Search for Axion-Like Particles in Photonic Final States with FASER

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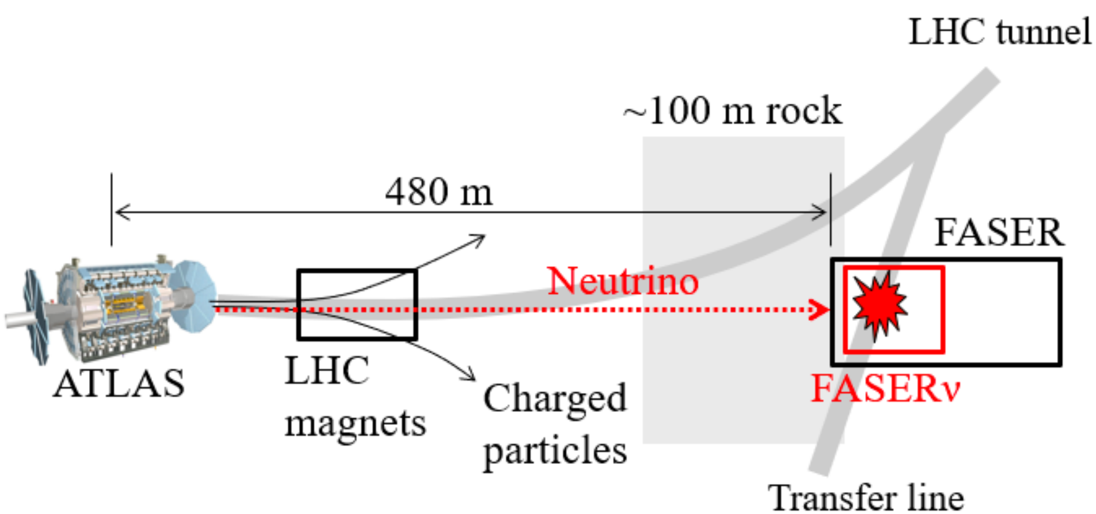
FASER and FASERν

- FASER is a new detector to search for light, weakly coupled long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022 together with ATLAS Run-3.

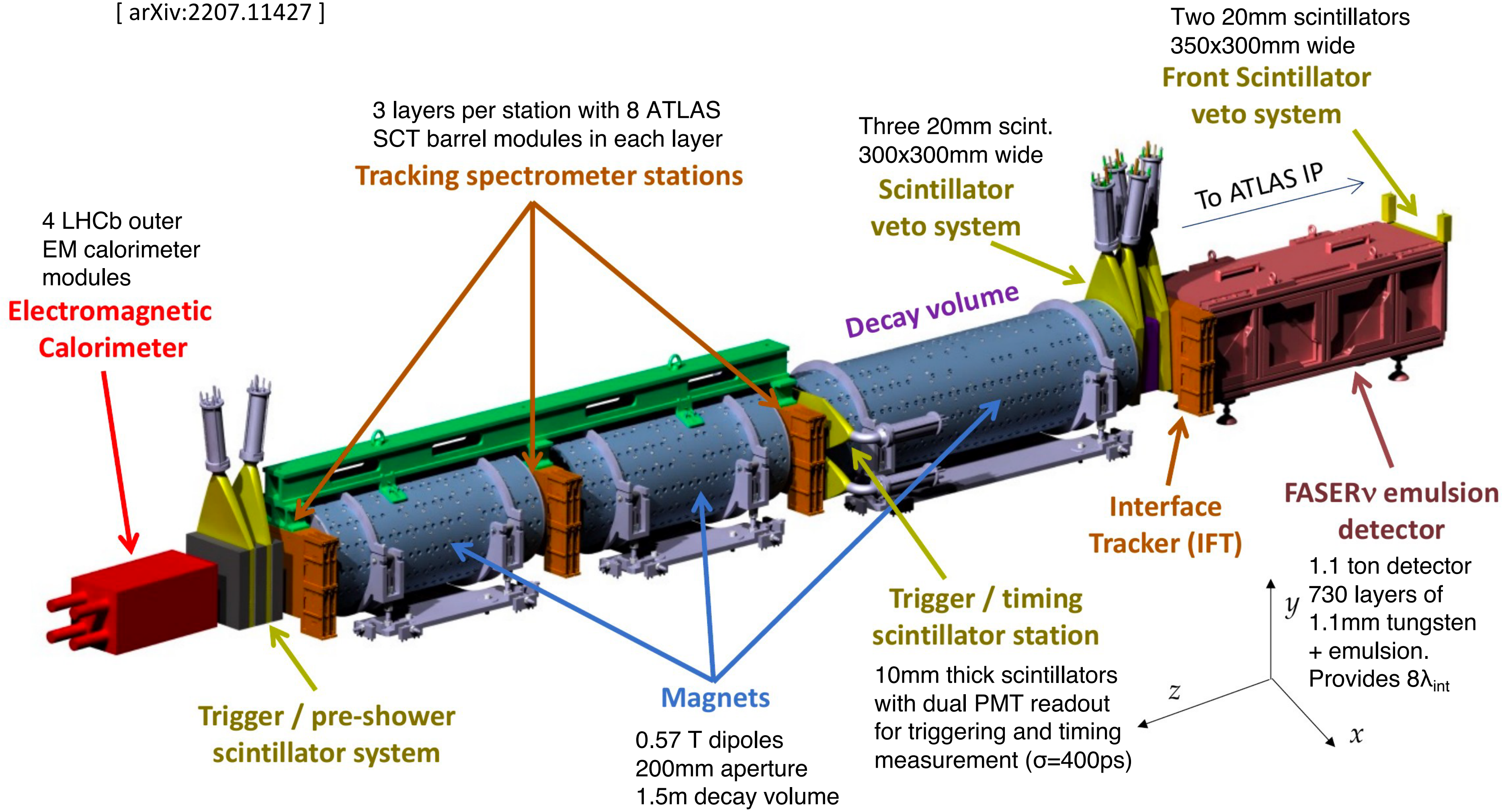
- FASERν is a detector (part of FASER) for neutrino measurements. Has made the first measurements of neutrinos from a collider and in unexplored energy regime.



FASER detector

Built from existing spare parts and some dedicated new components

[arXiv:2207.11427]



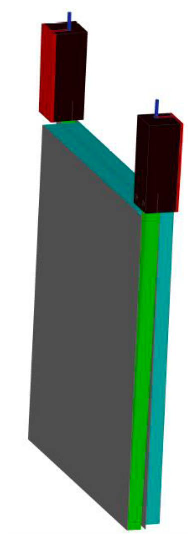
Tracking and scintillator system

- **3 tracking stations** with 3 tracking layers per station (9 layers in total), and 8 modules per plane, covering an area of 24cm × 24cm

  – Silicon strip detector with ATLAS SCT barrel modules
  – 80μm strip pitch, 40mrad stereo angle can provide resolution of 17μm (580 μm) in the bending (nonbending) direction

PMT (H11934-300)

Front veto scint.



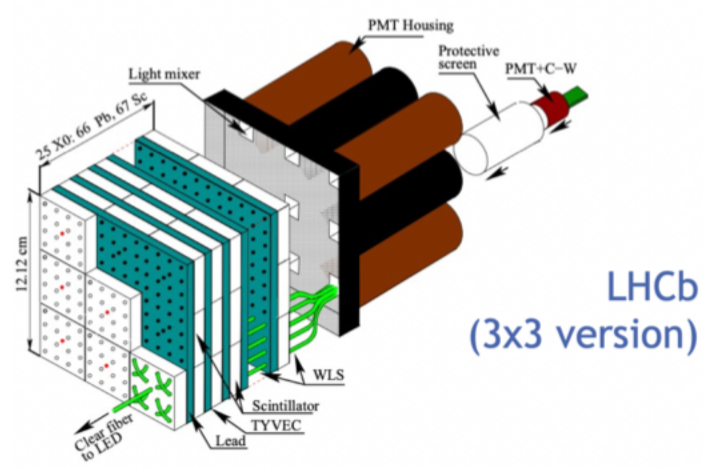
30 × 35 cm^2

- **4 scintillator stations** with efficiency >99.999% per layer, sufficient to veto all incoming muons (expect ~10^8), reject upstream charged particles

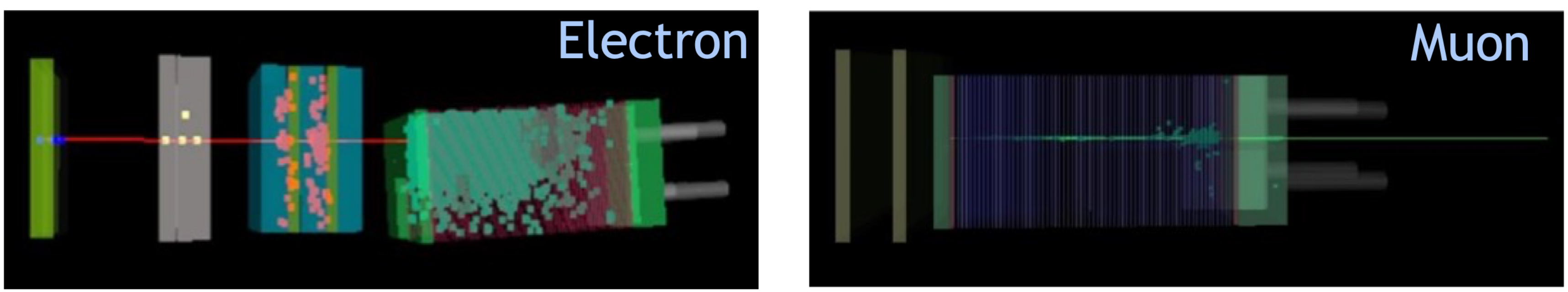
  – Scintillation light is guided by Light guides or Wave Length Shifting bars to PMTs
  – The scintillators have been tested with cosmic rays

Preshower scintillator and calorimeter

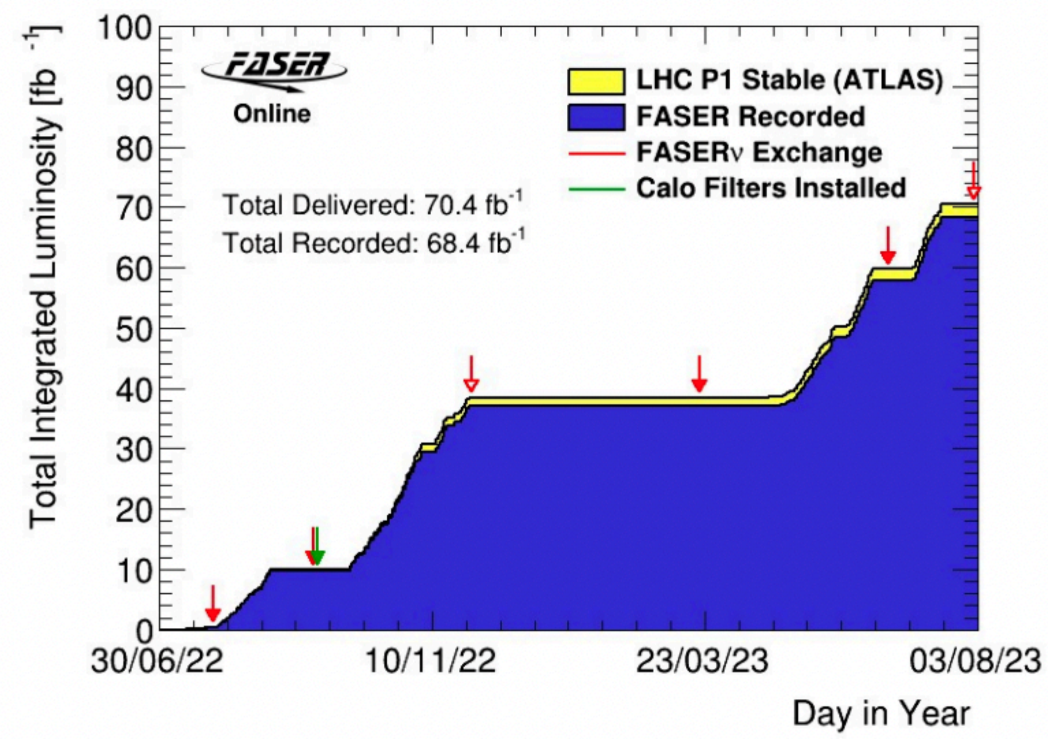
- A preshower detector of 2 scintillator layers, is placed just before the calorimeter
  - – Tungsten radiators are placed before each layer to create showers
  - – Differentiate between incoming EM showers and a neutrino interacting in the calorimeter
- EM calorimeter made of spare LHCb modules
  - – 66 layers of lead-scintillator plates read by 2×2 array of PMTs
  - – Each module $12\text{cm} \times 12\text{cm}$ and 25 radiation length deep



Simulated energy deposits for electrons and muons



Luminosity in 2022 & 2023



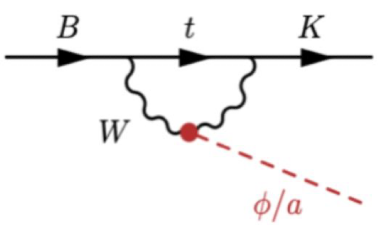
- Successfully operated during 2022 and 2023 run-3 data taking
  - Continuous and largely automatic data-taking at up to 1.3 kHz
- Recorded ~97% of delivered luminosity
  - DAQ dead time <2%, most loss due to DAQ crashes
- Emulsion detectors were exchanged a few times to manage background occupancy

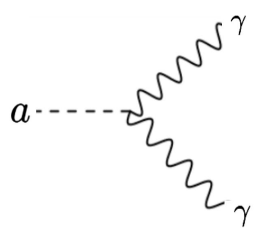
Search for Axion-Like Particles (ALPs)

Effective Lagrangian:

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW}\, a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu}$$

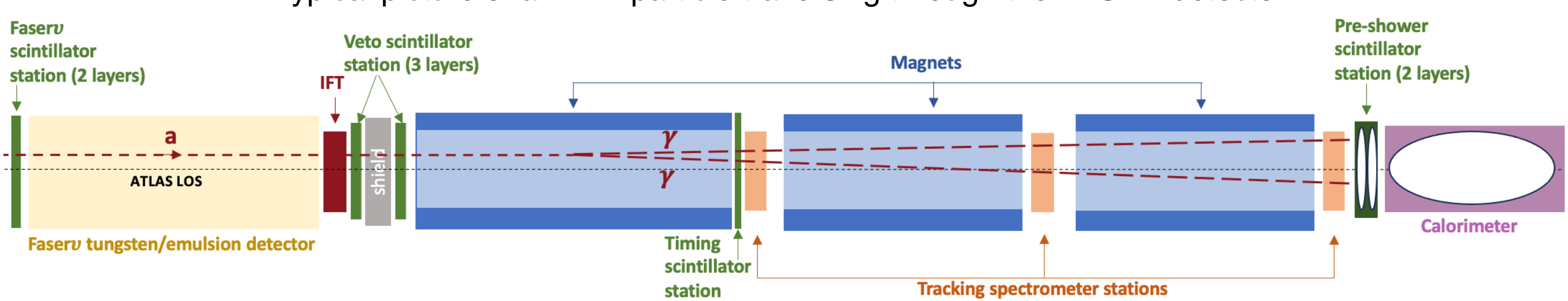
Production and decay:





- FASER is sensitive to axion-like particles (ALPs)
  - Couples to $SU(2)_L$ gauge bosons (photon and gluon couplings are also possible, cf. talk by Shunliang)
- Primarily produced in B meson decays in our sensitivity range
- May decay anywhere between veto scintillators and preshower
- Decays to 2 high energy photons
  - But cannot be resolved in our current calorimeter

Typical picture of an ALP particle traversing through the FASER detector



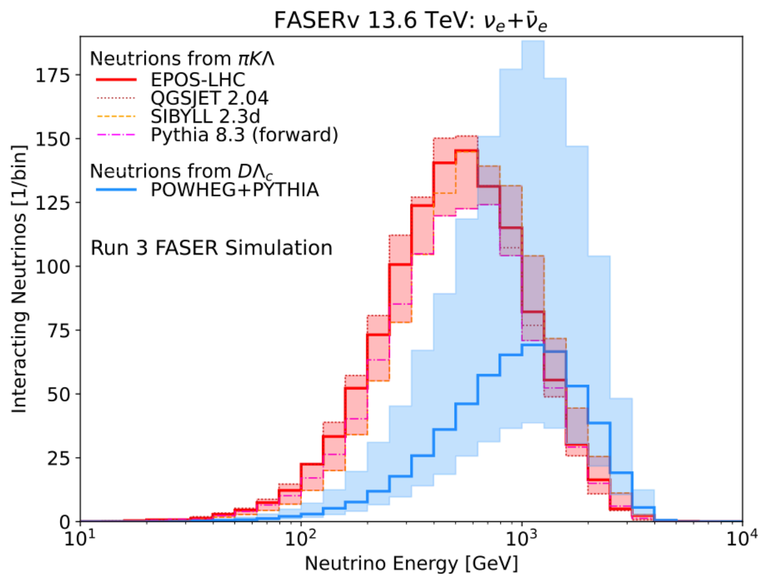
Generators and MC samples

- Signal samples
  - – A set of 55 ALP signal MC samples with different g_{aWW} vs m_a parameters are generated with FORESEE
  - – ALPs can decay anywhere between the veto station and the preshower layer
  - – Forward B-meson production evaluated by POWHEG+PYTHIA at NLO+NLLx accuracy
  - – Kaon decay rate prediction is based on EPOS-LHC. Alternative generators (SIBYLL 2.3d, QGSJET 2.04, Pythia and PYTHIAforward) are also used for systematics

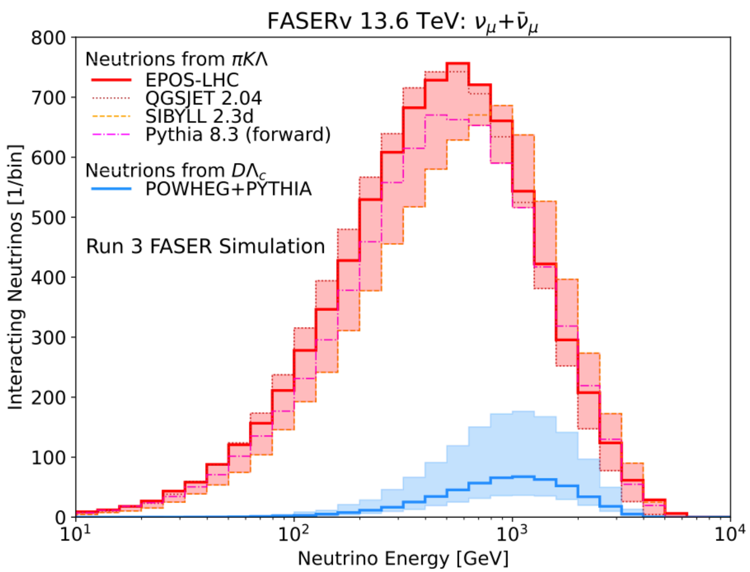
- Background samples
  - – Neutrinos from light and charmed hadron decays
  - – Central prediction of neutrino flux from light hadrons is based on EPOS-LHC. Other generators (SIBYLL, QGSJET and PYTHIAforward) are used for systematics
  - – POWHEG+PYTHIA is used for neutrinos from charmed hadrons
  - – Dedicated high-energy muon simulation samples from FLUKA

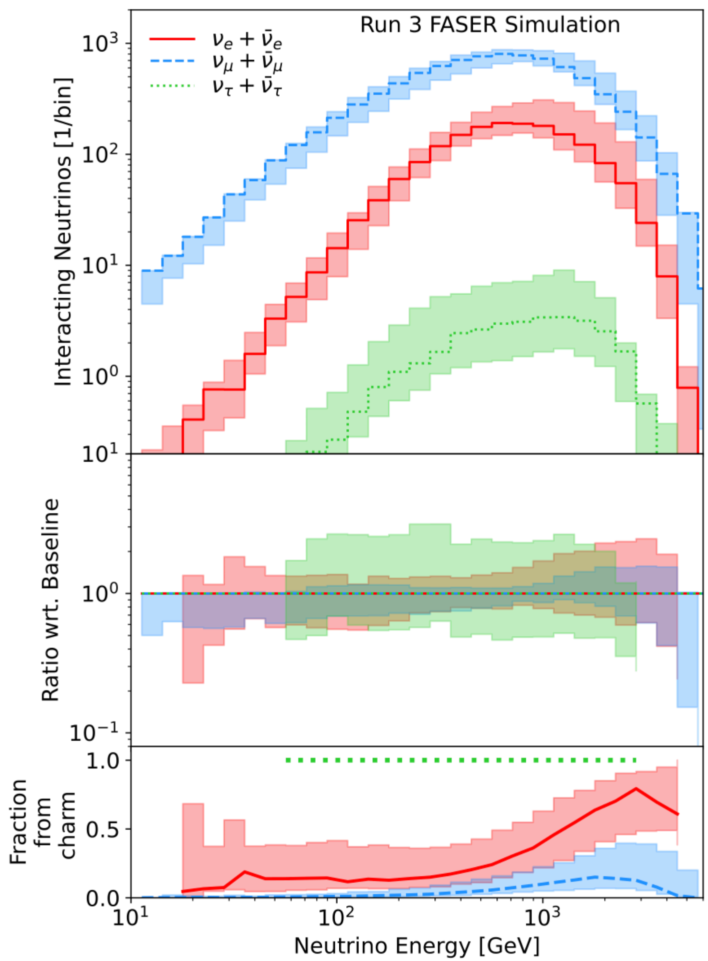
- Neutrino interaction with detector is simulated with GENIE. Other particle's propagation and interaction are simulated with GEANT4

Uncertainties on the neutrino flux



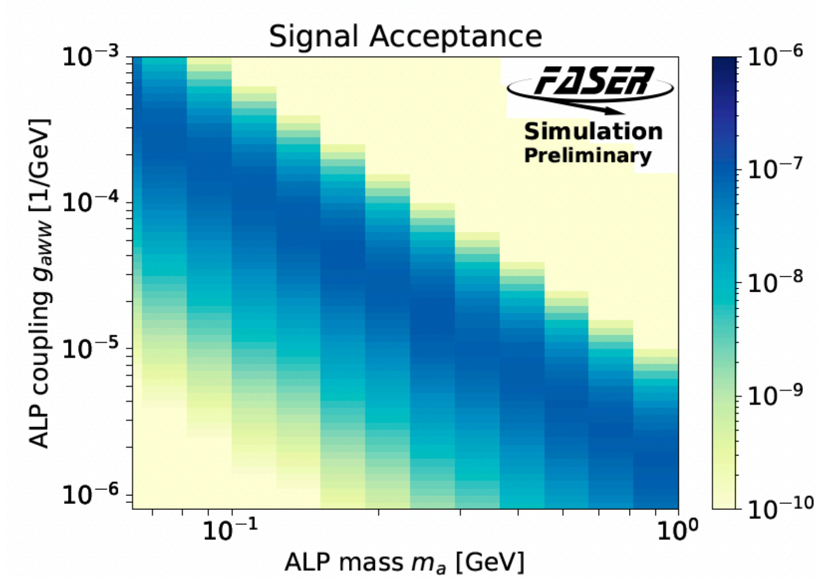
[arXiv:2402.13318]

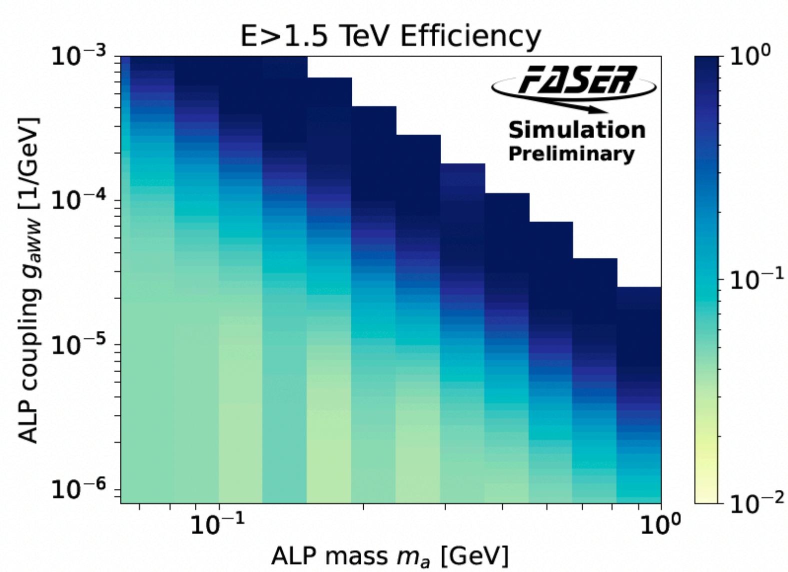




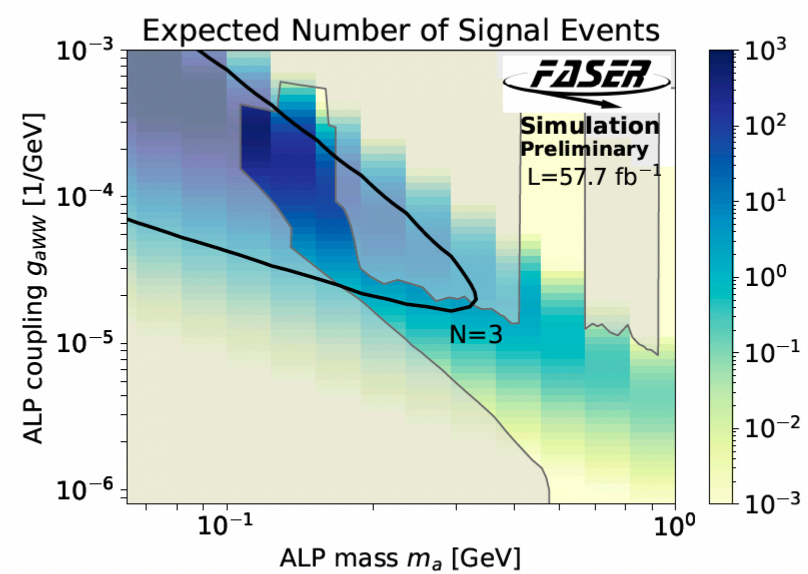
- Prediction of neutrinos from charmed hadrons suffer from *large uncertainty from scale variations*

Generator level study





[CERN-FASER-CONF-2024-001]



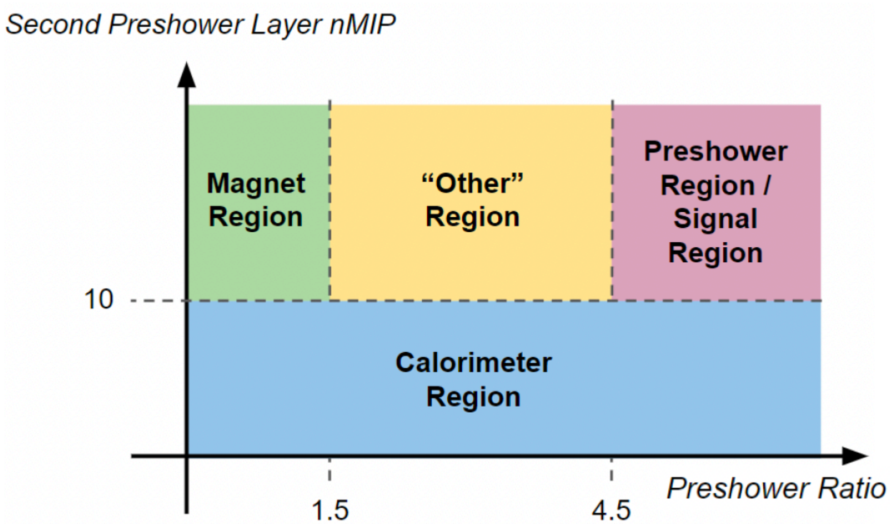
- Signal acceptance ~10^{-6}–10^{-7} (compare to the angular acceptance of 10^{-8} for FASER and the decay-in-volume probability is < 0.3%)
- The parameter space with m_a in 60 MeV−400 MeV and g_{aWW} in 10^{-5}−10^{-3} GeV^{-1} are unexplored and can be probed by FASER

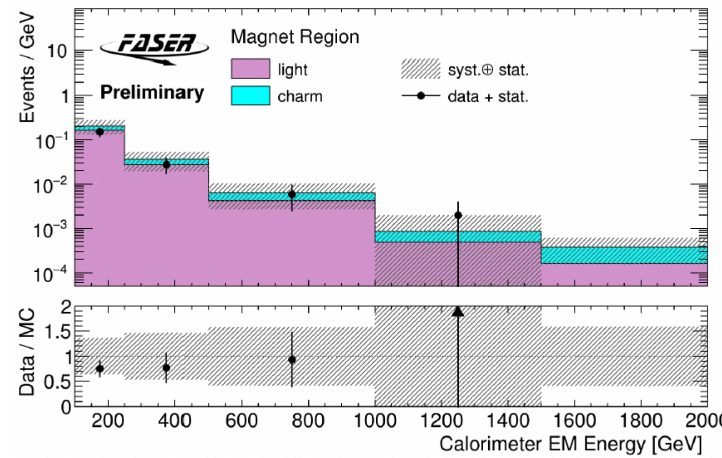
Event selection

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)

- No signal in any of the 5 veto scintillator layers. Energy deposit expressed in unit of charge induced by a MIP
- No signal in the timing scintillator station
- Evidence of an EM shower in the preshower detector
  - Preshower ratio: the ratio of the number of MIP equivalent charge in the second to the first preshower layer
- Significant energy deposit of >1.5 TeV in the EM calorimeter

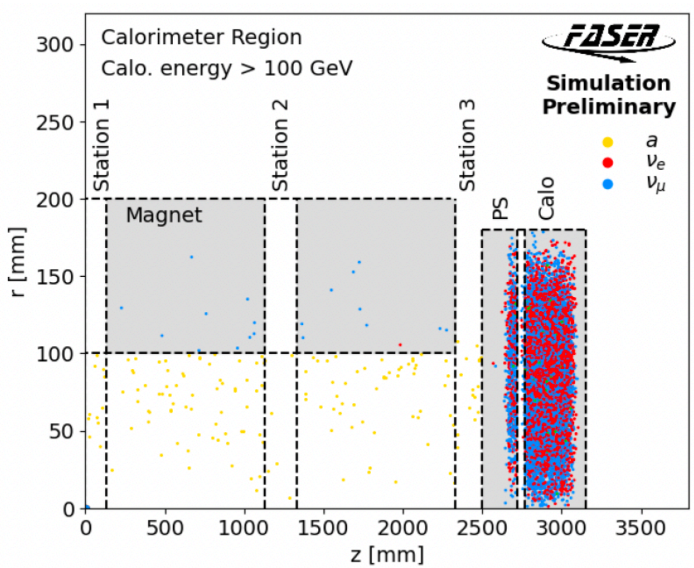
Neutrino background

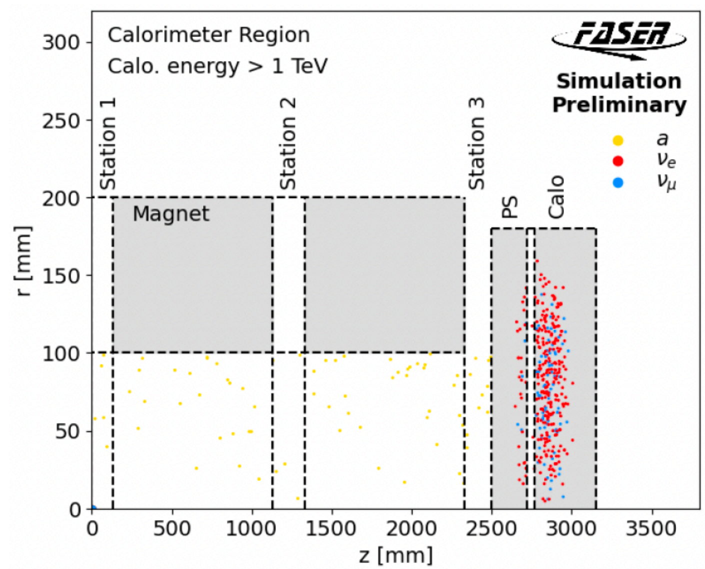




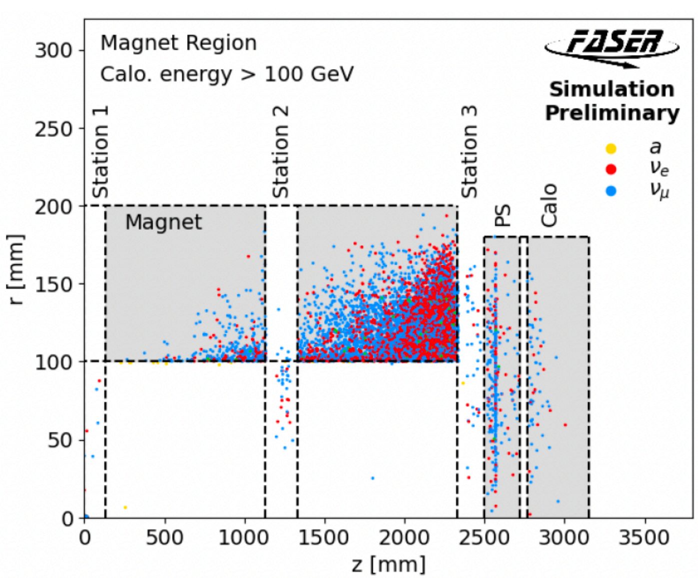
- Neutrino background is evaluated with MC simulations
- Effective distinction between neutrinos interacting in the magnet, calorimeter, and preshower is based on charge deposited in the 2nd preshower layer and the preshower energy ratio
  - Magnet Region: neutrinos interacting in the magnets lead to PS ratio ~1
  - Calorimeter Region: neutrinos interacting in the calorimeter tend to deposit lower energy in the 2nd layer
  - Preshower Region: neutrinos interacting in the preshower layers
  - "Other" Region: between the calorimeter and magnet regions

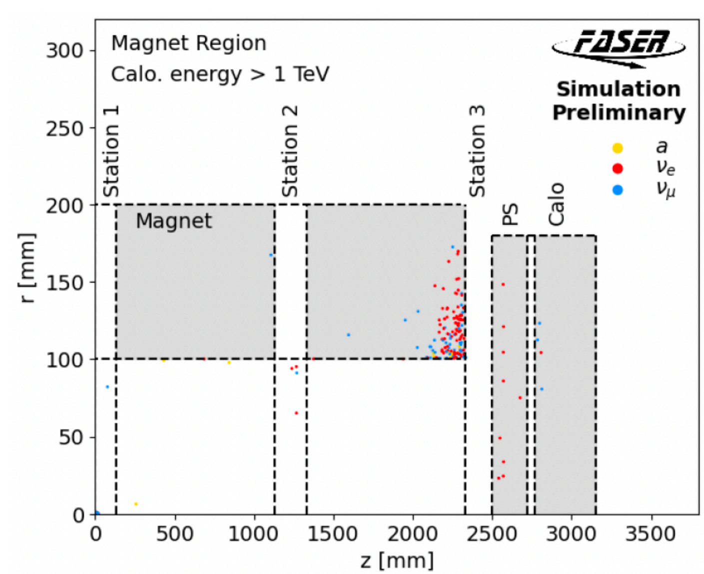
Calorimeter and Magnet regions





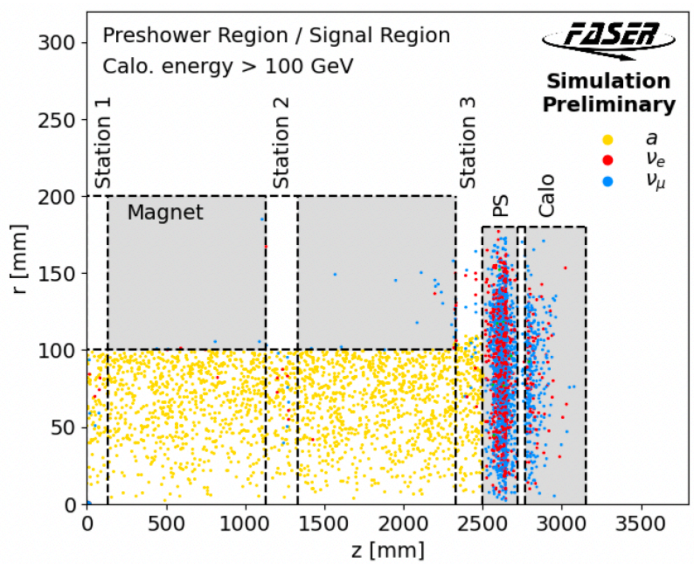
Exp. events: with E>100 GeV:
62.7 ± 19.7

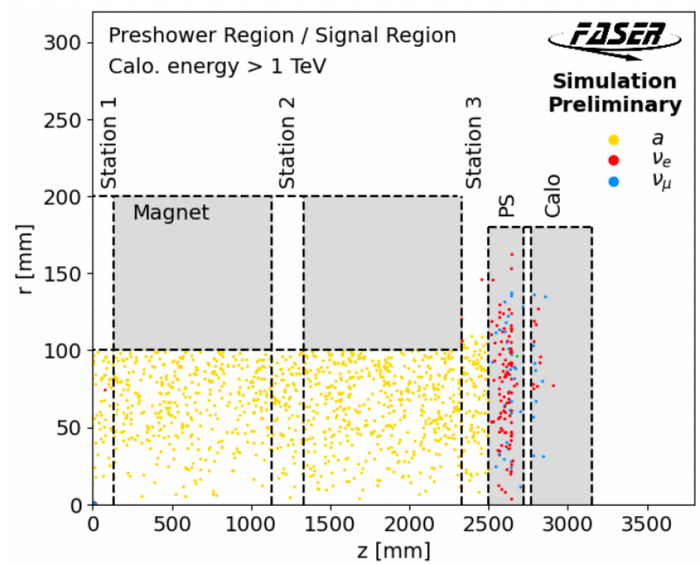




Exp. Events with E>100 GeV:
43.5 ± 18.2

Preshower/Signal region





Exp. events with E>100 GeV (but excluding sig. reg.): 17.8 ± 5.1

> 1.5 TeV signal region	
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	**0.42 ± 0.38 (90.6%)**

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

- The 4 regions serve as validations for MC simulations, in which the signal contamination is <30% for the unexplored signal parameter space
- Calorimeter region is dominated by muon neutrinos, while magnet region is dominated by neutrinos from light hadrons
- Signal region is dominated by electron neutrinos, and contributions from light and charmed hadrons are comparable

Other backgrounds

Apart from the main neutrino background, other backgrounds also need to be understood

- Veto System Inefficiency: Inefficiencies of each of the 5 veto scintillators are assessed by single track events, by looking for scintillator charge <40 pC (half the charge from a MIP). This background is estimated to be negligible
- Large-Angle Muons: Estimated with dedicated MC samples, and validated by a partially data-driven approach. Namely, using events with timing scintillator charge selection inverted, and PS-ratio cut inverted. This background is estimated to be negligible
- Neutral Hadrons: They are produced by the muons passing the rock, and the muons have to miss the scintillators. The 1.5 TeV calorimeter energy cut further suppresses this background. This background is estimated to be negligible
- Non-Collision Background: No events with calorimeter energy >100 GeV in cosmic ray data. Timing of non-collision single beam events and collision events are well separated. These backgrounds are estimated to be negligible

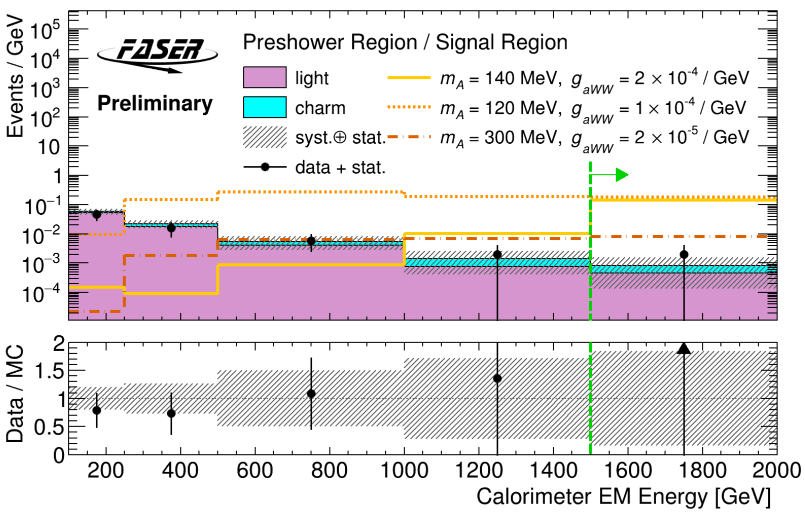
Systematics

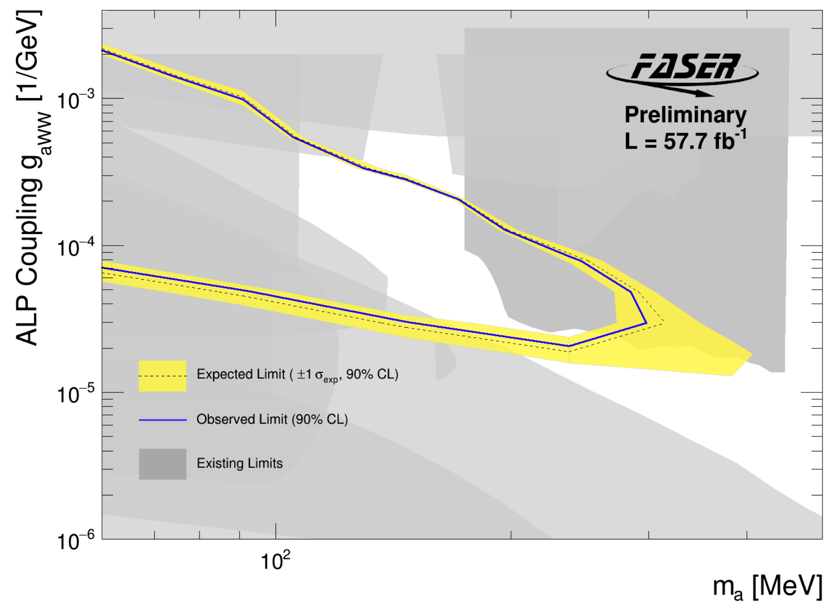
Various systematic uncertainties on the signal and backgrounds are studied

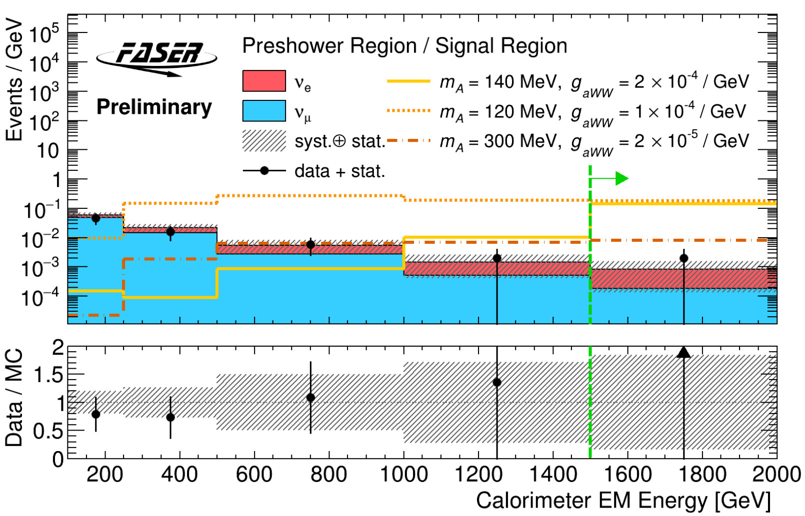
- Signal uncertainties (theoretical and experimental):
  – Theory: Largest uncertainty from flux of SM particles in the forward direction. Additional 20% uncertainty for B-hadrons decay to axions
  – Experimental: 6% for the calorimeter energy scale. 20% for the 2nd preshower layer and 13% for the PS ratio by comparing FASER and test beam data
- Background uncertainties: Largest uncertainty from the neutrino flux (~76%). Same experimental uncertainties as for the signal are also estimated

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**

Unblinded results





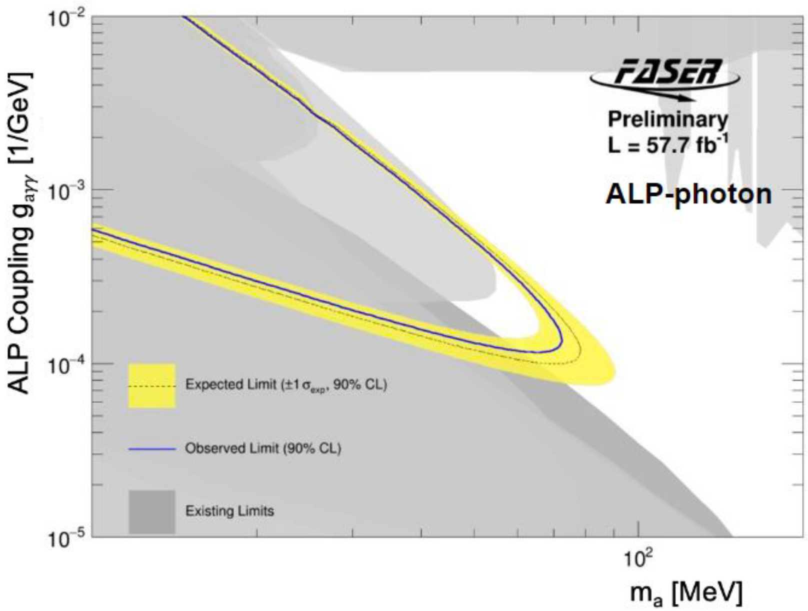


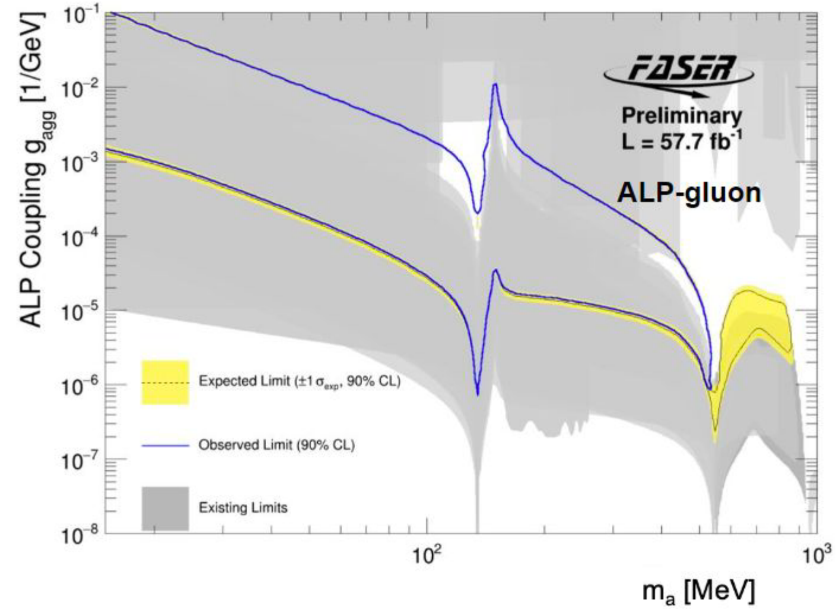
- Only 1 event observed in the signal region with 57.7 fb-1 of data, consistent with the expected background of 0.42 ± 0.38 (dominated by light hadrons and electron neutrinos)
- m_a in 100–250 MeV and g_{aWW} in 3×10^{-5}–5×10^{-4} GeV^{-1} are excluded

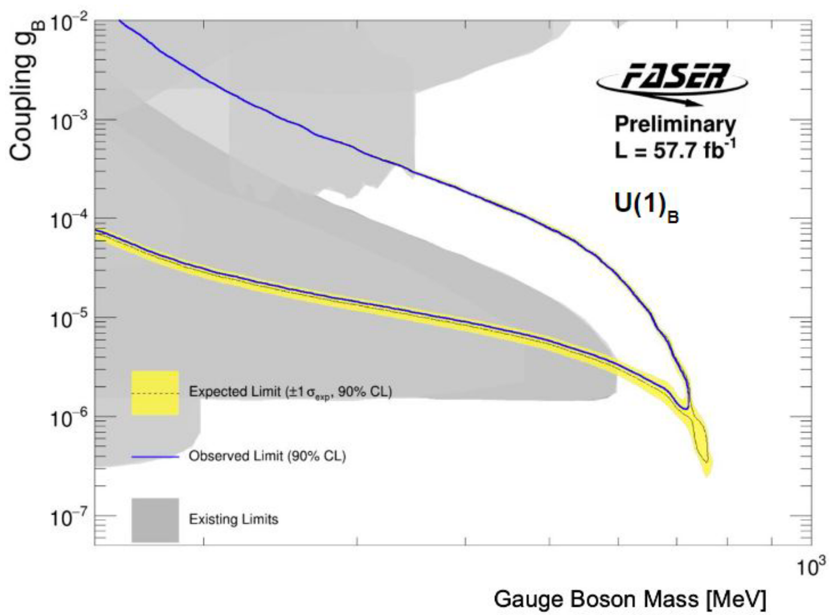
Other ALP models

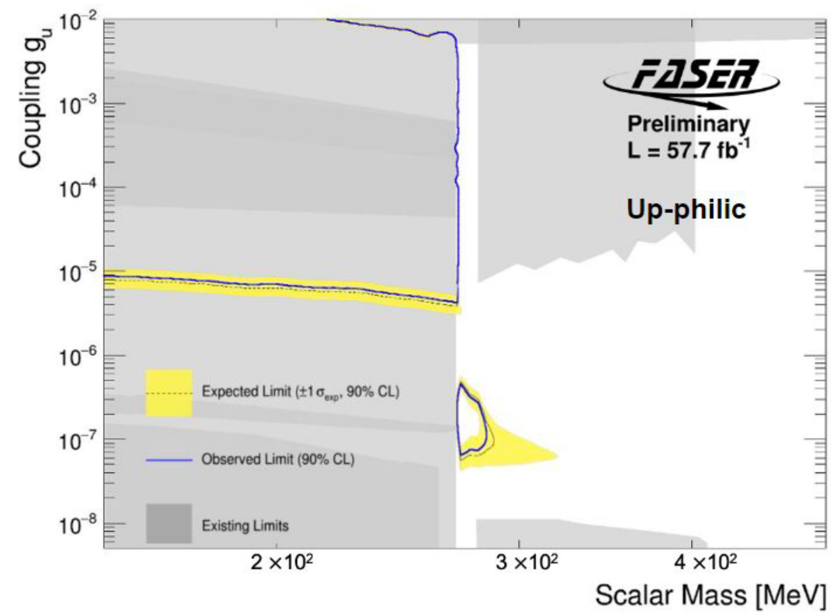
Model	Lagrangian	Production	Decay
ALP-photon	$-\frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$	Primakoff process	diphoton
ALP-gluon	$-\frac{1}{2}m_a^2 a^2 - \frac{g_s^2}{8}g_{agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$	a mixing with π^0, η and η'	diphoton, 3π and $\pi^+\pi^-\gamma$, depending on a mass
U(1)$_B$ gauge boson	$\frac{1}{2}m_{Z_B}^2 Z_B^2 - g_B \sum x_f \bar{f}\gamma^\mu f X_\mu$	π^0, η and η' decays, dark bremsstrahlung	ee, $\pi^0\gamma$, $\pi^+\pi^-\pi^0$, depending on Z_B mass
Up-philic scalar	$-\frac{1}{2}m_S^2 S^2 - g_u \bar{u}uS$	mainly η and η' decays, also FCNC kaon decays	diphoton, $\pi^0\pi^0$

Interpretation of other ALP models

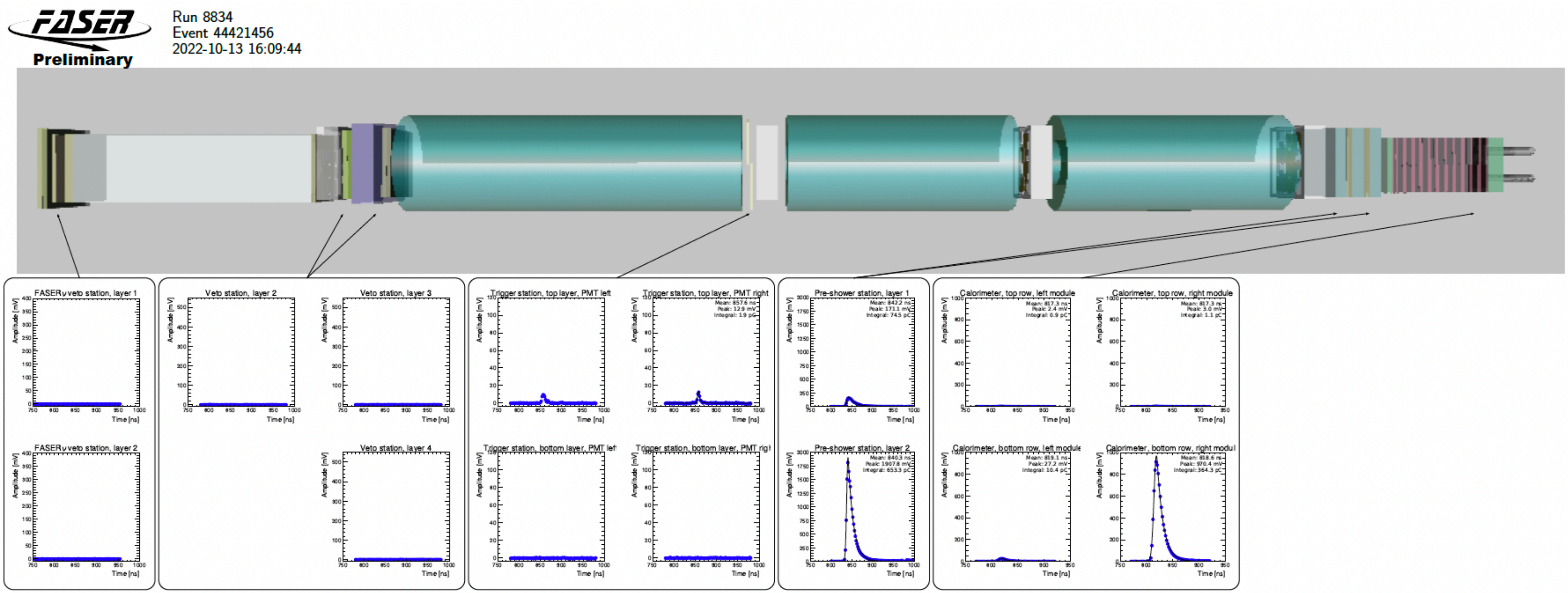








Event display



- This event has a calorimeter energy of 1.6 TeV
- The 2nd preshower layer charge is 146 MIPs
- Shows preshower deposits consistent with an EM shower

Summary

- Search for new particles decaying into photons and ALPs has been performed by FASER, using 57.7 fb^{-1} of Run-3 data collected in 2022-2023

- Models with an ALP coupling to different SM particles are considered. The axion's main signature is two energetic photons in the FASER calorimeter

- The main background is neutrinos interacting in FASER, while other backgrounds are negligible

- With 1 event observed in the signal region, m_a in 100−250 MeV and g_{aWW} in 3×10^{-5}–5×10^{-4} GeV^{-1} were excluded. ALPs as heavy as 300 MeV were excluded for a coupling strength of 7×10^{-5} GeV^{-1}

- 2024 data-taking is ongoing, stay tuned

Backup Slides

FASER location

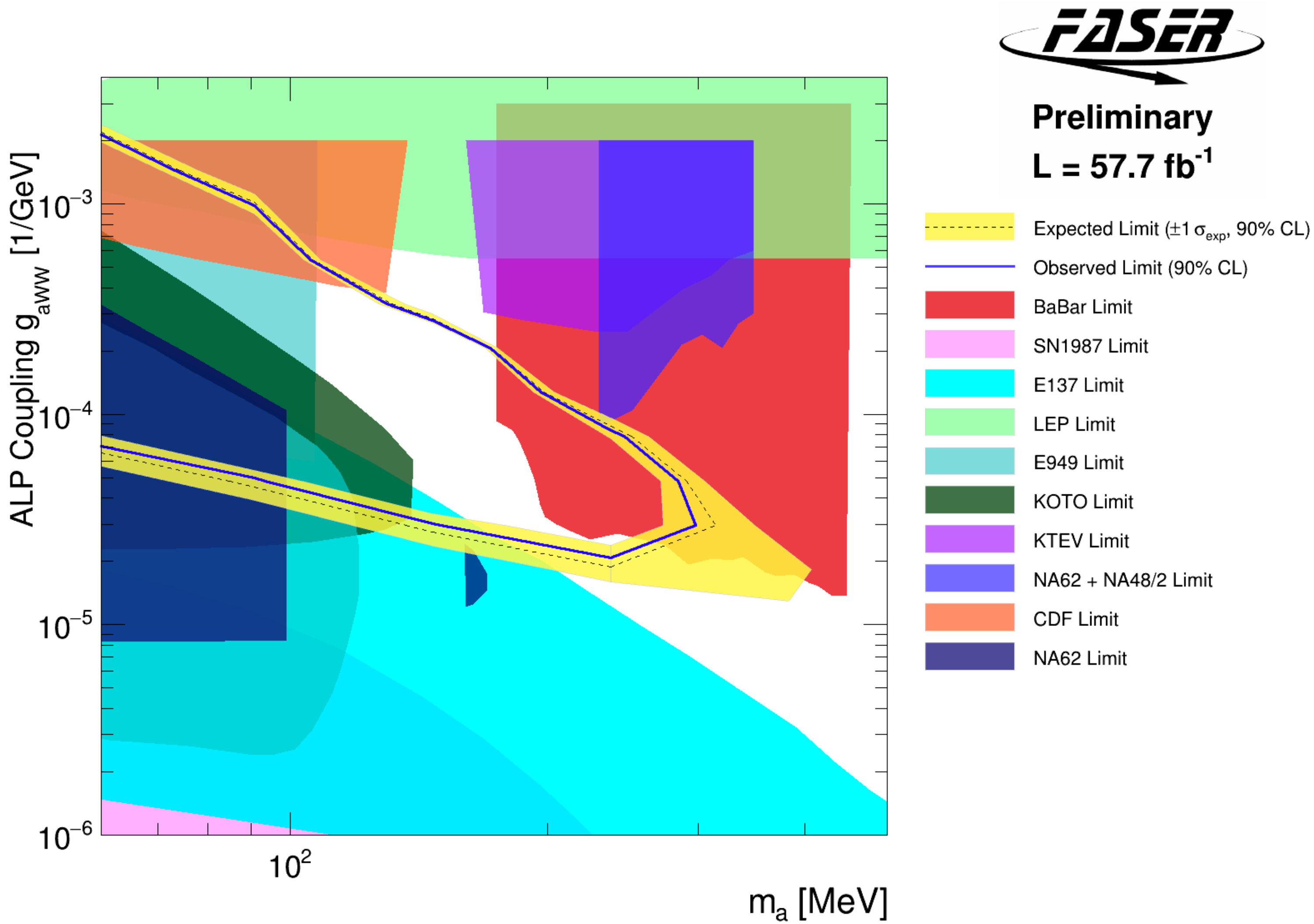
FASER experiment at CERN

Event yields

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

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

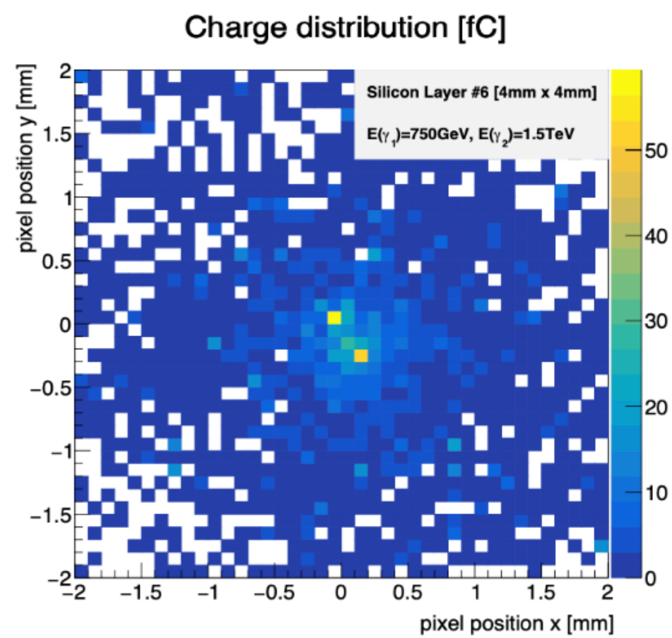
Sensitivity

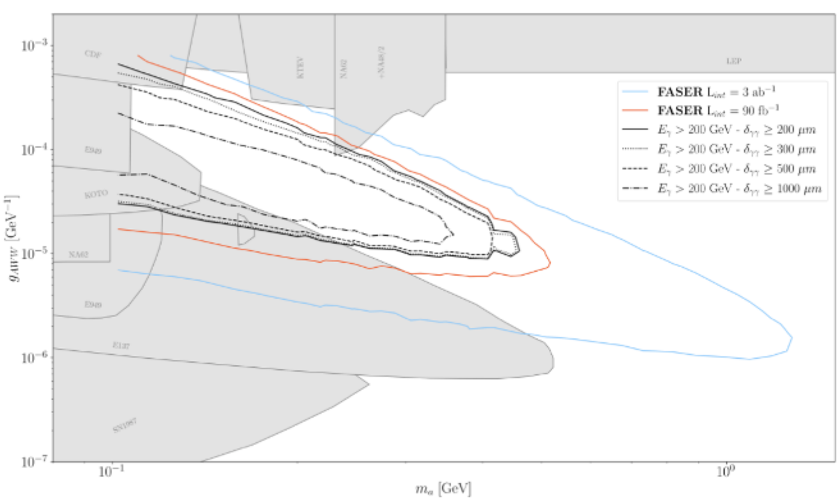


Future upgrades for ALPs

- Upgrade to enable 2-γ physics
  – enable to measure Axion Like Particles and long live particles decaying into two photons
  – current preshower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs: hexagonal pixels of 65 μm side

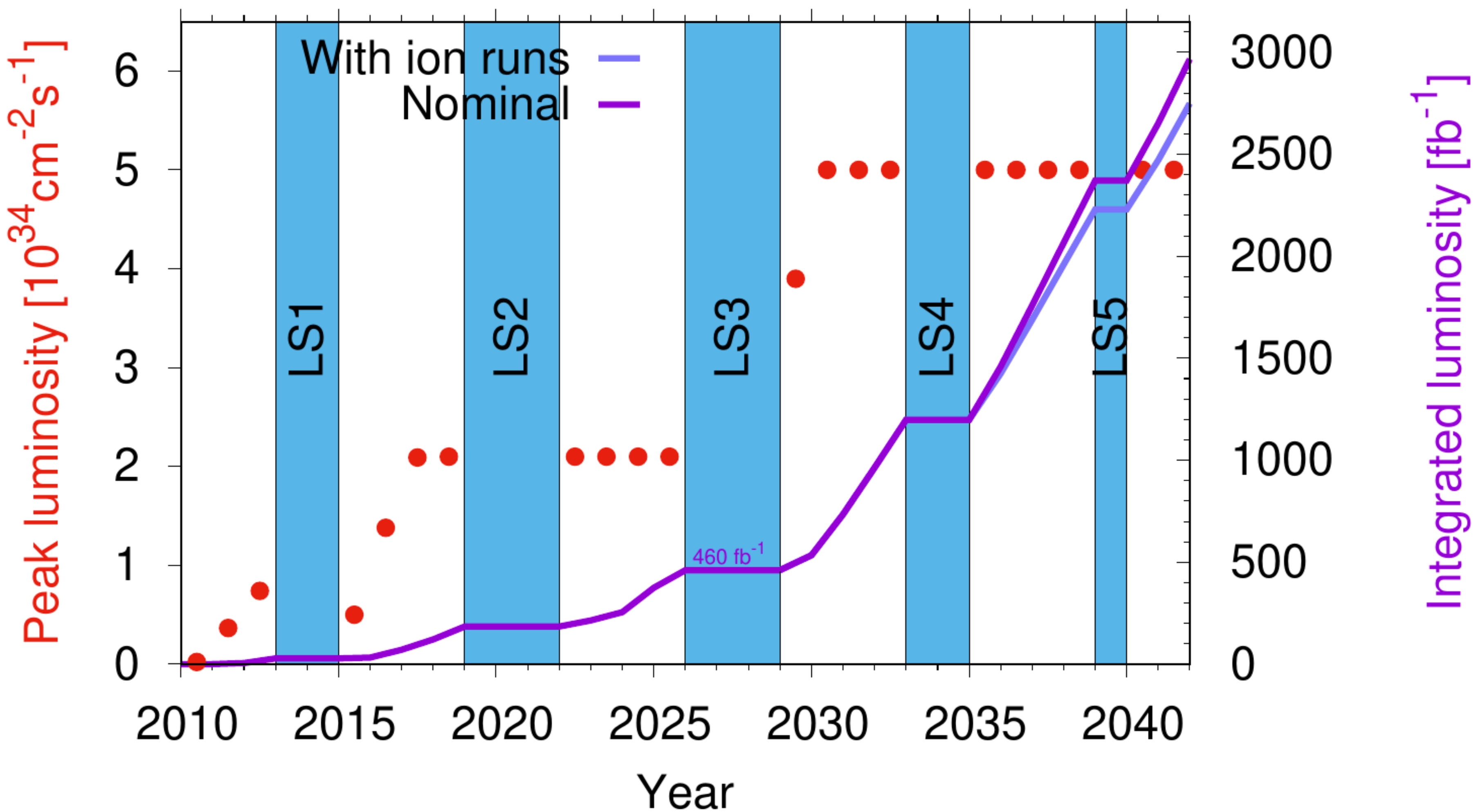
200 μm between two photons distinguishable





2-photon pairs with E>250 GeV and $\delta_{\gamma\gamma} > 0.2$mm

FASER schedule



Forward Physics Facility (FPF): large upgrade to FASER planned for HL-LHC (arXiv:2203.05090)

FASER collaboration

101 members from 27 institutions and 11 countries

International laboratory
covered by a cooperation
agreement with CERN