LONG LIVED PARTICLE SEARCHES AT FASER

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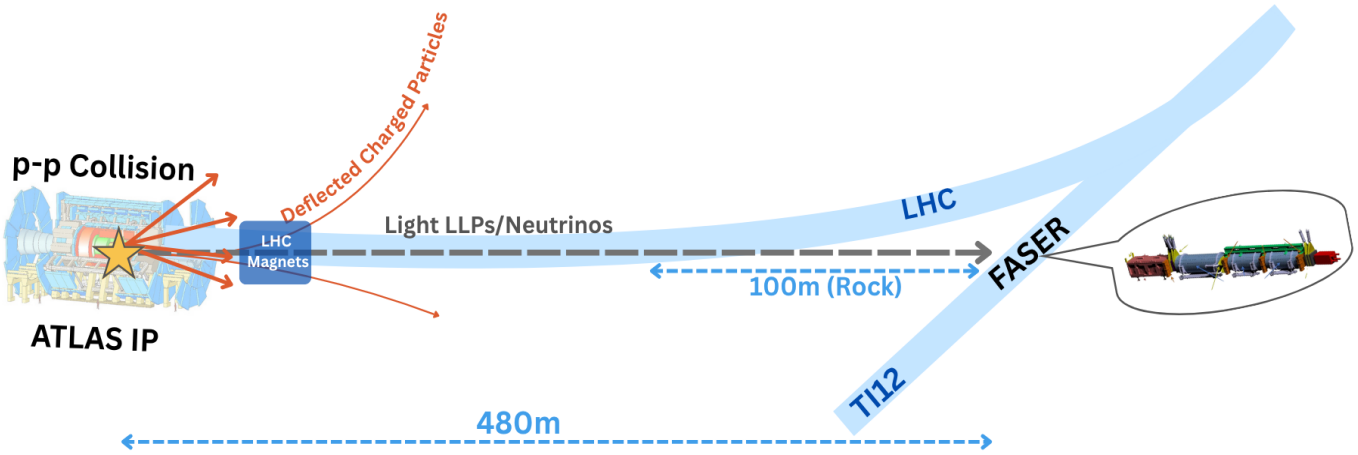
FASER

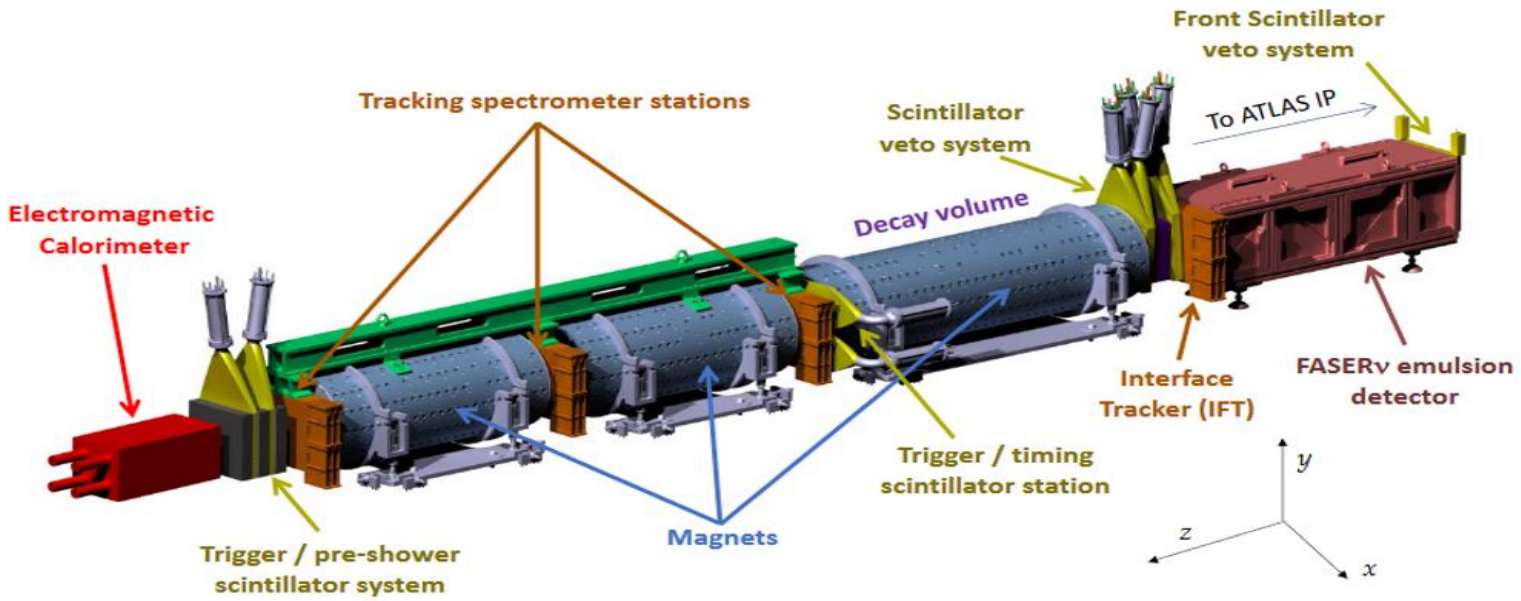
ForwArd Search ExpeRiment

- Purposefully designed for:
  - Searches for BSM particles i.e. light feebly-interacting particles (FIPs)
  - TeV neutrino studies
- Located 480 downstream, on the line of sight, of ATLAS IP
- Benefits from the highly collimated flux of light hadrons from ATLAS
- Uses the increased light particle production rate in the forward region to:
  - Search for long-lived BSM particles (particularly dark sector mediators)
  - Study collider-produced neutrinos at high energies [See Wissal's talk earlier]

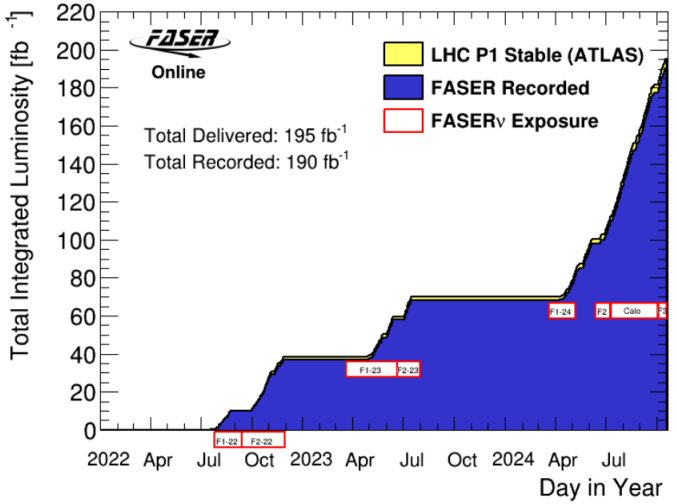


THE FASER DETECTOR

- Small inexpensive detector
  - 20cm aperture
  - ~7m in length



OPERATIONS



- Began taking data at start of LHC Run 3 (2022)
  - Successfully collected ~ 190fb^{-1} (>97% of delivered luminosity)
- All detector components working well
  - Successful operations during lifetime

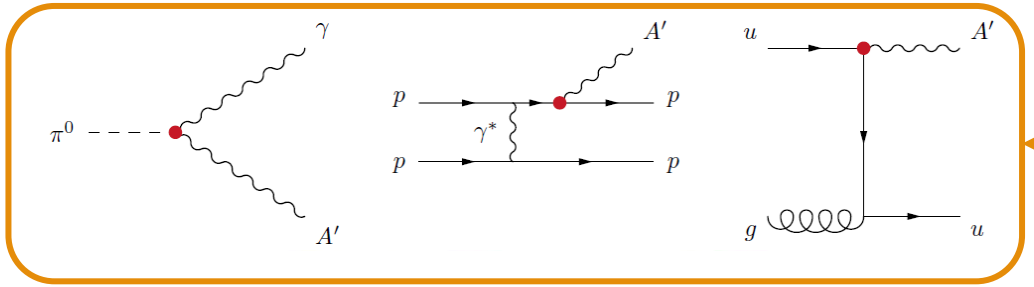
DARK PHOTON : THEORY

- Dark photons (A')
  - Predicted in dark sector models
  - New gauge boson for the vector portal

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum q_f A'^{\mu} \bar{f} \gamma_\mu f$$

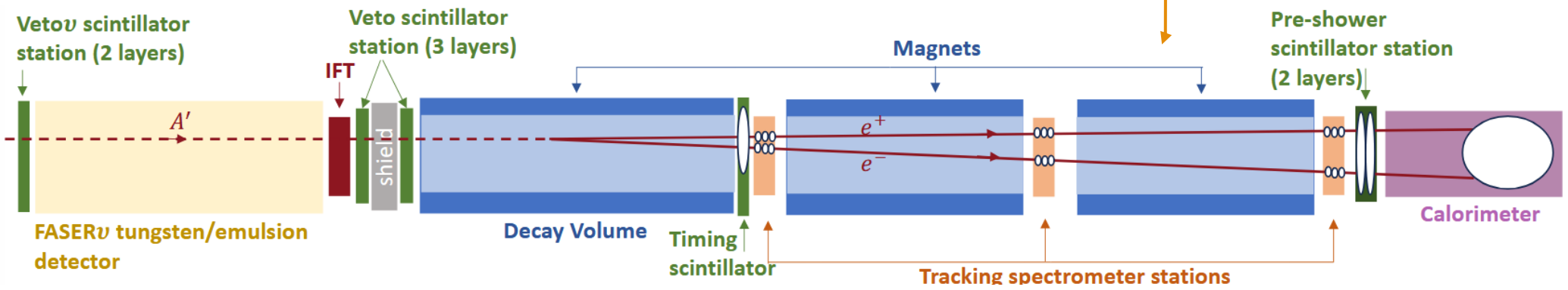
$m_{A'}$ and ϵ used to define lifetime of A' (and parameter space to search in)

  - Produced in light meson decays (neutral pion or eta mesons)
  - Can also be produced through dark bremsstrahlung
  - Interacts with the SM through kinetic mixing (ϵ)
  - Lifetime is dependent on kinetic mixing
    - FASER targets long-lived dark photons that decay ~480m from the IP
      - i.e. Those that are weakly-coupled to the SM
  - 1 TeV boost in far-forward π^0 production
  - A' decays most commonly to e^+e^- pair (below an $m_{A'}$ equal to $2m_\mu$)



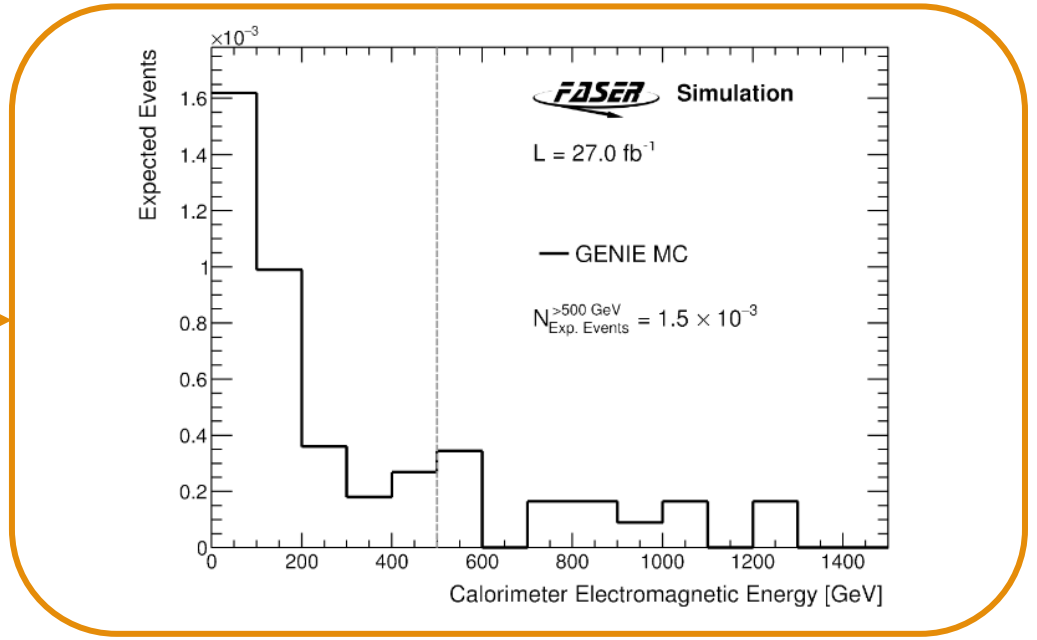
DARK PHOTON : SEARCH

- Uses only FASER's first year (2022) of data
  - Equivalent to 27 fb^{-1} of collision data at $\sqrt{s}$=13.6 TeV
- Probes the phase space for :
  - A' and A'_{B-L} (B-L gauge boson) ... among other models
- A' expected to decay within decay volume to e^+e^- pair
- Expected signature
  - No signal in veto
  - Two close by tracks reconstructed within the fiducial volume
  - Large energy deposit in EM calorimeter



DARK PHOTON: BACKGROUNDS

- Although in a low background environment, backgrounds could occur from:
  - Scintillator inefficiencies
    - Determined to be negligible
  - Neutral hadrons produced by muon decay
    - Determined to be negligible
  - Neutrino interactions inside the detector
    - Main source of background
    - Estimated through GENIE MC samples
  - Non-collision backgrounds
    - Determined to be negligible by data-driven extrapolations
- Most of these are significantly reduced by detector design and superb performance



Background	Central Value	Error (%)
Veto inefficiency	-	-
Non-collision	-	-
Neutral hadrons	0.8×10^{-3}	1.2×10^{-3} (140%)
Neutrinos	1.5×10^{-3}	2.0×10^{-3} (130%)
Total	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{2.3 \times 10^{-3}}$ **(100%)**

DARK PHOTON: SYSTEMATICS

- Systematic uncertainties on signal yield from :
  - event generator variation and flux modelling
  - luminosity measurement – from ATLAS
  - modelling preshower and calorimeter cuts using MC
  - MC Statistics
- Systematics for GENIE MC background
  - Different generators used in production of neutrino MC samples:
    - EPOS-LHC for light hadrons
    - POWHEG+Pythia for charm
  - Each generator has slightly different theoretical modelling
    - Estimate uncertainty from the spread of the event generator predictions
- Uncertainty ~ 130% for neutrino background

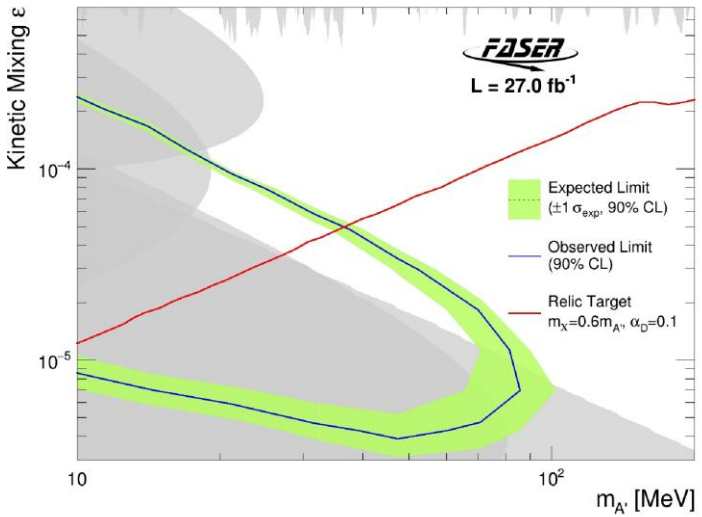
Systematic Uncertainties

Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Track Momentum Scale	5%	$< 0.5\%$
Track Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	7%	7%
Calo E scale	6%	0-8% ($< 1\%$)

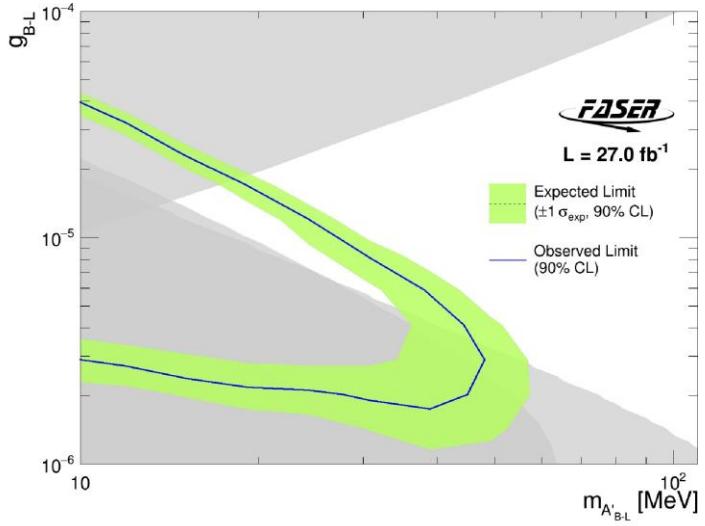
DARK PHOTON: RESULTS

- Zero events observed
  - Set limits on previous unconstrained parameter space
  - Region motivated by dark matter thermal relic density
  - First improvement of sensitivity in this region since 1990's!

Sensitivity Reach

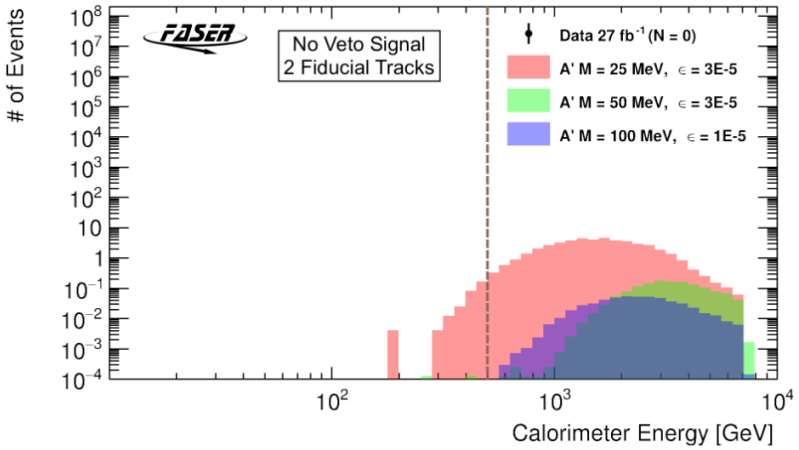


Dark Photon (A')



B-L Gauge Boson (A'_{B-L})

Calorimeter Energy Distribution for data (and A' MC samples)



AXION-LIKE PARTICLES @ FASER: THEORY

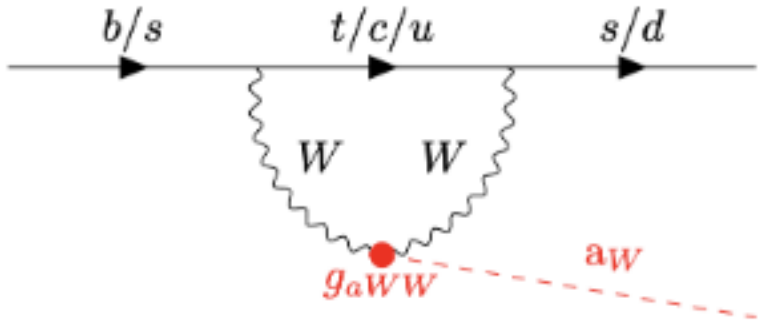
- Axion-like particles (ALPs)
  - Couples to $SU(2)_L$ gauge boson before electroweak symmetry breaking (EWSB) [In the case of ALP-W model]

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

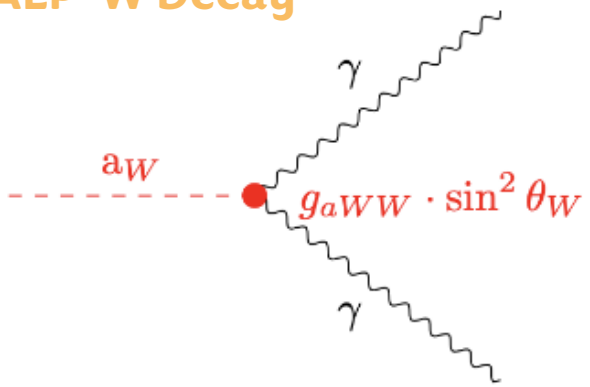
m_a and g_{aWW} used to define lifetime of ALPs (and parameter space to search in)

- Can be produced through **decay of b-/s- flavoured hadrons**
  - **Dominant** production through **B-meson decays**
- Decays to 2 photons within FASER

ALP-W Production

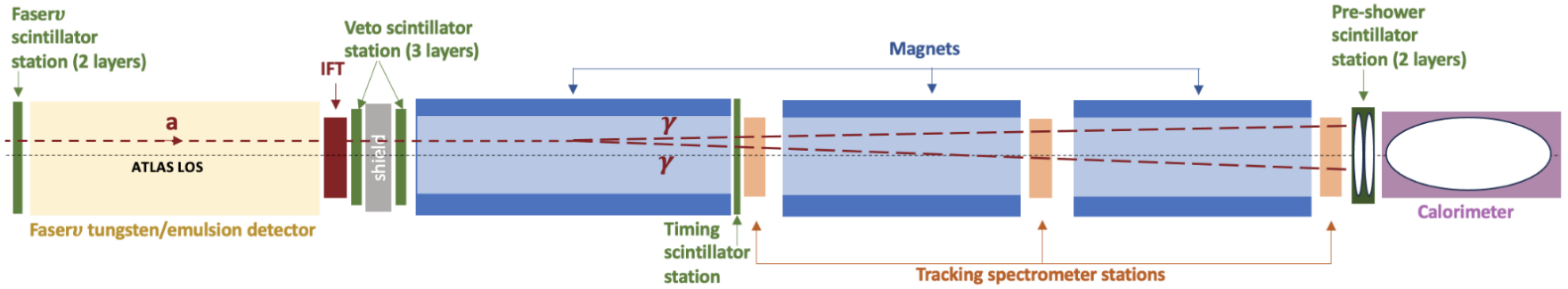


ALP-W Decay



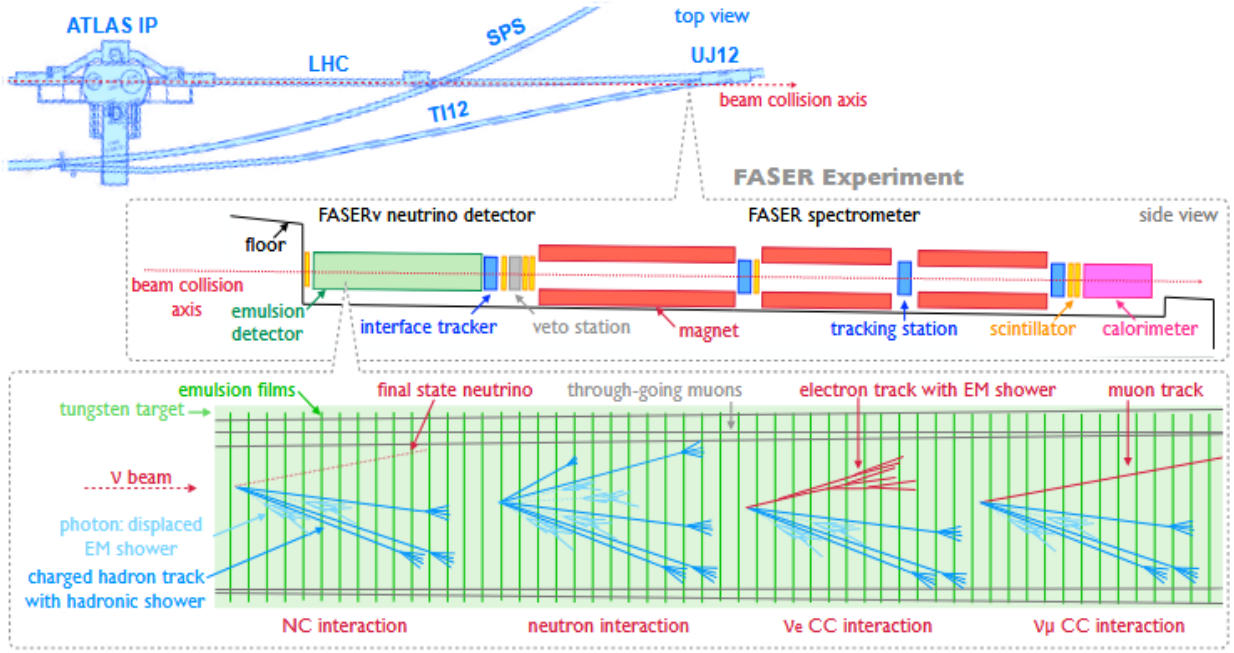
ALPS: SEARCH

- Using 2022/2023 dataset (57.7 fb^{-1})
- Could decay anywhere between veto and preshower scintillators
  - Decays to 2 high energy photons
  - These are not distinguishable in the preshower or calorimeter
- Irreducible background from neutrinos interacting in preshower & calorimeter
- Expected signature
  - No signal in either veto or timing scintillators
  - EM-like signature in pre-shower
  - Signal (>10 MIPs) in second preshower layer
  - Large energy deposit in calorimeter (E>1.5 TeV)



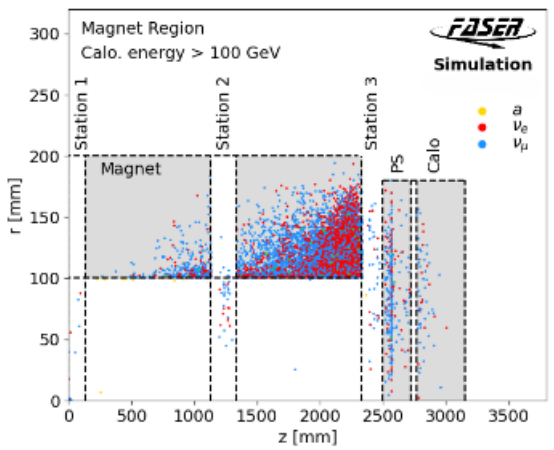
ALPS : BACKGROUNDS

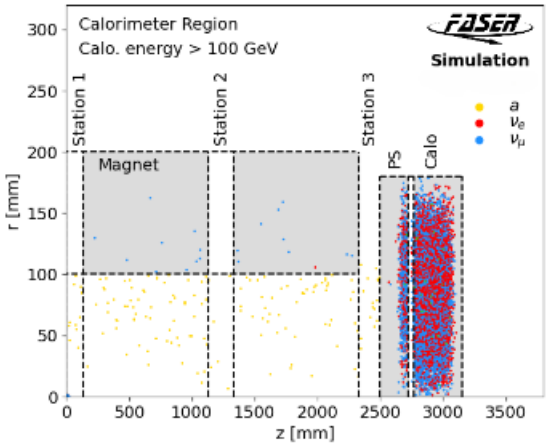
- Background occurs due to :
  - Large-angle muons
    - Data-driven approach used
  - Veto inefficiency
  - Neutral hadrons from muon interactions
    - Seen to be negligible
  - Neutrinos interacting inside the detector
    - Produced in hadron decays at IP1
      - Neutrinos are long-lived and don't interact in rock before FASER
  - Non-collision backgrounds
    - Seen to be negligible in data

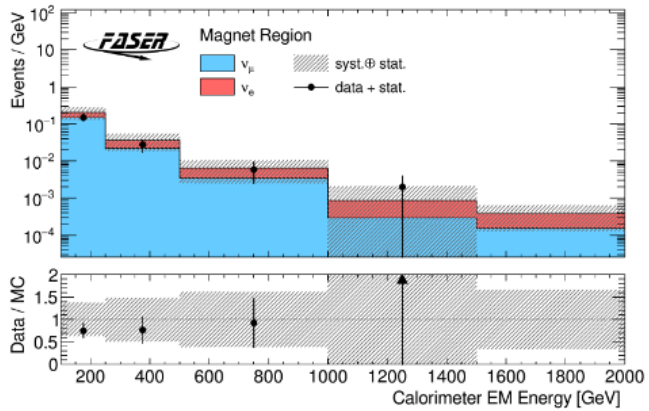


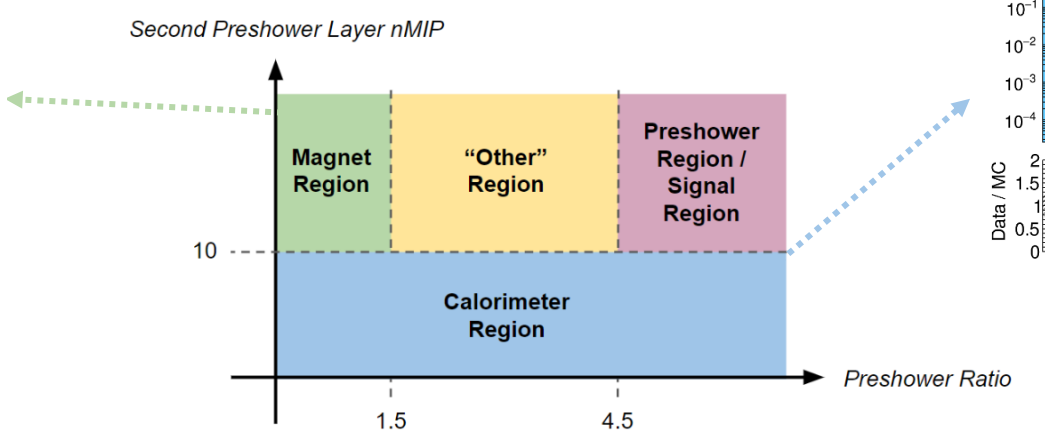
ALPS: NEUTRINO BACKGROUND

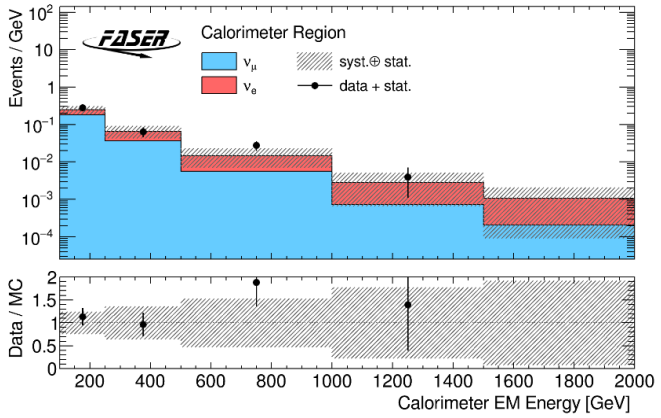
- Main source of background
- From MC simulations – validated using data
- Using preshower ratio and signal in 2nd preshower layer
  - Regions created which correspond to where a neutrino primarily interacts (used as control regions)











ALPS: SYSTEMATIC UNCERTAINTIES

- Systematic uncertainty from :
  - event generator variation and flux modelling
  - luminosity measurement – from ATLAS
  - modelling preshower and calorimeter cuts using MC
  - MC Statistics

Background

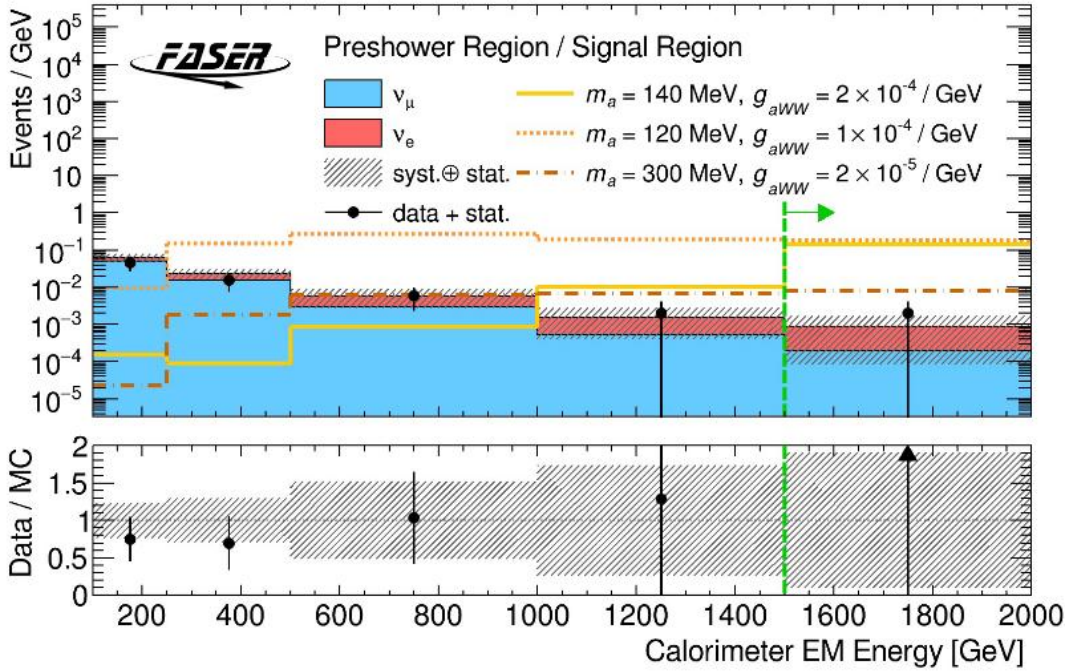
Event Rate
0.42 ± 0.32 (flux)
± 0.14 (calo. energy)
± 0.06 (PS ratio)
± 0.02 (PS 1 nMIP)
± 0.05 (stat.)
Total: 0.42 ± 0.38 (90.6%)

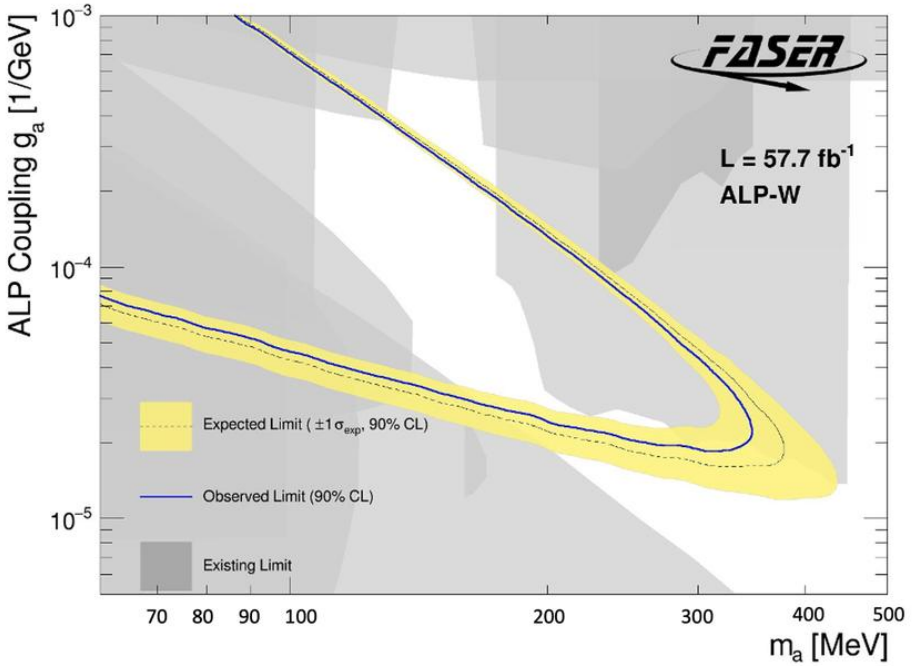
Signal

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: RESULTS

- Main model targeted (See backup for more model interpretations)
  - ALP-W (Coupling to W Boson)
  - 1 event observed
  - Compatible with background estimate
- Sets limits in previously unconstrained parameter space

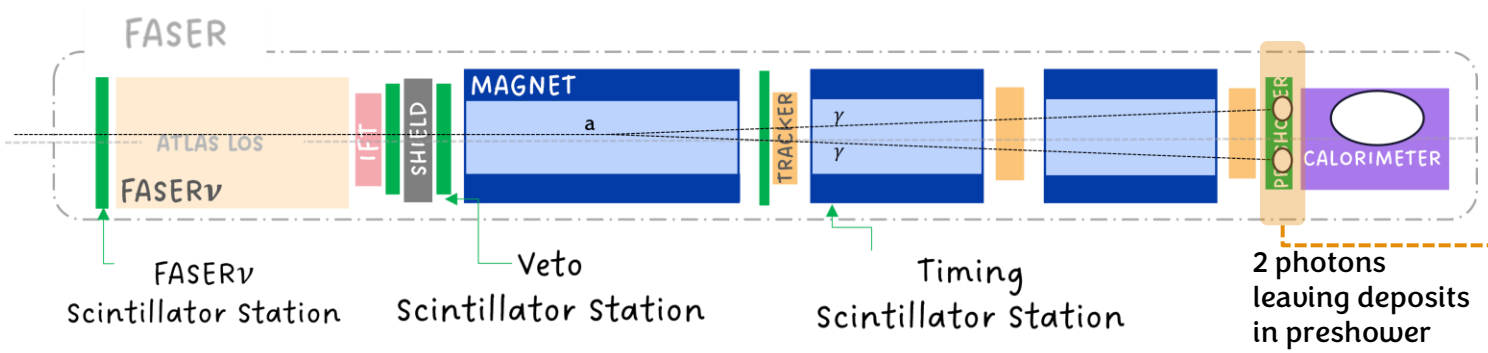




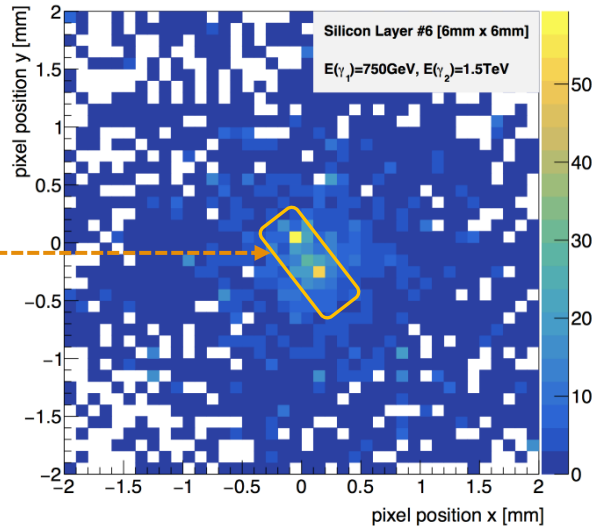
LOOKING FORWARD: FUTURE OF BSM @ FASER

PRESHOWER UPGRADE

- Brand new preshower scintillator installed in FASER during YETS
  - Ready for data taking this month!
  - High-granularity tungsten/ silicon-pixel preshower
  - Able to distinguish between very closed (~0.2mm) spaced photons
  - Will allow for a reduction in background .... And an improvement in sensitivity!

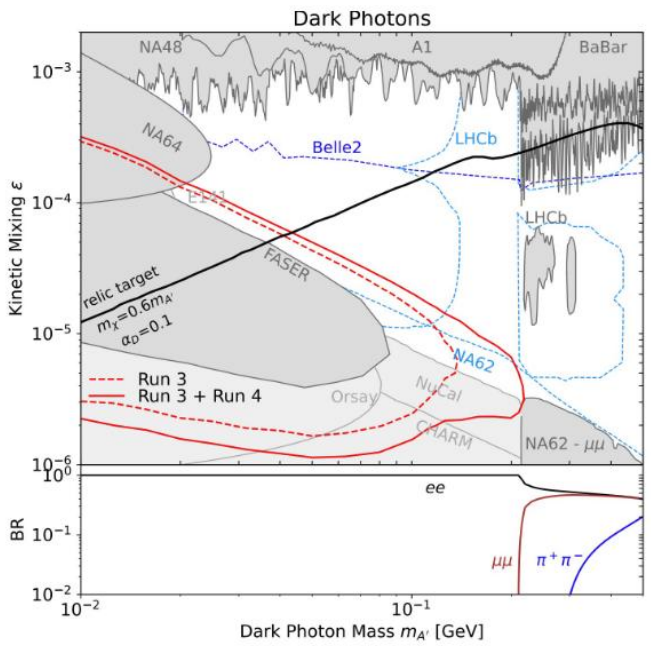


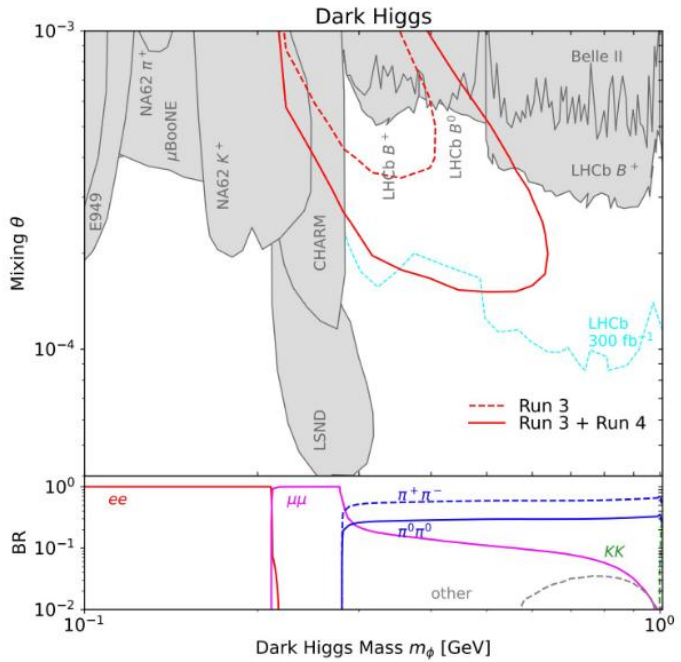
SIMULATION
Charge distribution [fC]

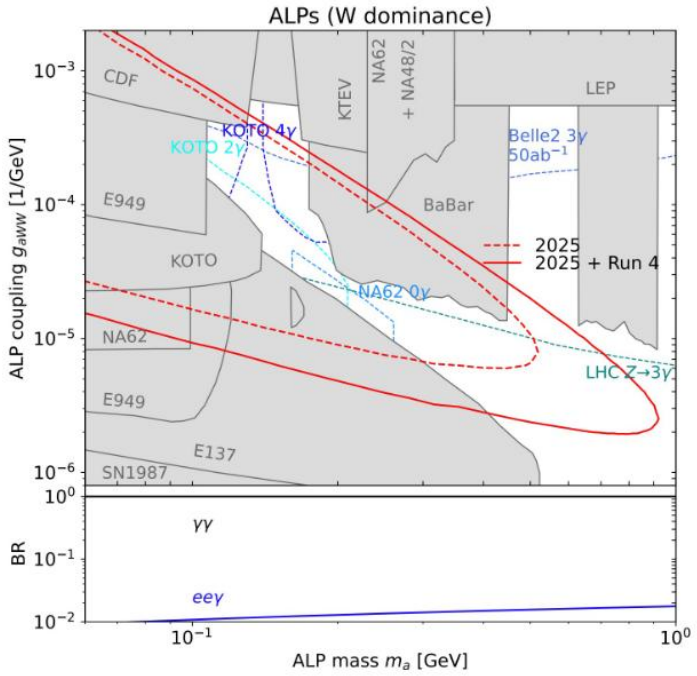


FASER @ HL-LHC

- FASER will continue to run in LHC Run 4
  - First run of the high-luminosity LHC!
- Increased luminosity leads to some exciting projected sensitivity for FASER!
  - Predicted to receive ~$680\ \mathrm{fb}^{-1}$ in Run 4, adding to the existing 190 fb^{-1} and a further 120 fb^{-1} is predicted during Run 3

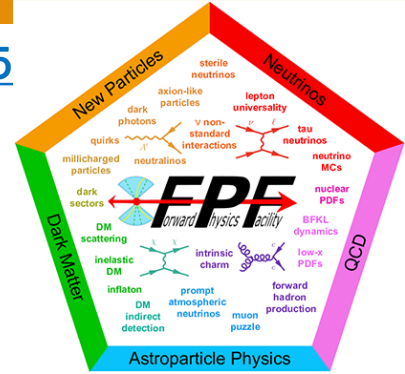






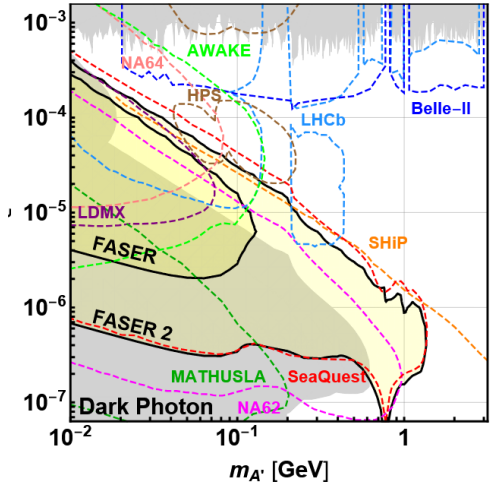
FASER2 Note 2025

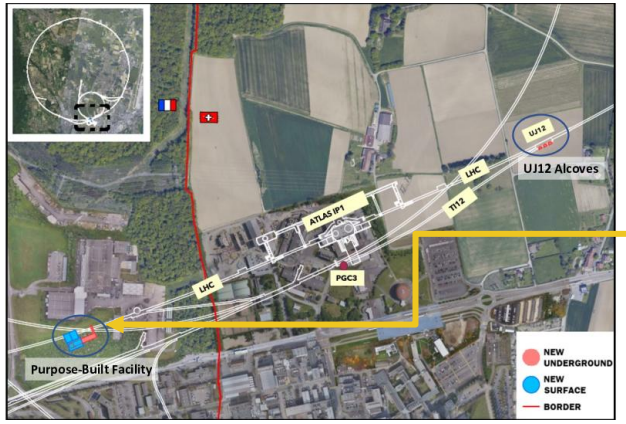
FPF ESPPU 2025

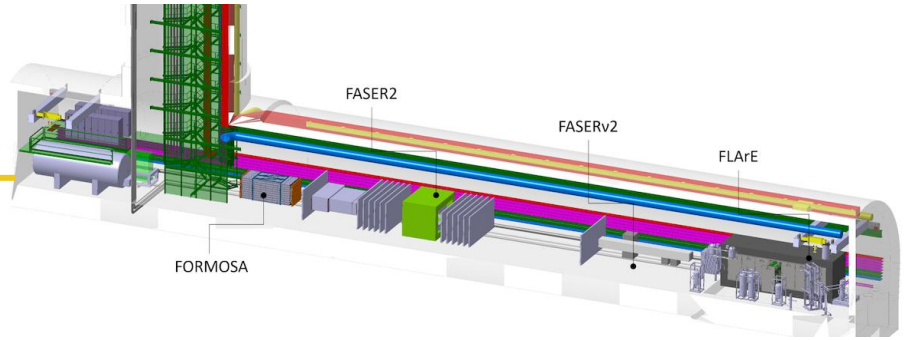


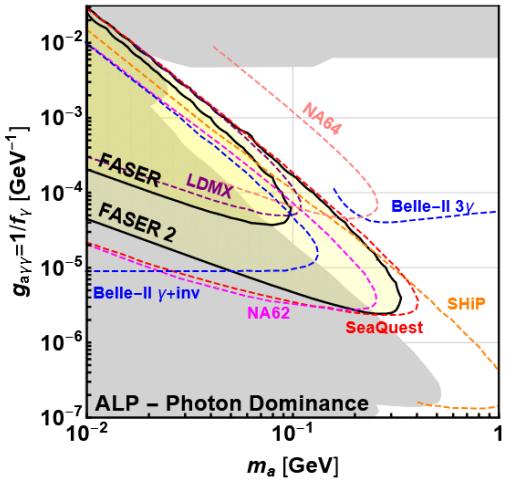
FORWARD PHYSICS FACILITY

- Extend physics potential in the high-luminosity LHC era
  - Proposal to have a purpose-built cavern in the far-forward region housing 4 experiments
- Would give significant new sensitivity in all dark sector PBC benchmark models
  - Extend neutrino program with higher possibility for ν_τ interactions and increase in the number of neutrinos produced



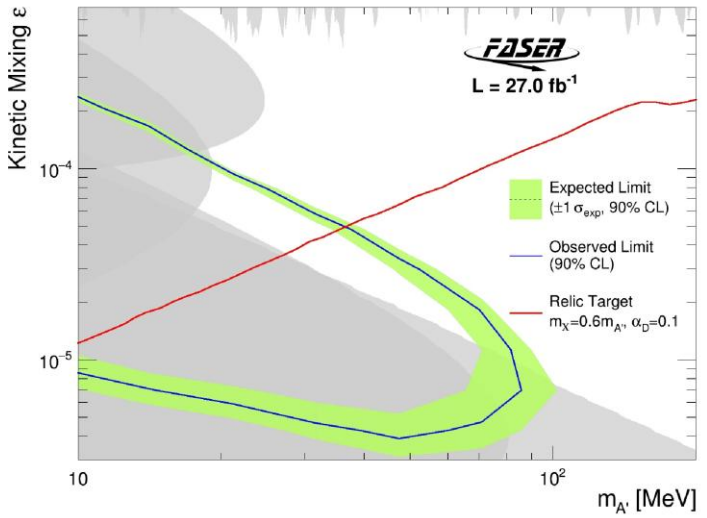


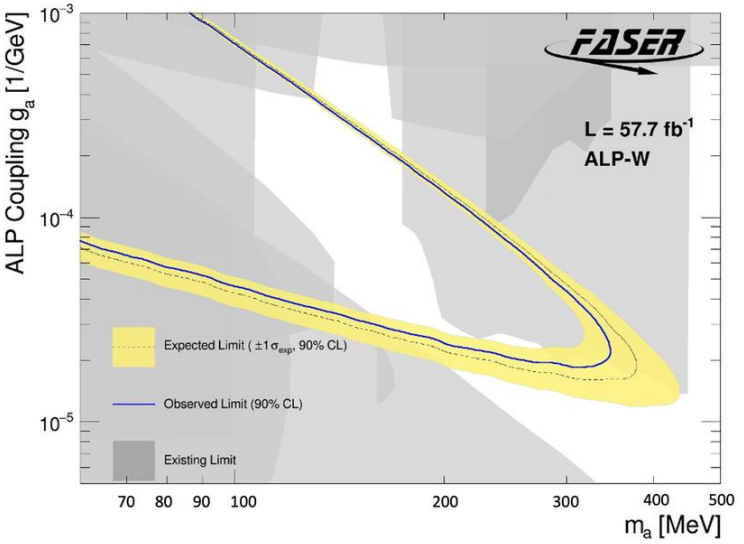




SUMMARY

- FASER successfully took data in the first 3 years of LHC Run 3
  - 190 fb^{-1} collected so far
  - Another 120 fb^{-1} amount expected by the end of Run 3
- Searches for both ALPs and Dark Photons were undertaken
  - 1 event seen in ALPs signal region -> Limits set for various models
  - 0 events seen in Dark Photon SR -> Limits set in this region for the first time since 1990's
- New preshower will help to reduce background and improve future BSM searches
- During Run4 FASER expects to provide even better sensitivity for BSM searches
  - Built upon by the Forward Physics Facility
    - Proposed new facility to house several detectors (inc. FASER2) in the far-forward region





Thank you for listening ☺

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CERN

Swiss National Science Foundation

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

NSF

科研費 KAKENHI

erc European Research Council Established by the European Commission

FASER COLLABORATION

107 collaborators, 27 institutions, 11 countries

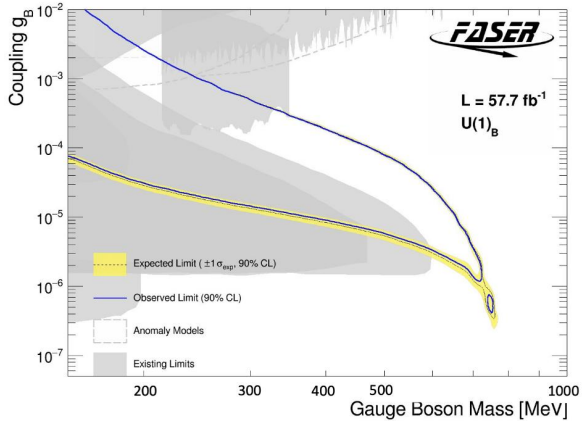
International laboratory covered by a cooperation agreement with CERN

BACK UP

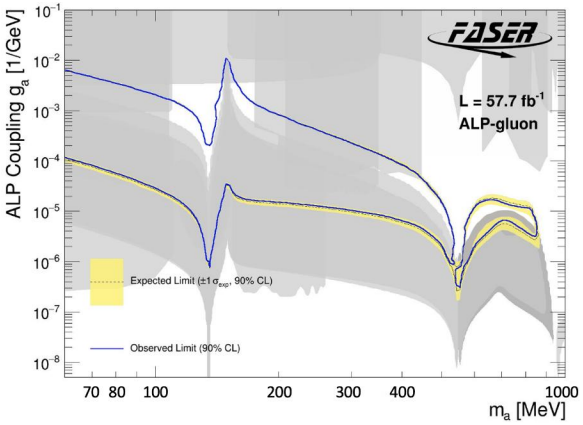
ALPS: ADDITIONAL MODELS

- ALPs results reinterpreted for several models
  - New since last year's LLP
- Probes physics beyond colliders benchmarks:
  - BC9 (Axion portal with photon-coupling)
  - BC11 (ALP-gluon)
  - BC1 (Dark Photon)

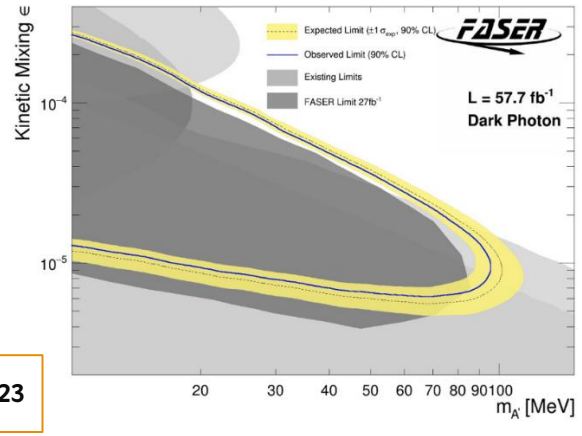
ALP-Photon



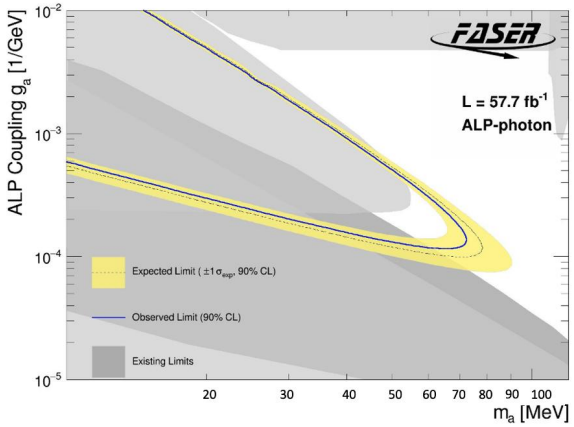
ALP-Gluon



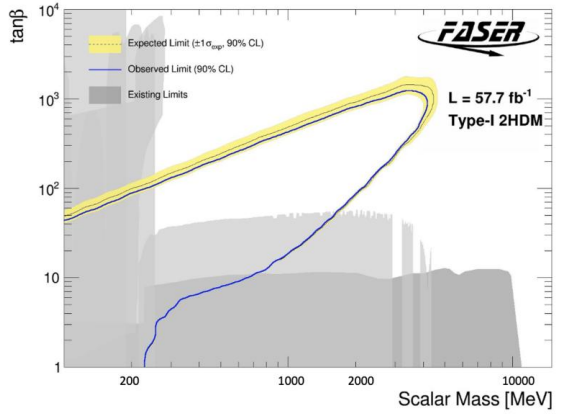
Dark Photon



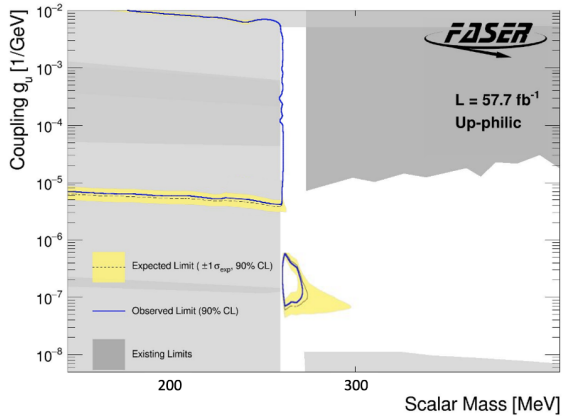
2HDM



U(1)B

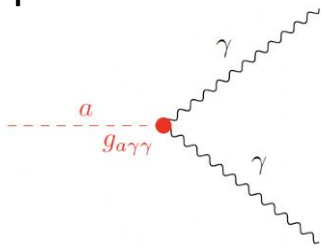


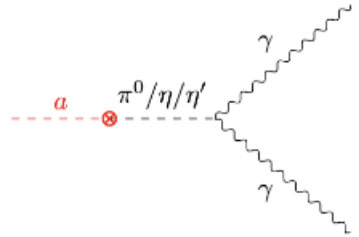
Up-Phillic

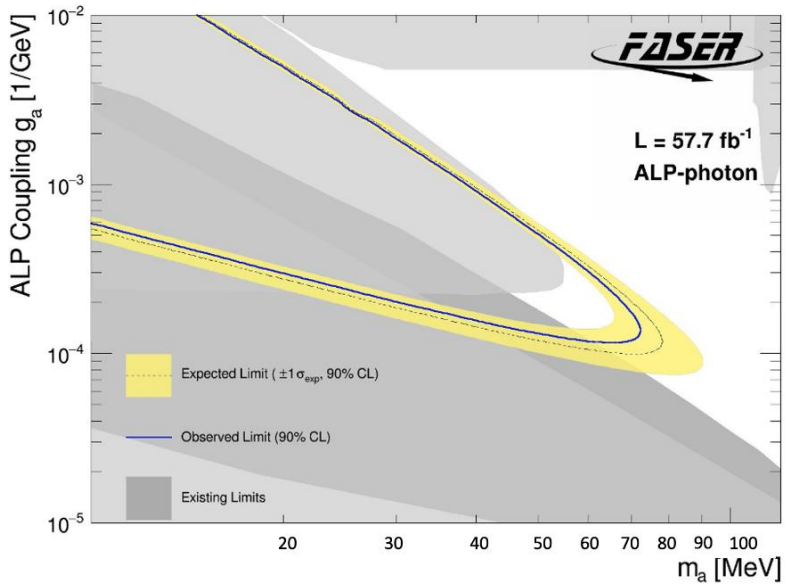


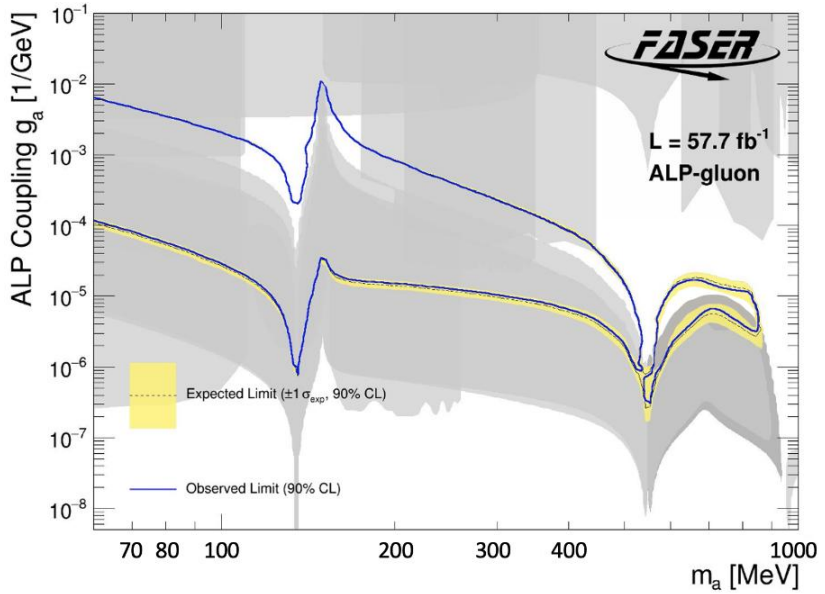
ALPS: ADDITIONAL MODELS

- ALP-Photon (left)
  - Produced through primakoff process
- ALP-gluon (right)
  - Mixing with pseudoscalars





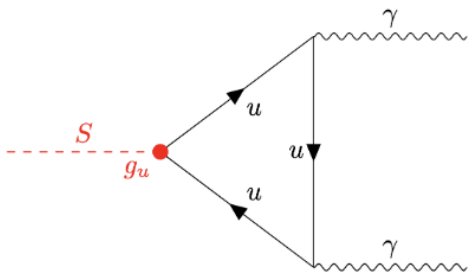




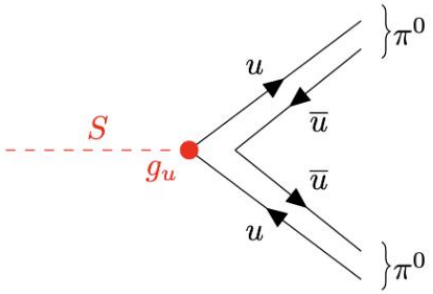
ALPS: ADDITIONAL MODELS

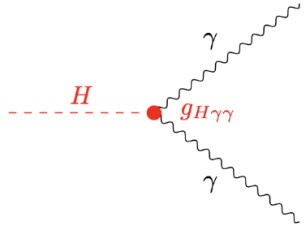
- 2 Higgs Doublet model [Boson] (left)
- $U(1)_B$ Scalar [Boson] (middle)
- Up-Phillic Scalar (right)

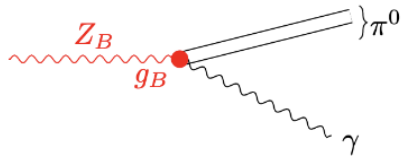
$m_s < 2 \times m_{\pi_0}$

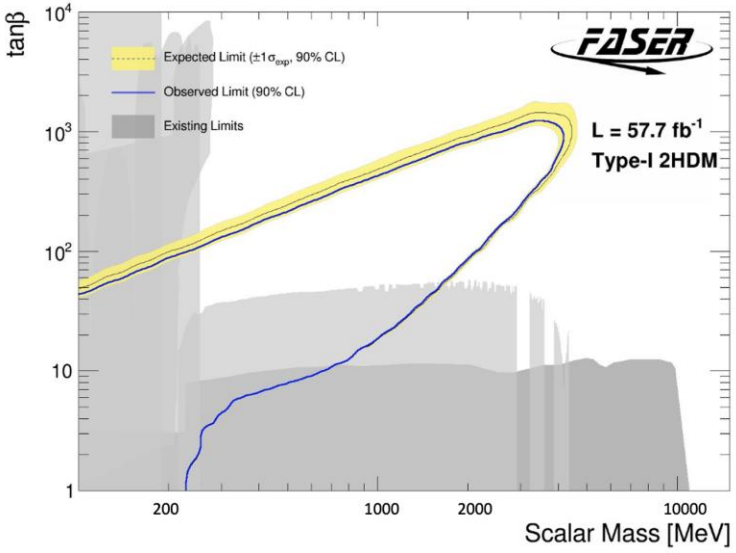


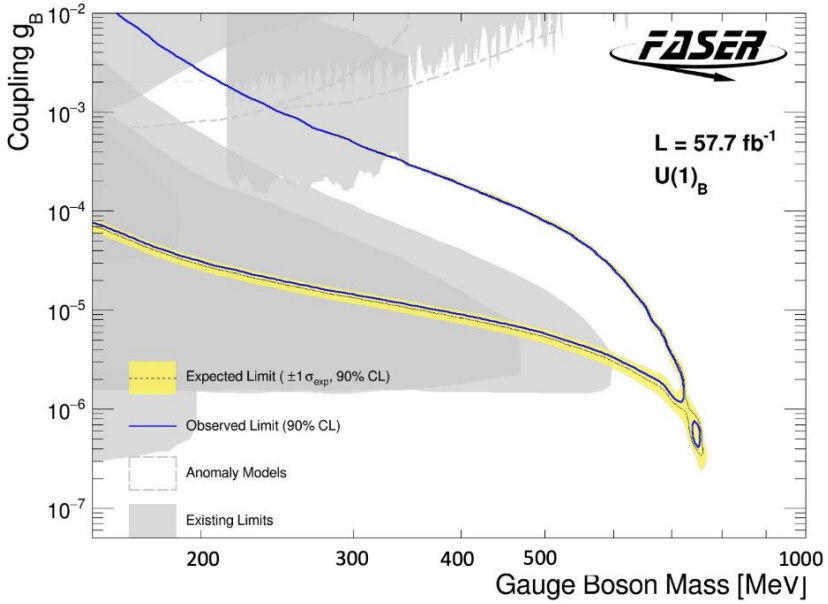
$m_s > 2 \times m_{\pi_0}$

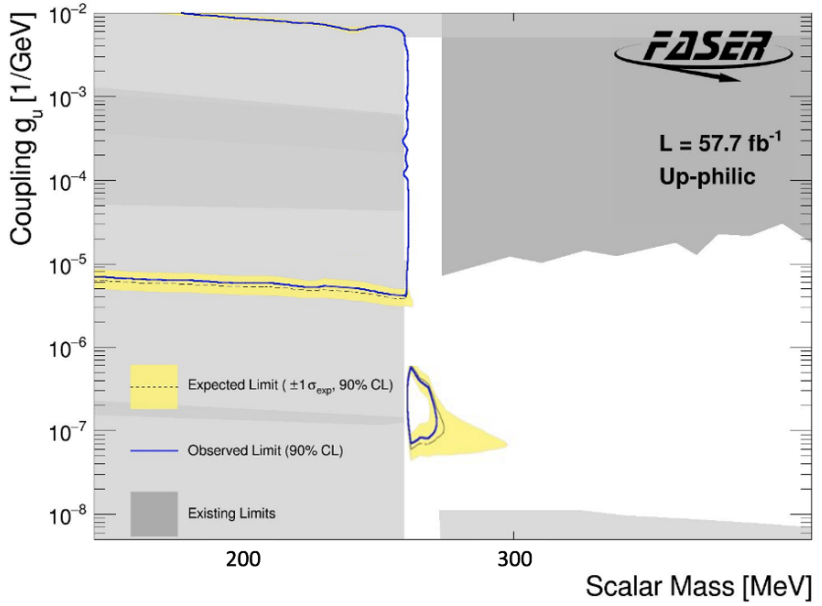












PBC BENCHMARKS

- Physics beyond colliders (PBC) working group define a framework for a set of benchmark cases for hidden sector searches
- Using hidden sectors as an extension of the standard model e.g. $\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

- Each individual portal has a number of benchmarks

LLPS AT FASER

- In example of dark photon:
  - Distance travelled before decay given by coupling to the standard model (ϵ) , mass ($m_{A'}$) and energy ($E_{A'}$)

$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$