FASER

Results from FASER:

Dark Photon and Collider Neutrino Studies

XX International Workshop on Neutrino Telescopes
October 2023

Savannah Shively on behalf of the FASER Collaboration

Supported by:

President's Pre-Professoriate Fellowship

The Nancy and Corwin Evans Award

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Overview

- Experiment description
- Dark Photon Search
  arXiv:2308.05587
- Direct detection of collider neutrinos with electronic detector
  arXiv:2303.14185
- Progress on collider neutrinos with emulsion detector
  CERN-FASER-CONF-2023-002
- Conclusions

The FASER Experiment

New, compact, efficient.

Fast Facts

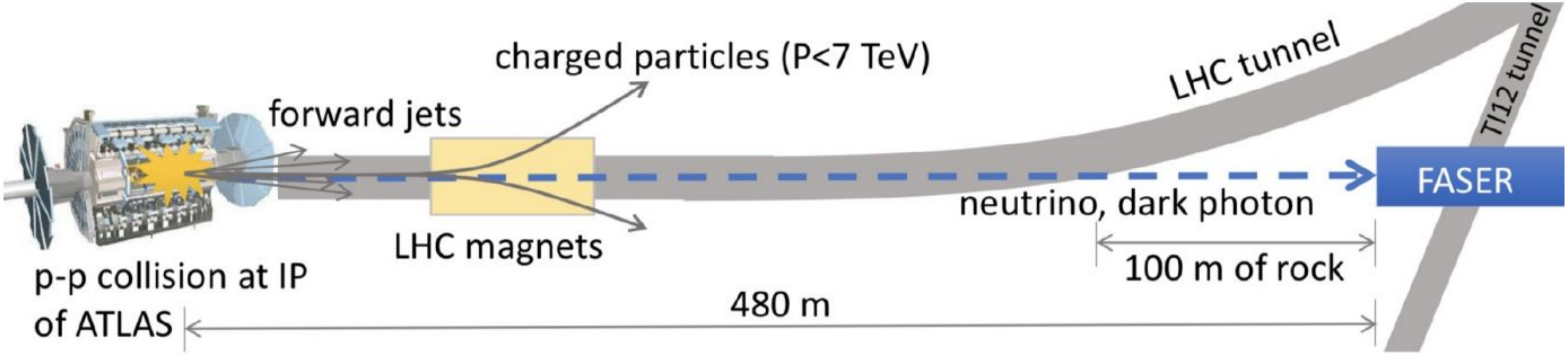
- Conceived in 2017
- Installation completed in 2021, ready for Run 3
- First physics results released this year

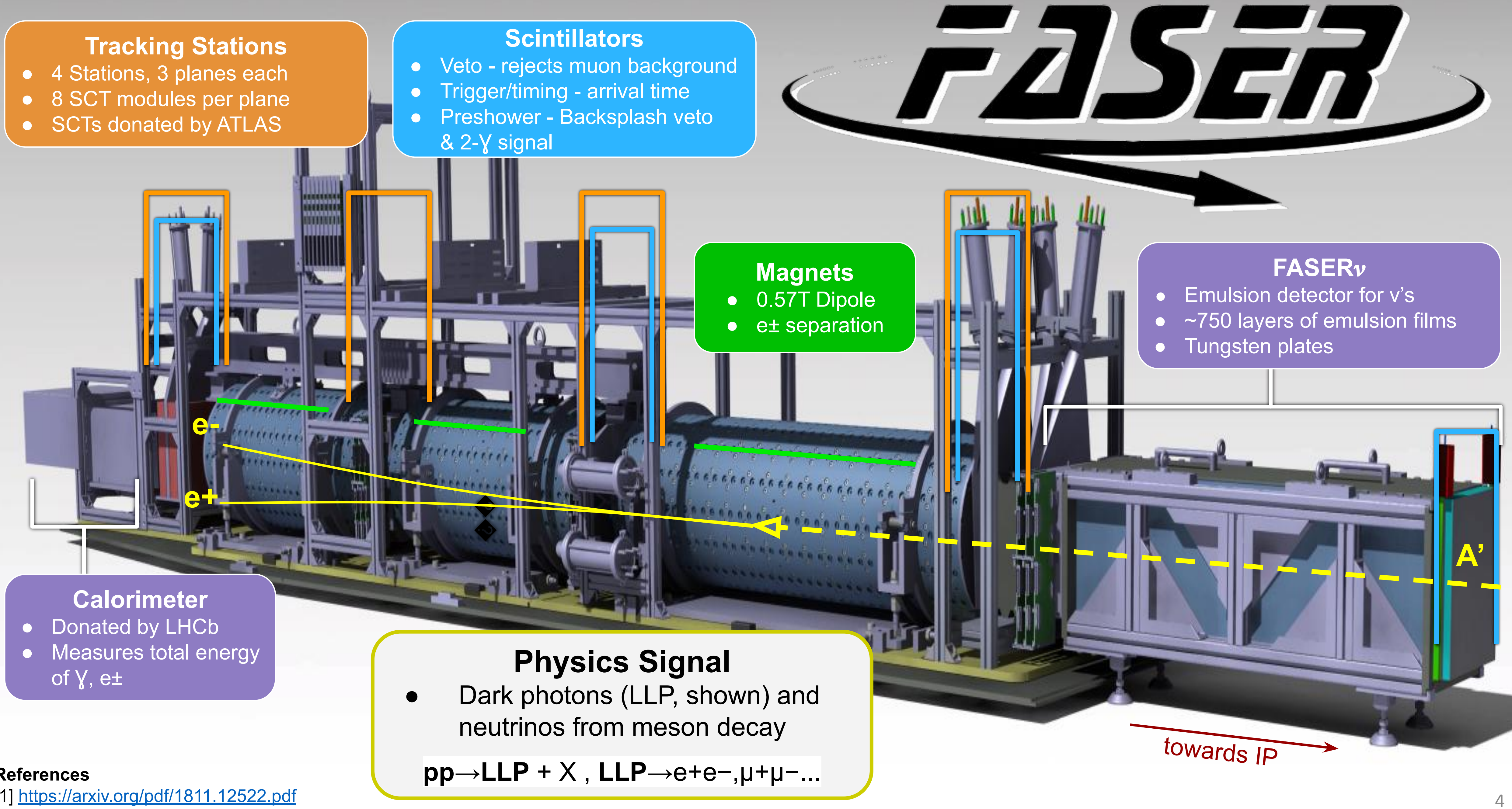
Physics Goals

- Low-mass and feebly-coupled particles
- Exploits high LHC collision rate + forward produced particles, which are highly collimated

Examples: **dark photons (A')**, axion-like particles, **neutrinos (ν)**, B-L gauge boson

Location





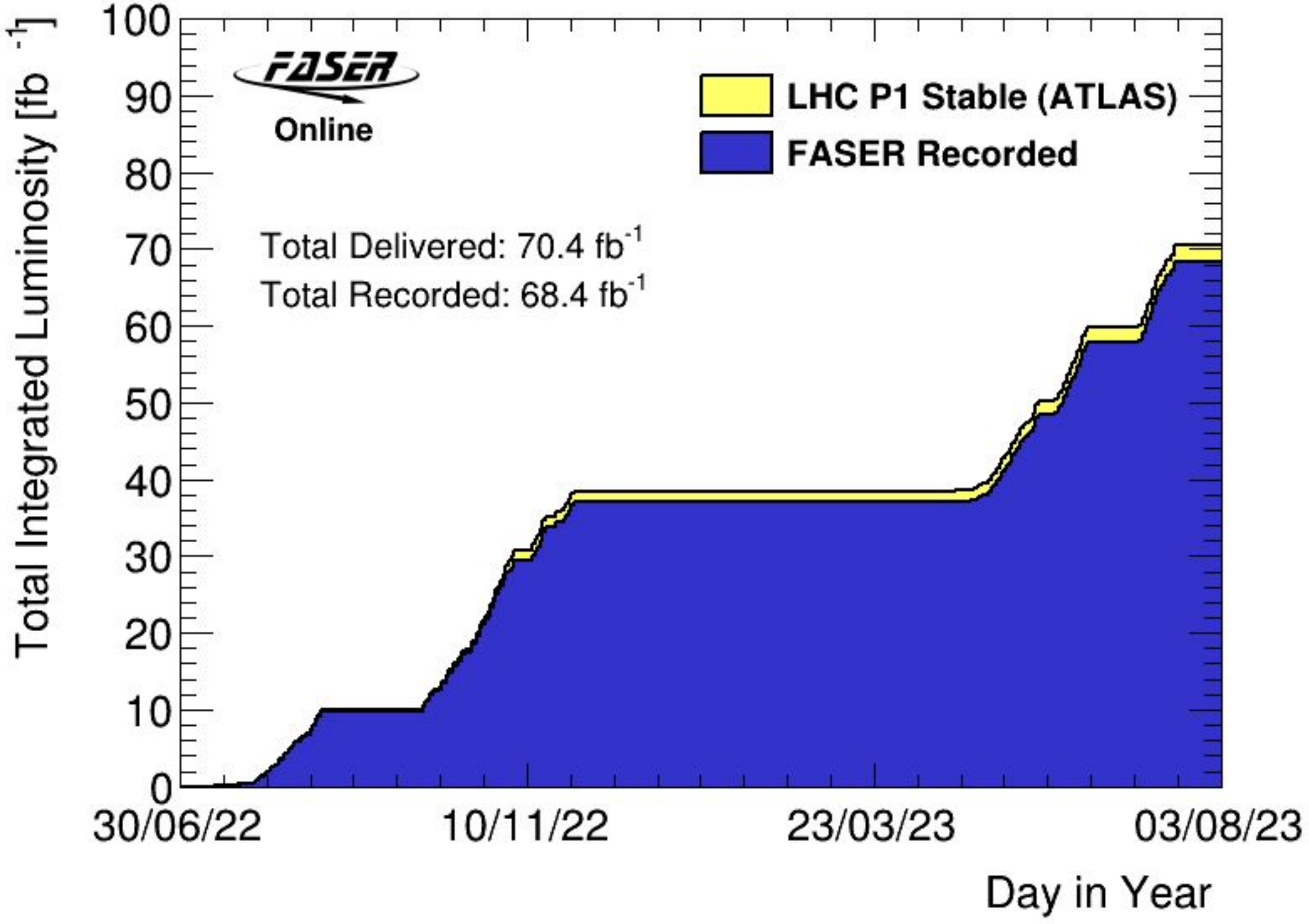
References

[1] https://arxiv.org/pdf/1811.12522.pdf

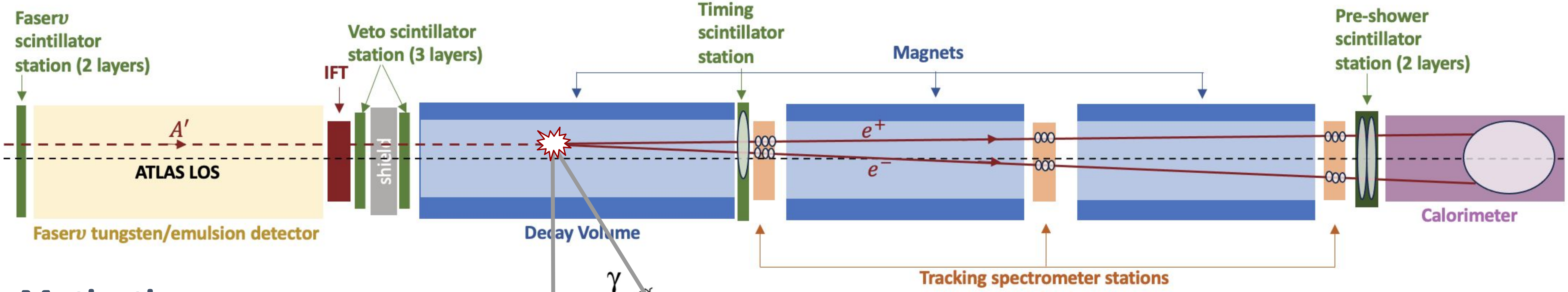
[2] https://arxiv.org/pdf/1812.09139.pdf

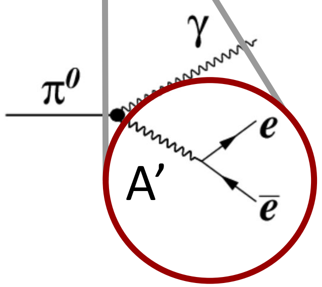
FASER and **LHC Run 3**

- Successfully took data **continuously** and mostly **automatically** during 2022.
- Recorded **97%** of the delivered luminosity
  - DAQ dead time of 1.3%
  - Other losses due to DAQ crashes
- Data acquisition ongoing in 2023 until yearly shut-down



Search for **Dark Photons**





$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f A'^{\mu} \bar{f} \gamma_\mu f$$

Motivation

- Common feature of hidden sector models
- Gauge boson mixing with SM photon

Production

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

The Signal

- Nothing in veto scintillators
- Evidence of two good tracks downstream from e+e-

Backgrounds

- Muons
- Neutrino interactions
- Cosmics
- Hadron-rock interactions

A’ Selection Criteria

- Collision event with good data quality
- **No signal** (<40 pC) in any of 5 **veto** scintillators
- **Timing and preshower scintillators** consistent with **2 MIPs**
- Exactly **2 good tracks** with **momentum > 20 GeV**
- Both tracks within fiducial tracking volume **r<95mm**
  - And extrapolate to front scintillators in the same region
- **Calorimeter** energy **> 500 GeV**
- **Signal efficiency ≈ 40%** across sensitivity parameter space
- Analysis was blinded for E>100 GeV events without any veto signals

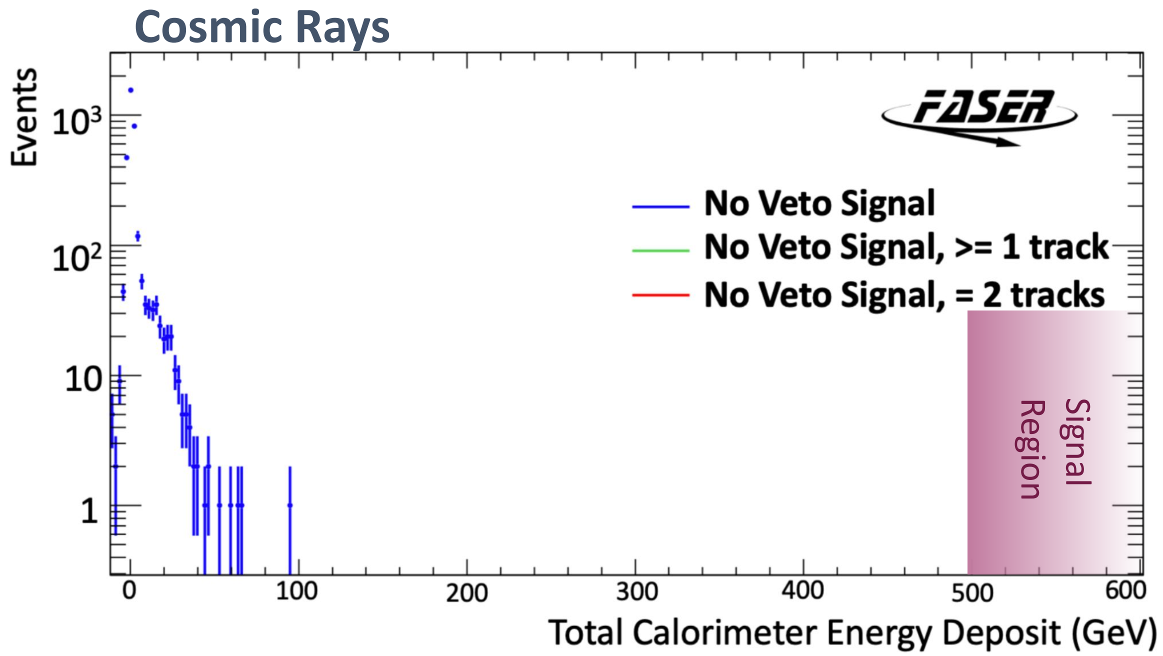
A' Background

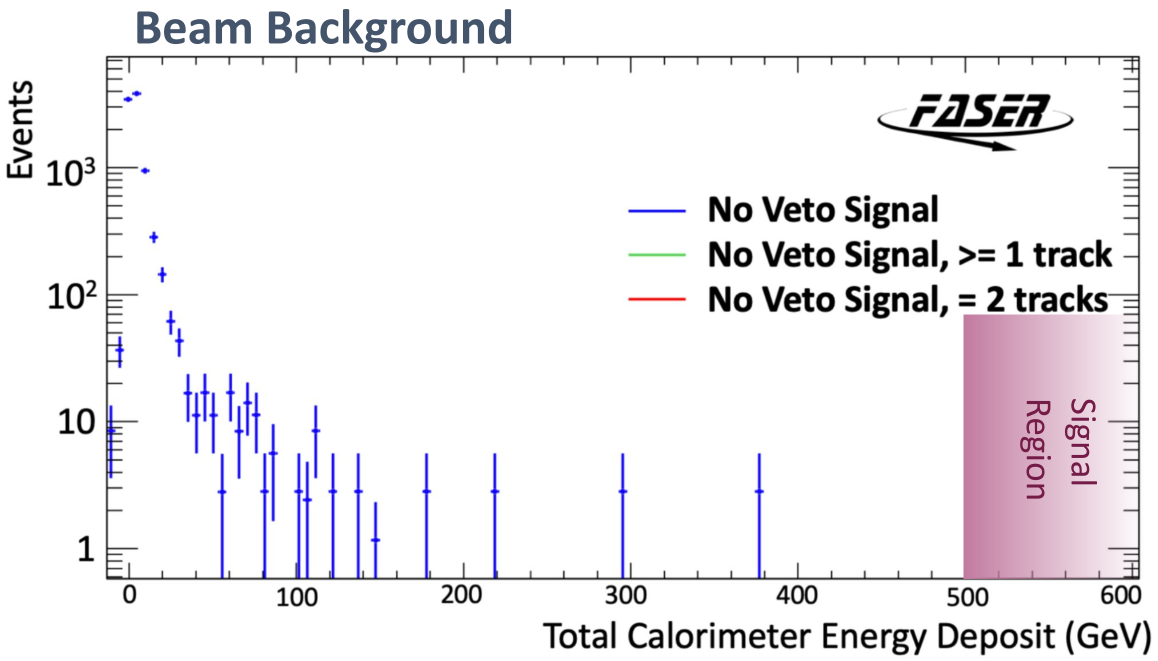
Veto inefficiency

- Measured layer-by-layer using muon tracks in spectrometer
- Layer inefficiencies uncorrelated
- *Completely negligible:* 10^{-12} expected for 10^{8} muons

Non-collision Backgrounds

- Cosmics measured during beam-down
- Beam debris from non-colliding bunches
- Both *negligible*
- **No events** seen with E>500 GeV **or** a reconstructed track





A' Background

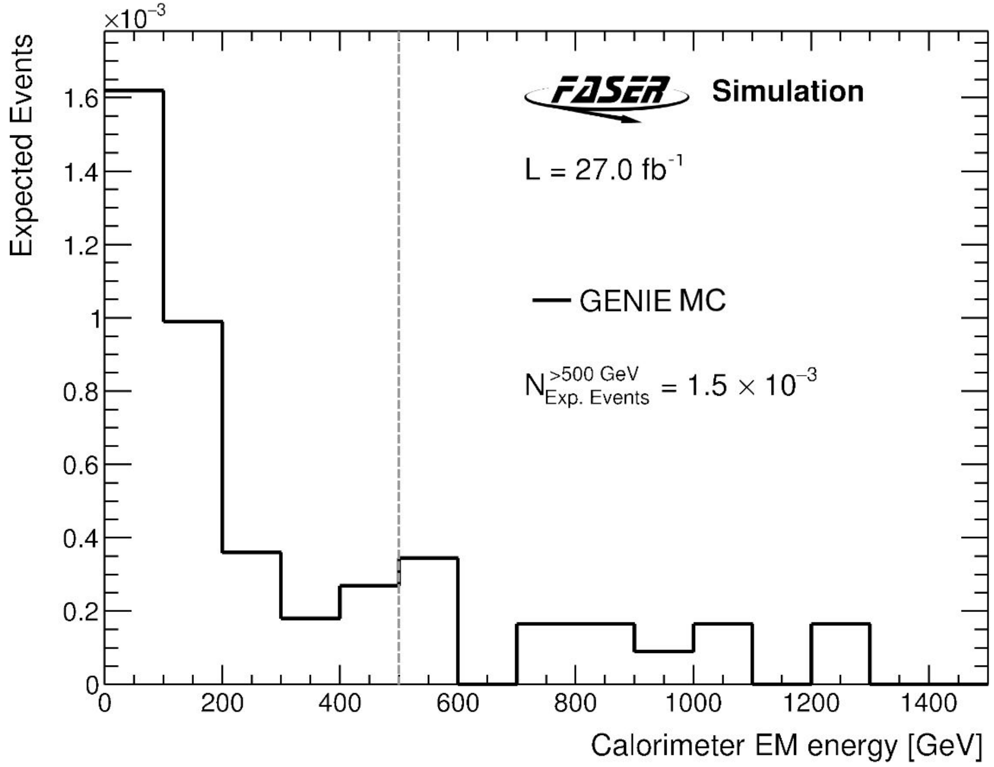
Neutral hadrons

- *Eg:* Muon-rock interactions
- Suppressed by muons triggering veto
  …And hadron energy loss in FASERν such that $E_{calo} < 500$GeV
- Estimated using lower energy events with 2-3 tracks and different veto conditions
- $(0.8 \pm 1.2) \times 10^{-3}$ events

Neutrino interactions

- Using GENIE generator (300 ab^{-1})
- Uncertainties from mismodelling and differences between DPMJET and SIBYLL
- $(1.5 \pm 2.0) \times 10^{-3}$ events
- **Dominant background!**

Simulated Neutrino Background Events

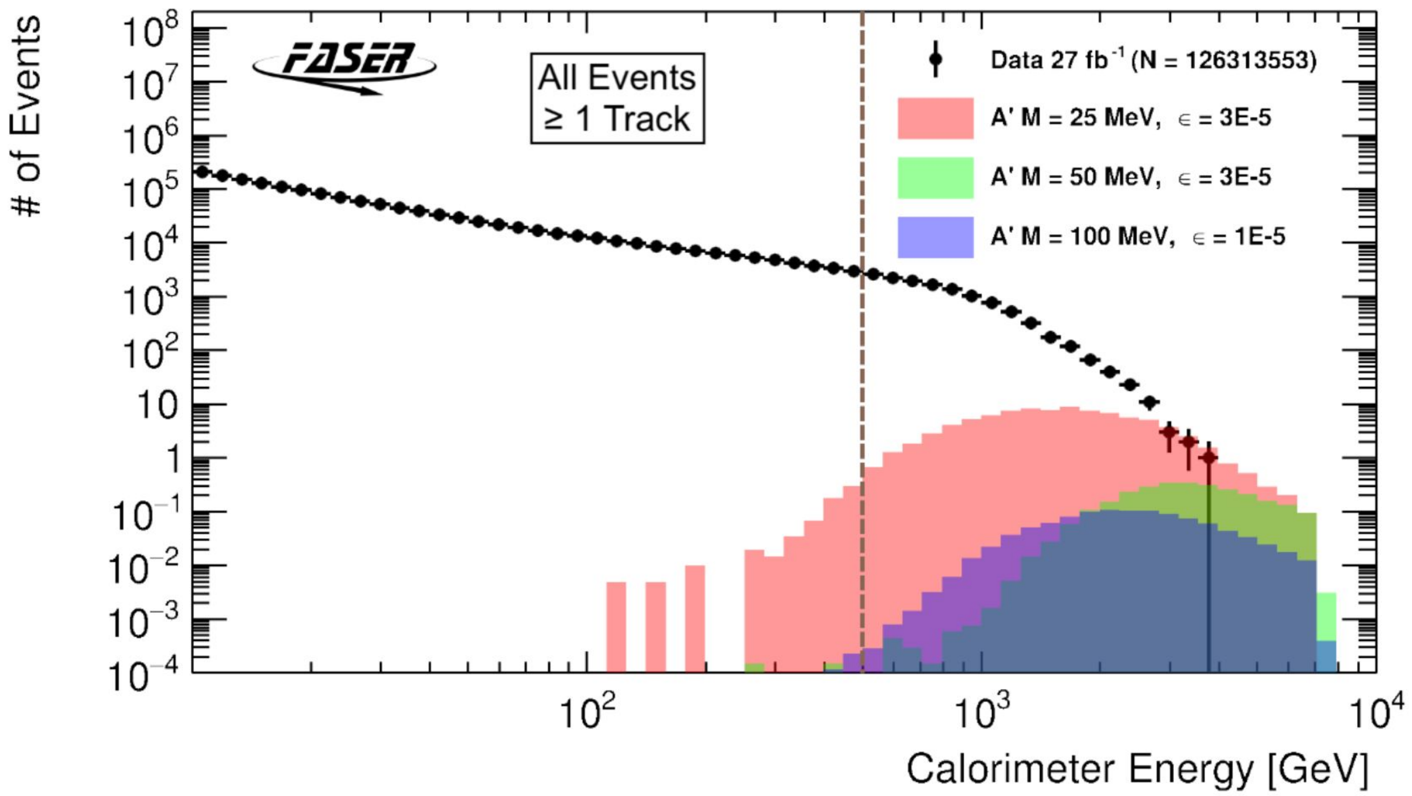


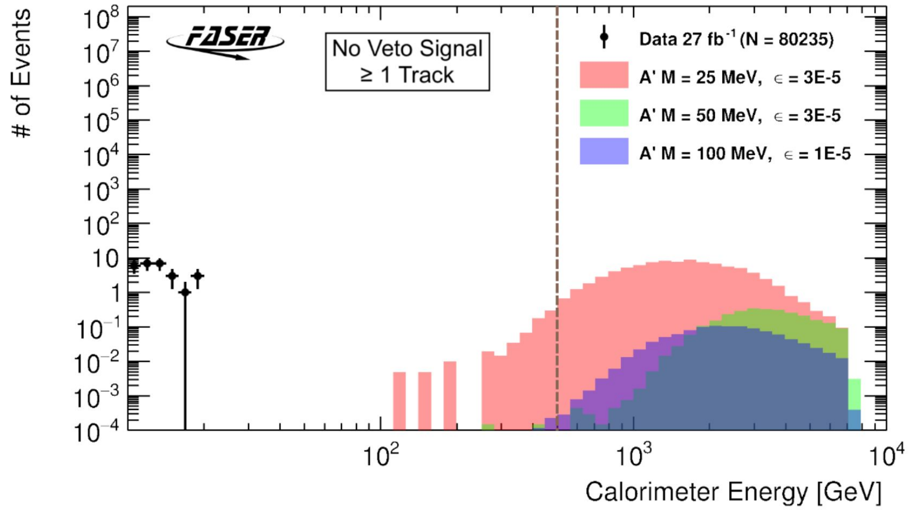
Total background:

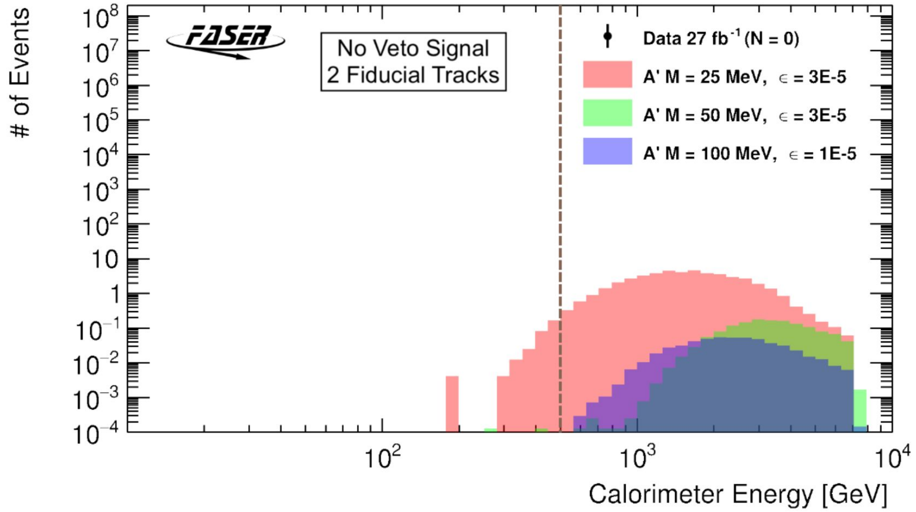
0.0023±0.0023 events

FASER Dark Photon Results

No events seen in unblinded signal region.

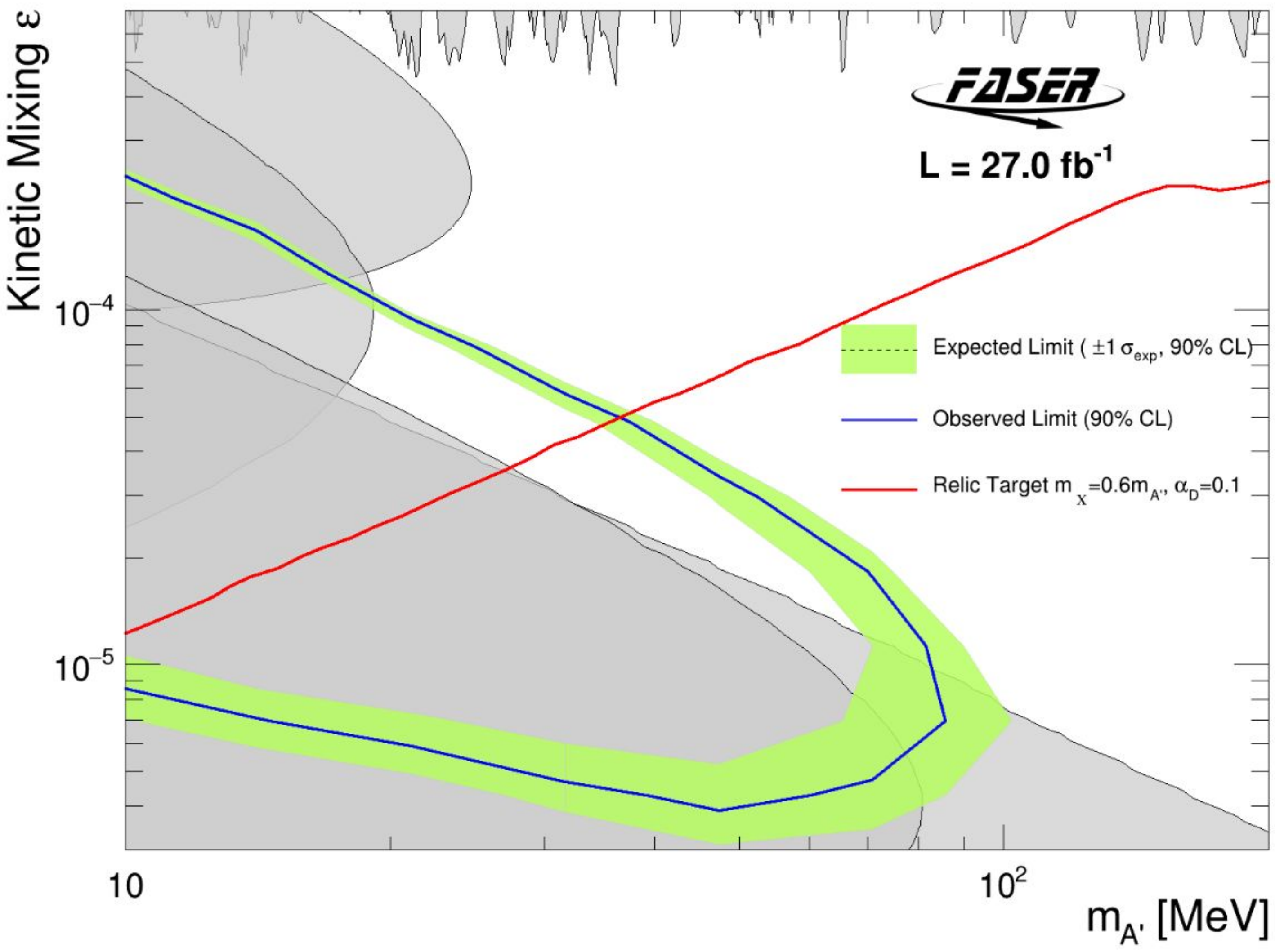






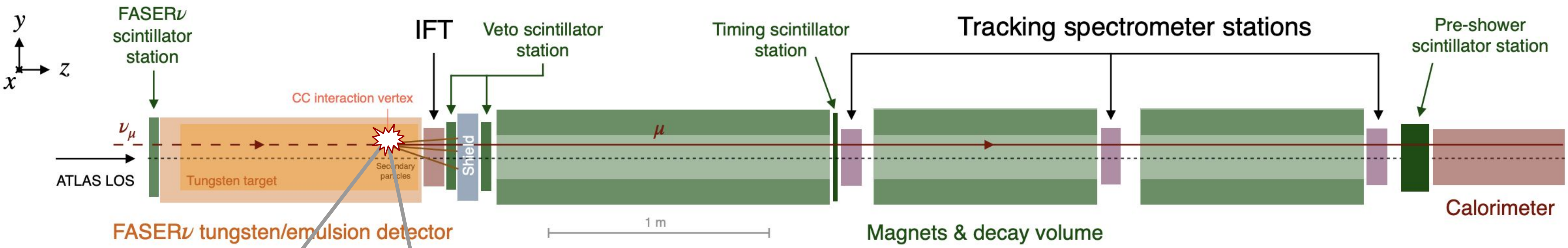
FASER Dark Photon Results

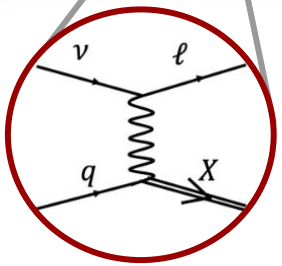
- Null result sets new limits on parameter space
- Exclusion extended into dark-matter-motivated region
- Background-free analysis is a good sign for sensitivity
- Total **250 fb^{-1}** expected in Run 3



Wait, isn’t this a neutrino conference?

*Electronic** Search for **Neutrinos**





Production

- Primarily forward hadron decay
- ν_μ from pion decay

Motivation

- Collider neutrinos never directly observed before
- Complimentary to other experiments

The Signal

- Nothing in FASERν veto
- One muon downstream from shield

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

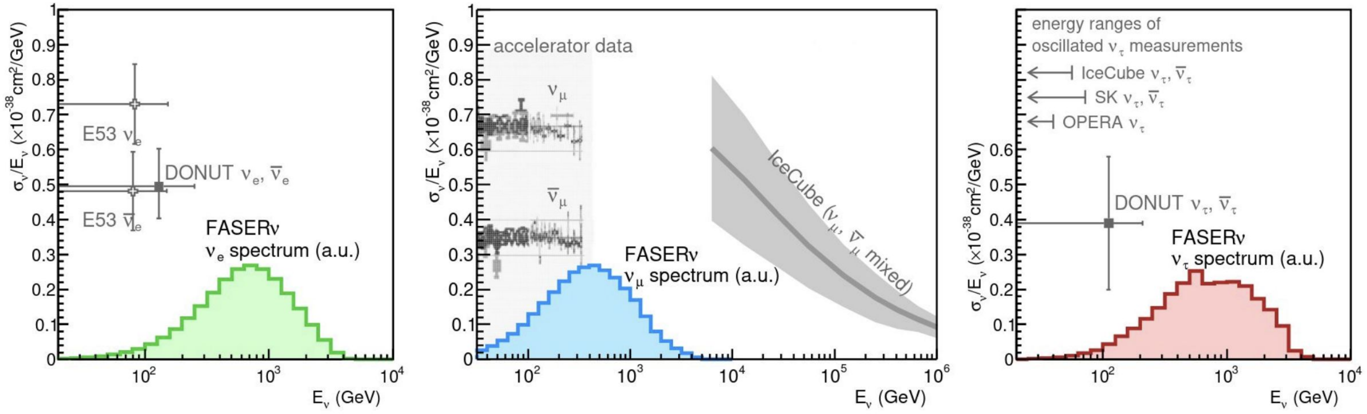
Backgrounds

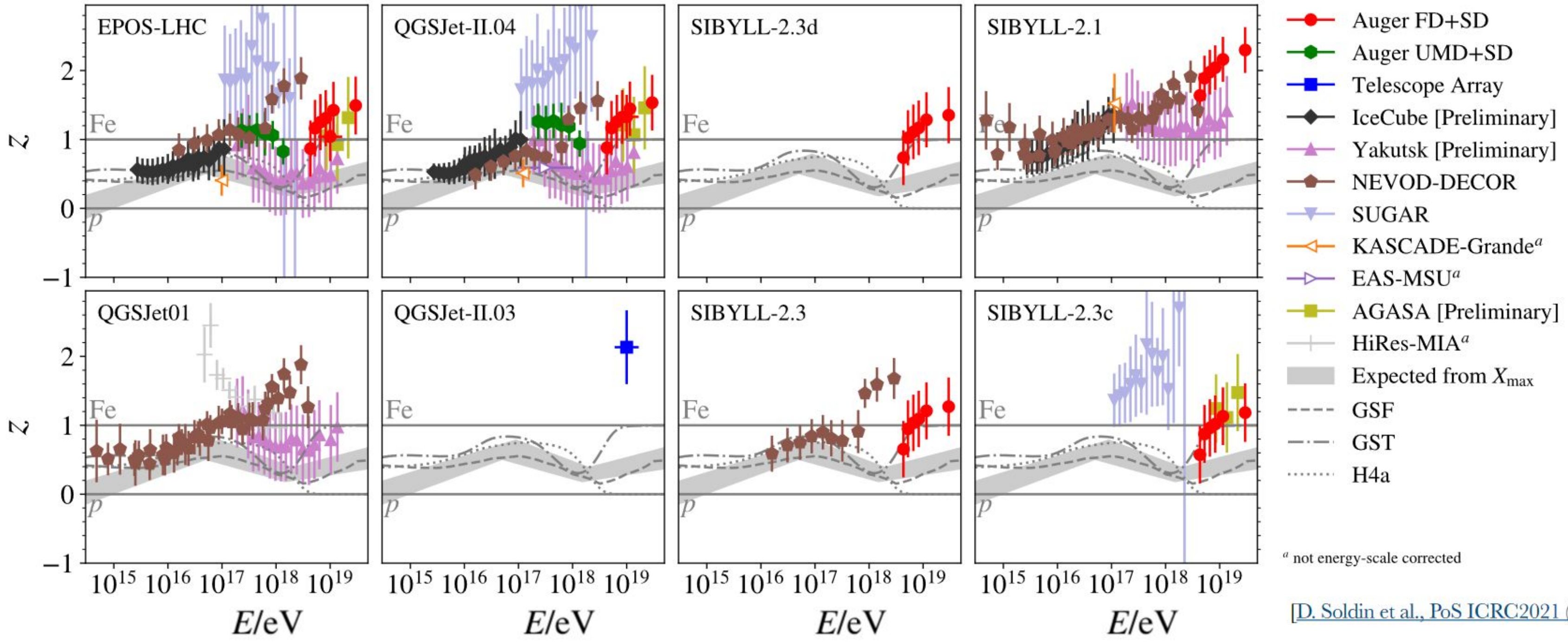
- Veto inefficiency
- Neutral hadrons
- Scattered muons

*Using FASERν as a target with scintillators and trackers as detectors; emulsion not used in this analysis

Additional Neutrino Motivation

- There are anomalies in neutrino and muon telescope data (IceCube)
- Collisions in LHC are comparable to cosmic showers in energy and products in the forward direction
- FASER and FASERnu can start measuring neutrino flux, with even more data to be collected with future LHC installations such as Forward Physics Facility (FPF)





[D. Soldin et al., PoS ICRC2021 (2021) 349]

- Telescope data suggests high energy composition higher than iron!

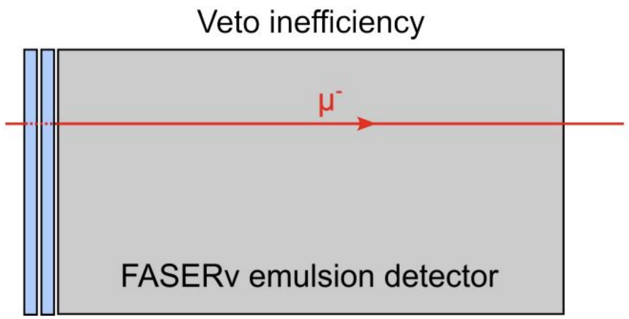
Neutrino Selection Criteria

- Collision event timing and good data quality
- **No signal** (<40 pC) in **front** (FASERν) veto **scintillators**
- Signal consistent with **1 muon in downstream scintillators**
- Exactly **1 good track** (fiducial)
    - extrapolated track must pass through central region of front veto
- Track momentum > 100 GeV
- Goal is **definitive observation**

Neutrino Background & Uncertainty

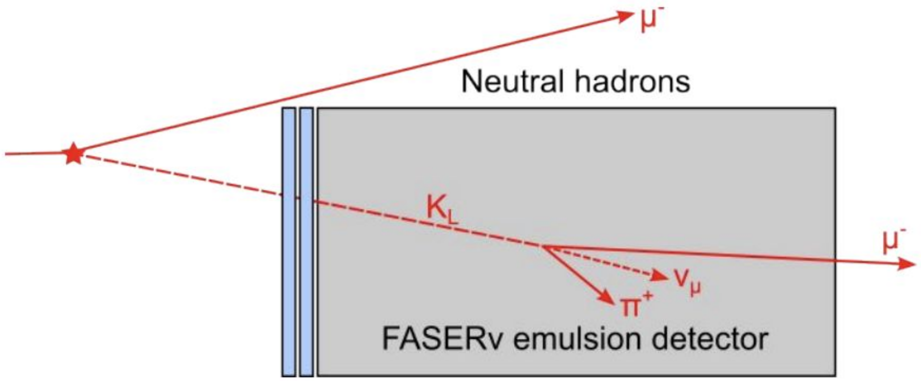
Veto inefficiency

- Estimated from events with only one veto scintillator firing
- Expect (3.7 ± 2.5) × 10^{-7} events



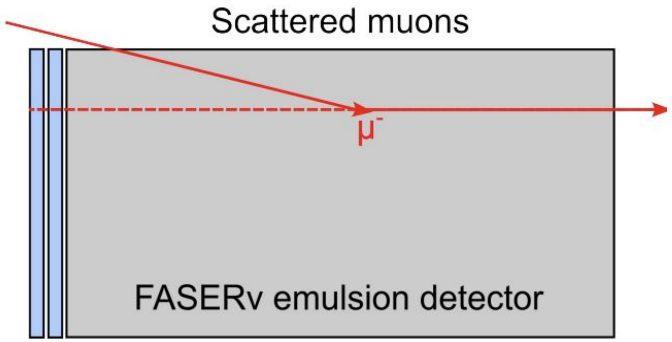
Neutral hadrons

- Expect O(300) neutral hadrons with E > 100 GeV
- Most absorbed in tungsten
- Expect 0.11 ± 0.06 events



Scattered muons

- Estimated from control region near edge of magnet aperture with few tracker interactions
- Expect 0.08 ± 1.83 events



Total background:

0.2±1.8 events

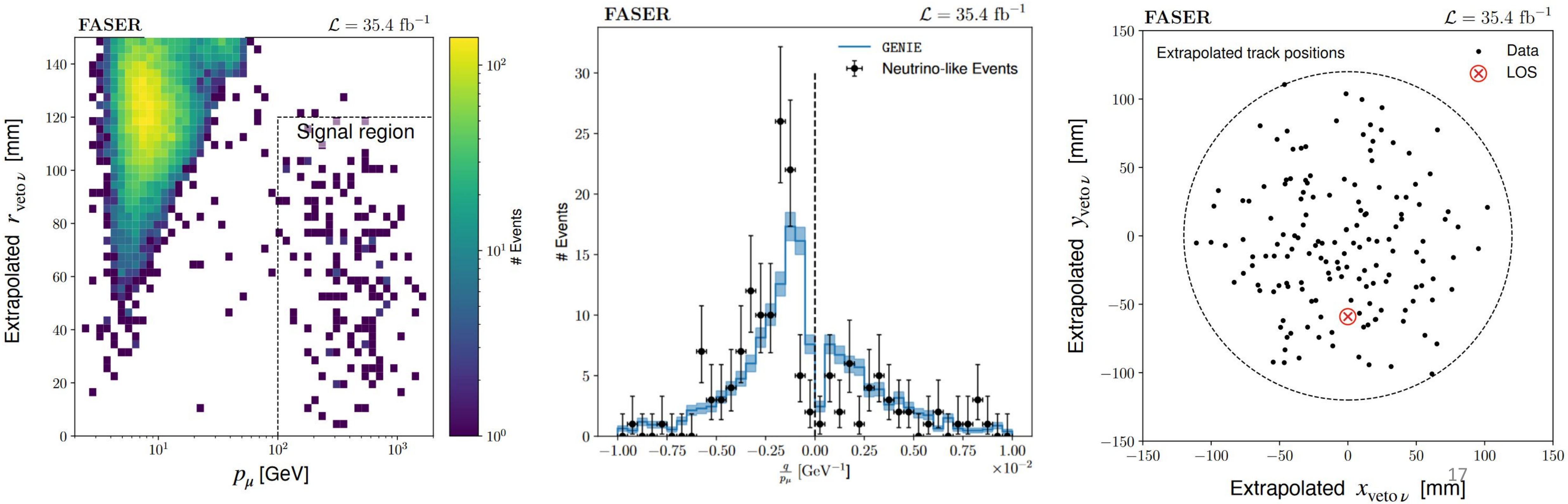
First Direct Observation of Collider Neutrinos

Based on Genie simulation, *expected 151 ± 41** neutrino events.

153 events observed with **16σ** significance!

* Uncertainty from 27% difference in average of the neutrino flux modeled by DPMJET and SIBYLL

- Selected neutrinos are high energy (>200 GeV)
- ν_μ/anti-ν_μ consistent with expectations
- Final analysis presented at Moriond 2023



FASERν

Detector

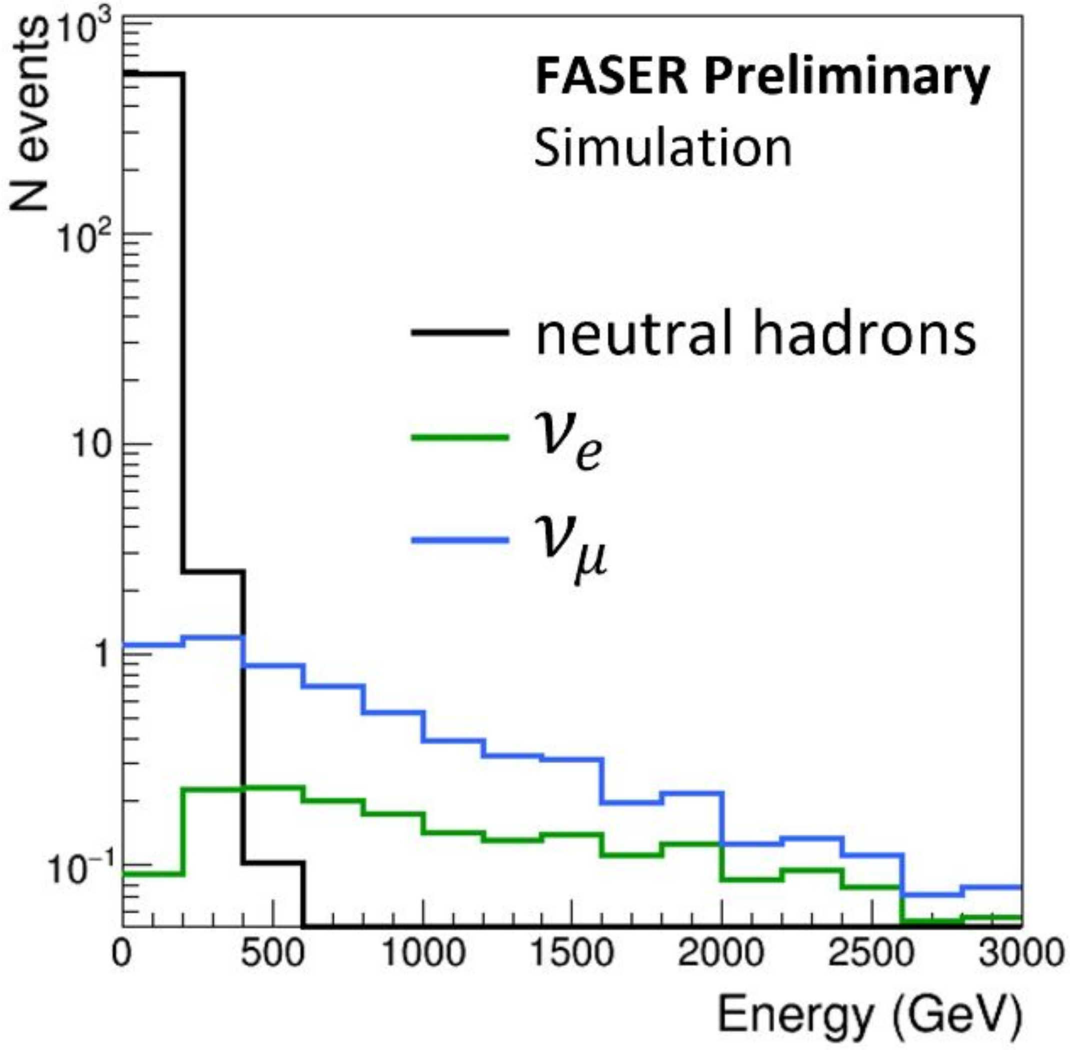
- Emulsion film & tungsten plates
- Film must be exchanged to avoid oversaturation of events
- Film must be developed prior to analysis; long workflow

Physics

- **Expect 29.4** ± 5.0 (ν_μ) and **11.8** ± 7.5 (ν_e) charged current (CC) neutrino interactions before selection
- Select vertices with associated lepton candidate (e or μ) and E>200 GeV

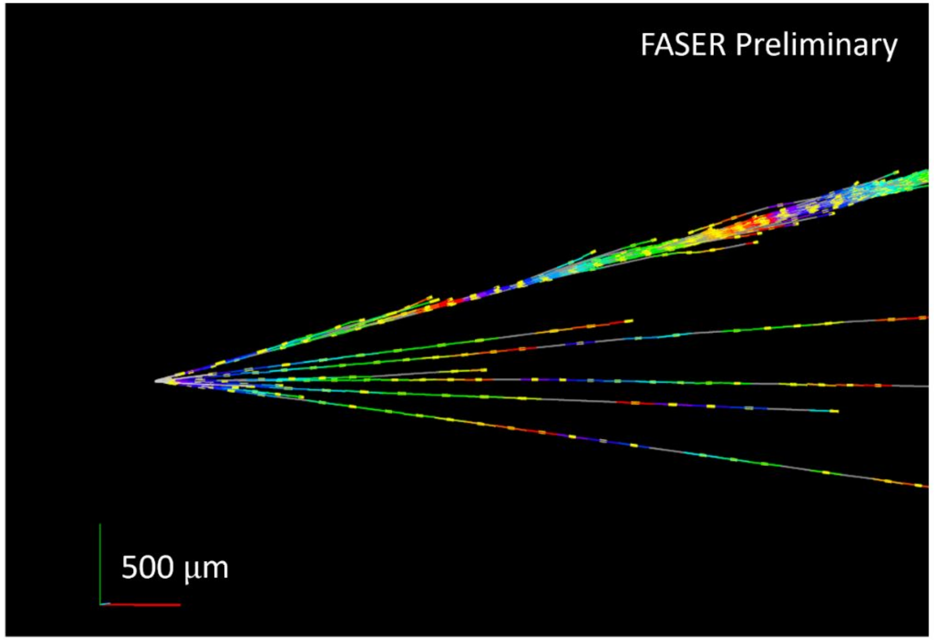
Background

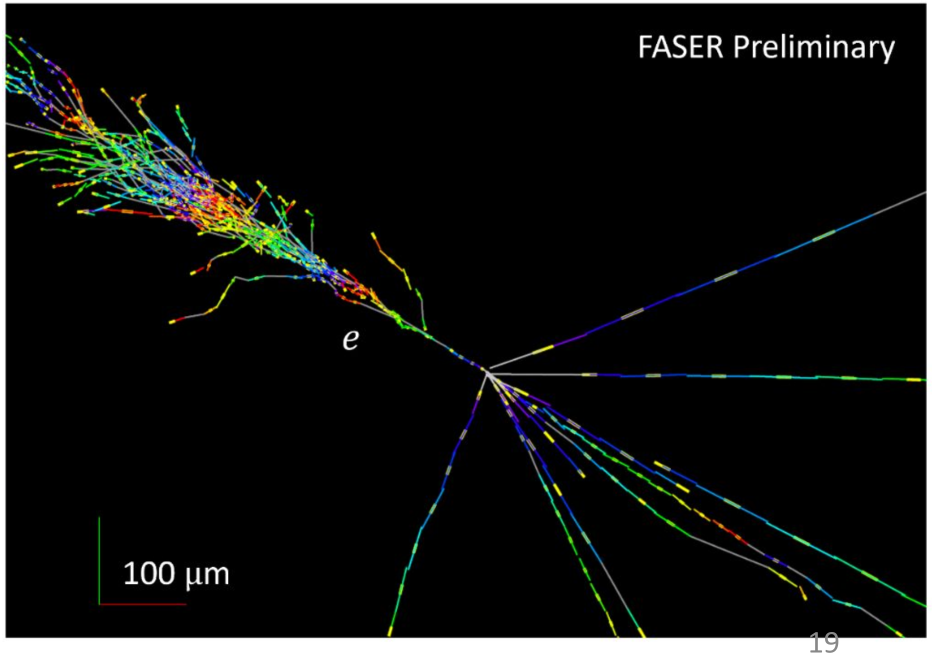
- Neutral hadron background; low-momentum signal
- High energy muons



FASERν First Physics

- First analysis includes 150 of 730 plates
  - 68kg target mass for this analysis
- **9.5 fb^{-1}** of LHC proton collision data
- Preliminary results: [CERN-FASER-CONF-2023-002]()
- **Expected 0.6–5.2** (ν_e CC) and 3.0–8.6 (ν_μ CC) passing selection
- **Observed 3 ν_e** vertices (5σ), and **4 ν_μ** vertices (2.5 σ)
- First direct observation of collider *electron* neutrinos!

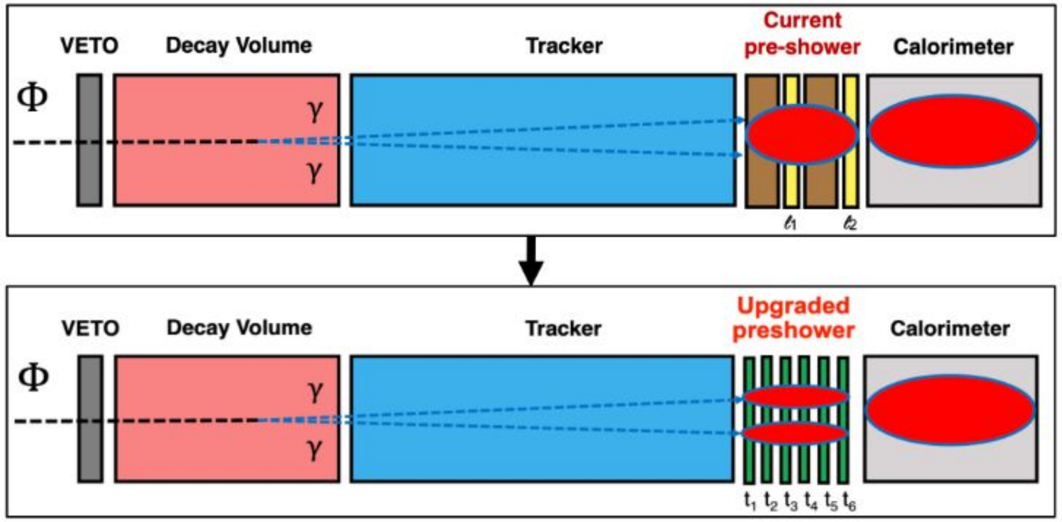




The Next Fase(r)

Preshower Upgrade

- More transverse information
- Beneficial for 2-photon signals, such as ALP searches
- Installation planned for YETS 24/25
  Technical proposal



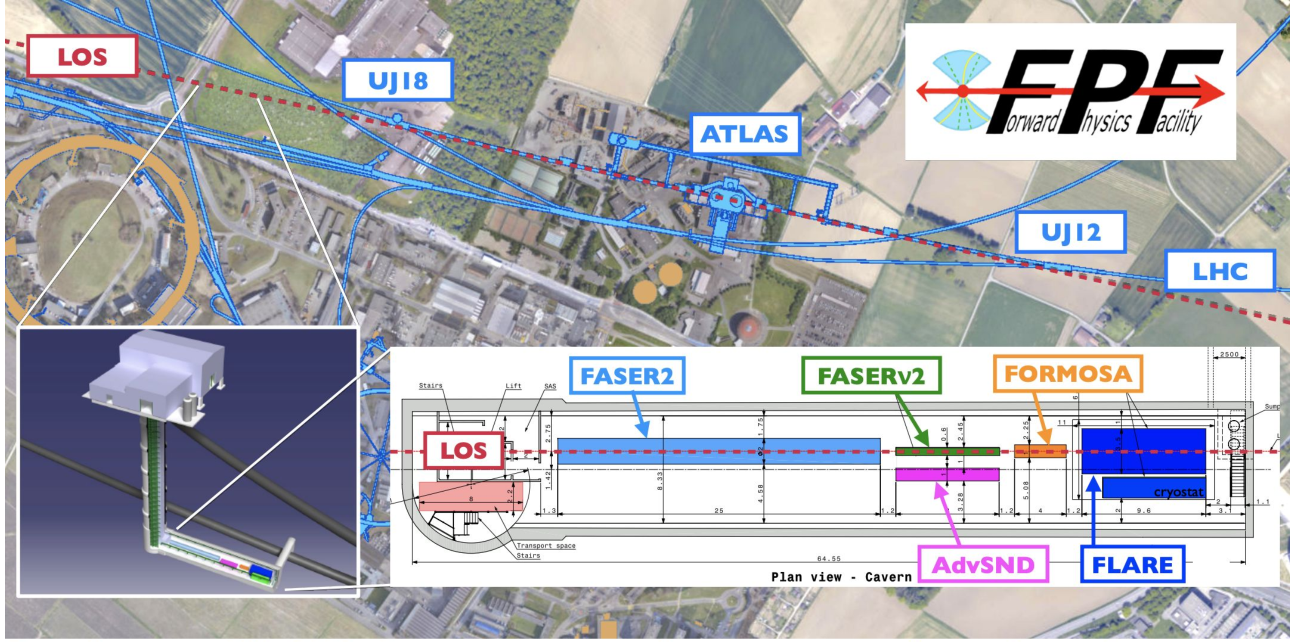
Run 3 and Beyond

- Expect to collect 250 fb^{-1} in Run 3
- Excellent performance so far therefore…
- Begun request process to continue operations after LS3
- Potentially succeeded by FASER2/FASERv2 in the planned Forward Physics Facility (FPF) during the HL-LHC era

Forward Physics Facility

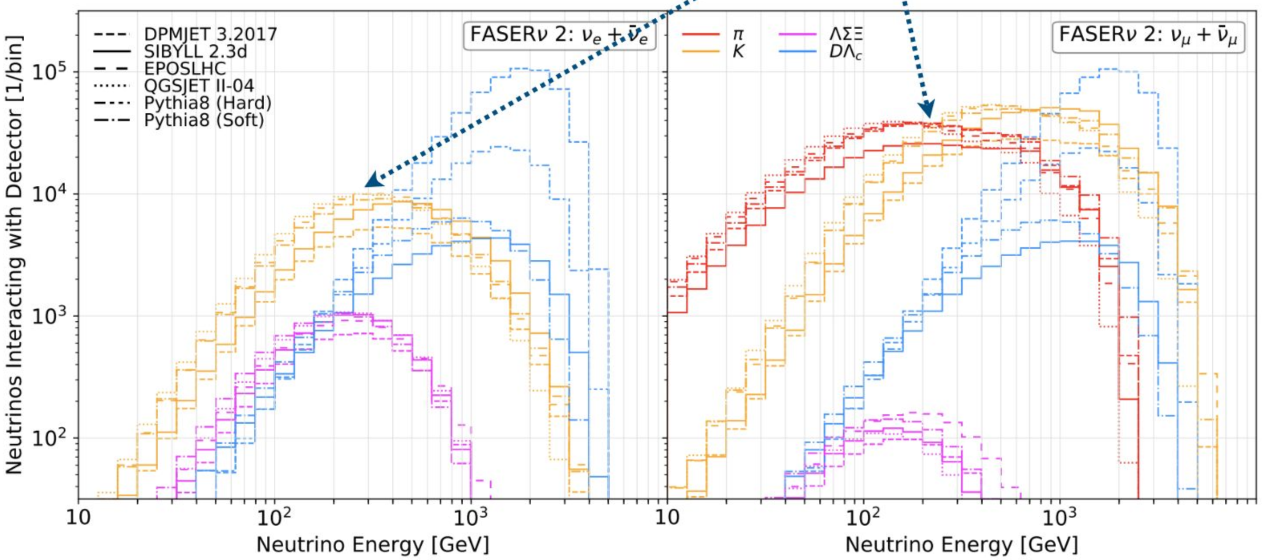
- Continues far forward studies of FASER in collaboration with other forward-probing experiments
- Each addition searches for different phenomenon
  - INCLUDING neutrinos!
- Muon and neutrino results will help clarify telescope data

FPF white paper



low energy region relevant!

FASERν2 Neutrino Fluxes



* Simulation code available at: https://github.com/KlingFelix/FastNeutrinoFluxSimulation, see also https://arxiv.org/abs/2105.08270

Summary

FASER Generally

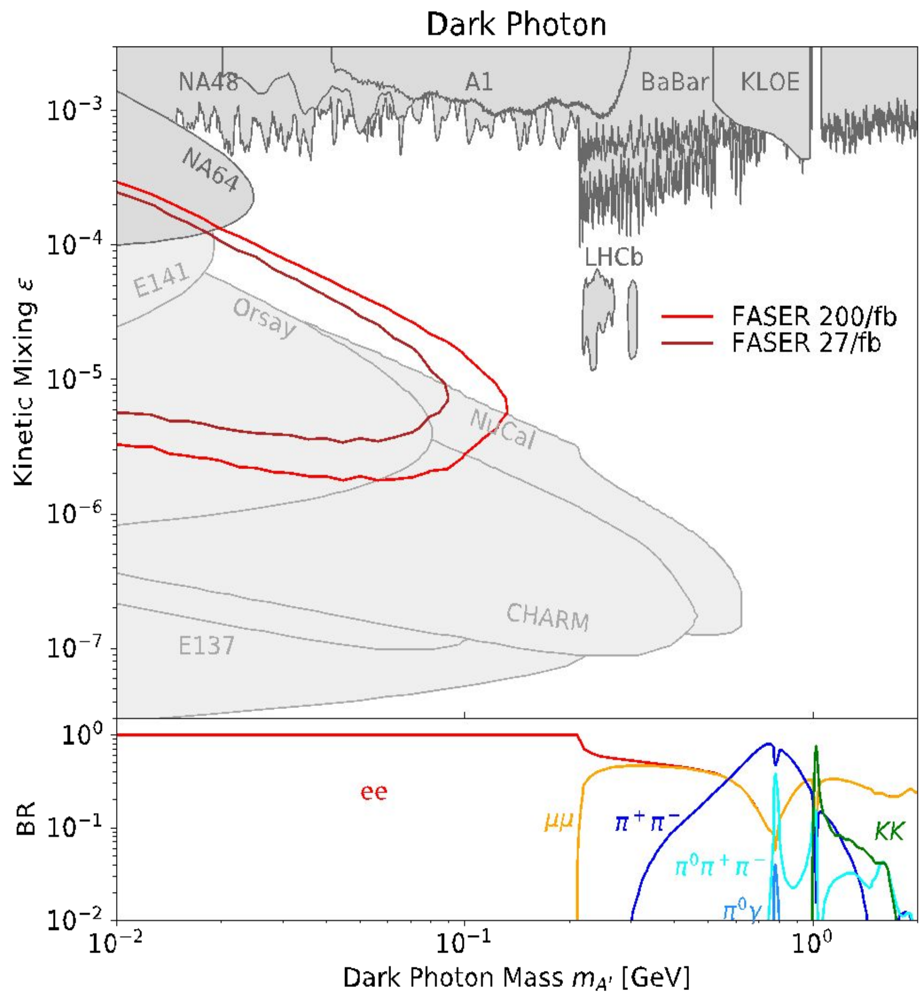
- Full lifecycle from conception to publication in under 6 years
- Taking data a year ahead of Run 3
- Upgrade to preshower planned for next year to enhance ALP search
- Next generation - FASER2 - planned for FPF

Dark Photons

- First analysis on 2022 data complete and submitted for publication
- Excluded new region of parameter space including Dark Matter relic-motivated region with 90% confidence level
- Search continues with new Run 3 data

Neutrinos

- FASERnu allows two avenues of analysis - electronic and emulsion
- Electronic analysis observed first collider neutrinos ever (muon neutrinos)
- Emulsion observed first collider electron-neutrinos
- Electronic analysis published this year with emulsion analysis note publicly available



Simulation made with FORESEE https://arxiv.org/abs/2105.07077

Publications

Dark Photon Search

- First results presented at Moriond in March 2023
- Results submitted to Physics Letters B

Electronic Neutrino Studies

- First results also presented at Moriond this year
- Results published in Phys.Rev.Lett. 131 (2023)

Emulsion Neutrino Studies

- Analysis ongoing
- Preliminary results: CERN-FASER-CONF-2023-002

Conferences

- 28 presentations this year and counting!

All FASER Publications

Thank you!

from FASER Collaboration Meeting #5, 2023

FASER COLLABORATION

87 members from 24 institutions and 10 countries

FASER Management

Spokespersons: Jonathan Feng (UC Irvine), Jamie Boyd (CERN)

Collaboration Board Chair: Matthias Schott (Mainz)

Executive Board: Akitaka Ariga (Chiba), Carl Gwilliam (Liverpool), Anna Sfyrla (Geneve), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Claire Antel (Geneve), Dave Casper (UC Irvine), Frank Raphael Cadoux (Geneve), Tomoko Ariga (Kyushu), Lorenzo Paolozzi (CERN)

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Administrative support for the collaboration is provided by Veronique Wedlake from the CERN, EP Secretariat.

FASER INSTITUTIONS

87 collaborators, 24 institutions, 10 countries

CERN

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KYUSHU UNIVERSITY

UC IRVINE

UNIVERSITÄT BERN

Technion Israel Institute of Technology

NAGOYA UNIVERSITY

UNIVERSITY of WASHINGTON

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מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

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UNIVERSITÄT BONN

INFN

清華大學 Tsinghua University

MANCHESTER 1824 The University of Manchester

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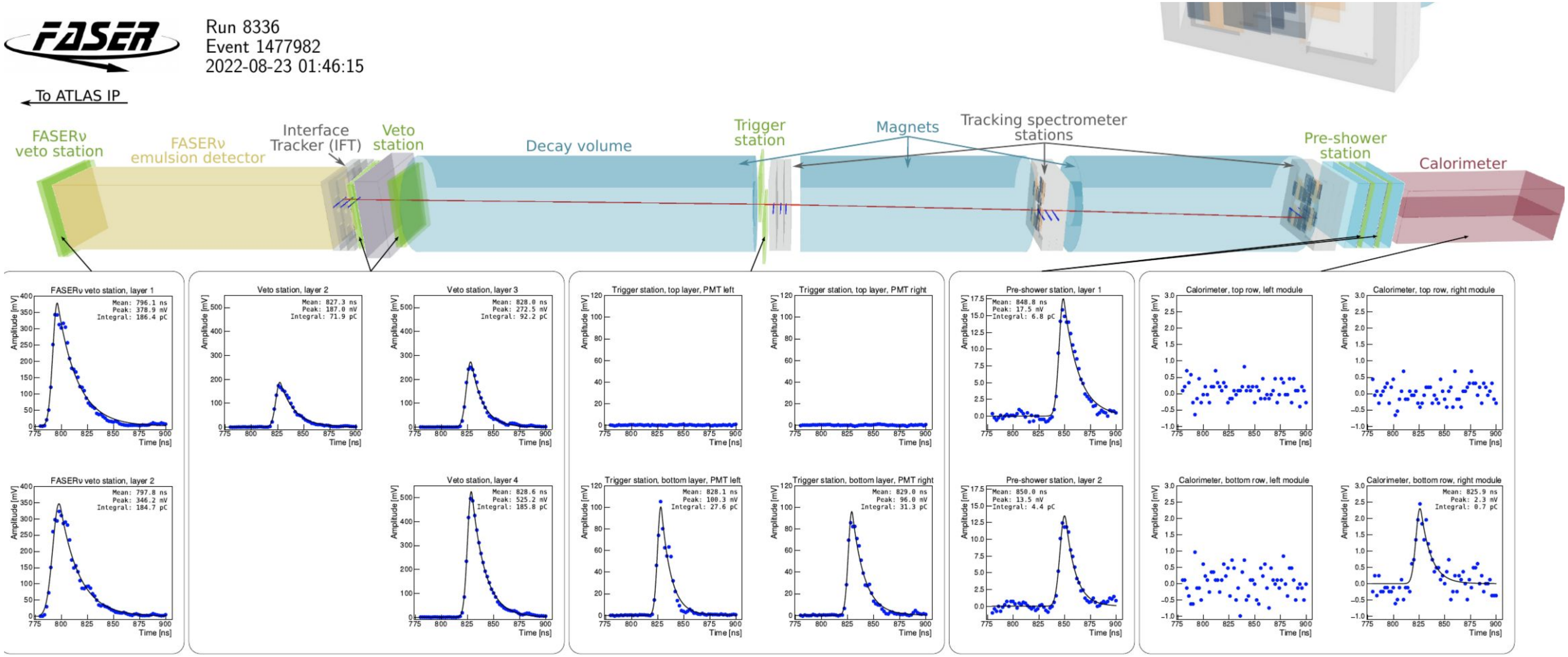
Backup Slides

Example Event - Complete Muon Track



Dark Photons – Systematic Uncertainties

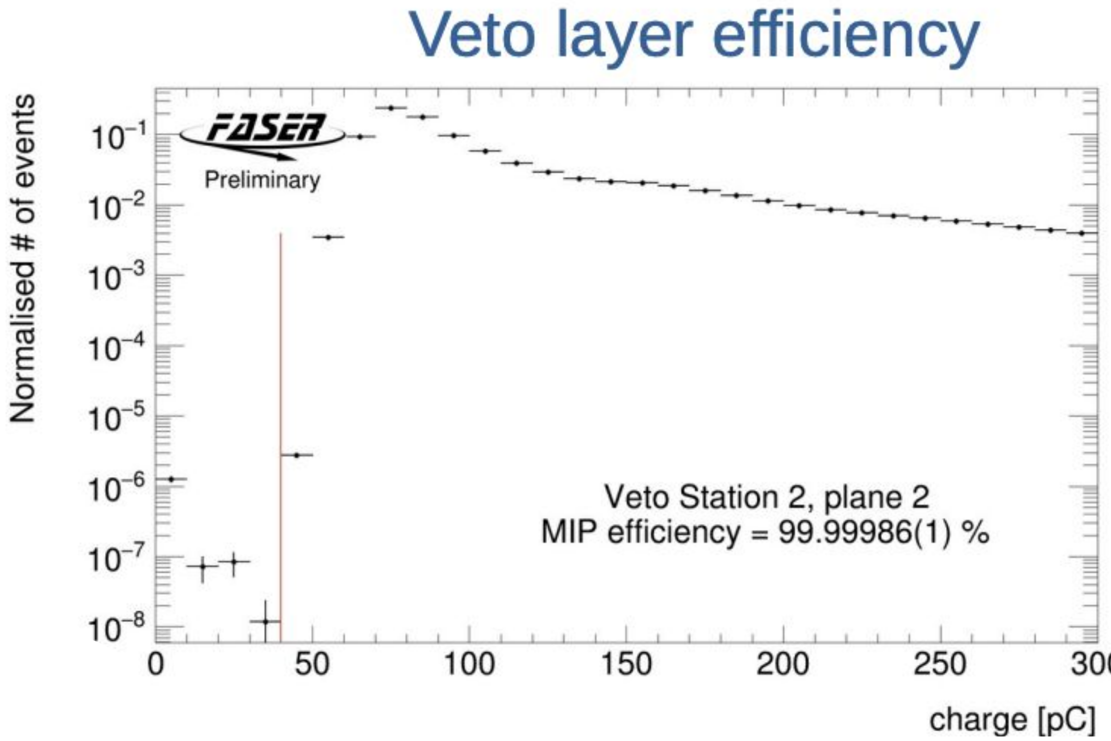
Complete list of systematic uncertainties and their impact on the signal yield

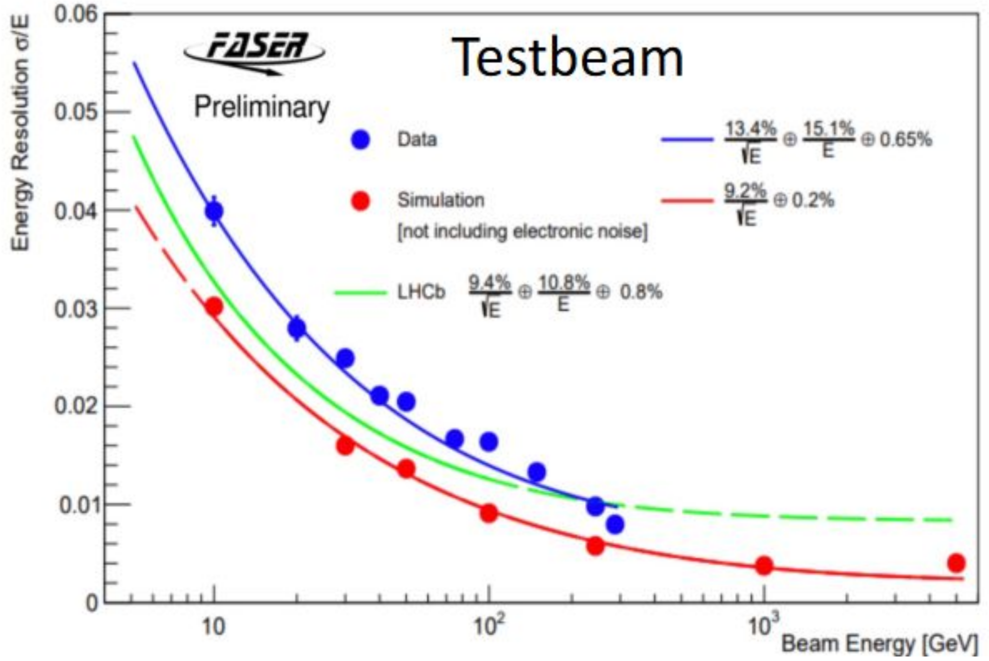
Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	$< 0.5\%$
Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	15%	15%
Calorimetry		
Calo E scale	6%	0-8% ($< 1\%$)

Veto and Calo Performance

- Veto *single*-layer scintillator efficiency >**99.998%**
- With five Veto layers, 10^8 muons produce negligible background before other selections.

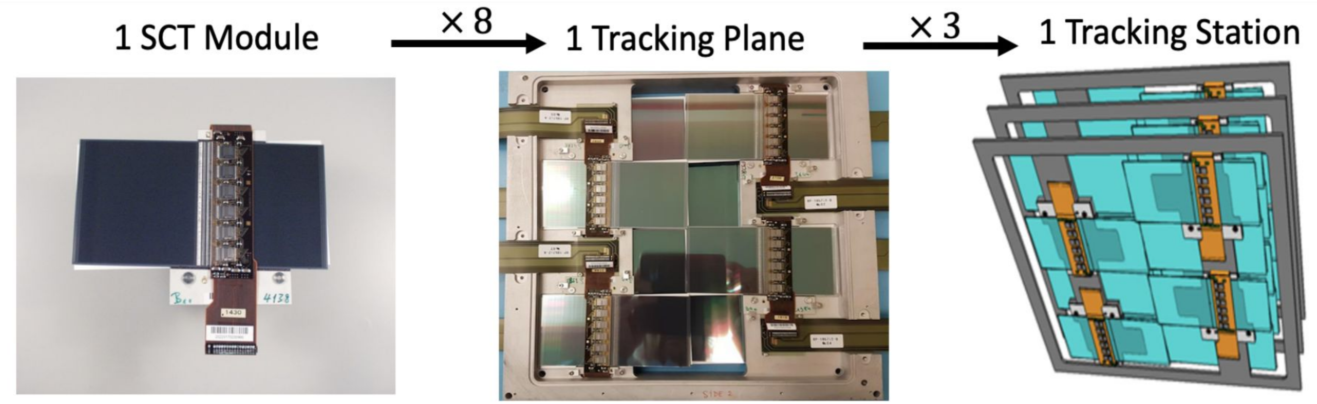
- Calorimeter energy resolution for high energy electrons in SPS testbeam ~1%
- Calo energy scale uncertainty of 6% derived from testbeam.

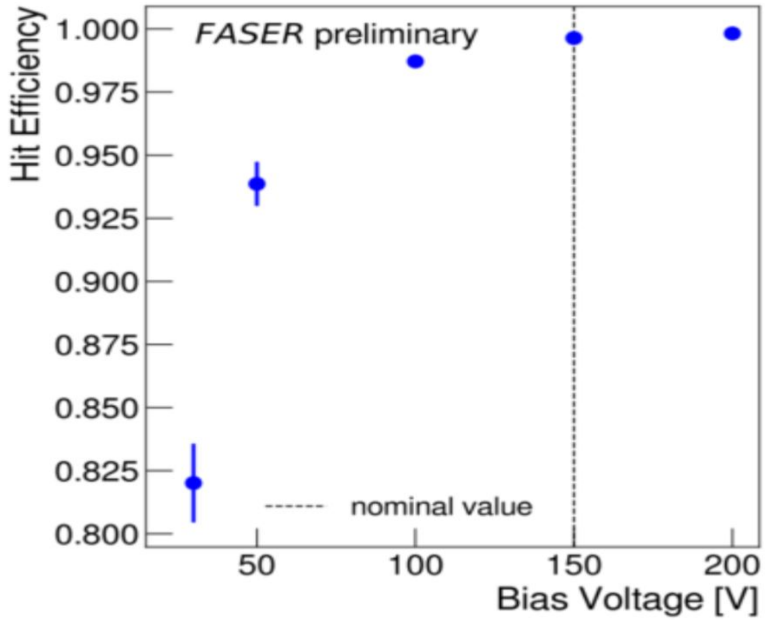


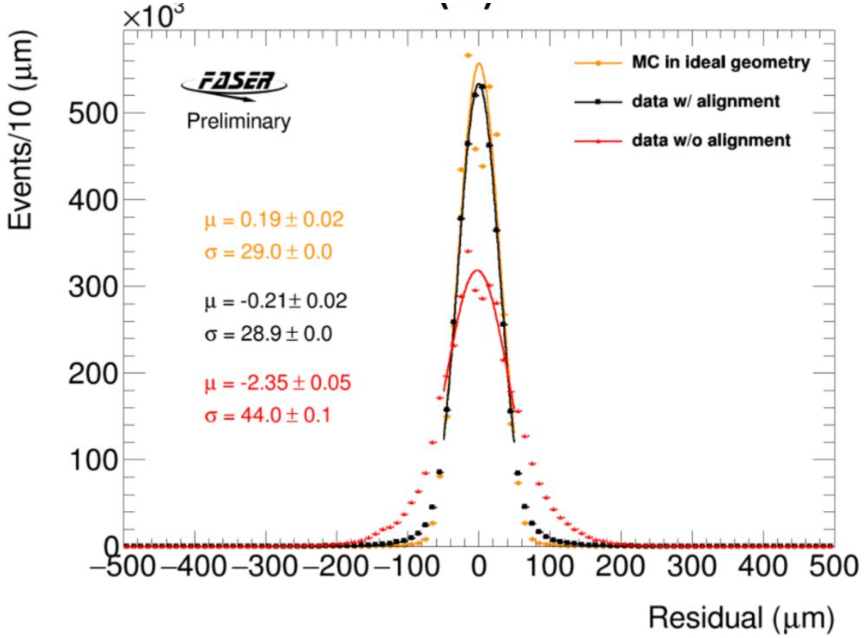


Tracker Performance

- Total number of dead/noisy strips < 0.5%
- Hit efficiency of 99.6±0.1%
- Spatial resolution of ~30 um x 500 um

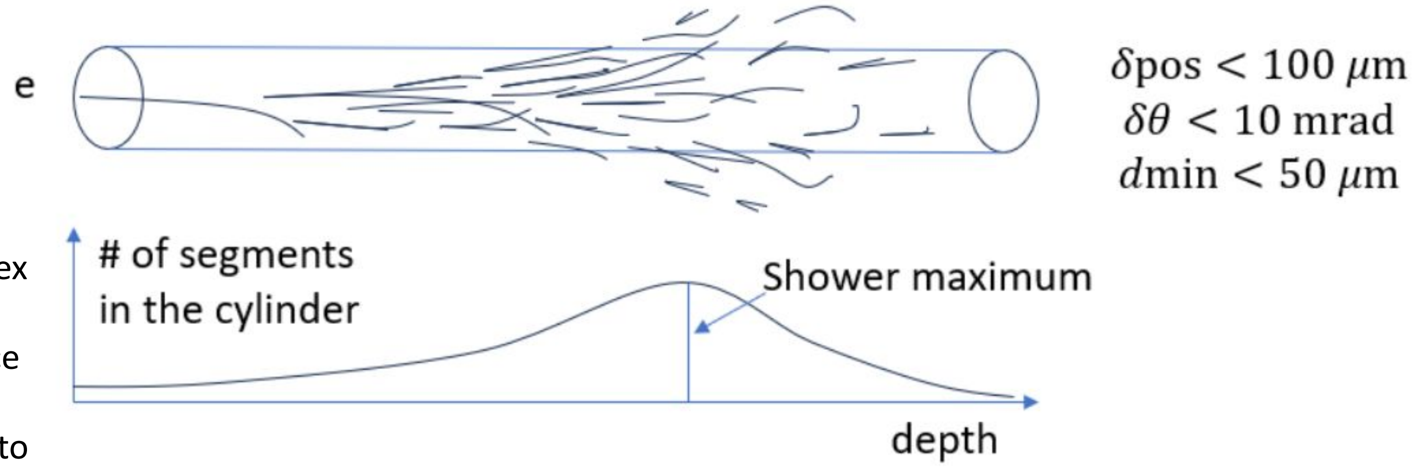




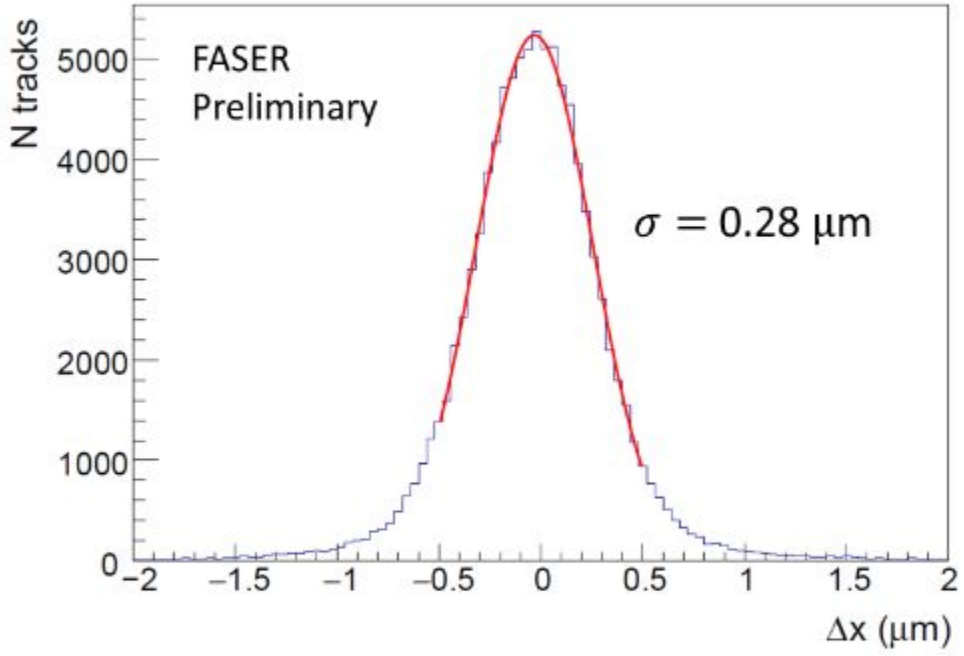


FASERnu Physics

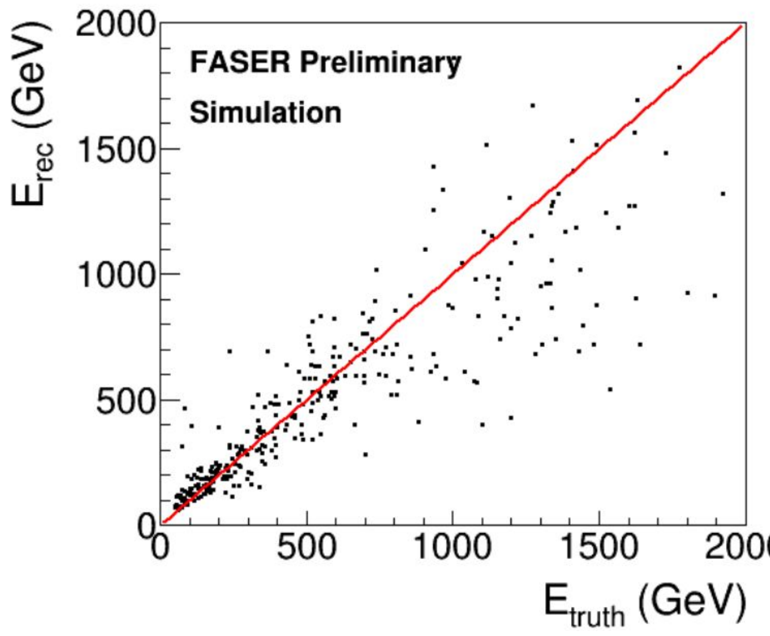
- Vertex reconstruction done by searching for converging patterns. Must have more than 4 tracks.
- Presence or absence of a parent track determines if the vertex is charged or neutral
- Electron neutrino CC interaction vertex identified by presence of EM shower
- EM shower formed from reconstructed segments; expected to be compact in tungsten



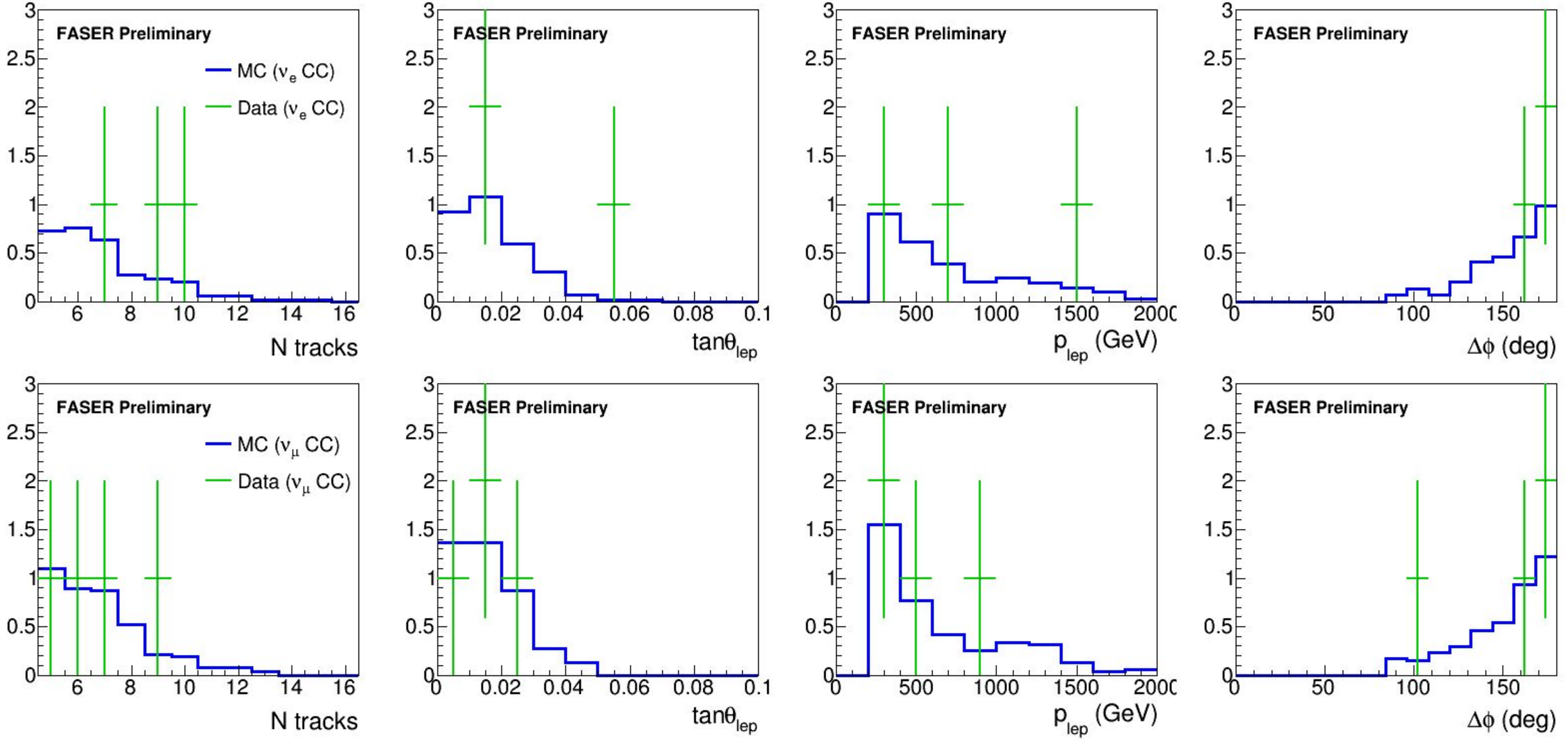
Transverse Position Resolution



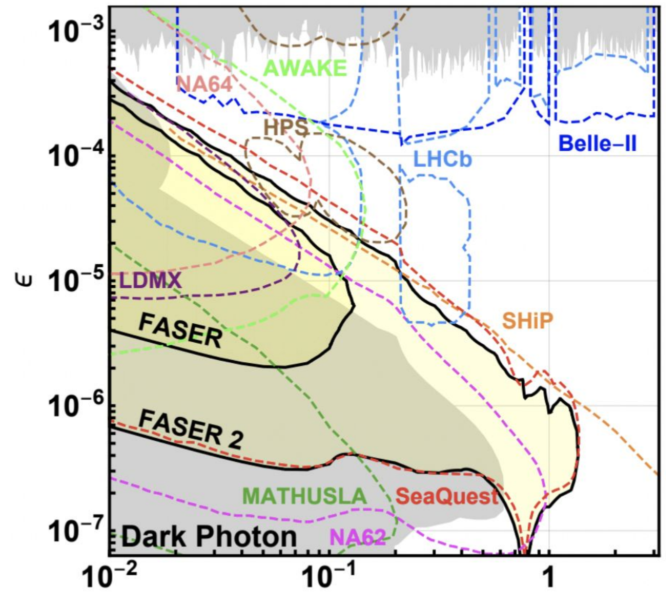
Electron energy - Reconstructed vs True (Simulation)

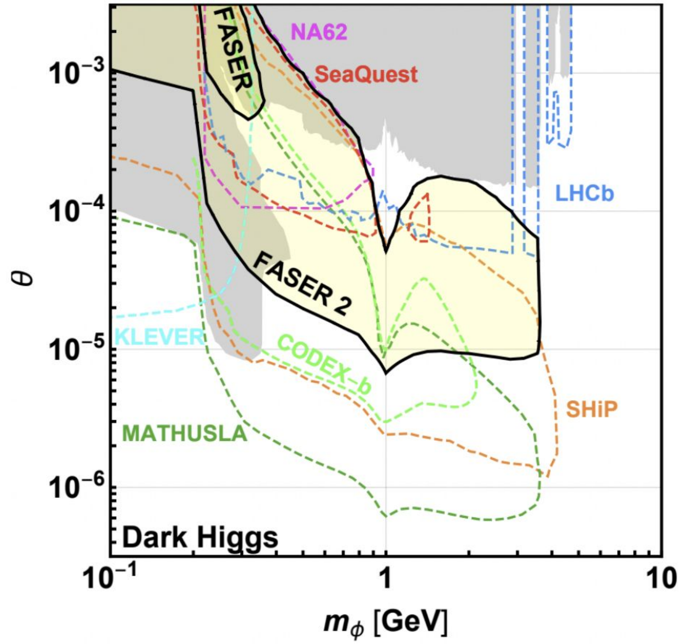


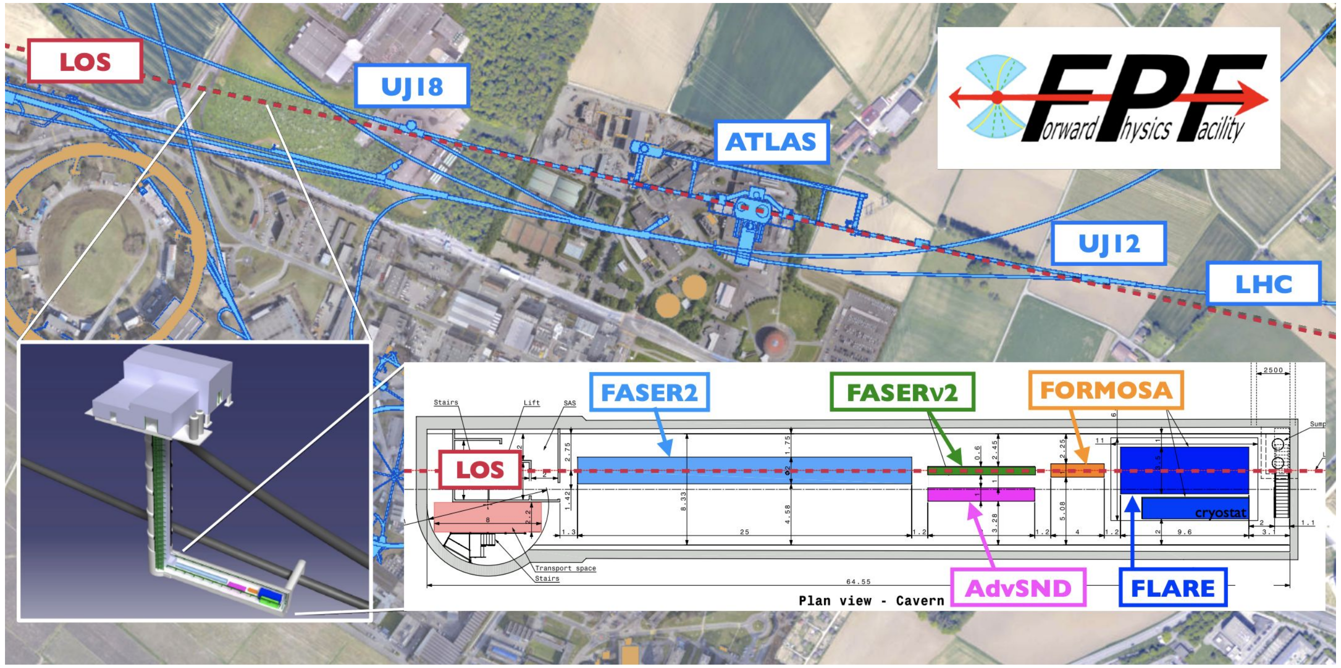
FASERnu Neutrino Properties



FASER 2 and Fasernu2







Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x