# The Search for BSM Physics with the FASER Experiment at the LHC

Large Hadron Collider Physics Conference 2024
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on behalf of the FASER Collaboration

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# The FASER Collaboration

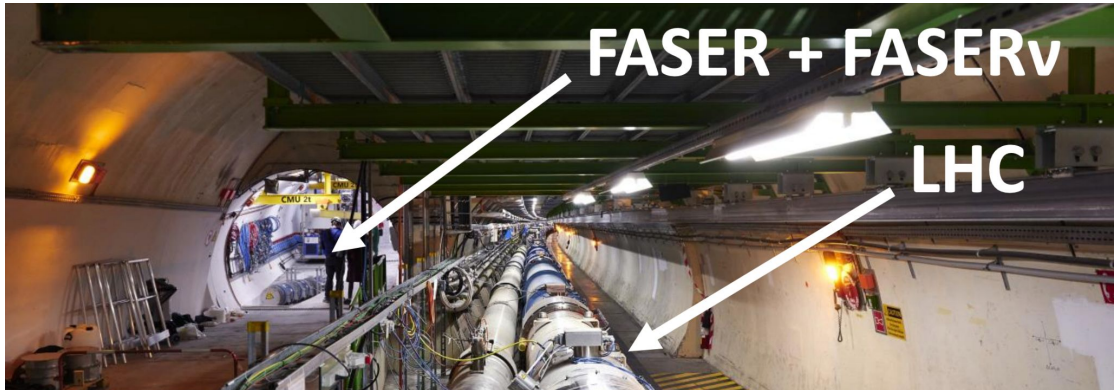
99 collaborators, 27 institutions, 11 countries

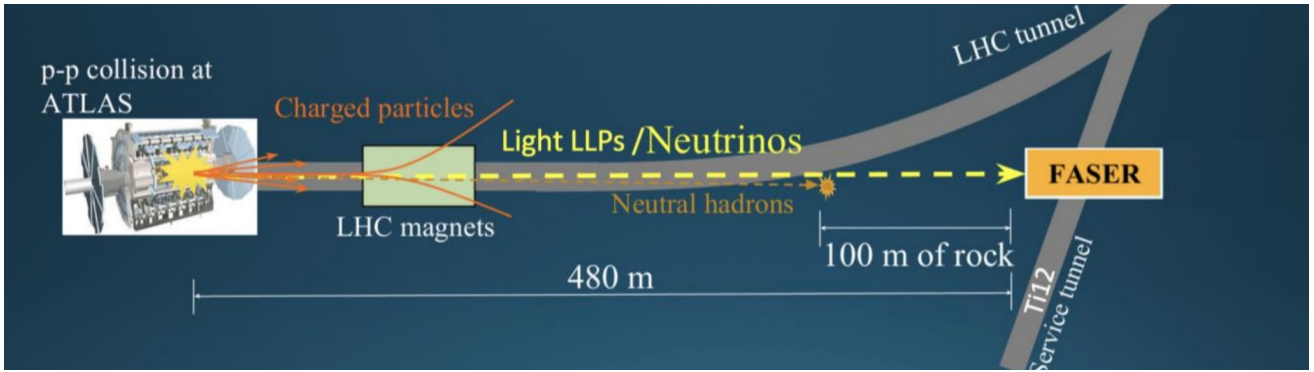
# Introduction

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.

Detector aligned with beam collision axis line of sight.

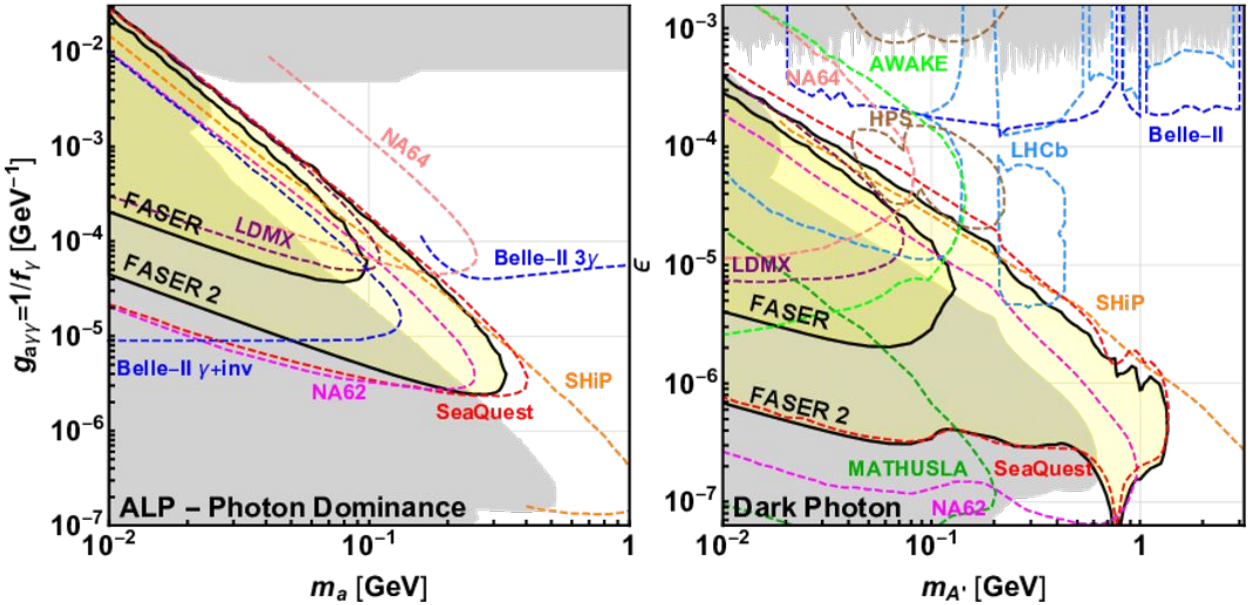


# Physics Motivation

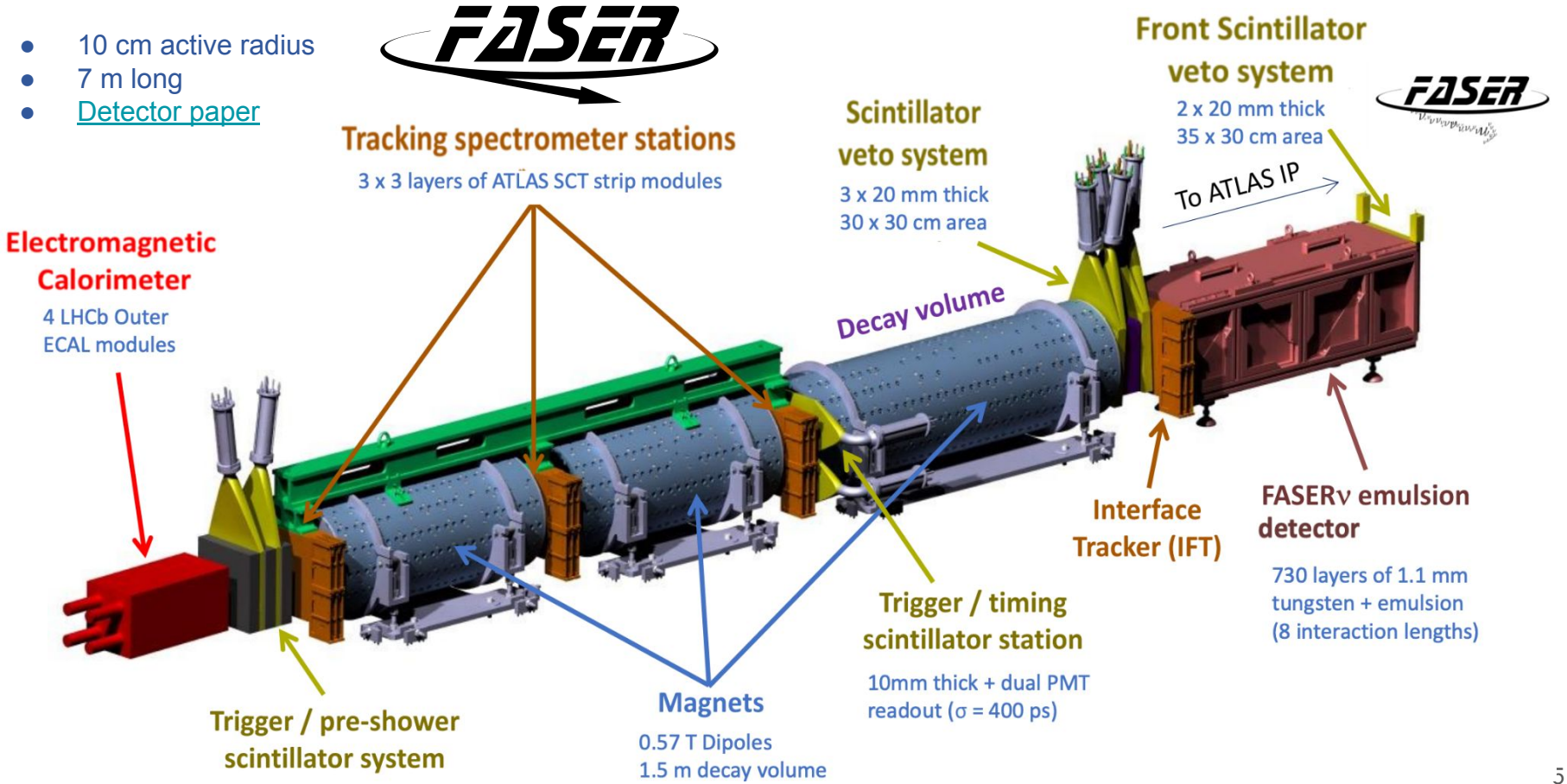
- Exploits large LHC collision rate with highly collimated forward production of light particles
- Particles produced in the FASER angular acceptance have a very large boost *O*(TeV)
- FASER targets new long-lived BSM particles including **dark photons** and **ALPs**

pp → LLP, LLP travels ~480m, LLP → ee, γγ, μμ, …



# The FASER Detector

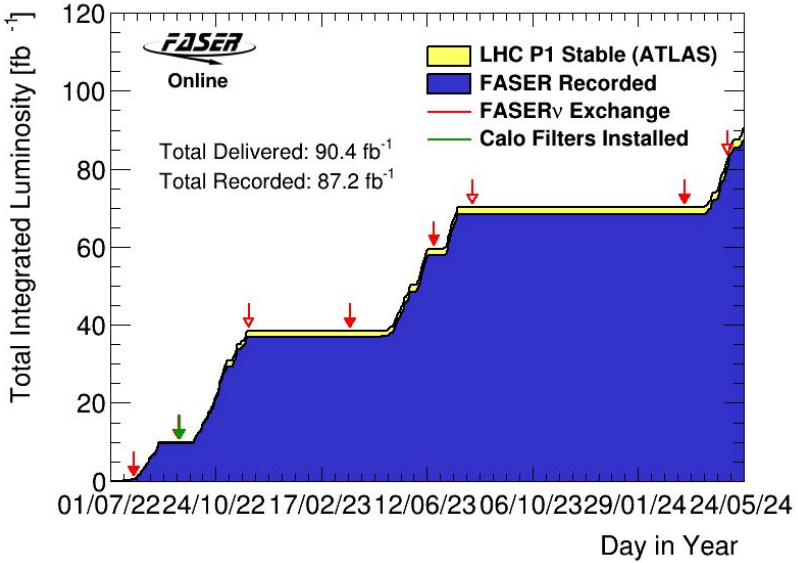
- 10 cm active radius
- 7 m long
- Detector paper

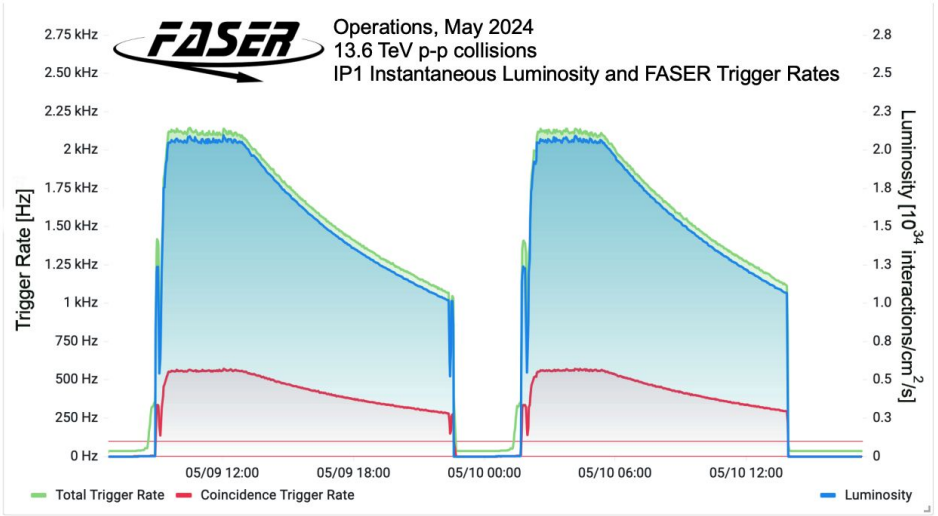


# FASER Location

# FASER Operations

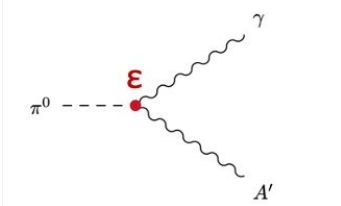
- Installed and commissioned in time for Run 3 data taking
  - Run 3 data recorded with 97% efficiency

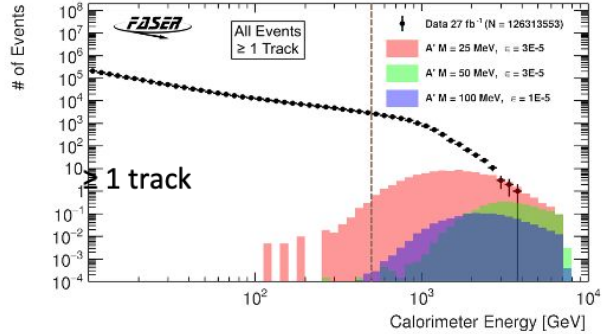


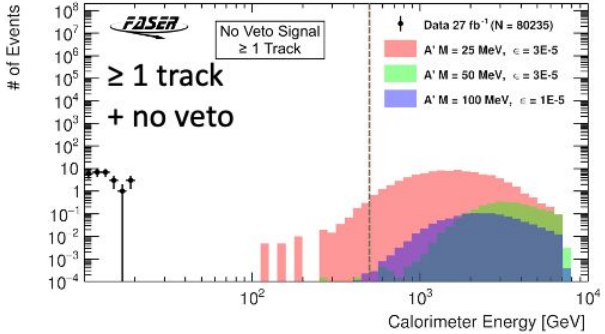



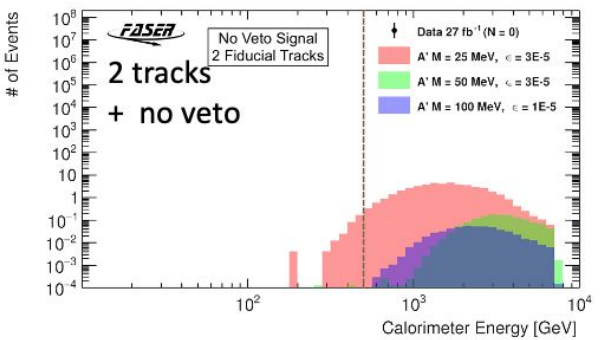
# Dark Photons in FASER

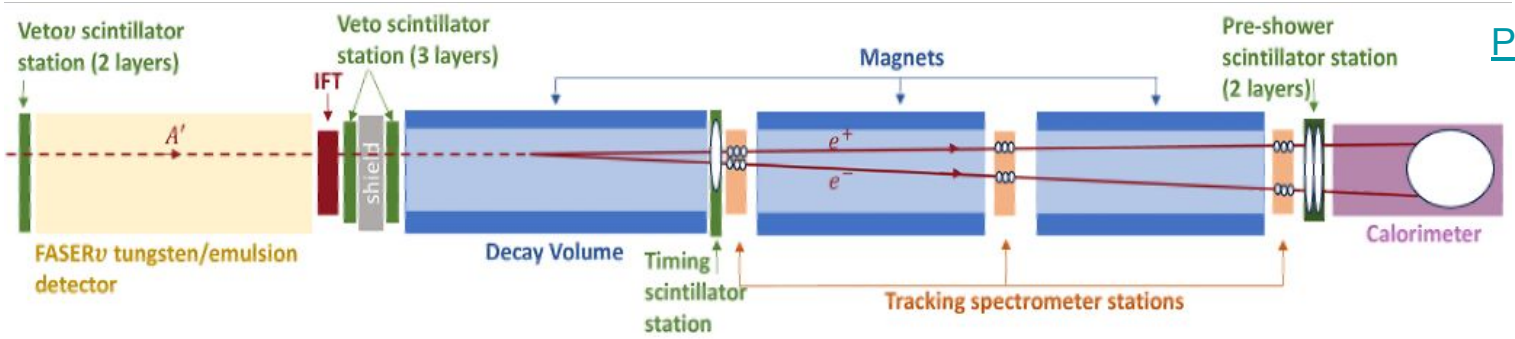
- Search for A' → $e^+e^-$ using 2022 data (27 $fb^{-1}$)
  - No signal in vetos, 2 good tracks with timing station/preshower signal, Calo E > 500 GeV
  - Small background from neutrino events



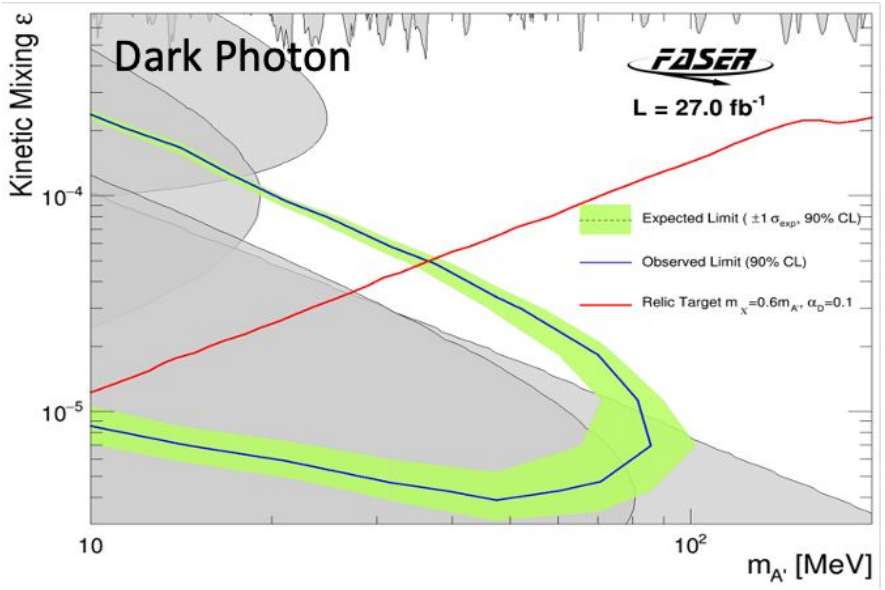




PhysLetB.848

# Dark Photons in FASER: Results

**Observed 0 events in 27 fb$^{-1}$ with a background prediction of (2.3 ± 2.3) x 10$^{-3}$ events**

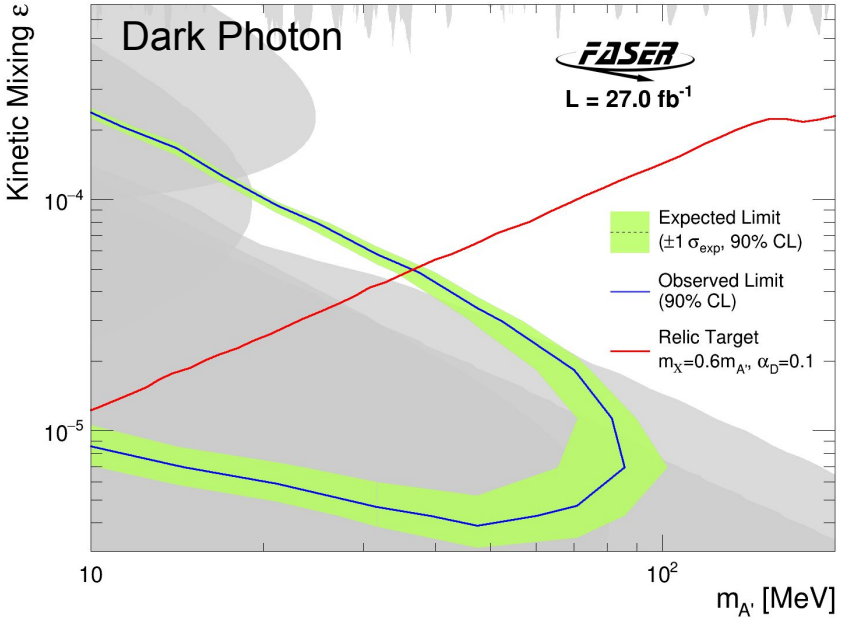
- Same dataset as shown last year
- Probes new parameter space motivated by the dark matter relic density PhysLetB.848

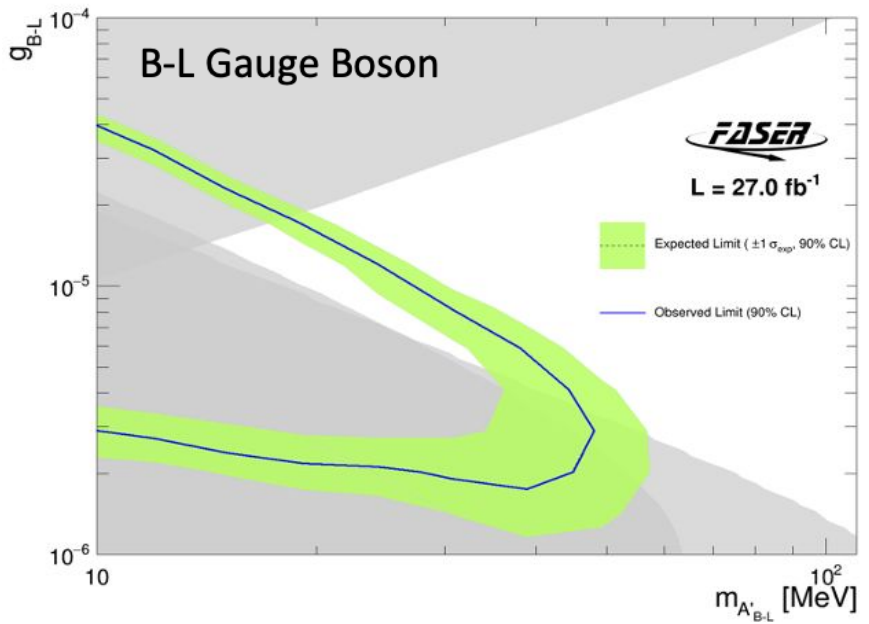


# Dark Photons in FASER: Updated Results

**Observed 0 events in 27 fb$^{-1}$ with a background prediction of (2.3 ± 2.3) x 10$^{-3}$ events**

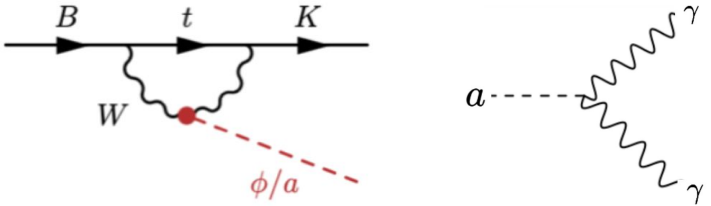
- Same dataset as shown last year – new preliminary NA62 Dark Photon result
- Now reinterpreted for B-L gauge boson model

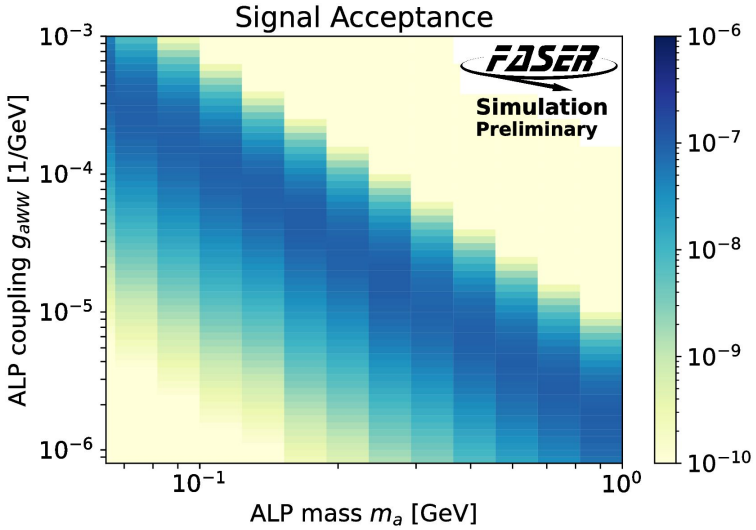


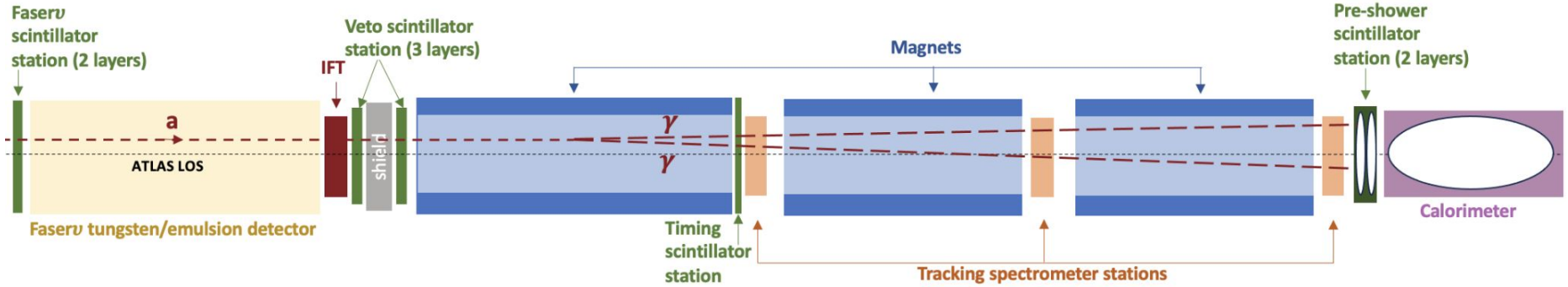
# ALPs in FASER

Link to conf paper




- 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
- Decays to 2 high energy photons
  - Cannot be distinguished in our calorimeter



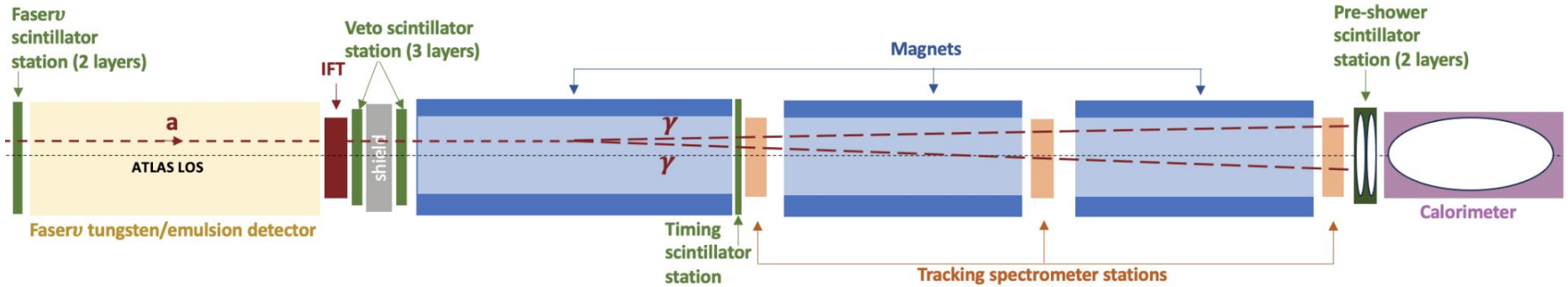
# ALPs: Event Selection

Link to conf paper

| 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) |

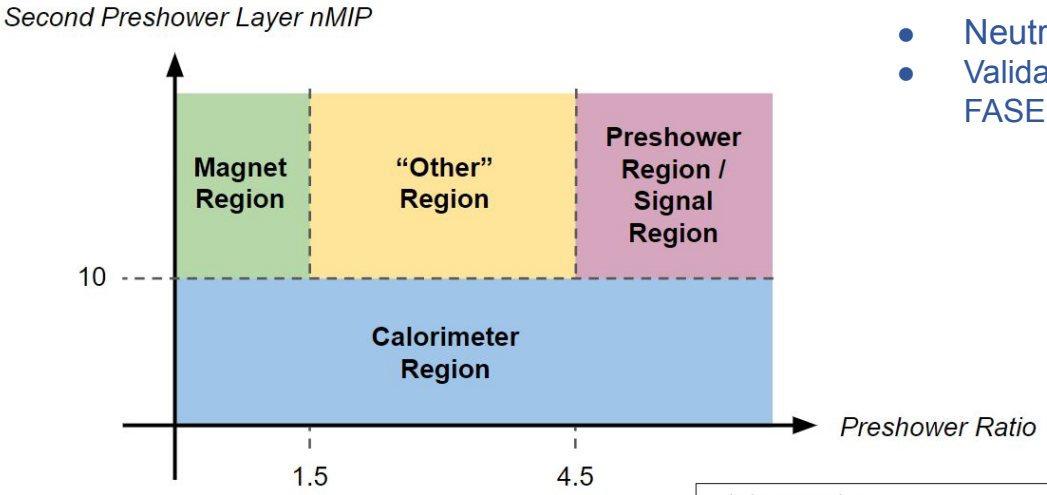
- Require that there is:
  - No signal in any of the 5 veto scintillators
  - No signal in the timing scintillator station
  - Evidence of an EM shower in the preshower detector
  - Significant energy deposits in the electromagnetic calorimeter
    - Of at least **1.5 TeV**

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



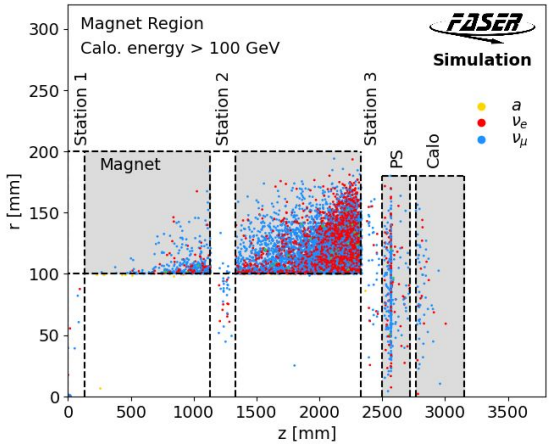
# ALPs: Background Estimation - Neutrino Interactions

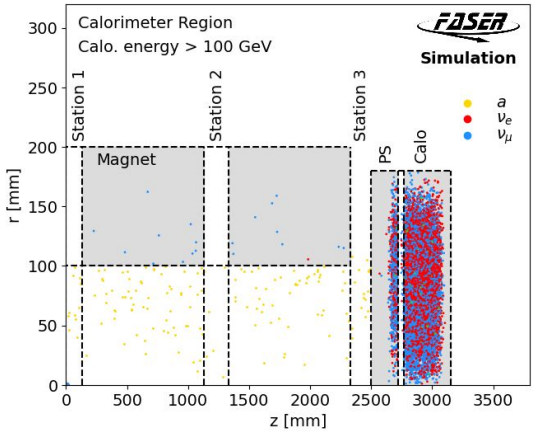
Link to conf paper

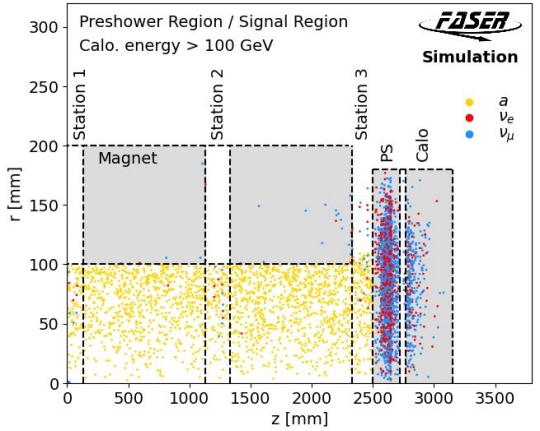



- Neutrino background evaluated using MC simulations
- Validated in data control regions defined based on where in FASER neutrinos interact

| **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%)** |

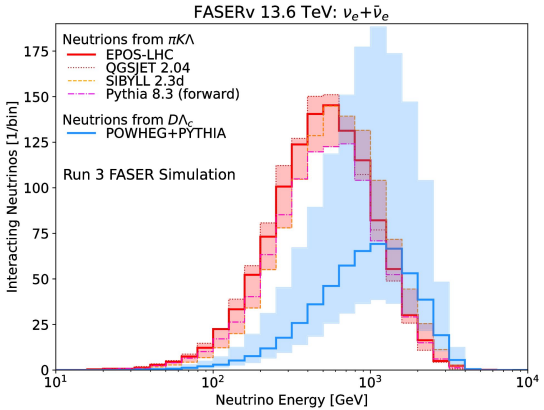


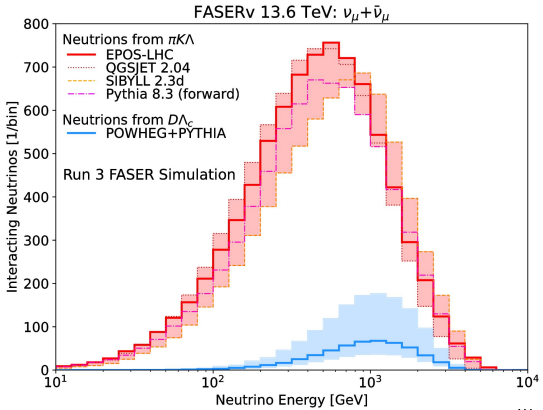



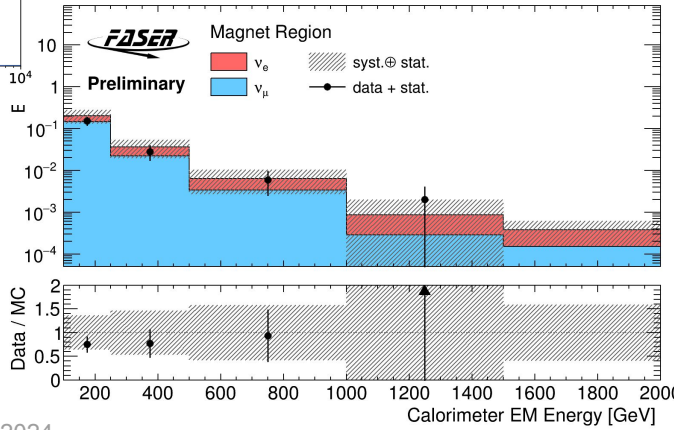
# ALPs: Background Estimation

- Good agreement between neutrino MC prediction and data in validation regions
  - Estimate for neutrinos produced from light hadron decay comes from envelope of several generators
  - Estimate for neutrinos produced from charm decay is from dedicated NLO calculation with POWHEG
    - With uncertainties from scale variation




| Region | MC | Data |
|---|---|---|
| Calorimeter | 62.7 ± 19.7 (31.4%) | 74 |
| Magnet | 43.5 ± 18.2 (41.9%) | 34 |
| Preshower | 17.8 ± 5.1 (28.8%) | 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

# ALPs: Systematic Uncertainties

Link to conf paper

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 (from ATLAS)
  - The uncertainty associated with the MC modelling of our preshower and calorimeter cuts
- MC Statistics

## Background systematics:

| Event Rate |
|---|
| $0.42 \pm 0.32$ (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%)** |

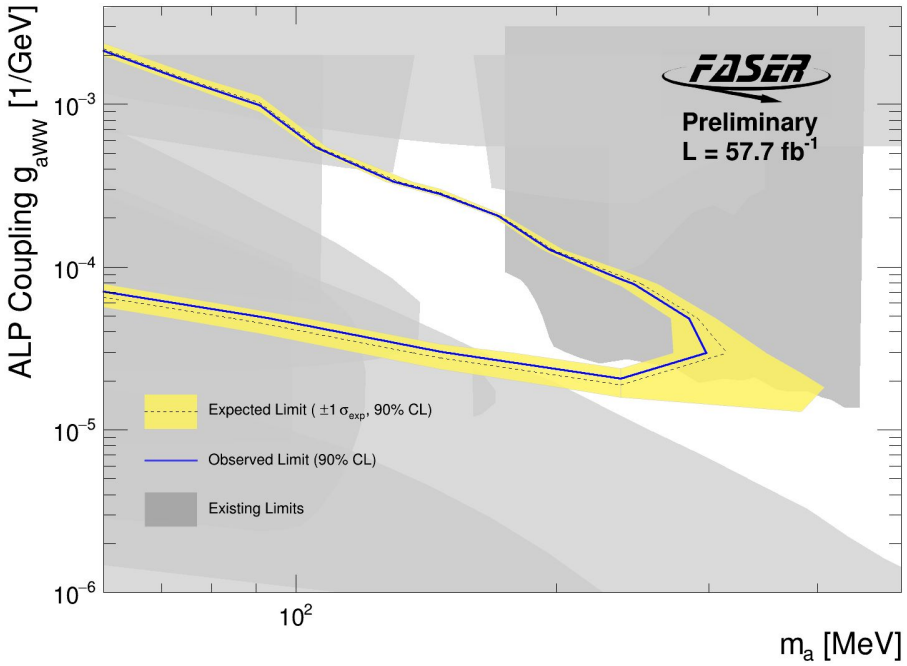
## Signal systematics:

| 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% |

# ALPs: Unblinded Results

Link to conf paper

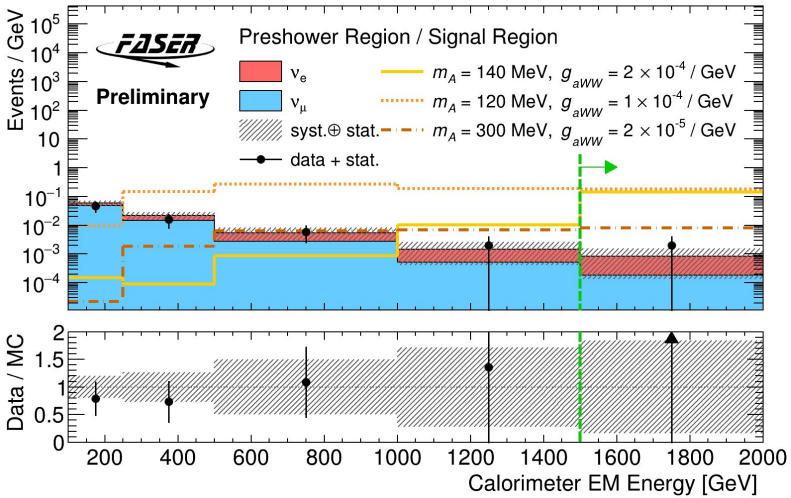
Observed limit:



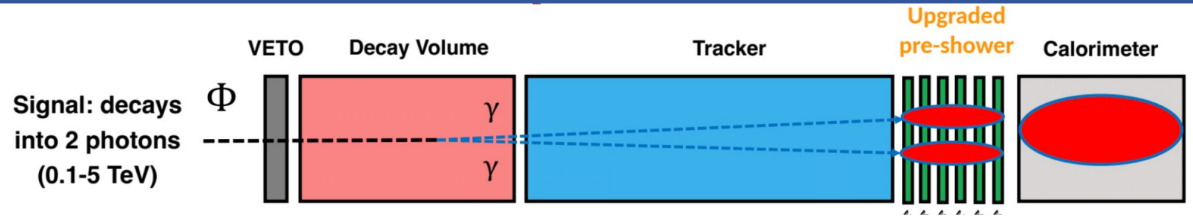

In 57.7 fb$^{-1}$ of data we saw **1 event** in our unblinded signal region

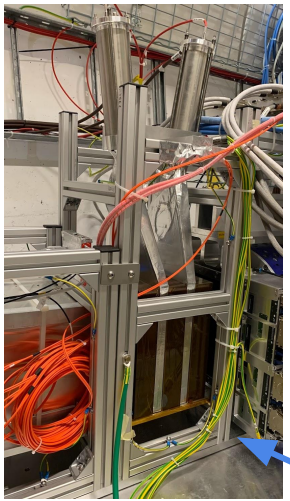
- Compared to expected background of 0.42 ± 0.38 events
- Shows preshower deposits consistent with an EM shower
- Calorimeter energy of **1.6 TeV**

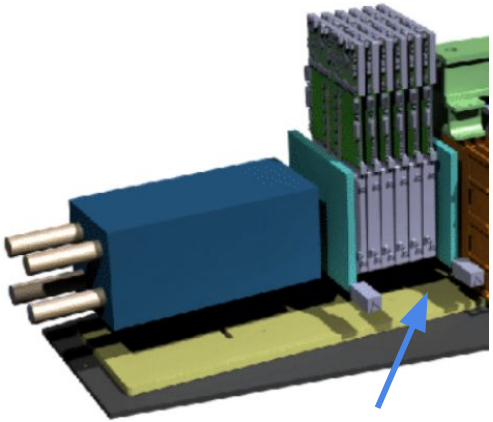
Unblinded Signal Region:



# Next Steps: Future Plans for YETS and Run 4





Current preshower

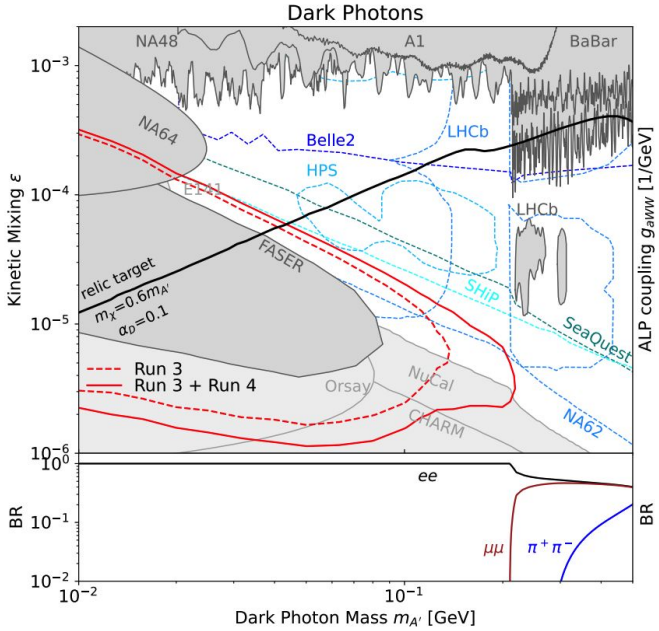
Planned upgrade (YETS 2024)

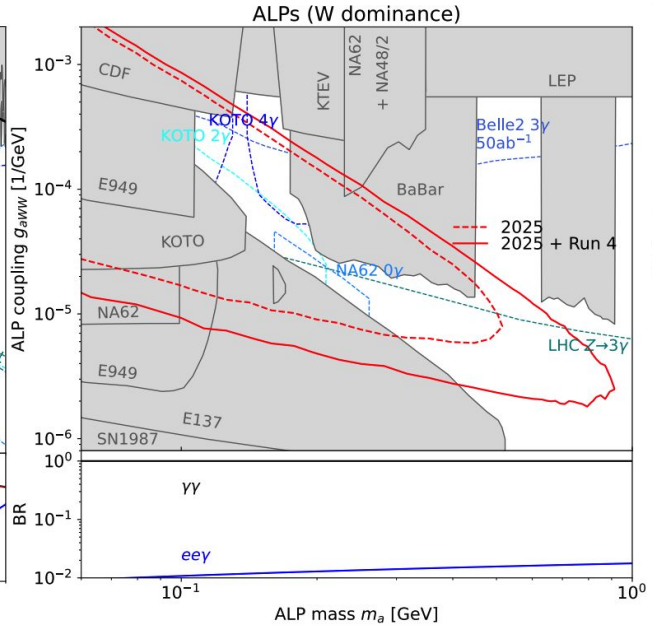
- Preshower sub-detector upgrade
  - Improve ability to resolve diphoton events with high X-Y granularity
  - Improve sensitivity and background suppression in ALPs searches
  - More details on planned FASER upgrades in Théo Moretti's talk
- FASER approved to run in Run 4
  - Large dataset with upgraded FASER at HL-LHC

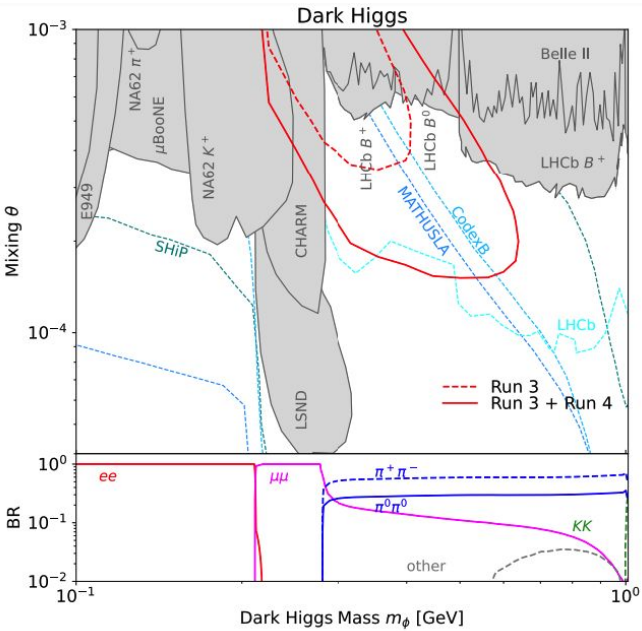
# Run 4 Projections

- Predicted reach for FASER's dark photon, ALP and dark Higgs searches with combined Run 3 + Run 4 dataset
  - Assuming a total 250 $fb^{-1}$ for Run 3
  - Assuming a total 680 $fb^{-1}$ for Run 4

[Request to run FASER in Run 4]



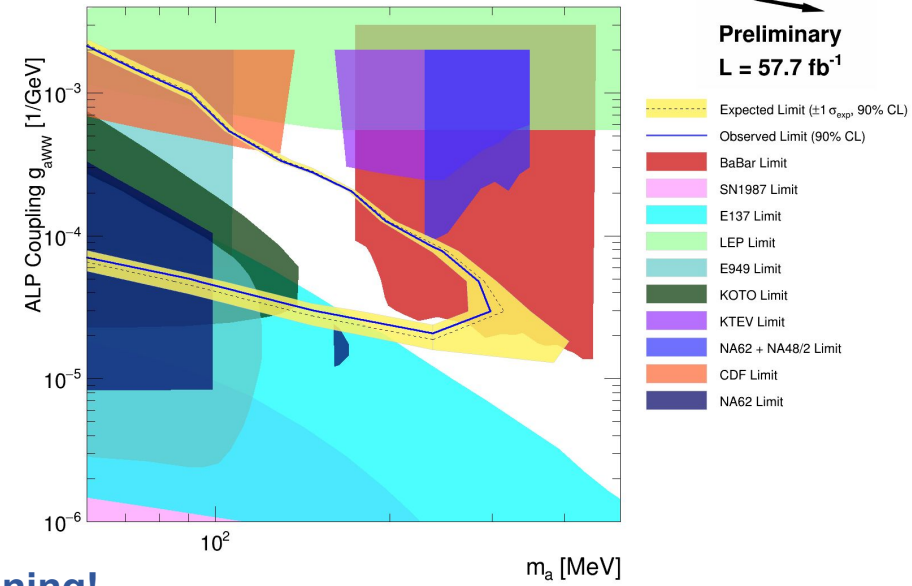



# Summary and Outlook

FASER has probed new parameter space with the ALP-W model

- At mass and coupling previously unexplored by existing experiments
- A conference note on these new results has been published!




Related talks at this conference:

- Overview of Neutrino Studies at FASER
- FASER Upgrades
- Forward Physics Facility: Proposed Experiments and Prospects

**Thank you for listening!**


FASER is supported by:

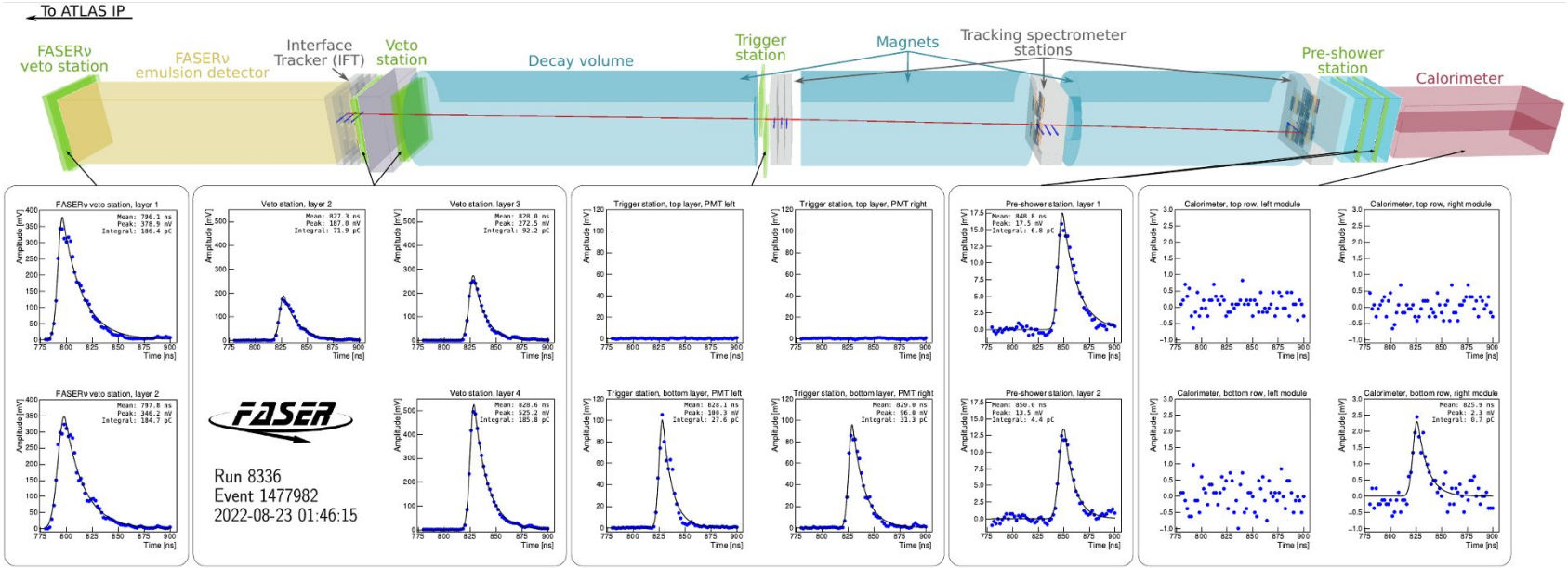
HEISING-SIMONS FOUNDATION · SIMONS FOUNDATION · 科研費 KAKENHI · Swiss National Science Foundation · NSF · CERN

# Backup Slides

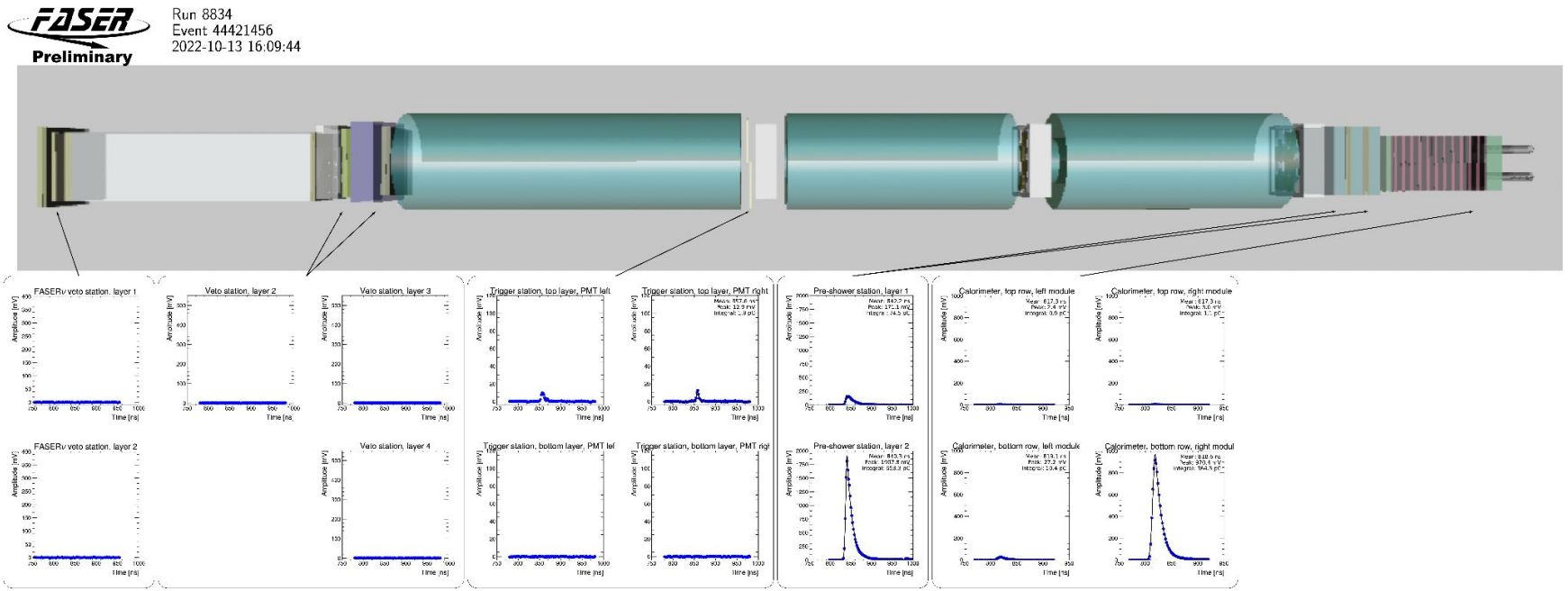
# Muons in FASER

- 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:

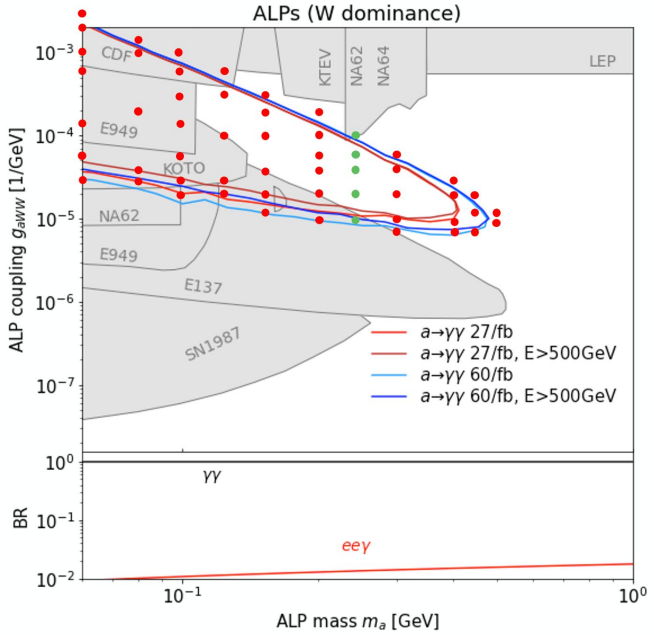


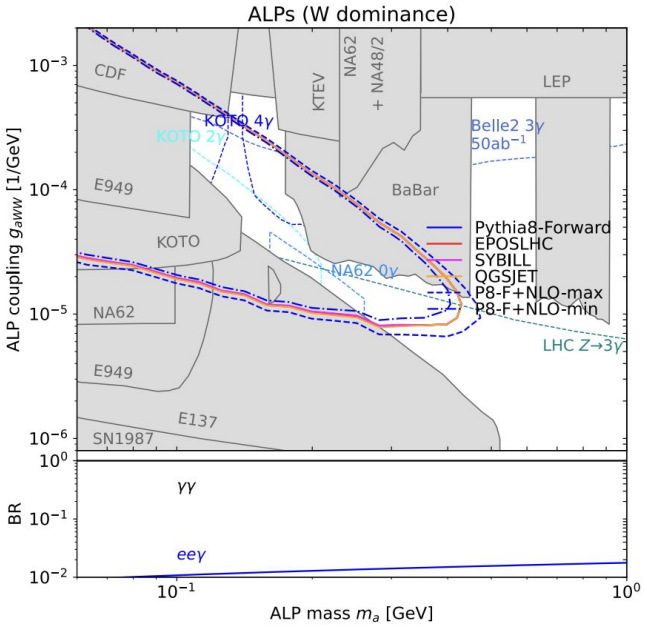
# Event Display

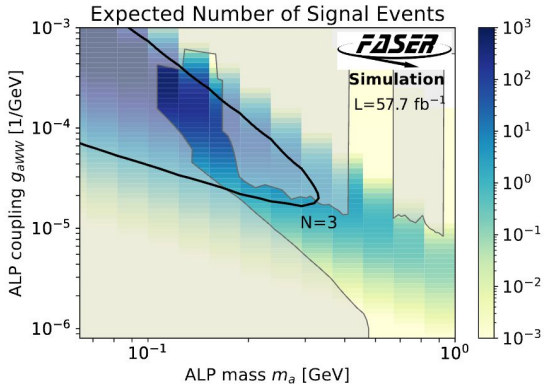



- This event has a calorimeter energy of **1.6 TeV**
- Shows preshower deposits consistent with an EM shower

# ALP Signal

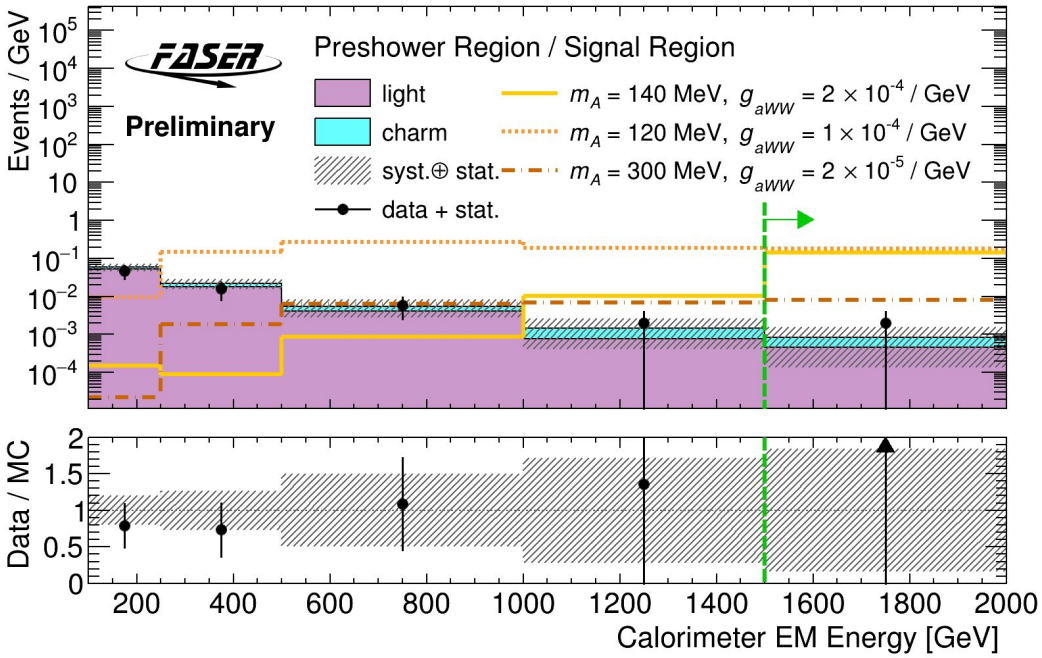


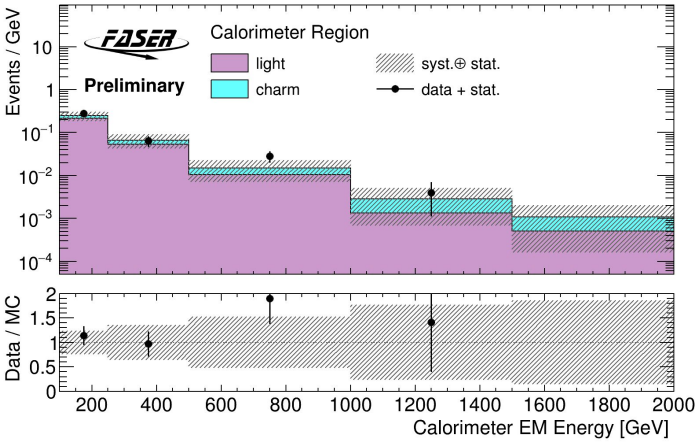



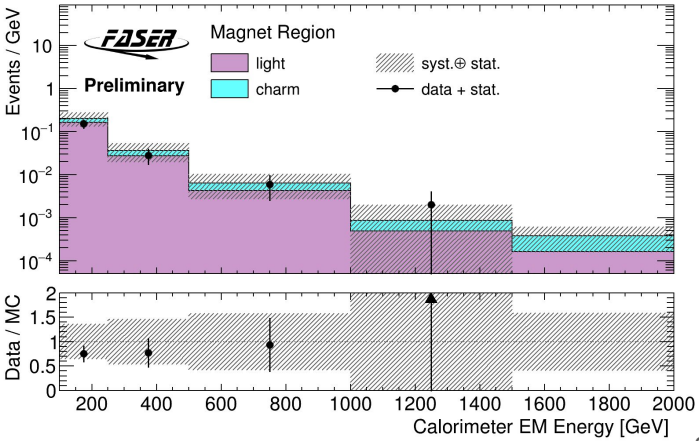




| Selection | Efficiency | Cum. Efficiency |
|---|---|---|
| $m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV$^{-1}$ | | |
| Veto Signal nMIP $< 0.5$ | 99.6% | 99.6% |
| Timing Scintillator Signal nMIP $< 0.5$ | 97.8% | 97.4% |
| Preshower Ratio $> 4.5$ | 85.7% | 83.5% |
| Second Preshower nMIP $> 10$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

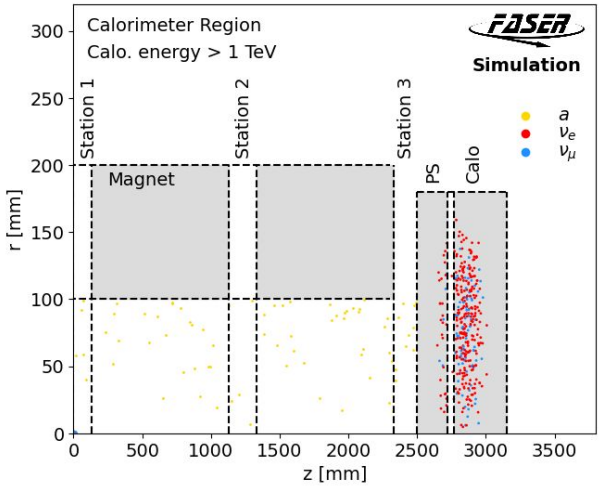
# ALP Results: Alternative Neutrino MC plot

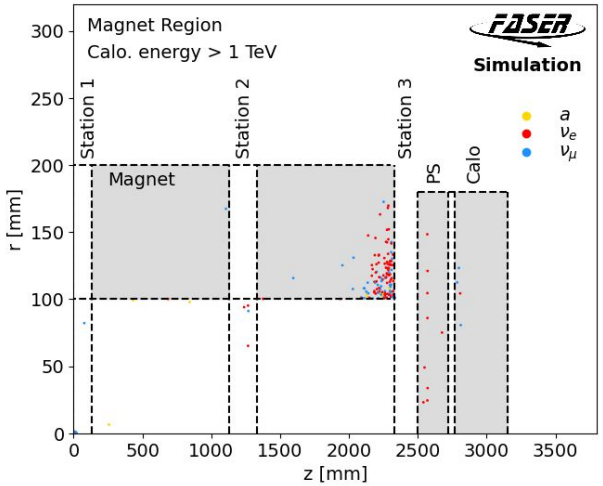


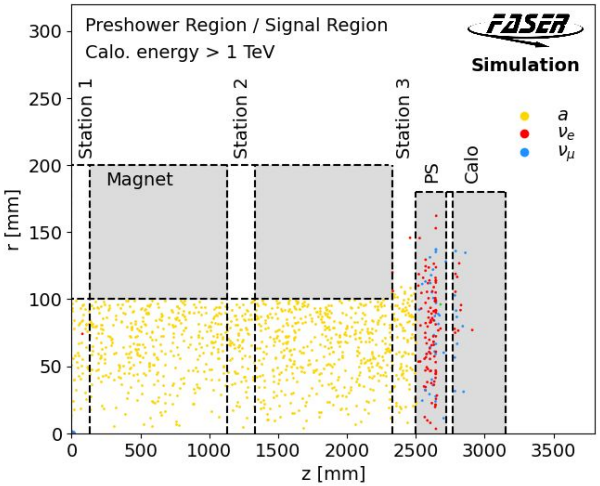



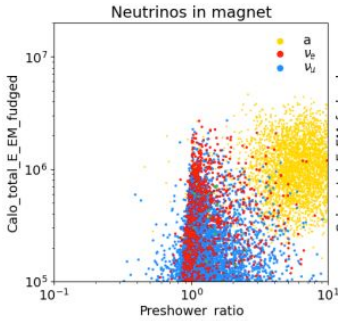
# Calorimeter, Magnet, Preshower Regions: 1 TeV cut

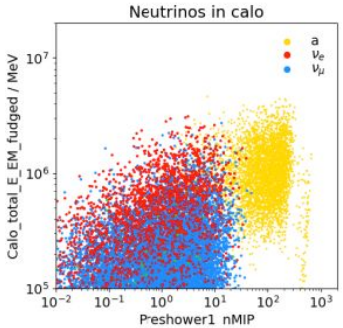



## Preshower variables:



# Neutrino Background Composition

- In terms of light and charm:

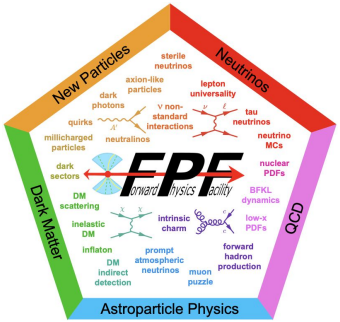
| Magnet region | |
|---|---|
| Light | $33.6^{+6.7}_{-3.4}$ (flux) ± 4.3 (exp.) ± 0.4 (stat.) |
| Charm | $9.9^{+16.1}_{-4.6}$ (flux) ± 0.9 (exp.) ± 0.2 (stat.) |
| Total | **43.5 ± 18.2 (41.9%)** |
| Data | **34** |
| "Other" region | |
| Light | $17.4^{+1.3}_{-0.8}$ (flux) ± 2.5 (exp.) ± 0.3 (stat.) |
| 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** |

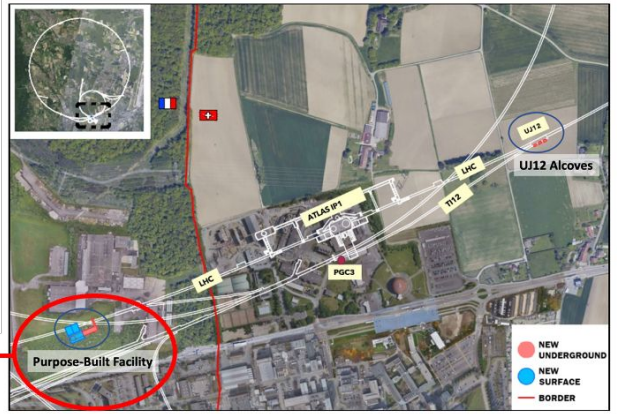
- In terms of neutrino type:

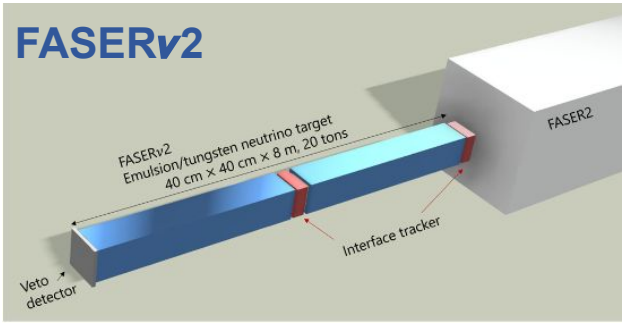
| SR | |
|---|---|
| $\nu_e$ | 0.32 ± 0.31 (flux) ± 0.10 (exp.) ± 0.04 (stat.) |
| $\nu_\mu$ | 0.09 ± 0.04 (flux) ± 0.05 (exp.) ± 0.02 (stat.) |
| Total | **0.42 ± 0.38 (90.6%)** |
| Data | 1 |
| Preshower region | |
| $\nu_e$ | 5.16 ± 2.59 (flux) ± 0.51 (exp.) ± 0.17 (stat.) |
| $\nu_\mu$ | 12.6 ± 2.3 (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 |

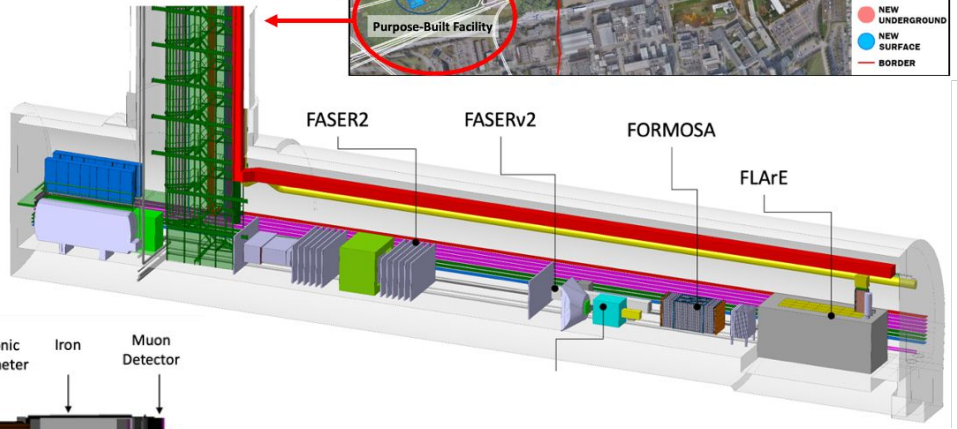
# FASER2 and the Forward Physics Facility

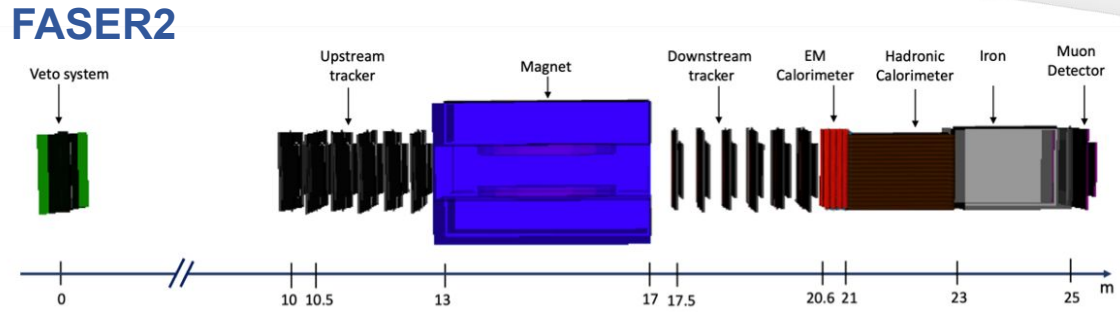
- Proposed dedicated forward-physics facility at HL-LHC
  - New ~65 m long cavern, 620 m from ATLAS
- 4 dedicated experiments including FASER2 and FASER*ν*2



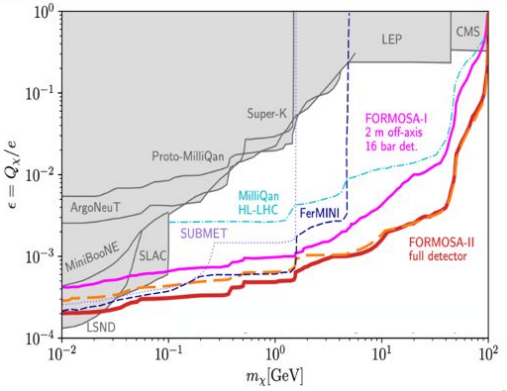



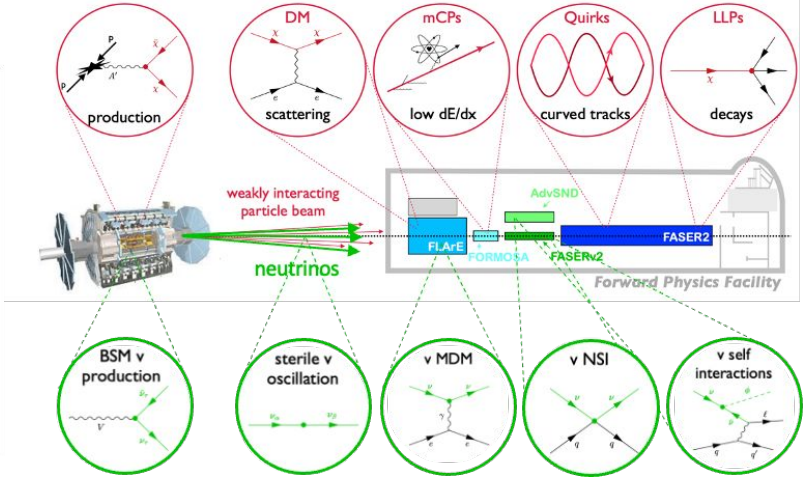
# FPF Physics Potential

- Hidden Sector

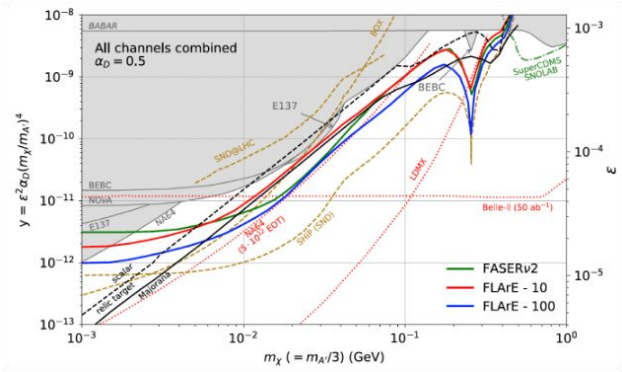
| Benchmark Model | FASER | FASER 2 |
|---|---|---|
| Dark Photons | √ | √ |
| $B-L$ Gauge Bosons | √ | √ |
| $L_i-L_j$ Gauge Bosons | — | — |
| Dark Higgs Bosons | — | √ |
| Dark Higgs Bosons with $hSS$ | — | √ |
| HNLs with $e$ | — | √ |
| HNLs with $\mu$ | — | √ |
| HNLs with $\tau$ | √ | √ |
| ALPs with Photon | √ | √ |
| ALPs with Fermion | — | √ |
| ALPs with Gluon | √ | √ |
| Dark Pseudoscalars | — | √ |

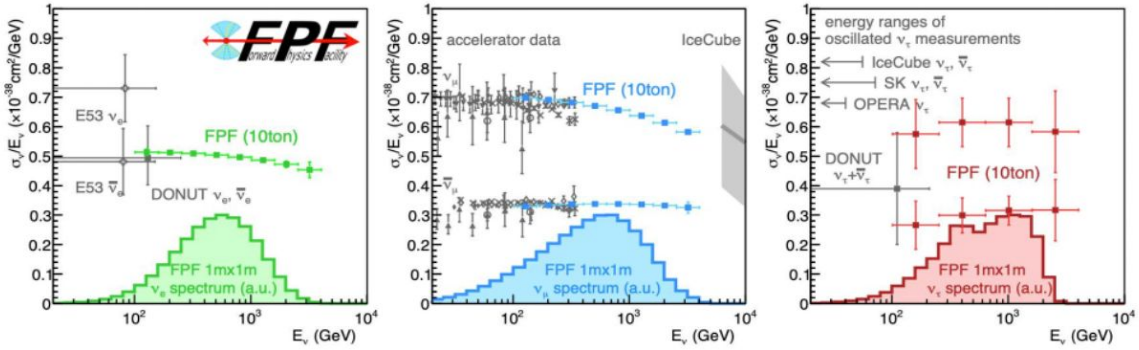
- Millicharged particles




- Light DM scattering



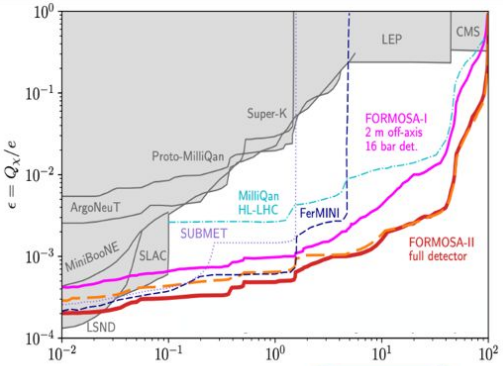

- Differential neutrino flux measurements for all flavours at TeV energies

# FPF Physics Potential (2)

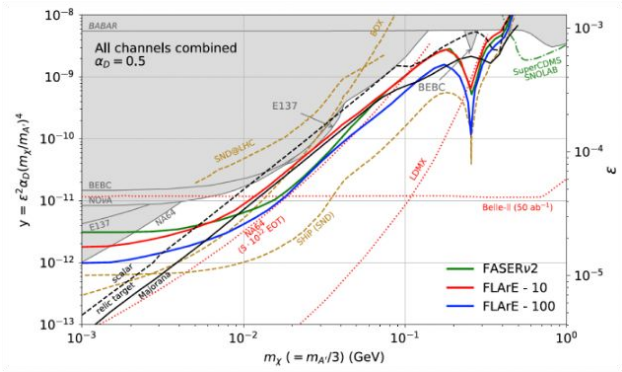
- Hidden Sector

| Benchmark Model | FASER | FASER 2 |
|---|---|---|
| Dark Photons | √ | √ |
| $B-L$ Gauge Bosons | √ | √ |
| $L_i-L_j$ Gauge Bosons | — | — |
| Dark Higgs Bosons | — | √ |
| Dark Higgs Bosons with $hSS$ | — | √ |
| HNLs with $e$ | — | √ |
| HNLs with $\mu$ | — | √ |
| HNLs with $\tau$ | √ | √ |
| ALPs with Photon | √ | √ |
| ALPs with Fermion | — | √ |
| ALPs with Gluon | √ | √ |
| Dark Pseudoscalars | — | √ |

- Millicharged particles




- Light DM scattering




- FPF probes unexplored physics, with very broad physics spectrum:
  - New particles, DM, neutrinos, QCD, astroparticle physics, quirks, mCP