Dave Casper
University of California, Irvine
(for the FASER collaboration)

Results from FASER

Dark photon search CONF note on CERN Document Server

Collider neutrino direct detection paper (accepted by PRL)

FASER collaboration

- 84 members from 24 institutes in 10 countries

CERN | UNIVERSITÉ DE GENÈVE | KYUSHU UNIVERSITY | UC IRVINE

UNIVERSITÄT BERN | Technion Israel Institute of Technology | NAGOYA UNIVERSITY | UNIVERSITY of WASHINGTON

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Outline

- Physics motivation and goals
- The FASER detector
- 2022 operations and results

Motivation: search for long-lived A'

- Dark photon coupling to Standard Model fermions:
  - $\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \, A'_\mu \bar{f} \gamma^\mu f$
- Assuming $m_{A'} < 2m_\chi$, $m_{A'} \sim$ (MeV − GeV) and $\epsilon \sim (10^{-6} - 10^{-3})$ give thermal relic density in range expected for dark matter
- Dark photon sources at LHC:
  - Neutral pion decay: $\pi^0 \to \gamma A'$
  - Eta meson decay: $\eta \to \gamma A'$
  - Dark bremsstrahlung: $pp \to ppA'$
- For $2m_e < m_{A'} < 2m_\mu$, $A' \to e^+e^-$ is ~100% of branching ratio
- Long decay length for boosted A', assuming $E'_A \gg m_{A'} \gg m_e$:
  - $L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left(\frac{10^{-5}}{\epsilon}\right)^2 \left(\frac{\mathrm{E'_A}}{\mathrm{TeV}}\right) \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)^2$

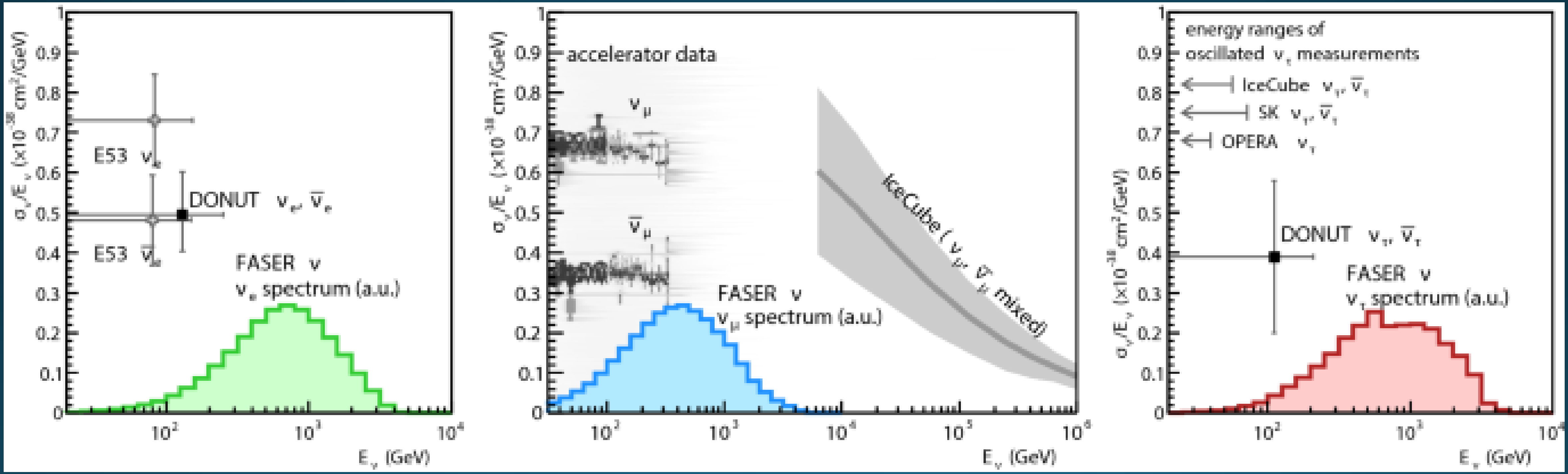
Feng, Galon, Kling and Trojanowski, *Phys. Rev. D* 97 (2018) no. 3, 035001

Motivation: ALP's and other searches

- Re-casts of dark photon searches:
  - $B - L$ gauge boson
  - "Proto-phobic" gauge boson
- Axion-like particles
  - Photon coupling (see Feng, Galon, Kling and Trojanowski)
  - W coupling (see Kling and Trojanowski)
  - Gluon coupling (see Aloni, Soreq and Williams)
  - Typically decay to $\gamma\gamma$
    - Sensitive to decays in decay volume and spectrometer (~4 meters)
- Work in progress; will not discuss these further today

FASER's Physics Reach for Long-Lived Particles: PRD 99 090511 (2019)

Motivation: collider neutrinos



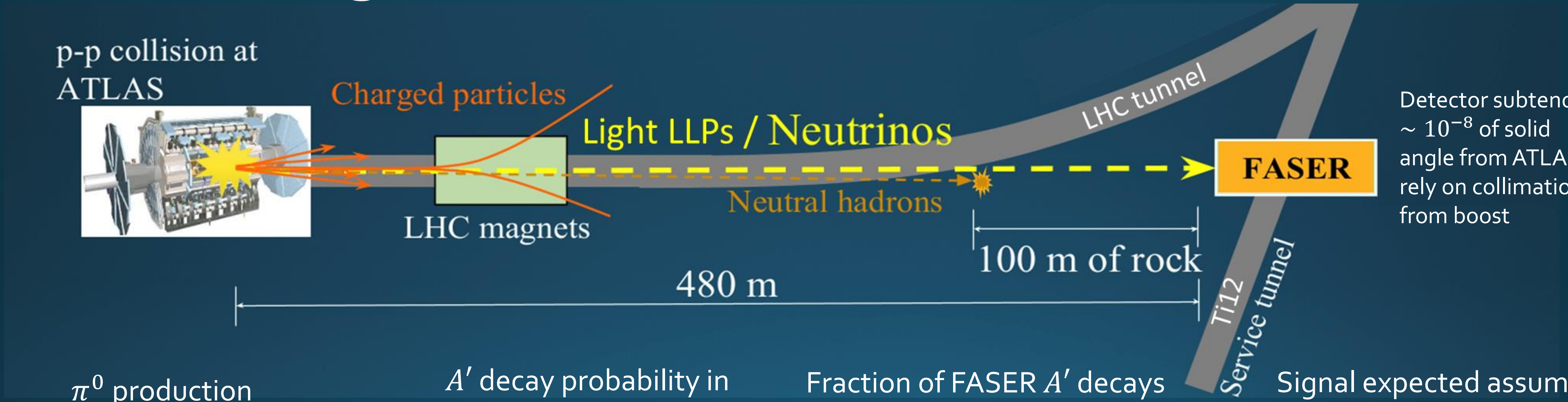
Expect ~1300 $\nu_e + \bar{\nu}_e$ interactions in 150/fb

Expect ~20,000 $\nu_\mu + \bar{\nu}_\mu$ interactions in 150/fb

Expect ~20 $\nu_\tau + \bar{\nu}_\tau$ interactions in 150/fb

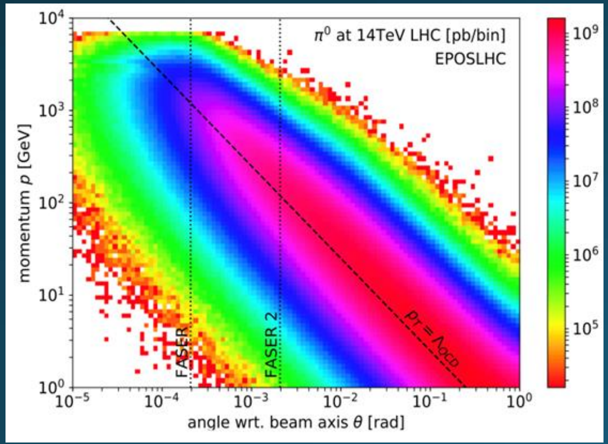
"Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC," EPJC 80, 61 (2020)

Looking forward in FASER

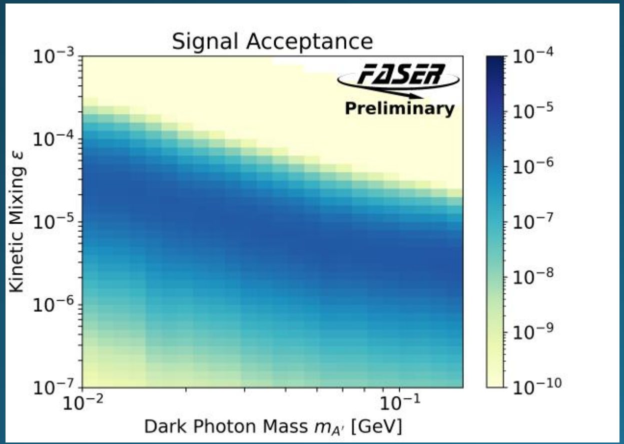


Detector subtends $\sim 10^{-8}$ of solid angle from ATLAS; rely on collimation from boost

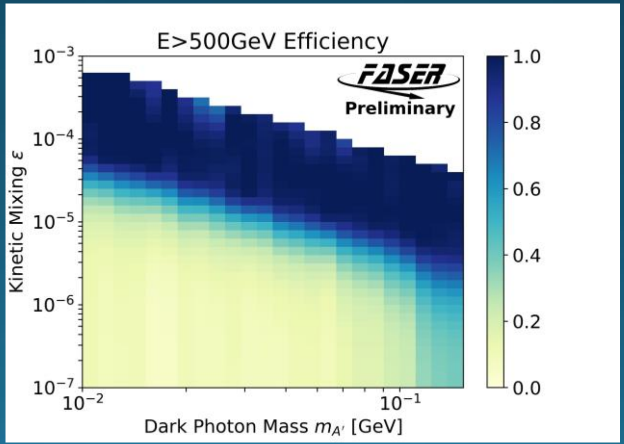
π^0 production
Kling & Trojanowski, FORESEE



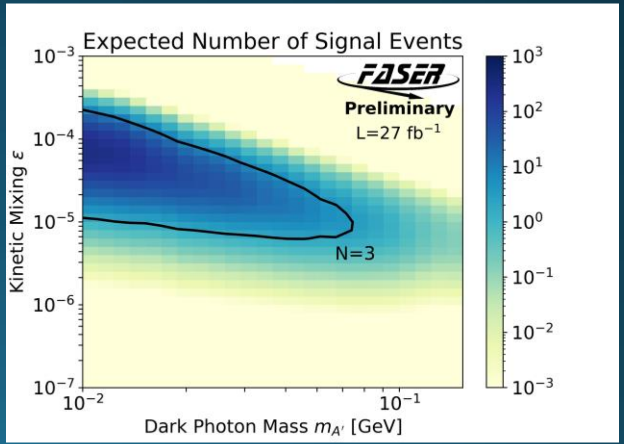
A' decay probability in 1.5 m decay volume @480 m



Fraction of FASER A' decays with $E > 500$ GeV

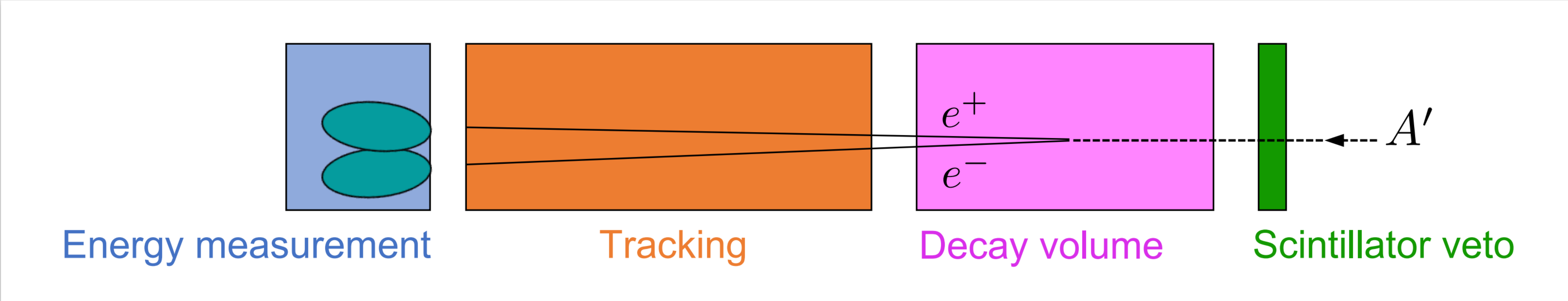


Signal expected assuming 50% selection efficiency



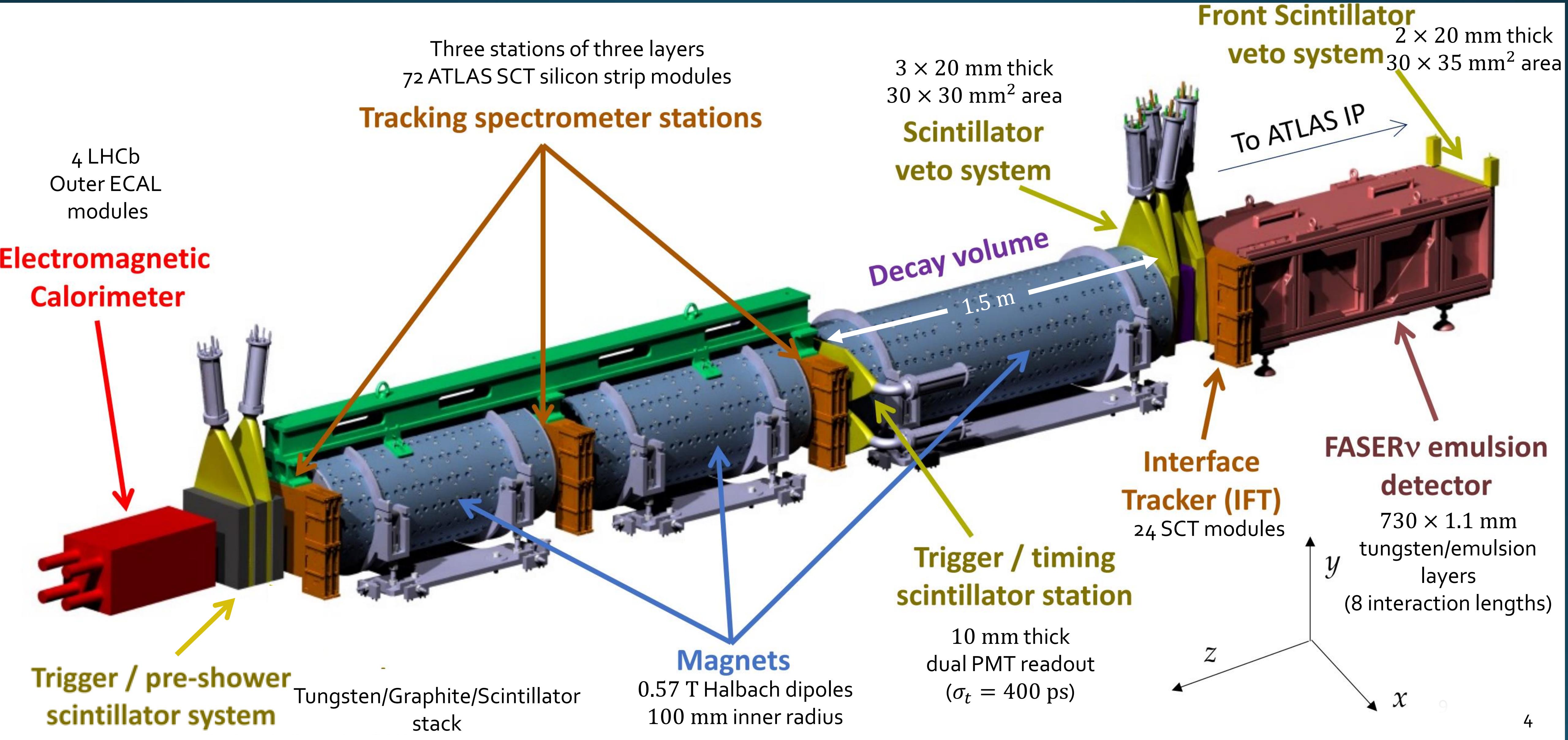
Generator level studies

$A' \to e^+e^-$ signature



- Veto entering charged particles
- Reconstruct two energetic charged tracks
- Confirm particle ID and energy with large shower in EM Calorimeter

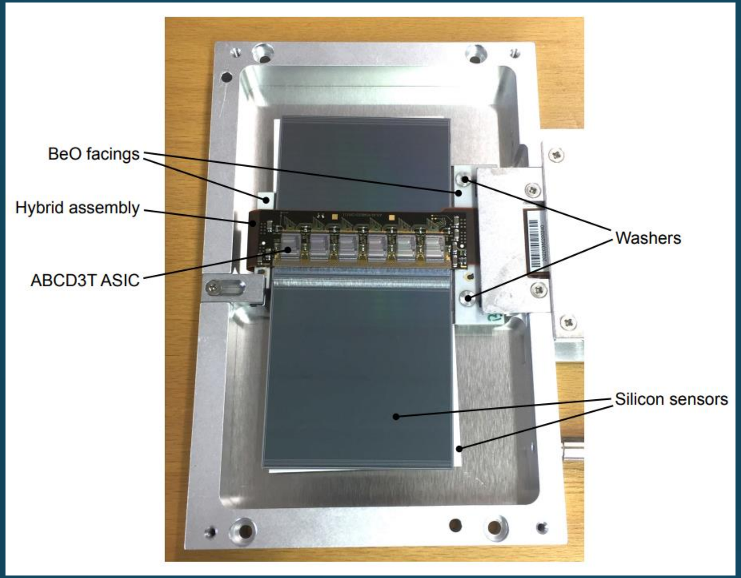
FASER Detector (arXiv:2207.11427)

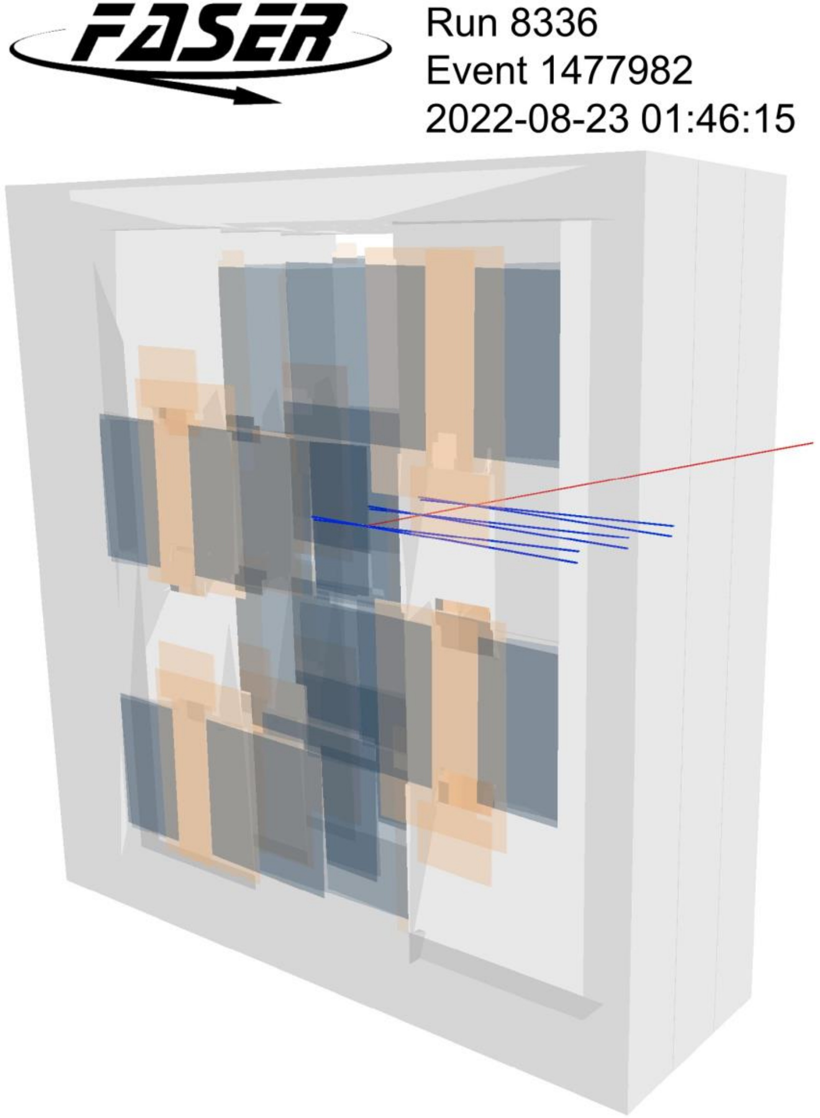



In 2018…

Tracker

- Silicon microstrip detector modules (SCT) gifted by ATLAS
  - 1 plane = 8 modules (two-sided)
  - 1 station = 3 planes
  - Full detector = 4 stations



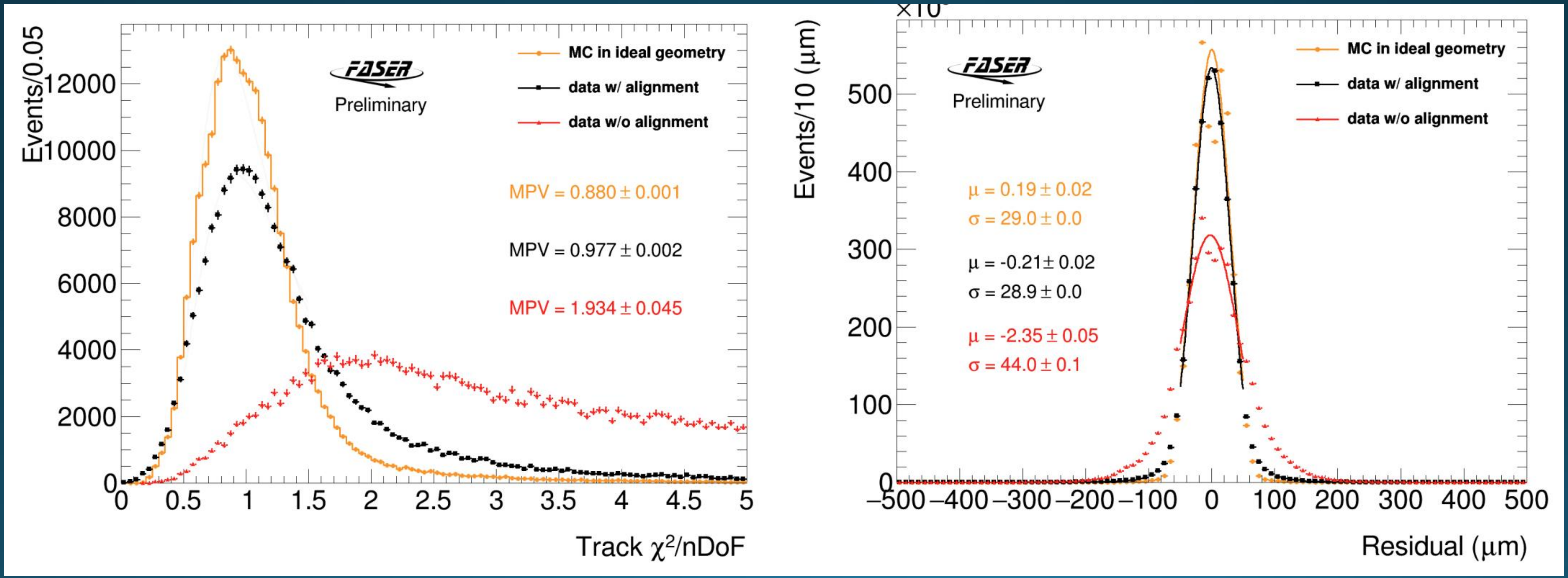


- Extremely precise ($\sim 20\ \mu\text{m}$) position resolution in one direction
  - Use two sensors with 40 mrad stereo angle to get 3D space point
- Reconstruct charged particle trajectories
- Measure momenta using bending in field

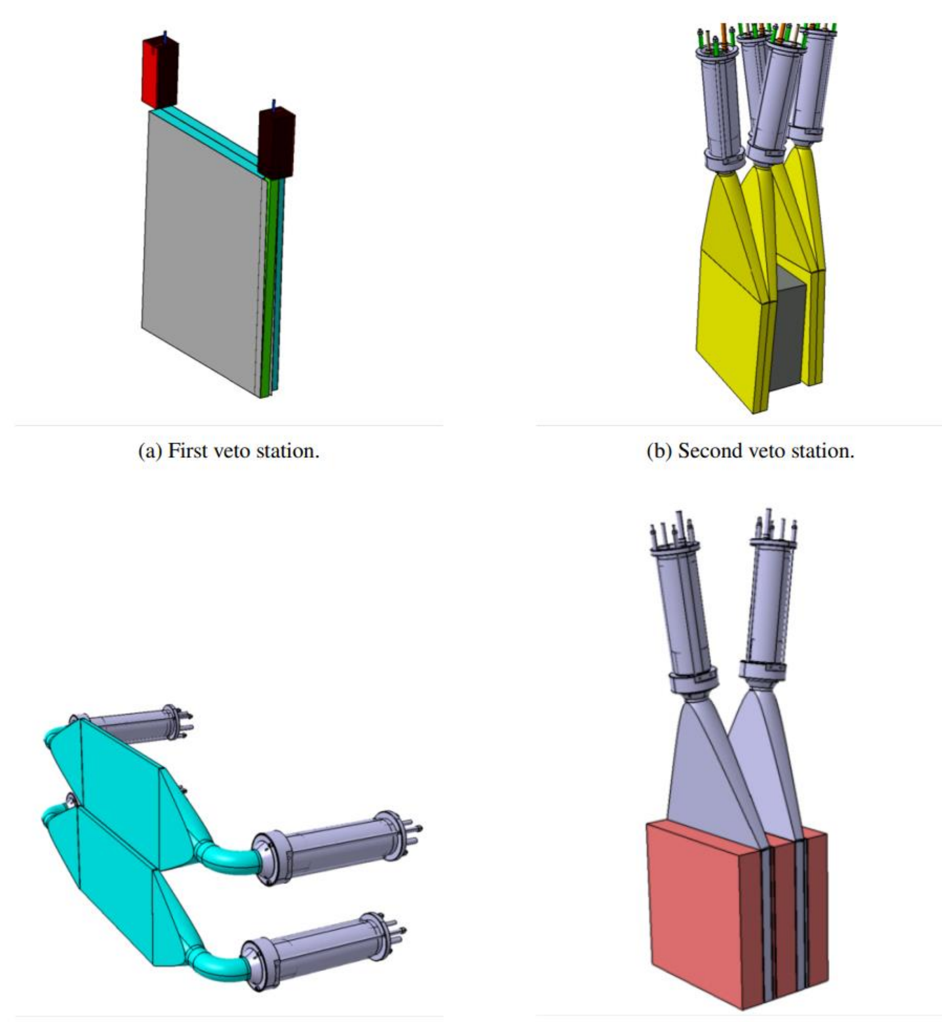
"The tracking detector of the FASER experiment," NIM 166825 (2022)

Tracker alignment

- Preliminary alignment of three downstream tracker stations used in dark photon and neutrino searches



Scintillators

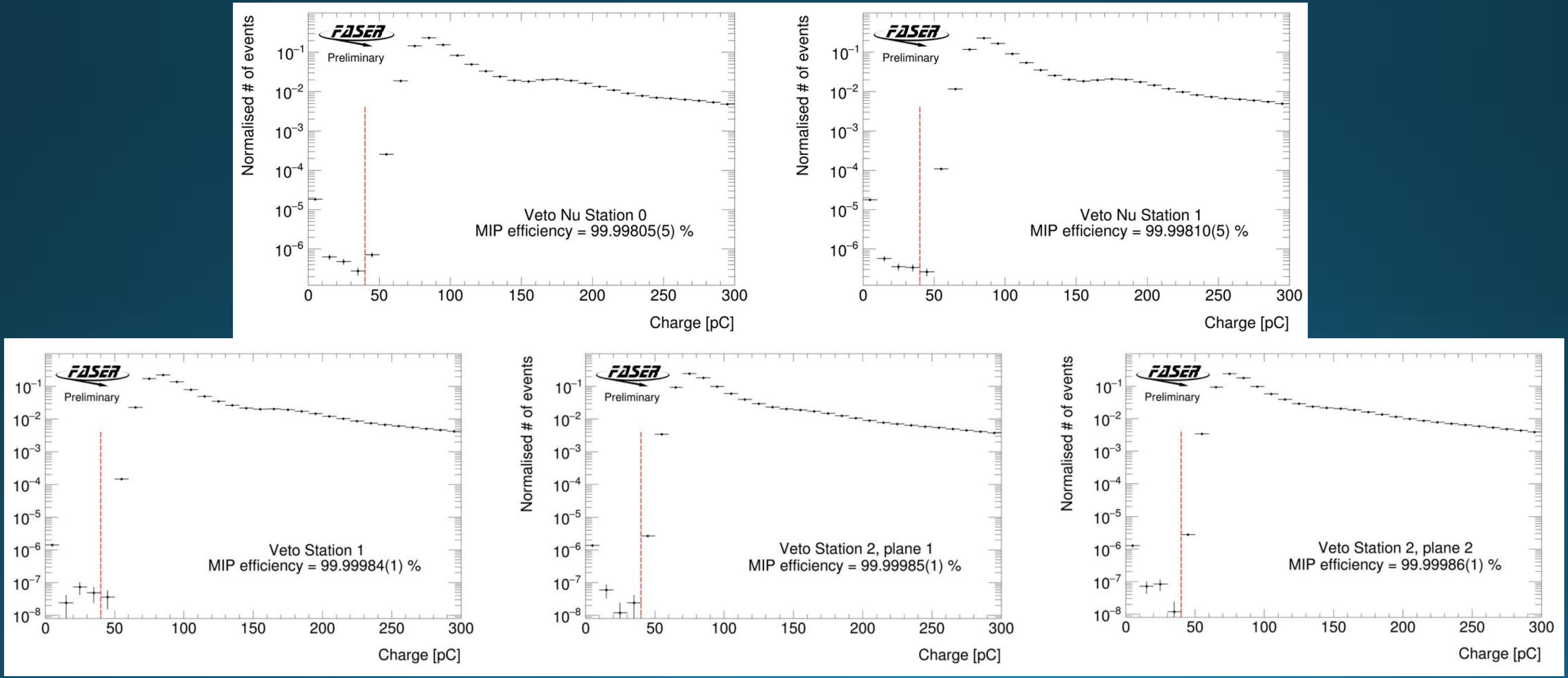


(a) First veto station. (b) Second veto station. (c) Timing station. (d) Preshower station.

- Scintillators used to veto charged particles, trigger and measure timing
- Veto scintillators:
  - Upstream and downstream of FASERν
  - 20 mm thick, single PMT readout
- Timing scintillators
  - Between decay volume and first spectrometer tracking station
  - 10 mm thick, dual PMT readout ($\sigma_t \approx 400$ ps)
- Preshower scintillators
  - In front of calorimeter
  - 20 mm thick, single PMT readout
- CAEN digitizer records waveform for all 15 PMT channels (including calorimeter)

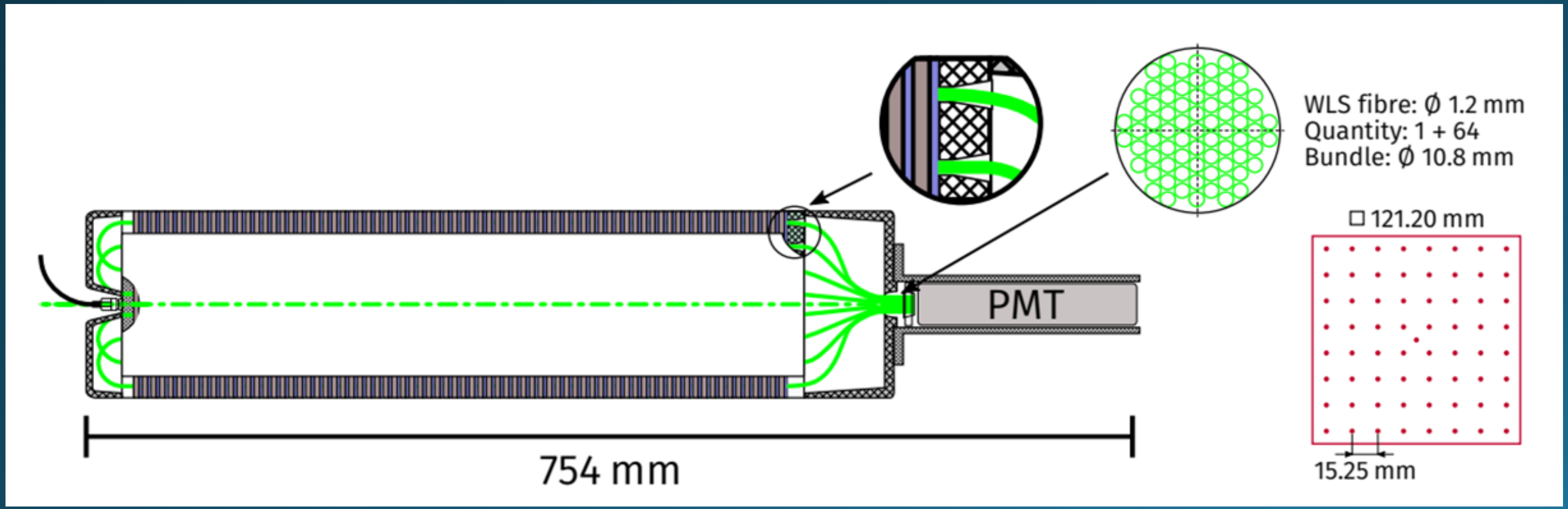
Scintillator performance

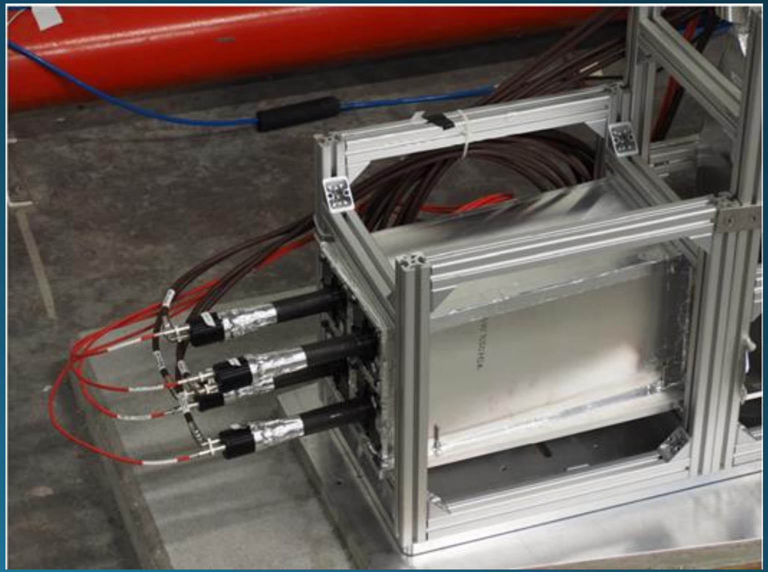
- All veto scintillator inefficiencies measured to be $< 2 \times 10^{-5}$



Calorimeter

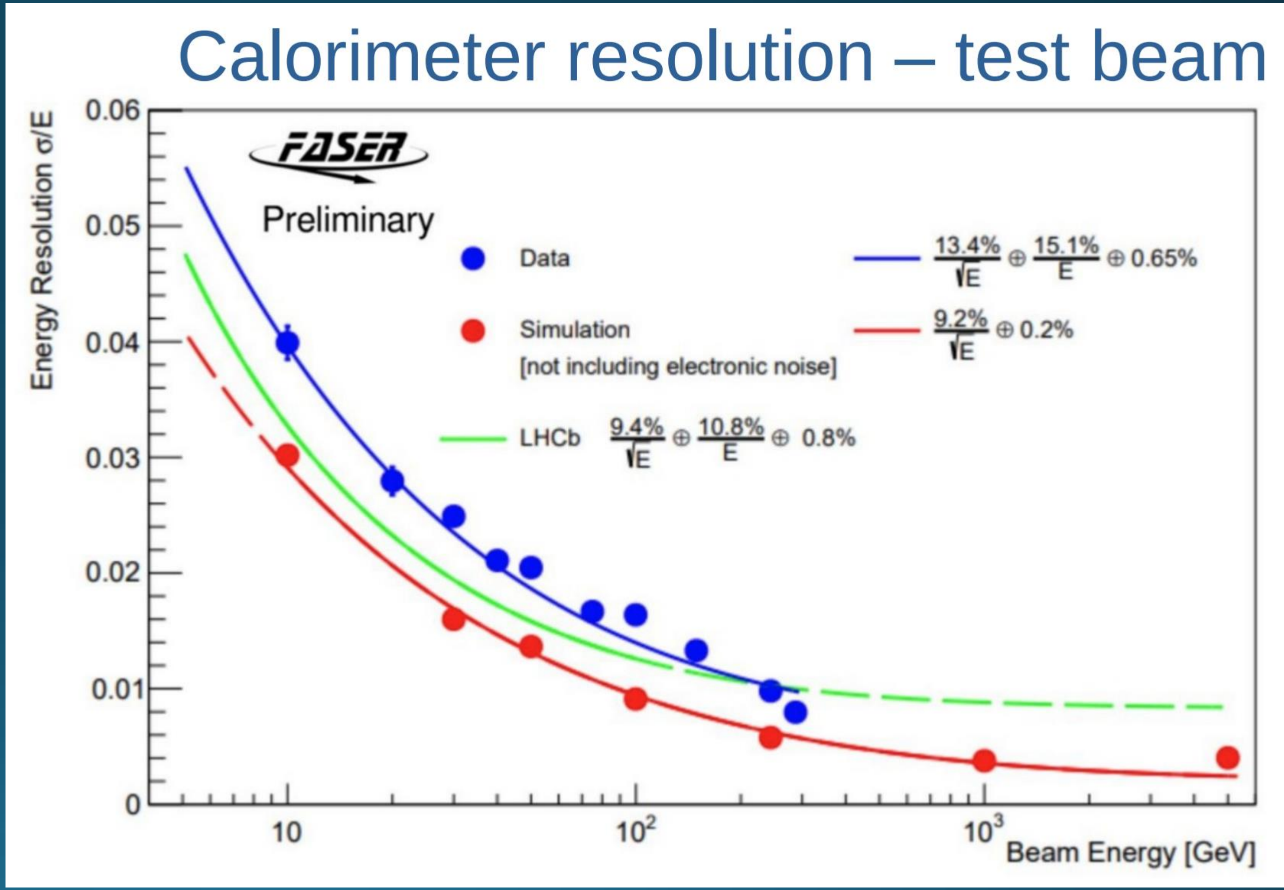
- 4 LHCb outer ECAL modules loaned to us
  - “Shashlik” design with fibers readout by PMT
  - 67 layers of scintillator alternating with 66 layers of tungsten
  - Total depth: 25 radiation lengths





Calorimeter: energy resolution

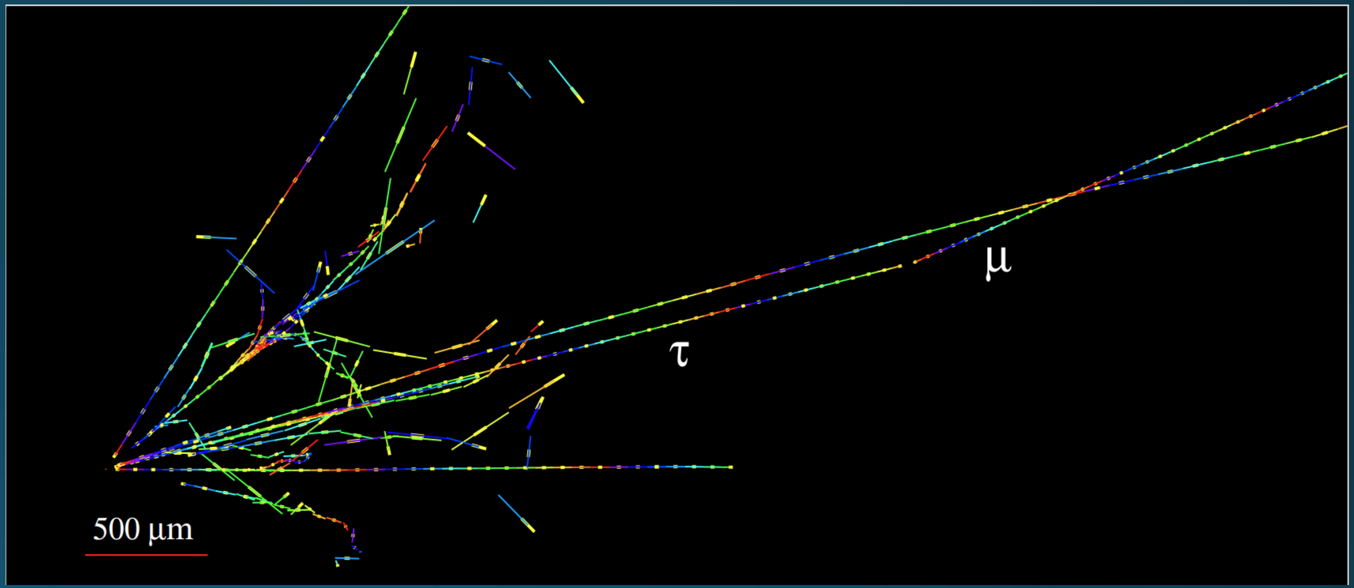
- Calorimeter response measured in dedicated 2021 test-beam campaign
  - Results close to performance quoted by LHCb
- Resolution ~1% or better at energies of interest in dark photon search



Test-beam paper in preparation!

FASERν

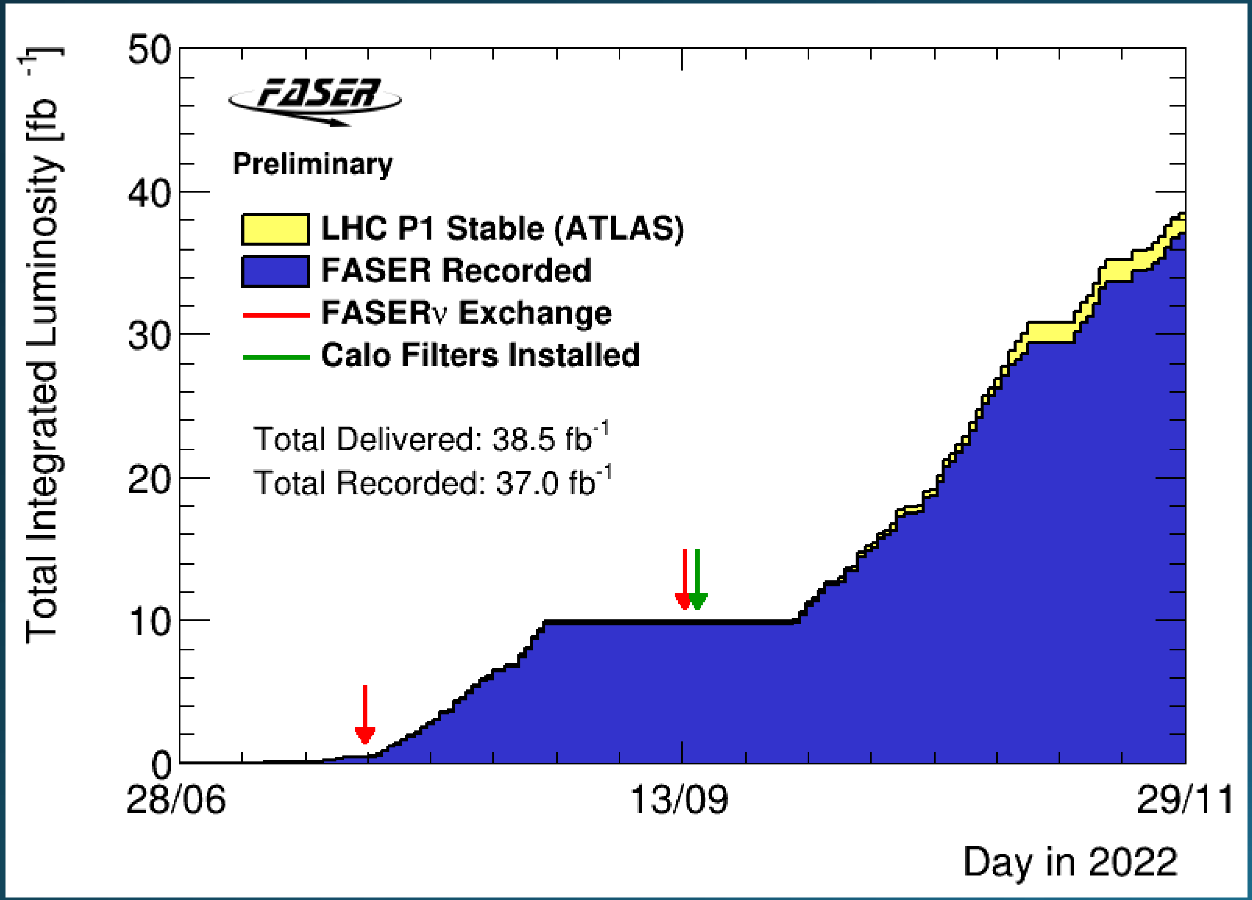
- 730 layers of 1.1 mm thick Tungsten plates interleaved with emulsion films
- 30 cm height, 25 cm width
- Total mass 1.1 tons
- Sub-micron spatial resolution
- Replaced over course of each year's run to limit track density
- Development and scanning of films from 2022 underway



Simulated ν_τ charged-current interaction, and $\tau \to \mu$ decay, in FASERν

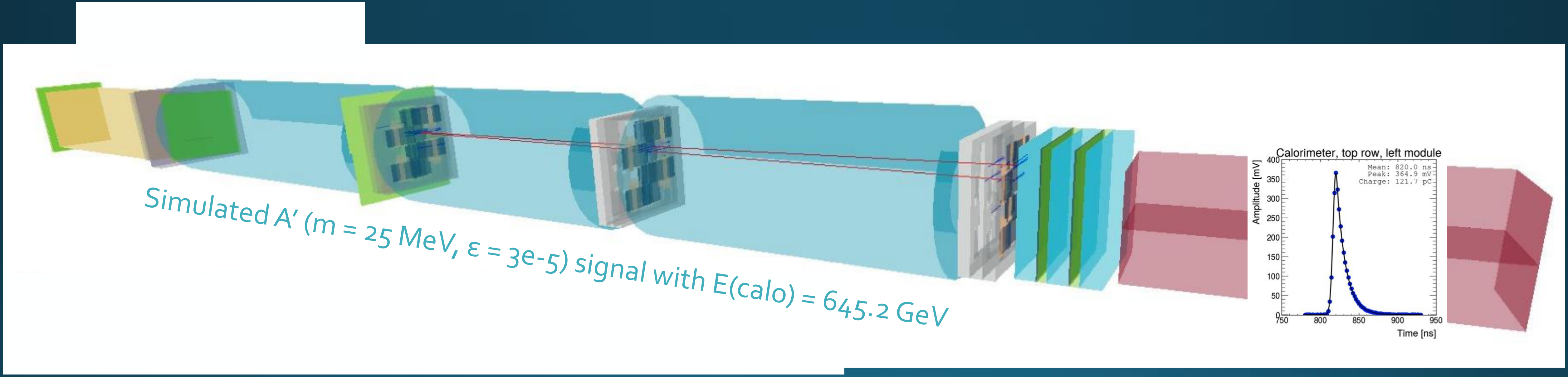
"Technical Proposal of FASERν neutrino detector," arXiv:2001.03073

Operations and data set



- Detector performed almost flawlessly in 2022
  - Trigger rates up to 1.3 kHz
  - DAQ deadtime: 1.3%
  - Recorded 96.1% of delivered luminosity
  - Over 350M single muon events
- Calorimeter gain optimized for TeV energies after second emulsion exchange (green arrow)
  - 27.1/fb used for dark photon search

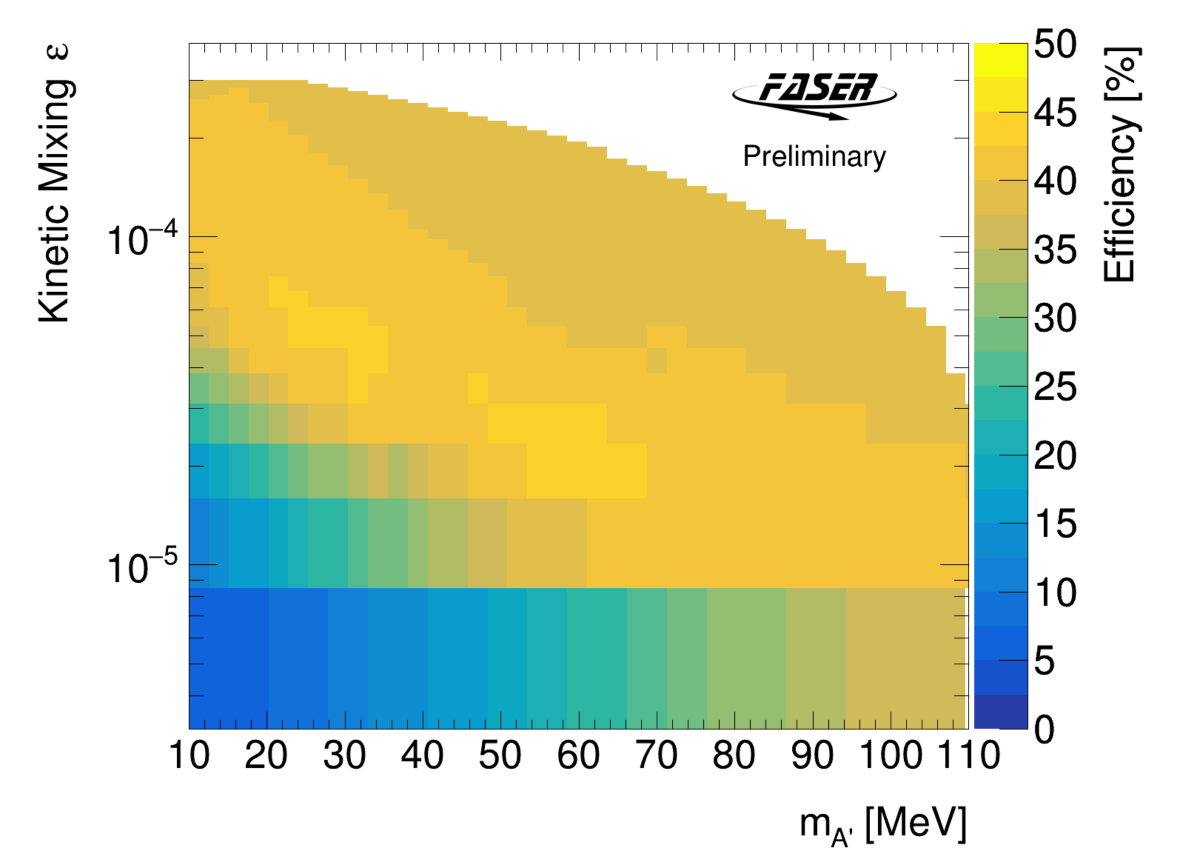
Simulated $A' \to e^+e^-$



Simulated A′ (m = 25 MeV, ε = 3e-5) signal with E(calo) = 645.2 GeV

$A' \to e^+e^-$ selection

- Events with no veto activity and $E_{\text{calo}} > 100$ GeV blinded until selection finalized.
- Simple selection optimized for discovery:
  - Collision event with good data quality
  - No signal (> 40 pC) in any veto
  - Timing and preshower consistent with ≥ 2 minimum ionizing tracks
  - Exactly two good fiducial tracks:
    - $p > 20$ GeV and $r < 95$ mm
    - Extrapolate to $r < 95$ mm at vetos
  - $E > 500$ GeV in EM calorimeter



Selection efficiency $\sim 40\%$ over region of sensitivity

Dark photon backgrounds

- Veto inefficiency
  - Negligible
- Muon-induced neutral hadrons
  - Estimated from three-track sample, ignoring muon and removing photon conversions
- Geometric muon background
  - Negligible
- Neutrino interactions in detector material
  - Estimated from GENIE sample, corrected for material missing in simulation
  - Small, but dominant background
- Non-collision (cosmic or beam) background
  - Negligible

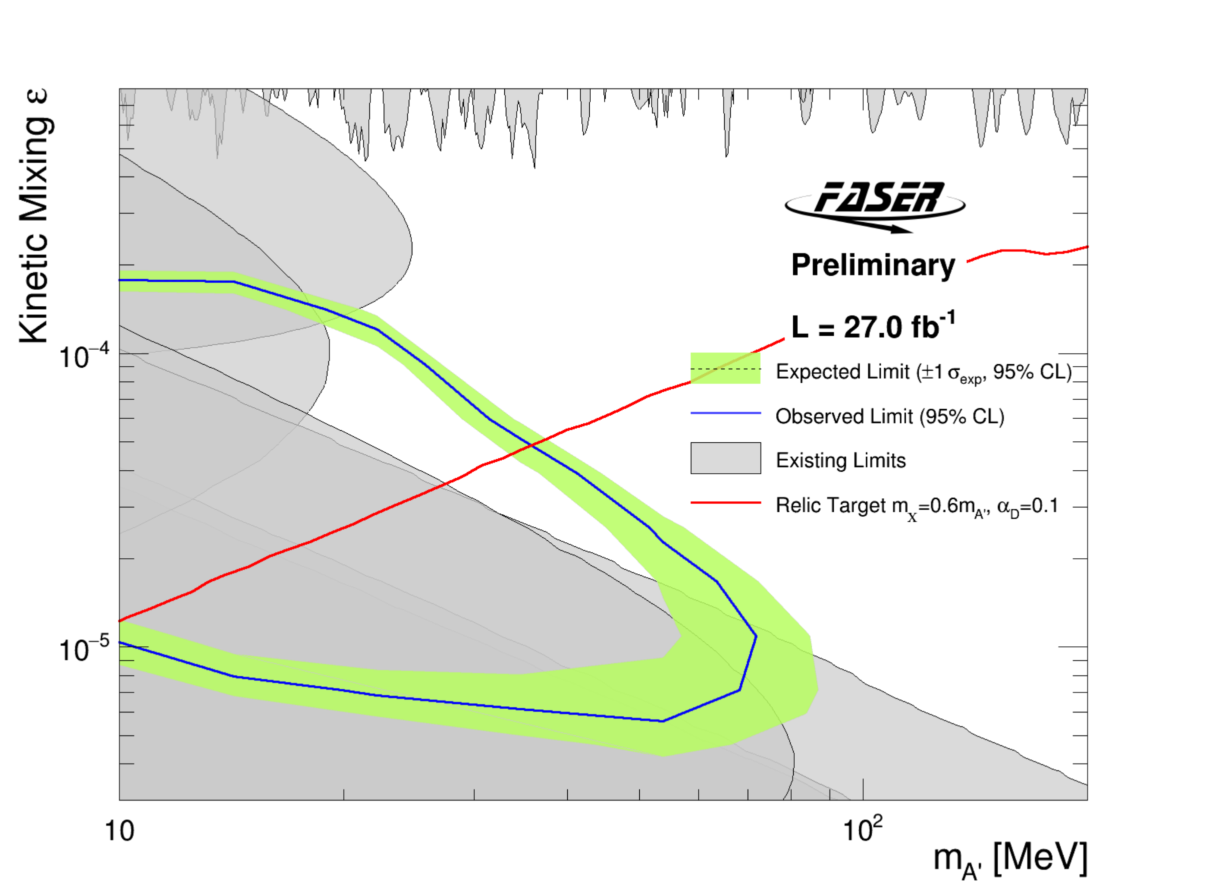
Scintillator	Efficiency
NuVeto-0	0.9999805(5)
NuVet0-1	0.9999810(5)
Veto-0	0.9999985(1)
Veto-1	0.9999984(1)
Veto-2	0.9999986(1)

Process	Background Estimate
Veto inefficiency	Negligible
Neutral hadron & geometric muon background	$(0.22 \pm 0.31) \times 10^{-3}$
Neutrino interactions	$(1.8 \pm 2.4) \times 10^{-3}$
Non-collision background	Negligible
Total background	$(2.0 \pm 2.4) \times 10^{-3}$

See https://cds.cern.ch/record/2853210/files/CERN-FASER-CONF-2023-001.pdf for more details and validation studies

$A' \to e^+e^-$ result

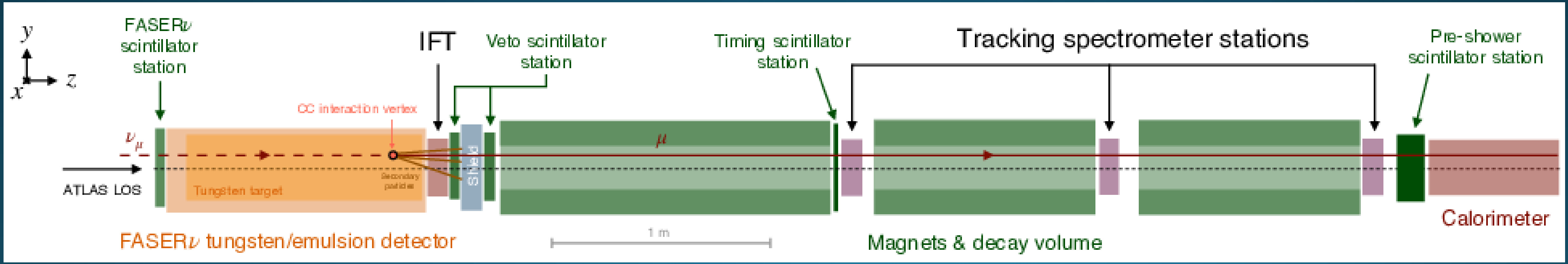
- 95% CL excluded region based on 0 events passing selection
  - 0 events with even 1 fiducial track



Source	Systematic Uncertainty	Typical Effect on Signal Yield
Theory, Statistics and Luminosity		
A' cross section	$\frac{0.15 + (E_{A'}/4\ \mathrm{TeV})^3}{1 + (E_{A'}/4\ \mathrm{TeV})^3}$	15-45%
Luminosity	2.2%	2.2%
MC statistics	$\sqrt{\sum W^2}$	1-2%
Tracking		
Momentum scale	5%	< 0.5%
Momentum resolution	5%	< 0.5%
1-track efficiency	3%	3%
2-track efficiency	15%	15%
Calorimetry		
Energy scale	6%	< 1%

Collider neutrino search

- Active electronic detector can find ν_μ and $\bar{\nu}_\mu$ CC interaction signal above background:
  - Long, high-momentum fiducial track
  - No activity in forward veto station
  - Blinded analysis (35.4/fb Run-3 luminosity used for neutrino search)



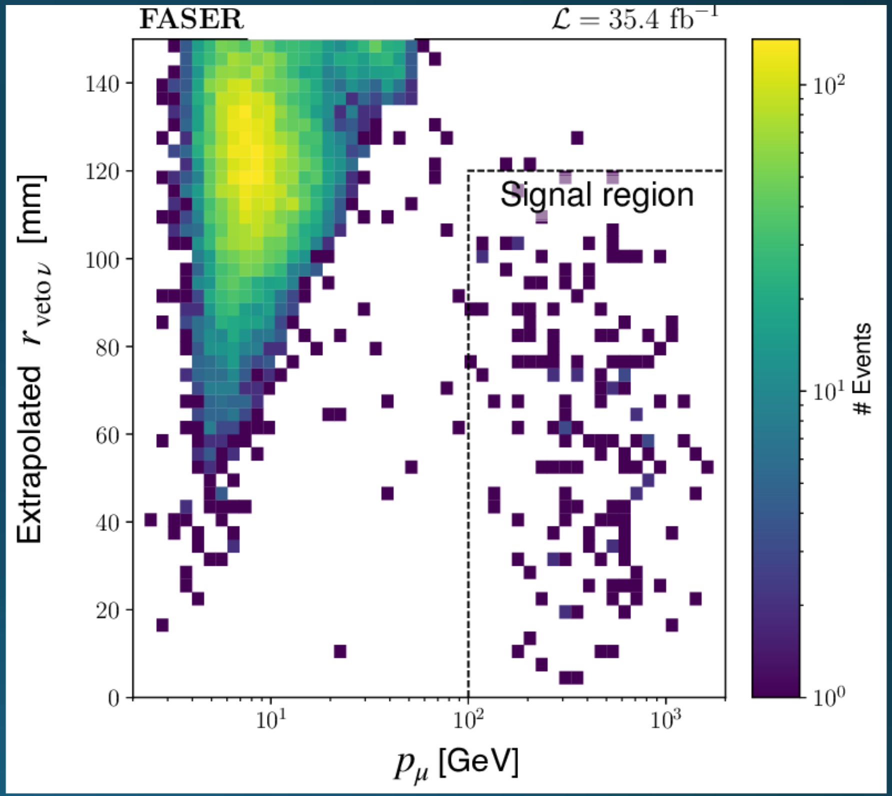
Expected backgrounds

- Veto inefficiency
  - Measured using singles rate in forward veto (only one of two layers fire)
  - Negligible
- Muon-induced neutral hadrons
  - $n_{had} = 0.11 \pm 0.06$ (stat) estimated from simulation
  - Conservative; ignores likely veto signal from parent muon
- Geometric muons (leakage around veto)
  - $n_{geo} = 0.08 \pm 1.83$ (stat) extrapolated from side-band

Please see https://arxiv.org/pdf/2303.14185.pdf for details

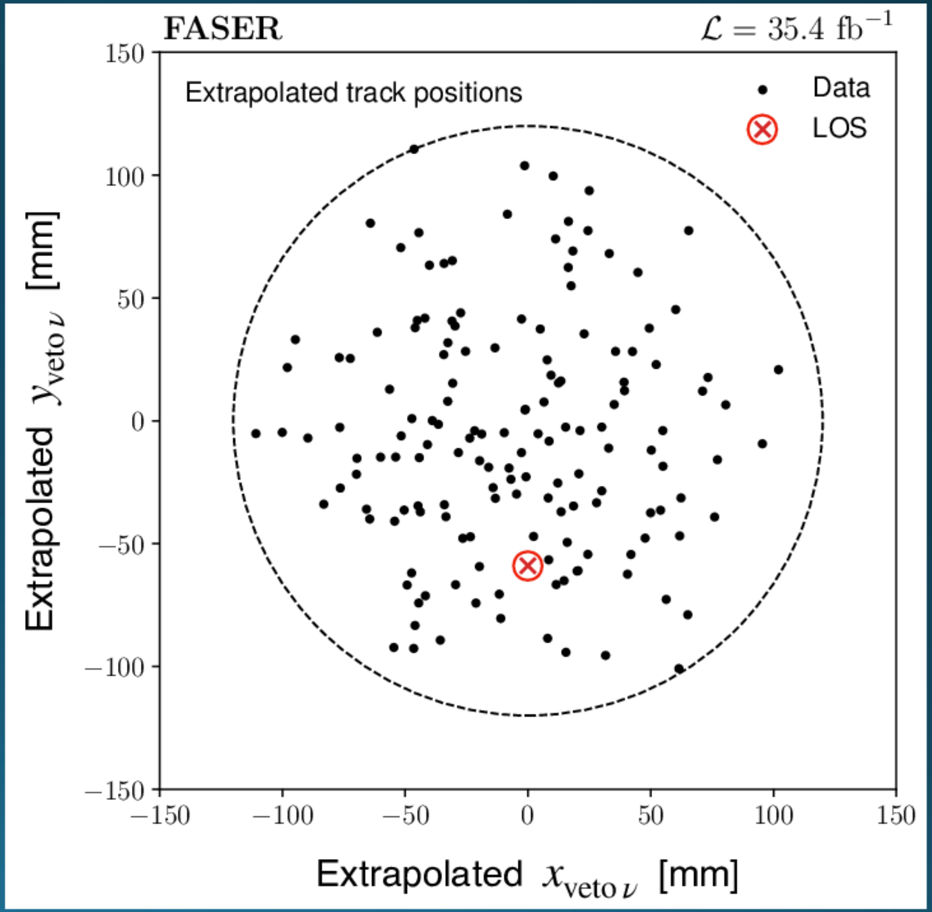
Collider neutrinos: results

- 153^{+12}_{-13} neutrino-like events observed over backgrounds
- "No signal" hypothesis excluded at 16 σ
- No attempt to measure cross section, but luminosity-normalized prediction agrees well with data.



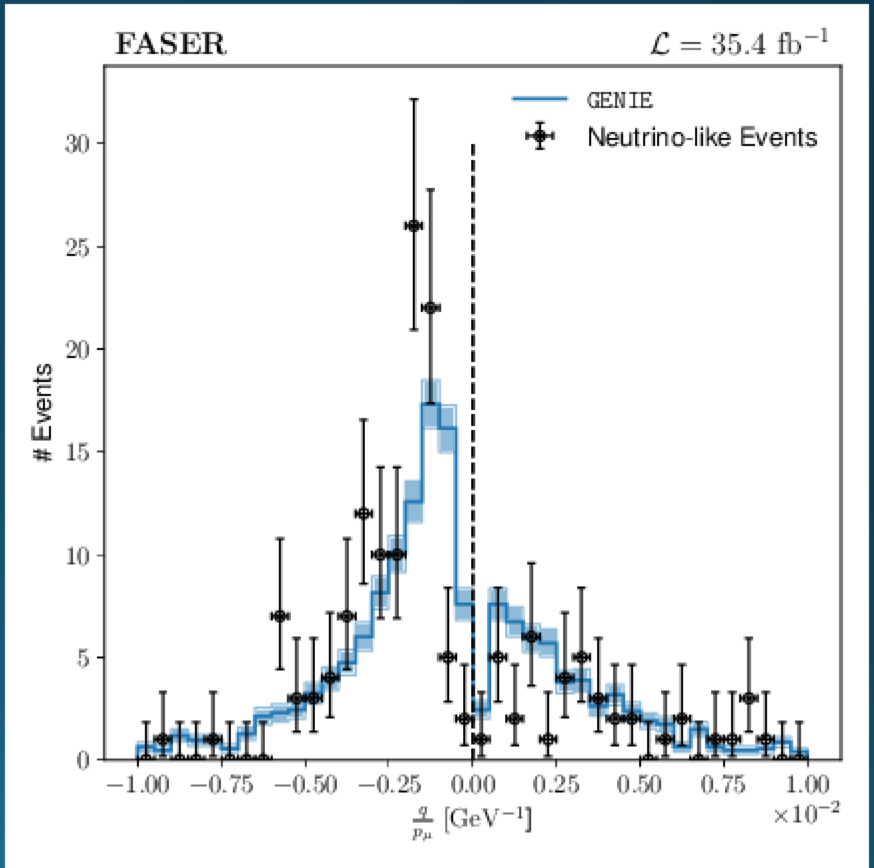
Collider neutrinos: extrapolation

- Extrapolate candidate charged tracks to front veto position
  - Uniform distribution not expected due to tighter cuts downstream
- No evidence of entering contamination near edges

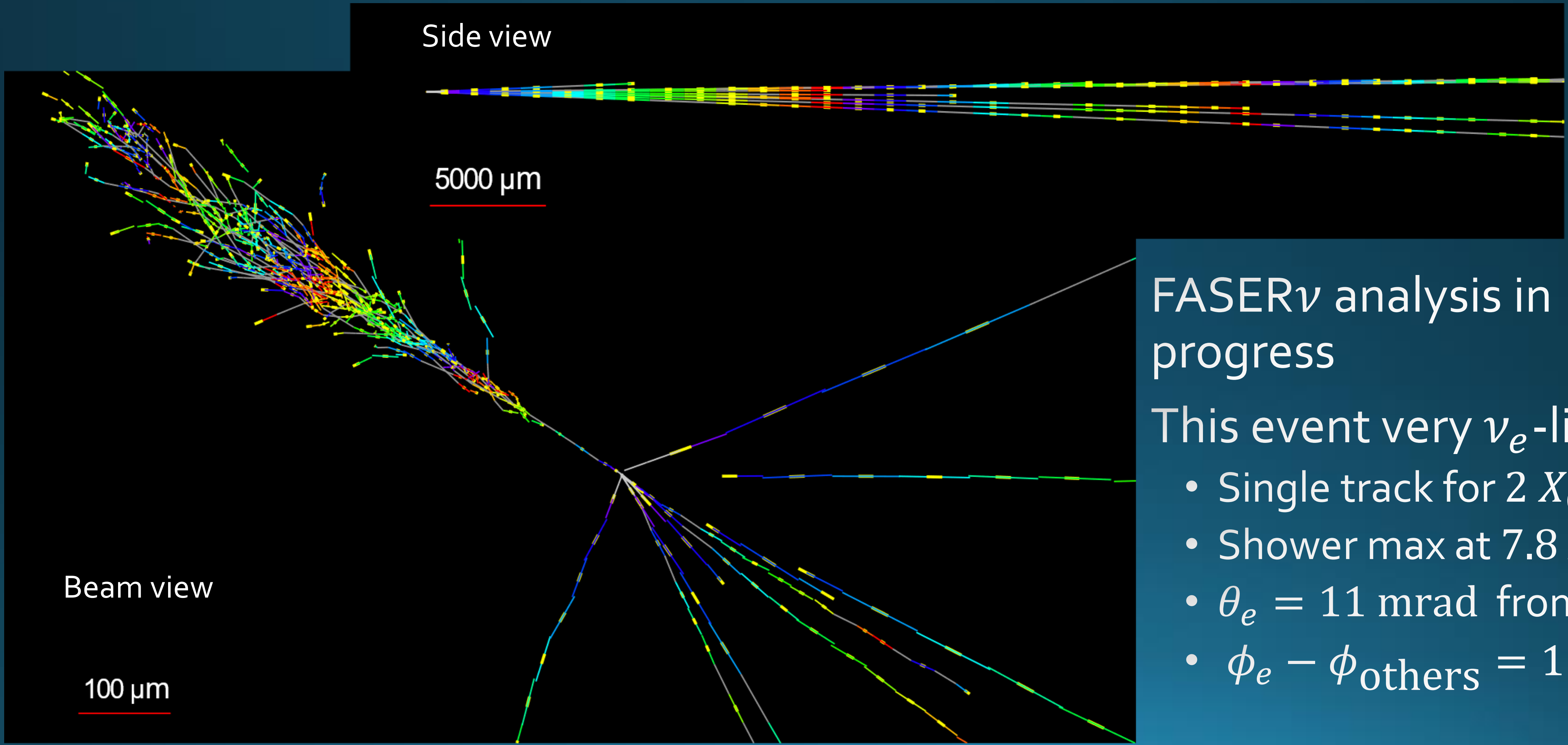


Collider neutrinos: q/p

- Clear evidence of both ν_μ and $\bar{\nu}_\mu$ interactions with $E_\nu > 300$ GeV
- Luminosity-normalized prediction from GENIE and F. Kling fluxes



Teaser: ν_e candidate in FASERν



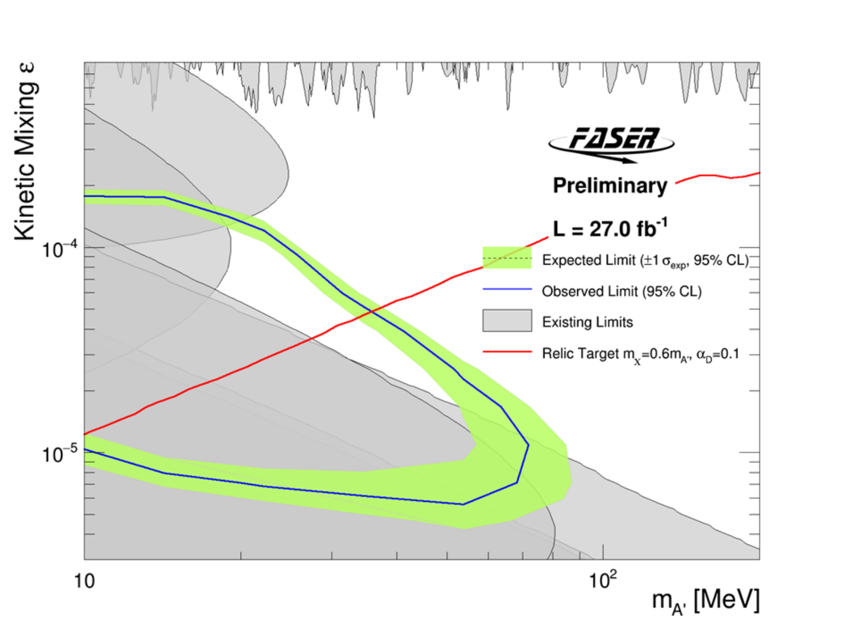
FASERν analysis in progress

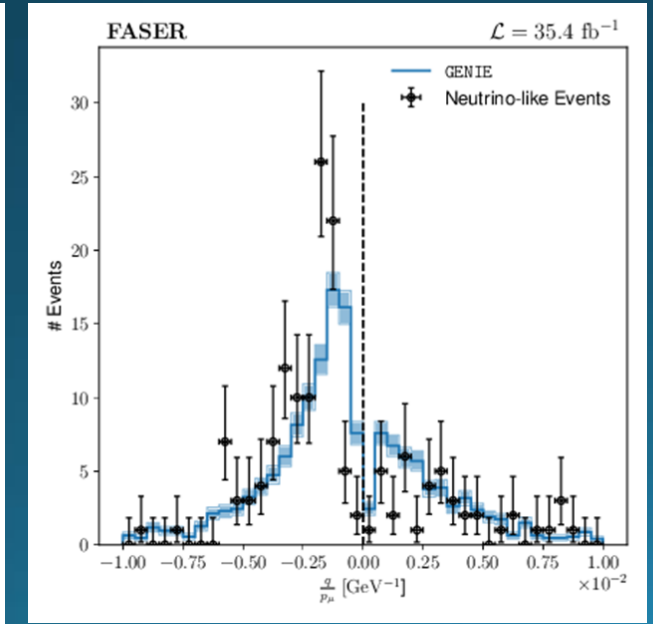
This event very ν_e-like

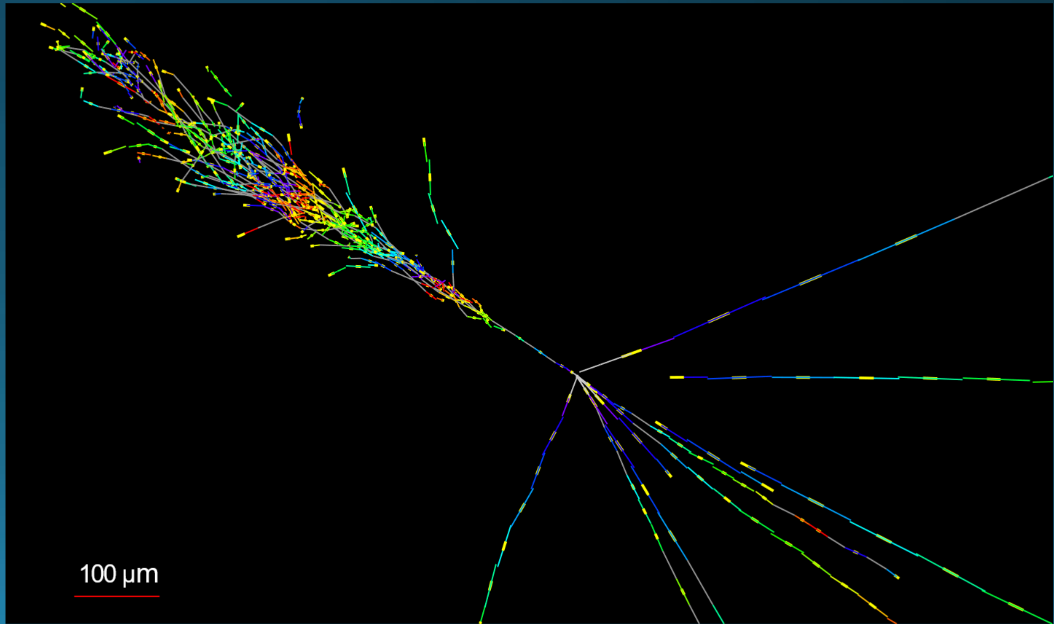
- Single track for 2 X_0
- Shower max at 7.8 X_0
- $\theta_e = 11\ \mathrm{mrad}$ from beam
- $\phi_e - \phi_{\mathrm{others}} = 175°$

FASER Summary

- FASER had a very successful start to Run-3
- A' exclusion in interesting thermal relic region
- First direct detection of 153 collider neutrino interactions
- High-resolution neutrino studies with FASERν underway
- Much more data to come!







Acknowledgements

- Financial support for FASER comes from:

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

NSF

CERN

erc

Swiss National Science Foundation

科研費 KAKENHI

- We also thank:
  - LHC for successful 2022 run
  - ATLAS for accurate luminosity data
  - ATLAS SCT for donated tracker modules
  - ATLAS for Athena software framework
  - LHCb for donated ECAL modules
  - CERN FLUKA team for simulations
  - CERN PBC and technical infrastructure teams for excellent support during design, construction and installation

FASER publications

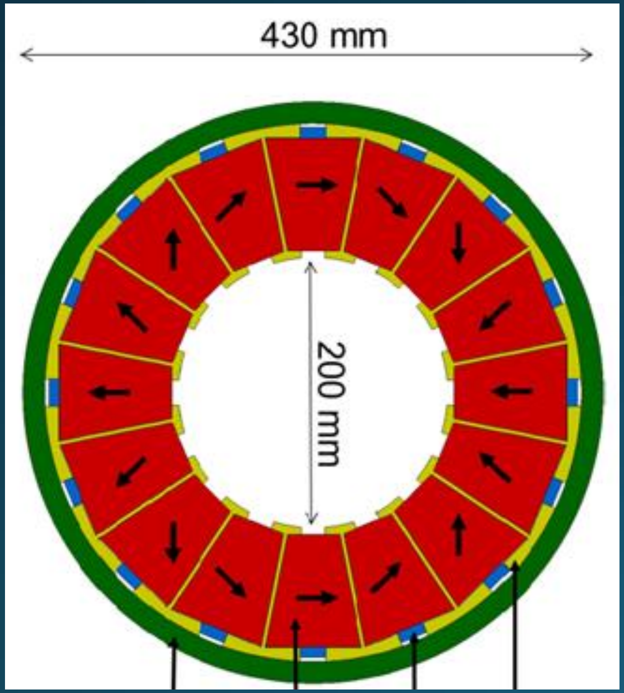
- The FASER Detector: arXiv:2207.11427
- The FASER W-Si High Precision Preshower Technical Proposal: CERN Document Server
- The tracking detector of the FASER experiment: NIM 166825 (2022)
- The trigger and data acquisition system of the FASER experiment: JINST 16 P12028 (2021)
- First neutrino interaction 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 Particles: PRD 99 090511 (2019)
- Letter of Intent: arXiv:1812.09139
- Technical Proposal: arXiv:1811.10243

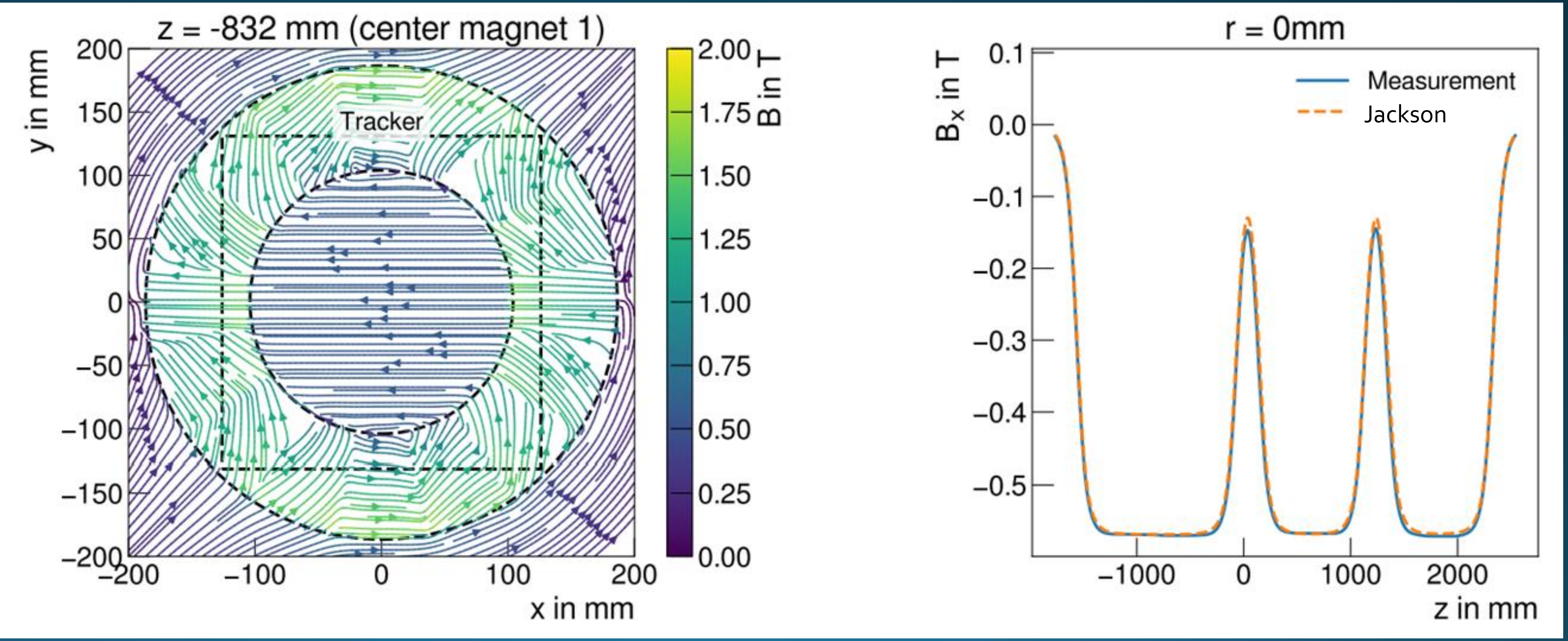
Supplemental material

Backup

Magnets

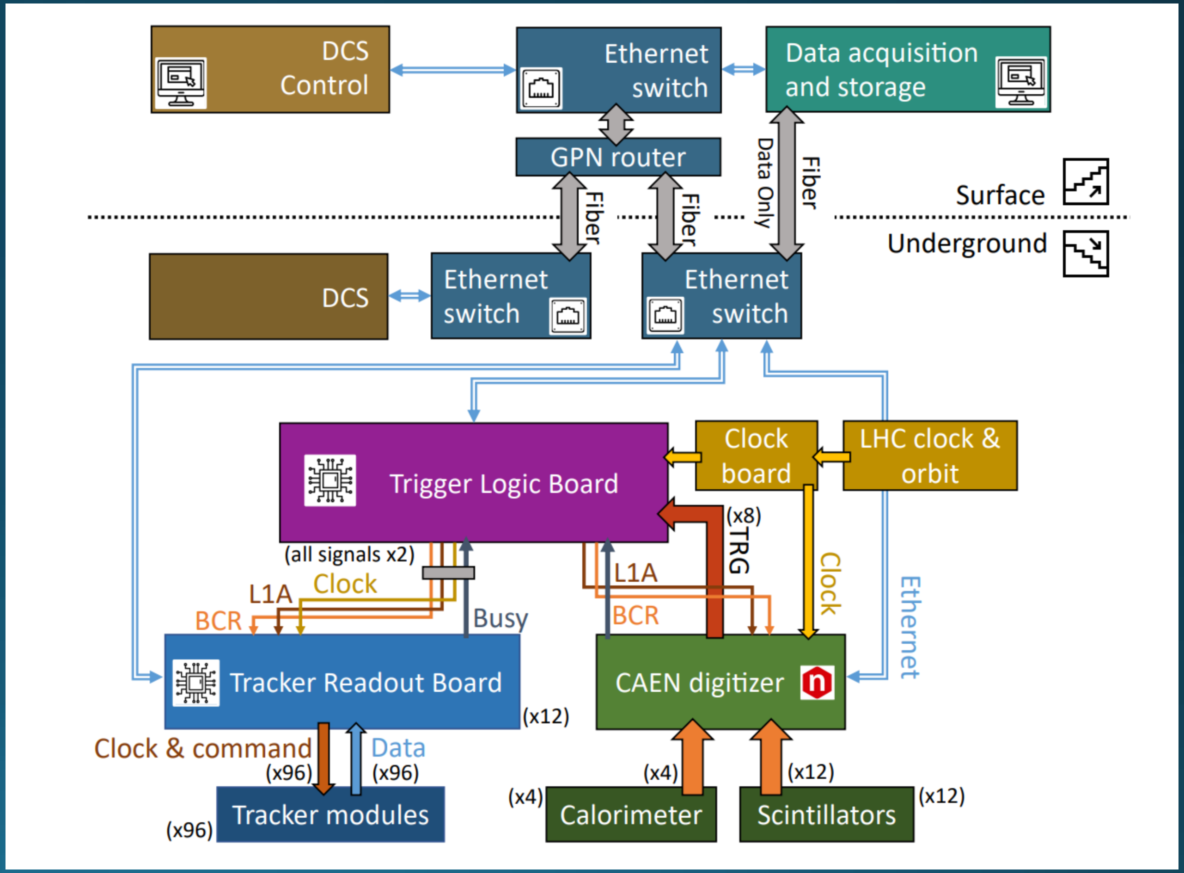
- Three permanent magnets with “Halbach” design produce very uniform dipole field of 0.57 T
- The most expensive part of the experiment!





Trigger and Data acquisition

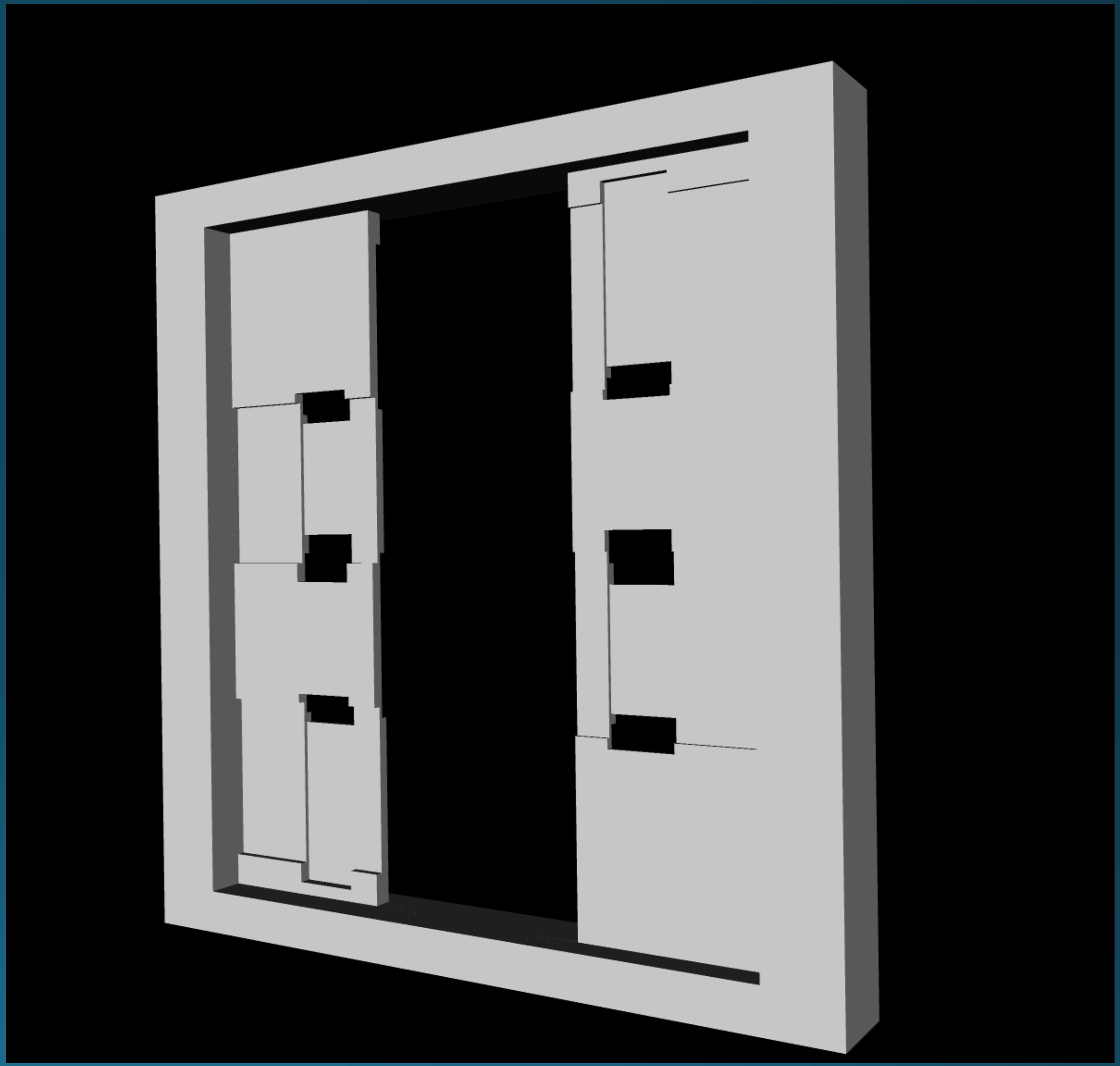
- Based on open-source DAQling framework
- Automated, continuous data-taking
  - No control room or dedicated shift-takers
- Trigger rates up to 1.3 kHz
  - Inputs from scintillators and calorimeter (CAEN digitizer)
- DAQ deadtime in 2022 run: 1.3%
- Event size: 21.5 kB, dominated by PMT waveform data



“The trigger and data acquisition system of the FASER experiment,” JINST 16 P12028 (2021)

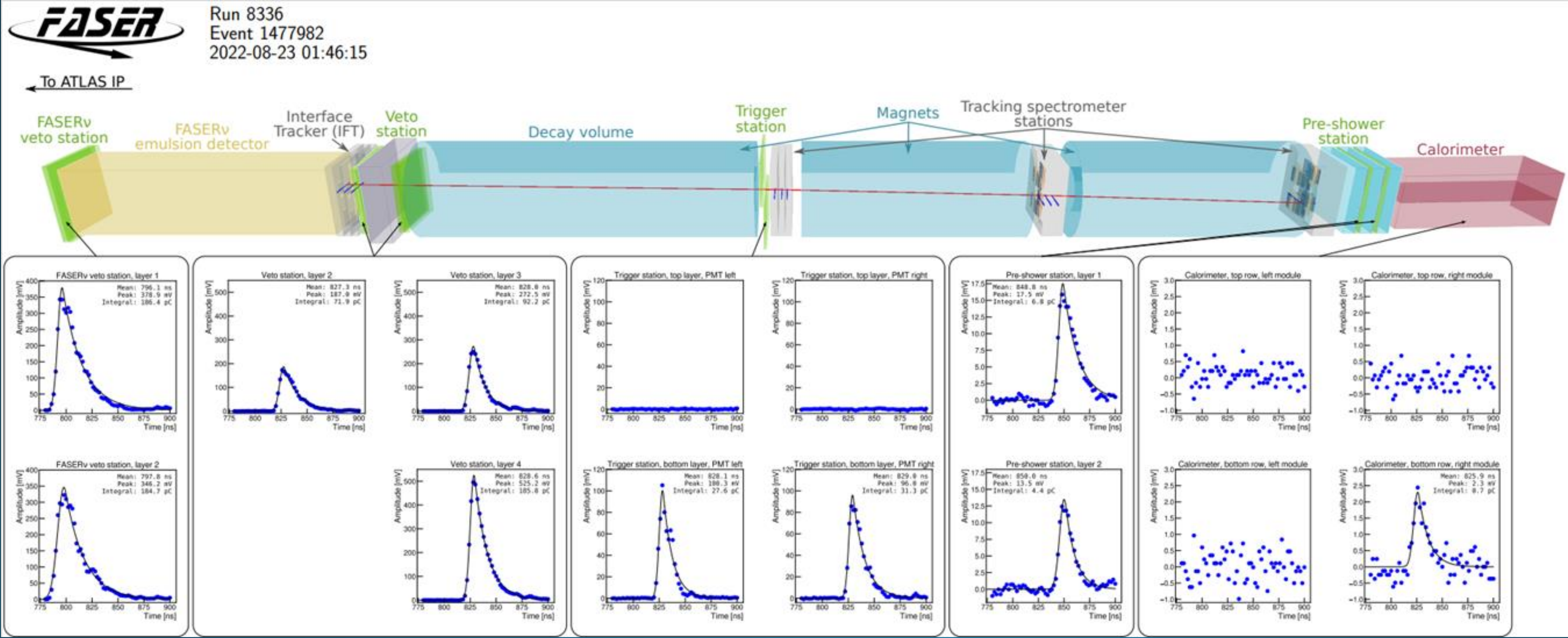
Offline software

- Adapted open-source Gaudi/Athena framework to FASER
  - "Calypso"
  - No time/person-power to build our own from scratch
- Use native ATLAS/LHCb geometry descriptions for SCT/Calorimeter modules, respectively
- ACTS track reconstruction in production before ATLAS…

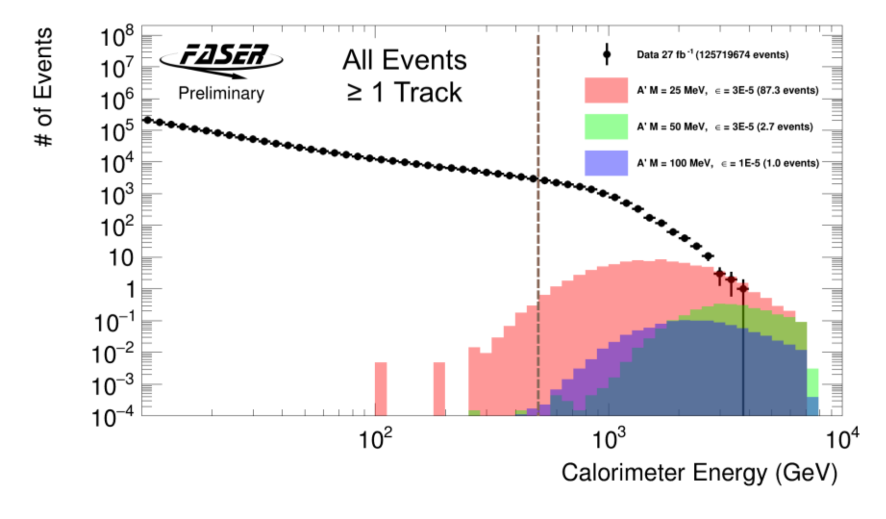


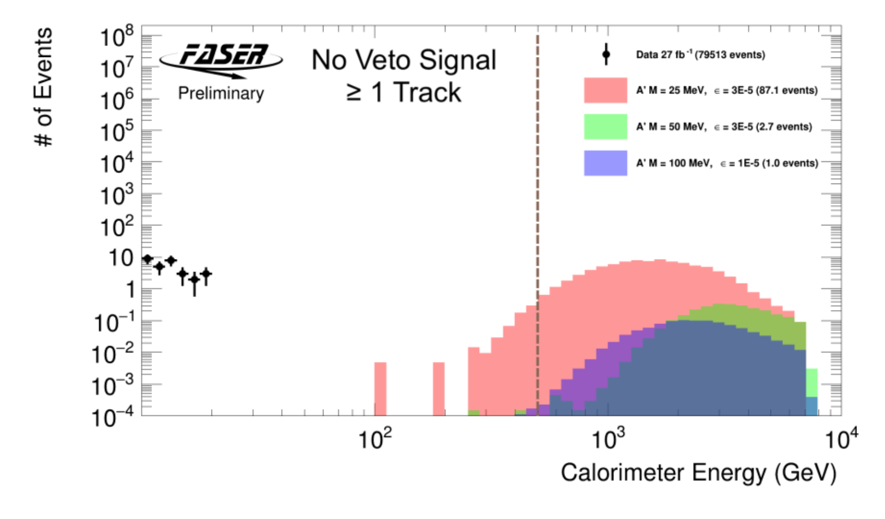
FASER tracker frame, as constructed and rendered in Calypso/Athena

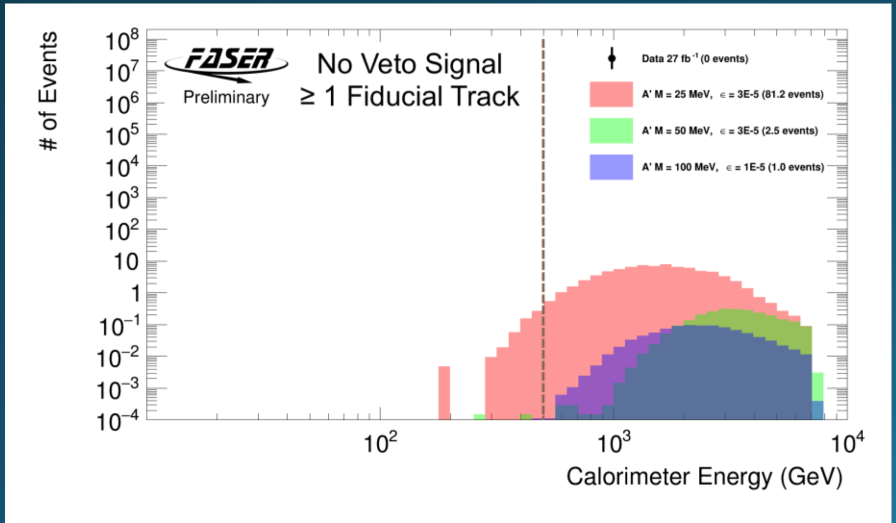
A muon traversing FASER

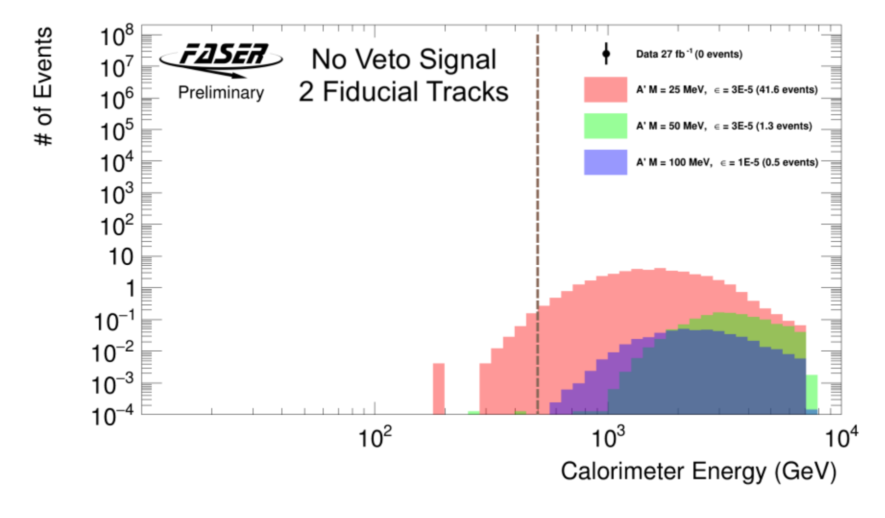


$A' \to e^+e^-$ cut flow: calorimeter energy

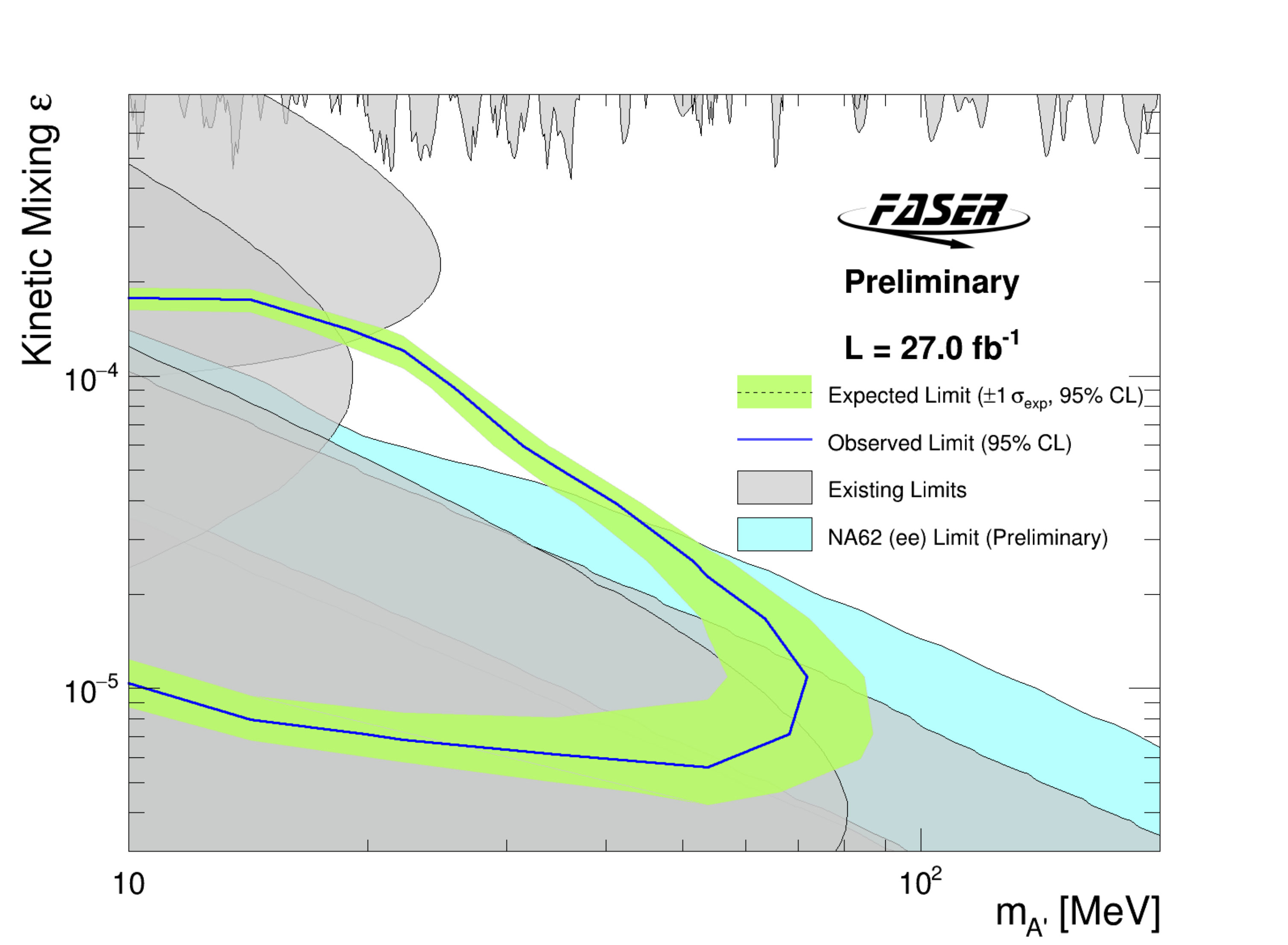






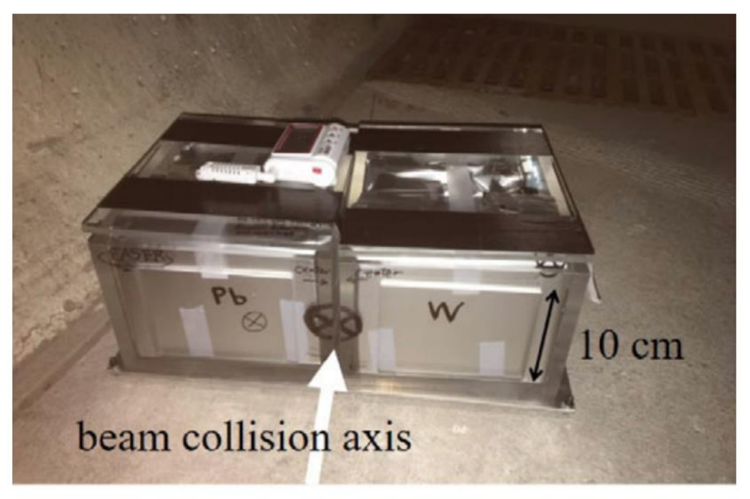


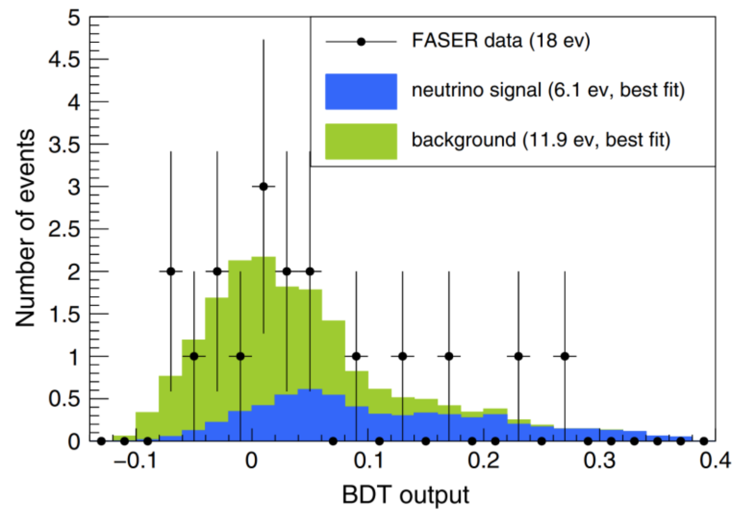
FASER and NA-62 result from Moriond



Collider Neutrinos: Pilot search

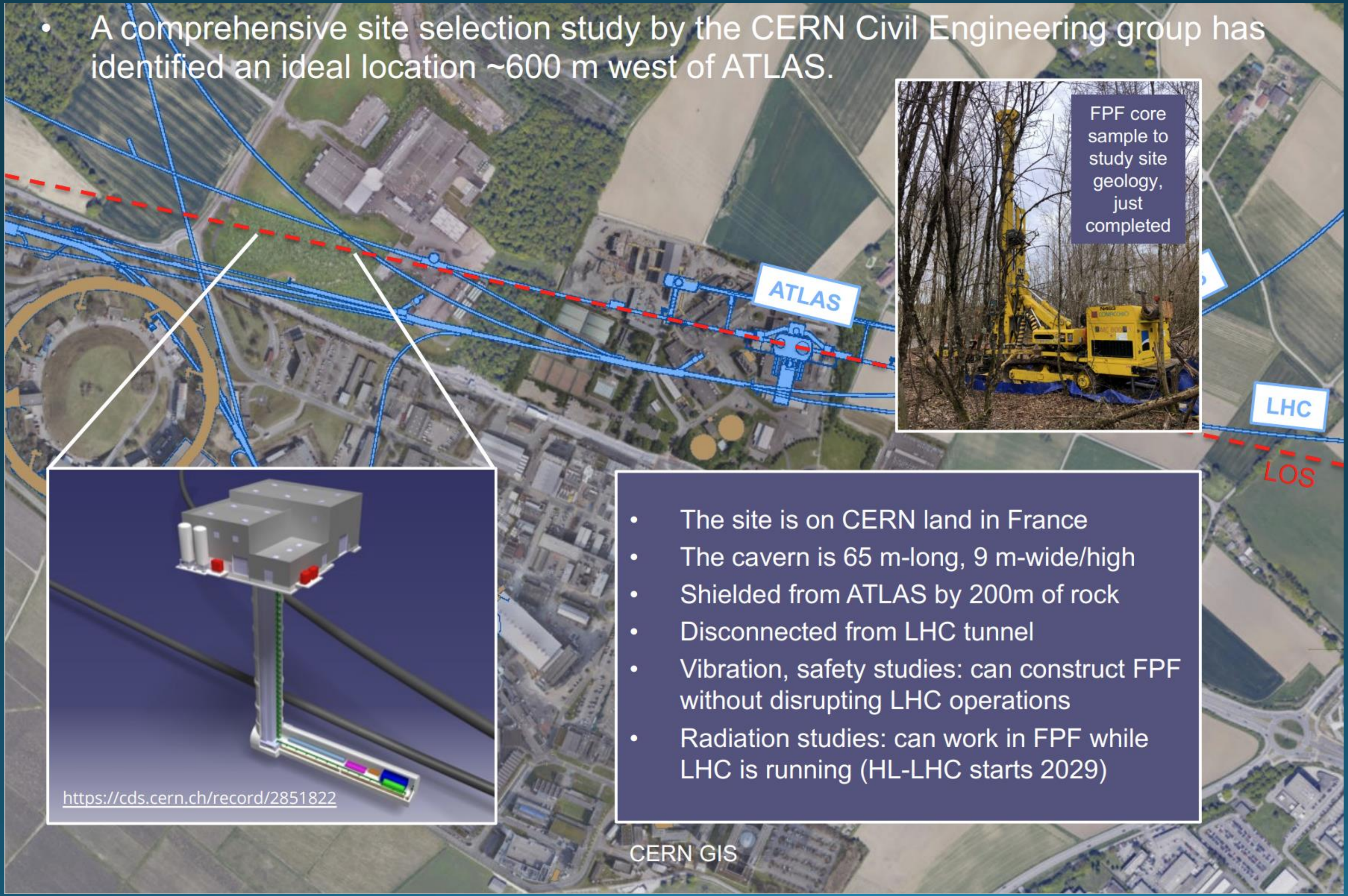
- Copious meson production makes the LHC an intense source of the world's highest energy man-made neutrinos
  - De Rujula and Ruckl (1984)
- First search using 29 kg emulsion detector in 2018
  - 12.2/fb at 13 TeV CMS energy
  - 2.7 σ excess of neutrino-like neutral vertices
- FASERν emulsion detector will study in detail with Run-3 data





"First neutrino interaction candidates at the LHC," PRD 104 L091101 (2021)

Forward Physics Facility for HL-LHC



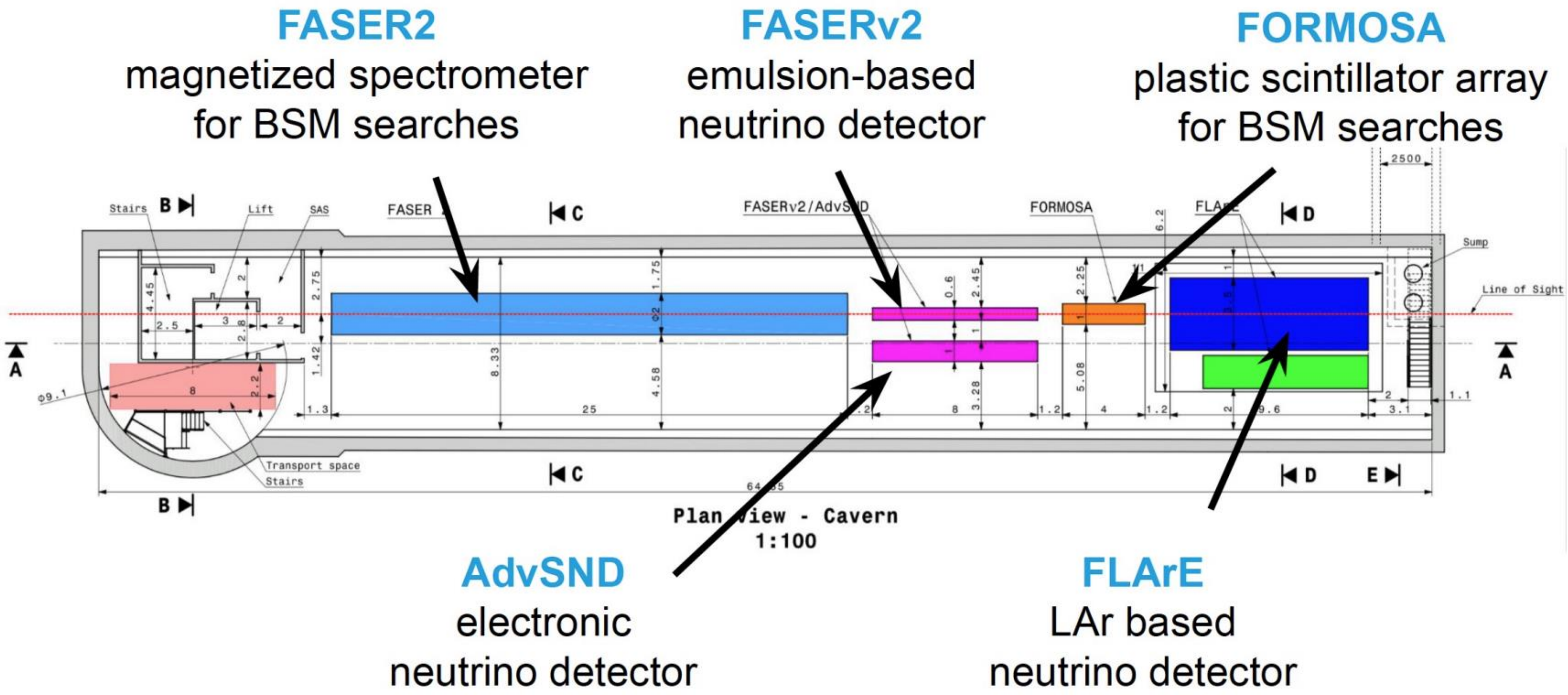
FPF slide credits:
April 12 P5 report by Jonathan Feng

FPF Website

FPF Whitepaper:
arXiv: 2203:05090

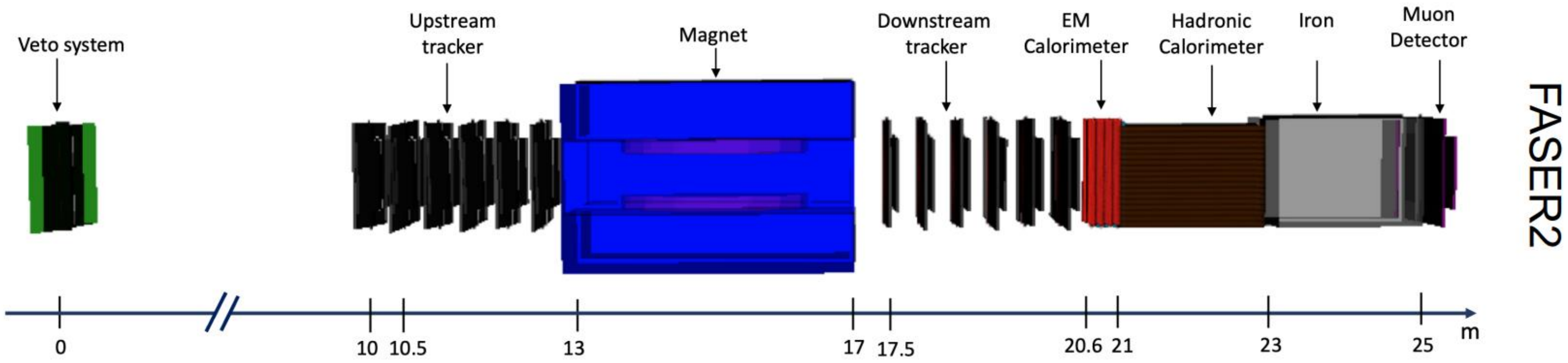
Forward Physics Facility for HL-LHC

- At present there are 5 experiments being designed for the FPF.
- Diverse technologies optimized for particular SM and BSM topics.
- FPF covers $\eta > 5.5$, experiments on LOS cover $\eta \gtrsim 7$.



FASER2 working design

- On-axis magnetic spectrometer
  - Superconducting magnet with 4 Tm bending power
  - Trackers based on LHCb's SciFi detector
- FASER → FASER2
  - R = 10 cm, L = 1.5 m (V = 0.05 m^3) → 3 m x 1 m x 10 m (V = 30 m^3)
  - Luminosity ~ 30 fb^{-1} → 3 ab^{-1}
  - Sensitivity increases over current bounds by ~60,000 for many models



Looking for additional U.S. groups interested in FASER2!

6th Forward Physics Facility Meeting: CERN, June 8-9