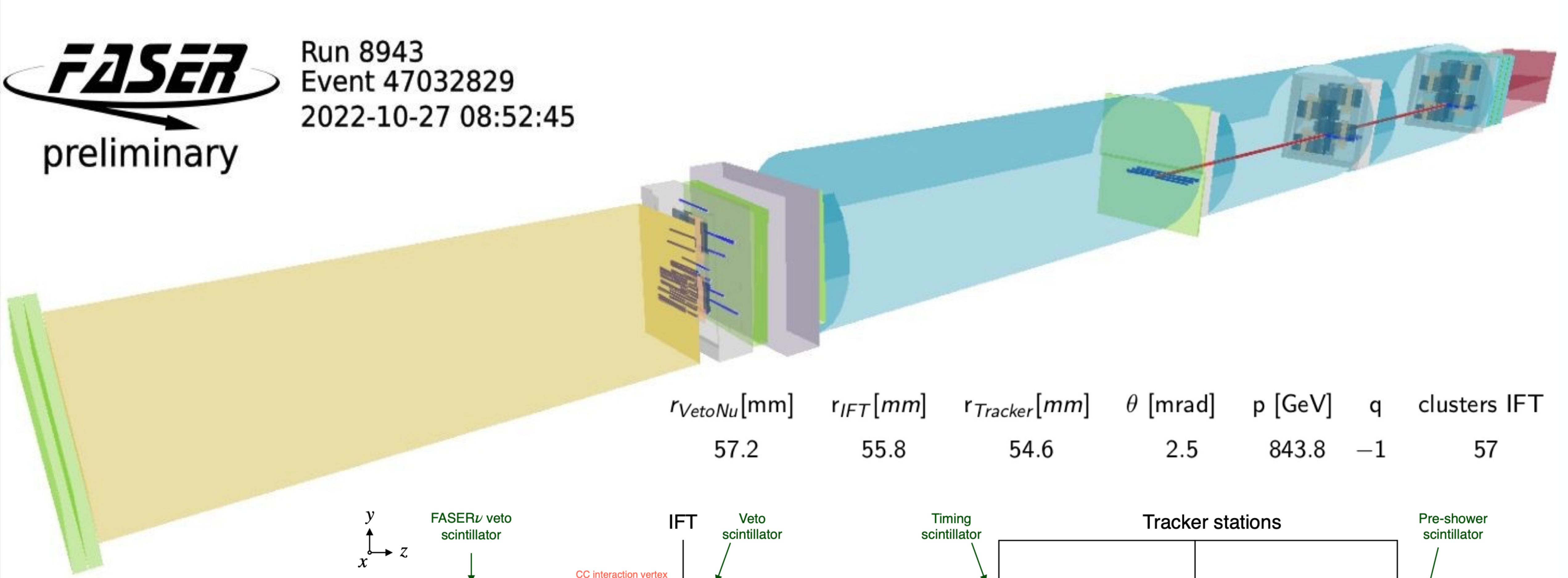
For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERν	~10^{10}	~10^{11}	~10^{8}
# interacting in FASERν	≈200	≈1200	≈4

PRD 104, 113008



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

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

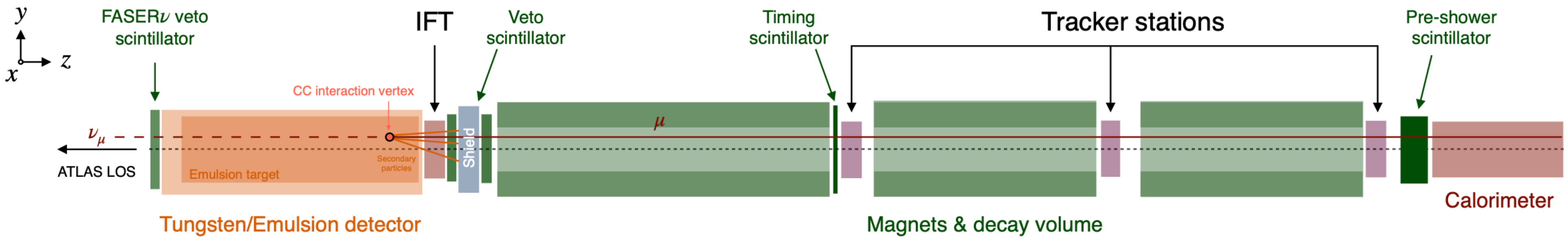
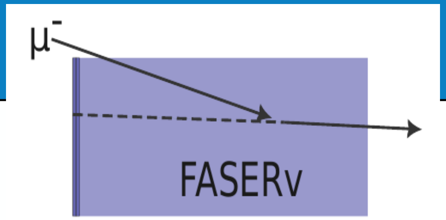
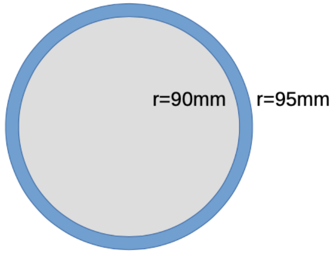


FIG. 1. Illustration of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion target.

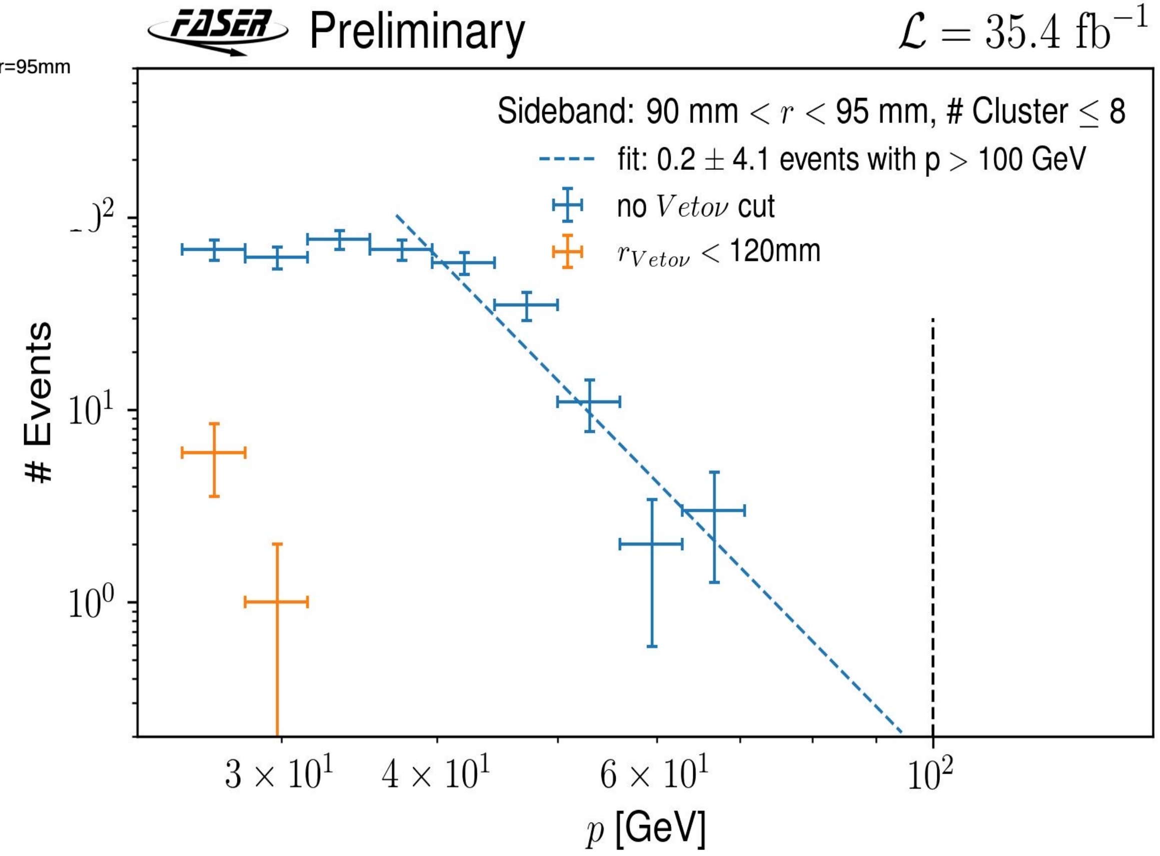
Neutrinos: Geometric Background



- 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

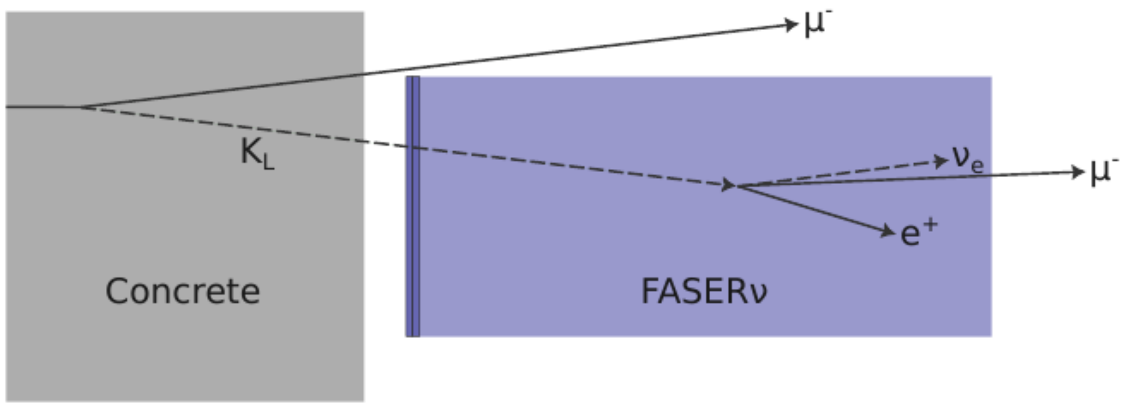


- Fit mom. to extrapolate to p > 100 GeV
- Scale to rate of events with r_{VetoNu} < 120 mm
  - 0 events so use 5.9 events as 3σ upper limit
- Scale from anulus to full acceptance
  - Using large angle muon simulation
- Expect 0.08 ± 1.83 events



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 background and the extrapolation factor

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

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

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

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

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.

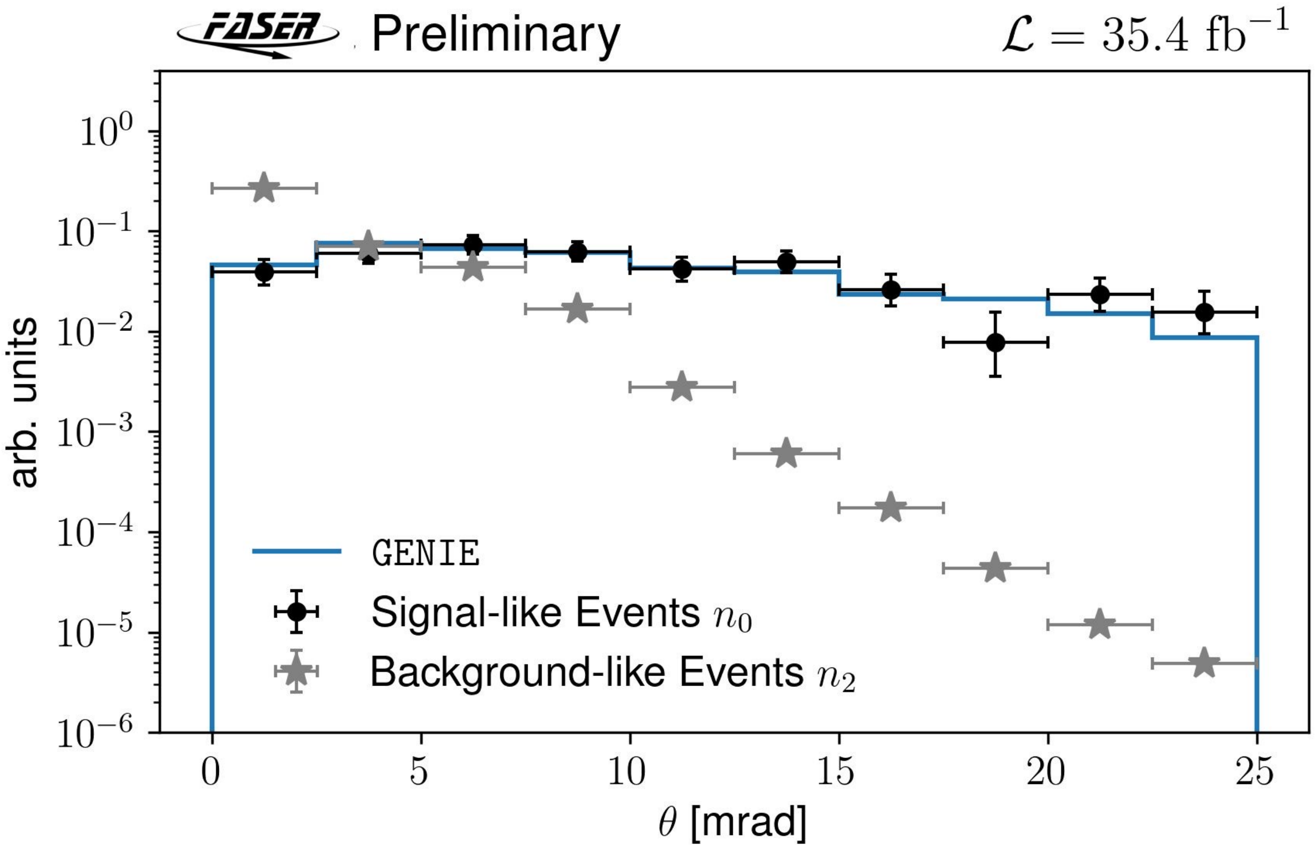
n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

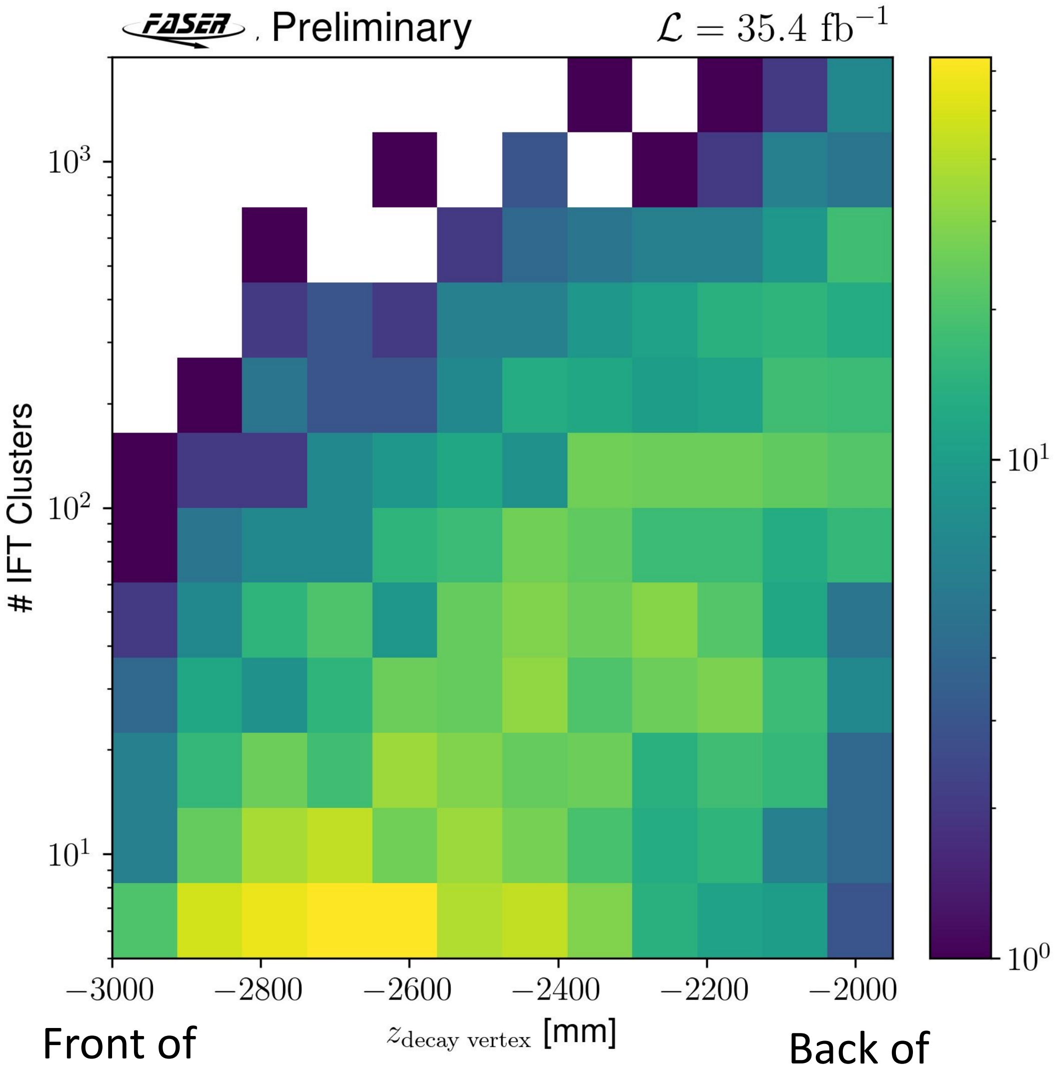
n_2: Events for which both layers observe more than 40 pC of charge.

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

FASER Collaboration

- 87 members across 24 institutes from 10 countries

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