Searches for new physics with the FASER experiment

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Jack C. MacDonald

on behalf of the FASER collaboration

arXiv:2308.05587

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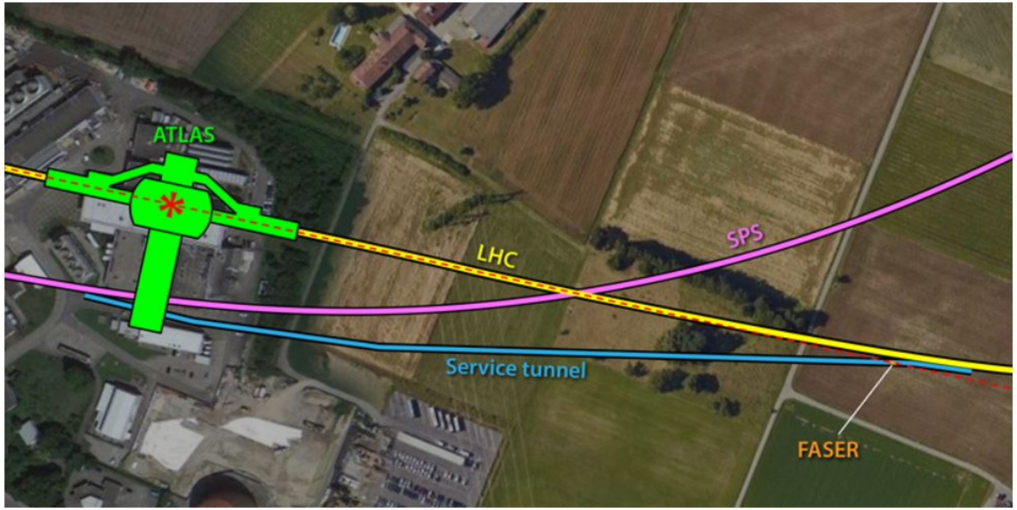
What is FASER?

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

- ➔ New experiment at the LHC built and installed in 2019-2021
  - Successful data taking in June-Nov 2022 and April-August 2023



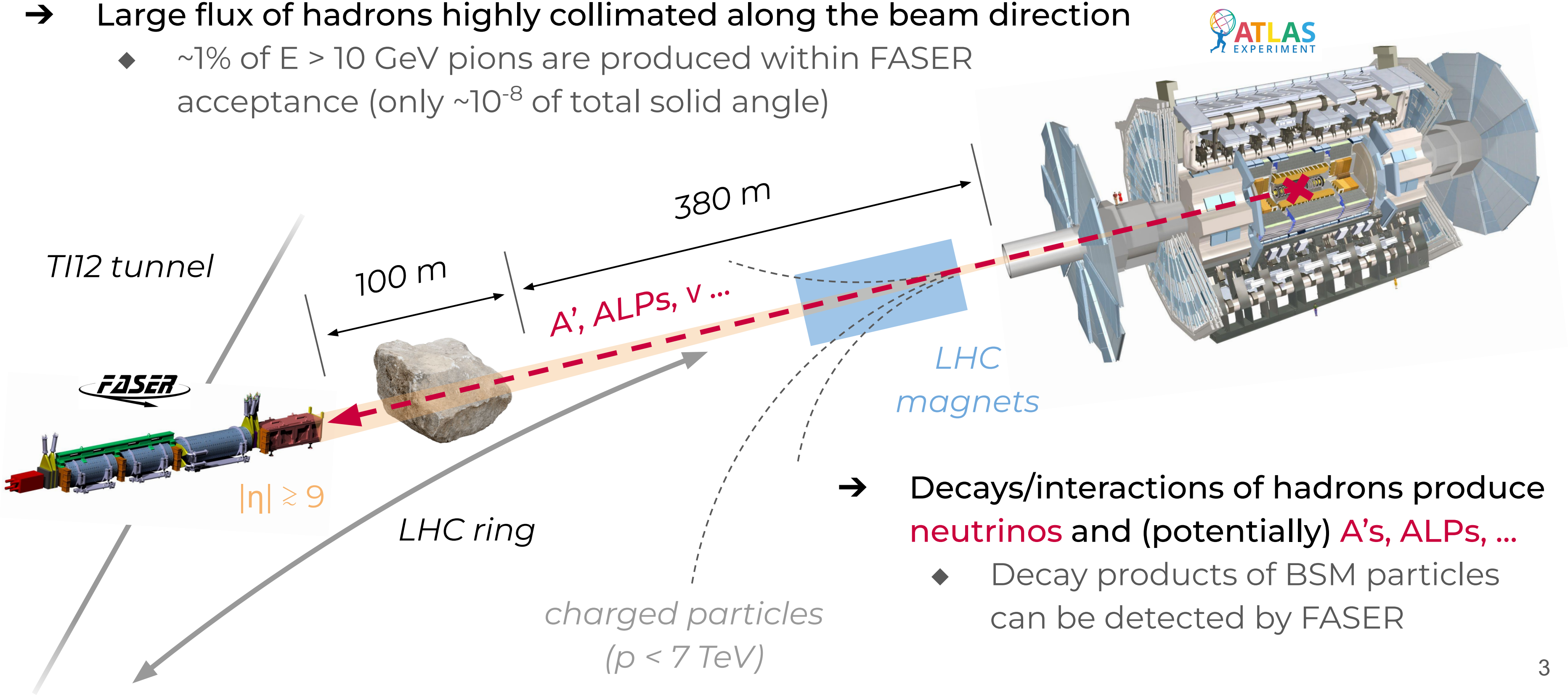
Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker

- ➔ 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

See also Florian's talk tomorrow

ATLAS forward region

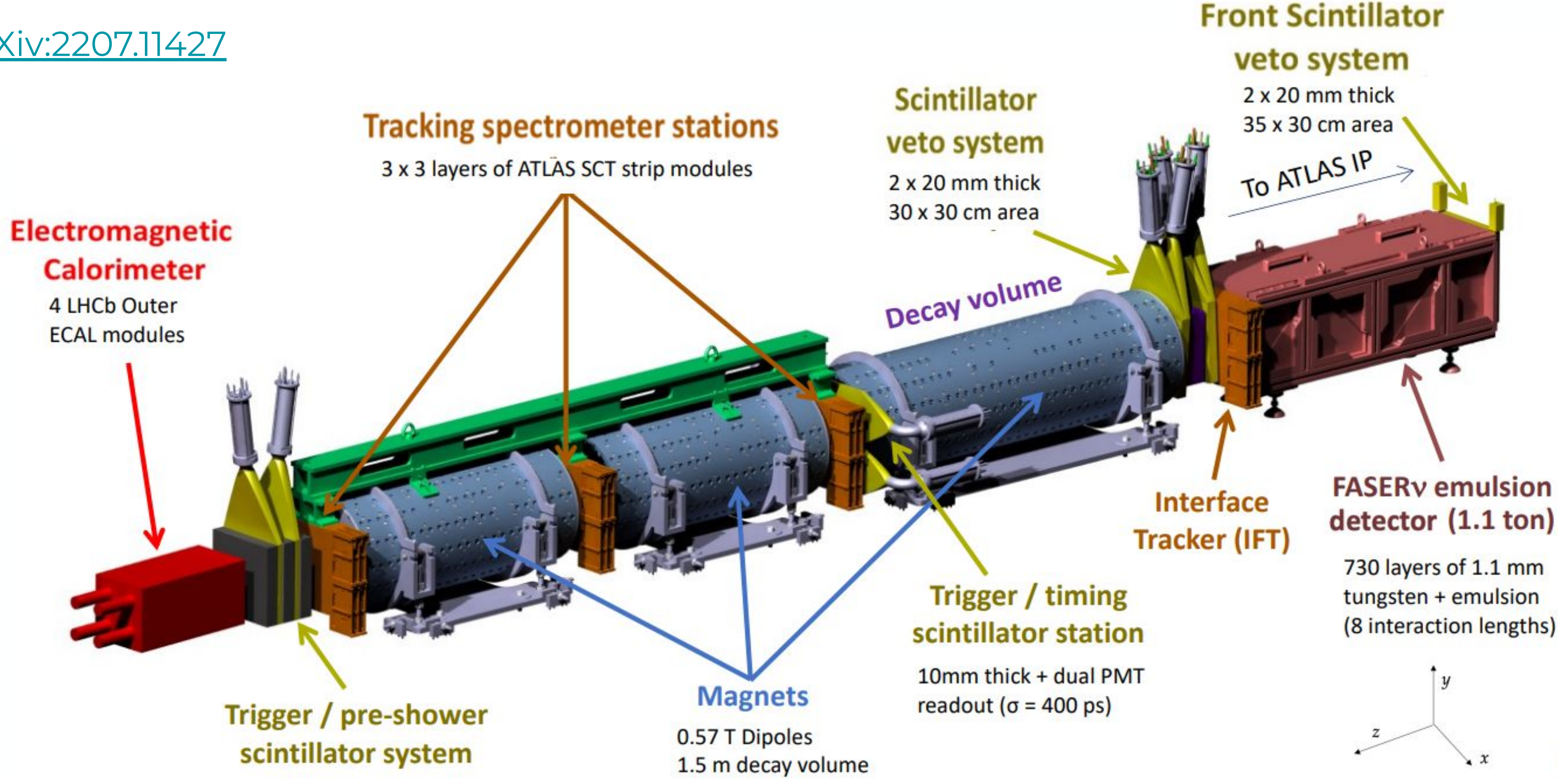
- ➔ Large flux of hadrons highly collimated along the beam direction
  - ~1% of E > 10 GeV pions are produced within FASER acceptance (only ~10^{-8} of total solid angle)



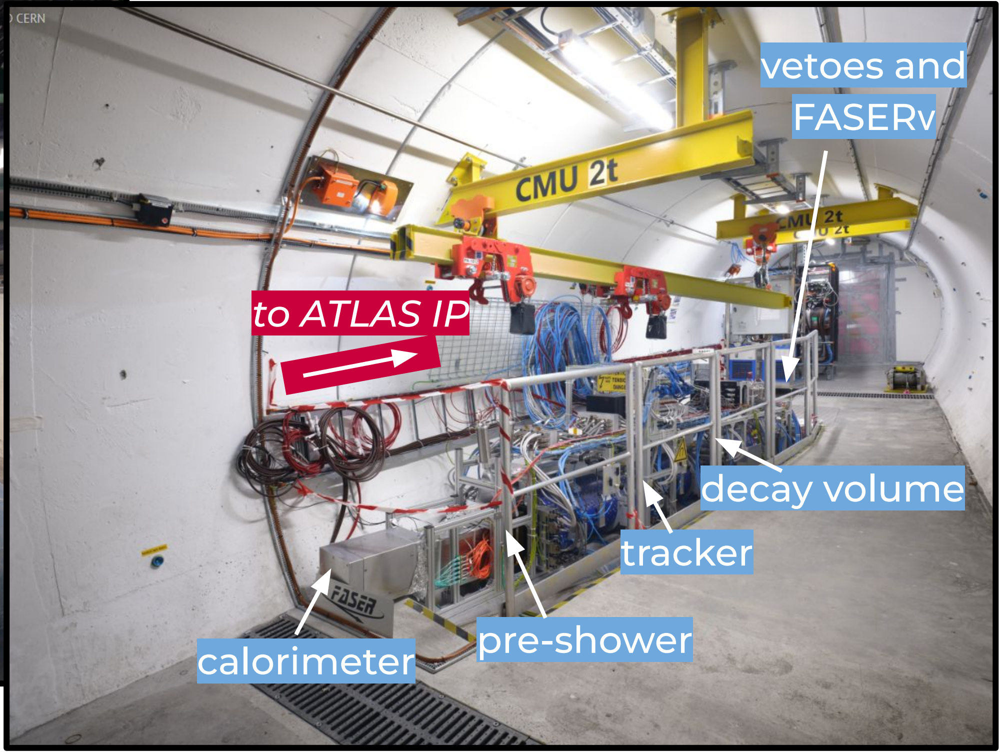
- ➔ Decays/interactions of hadrons produce neutrinos and (potentially) A's, ALPs, ...
  - Decay products of BSM particles can be detected by FASER

The FASER detector

[arXiv:2207.11427](https://arxiv.org/abs/2207.11427)

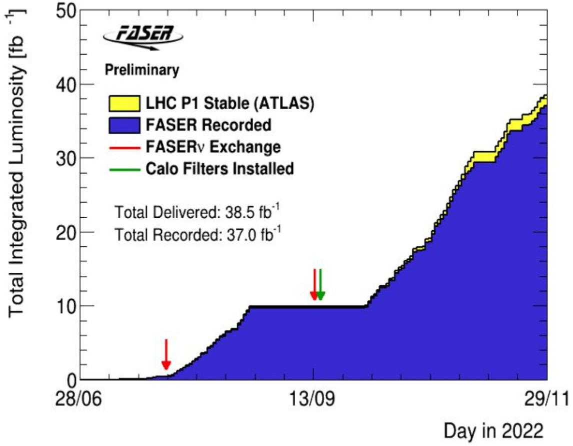


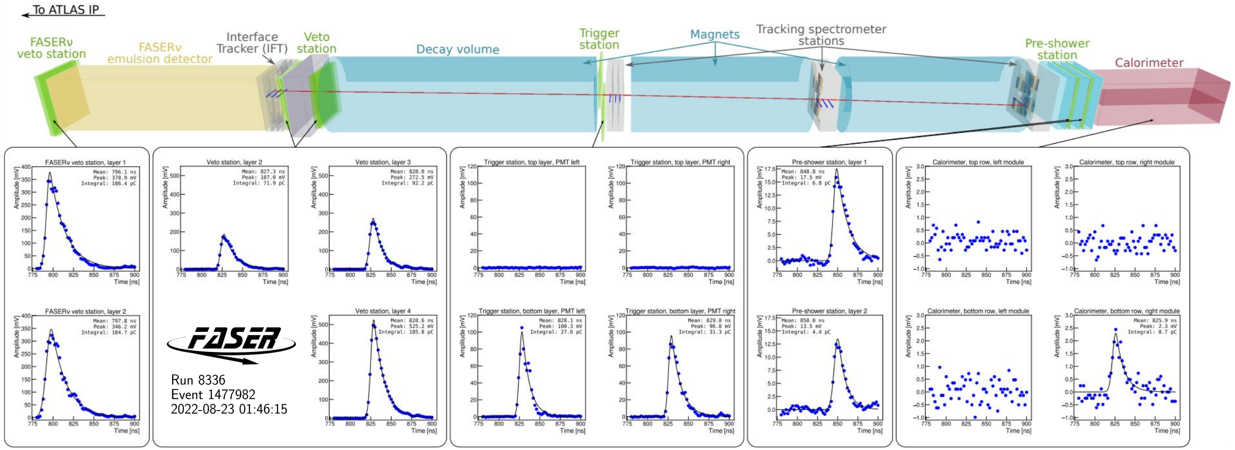
The FASER detector

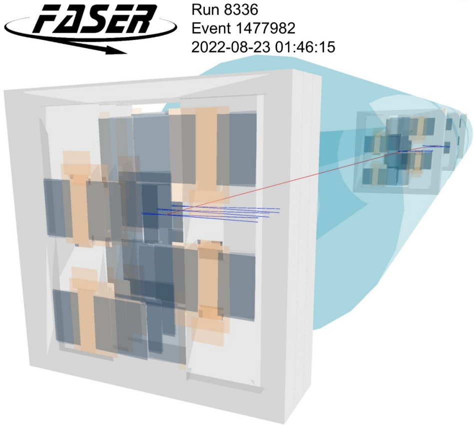


FASER operations

- ➔ Continuous and largely automatic data taking in 2022
  - Up to 1.3 kHz trigger rate
  - More than 350M single muon events recorded
- ➔ Recorded 96.1% of delivered luminosity
  - Limited by DAQ deadtime (1.3%) and a couple of crashes
  - Dark photon analysis uses 27.0 fb^{-1} (with optical filters)







Dark photons at FASER

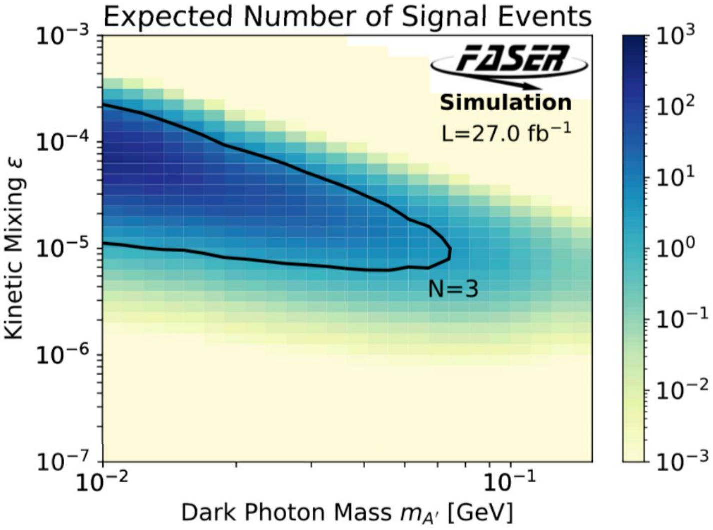
- Dark photons are a general feature of "hidden sector" models
  - Weakly coupled to SM with strength determined by kinetic mixing, ε

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

- FASER most sensitive to parameter space with $m_{A'}$ ~ 10 - 100 MeV and $\varepsilon \sim 10^{-5} - 10^{-4}$

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

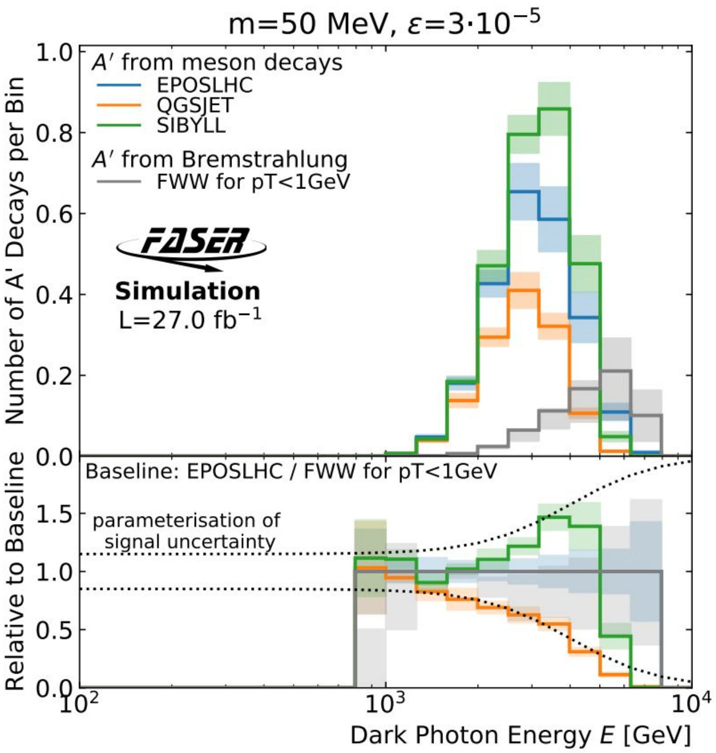
  - $\pi^0 \to A'\gamma$ dominant production mechanism
  - $m_{A'} < 2\, m_\mu \Rightarrow \text{BR}(A' \to e^+e^-) \sim 100\%$



Dark photon modelling

➔ **Dark photon signal events modelled using FORESEE** arXiv:2105.07077
   - EPOS-LHC used to model very forward π^0 and η production
      - Also includes subdominant dark-bremsstrahlung contribution

➔ **Systematic uncertainties from signal modelling are the dominant contribution**
   - Mainly from forward hadron production
   - Envelope from parameterised difference between EPOS-LHC and QGSJET/SIBYLL

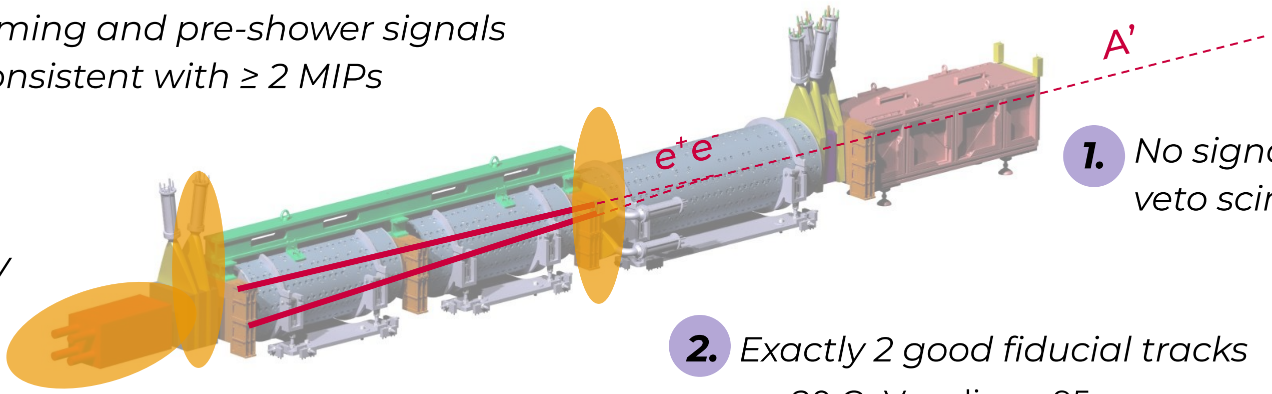


Dark photon event selection

- ➔ **Simple event selection optimised for discovery**
  - ◆ Require LHC collision event with good quality data
  - ◆ Blind data with no veto signal and E_{calo} > 100 GeV

- ➔ **Find ~40% signal selection efficiency over parameter space FASER is sensitive to**

3. *Timing and pre-shower signals consistent with ≥ 2 MIPs*



1. *No signal in any veto scintillator*

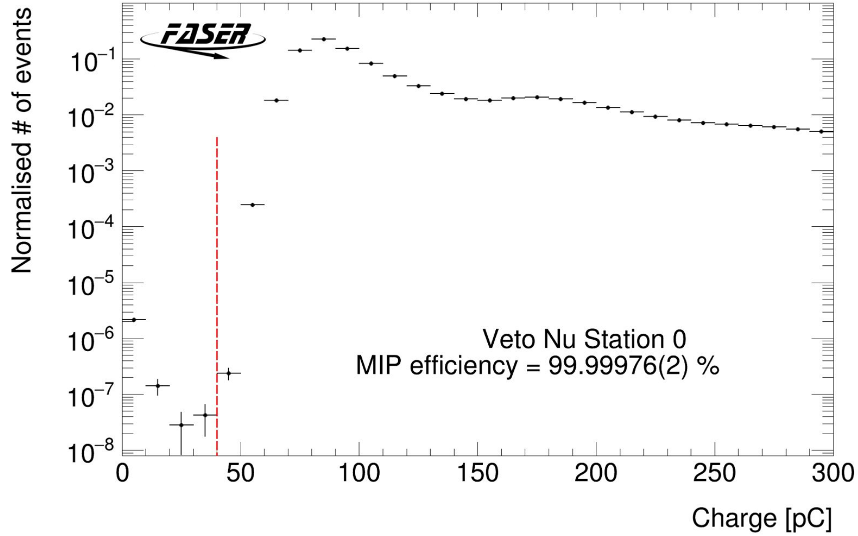
4. *E_{calo} > 500 GeV*

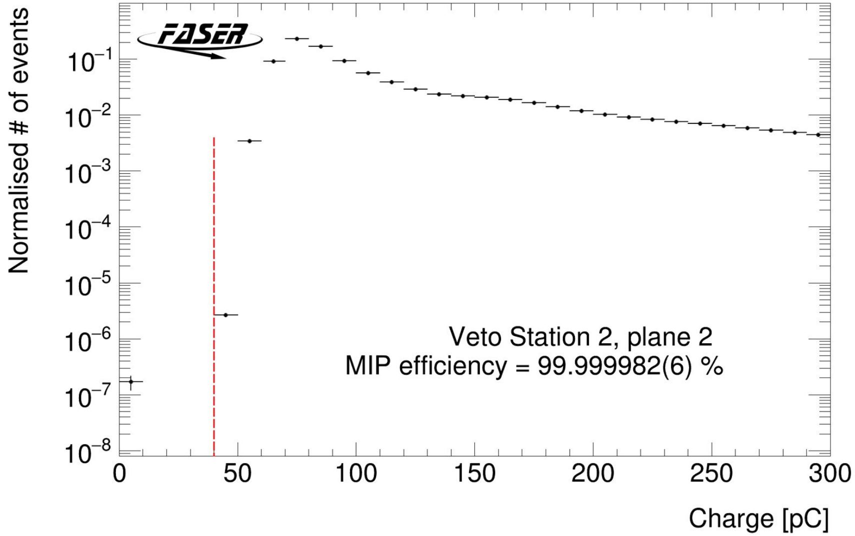
2. *Exactly 2 good fiducial tracks*
p > 20 GeV, radius < 95 mm

Dark photon backgrounds - I

➔ Veto station inefficiency

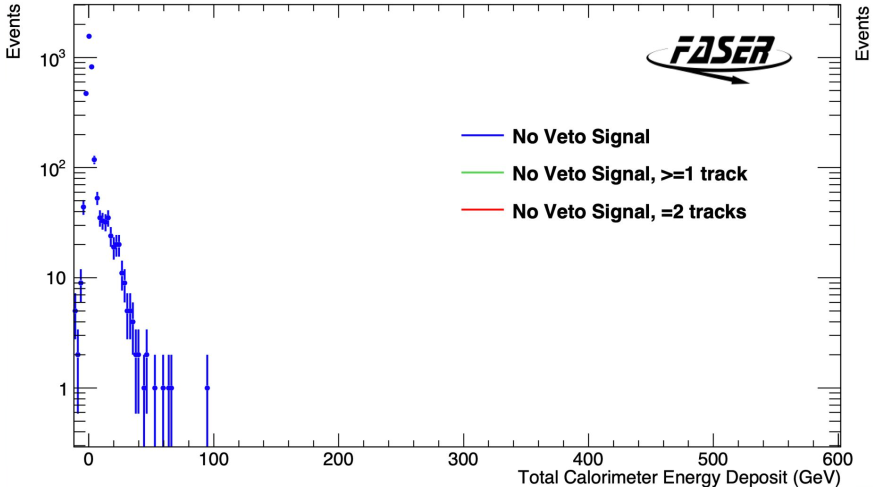
- Measured layer-by-layer with muon tracks pointing to veto layers
- Layer efficiency > 99.9997%
- With 5 layers reduce expected 10^8 muons to negligible level
- **0 events expected**

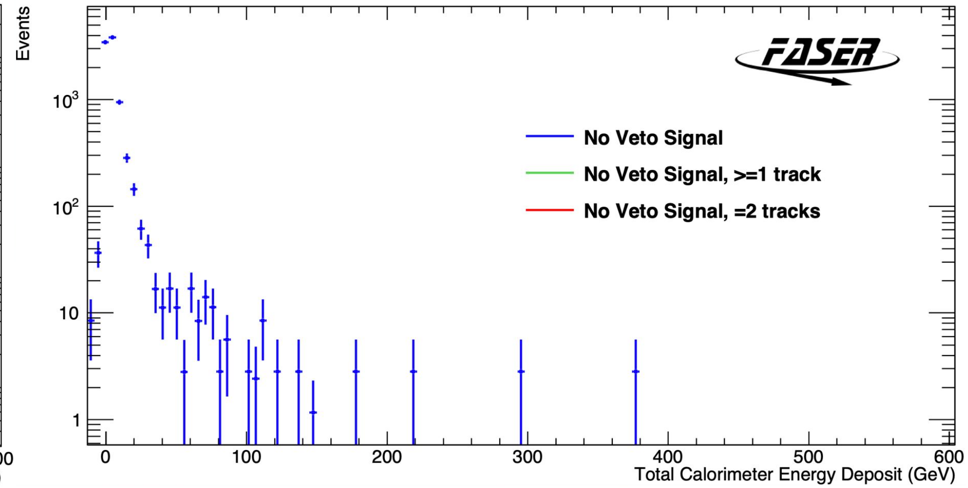




Dark photon backgrounds - II

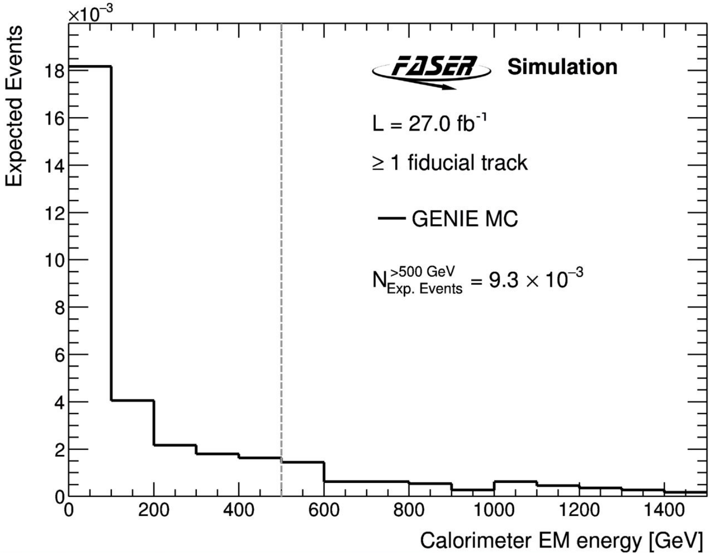
- Non-collision backgrounds
  - Cosmics measured in runs without beam
  - Nearby beam debris measured in non-colliding bunches
  - No events observed with ≥ 1 track or E_{calo} > 500 GeV
  - **0 events expected**

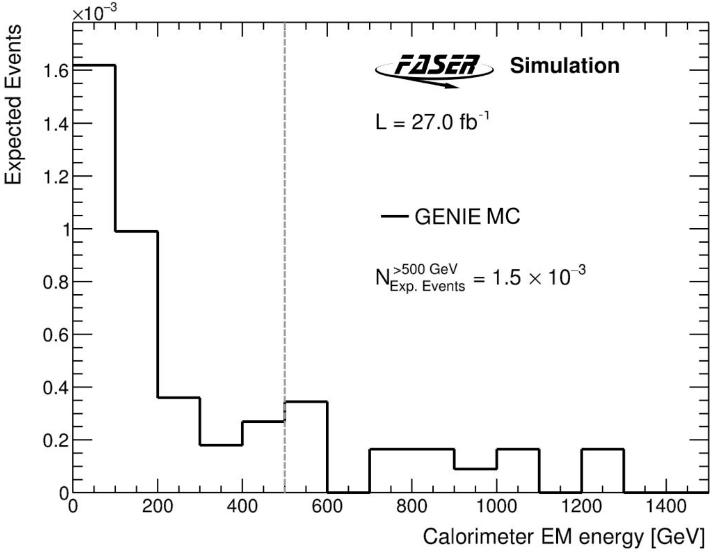




Dark photon backgrounds - III

- Neutrinos (main background)
  - Mostly from interactions in the timing layer
  - Estimated using 300 ab^{-1} GENIE simulation
    - Uncertainties from flux and interaction modelling
  - **1.5 x 10^{-3} events expected**



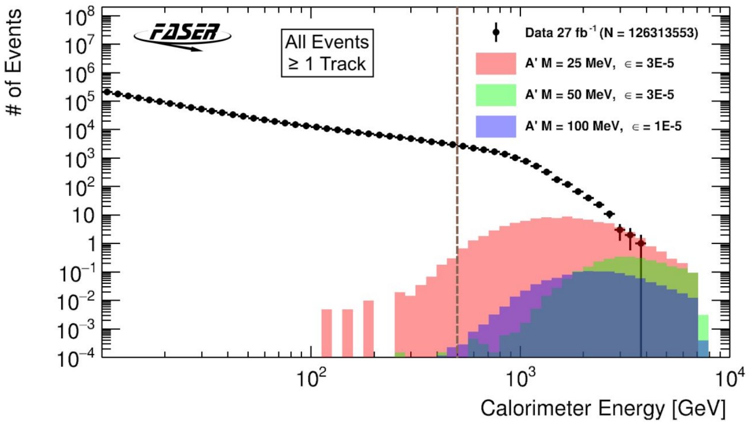


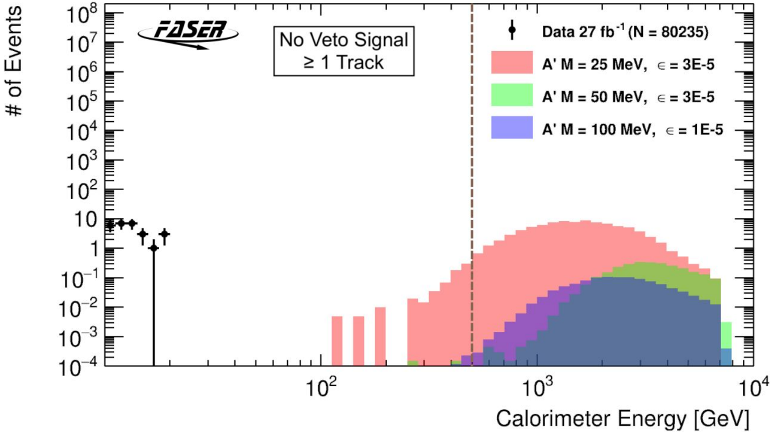
Dark photon backgrounds - IV

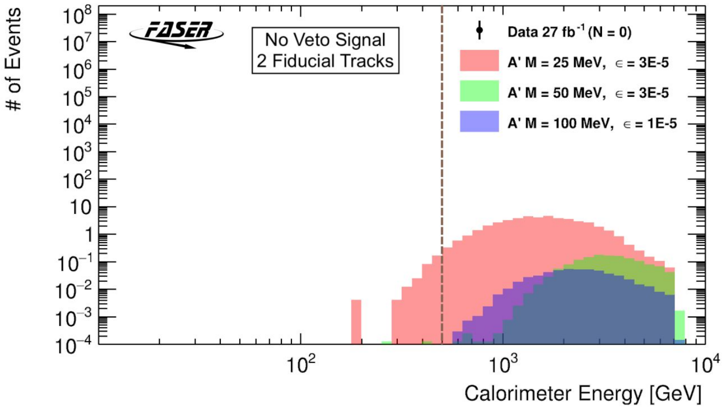
- **Neutral hadrons**
  - From upstream muons interacting in the rock in front of FASER
  - Heavily suppressed since:
    - The muon typically continues through FASER and so is vetoed
    - The neutral hadron must pass through 8 interaction lengths before decaying
    - The decay products must have high energy
  - Estimated by extrapolating events with 2 or 3 tracks and different veto conditions
  - **0.84 x 10^{-3} events expected**

Background	**Central Value**	**Error (%)**
Veto inefficiency	-	-
Non-collision	-	-
Neutral hadrons	0.84×10^{-3}	1.19×10^{-3} (141%)
Neutrinos	1.5×10^{-3}	2.0×10^{-3} (133%)
Total	$\mathbf{2.33 \times 10^{-3}}$	$\mathbf{2.32 \times 10^{-3}}$ **(99%)**

Unblinded results

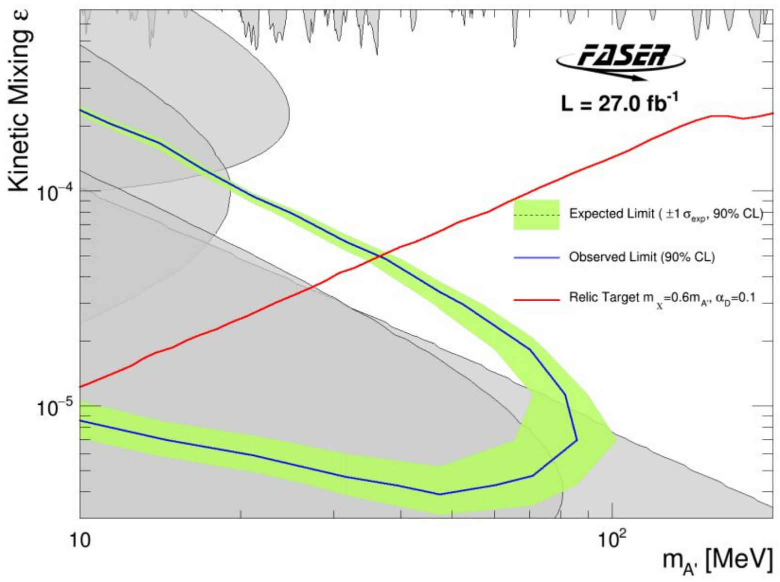


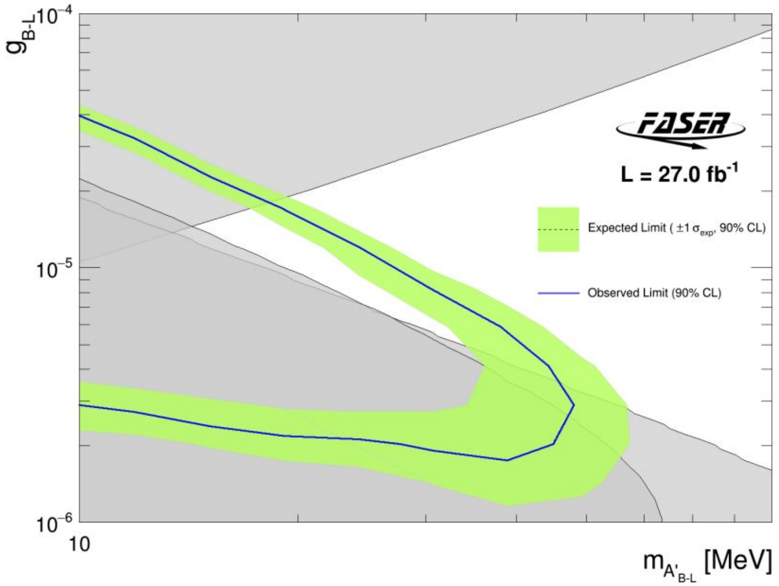




Limit setting

➔ No events seen in unblinded SR
- Set (90% CL) limits in previously unprobed parameter space
- Excludes region relevant for dark matter thermal relic target
- Result reinterpreted in terms of B-L model





Summary

➔ FASER successfully took data throughout first year of Run 3
  - Detector fully functional with high efficiency

➔ Constraints on previously unexplored dark photon / B-L parameter space
  - Includes exclusion of interesting thermal relic region

➔ 10x more LHC Run 3 data to look forward to
  - Recorded an additional ~30 fb^{-1} of data
  - New searches, e.g. ALPs and other multiphoton signatures underway

➔ Large upgrade to FASER planned for HL-LHC
  - Part of Forward Physics Facility arXiv:2203.05090
  - Significant improvement in sensitivity expected

Thank you for your attention!

Backup

Dark photon selection

Description	Value
Pre-selecton	
Time consistent with a colliding bunch identifier Timing scintillator trigger	
Scintillator	
Timing station: Top or Bottom Scintillator charge OR Top and Bottom charge	 > 70 pC > 30 pC
Each Pre-shower scintillator charge Each Veto scintillator charge	>2.5 pC <40 pC
Tracking	
Exactly 2 Good Tracks Momentum χ^2/NDF Number of tracker layers on track Number of tracker hits on track	 > 20 GeV < 25 $>= 7$ $>= 12$
Fiducial selection	
Track extrapolated to all scintillators and tracking stations	 < 95mm
Calorimeter	
Calorimeter energy (sum of four channels)	> 500 GeV

Selection Criteria	Efficiency
Good collision event	99.7%
No Veto Signal	99.7%
Timing+Preshower Signal	97.9%
≥ 1 good track	91.6%
$= 2$ good tracks	57.3% *
Track radius < 95 mm	51.8% *
Calo E > 500 GeV	50.8% *

$\epsilon = 3 \times 10^{-5}$ $m_{A'} = 25.1$ MeV

*scaled down by 7% following data-driven estimate of two-track tracking efficiency

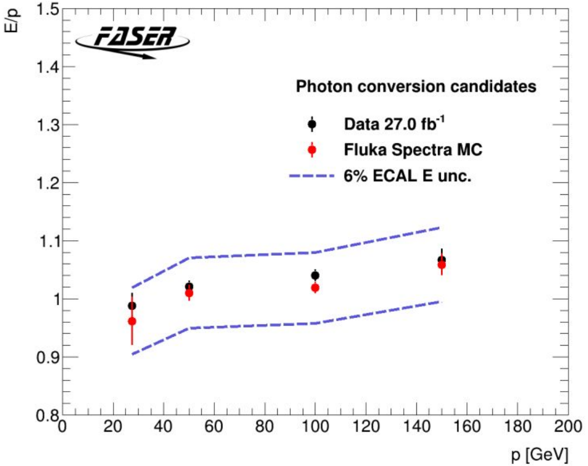
Cut	Data	
	Events	Efficiency
Good collision event	151231009	–
No Veto Signal	1250092	0.827%
Timing + Preshower Signal	332549	0.220%
≥ 1 good track	22224	0.015%
$= 2$ good tracks	0	0.000%
Track radius < 95 mm	0	0.000%
Calo E > 500 GeV	0	0.000%

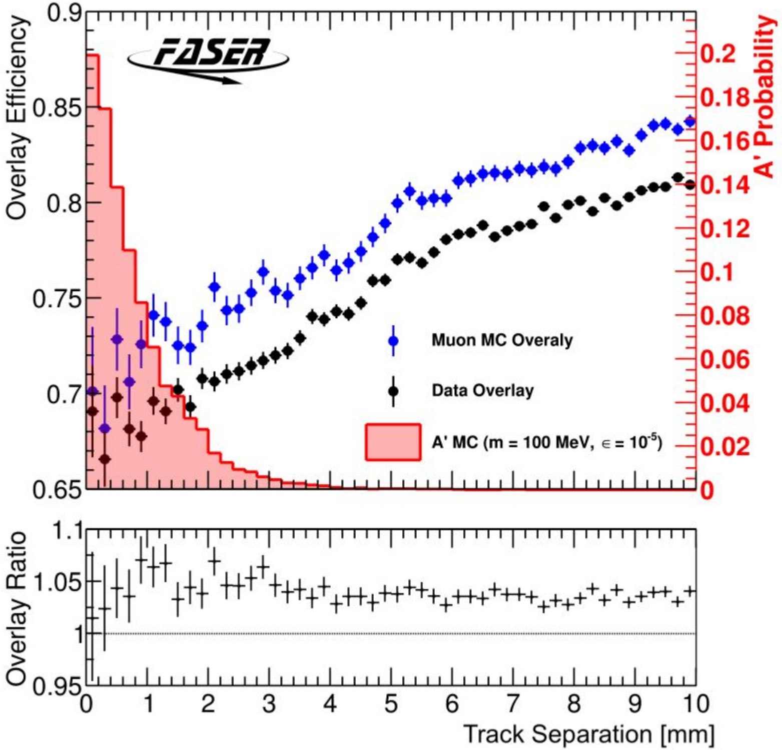
Dark photon neutral hadrons

Selection	Nevents E<100 GeV	Nevents E>500 GeV
3 tracks (VetoNu signal)	404	19
2 tracks (No VetoNu signal)	1	Predicted: 0.047

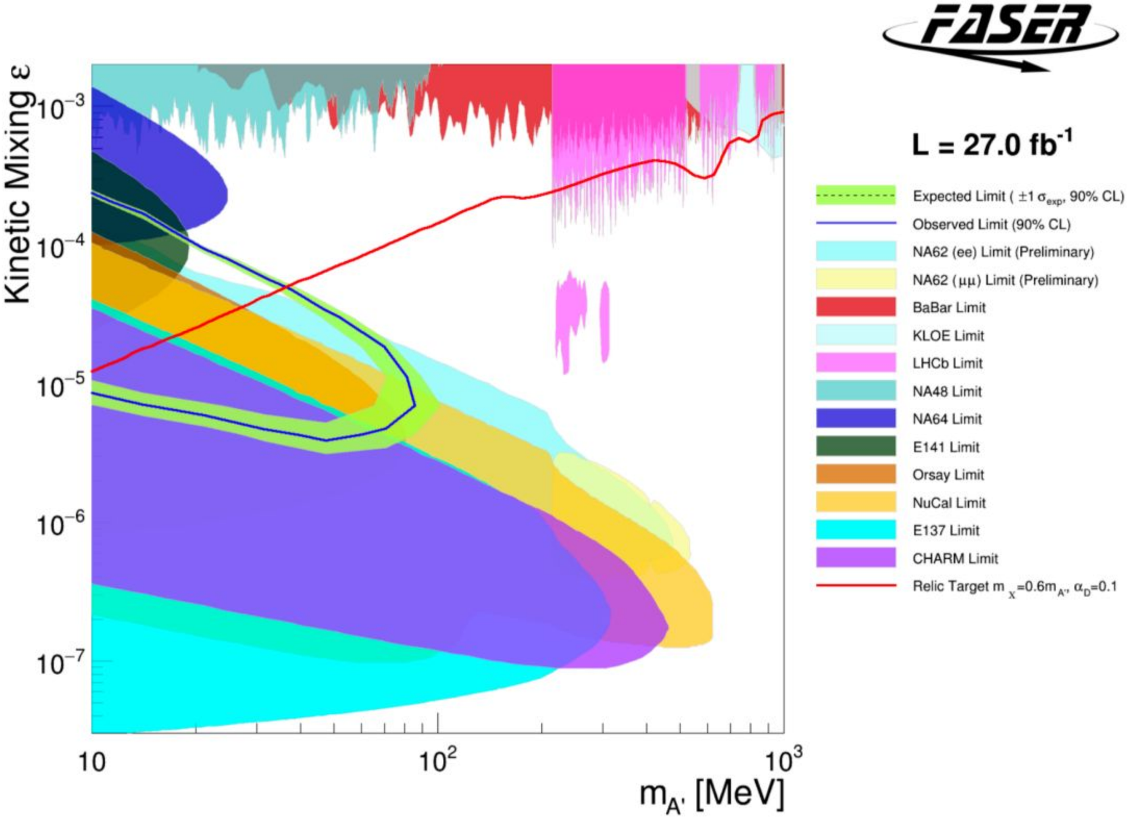
Dark photon systematics

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%
Calo E scale	6%	0-8% ($< 1\%$)

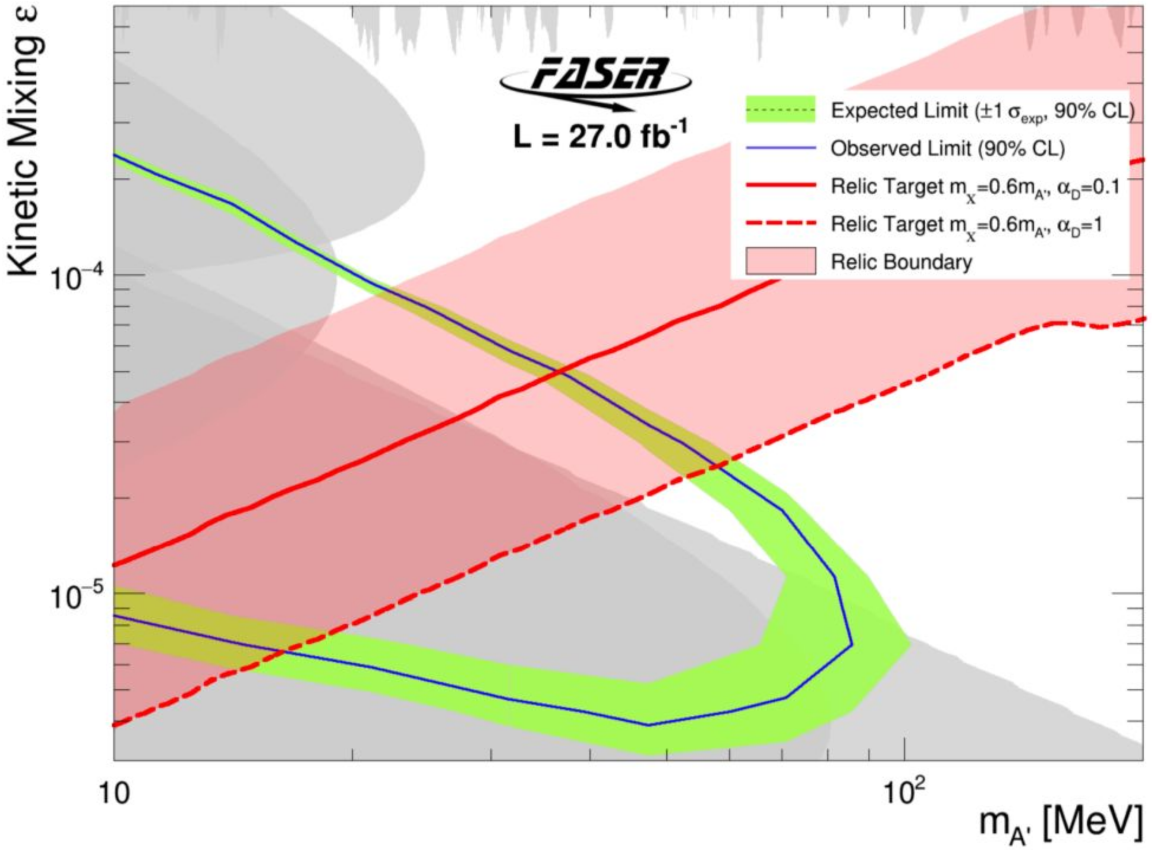




Dark photon limits



Thermal relic target



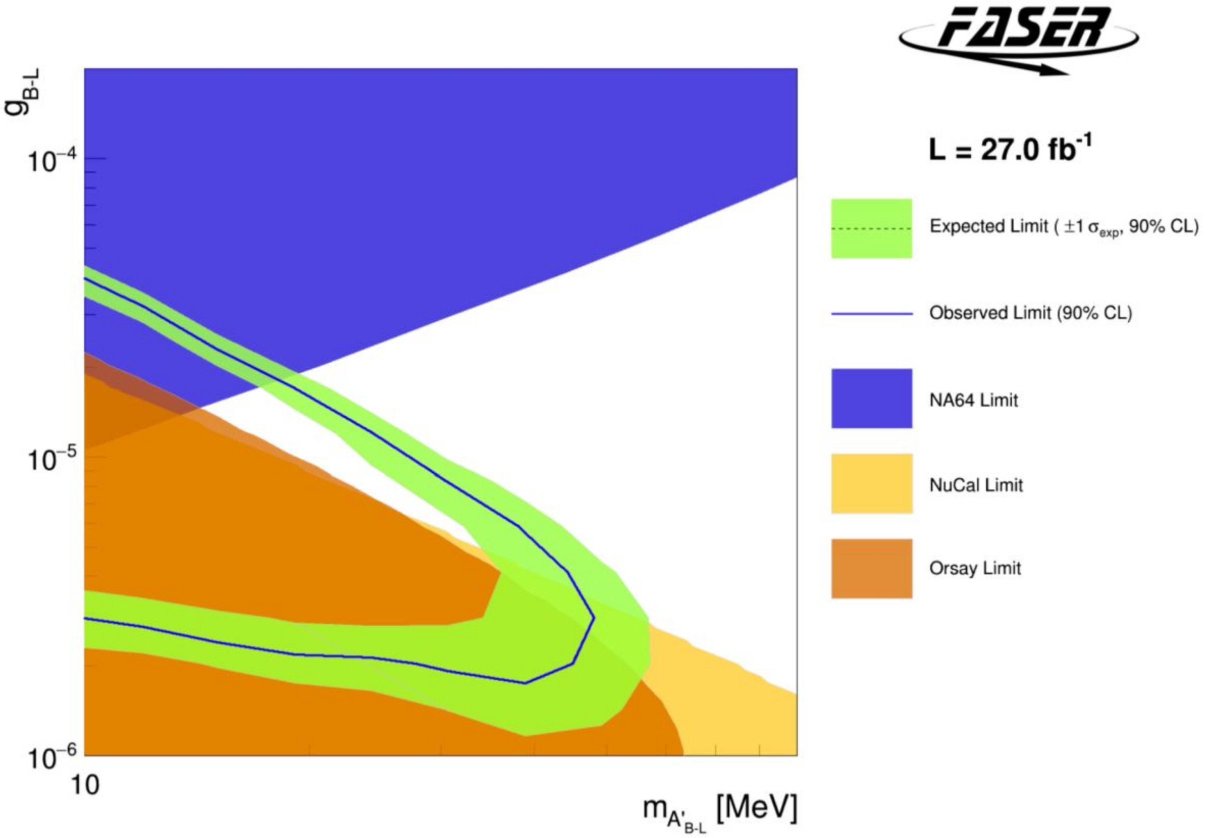
B-L at FASER

➔ Accidental conservation of B and L in SM suggests new local symmetries
- ◆ $U(1)_{B\text{-}L}$ gauge symmetry is one well-motivated example
- ◆ Associated with B-L boson, coupled to SM with strength $g_{B\text{-}L}$

$$\mathcal{L} \supset \frac{1}{2} m^2_{A'_{B-L}} A'^2_{B-L} - g_{B-L} \sum_f Q^f_{B-L} A'^{\mu}_{B-L} \bar{f} \gamma_\mu f$$

➔ FASER sensitivity constrained to mass range $2\,m_e < m_{A'} < 2\,m_\mu \sim 211$ MeV
- ◆ Light meson decays and dark bremsstrahlung dominant production modes
- ◆ Can decay to electrons, SM neutrinos, and possibly sterile neutrinos
  - ● Assume decays to sterile neutrinos kinematically inaccessible
- ◆ $BR(A'_{B\text{-}L} \to e^+e^-) \sim 40\%$

B-L limits



FASER
L = 27.0 fb^{-1}
Expected Limit (±1 σ_{exp}, 90% CL)
Observed Limit (90% CL)
NA64 Limit
NuCal Limit
Orsay Limit
g_{B-L}
10^{-4}
10^{-5}
10^{-6}
10
$m_{A'_{B-L}}$ [MeV]

The FASER collaboration

84 members from **24 institutions** and **10 countries**

International laboratory covered by a cooperation agreement with CERN

Acknowledgements