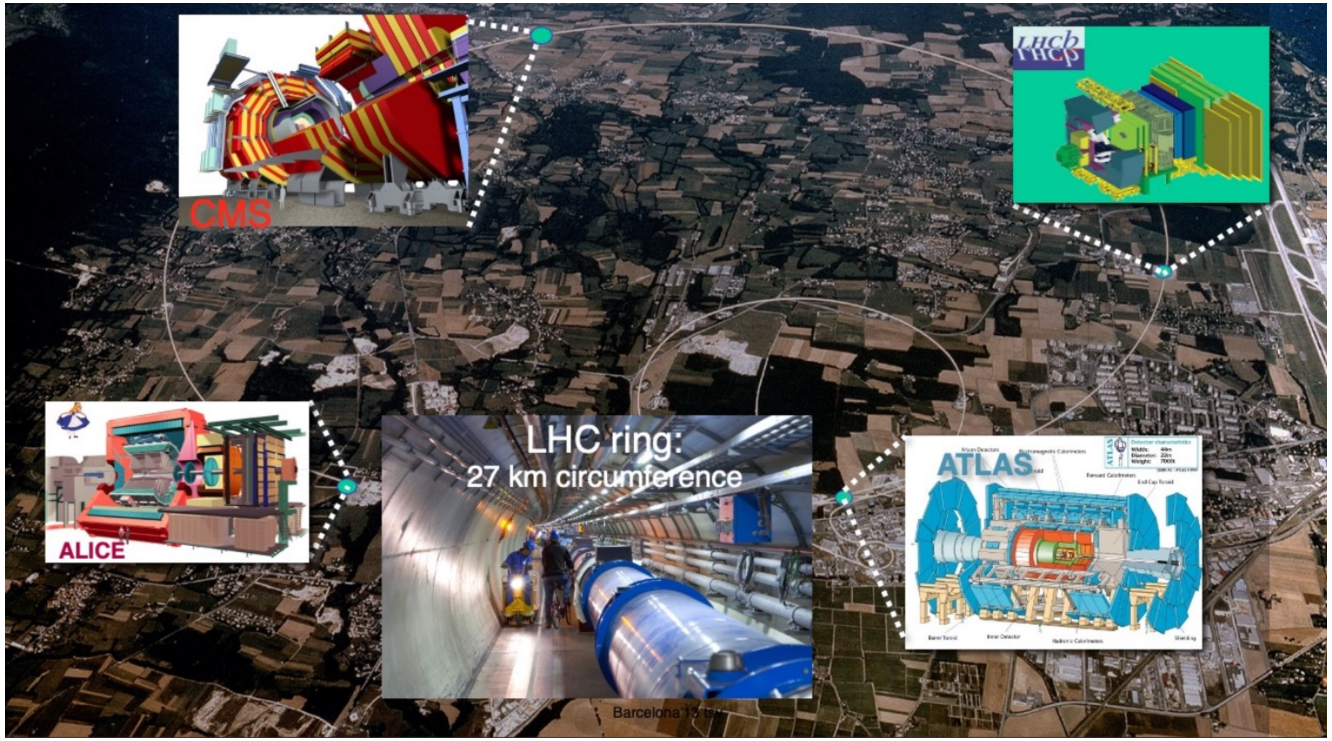
# *Shining light on the dark sector: Searches for new physics in photonic final states with FASER (Axion Like Particles and Beyond)*

SPS Annual Meeting 2024

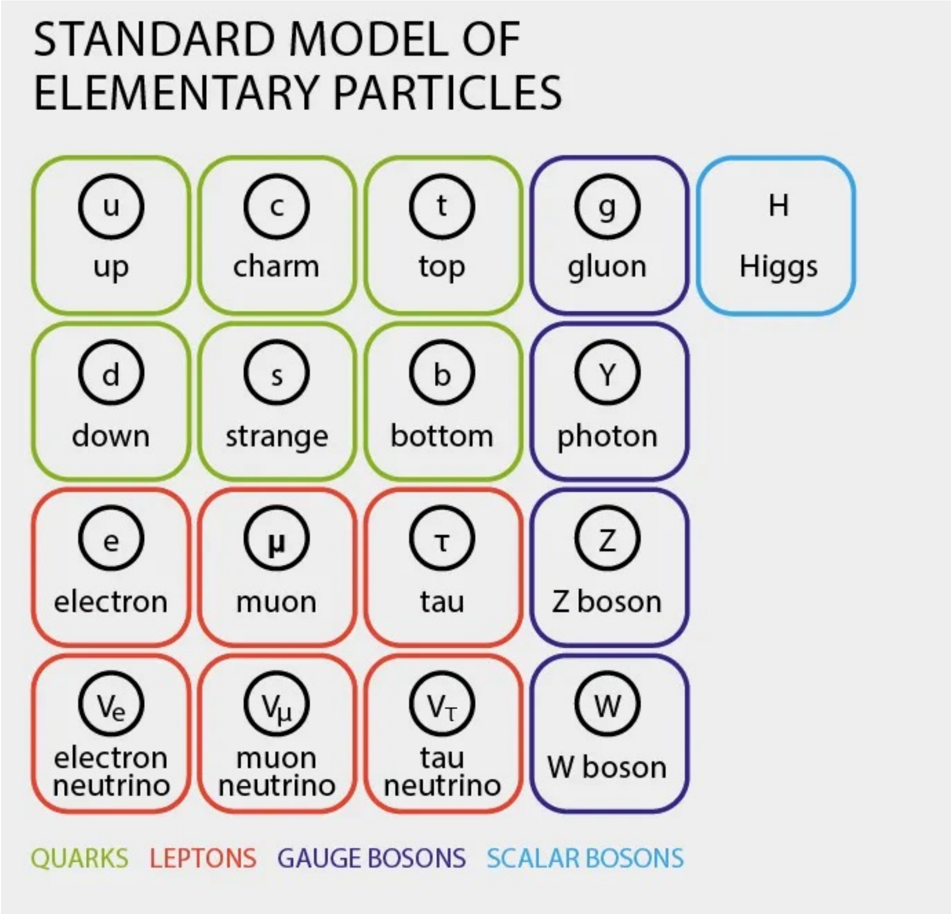
Noshin Tarannum on behalf of the FASER Collaboration

# To start with

**LHC and the Detectors**



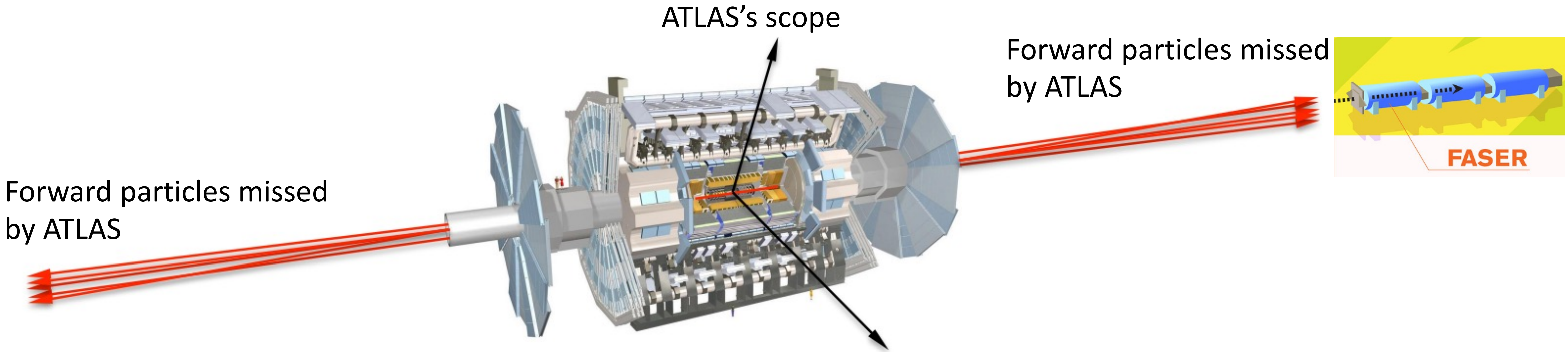

1. General purpose (ATLAS and CMS) studying origin of mass, SUSY…
2. Dedicated (LHCb) studying origin of matter-antimatter asymmetry ….
3. Dedicated (ALICE) studying general properties of quark- gluon plasma




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

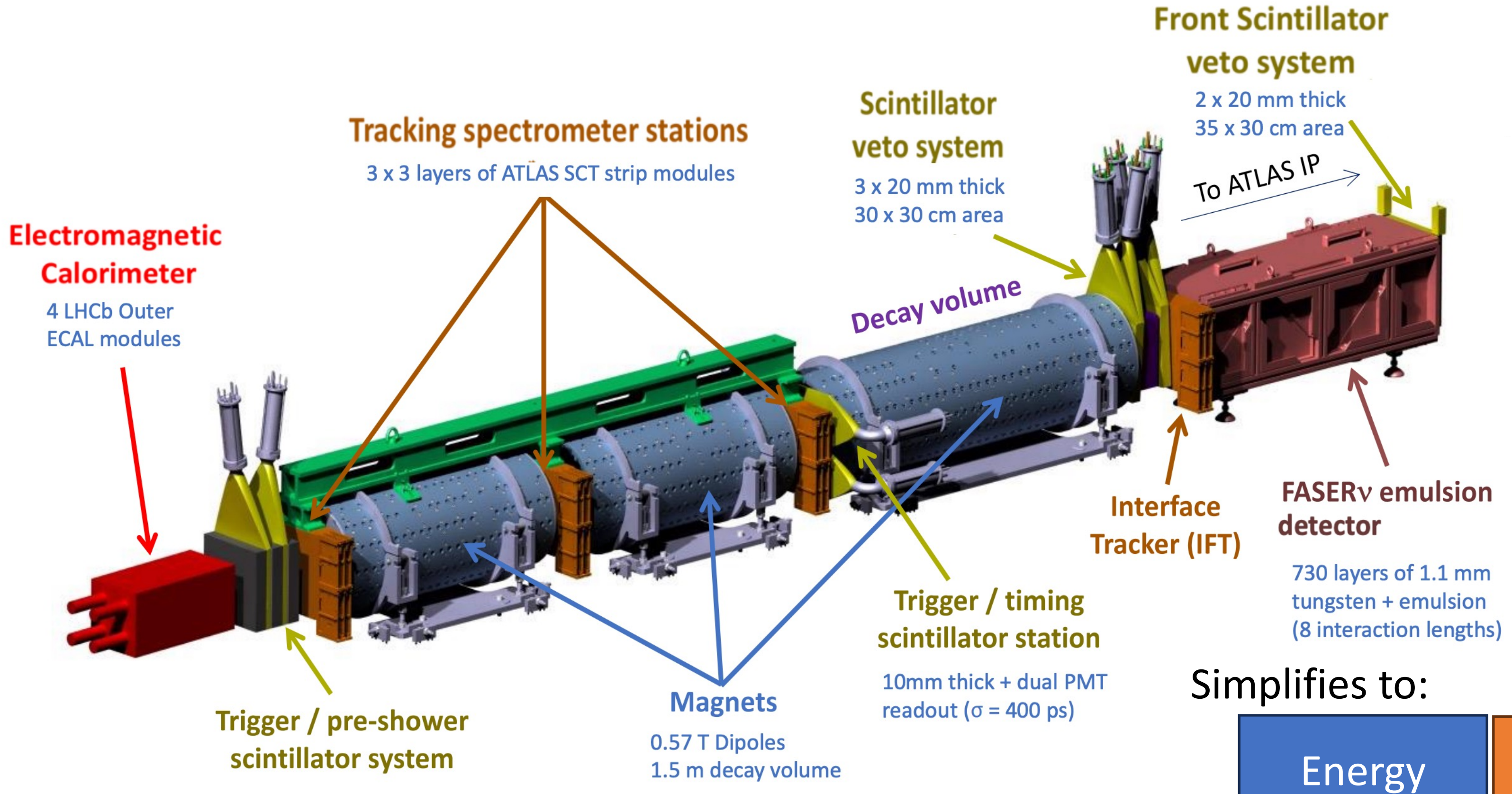
# FASER: THE IDEA

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



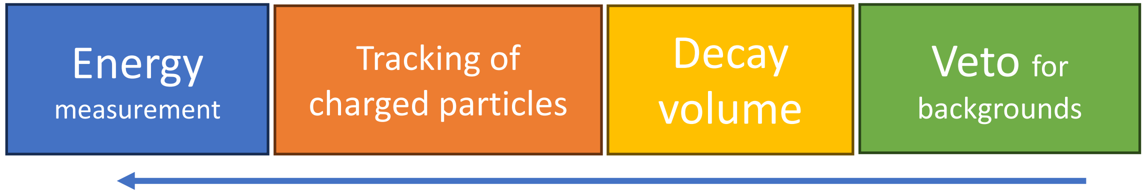

FASER is a proposed experiment designed to cover this scenario at the LHC

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



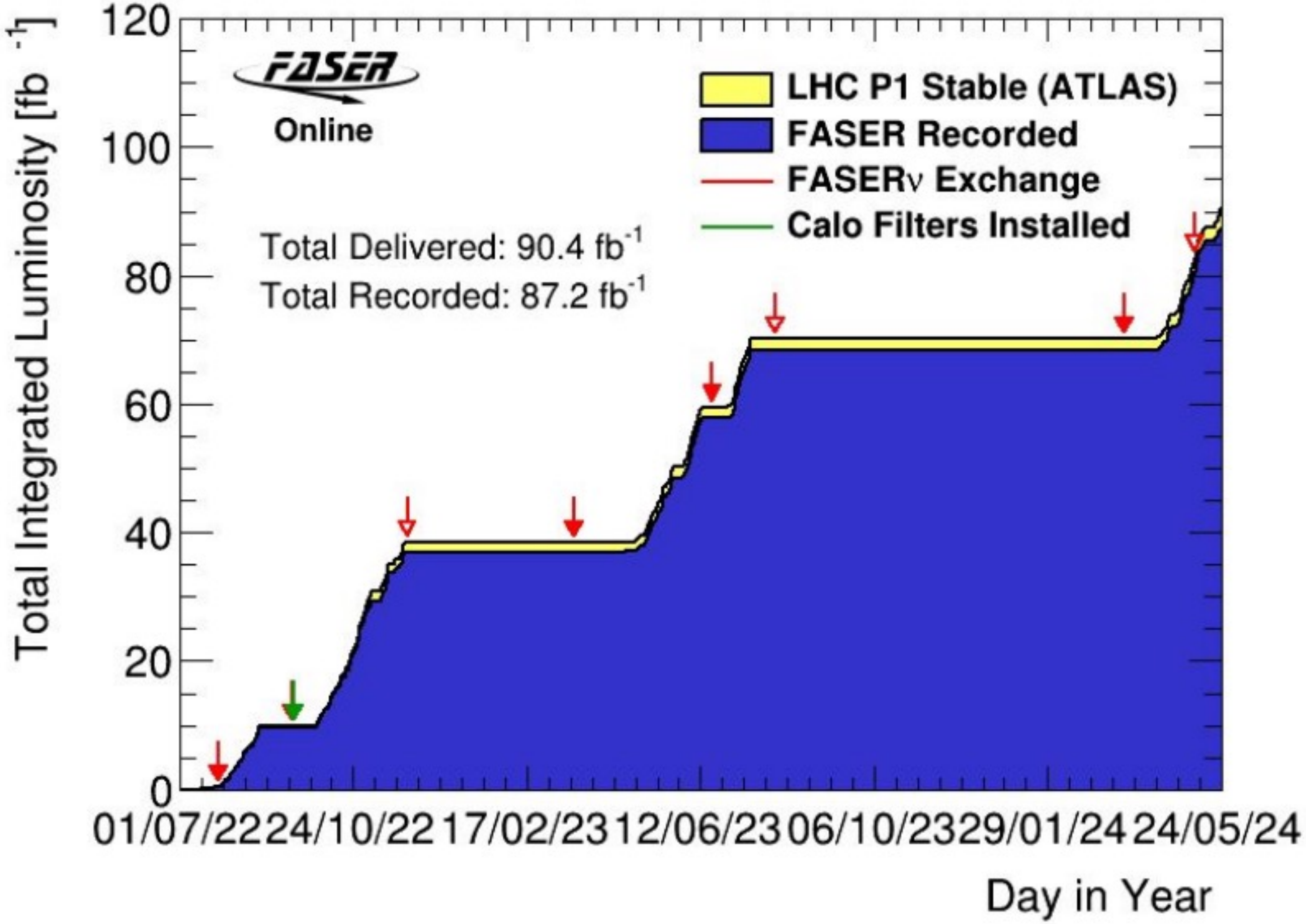


Simplifies to:



# 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.



# Physics outcomes of FASER

**FASER's target**

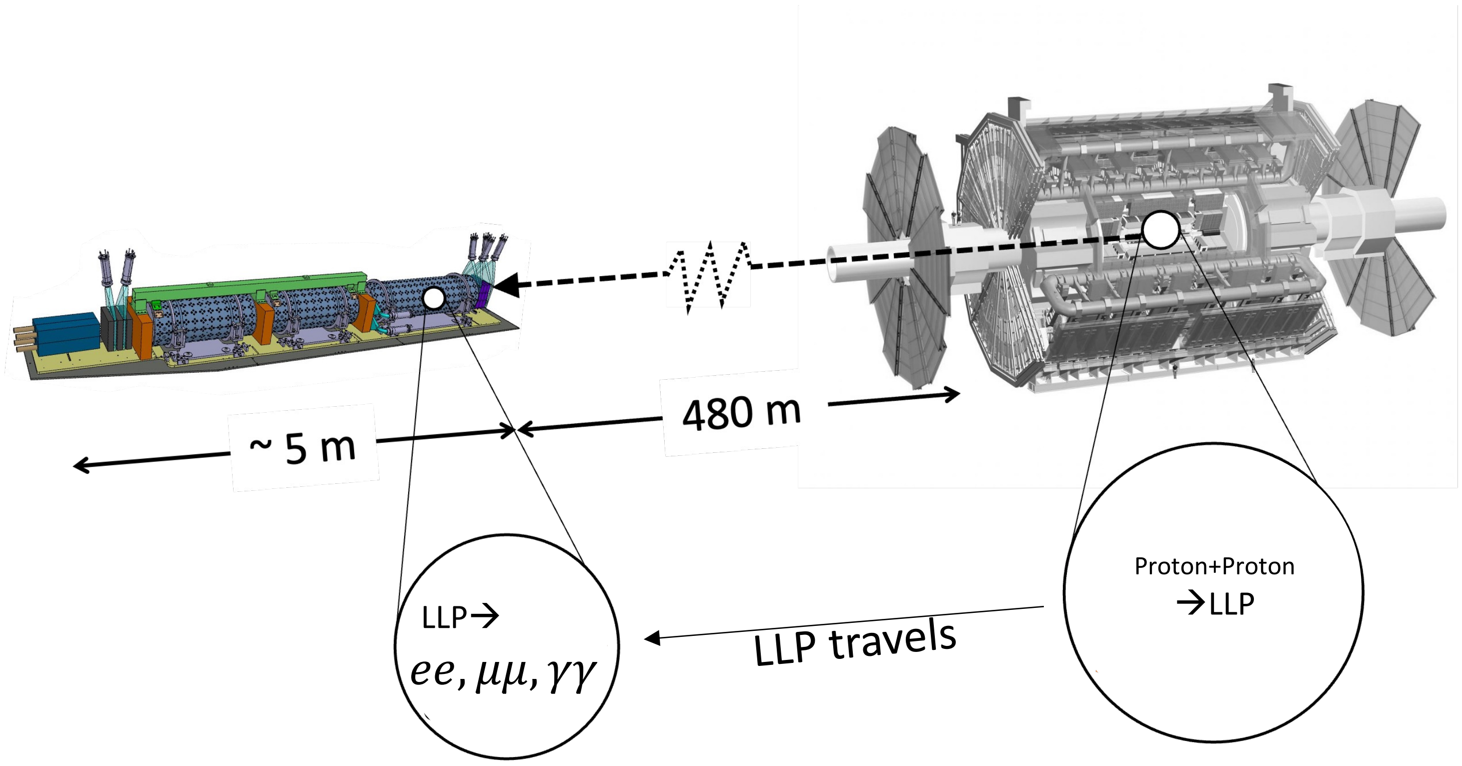
1. Exploits high LHC collision rate + forward produced light particles which are highly collimated and highly energetic
2. Light and weakly coupled particles, such as **dark photons (More), axion-like particles** etc.
3. Additionally, one of the major background sources comes from **neutrinos**, as they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

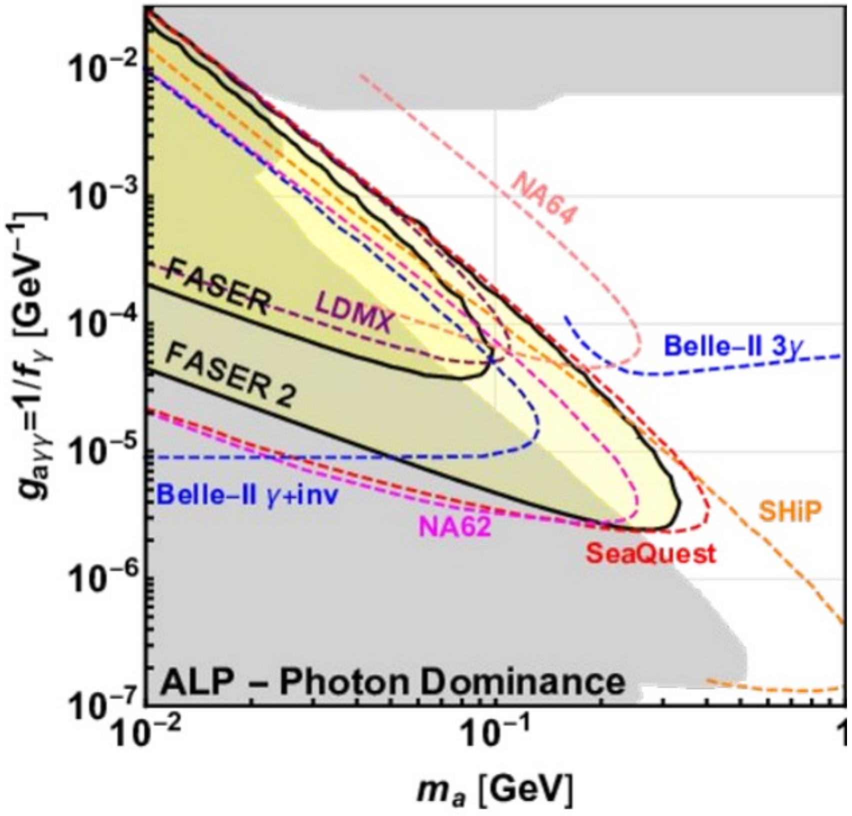
| 150/fb @14TeV | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
| --- | --- | --- | --- |
| Main production source | kaon decay | pion decay | charm decay |
| # traversing FASERnu 25cm x 25cm | $O(10^{11})$ | $O(10^{12})$ | $O(10^{9})$ |
| # interacting in FASERnu (1 tn Tungsten) | ~1000 | ~20000 | ~10 |

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)

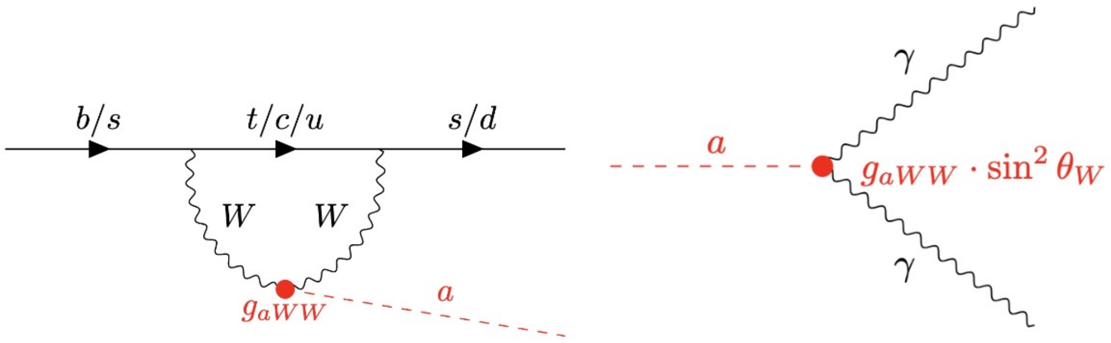


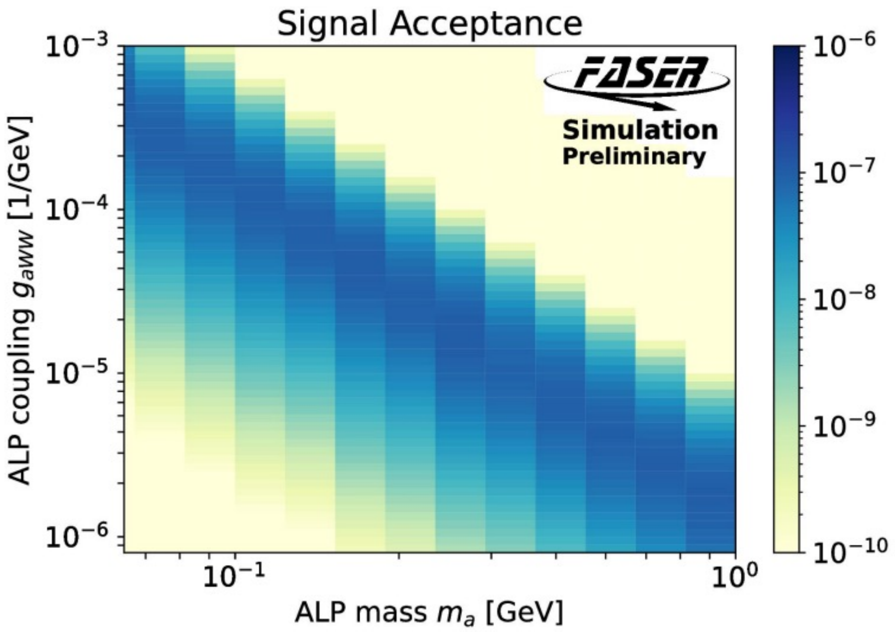
# ALP-W model

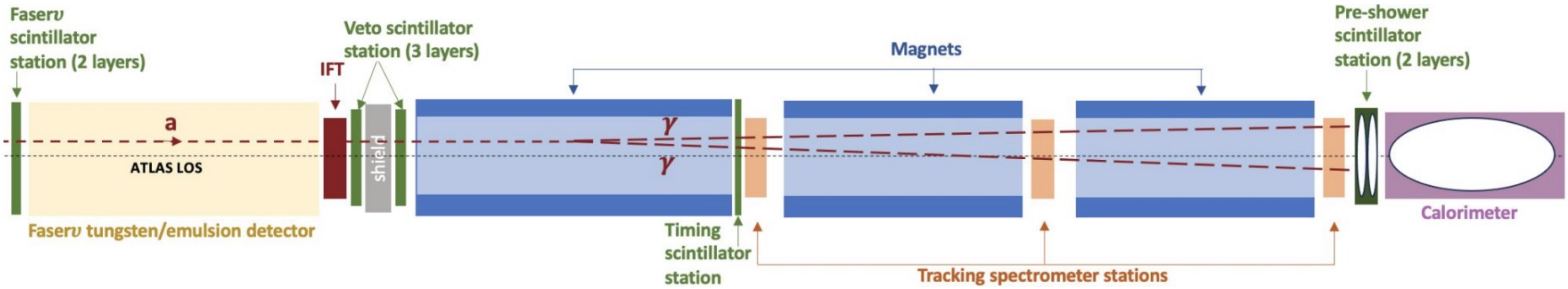
FASER is sensitive to axion-like particles (ALPs)

- 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



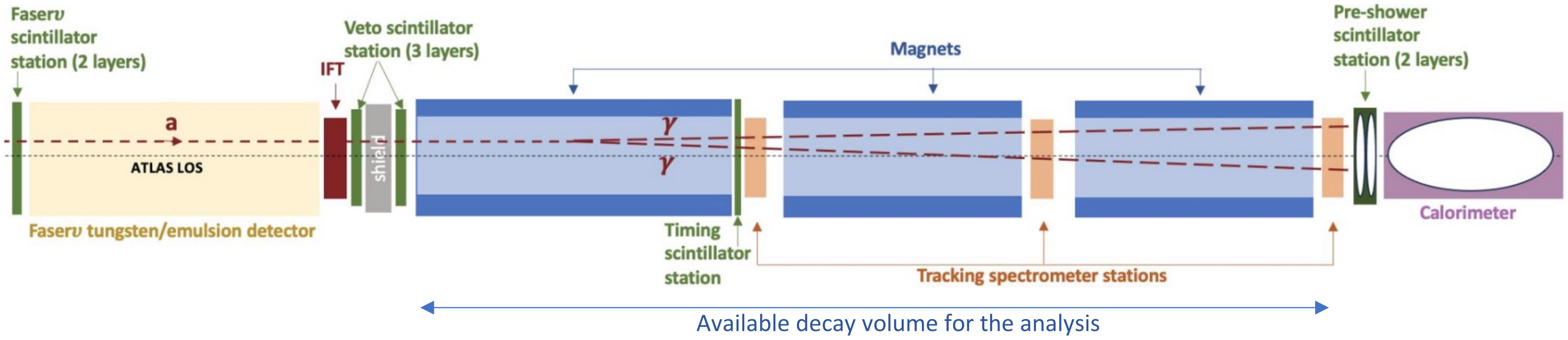

(a) ALP-W production (b) ALP-W decay

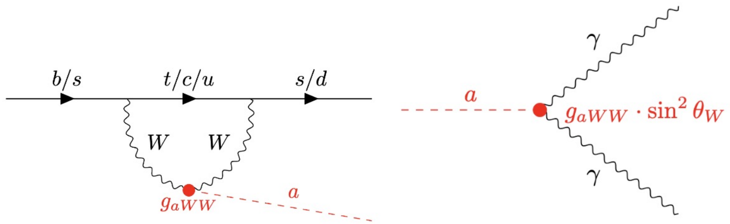


# Selection for ALPs Search

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




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

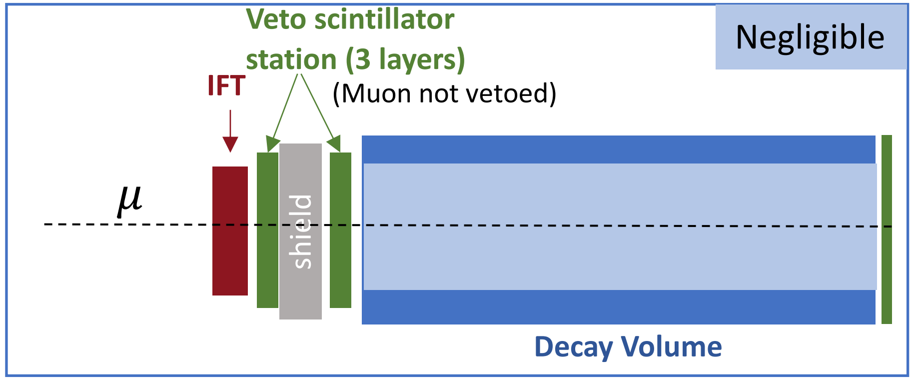
**The selection criteria we had in place:**

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

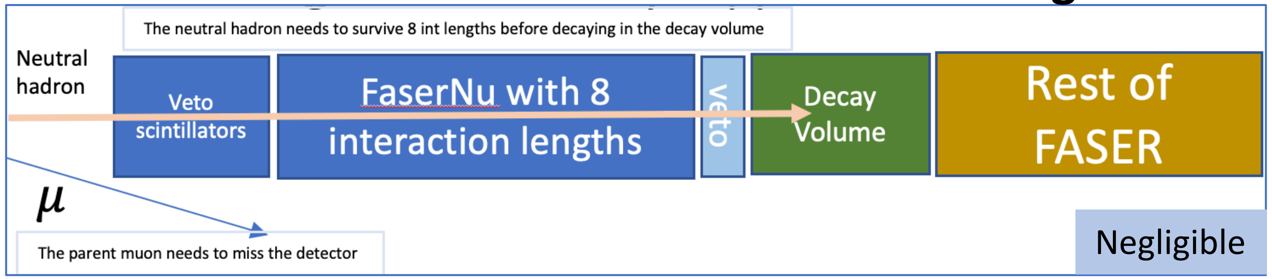
# Background

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

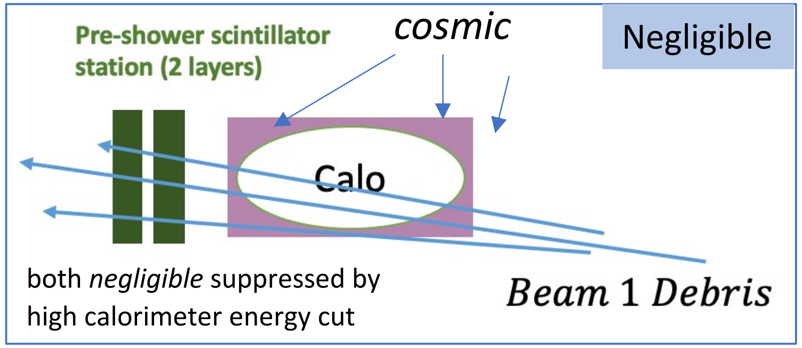
## Veto inefficiency:




## Neutral hadron background

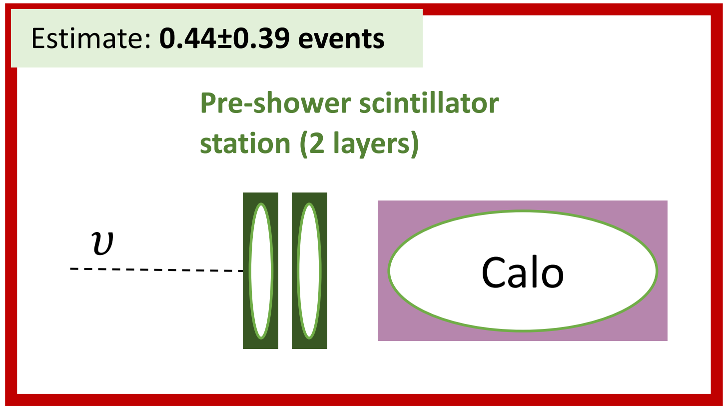



## Non-collision background

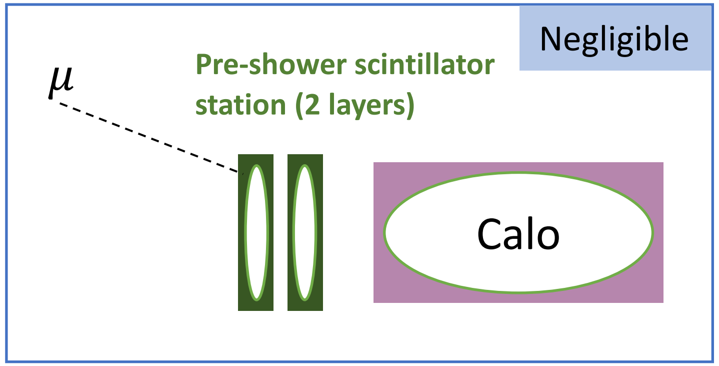



**Biggest Background**

Neutrino interactions




Geometric Muons



# 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 $\pm$ 0.35 (flux) $\pm$ 0.15 (calo. energy) $\pm$ 0.06 (PS ratio) $\pm$ 0.02 (PS 1 nMIP) $\pm$ 0.02 (PS geometry) $\pm$ 0.05 (stat.) **Total: 0.44 $\pm$ 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

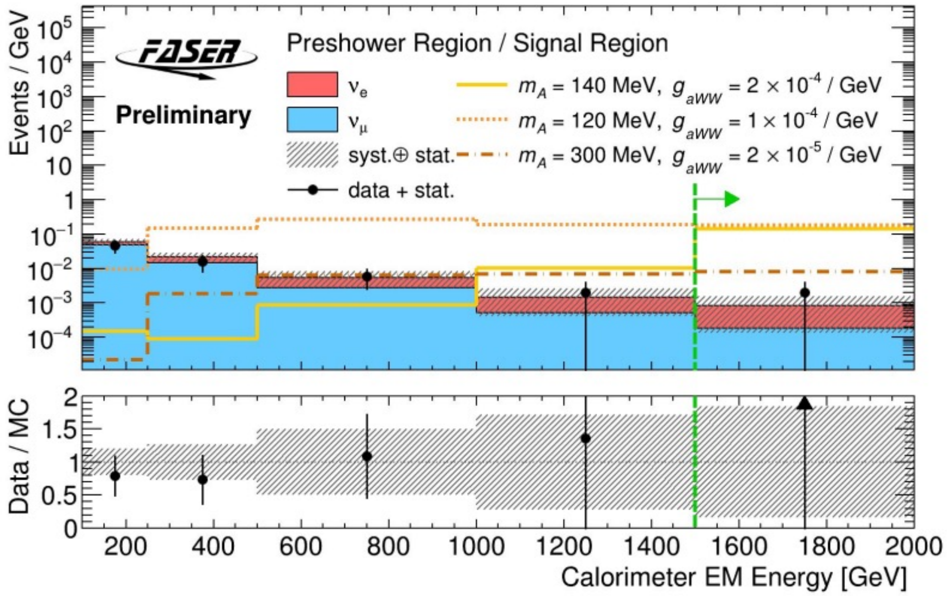
In 57.7 $fb^{-1}$ of data we saw 1 event in our unblinded signal region

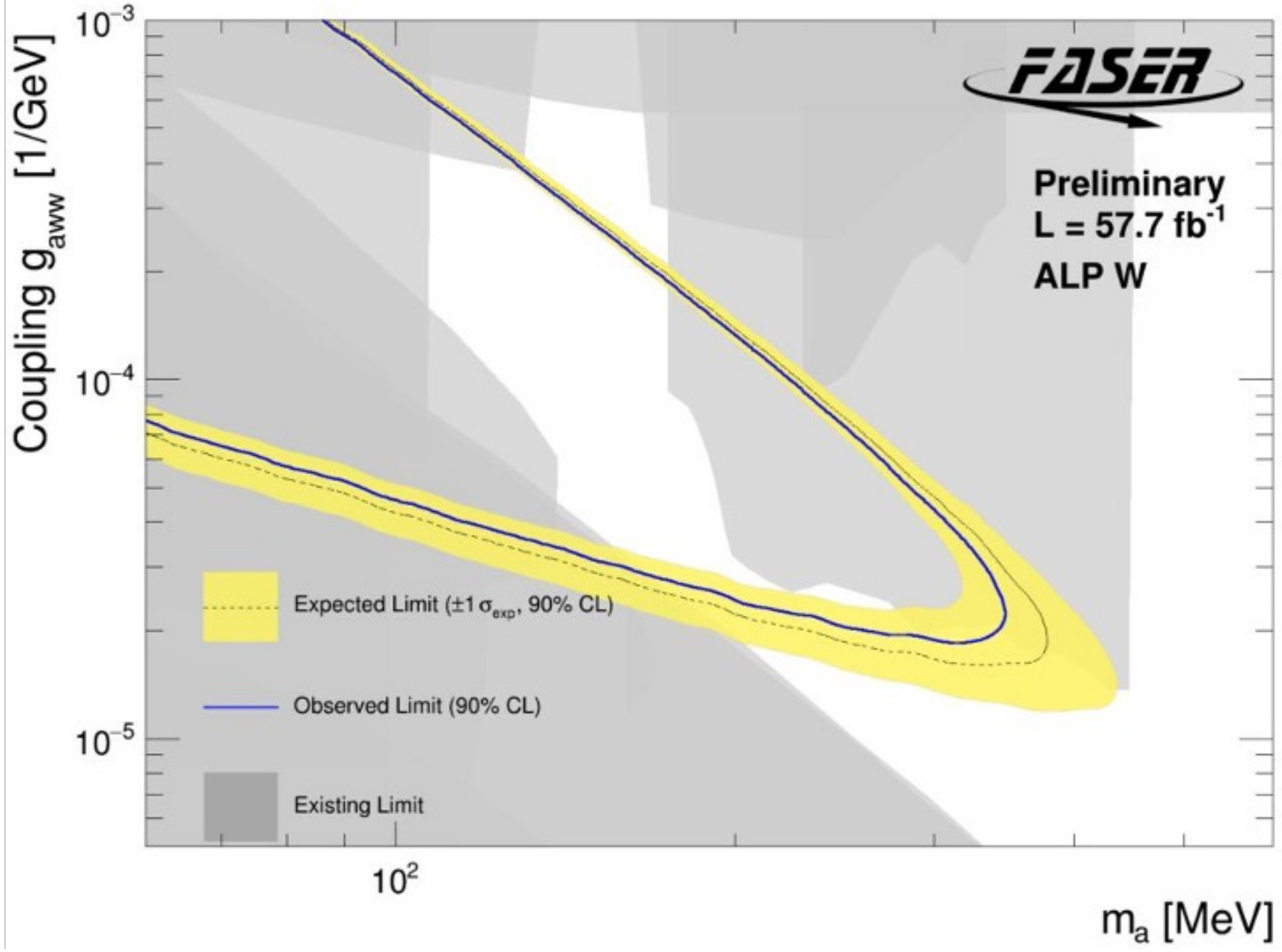
-Compared to expected background of 0.44 ± 0.39 events

- 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)

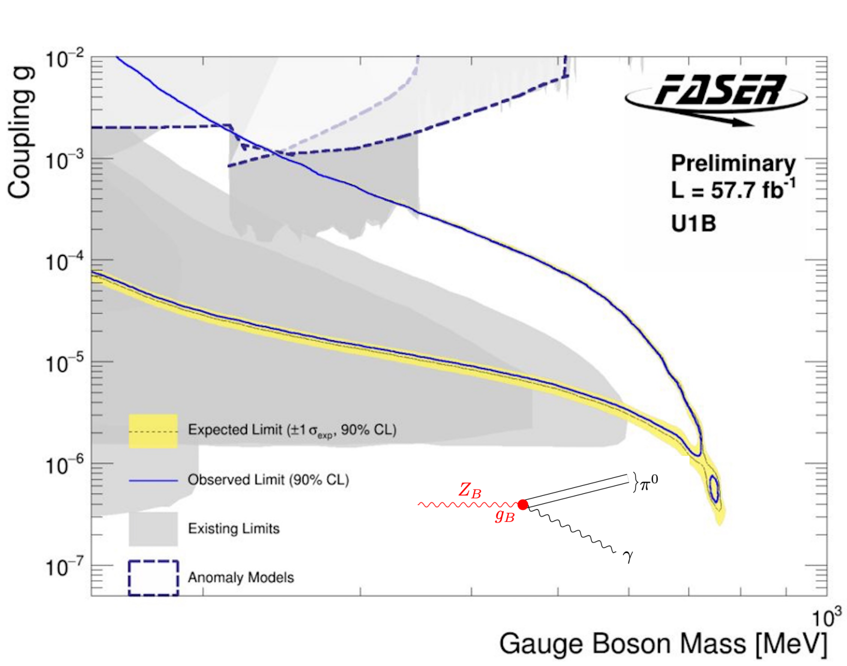
- U(1)B Scalar
- 2 Higgs Doublet Model

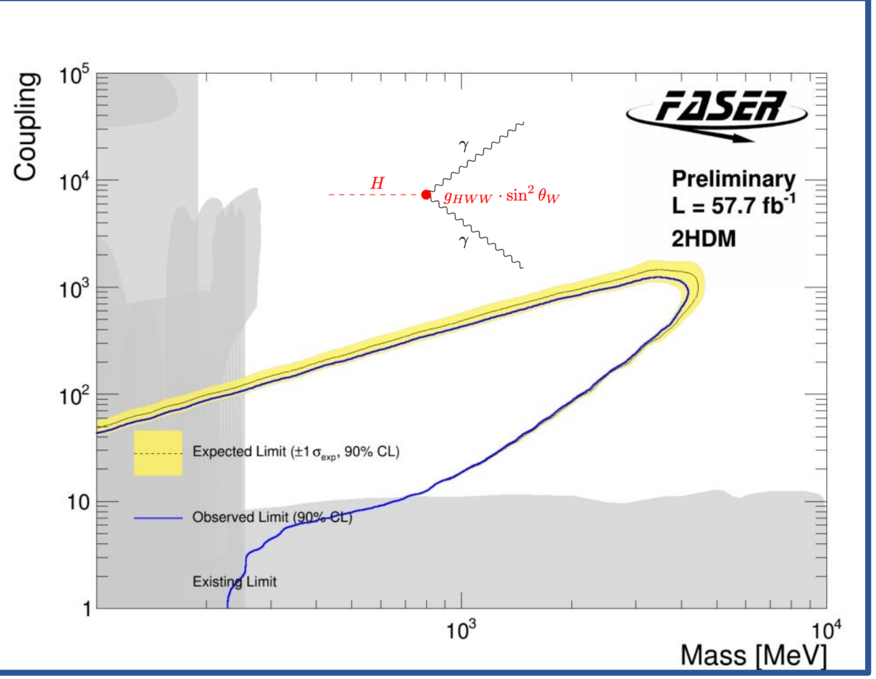
**Bottom:**

(Left to Right)

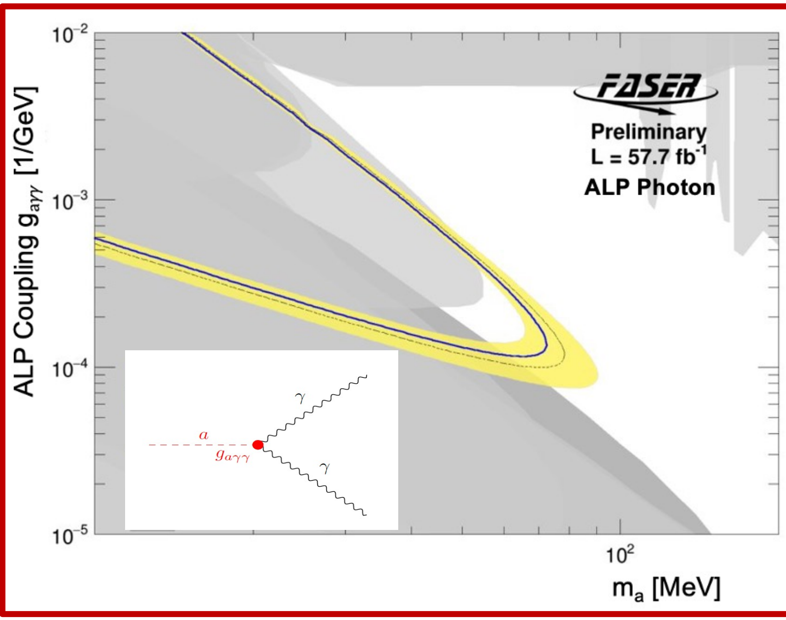
- ALP- Photon
- ALP- Gluon
- Up-Philic Scalar

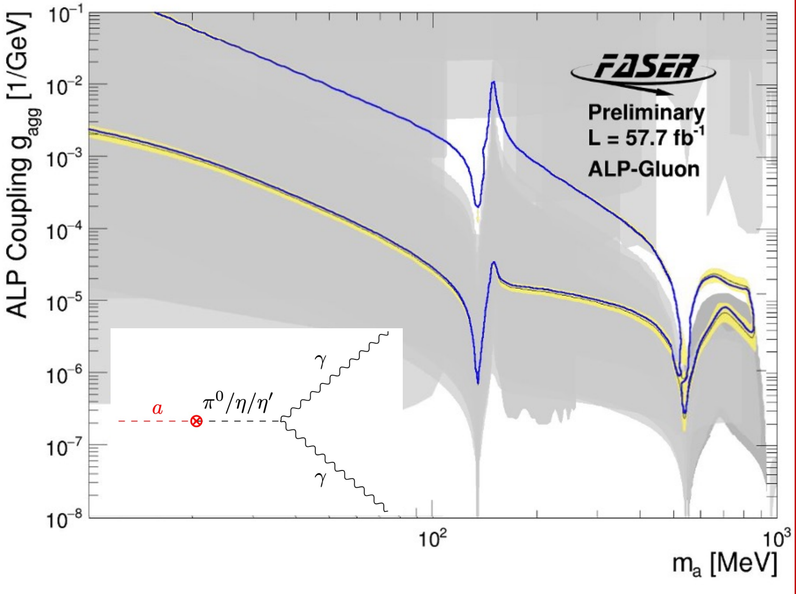
**Boson Models**



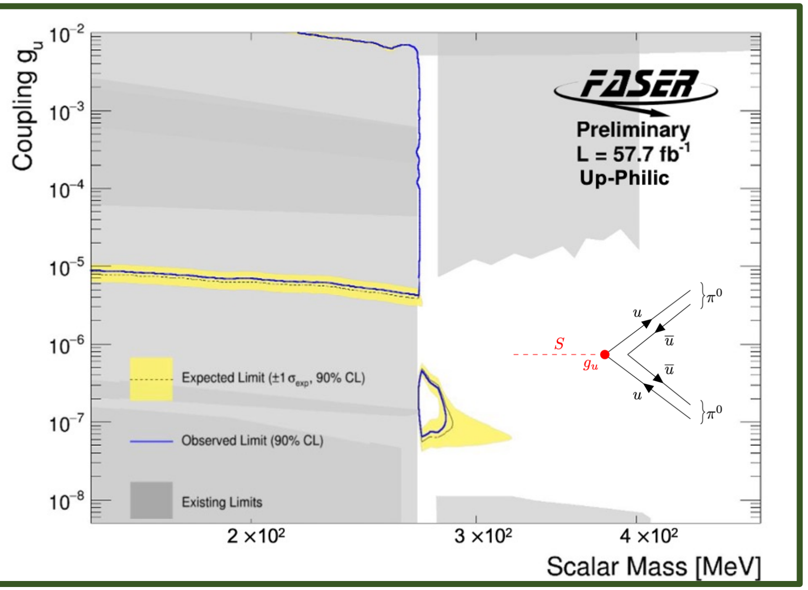




**Pseudoscalar (ALPs)**

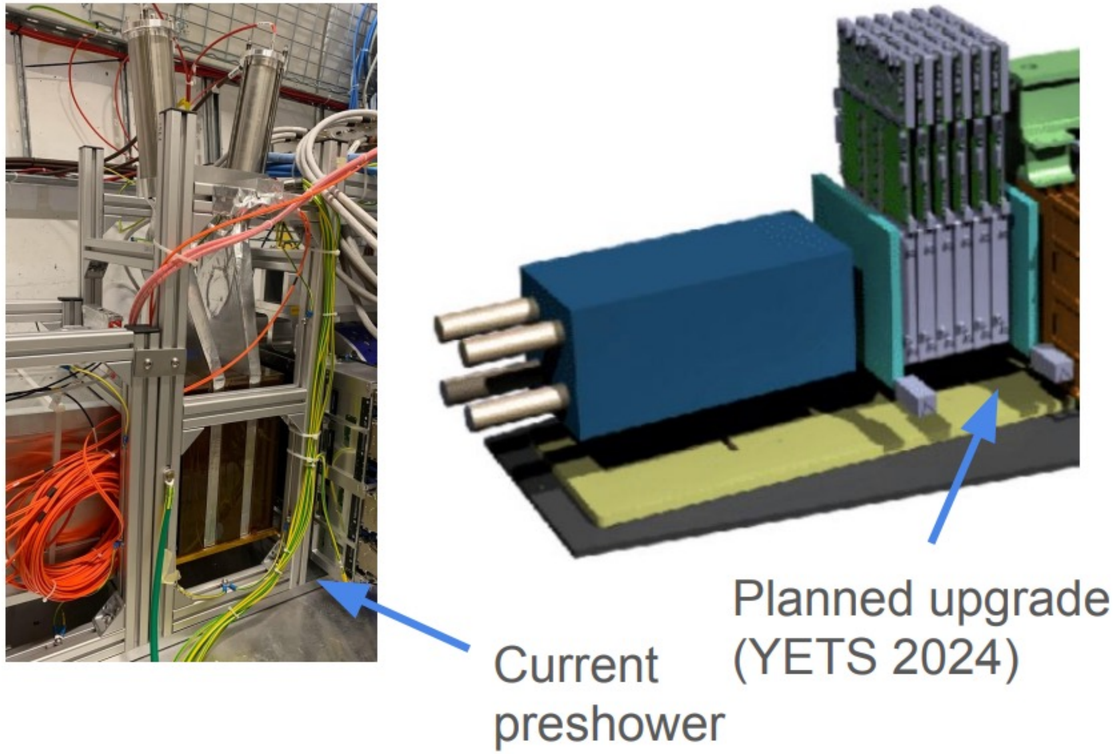


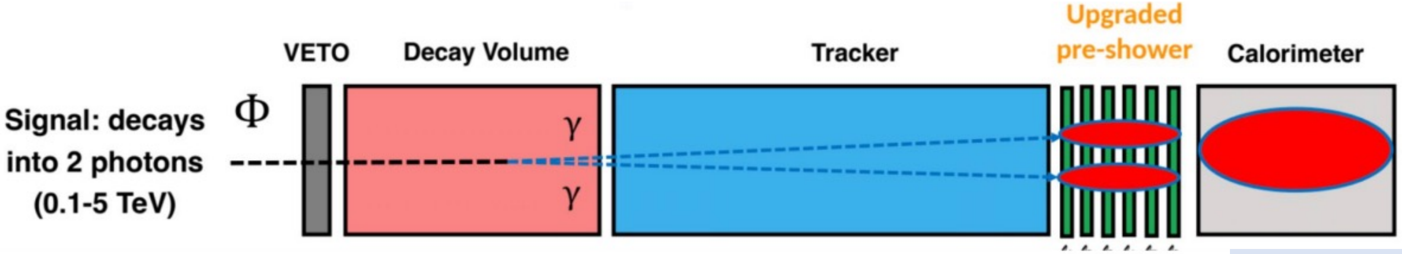




**Scalar**



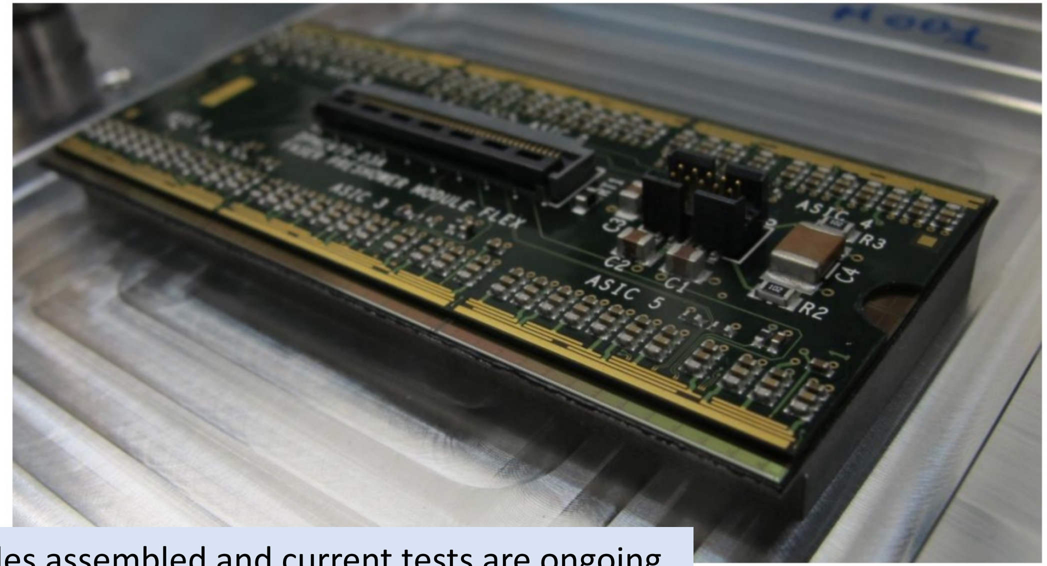
# FASER Preshower Upgrade




**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

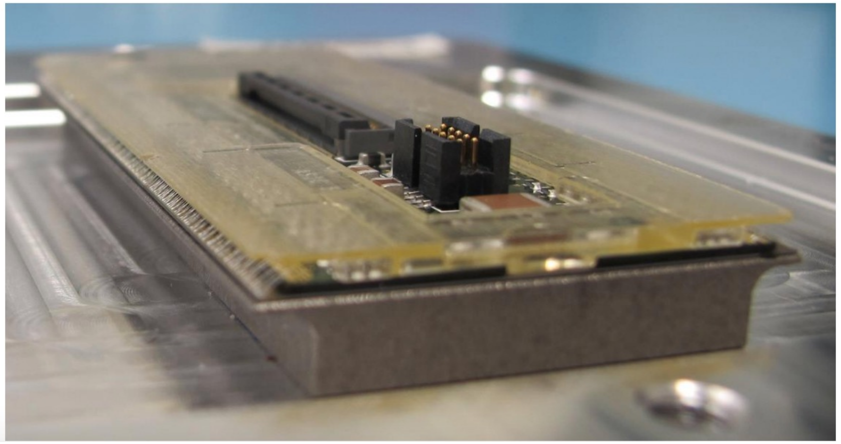


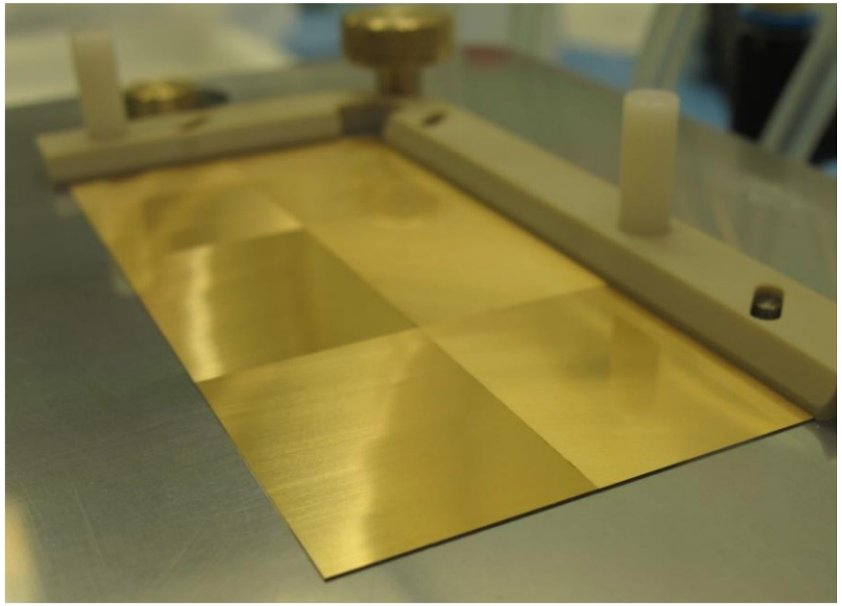
First modules assembled and current tests are ongoing

# Conclusion

- FASER successfully took data in Run2 and Run 3, running at very good efficiency with a fully functional detector!
- Excluded ALPs and other multiphoton models in various regions.
- Will continue data-taking throughout LHC Run 3 with up to 10 times more data coming in the next years
- Currently ongoing: FASER Preshower upgrade, Forward Physics Facility

All FASER publications





FASER Preshower Upgrade

# Thank you for listening!

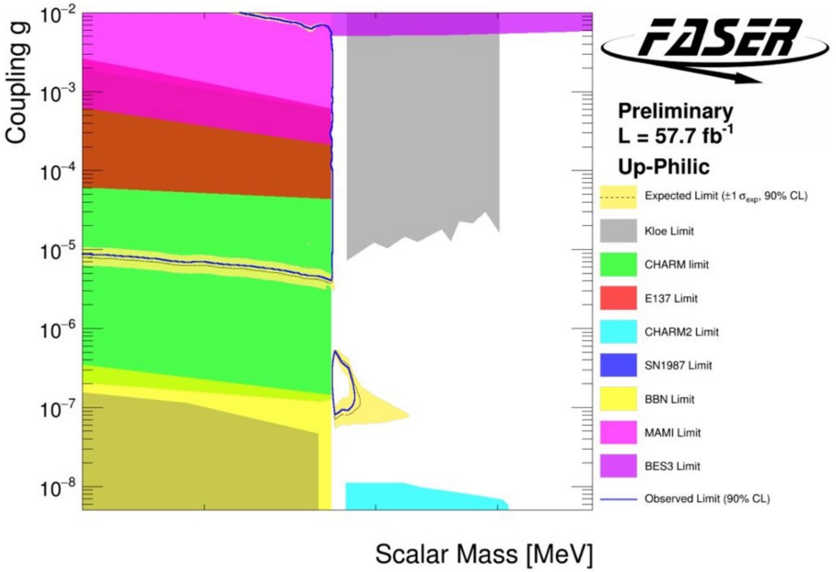

from FASER Collaboration Meeting #5, 2023

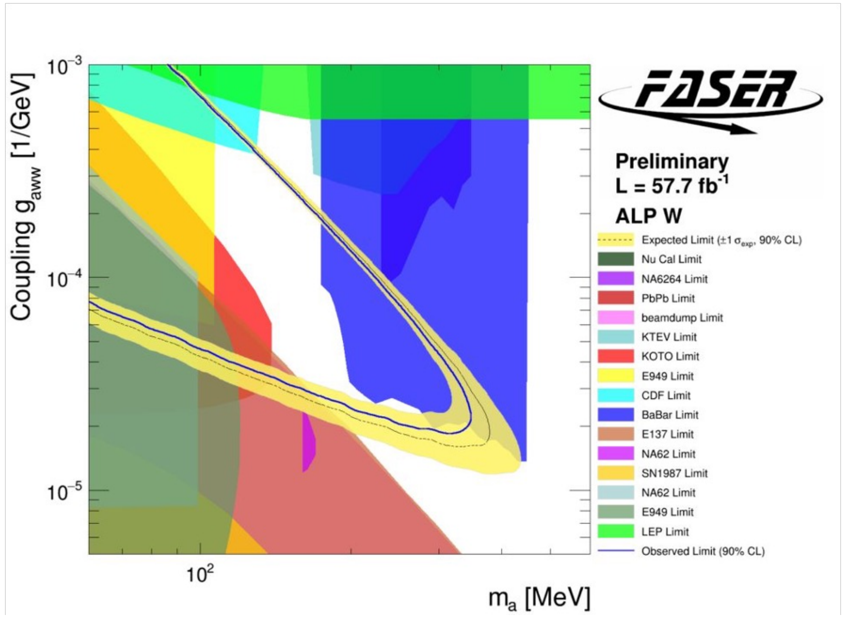
# FASER Institutions

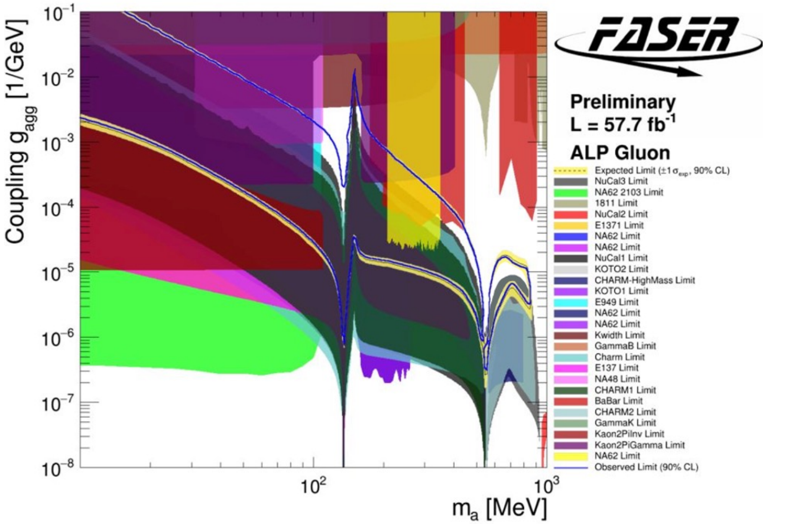
- CERN
- UNIVERSITÉ DE GENÈVE
- KYUSHU UNIVERSITY
- UC IRVINE
- UNIVERSITÄT BERN
- Technion Israel Institute of Technology
- NAGOYA UNIVERSITY
- UNIVERSITY of WASHINGTON
- JOHANNES GUTENBERG UNIVERSITÄT MAINZ
- מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
- KEK
- UNIVERSITY OF OREGON
- DESY.
- INFN
- 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

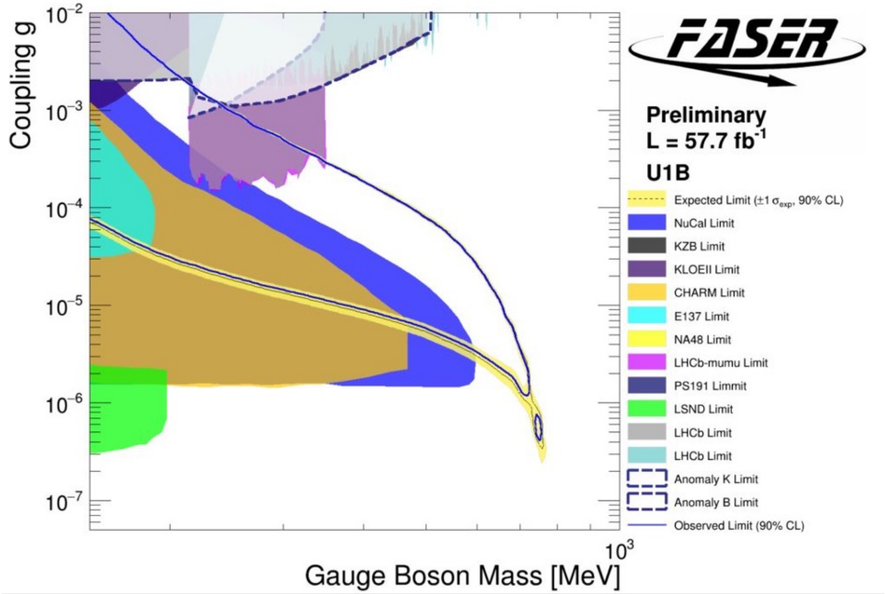
# Backup

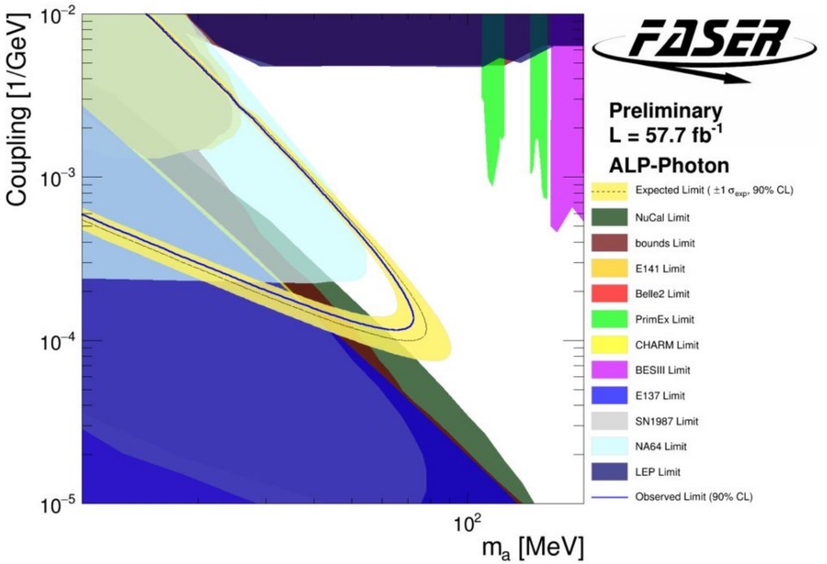
# Limit Plots

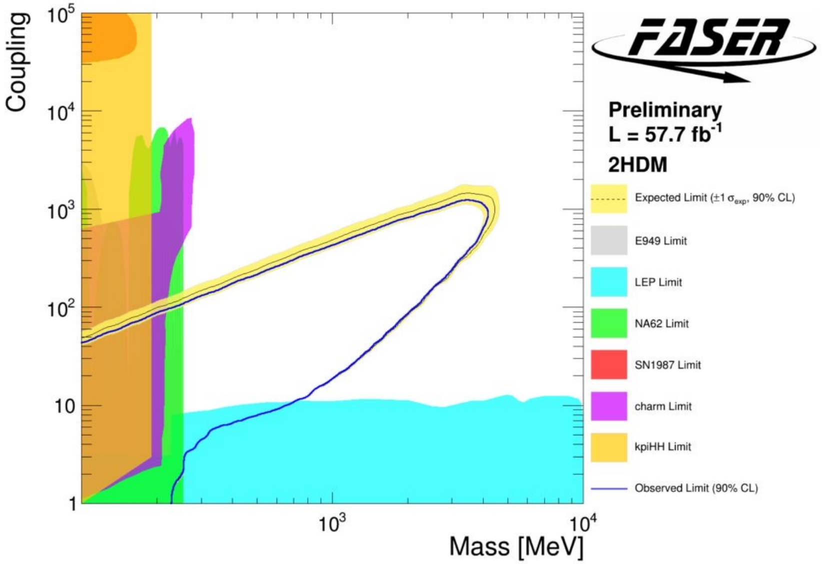

FASER
Preliminary
L = 57.7 fb$^{-1}$
Up-Philic
Expected Limit (±1 $\sigma_{exp}$, 90% CL)
Kloe Limit
CHARM limit
E137 Limit
CHARM2 Limit
SN1987 Limit
BBN Limit
MAMI Limit
BES3 Limit
Observed Limit (90% CL)
Coupling g
Scalar Mass [MeV]


FASER
Preliminary
L = 57.7 fb$^{-1}$
ALP W
Expected Limit (±1 $\sigma_{exp}$, 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]

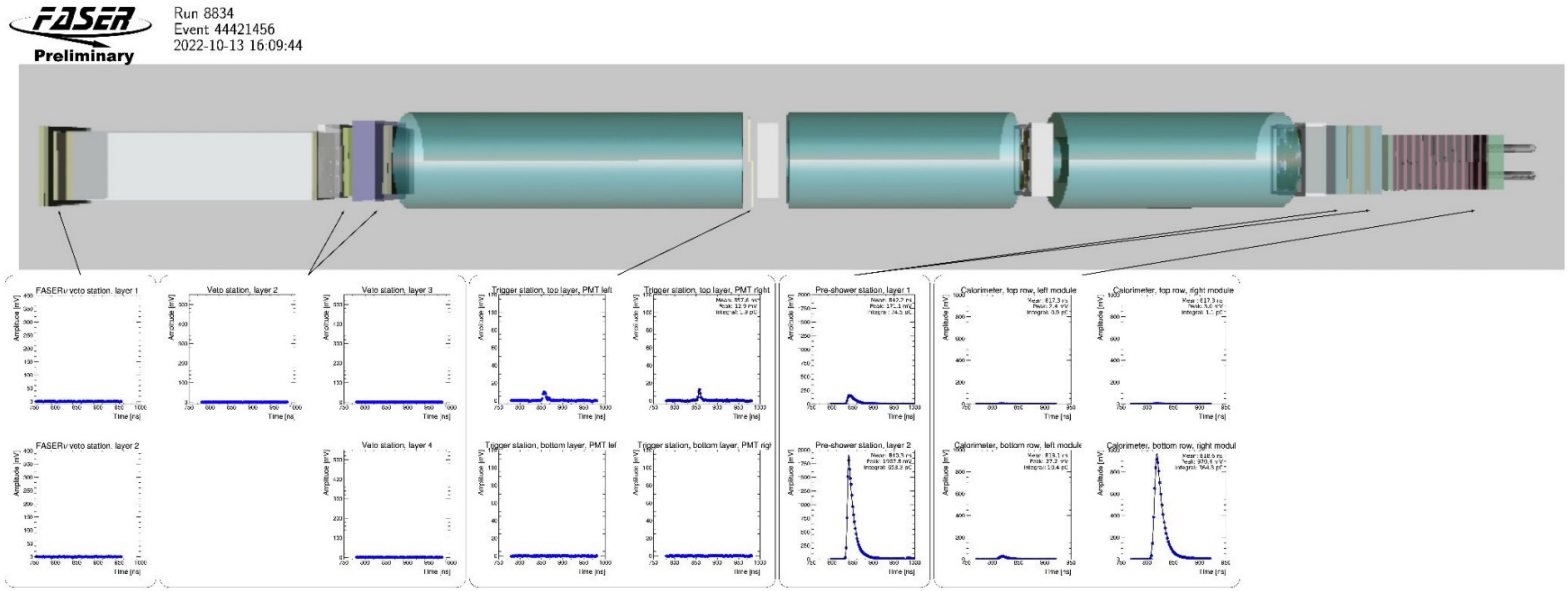

FASER
Preliminary
L = 57.7 fb$^{-1}$
ALP Gluon
Expected Limit (±1 $\sigma_{exp}$, 90% CL)
NuCal3 Limit
NA62 2103 Limit
1811 Limit
NuCal2 Limit
E1371 Limit
NA62 Limit
NA62 Limit
NuCal1 Limit
KOTO2 Limit
CHARM-HighMass Limit
KOTO1 Limit
E949 Limit
NA62 Limit
NA62 Limit
Kwidth Limit
GammaB Limit
Charm Limit
E137 Limit
NA48 Limit
CHARM1 Limit
BaBar Limit
CHARM2 Limit
GammaK Limit
Kaon2PiInv Limit
Kaon2PiGamma Limit
NA62 Limit
Observed Limit (90% CL)
Coupling $g_{agg}$ [1/GeV]
$m_a$ [MeV]


FASER
Preliminary
L = 57.7 fb$^{-1}$
U1B
Expected Limit (±1 $\sigma_{exp}$, 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 $\sigma_{exp}$, 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 $\sigma_{exp}$, 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

# The FASER Experiment

- FASER is a new, small experiment at the LHC

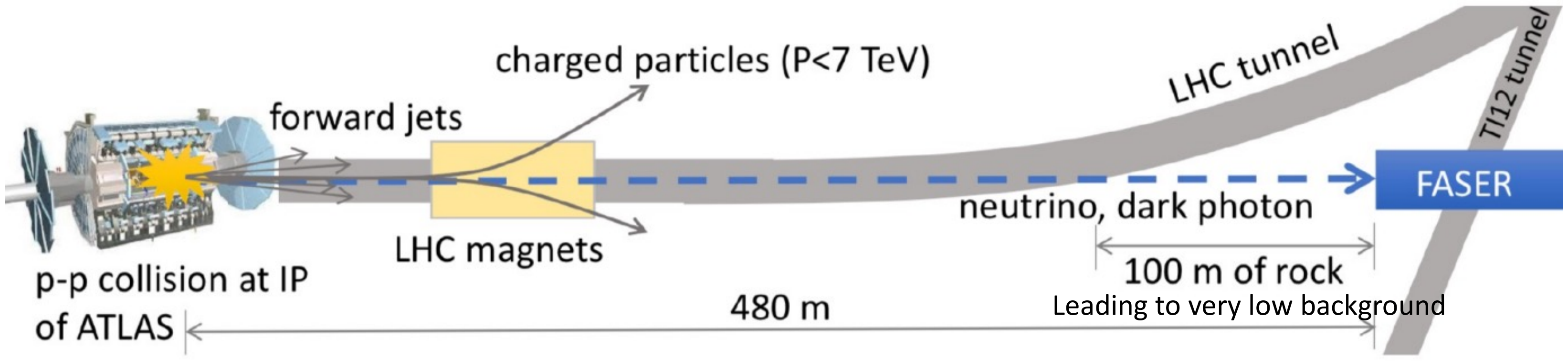
**FASER's target**

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

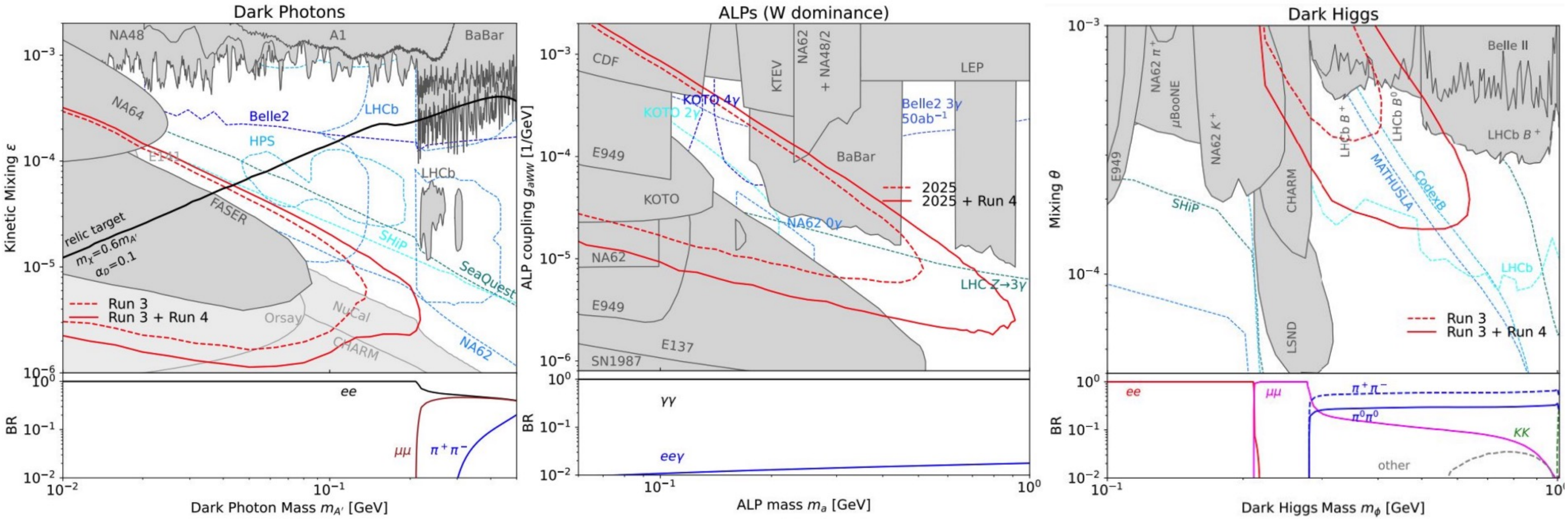
In terms of production mechanism

| 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

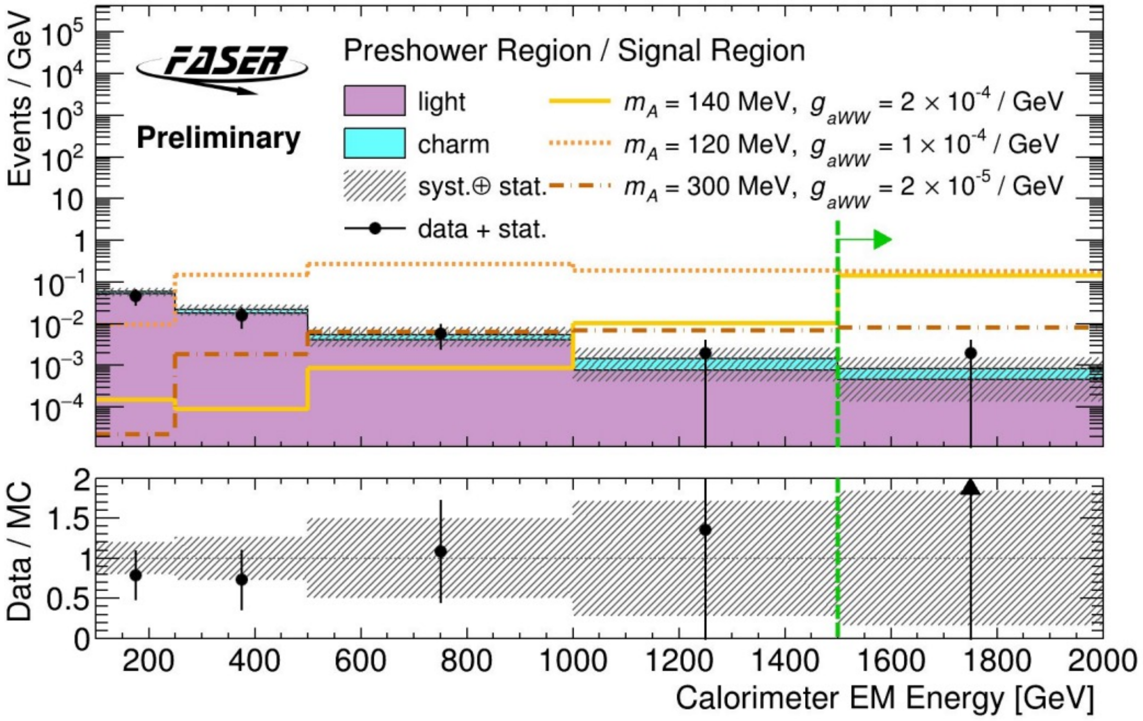
| SR | |
|---|---|
| $\nu_e$ | 0.32 ± 0.31 (flux) ± 0.10 (exp.) ± 0.04 (stat.) |
| $\nu_\mu$ | 0.09 ± 0.04 (flux) ± 0.05 (exp.) ± 0.02 (stat.) |
| Total | **0.42 ± 0.38 (90.6%)** |
| Data | 1 |
| Preshower region | |
| $\nu_e$ | 5.16 ± 2.59 (flux) ± 0.51 (exp.) ± 0.17 (stat.) |
| $\nu_\mu$ | 12.6 ± 2.3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

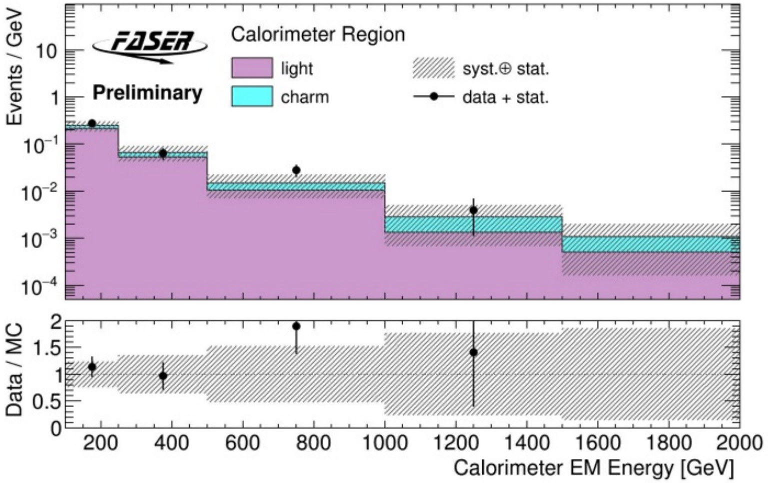
# Run 4 Projections

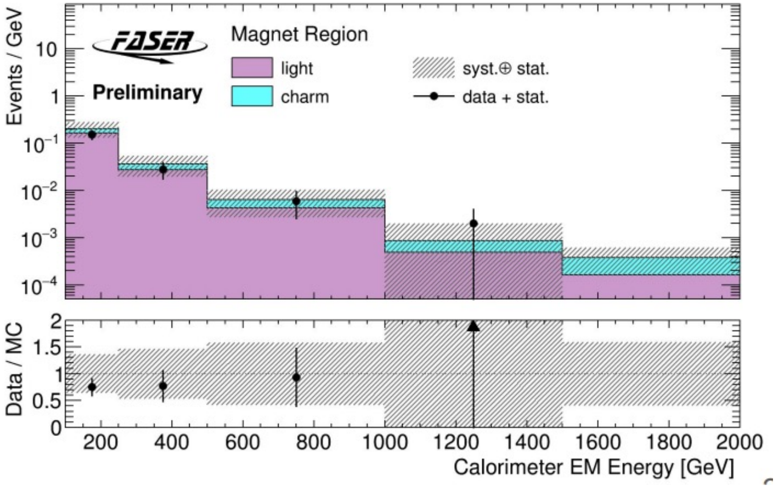



[FASER Run4 Request]

# Neutrino Background
(Production mechanism breakdown)

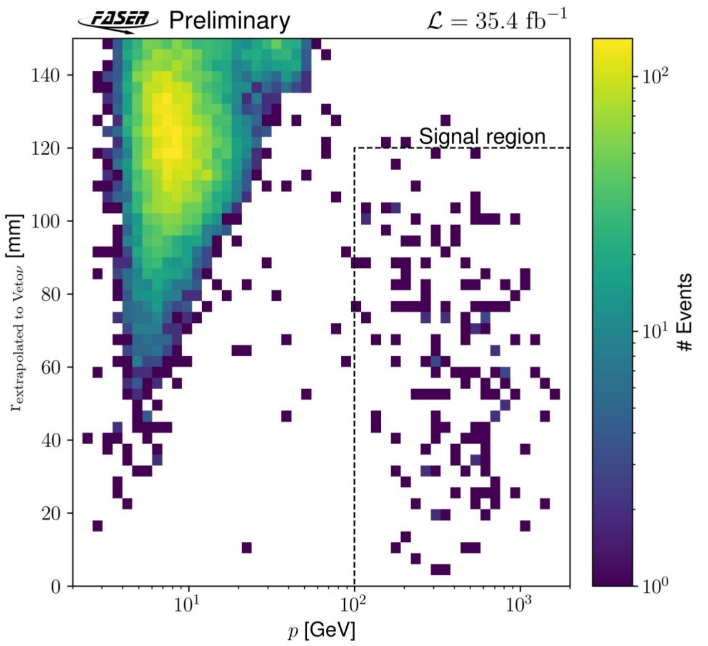


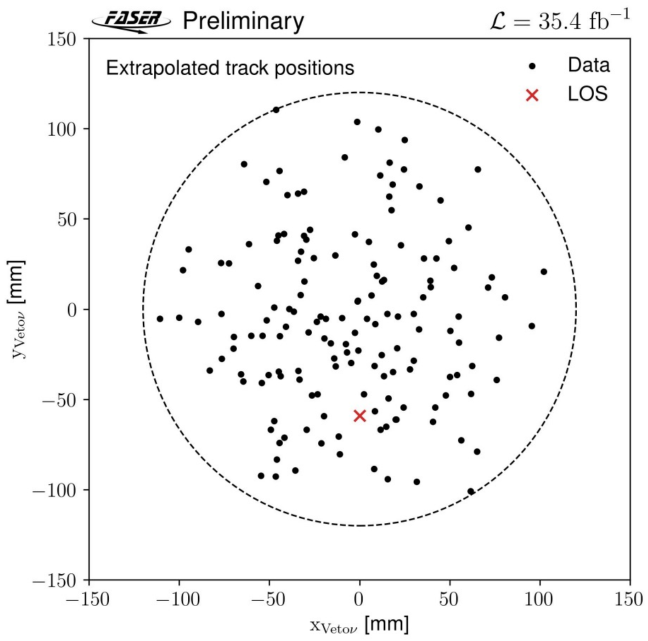



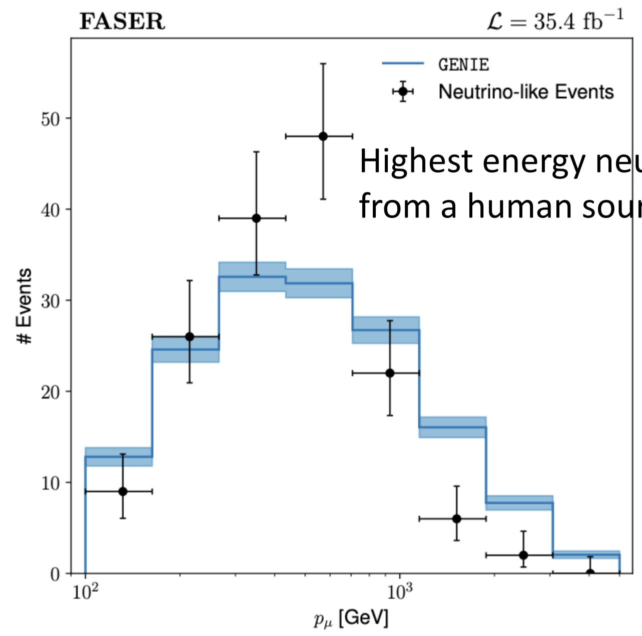



# Collider Neutrino Observation

- 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**



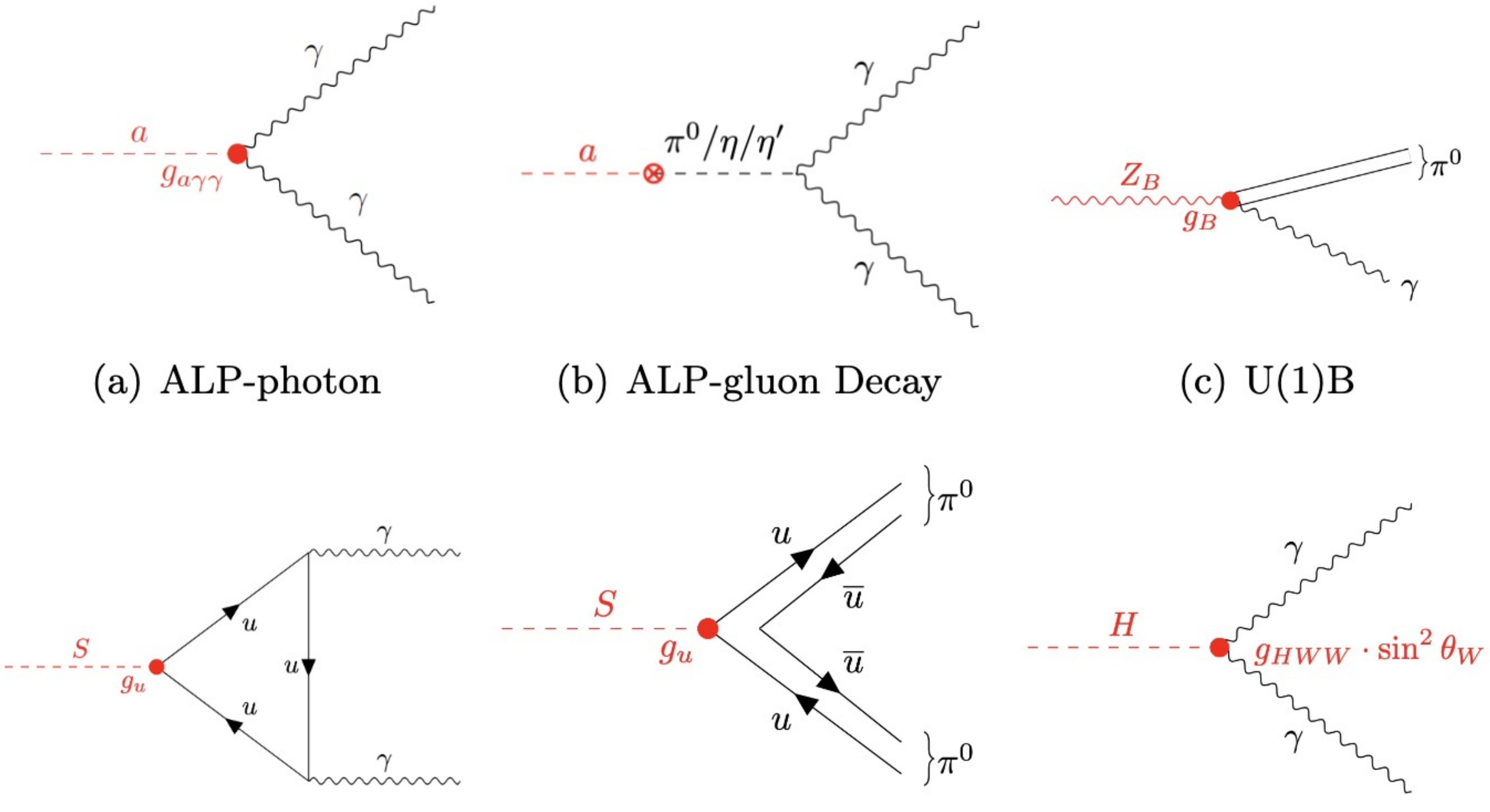




Highest energy neutrinos from a human source!

# Other Models also considered (Decay Diagrams)

All Photonic Final States




(a) ALP-photon

(b) ALP-gluon Decay

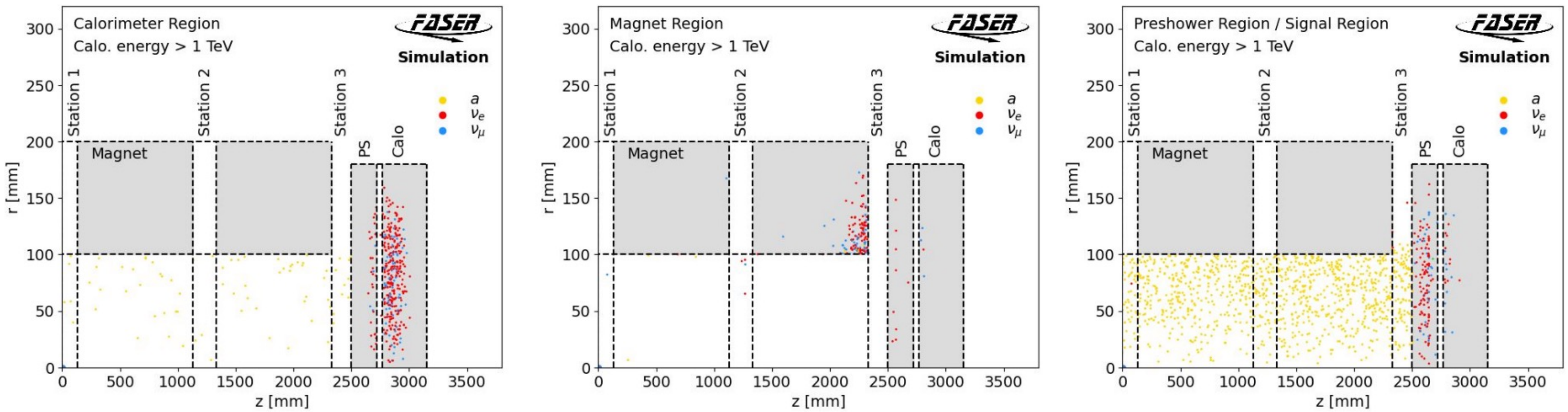
(c) U(1)B

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

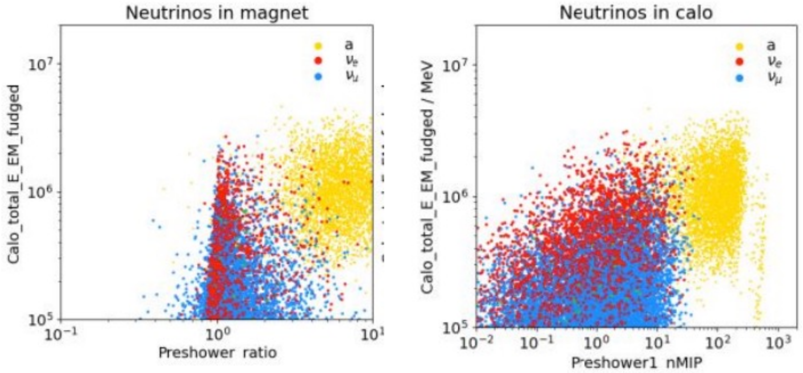
(e) Up-Philic Decay ($m_S > 2 \times m_{\pi^0}$)

(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 FASER**ν**2