FASER
Forward Search Experiment

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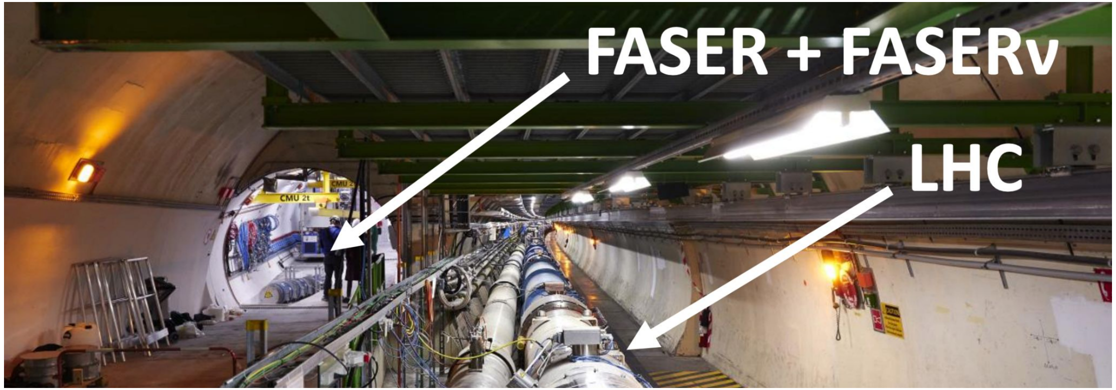
24th May 2024

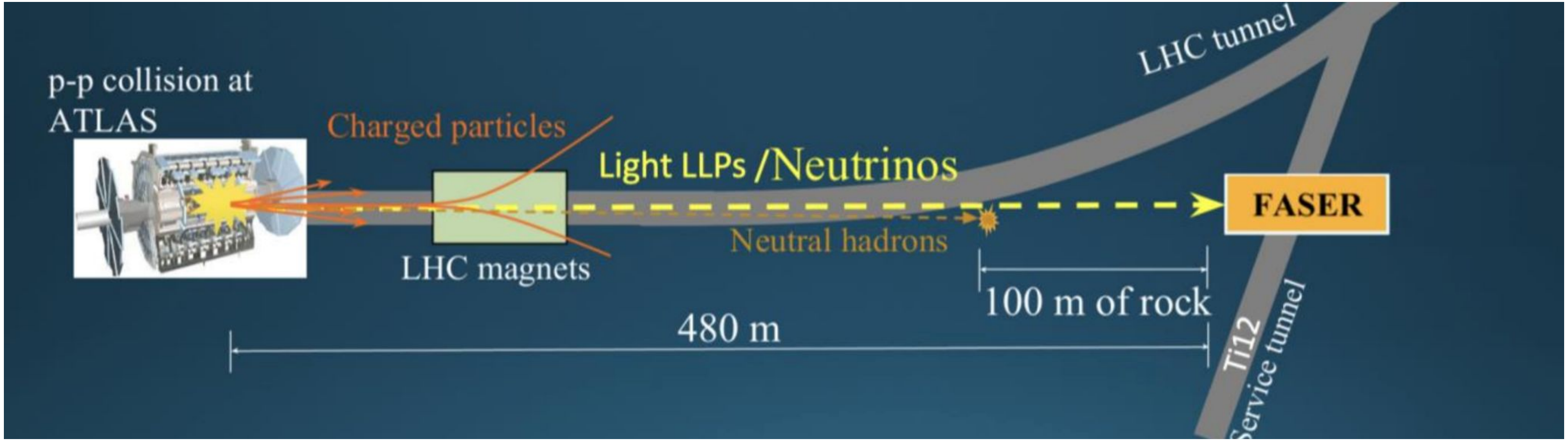
Liverpool HEP Annual Meeting

FASER Location

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

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





The FASER Collaboration

4 UK institutes

Monica: UK PI

96 collaborators, 26 institutions, 10 countries

International laboratory covered by a cooperation agreement with CERN

FASER is supported by:

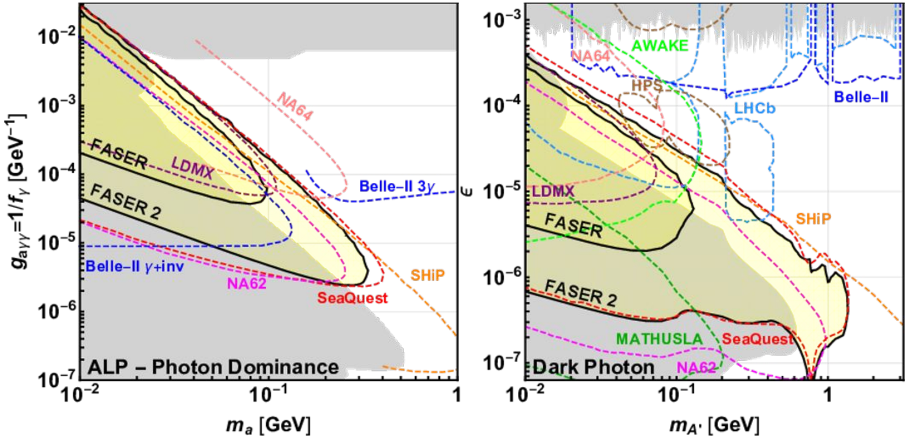
Physics Motivation

Carl: FASER Physics Coordinator (2022 - Sept 2024)

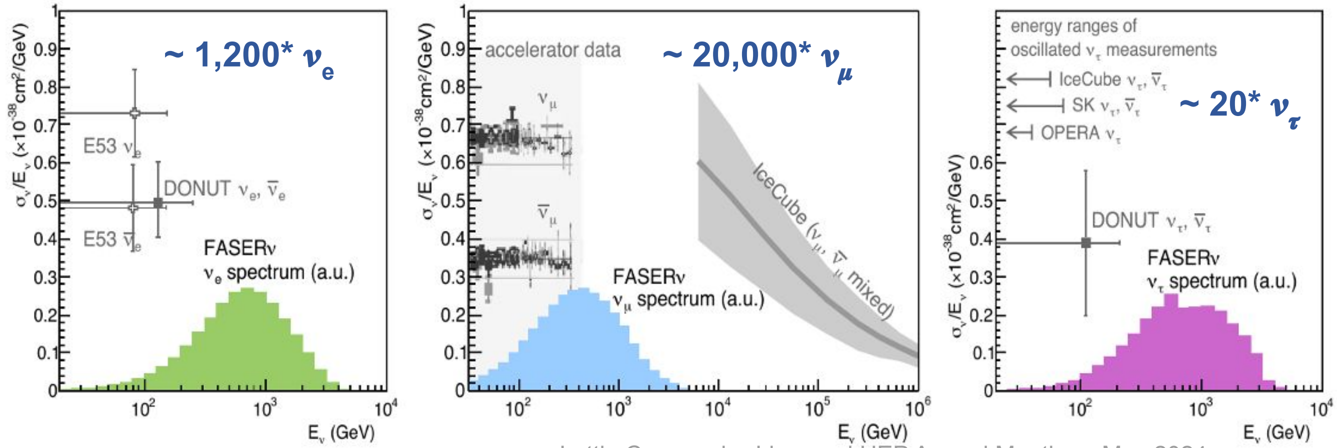
FASER exploits large LHC collision rate with highly collimated forward production of light particles

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

- Complementarity with GPDs



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

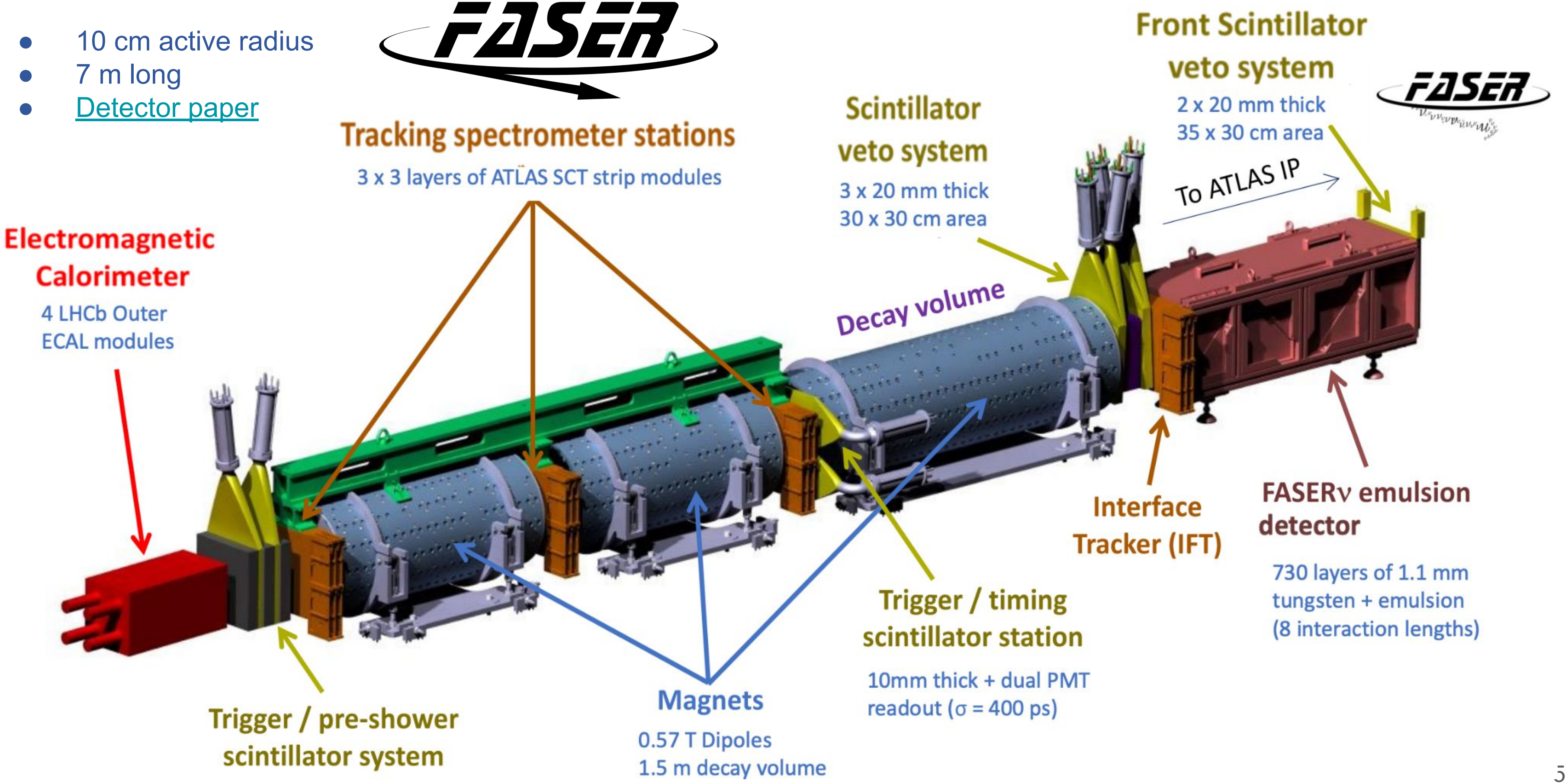


- Dedicated FASERν detector on LOS
- First observation of collider **neutrinos**
- Cross-section measurement in unexplored TeV range

*** ν numbers for full Run 3**

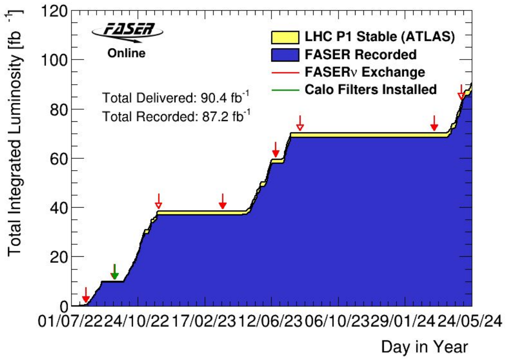
The FASER Detector

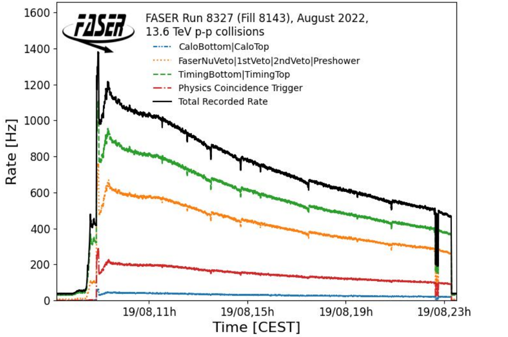
- 10 cm active radius
- 7 m long
- [Detector paper]

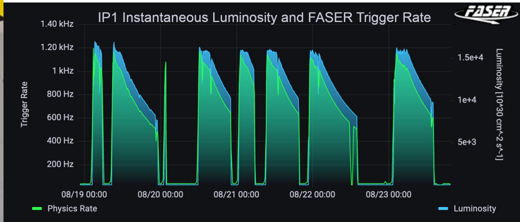


FASER Operations

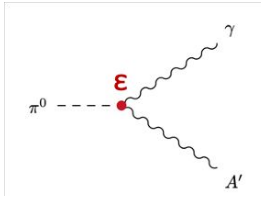
Liverpool: Run Manager and Monitoring shifts (**Lottie** and **Sinead**)

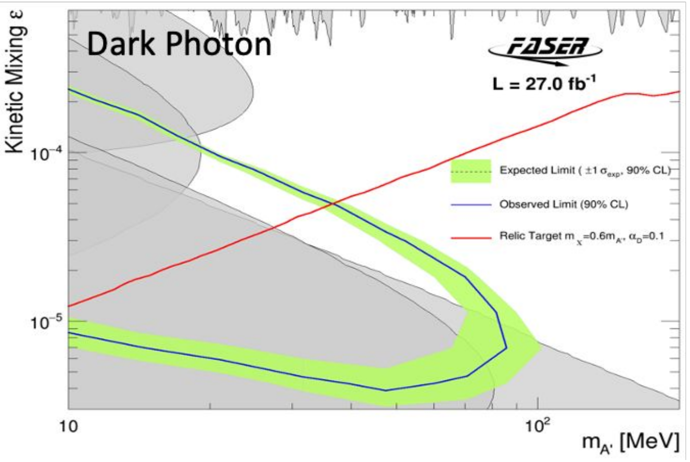






- Search for **A’ → e^+e^-** using 2022 data (27 fb^{-1})
  - No signal in vetos, 2 good tracks with timing station/preshower signal, Calo E > 500 GeV
  - Small background from neutrino events



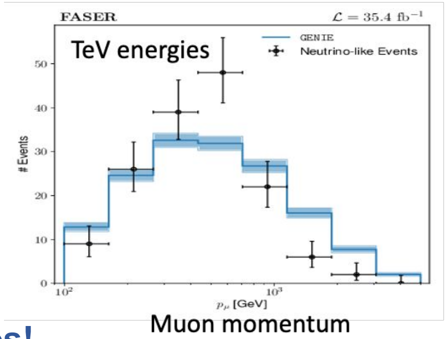


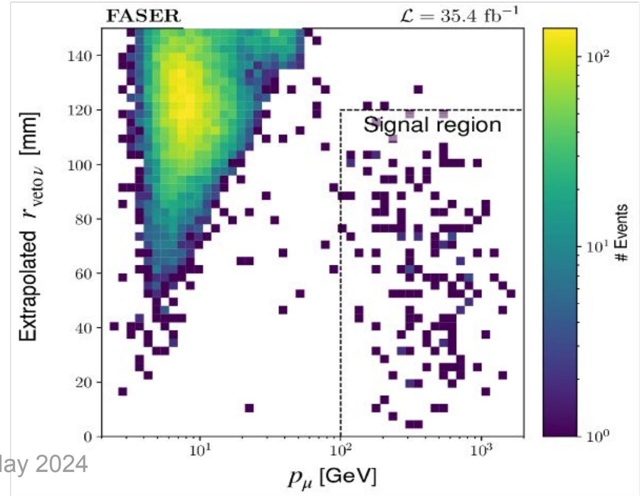
Liverpool: Analysis contact (**Carl**), Background estimation (**Monica** and **Lottie**), Calorimeter systematics studies (**Lottie**)

PhysLetB.848

Sinead: Currently working on tracking performance using A’ MC samples
Link to her slide at this meeting

- **Muon neutrinos** in FASER***ν*** produce a muon that can be detected in FASER’s tracking spectrometer (35.4 fb^{-1})
  - No signal in front veto, signal in second veto station, 1 good track with timing/preshower MIP signal
  - Background from neutral hadrons
  - and large-angle muons



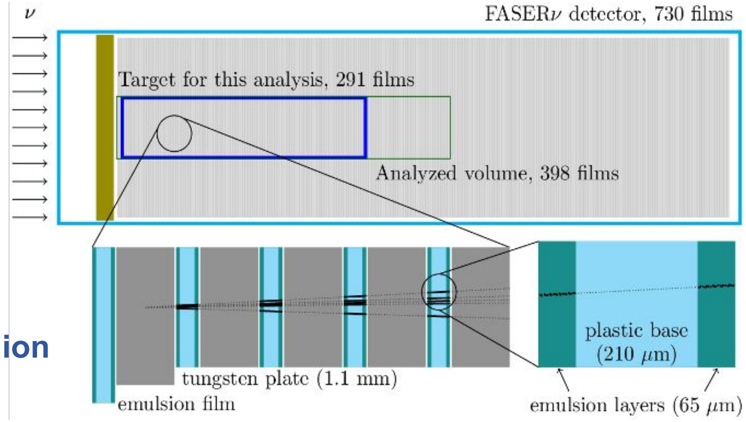


- **First observation of collider neutrinos!**
  PhysRevLett.131.031801

Neutrinos in FASERν (Emulsion Detector)

New Results

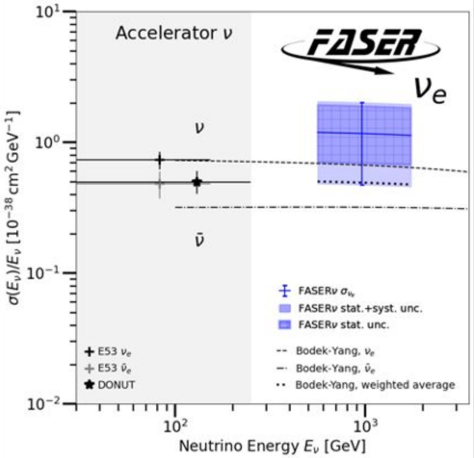
- Analysed a fraction of 2022 exposure (9.5 fb^{-1})
  - Candidate CC vertices reconstructed and selected by scanning emulsion films
  - Can detect ν_μ (momentum from RMS of multiple scattering) and ν_e (energy from shower multiplicity)
  - Background from muon interactions in rock

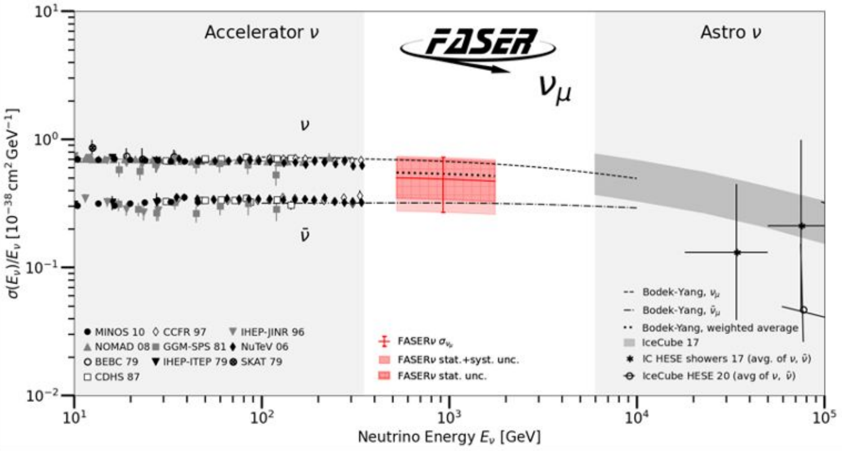


- **Cross-section measurements for both ν_μ and ν_e in unexplored region**

arXiv:2403.12520

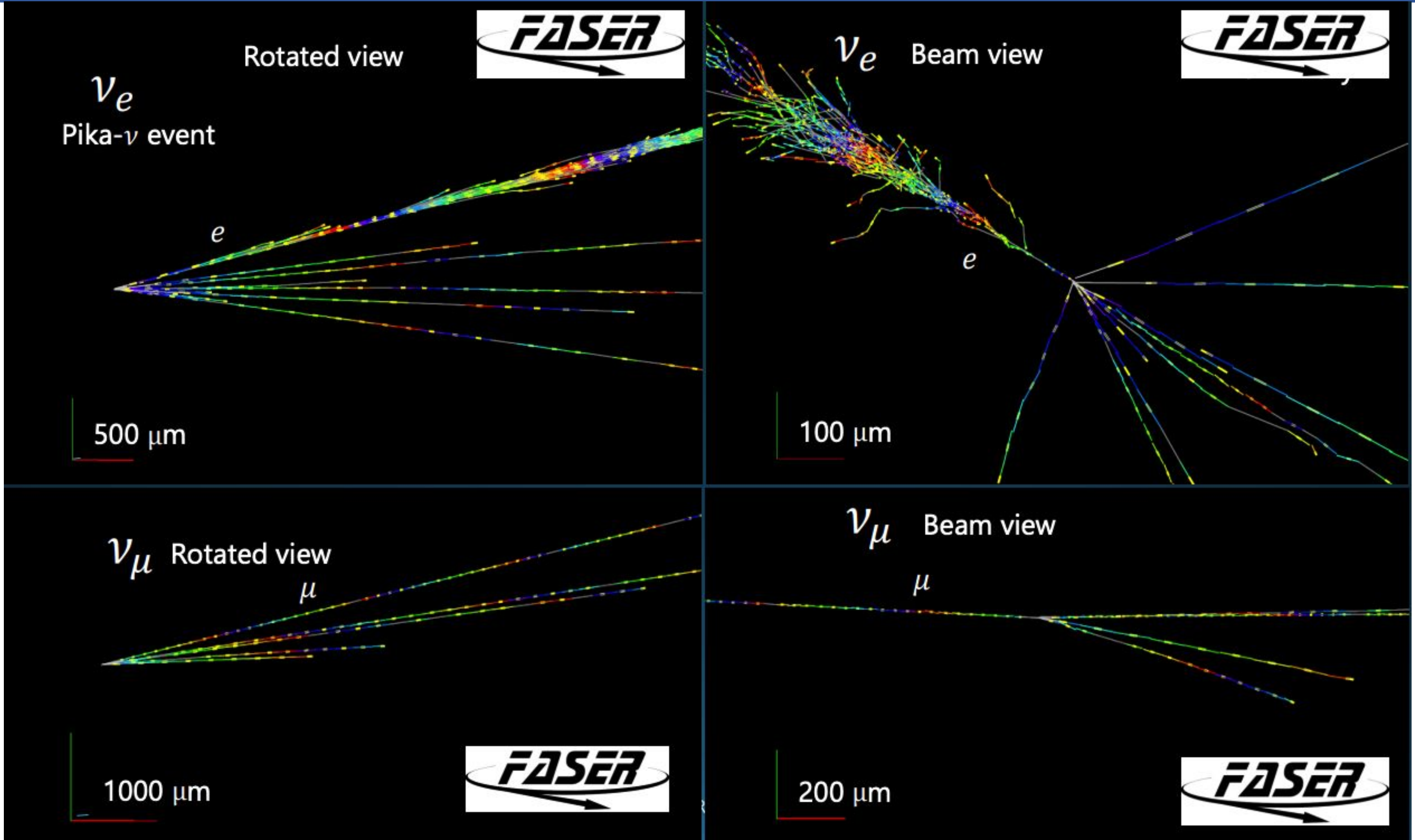
	ν_μ	ν_e
Bkg	0.03 ± 0.01	0.22 ± 0.08
Exp	1.1 – 3.3	6.5 – 12.4
Obs	4	8
Sig	**5.2σ**	**5.7σ**



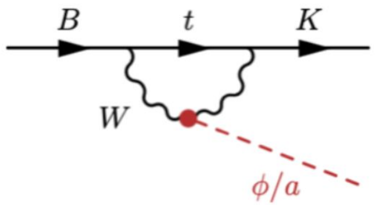


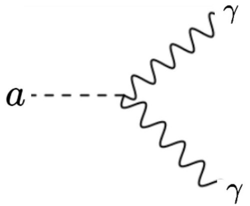
Neutrinos in FASERν Event Displays

New Results



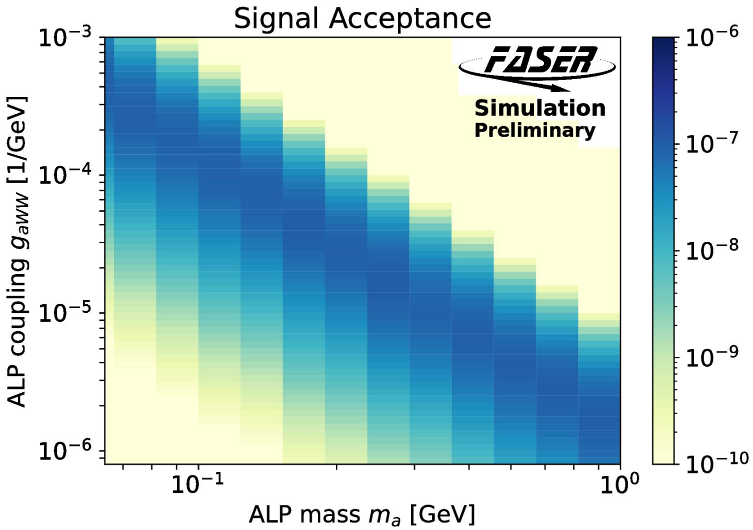
New Results

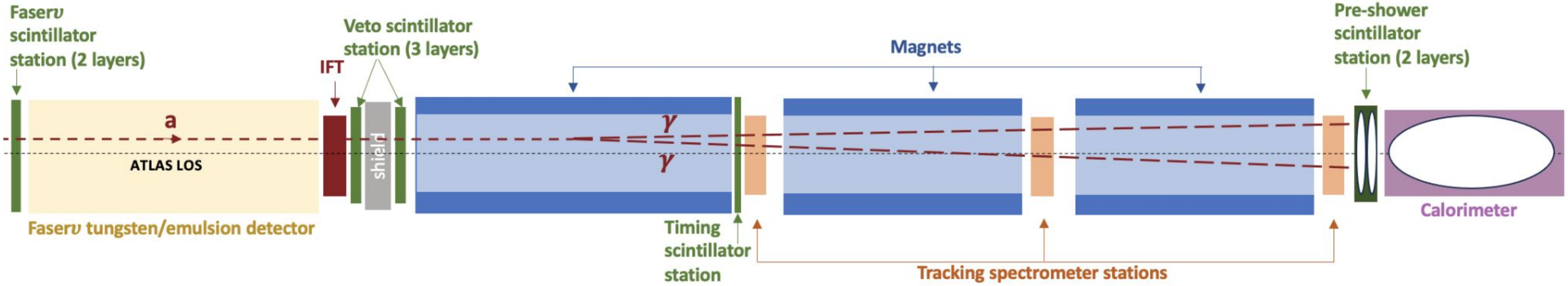




- FASER is sensitive to axion-like particles (ALPs)
  - Coupling to SU(2)L gauge bosons

- Primarily produced in B meson decays in our sensitivity range
- Can decay anywhere in FASER spectrometer
- Decays to 2 high energy photons
  - Cannot be distinguished in our calorimeter





ALP Analysis: 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)

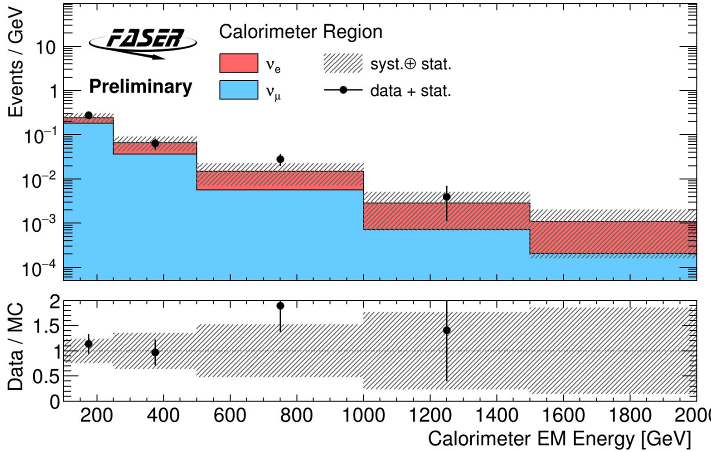
Liverpool-led analysis:
Event selection and signal optimisation (**Lottie**)
ALP signal grid MC generation (**Carl**)
Geometric muon background estimation (**Lottie + Monica**)
Signal systematics (**Lottie**)
Statistical interpretation of results (**Lottie**)

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%)**

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

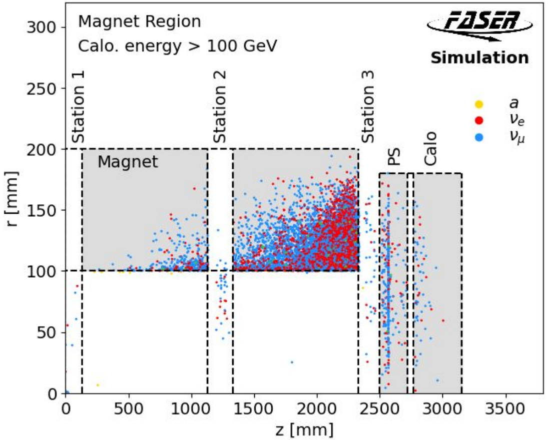
ALP Background Estimation

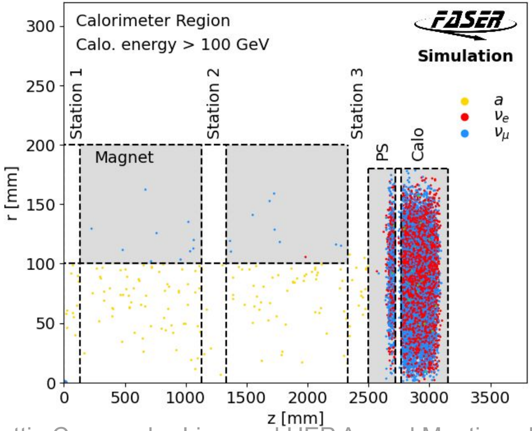
- Neutrino background evaluated using MC simulations
- Validated in data control regions defined based on where in FASER neutrinos interact

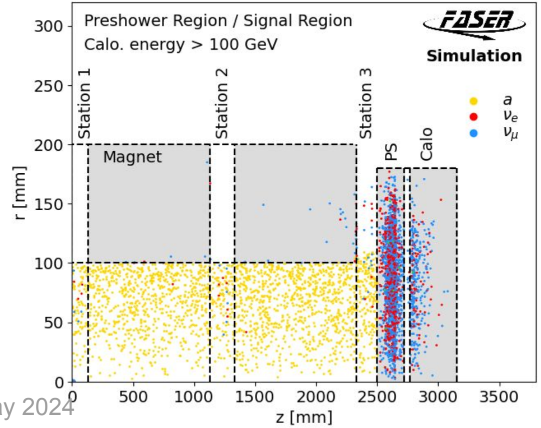


Other sources of (negligible) background considered in this analysis:

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







Systematic Uncertainties

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

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

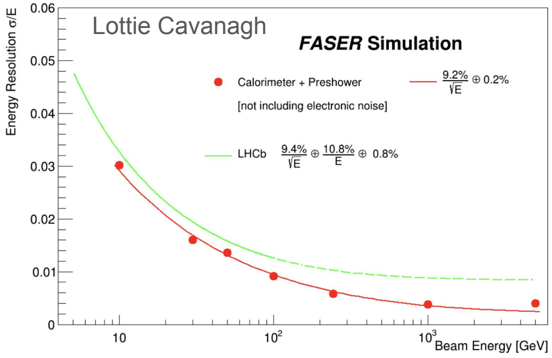
The dominant source of uncertainty is the uncertainty derived from the different MC generators

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%

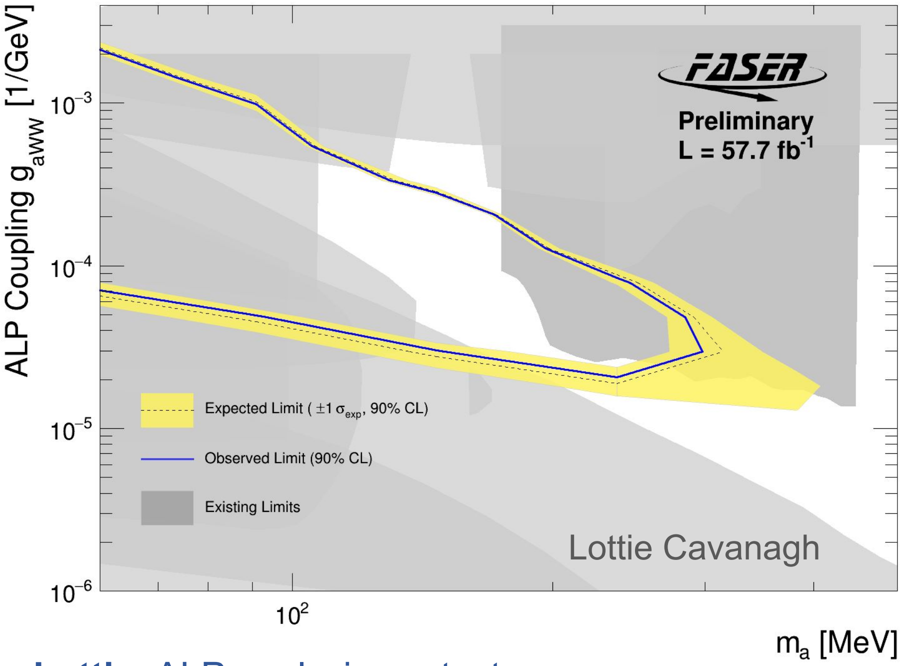
Experimental uncertainties evaluated using test beam data/MC

- From 2021 calorimeter test beam
- Test beam paper in progress (**Lottie**: paper editor)



ALP Unblinded Results **New Results**

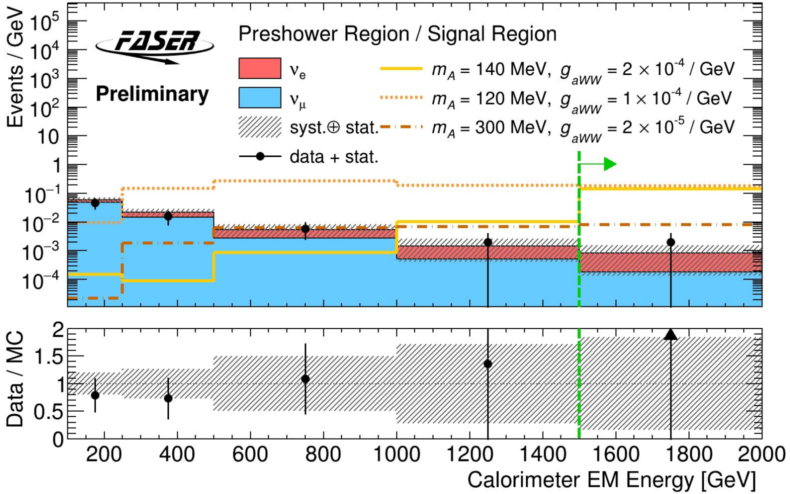
Observed limit:



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

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

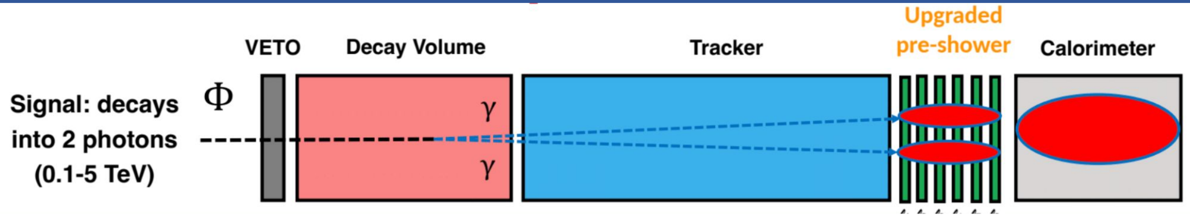
Unblinded Signal Region:



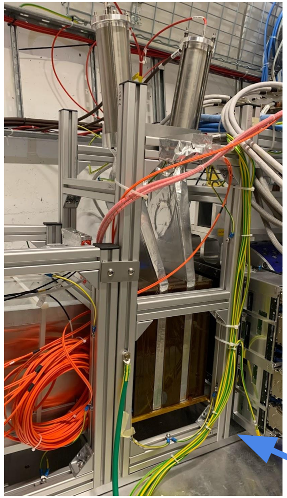
Lottie: ALP analysis contact
Monica: ALP paper editor
Carl: Signal generation and validation

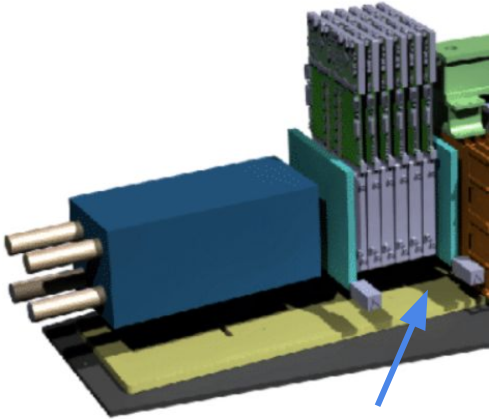
[Link to conf paper]

FASER's Preshower Upgrade



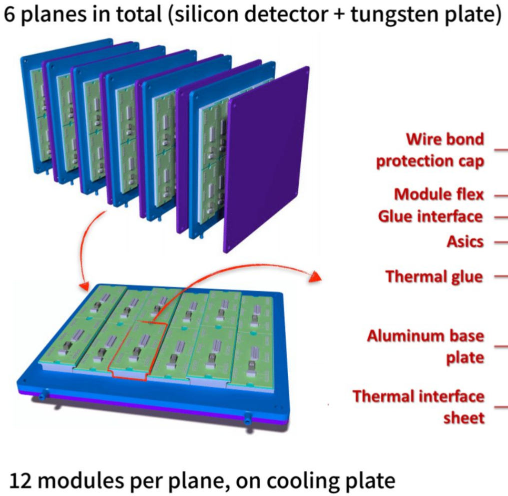
- Resolve diphoton events by upgrading pre-shower with high X-Y granularity
- Improve sensitivity and background suppression in ALPs and other LLP searches

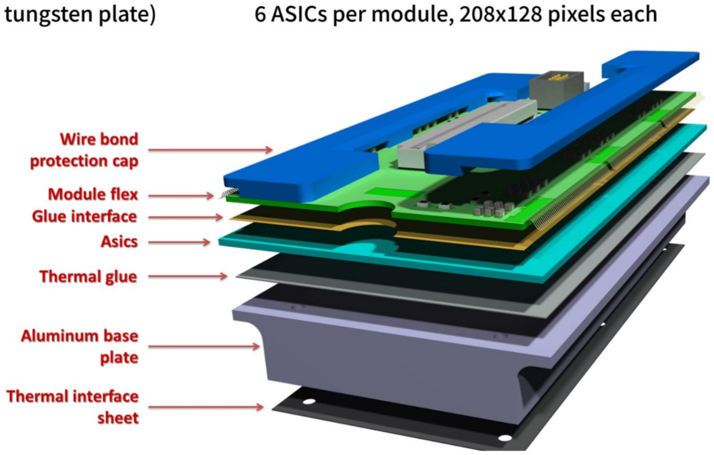




Current preshower

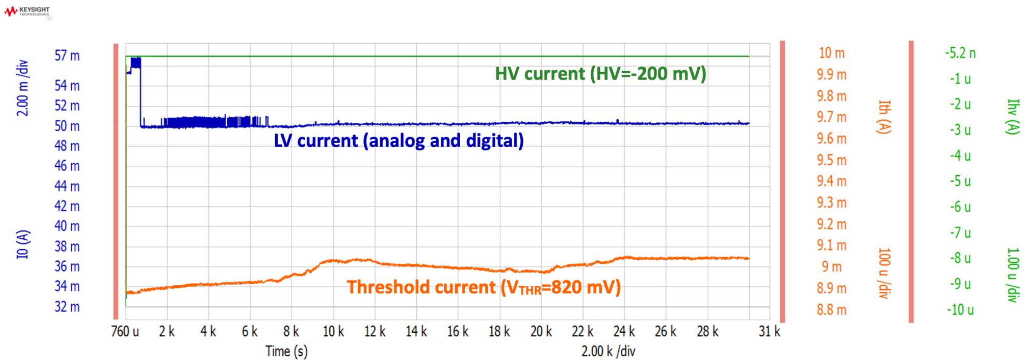
Planned upgrade (YETS 2024)

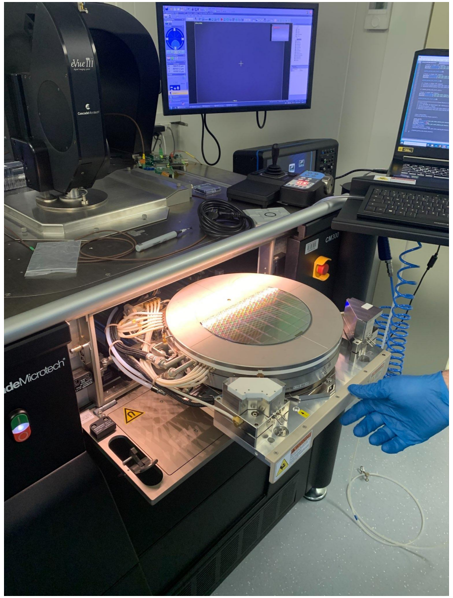


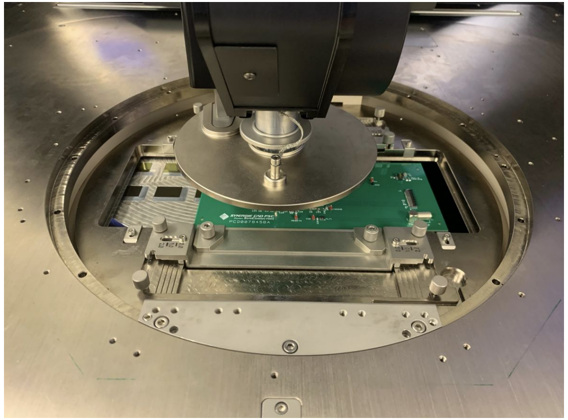


FASER's Preshower Upgrade (2)

- **Liverpool**: involvement in hardware and chip testing since September 2023
  - **Lottie:** Recently returned from a month at CERN/University of Geneva cleanroom





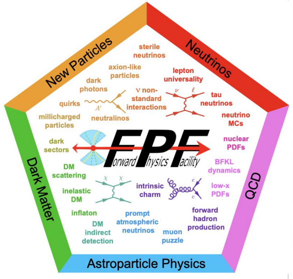


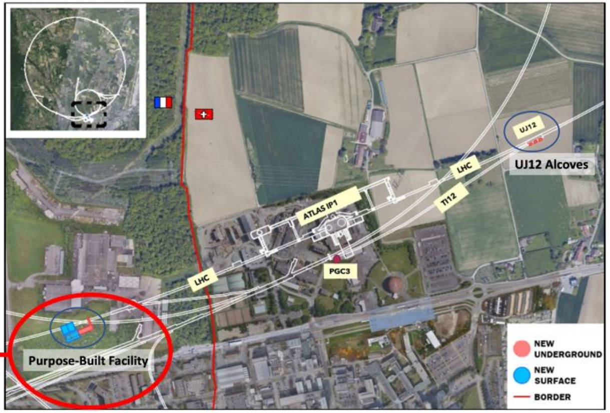
- Production chip characterisation at probe station:
  - Electrical tests: HV, LV, threshold tests
  - ASIC masking and pixel matrix readout
  - Testing and debugging firmware
  - Gain measurements

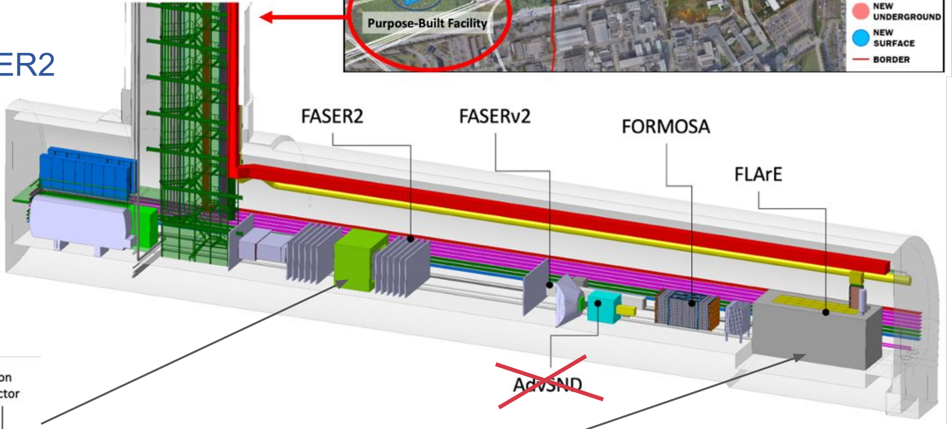
Forward Physics Facility and FASER2

- Proposed dedicated forward-physics facility at HL-LHC, aiming for LOI in early 2025
  - New ~65 m long cavern, 620 m from ATLAS
- 5→4 dedicated experiments including FASER2 and FASER*ν*2

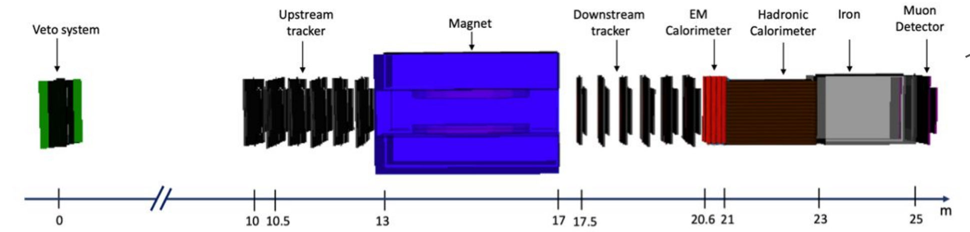
- [IoP half-day meeting hosted by Liverpool last October]
  - **Monica** and **Carl**: Feasibility studies, optimisation of tracker layout
    - **Sinead** completed her MPHYS project on FASER2
  - **Eva Vilella-Figueraz**
    - Contributions to FASER2 tracking system







FASER2



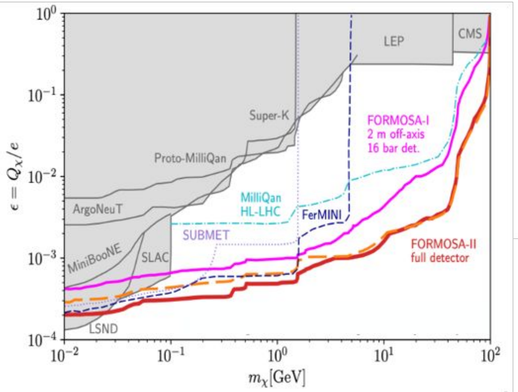
- **Kostas Mavrokoridis**
  - FLArE TPC based on ARIADNE optical readout technology

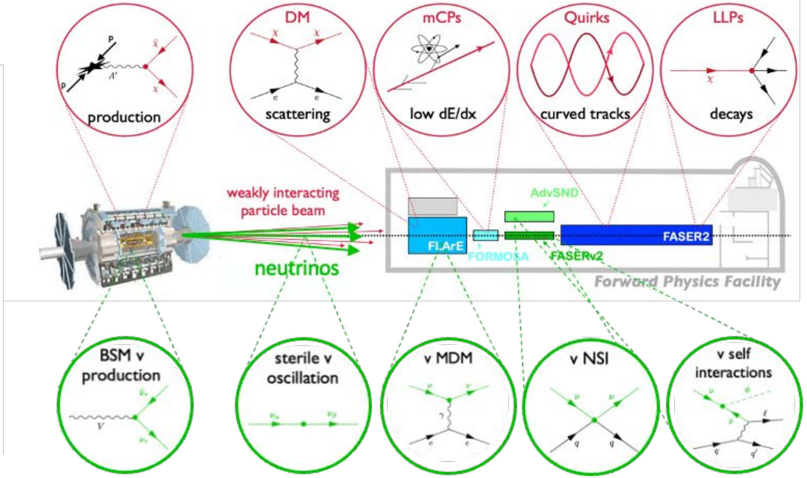
FPF Physics Potential

- Hidden Sector

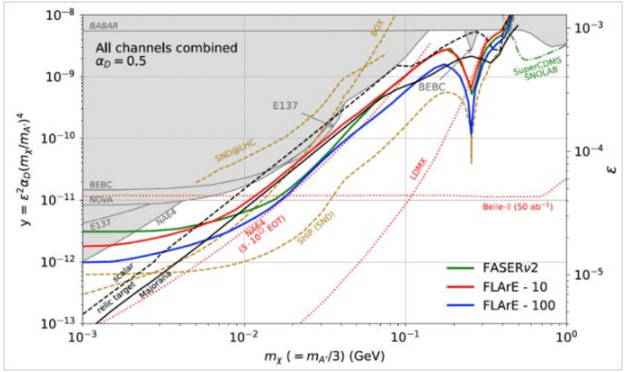
Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√

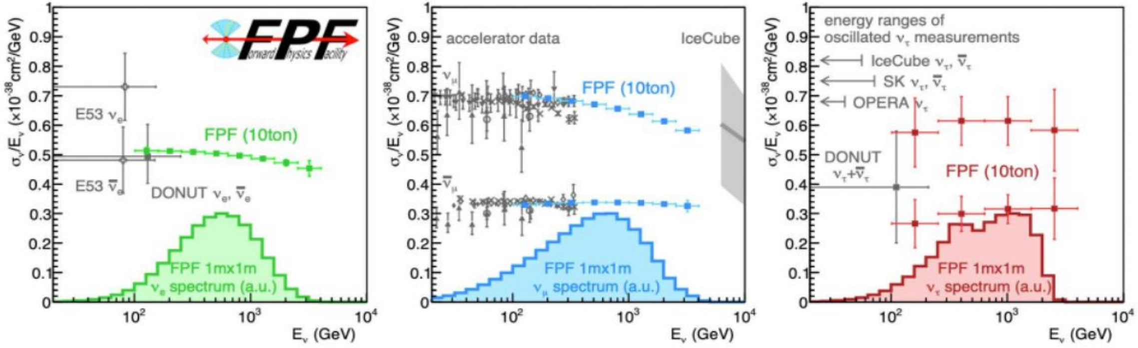
- Millicharged particles





- Light DM scattering





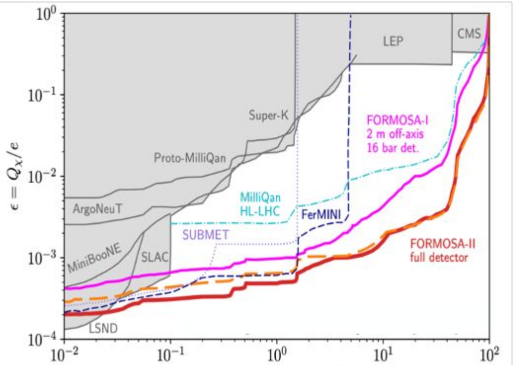
- Differential neutrino flux measurements for all flavours at TeV energies

FPF Physics Potential (2)

- Hidden Sector

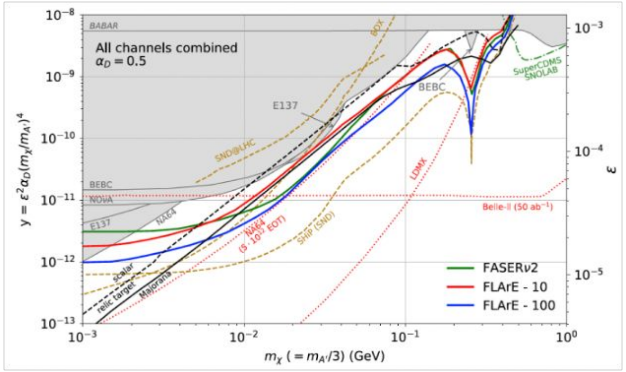
Benchmark Model	FASER	FASER 2
Dark Photons	√	√
$B-L$ Gauge Bosons	√	√
$L_i - L_j$ Gauge Bosons	—	—
Dark Higgs Bosons	—	√
Dark Higgs Bosons with hSS	—	√
HNLs with e	—	√
HNLs with μ	—	√
HNLs with τ	√	√
ALPs with Photon	√	√
ALPs with Fermion	—	√
ALPs with Gluon	√	√
Dark Pseudoscalars	—	√

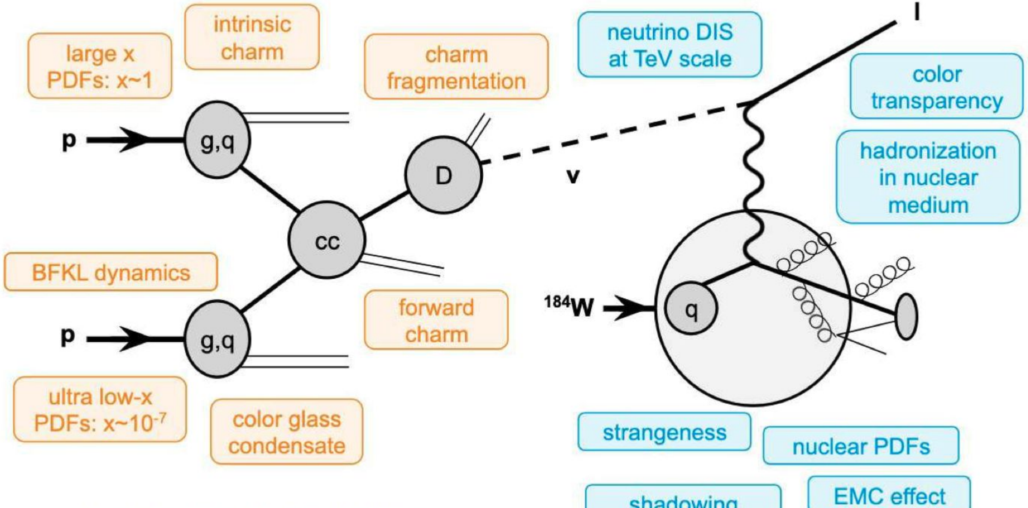
- Millicharged particles



- FPF probes unexplored physics, with very broad physics spectrum:
  - New particles, DM, neutrinos, QCD, astroparticle physics, quirks, mCP
- SHiP approval and P5 comments
  - FPF has many areas not covered by SHiP
  - Costs associated with FPF can be revisited

- Light DM scattering





Forward Particle Production

Summary and Outlook

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

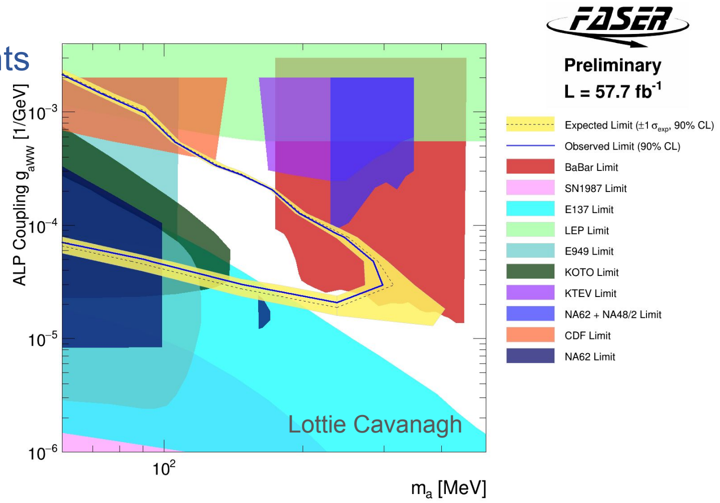
- At mass and coupling previously unexplored by existing experiments
- A conference note on these new results has been published!
- Will present results at LHCP in Boston next month
- Analysis efforts led by Liverpool

More searches and neutrino measurements to come

- ALP event selection will be used to probe additional models
- Electronic neutrino analysis update in progress

Proposal for dedicated HL-LHC forward physics facility

- Major involvement from Liverpool



Thank you for listening!

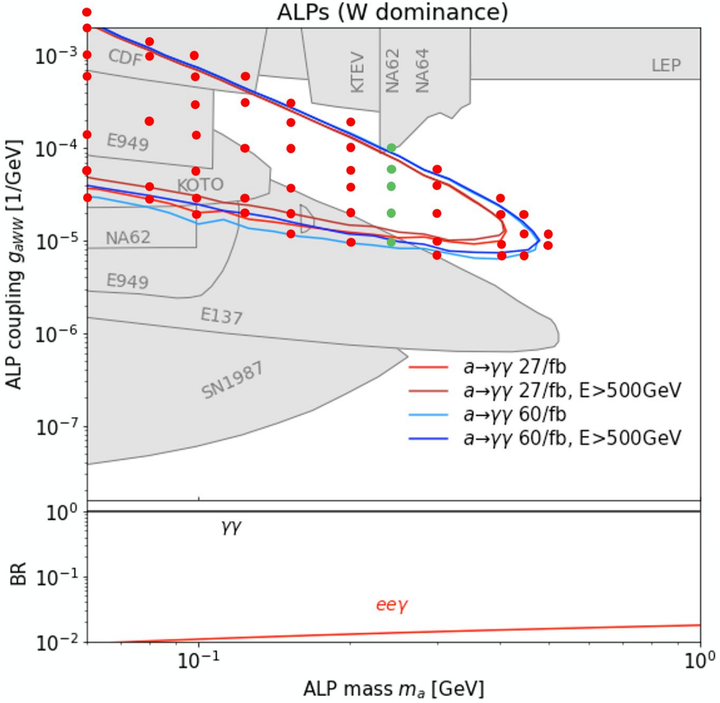
Next steps for LivFASER team:

- *Incoming PhD student Pawan joining in October 2024 (joint with RAL)*
- Sinead to begin LTA at CERN in October 2024
- Lottie currently writing up, accepted post doc position at ETH Zurich (FASER + HyperK)

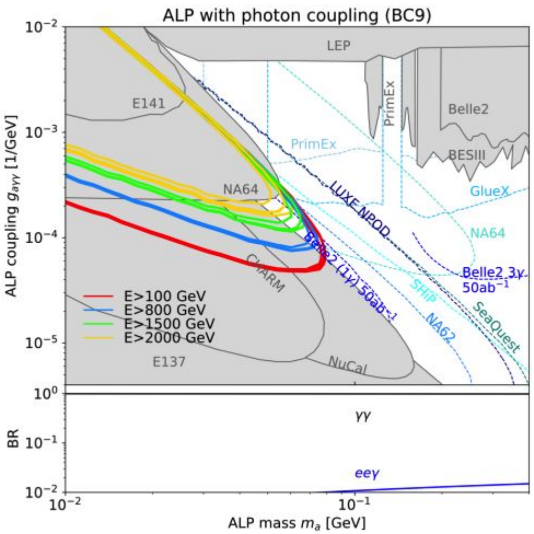
Backup Slides

Models Considered in this Analysis: ALPs

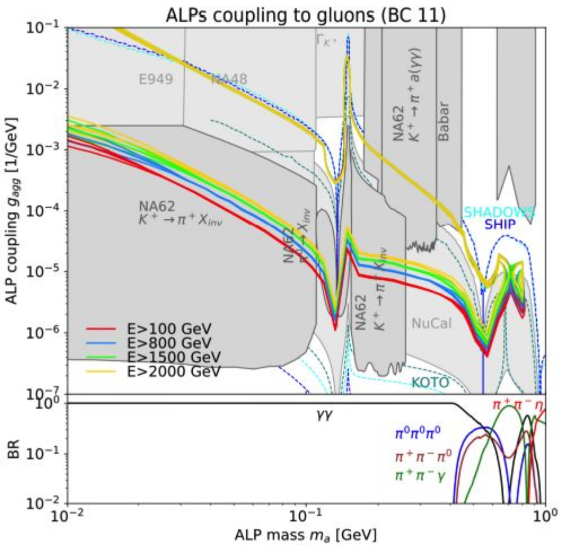
- ALP-W signal grid



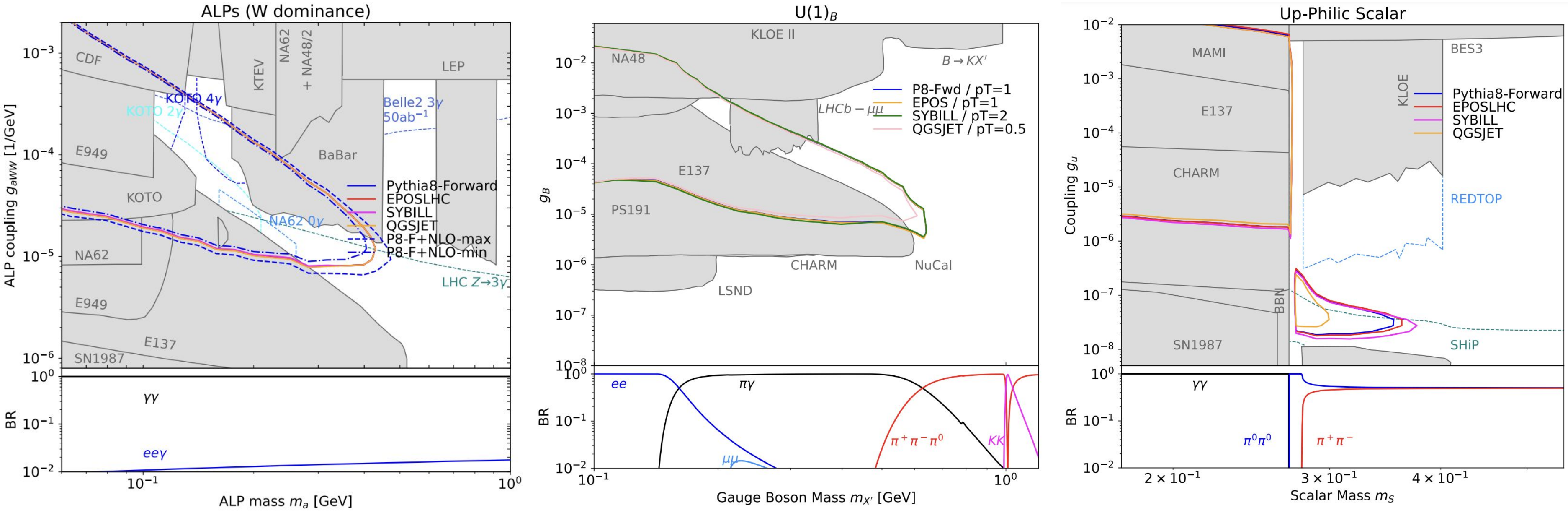
- ALP-photon



- ALP-gluon



ALP-W + multiphoton models



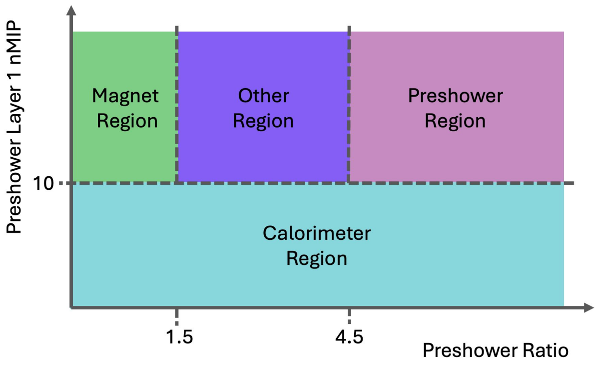
Neutrino Background Estimation

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

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

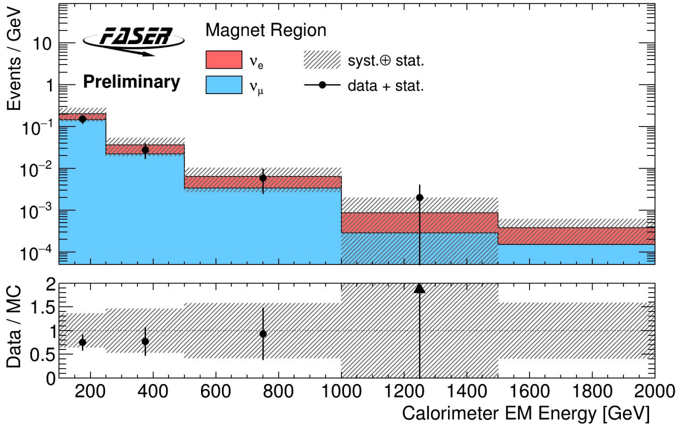
Magnet Region	
MC	43.5 ± 18.2 (41.9%)
Data	34

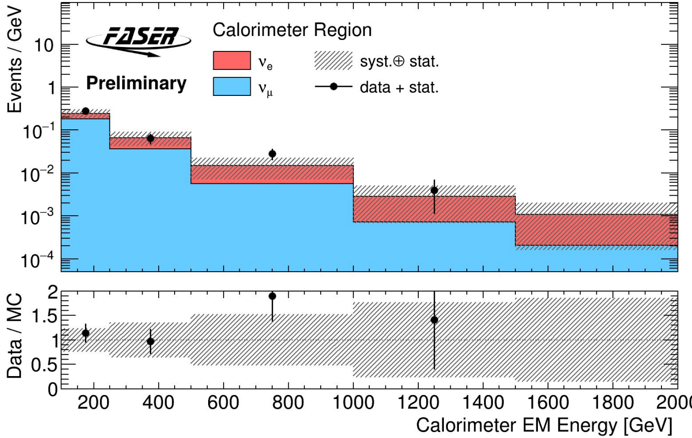
Preshower Region	
MC	17.8 ± 5.1 (28.8%)
Data	15



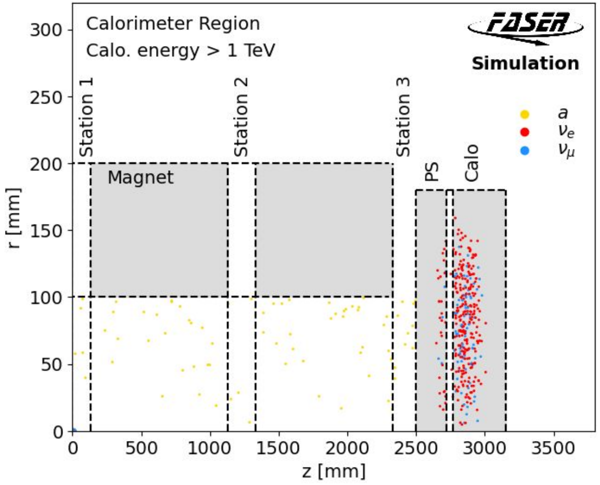
Background systematics:

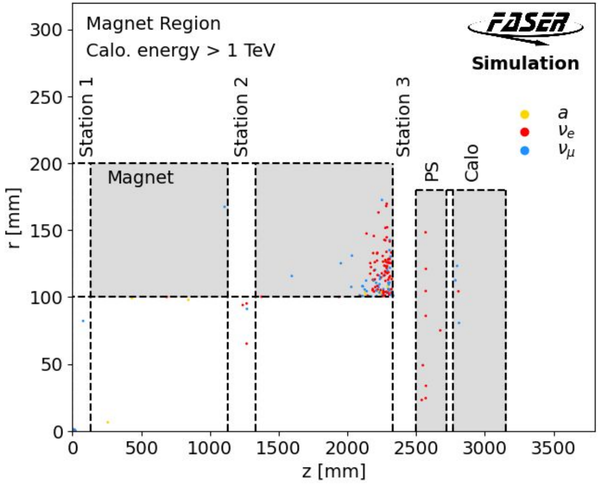
Event Rate	
0.42	± 0.32 (flux)
	± 0.14 (calo. energy)
	± 0.06 (PS ratio)
	± 0.02 (PS 1 nMIP)
	± 0.05 (stat.)
Total: 0.42	**± 0.38 (90.6%)**

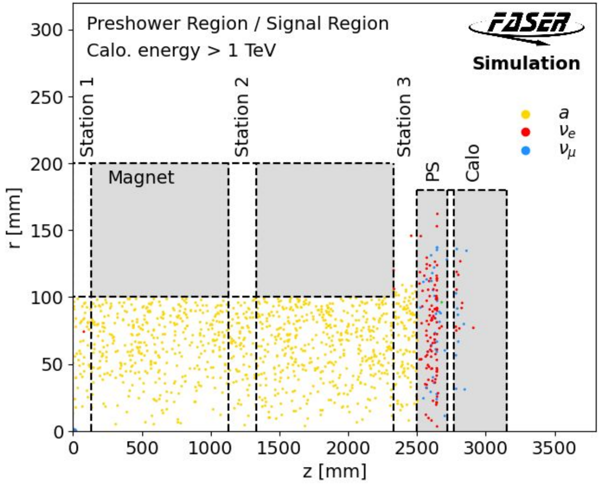




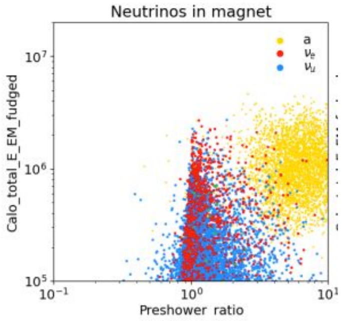
Calorimeter, Magnet, Preshower Regions: 1 TeV cut

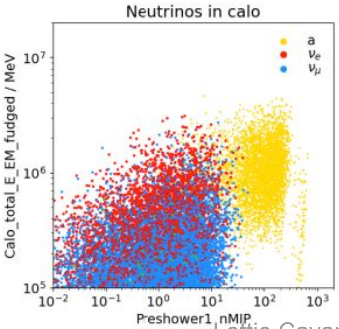




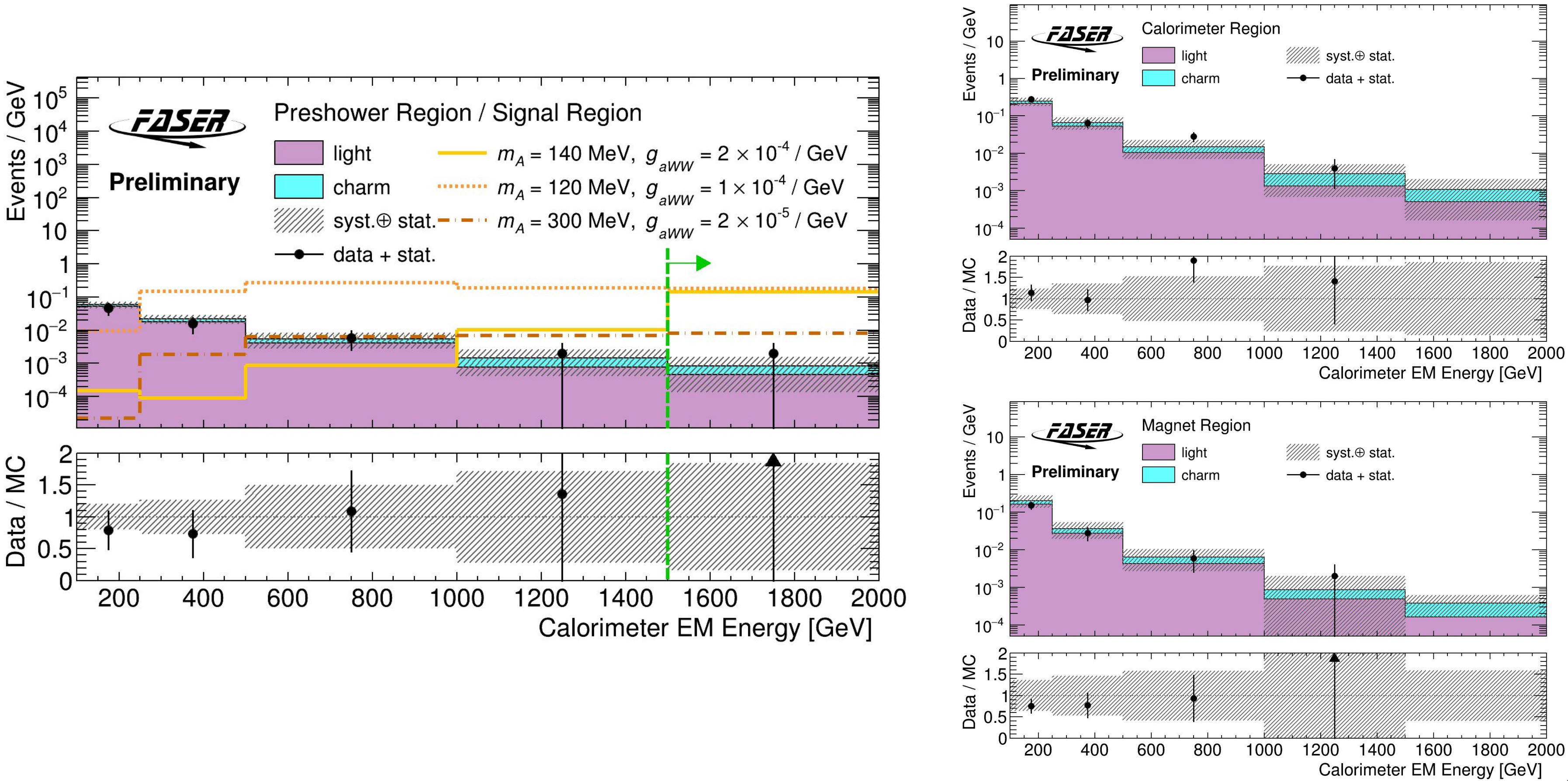


Preshower variables:





ALP Results: Alternative Neutrino MC plot



Neutrino Background Composition

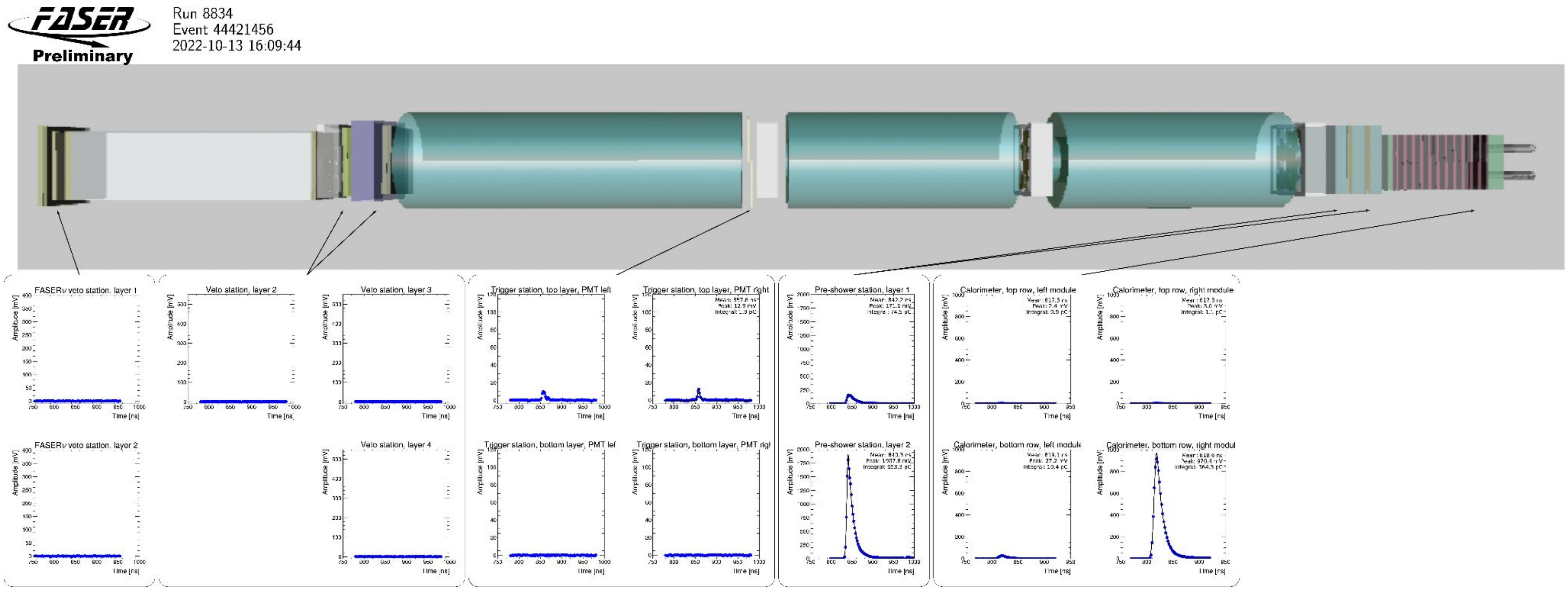
- In terms of light and charm:

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 type:

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 ± 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 ± 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 ± 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 ± 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 ± 6.9 (32.2%)**
Data	17

Event Display

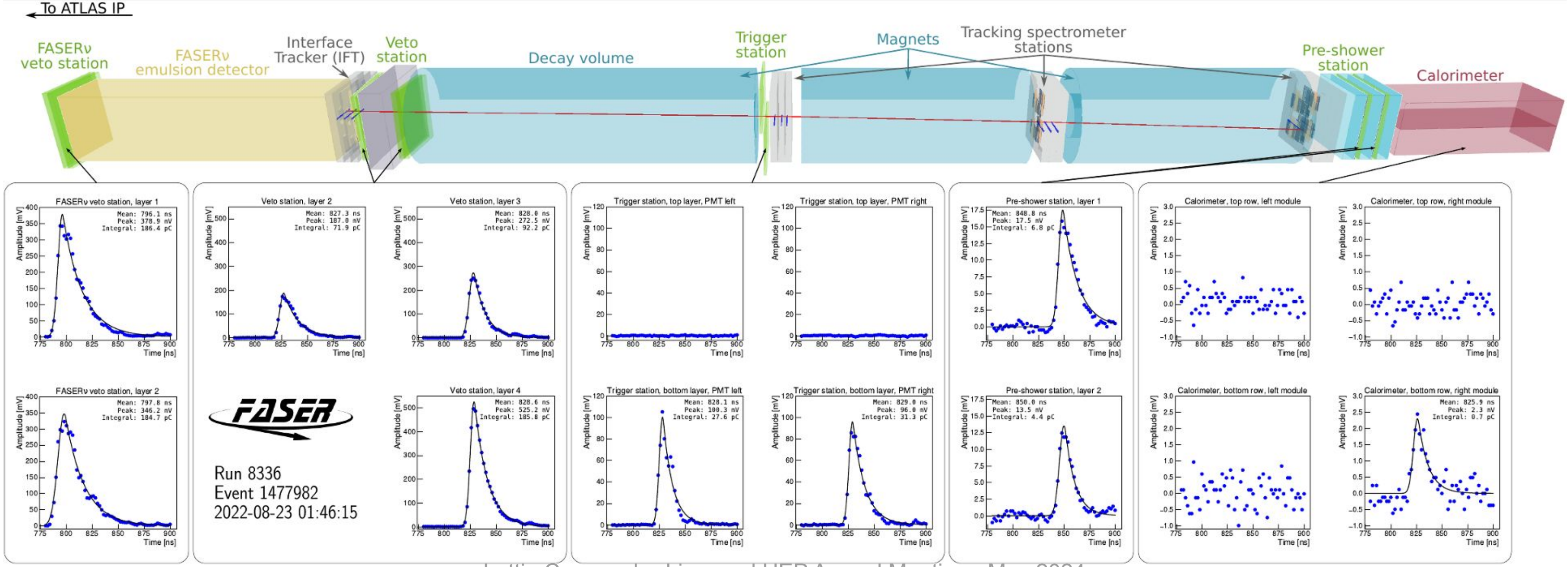


- This event has a calorimeter energy of **1.6 TeV**
- Shows preshower deposits consistent with an EM shower

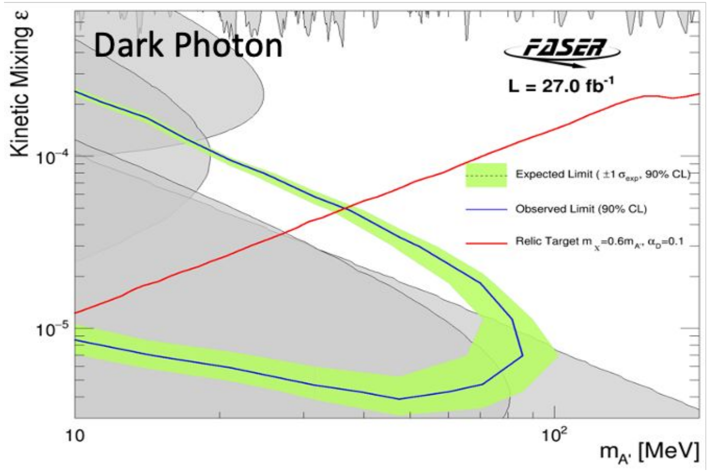
Muons in FASER

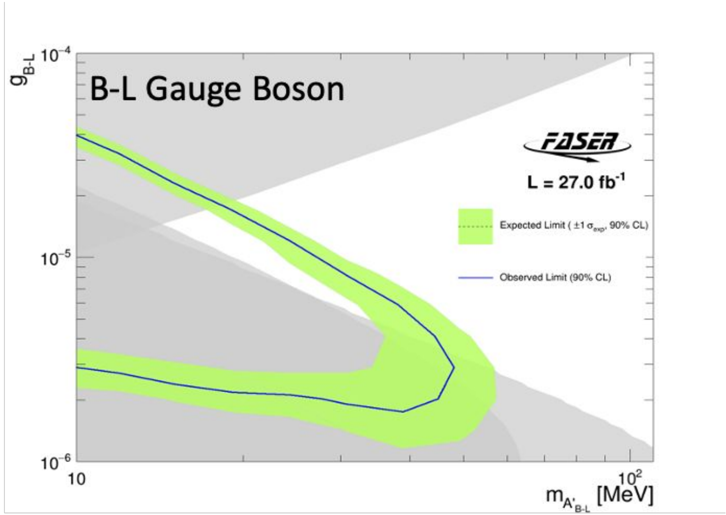
Veto scintillator layer efficiency > 99.998%
5 layers reduces the expected 10^8 muons to negligible level (even before cuts)

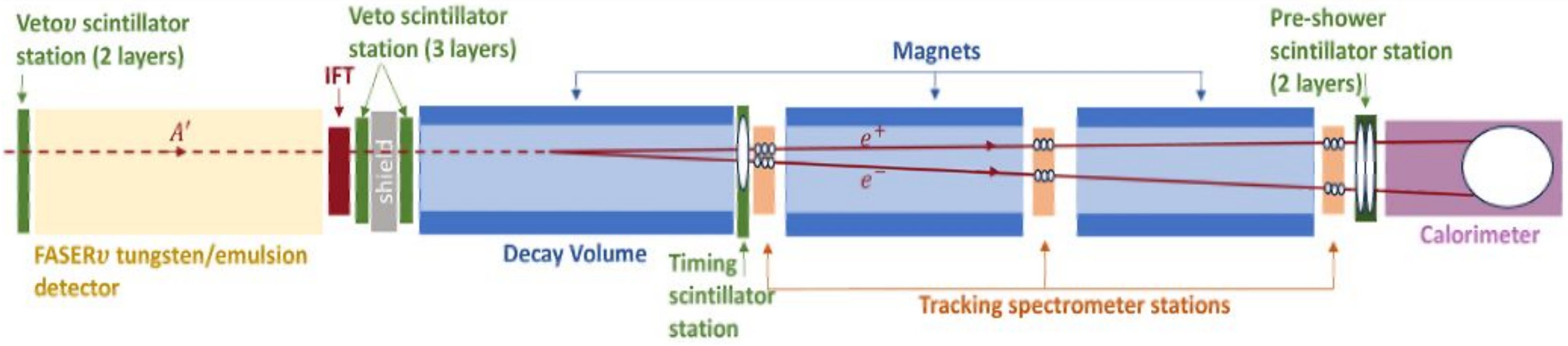
Single muon event in FASER:



Dark Photons and B-L Gauge Boson Limits





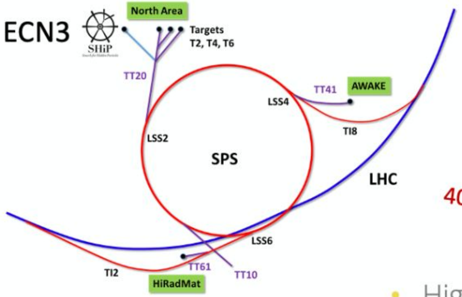


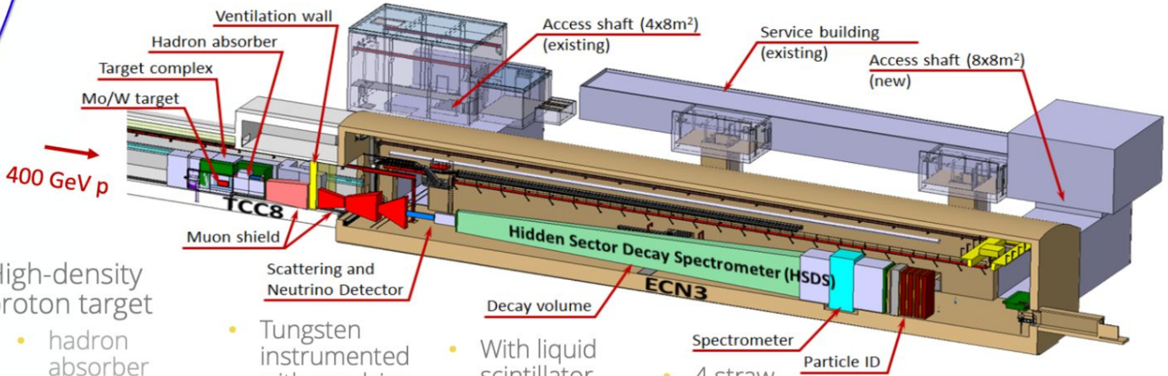
SHiP (Slide from Carl's IoP talk in April)

SHiP Experiment

Letter of Intent

- New dedicated beam-dump experiment recently approved for ENC3 cavern at CERN's SPS NA
  - Aiming for TDR in 2026, followed by PRR and installation in 2028/9
  - Start data-taking in latter half of run 4, aiming to collect 6 x 10^{20} POT over 15 years





- High-density proton target
  - hadron absorber
  - muon shield
- Tungsten instrumented with emulsion
- With liquid scintillator bkg tagger
- 4 straw trackers in B=1 T
- EM Calorimeter
- 3 muon layers

- Currently 4 UK institutes: Bristol, Imperial (spokesperson), UCL, Warwick
  - But several more interested in joining now formally approved