BSM Results from the FASER Experiment at the LHC

Fourteenth workshop of the Long-Lived Particle Community
July 5th, 2024

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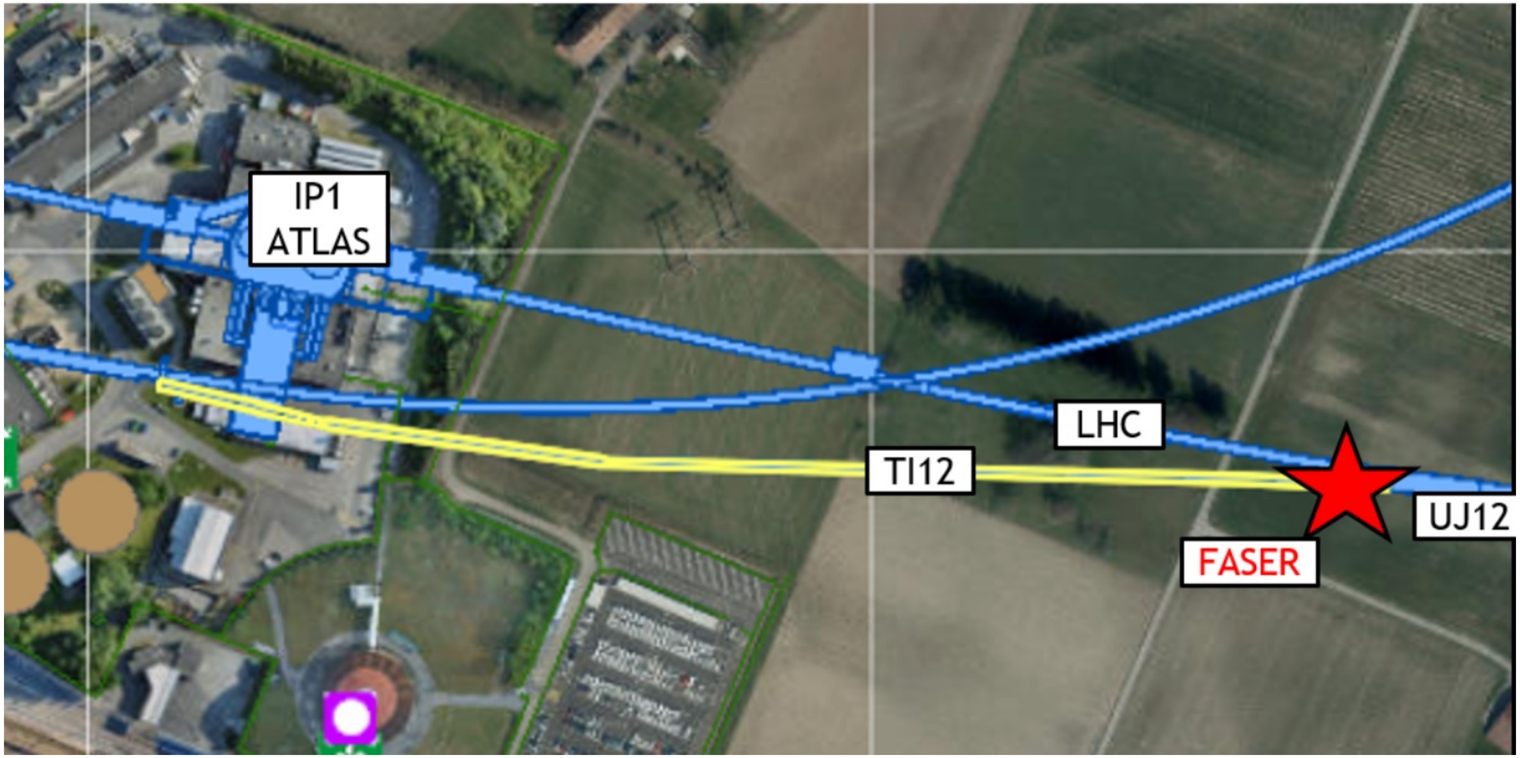
on behalf of the FASER Collaboration

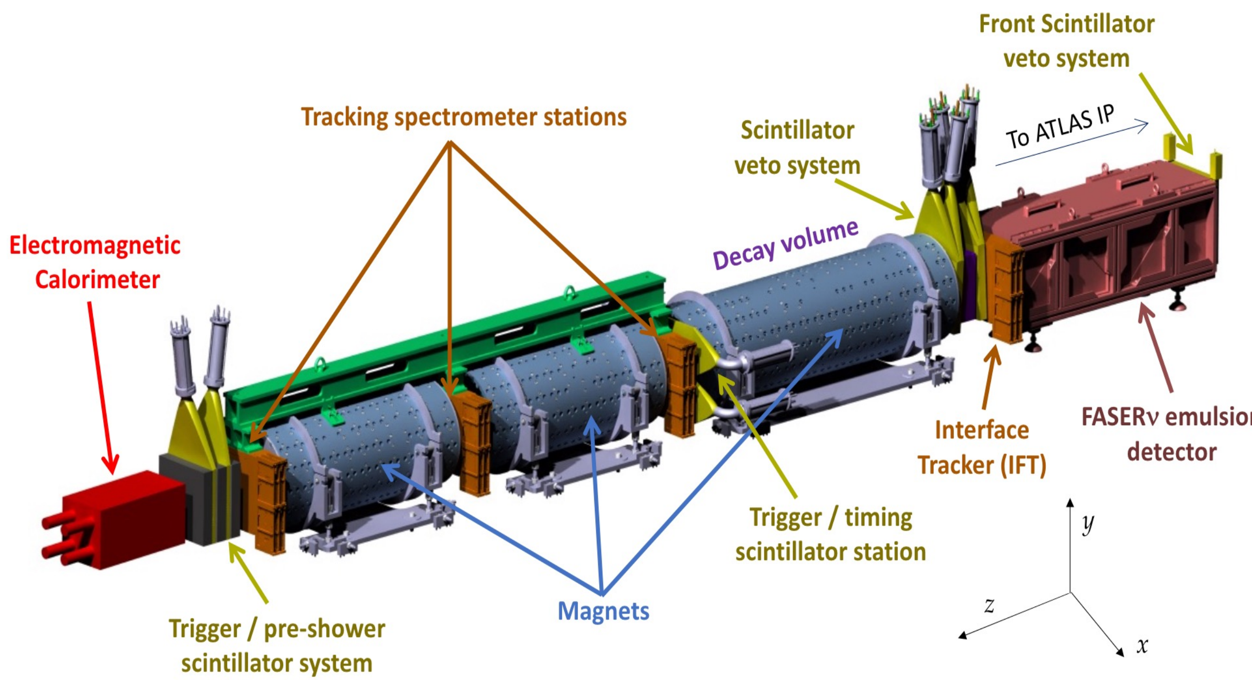
FASER Introduction

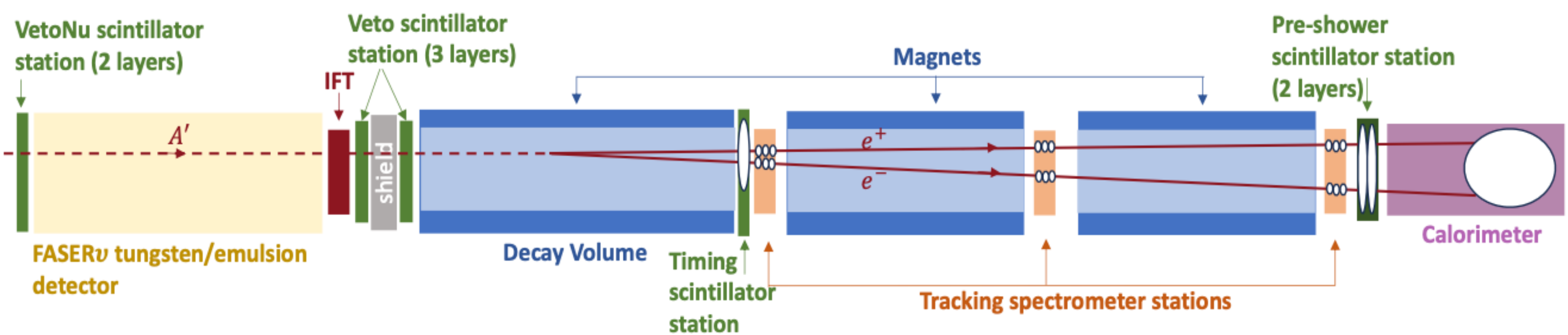
- ForwArd Search ExpeRiment.
- Search for new physics and neutrinos in the very forward physics region.
- The detector location (480 m downstream of the ATLAS interaction point) allows near background-free searches.



the FASER Detector

- small
- inexpensive
- 480 m downstream of the ATLAS collision point
- 10 cm radius of active volume
- 7 m long





BSM Program at FASER

- Open questions:
  - Understanding the nature of dark matter
  - the origin of neutrino masses
  - relative asymmetry in matter and anti-matter abundances in the Universe
- FASER is searching for light long-lived particles (LLPs) that are produced at or close to the ATLAS collision point:

  pp → LLP + X, LLP travels ~480 m, LLP → charged tracks + X or 2 photons

- FASER is sensitive to such decay signatures of LLP models:
  - dark photons
  - dark Higgs bosons
  - heavy neutral leptons (HNL)
  - axion-like particles (ALP)
- FASER probes unexcluded regions of the parameter space of LLP with Run 3 data.

Dark Photons at FASER

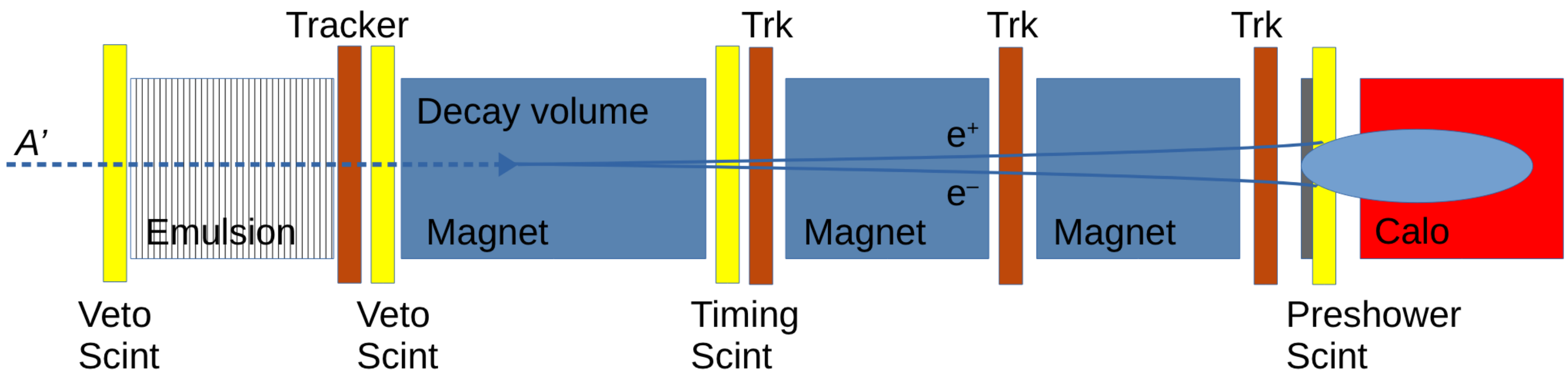
- Dark photons :
  - Hypothetical gauge bosons associated with a new U(1) gauge symmetry
  - Vector particles (spin-1)
  - Can act as a mediator to dark matter
- Defined through the Lagrangian items:

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

  - $m_{A'}$: dark photon's mass
  - ϵ: dark photon's kinematic mixing parameter
  - $\sum$: over all SM fermions f with SM electric charge q_f
- At the LHC, the dominant source of dark photons:
  - SM meson decay:
    - Neutral pion decay $\pi^0 \to A'\gamma$
    - Eta meson decay $\eta \to A'\gamma$
  - Dark bremsstrahlung $pp \to ppA'$

Dark Photons: Event Selection

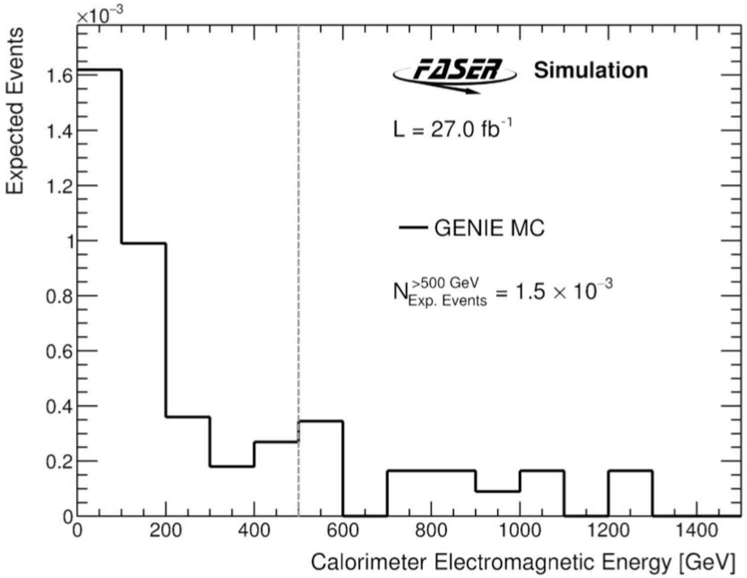
- Blinded for E > 100 GeV events without any veto signals.
- Select $e^{+}e^{-}$ pairs emerging in the decay volume:



- The signal region event selection requires:
  - In time with the LHC collisions;
  - no signal in veto scintillators;
  - signal in the donwstream scintillators;
  - two opposite sign tracks within fiducial volume;
  - total calorimeter energy > 500 GeV;
- The selection efficiency is about 50% in the parameter space where the analysis is most sensitive ($\epsilon = 3\times10^{-5}, m_{A'} = 25.1$ MeV)

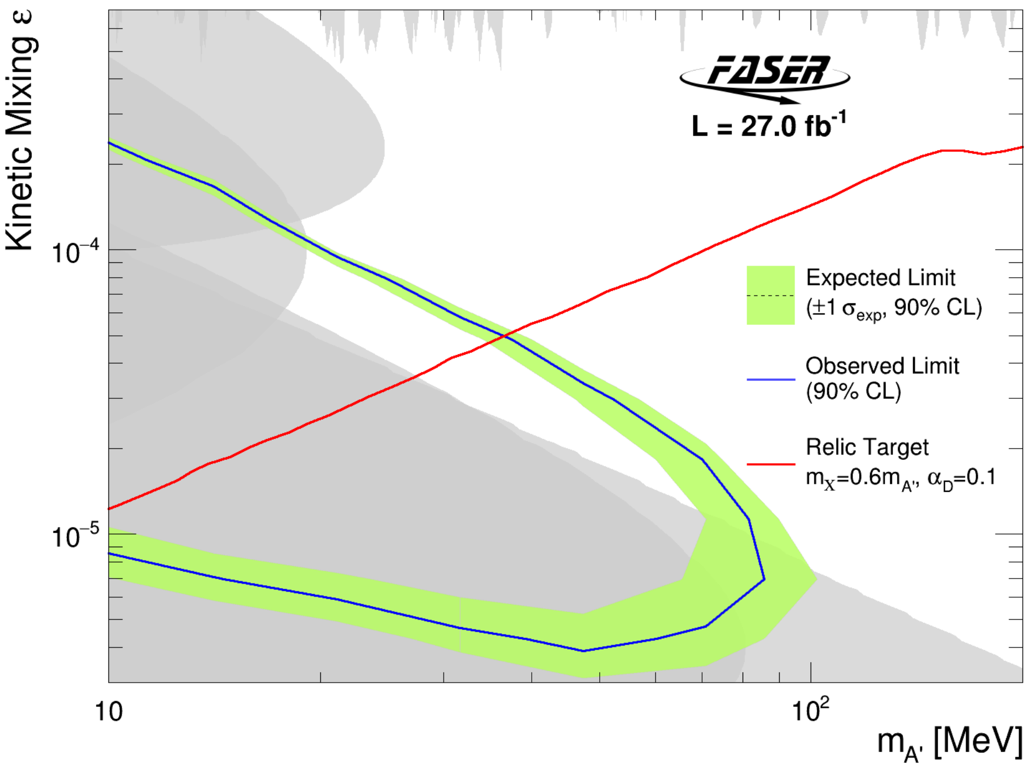
Dark Photons: Backgrounds

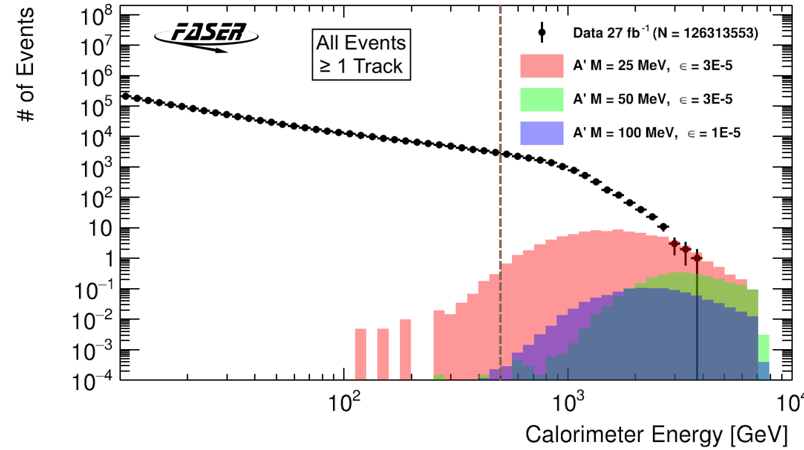
- Veto inefficiency
  - smaller than 10^{-20}; incoming muons 10^8 ⇒ negligible!
- Neutral hadrons
  - produced by upstream muon interactions
  - A final estimate of $(8.4 \pm 11.9) \times 10^{-4}$ events is found.
- Large-angle muons
  - zero events with E>500 GeV or extrapolated in the fiducial volume ⇒ negligible!
- neutrinos
  - use neutrino MC sample of 300 ab^{-1}
  - The total neutrino background scaled to 27.0 fb^{-1} is estimated to be $(1.5 \pm 0.5\ (stat.) \pm 1.9\ (syst.)) \times 10^{-3}$ events.
- non-collision events
  - zero events with E>500 GeV or a reconstructed track ⇒ negligible!

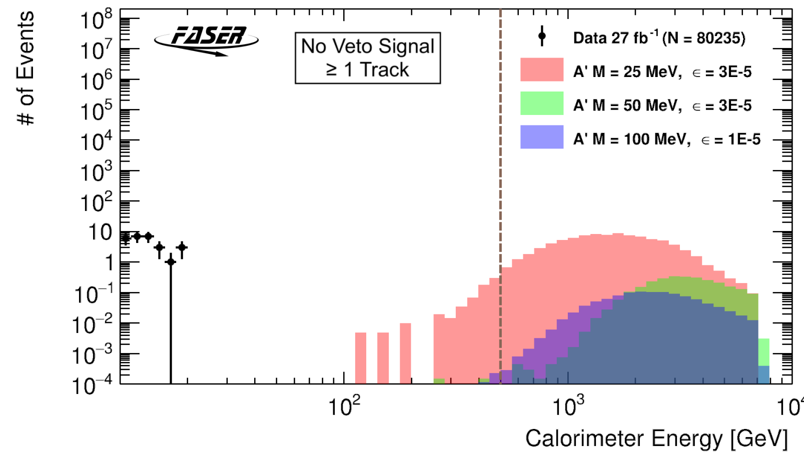


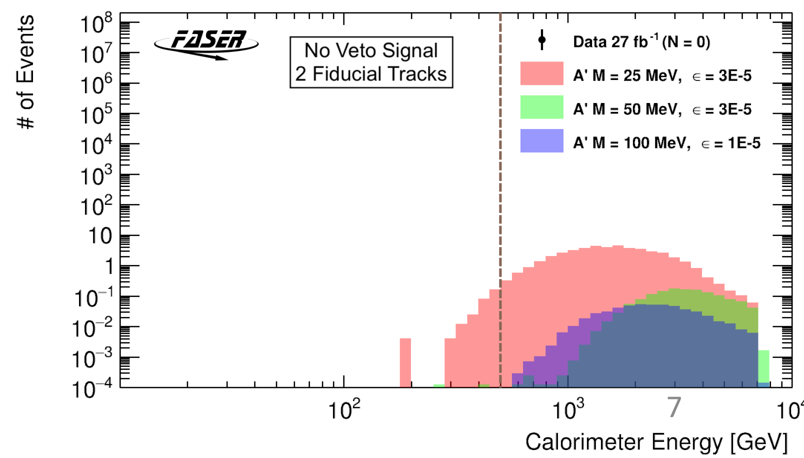
Dark Photons: Results

- No events observed in 27.0 fb^{-1} from 2022
- FASER set limits on previously unexplored parameter space
- $(2.3 \pm 2.3)\times 10^{-3}$ background events are expected.







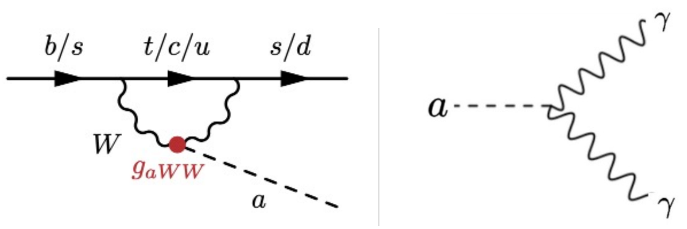


ALPs at FASER

- Axion-like particles (ALP):
  - The generalizations of the axion, can couple to $\mathrm{SU}(2)_\mathrm{L}$ gauge bosons
  - Pseudoscalar particles (spin-0)
  - Can be a form of dark matter
- Defined through the Lagrangian items:

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

  - m_a: the ALP mass
  - g_{aWW}: the ALP coupling parameter
  - $W^{\mu\nu}$: the $\mathrm{SU}(2)_\mathrm{L}$ field strength tensor



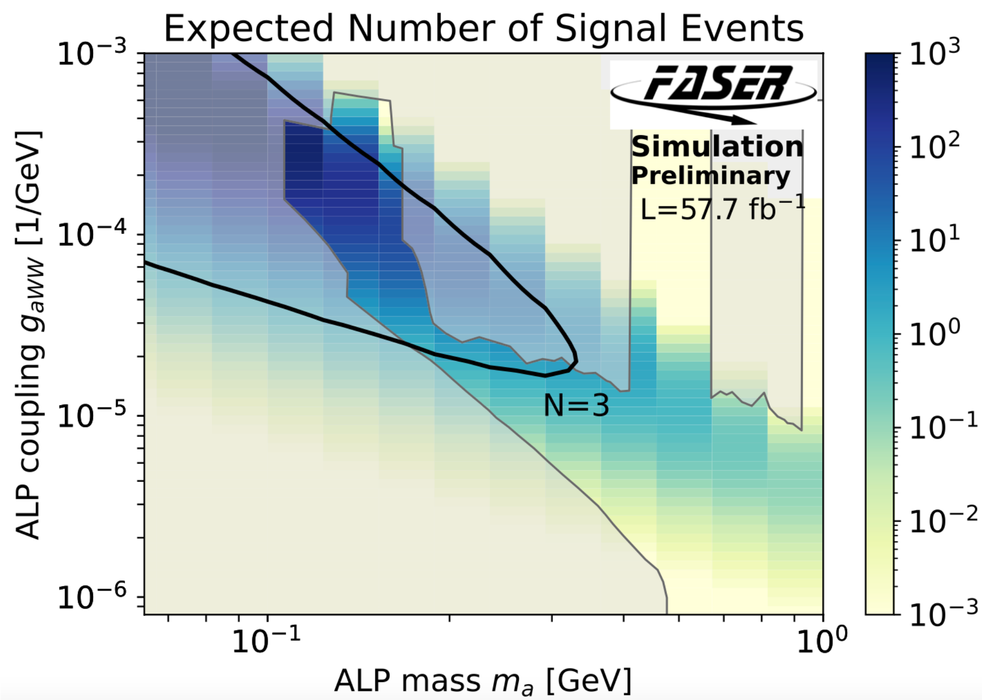
- Main source: $B^0, B^\pm$ meson decays
- Once produced, the ALP decays into two high energy photons
- Signal: Two photons appearing from "nothing" with ~TeV of EM energy
- Can decay anywhere between veto scintillators and preshower

ALPs: Event Selection

Blinded for E > 100 GeV events with a limited deposited charge in any veto scintillators.

Requirements:

- No signal in the veto scintillators
- No signal in the timing scintillator
- Evidence of EM Shower in preshower detector
- Significant energy deposit in electromagnetic calorimeter



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)

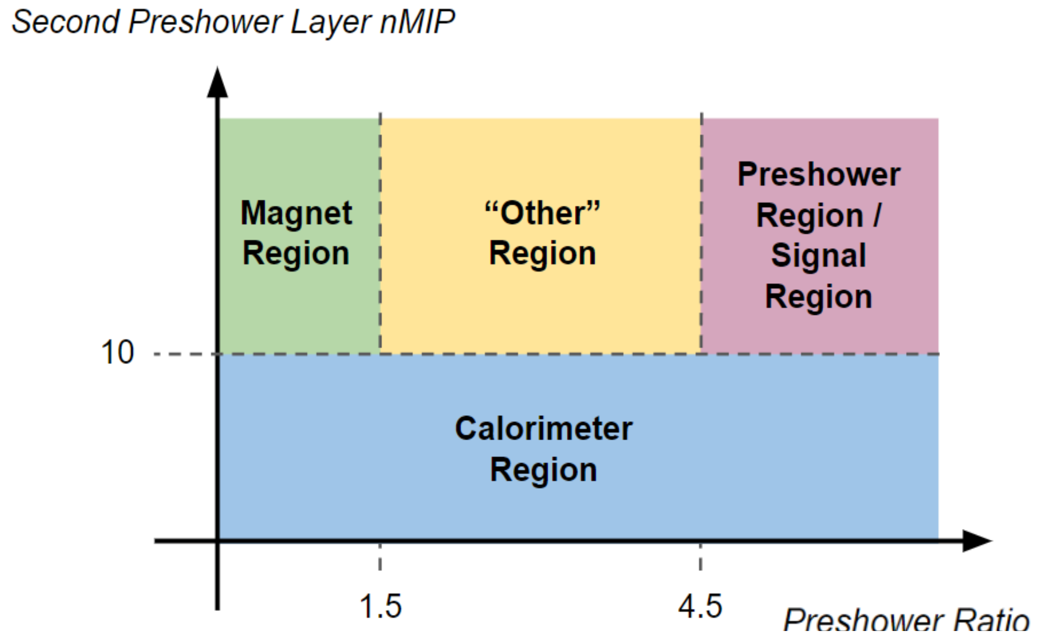
Selection efficiencies using MC:

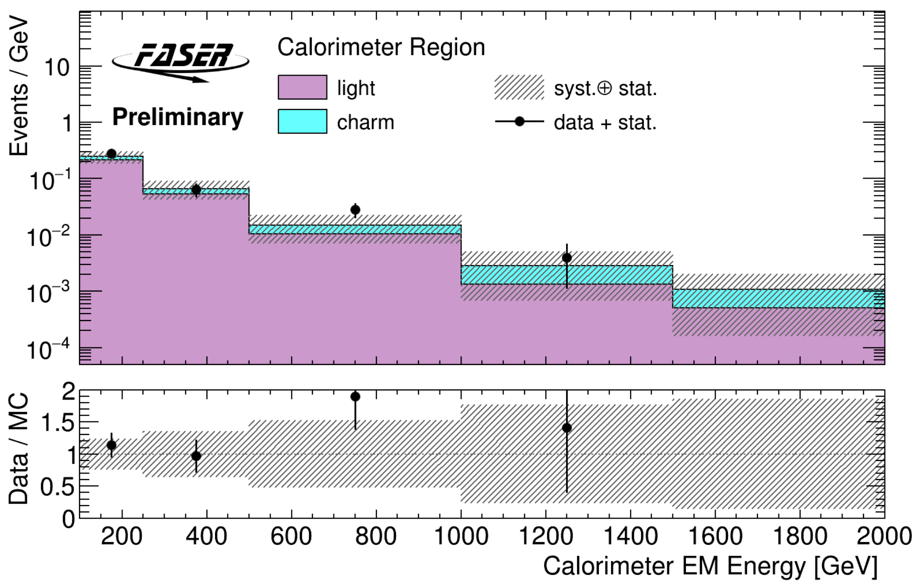
- $m_a = 140$ MeV, $g_{aWW} = 2{\times}10^{-4}$ GeV^{-1}
- Cum. efficiency: calorimeter E > 20 GeV, to emulate calorimeter trigger in MC

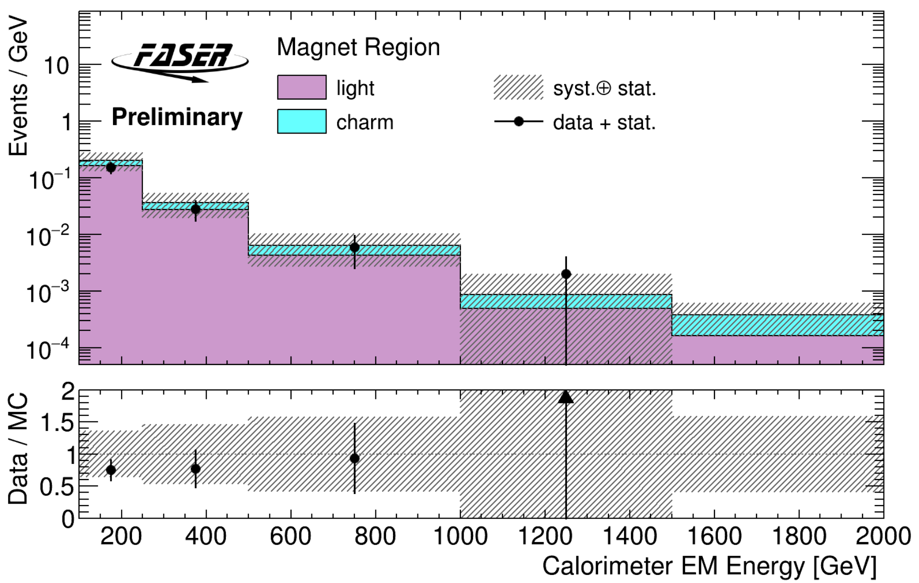
Selection	Efficiency	Cum. Efficiency
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}		
Veto Signal nMIP < 0.5	99.6%	99.6%
Timing Scintillator Signal nMIP < 0.5	97.8%	97.4%
Preshower Ratio > 4.5	85.7%	83.5%
Second Preshower nMIP > 10	98.6%	82.3%
Calo $E > 1.5$ TeV	91.6%	75.4%

ALPs: Backgrounds - Neutrinos

- Neutrino interactions: the primary background
- From light and charm hadron decays
- Evaluated using MC simulations
- Four regions are defined based on the location of neutrino interactions used to validate the neutrino background estimation

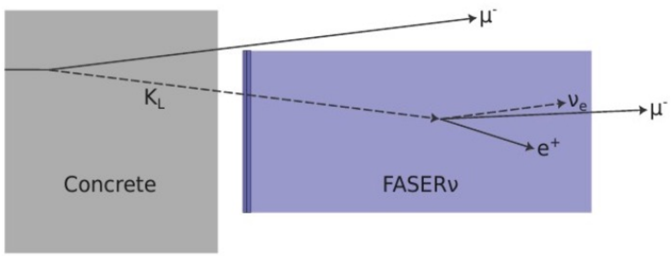




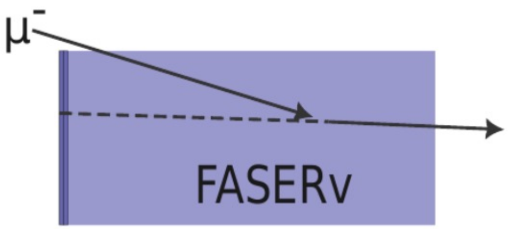


ALPs: Backgrounds

Neutral hadrons



Scattered muons

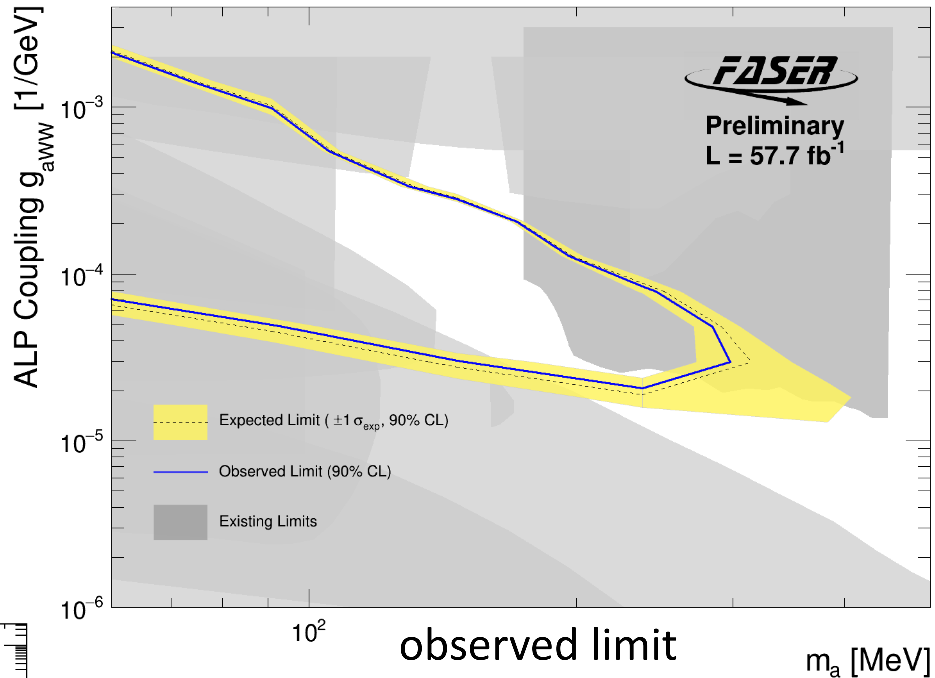


Veto inefficiency

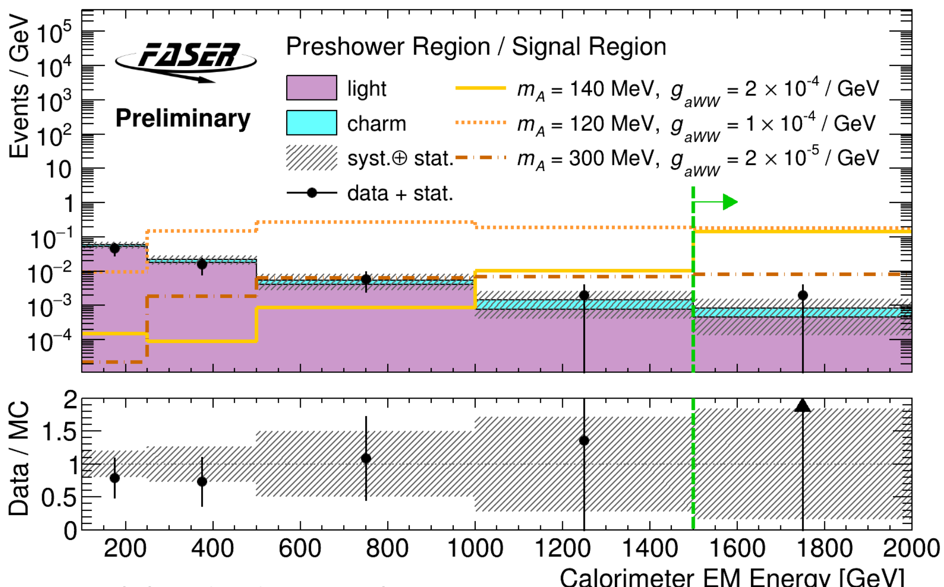
- Veto inefficiency
  - smaller than 10^{-20}; incoming muons 10^8 ⇒ negligible!
- Neutral hadrons
  - produced by upstream muon interactions
  - Calorimeter energy requirement E > 1.5 TeV ⇒ negligible!
- Large-angle muons
  - Evaluated using MC simulations
  - No events pass the selections applied ⇒ negligible!
- non-collision events
  - zero events with E>1.5 TeV or passing the calorimeter timing selections ⇒ negligible!

ALPs: Unblinded Results

- data luminosity $57.7\ \text{fb}^{-1}$.
- 1 data event observed in the signal region.
- Backgound expectation 0.42 ± 0.38.
- Set limits on the previously unprobed parameter space.



observed limit

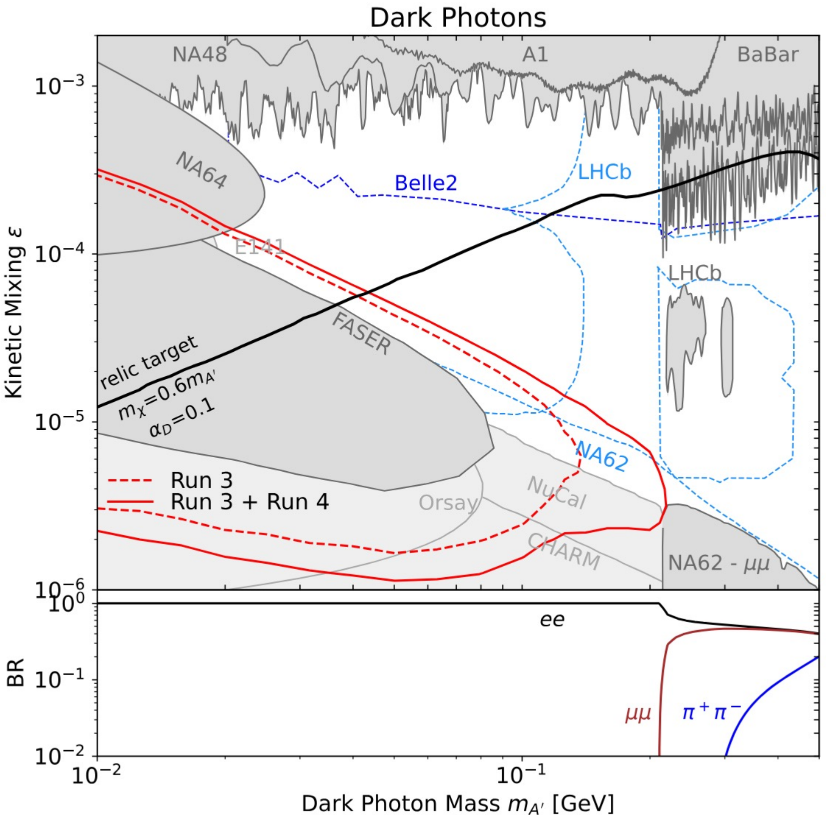


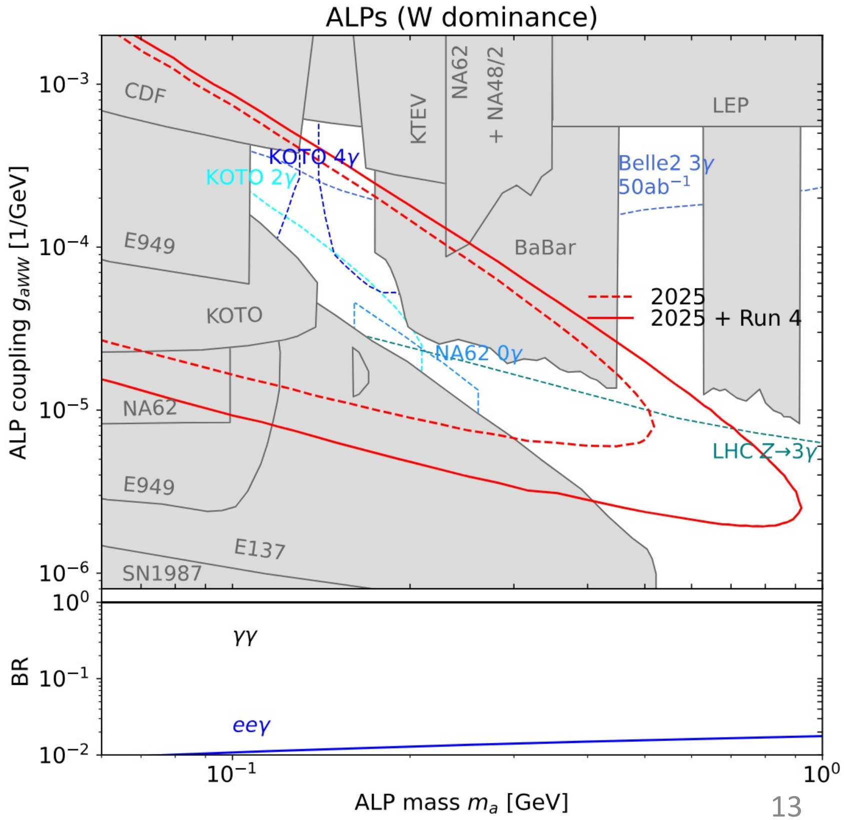
unblinded signal region

- Shows preshower deposits consistent with an EM shower
- Calorimeter energy of 1.6 TeV

Future Plans

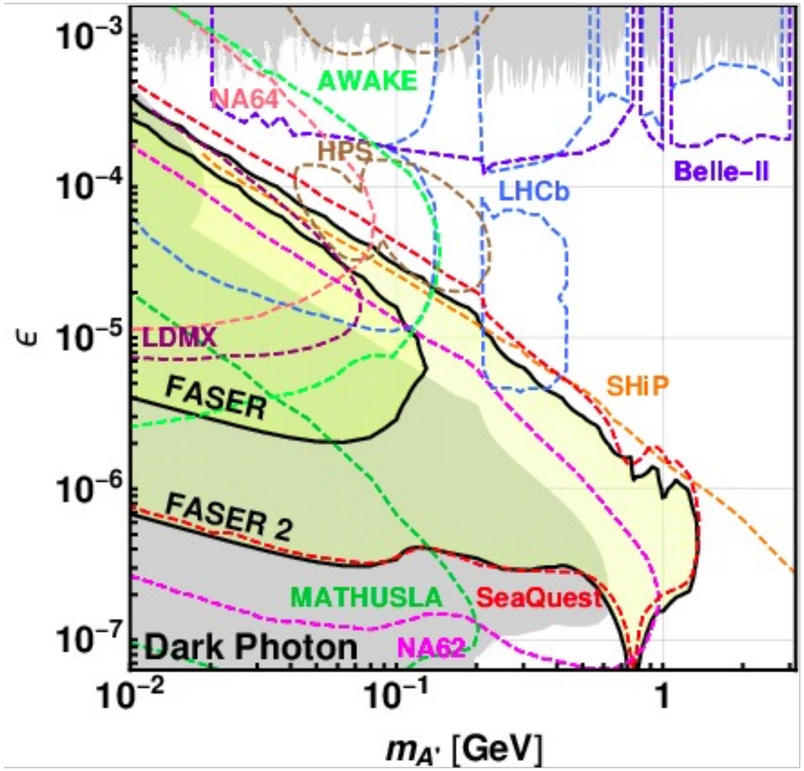
- FASER approved to run in Run4
  - large dataset with upgraded FASER at HL-LHC
- Predicted reach for FASER's dark photon and ALP searches with combined Run 3 + Run 4 datasets
  - Assuming a total $250\ \mathrm{fb}^{-1}$ for Run 3
  - Assuming a total $680\ \mathrm{fb}^{-1}$ for Run 4

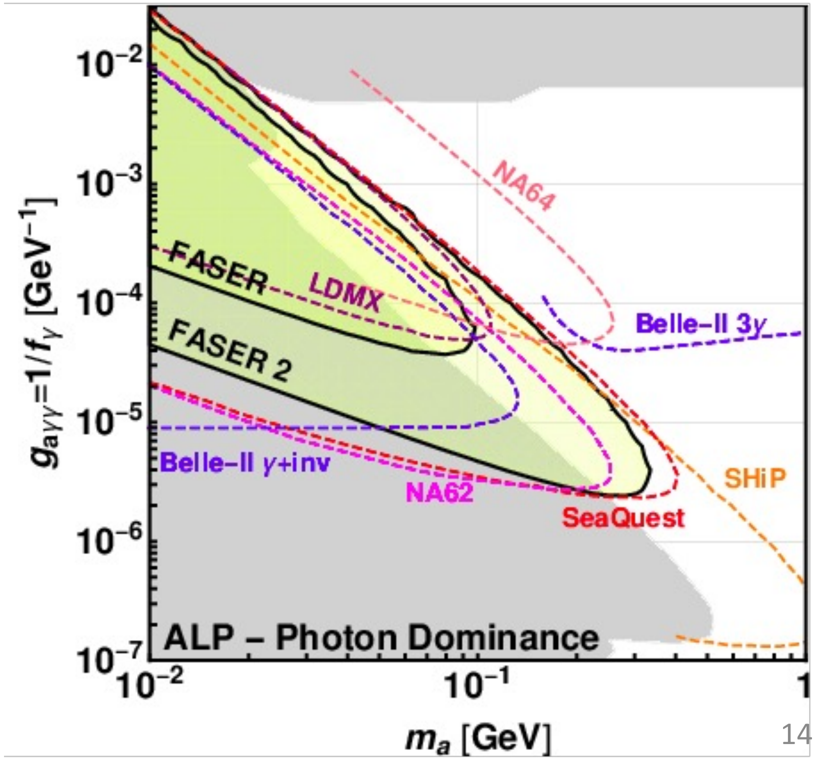




Summary and Outlook

- FASER explored new regions in the dark photon parameter space
- FASER has probed new ALPs parameter space at mass and coupling previously unexplored by previous experiments
- FASER expects to collect much more data in Run 3 and 4 allowing for more powerful searches for dark photons, ALPs, and other new physics models





The FASER Collaboration

99 collaborators, 27 institutions, 11 countries

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UC IRVINE

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NAGOYA UNIVERSITY
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THANKS!

BACKUP

Dark Photons: Systematics

Main sources of systematic uncertainties:

- signal generators used
- integrated luminosity
- stat. from MC simulated events
- track momentum scale and resolution
- tracking efficiency of single tracks
- tracking efficiency of two closely-spaced tracks
- the calorimeter energy scale calibration

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% ($< 1\%$)

ALPs: Systematics

- Sources of systematic uncertainties:
  - Theoretical: flux modelling and generator variations
  - Experimental:
    - MC modelling of detector response
    - luminosity uncertainties
  - MC statistics

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%)

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: Backgrounds - Neutrinos

> 1.5 TeV signal region	
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	**0.42 $\pm$ 0.38 (90.6%)**