# Detector and First Physics Results

Supported by:

Deion Fellers (University of Oregon)

on behalf of the FASER collaboration

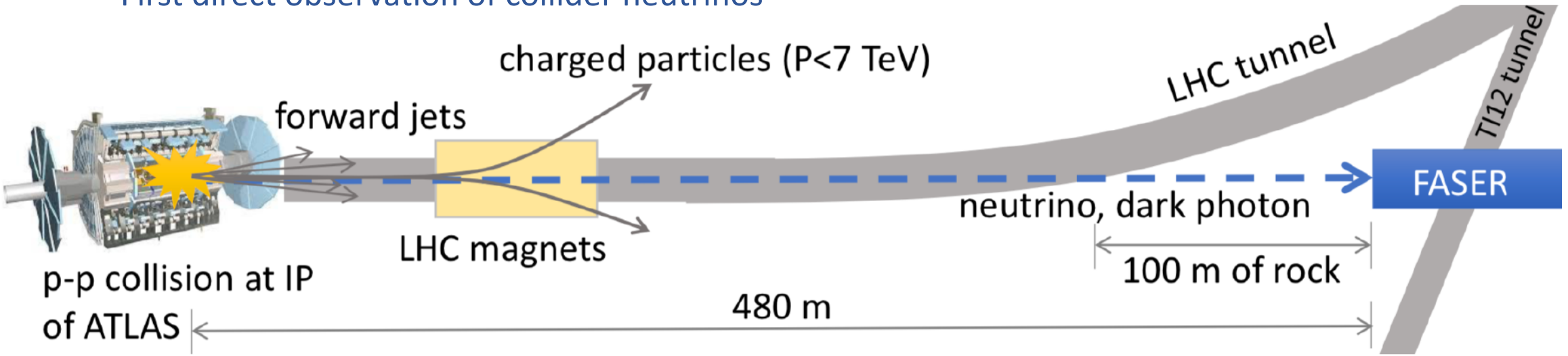
TIPP Conference

September 4th, 2023

Additional US support from:

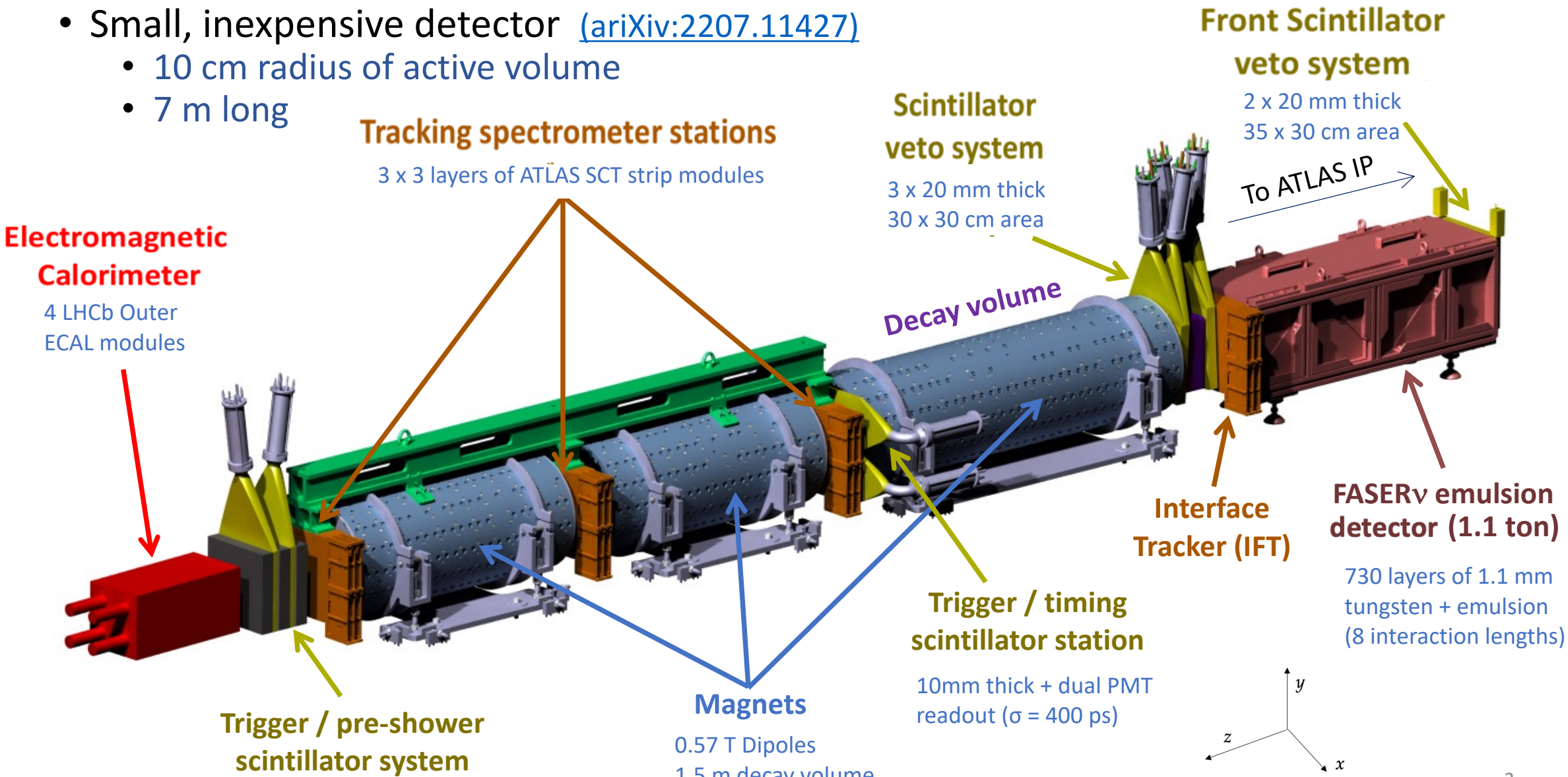
# FASER Overview

- FASER is a new experiment at the LHC
  - Built in 2019-2021
  - Successfully collected data throughout current LHC Run 3 (2022 and 2023)
- Located along the longitudinal beam axis, 480m from the ATLAS interaction point
  - LHC magnets and 100m of rock stop most particles
  - Sensitive to light and weakly interacting particles
- Our first physics results were released this year (using 2022 data)
  - Probed dark photon phase space that was previously unconstrained
  - First direct observation of collider neutrinos



# FASER Detector

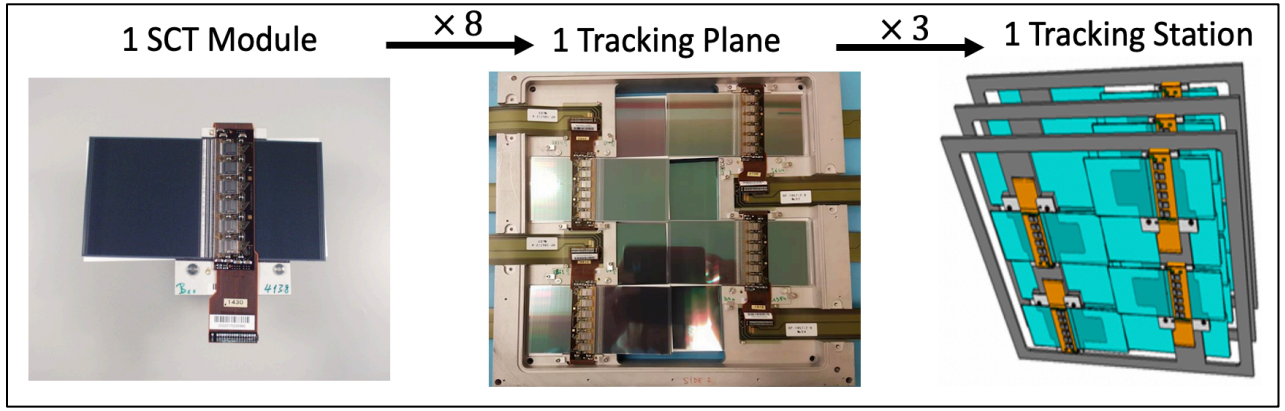
- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius of active volume
  - 7 m long



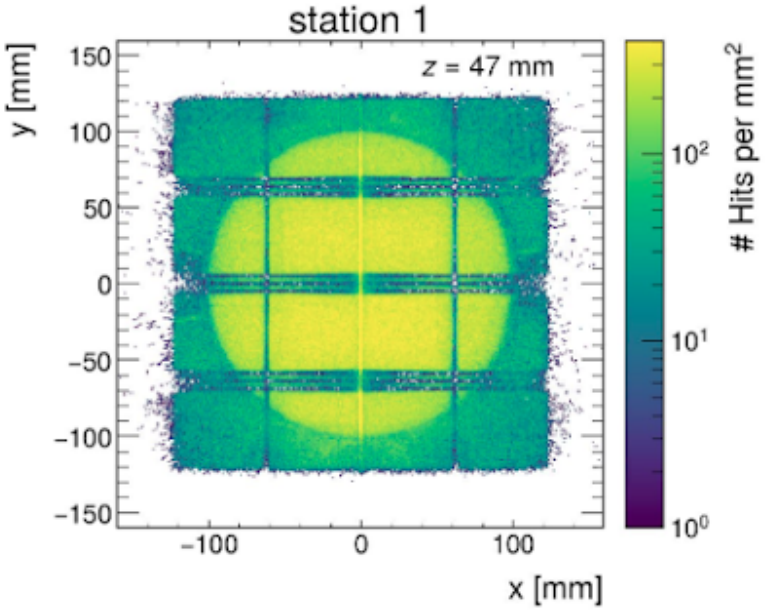

- Detector installed between March – Nov 2021, ready for LHC run 3

# Detector Performance

- Tracking spectrometer
  1. Total number of dead/noisy strips < 0.5%
  2. Hit efficiency of 99.6±0.1%
  3. Spatial resolution of ~30 um in precision direction after alignment
     - ~ 500 um in other direction




(1)

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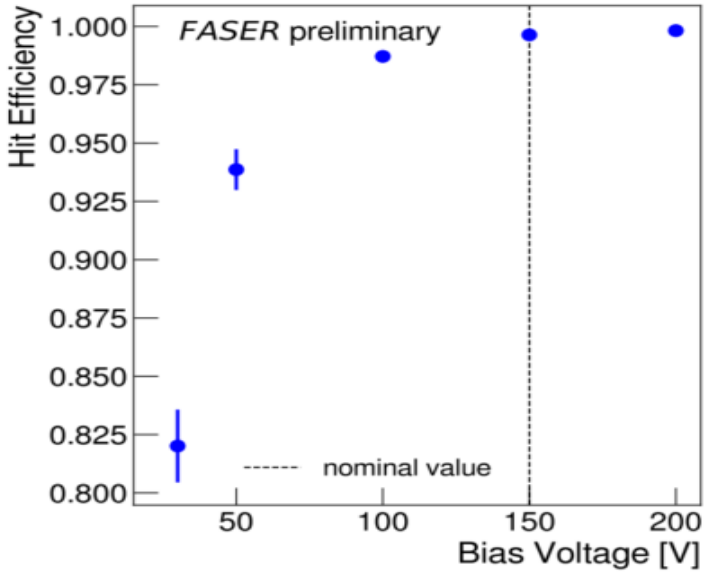


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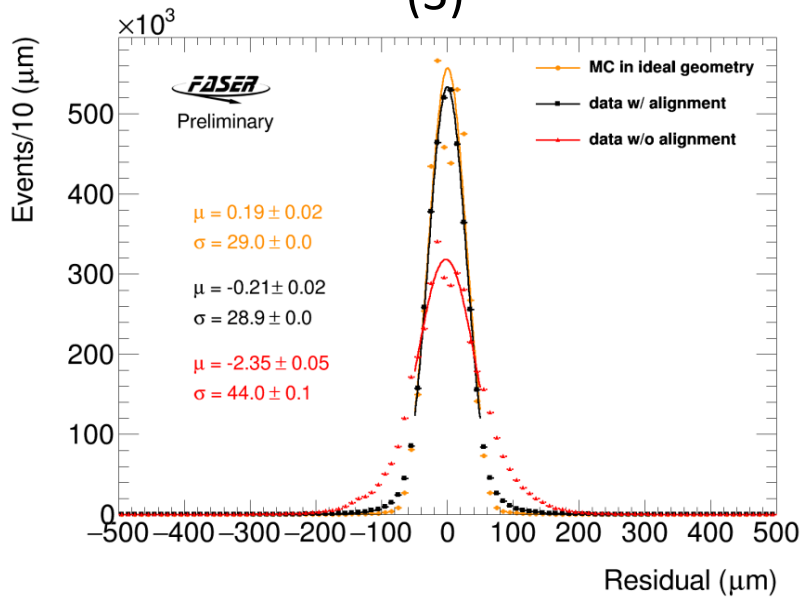
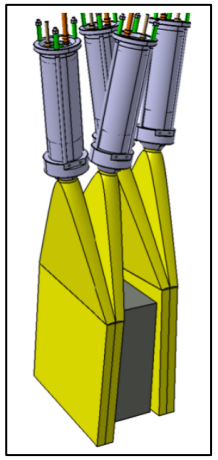


# Detector Performance (2)

- Veto Scintillators
  4. >99.999% veto efficiency for each veto scintillator



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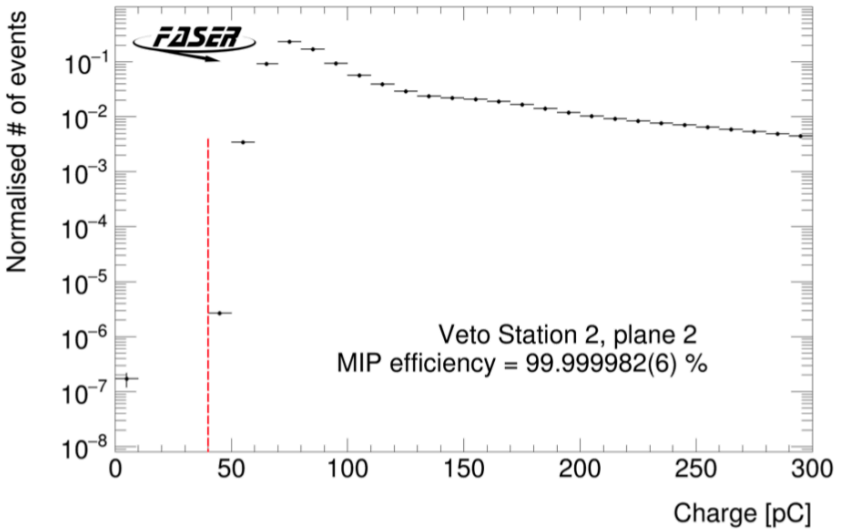
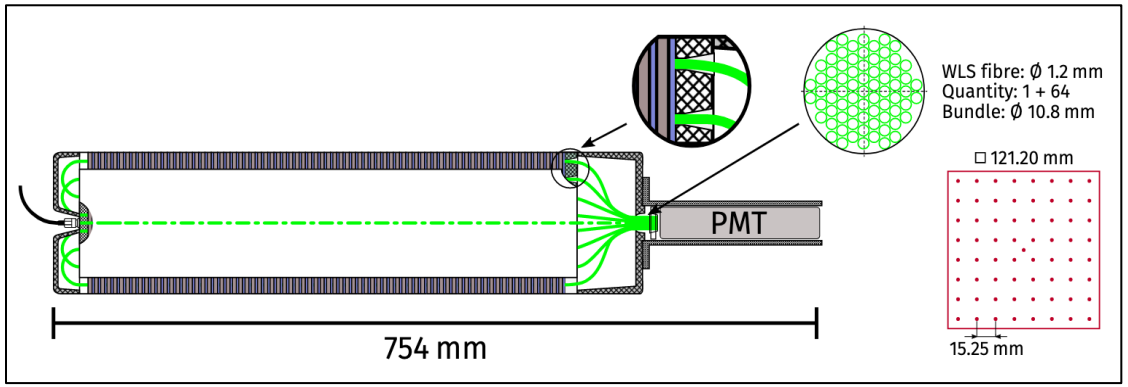



- Calorimeter
  5. Energy resolution of O(1%) at high energy
  6. Timing resolution of ~250 ps allows for efficient rejection of beam-induced background

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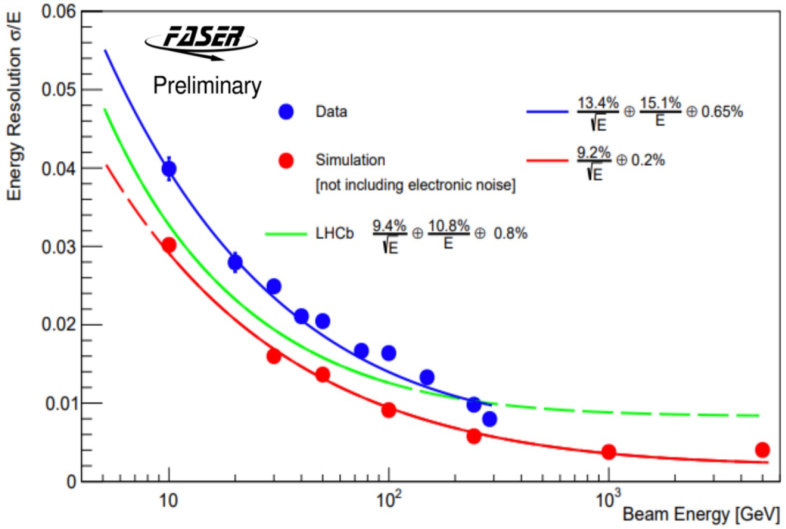


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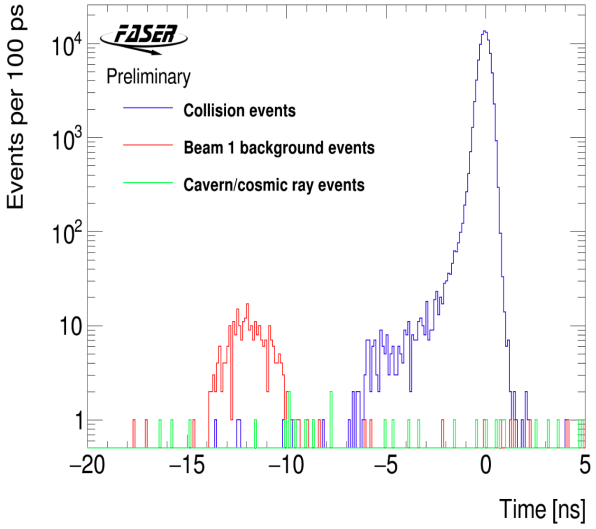
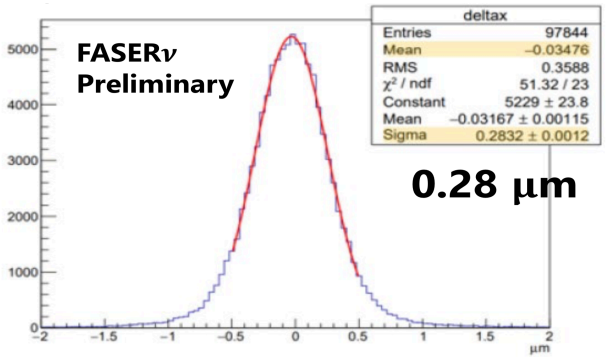
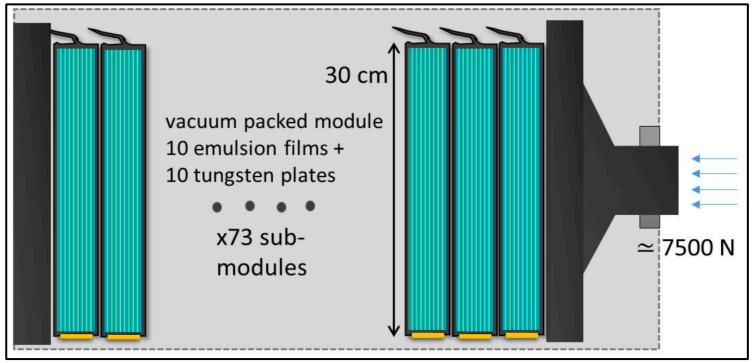


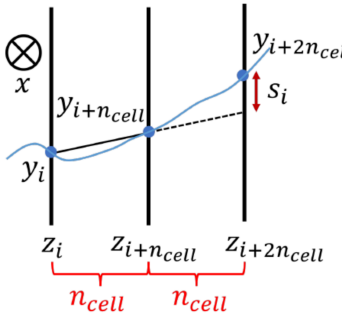
# FASERν Detector Performance

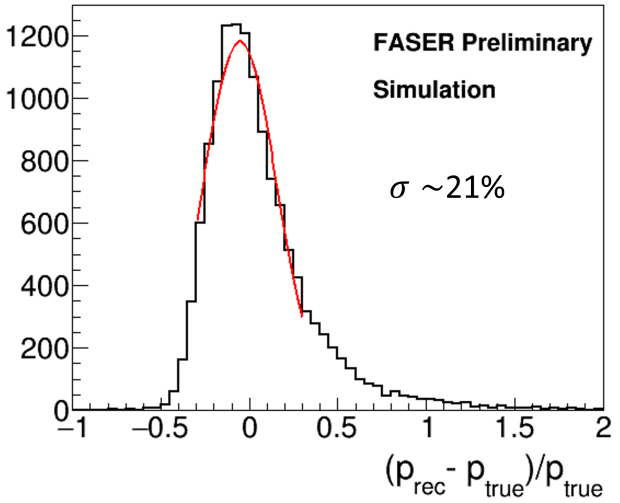
- FASERν emulsion
  - Spatial resolution of 0.28 um



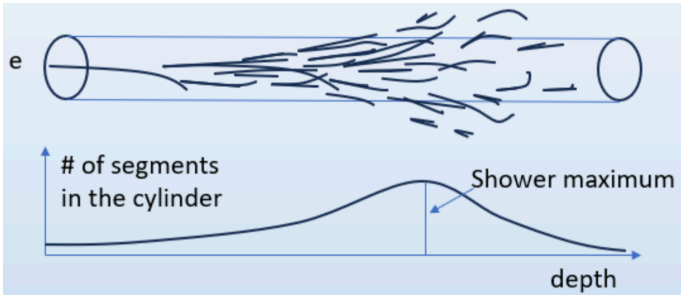



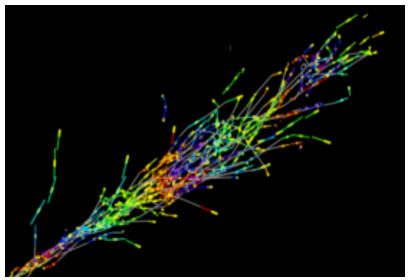

  - Momentum resolution of ~20% $\frac{\Delta p}{p}$ (at p = 200 GeV)
    - Measured via multiple Coulomb scattering

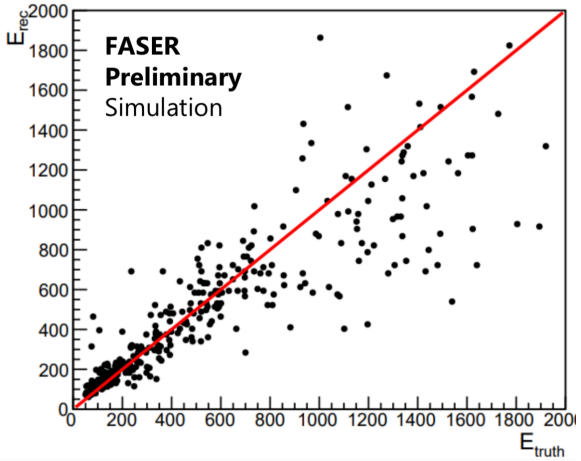



  - Electron energy resolution of ~25% $\frac{\Delta E}{E}$ (at p = 200 GeV)
    - Measured through track segment multiplicity around shower max



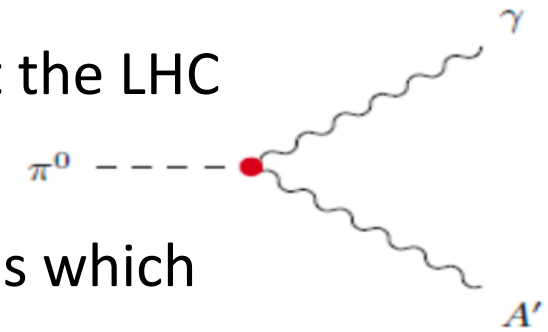


# Search for Dark Photons

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

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

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



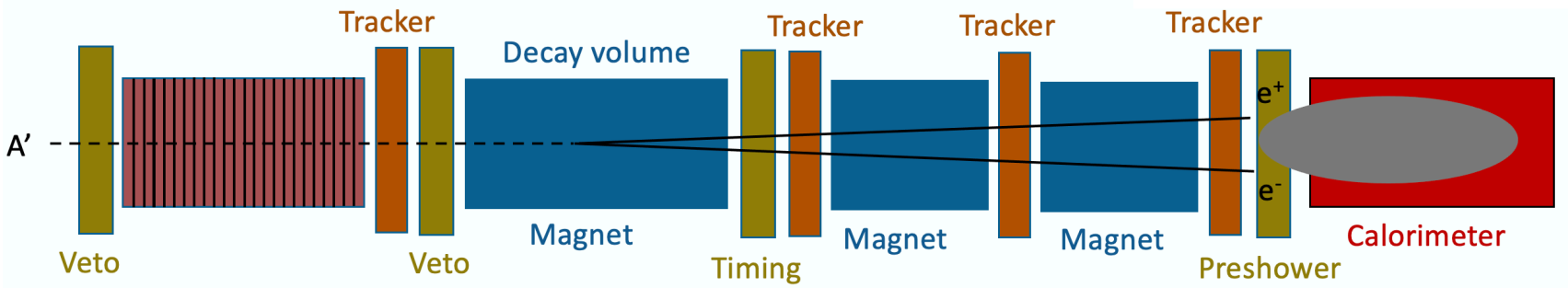

- FASER targets small ε, highly boosted, MeV-scale massive dark photons which have decay lengths ideal for FASER

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

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

# Dark Photon Event Selection

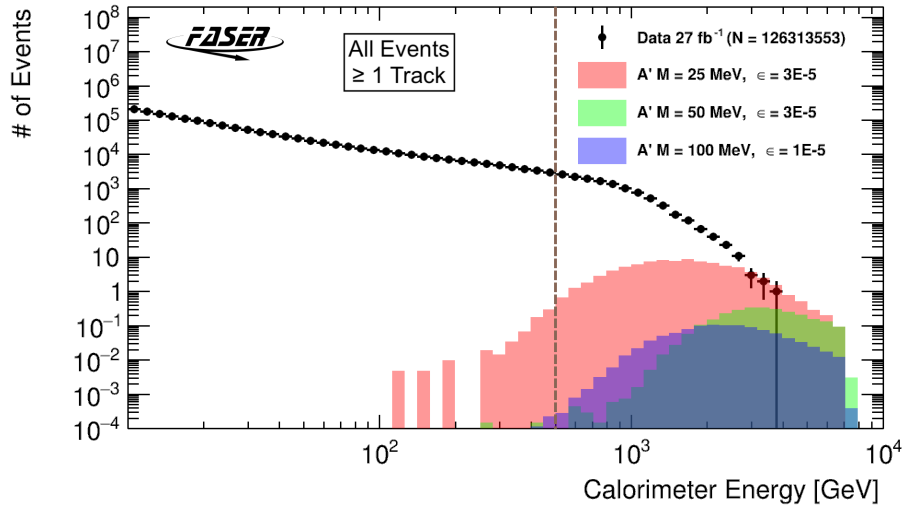
- Signal: $\pi/\eta \to A'\gamma$, $A'$ travels hundreds of meters through LHC magnets and rock/concrete, then decays $A' \to e^+e^-$ inside FASER

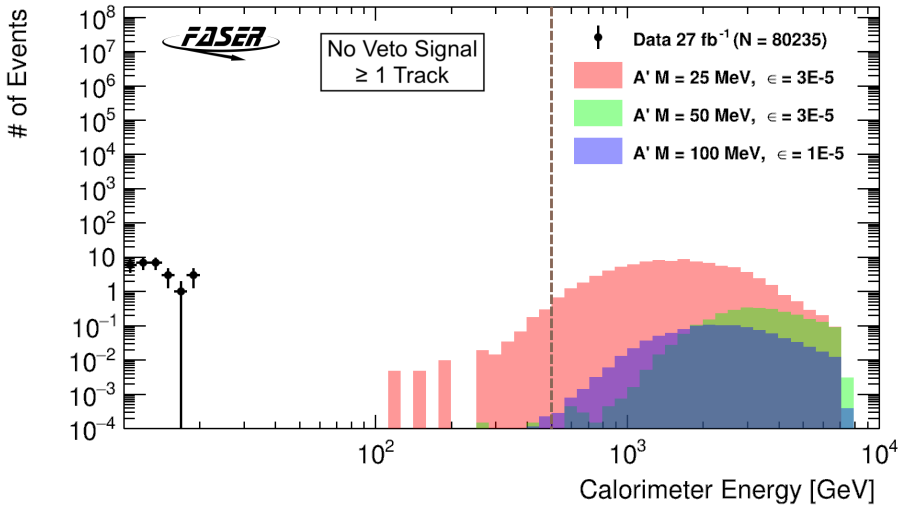


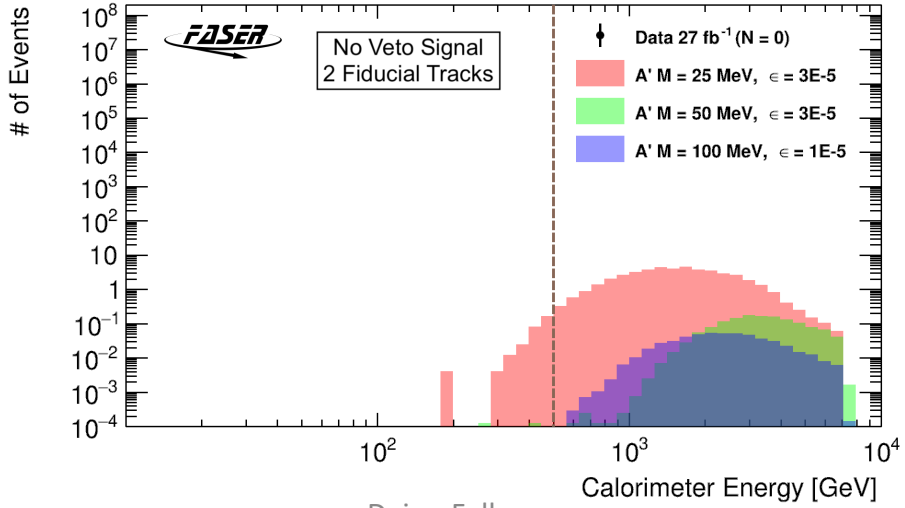

- Event selection:
  - LHC collision event with good data quality
  - No signal in any of the 5 veto scintillators
  - Timing and preshower scintillators consistent with $\geq$ 2 MIPs
  - Exactly 2 good tracks (p > 20 GeV and r < 95 mm, extrapolating to r < 95 mm at vetos)
  - Calorimeter energy > 500 GeV
- Provides a nearly background free analysis
  - Neutrino interactions constitute the main background
  - Total background estimated to be $(2.3 \pm 2.3)\times10^{-3}$ events in 27 fb$^{-1}$ of data

# Dark Photon Unblinded Data

- No events seen in unblinded signal region



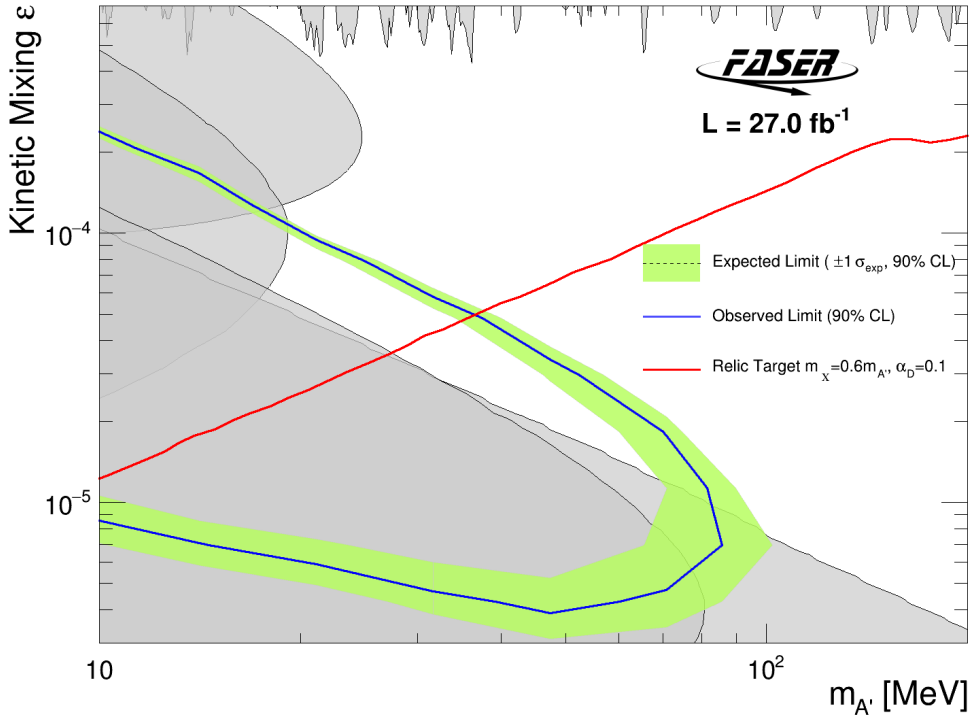



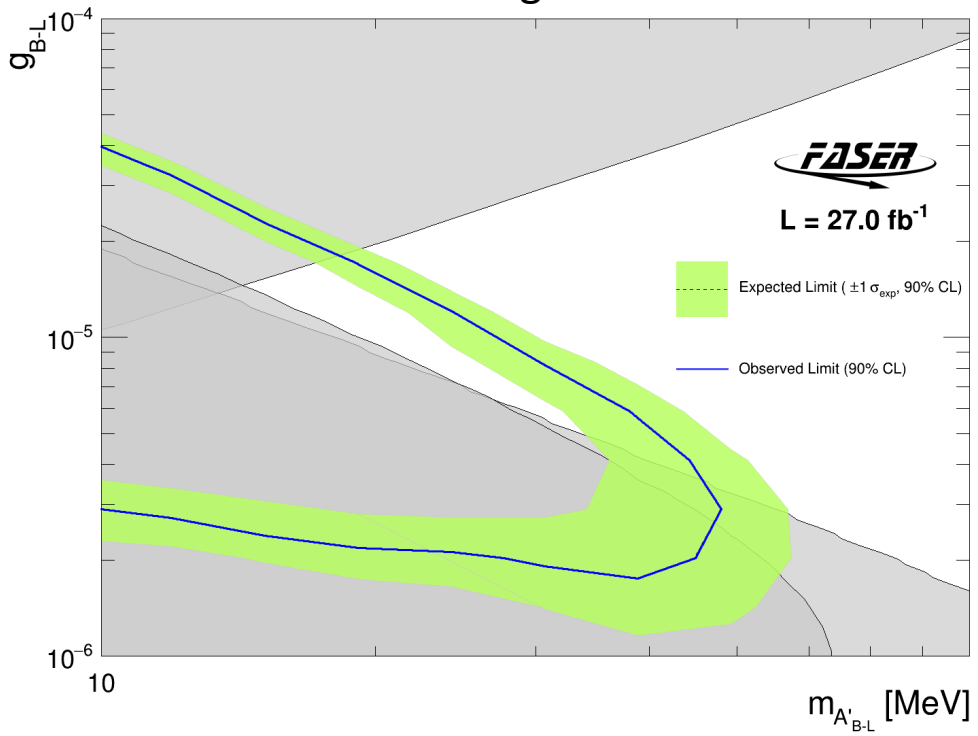
# Dark Photon Exclusion

- With null-result, FASER sets limits on previously unexplored parameter space
  - Extends exclusion into region motivated by thermal relic dark matter
- Analysis also excludes new parameter space of a massive gauge boson from a $U(1)_{B-L}$ model
- See paper for more details on A' and B-L analysis: https://arxiv.org/abs/2308.05587

Dark Photon




B-L Gauge Boson

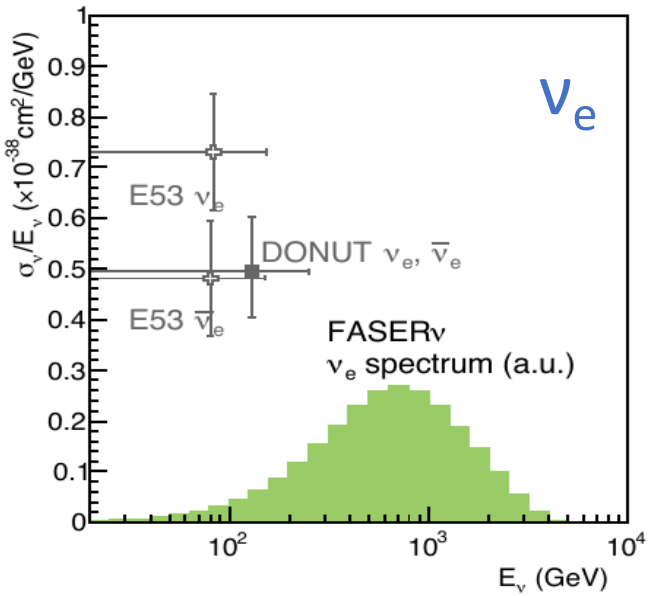


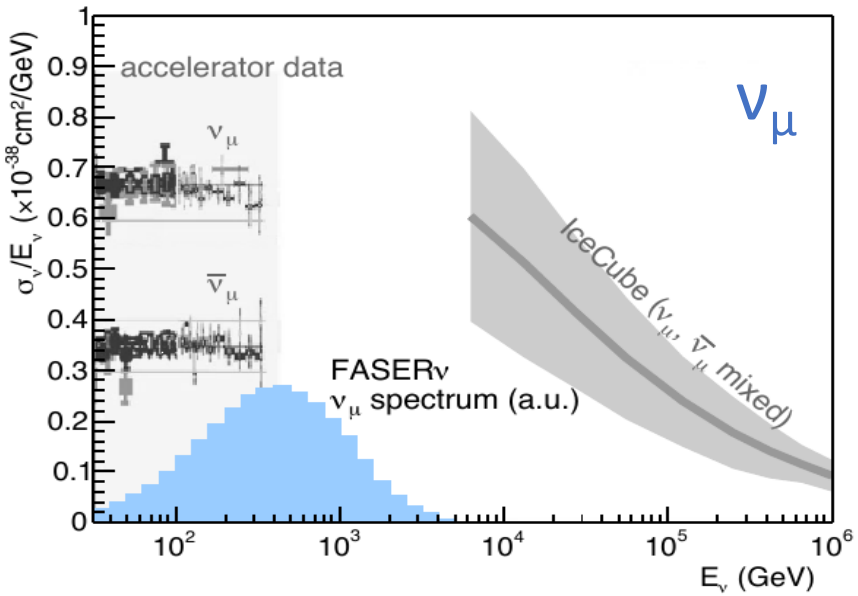
# Collider Neutrinos

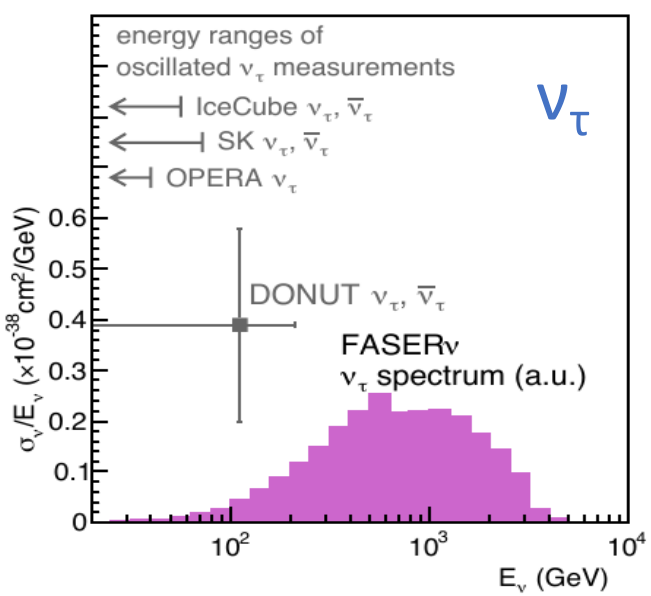
- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → larger interaction cross section
- FASER is sensitive to an exciting neutrino program
  - Collider neutrinos have never been directly observed before
  - Energy range complementary to existing neutrino experiments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

PRD 104, 113008

| For 35 fb$^{-1}$ | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|---|
| Main source | Kaons | Pions | Charm |
| # traversing FASERν | ~$10^{10}$ | ~$10^{11}$ | ~$10^{8}$ |
| # interacting in FASERν | ≈200 | ≈1200 | ≈4 |



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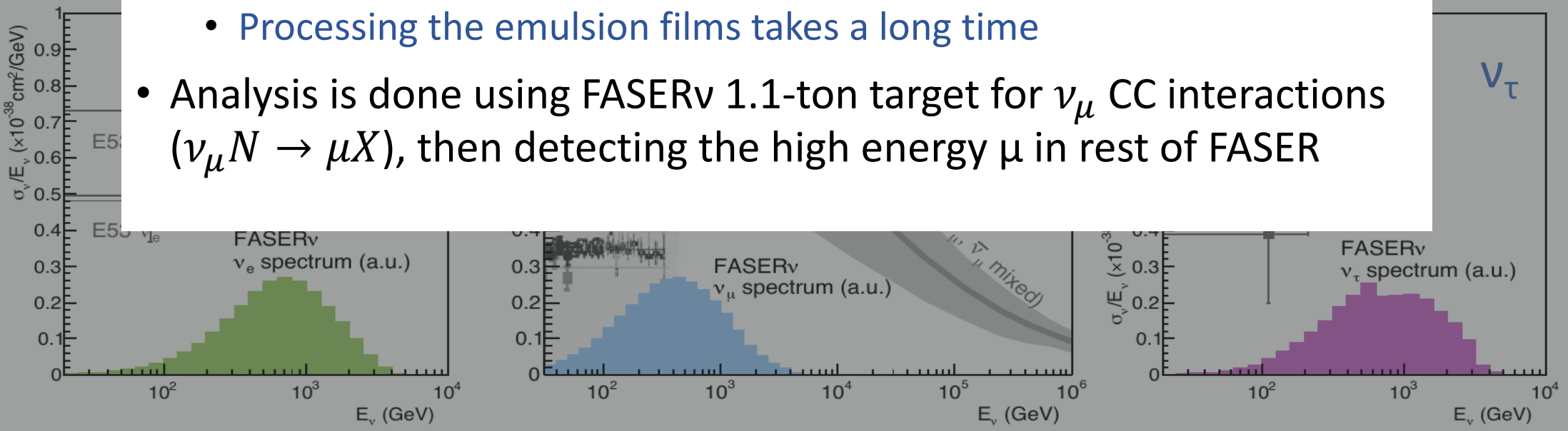
PRD 104, 113008

| For 35 fb$^{-1}$ | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|---|
| Main source | Kaons | Pions | Charm |
| # traversing FASERν | ~$10^{10}$ | ~$10^{11}$ | ~$10^{8}$ |
| # interacting | | 1200 | ≈4 |

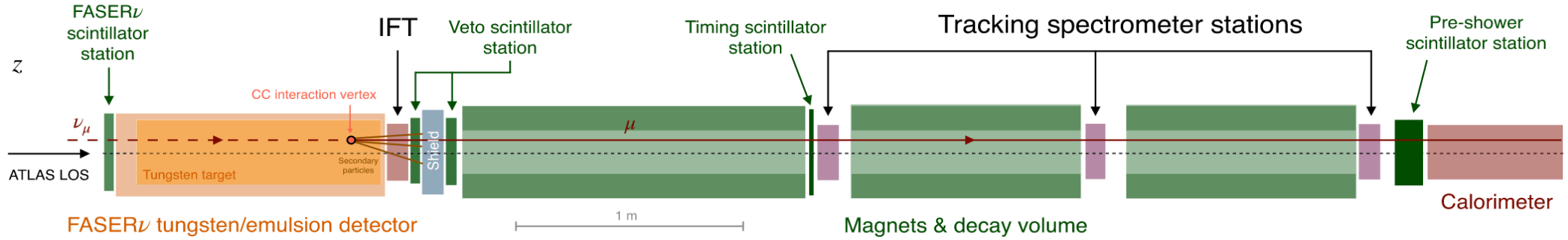
Our first ever ν analysis only strives to claim observation

- The FASERν emulsion was not used for our first analysis
  - Processing the emulsion films takes a long time
- Analysis is done using FASERν 1.1-ton target for $\nu_\mu$ CC interactions ($\nu_\mu N \rightarrow \mu X$), then detecting the high energy μ in rest of FASER



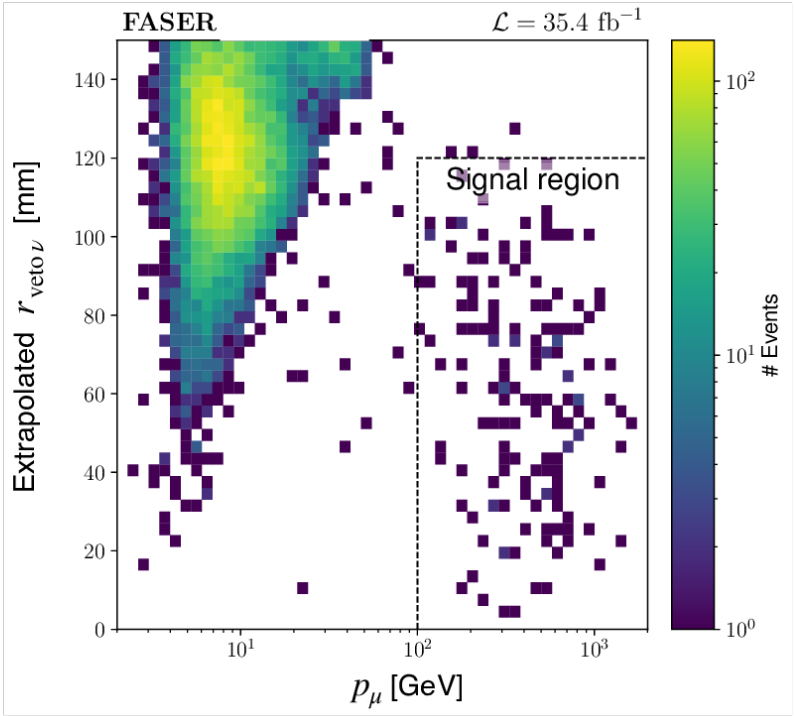
# Muon Neutrinos in FASER

Signal: $\nu_\mu$ passes through front veto station undetected, then interacts in FASER$\nu$ tungsten and emits a high energy muon through the rest of FASER



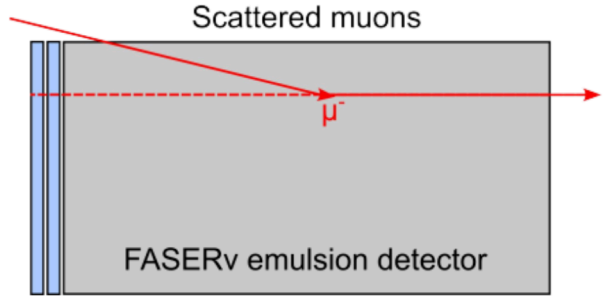

Event Selection:

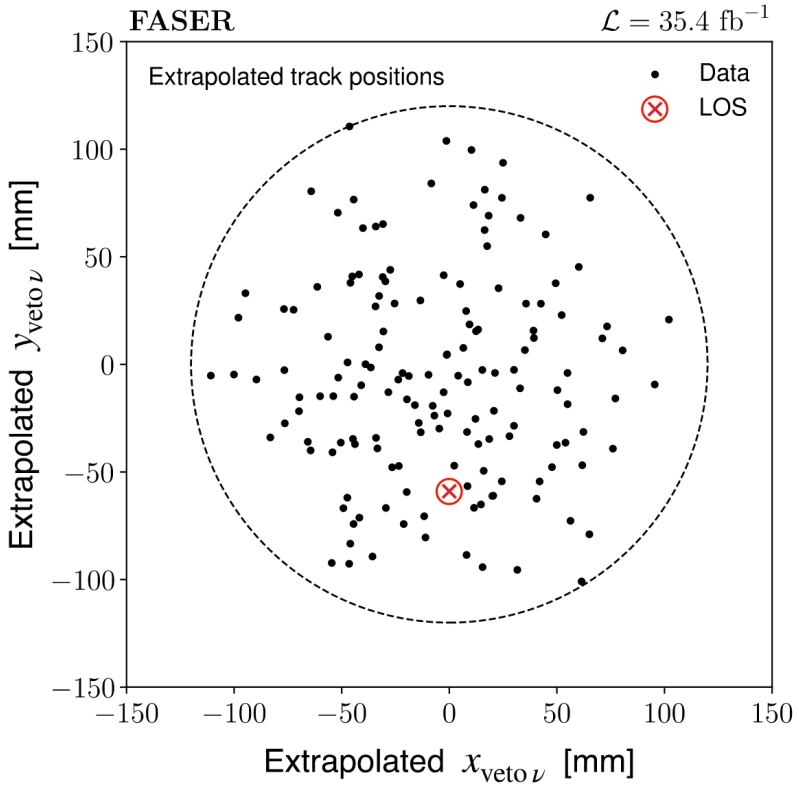
1. LHC collision event and good data quality
2. No signal in front veto station
   - Signal in all other scintillator stations
3. Exactly 1 high momentum track that passes through the front veto station when extrapolated back
   - p > 100 GeV and θ < 25 mrad
   - r < 95 mm in tracking stations
   - r < 120 mm when extrapolating to front veto

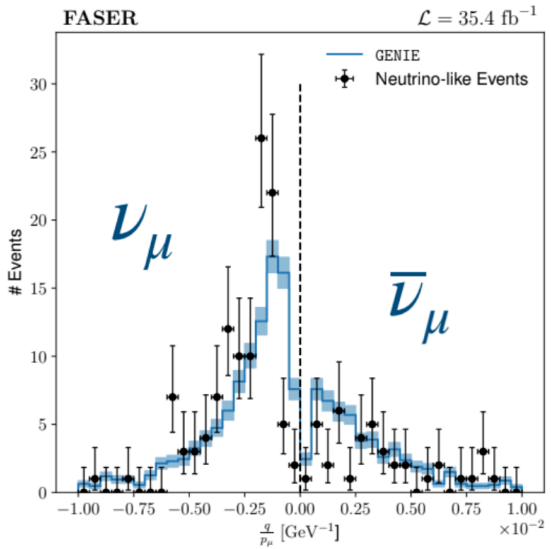


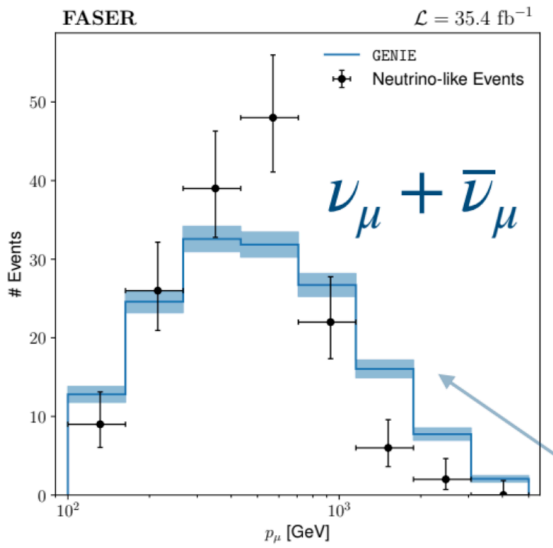
# Muon Neutrino Results

- Upon unblinding find $153\ ^{+12}_{-13}\ (stat.)\ ^{+2}_{-2}\ (bkg.)\ \nu_\mu$ events
  - Main bkg. from uncertainty in estimation of large-angled muons that miss the front veto station and then scatter in FASER$\nu$ emulsion
  - Significance of 16σ
- First direct detection of collider neutrinos!
  - Published in PRL: PhysRevLett.131.031801
- Candidate neutrino event distributions match expectations from GENIE MC



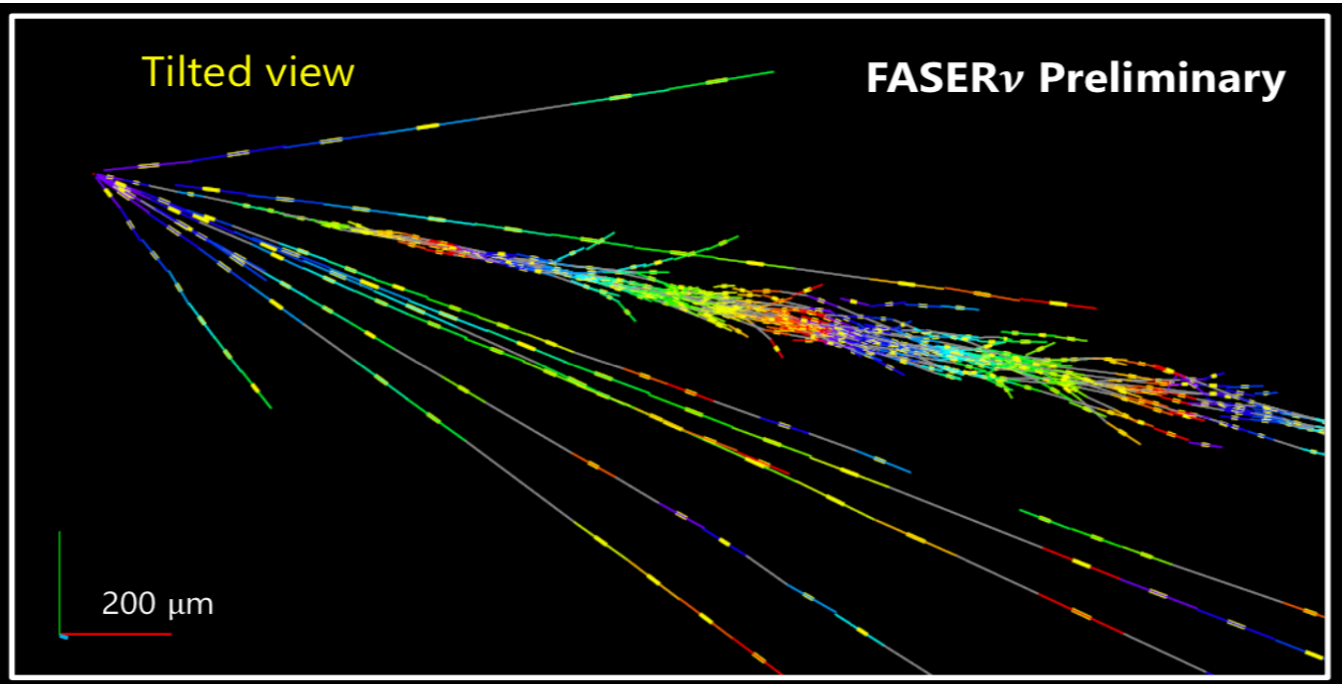



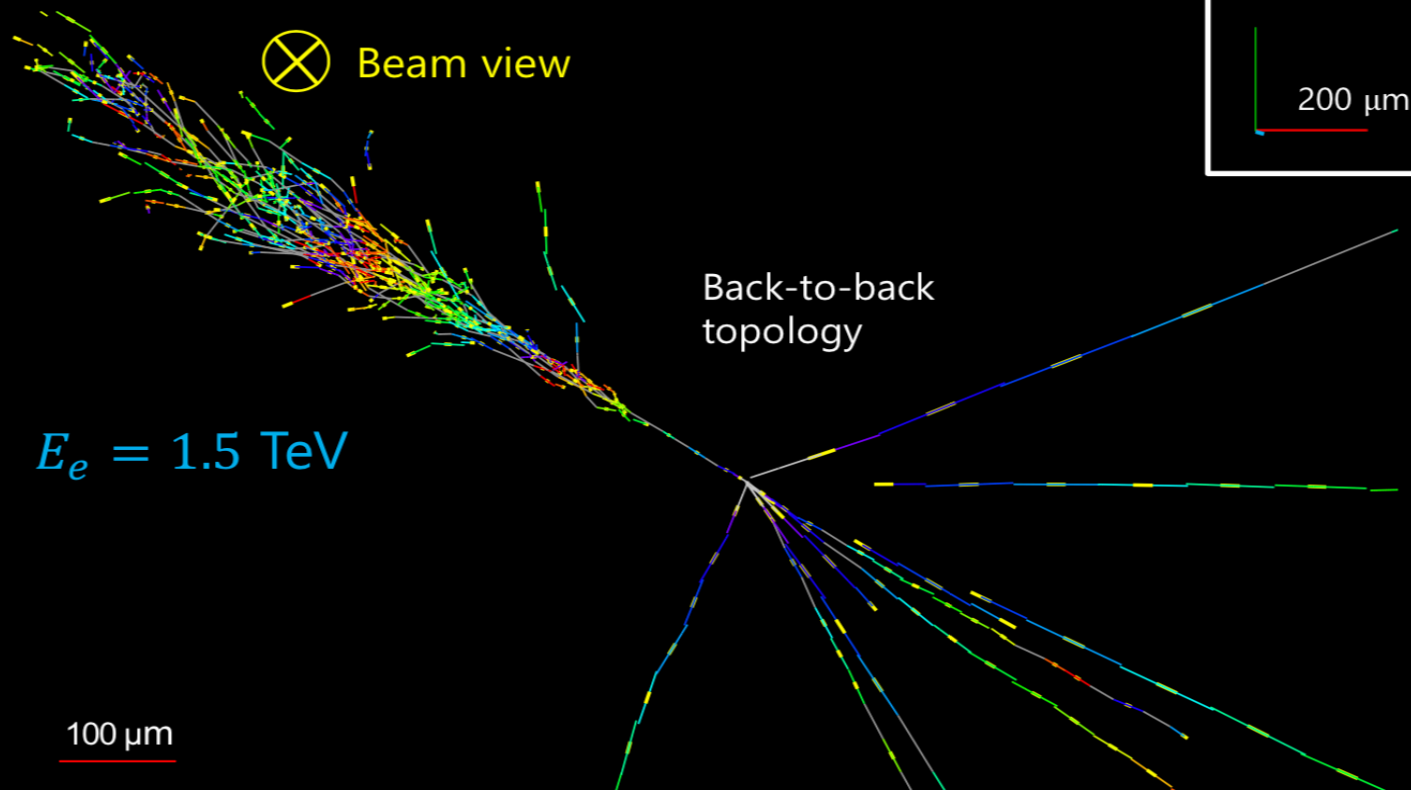

Note that no experimental uncertainties are included on the simulated sample (e.g. assume perfect alignment, no errors on efficiencies, etc. )

# Electron Neutrinos in FASERν

Recent analysis of FAESRν emulsion detector found 3 $\nu_e$ CC candidate events (CERN-FASER-CONF-2023-002)

- Only used subset of data (68 kg target mass)
- Probability these are due to background fluctuation is $1.6 \times 10^{-7} \rightarrow 5\sigma$
- First observation of $\nu_e$ at the LHC, with the highest energies ever observed by accelerator-based experiments!
- One $\nu_e$ CC candidate event is shown here

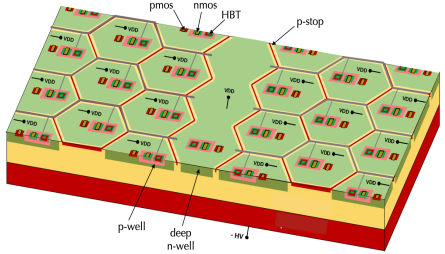



- 11 tracks at the vertex, 615 μm inside tungsten
- $e$-like track from vertex
- Single track for 2 $X_0$
- Shower max at 7.8 $X_0$
- 175° between $e$-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

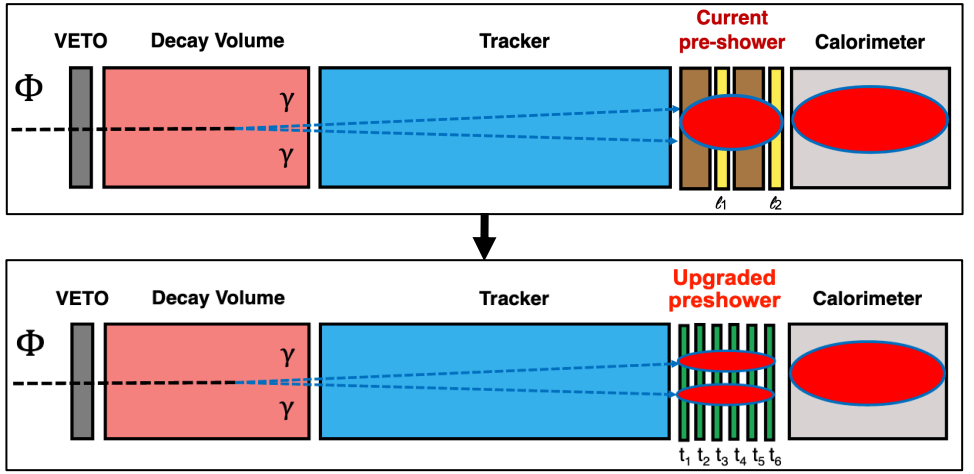
# Future Preshower Upgrade

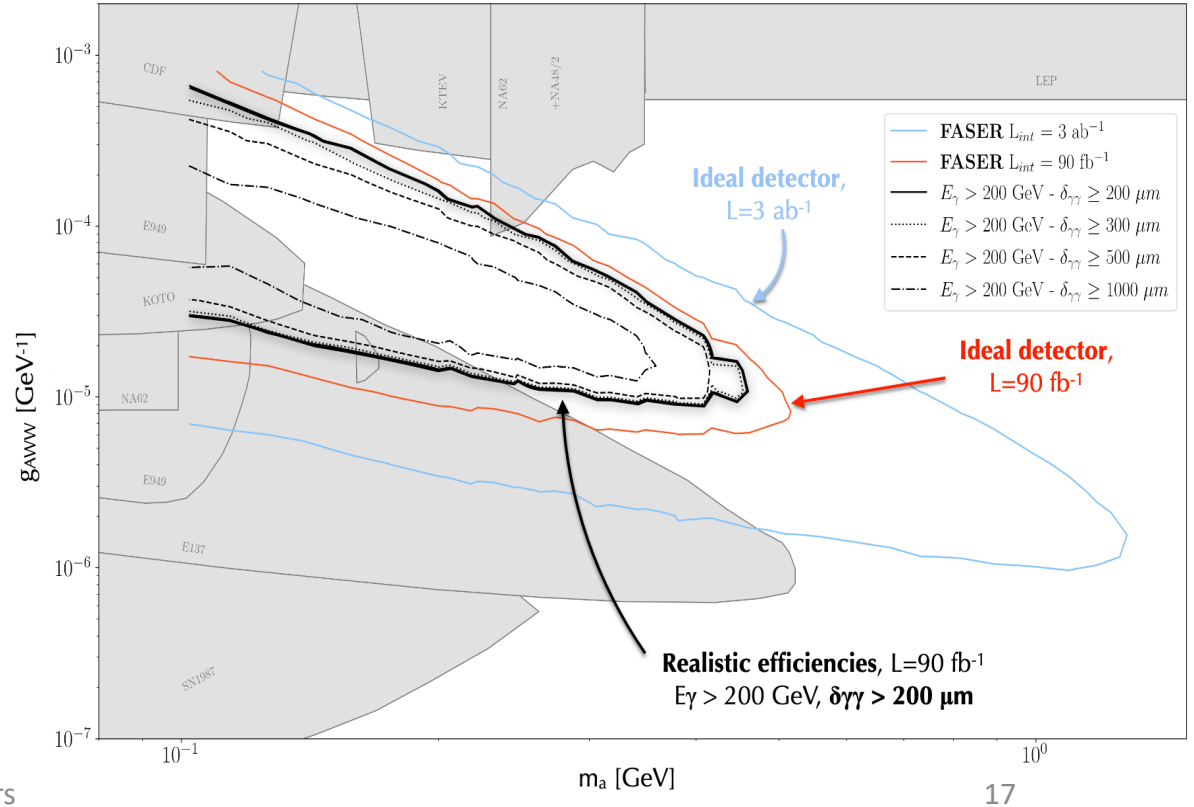
- Approved detector upgrade to add high resolution spatial sensitivity to our preshower
  - https://cds.cern.ch/record/2803084
  - Can identify 2 high energy photon showers separated by ≥ 200 um
  - Will allow for sensitivity to di-photon signals
    - e.g. axion-like particles
- Upgrade to 6 layers of tungsten and monolithic silicon pixel sensors
  - Currently have 2 layers of tungsten and scintillator
- Si pixel layers allow for ~100 µm resolution
  - 11.5 million pixels total in preshower




- 130 nm SiGe BiCMOS technology
- Hexagons with 65 µm sides
- 50 $\mu$m thick Si
- < 300 ps timing resolution

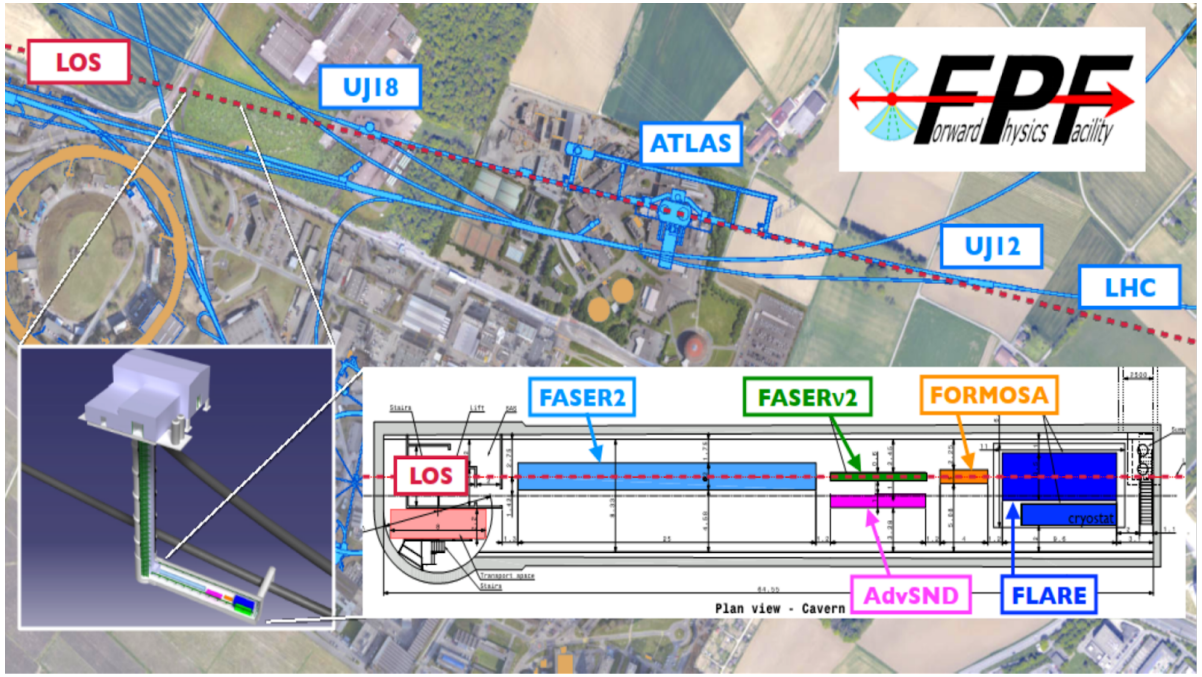
- Plan to install in late 2024
  - Construction and commissioning in progress



# Forward Physics Facility (FPF)

- Proposed facility at CERN to host suite of forward experiments during HL-LHC era
- FASER2
  - Radius increased from 10 cm to 1 m
  - Acceptance ($\pi_0$) increased from 0.6% to 10%
  - Sensitivity improved by several orders of magnitude in many models
- FASER$\nu$2
  - Increase target from 1 ton to 20 tons
    - 25×30×100 cm → 40×40×800 cm
  - O($10^5$)$\nu_e$ , O($10^6$)$\nu_\mu$ , and O($10^4$)$\nu_\tau$ expected in O(10) ton detector
- Checkout FPF white-paper for more details
  - https://arxiv.org/abs/2203.05090




FPF studies supported by:

# Summary

- FASER is a new far-forward detector at the LHC that is sensitive to long-lived particles
- Successfully took data in the first 2 years of LHC Run 3
- Excluded previously unprobed parameter phase space of both the dark photon and B-L gauge boson
  - Probes new territory in interesting thermal-relic region
- First *direct* detection of collider neutrinos!
  - Reconstructed ~150 $\nu_\mu$ CC interactions in FASER spectrometer
  - Found 3 $\nu_e$ CC candidate events in subset of FASERν emulsion
- More BSM searches and neutrino measurements to come
- Future planned and proposed detector upgrades will expand FASER's physics reach