First Physics Results from the FASER Experiment

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19 March 2023

57th Recontres de Moriond

HEISING-SIMONS FOUNDATION

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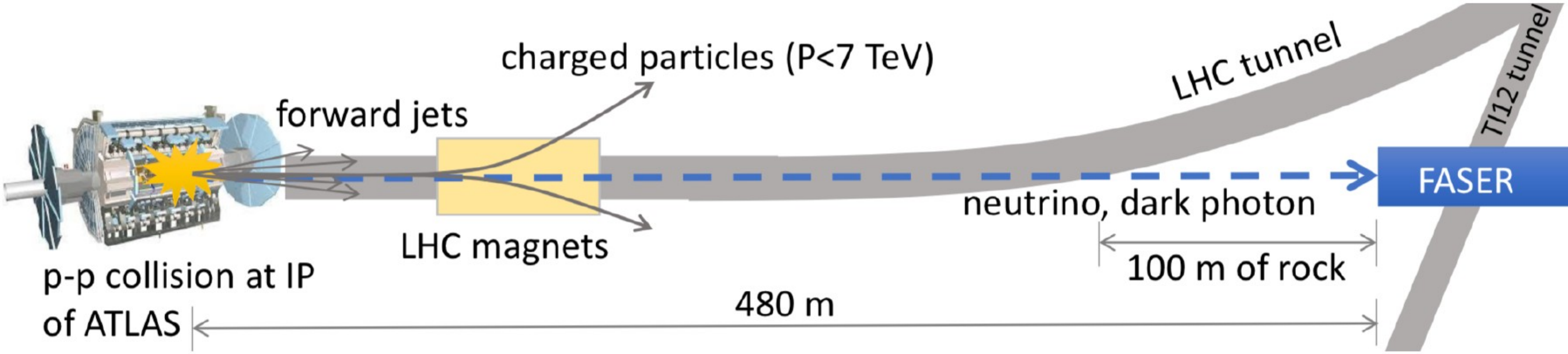
The FASER Experiment

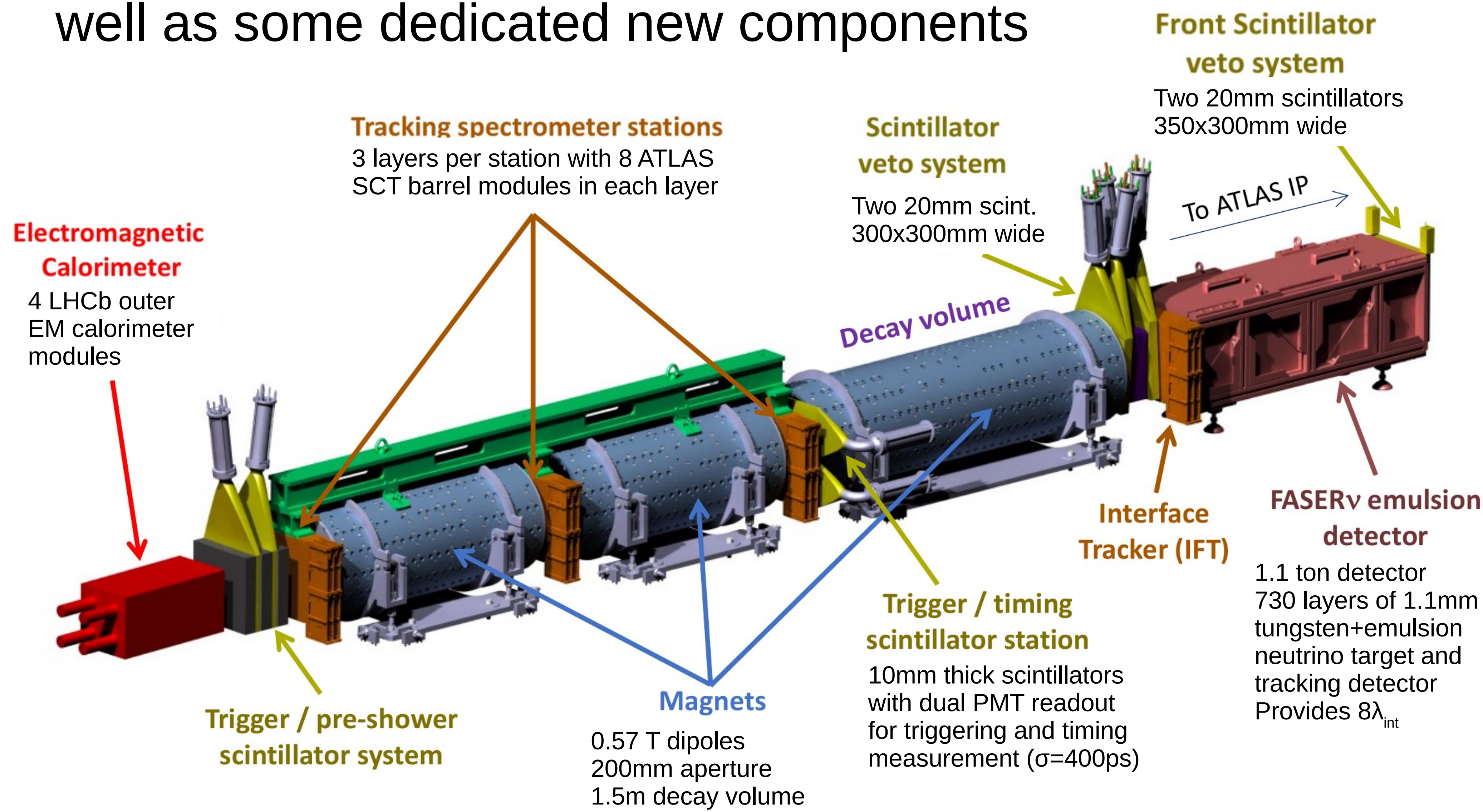
- FASER is new, small experiment at the LHC
  - Constructed and installed in 2019-2021
- FASER targets light and weakly coupled particles
  - Exploits large LHC collision rate and highly collimated forward production of light particles, for instance in pion decays
    - 1% of pions with E>10 GeV produced at η>9.2
  - Designed to detect both new long-lived BSM particles, such as dark photons and ALPs as well as neutrinos
- Located 480m from ATLAS interaction point
  - LHC magnets as well 100m of rock shields most backgrounds



arxiv: 2207.11427

FASER Detector

Experiment built from existing spare parts as well as some dedicated new components

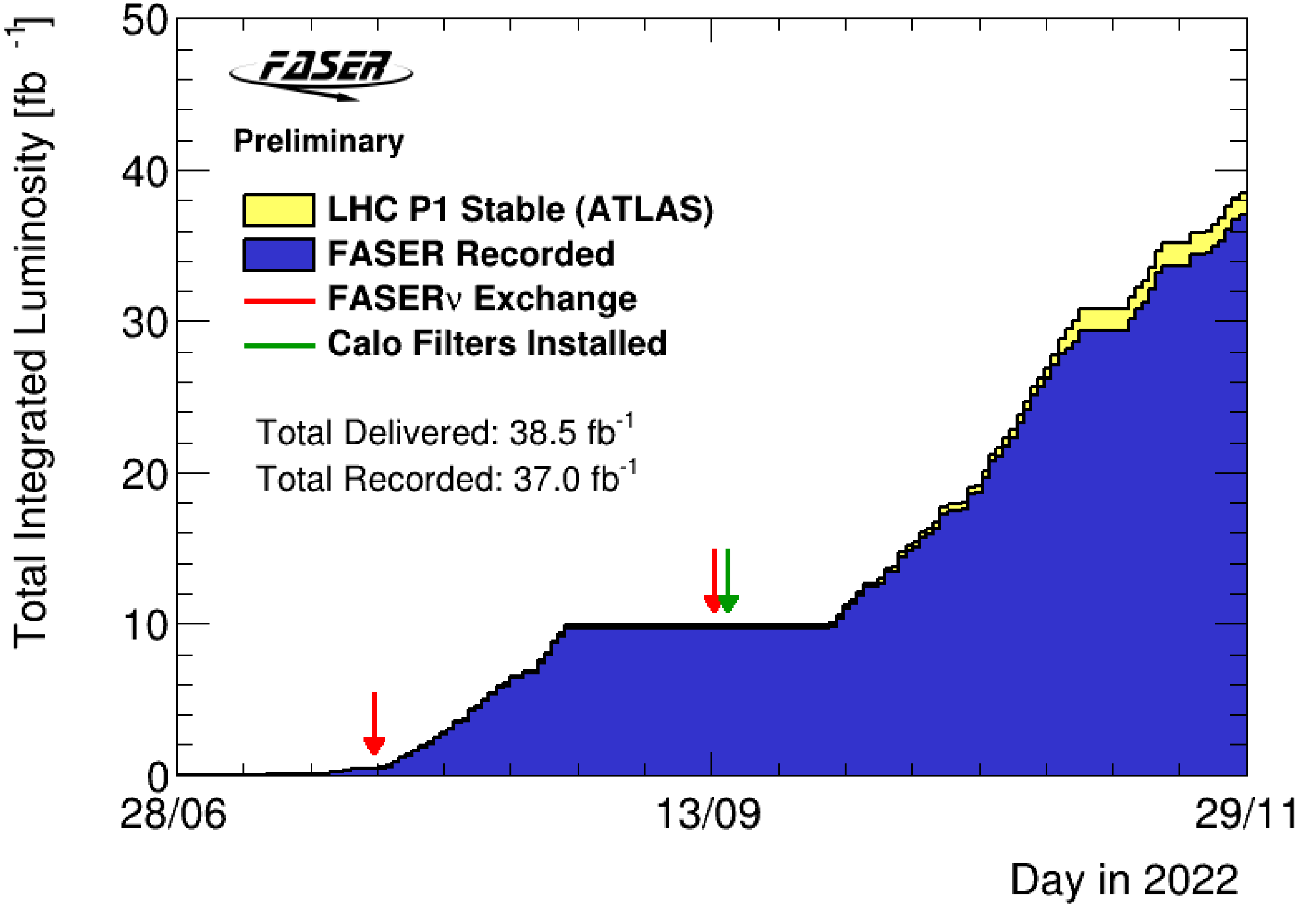


FASER Installation

- Experiment mostly installed in March 2021
- Fully completed in November 2021, ahead of Run 3

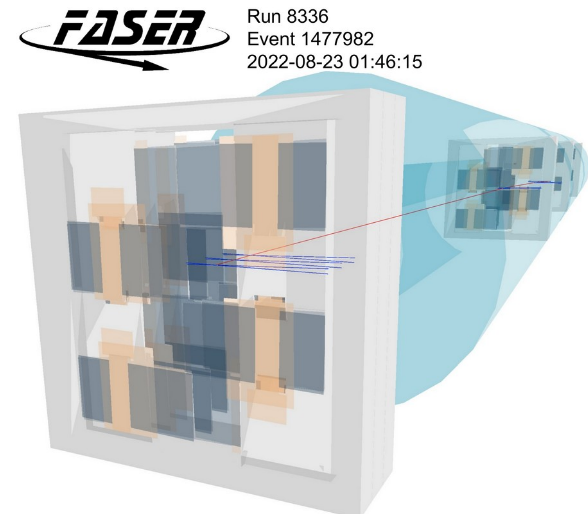
FASER Operations

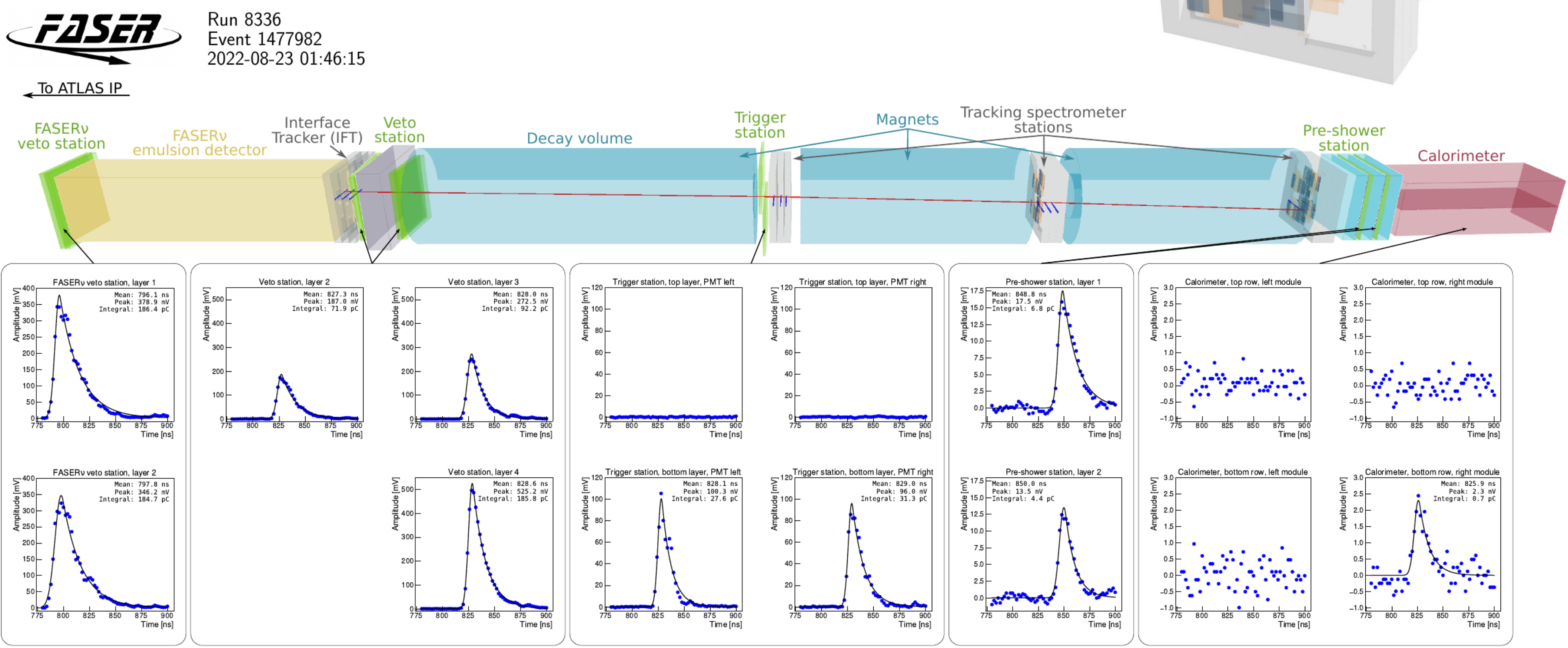
- Successfully operated during all of 2022
  - Continuous and largely automatic data-taking at up to 1.3 kHz
- Recorded 96.1% of delivered luminosity
  - DAQ dead time of 1.3%, rest lost to a couple of DAQ crashes
- Emulsion detector exchanged twice to manage bkgd occupancy
  - First box was only partially filled with emulsion
- Calorimeter gain was optimized for low energy (<300 GeV) until second exchange



Example Collision Event

- Muon traversing full detector
  - More than 350 million such events recorded
- All parts of detector working very well





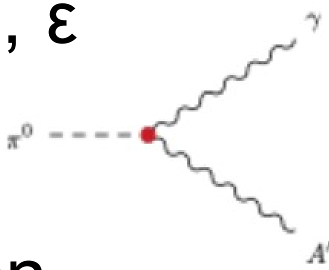
Search for Dark Photons

- Dark Photon common feature of hidden sector models where hidden gauge boson can mix with SM photons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^2 + \sum_f \bar{f}(i\,\partial\!\!\!/ - eq_f\,A\!\!\!/ - \epsilon e q_f\,A\!\!\!/' - m_f)f$$

- MeV-scale dark photons, A', are produced copiously in meson decays depending on kinematic mixing, ε

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



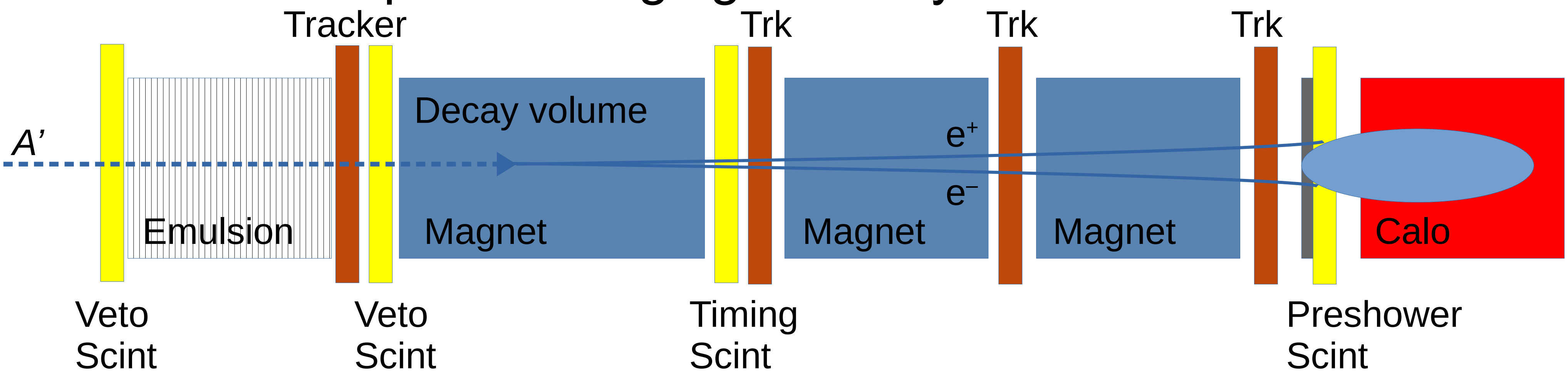
- At small coupling, high energy in forward region, results in long decay lengths – ideal for FASER

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

- For $1<m_{A'}<211$ MeV, will decay 100% to e^+e^- pair

Dark Photon Event Selection

- Select e^+e^- pairs emerging in decay volume



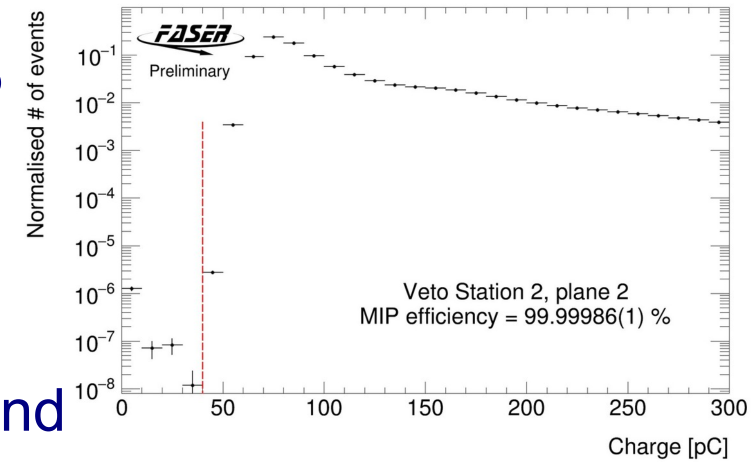
- Simple, robust selection criteria optimized for discovery
  - Events in collision crossing, during good physics data period
  - No signal in any of five veto scintillators (<40 pC ~ 0.5 MIP)
  - Timing and preshower scintillators consistent with ≥2 MIPs
  - Exactly two good quality tracks with p>20 GeV
  - Both tracks in fiducial tracking volume, r_{max}<95mm
  - Both tracks extrapolate to r<95mm in veto scintillators
  - Calorimeter energy above 500 GeV
- Signal efficiency of 40-45% in most interesting region

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

Background Estimates

- Veto inefficiency
  - Veto layer scintillators efficiency >99.998%
  - Measured layer-by-layer using muon tracks in spectrometer pointing back
    - Layer inefficiencies uncorrelated
  - With five layers, even 10^8 muons going through veto produces negligible background even before any other selections applied

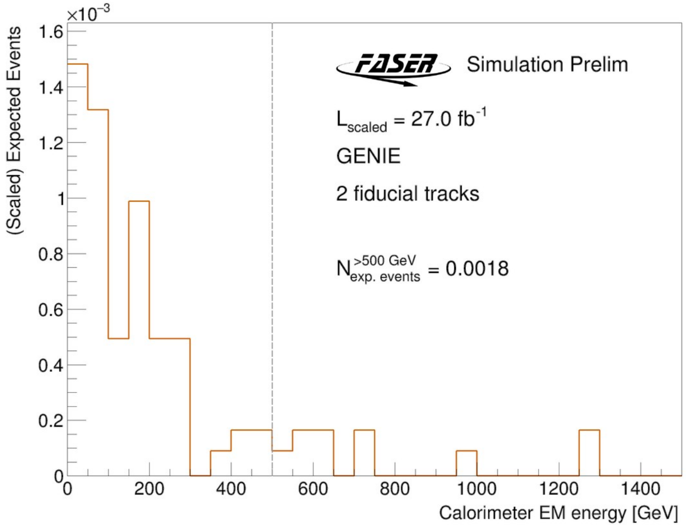
Veto layer efficiency



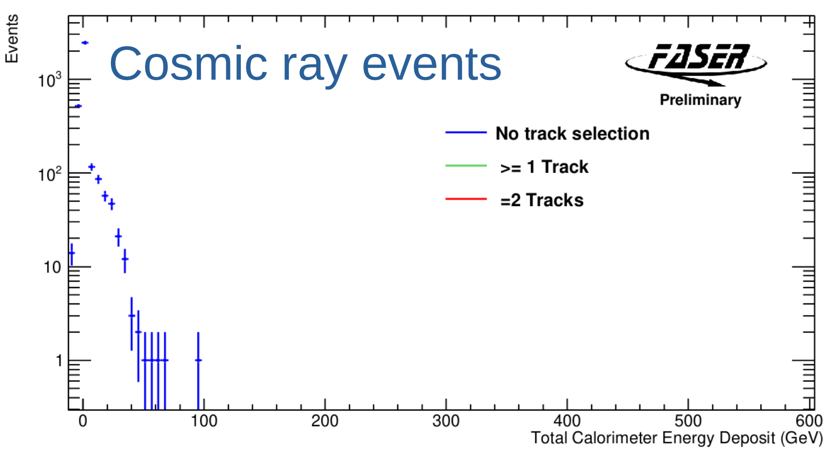
- Background from neutral hadrons from upstream muon interactions decaying in decay volume
  - Heavily suppressed:
    - Muons nearly always continues after interaction
    - Hadron has to pass through eight interactions lengths of tungsten
    - Hadron decay products has to leave >500 GeV in calorimeter
  - Background estimated using lower energy events with two and three tracks reconstructed and different veto conditions
  - Estimated background: $(2.2\pm3.1)\times10^{-4}$

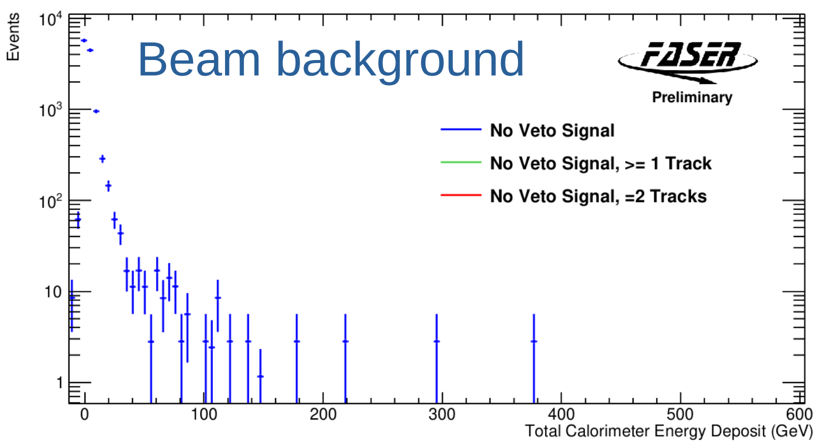
Background Estimates

- Neutrino background estimated from simulation
  - Using GENIE generator (300 ab-1)
  - With uncertainties for mismodelling and neutrino flux: 0.0018±0.0024 events
    - Mainly in trigger/timing scintillator
    - *Largest background in analysis*
  - Background from neutrino induced hadrons upstream found to be negligible



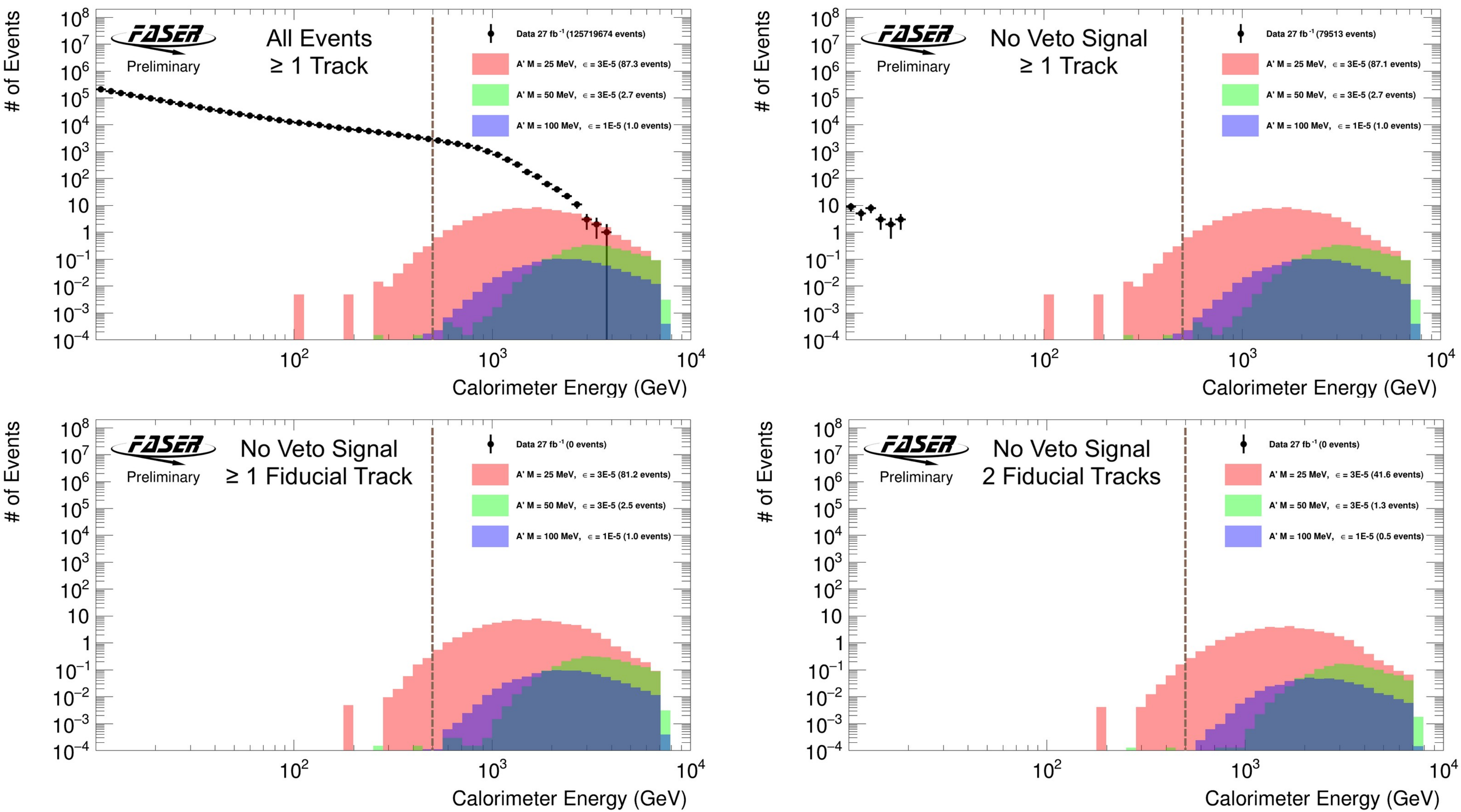
- Non-collision background from cosmics and near-by beam debris is negligible
  - Studied in non-colliding bunches and runs without beam
  - No such events seen with E>500 GeV or a reconstructed track





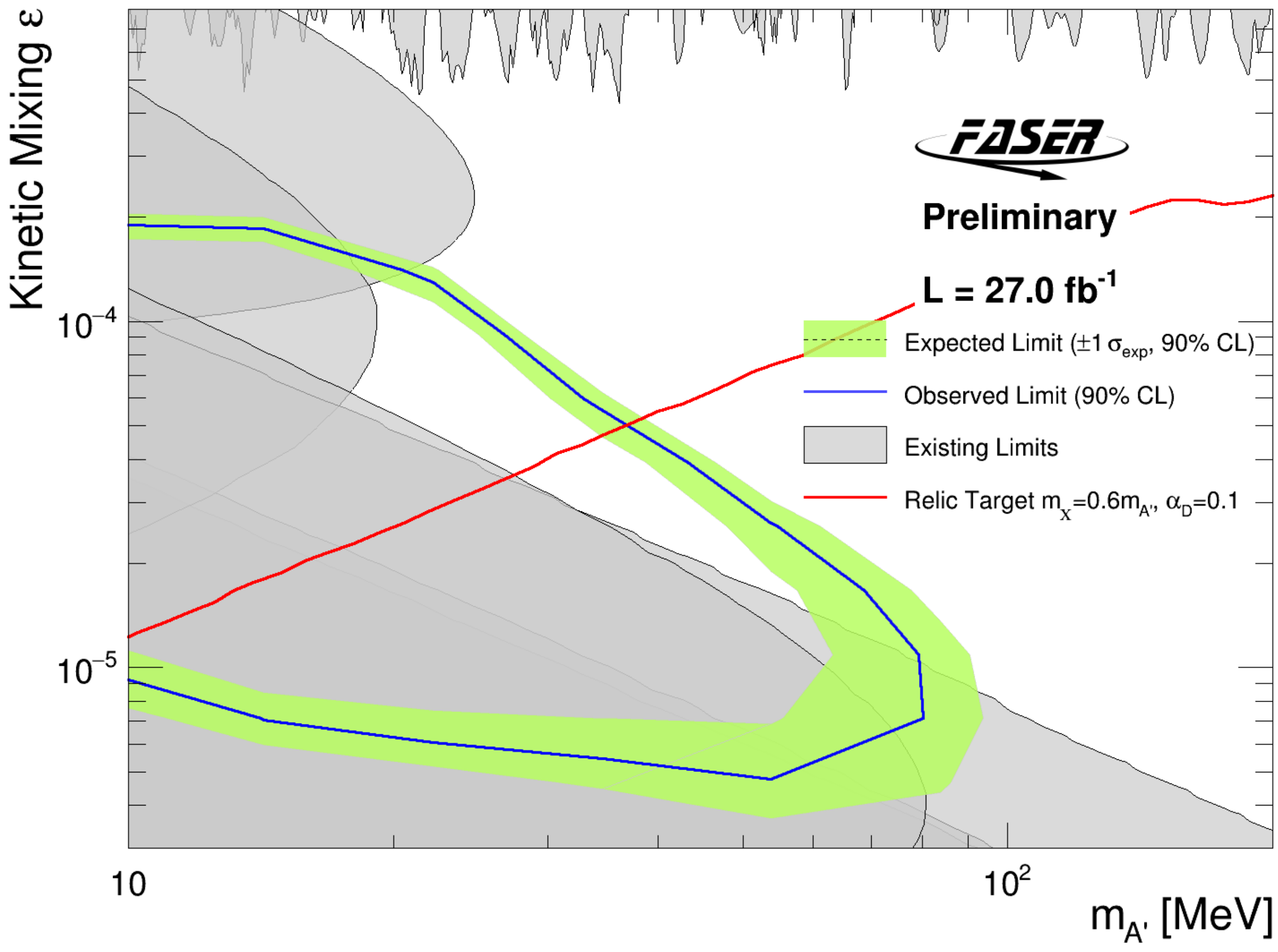
Dark Photon - data

- Total background: 0.0020±0.0024 evts
- No events seen in unblinded signal region



Dark Photon Exclusion

- With null-result, FASER sets limits on previously unexplored parameter space
  - Extends exclusion into region motivated by dark matter

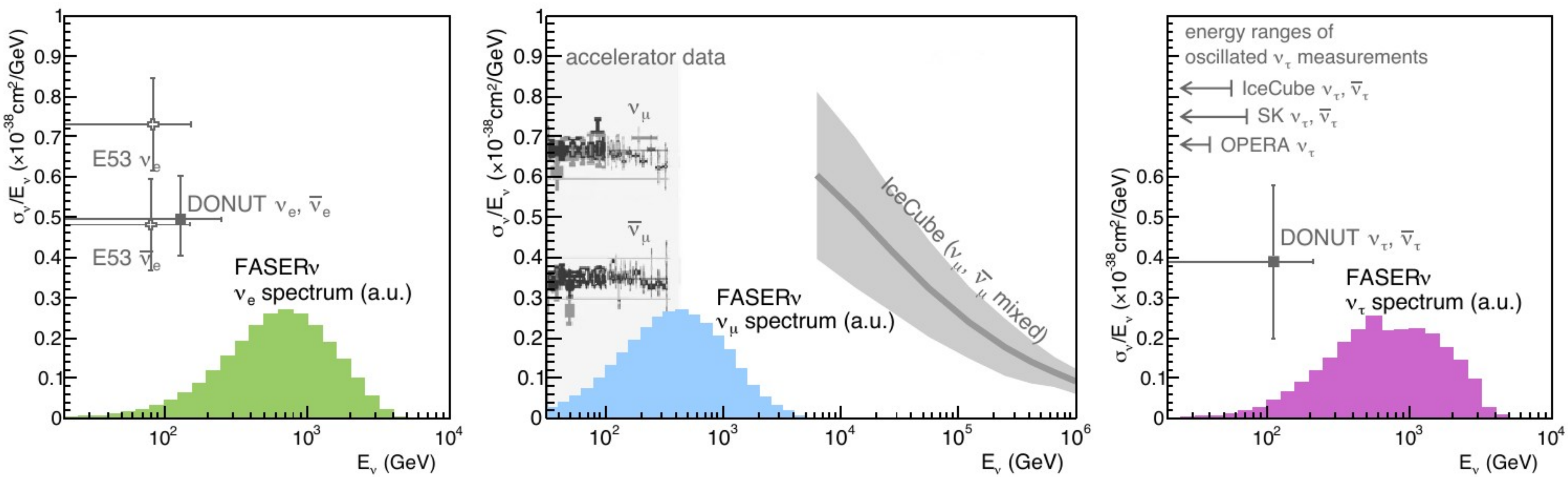


Neutrinos in FASER

Phys. Rev. D 104, 113008

For 35/fb	ν_e	ν_μ	ν_τ
Main source	Kaon decay	Pion decay	Charm decay
#Traversing FASERν	O(10^{10})	O(10^{11})	O(10^{8})
#Interacting in FASERν	~200	~1200	~4

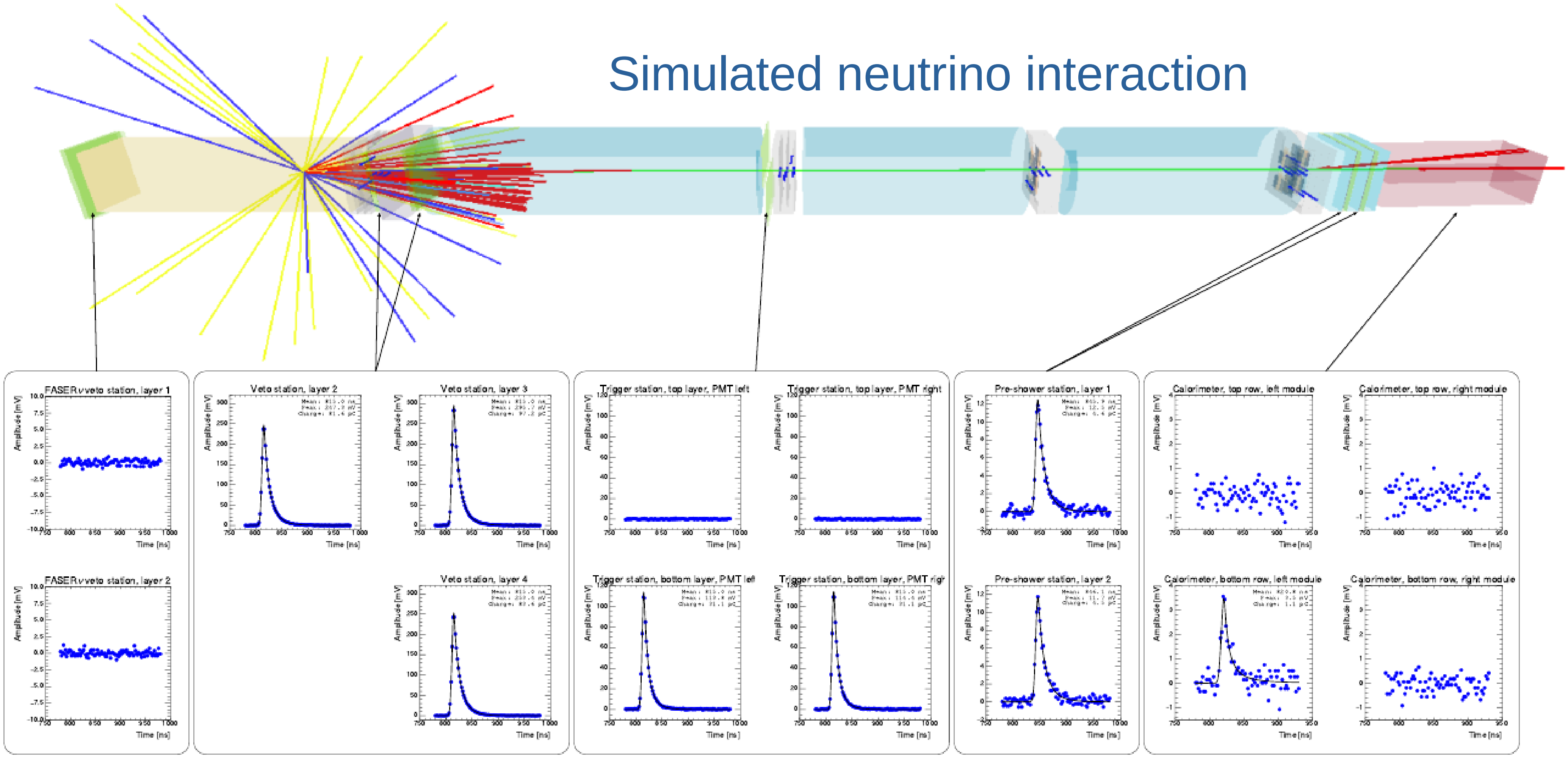
- Large production of neutrinos decays of forward hadrons
  - Very energetic (TeV scale) and thus have high interaction xsection
- Extends FASER physics program with SM measurements
- Neutrino energy spectrum in FASER complementary to existing neutrino experiments
  - Measurement at highest man-made neutrino energies



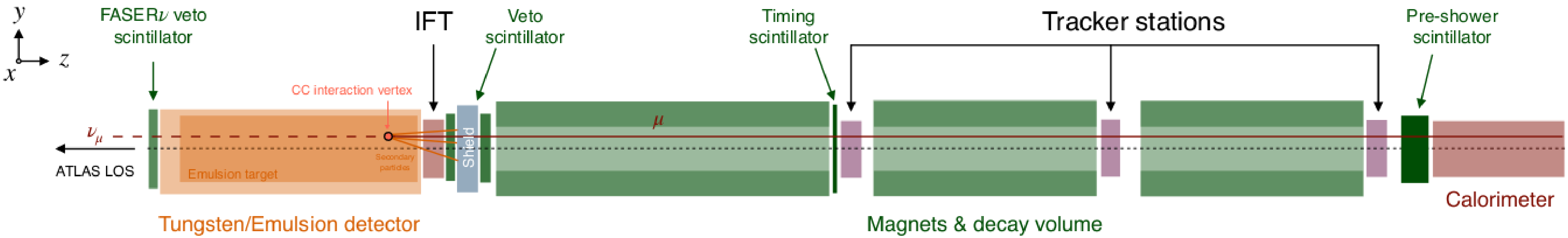
Originally proposed by De Rujula and Ruckl in 1984!

Observing Neutrinos 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 veto and one high momentum track in the rest of detector



Neutrino Event Selection



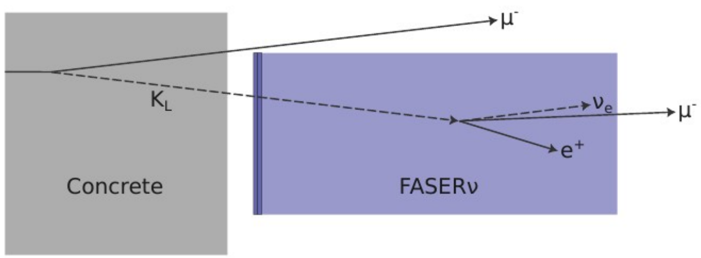
- Selection criteria applied:
  - Events in collision crossing, during good physics data periods (35.4/fb)
  - No signal in two front veto scintillators (<40 pC ~ 0.5 MIP)
  - Signal in last two veto layers (>40pC ~0.5 MIP)
  - Signal and preshower scintillators consistent with ≥1 MIPs
  - Exactly one good quality spectrometer track with p>100 GeV
  - Track in fiducial tracking volume, r_{max}<95mm
  - Track extrapolate to r<120mm in front veto scintillator
  - Track polar angle less than 25mrad

- Based on simulation expect 151±41 neutrino events
  - Uncertainty given by difference between two event generators
  - Experimental uncertainties not included at this time
    - Currently not trying to make cross section measurement

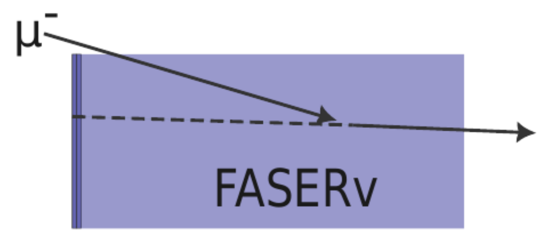
Background Estimate

- Consider three backgrounds:

Neutral hadrons



Scattered muons



Veto inefficiency

- Neutral hadrons estimated from two-step simulation
  - Expect O(300) neutral hadrons with E>100 GeV from concrete to reach FASERnu
    - Most will be accompanied by muon, but conservatively assume it is missed
  - Most neutral hadrons absorbed in tungsten without producing high-momentum track
  - In total expect just 0.11±0.06 events

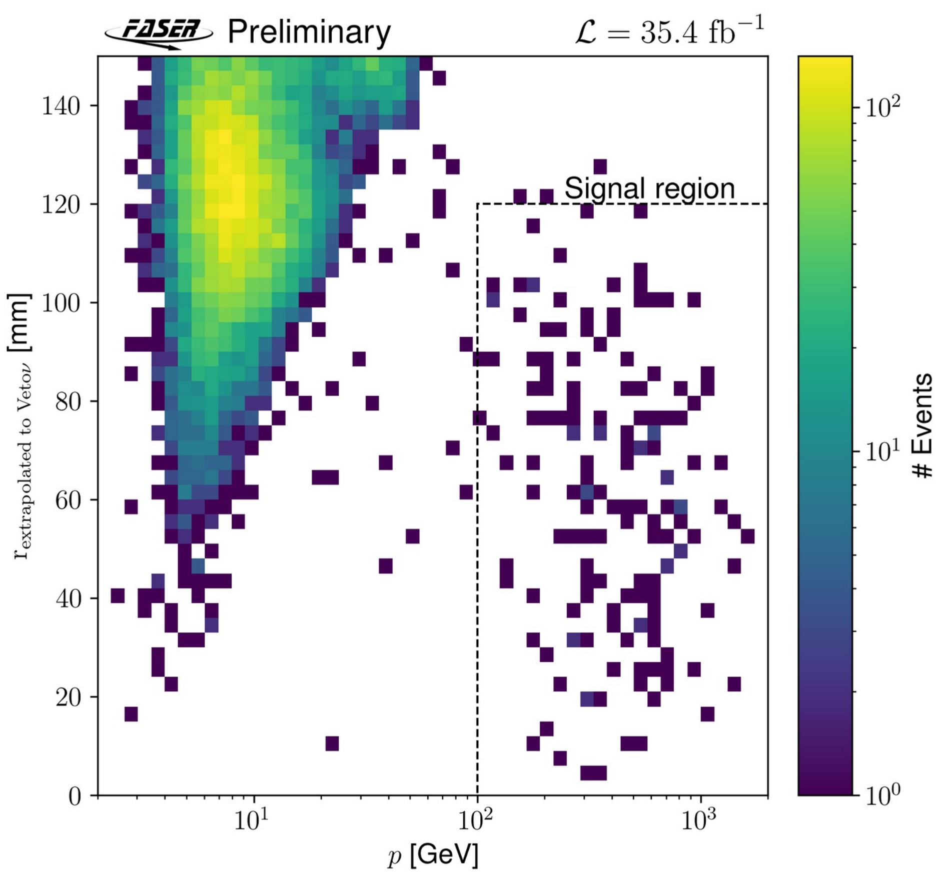
- Scattered muons estimated from control region of events with single track segment in front tracker station at large radius (90<r<95mm)
  - Expect 0.08±1.83 events

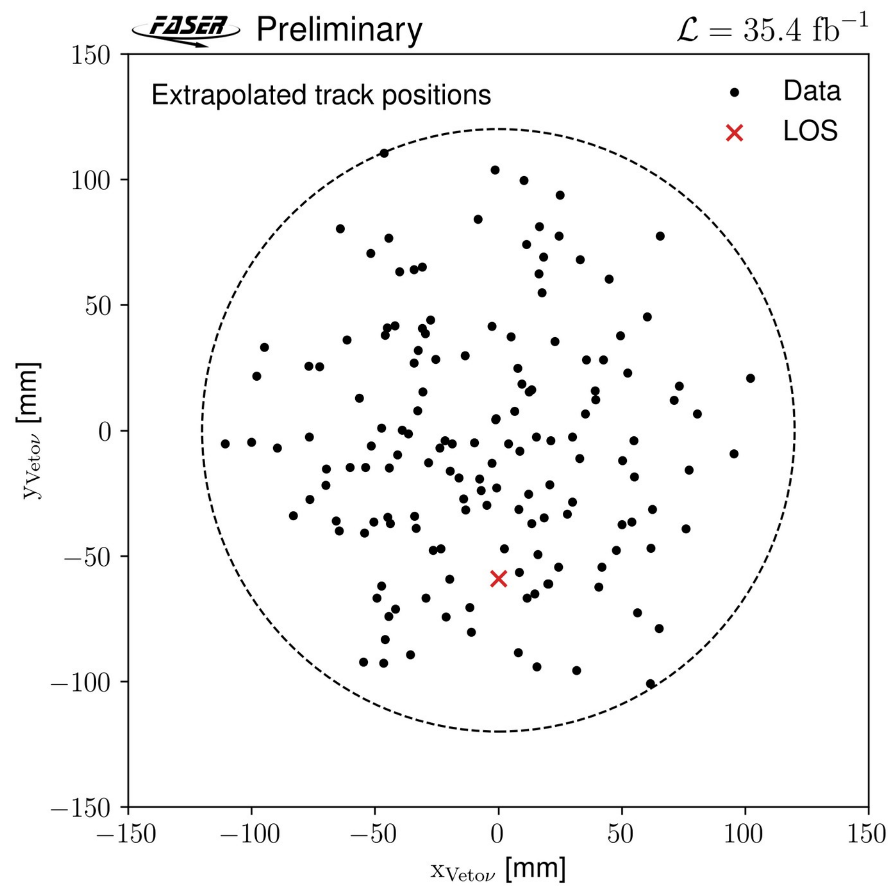
- Veto inefficiency estimated from events with just one veto scintillator firing
  - Veto efficiencies fitted in final fit of events with 0, 1 or 2 veto layers firing
  - Negligible background due to the very high veto efficiency

Neutrino Observation

- Unblinded results:
  - 153 events with no veto signal
  - Just 10 events with one veto signal
- Signal significance of 16σ

Category	Events
n_0	153
n_{10}	4
n_{01}	6
n_2	64014695





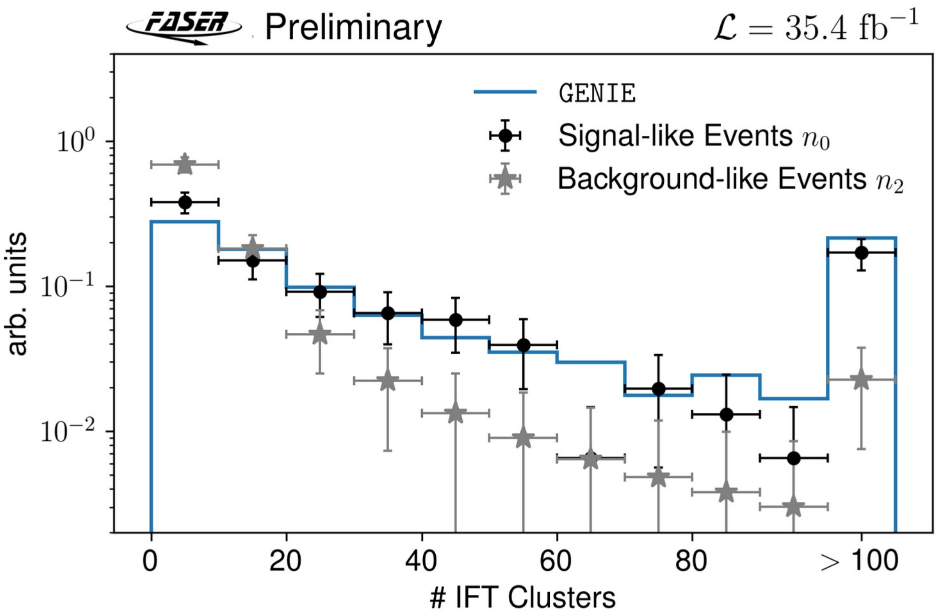
First direct observation of collider neutrinos

Neutrino Distributions

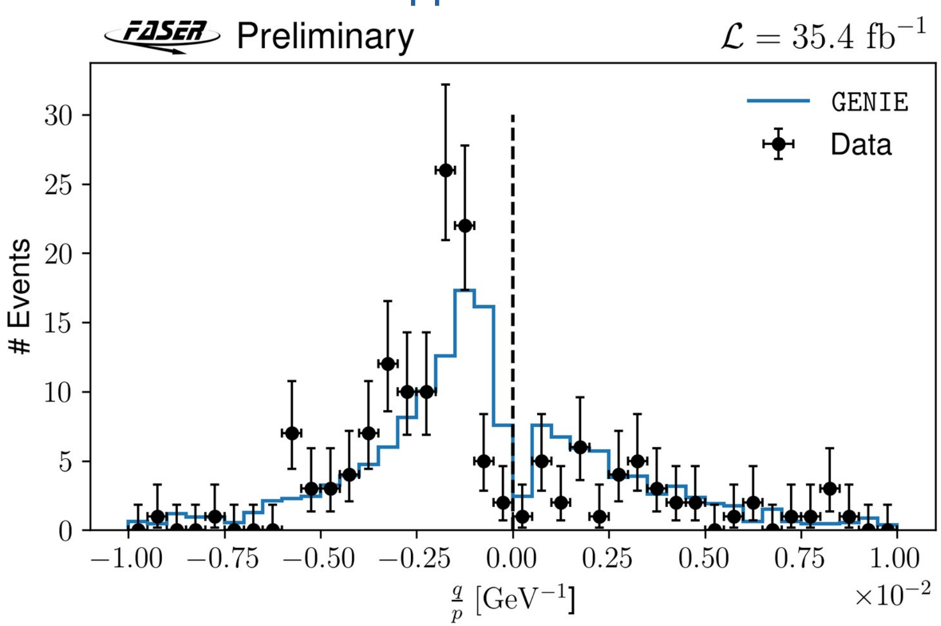
- Neutrino events match expectations from simulation
  - High occupancy in front tracker station
  - More ν_μ than anti-ν_μ
  - Most events at high momentum

Note plots are "reco-level" and not acceptance-corrected, etc.

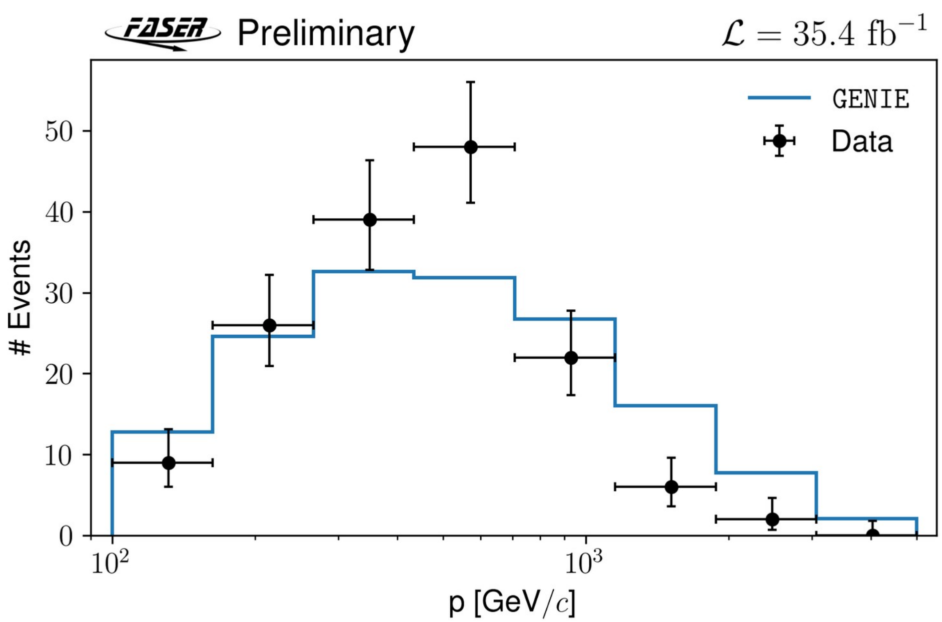
Clusters in front tracker station



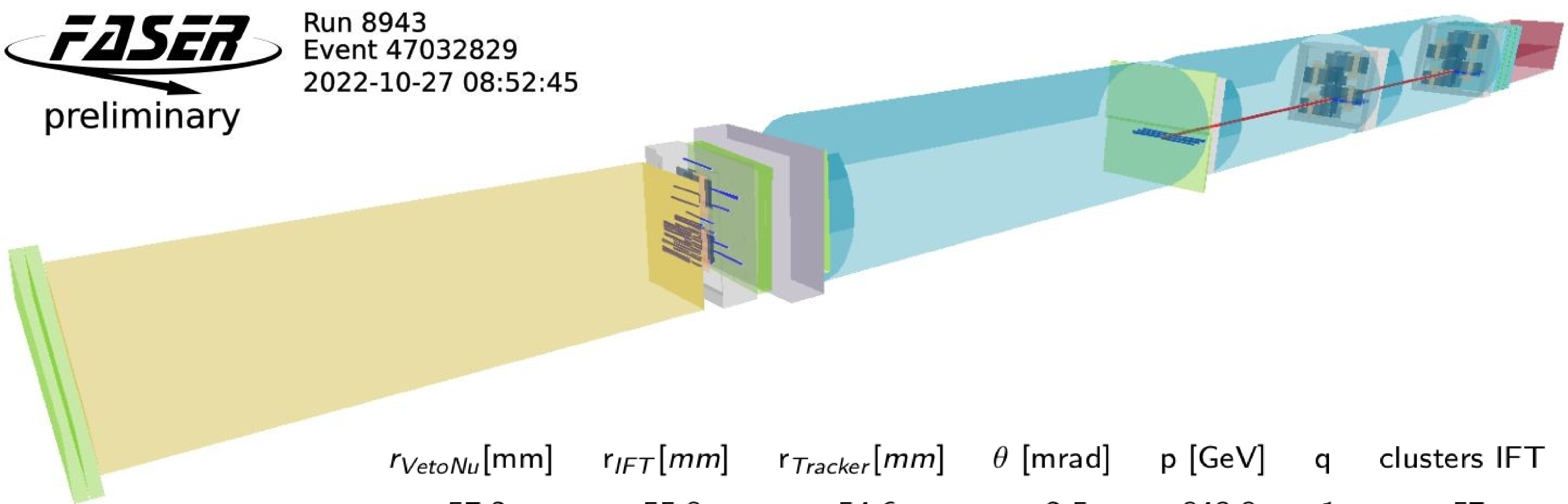
Track q/p distribution



Track momentum distribution



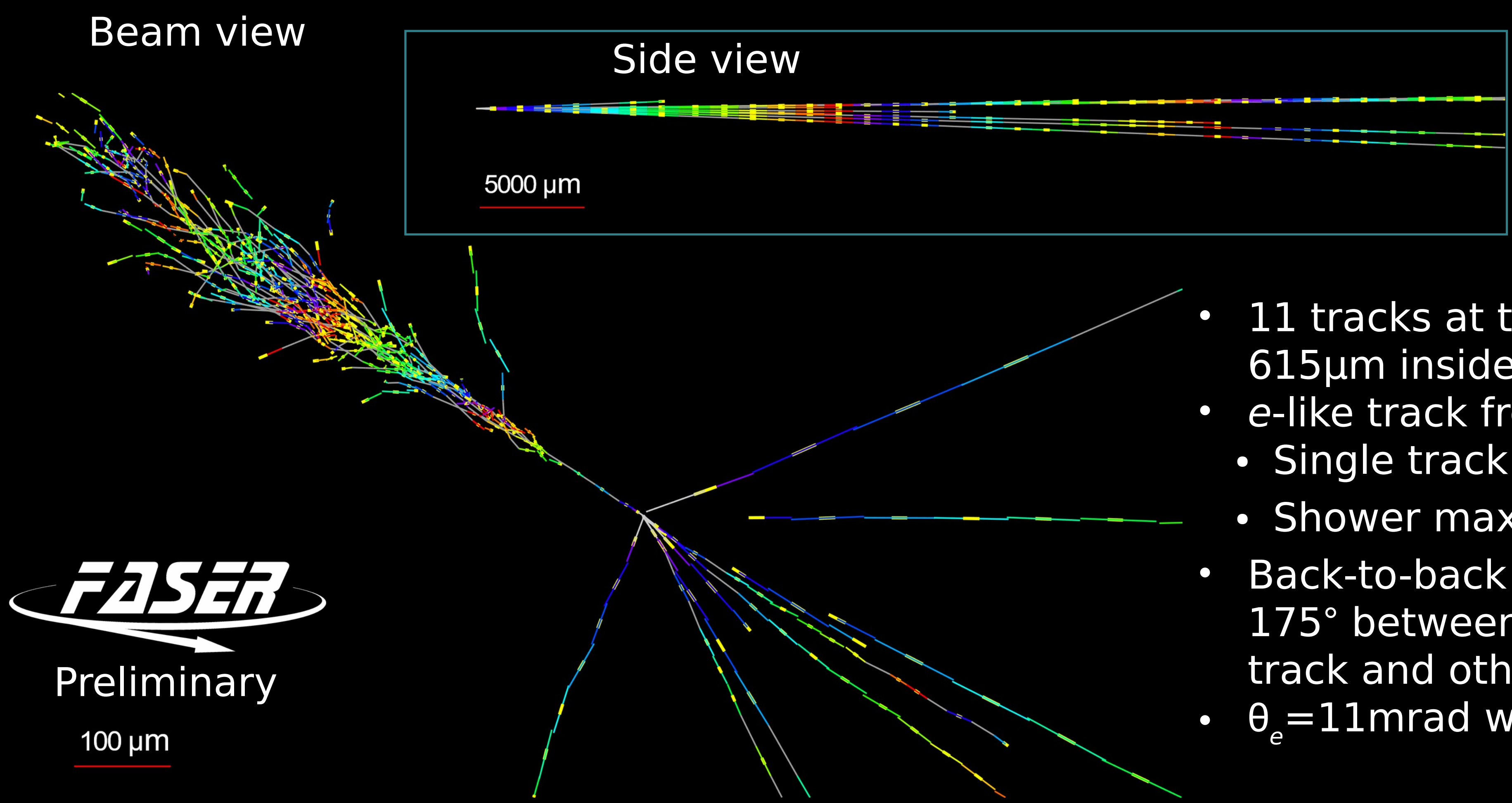
Example Neutrino Event Display



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

Neutrinos in FASERν

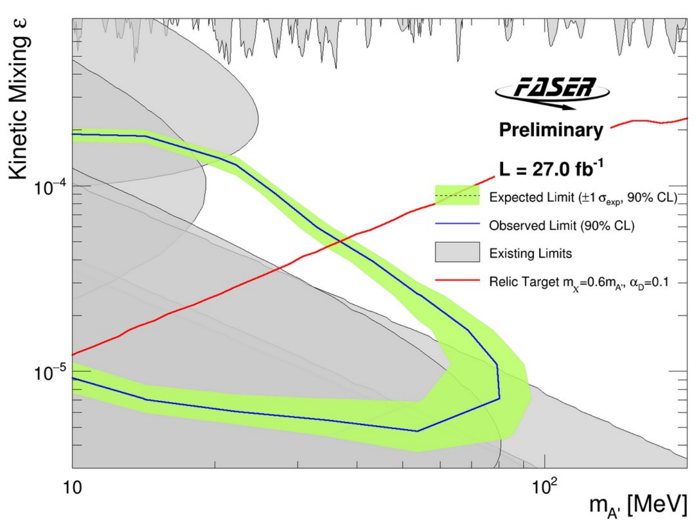
Analysis of emulsion detector still underway
Have multiple candidates, including highly ν_e like event:

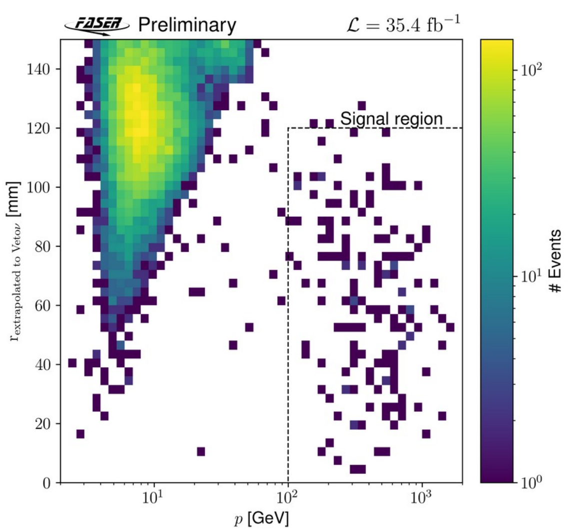


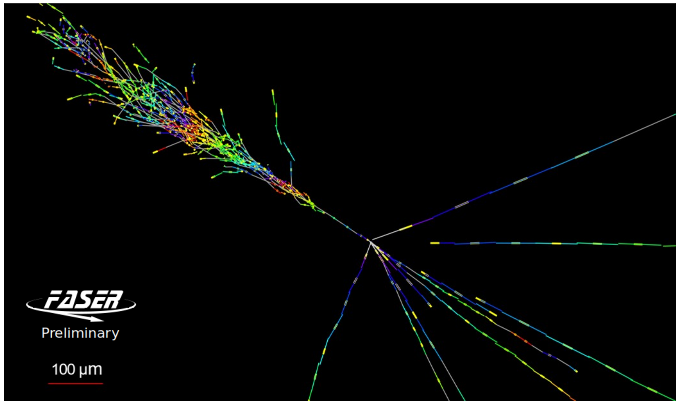
- 11 tracks at the vertex, 615μm inside tungsten
- *e*-like track from vertex
  - Single track for $2X_0$
  - Shower max at $7.82X_0$
- Back-to-back topology, 175° between *e*-like track and others
- θ_e=11mrad w.r.t. beam

Summary

- FASER successfully took data in first year of Run 3
  - Running at very good efficiency with fully functional detector
- First physics results presented
  - Excluded dark photon in region of low mass, low kinetic mixing
    - Probing new territory in thermal relic region
  - ~150 neutrino interaction reconstructed in spectrometer
    - First direct observation of collider neutrinos – *opening new window for studying high energy neutrinos*
- More searches and neutrino measurements to come
- Will continue data-taking throughout LHC Run 3
  - Up to 10 times more data coming in the next years







Acknowledgments

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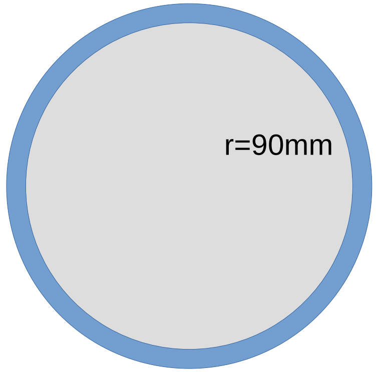
NSF

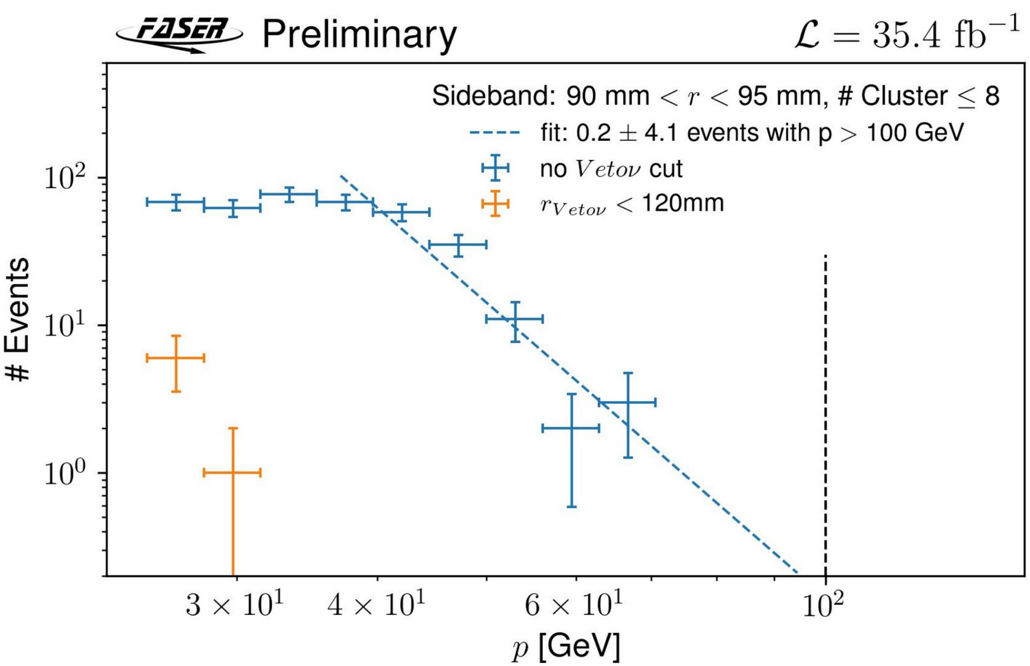
- Additionally would like to thank:
  - LHC for the excellent performance in 2022
  - ATLAS Collaboration for providing luminosity information
  - ATLAS SCT Collaboration for spare tracker modules
  - ATLAS for the use of their ATHENA software framework
  - LHCb Collaboration for spare ECAL modules
  - CERN FLUKA team for background simulation
  - CERN PBC and technical infrastructure groups for excellent support during design, construction and installation

Backup Slides

Neutrino Analysis – Geometric Bkgd

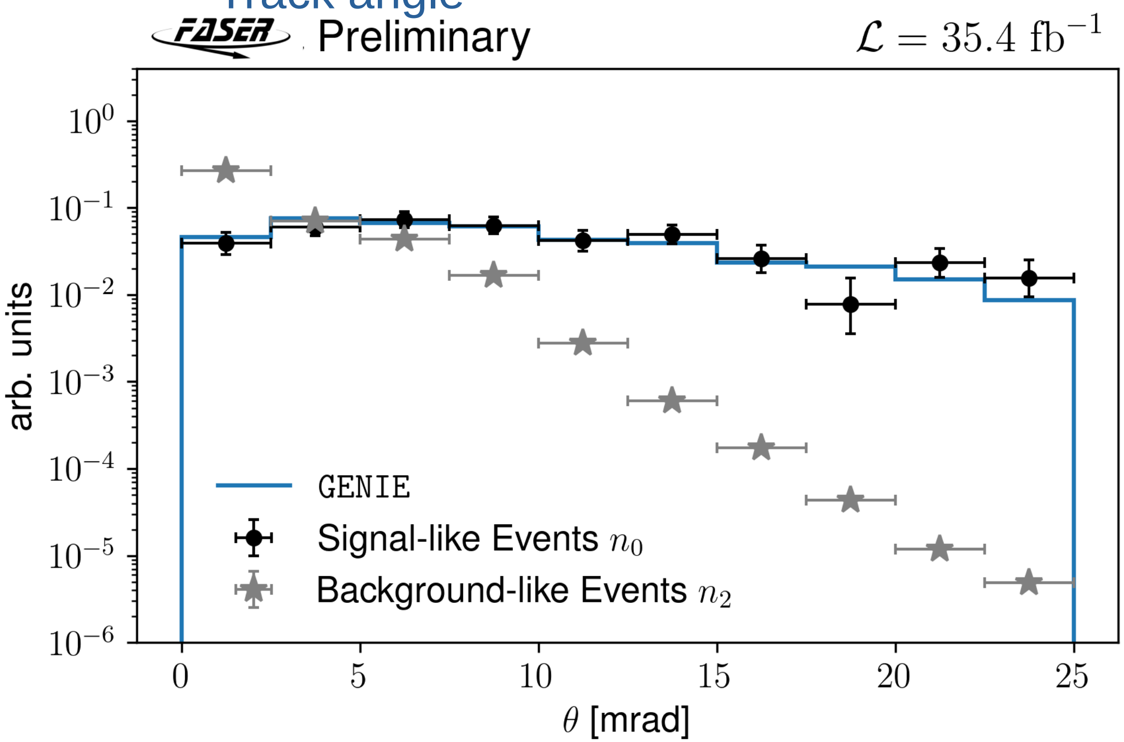
- Geometric background of muons by-passing veto measured in outer annulus at 50<p<100 GeV without radius requirement at VetoNu
  - Also require tracker station hits consistent with 1 track
  - Negligible neutrino bkgd
- Fit momentum to extrapolate to p>100 GeV
- Scale with rate of events inside r_{VetoNu}<120mm
  - 0 events, so use 5.9 evts as upper limit
- Scale from annulus to full acceptance using large angle muon simulatior.
  - Estimate 0.08±1.83 bkgd events



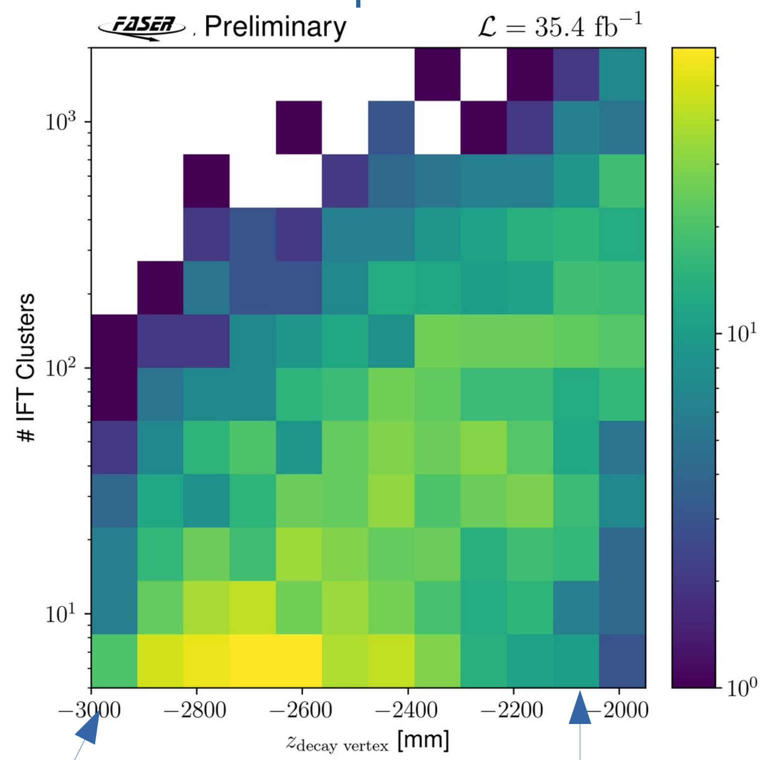


Neutrino Analysis – More distributions

Track angle



Simulation:
track clusters vs neutrino interaction point

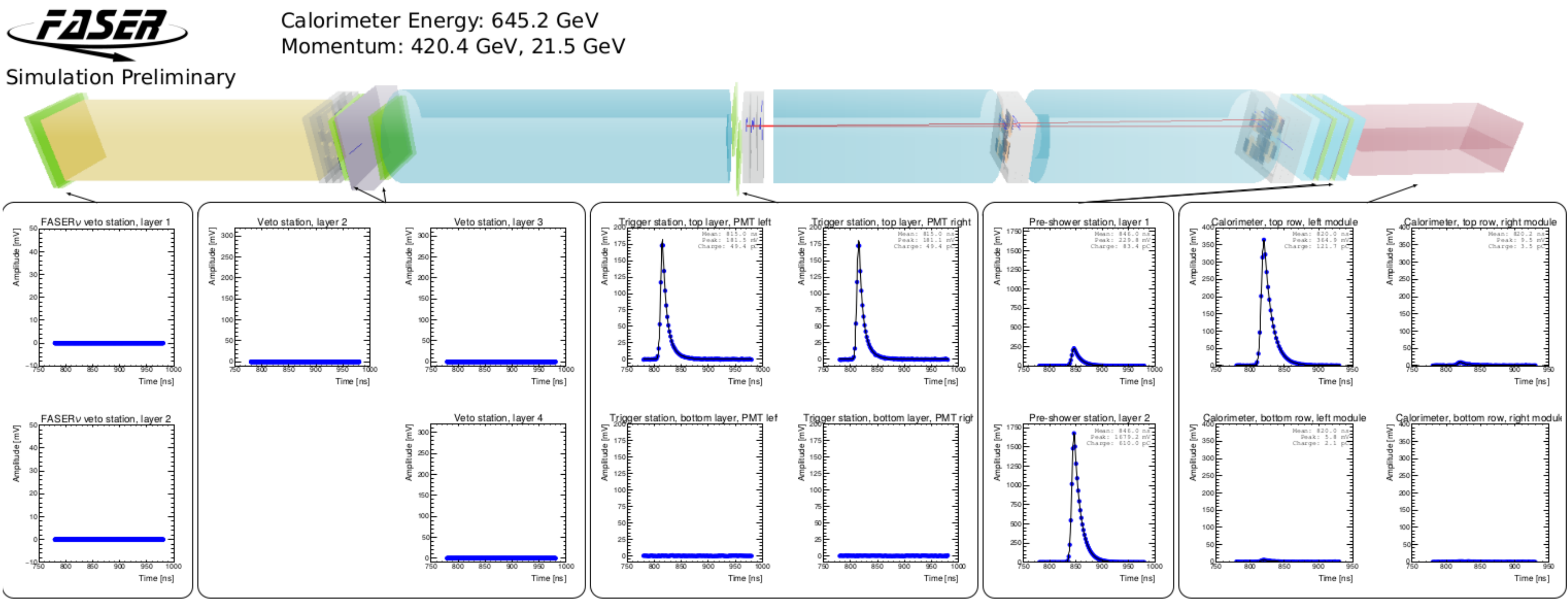


Front of emulsion box

Back of emulsion box

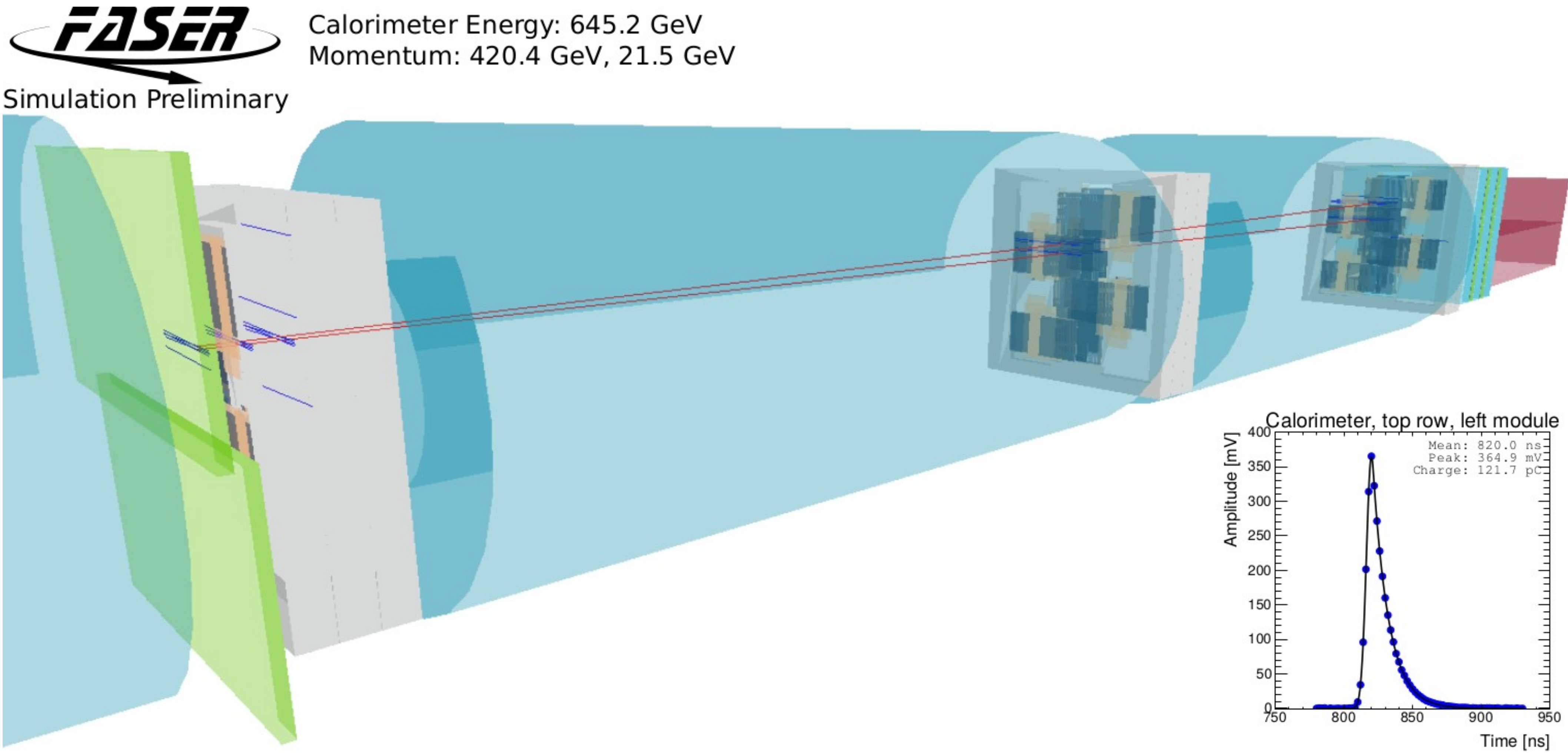
Dark Photon – Signal

- Example of a simulated Dark Photon decay



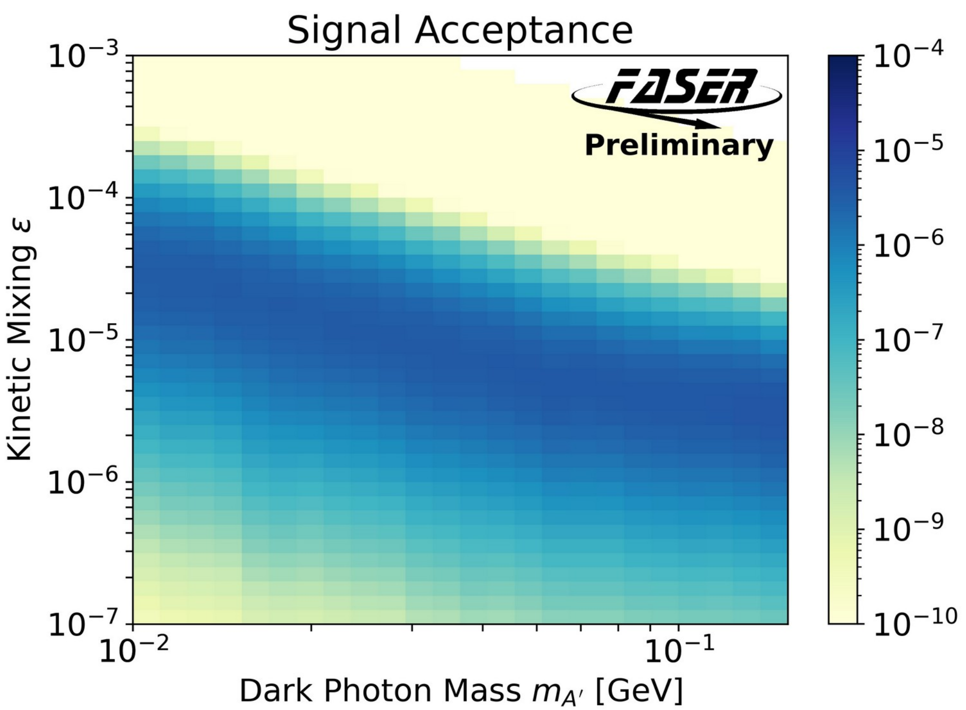
Dark Photon – Signal

- Example of a simulated Dark Photon decay

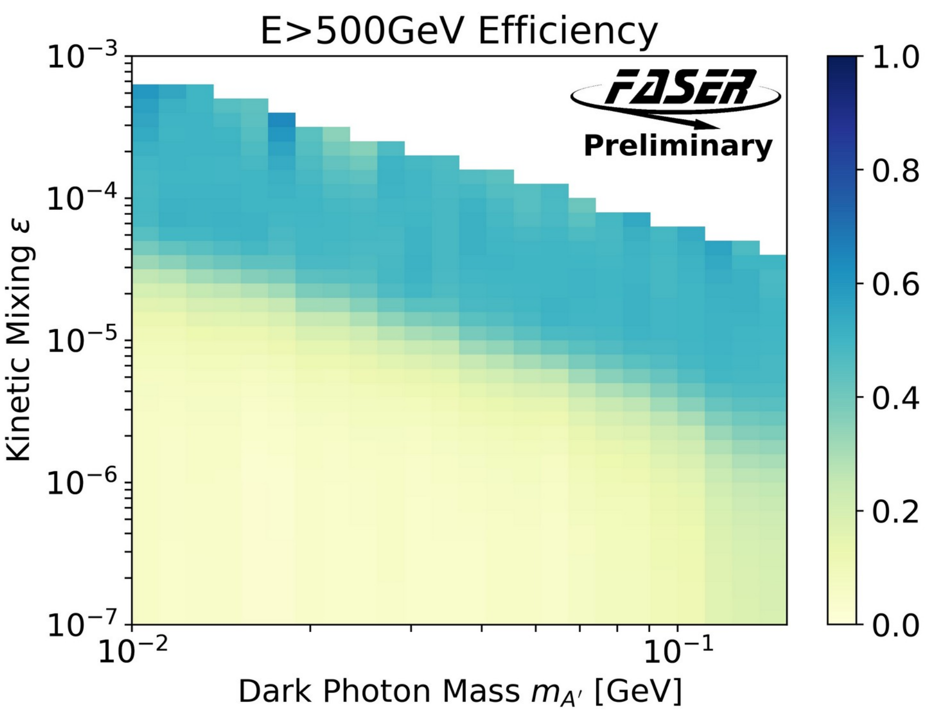


Dark Photon – Signal Acceptance

For dark photon produced in IP1 and decaying in decay volume



For dark photon decaying in FASER decay volume



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

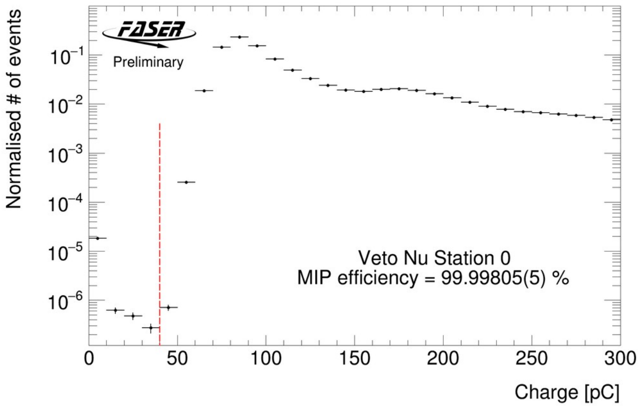
Dark Photon – Cut Flow

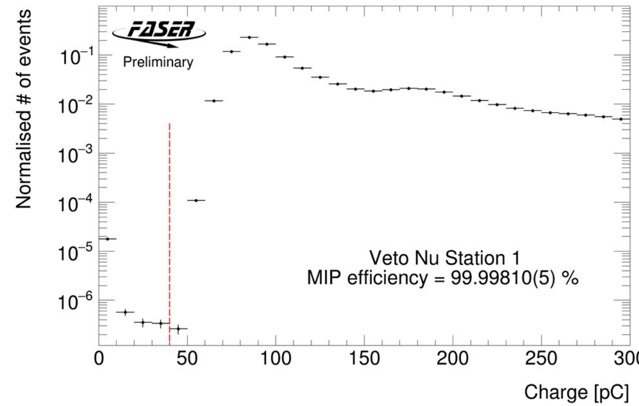
- Data and example signal efficiency as a function of analysis selections
  - Note the data column was pre-selected to have at least one reconstructed track (no quality cuts) in the event

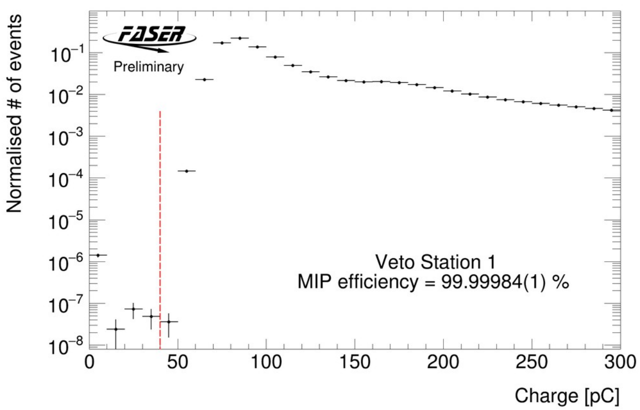
Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\mathrm{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good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

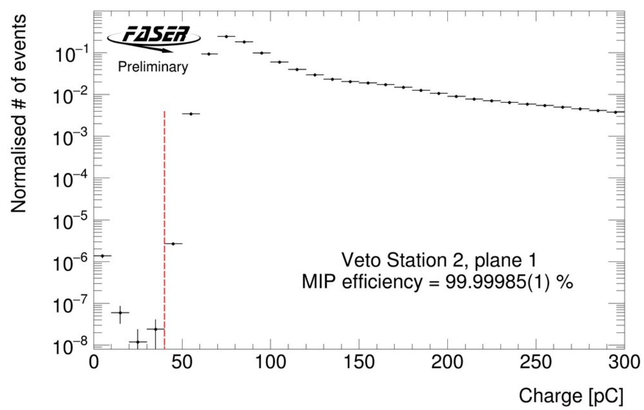
Dark Photon – Veto Scintillators

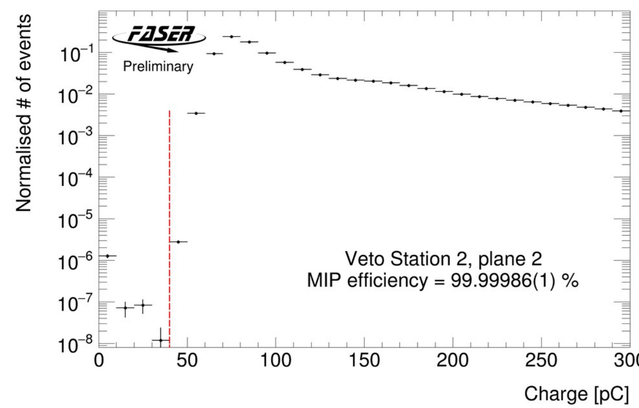
- Veto scintillator efficiencies measured extrapolating tracks triggered in timing scintillator to layer
  - No requirement on other scintillator layers
  - All inefficiencies below 2×10^{-5}











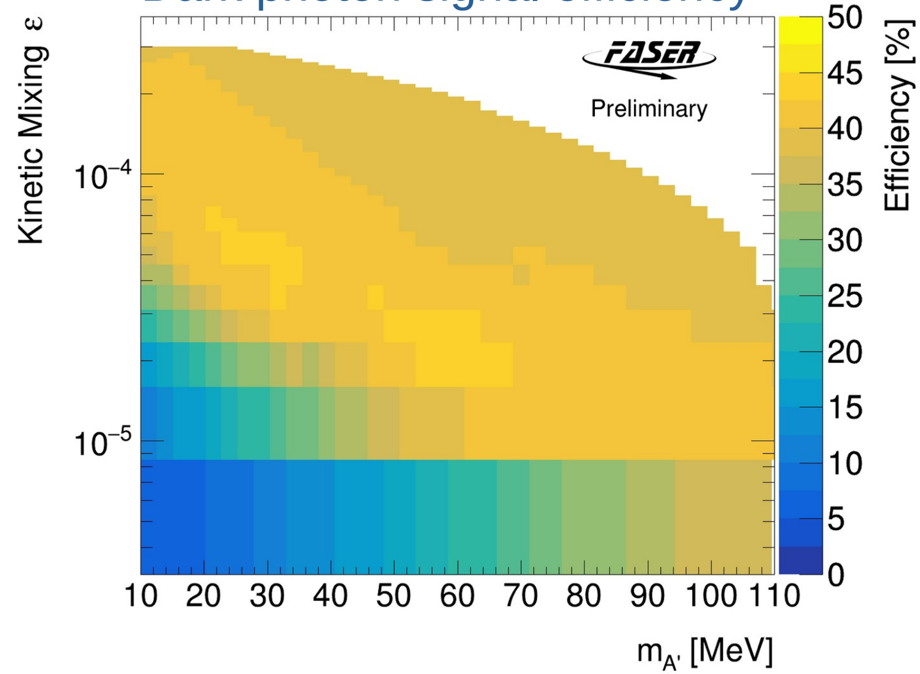
Dark Photon Signal Expectations

- Signal simulated w. FORESEE
  - π^0 and η^0 production with EPOS-LHC generator
  - Dark bremsstrahlung of protons included, but sub-dominant
  - Only decays to e^+e^- in FASER decay volume considered
- Main signal uncertainties
  - Generator uncertainty parameterized vs A' energy as:

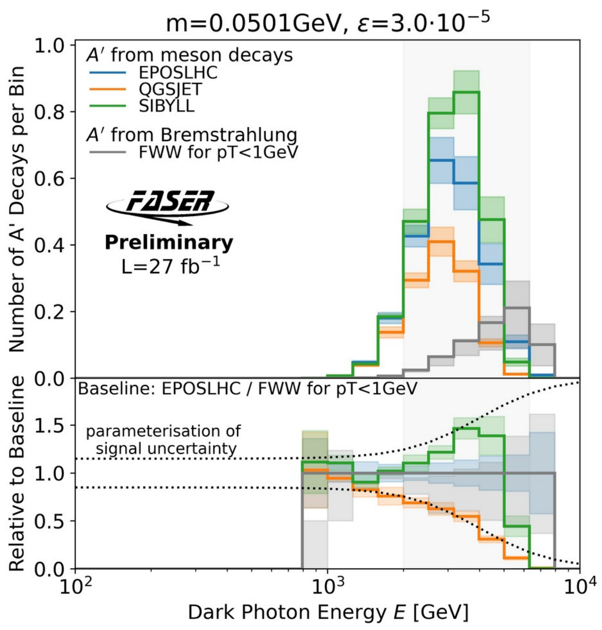
$$\frac{\Delta N}{N} = \frac{0.15 + (E_{A'}/4\ \text{TeV})^3}{1 + (E_{A'}/4\ \text{TeV})^3}$$

    - Based on difference to QGSJET/SIBYLL
  - Tracking efficiency
    - 15% uncertainty for two close-by tracks
  - Calorimeter energy scale
    - 6% uncertainty on energy scale at 500 GeV

Dark photon signal efficiency



Signal generator uncertainty



Dark Photons – Systematic Uncertainties

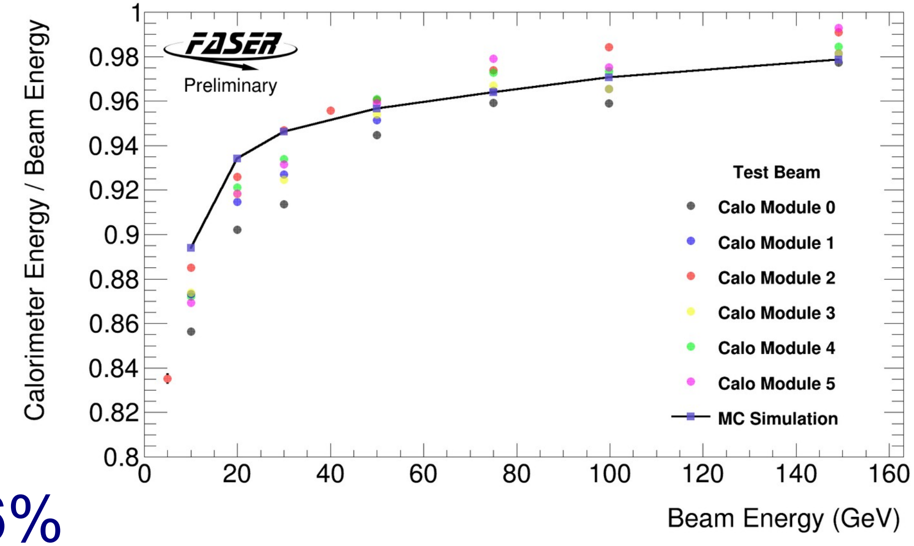
- Complete list of systematic uncertainties and their impact on the signal yield

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% ($< 1\%$)

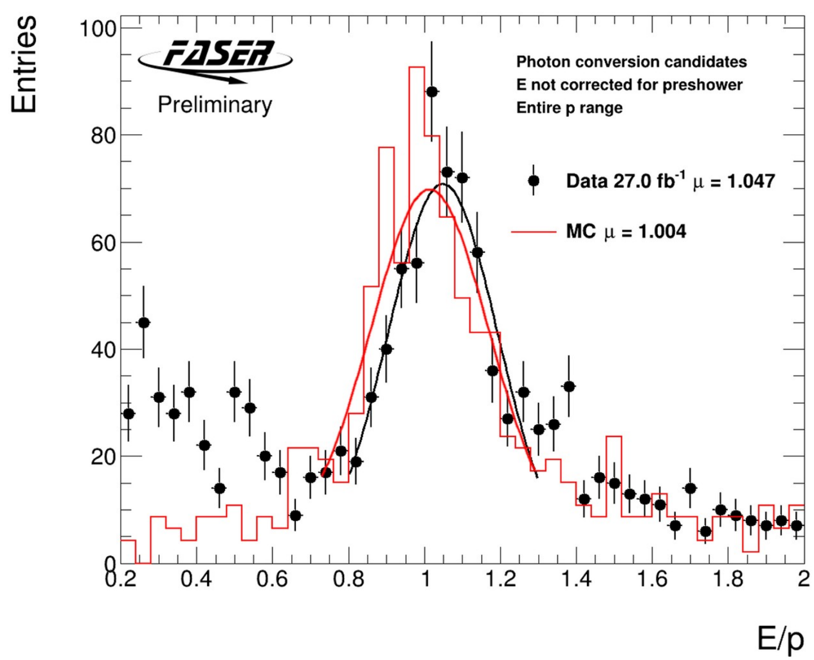
Dark Photon – Energy Scale Systematics

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

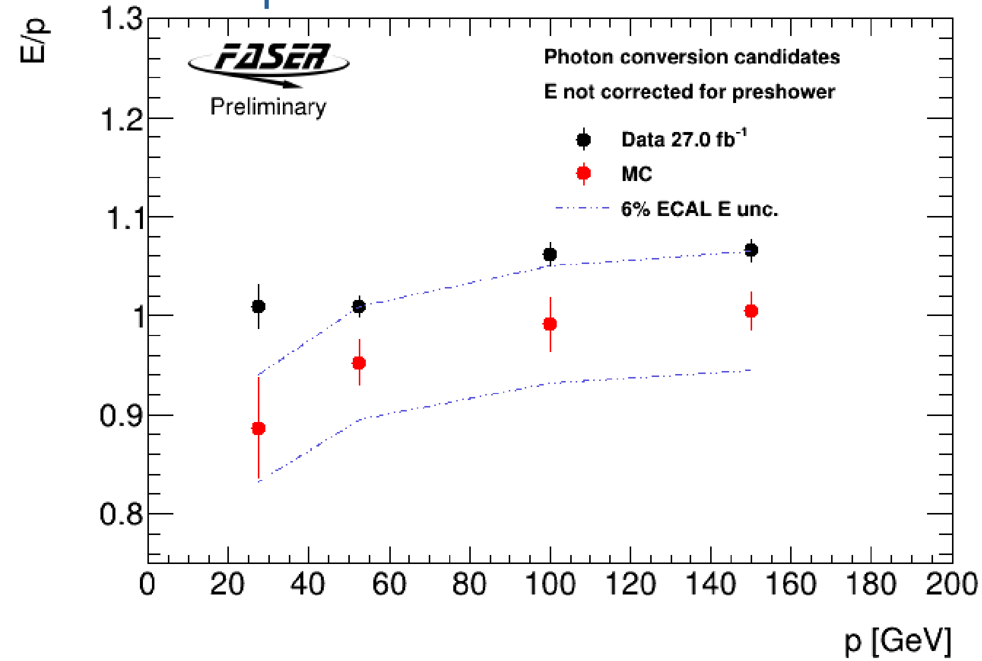
Calorimeter test beam response



E/p in conversions



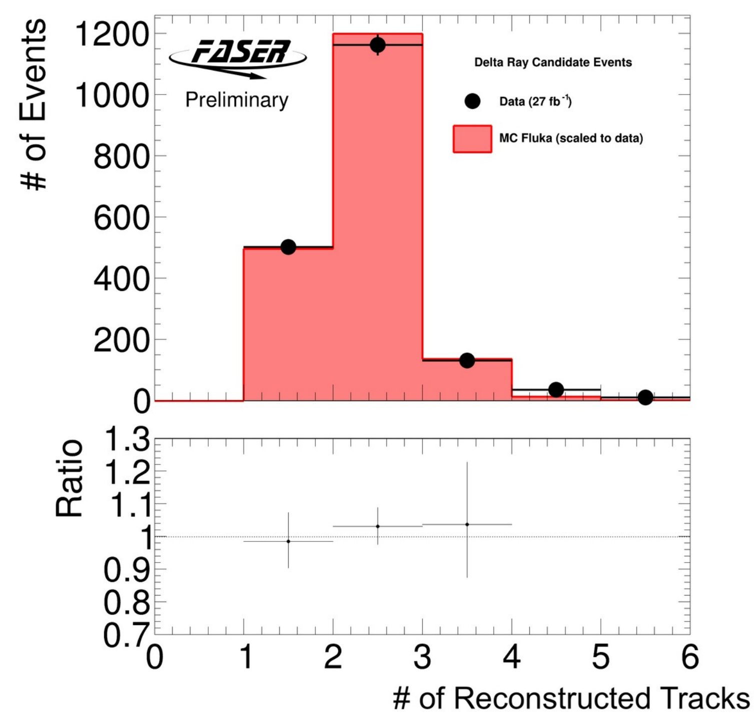
E/p in conversions vs momentum



Dark Photon – Tracking Systematics

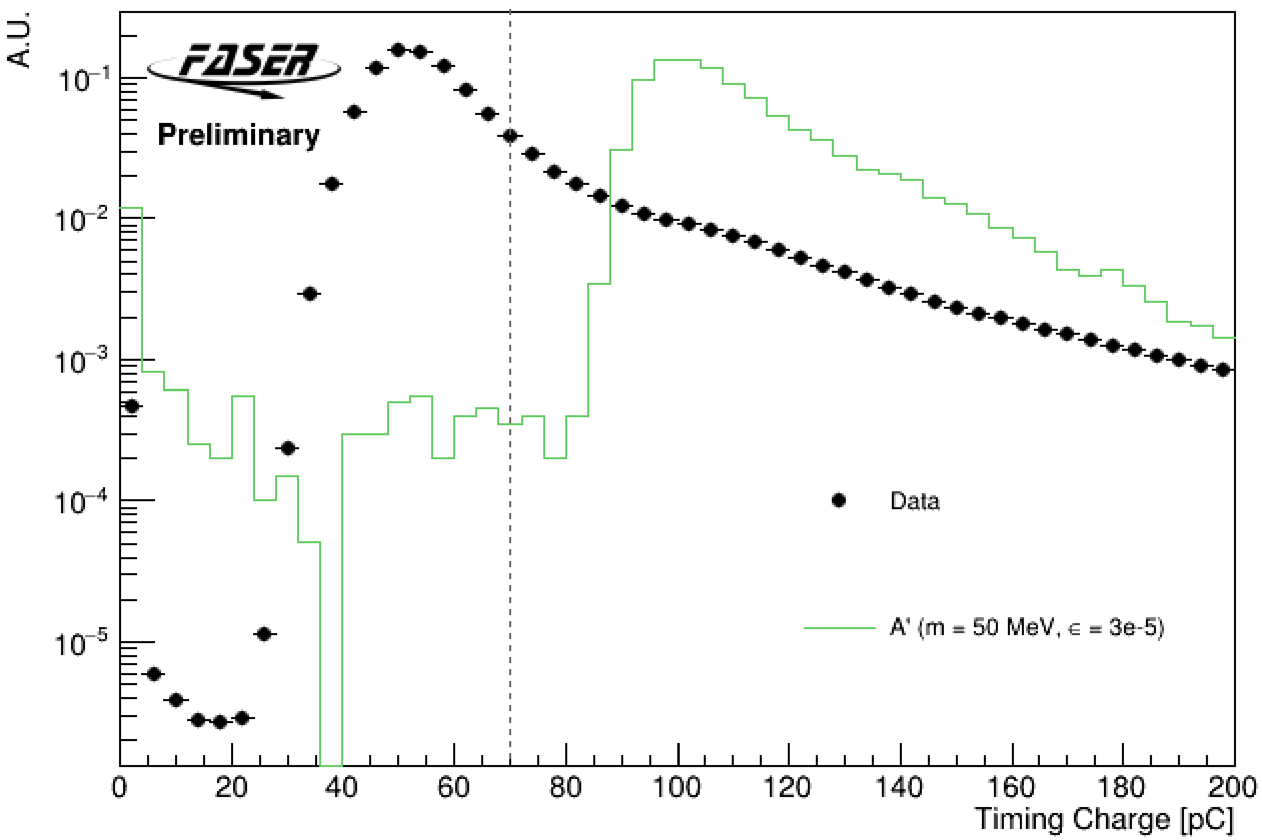
- Single track efficiency uncertainty studied in muon events with track segments found in each station
  - Data efficiency of 98.4%
  - Data-MC agrees at 1.5% level
- Tracking efficiency lower for two (close-by) tracks
  - Studied in conversions and delta-ray events requiring one less track than needed, but preshower and calorimeter consistent with electromagnetic signals
  - Further studied overlaying two events with one reconstructed track at hit level
    - Taking largest data/MC deviations conservatively assign 15% uncertainty

Tracks in delta ray-like events



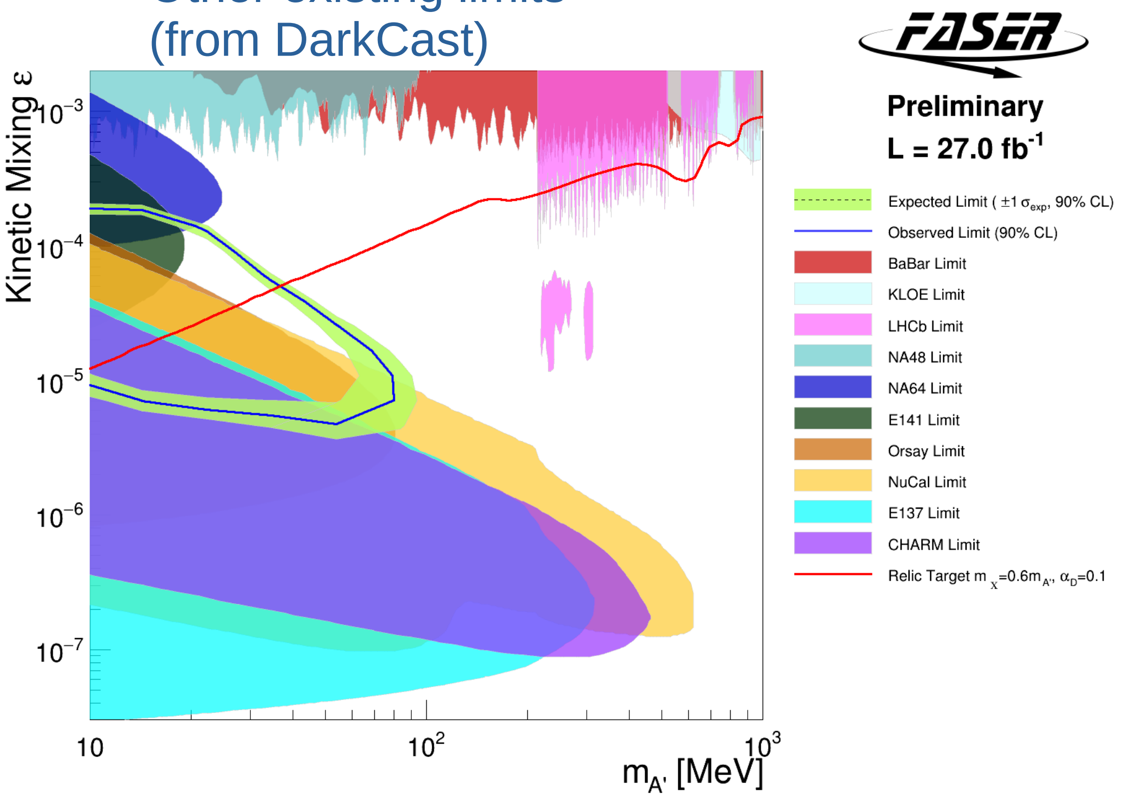
Dark Photon – Timing Scint. Selection

- Selecting events with more than 70pC in timing layer is ~100% efficient for signal, while also suppressing a large fraction of single track events

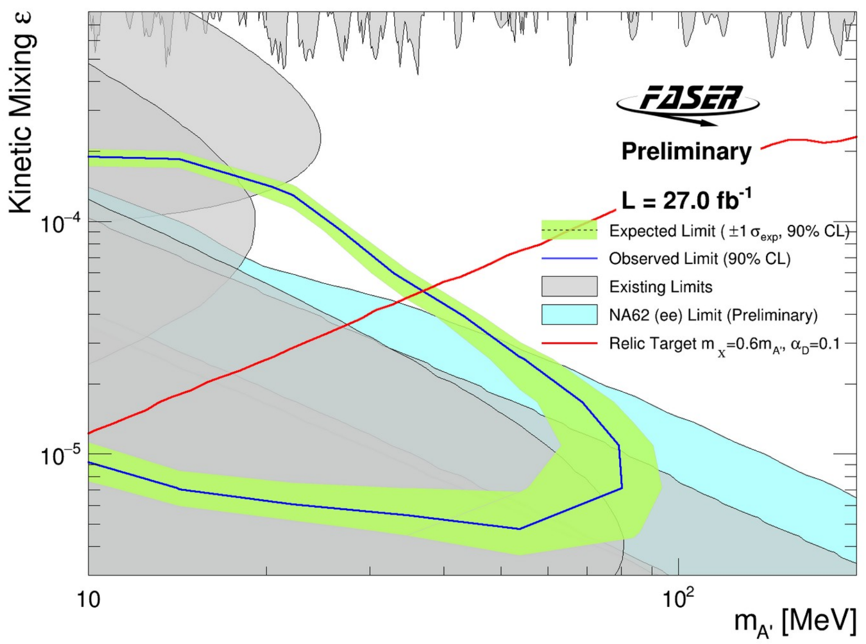


Dark Photon – Other Exclusion Limits

Other existing limits
(from DarkCast)



Very recent result from NA62, partially overlaps with FASER exclusion



FASER Collaboration

85 members from 22 institutions and 9 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
NIMA 166825 (2022) and arXiv: 2112.01116

The trigger and data acquisition system of the FASER experiment
Journal of Instrumentation and arXiv: 2110.15186

First neutrino interaction candidates at the LHC
Physical Review D and arXiv: 2105.06197

Technical Proposal of FASERν neutrino detector
CERN document server and arXiv: 2001.03073

Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC
European Physical Journal C and arXiv: 1908.02310

Input to the European Strategy for Particle Physics Update
arXiv: 1901.04468

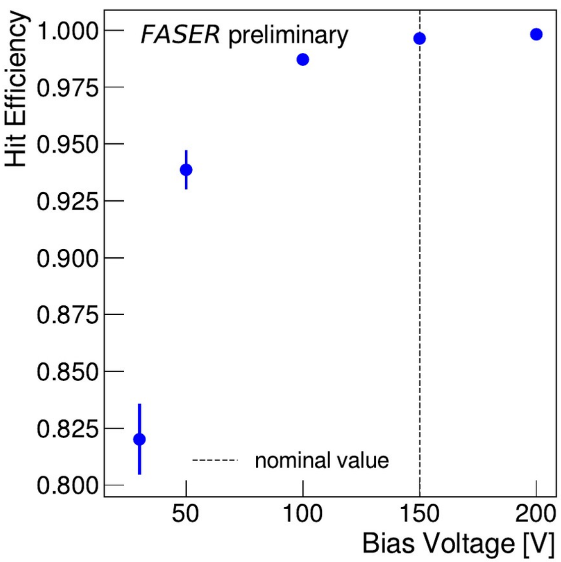
FASER's Physics Reach for Long-Lived Particles
Physical Review D and arXiv: 1811.12522

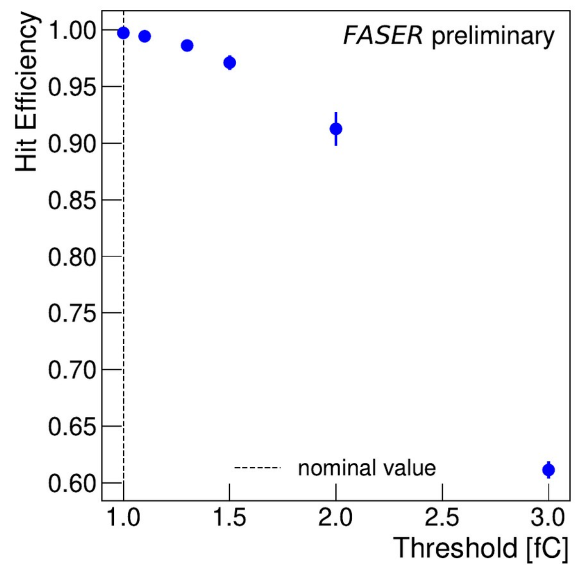
Technical Proposal
CERN document server and arXiv: 1812.09139

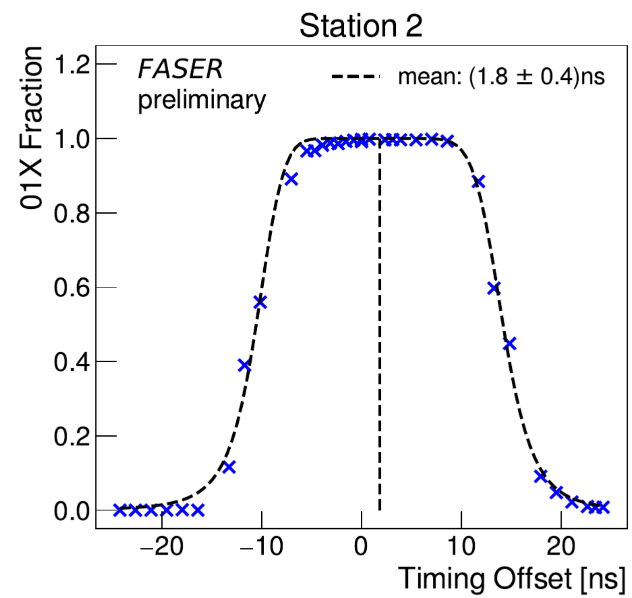
Letter of Intent
CERN document server and arXiv: 1811.10243

Detector Performance Tracker

- Tracker fully timed in with respect to LHC clock
- Hit efficiency of 99.64% at 150V bias and 1fC threshold

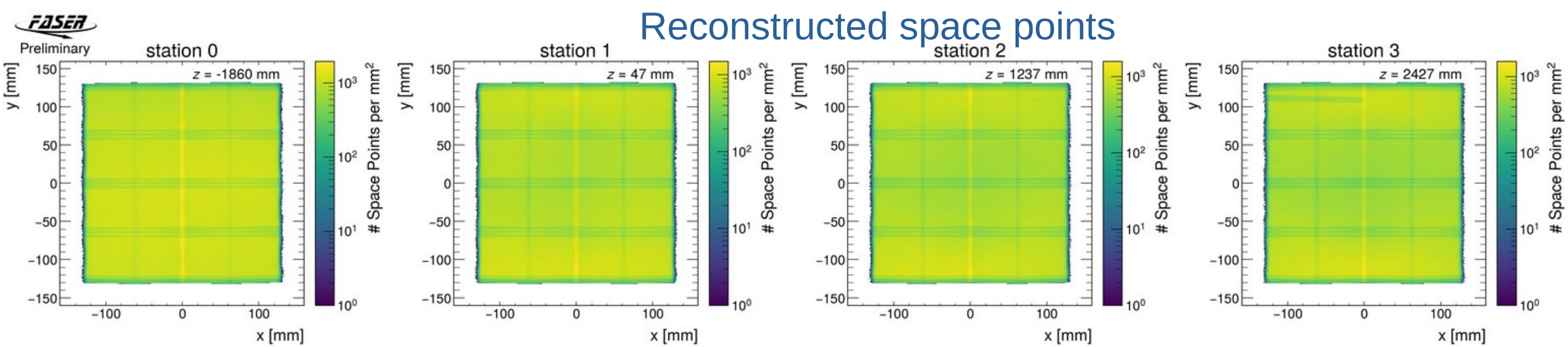






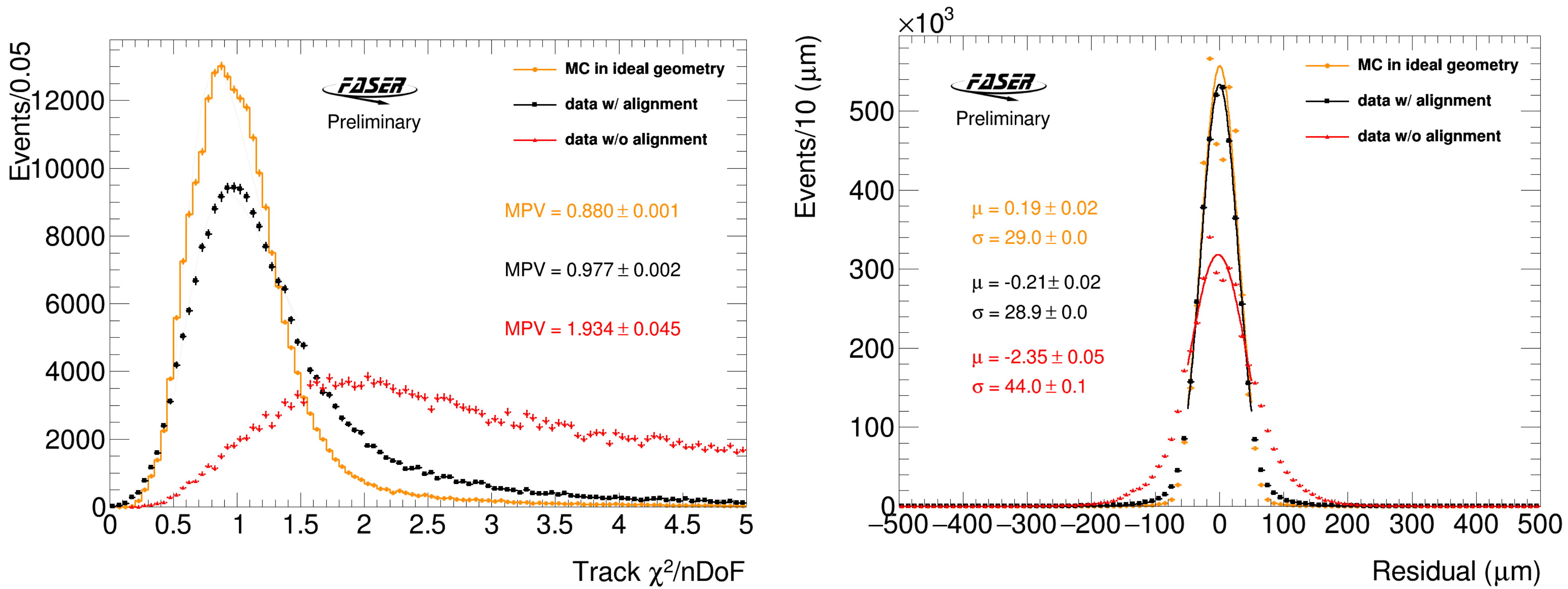
- <0.5% dead/noisy strips – inefficiency at edges expected

Reconstructed space points



Detector Performance - Alignment

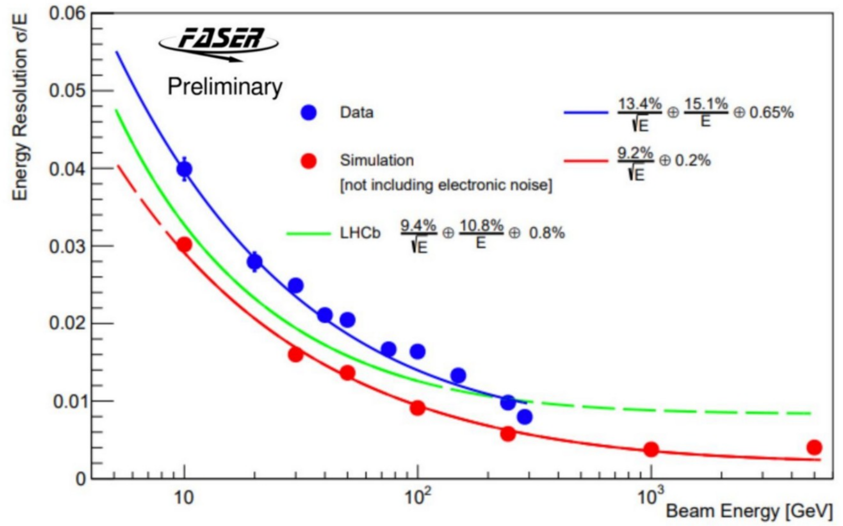
- Tracker modules aligned using local iterative χ^2 proc.
- Validated using simulation with misalignments
- Currently only applying alignment in two most sensitive parameters (vertical shift, in-plane rotation)
  - Aligned resolution close to simulation expectation



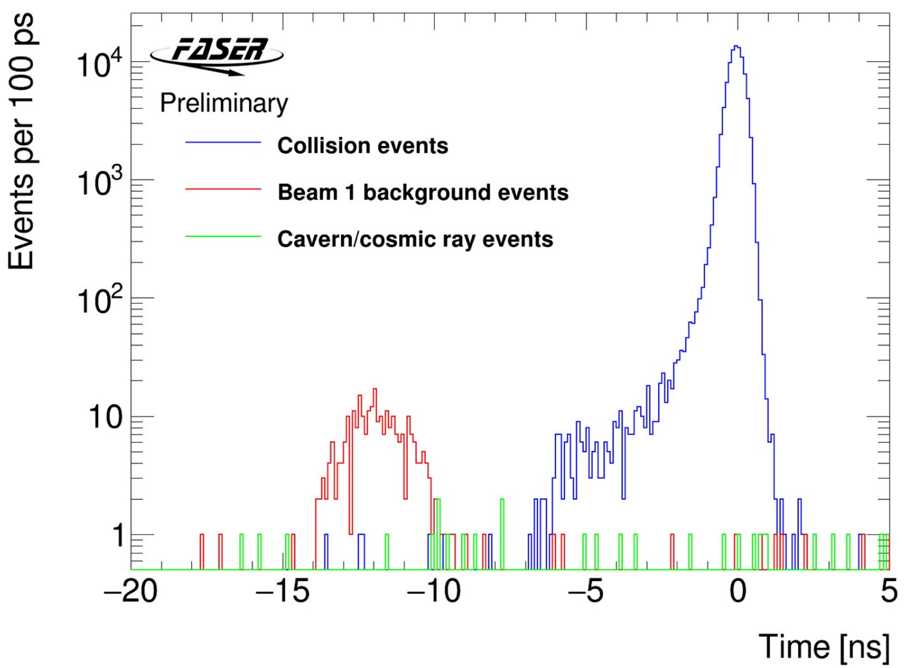
Detector Performance - Calo/Scint

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

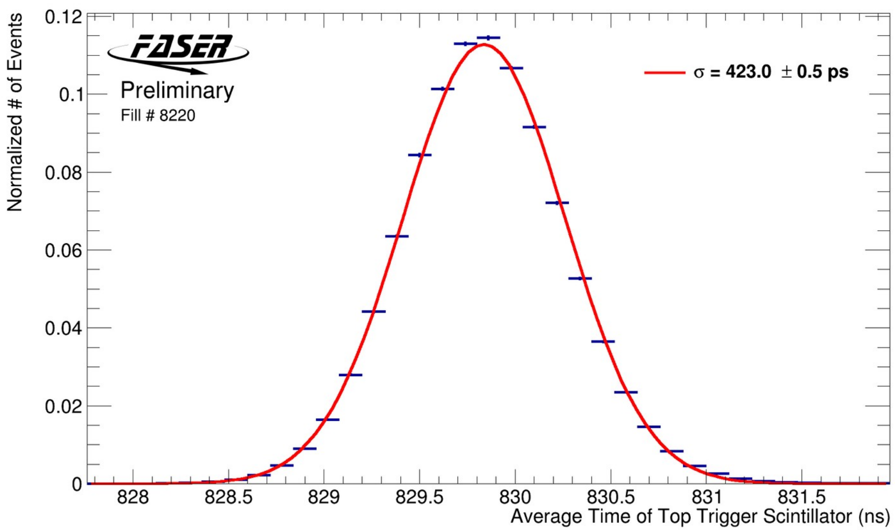
Calorimeter resolution – test beam



Calorimeter timing for different events

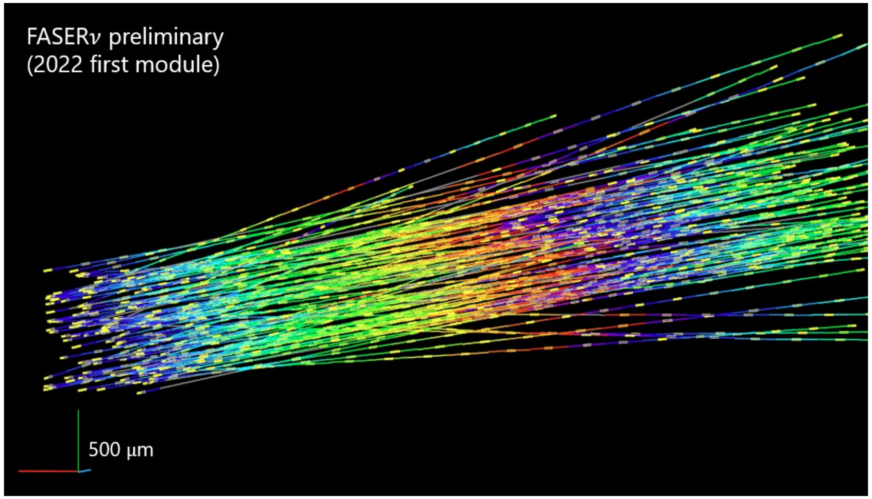


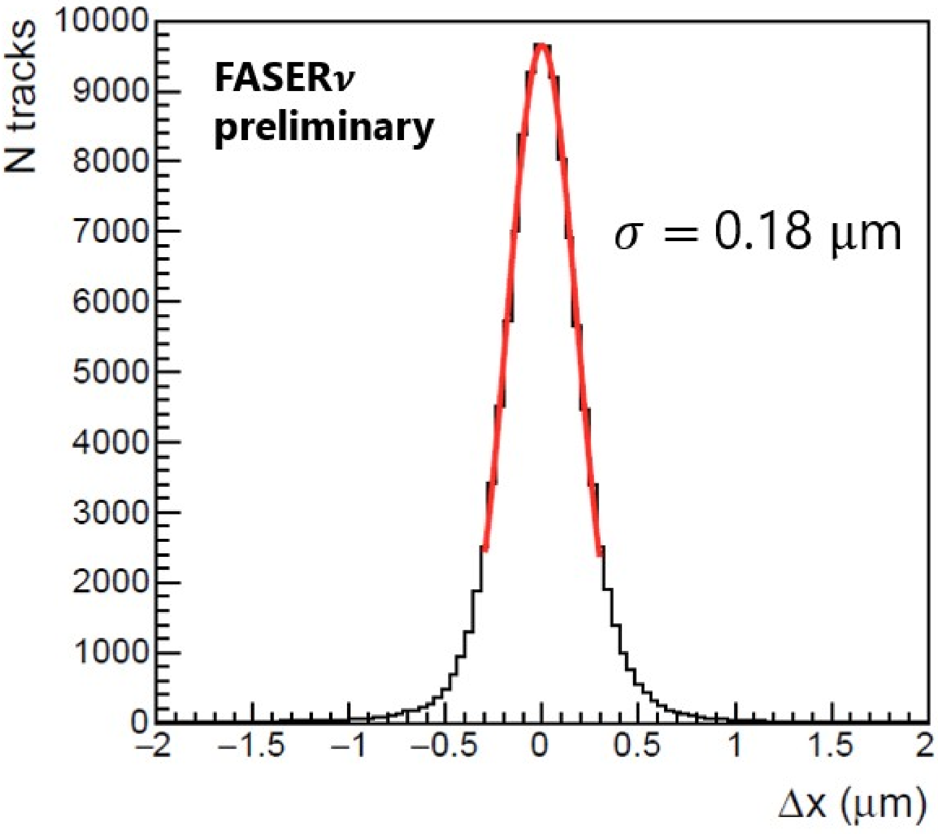
Timing scintillator resolution

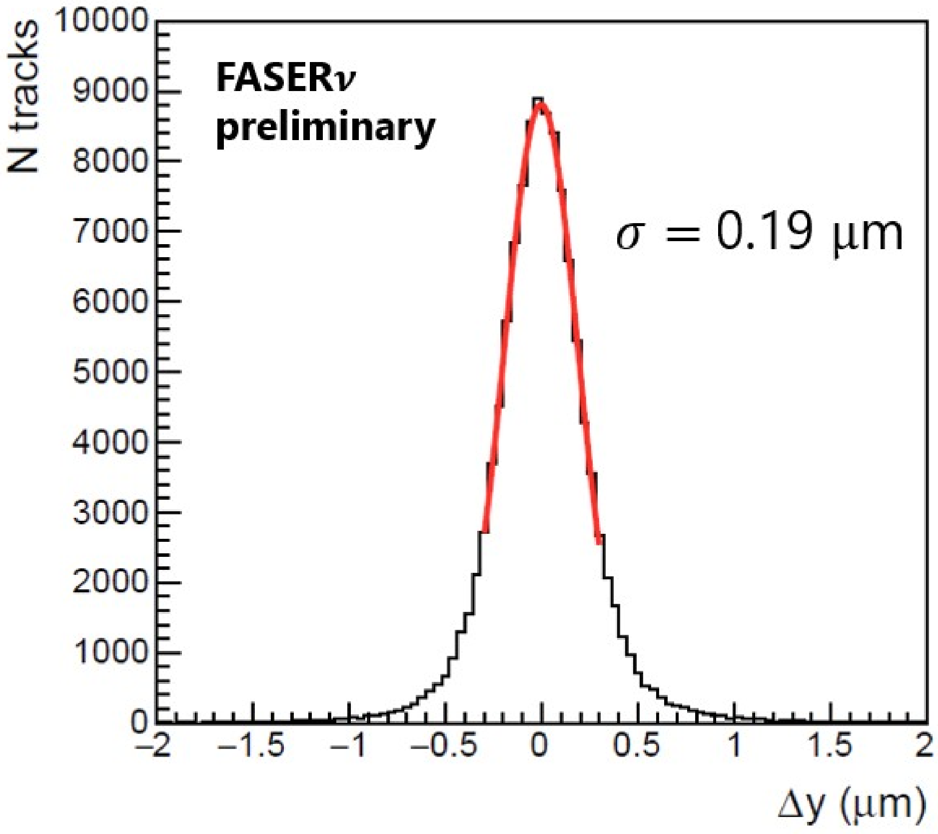


Detector Performance – Emulsion

- Track multiplicity measured in initial emulsion
  - Consistent with FLUKA simulation
- Excellent hit resolution (0.2µm) after layer alignment







Detector Performance - Trigger/DAQ

- Smoothly running DAQ at up to 1.3 kHz
- Physics deadtime below 2%
- Only two stops of data-taking due to DAQ failures