LLPs searches at FASER

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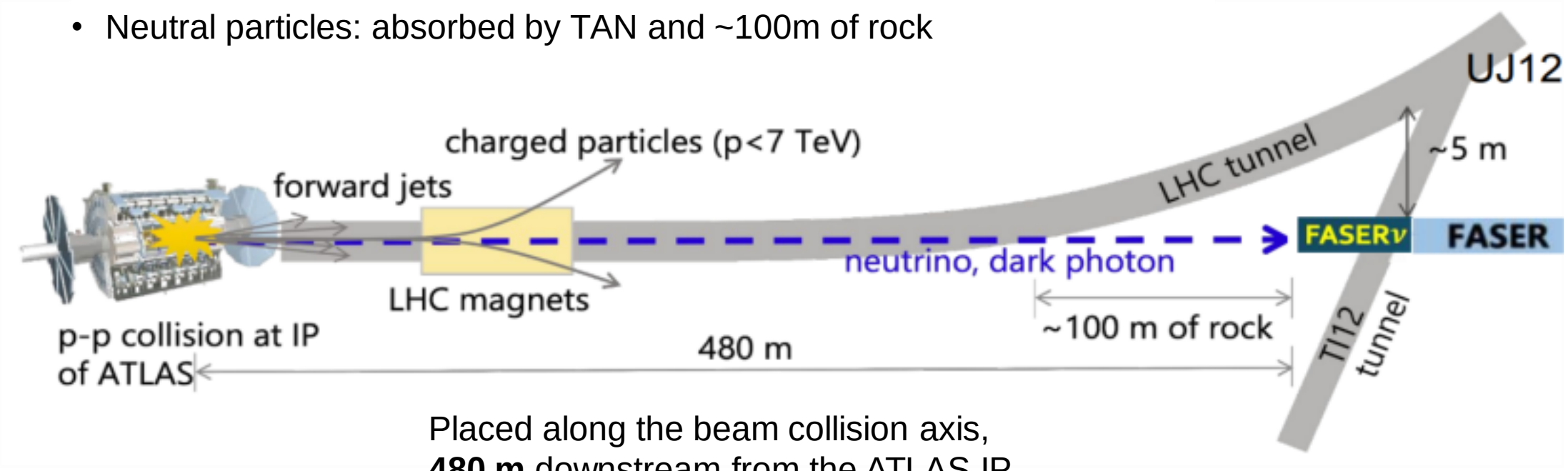
on behalf of FASER Collaboration

EPS-HEP 2025, Marseille, July 11, 2025

ForwArd Search ExpeRiment (FASER)

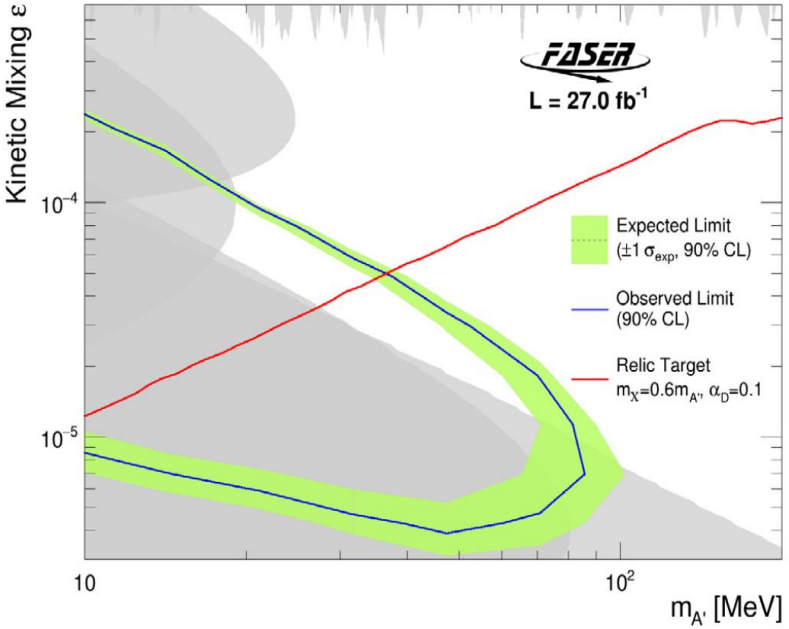
- Designed to **search for Long-Lived Particles** (LLPs) and **study TeV neutrinos** produced in pp collisions at the ATLAS IP
- Unique opportunities from high flux light TeV particles produced in π, K, D mesons
  - 10^{16} pions, 10^{12} neutrinos produced in FASER angular acceptance in LHC Run3 (2022-2026)
- Clean environment (low background)
  - Charged particles: bent by LHC magnets
  - Neutral particles: absorbed by TAN and ~100m of rock



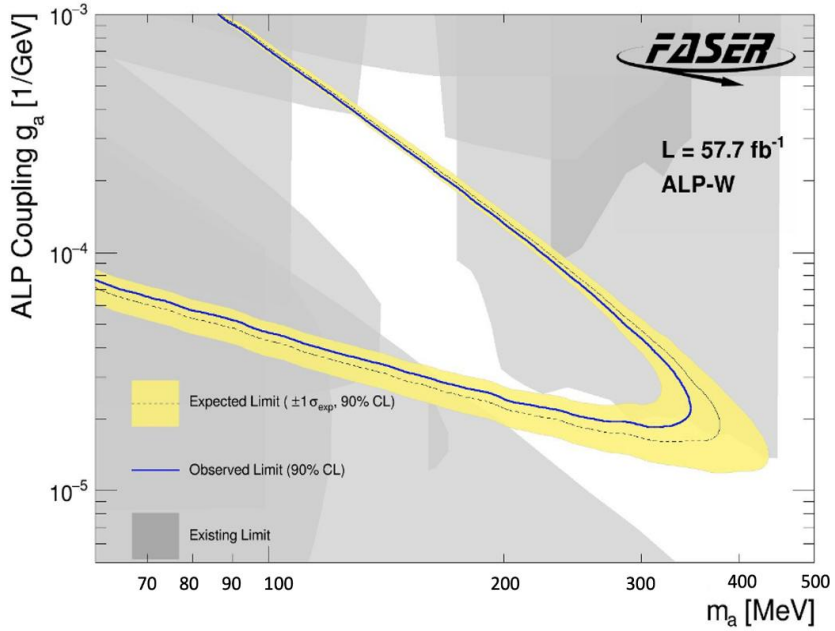
Placed along the beam collision axis,
480 m downstream from the ATLAS IP

FASER physics goals

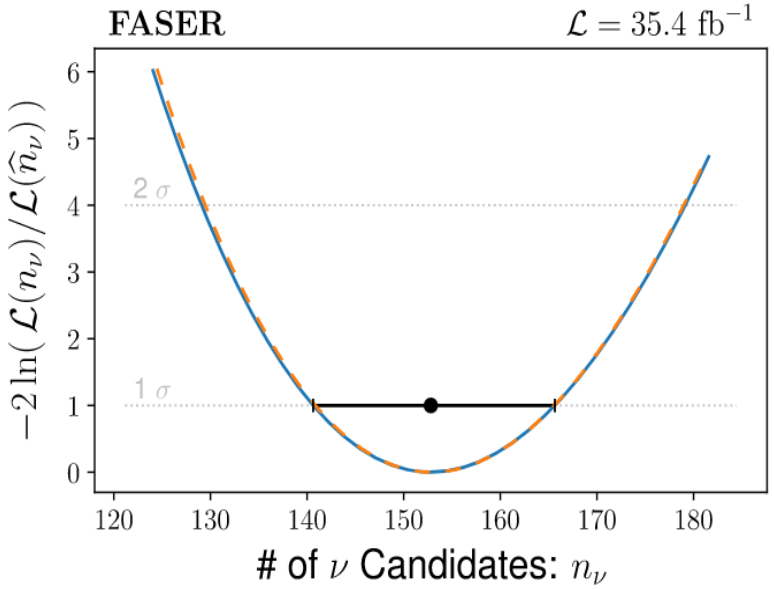
- **LLPs search**: dark photon, Axion-like particles (ALPs) … ⟶ this talk
- **Direct collider neutrinos studies**: ν_e, ν_μ, ν_τ from hadron decays ⟶ See Akitaka Ariga's talk on Tuesday



Dark photons search at FASER
PLB 848 (2024) 138378



ALPs search at FASER
JHEP 01 (2025) 199

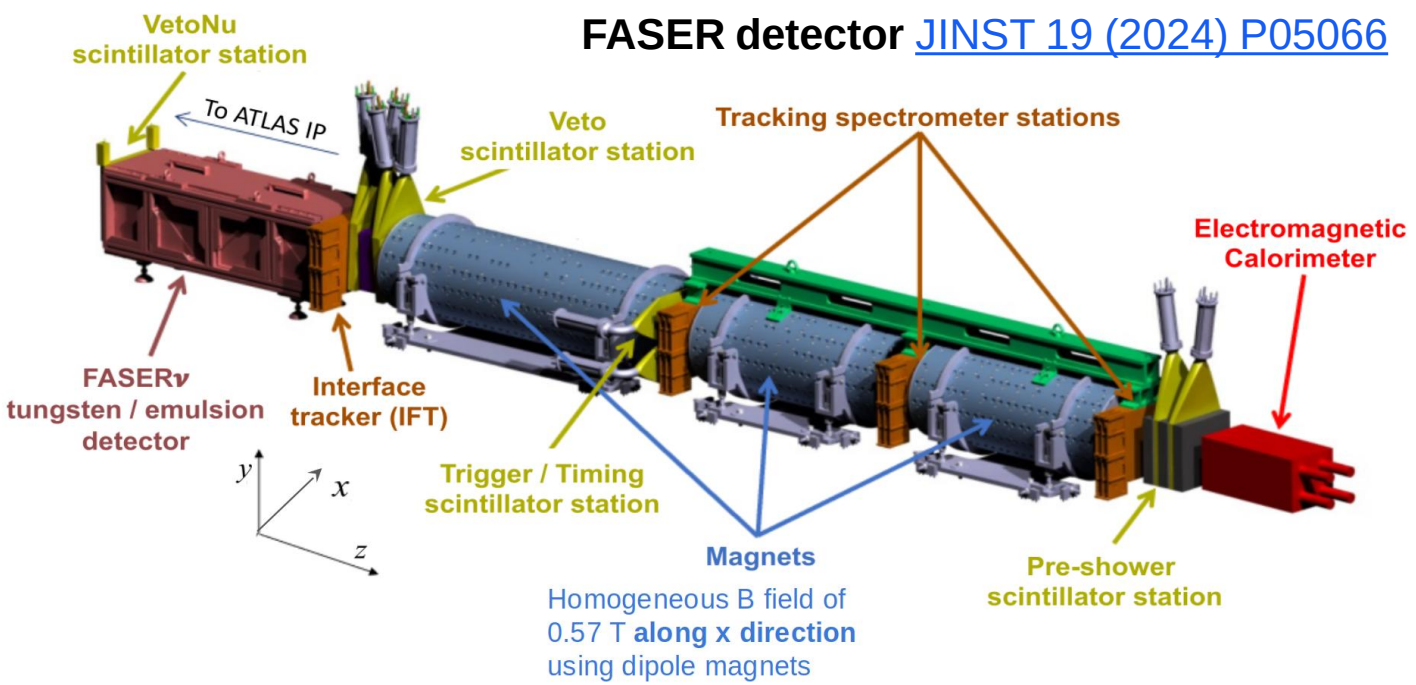


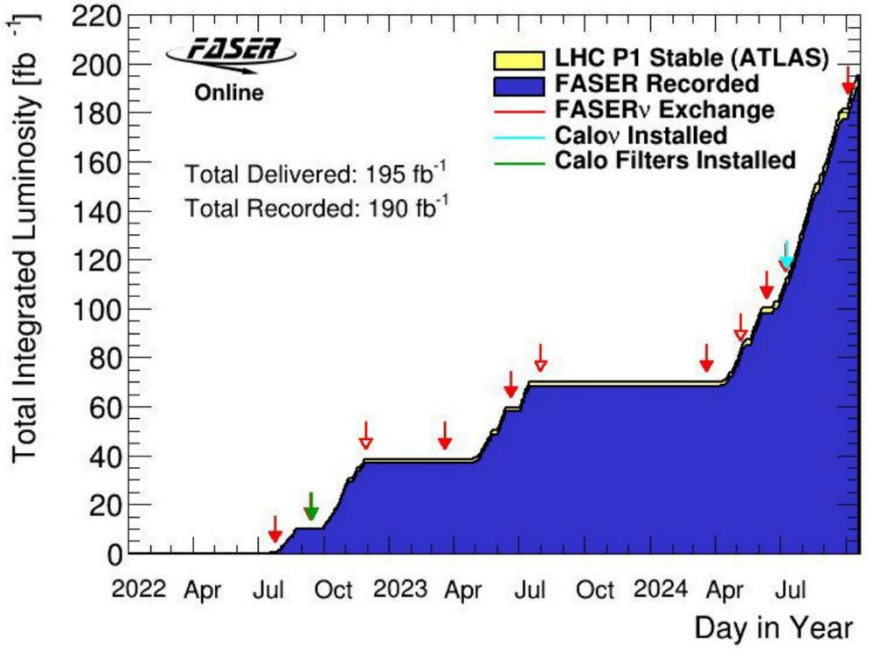
Collider neutrino measurements
PRL 131 (2023) 031801
PRL 133 (2024) 021802

FASER detector

- Small inexpensive detector
  - ~7 m length, 20 cm aperture ($\eta > 9.1$) , ~1.5 m magnetized decay volume
- Began taking data at start of LHC Run 3 (2022)
  - All detector components working as expected
  - Successfully collected ~214 fb^{-1} (>97% of delivered luminosity). A further ~100 fb^{-1} expected from Run3

FASER detector JINST 19 (2024) P05066





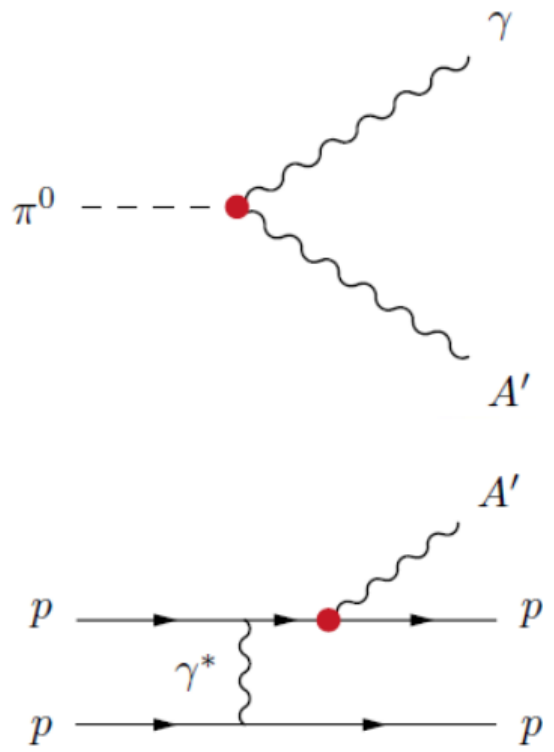
Dark photon search

Production and decay

- SM extended by $U(1)_D$ gauge field with dark gauge boson, which mix with SM photon (coupling ϵ <<1) resulting in dark photon A' (mass $m_{A'}$) interacting with SM

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

- **Dominant dark photon production at FASER**:
  - Light meson decays (neutral pion or η, $m_{A'} < m_{\eta/\pi^0}$)
  - Dark bremsstrahlung ($m_{A'}$ up to $O(2\ \text{GeV})$)
- TeV dark photon decay:
  - FASER sensitive to $\epsilon \sim 10^{-5}$ and $m_{A'} \sim$ 10 - 100 MeV
  - For $2m_e < m_{A'} < 2m_\mu \sim 211$ MeV, $\text{Br}(A' \to e^+e^-) \approx 100\%$



Dark photon search- event selection

- Uses FASER's first year (2022) of data (27 fb^{-1} ,13.6 TeV)
- Probes the phase space for A' and $A'_{B\text{-}L}$ (B-L gauge boson) …
- 50% efficiency for representative sensitive parameter space $\epsilon = 3\times10^{-5}$, $m_{A'} = 25.1$ MeV with A' decaying in FASER decay volume

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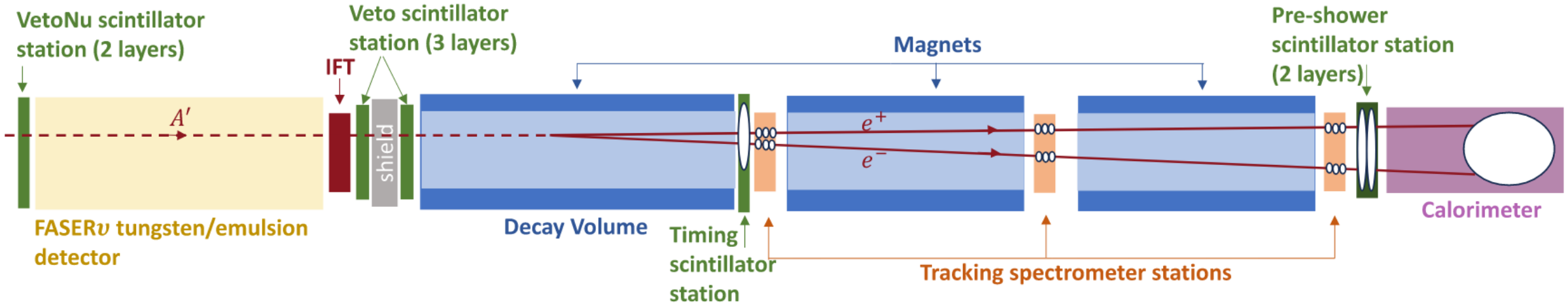
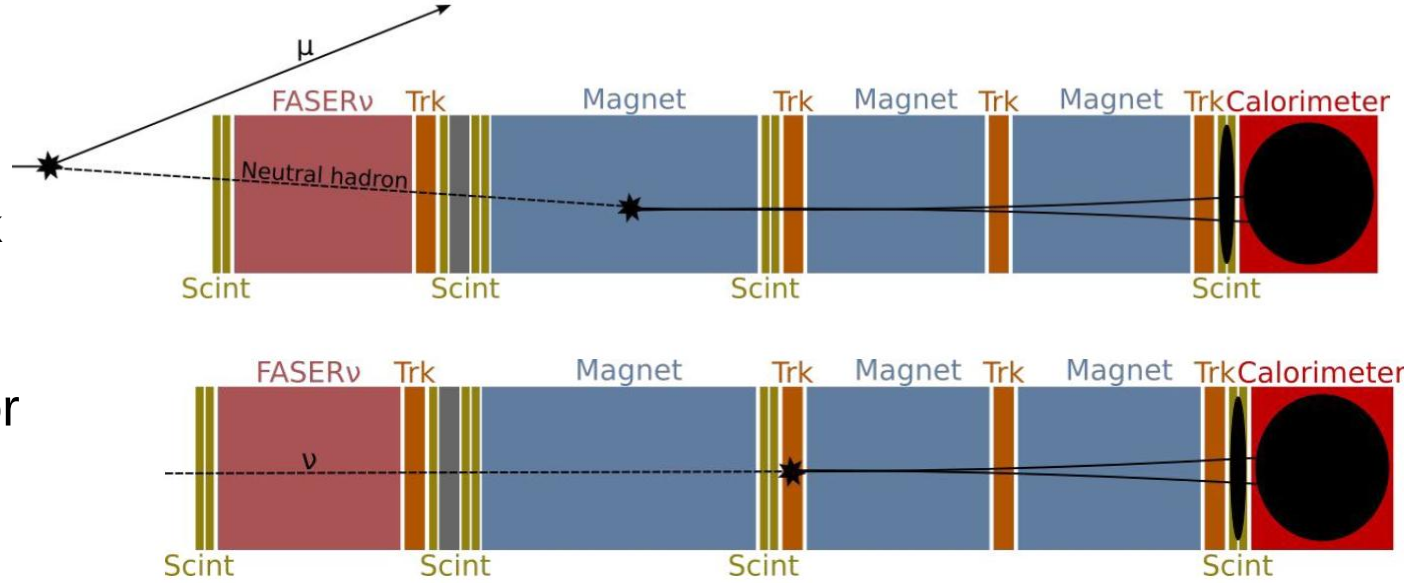


- No signals in 5 Veto scintillator layers
- Signal in the Timing and Preshower scintillators

- Two tracks:
  - χ^2/ndf < 25, nHits >=12, p > 20 GeV, r_{tracks} < 95 mm
- E_{calo} > 500 GeV

Dark photon search - backgrounds

- Neutral hadrons from muons interacting with rock
  - Data-driven estimation using three-track control region (lower EM energy)
- Neutrinos interacting in Timing scintillator or first tracking station
  - Suppressed by E_{calo} > 500 GeV
  - Estimated using MC
- Backgrounds due to veto inefficiency, large-angle muons, non-collision events
  - Negligible



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%)**

Close to background free analysis!

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Dark photon search – systematics

- Signal yield
  - MC statistics
  - Theoretical modelling
  - Experimental: luminosity, scintillators efficiency, calo energy scale, tracking efficiency and resolution
- Neutral hadron background
  - 100% assigned
- Neutrino background
  - 127% uncertainty from MC modelling

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Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\ \mathrm{TeV})^3}{1+(E_{A'}/4\ \mathrm{TeV})^3}$	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%
Calorimeter Energy Scale	6%	0-8% (< 1%)

Dark photon search - results

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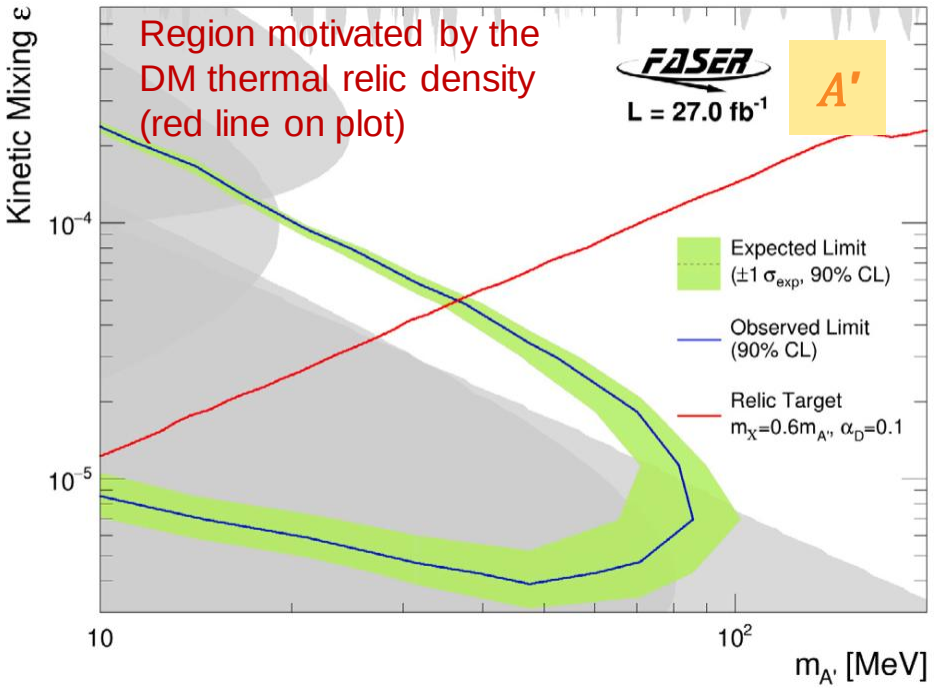
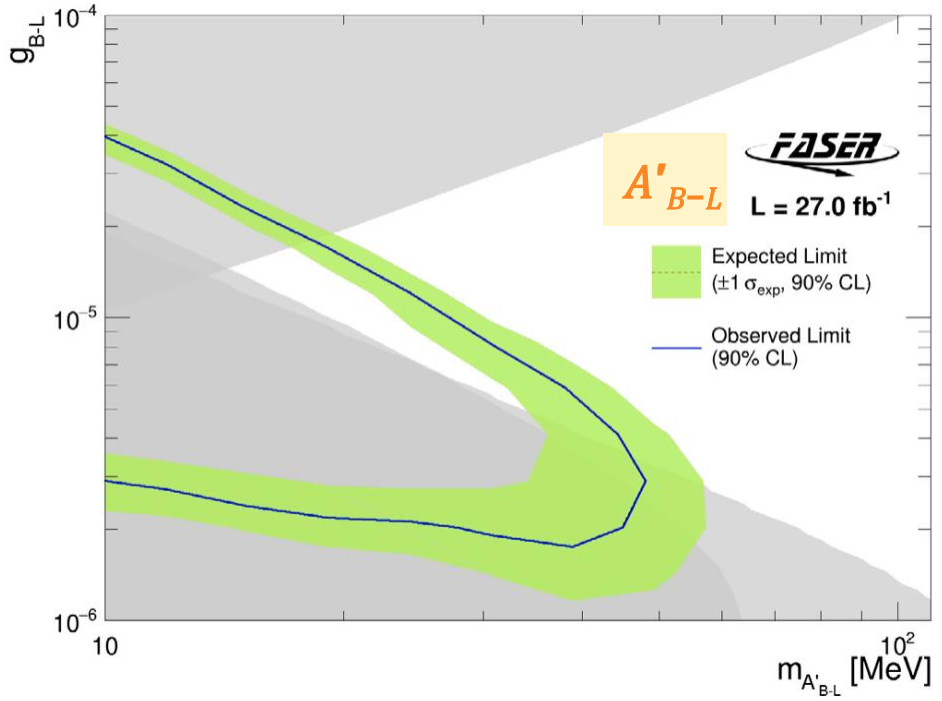
- Zero observed events with N_{bkg}^{exp} = (2.3 ± 2.3) ×10$^{-3.}$ Limits set in unexplored region.





- Exclude region $\epsilon \sim 4\times10^{-6}$ -2×10^{-4} and $m_{A'}$ ~10-80 MeV
  - World-leading exclusion in the range $\epsilon \sim 2\times10^{-5}$ - 1×10^{-4} and $m_{A'} \sim$ 17 - 70 MeV
- Exclude region $g_{B-L} \sim 3\times10^{-6}$ - 4×10^{-5} and $m_{A'_{B-L}}$ ~10-50 MeV
  - First exclusion in the range $g_{B-L} \sim 5\times10^{-6}$ - 2×10^{-5} and $m_{A'_{B-L}} \sim$ 15 - 40 MeV

Axion-like particles search

Production and decay

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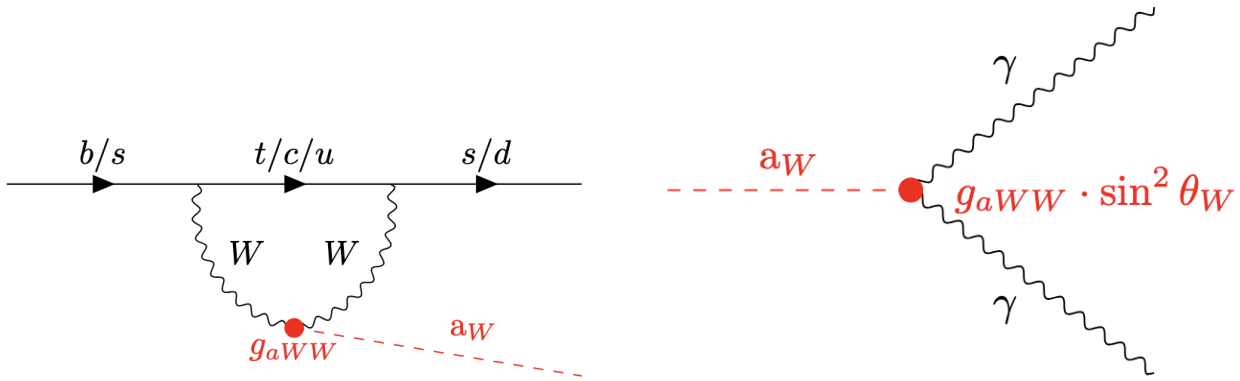
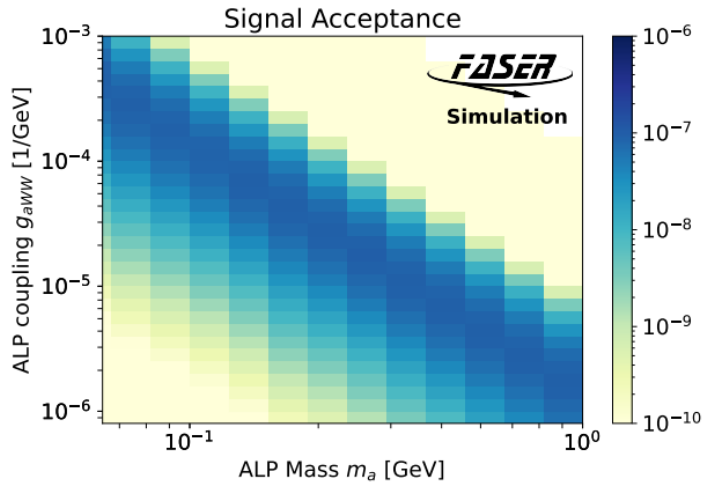
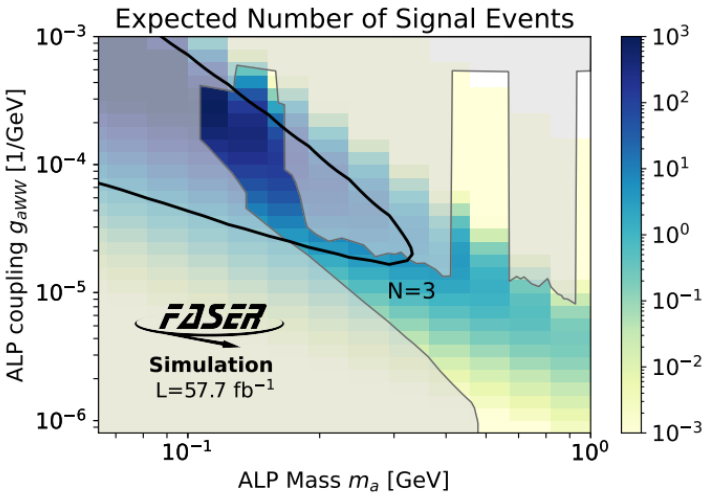
- FASER has largest sensitivity to model where ALPs (a_W) with mass m_a coupling to $SU(2)_L$ gauge boson (coupling g_{aWW}) after EW symmetry breaking

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

- Produced in decays of b- or s-flavoured hadrons
  - Dominant production from B^0 and $B^\pm$ decays
- Decaying into photon pair







ALPs search – event selection

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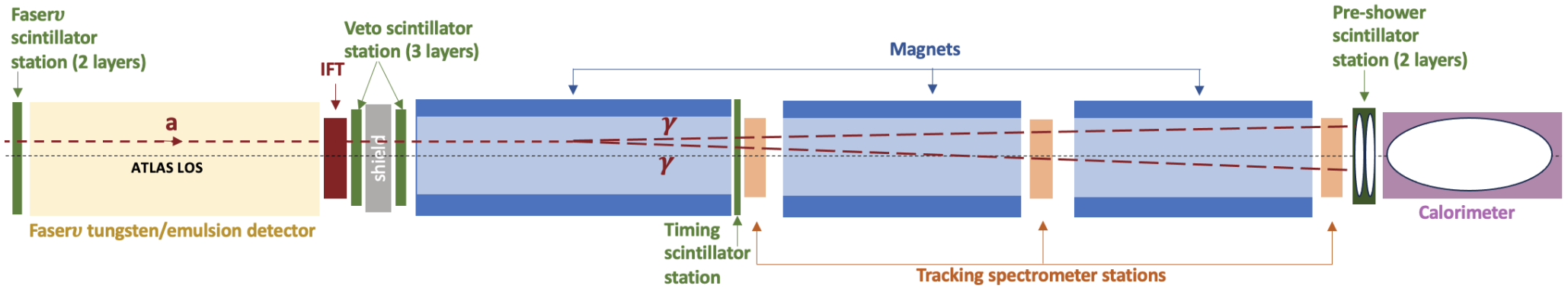
- Uses FASER's 2022 + 2023 data (57.7 fb^{-1} ,13.6 TeV)
- Selection efficiency about 75% for representative parameter space: m_a = 140 MeV and g_{aWW} = 2 × 10^{-4} GeV^{-1} with ALPs decaying in FASER decay volume



- No signals in 5 Veto and Timing scintillator layers
- EM-like signature in Preshower to reduce background of neutrinos interacting in the calorimeter
  - Energy in 2nd layer to 1st layer (Preshower Ratio) larger than 4.5
  - Energy deposits in second layer > 10 MIPs
- Large energy deposits in calorimeter (> 1.5 TeV)

ALPs search – backgrounds

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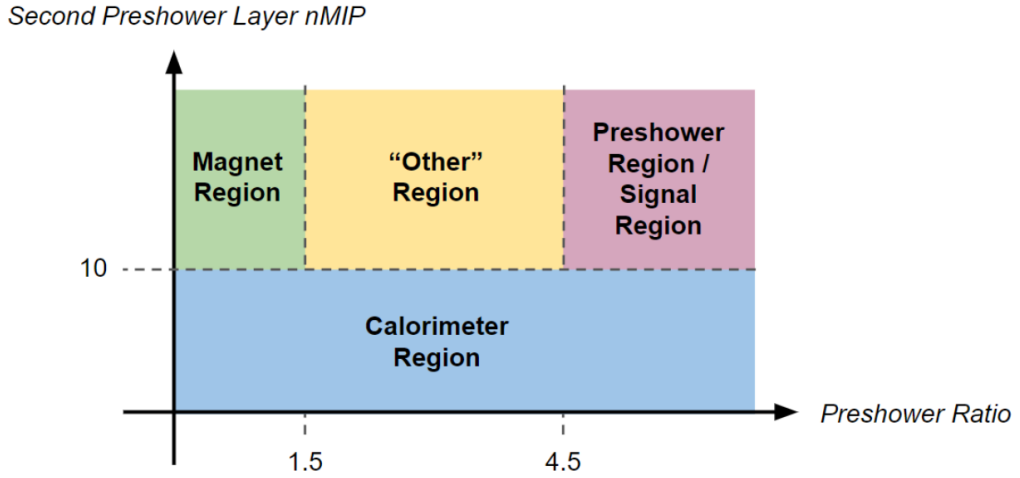
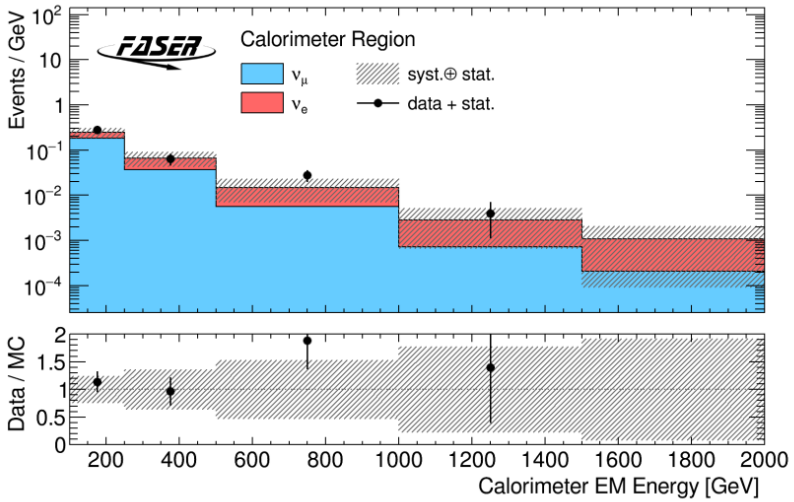
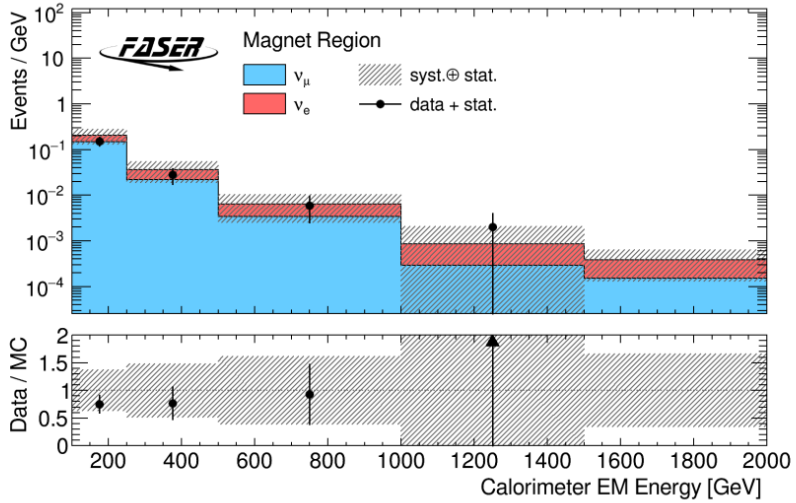
- Dominated by neutrinos interacting in the Preshower or the calorimeter
  - Estimated using MC (0.44 ± 0.39 events) modelling [PRD 110, (2014) 012009]
  - Validated in different neutrino interaction regions (separated by Preshower Ratio)



- Other backgrounds negligible
  - Veto System Inefficiency
  - Background from Large-Angle Muons
  - Neutral Hadron Background
  - Non-Collision Background





ALPs search – systematics

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- Signal yield
  - MC modelling (B meson production and decay
  - MC statistics
  - Experimental: luminosity, scintillators efficiency, calo energy scale, tracking efficiency and resolution
- Neutrino background
  - 90% uncertainty from MC modelling [PRD 110, (2014) 012009]

Uncertainties	Signal Samples $m_a = 140$ MeV $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}	 $m_a = 120$ MeV $g_{aWW} = 1 \times 10^{-4}$ GeV^{-1}	 $m_a = 300$ MeV $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1}
Theo.	59.4%	57.3%	58.0%
	theoretical uncertainties including flux and branching ratio		
Luminosity	2.0%	2.0%	2.0%
	uncertainty on the luminosity estimate		
Calo E-scale	3.6%	16.3%	15.8%
	uncertainty on calorimeter energy scale		
PS ratio	7.9%	6.9%	8.4%
	uncertainty on the preshower ratio		
Second PS	0.6%	0.6%	0.6%
	uncertainty on the second preshower layer charge deposit		
MC stat.	1.8%	3.5%	2.9%
	statistical uncertainty of the MC sample		

Results

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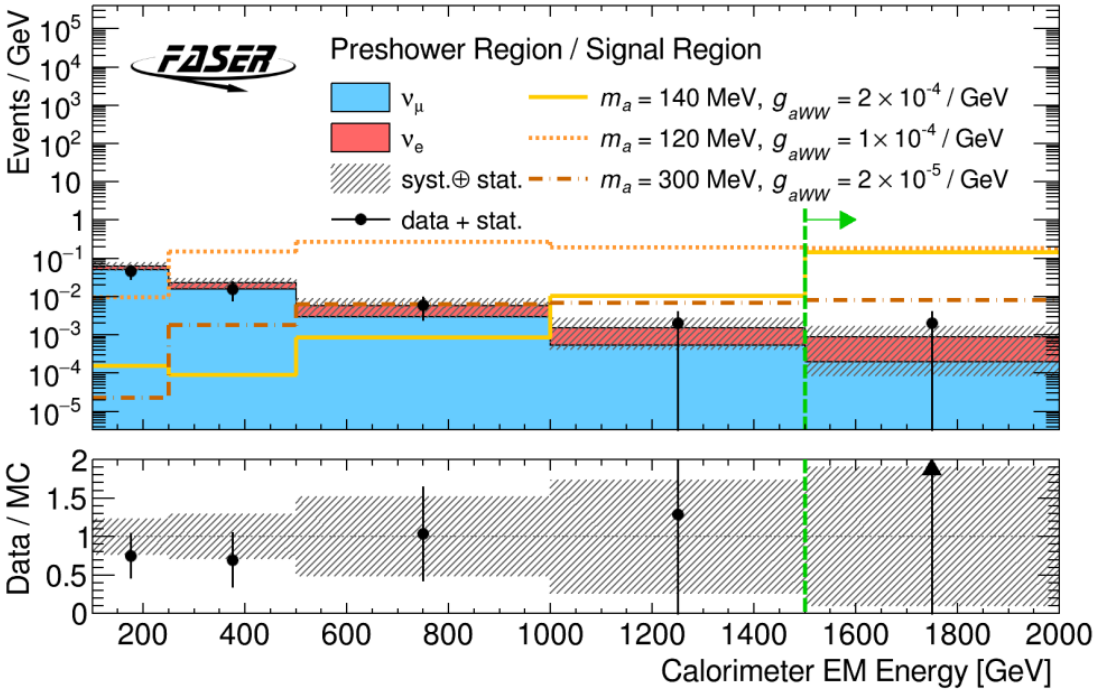
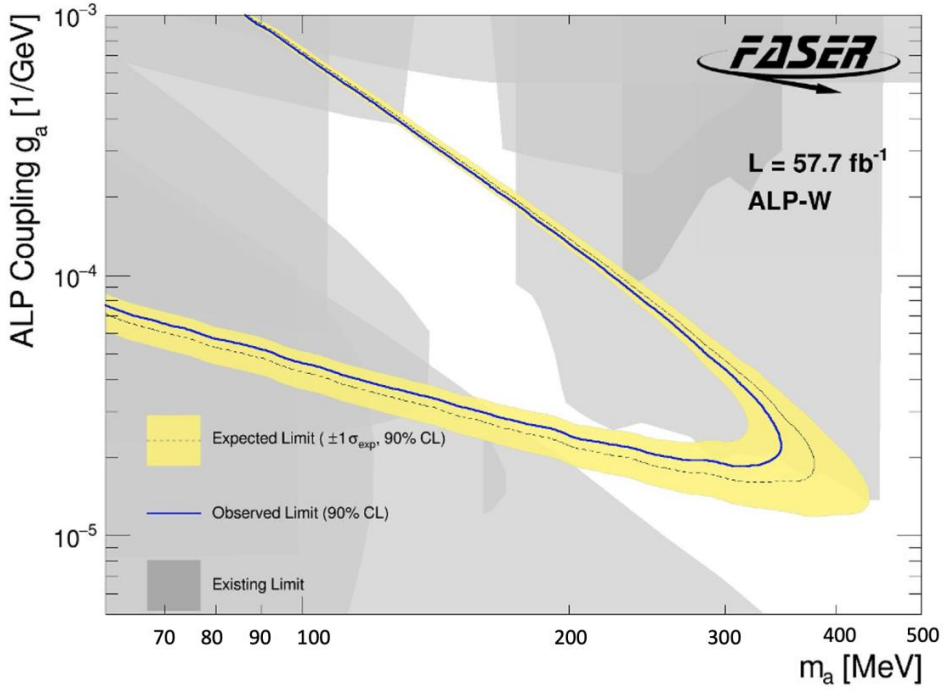
- 1 event observed
  - Compatible with background estimation
- World-leading constraints on ALPs coupling to W boson for m_a up to 300 MeV and g_{aWW} ~10^{-4} GeV (unexplored region)
  - Result interpreted in several other scenarios - see backup



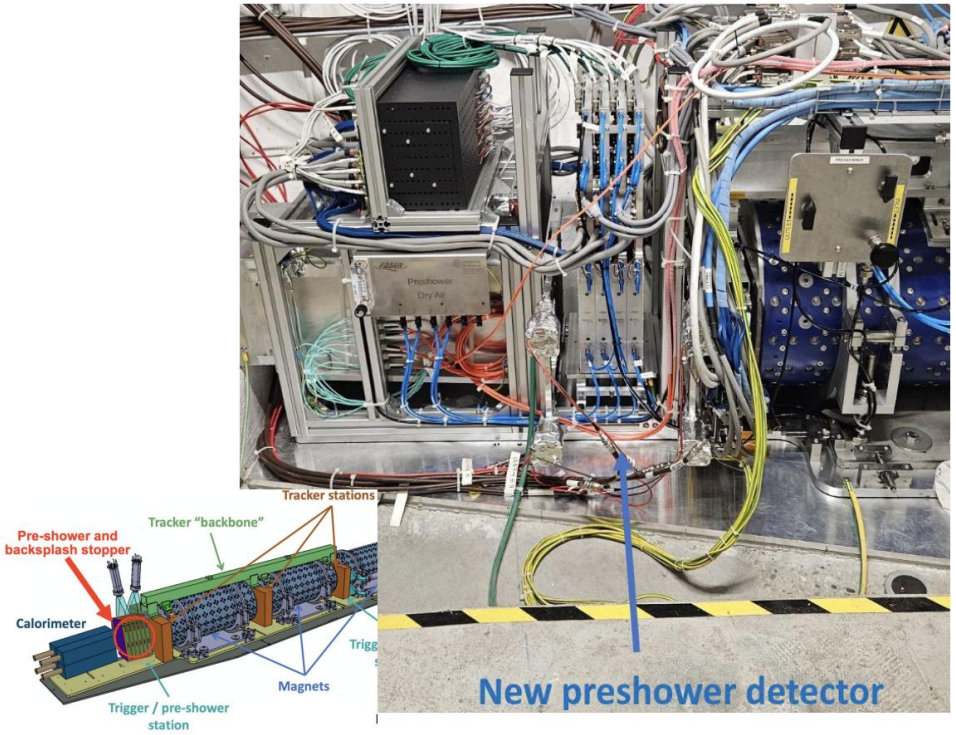


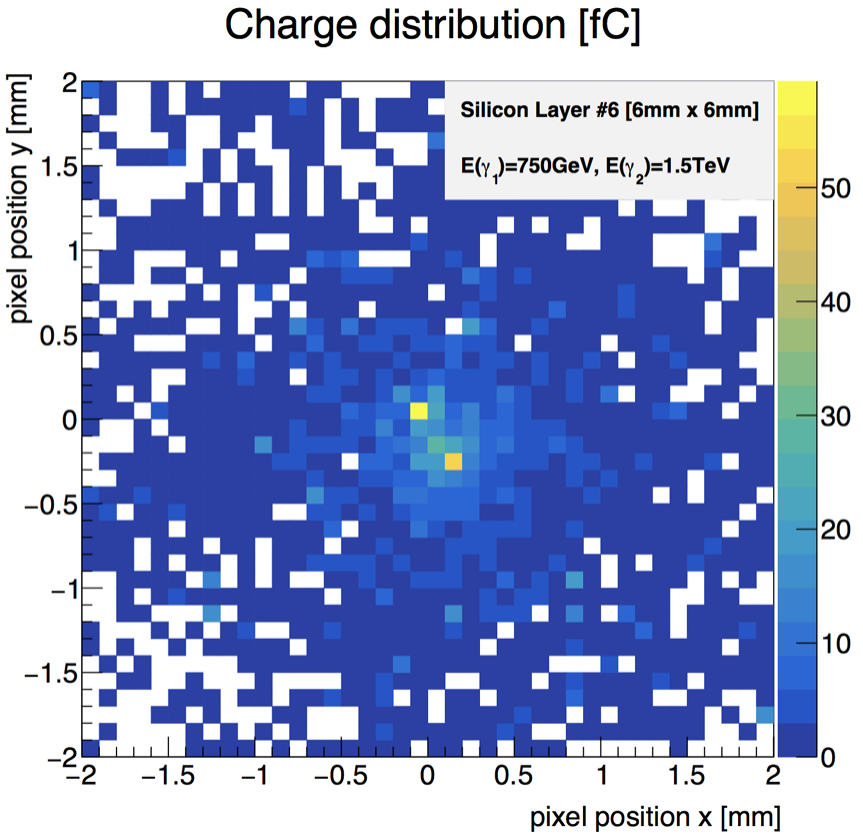
Prospects

New Preshower detector

Preshower TDR [LHCC-P-023]

- New high-granularity tungsten-silicon pixel pre-shower detector installed
  - Enable distinguishing between very closed (~0.2 mm) spaced photons
  - Improved sensitivity for ALPs analysis

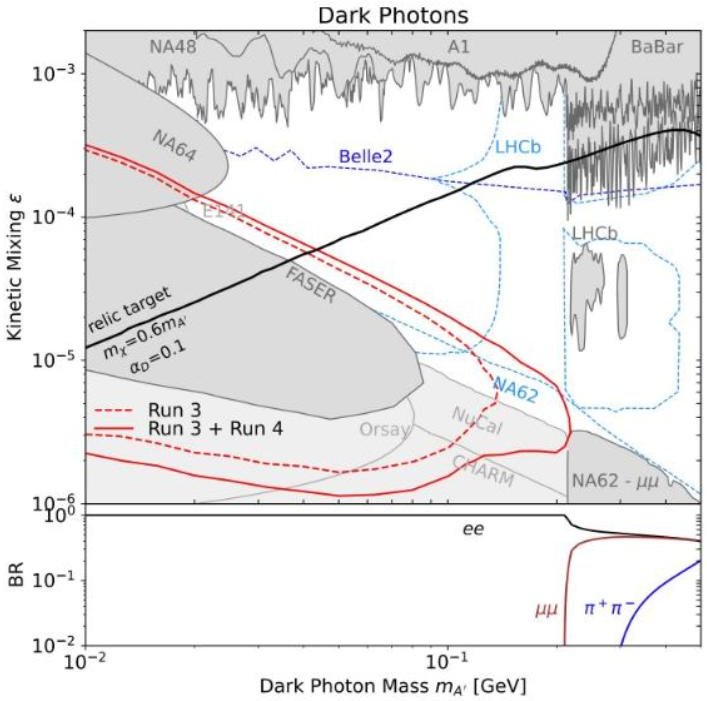


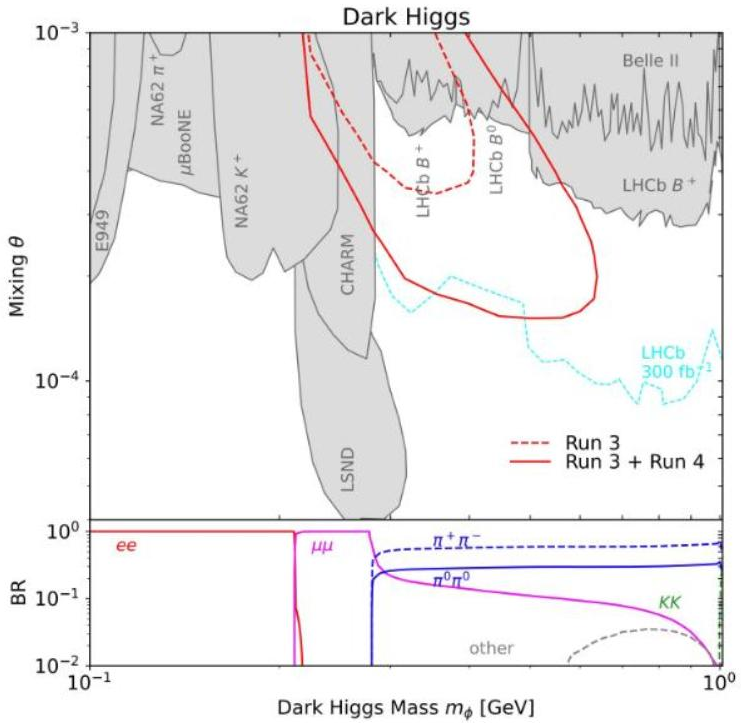


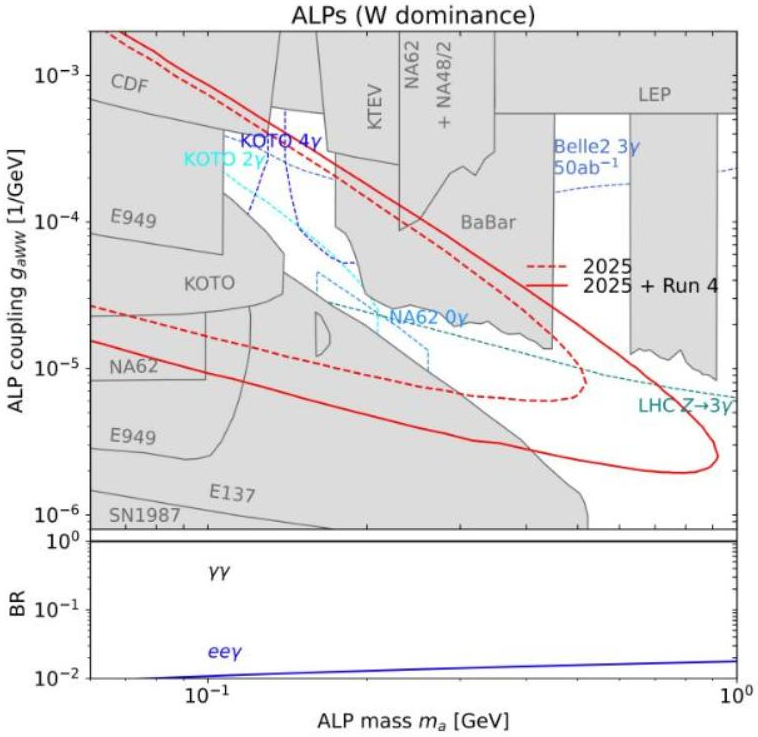
FASER at HL-LHC

- FASER is approved to run in Run4 (expected ~680 fb^{-1})
  - Will push the limits with higher statistics!

FASER Run4 request

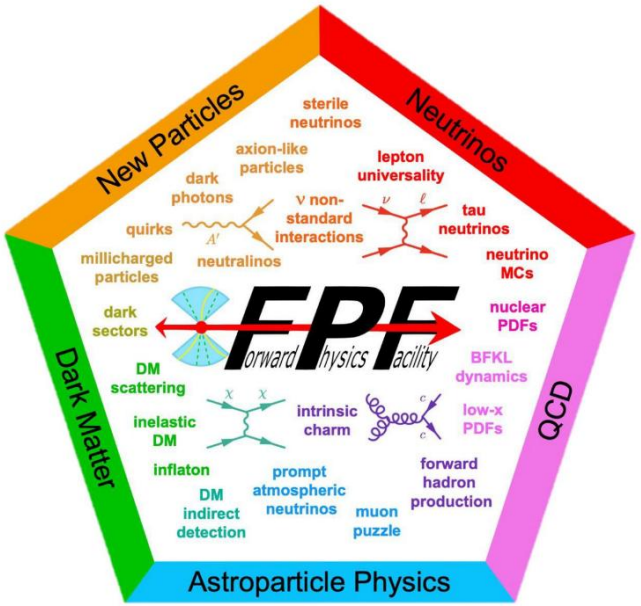


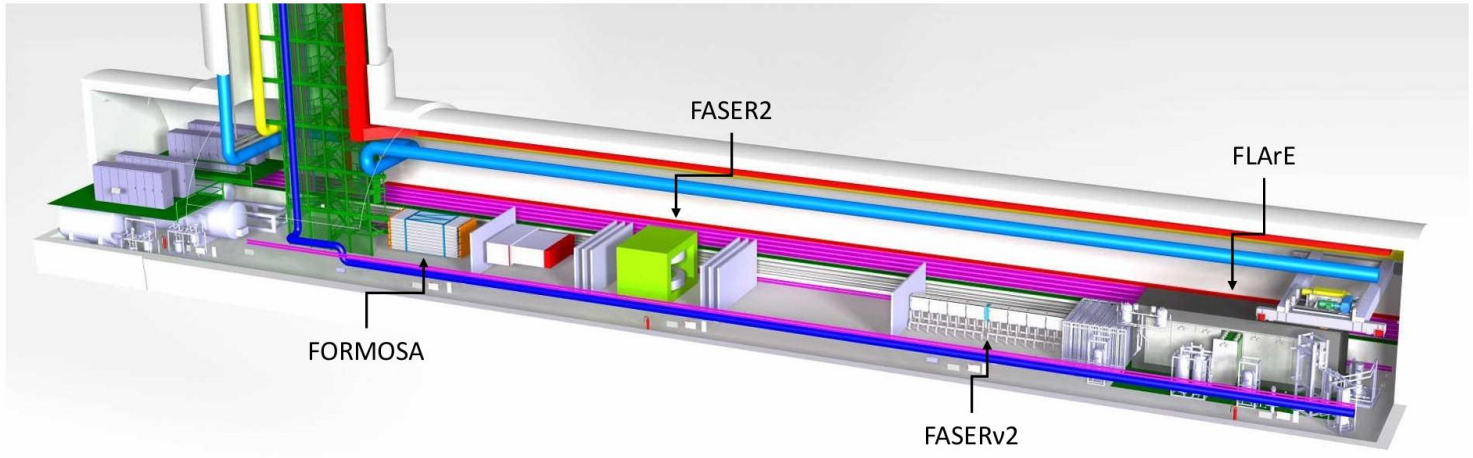


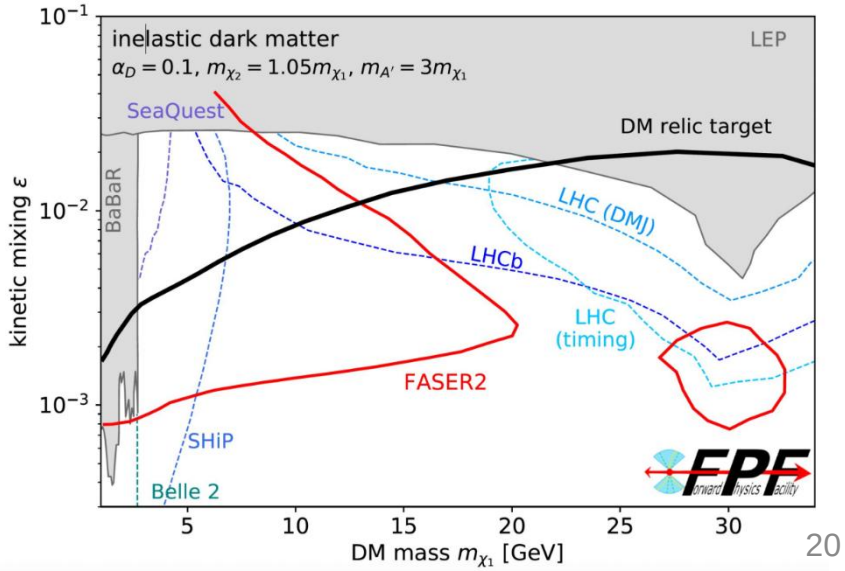


Expansion for HL-LHC: Forward Physics Facility

- Proposal to have a cavern housing 4 experiments 627m away from the LHC interactions
- Unique potential to shed light on neutrino physics (10^3-10^4 ν_τ interactions), and search for dark matter and other new particles …







See Akitaka Ariga's talk on Monday

FPF proposal

Summary

- FASER provides word-leading limits for dark photon (27 fb^{-1}) and ALPs (57.7 fb^{-1}) search
- New Preshower detector installed during Run3 upgrade
  - Will help with BSM searches (e.g. ALPs)
- FASER approved at Run4
  - More statistics will boost the sensitivities
- Forward Physics Facility (FPF) housing several detectors (inc. FASER2) is under discussion
  - Will provide significant new sensitivity in all dark sector

Thank you!

Backup

Dark photon decay

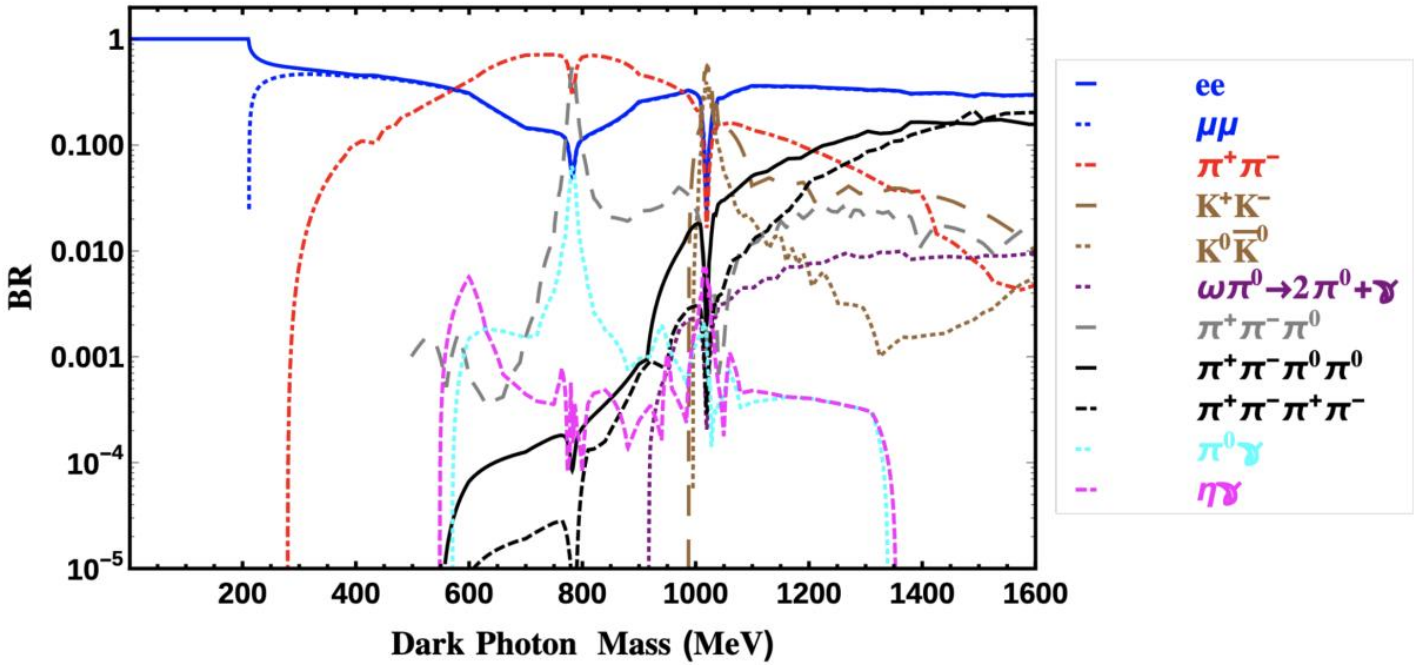


FIGURE 2.8. The dark photon decay branching ratios are shown for varying dark photon mass. Plot taken from Ref [8].

FASER

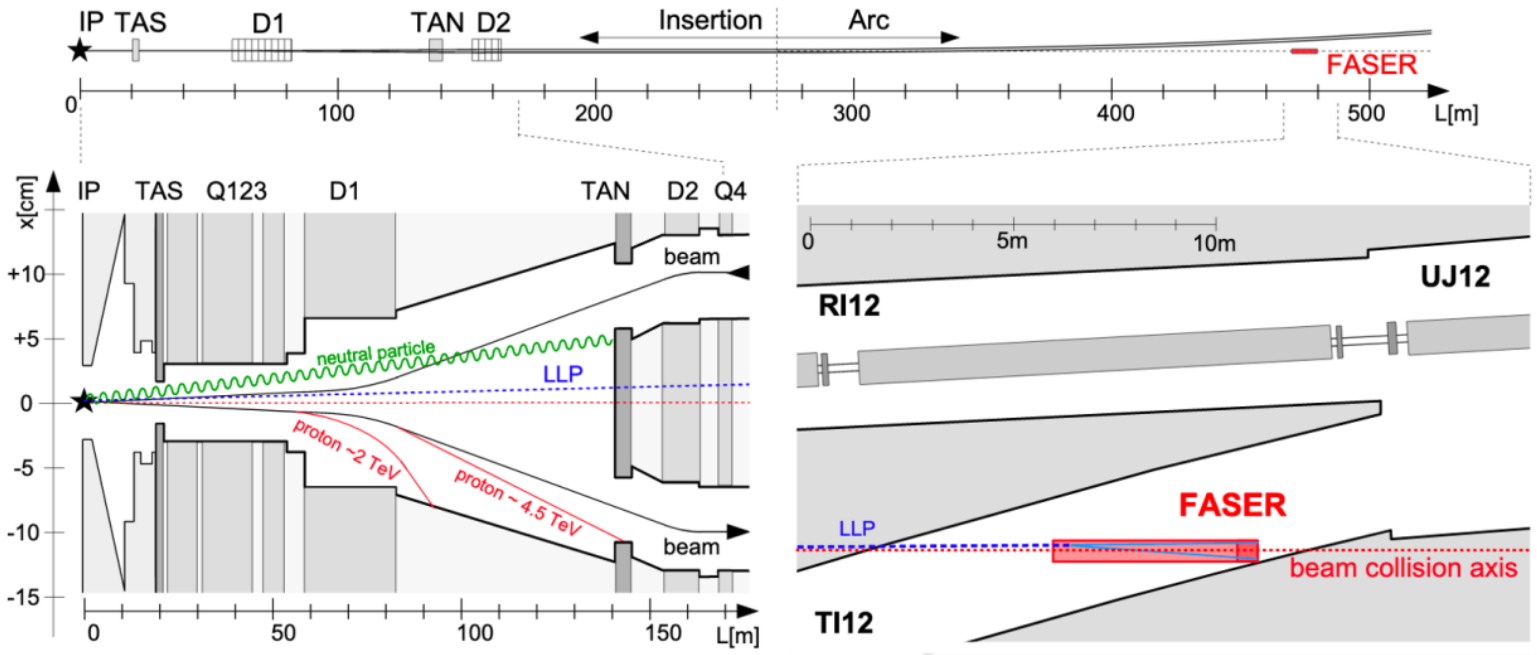


FIGURE 3.4. A schematic showing the location of FASER with respect to the LHC beam and IP1. More detailed views of the LHC beam are shown in the BOTTOM LEFT for distances up to 170 m from the IP, and in the BOTTOM RIGHT for the area around FASER at ∼480 m. The beam collision axis line-of-sight is shown as a dashed red line.

Pi0 production

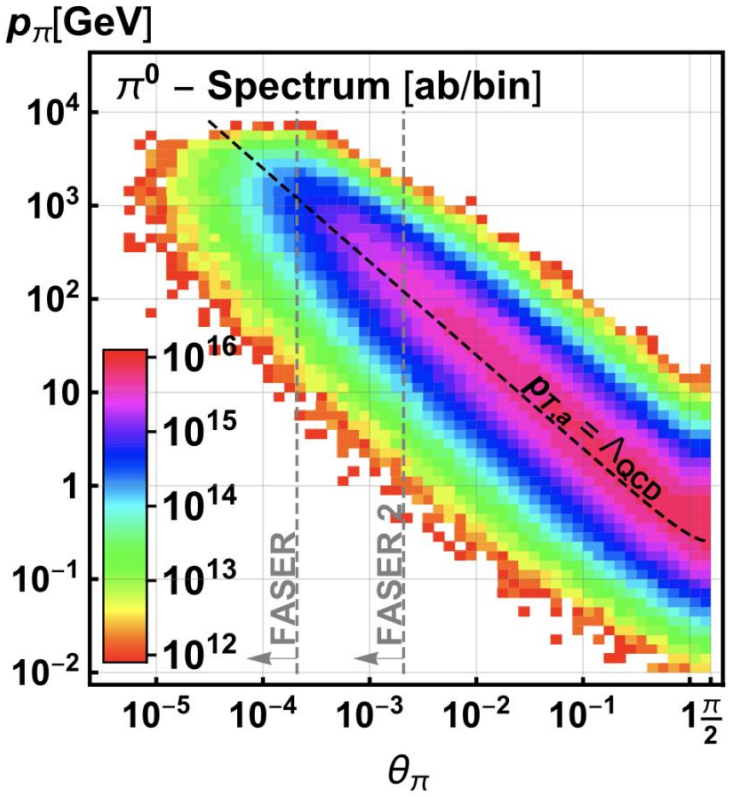
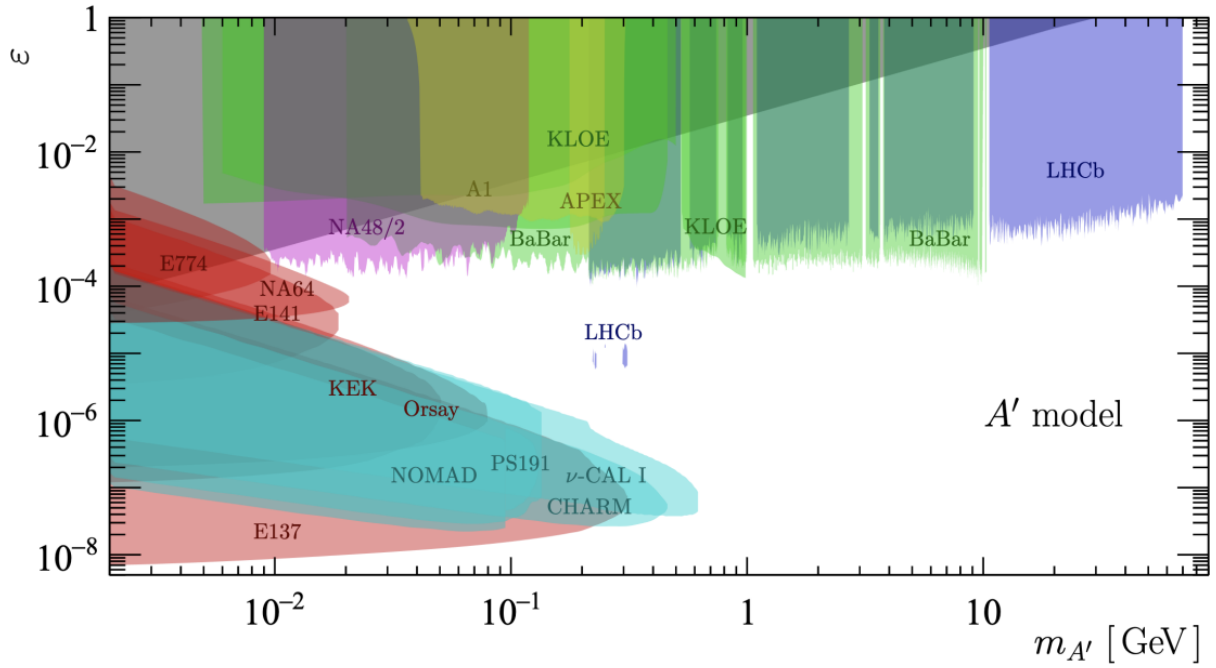


FIGURE 3.5. The production rates of π^0 from the LHC IP, obtained via EPOS-LHC [13], are shown as a function of the meson's angle with respect to the beam axis (θ_π) and momentum (p_π). The angular acceptances for FASER and FASER2 (a proposed future detector) are indicated by the vertical gray dashed lines. Figure is from Ref [14]

Dark photon previous measurements

JHEP, 06, 004, 2018



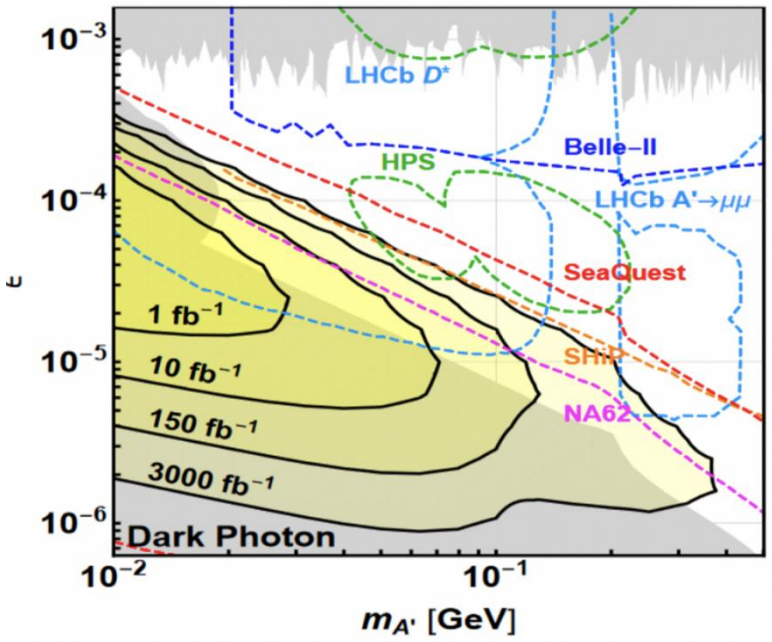


FIGURE 2.9. The dark photon parameter space is depicted with shaded regions showing the dark photon mass ($m_{A'}$) and kinetic mixing constant (ϵ) that have been excluded from past experiments. The colors of the shaded regions refer to experiments that utilized a similar A' production mechanism where experiments shaded in RED used electron beam dumps, CYAN used proton beam dumps, GREEN used e+e- colliders, BLUE used pp collisions, MAGENTA used meson decays, and YELLOW used electrons on a fixed target. The GREY constraint comes from the precise measurement of the electron magnetic dipole moment. Figure is from Ref [9].

Dark photon affects the electron magnetic dipole moment scaling with $\frac{\epsilon^2}{m^2_{A'}}$

Visible decay with decay length: $\frac{E_{A'}}{\epsilon^2 m^2_{A'}}$

More ALPs interpretations

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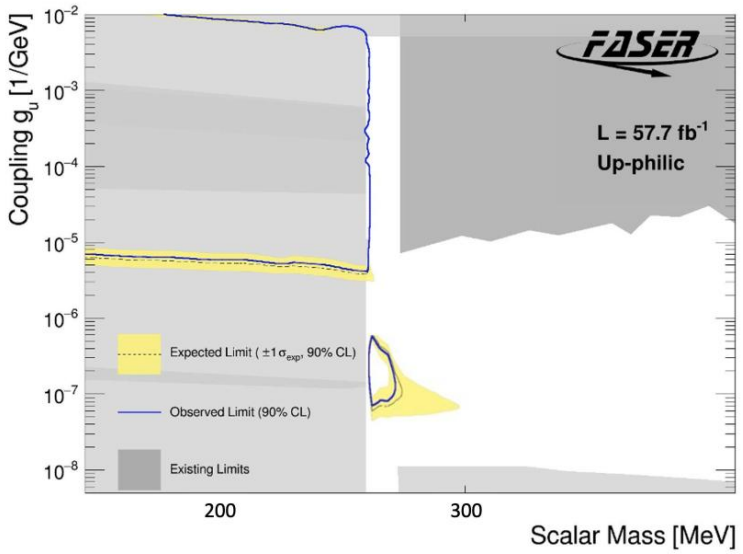

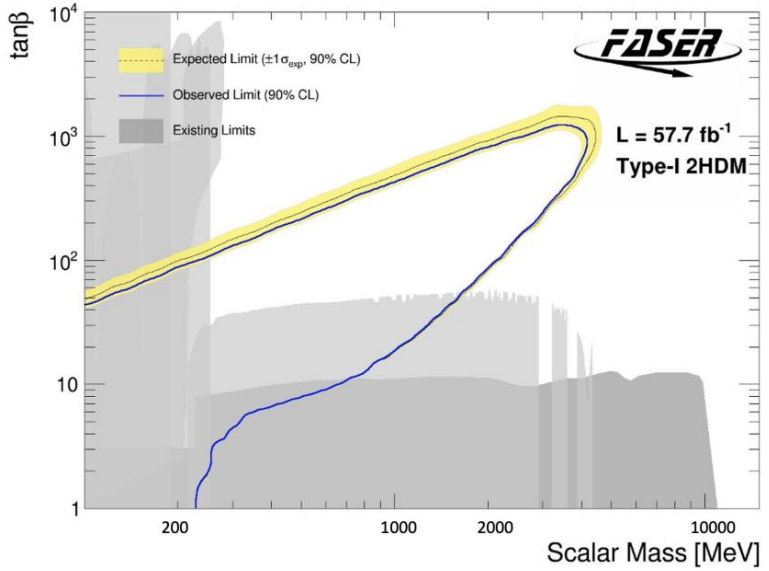

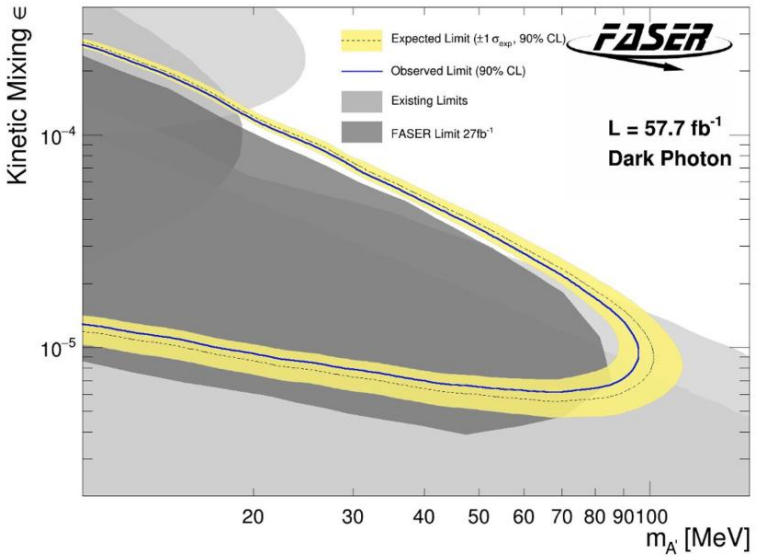

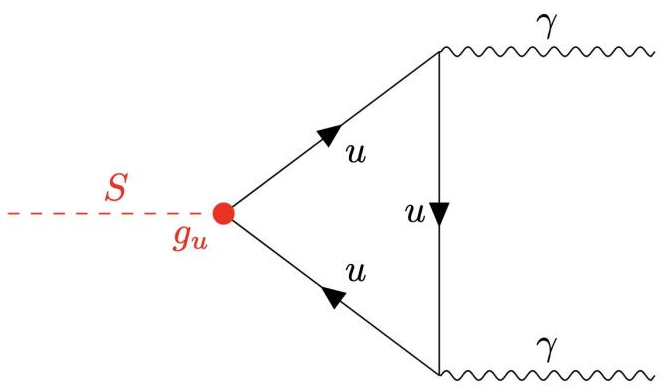

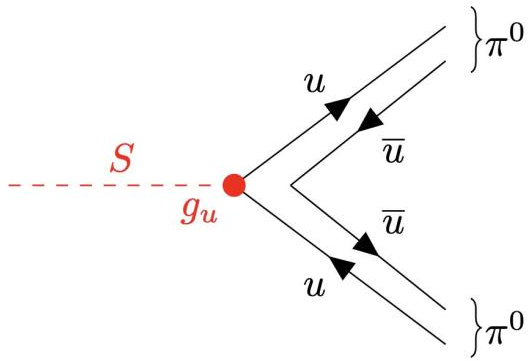

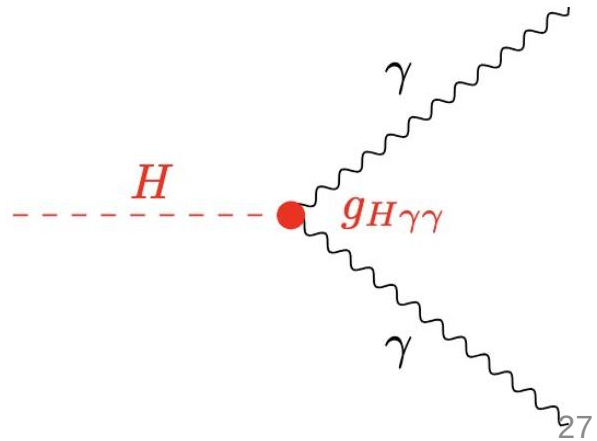

More ALPs interpretations

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