UNIVERSITY OF LIVERPOOL

FASER

The Search for Axion-Like Particles with the FASER Experiment at the LHC

IOP Joint APP, HEPP and NP Annual Conference 2024

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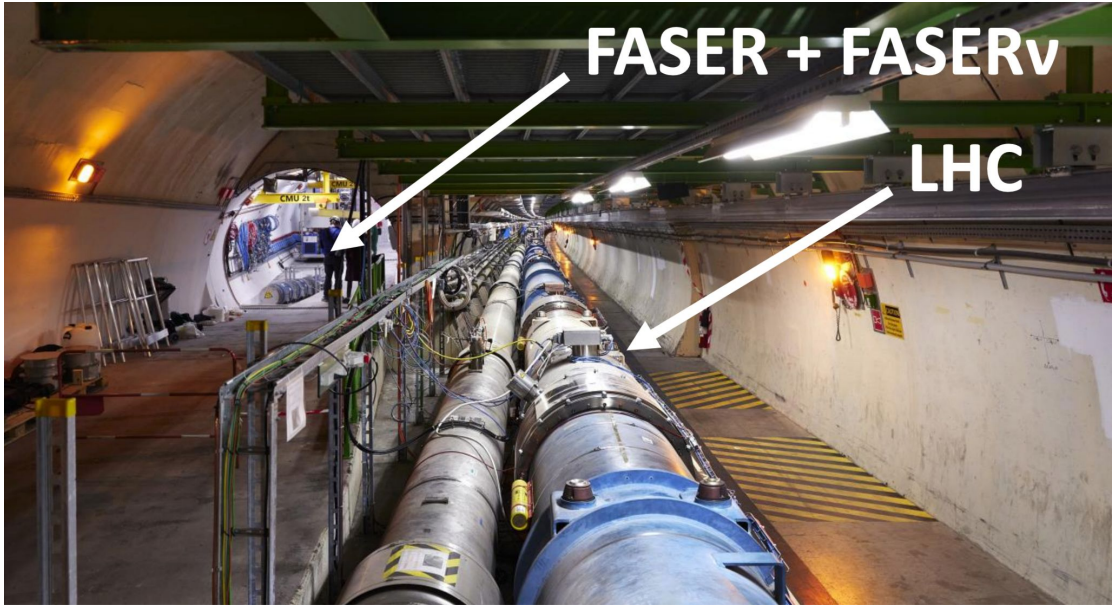
FASER Location

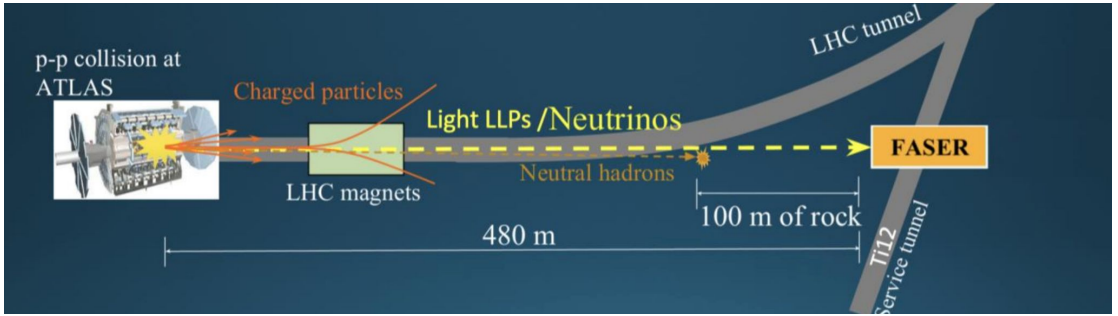
FASER is a small experiment designed to search for new long-lived particles (LLPs), and to study high energy neutrinos, produced at the ATLAS Interaction Point.

Located 480m downstream of ATLAS, shielded with 100m of rock and concrete

Exploits large LHC collision rate with highly collimated forward production of light particles

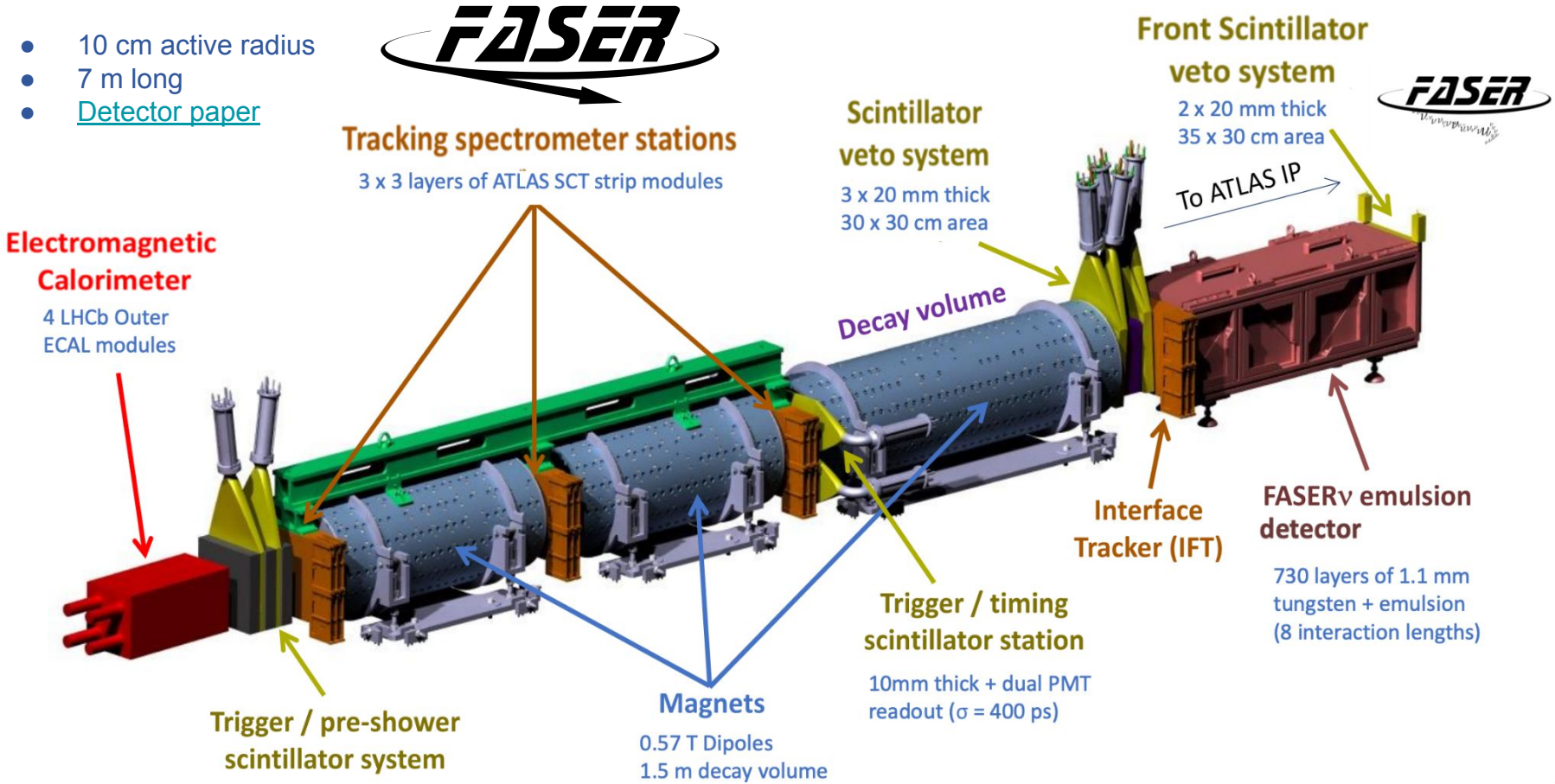
FASER targets new long-lived BSM particles including dark photons and **ALPs**



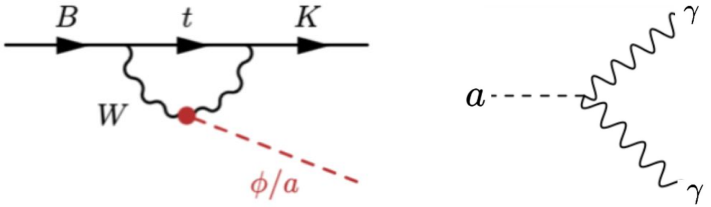


The FASER Detector

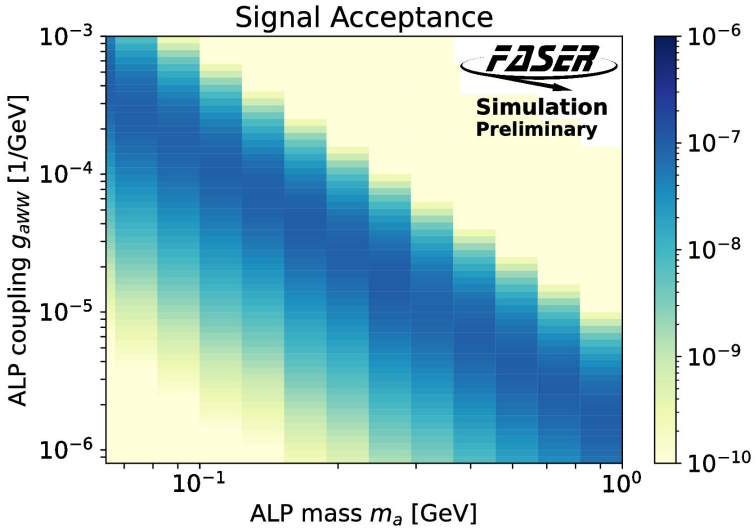
- 10 cm active radius
- 7 m long
- Detector paper

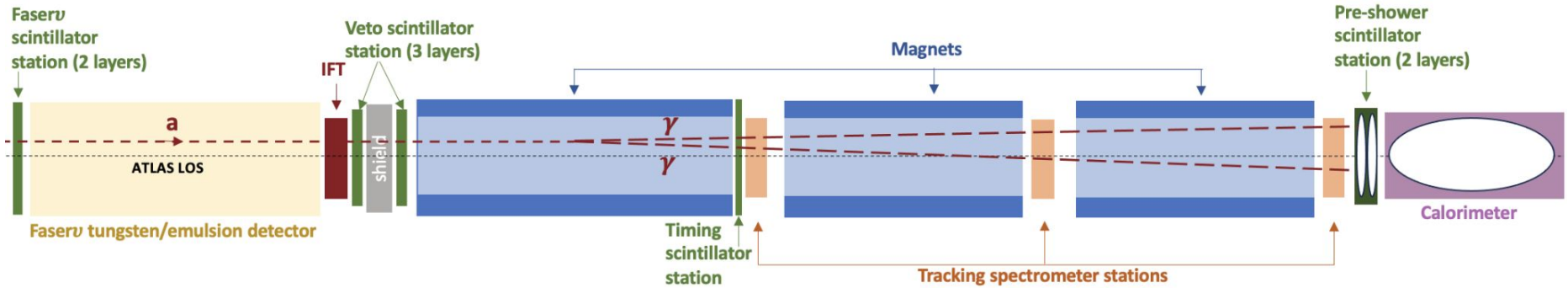


ALPs in FASER



- FASER is sensitive to axion-like particles (ALPs)
  - Coupling to SU(2)L gauge bosons
- Primarily produced in B meson decays in our sensitivity range
- Can decay anywhere in FASER spectrometer
- Decays to 2 high energy photons
  - Cannot be distinguished in our calorimeter



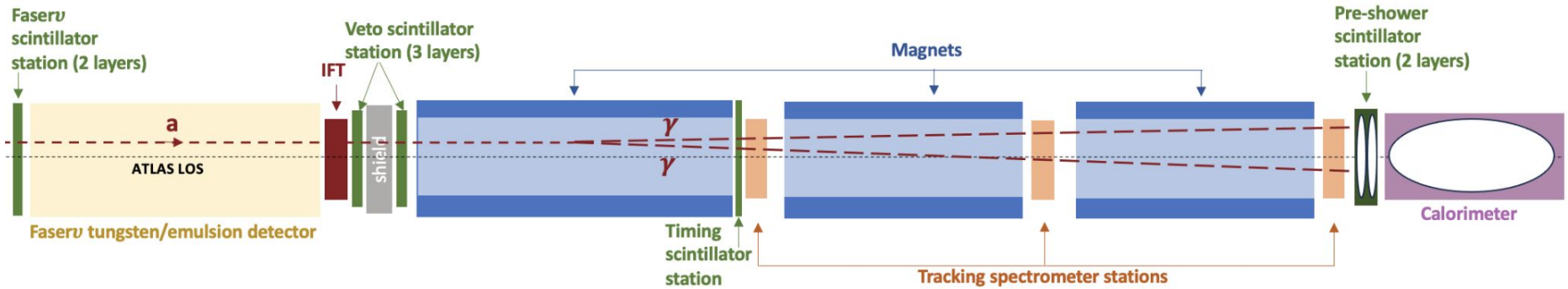


ALP Event Selection

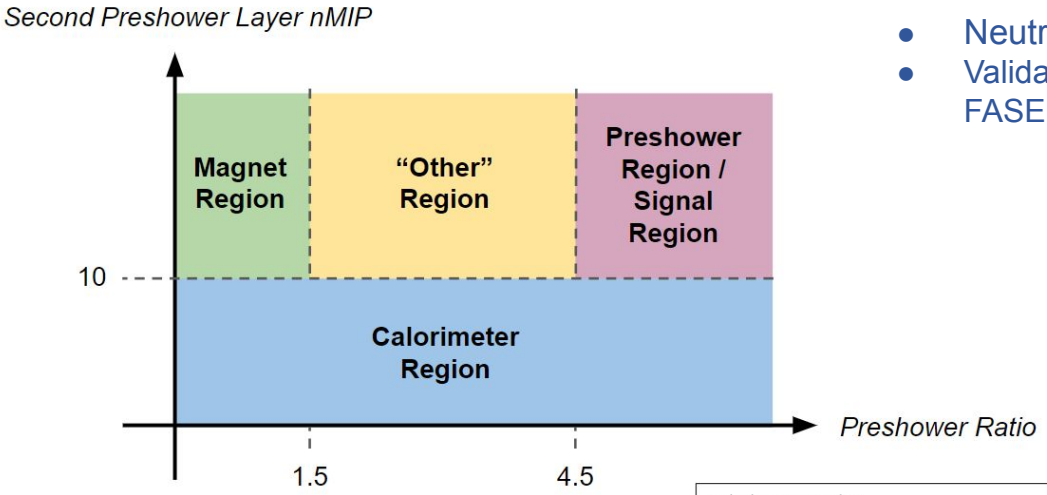
Trigger and Data Quality
Selecting events with calorimeter triggers
Calorimeter timing (> -5 ns and < 10 ns)
Baseline Selection
Veto/VetoNu Scintillator to have no signal (< 0.5 MIPs)
Timing Scintillator to have no signal (< 0.5 MIPs)
Signal Region
Preshower Ratio to have EM shower in the Preshower (> 4.5)
Second Preshower Layer to have signal (> 10 MIPs)
Calorimeter to have a large deposit (> 1.5 TeV)

- Require that there is:
  - No signal in any of the 5 veto scintillators
  - No signal in the timing scintillator station
  - Evidence of an EM shower in the preshower detector
  - Significant energy deposits in the electromagnetic calorimeter
    - Of at least **1.5 TeV**

The main background in this analysis arises from non-negligible charged-current neutrino interactions

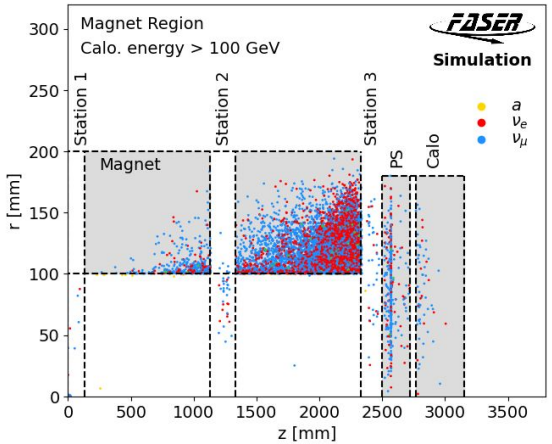


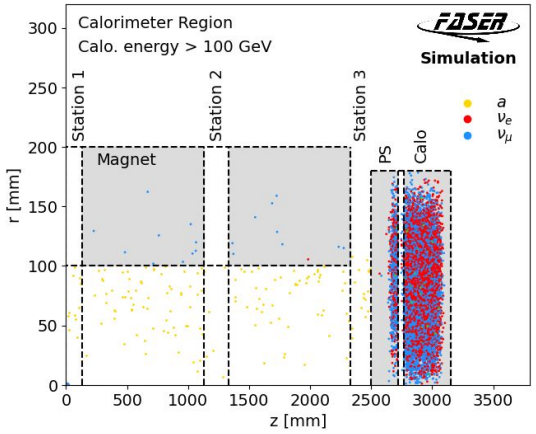
Background Estimation - Neutrino Interactions

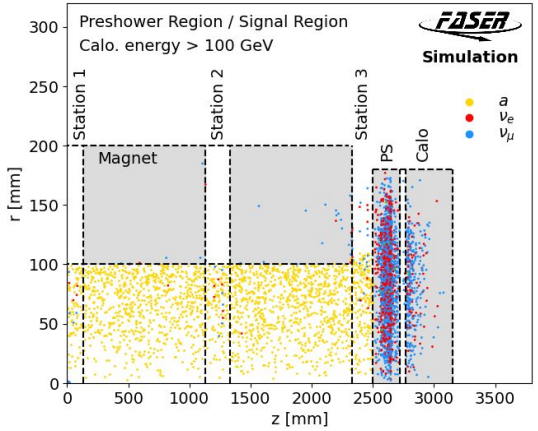


- Neutrino background evaluated using MC simulations
- Validated in data control regions defined based on where in FASER neutrinos interact

Neutrino MC Prediction for 57.7 fb^{-1}	
Light	$0.23^{+0.01}_{-0.11}$ (flux) ± 0.11 (exp.) ± 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) ± 0.06 (exp.) ± 0.03 (stat.)
Total	**0.42 ± 0.38 (90.6%)**







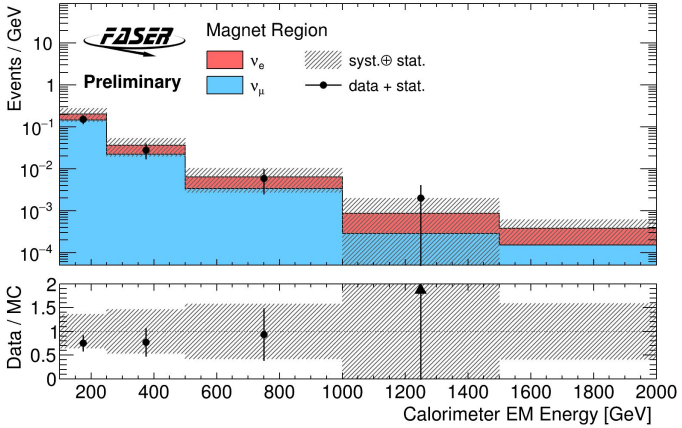
Background Estimation

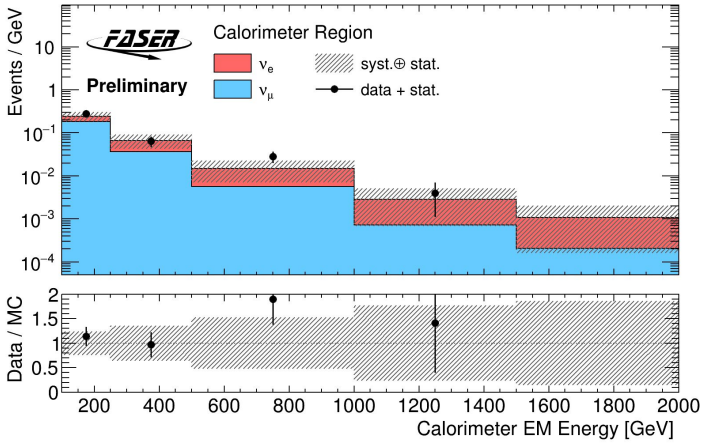
- Good agreement between neutrino MC prediction and data in validation regions

Calorimeter Region	
MC	62.7 ± 19.7 (31.4%)
Data	74

Magnet Region	
MC	43.5 ± 18.2 (41.9%)
Data	34

Preshower Region	
MC	17.8 ± 5.1 (28.8%)
Data	15





Other sources of (negligible) background considered in this analysis:

- Large angle muons
  - Those not dealt with by veto scintillators
- Neutral hadrons
- Non-collision beam 1 background and cosmics

A Note on Systematic Uncertainties

The various sources of systematic uncertainty in this analysis can be defined in 3 categories:

- Theory
  - The uncertainty associated with flux modelling and generator variation
- Experimental
  - The uncertainty on luminosity measurement
  - The uncertainty associated with our preshower and calorimeter cuts
- Statistical uncertainty

The dominant source of uncertainty is the uncertainty derived from the different MC generators

Background systematics:

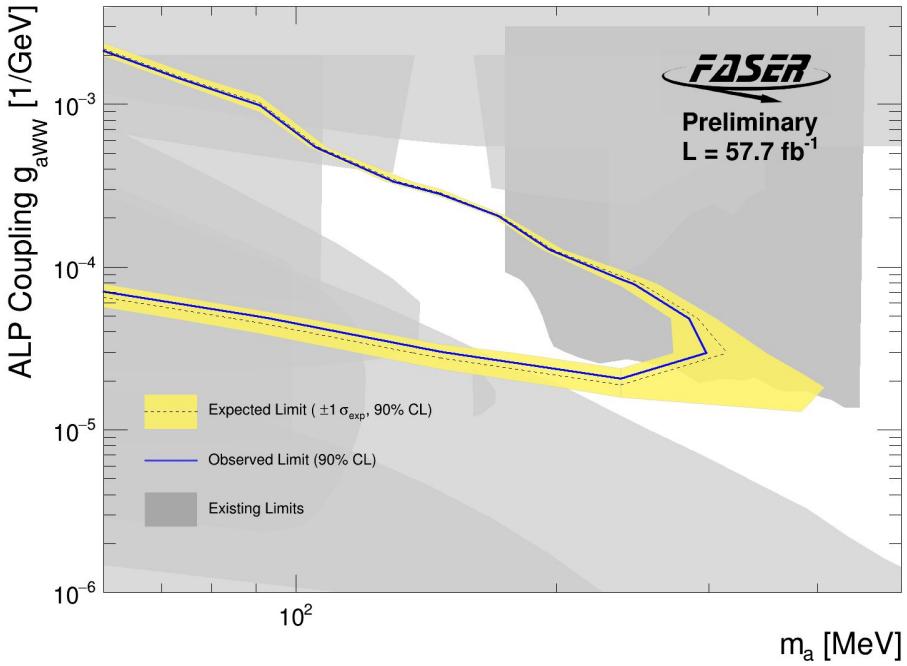
Event Rate
0.42 ± 0.32 (flux)
± 0.14 (calo. energy)
± 0.06 (PS ratio)
± 0.02 (PS 1 nMIP)
± 0.05 (stat.)
Total: 0.42 ± 0.38 (90.6%)

Signal systematics:

Signal Sample	Flux	Stat.	Luminosity	Calorimeter	Second Preshower Layer	Preshower Ratio
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}	59.4%	1.8%	2.2%	3.6%	0.6%	7.9%
$m_a = 120$ MeV, $g_{aWW} = 10^{-4}$ GeV^{-1}	57.3%	3.5%	2.2%	16.3%	0.6%	6.9%
$m_a = 300$ MeV, $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1}	58.0%	2.9%	2.2%	15.8%	0.6%	8.4%

ALP Unblinded Results

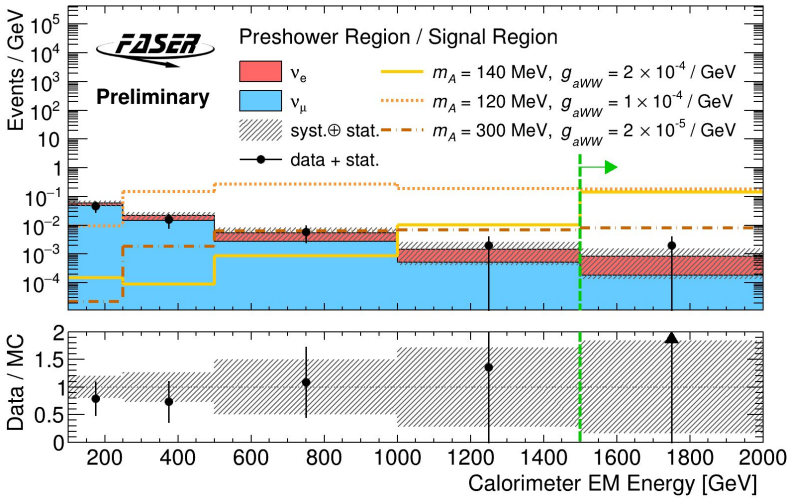
Observed limit:



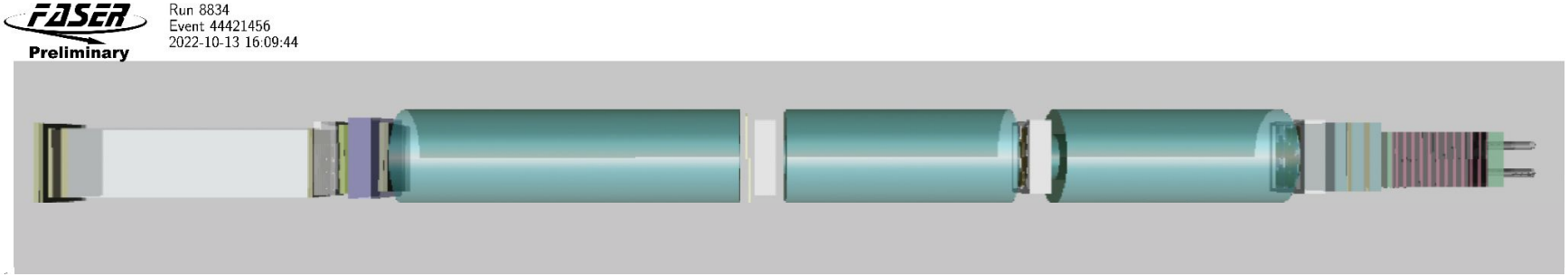
In 57.7 fb^{-1} of data we saw **1 event** in our unblinded signal region

- Compared to expected background of 0.42 ± 0.38 events
- Shows preshower deposits consistent with an EM shower
- Calorimeter energy of **1.6 TeV**

Unblinded Signal Region:



Summary



FASER has probed new parameter space with the ALP model

- At mass and coupling previously unexplored by existing experiments

A conference note on these new results has been published! Link to conf paper

Thank you for listening!

FASER is supported by:

The FASER Collaboration

96 collaborators, 26 institutions, 10 countries

International laboratory covered by a cooperation agreement with CERN

Backup Slides

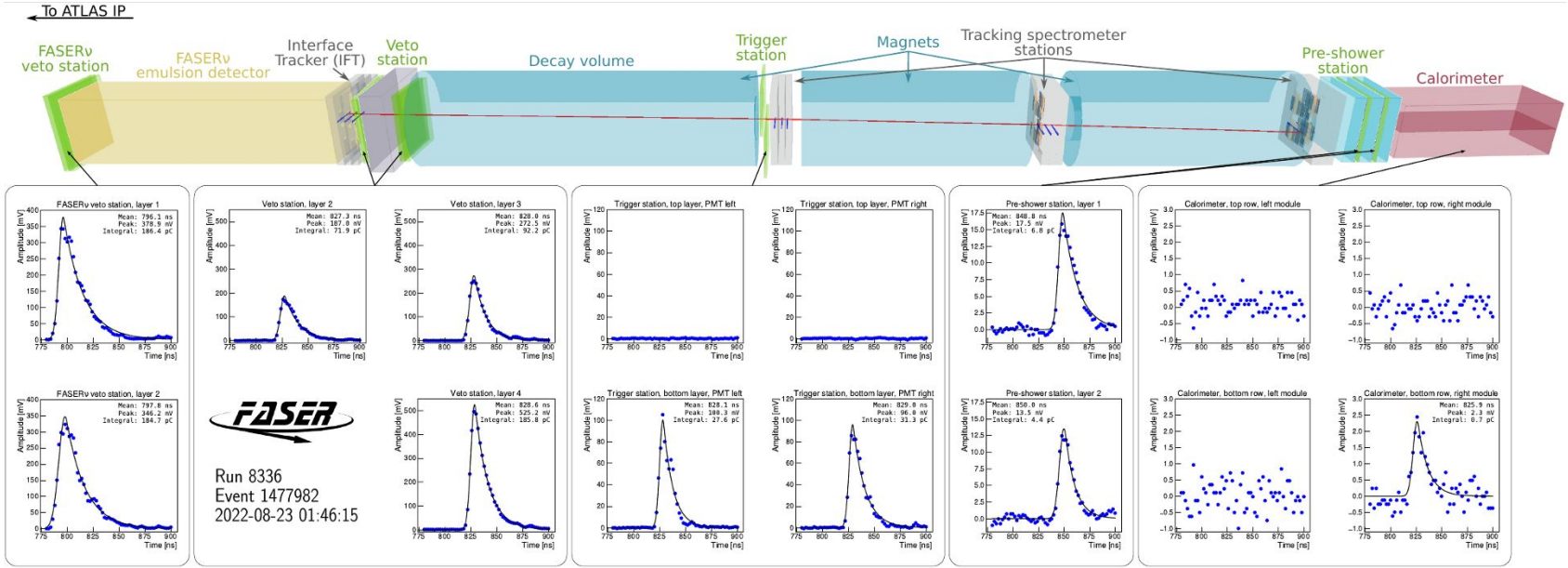
FASER Photographs

(Taken from Carl Gwilliam's slides)

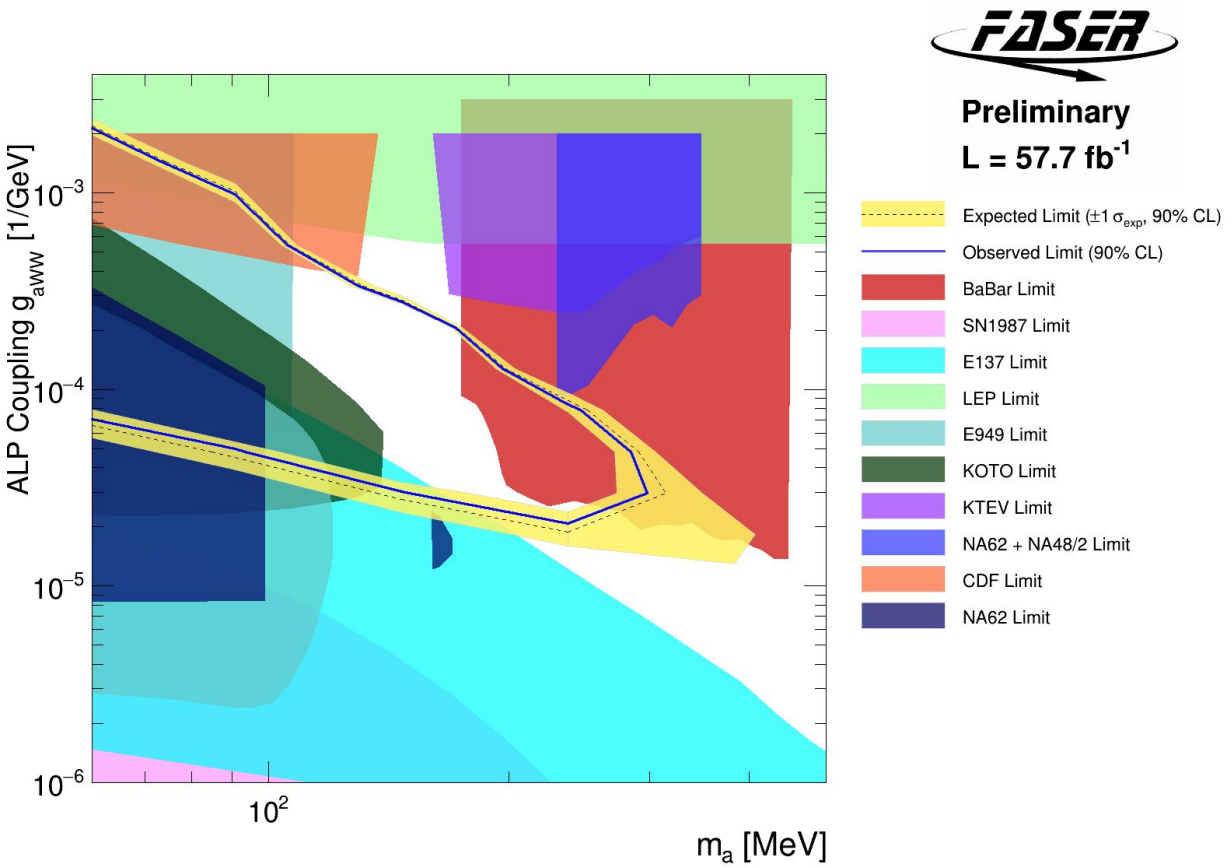
Muons in FASER

Veto scintillator layer efficiency > 99.998%
5 layers reduces the expected 10^8 muons to negligible level (even before cuts)

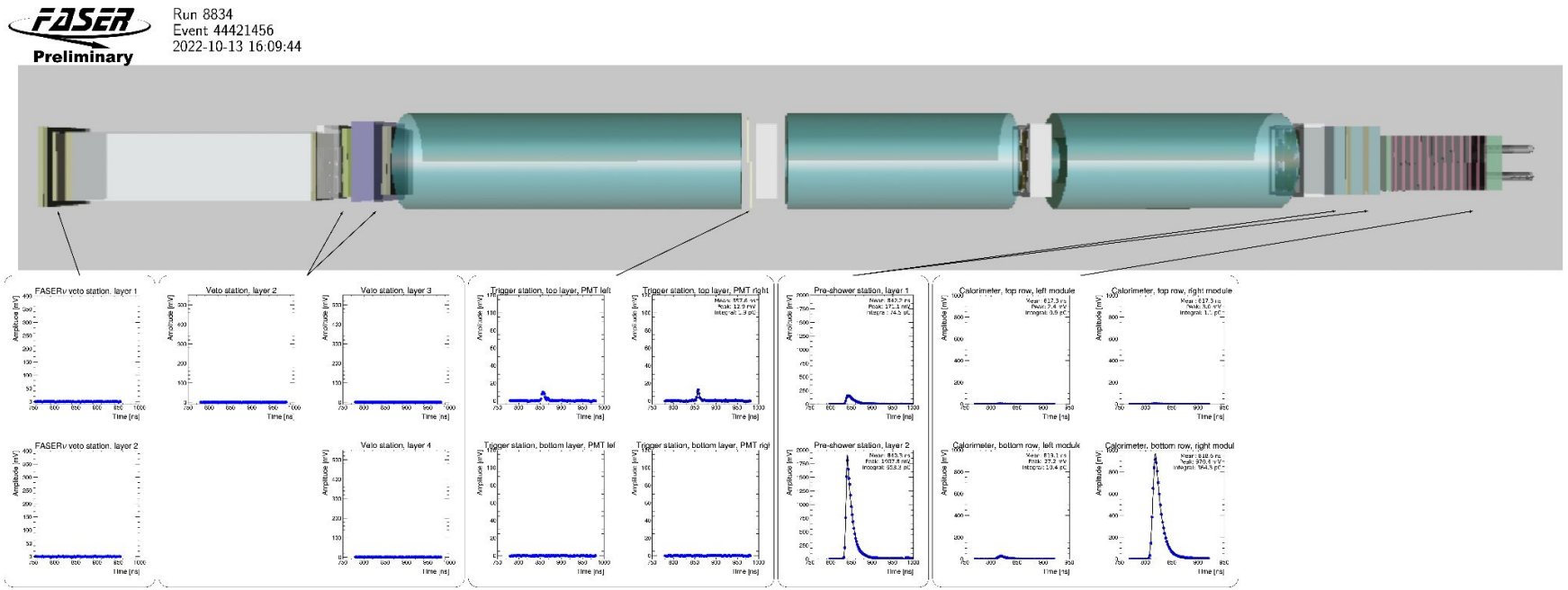
Single muon event in FASER:



Alternative ALP Results Plot

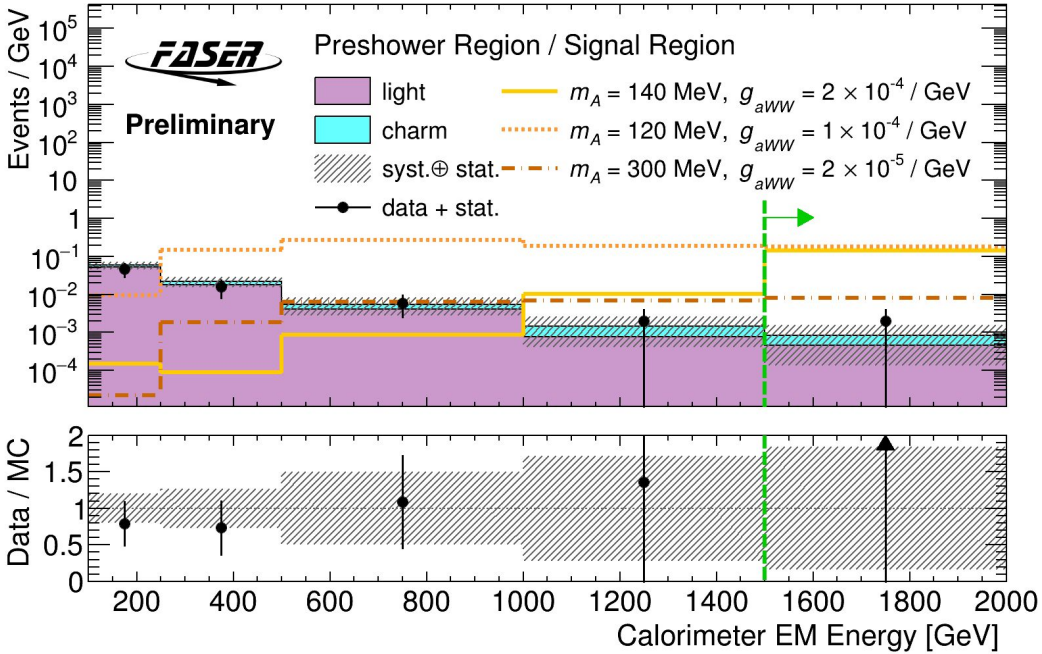


Event Display

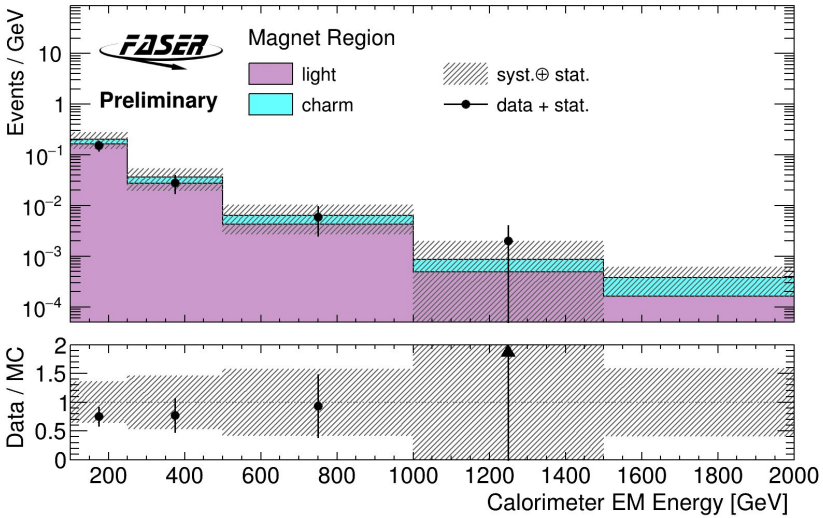


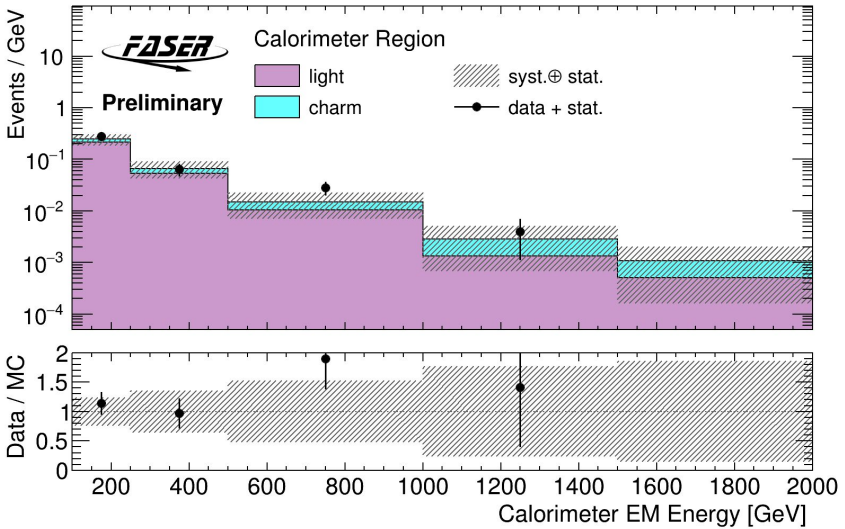
- This event has a calorimeter energy of **1.6 TeV**
- Shows preshower deposits consistent with an EM shower

ALP Results: Alternative Neutrino MC plot

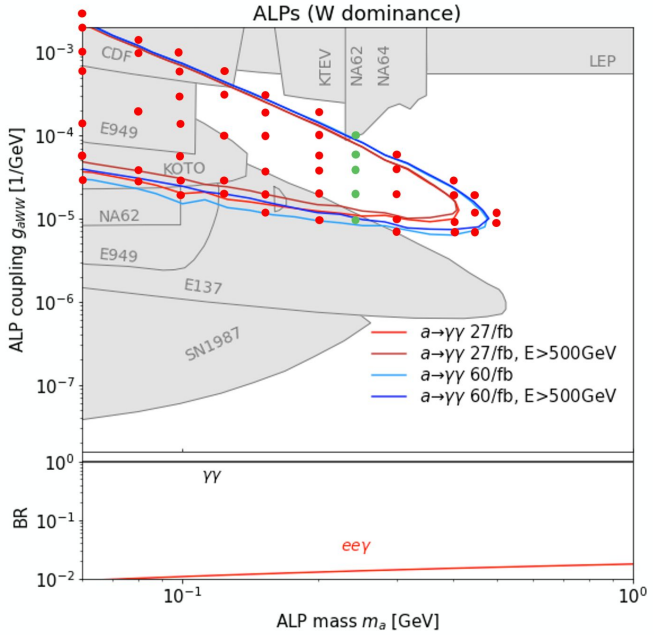


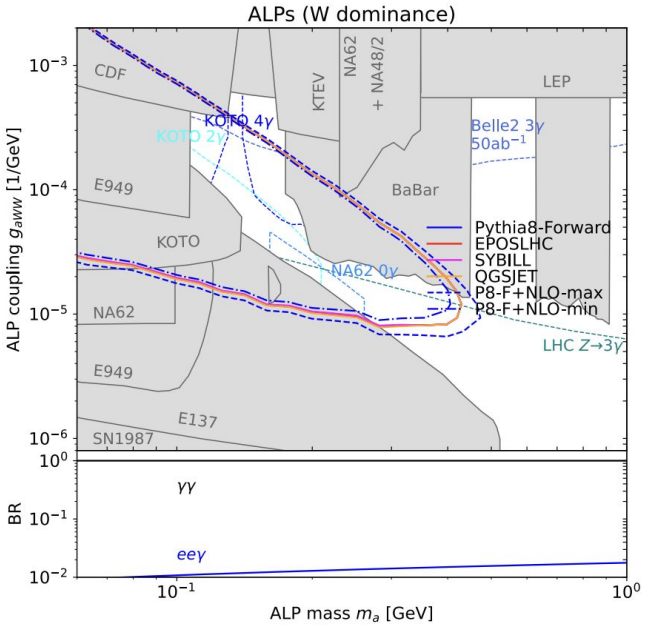
Control Region Plots: Light and Charm

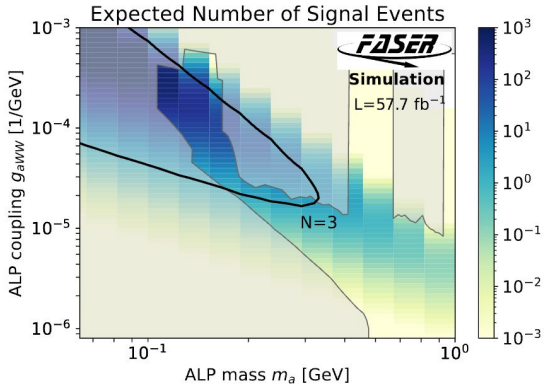




ALP Signal

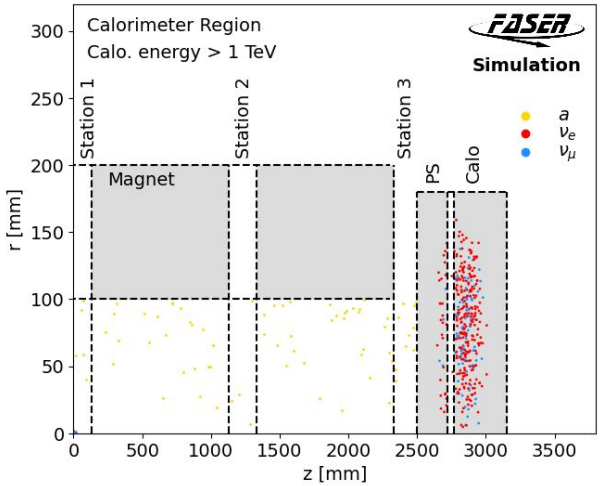


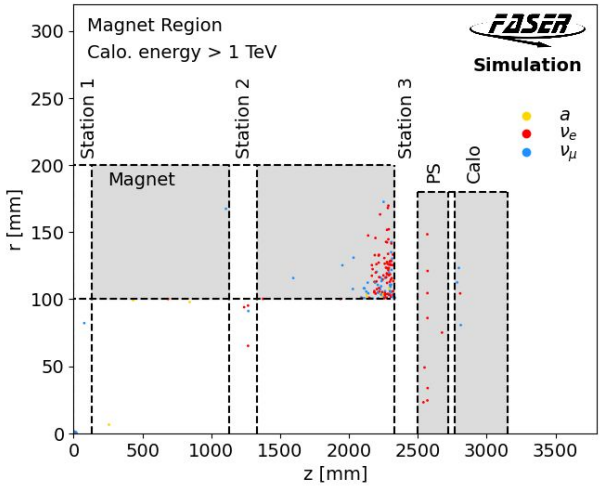


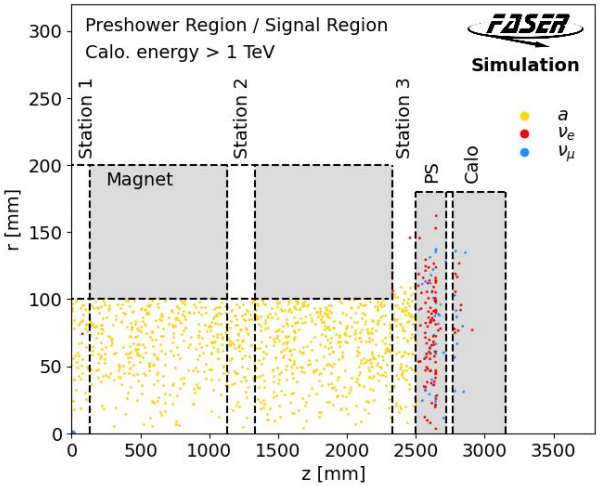


Selection	Efficiency	Cum. Efficiency
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}		
Veto Signal nMIP < 0.5	99.6%	99.6%
Timing Scintillator Signal nMIP < 0.5	97.8%	97.4%
Preshower Ratio > 4.5	85.7%	83.5%
Second Preshower nMIP > 10	98.6%	82.3%
Calo $E > 1.5$ TeV	91.6%	75.4%

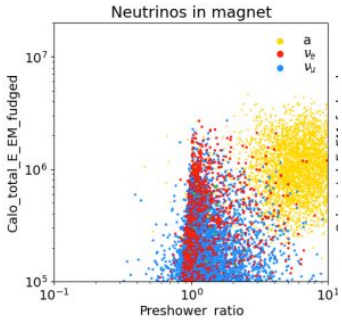
Calorimeter, Magnet, Preshower Regions: 1 TeV cut

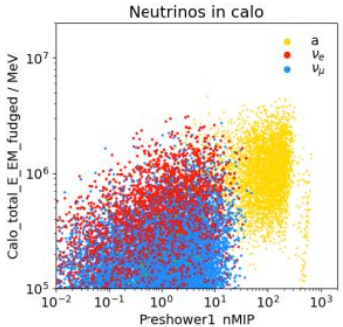






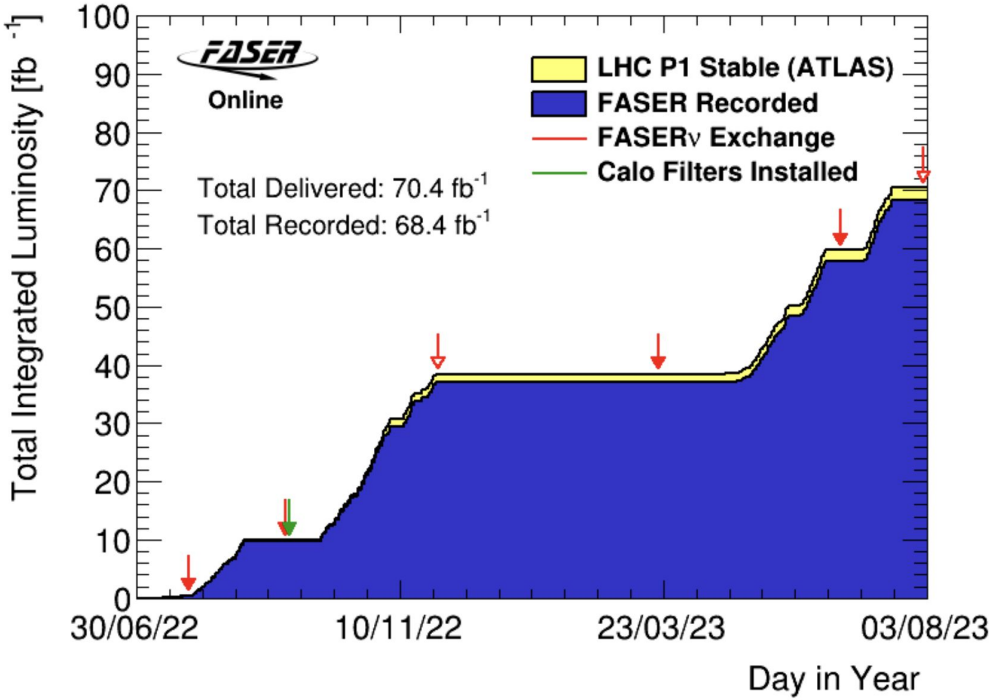
Preshower variables:





FASER Operations

- The ALPs analysis uses 57.7 fb^{-1} collected from 2022 and 2023 Run 3 datasets



Systematic Uncertainties

Signal Sample	Flux	Stat.	Luminosity	Calorimeter	Second Preshower Layer	Preshower Ratio
$m_a = 140$ MeV $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}	59.4%	1.8%	2.2%	3.6%	0.6%	7.9%
$m_a = 120$ MeV $g_{aWW} = 10^{-4}$ GeV^{-1}	57.3%	3.5%	2.2%	16.3%	0.6%	6.9%
$m_a = 300$ MeV $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1}	58.0%	2.9%	2.2%	15.8%	0.6%	8.4%

Source	**Event Rate**
Neutrino Background	0.42 $\pm$ 0.32 (flux) $\pm$ 0.14 (calo. energy) $\pm$ 0.06 (PS ratio) $\pm$ 0.02 (PS 1 nMIP) $\pm$ 0.05 (stat.) **Total: 0.42 $\pm$ 0.38 (90.6%)**
ALP ($m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1})	70.7 $\pm$ 42.0 (theo.) $\pm$ 6.4 (exp.) $\pm$ 1.3 (stat.)
ALP ($m_a = 120$ MeV, $g_{aWW} = 1 \times 10^{-4}$ GeV^{-1})	91.1 $\pm$ 52.2 (theo.) $\pm$ 16.2 (exp.) $\pm$ 3.2 (stat.)
ALP ($m_a = 300$ MeV, $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1})	4.0 $\pm$ 2.3 (theo.) $\pm$ 0.6 (exp.) $\pm$ 0.1 (stat.)
Data	**1**

Neutrino Background Composition

- In terms of light and charm:

Magnet region	
Light	$33.6^{+6.7}_{-3.4}$ (flux) ± 4.3 (exp.) ± 0.4 (stat.)
Charm	$9.9^{+16.1}_{-4.6}$ (flux) ± 0.9 (exp.) ± 0.2 (stat.)
Total	**43.5 ± 18.2 (41.9%)**
Data	**34**
"Other" region	
Light	$17.4^{+1.3}_{-0.8}$ (flux) ± 2.5 (exp.) ± 0.3 (stat.)
Charm	$3.9^{+6.0}_{-1.8}$ (flux) ± 0.5 (exp.) ± 0.2 (stat.)
Total	**21.3 ± 6.9 (32.2%)**
Data	**17**
Calorimeter region	
Light	$51.6^{+2.0}_{-3.4}$ (flux) ± 3.1 (exp.) ± 0.5 (stat.)
Charm	$11.1^{+19.1}_{-5.1}$ (flux) ± 0.4 (exp.) ± 0.3 (stat.)
Total	**62.7 ± 19.7 (31.4%)**
Data	**74**
Preshower region	
Light	$14.8^{+0.9}_{-1.2}$ (flux) ± 1.8 (exp.) ± 0.3 (stat.)
Charm	$3.0^{+4.5}_{-1.4}$ (flux) ± 0.3 (exp.) ± 0.1 (stat.)
Total	**17.8 ± 5.1 (28.8%)**
Data	**15**

- In terms of neutrino type:

SR	
ν_e	0.32 ± 0.31 (flux) ± 0.10 (exp.) ± 0.04 (stat.)
ν_μ	0.09 ± 0.04 (flux) ± 0.05 (exp.) ± 0.02 (stat.)
Total	**0.42 ± 0.38 (90.6%)**
Data	1
Preshower region	
ν_e	5.16 ± 2.59 (flux) ± 0.51 (exp.) ± 0.17 (stat.)
ν_μ	12.6 ± 2.3 (flux) ± 1.61 (exp.) ± 0.3 (stat.)
Total	**17.8 ± 5.1 (28.8%)**
Data	**15**
Calorimeter region	
ν_e	22.6 ± 12.8 (flux) ± 0.7 (exp.) ± 0.4 (stat.)
ν_μ	39.9 ± 6.8 (flux) ± 2.8 (exp.) ± 0.5 (stat.)
Total	**62.7 ± 19.7 (31.4%)**
Data	74
Magnet region	
ν_e	13.8 ± 10.3 (flux) ± 1.4 (exp.) ± 0.3 (stat.)
ν_μ	29.4 ± 8.0 (flux) ± 3.8 (exp.) ± 0.4 (stat.)
Total	**43.5 ± 18.2 (41.9%)**
Data	34
"Other" region	
ν_e	6.3 ± 3.6 (flux) ± 0.8 (exp.) ± 0.19 (stat.)
ν_μ	14.9 ± 2.7 (flux) ± 2.2 (exp.) ± 0.3 (stat.)
Total	**21.3 ± 6.9 (32.2%)**
Data	17