Recent Results from FASER

La Thuile, 11. March 2025

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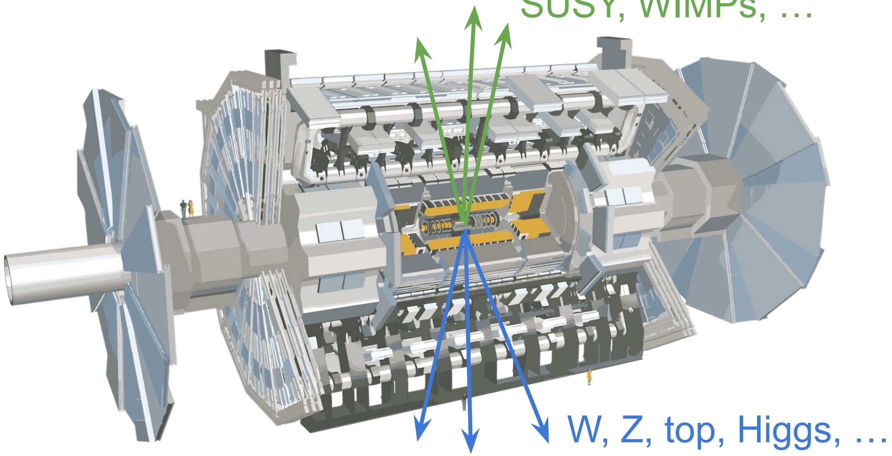
HEISING-SIMONS FOUNDATION SIMONS FOUNDATION CERN FASER UNIVERSITÄT BONN

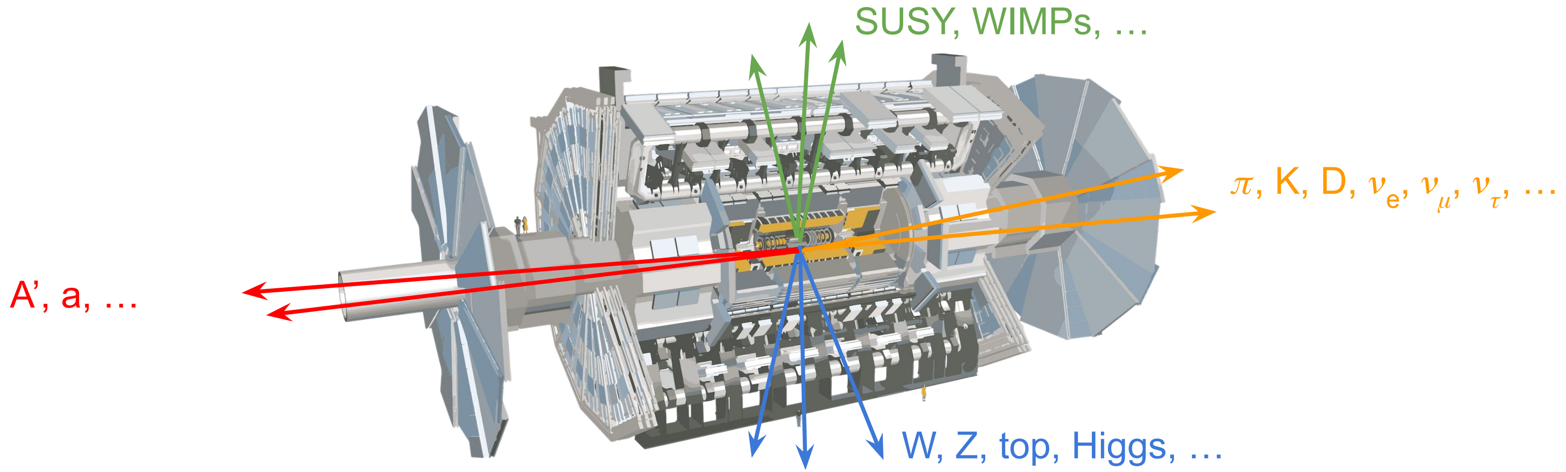
The Intensity Frontier at the LHC

- The LHC is the **highest energy** collider in the world
  - Large-scale experiments to search for **heavy, strongly produced SM** and **BSM** particles



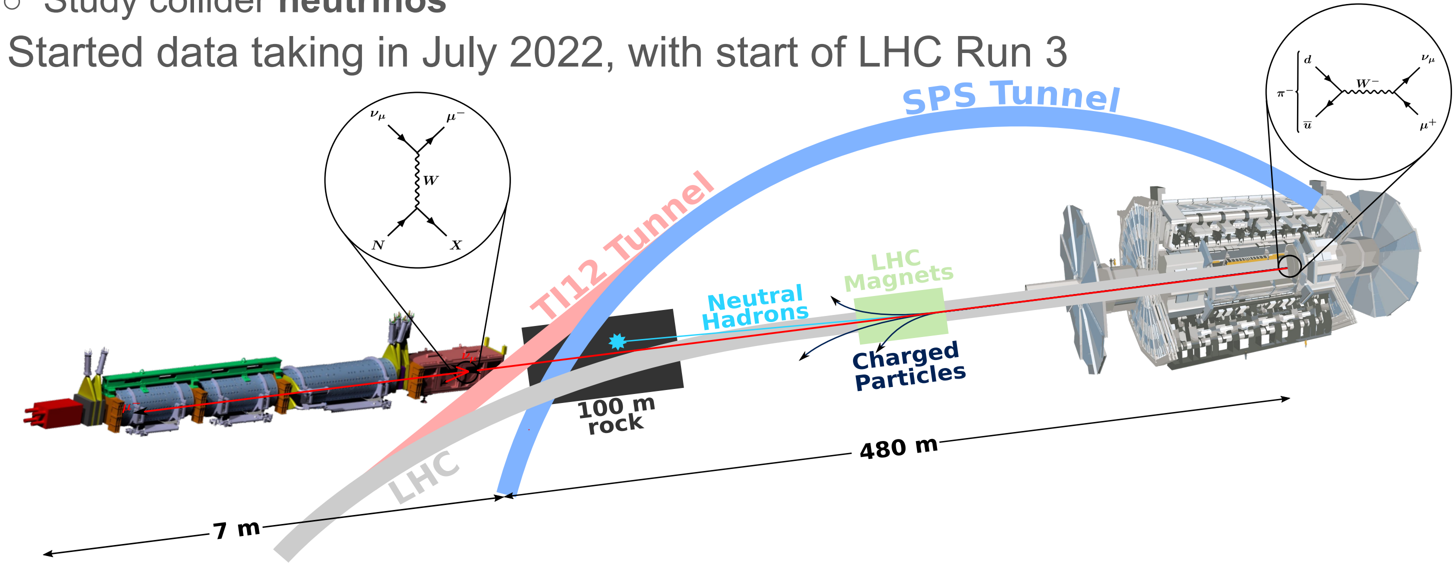
The Intensity Frontier at the LHC

- The LHC is the **highest energy** collider in the world
  - Large-scale experiments to search for **heavy, strongly produced SM** and **BSM** particles
- But, also **huge number of light SM hadrons**
  - Search for **weakly coupled, light new particles**
  - Study **neutrinos** produced in hadron decays
  - Light hadrons collimated around the beam collision axis:
    - About 1% of all pions with E > 10 GeV are produced in the forward 10^{-6} % of solid angle
    - Small detector in this region would have impressive sensitivity



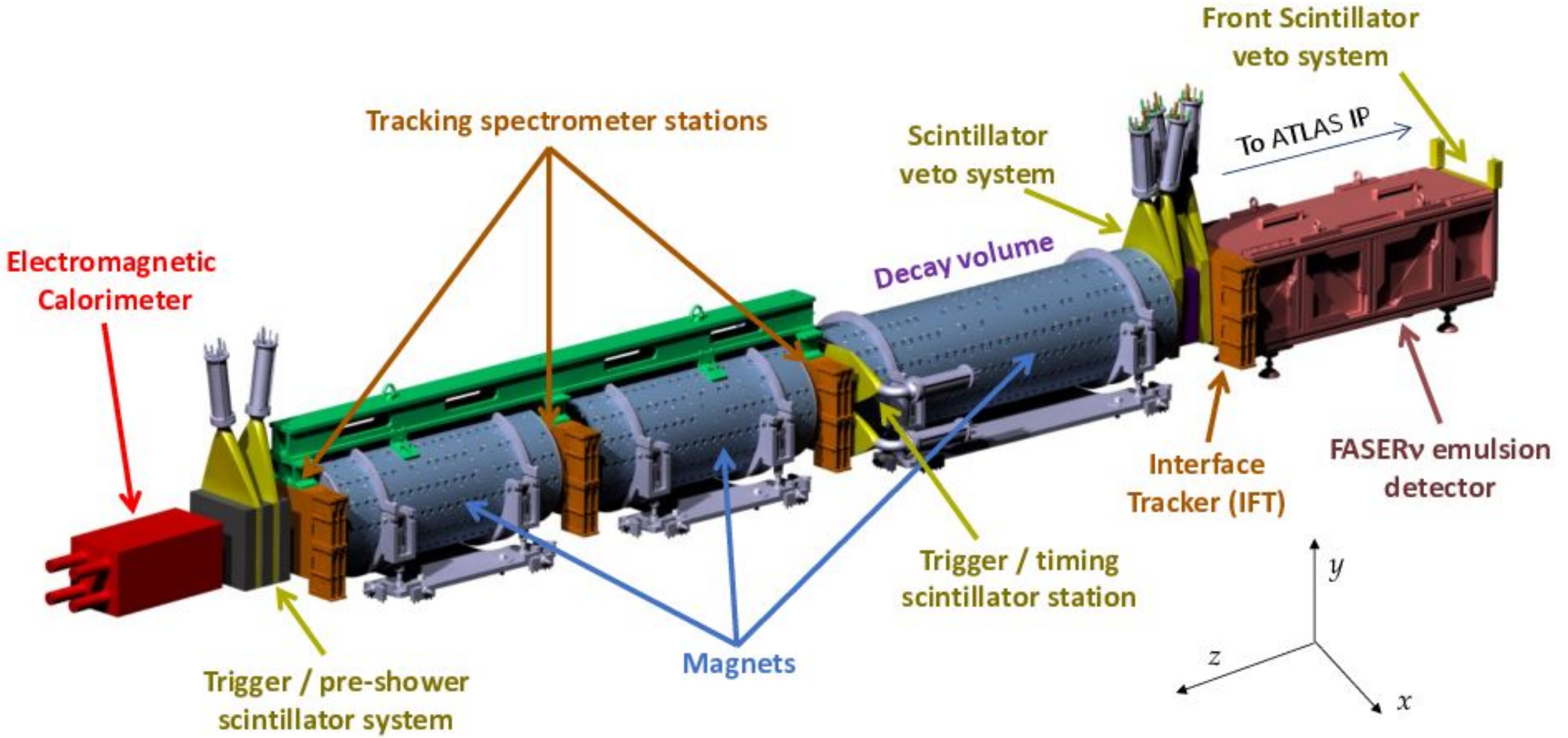
FASER – The **F**orw**A**rd **S**earch **E**xpe**R**iment

- Located 480 m downstream of ATLAS IP on beam collision axis in TI12 tunnel, $\eta > 8.8$
- Shielded from ATLAS IP by ~ 100 m of rock
- Charged particles are additionally deflected by LHC magnets
  → **Clean environment**, main background from high-energy muons
- Goals:
  - Search for **new, light, long-lived particles**, e.g. dark photons, ALPs, …
  - Study collider **neutrinos**
- Started data taking in July 2022, with start of LHC Run 3

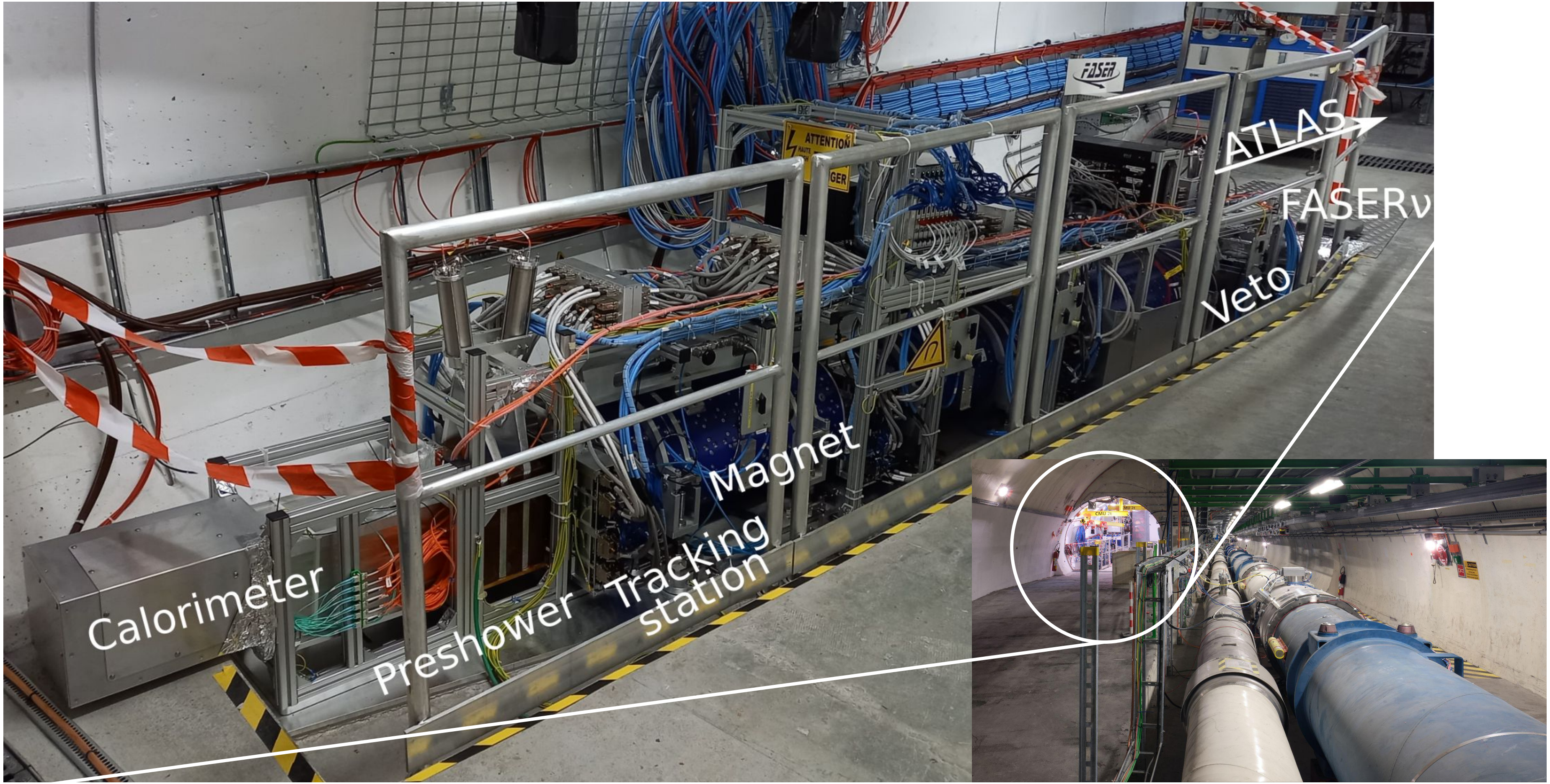


FASER Detector

arXiv:2207.11427
JINST 19 P05066

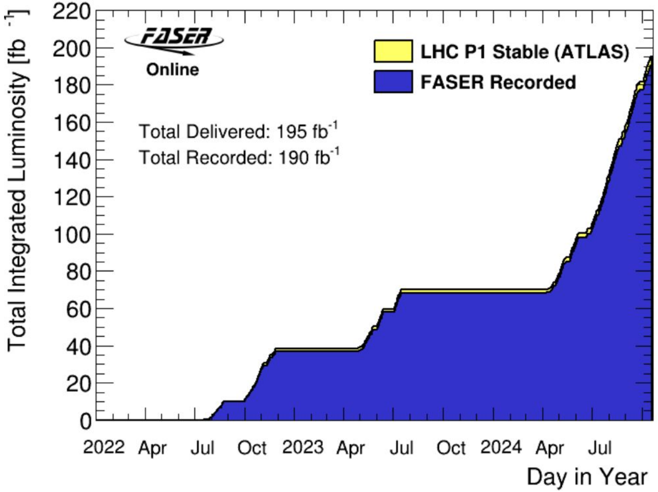


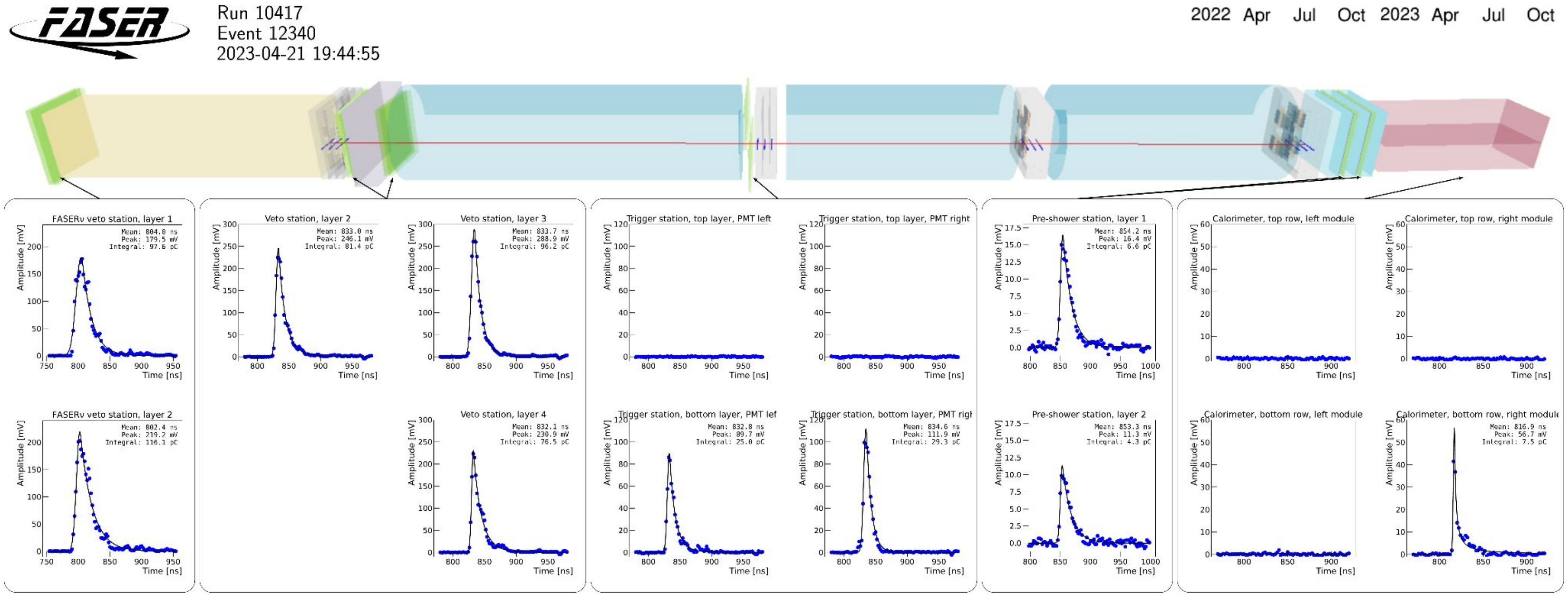
FASER Detector



FASER Operations

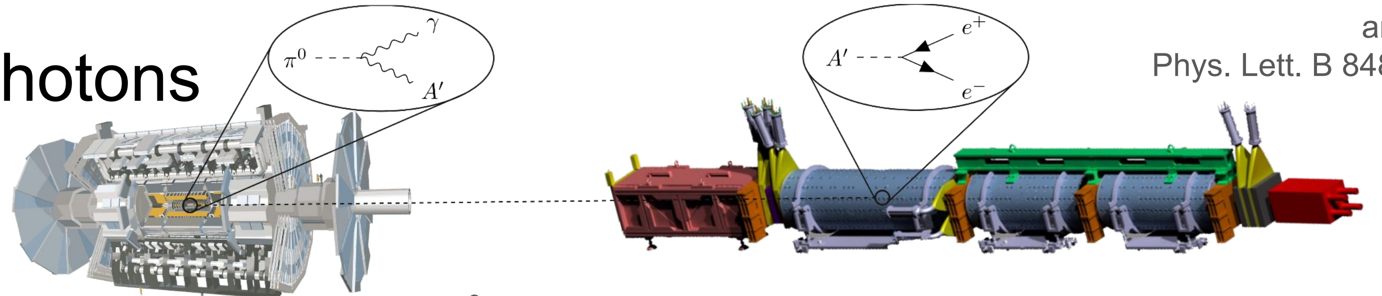
- Detector operated very smoothly since July 2022
- Collected > 97% of delivered data
  - Average physics trigger rates of 1 kHz
  - 190 fb^{-1} of data recorded
- All components working as expected!



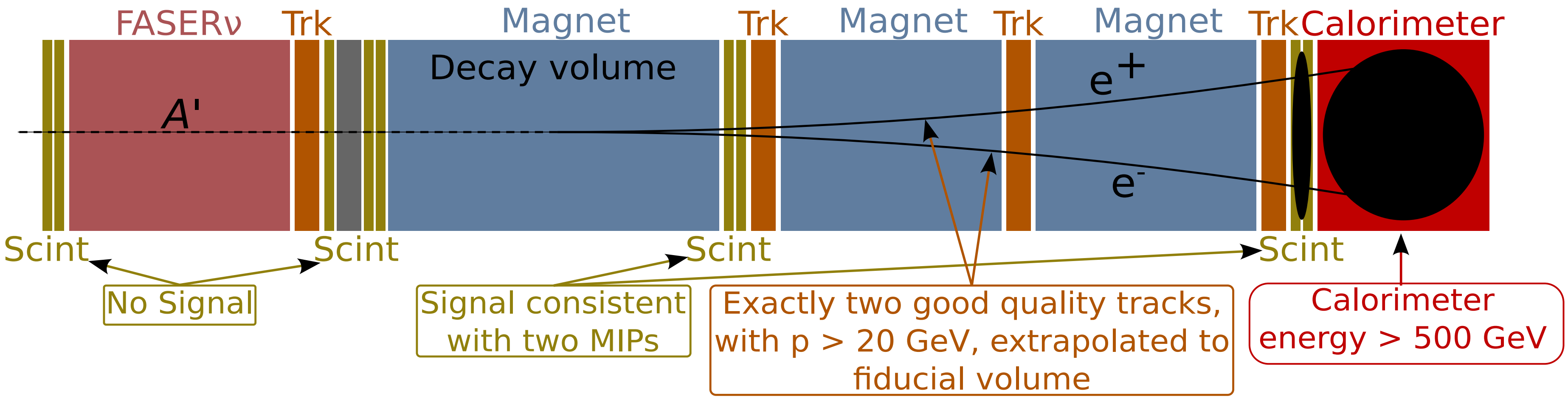


Dark Photons

arXiv:2308.05587
Phys. Lett. B 848 (2024) 138378



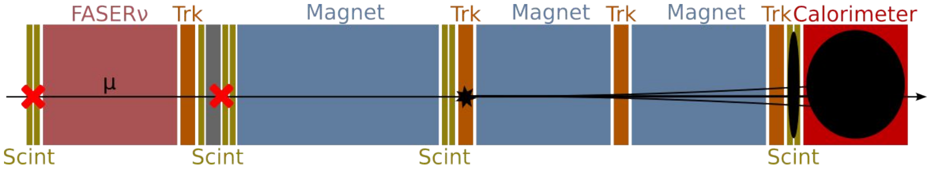
- Huge number of light mesons (π^0, η, …) in forward direction → May decay in dark photons
- First analysis, designed to be simple and robust
- Event selection:



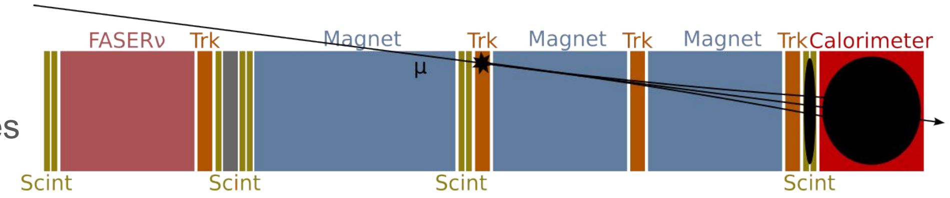
arXiv:2308.05587
Phys. Lett. B 848 (2024) 138378

Dark Photon Search – Backgrounds

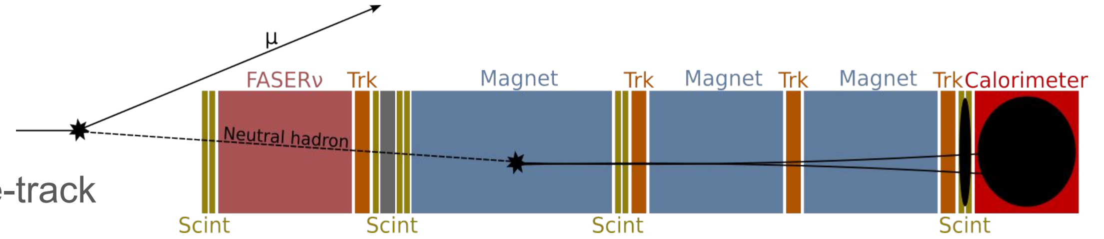
1. Muons that are **not vetoed** by any of the scintillators:
   Negligible - estimated from scintillator inefficiency



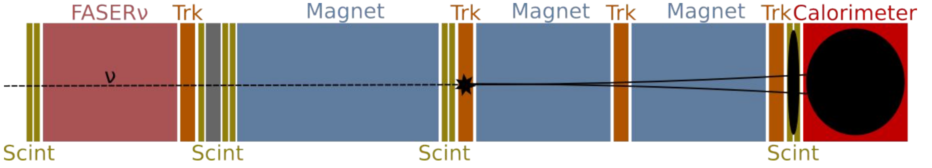
2. (Cosmic) muons **missing veto**:
   Negligible - evaluated using MC and non-colliding bunches



3. **Neutral hadrons** from upstream muon interactions decaying in detector:
   (2.2 ± 3.1) 10^{-4} events - evaluated from three-track events in side-band



4. **Neutrinos**:
   (1.8 ± 2.4) 10^{-3} events - evaluated using MC

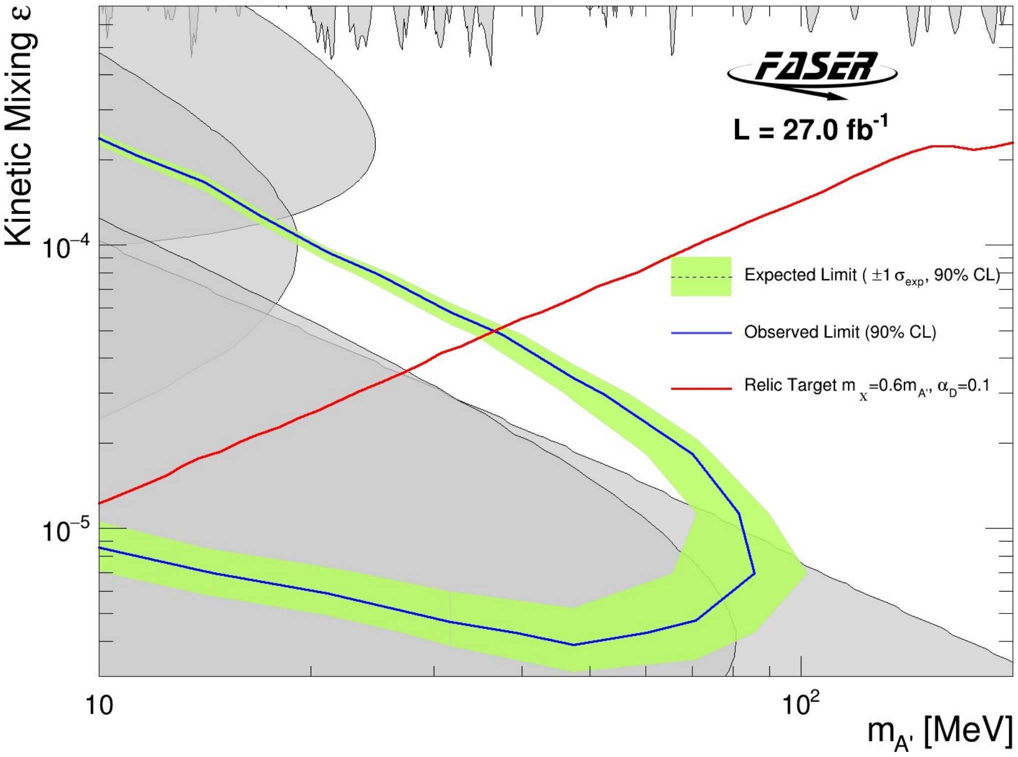


Total background: (0.0020 ± 0.0024) events
→ Achieved essentially background free search

arXiv:2308.05587
Phys. Lett. B 848 (2024) 138378

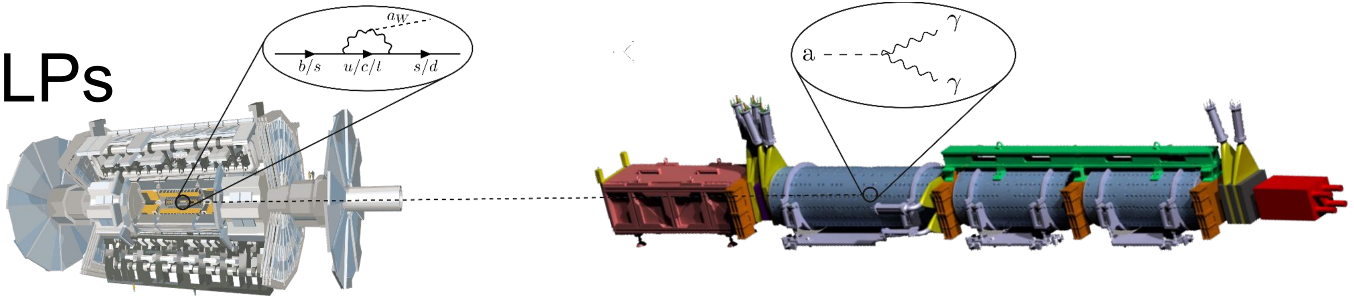
Dark Photon Search

- Zero events observed, limits in unconstrained regions of parameter space
- Result also interpreted in B-L gauge boson model

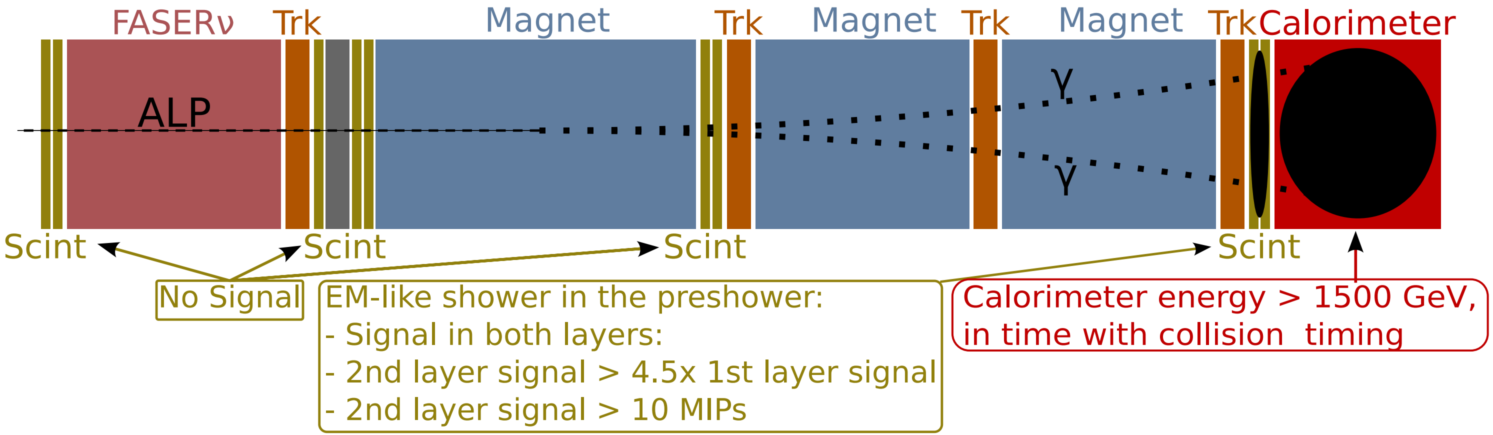


ALPs

arXiv:2410.10363
JHEP, 2025, 199 (2025)



- Search for Axion-like particles (ALPs) in FASER using 2022+2023 data (60 fb^{-1})
  - First FASER search for all neutral final state

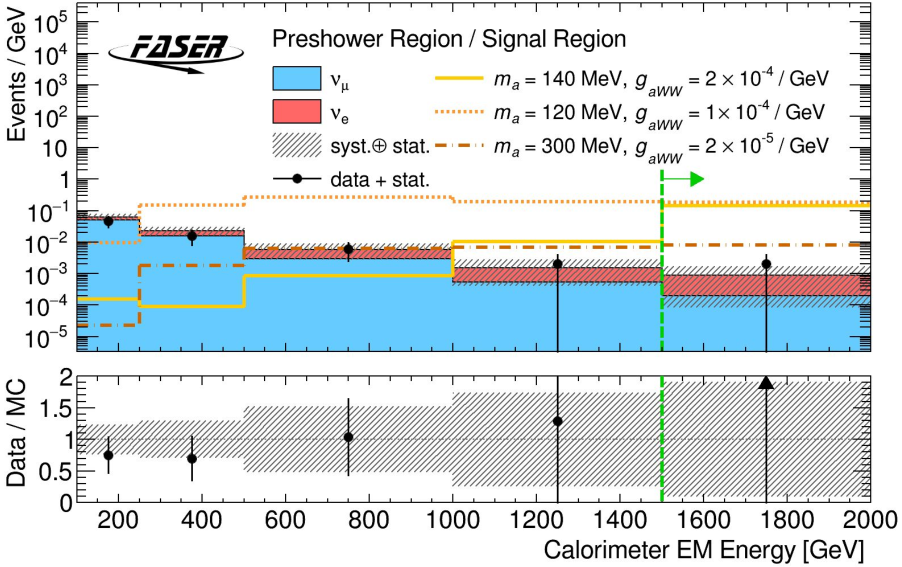


- Similar backgrounds as dark photon search
  - With current detector irreducible background from neutrino interactions in preshower
  - Expected background: 0.44 ± 0.39 events (from neutrino simulation, validated in data regions)
- In future, new preshower scintillator will allow to remove this background

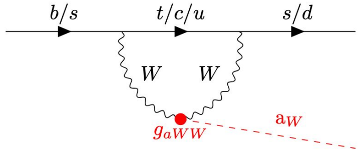
arXiv:2410.10363
JHEP, 2025, 199 (2025)

ALPs Search – Results

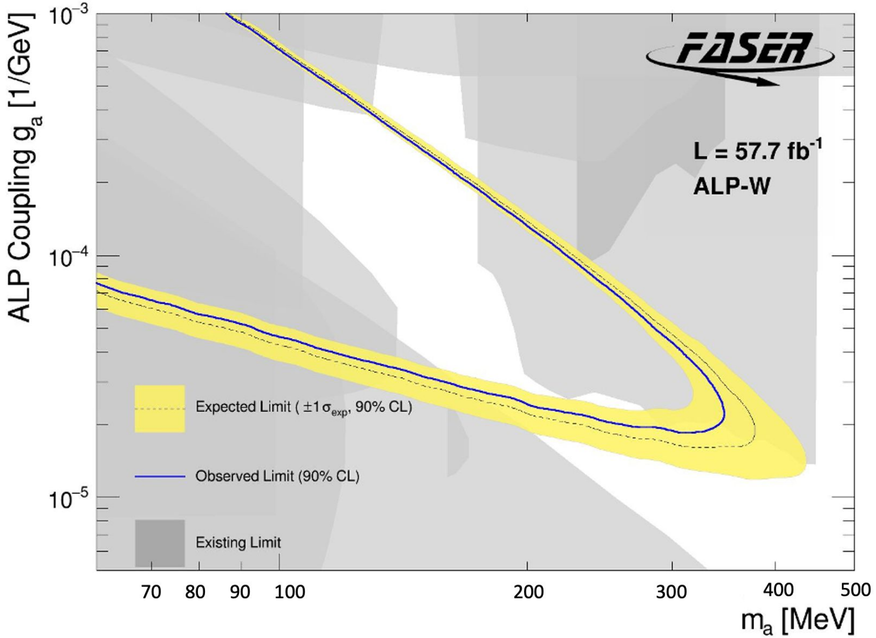
- 1 event observed in unblinded signal region (compatible with background estimate)



- More interpretations produced by FASER, not shown here



ALP-W model



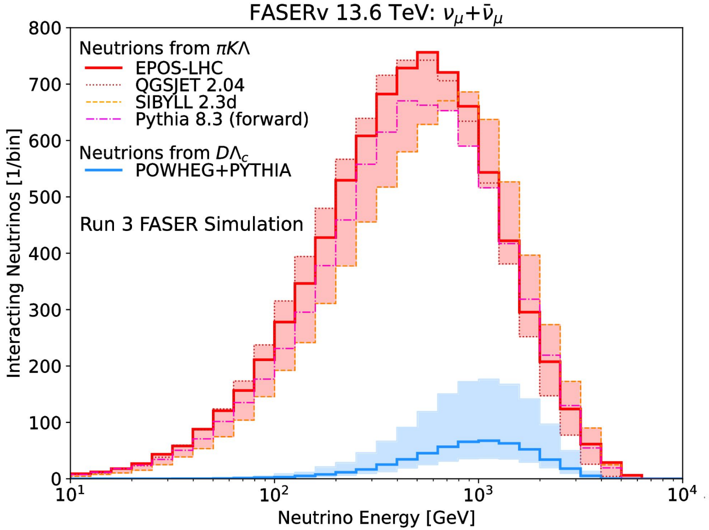
Neutrinos at FASER

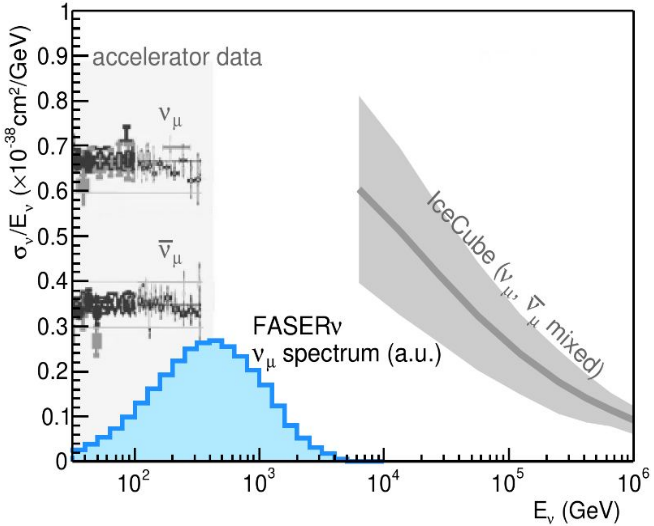
Run 3 365 fb^{-1}	ν_e	ν_μ	ν_τ
Production	K	π	D
$\#\nu$ traversing FASERν	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{9})$
$\#\nu$ interactions in FASERν	2400	12400	40

arXiv:1908.02310
arXiv:2402.13318
Phys. Rev. D 110, 012009

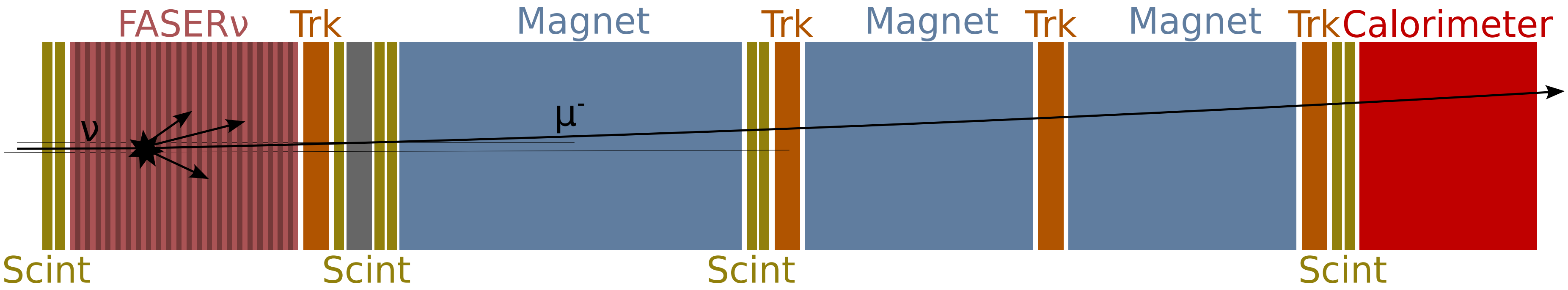
- Large neutrino flux in forward direction
- All flavors produced: $\pi \rightarrow \nu_\mu$, $K \rightarrow \nu_e$, $D \rightarrow \nu_\tau$
- Cross sections of all neutrino flavors at TeV energies unexplored
- Neutrinos are proxy for forward hadron production
  - Input for QCD, forward charm production, …

- Example: neutrino interactions and cross section of muon neutrinos:





Observing Neutrinos with FASER



FASERν emulsion detector:

- 730 layers of tungsten + emulsion film, 1.1 ton
- Excellent position & angular resolution (0.3 μm), but no time resolution
- Films saturate at ~ 5×10^5 tracks/cm^2
  → Replace films about 3 times/year, develop the emulsion films

Electronic detectors:

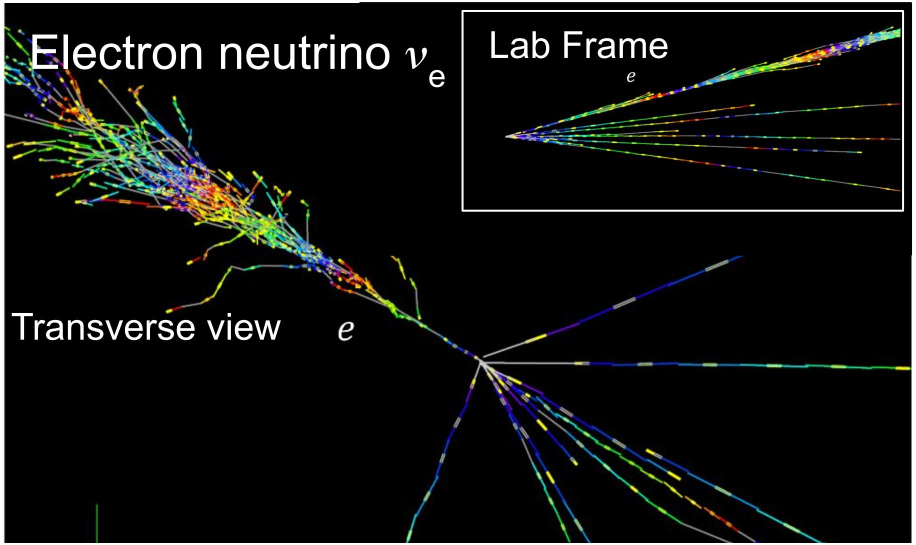
- Use FASERν only as target for neutrino interaction
- Reconstruct muon, produced in CC ν_μ interactions, with electronic detectors
- Other particles are absorbed in tungsten
  → Observe only CC ν_μ interactions
- Charge of muon used to separate ν and $\bar{\nu}$

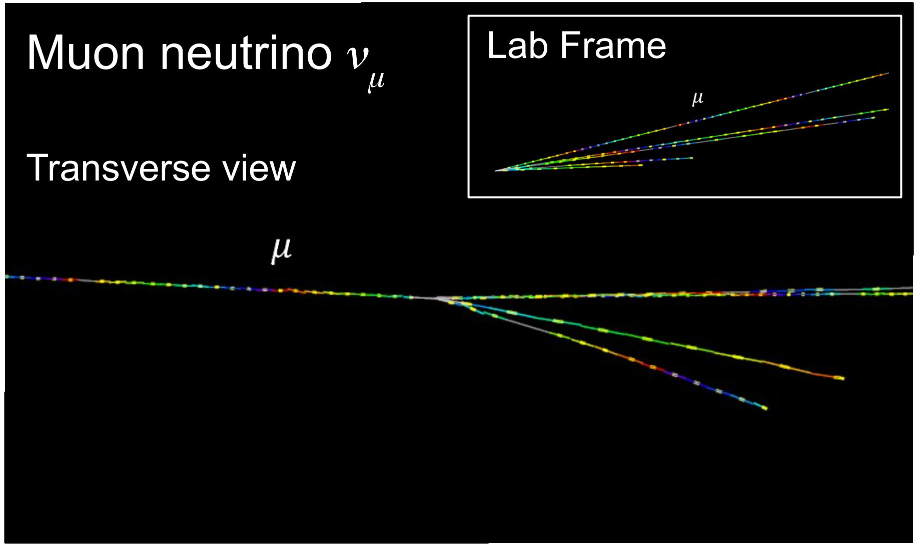
→ **Two complementary approaches to study neutrinos**

arxiv 2403.12520
Phys. Rev. Lett. 133, 021802 (2024)

FASERν Emulsion Detector – Events

- Readout of emulsion films is time-consuming → First analysis uses 283 films 128.6 kg (9.5 fb^{-1})





- Short tracks + EM shower
- Expect 0.6 - 5.2 CC ν_e interactions
- Observed 4 ν_e events with a background of 0.025 ± 0.018 neutral hadrons (5.2σ)

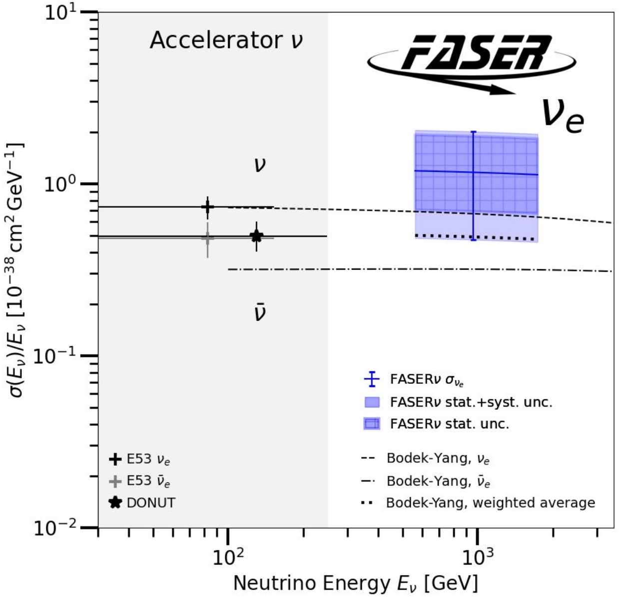
- Long tracks + no shower
- Expect 3.0 - 8.6 CC ν_μ interactions
- Observed 8 ν_μ events with a background of 0.22 ± 0.11 neutral hadrons (5.7σ)

First observation of collider ν_e!

arxiv 2403.12520
Phys. Rev. Lett. 133, 021802 (2024)

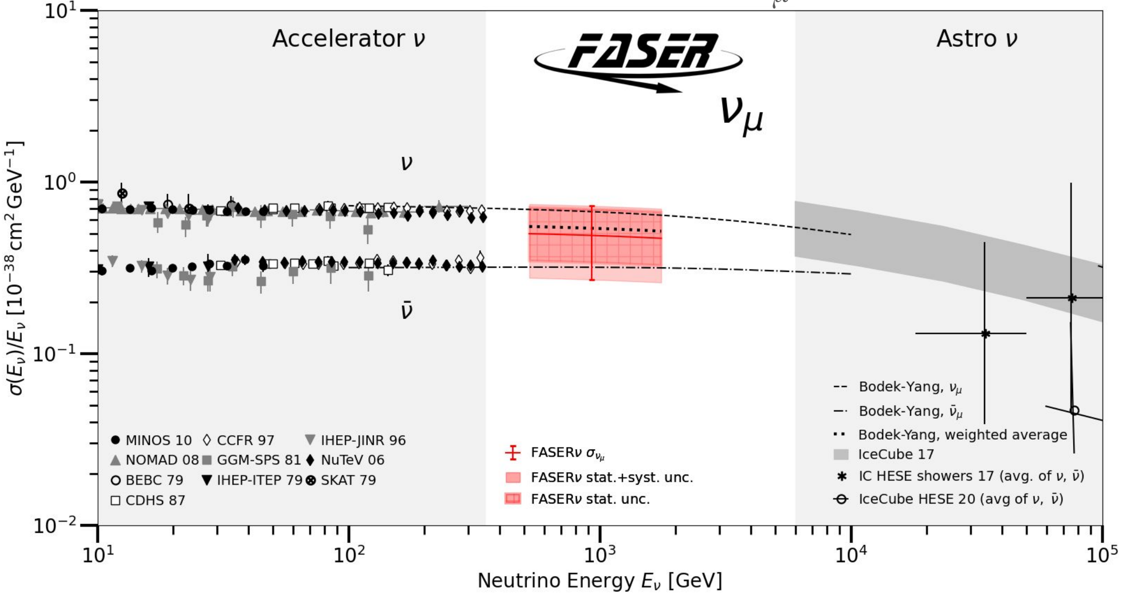
FASERν Emulsion Detector - Cross section

Electron neutrino ν_e



$\sigma_{\nu,\,CC} = (1.2^{+0.8})$ x 10^{-38} cm^2 GeV^{-1}

Muon neutrino ν_μ



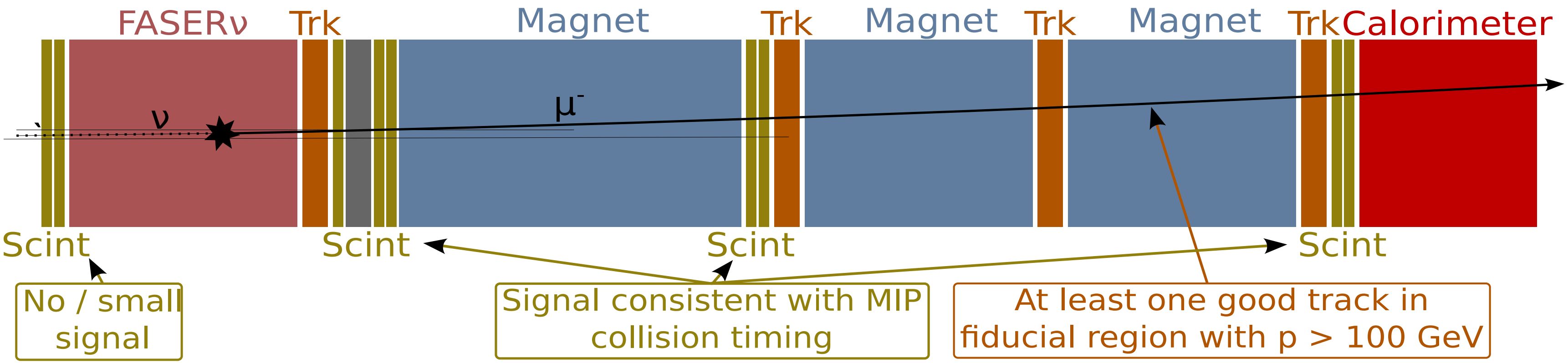
$\sigma_{\nu,\,CC} = (0.5 \pm 0.2)$ x 10^{-38} cm^2 GeV^{-1}

First measurement of cross section of collider neutrinos!

Electronic neutrino analysis – Event selection

arXiv:2303.14185,
Phys. Rev. Lett. 131, 031801
arXiv:2412.03186

- Reconstruct muon, produced in CC ν_μ interactions, with electronic detectors:

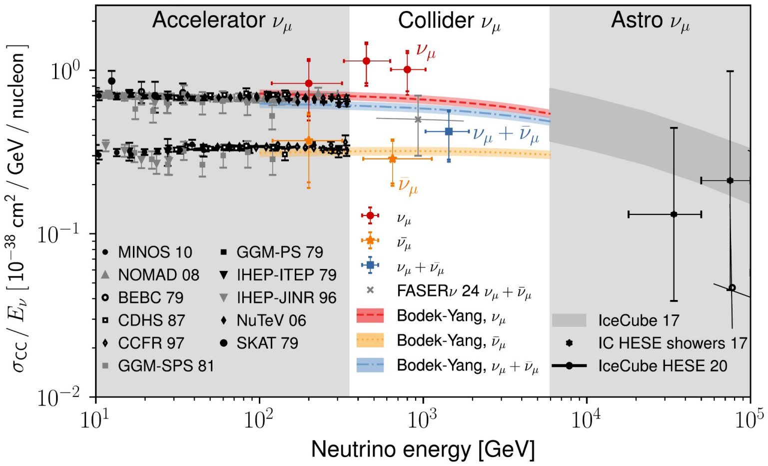


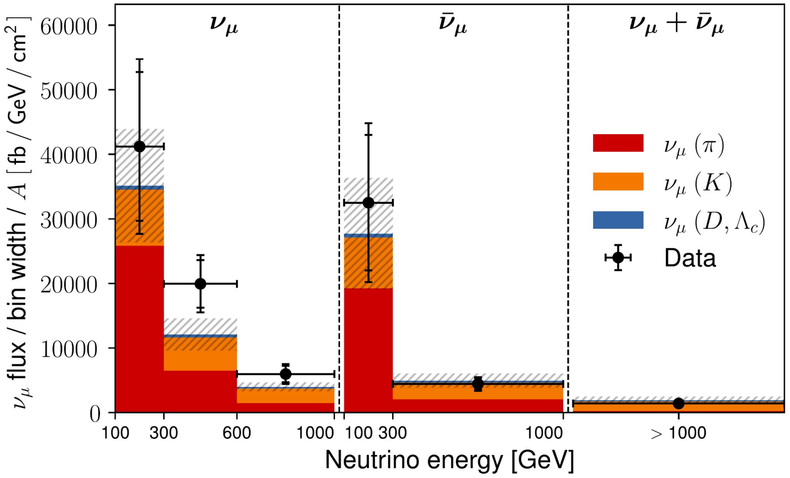
- Background from ν_e, ν_τ, NC, ν interactions outside of the FV, and muons missing veto

Electronic neutrino analysis – Results

arXiv:2303.14185,
Phys. Rev. Lett. 131, 031801

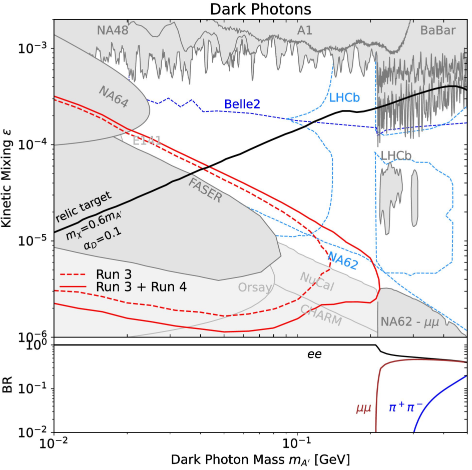
- 2023: First direct observation of collider neutrinos!
  - Using 2022 data (35.1 fb^{-1})
  - Observed 153 neutrino candidates with background of 0.19 ± 1.83 events (> 15 σ)
- 2024: Measurement of neutrino cross section and flux as function of energy arXiv:2412.03186
  - Using 2022 and 2023 data (65.6 fb^{-1})
  - Unfold number of neutrino interactions
  - Interpret result in two ways:
    1. Assume flux from MC (with uncertainty) and measure cross section
    2. Assume theoretical cross section (with uncertainty) and measure flux

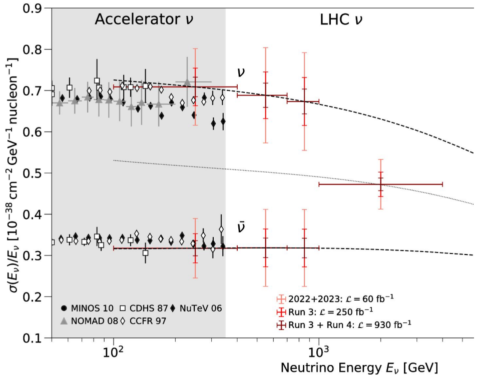


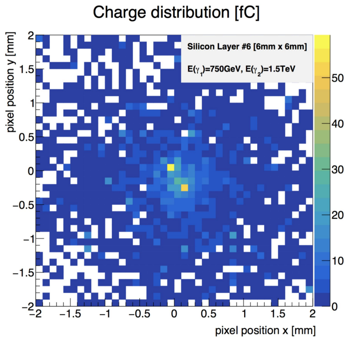


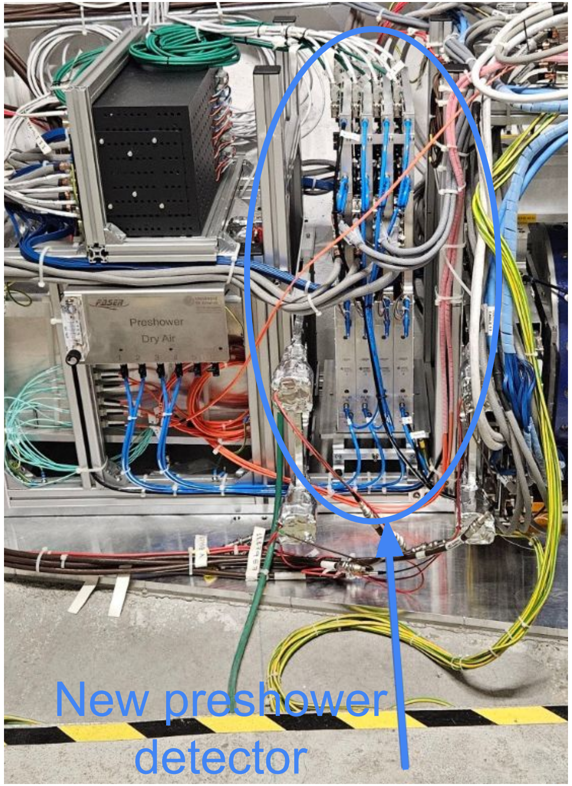
What is next ?

- Installed new high-resolution tungsten/silicon-pixel preshower station in February 2025
  - Separate closely spaced high-energy photons
  - Helps with background for ALPs analysis → Improves sensitivity
- FASER is approved to operate during Run 4!
  - Increased sensitivity for higher luminosity
  - Higher muon rates challenging for FASERν emulsion detector
    → Explorations for minimal detector additions ongoing
- FASER2 and FASERν2 at the FPF (awaiting approval)



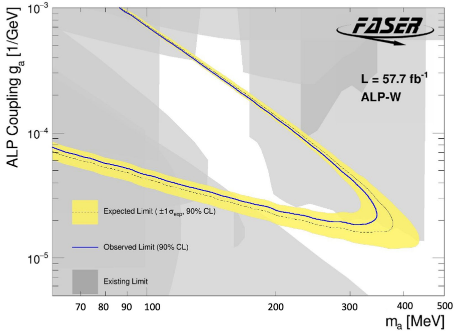


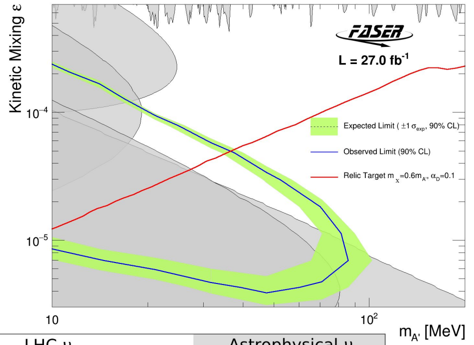




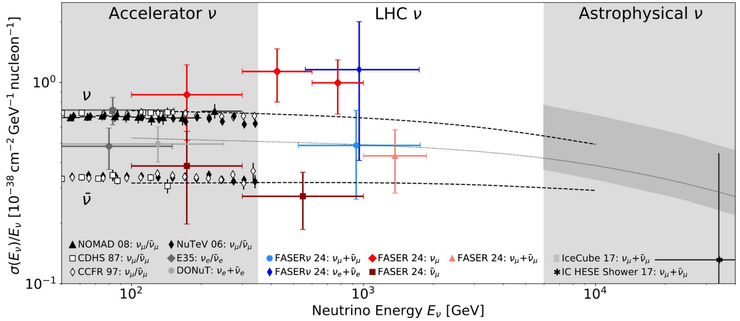
Summary

- FASER operating since the start of LHC Run 3
  - 190 fb^{-1} of data recorded
- Dark photon & ALPs searches
  - Exclude interesting parameter space motivated by dark matter
  - Almost background free search validates detector design/performance
  - Preshower upgrade will improve sensitivity
- Neutrinos
  - First direct observation of collider muon and electron neutrinos
  - Measured ν_e and ν_μ cross sections (as a function of energy)
  - Measured forward neutrino flux at the LHC
    → Opened door to collider neutrino studies at at the LHC
- Looking forward to updated analysis





The future is forward!



FASER Collaboration

The FASER collaboration consists of 112 members from 28 institutions and 11 countries

International laboratory covered by a cooperation agreement with CERN

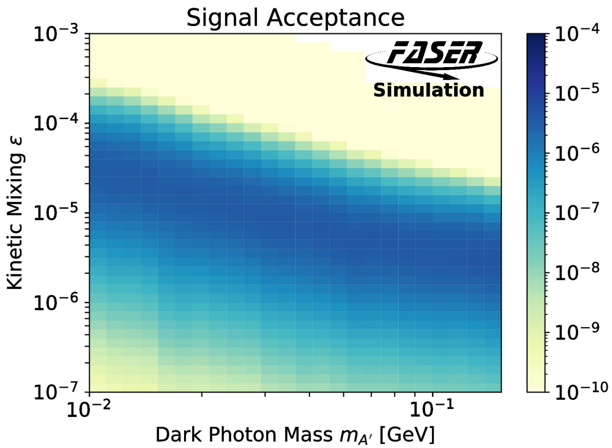
FASER Acknowledgements

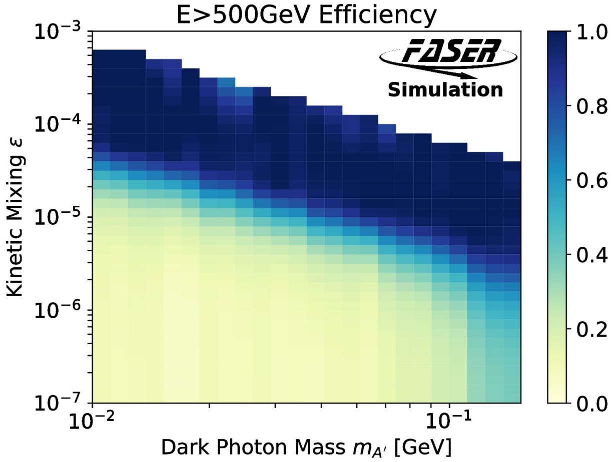
- FASER is supported by

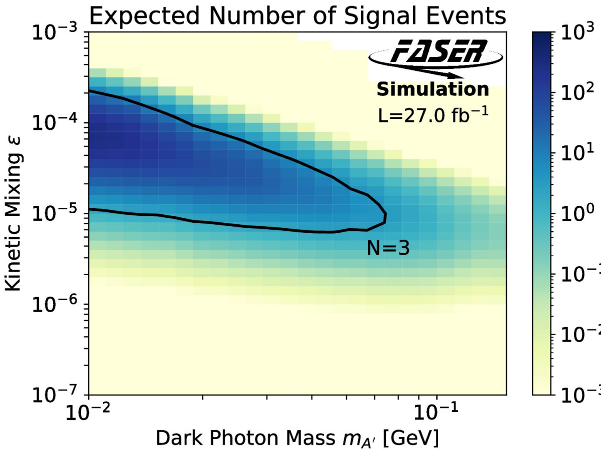
- We also thank:
    - LHC for the excellent performance
    - ATLAS Collaboration for providing luminosity information
    - ATLAS SCT Collaboration for spare tracker modules
    - ATLAS for the use of their ATHENA software framework
    - LHCb Collaboration for spare ECAL module
    - CERN FLUKA team for the background simulation
    - CERN PBC and technical infrastructure groups for the excellent support

Additional Slides

Dark Photon – Event selection

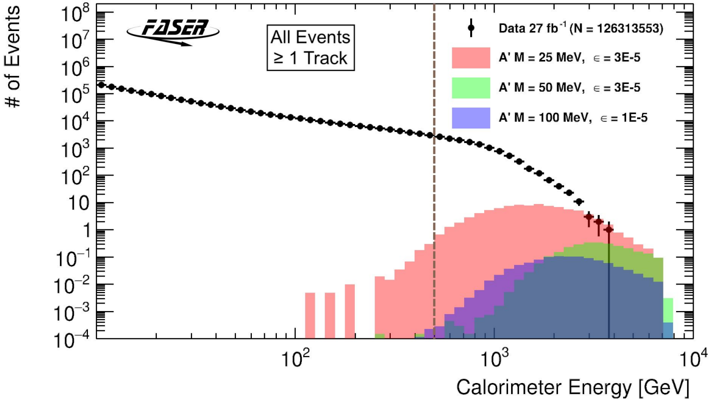


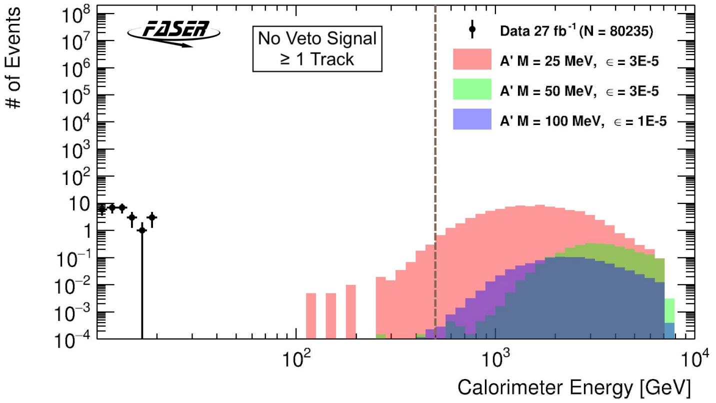


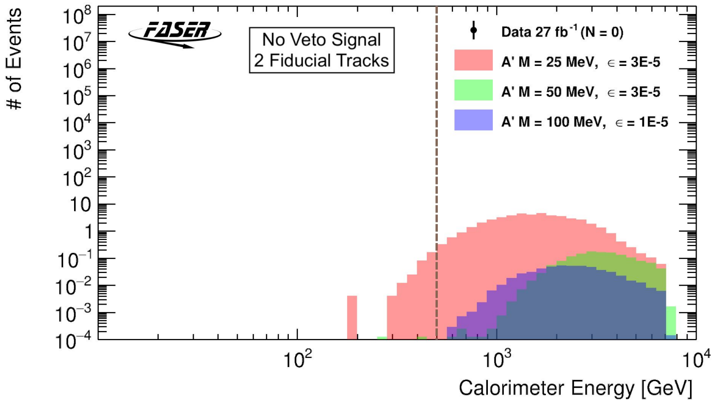


Dark photon

- Calorimeter energy distribution for different cuts



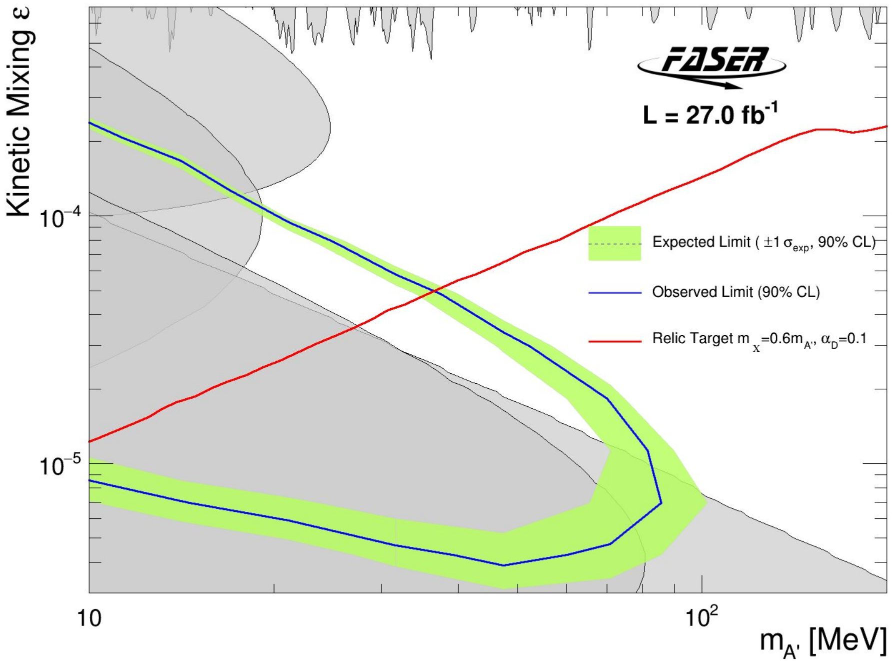




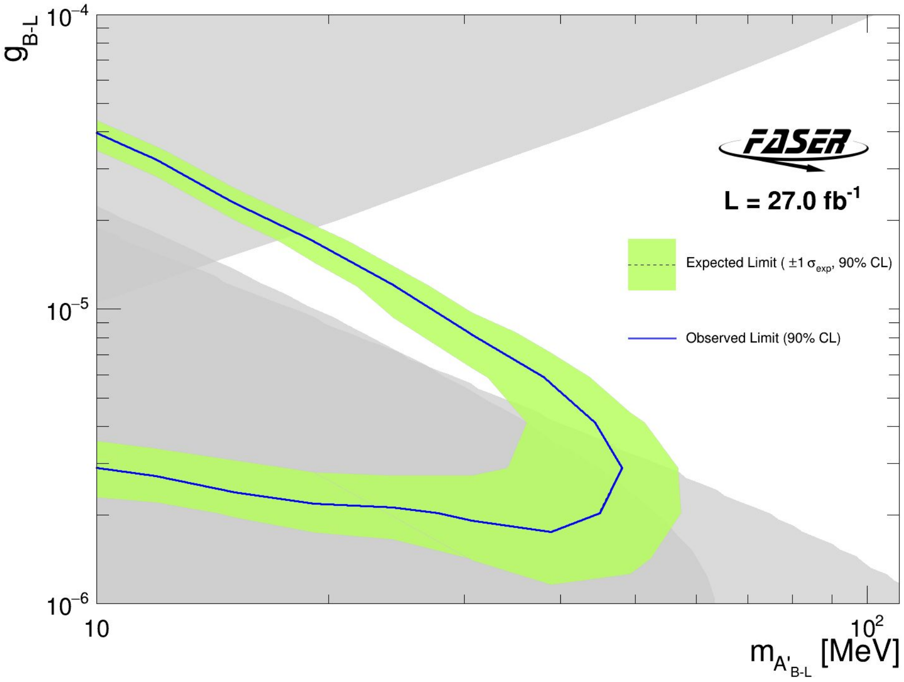
no events in unblinded region

Dark photon – Exclusion contours

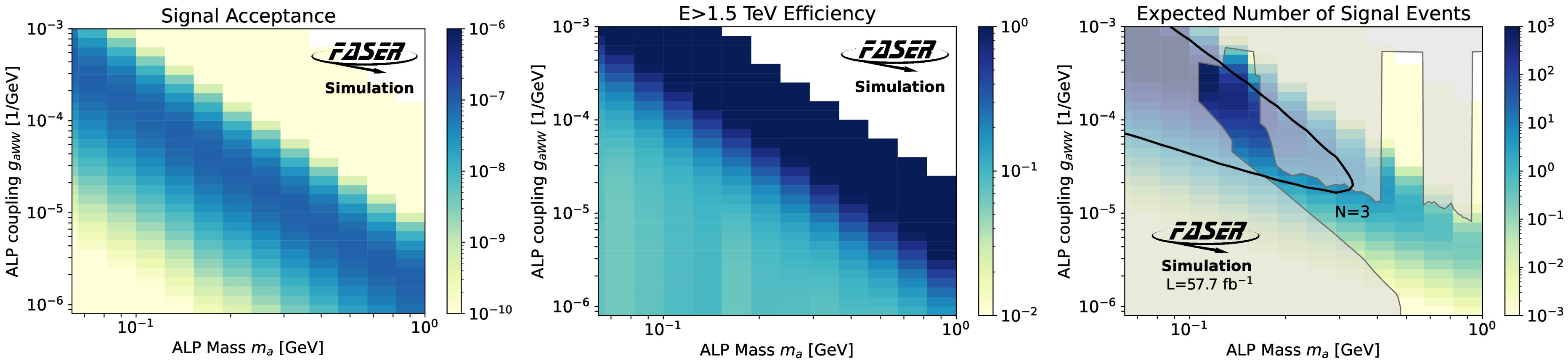
Dark photon



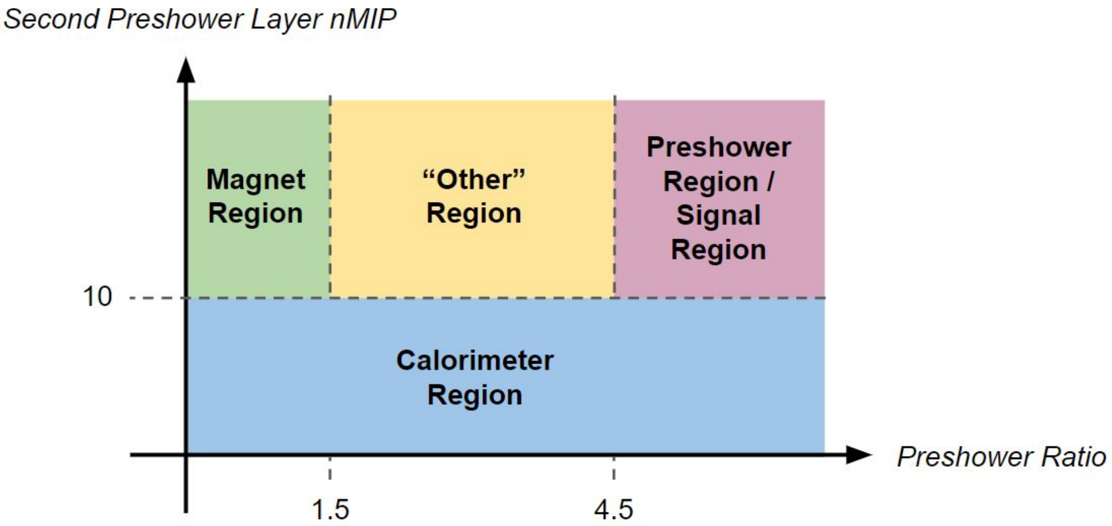
B-L gauge boson

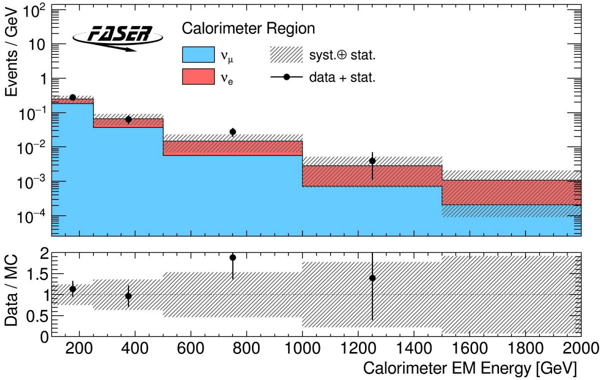


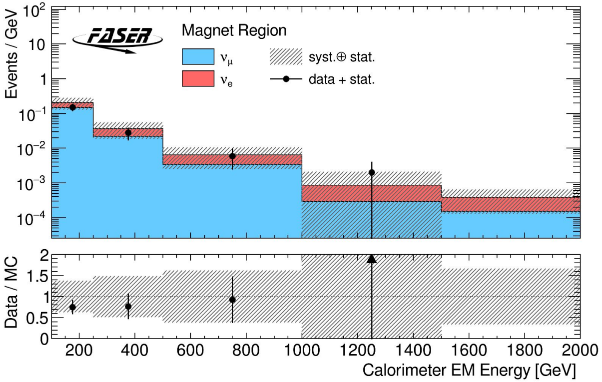
ALPs – Event selection

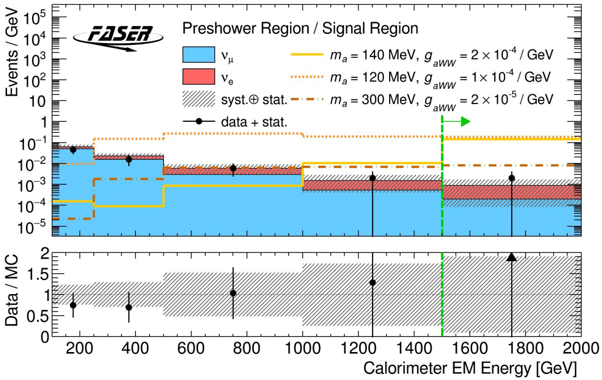


ALPs – Validation & Signal regions

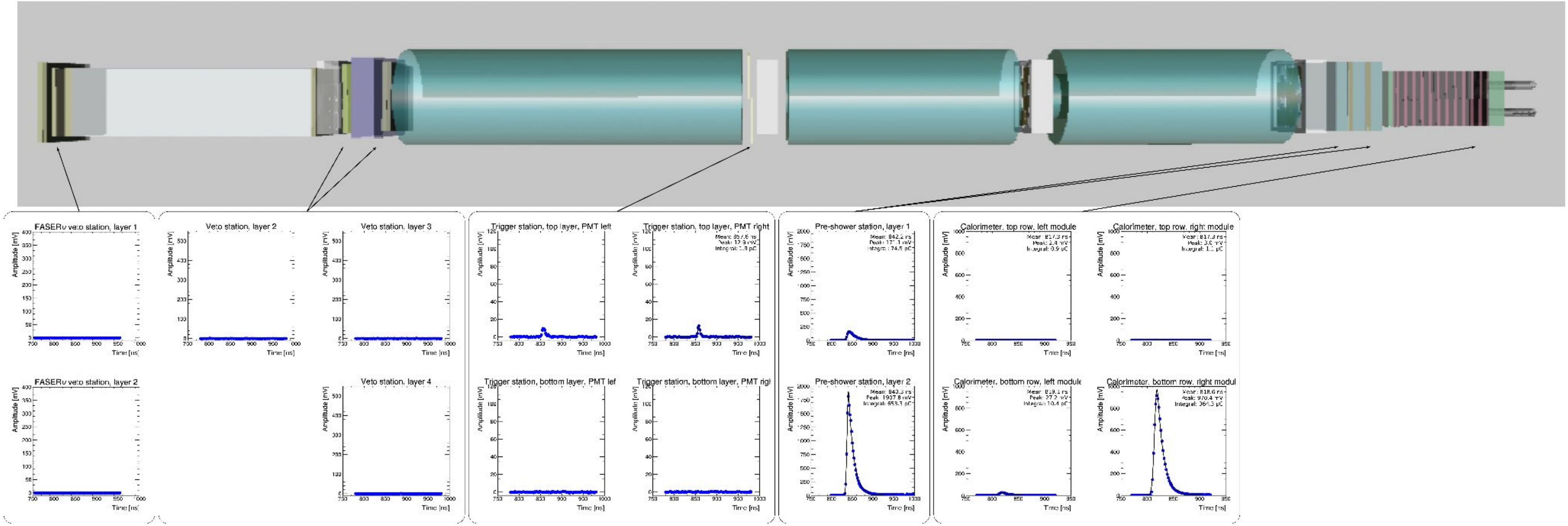




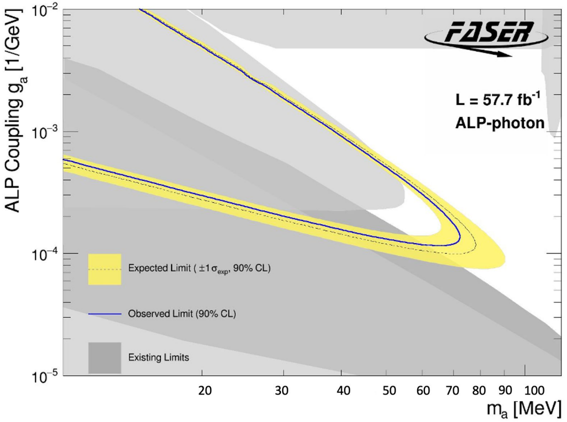


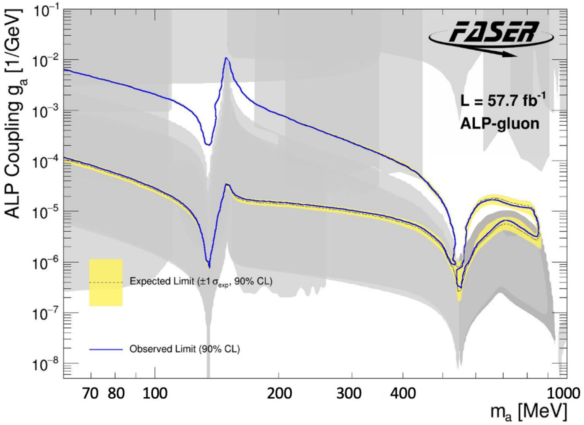


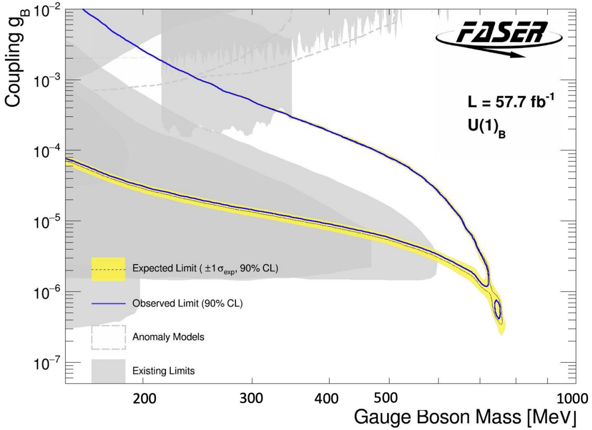
Run 8834
Event 44421456
2022-10-13 16:09:44

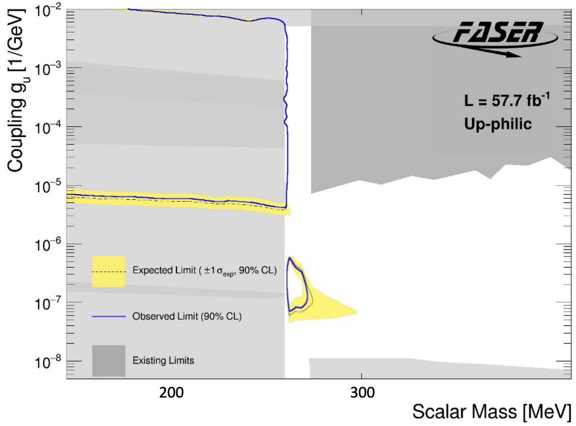


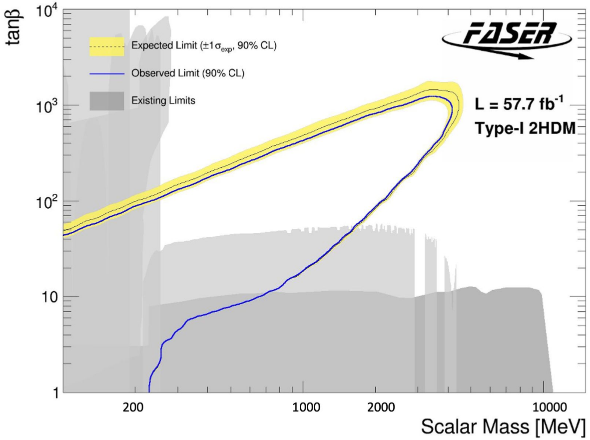
ALPs – Additional interpretations

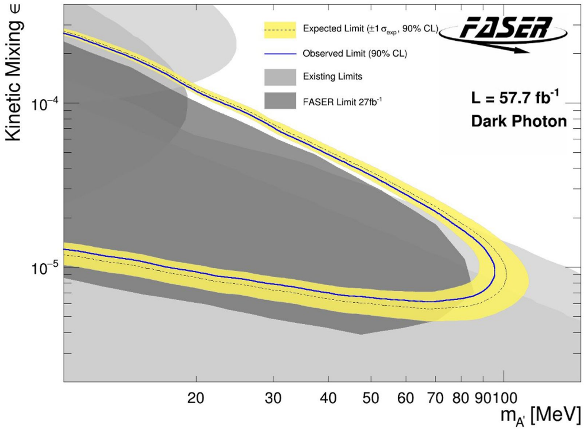




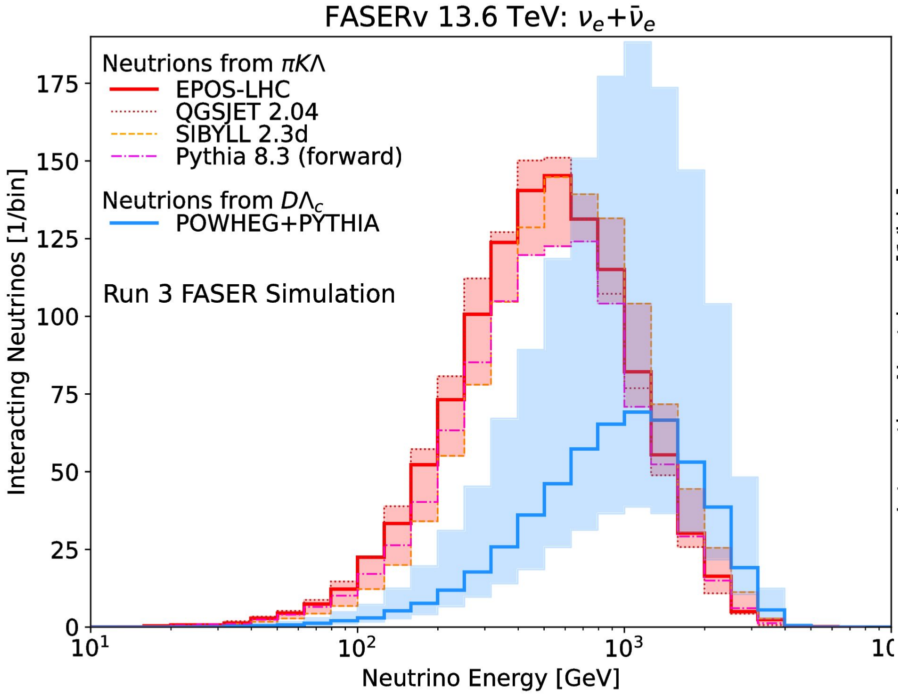


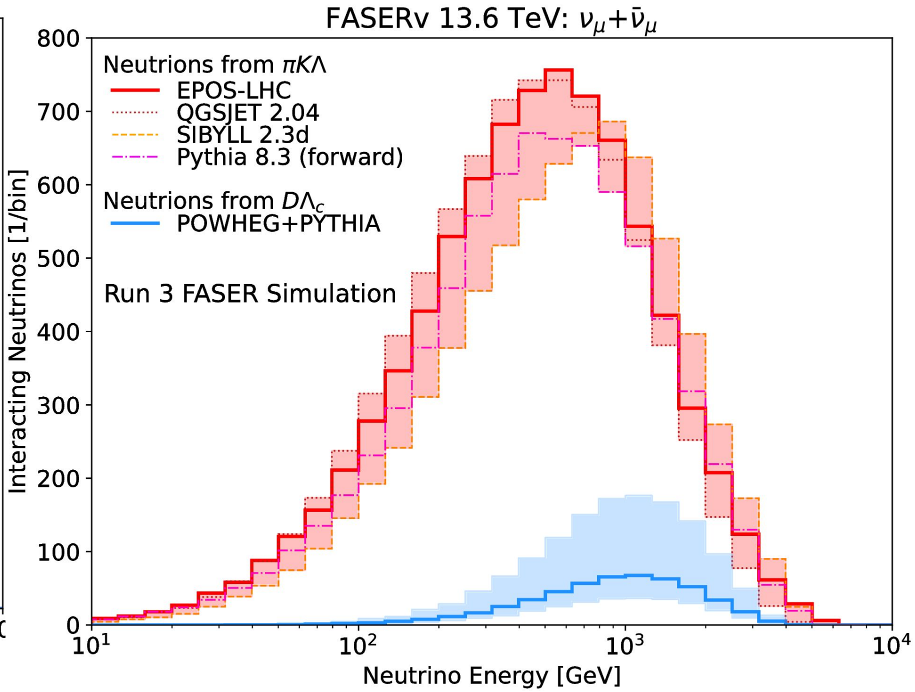




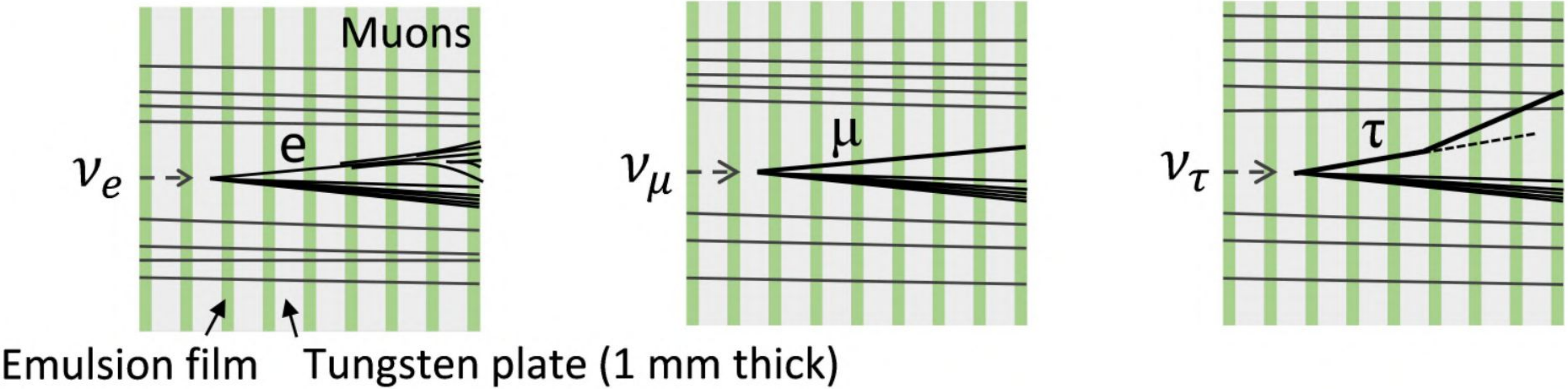


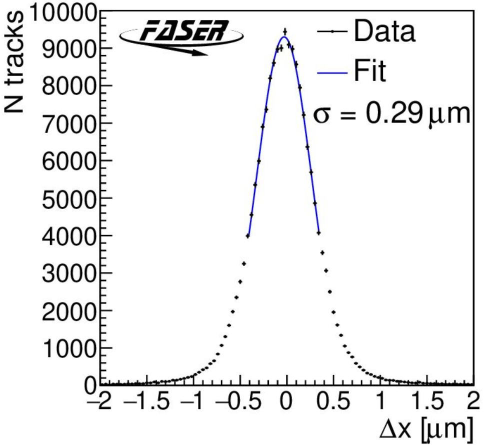
Neutrino Rates

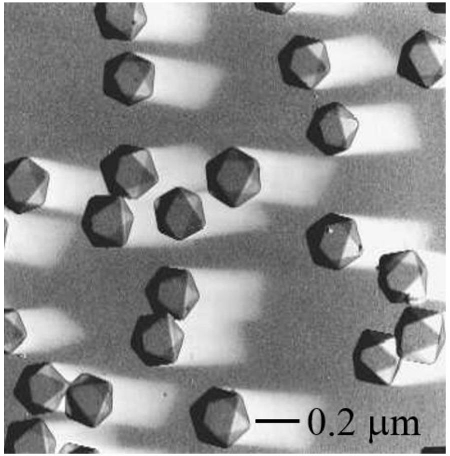


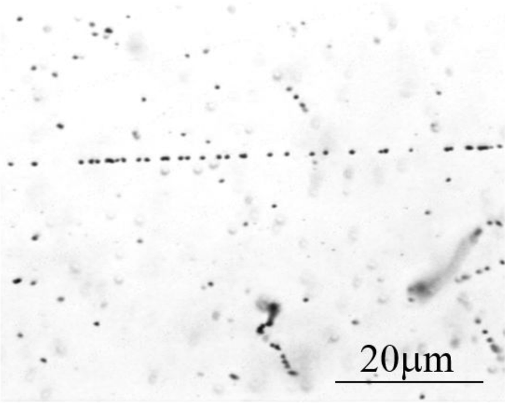


Emulsion film





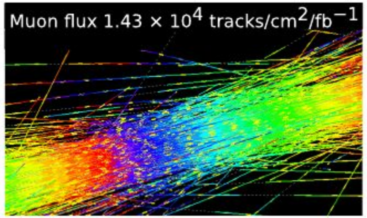


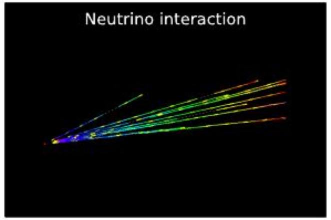


FASERν Neutrino Analysis – Event selection

1. Reconstruct vertices

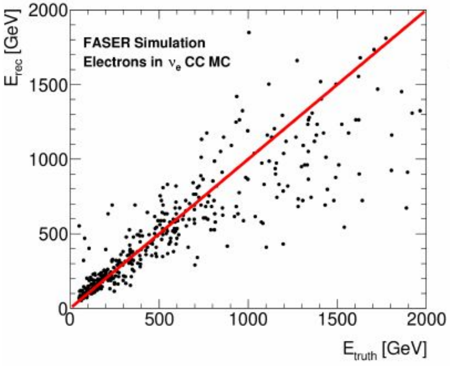
- $N_{\mathrm{track}} \geq 5$, $N_{\mathrm{track}\,(\tan\theta \leq 0.1)} \geq 4$
- Impact parameter $d < 5\,\mu\mathrm{m}$
- No parent / incoming track

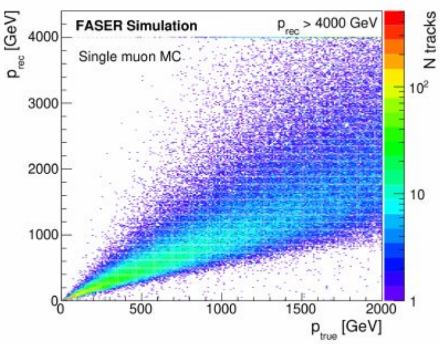




2. Lepton identification

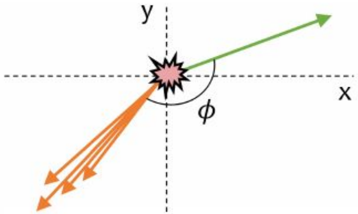
- **Electron**: vertex with EM shower
  - Energy measured by counting # of track segments around EM shower maximum
  - $\Delta E/E \sim 0.25$ at 200 GeV
- **Muon**: vertex with track traversing > 100 plates
  - Muon momentum from multiple coulomb scattering as muon traverses tungsten
  - $\Delta p/p \sim 0.3$ at 200 GeV





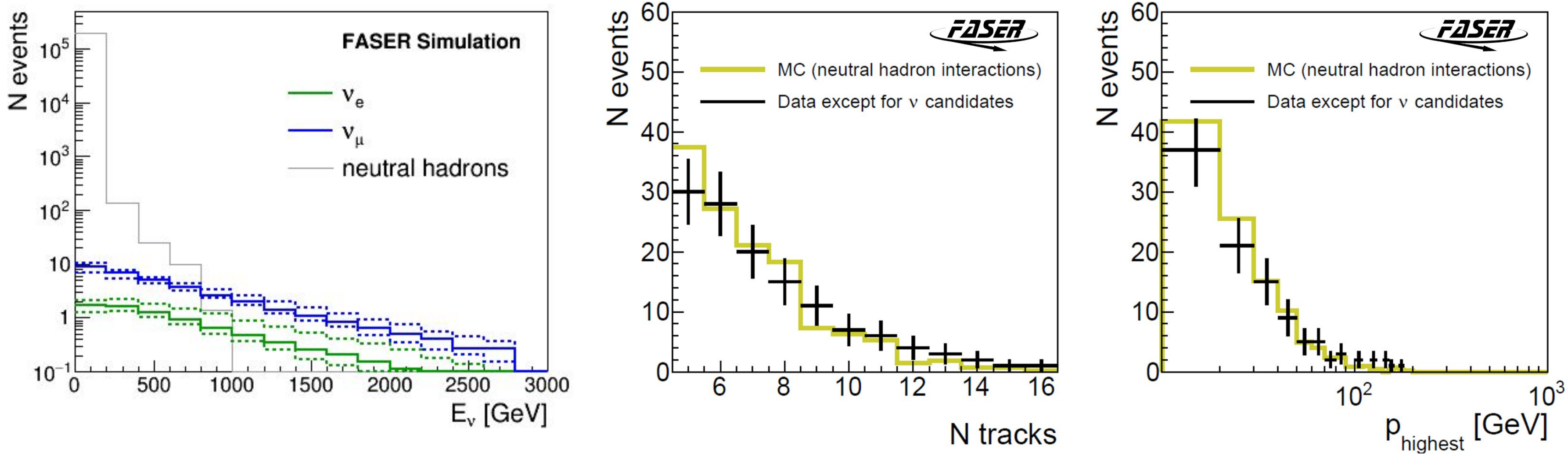
3. Event selection

- E_e or $p_\mu > 200$ GeV
- $\tan\theta_\ell > 0.005$
- $\phi > 90^\circ$ with respect to other tracks

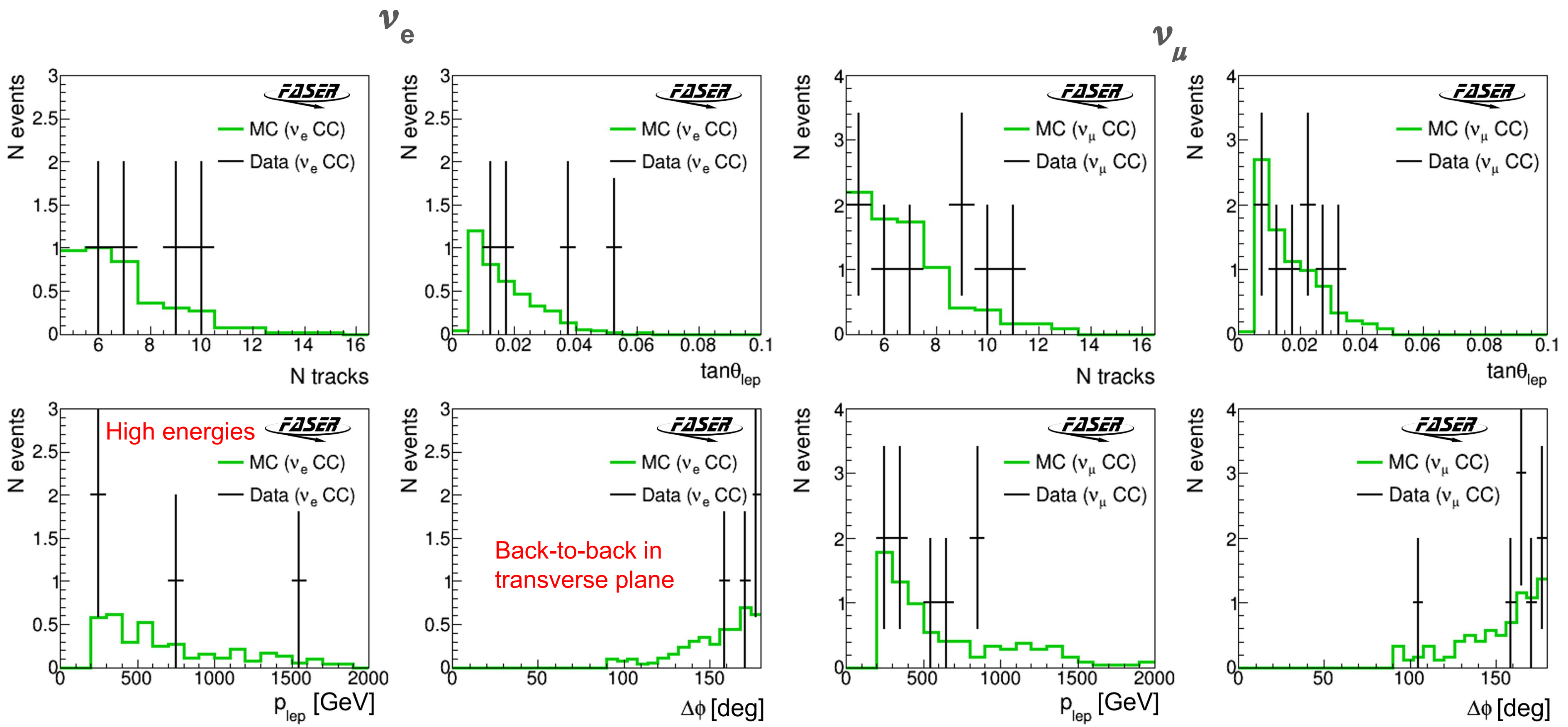


FASERν Neutrino Analysis – Backgrounds

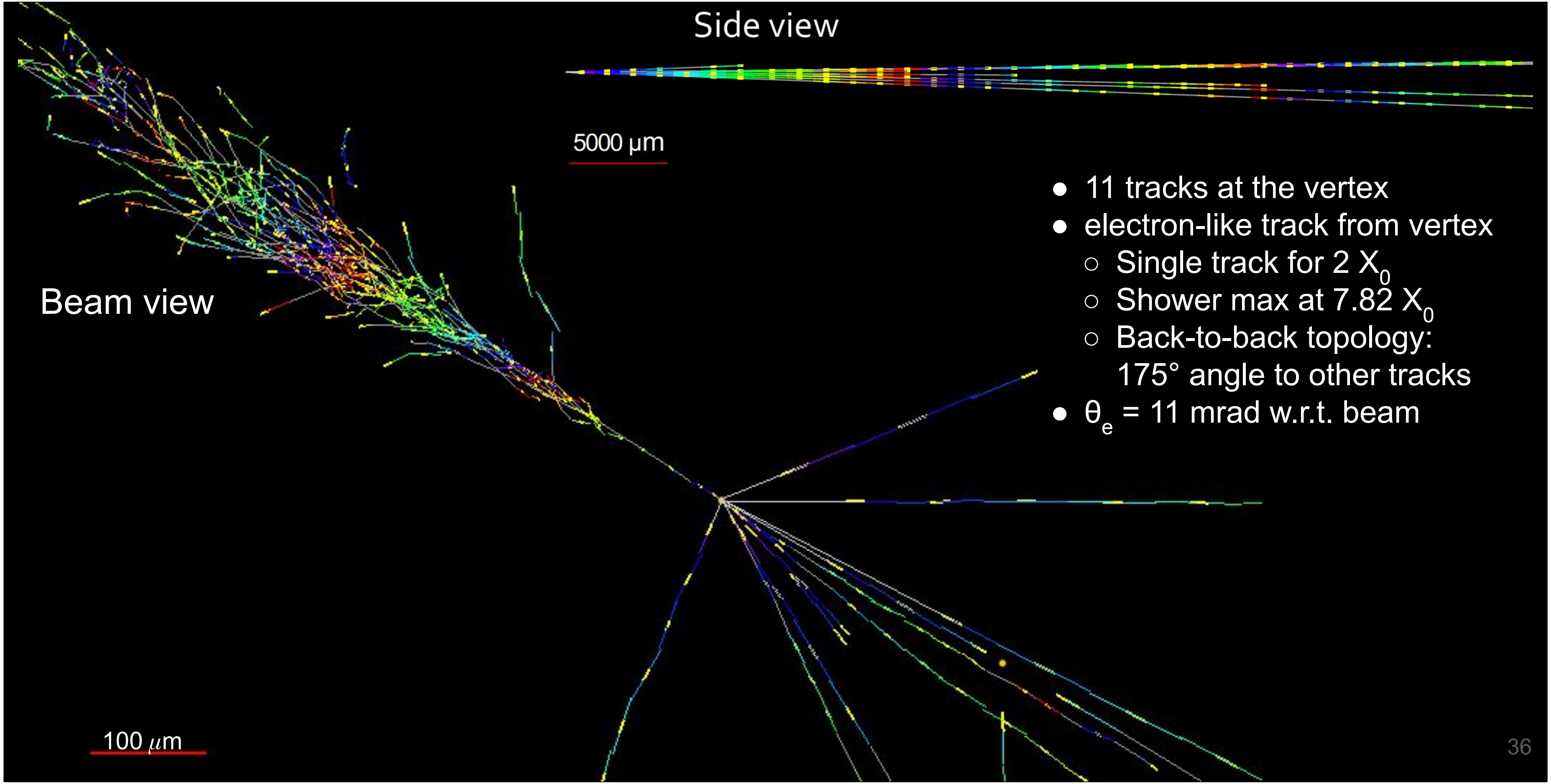
- Main background: neutral hadrons interacting with detector
  - Reduced by momentum / energy cut
  - Estimated from simulation and validated using vertices with lower energy
- Few neutral current interactions for ν_μ



FASERν Neutrino Analysis – Signal Events

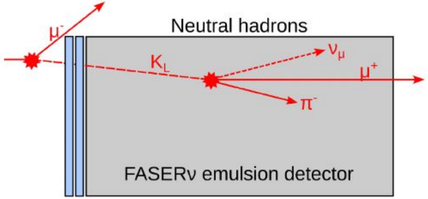


“Pika-ν” Event



- 11 tracks at the vertex
- electron-like track from vertex
  - Single track for 2 X_0
  - Shower max at 7.82 X_0
  - Back-to-back topology: 175° angle to other tracks
- θ_e = 11 mrad w.r.t. beam

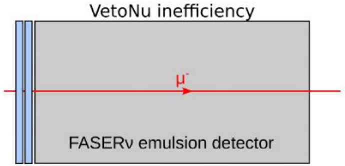
Electronic Neutrino Analysis - Backgrounds



- Neutral hadrons has to be produced in last meter in front of FASER (otherwise absorbed in concrete)

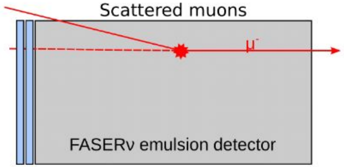
  $\rightarrow$ Almost always also parent muon hits VetoNu scintillator
- Momentum and track cut reduce background further

  $\rightarrow$ Negligible

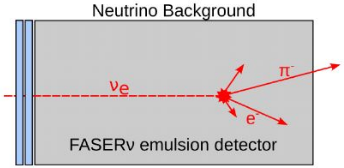


- Inefficiency of each layer $< 10^{-7}$
- Expect $< 10^{-6}$ background events

  $\rightarrow$ Negligible



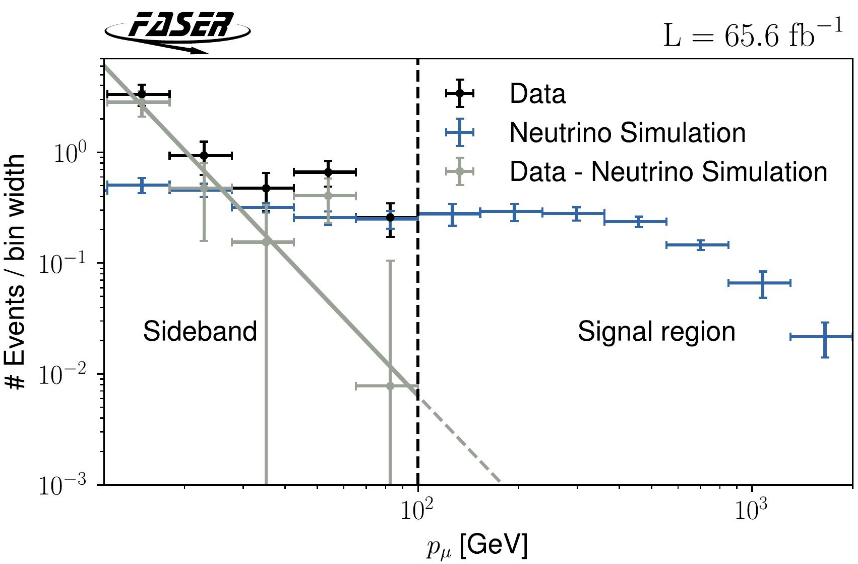
- Estimated from low momentum sideband
- Expect in total 0.3 ± 0.6 background events

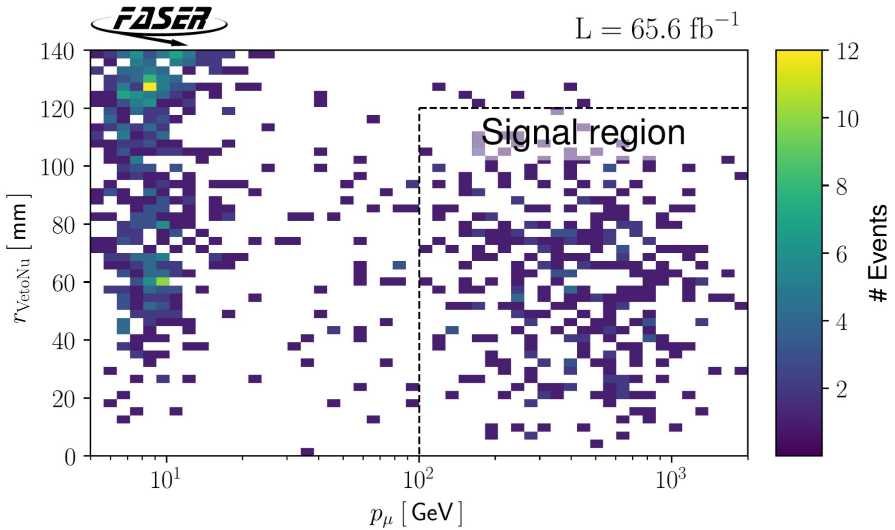


- Small contribution from ν_e, ν_τ, NC, or ν_μ interactions outside fiducial volume
- Estimated from simulations

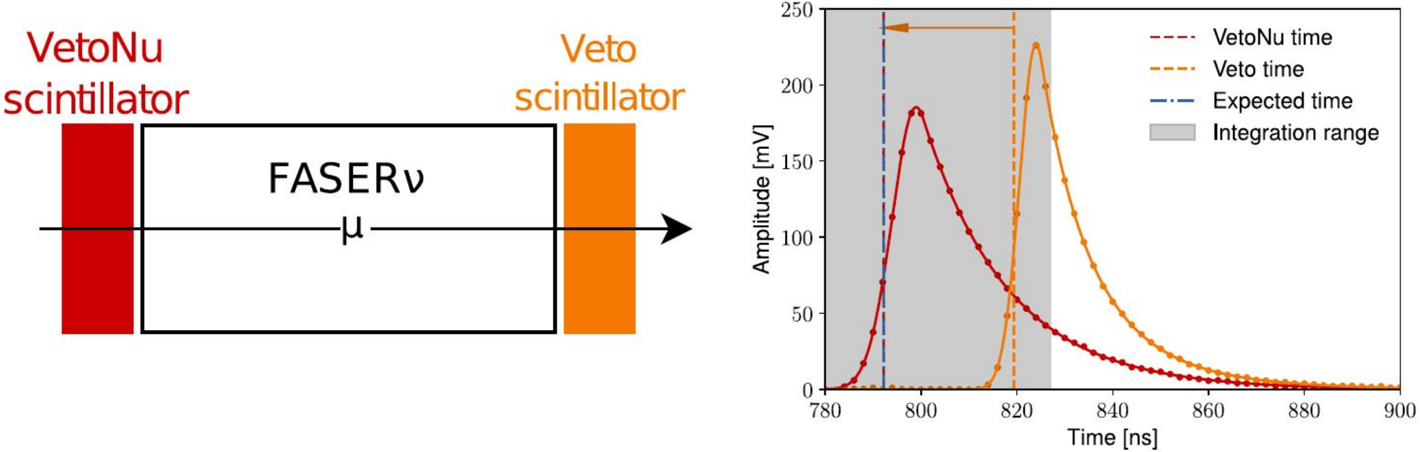
Signal	Background				
ν_μ CC (fid.)	ν_μ CC (non-fid.)	ν_e CC	ν_τ CC	ν NC	Geo. bgr
298.4 ± 42.6	17.1 ± 6.6	2.3 ± 1.9	0.2 ± 0.4	4.0 ± 1.4	0.3 ± 0.6

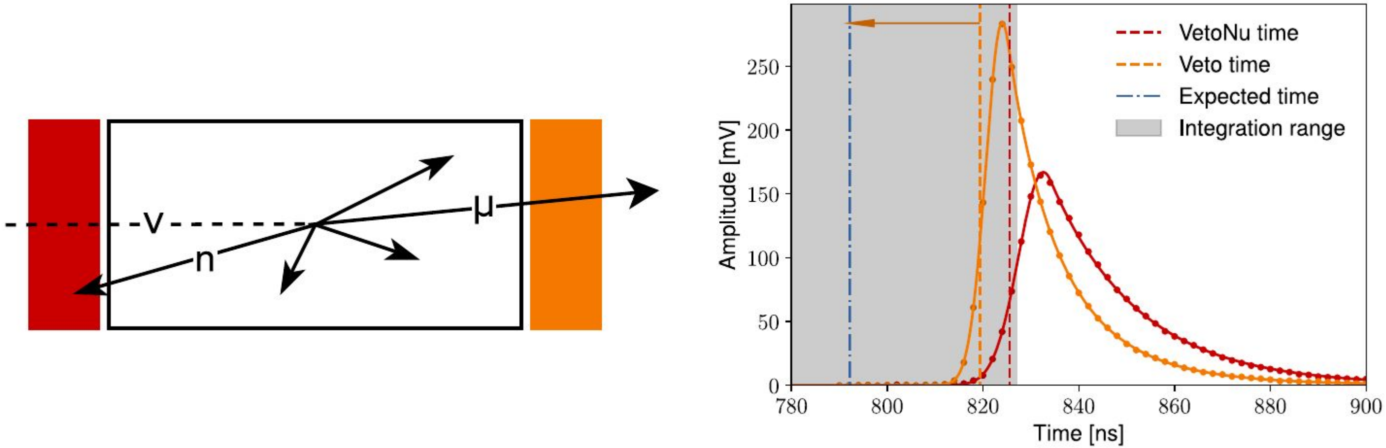
Electronic Neutrino Analysis – Geometric Backgrounds



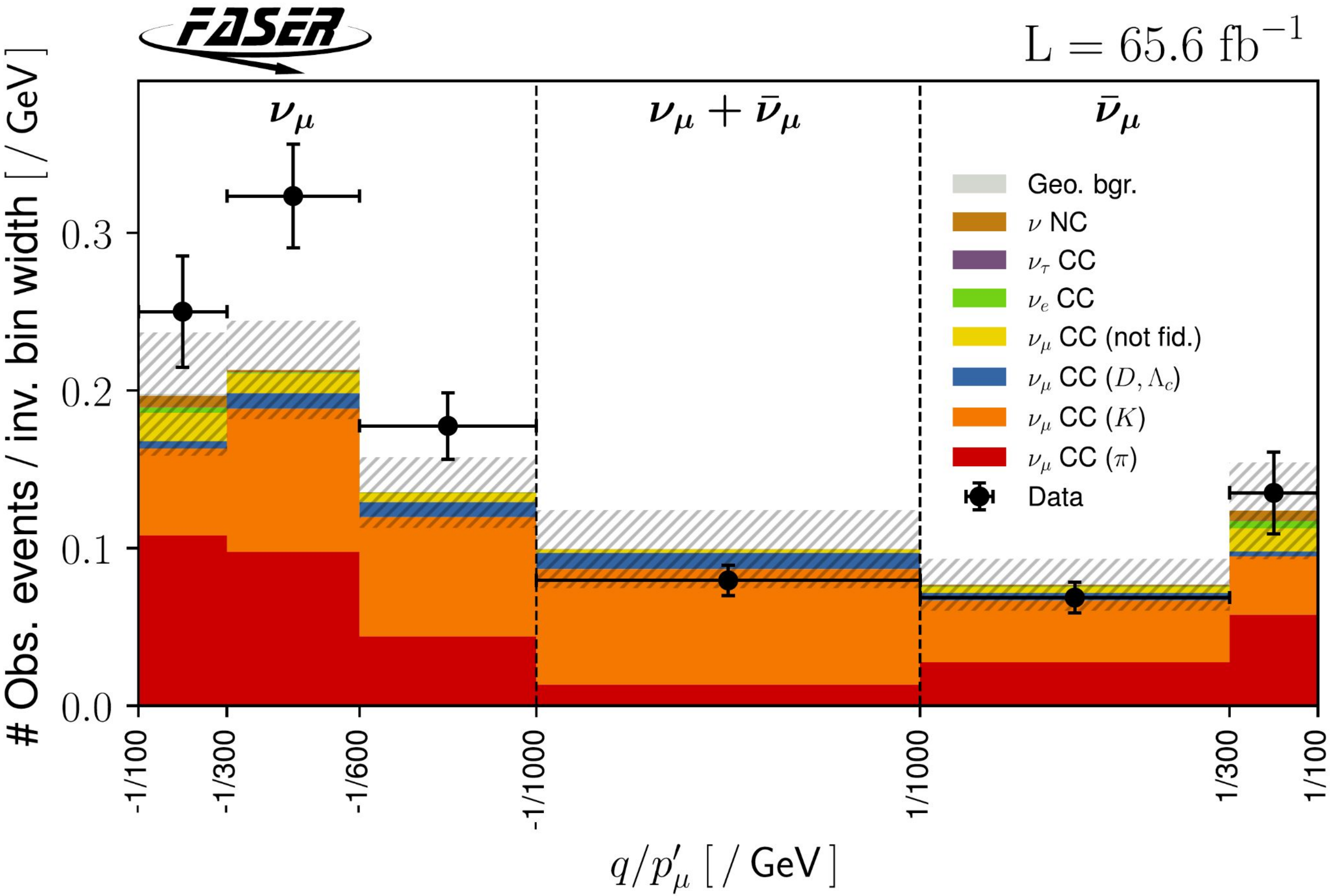


Reduced Vetoν Charge

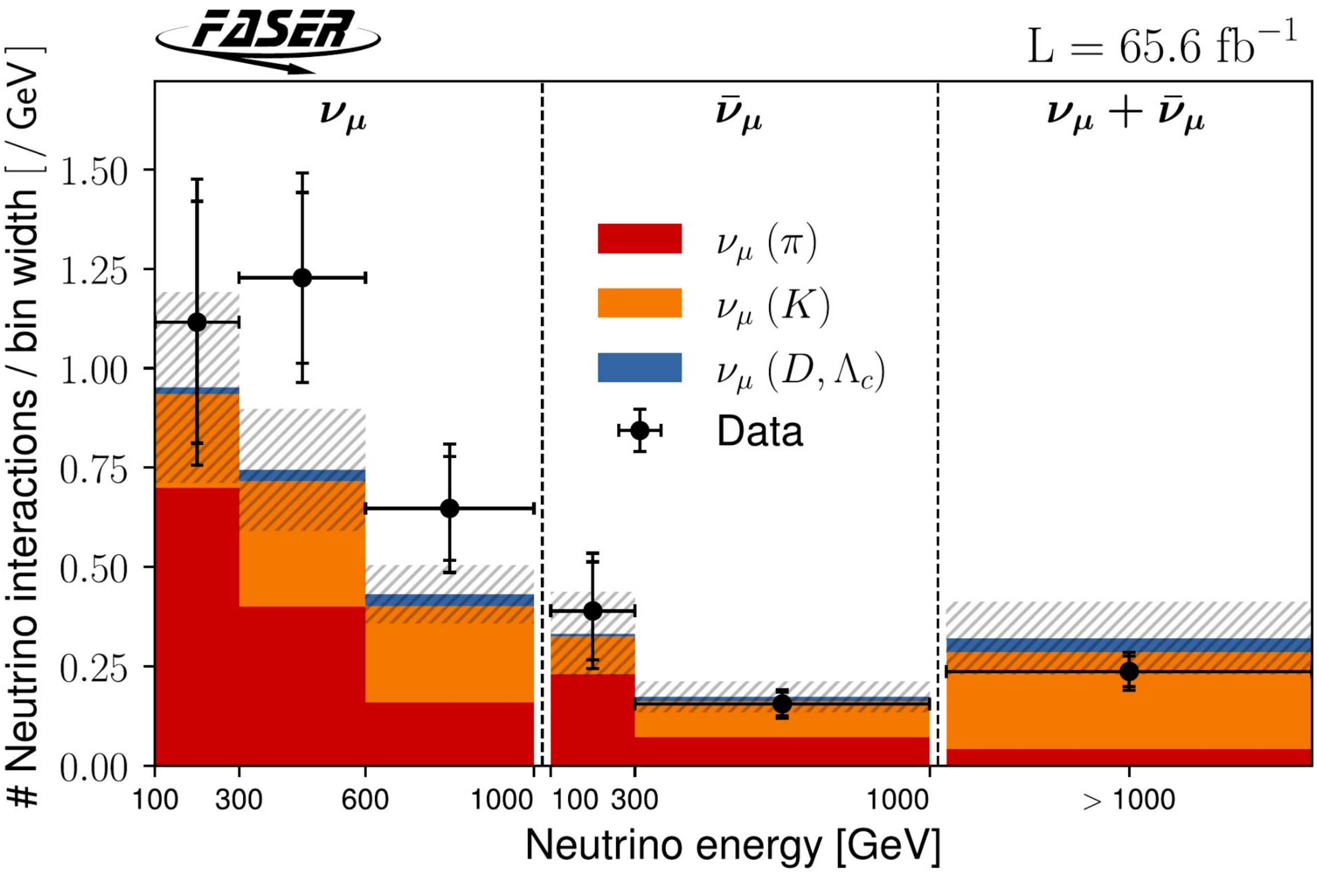




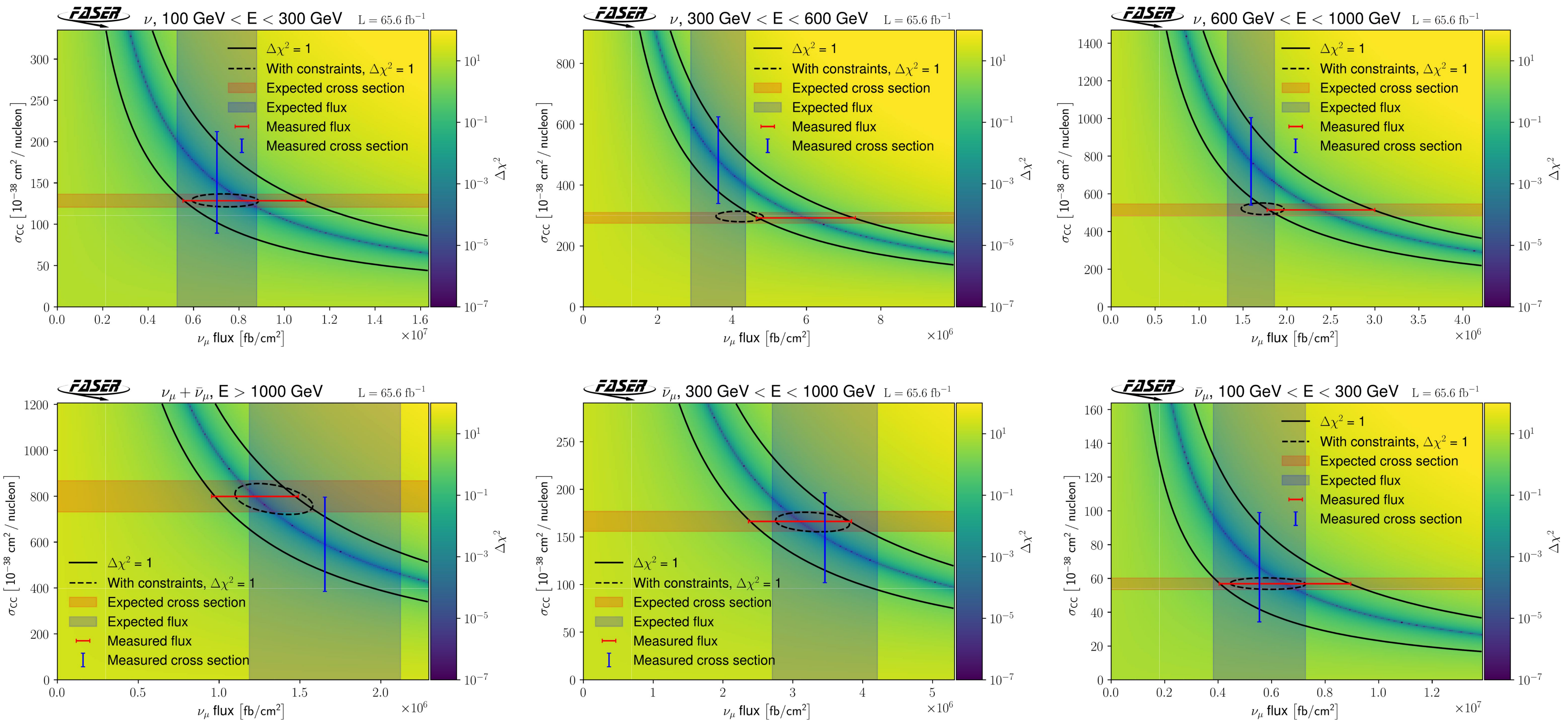
Electronic Neutrino Analysis – Observed Events



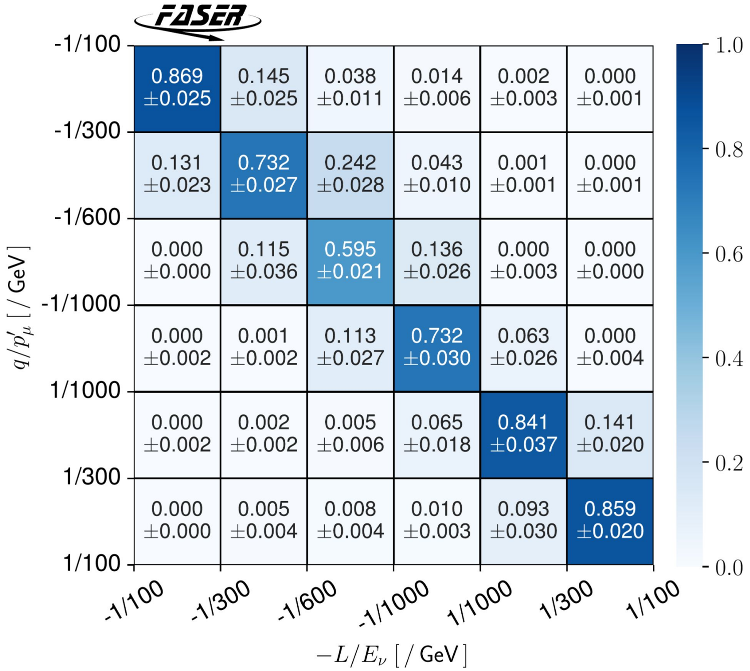
Electronic Neutrino Analysis – Neutrino Interactions



Combined flux and cross section fit



Unfolding

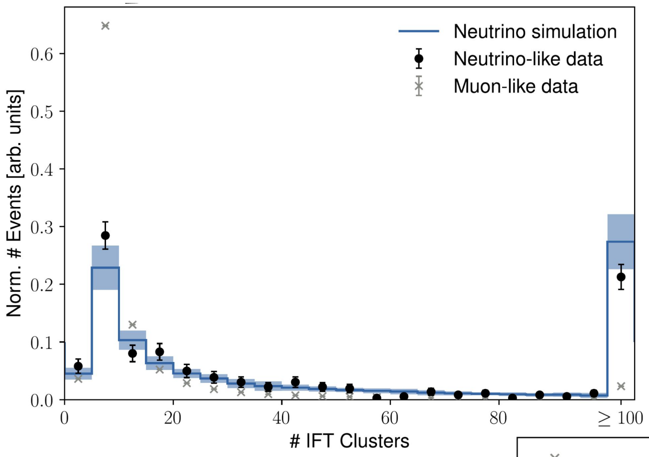


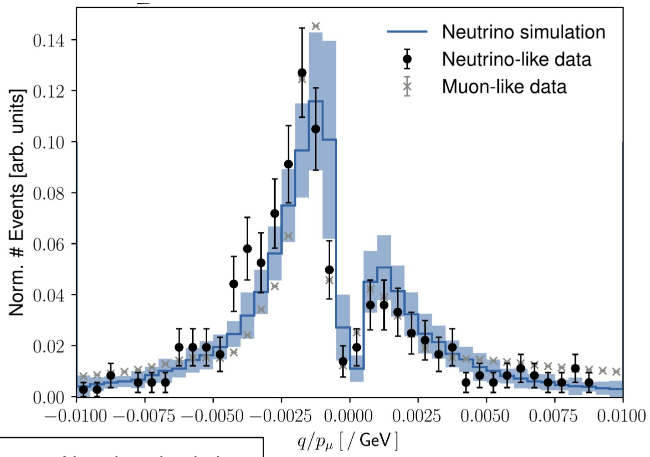
$$\mathcal{L} = \prod_i^{\text{bins}} \mathcal{P}(N_\mu^i | n_\mu^i) \times \prod_l \mathcal{G}_l$$

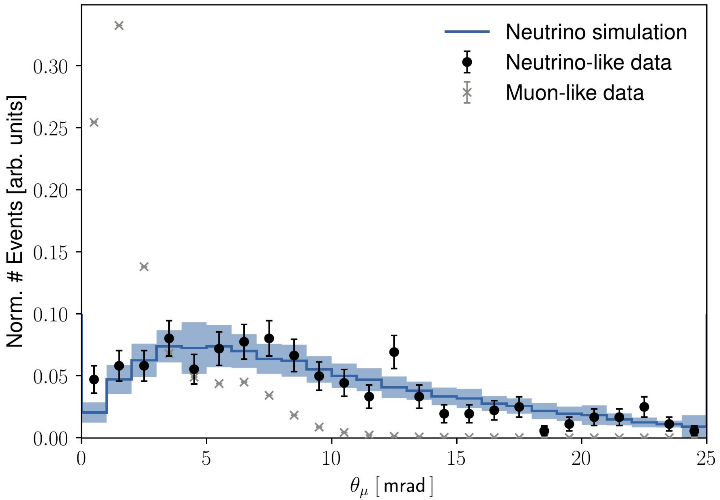
$$n_\mu^i = \sum_k M_{ik}\, \epsilon_k\, n_\nu^k + n_{\text{bkg}}^i$$

$-L/E_\nu$ $\left[\text{GeV}^{-1}\right]$	$\left[\frac{-1}{100}, \frac{-1}{300}\right]$	$\left[\frac{-1}{300}, \frac{-1}{600}\right]$	$\left[\frac{-1}{600}, \frac{-1}{1000}\right]$	$\left[\frac{-1}{1000}, \frac{1}{1000}\right]$	$\left[\frac{1}{1000}, \frac{1}{300}\right]$	$\left[\frac{1}{300}, \frac{1}{100}\right]$	Total
Acceptance α [%]	16.7 ± 0.6	30.0 ± 1.2	38.8 ± 2.6	46.6 ± 3.0	47.5 ± 1.9	27.8 ± 2.5	35.3 ± 2.0
Reco. efficiency $\epsilon_{\text{reco.}}$ [%]	80.8 ± 7.2	79.0 ± 4.9	79.3 ± 5.0	78.8 ± 5.5	84.4 ± 4.7	84.5 ± 6.9	80.3 ± 4.5
Efficiency $\epsilon = \alpha \cdot \epsilon_{\text{reco}}$ [%]	13.5 ± 1.2	23.7 ± 1.7	30.8 ± 2.6	36.8 ± 3.0	40.1 ± 3.1	23.5 ± 2.4	28.3 ± 1.9

Distribution of observed muons







Neutrino production modes

$$\chi^2 = (\vec{\nu} - \vec{n})^T \, \mathrm{Cov}^{-1} \, (\vec{\nu} - \vec{n}) + \mathcal{G}$$