New physics results from the FASER experiment

ICHEP 2024

18-24 July 2024

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on behalf of the FASER collaboration

CERN-FASER-CONF-2024-001

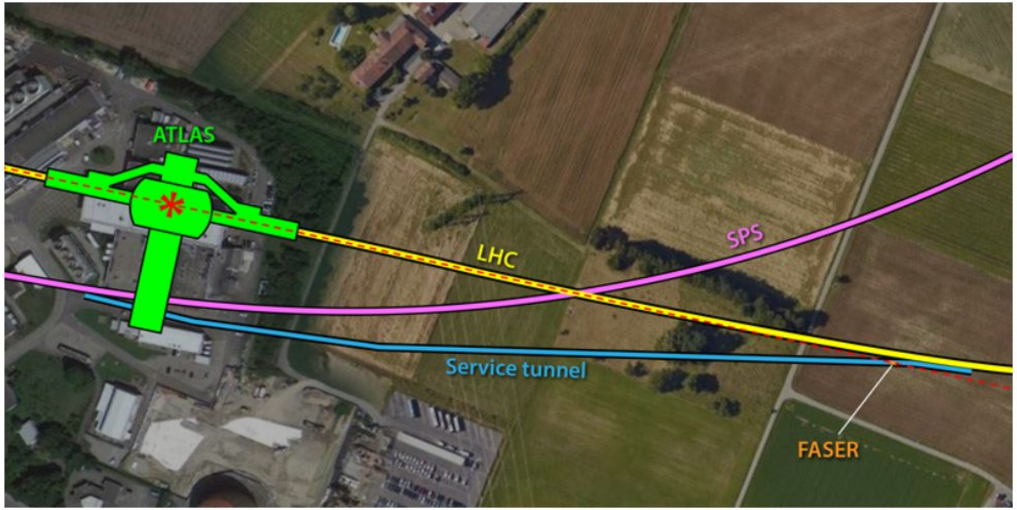
SIMONS FOUNDATION HEISING-SIMONS FOUNDATION

FASER CERN JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

What is FASER?

FASER = ***F****orw****A****rd* ***S****earch* ***E****xpe****R****iment* faser.web.cern.ch

- ➔ (Relatively) new experiment at the LHC built and installed in 2019-2021
  - Successful data-taking throughout Run 3



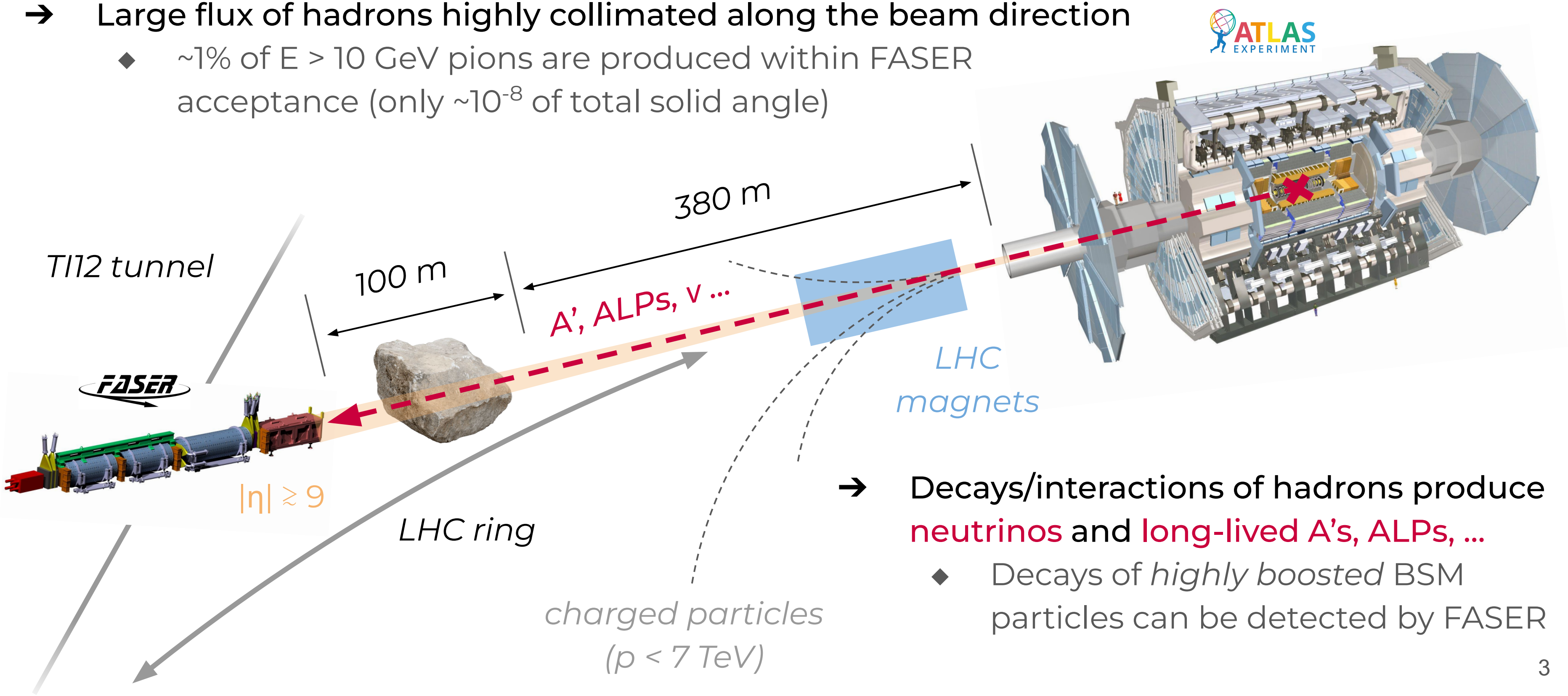
Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

- ➔ Targets light and weakly interacting particles
- ➔ ~7 m x 25 cm x 30 cm detector
- ➔ ~480 m downstream of ATLAS IP
- ➔ On collision axis line-of-sight

ATLAS forward region

➔ Large flux of hadrons highly collimated along the beam direction

- ~1% of E > 10 GeV pions are produced within FASER acceptance (only ~10^{-8} of total solid angle)

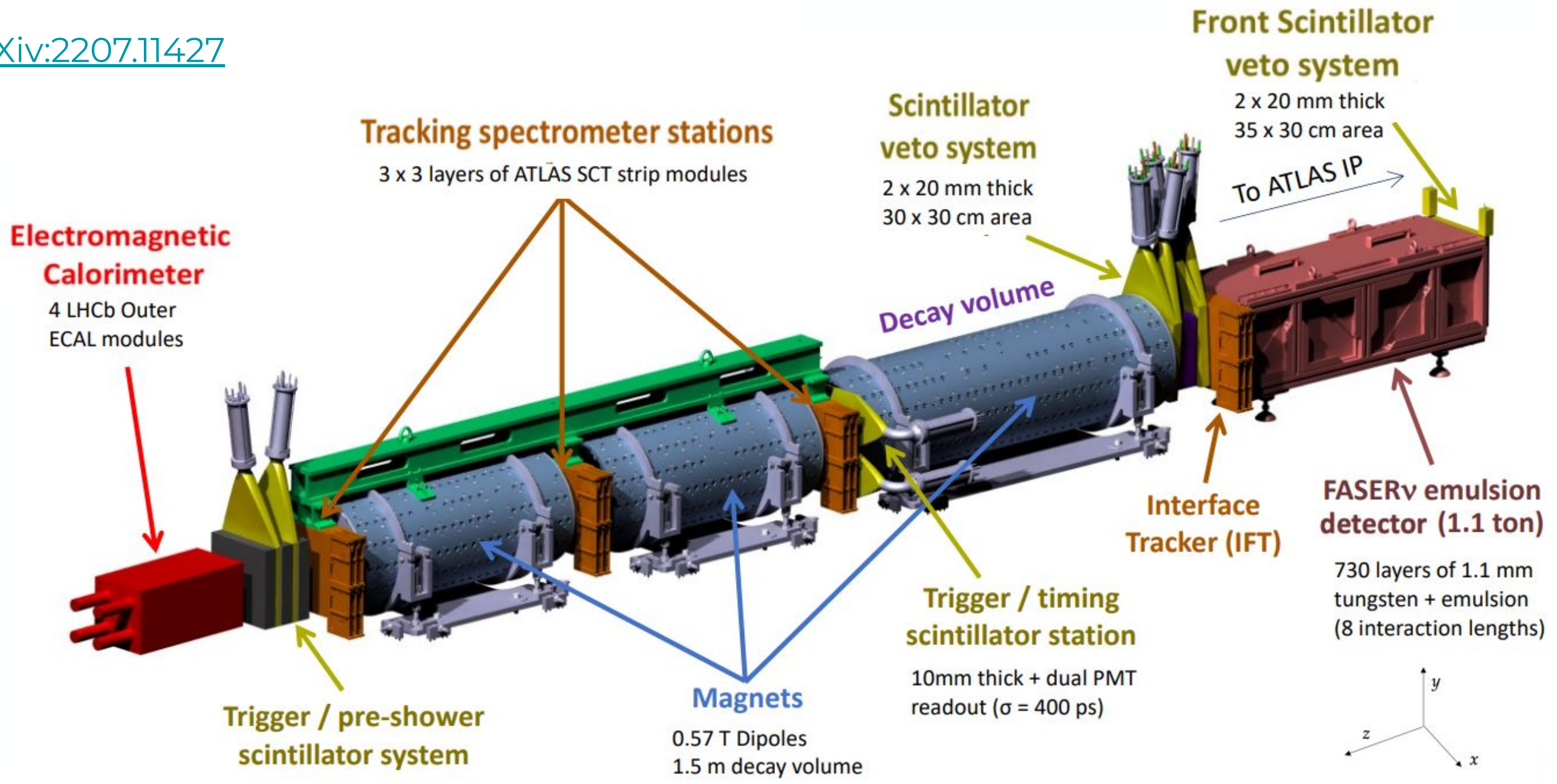


➔ Decays/interactions of hadrons produce neutrinos and long-lived A's, ALPs, ...

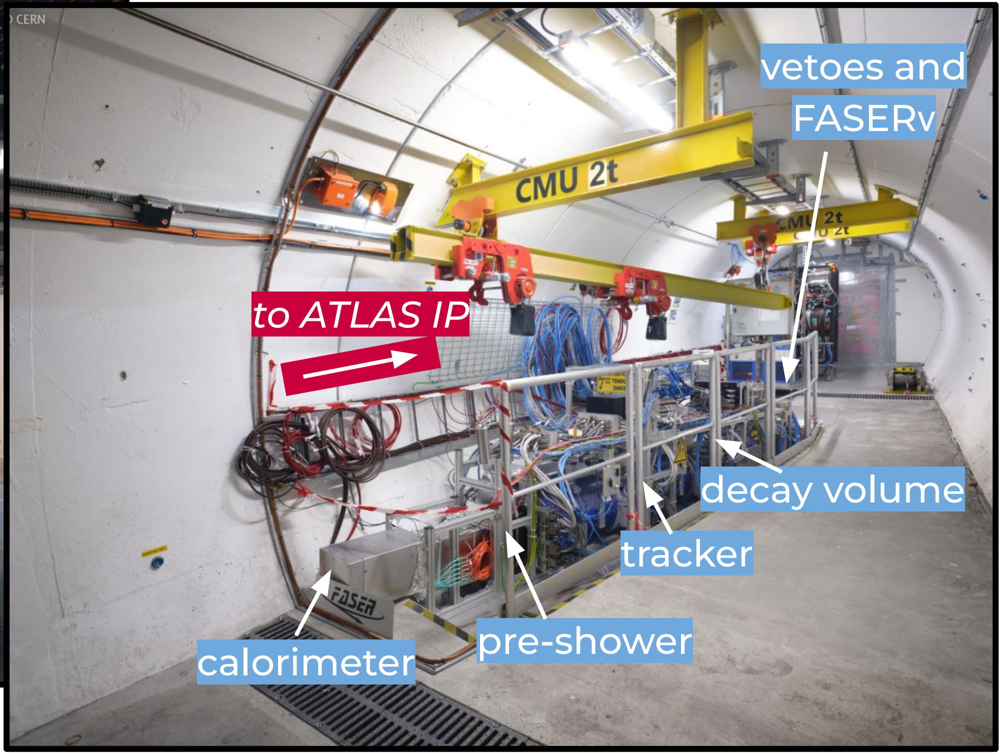
- Decays of *highly boosted* BSM particles can be detected by FASER

The FASER detector

arXiv:2207.11427

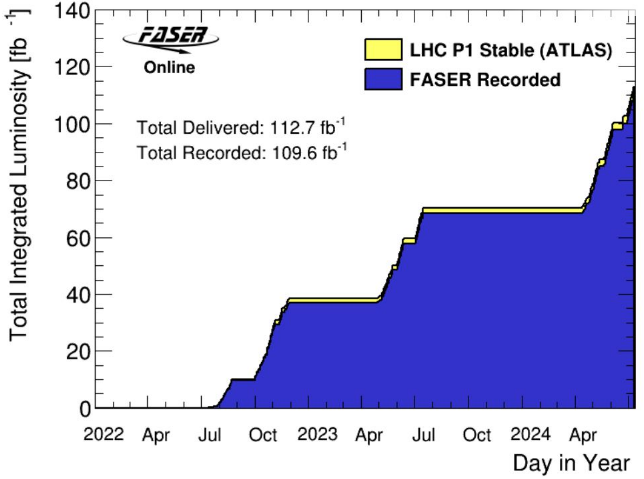


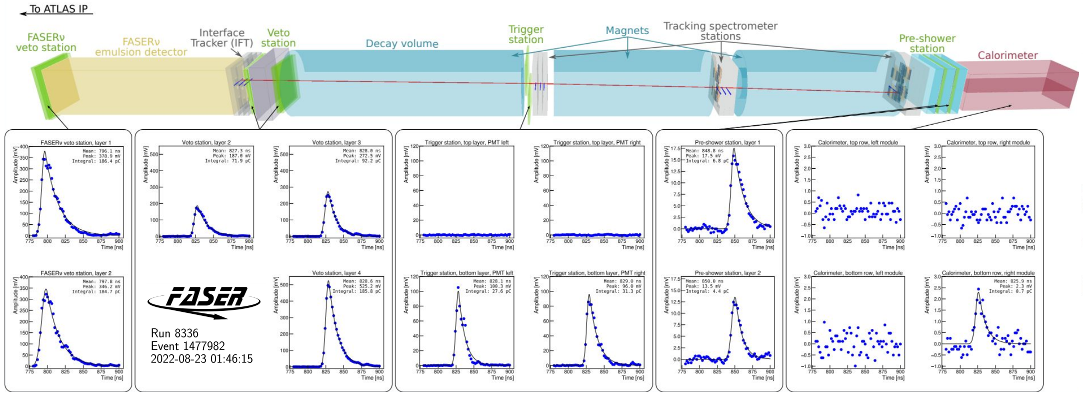
The FASER detector

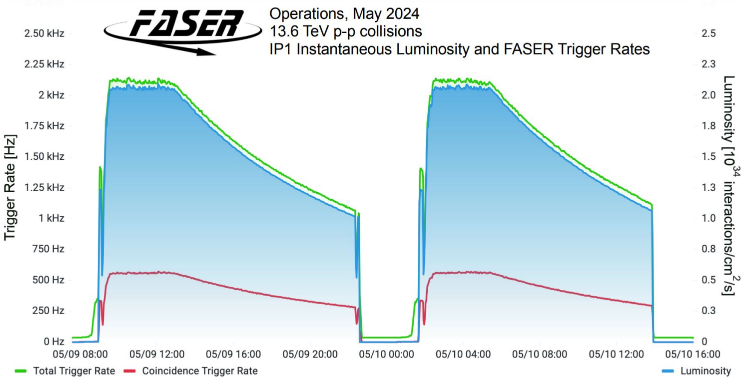


FASER operations

- ➔ Continuous and largely automatic data taking in Run 3
  - ◆ Up to 2 kHz trigger rate in 2024
- ➔ Recorded 97.4% of delivered luminosity
  - ◆ Limited by deadtime (<3%)
  - ◆ Luminosity information provided by ATLAS
  - ◆ Recently passed 100 fb^{-1} of data collected!





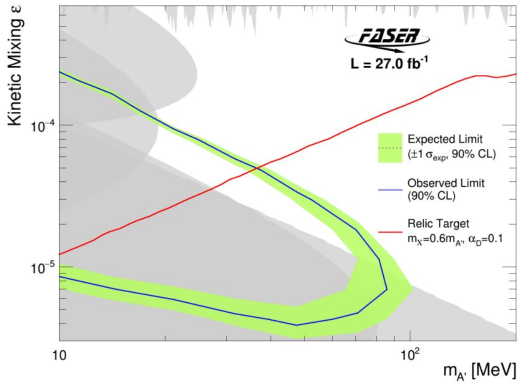


BSM searches with FASER

Charged particle searches

➔ Search for dark photons ($A' \to e^+e^-$)
Phys. Lett. B 848 (2024) 138378

- Track-based analysis
- 27.0 fb^{-1}



Multi-photon searches

➔ Search for axion-like particles (ALPs)
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- Final state contains photons
- Calorimeter/pre-shower-based analysis
- 57.7 fb^{-1}

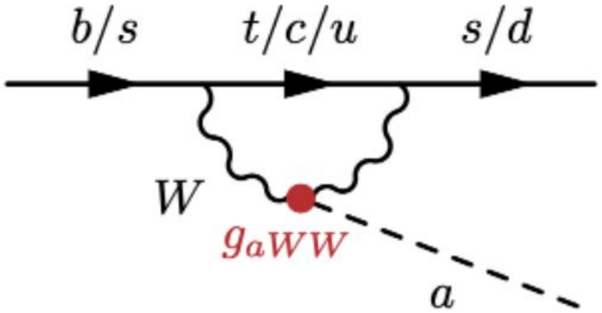
Focus of this talk

Axion-like particles at FASER

- ➔ Axion-like particles (ALPs) are a general class of pseudoscalar SM-singlets
  - Appear in multiple proposed extensions to the SM
  - FASER is particularly sensitive to ALPs coupling to SU(2) gauge bosons → "ALP-W"

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

  - ALP couples to weak gauge bosons and photons after EWSB

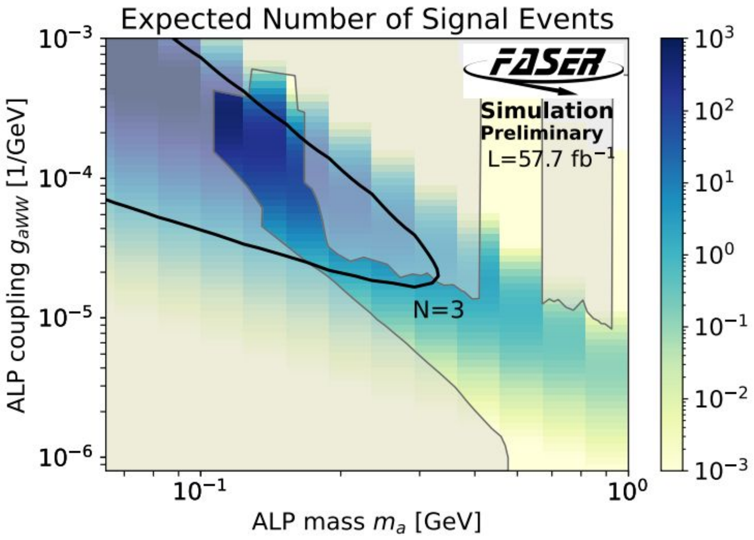


- ➔ FASER is most sensitive to parameter space with m_a ~ 50 - 500 MeV and g_{aWW} ~ 10^{-5} - 10^{-3} / GeV
  - Dominant production mechanism is via FCNC decays of B-mesons
  - Low mass ALPs ⇒ BR(ALP → γγ) ~ 100%

ALP signal simulation

- ➔ ALP signal events are generated using the FORESEE package arXiv:2105.07077
  - ◆ POWHEG+Pythia8 is used to model production of B mesons
  - ◆ Subdominant contribution from kaons simulated with EPOS-LHC

- ➔ Uncertainties on signal flux are the largest signal systematic in the analysis (~60%)
  - ◆ Scale variations for B hadron flux
    - ● Additional 20% uncertainty on BR for decays to LLPs
  - ◆ Envelope of generators for kaon flux

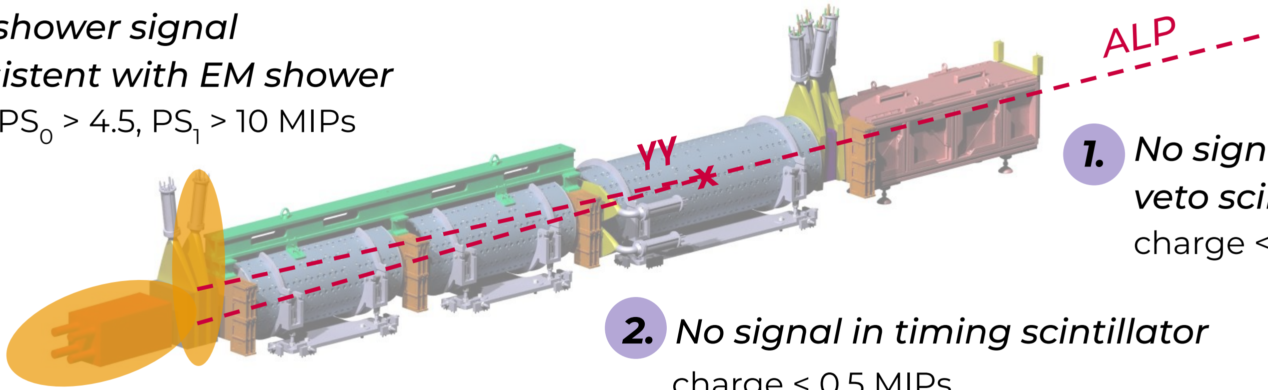


ALP event selection

- ➔ Simple event selection optimised for discovery
  - Require LHC collision event with good quality data - analysis uses 57.7 fb^{-1}
  - Initially blind data with no veto signal and E_{calo} > 100 GeV
  - Calorimeter and pre-shower currently not able to resolve two photons

3. *Pre-shower signal consistent with EM shower*
$PS_1 / PS_0 > 4.5$, $PS_1 > 10$ MIPs

4. *E_{calo} > 1.5 TeV*



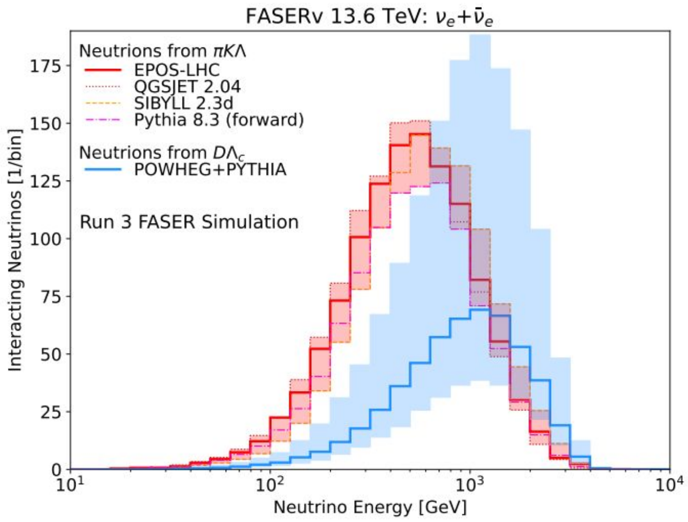
1. *No signal in any veto scintillator*
charge < 0.5 MIPs

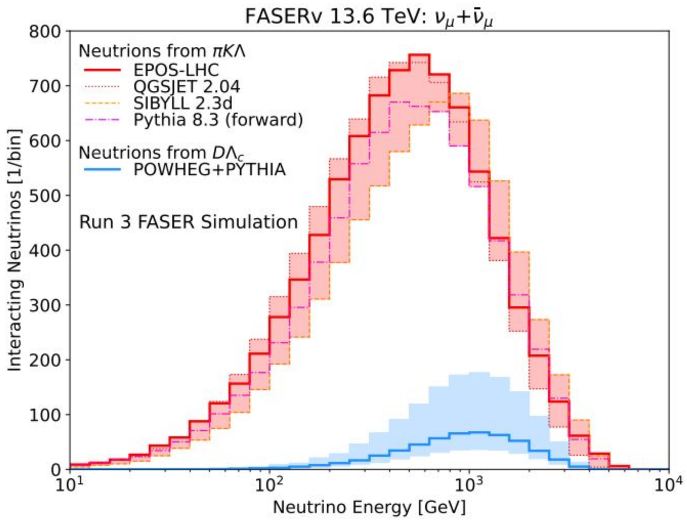
2. *No signal in timing scintillator*
charge < 0.5 MIPs

- ➔ Find ~5-80% signal selection efficiency over parameter space FASER is sensitive to

Backgrounds - I

- ➔ By far the dominant background is from CC neutrino interactions (ν_e and ν_μ)
  - Estimated using neutrino MC predictions [Phys. Rev. D 110 (2024) 012009]
  - Neutrinos mostly produced from the decays of *light* and *charm* hadrons
    - Light: EPOS-LHC, with flux uncertainties from envelope of generators
    - Charm: NLO POWHEG+Pythia8, with flux uncertainties from scale variations

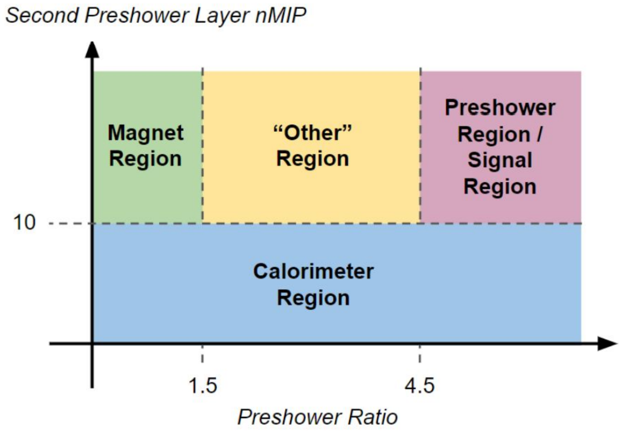


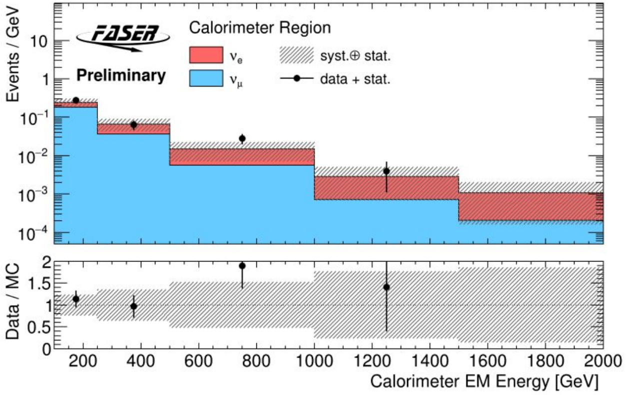


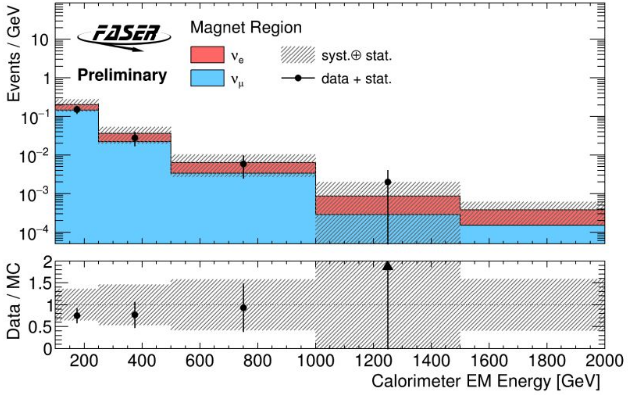
Backgrounds - II

➔ Neutrinos interact in the magnets, calorimeter and pre-shower

- Can select these populations with good purity using cuts on pre-shower variables
- The signal region is dominated by neutrino interactions in the pre-shower
- The “magnet” and “calorimeter” regions are used for validation → good agreement



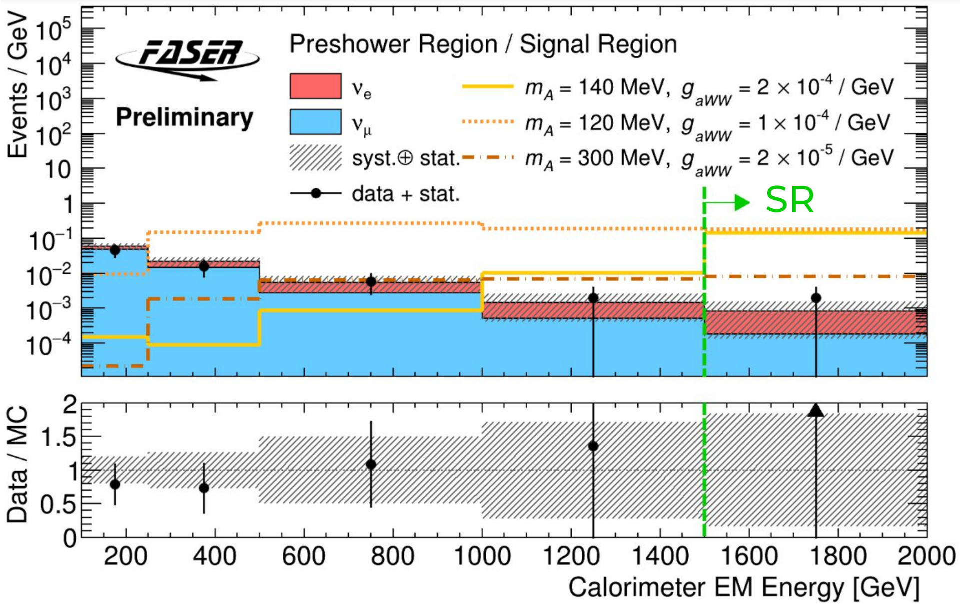


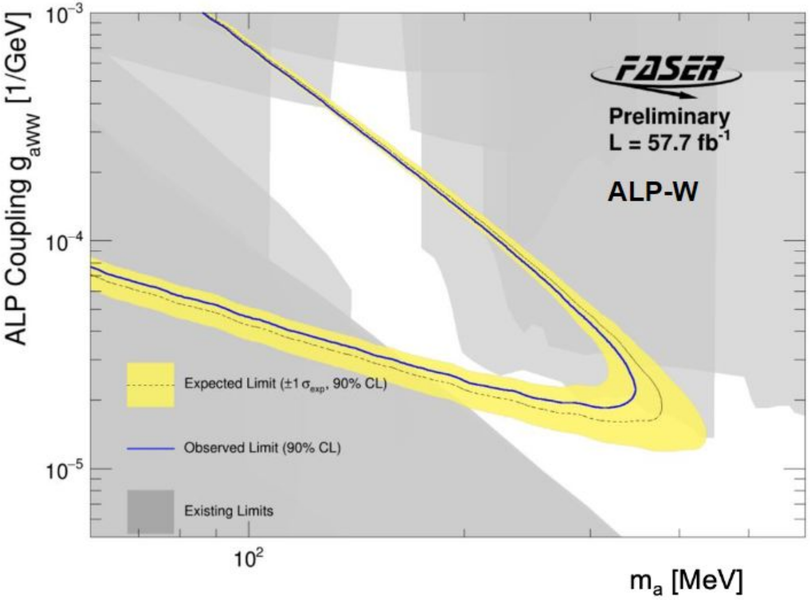


➔ Neutral hadrons, large-angle muons, and cosmics/beam 1 background found negligible

Unblinded results - I

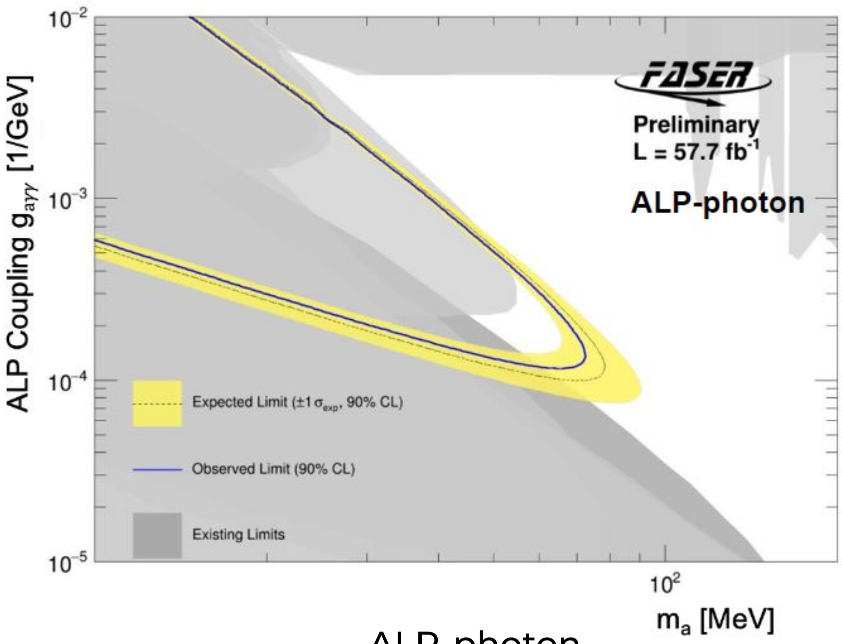
➔ 1 event observed in the SR with expectation of 0.42 ± 0.38 background events
- Background uncertainty dominated by the neutrino flux uncertainty (~80%)
- No discovery, but new exclusion limits set in previously uncovered parameter space
- Single event in SR has calorimeter energy of 1.6 TeV



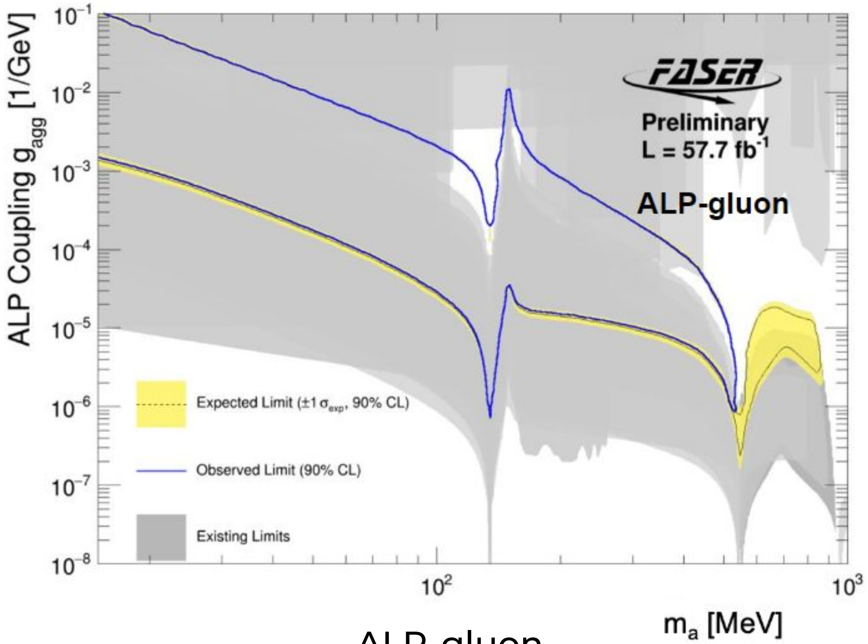


Unblinded results - II

➔ Analysis also sensitive to other multi-photon signatures
  - Exclude new parameter space for ALP-photon, ALP-gluon, $U(1)_B$ and up-philic scalar



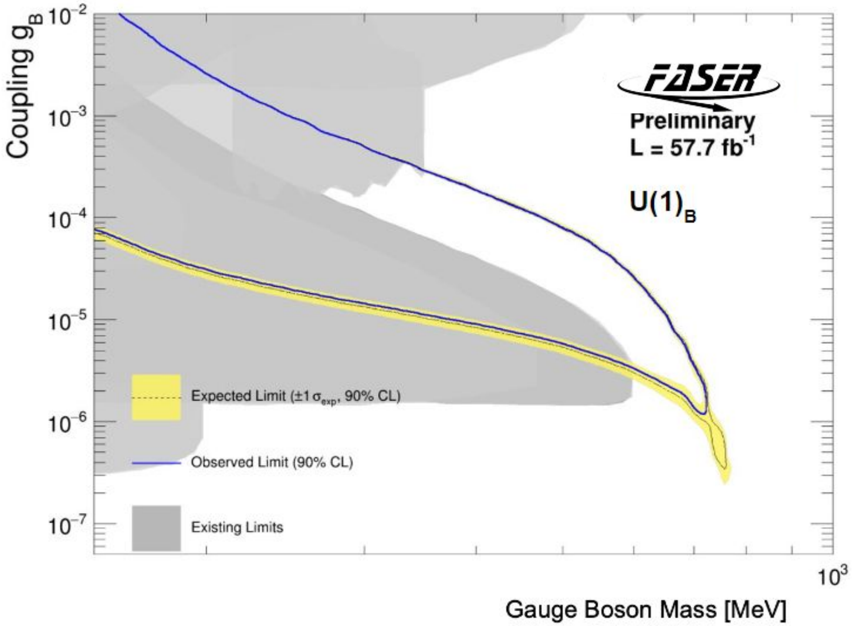
ALP-photon



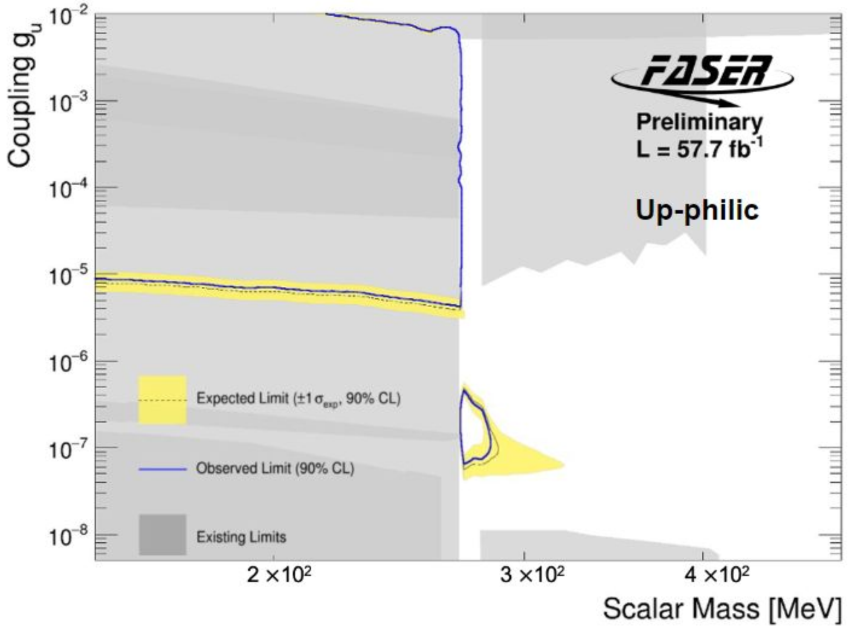
ALP-gluon

Unblinded results - III

- Analysis also sensitive to other multi-photon signatures
  - Exclude new parameter space for ALP-photon, ALP-gluon, $U(1)_B$ and up-philic scalar



$U(1)_B$



Up-philic scalar

Summary

→ FASER continuing to operate successfully in Run 3
  - Also approved to operate in Run 4

→ Constraints on previously unexplored ALP-W (and multi-photon) parameter space
  - Second of our BSM results following dark photon search
  - Big improvement expected with planned preshower upgrade → see Andrea's talk

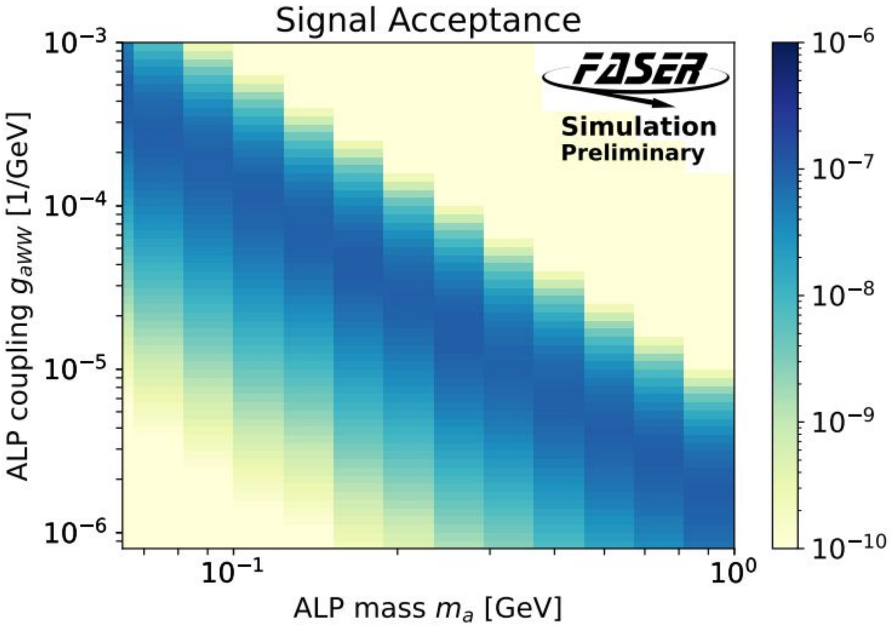
→ FASER also has an extensive neutrino physics program
  - Both emulsion and electronic analyses → see Sergey's talk

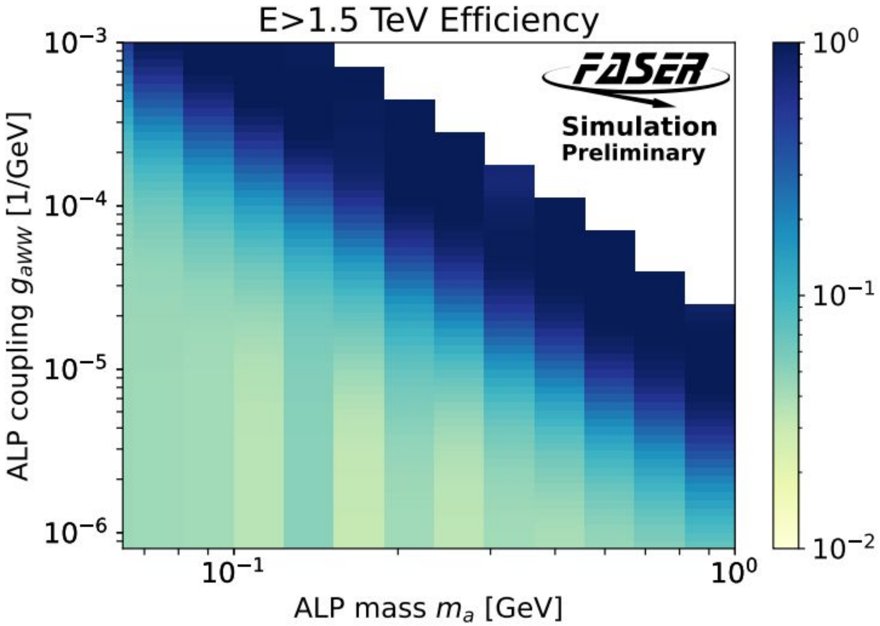
→ Large upgrade to FASER planned for HL-LHC
  - Part of Forward Physics Facility (FPF) arXiv:2203.05090
  - Significant improvement to sensitivity expected → see Alan's talk

Thank you for your attention!

Backup

ALP signal simulation



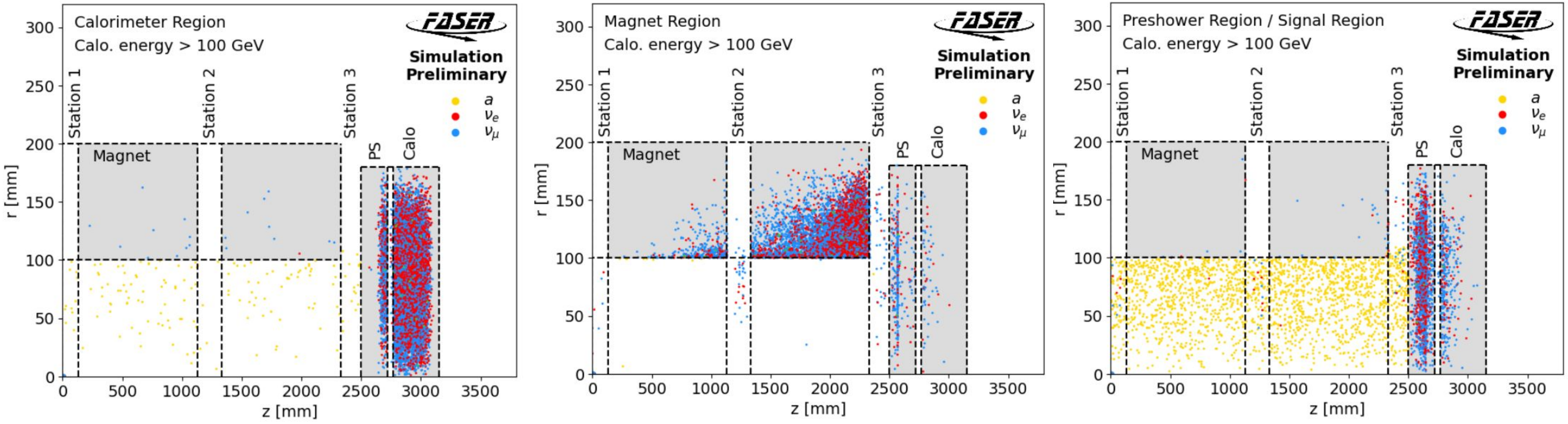


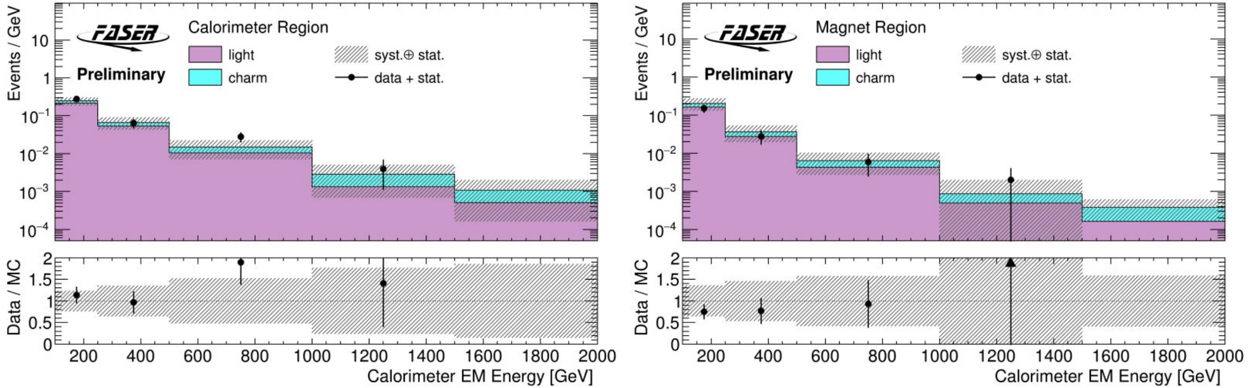
ALP event selection

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)

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%

Backgrounds





Backgrounds

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 $\pm$ 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 $\pm$ 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 $\pm$ 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 $\pm$ 5.1 (28.8%)**
Data	**15**

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 $\pm$ 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 $\pm$ 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 $\pm$ 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 $\pm$ 6.9 (32.2%)**
Data	17

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 $\pm$ 0.38 (90.6%)**
Data	1

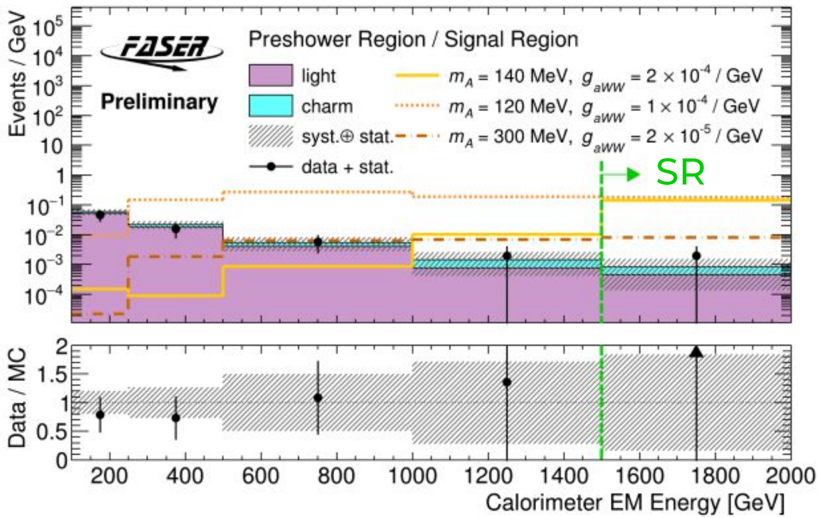
> 1.5 TeV signal region	
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	**0.42 $\pm$ 0.38 (90.6%)**

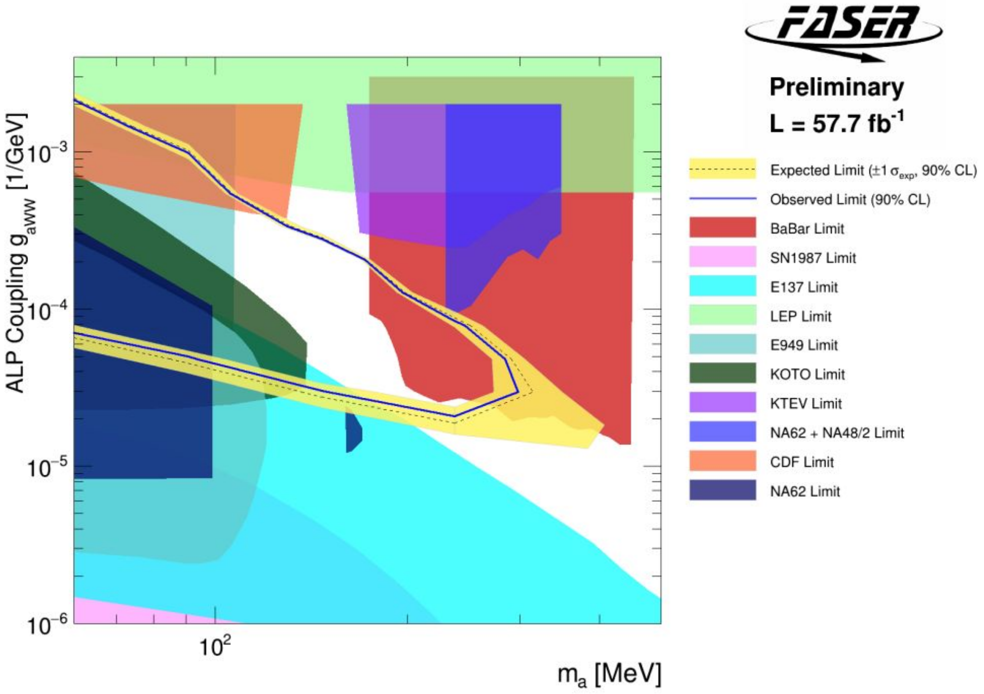
Systematics

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%

Source	**Event Rate**
Neutrino Background	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%)**
ALP ($m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1})	70.7 ± 42.0 (theo.) ± 6.4 (exp.) ± 1.3 (stat.)
ALP ($m_a = 120$ MeV, $g_{aWW} = 1 \times 10^{-4}$ GeV^{-1})	91.1 ± 52.2 (theo.) ± 16.2 (exp.) ± 3.2 (stat.)
ALP ($m_a = 300$ MeV, $g_{aWW} = 2 \times 10^{-5}$ GeV^{-1})	4.0 ± 2.3 (theo.) ± 0.6 (exp.) ± 0.1 (stat.)
Data	**1**

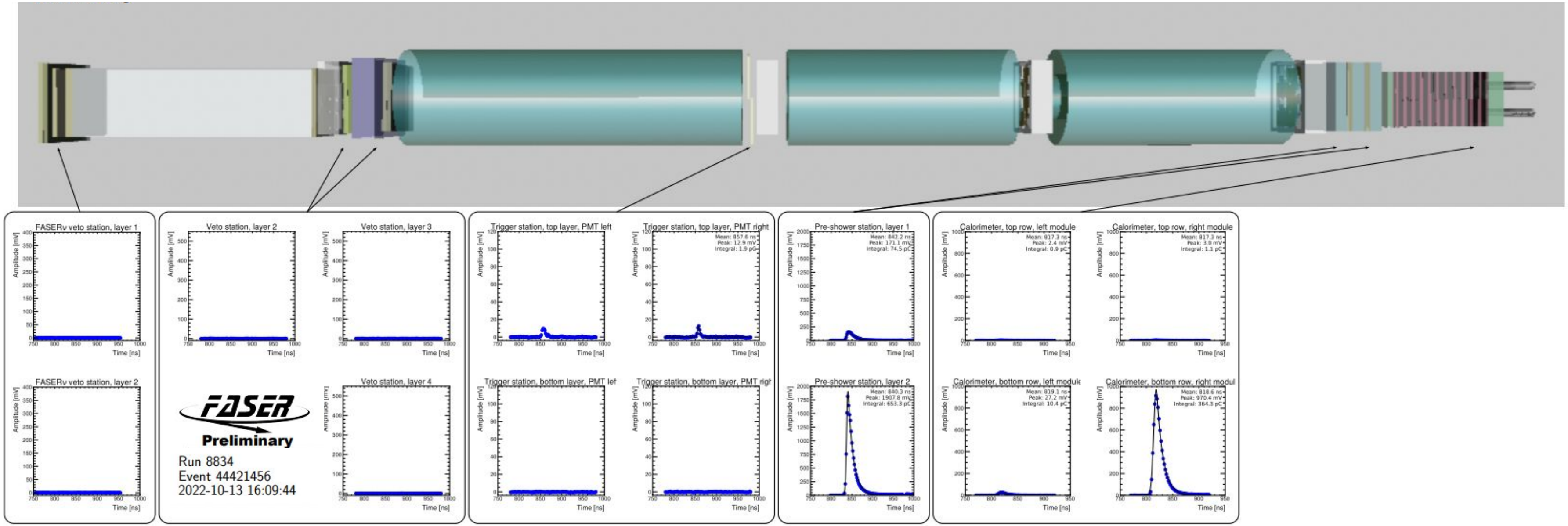
Unblinded results





“ALPtrino” event

➔ Event display of single event observed in the SR
  - Calorimeter energy of 1.6 TeV
  - Pre-shower deposits consistent with EM shower



Timing Layer PS Calorimeter

Scintillator efficiencies

Scintillator	2022	2023
Veto-0	99.999988(5)	99.999994(4)
Veto-1	99.999992(5)	99.999994(4)
Veto-2	99.999992(5)	99.999994(4)
NuVeto-0	99.99989(1)	99.99988(1)
NuVeto-1	99.99988(1)	99.99986(1)

Multi-photon models

- ALP-photon
  - Production: Primakoff process
  - Decay: $\gamma\gamma$

$$\mathcal{L} = -\frac{1}{2}{m_a}^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- ALP-gluon
  - Production: a mixing with π^0, η and η'
  - Decay: $\gamma\gamma$ (low masses), 3π and $\pi^+\pi^-\gamma$ (ma ~ 0.5 GeV)

$$\mathcal{L} = -\frac{1}{2}{m_a}^2 a^2 - \frac{g_s^2}{8} g_{agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

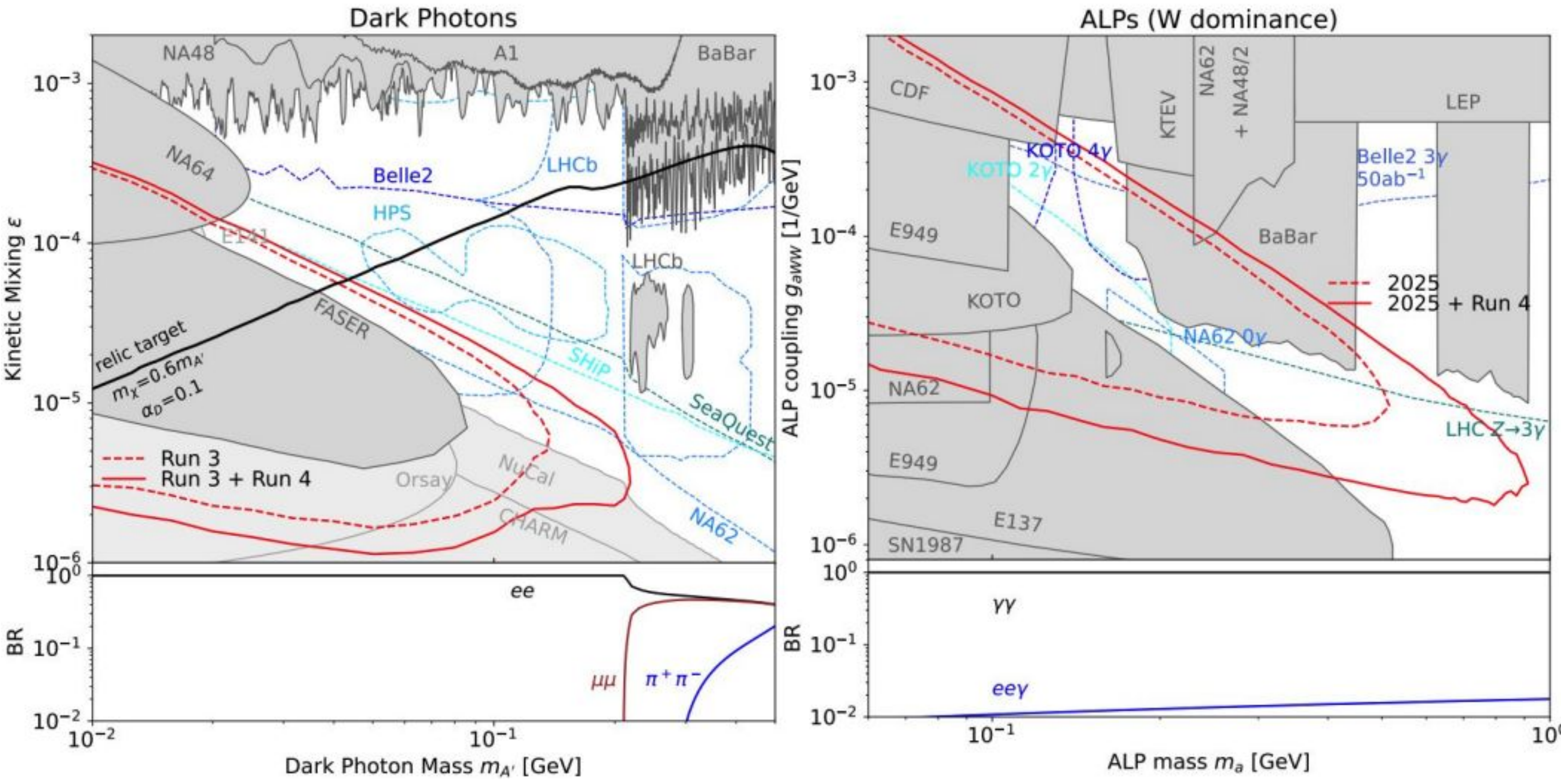
- $U(1)_B$ gauge boson
  - Production: π^0, η and η' decays, dark bremsstrahlung
  - Decay: ee ($m_{ZB} < m_{\pi 0}$), $\pi^0\gamma$, $\pi^0\pi^+\pi^-$ (m_{ZB} ~ 600 MeV)

$$\mathcal{L} = \frac{1}{2}{m_{Z_B}}^2 Z_B^2 - g_B \sum x_f\, \bar{f}\gamma^\mu f X_\mu$$

- Up-philic scalar
  - Production: mainly η and η' decays, also FCNC kaon decays
  - Decay: $\gamma\gamma$ ($m_S < 2m_{\pi 0}$), $\pi^0\pi^0$ ($m_S > 2m_{\pi 0}$)

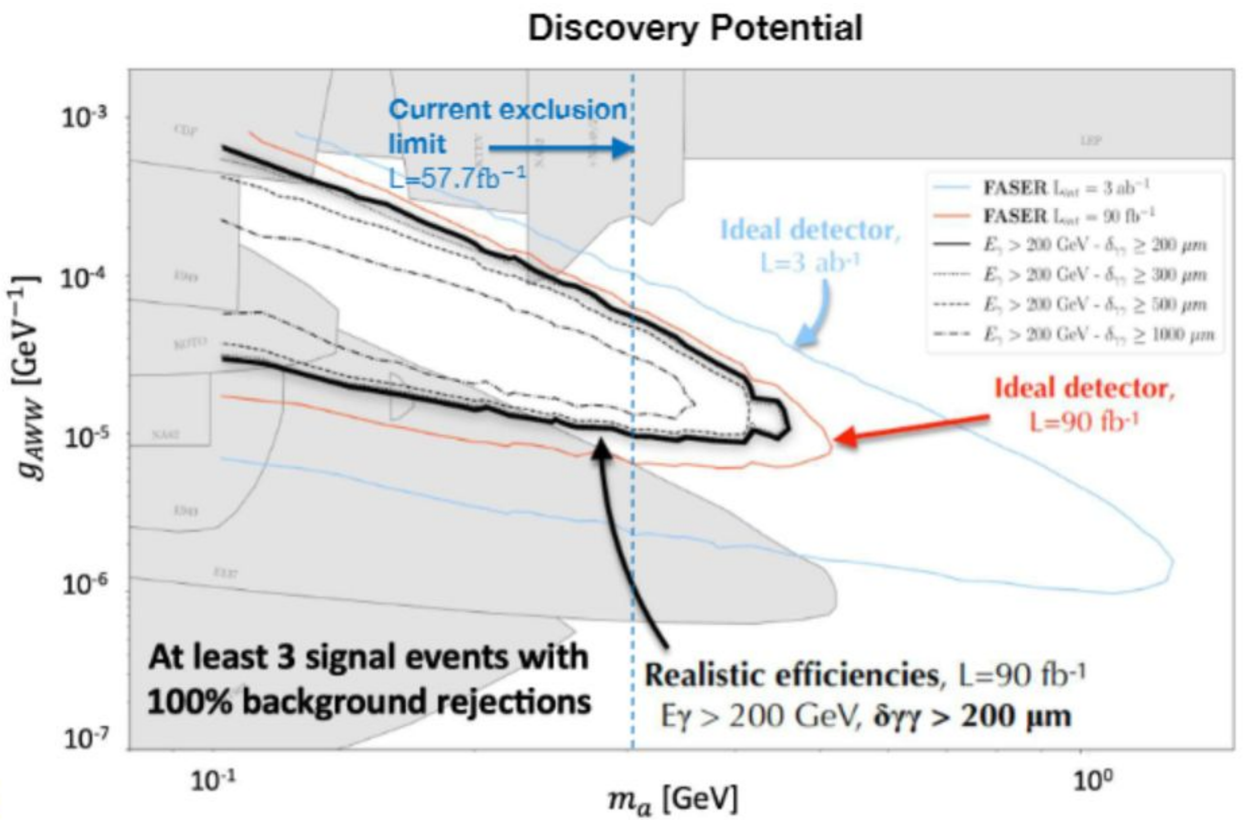
$$\mathcal{L} = -\frac{1}{2}{m_S}^2\, S^2 - g_u \bar{u}\, u\, S$$

Run 4



Dark Photons
NA48
A1
BaBar
NA64
Belle2
LHCb
HPS
E141
LHCb
FASER
relic target
$m_\chi=0.6m_{A'}$
$\alpha_D=0.1$
SHiP
SeaQuest
NuCal
Orsay
CHARM
NA62
Run 3
Run 3 + Run 4
Kinetic Mixing ϵ
ee
$\mu\mu$
$\pi^+\pi^-$
BR
Dark Photon Mass $m_{A'}$ [GeV]
ALPs (W dominance)
CDF
KTEV
NA62 + NA48/2
LEP
KOTO 4γ
KOTO 2γ
Belle2 3γ 50ab^{-1}
E949
BaBar
KOTO
2025
2025 + Run 4
NA62 0γ
NA62
LHC Z→3γ
E949
E137
SN1987
ALP coupling g_{aWW} [1/GeV]
γγ
eeγ
BR
ALP mass m_a [GeV]

Preshower upgrade



The FASER collaboration

101 members from **27 institutions** and **11 countries**

International laboratory covered by a cooperation agreement with CERN

Acknowledgements

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HEISING-SIMONS FOUNDATION

NSF

CERN

erc

Swiss National Science Foundation

科研費 KAKENHI