Status of FASER

LHCC Open Session: 13/9/2023

Jamie Boyd (CERN) on behalf of the FASER Collaboration

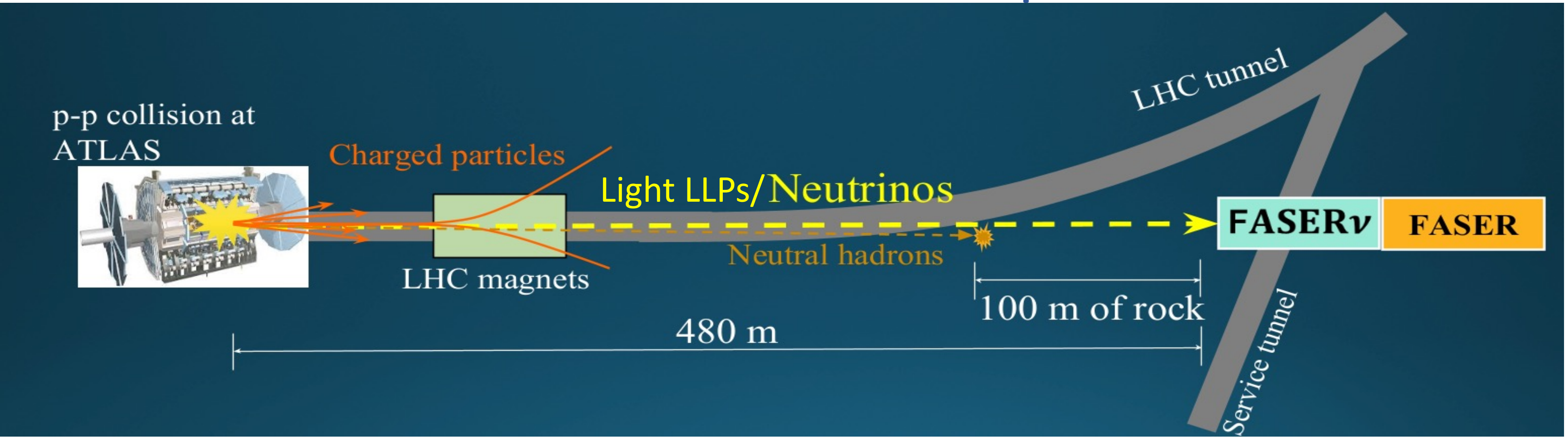
Part of the FASER Collaboration at the Collaboration Meeting in June

Introduction

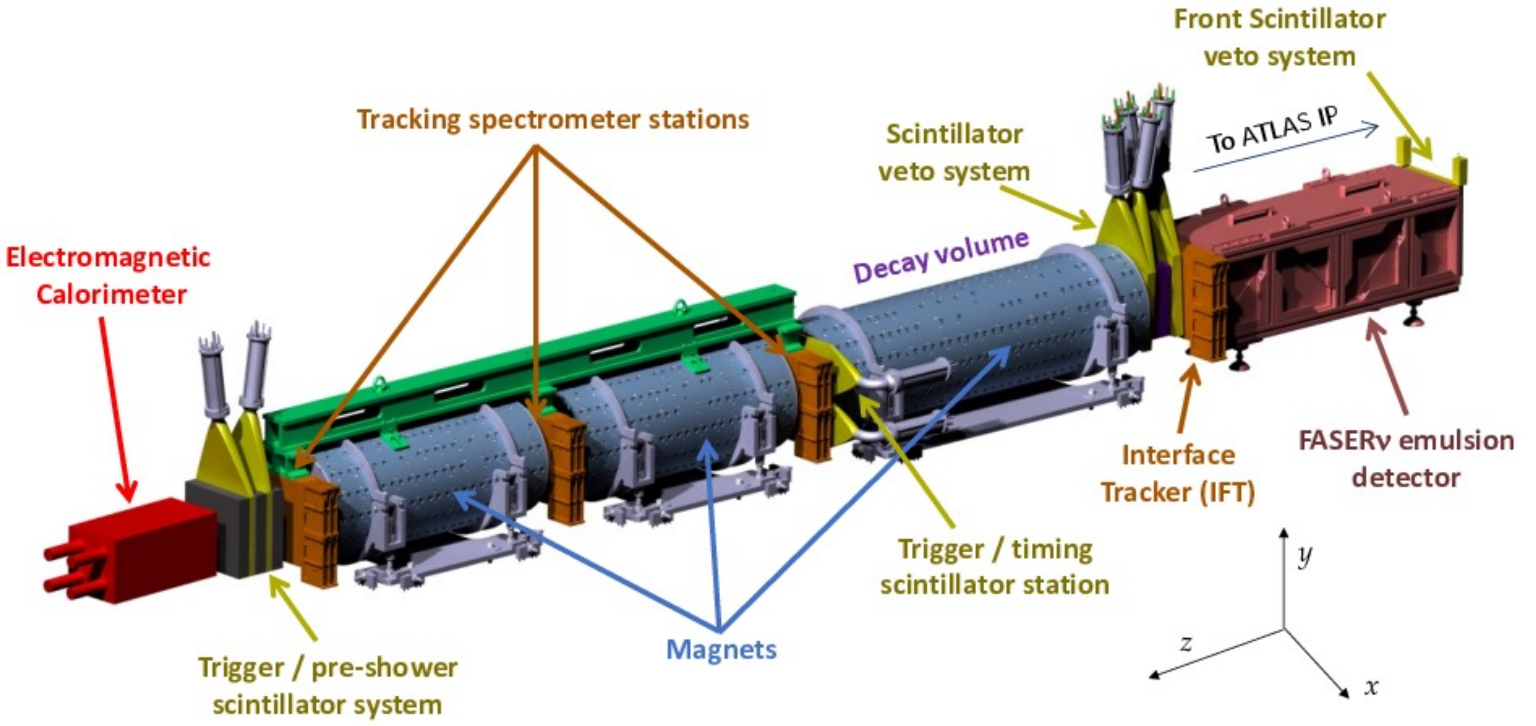
- FASER is a new experiment:
  - Installed into the LHC complex during LS2
  - First data taking in July 2022 at the start of Run 3
  - Designed to search for weakly interacting, light new particles and to study high energy neutrinos of all flavours
- Last report in the LHCC Open session in November 2022: https://indico.cern.ch/event/1219913/
  - Reporting on first operational experience and detector performance
- This talk will focus on **the first physics results** released during 2023:
  - Search for dark photons
  - First direct observation of collider neutrinos
  - First observation of electron neutrinos at the LHC with the FASERν sub-detector
- While also briefly covering:
  - Detector operations and performance
  - Upgrade plans
  - Long term future plans (the Forward Physics Facility)

Reminder: # The FASER Experiment

arxiv: 2207.11427

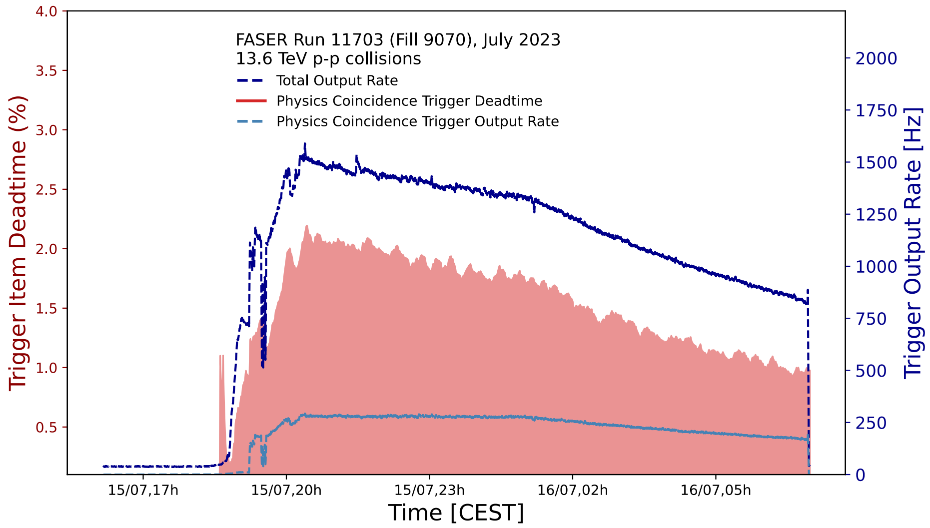


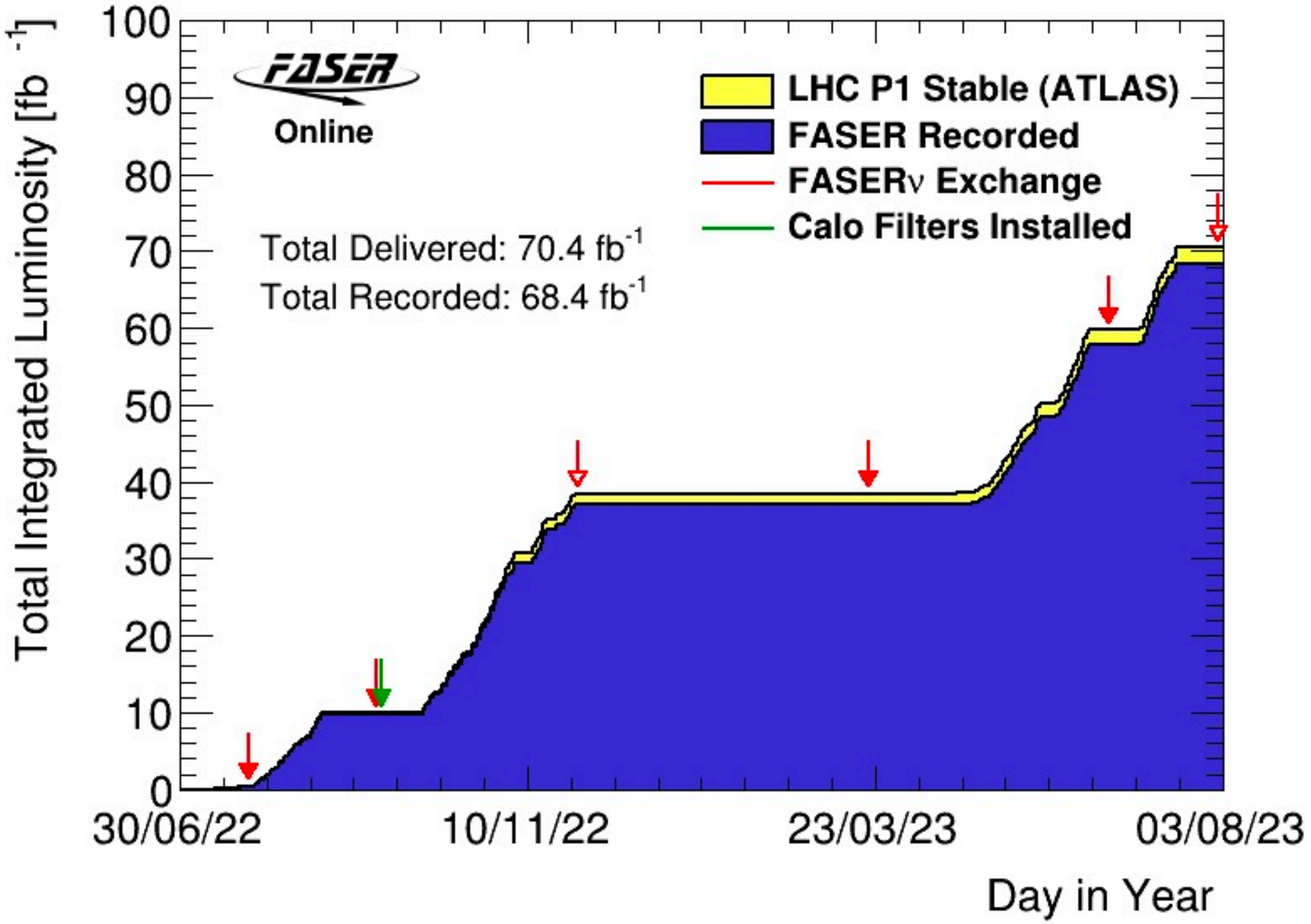
- FASERν: 730 layers of 1.1mm thick tungsten plates and emulsion films
  - 1.1tonne target mass
- Tracking using spare ATLAS SCT silicon strip modules
  - 80µm strip pitch
- Main detector volume in 0.6T dipole field
- Calorimeter uses 4 LHCb outer ECAL modules
- Trigger on signal in pairs of scintillators or energy in calorimeter
  - Maximum trigger rate $\mathcal{O}$(1.5kHz) dominated by muons from IP



FASER Operations

- FASER detector operations have gone extremely well to date
- Recorded ~97% of the delivered data
  - DAQ deadtime <2%
- No significant operational issues
- Lightweight operational model
  - No control room
  - Two shifters, controling and monitoring the experiment from their laptop





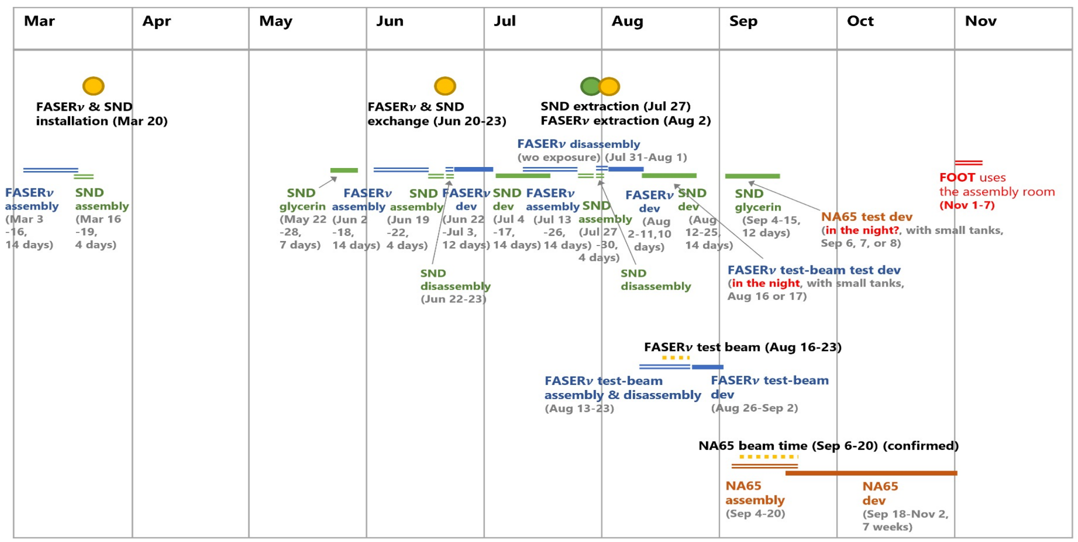
Many thanks to ATLAS Collaboration for providing IP1 luminosity information!

FASERν Operations

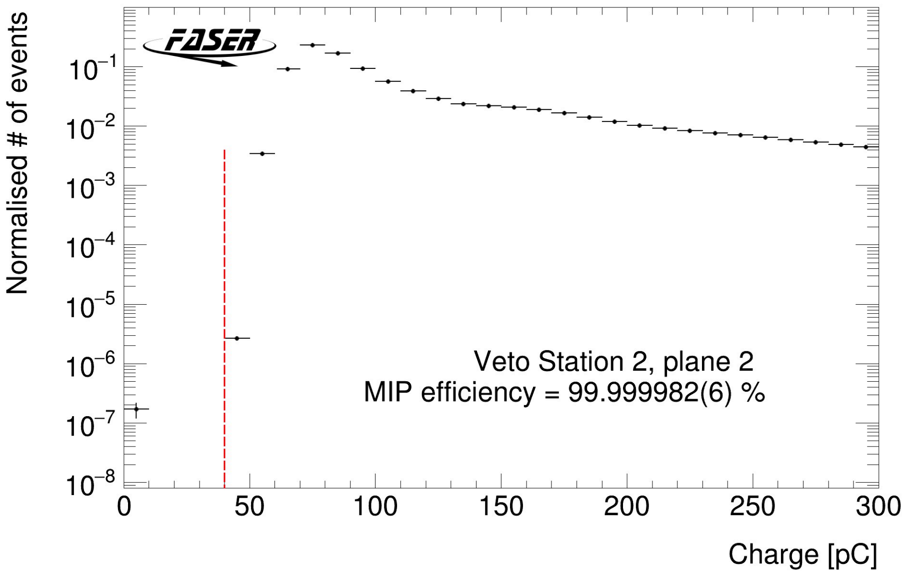
- FASERν is a passive detector, that records signals from all traversing charged particles while it is installed
- Needs to be replaced every ~25/fb to keep the detector occupancy at an acceptable level for analysis - $\mathcal{O}(10^6)$ tracks/cm^2
- Typically exchange during LHC Technical Stops
- Heavy workflow:
  - New detector assembled in dark room before exchange (~2 weeks)
  - Removed detector needs to be developed in dark room (~2 weeks)
- Detector exchange <4hrs
  - Thanks to well developed procedure with CERN EN-HE and RP teams
- Dark room activities well coordinated with SND@LHC and DsTau experiments
  - Thanks to CERN EP department for support renovating the dark room facility

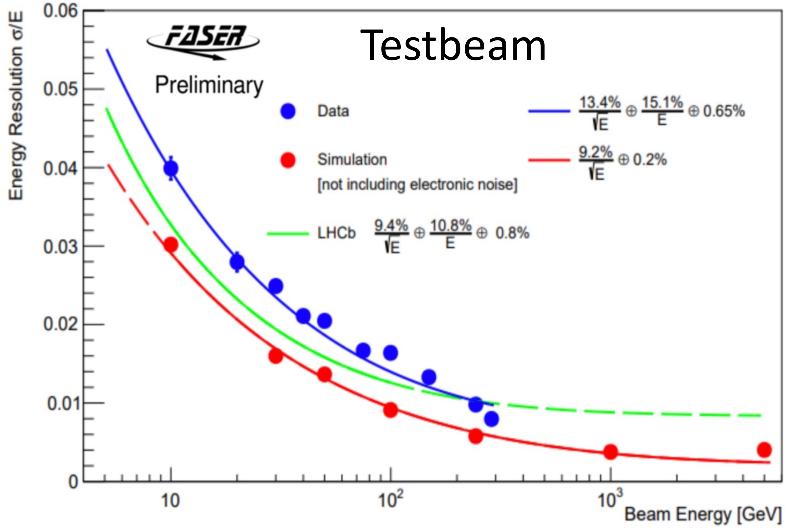
Reminder:
In Run 3 (250/fb) we expect: $\mathcal{O}$(3k) ν_e, $\mathcal{O}$(10k) ν_μ, $\mathcal{O}$(70) ν_τ charged current neutrino interactions in FASERν.

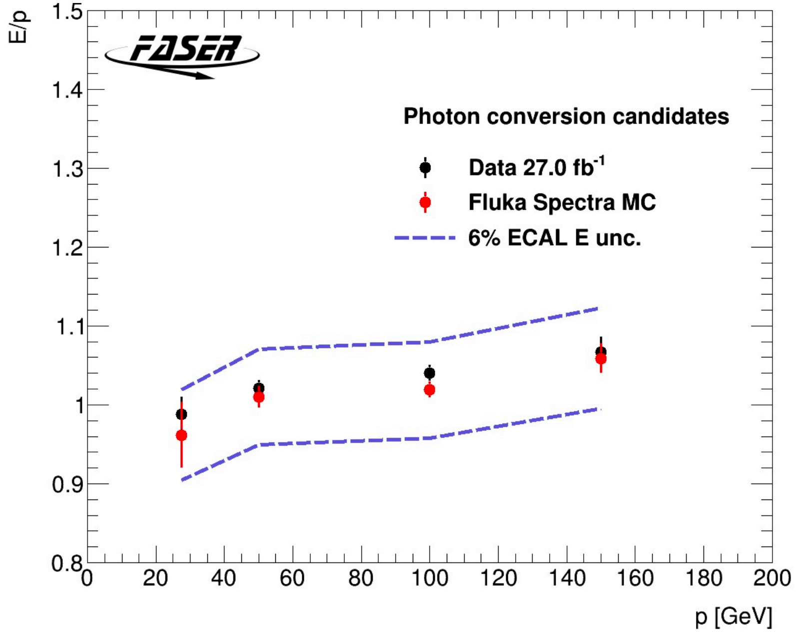
2023 schedule (updated on Aug 9)



Scintillator/Calorimeter Performance

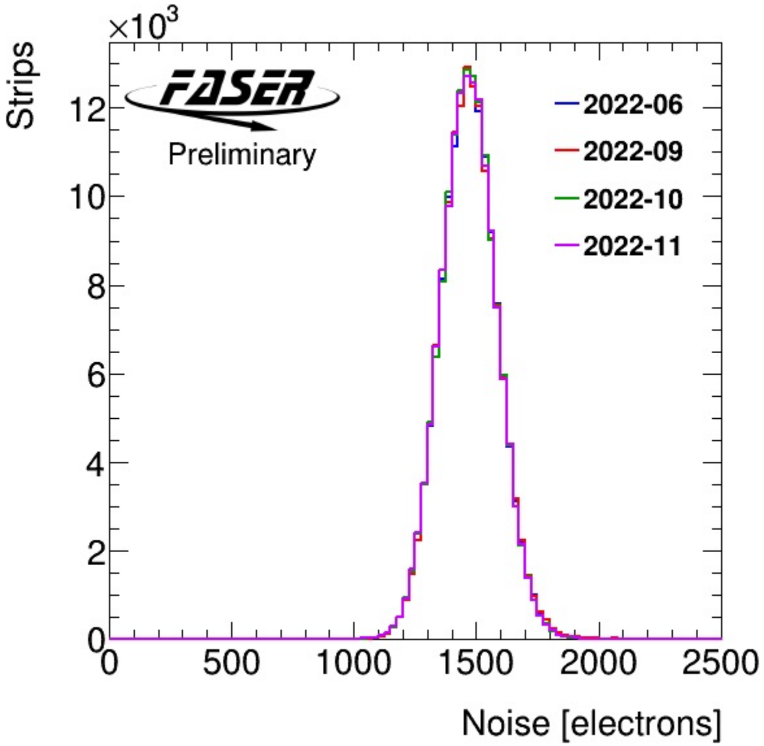


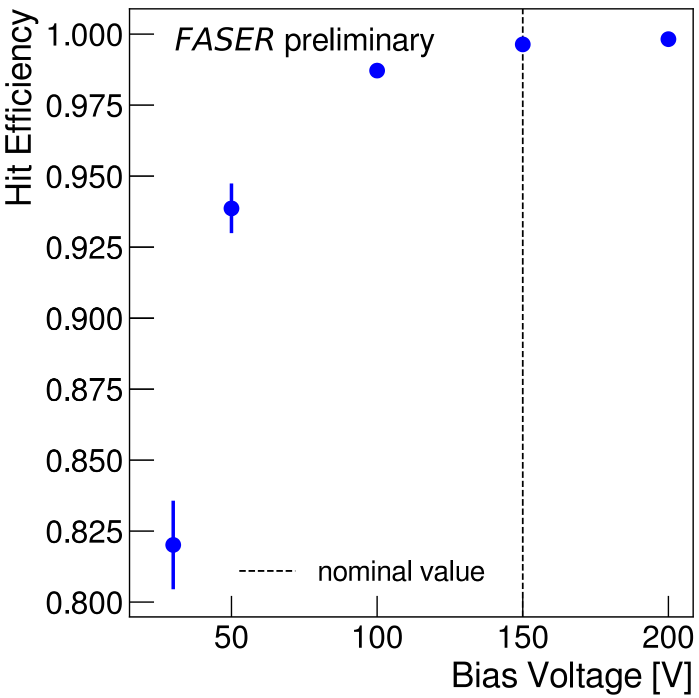


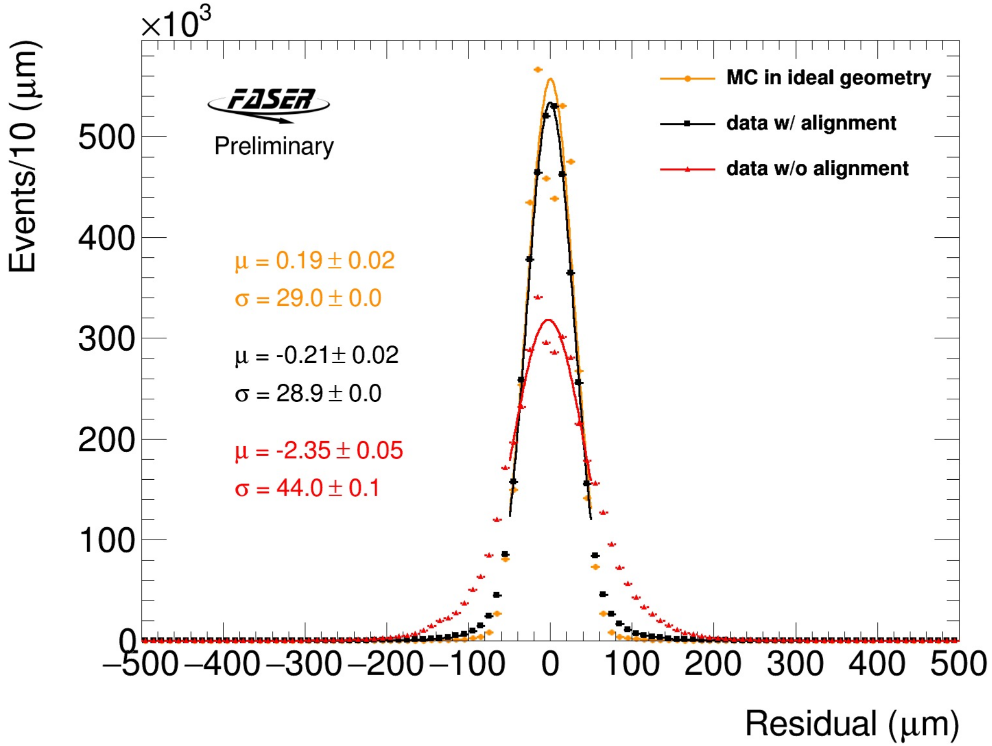


- 5 veto scintillators plane. Per plane inefficiency measured with data to be $\mathcal{O}(10^{-5})$
- Calorimeter energy resolution measured to be ~1% for high energy electrons in SPS testbeam
- Calorimeter energy scale uncertainty of 6% derived from testbeam. Checked using E/p in collision data photon conversion events

Tracker Performance



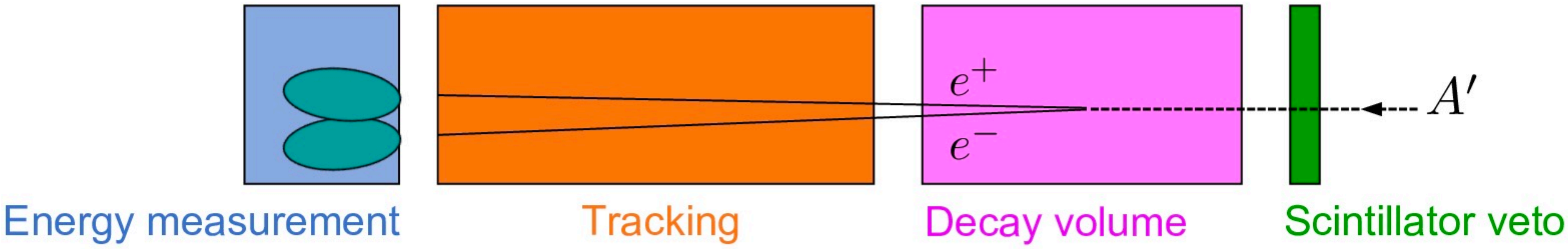


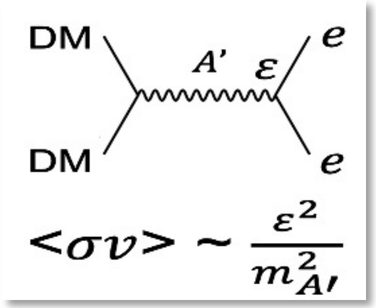


- Noise measured in regular calibrations, stable versus time. Corresponds to noise occupancy <5x10^{-4}
- <0.5% bad channels
- High hit efficiency 99.6+/-0.1% at nominal bias voltage of 150V
- Unbiased track hit residuals of <30μm in precision coordinate after first detector alignment

Dark Photon Search

[arxiv:2308.05587](https://arxiv.org/abs/2308.05587)
(submitted to PLB)





- FASER designed to search for light, weakly coupled dark photons
  - Region of parameter space where dark photon can act as dark matter mediator yielding observed relic density
    - Assuming standard thermal evolution of universe
  - Dark photon produced in light meson decay (primarily π^0), and with large, $\mathcal{O}$(TeV), boost along the beam direction

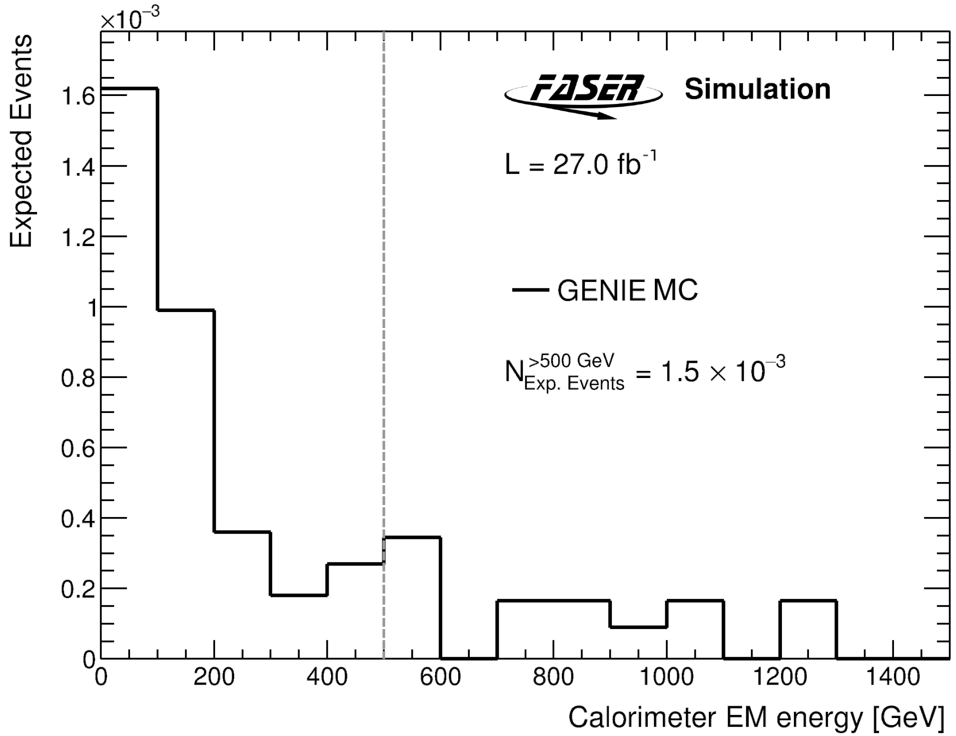
- First FASER analysis, designed to be simple and robust (blind analysis to avoid unconscious bias)
  - Using 27/fb of 2022 data
    - First 10/fb of 2022 data taken without calorimeter optical filters installed – signals saturate for high energy deposits
  - Event selection:
    - No signal in any of 5 veto scintillators
    - 2 reconstructed tracks (extrapolate into veto scintillators)
    - >500 GeV energy in calorimeter
  - ~50% signal efficiency in relevant region of signal parameter space

Dark Photon Search

arxiv:2308.05587
(submitted to PLB)

Studied backgrounds from:

- Scintillator inefficiencies
  - Measured in data
- Neutral hadrons produced by upstream muon interactions
  - Measured using data control regions with different requirements on veto scintillators and number of reconstructed tracks
- Neutrino interactions inside main detector volume
  - Estimated using high statistics MC sample (10^4 x dataset)
  - Dominant background
- Non-collision backgrounds
  - Studied using events without colliding bunch in IP1



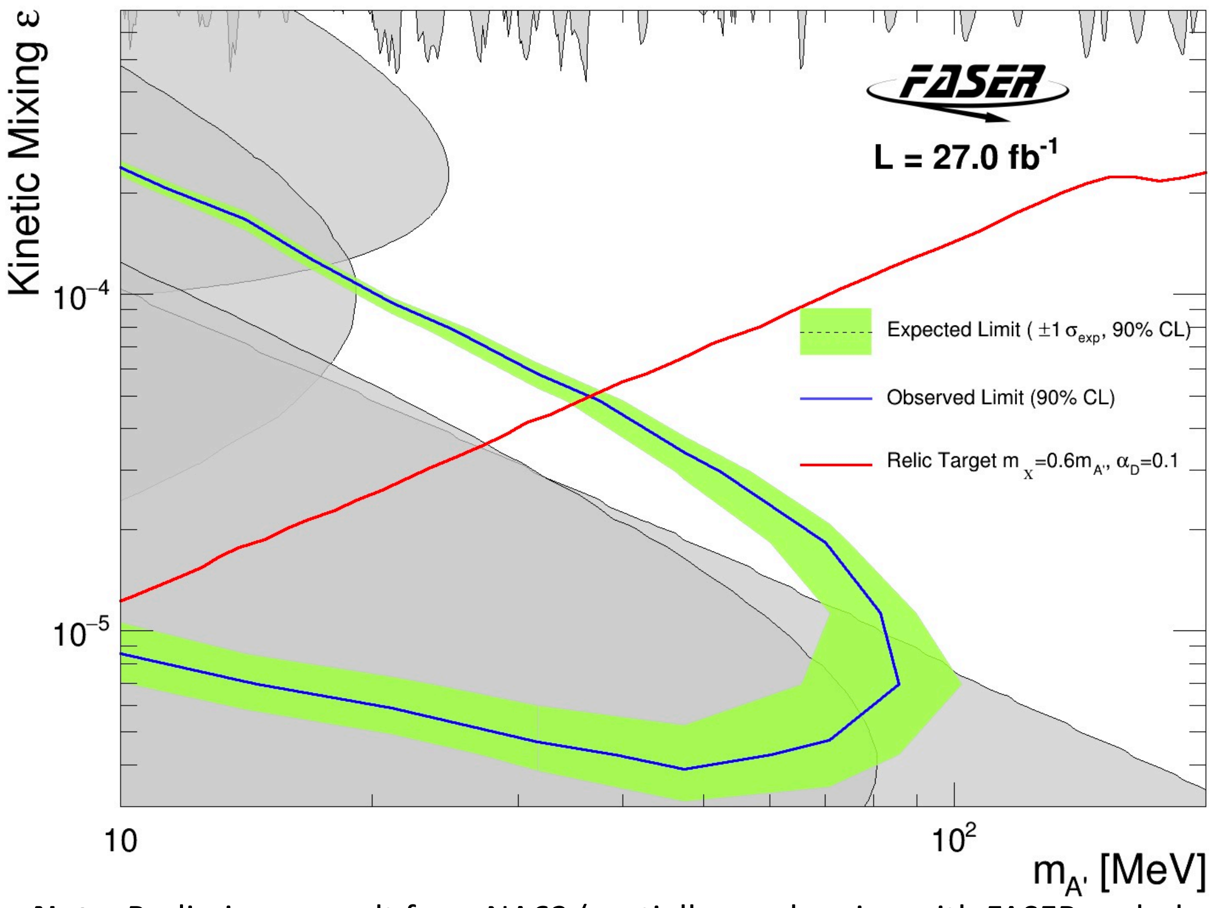
Background	Central Value	Error (%)
Veto inefficiency	-	-
Non-collision	-	-
Neutral hadrons	0.8×10^{-3}	1.2×10^{-3} (140%)
Neutrinos	1.5×10^{-3}	2.0×10^{-3} (130%)
Total	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{2.3 \times 10^{-3}}$ **(100%)**

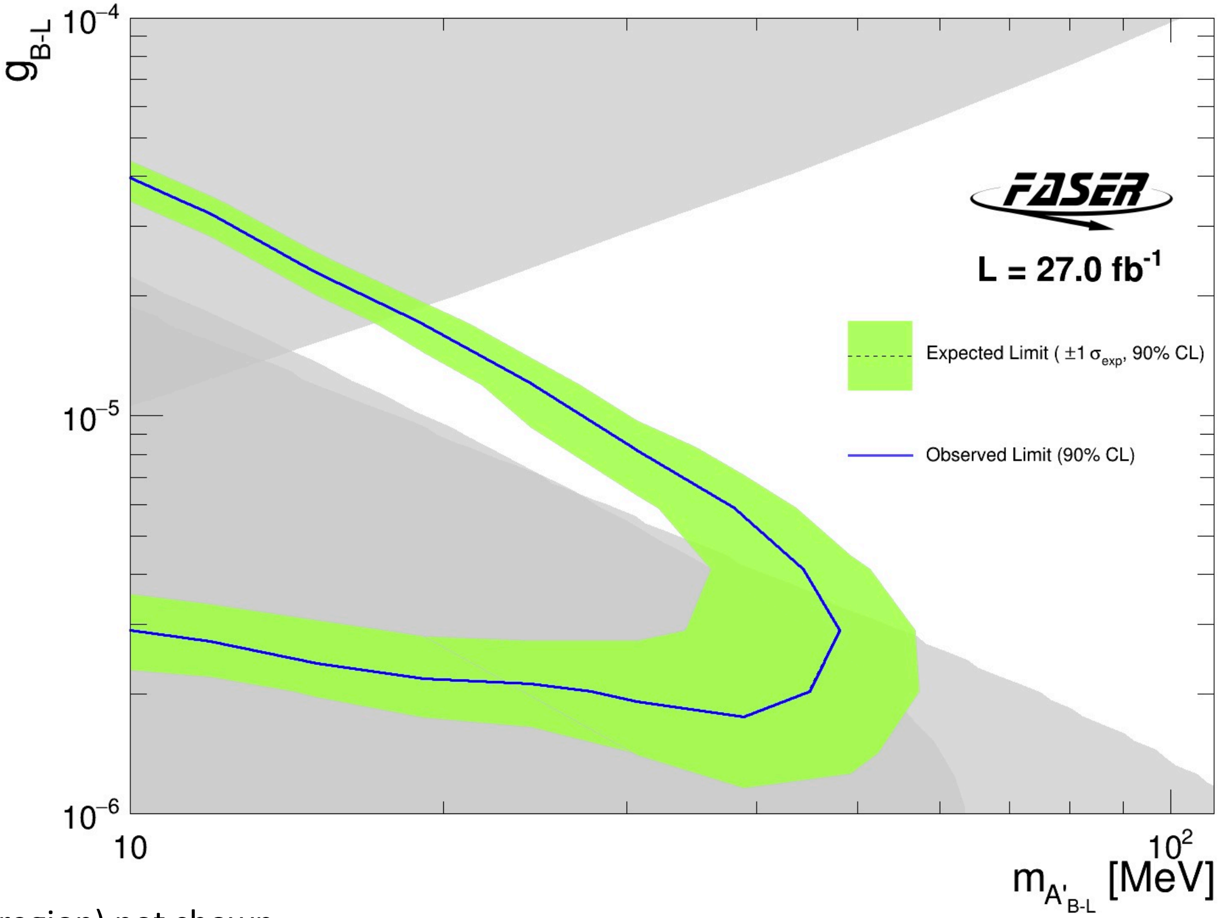
Detector design and excellent performance leads to an essentially background free analysis

Dark Photon Search

arxiv:2308.05587
(submitted to PLB)

- Zero events observed
  - Set limits in unconstrained regions of parameter space
  - First improvement of sensitivity into the thermal relic region from weak coupling since the 1990’s
  - Result also interpretted in B-L gauge boson model





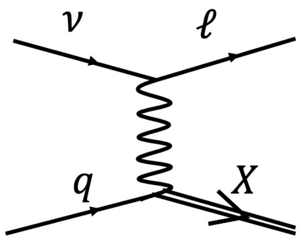
Note: Preliminary result from NA62 (partially overlapping with FASER excluded region) not shown.

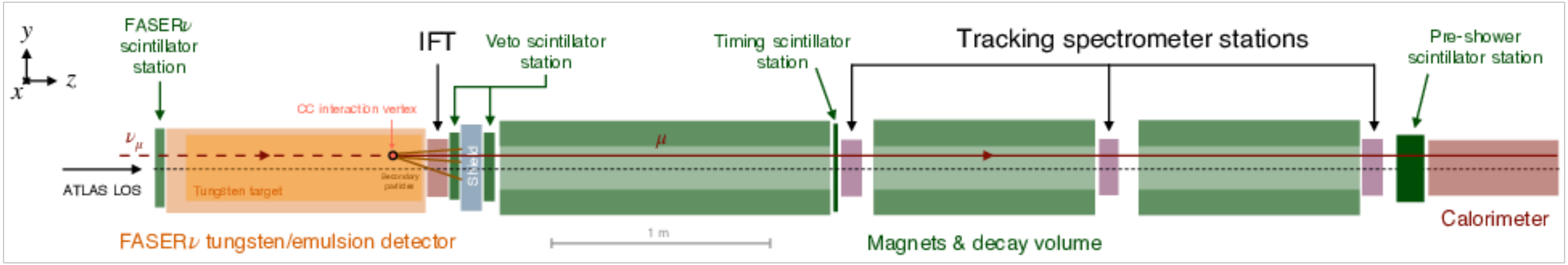
Phys. Rev. Lett. 131 no. 3, (2023) 031801

Observation of collider neutrinos

A huge number of high energy neutrinos traverse the FASER location.
Allows to detect neutrino interactions at a collider for the first time, using the electronic detector components (not using the FASERν emulsion, which has a slower data processing workflow).

Search for events with no signal in veto scintillators in front of FASERν, and a reconstructed track with p>100GeV (extrapolated track must pass through central region of front veto's).
Topology consistent with a ν_μ charged current interaction in 1.1tonne FASERν tungsten target.
Expect 151+/-40 neutrino interactions to pass the events selection
(error envelope from generators SIBYLL/DPMJET – no experimental uncertainties included)





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Expect 151+/-40 neutrino interactions to pass the events selection
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Background studied from:

- Veto inefficiency
  - measured in situ
- Neutral hadrons from upstream muon interactions
  - estimated using high statistics MC samples
- Muon passing veto and scattering to pass analysis selection
  - estimated using data control regions, extrapolated to signal region using MC

Total background estimate 0.2+/-1.8 events

Phys. Rev. Lett. 131 no. 3, (2023) 031801

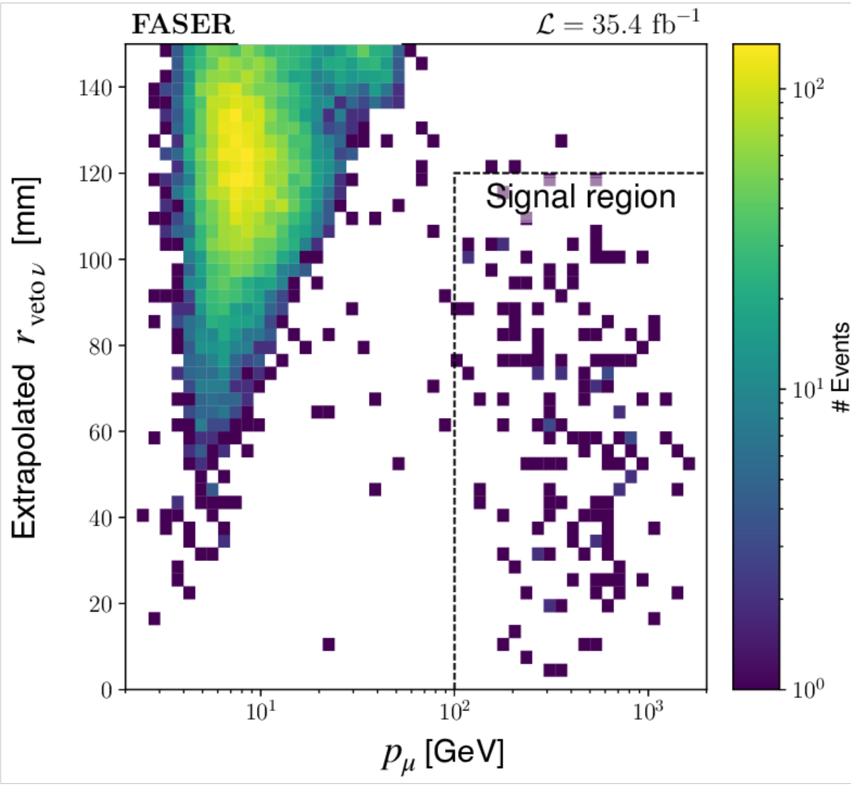
Observation of collider neutrinos

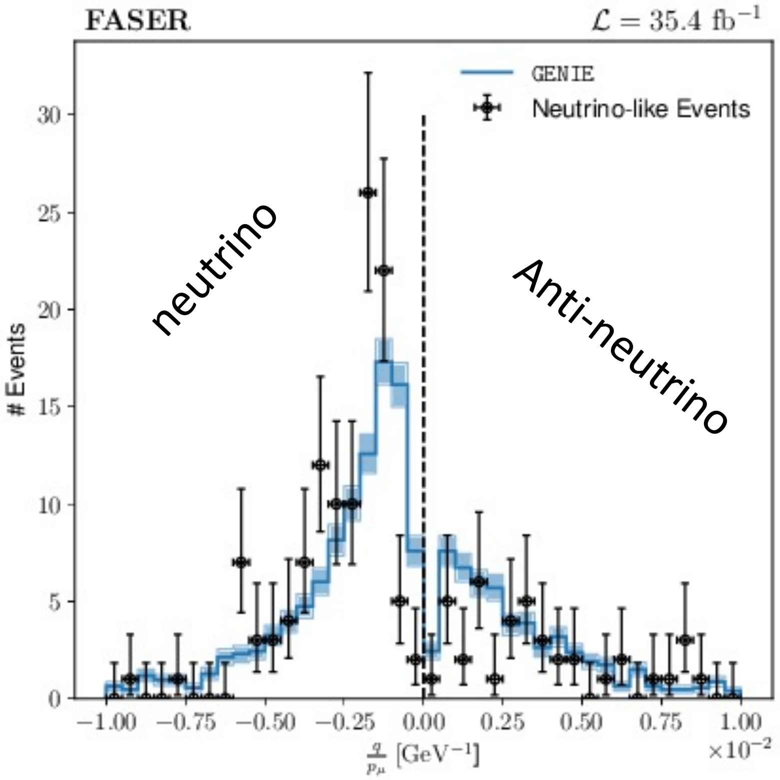
After unblinding, observe 153 neutrino candidates (statistical significance ~16sigma)

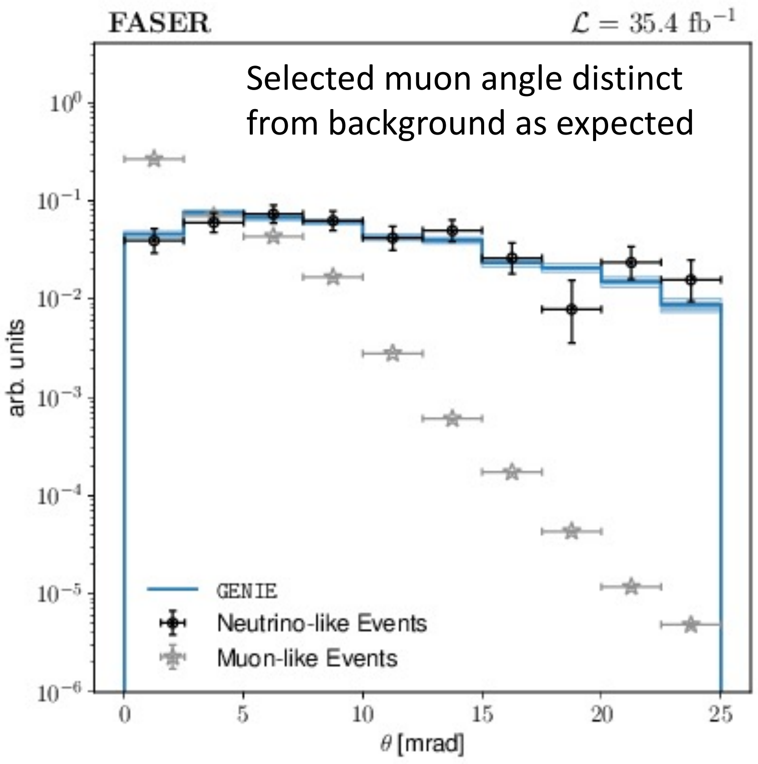
First direct observation of collider neutrinos.

Characterization of candidates consisent with expectation:

- Observe both neutrino/anti-neutrinos with rates consistent with expectation,
- Selected neutrinos are of high energy (>200GeV)







In above plots experimental systematic uncertainties are not included on the GENIE MC histograms

FASER

[Phys. Rev. Lett. 131 no. 3, (2023) 031801](https://doi.org/10.1103/PhysRevLett.131.031801)

Observation of collider neutrinos

Final analysis presented at Moriond 2023

Paper Timeline:
Submitted: 24 March 2023
Accepted: 8 May 2023
Published: 19 July 2023

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First Direct Observation of Collider Neutrinos with FASER at the LHC

Henso Abreu *et al.* (FASER Collaboration)
Phys. Rev. Lett. **131**, 031801 – Published 19 July 2023

Physics See Viewpoint: The Dawn of Collider Neutrino Physics

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of $35.4\,\mathrm{fb}^{-1}$ using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

Accompanied by nice APS Viewpoint article
https://physics.aps.org/articles/v16/113

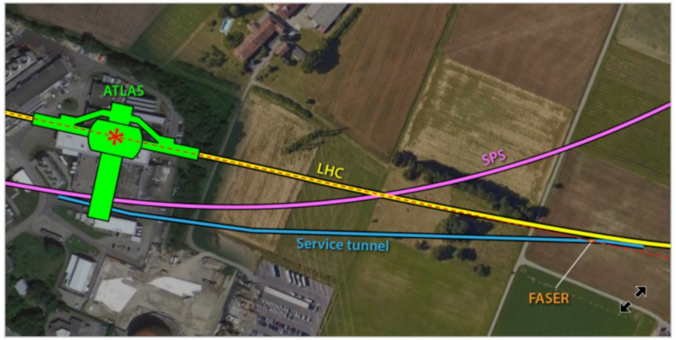
VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



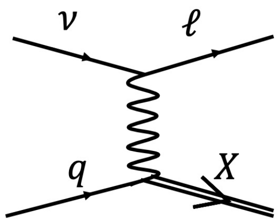
Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

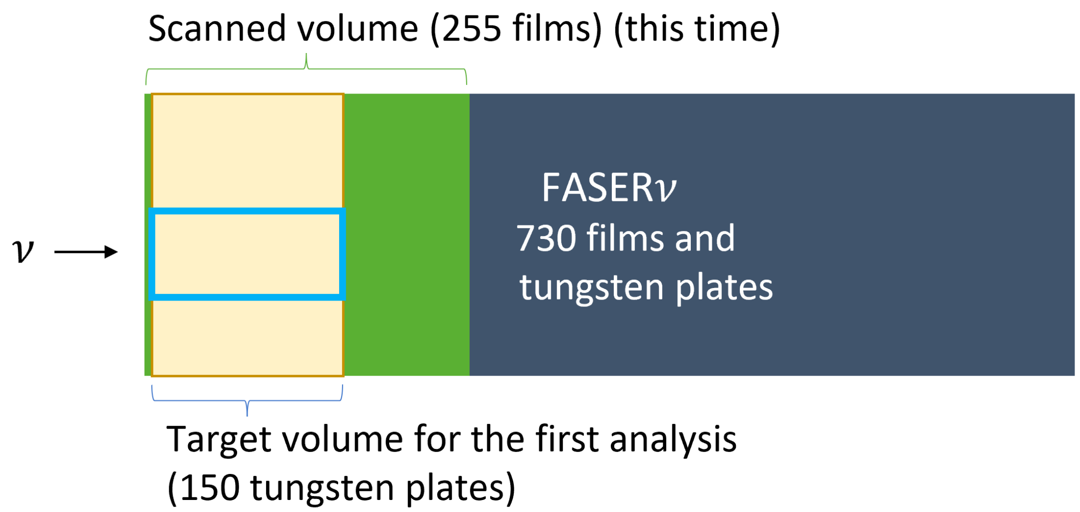
Figure 1: The Forward Search Experiment (FASER) is installed in a service tunnel that connects the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS). Proton collisions at the ATLAS experiment's interaction point (red star) generate beams of ne... Show more

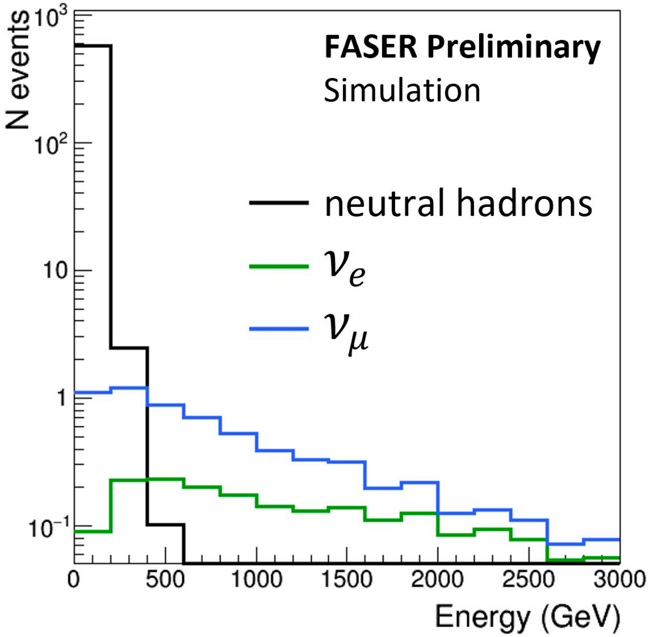
Neutrinos are among the most abundant particles in the Universe, but they rarely interact with matter: trillions pass through us every second, but most of us will never have even a single one interact with the matter in our bodies. Nonetheless, scientists can study these particles using high-intensity neutrino sources and detectors that are large enough to overcome the rarity of neutrino interactions. In this way, neutrinos have been observed from the Sun,

First FASERν Physics

- First public result using FASERν emulsion detector
  - Emulsion processing workflow slow, only use a subset of the full detector for this first result
  - Search for neutrino interaction vertices in 150 plates (105 further plates for following down tracks for momentum measurement and muon ID). Only considering 1/3 of area of each plate, closest to LOS.
    - 68 kg target mass used (6% of total target)
  - Use 2nd FASERν box from 2022, exposed to 9.5/fb of data.
- Expect 29.4 ± 5.0 (ν_μ) and 11.8 ± 7.5 (ν_e) charged current neutrino interactions in target volume before selections
  - Average from SIBYLL/DPMJET generators, error is envelope
- Background from Neutral Hadrons, much lower momentum than neutrino signal
  - Select vertices with associated lepton candidate (e or μ) with E>200 GeV



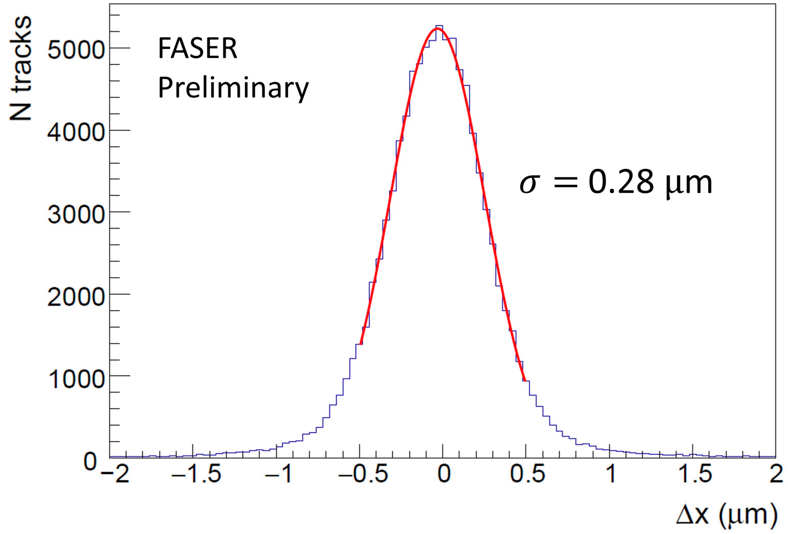




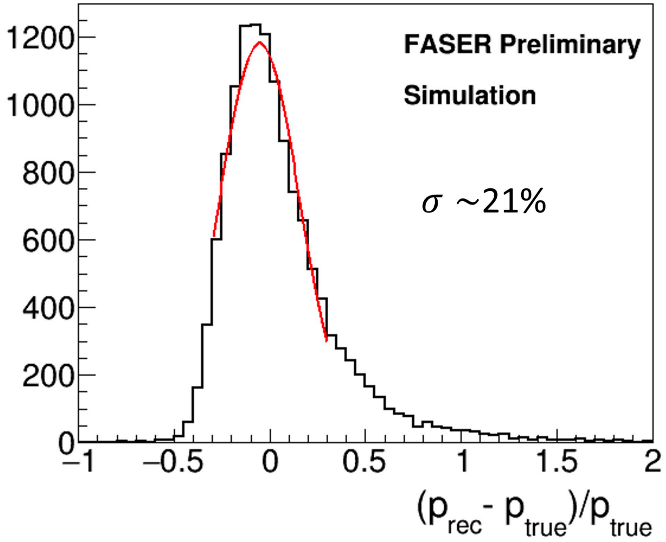
First FASERν Physics

CERN-FASER-CONF-2023-002

Track resolution measured in data ~0.3μm

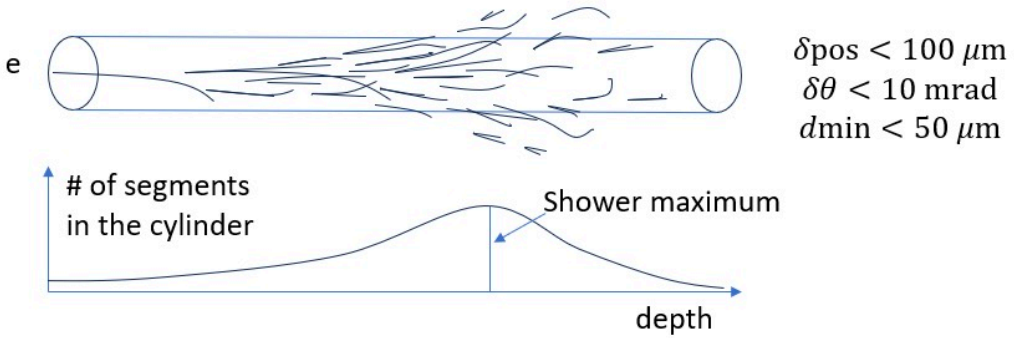


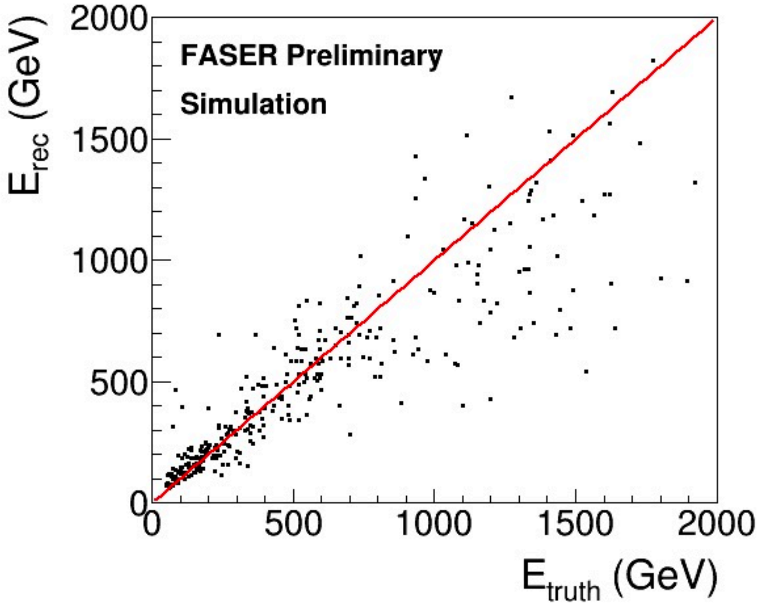
Muon momentum measured by multiple columb scattering



Resolution from simulation ~20% at p=200 GeV. Validated by splitting long tracks in data.

Electron ID and energy measurement.
Reconstruct EM shower in thin cone.
Energy from counting segments in 7 plates around shower maximum





Resolution from MC ~25% at p=200 GeV

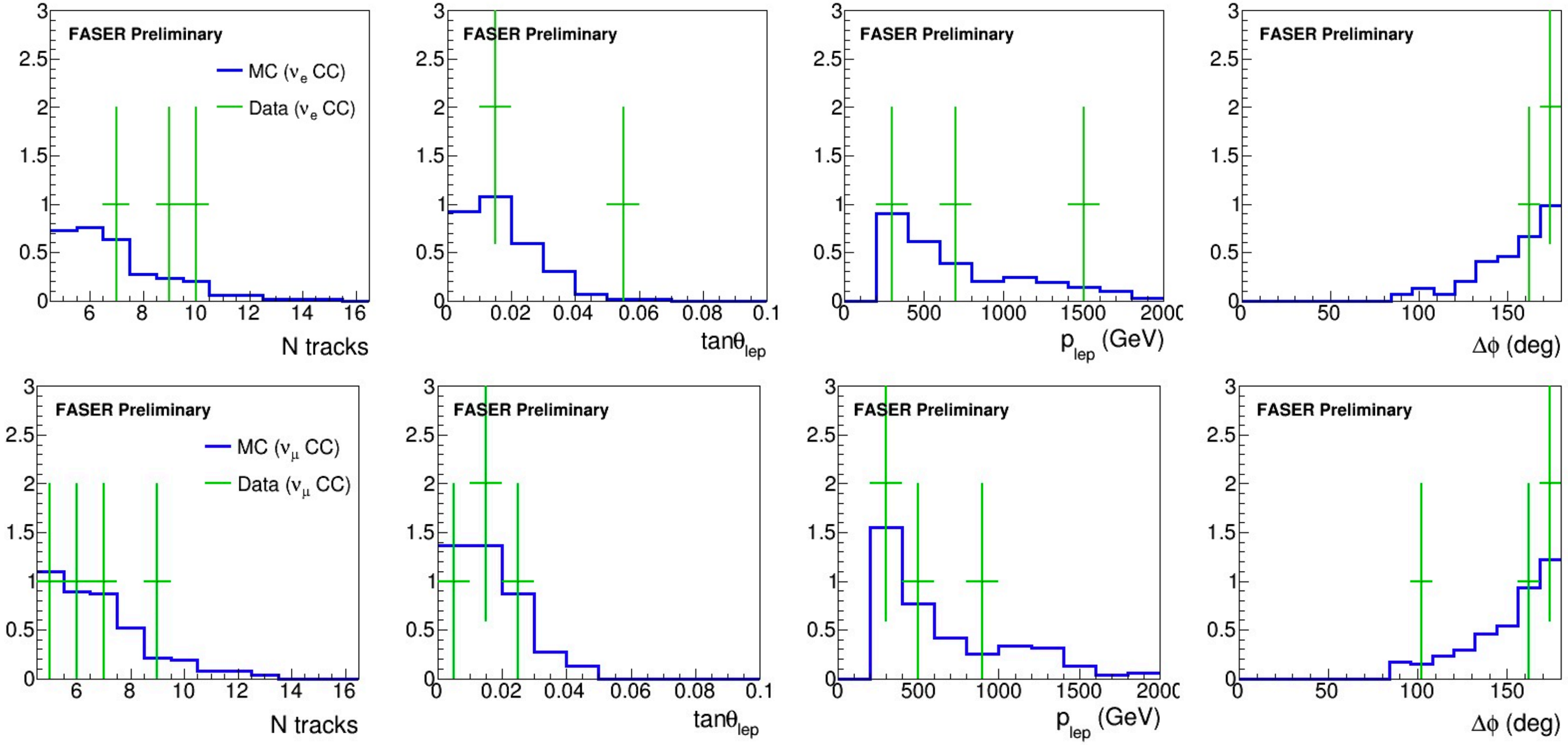
First FASERν Physics

CERN-FASER-CONF-2023-002

Background estimated from MC. Modelling of neutral hadron vertex quantities validated using data at lower energy (before lepton requirement). Expected background:

Background	ν_μ CC	ν_e CC
Neutral-hadron interactions	0.32 ± 0.15 (stat.) ± 0.16 (syst.)	0.002 ± 0.002 (stat.) ± 0.002 (syst.)
NC neutrino interactions	0.19 ± 0.15	-
Total	0.51 ± 0.27	0.002 ± 0.003

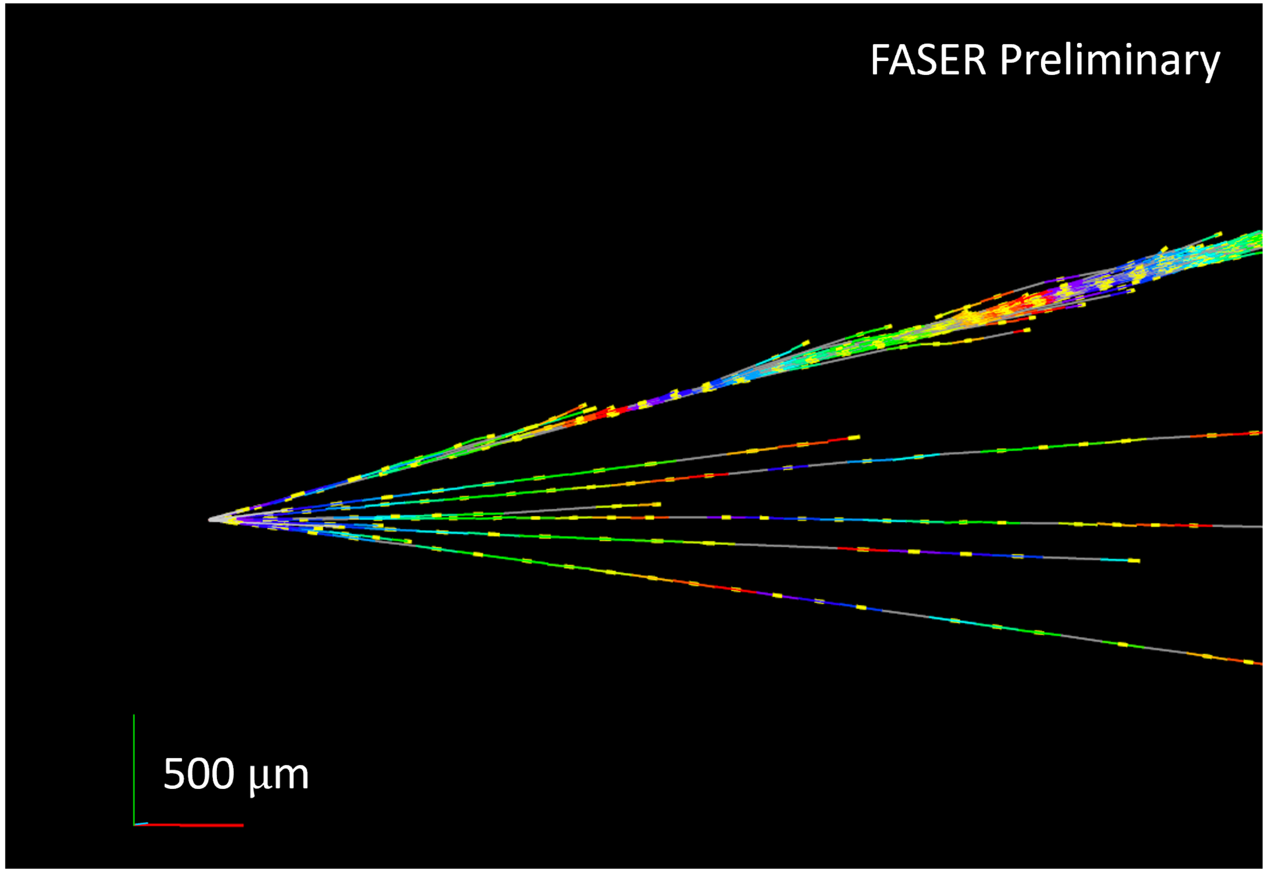
Observe 3 ν_e vertices (5sigma), and 4 ν_μ vertices (2.5sigma). Expect 0.6–5.2 (ν_e CC) and 3.0–8.6 (ν_μ CC) passing selection.

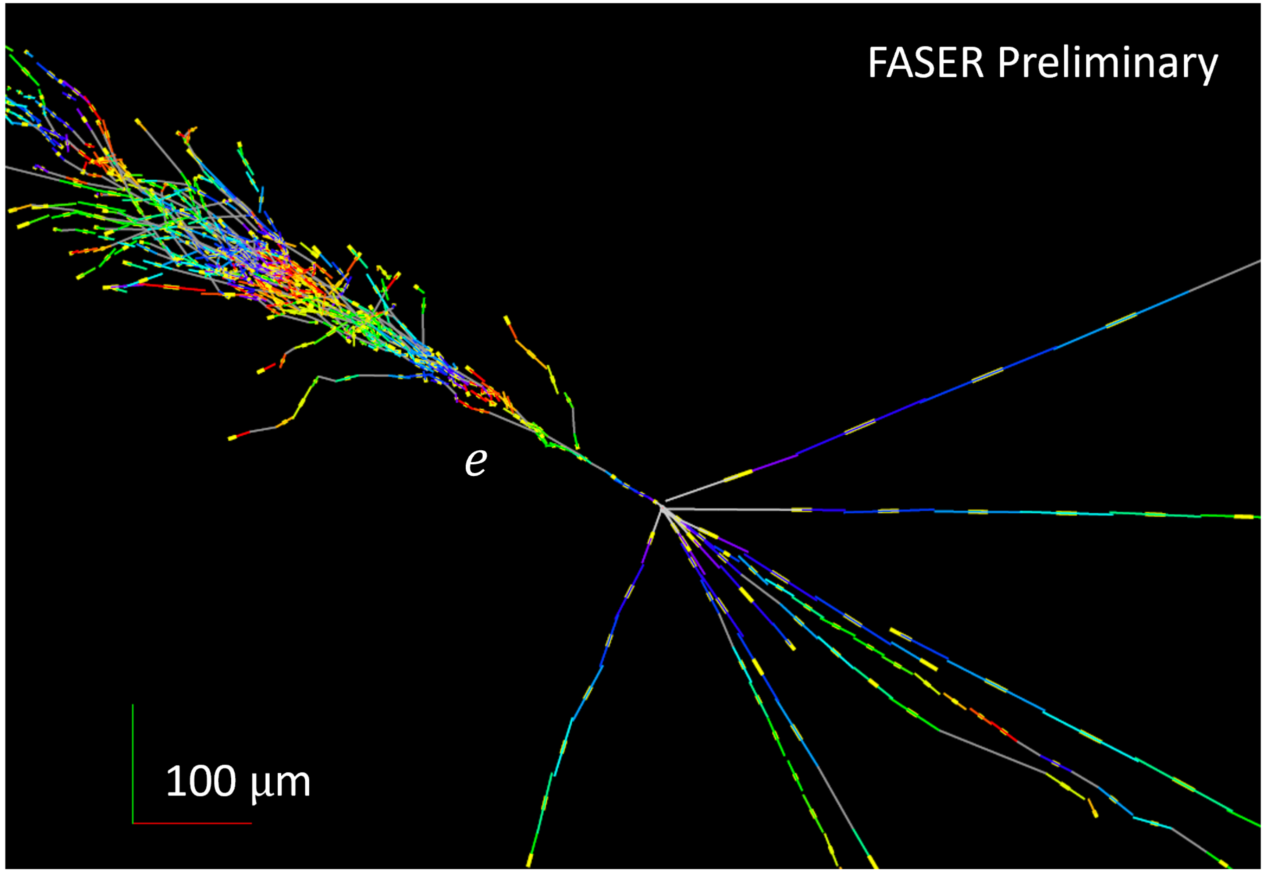


Properties of selected vertices agree with MC expectation within low statistics.

First FASERν Physics

One of selected ν_e vertices:



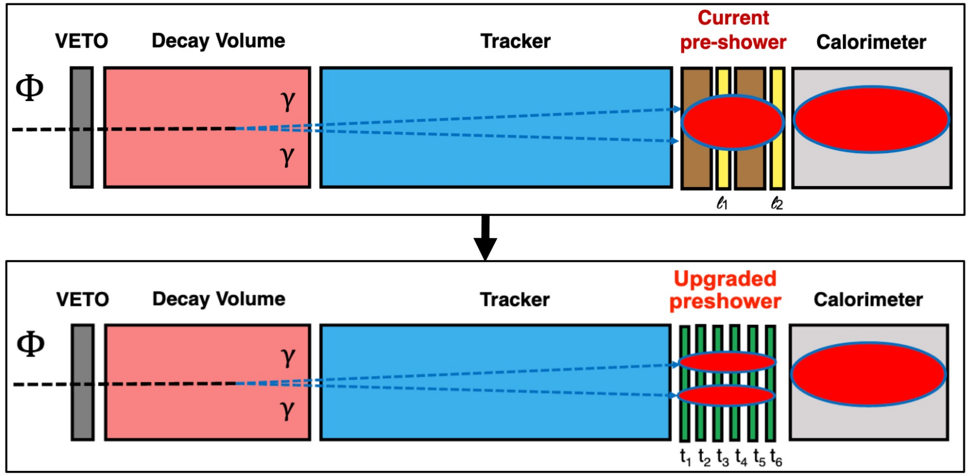


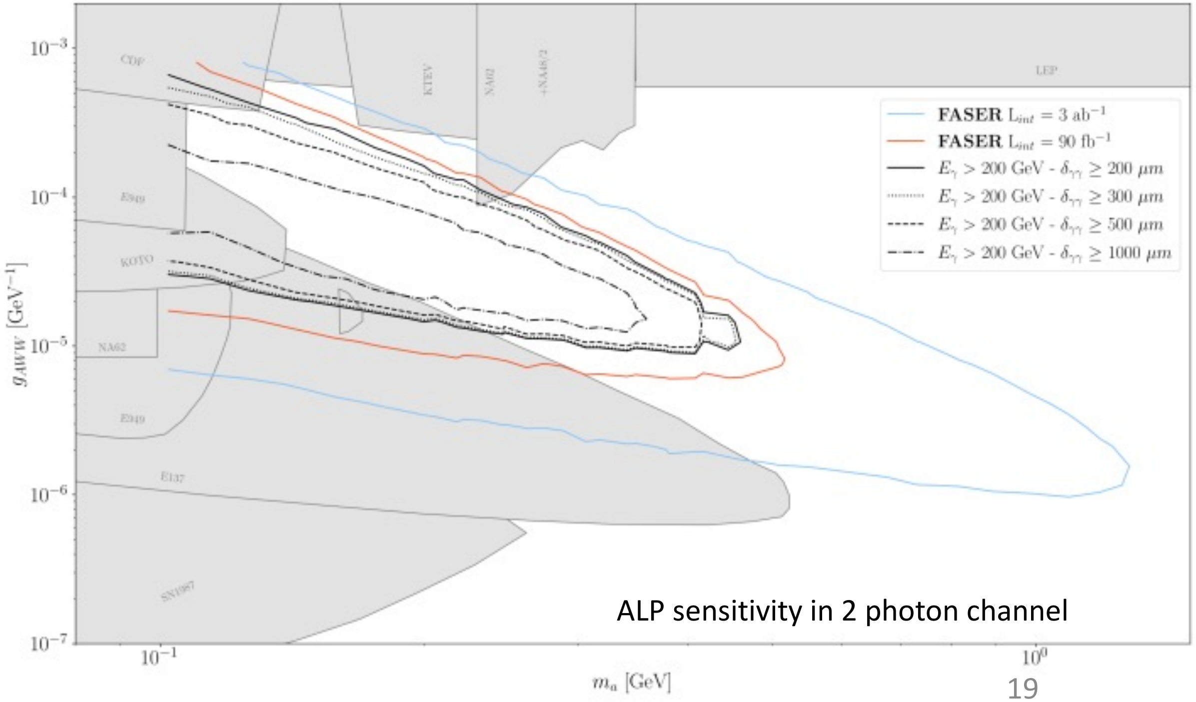
Reconstructed electron energy – 1.5 TeV, highest ever recorded electron neutrino interaction from an artificial source!

Preshower upgrade

CERN-LHCC-2022-006

- Current FASER preshower adds some longitudinal information on EM shower development, but no information in transverse plane
- For new particles decaying to 2 photons (such as ALPs) want to be able to reconstruct the 2 photons separately to control background (ν interactions in the calorimeter)
  - In FASER context, high energy photons with very small spatial separation (due to low mass and large boost of mother particle)
- Ongoing project to upgrade the preshower to high resolution silicon-pixel / tungsten detector
  - Designed to be able to identify showers separated by 0.2mm
  - 6 layers of pixels and tungsten plates
  - 130 nm SiGe BiCMOS technology
    - Hexagonal pixels with 65 µm sides
- Current status
  - Preproduction chips available in 6/22 and tested
    - Testbeam, and lab tests
  - Final ASIC production launched 5/23 with delivery expected in early 2024
  - Lots of progress on mechanics, readout, integration etc..
  - Plan to install into FASER during YETS 24/25



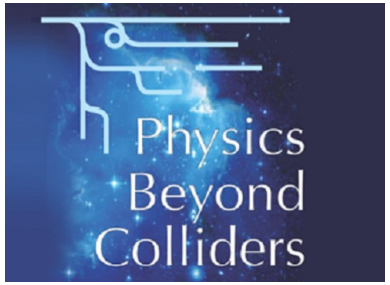


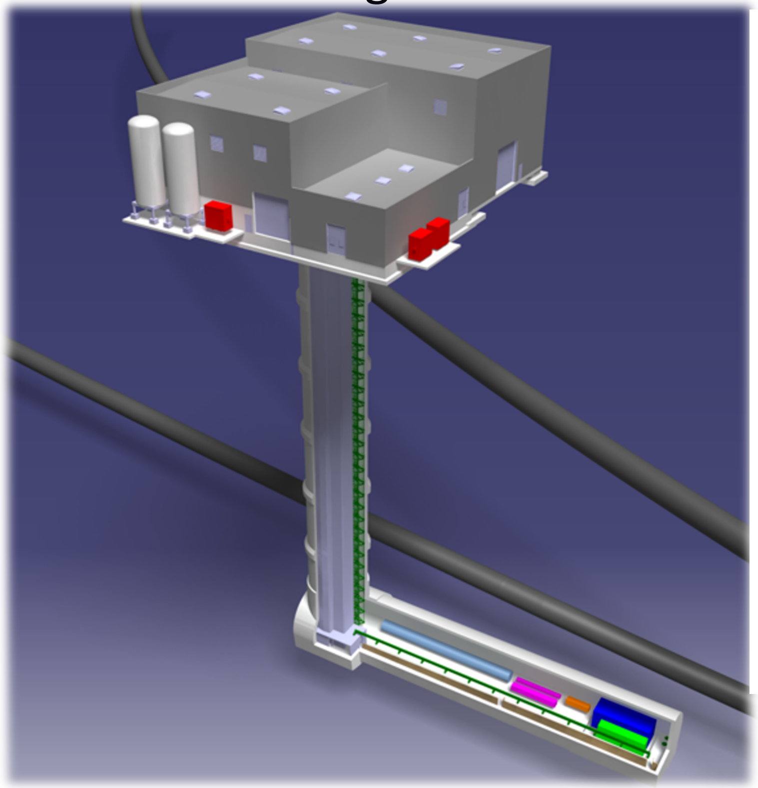
ALP sensitivity in 2 photon channel

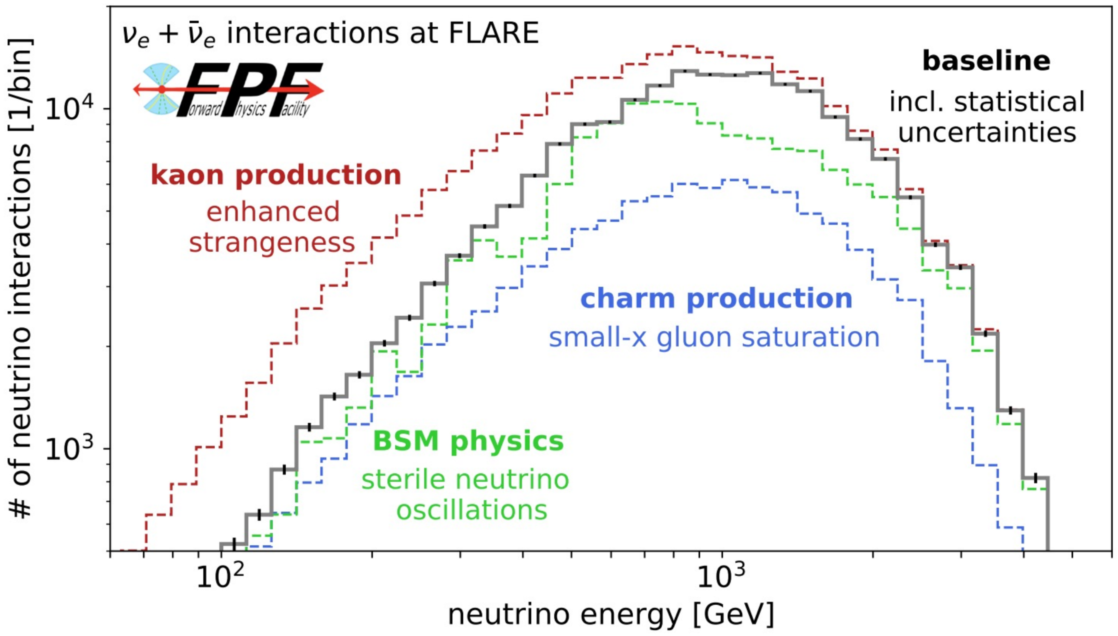
Forward Physics Facility (FPF)

arxiv:2203.05090

- FPF is proposed new facility to fully exploit the interesting physics along the LOS in the HL-LHC
- New cavern and shaft, 600m from IP1
- Would allow several new BSM and neutrino experiments
  - Up to 4 orders of magnitude increase in sensitivity for many BSM searches
  - Increase target mass, and rapidity coverage for neutrino experiments
- Study $\mathcal{O}(10^5)$ ν_e, $\mathcal{O}(10^6)$ ν_μ, $\mathcal{O}(10^4)$ ν_τ interactions at highest energies
  - Broad physics case covering QCD, neutrino physics, dark matter with stong links to astroparticle physics
- Site investigation carried out in Q1 2023 – geological conditions looks good for CE works







https://cerncourier.com/a/looking-forward-at-the-lhc/

Summary

https://faser.web.cern.ch/index.php/physics/publications

- FASER detector operating extremely well so far in Run 3
  - Nearly 70/fb of data recorded with data taking efficiency of 97%
  - Excellent detector performance
- First search for dark photons:
  - Exclude interesting parameter space motivated by dark matter
  - Almost background free search validates detector design/performance and bodes well for future searches with up to 10x more data in Run 3
- FASER has opened the door to neutrino studies at the LHC
  - First observation of collider muon neutrino interactions
  - First observation of electron neutrino interactions at a collider
    - Highest energy recorded neutrino events from an artificial source
  - Demonstrate emulsion-based neutrino experiments can make measurents in challenging conditons at the LHC
- FASER preshower upgrade
  - To be installed in YETS 24/25
  - Will enable sensitive ALP searches
- Based on the excellent performance and smooth operations, we have started the process to request to continue running FASER after LS3
- Longer term Forward Physics Facility proposal to fully exploit the huge physics potential in the very forward region during the HL-LHC era

Huge thanks to everyone who has helped with FASER over the last 4 years

FASER Acknowledgements

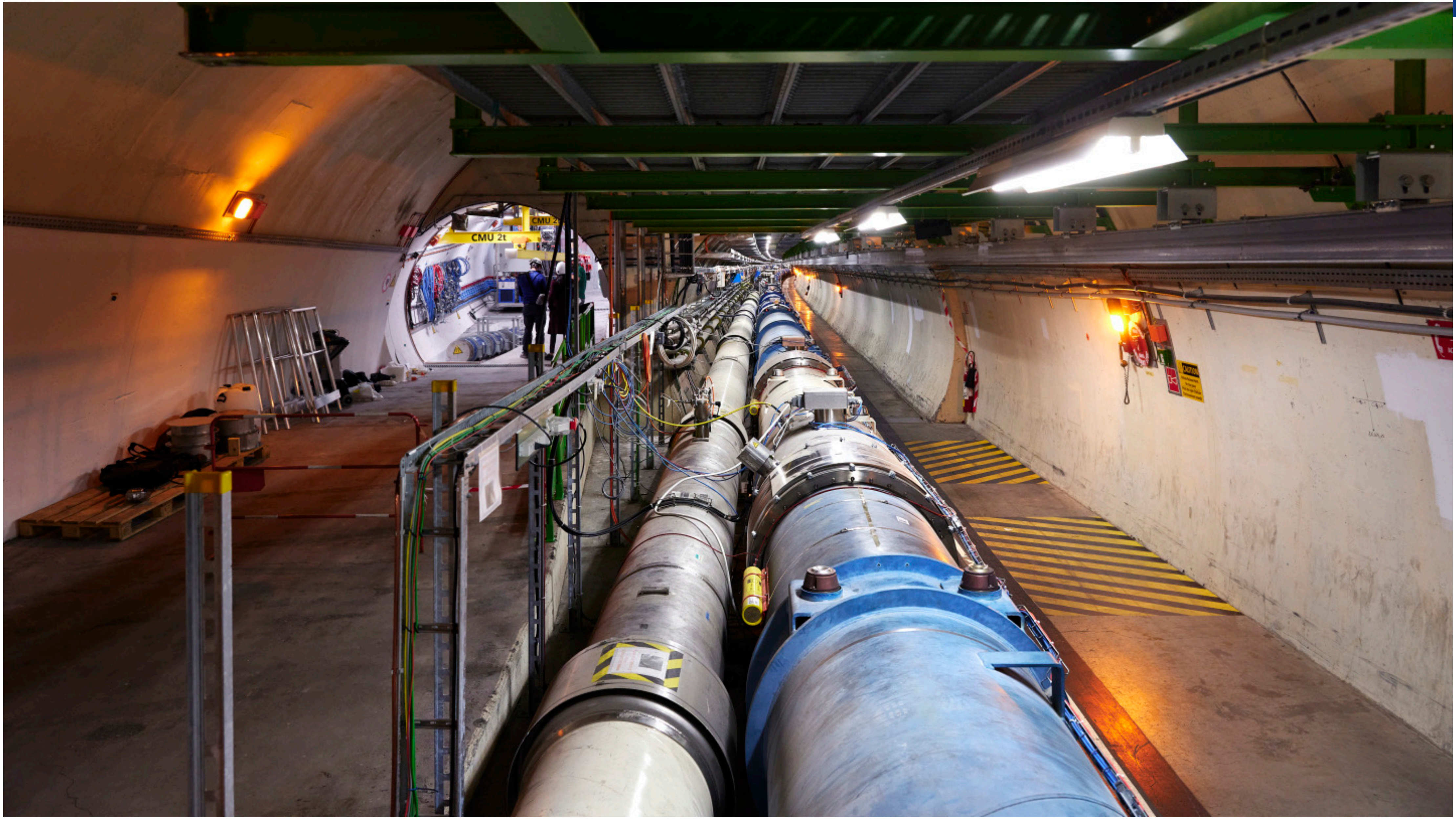
- FASER is supported by:

HEISING-SIMONS FOUNDATION · SIMONS FOUNDATION · CERN · erc · 科研費 KAKENHI · NSF · Swiss National Science Foundation

- 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 modules
  - CERN FLUKA team for the background simulation
  - CERN PBC and technical infrastructure groups for the excellent support

Visit of Jim Simons and Mark Heising to FASER in 1/23

Backup

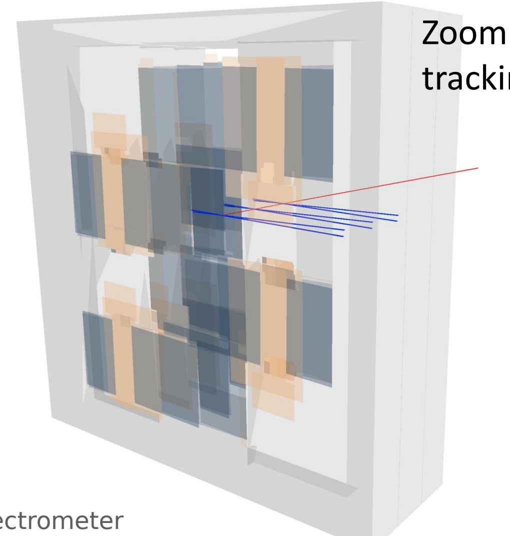


FASER Collaboration

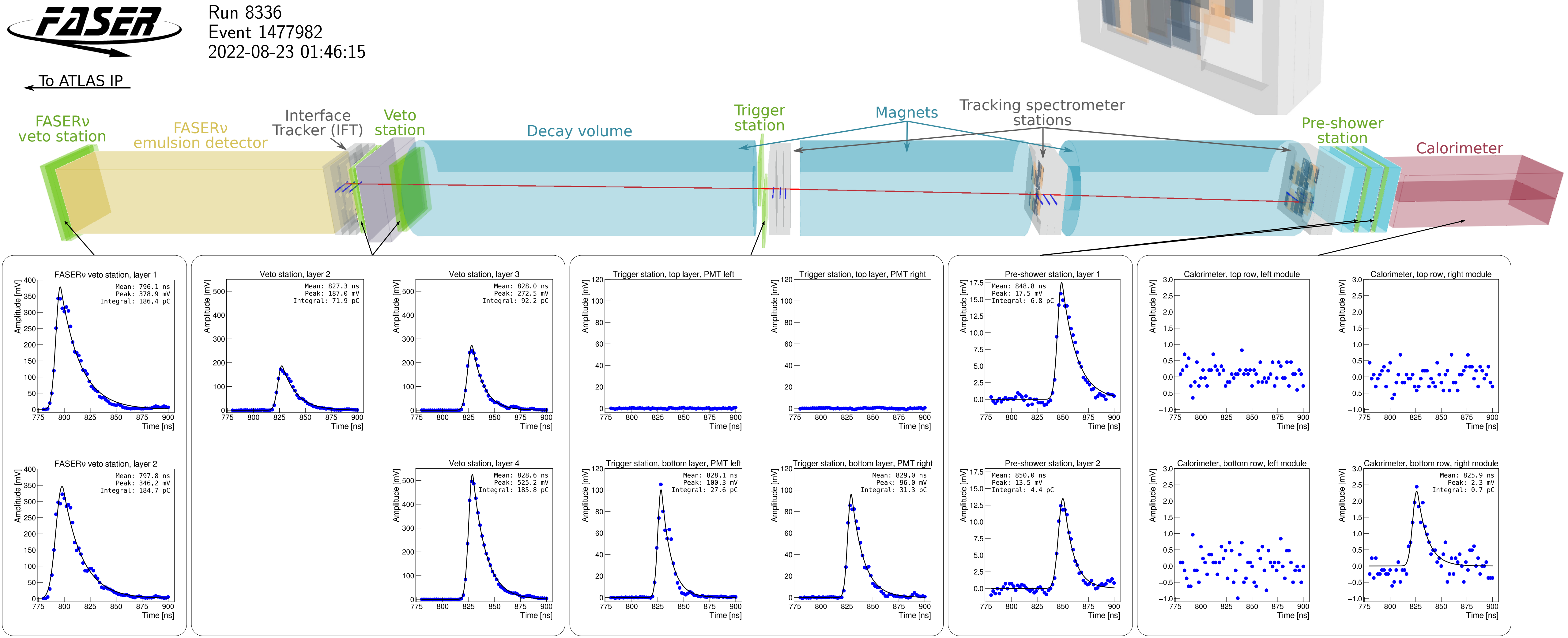
The FASER collaboration consists of 84 members from 24 institutions and 10 countries

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大學 Tsinghua University
MANCHESTER 1824 The University of Manchester
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX
Nikhef
DESY.
International laboratory covered by a cooperation agreement with CERN
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Event display showing a muon traversing the full detector.
All parts of the detector performing as expected.



Zoom in of 1st tracking station

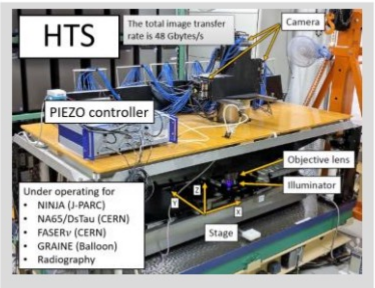


FASERν

Workflow







In Japan
- **Emulsion film production** →

At CERN
- **Detector assembling** → **Exposure** → **Disassembling** → **Development** →

In Japan
- **Full area readout**

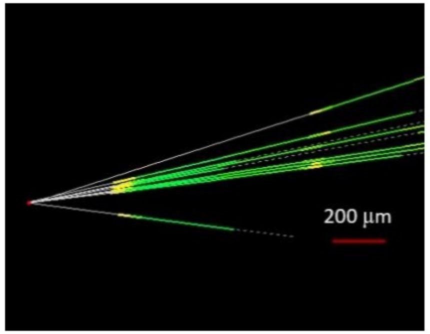
↓

Off-line analysis

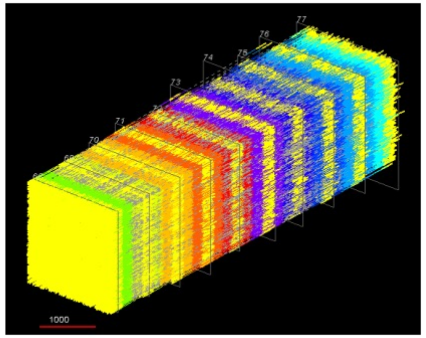
Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

Interface tracker data

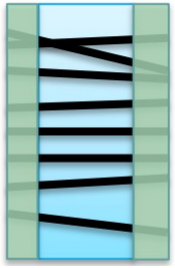
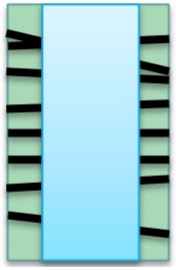
Spectrometer data



500-1000 TB/Run3



~500 TB/Run3

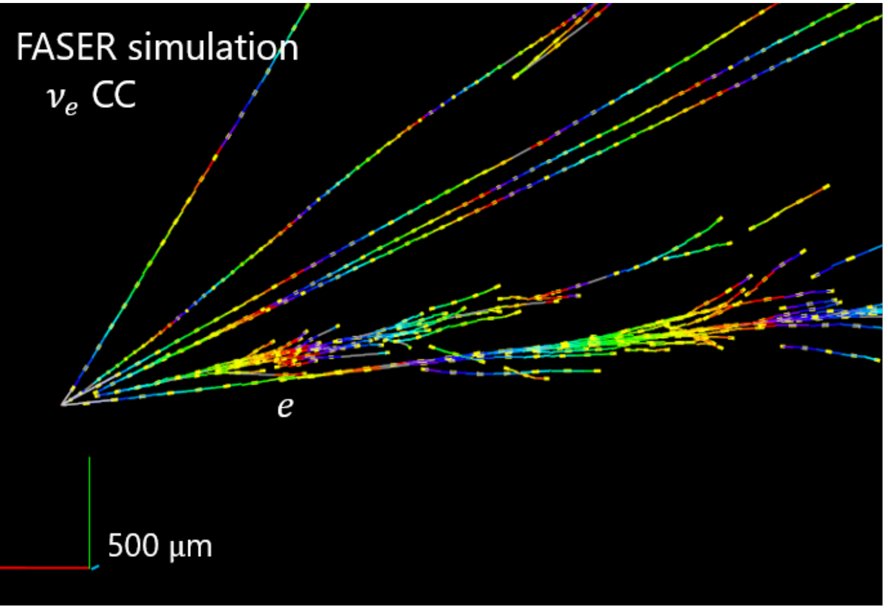



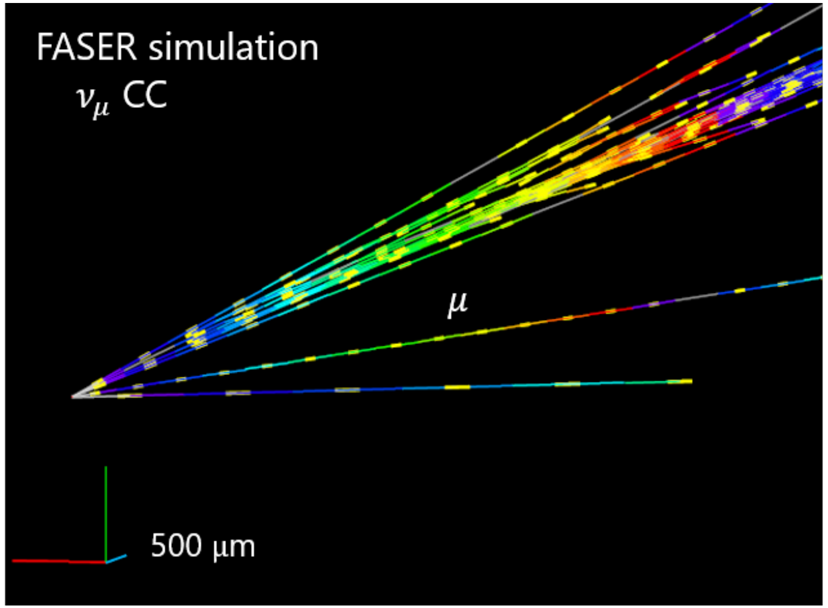
FASERν expected signal rate

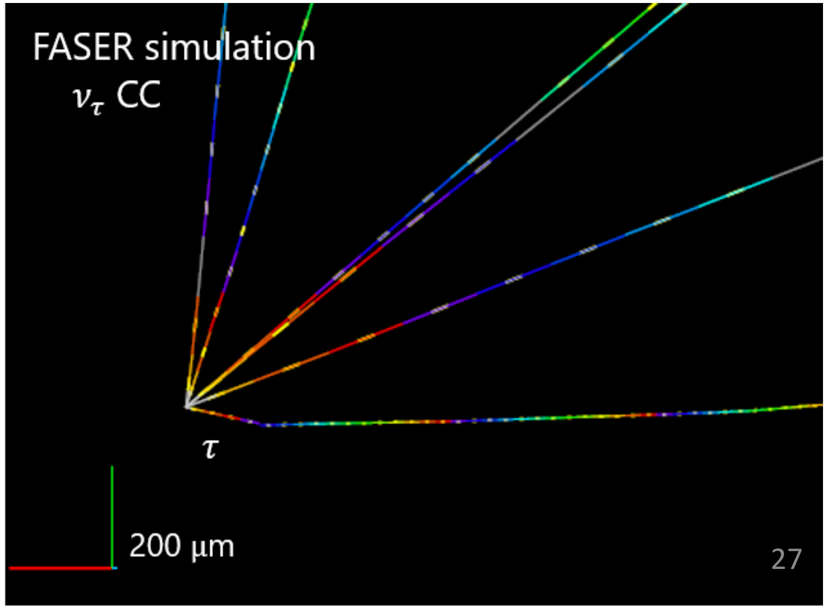
Based on
F. Kling and L. J. Nevay,
"Forward Neutrino Fluxes at the LHC",
Phys. Rev. D 104, 113008

Expected number of CC interactions (250 fb^{-1})

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$

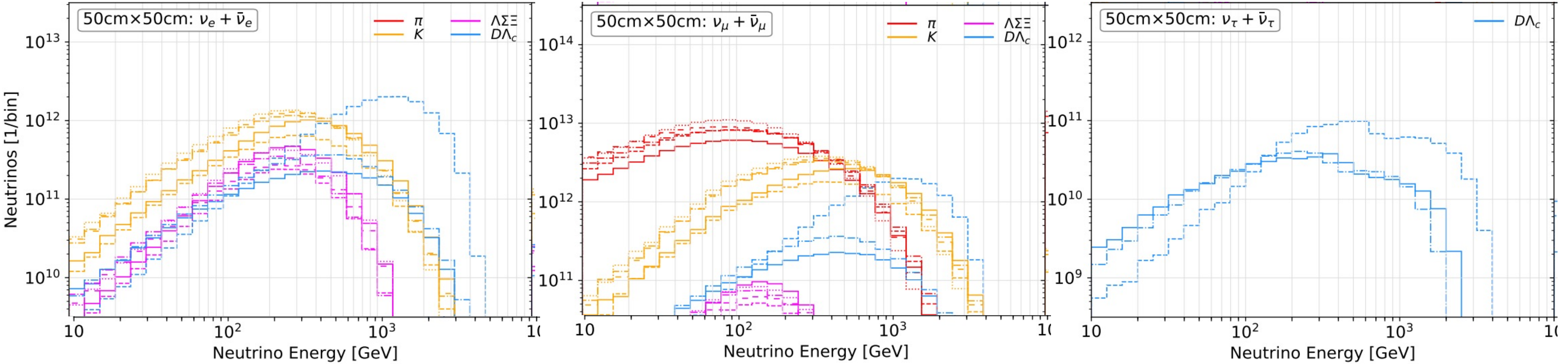






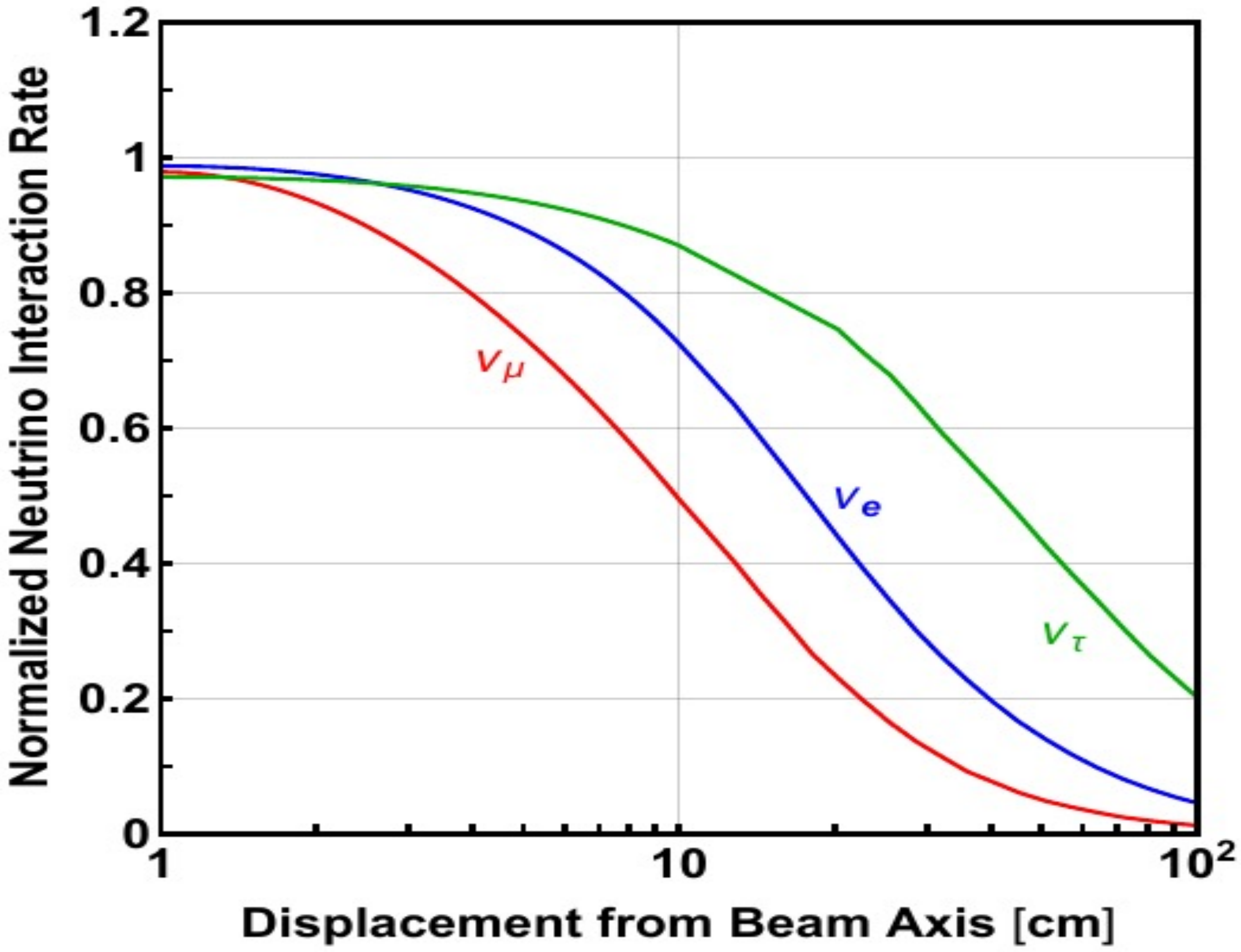
Neutrino production at LHC

- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \rightarrow \nu\mu$, $K \rightarrow \nu_e$ (at high-energy/off-axis $D \rightarrow \nu_e$), $D \rightarrow \nu\tau$



Large differences between generators on rate of forward hadron production, especially for charm:
SIBYLL 2.3d (solid), DPMJet 3.2017 (short dashed), EPOS-LHC (long dashed), QGSJet II-04(dotted), and Pythia 8.2 (dot-dashed)

Neutrino production at LHC

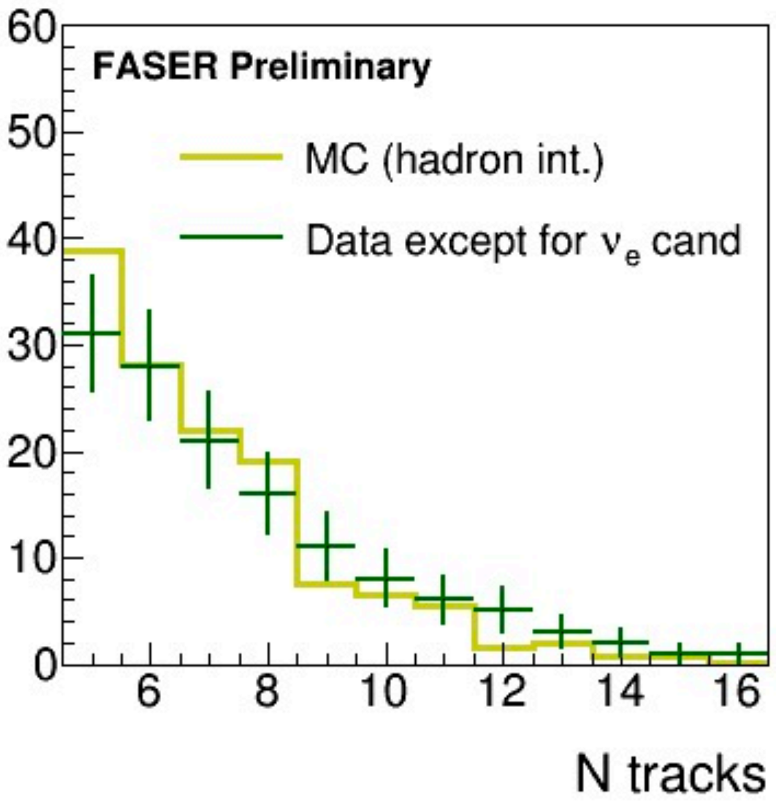


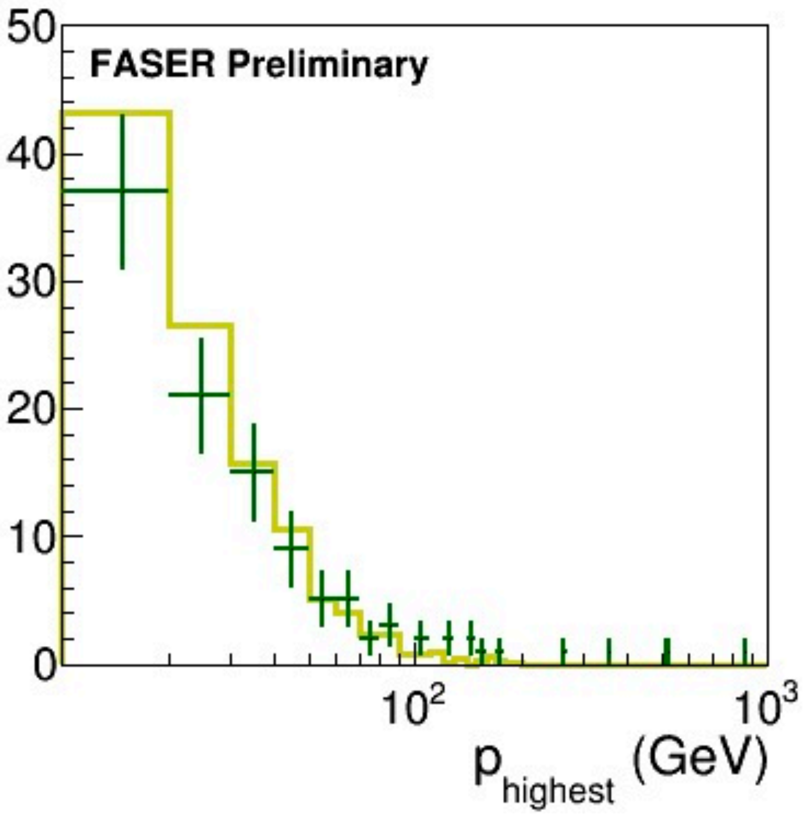
Neutrino flux for all flavours maximized on the collision axis line of sight.

- Muon neutrinos (mostly from pion decay) are very collimated (~50% flux 10cm from LOS)
- Electrons neutrinos (mostluy from kaon decay) are more spread out (~50% at 20cm)
- Tau neutrinos (from charm decay) are much more spread out (~50% at 50cm)

FASERν Background Validation

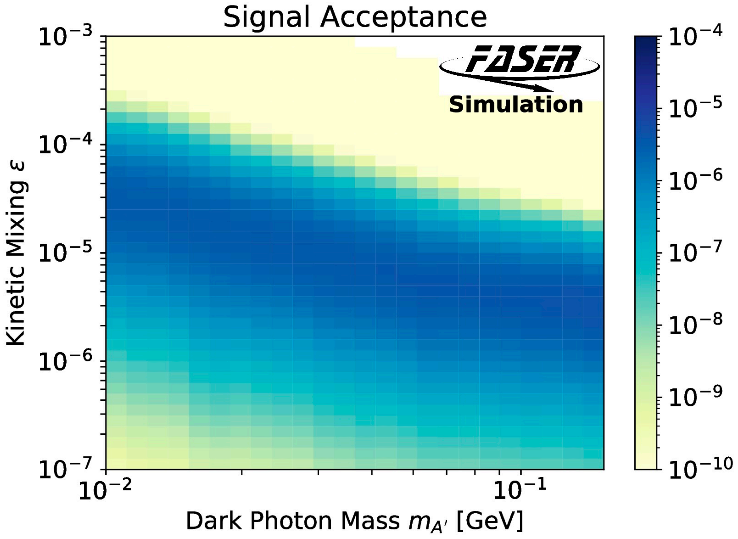
MC predicts 216 neutral hadron vertices in analyzed volume.
Observe 133 neutral vertices (not passing high energy neutrino selection).
Comparsion between data/MC shown (MC normalized to data)



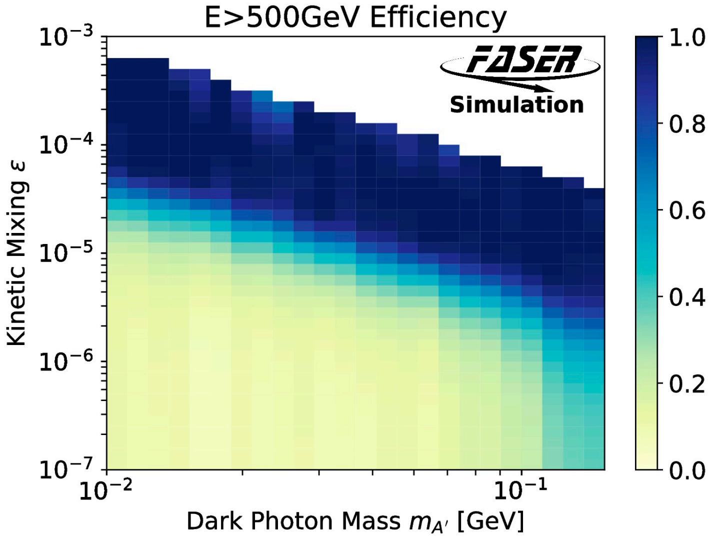


Dark Photon Search

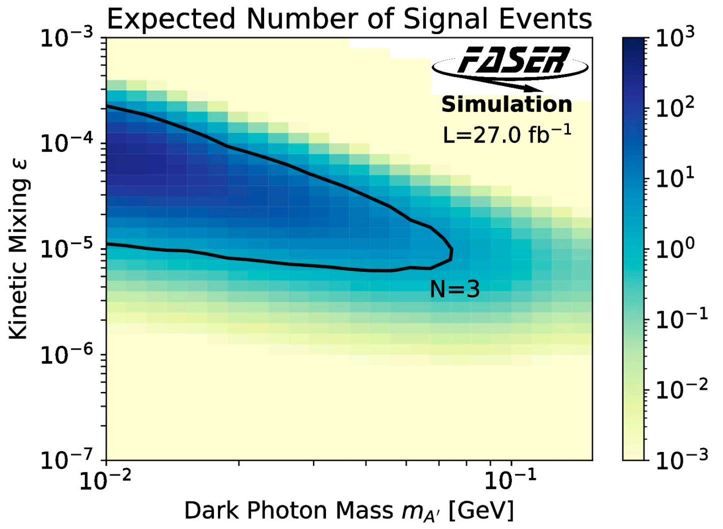
arxiv:2308.05587
(submitted to PLB)



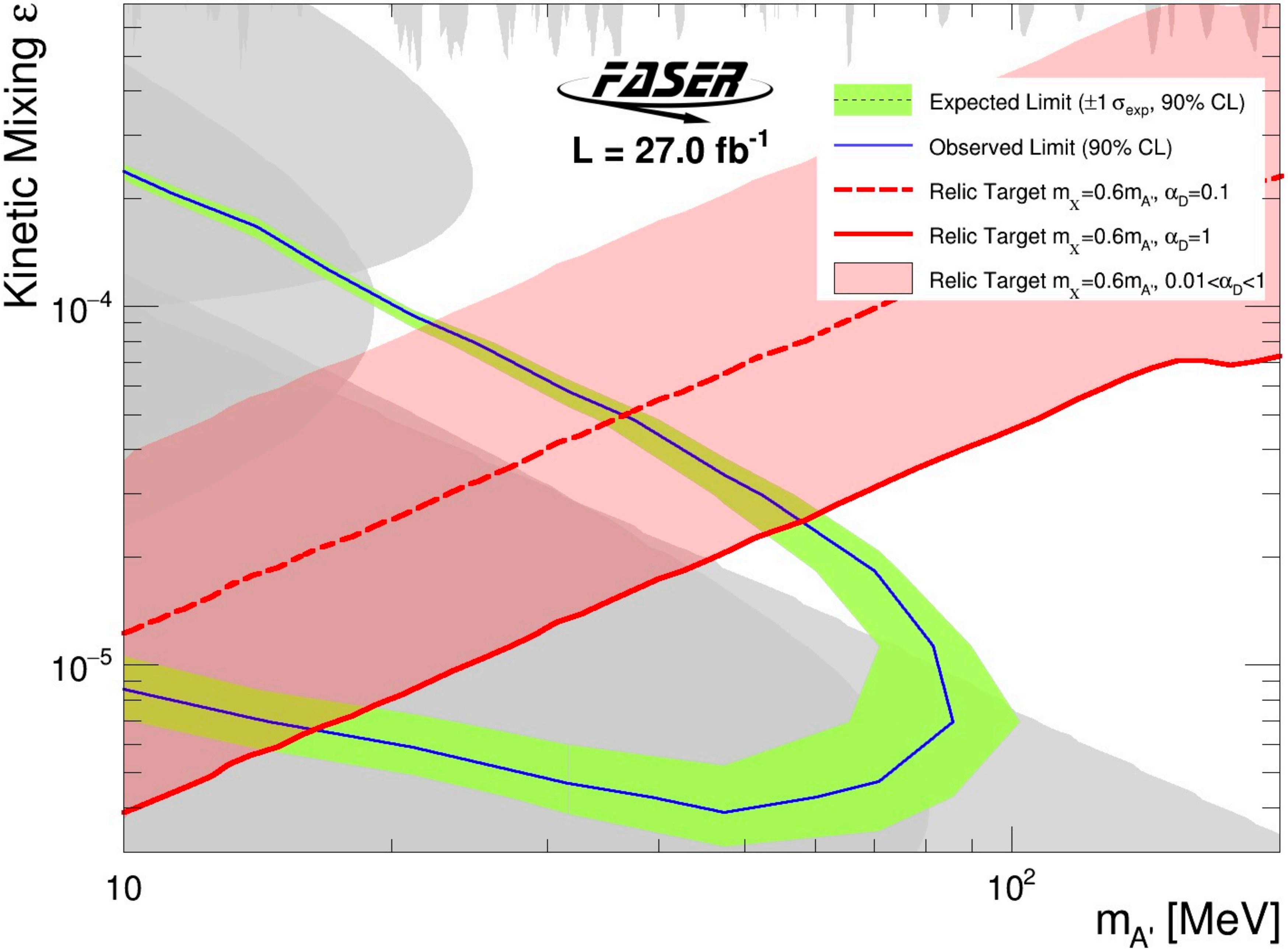
Acceptance for dark photon to decay inside FASER



Fraction of these with E>500 GeV



Truth level expected number of signal events with E>500GeV and 50% efficiency



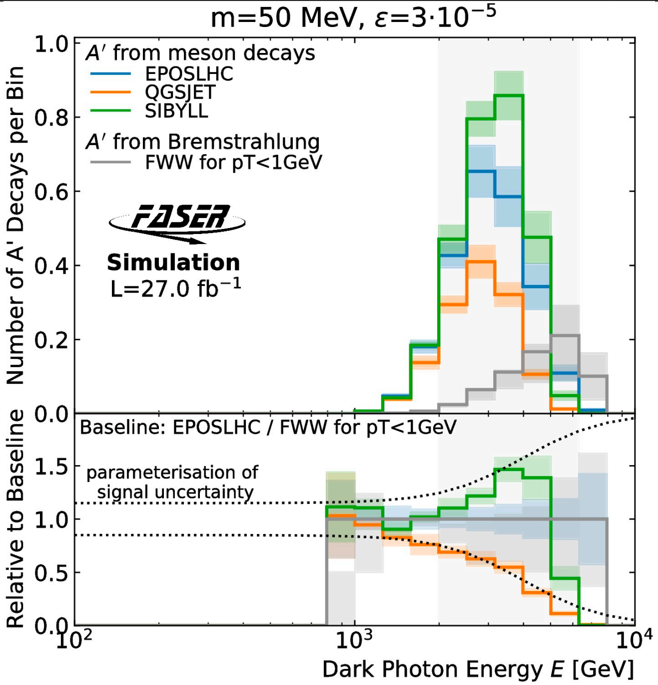
FASER
L = 27.0 fb-1
Expected Limit (±1 σexp, 90% CL)
Observed Limit (90% CL)
Relic Target mX=0.6mA', αD=0.1
Relic Target mX=0.6mA', αD=1
Relic Target mX=0.6mA', 0.01<αD<1
Kinetic Mixing ε
10−4
10−5
10
102
mA' [MeV]

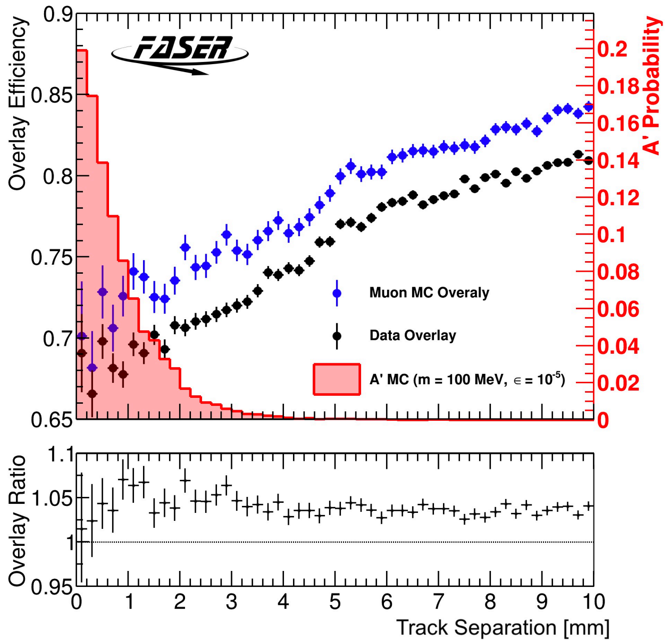
Dark Photon Search

arxiv:2308.05587
(submitted to PLB)

Systematic uncertainties on expected signal yield:

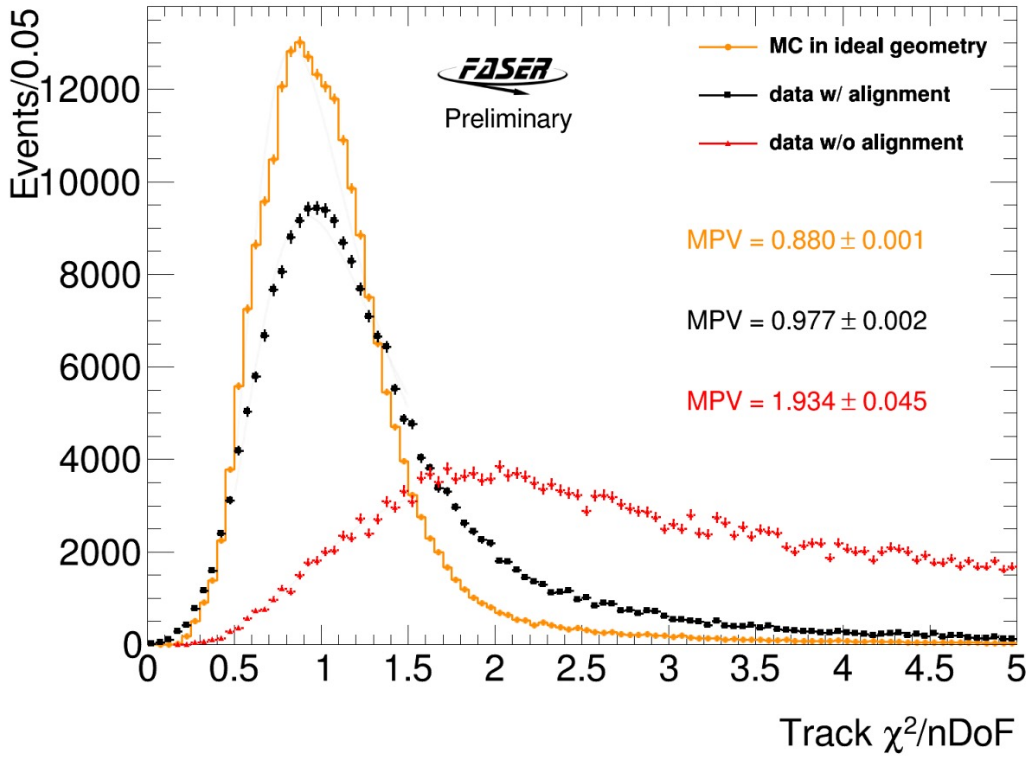
Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Track Momentum Scale	5%	$< 0.5\%$
Track Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	7%	7%
Calo E scale	6%	0-8% ($< 1\%$)

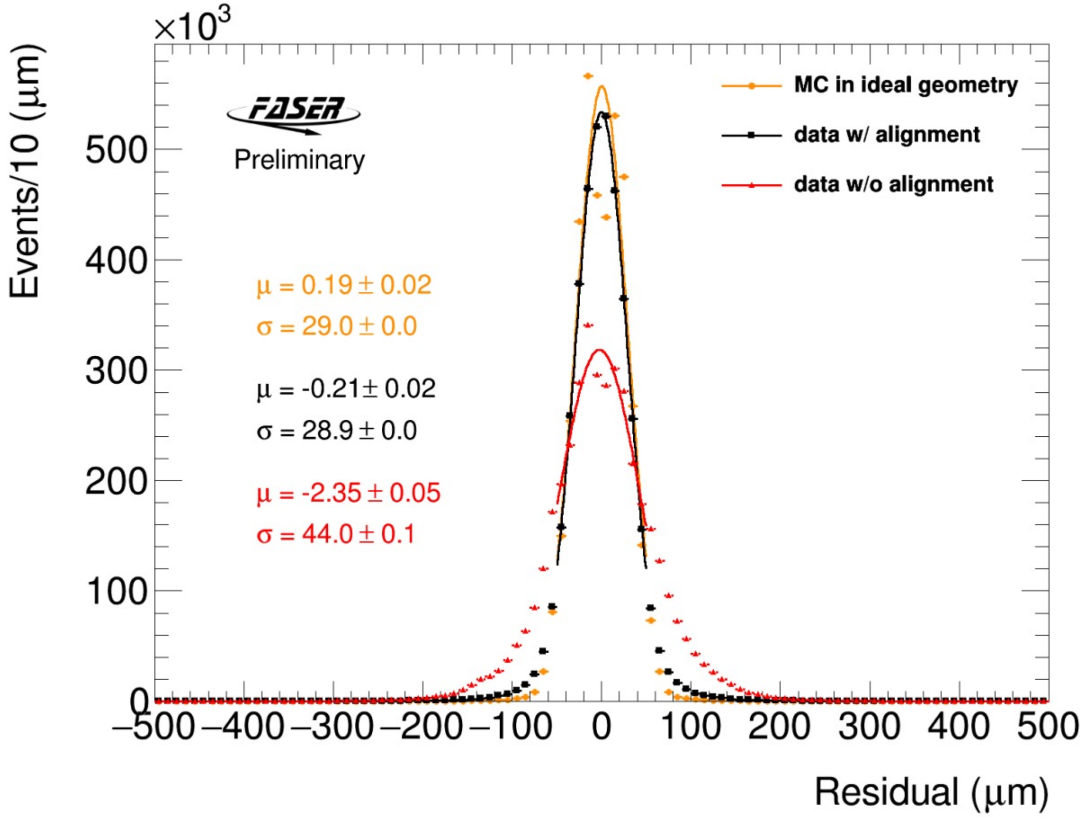




Tracker Alignment

Current tracker alignment of 2 most sensitive degrees of freedom at module level:



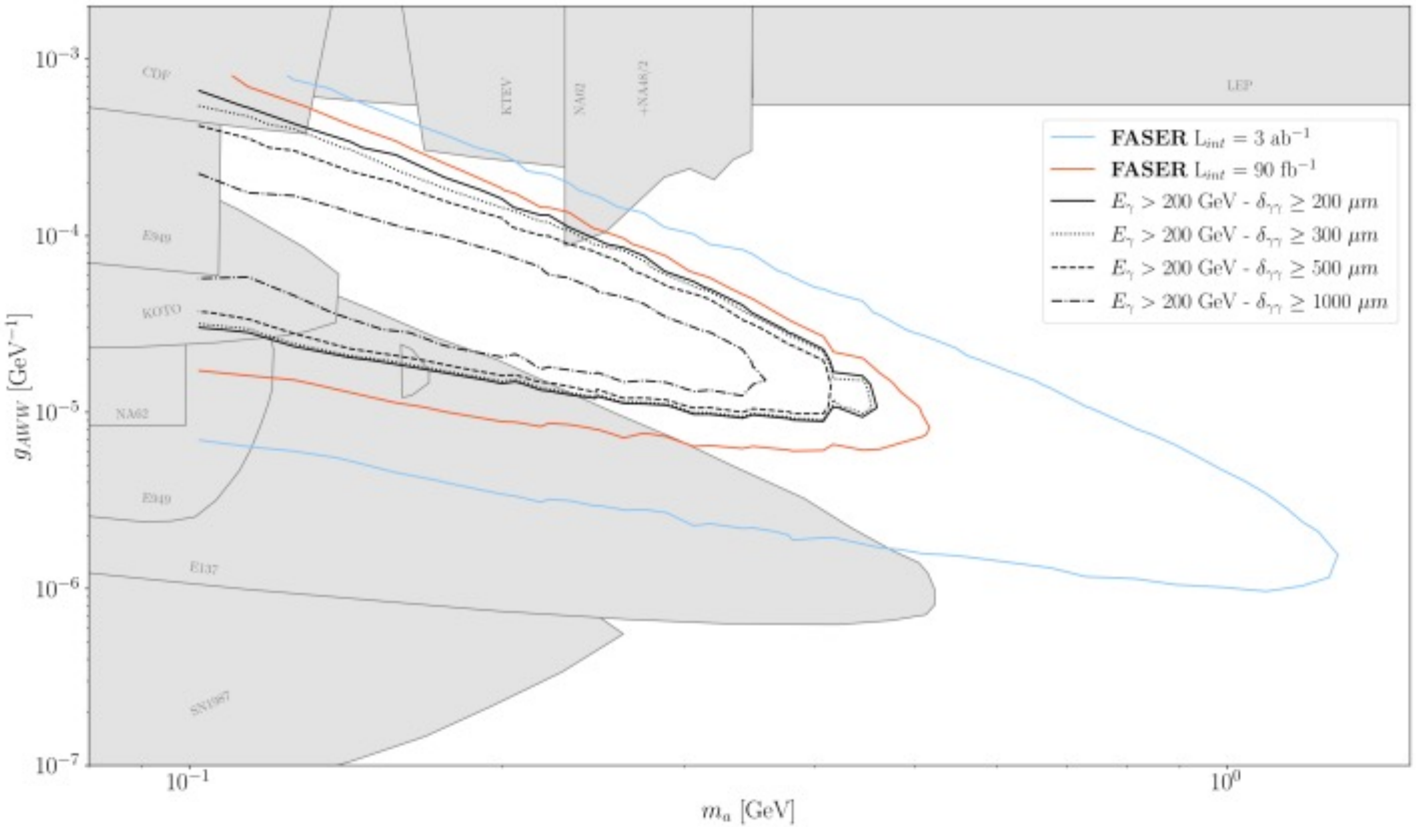


Work ongoing to improve alignment with 6 DOF.

Request to keep operating FASER after LS3

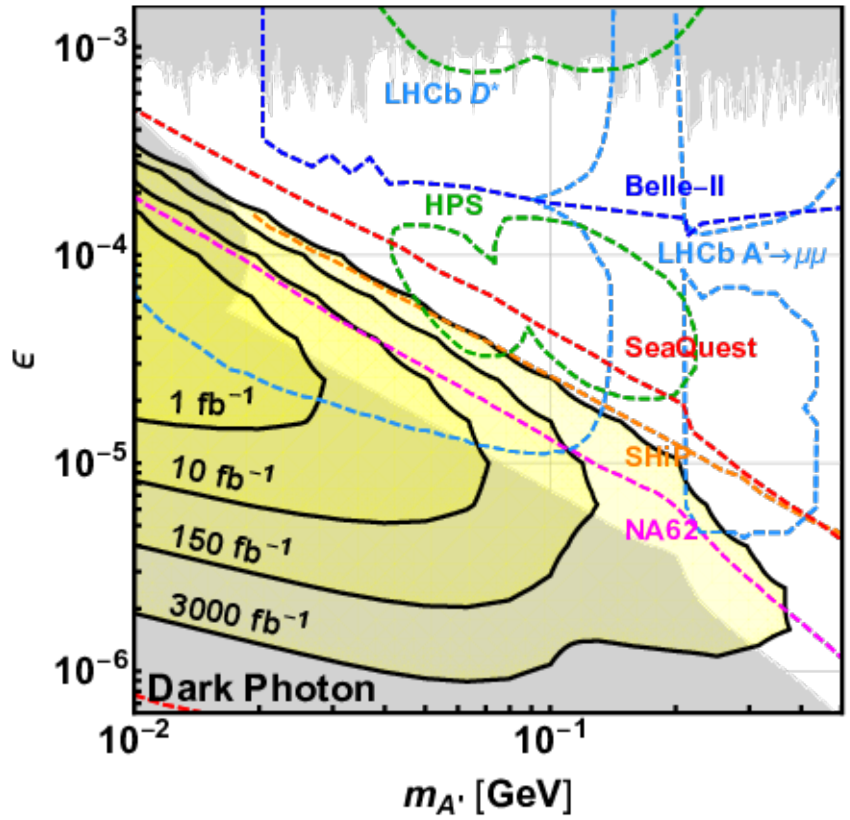
Example increase in sensitivity for FASER after Run 3:

CERN-LHCC-2022-006



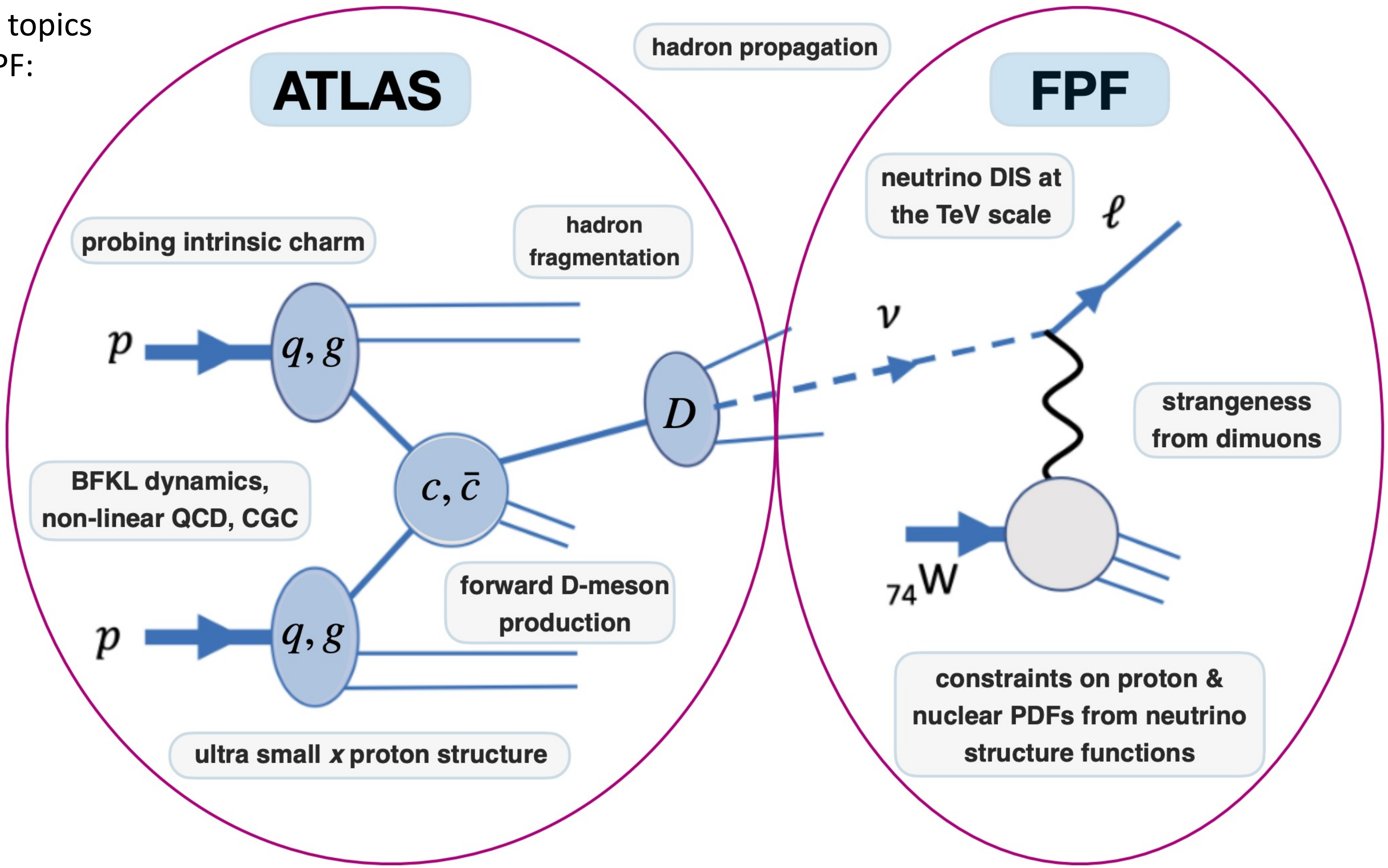
Large increase in sensitivity for ALP search with upgraded preshower

[2207.11427](2207.11427)



QCD at the FPF

Many interesting QCD topics to be studied at the FPF:



FPF Location