FASER

Shining light on the dark sector:
Searches for new physics in photonic final states with FASER
(Axion Like Particles)

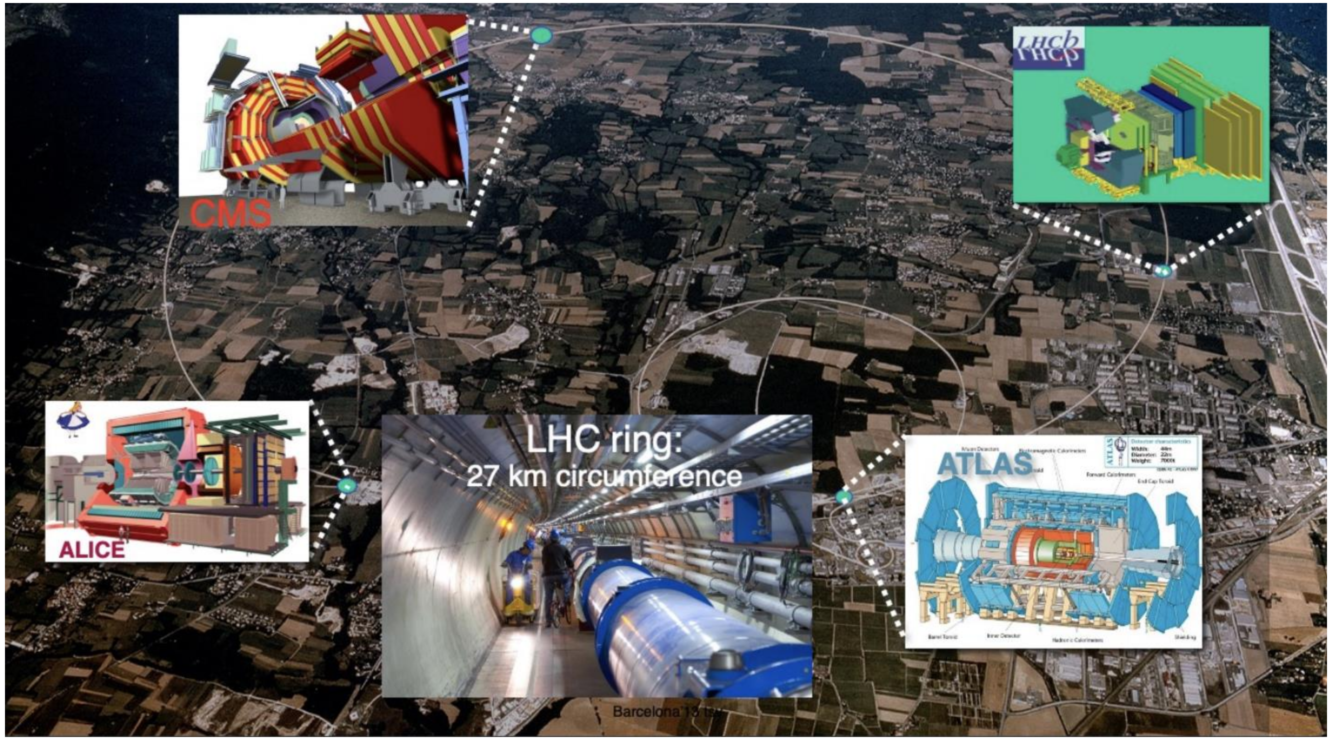
Light Dark Matter @ Accelerators (LDMA)

Noshin Tarannum on behalf of the FASER Collaboration

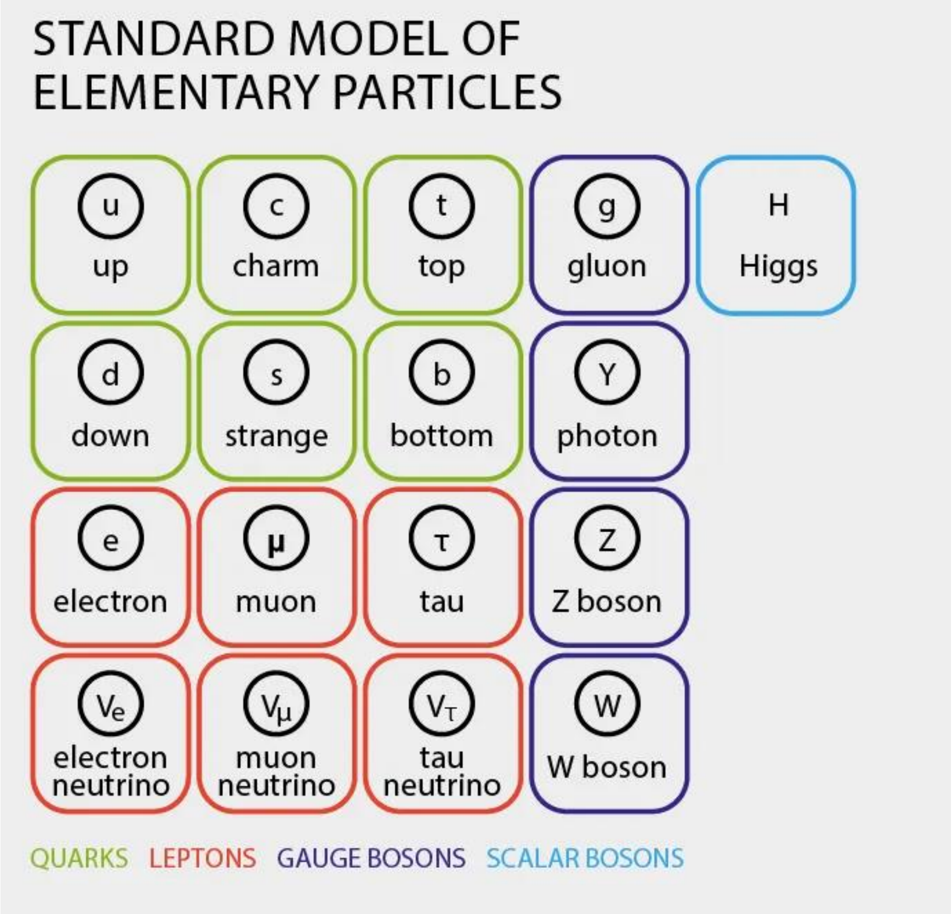
CERN · Université de Genève · Swiss National Science Foundation · Heising-Simons Foundation · Simons Foundation

To start with (More in Andrea's Talk)

LHC and the Detectors



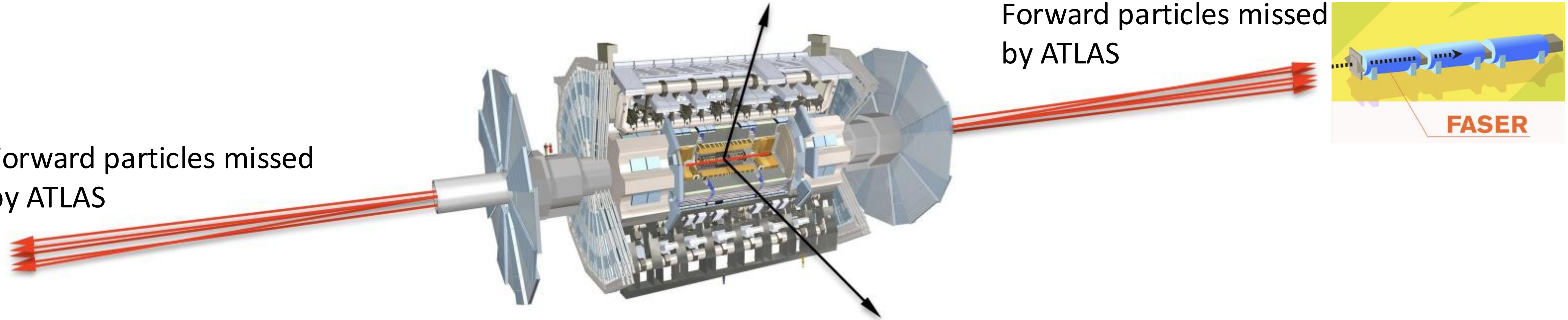
1. General purpose (ATLAS and CMS) studying origin of mass, SUSY…
2. Dedicated (LHCb) studying origin of matter-antimatter asymmetry ….
3. Dedicated (ALICE) studying general properties of quark- gluon plasma



1. Although the SM is a very successful theory there are some questions that remain unanswered
2. One of them being the composition of **dark matter** which is what FASER is designed to explore

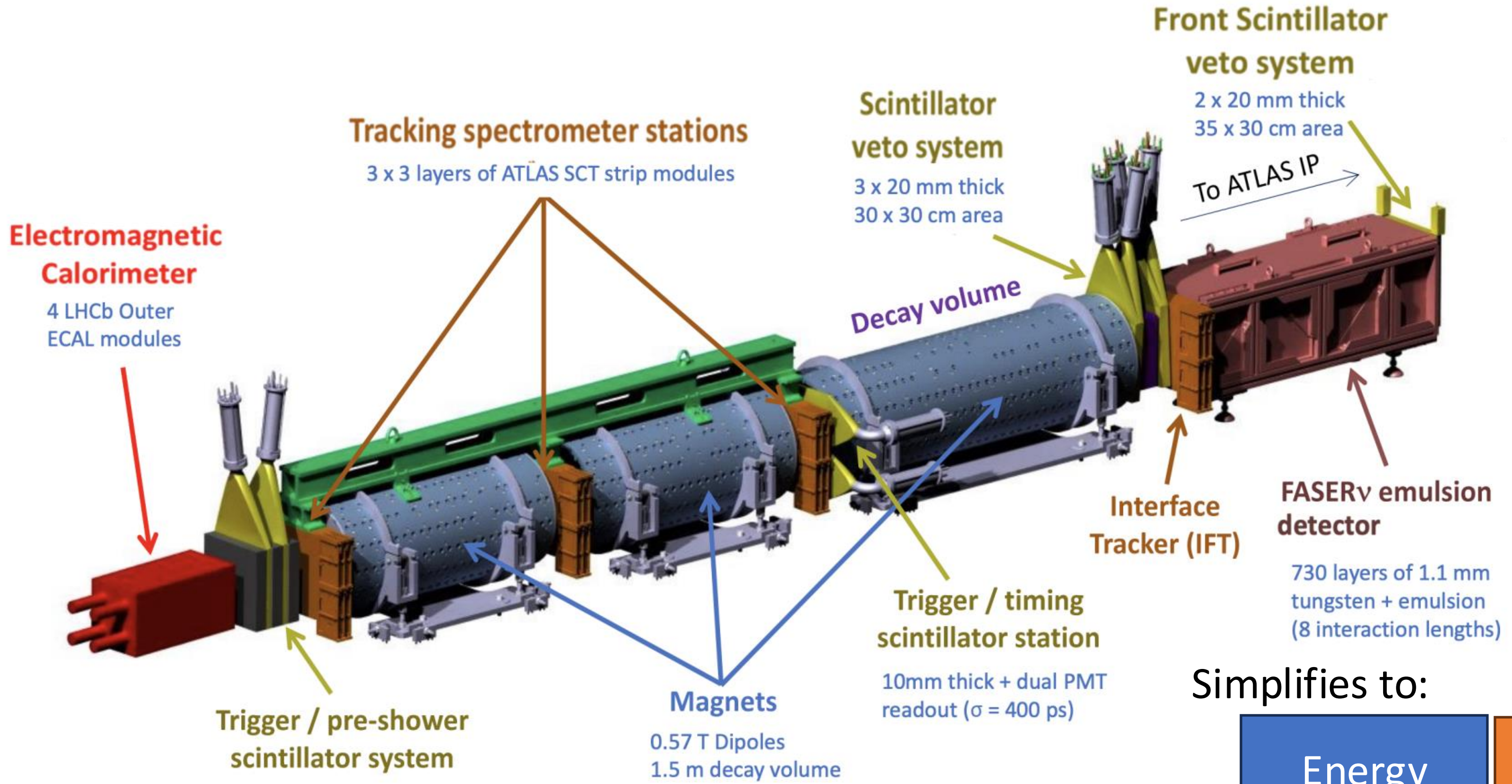
FASER: THE IDEA

Dark Matter models predict new particles which are ***light and weakly interacting*** and with the current detectors at the LHC these cannot be explored as the Large LHC experiments are focused on high transverse momentum



FASER is a proposed experiment designed to cover this scenario at the LHC

FASER's Design (https://arxiv.org/abs/2207.11427)



Simplifies to:

Energy measurement	Tracking of charged particles	Decay volume	Veto for backgrounds

Physics outcomes of FASER

FASER's target

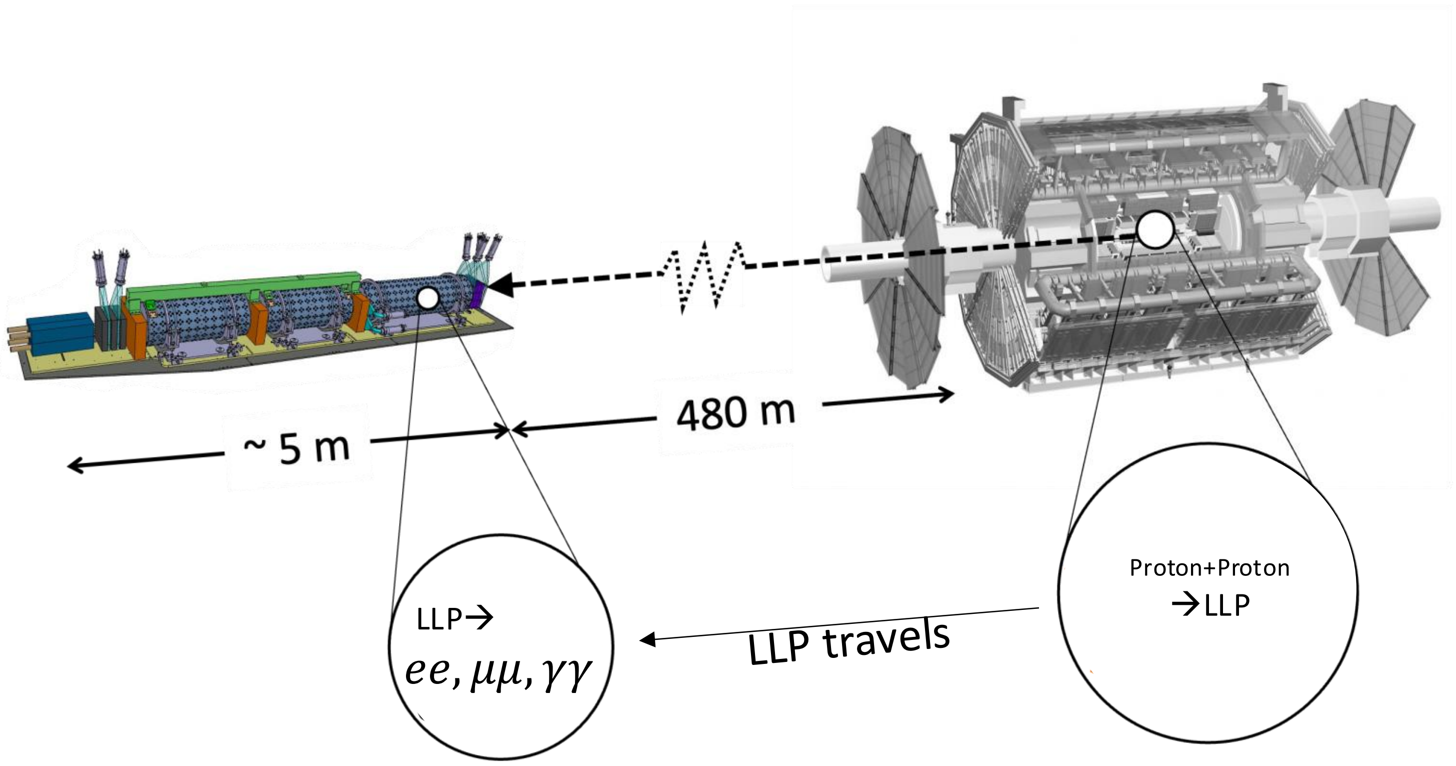
1. Exploits high LHC collision rate + forward produced light particles which are highly collimated and highly energetic
2. Light and weakly coupled particles, such as **dark photons (More), axion-like particles** etc.
3. Additionally, one of the major background sources comes from **neutrinos**, as they are produced in large quantities at hadron colliders, making them an excellent target for study at FASER as well. (More)

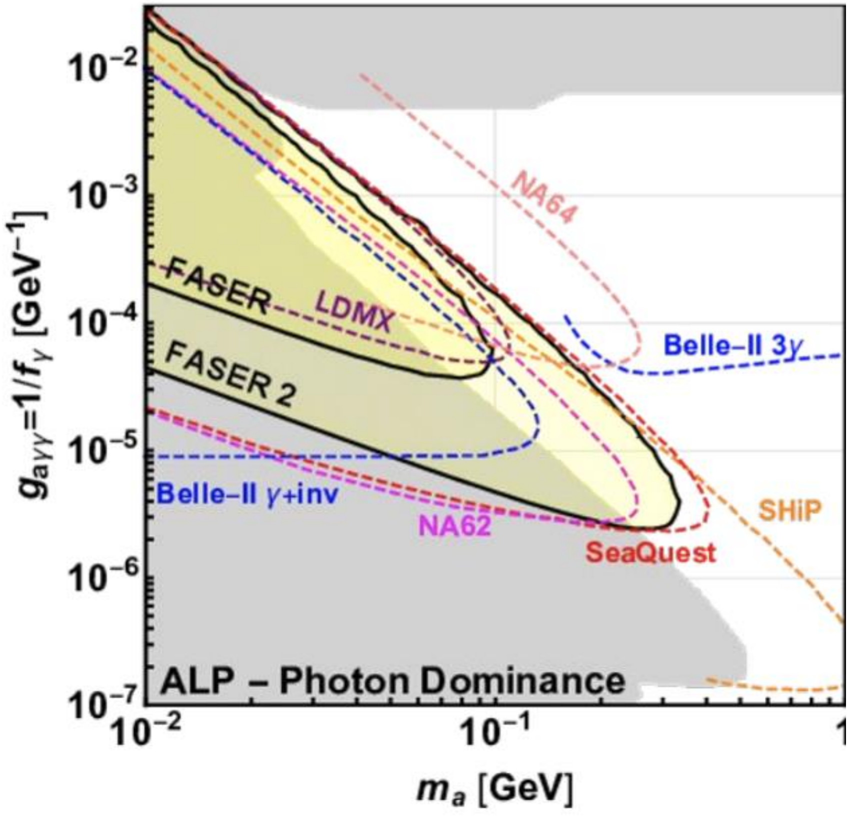
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1 tn Tungsten)	~1000	~20000	~10

Expected Neutrinos in FASER

FASER's Possible Target (Long Lived Particles (LLPs)):

- Exploits large LHC collision rate with highly collimated forward production of light particles
- Particles produced in the FASER angular acceptance have a very large boost O(TeV)

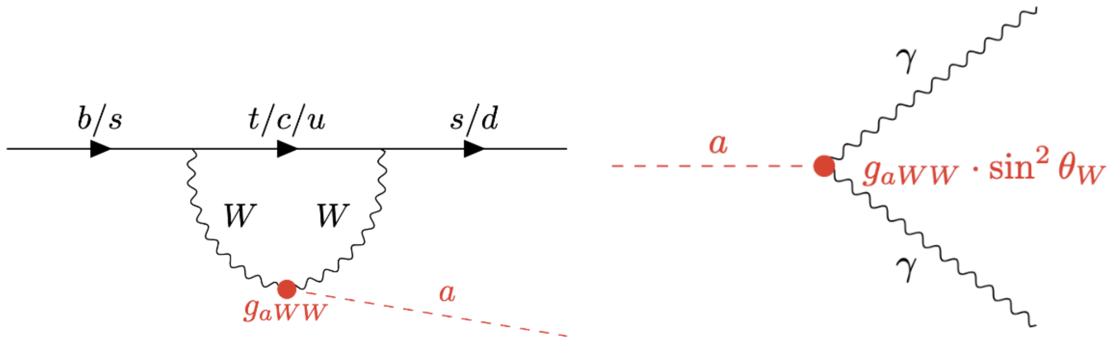




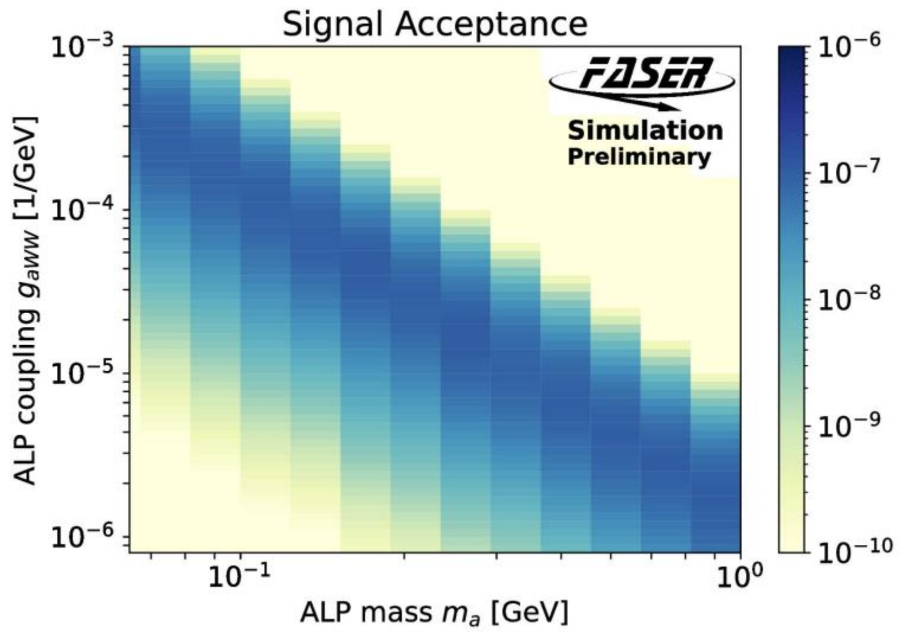
ALP-W model

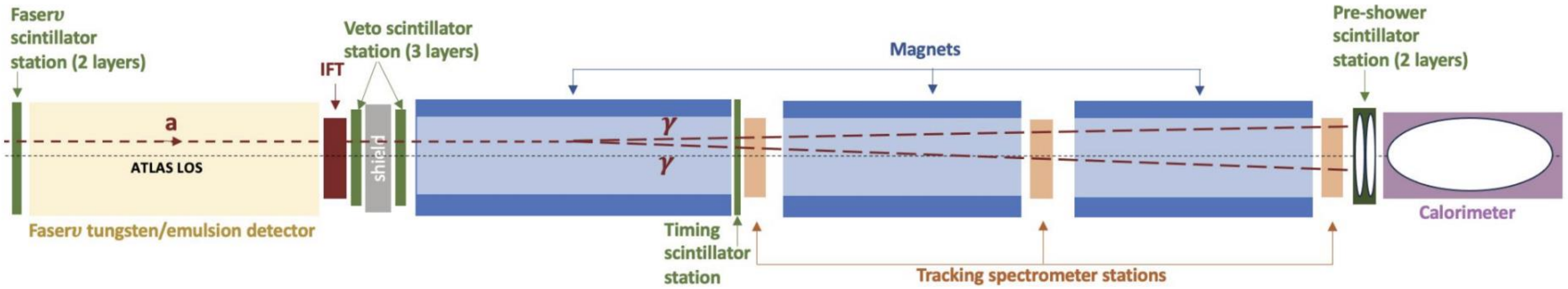
FASER is sensitive to axion-like particles (ALPs)

- Coupling to SU(2)L gauge bosons
- Primarily produced in B meson decays in our sensitivity range
- Can decay anywhere between veto scintillators and preshower, decaying into 2 high energy photons
- Cannot be distinguished in our calorimeter



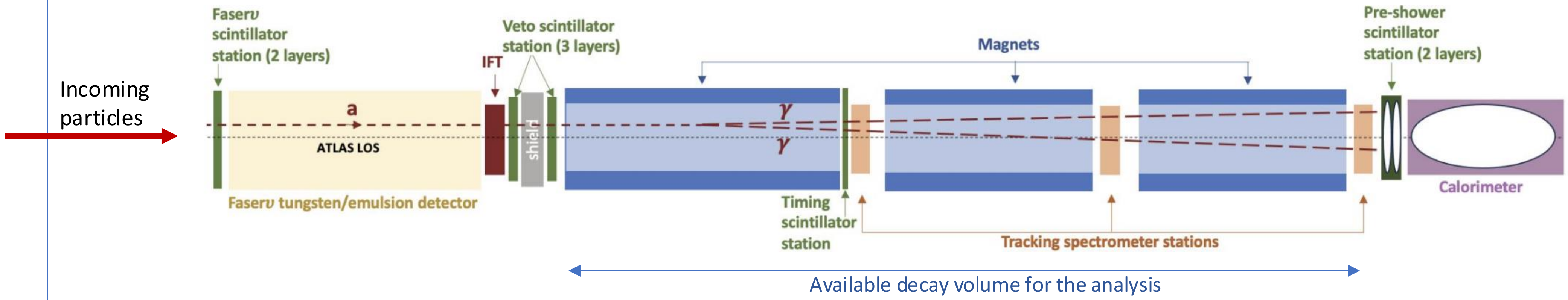
(a) ALP-W production (b) ALP-W decay

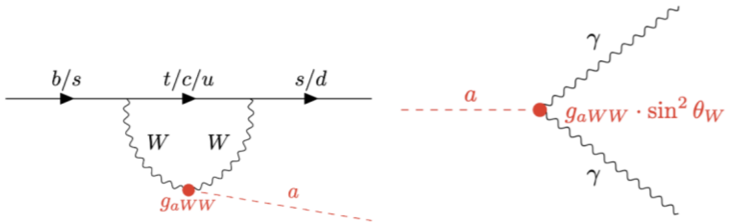




Selection for ALPs Search

Example of a signal event; want $\gamma\gamma$ emerging in the decay volume





(a) ALP-W production (b) ALP-W decay

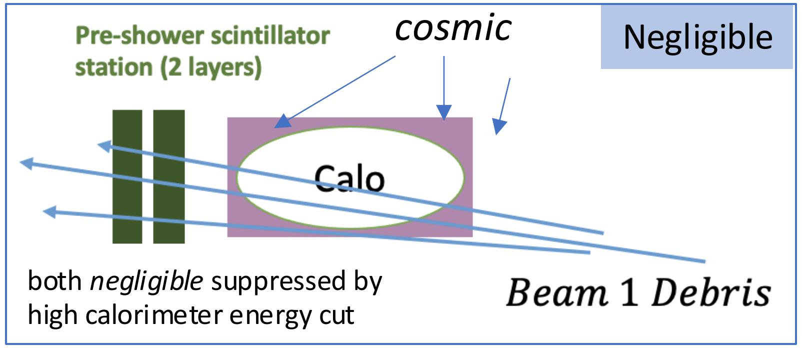
The selection criteria we had in place:

1. No signal (<40 pC) in all scintillators upstream of decay volume
2. Signal (>40 pC) in all scintillators downstream of decay volume
3. Energy deposit in the pre-shower
4. High calorimeter deposit

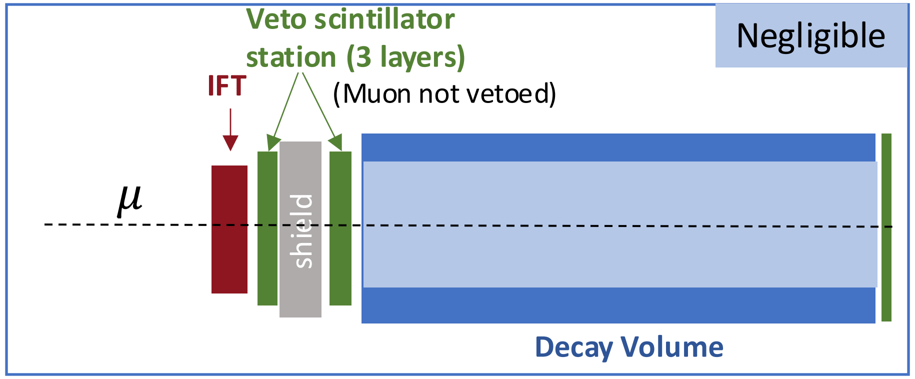
Background

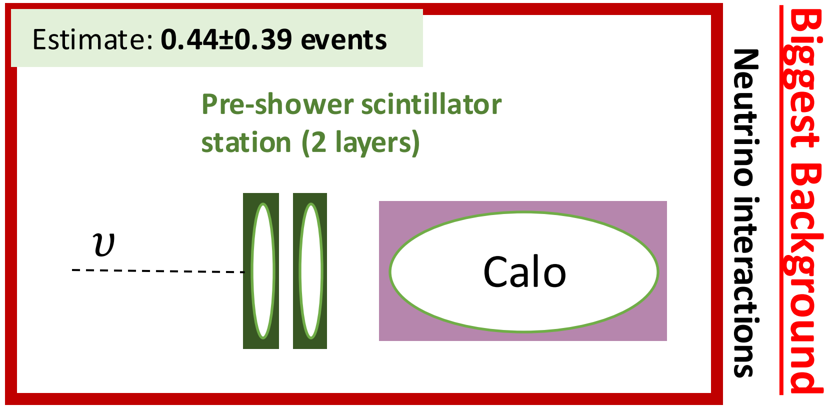
The total background estimate was: 0.44±0.39 events
With the main background coming from charged-current neutrino interactions

Non-collision background

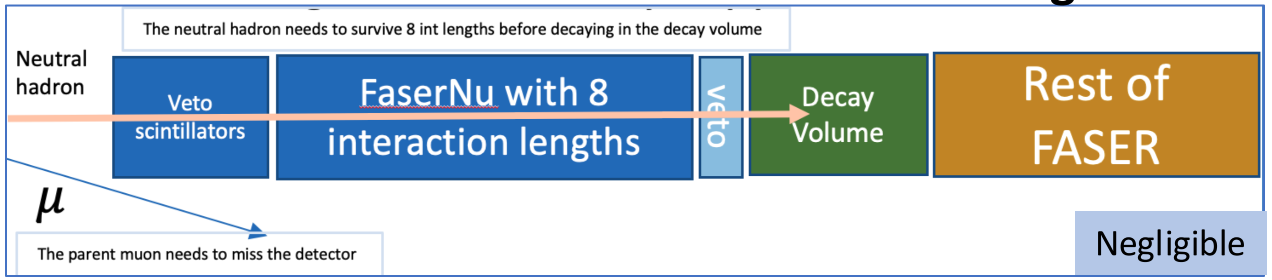


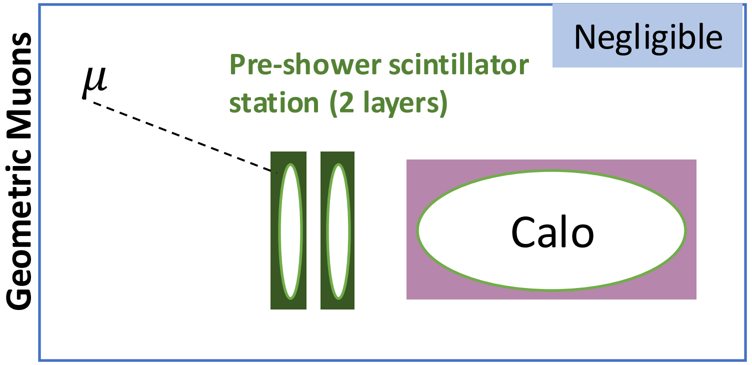
Veto inefficiency:





Neutral hadron background



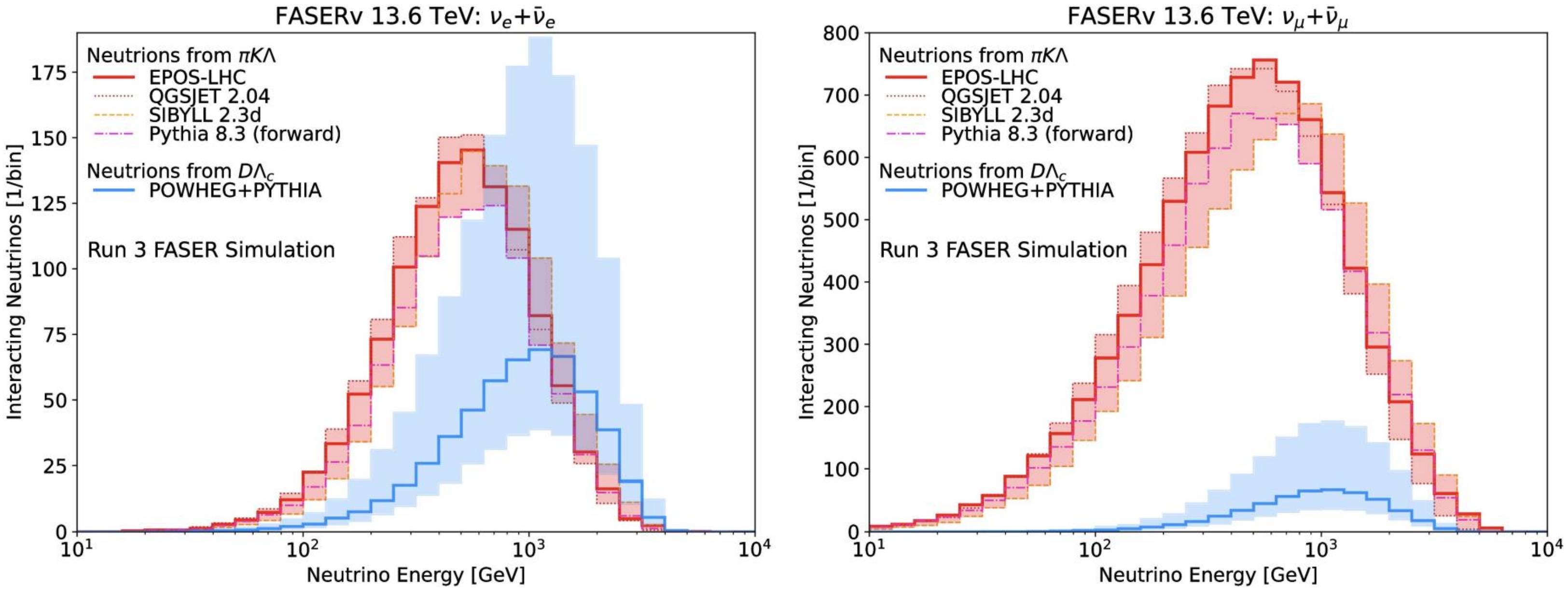


Estimation of Neutrino Background (biggest background)

Neutrinos in FASER acceptance produced by hadron decay:
- ν_e: mostly from kaon decay and at high energy from charm
- $\nu\mu$: mostly from pion decay, at high energy kaons
- ν_τ: only from charm

- Forward production of light mesons (π/K) can not be calculated in pQCD, rather rely on phenomenological models used for cosmic ray physics (validated with LHCf data)
  - We use EPOS to estimate the light hadron flux, using the envelope of other generators as an uncertainty

- Forward charm production can be calculated in pQCD, and we use Powheg+pythia NLO calculation for this
  - Large uncertainty from scale variations



Flux and uncertainty prediction coming from here

Systematics

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%

Background Systematics

Source	Event Rate
Neutrino Background	0.44 ± 0.35 (flux) ± 0.15 (calo. energy) ± 0.06 (PS ratio) ± 0.02 (PS 1 nMIP) ± 0.02 (PS geometry) ± 0.05 (stat.) **Total: 0.44 ± 0.39 (88.6%)**

The various sources of systematic uncertainty in this analysis are:

- Theory
  - The uncertainty associated with flux modelling and generator variation
- Experimental
  - The uncertainty on luminosity measurement (from ATLAS)
  - The uncertainty associated with the MC modelling of our preshower and calorimeter cuts
- MC Statistics

ALP-W Reach

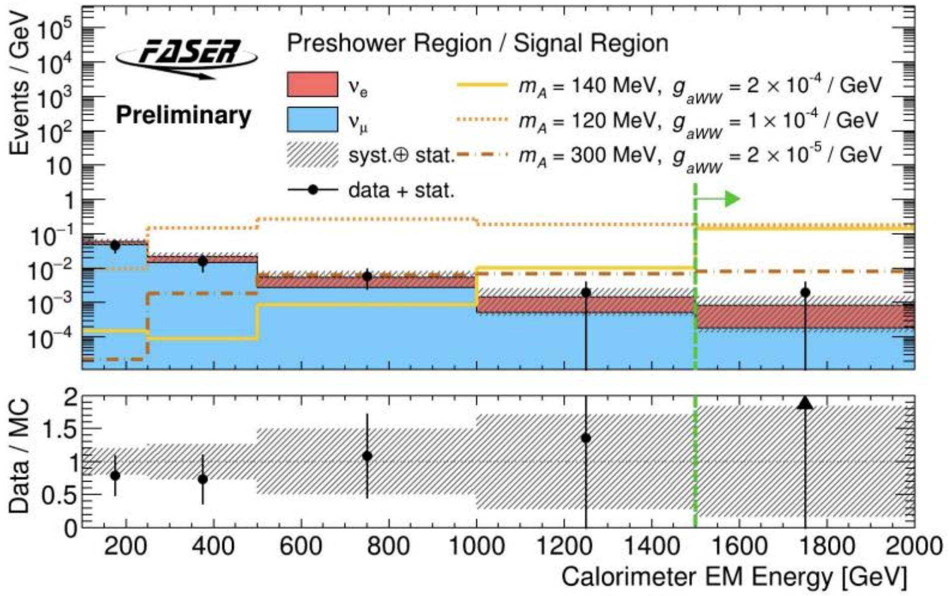
In 57.7 fb^{-1} of data we saw 1 event in our unblinded signal region

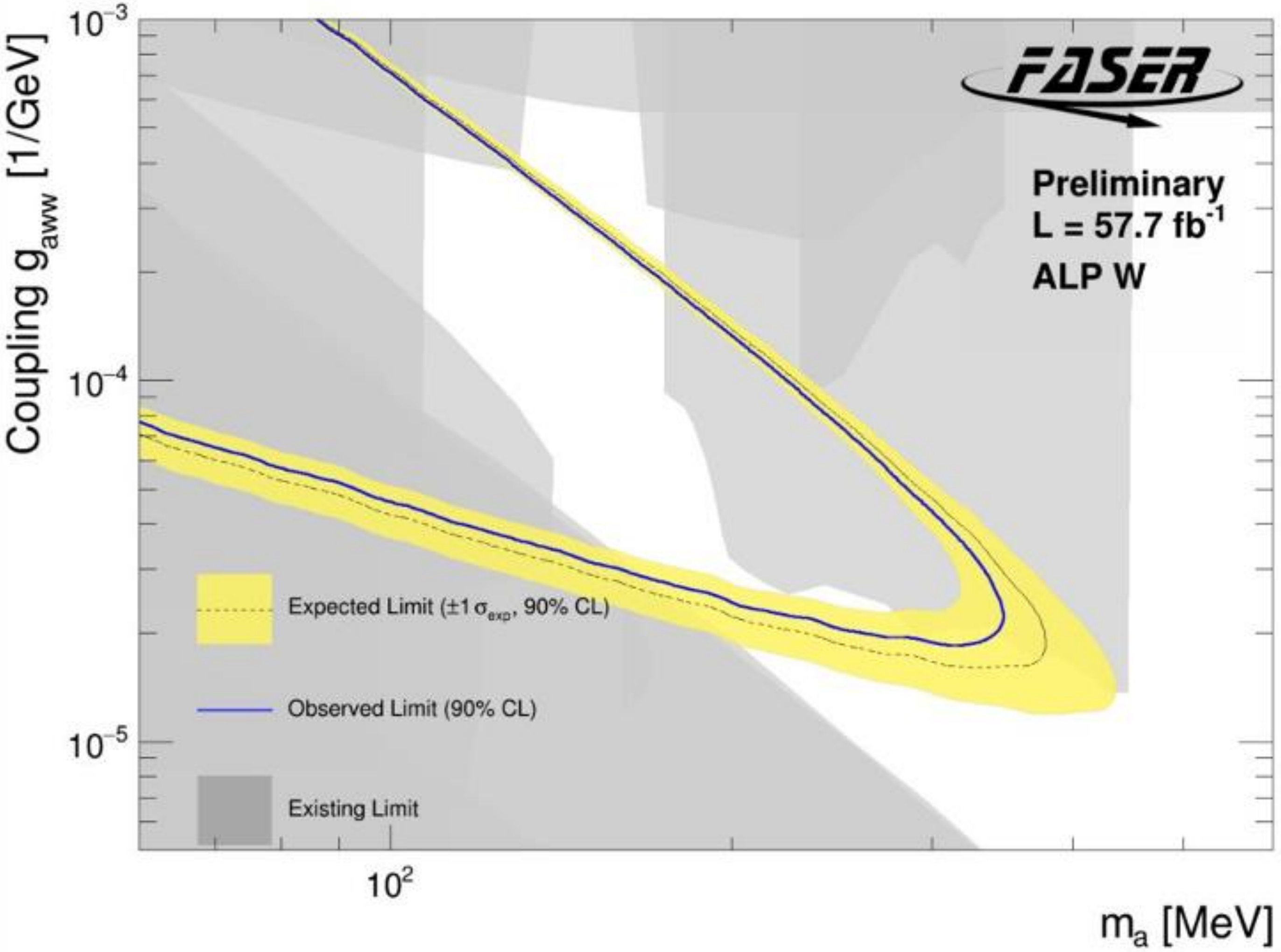
-Compared to expected background of 0.44 ± 0.39 events

- Shows preshower deposits consistent with an EM shower

-Calorimeter energy of 1.6 TeV

With this FASER has set new limits into unprobed parameter space!



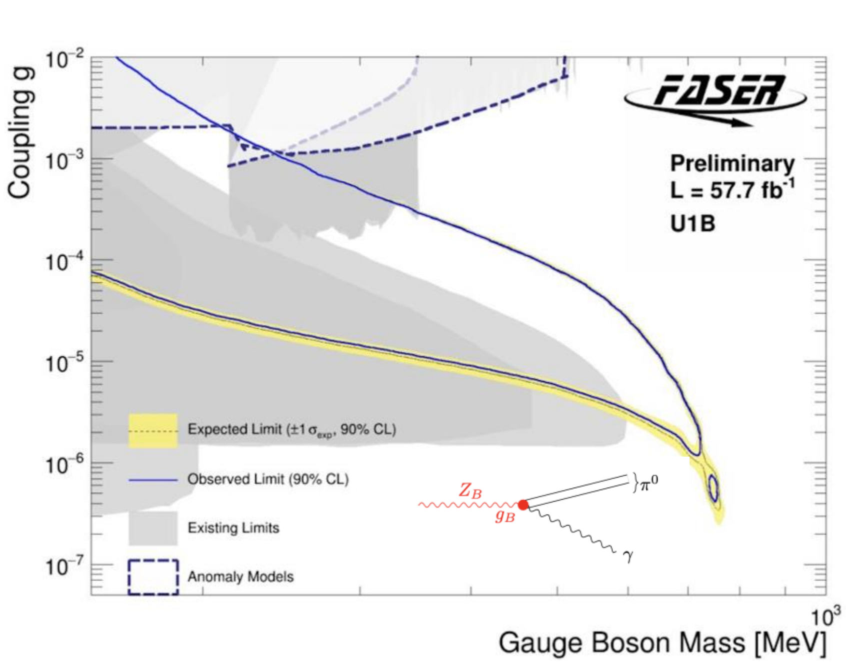


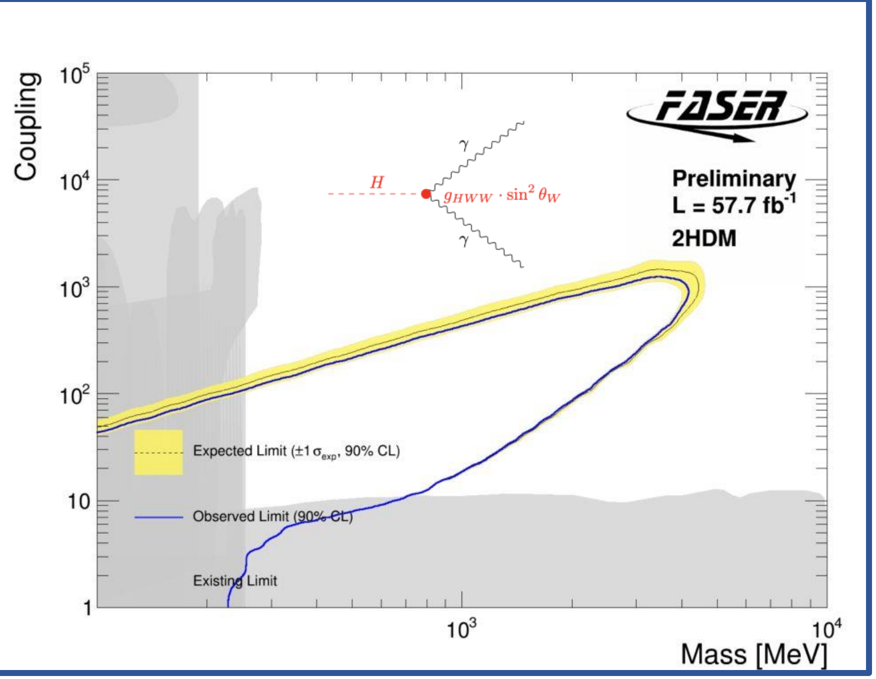
Additional models considered

Top:
(Left to Right)
- U(1)B Scalar
-2 Higgs Doublet Model

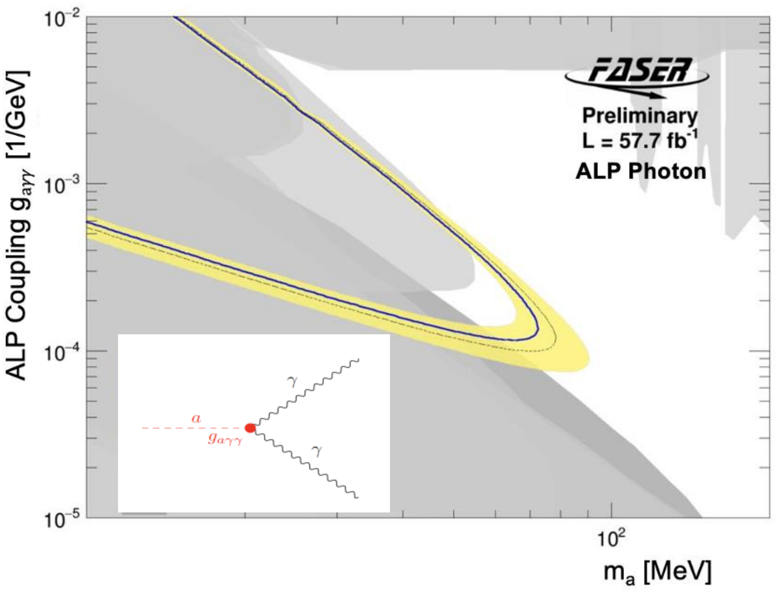
Bottom:
(Left to Right)
- ALP- Photon
- ALP- Gluon
-Up-Philic Scalar

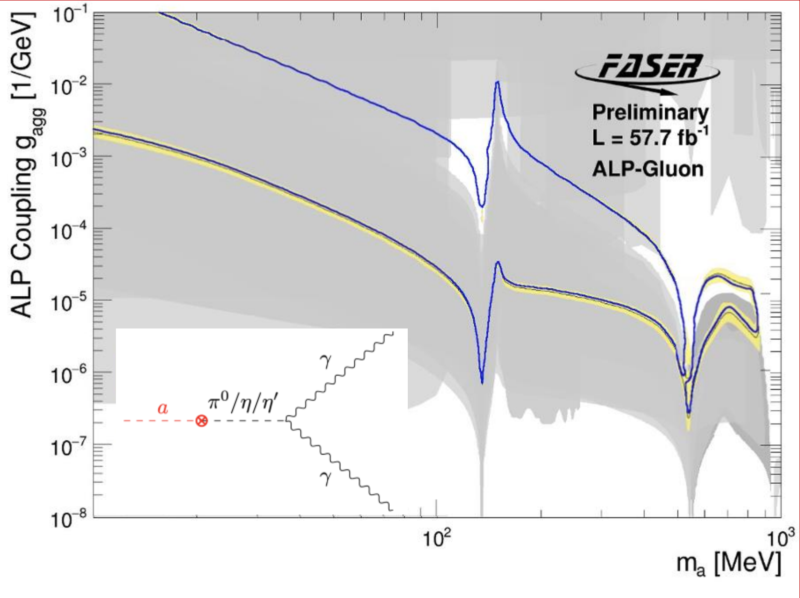
Boson Models



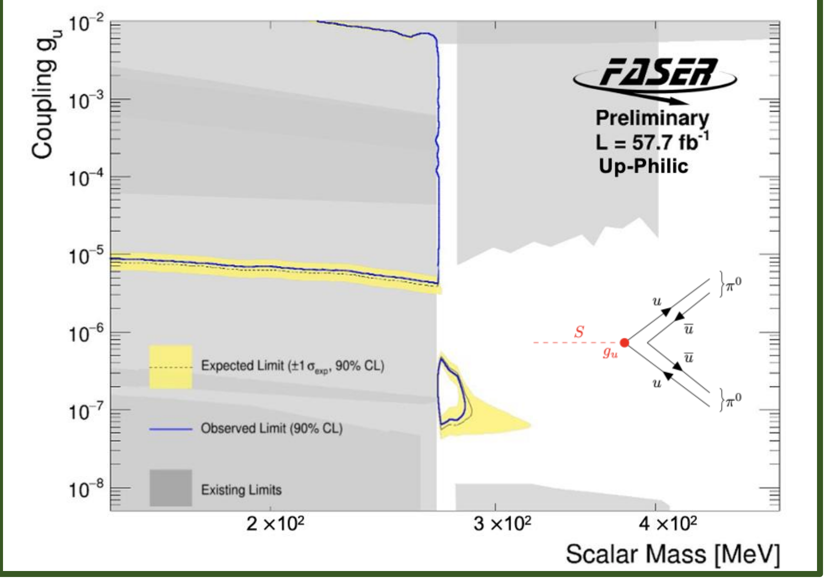


Pseudoscalar (ALPs)

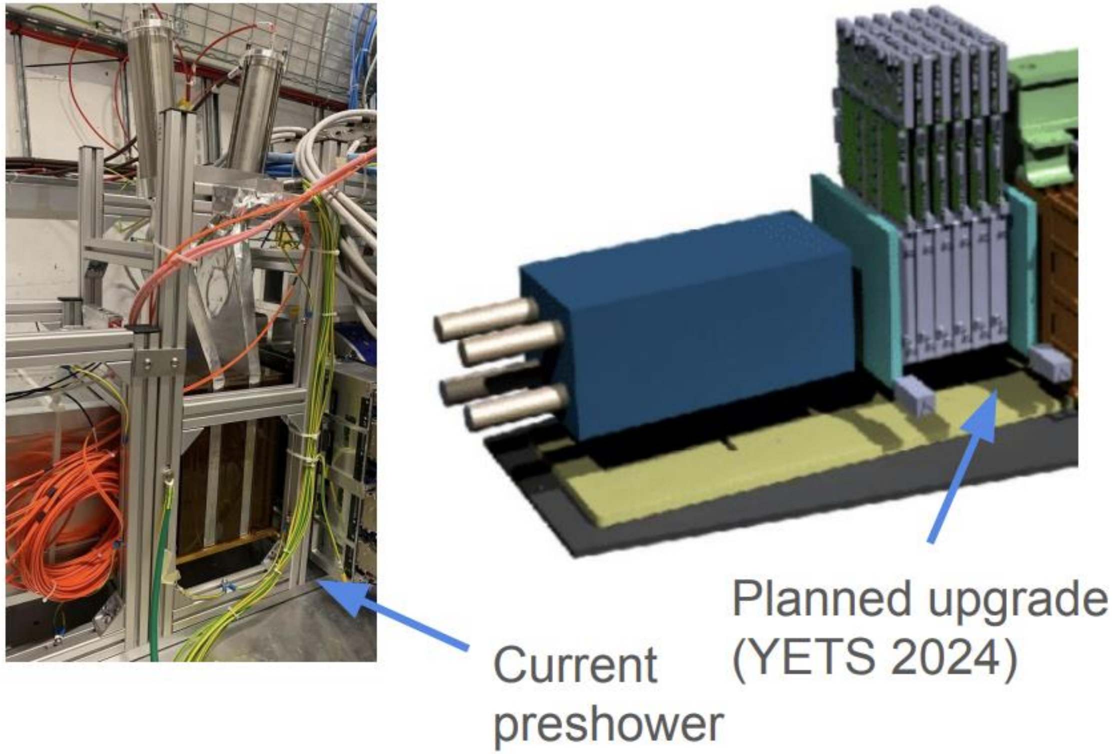


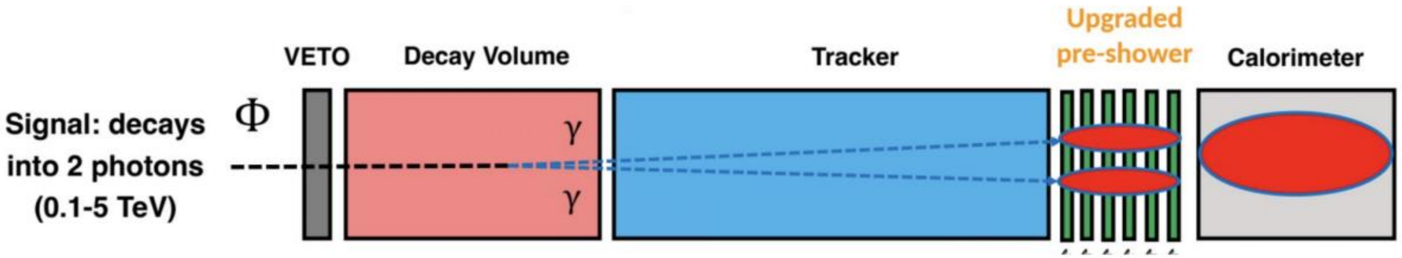


Scalar



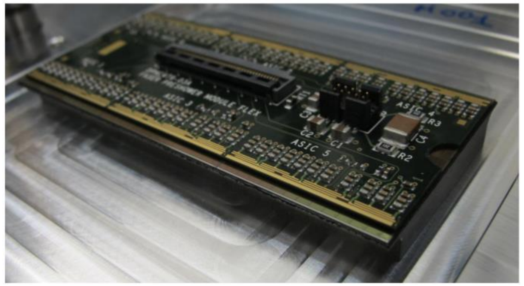
FASER Preshower Upgrade





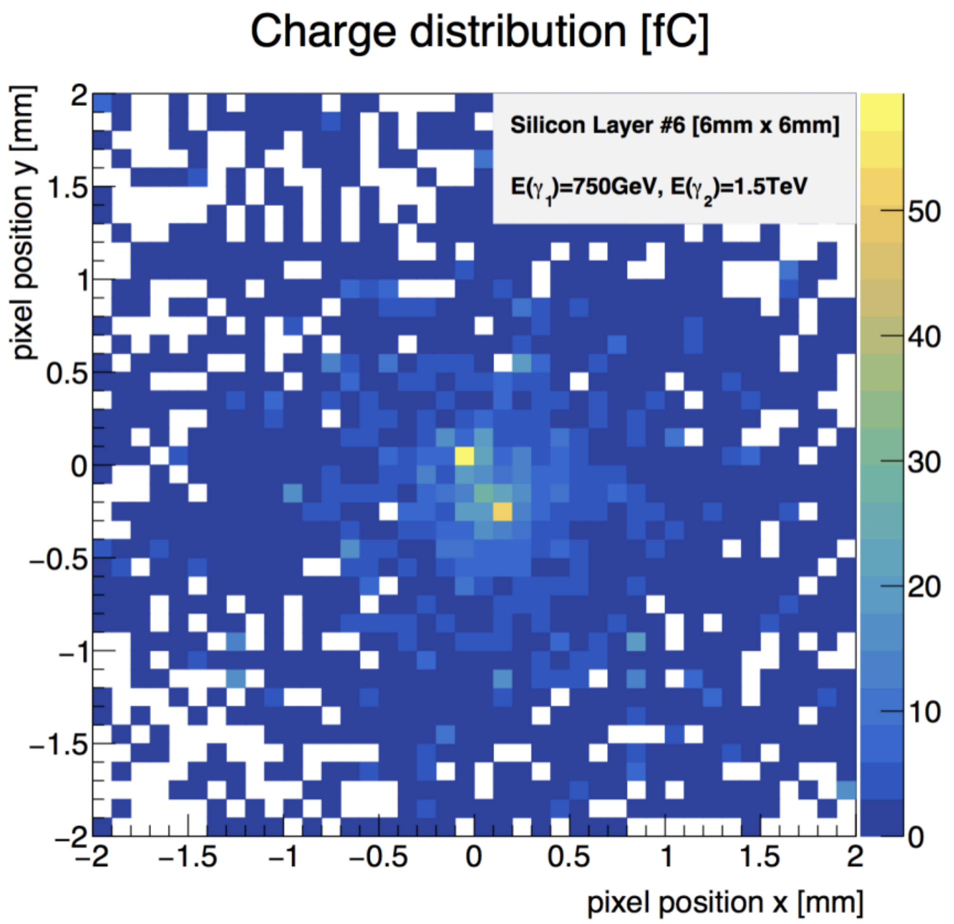
Preshower sub-detector upgrade (More)
- Improve ability to resolve diphoton events with high X-Y granularity
- Improve sensitivity and background suppression in ALPs searches

FASER approved to run in Run 4
- Large dataset with upgraded FASER at HL-LHC



Module/Plane assembly and qualifications are completed

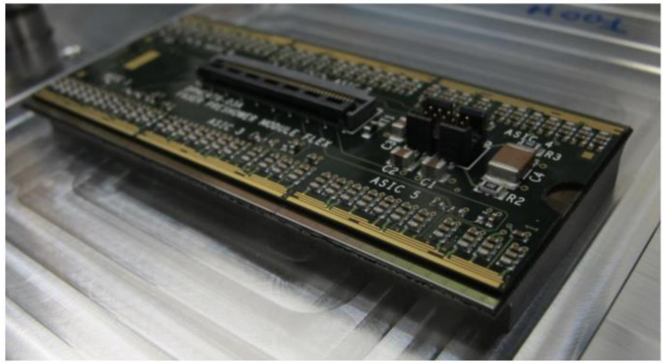
FASER preshower upgrade



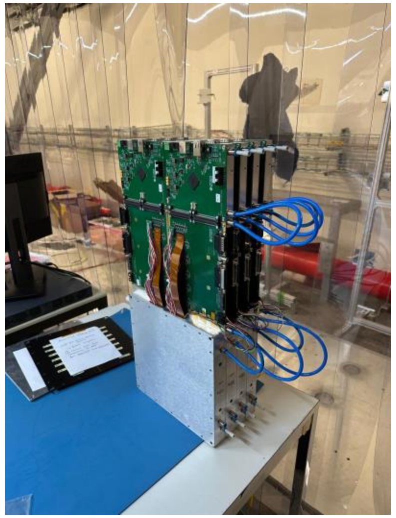
1. Simulation result. Charge deposition across the pixels of the last silicon layer by two photons of energies of 750 GeV and 1 TeV and a separation of 0.2 mm.
2. Only a small area of 4 × 4 mm2 around the photon positions is shown.
3. The two photons are clearly distinguishable by the charge distribution and position of hits

Preshower Project Development

6 ASICs for each module



4 planes for upgraded detector

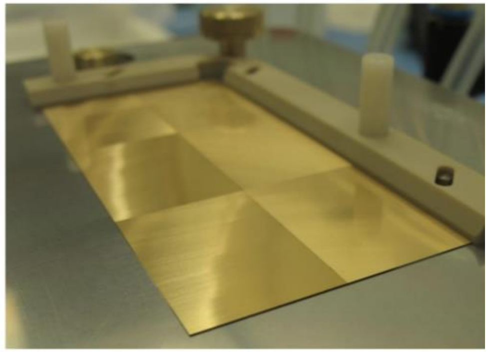


ASIC qualification (Completed)

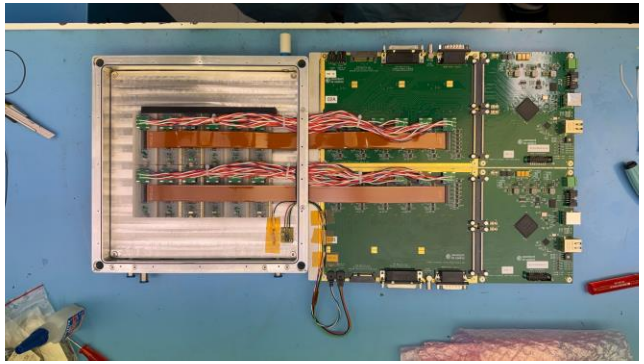
→ Module Qualification (Completed)

→ Plane qualification (Completed)

→ Upgraded Preshower Detector commissioning (Completed)

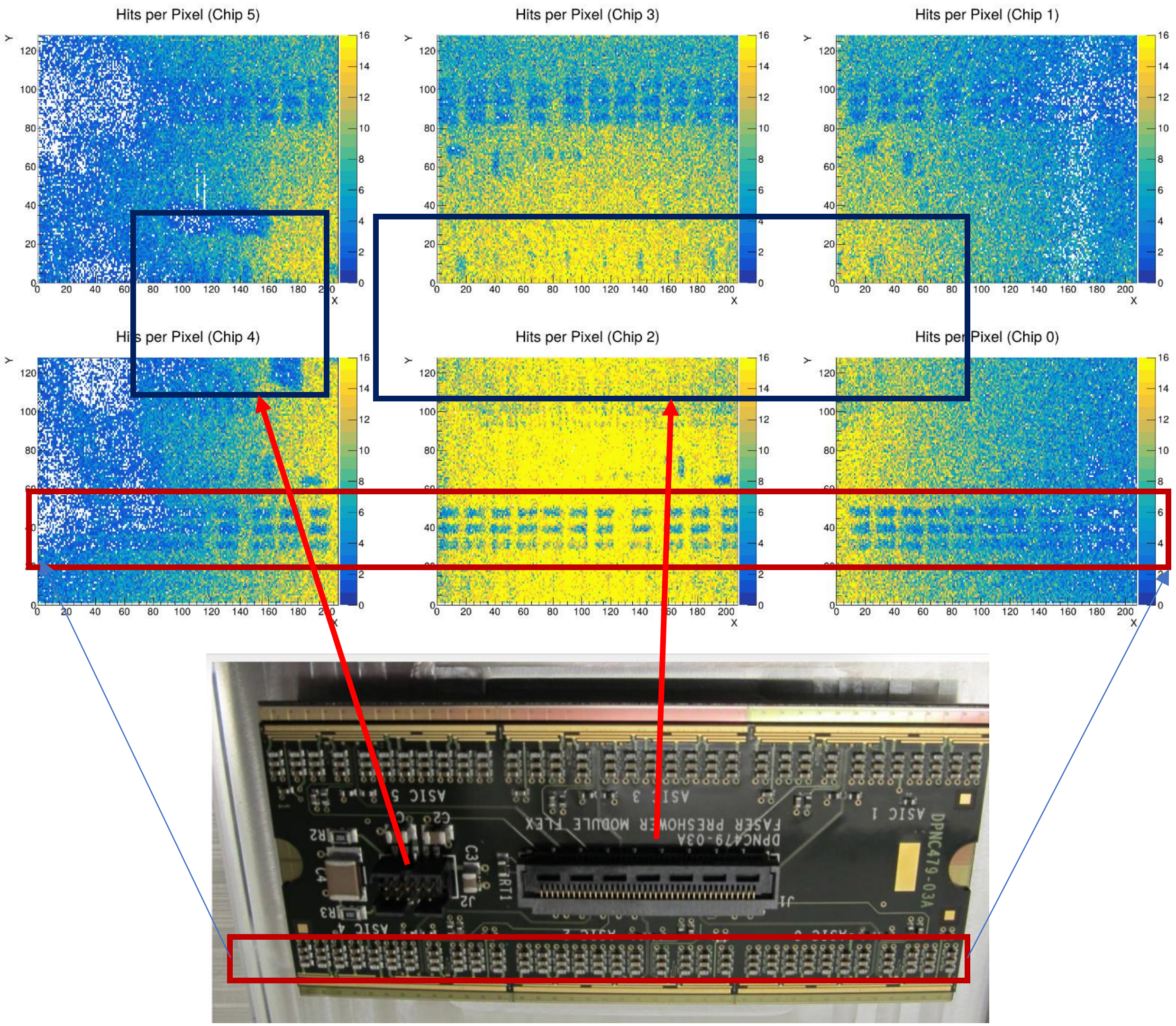


6 chips being loaded for a module



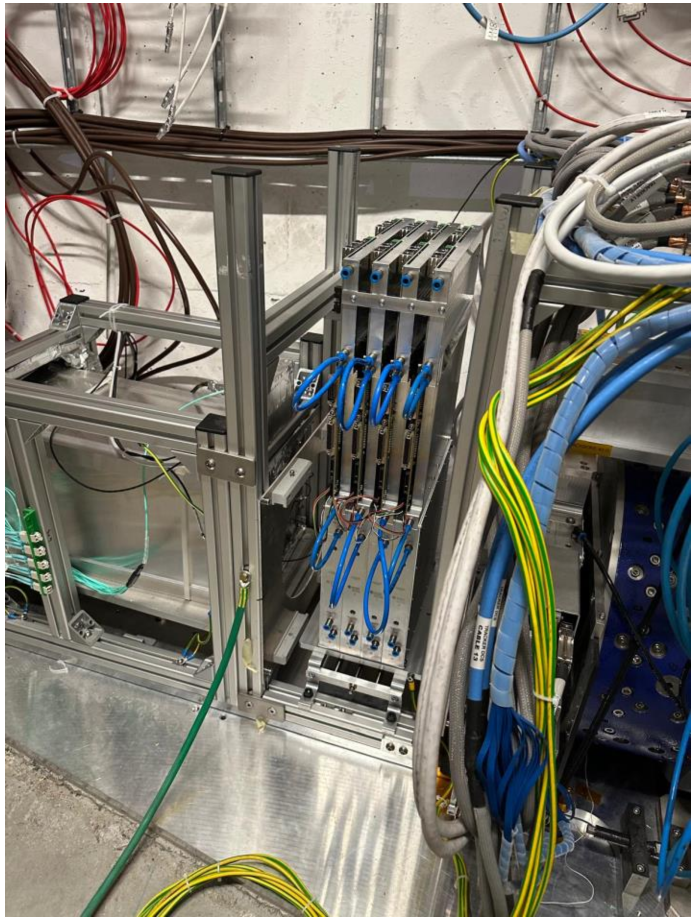
12 modules for each plane

Results from Radioactive sources



- Am-241 source placed on each module for scans
- Results focusing on module here where the source was on chip 2
- The six chips shown separately
- Almost like taking an x ray image of the module
- Tiny structures of the flex also visible including the tiny resistors
- Demonstrating really nice behavior of the modules

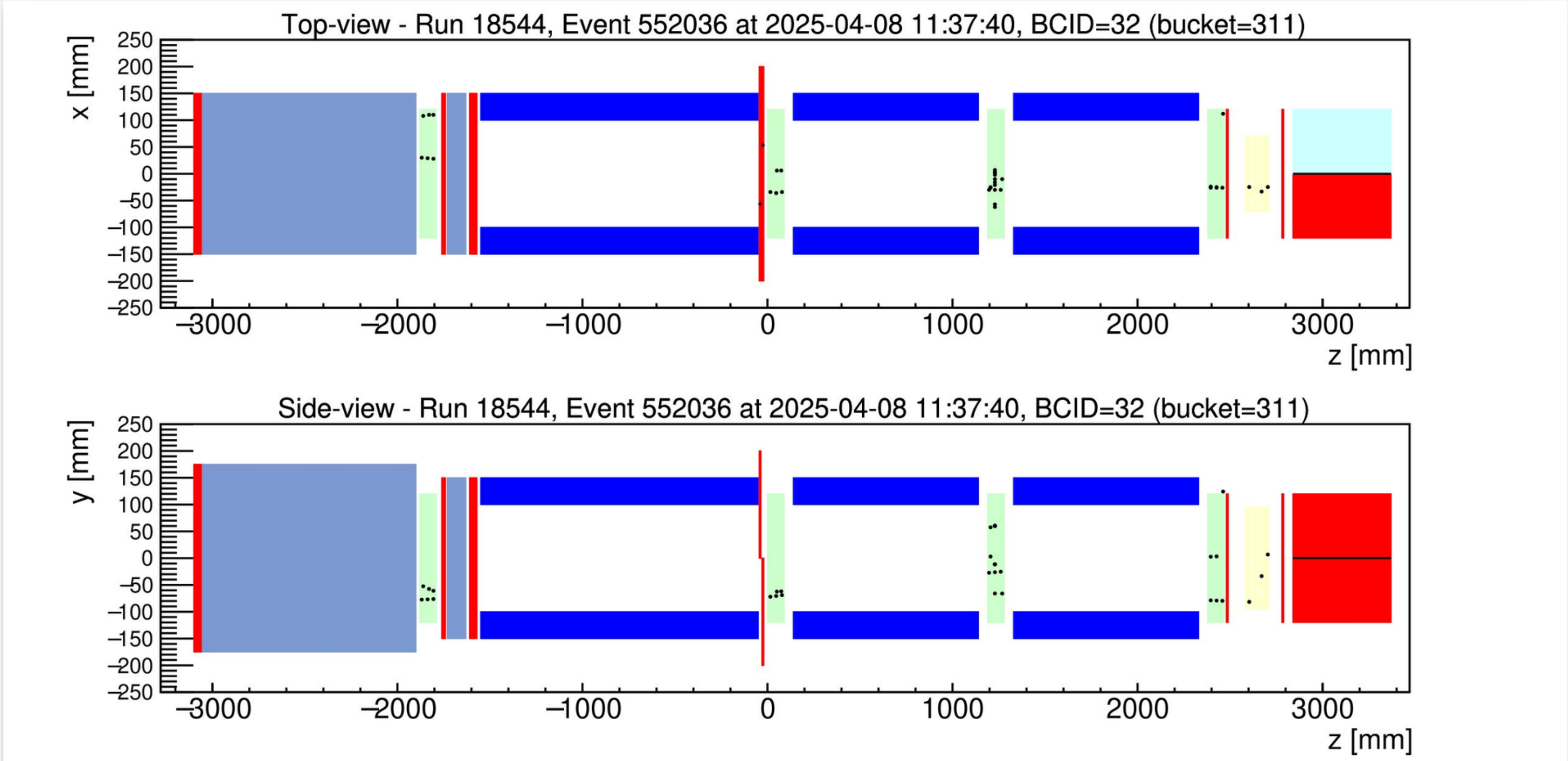
Preshower Upgrade Status



1. (Left): Full detector assembled and qualified
1.2. (Right): Upgraded detector installed into the FASER detector in the tunnel

3. Calibrations of the full detector ongoing
4. Aiming to take physics data in 2025 run

First Event Displays from Beam



- Beam in the LHC, this week
- FASER to see something if beam hits the collimator and makes a shower of particles that go through the detector
- Example event on the left
- First time seeing full system lighting up throughout including the upgraded detector (in yellow)

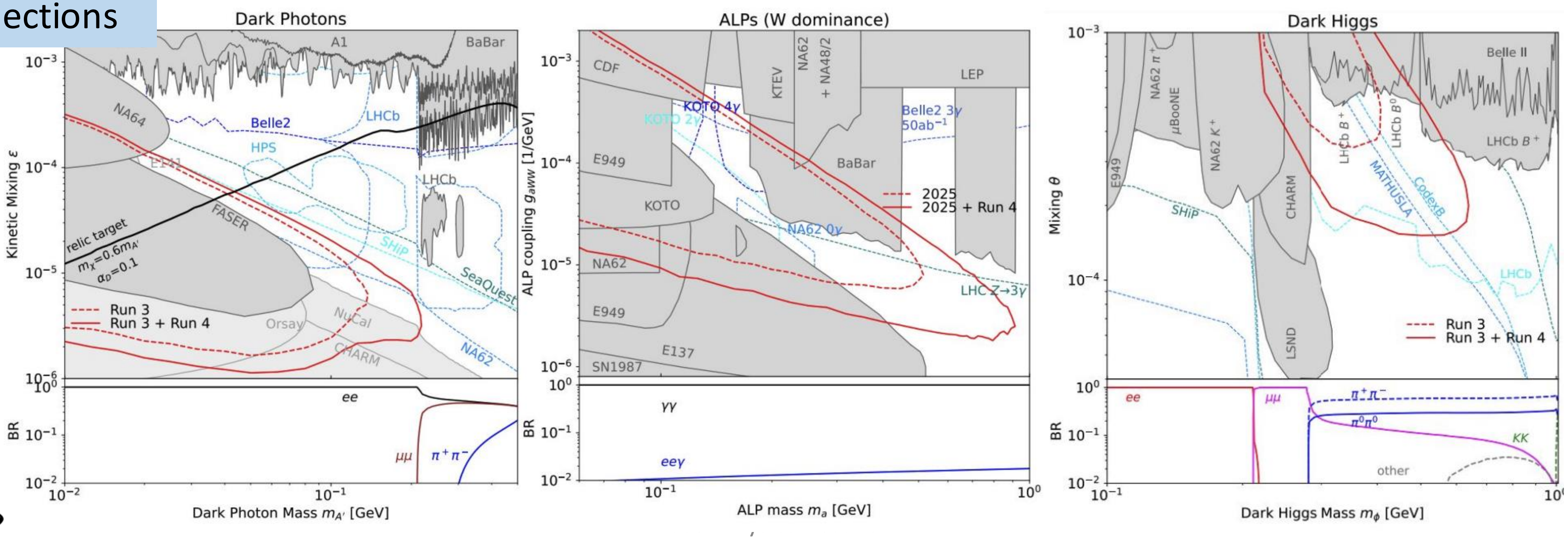
Conclusion

- FASER successfully took data in Run3 (since July 2022), running at very good efficiency with a fully functional detector!
- Excluded ALPs and other multiphoton models in various regions.
- 190fb^{-1} of data already collected expect up to 2x more by the end of Run 2 (mid-2026)
- Preshower upgrade recently installed and being commissioned
- The Forward Physics Facility(FPF) is a proposed new facility to house several detectors in the far-forward region including FASER2

[All FASER publications]

[FASER Preshower Upgrade]

Run4 Projections



[FASER Run4 Request]

Thank you for listening!

from FASER Collaboration Meeting #5, 2023

FASER Institutions

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE

UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON

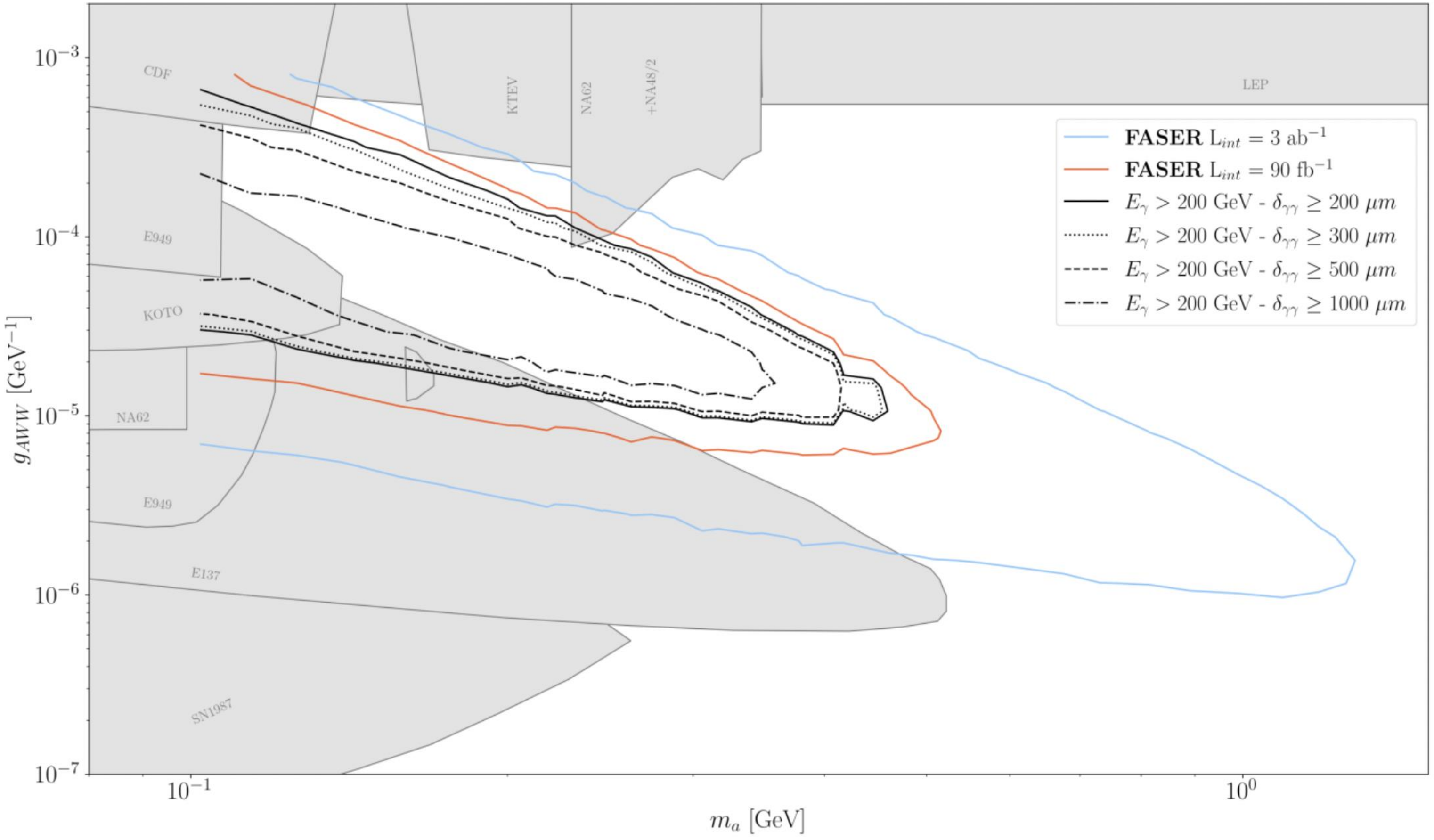
DESY.
INFN
ISS
International laboratory covered by a cooperation agreement with CERN
清華大學 Tsinghua University
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX

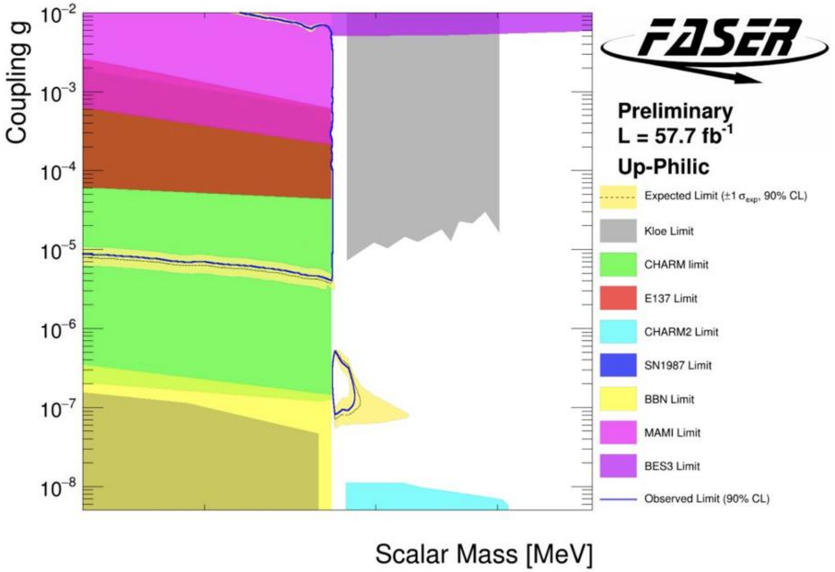
Nikhef
UNIVERSITÄT BONN
ETH zürich
MANCHESTER 1824 The University of Manchester

Backup

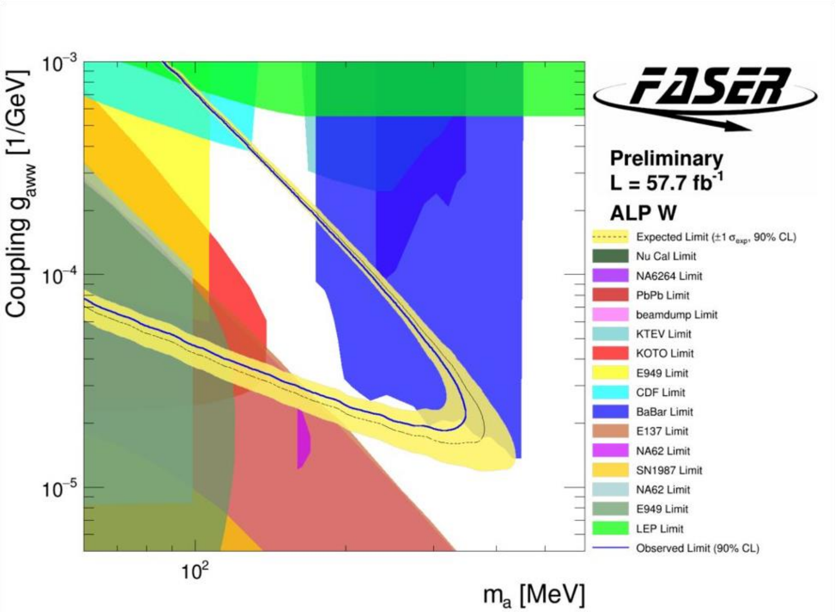
Expected reach with the Preshower Upgrade



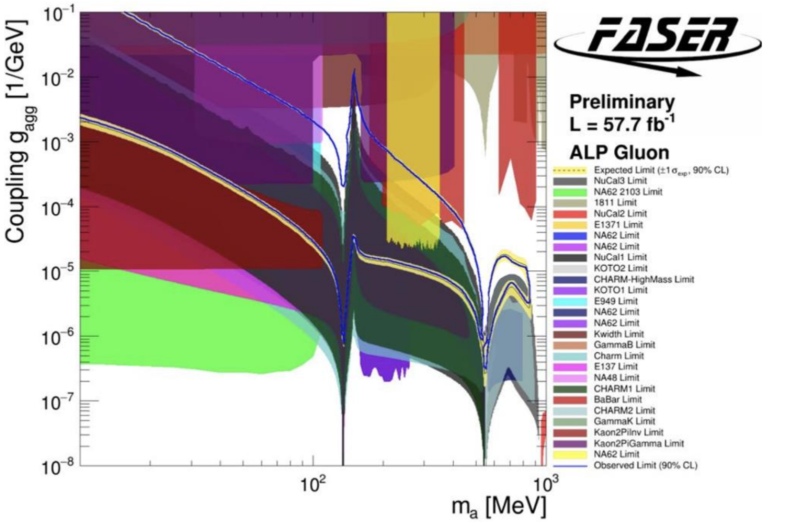
Limit Plots



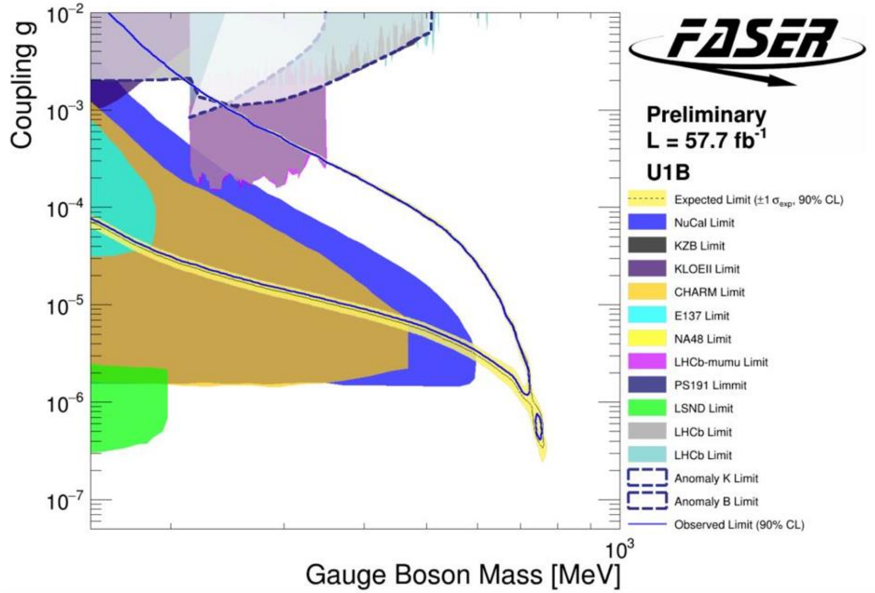
FASER
Preliminary
L = 57.7 fb^{-1}
Up-Philic
Expected Limit (±1 σ$_{exp}$, 90% CL)
Kloe Limit
CHARM limit
E137 Limit
CHARM2 Limit
SN1987 Limit
BBN Limit
MAMI Limit
BES3 Limit
Observed Limit (90% CL)
Coupling g
Scalar Mass [MeV]



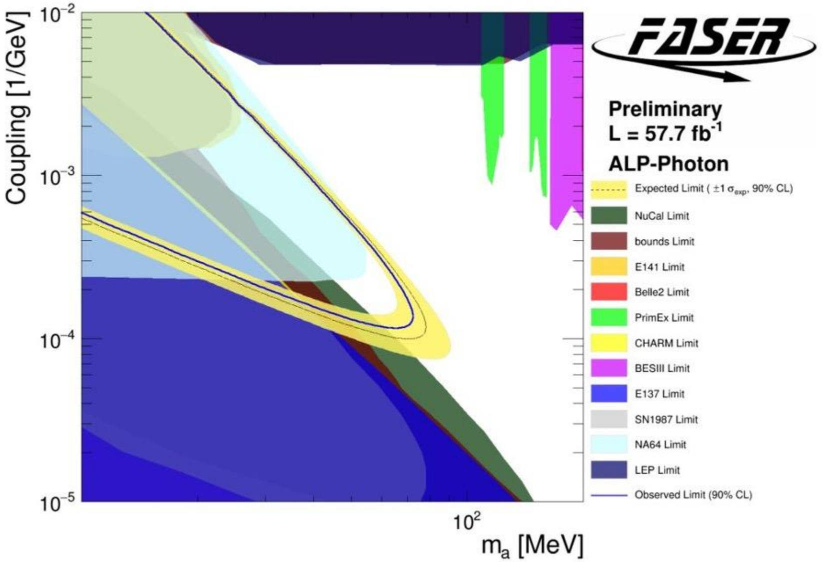
FASER
Preliminary
L = 57.7 fb^{-1}
ALP W
Expected Limit (±1 σ$_{exp}$, 90% CL)
Nu Cal Limit
NA6264 Limit
PbPb Limit
beamdump Limit
KTEV Limit
KOTO Limit
E949 Limit
CDF Limit
BaBar Limit
E137 Limit
NA62 Limit
SN1987 Limit
NA62 Limit
E949 Limit
LEP Limit
Observed Limit (90% CL)
Coupling g$_{aWW}$ [1/GeV]
m$_a$ [MeV]



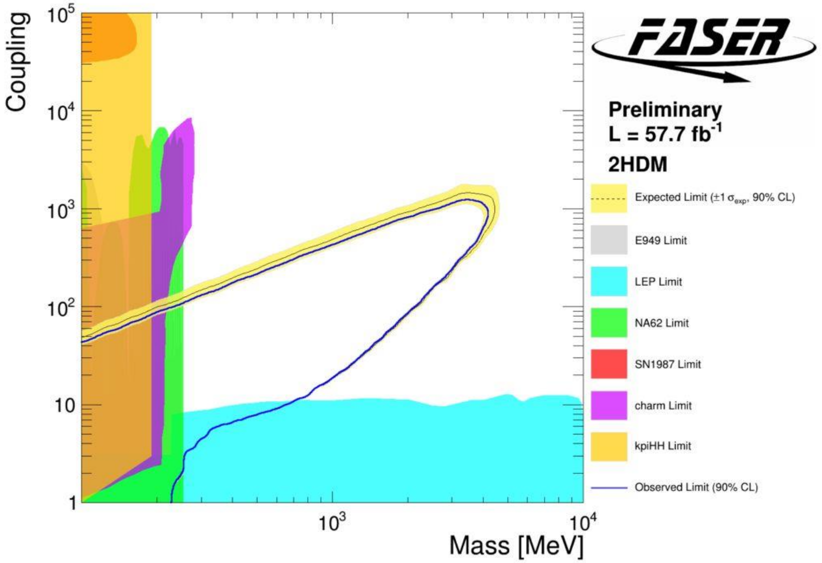
FASER
Preliminary
L = 57.7 fb^{-1}
ALP Gluon
Expected Limit (±1 σ$_{exp}$, 90% CL)
Coupling g$_{agg}$ [1/GeV]
m$_a$ [MeV]



FASER
Preliminary
L = 57.7 fb^{-1}
U1B
Expected Limit (±1 σ$_{exp}$, 90% CL)
NuCal Limit
KZB Limit
KLOEII Limit
CHARM Limit
E137 Limit
NA48 Limit
LHCb-mumu Limit
PS191 Limmit
LSND Limit
LHCb Limit
LHCb Limit
Anomaly K Limit
Anomaly B Limit
Observed Limit (90% CL)
Coupling g
Gauge Boson Mass [MeV]

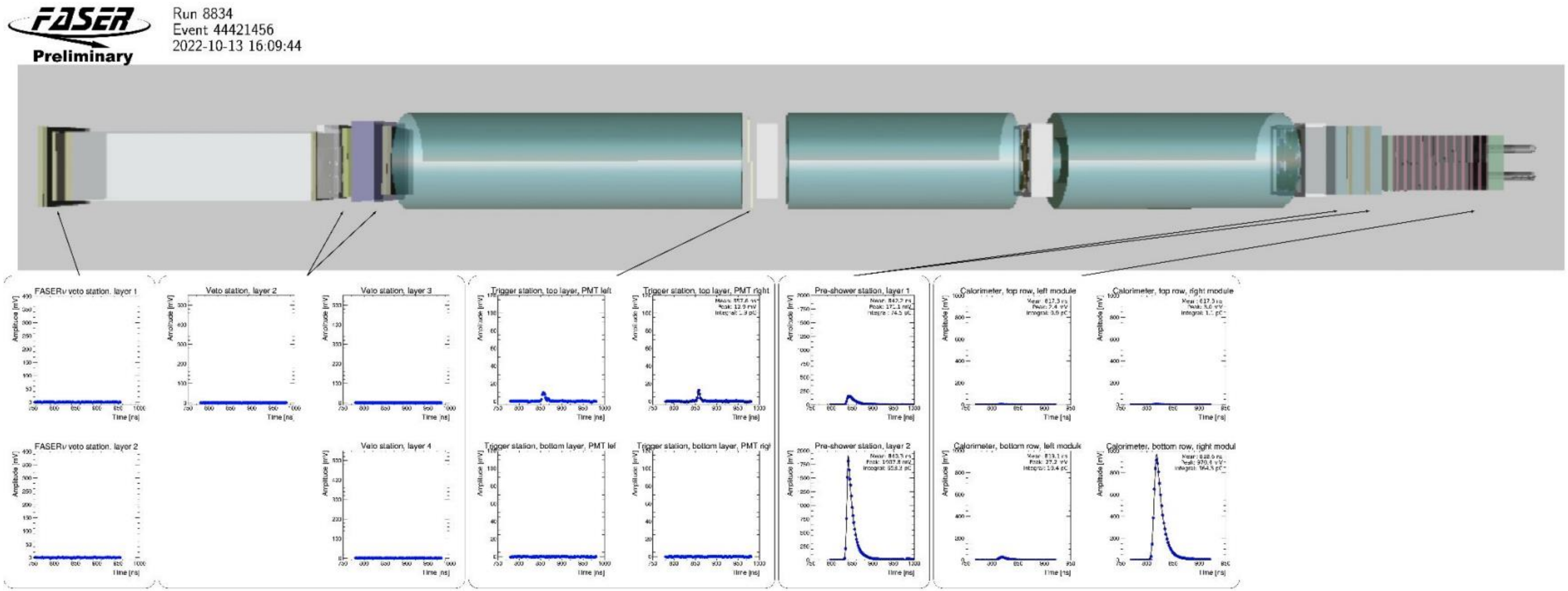


FASER
Preliminary
L = 57.7 fb^{-1}
ALP-Photon
Expected Limit (±1 σ$_{exp}$, 90% CL)
NuCal Limit
bounds Limit
E141 Limit
Belle2 Limit
PrimEx Limit
CHARM Limit
BESIII Limit
E137 Limit
SN1987 Limit
NA64 Limit
LEP Limit
Observed Limit (90% CL)
Coupling [1/GeV]
m$_a$ [MeV]



FASER
Preliminary
L = 57.7 fb^{-1}
2HDM
Expected Limit (±1 σ$_{exp}$, 90% CL)
E949 Limit
LEP Limit
NA62 Limit
SN1987 Limit
charm Limit
kpiHH Limit
Observed Limit (90% CL)
Coupling
Mass [MeV]

Event Display

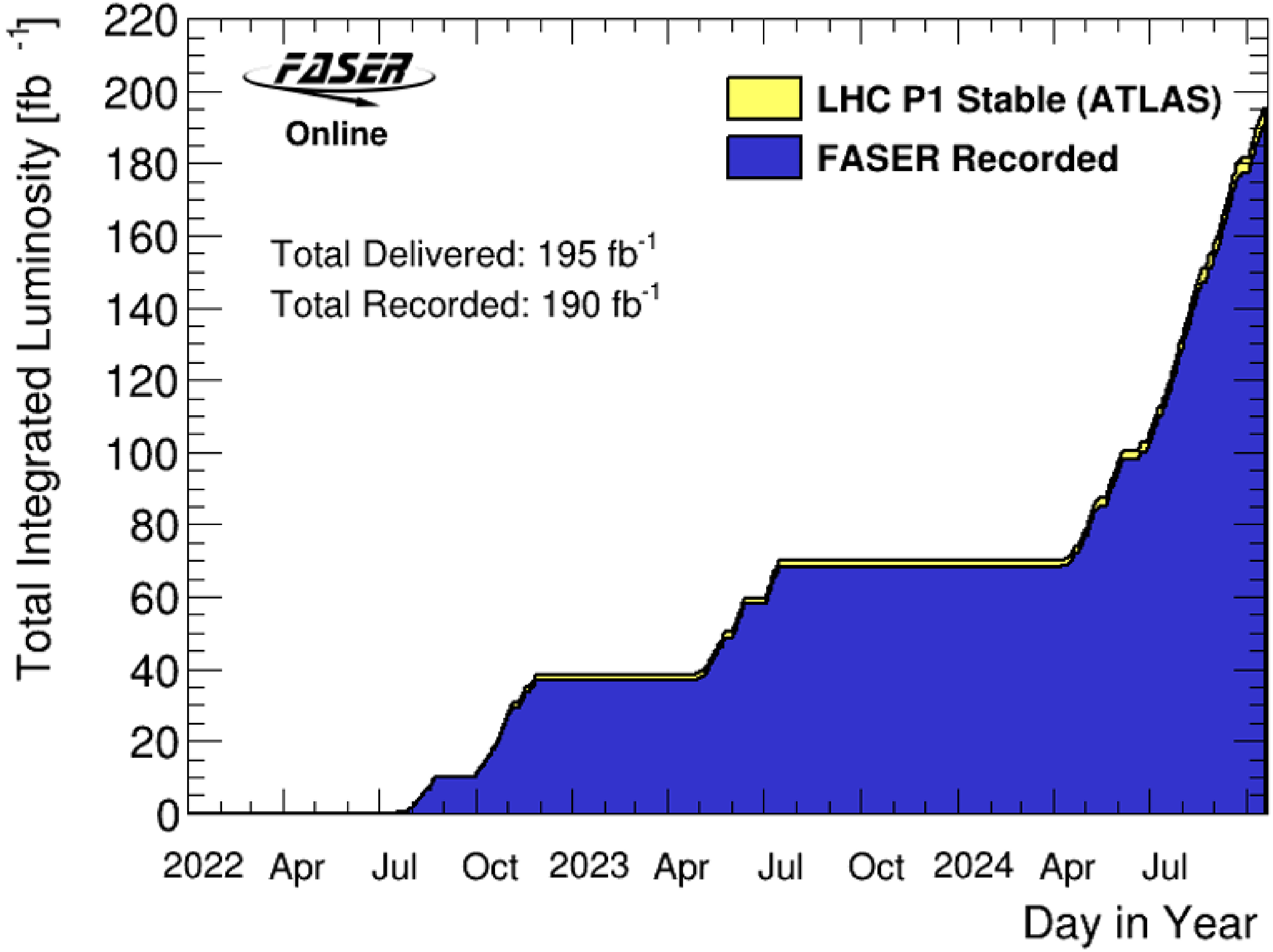


This event has a calorimeter energy of 1.6 TeV

-Shows preshower deposits consistent with an EM shower

FASER and Run3

- Successfully took data continuously and mostly automatically during 2022, 2023 and 2024.
- FASER recorded 97% of the delivered luminosity with 1.3% recording inefficiency due to DAQ deadtime and the rest due to DAQ crashes.



The FASER Experiment

- FASER is a new, small experiment at the LHC

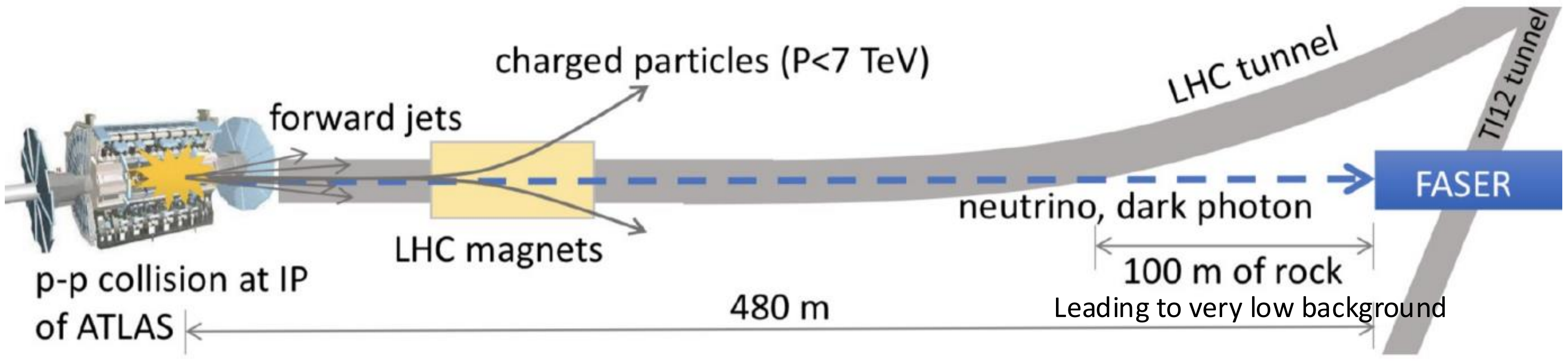
FASER's target

1. Light and weakly coupled particles, such as dark photons, axion-like particles, as well as Standard Model neutrinos
2. Exploits high LHC collision rate + forward produced light particles which are highly collimated and highly energetic

FASER's Installation

1. Mostly installed in March 2021
2. Fully completed in November 2021, ahead of Run3

FASER's positioning



Leading to very low background

Neutrino Background Composition

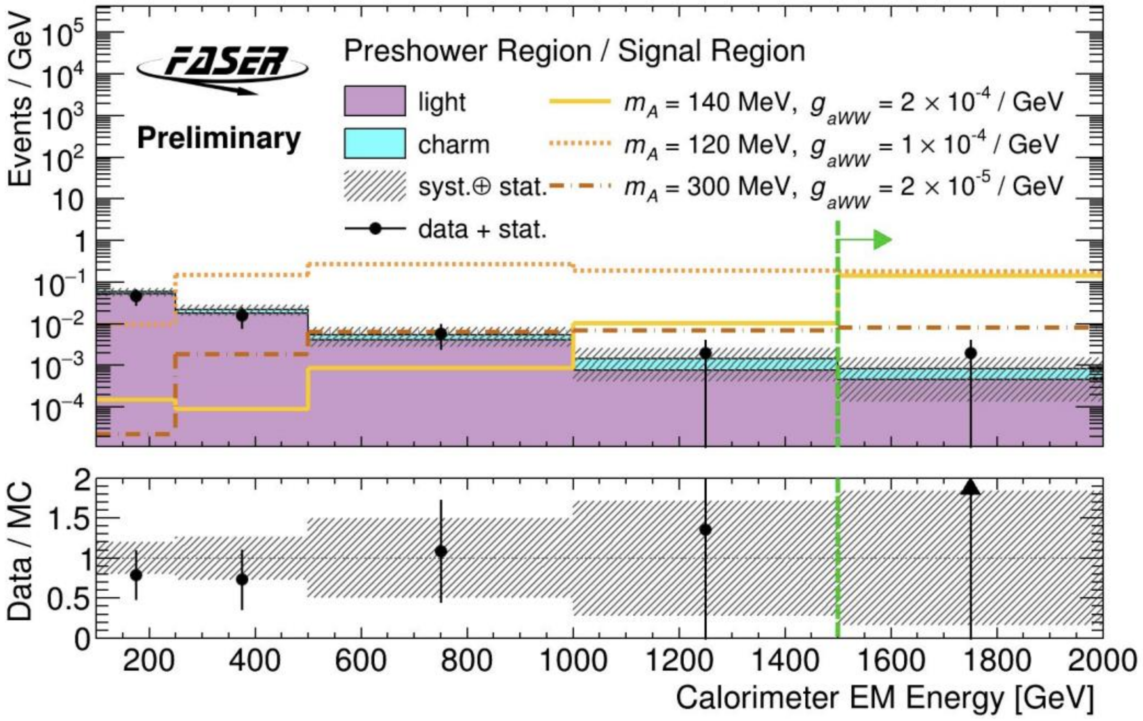
In terms of production mechanism

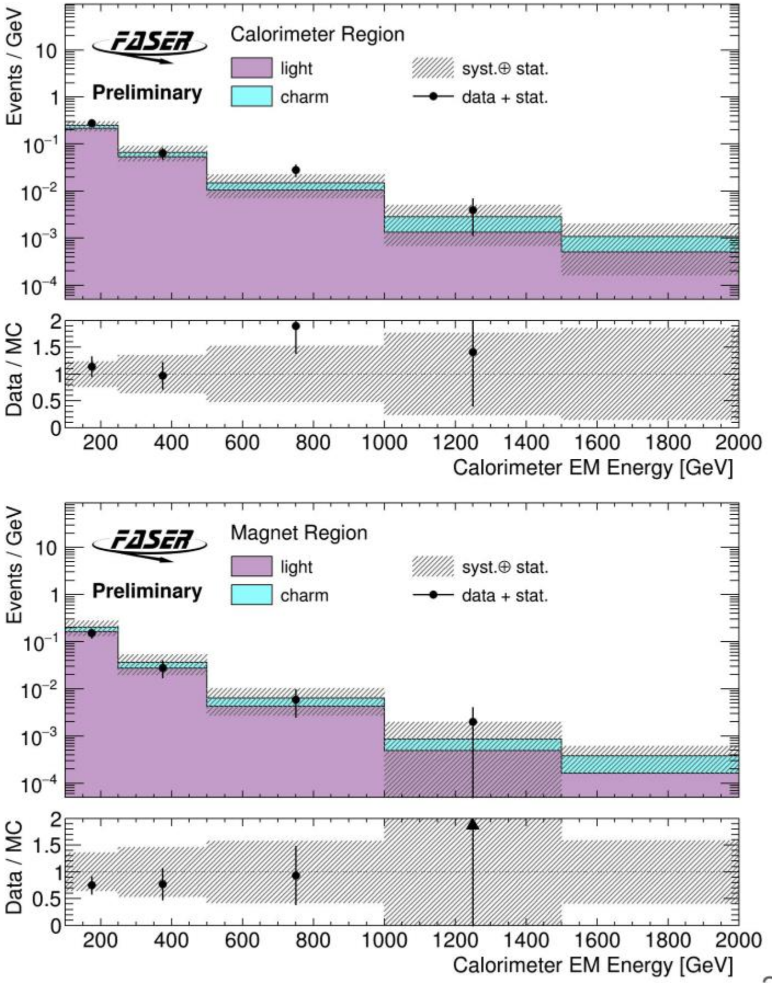
Magnet region	
Light	$33.6^{+6.7}_{-3.4}$ (flux) $\pm$ 4.3 (exp.) $\pm$ 0.4 (stat.)
Charm	$9.9^{+16.1}_{-4.6}$ (flux) $\pm$ 0.9 (exp.) $\pm$ 0.2 (stat.)
Total	**43.5 ± 18.2 (41.9%)**
Data	**34**
"Other" region	
Light	$17.4^{+1.3}_{-0.8}$ (flux) $\pm$ 2.5 (exp.) $\pm$ 0.3 (stat.)
Charm	$3.9^{+6.0}_{-1.8}$ (flux) $\pm$ 0.5 (exp.) $\pm$ 0.2 (stat.)
Total	**21.3 ± 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 ± 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 ± 5.1 (28.8%)**
Data	**15**

In terms of neutrino flavour

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

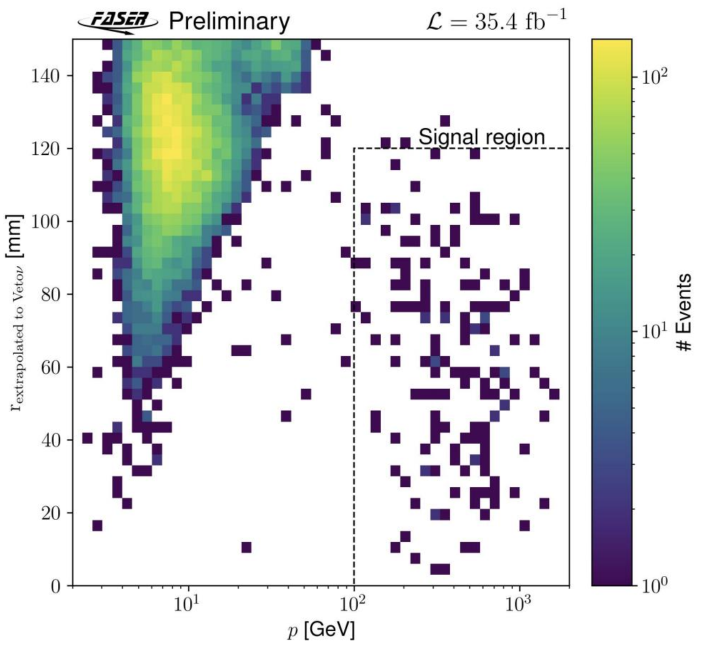
Neutrino Background
(Production mechanism breakdown)

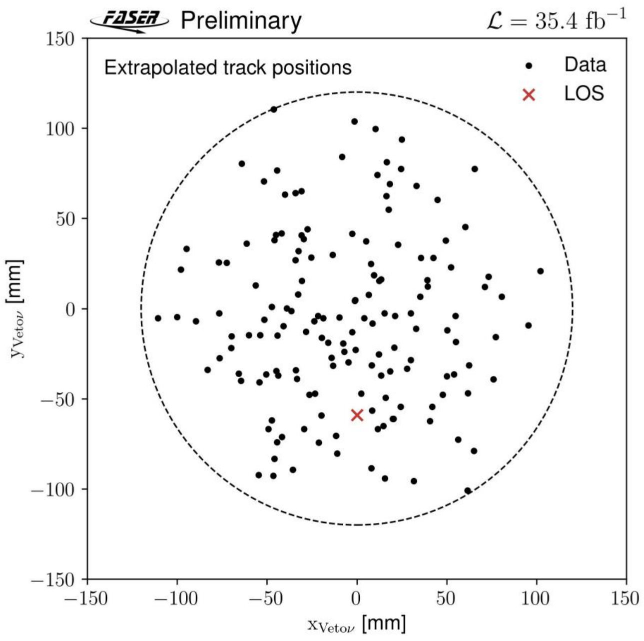


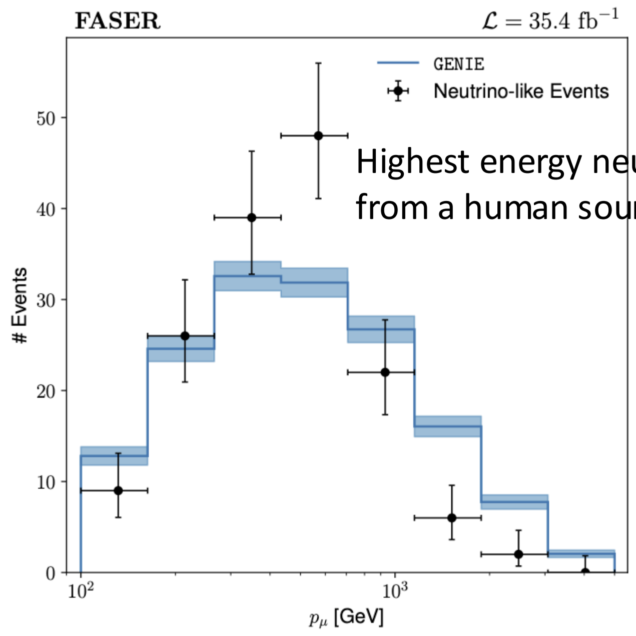


Collider Neutrino Observation

- Based on simulation expect 151 ± 41 neutrino events
- Observe **153 events** with no veto signal with an expected background of **0.2 ± 1.8**
- **First direct observation of collider neutrinos!**
- Signal significance of **16 σ**



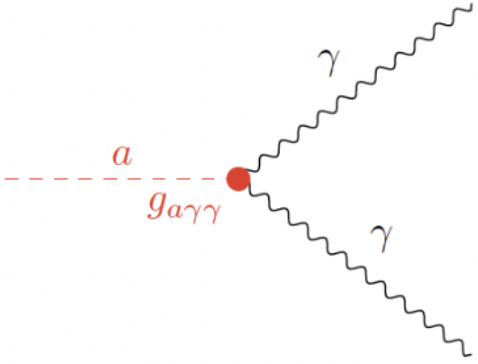




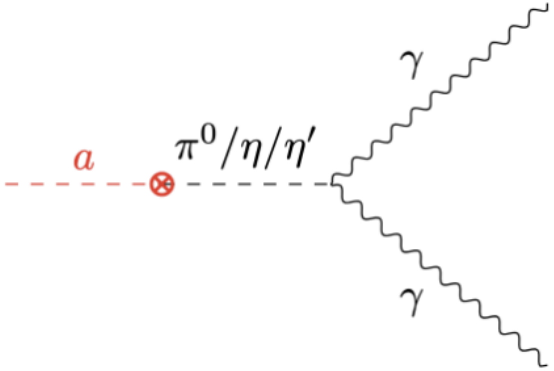
Highest energy neutrinos from a human source!

Other Models also considered (Decay Diagrams)

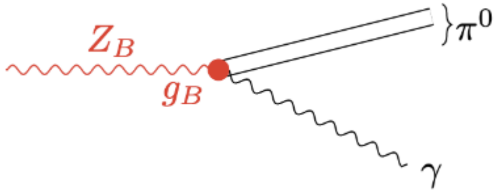
All Photonic Final States



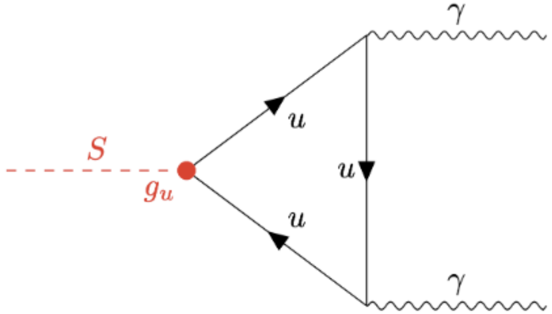
(a) ALP-photon



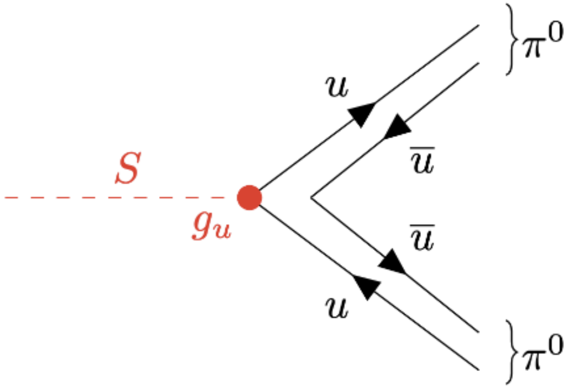
(b) ALP-gluon Decay



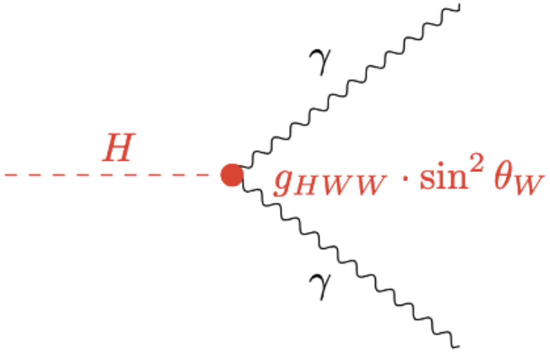
(c) U(1)B



(d) Up-Philic Decay
$(m_S < 2 \times m_{\pi^0})$

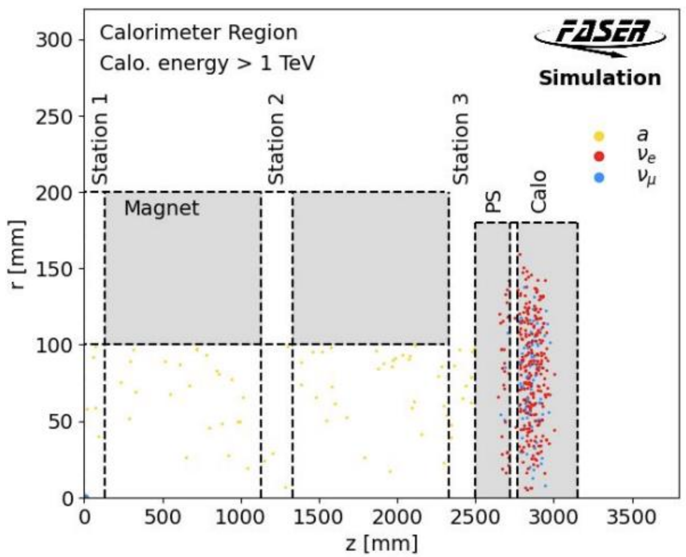


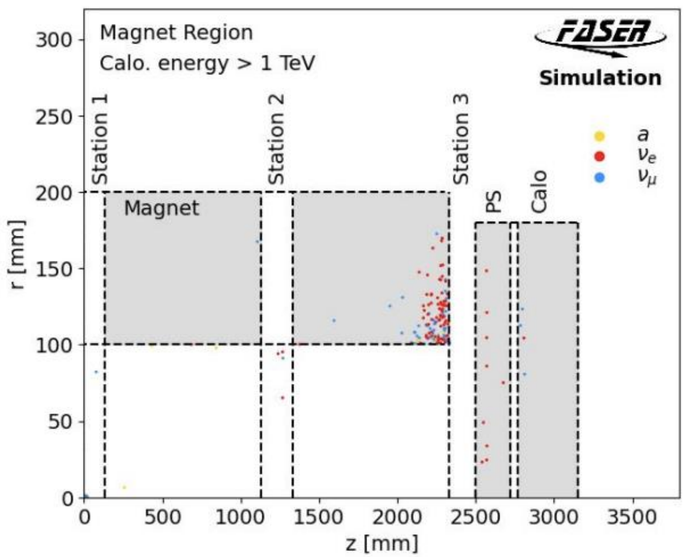
(e) Up-Philic Decay
$(m_S > 2 \times m_{\pi^0})$

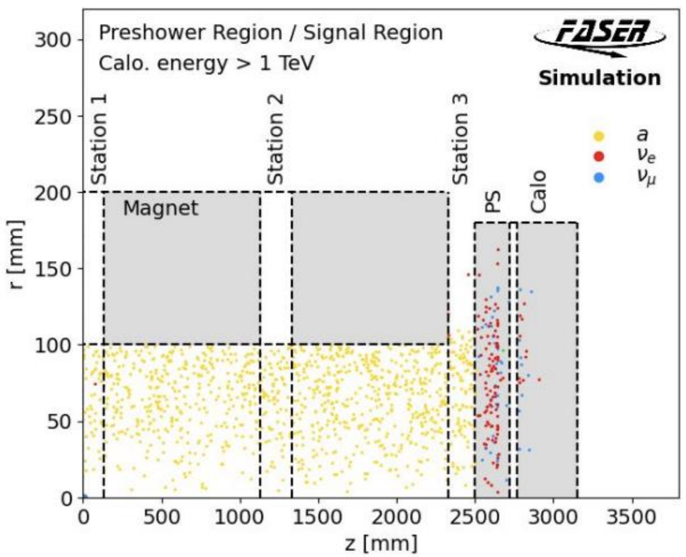


(f) 2HDM Decay

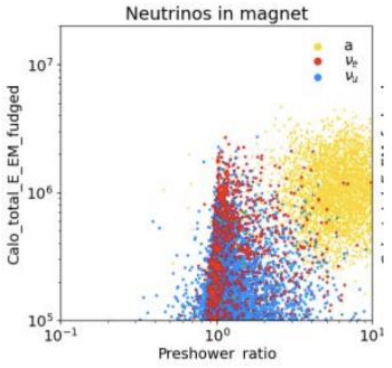
Neutrino Background (Validation Regions)

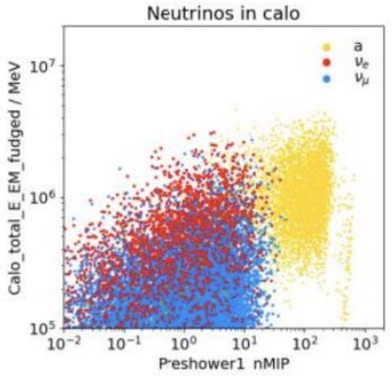






Preshower variables:





FASER 2 and FPF

Proposed dedicated forward-physics facility at HL-LHC

-New ~65 m long cavern, 620 m from ATLAS

- 4 dedicated experiments including FASER2 and FASERν2