Physics Results from FASER –Dark Photon and Electronic Muon-Neutrino Studies

LHC Forward Physics Meeting

Savannah Shively, Noshin Tarannum on behalf of the FASER Collaboration

Swiss National Science Foundation
HEISING-SIMONS FOUNDATION
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Overview

- What is FASER?
- How FASER takes data
- Handling background
- Analysis and Results
  - Dark Photon
  - Neutrino
- Conclusion

The FASER Experiment

- New, small experiment at the LHC - tangent to ATLAS
- Exploits high LHC collision rate + highly collimated, forward-produced, low-mass particles

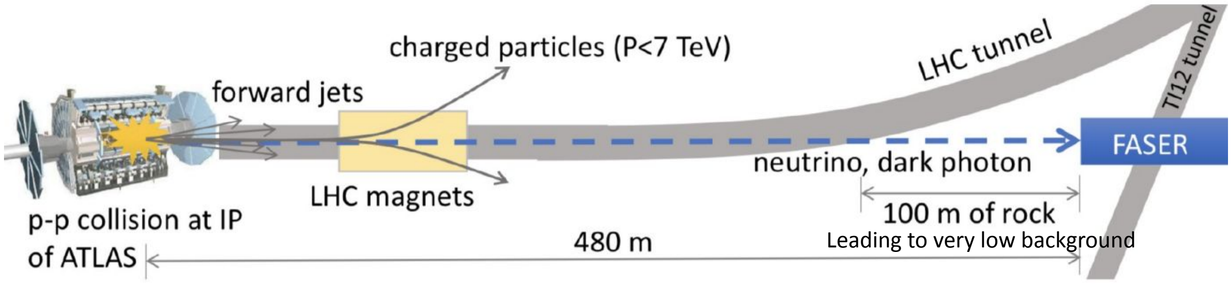
FASER's Targets

Long-lived particles (LLPs, Ex: **dark photons**), axion like particles (ALPs), **neutrinos**

FASER's Installation

- Mostly installed in March 2021
- Fully completed in November 2021, ahead of Run3

FASER's Positioning



Savannah Shively on behalf of the FASER Collaboration
LHCP 2021, 7 - 12 June 2021

FASER

Tracking Stations

- 4 Stations, 3 planes each
- 8 SCT modules per plane
- SCTs donated by ATLAS

Scintillators

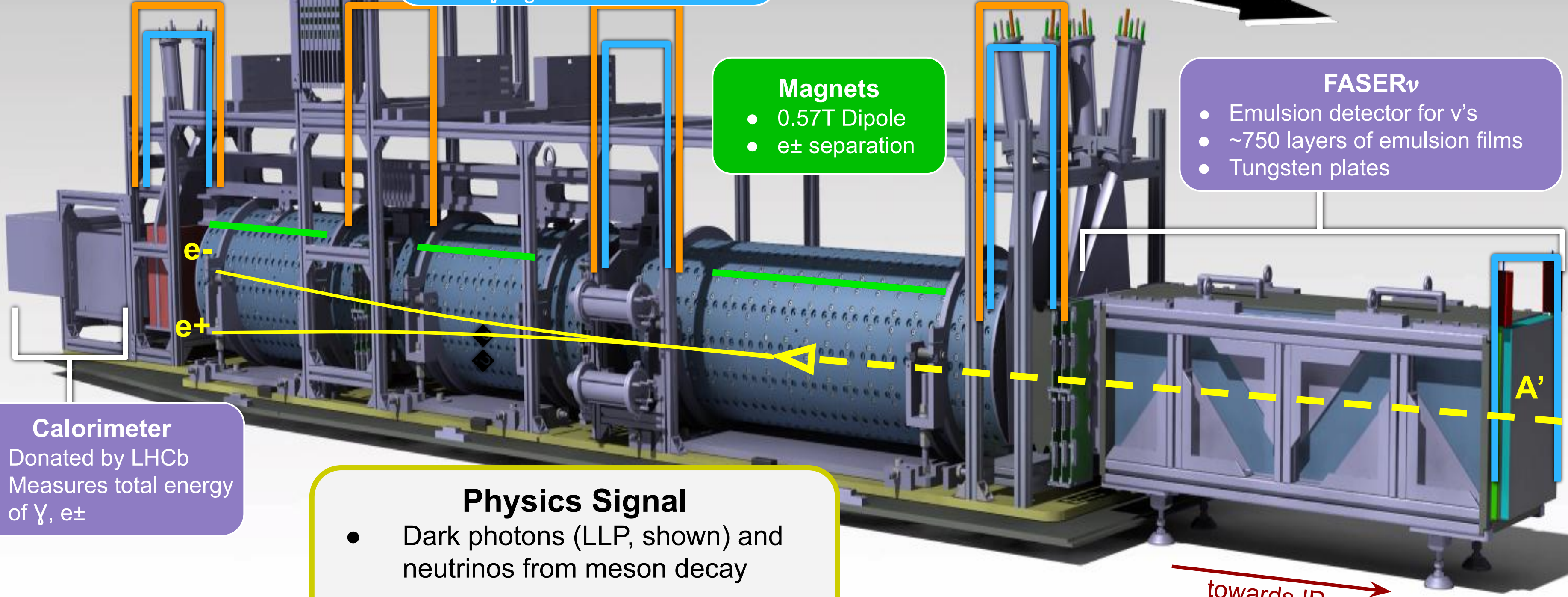
- Veto - rejects muon background
- Trigger/timing - arrival time
- Preshower - Backsplash veto & 2-ɣ signal

Magnets

- 0.57T Dipole
- e± separation

FASERν

- Emulsion detector for ν's
- ~750 layers of emulsion films
- Tungsten plates



Calorimeter

- Donated by LHCb
- Measures total energy of ɣ, e±

Physics Signal

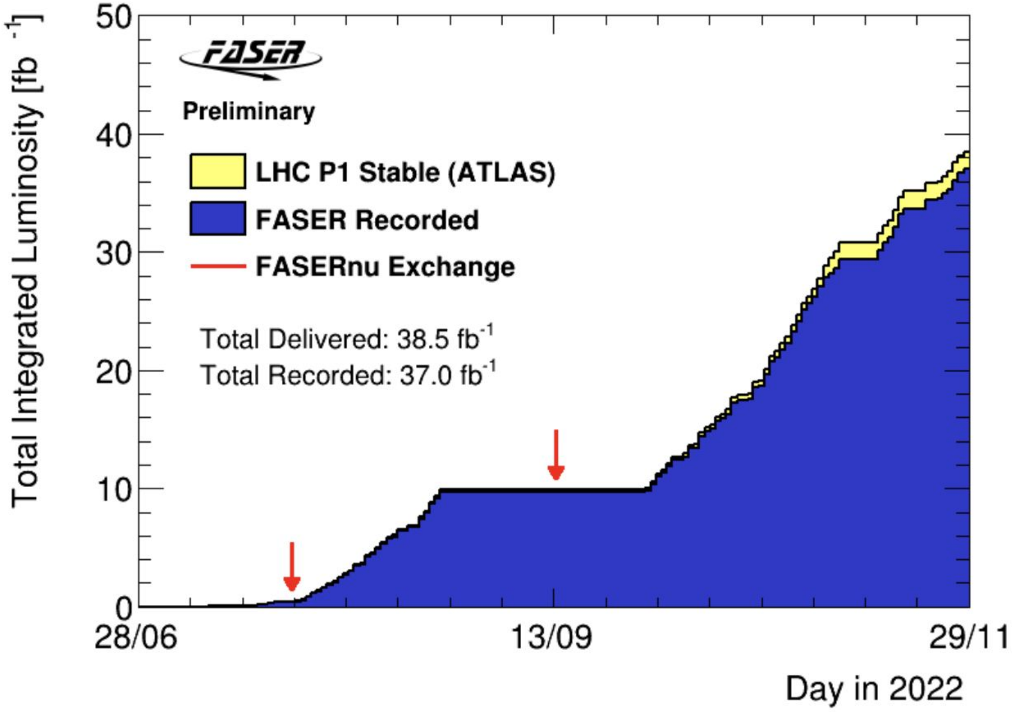
- Dark photons (LLP, shown) and neutrinos from meson decay

pp→LLP + X , **LLP**→e+e−,μ+μ−...

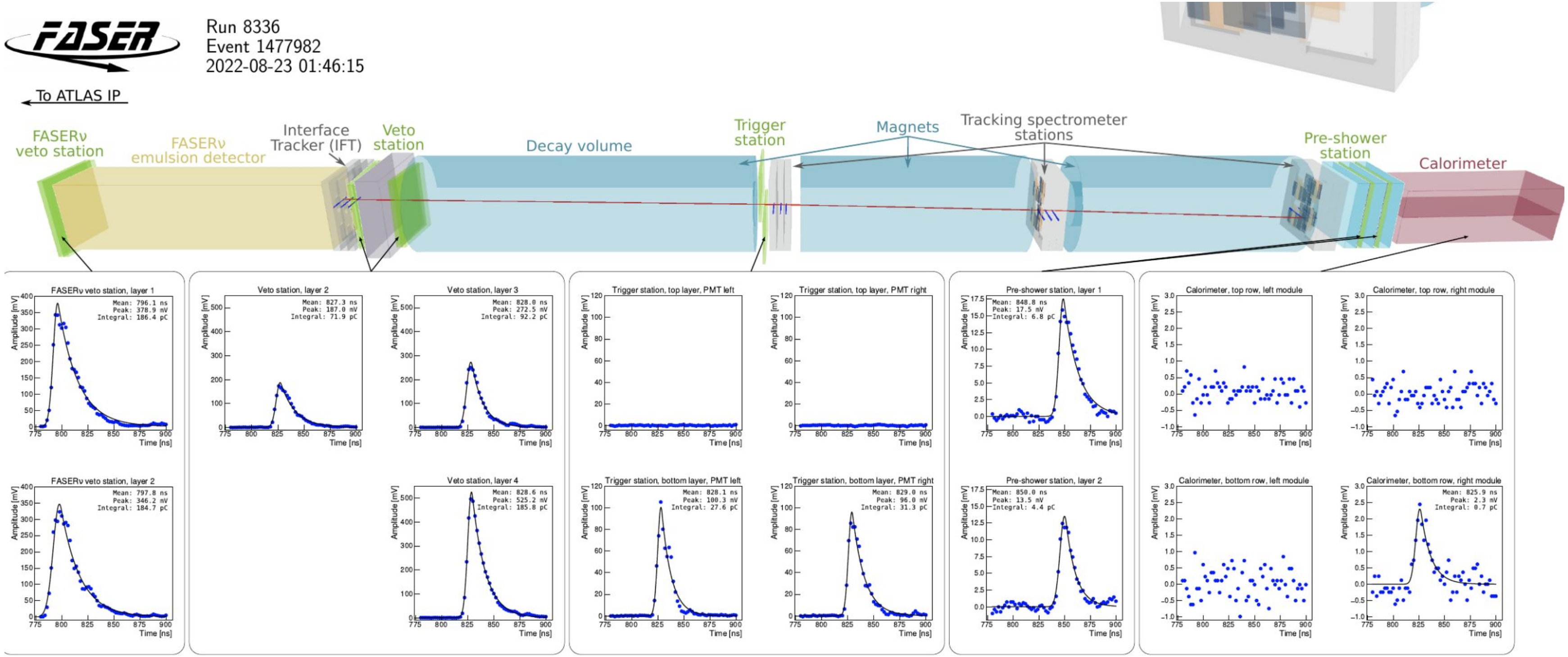
References
[1] https://arxiv.org/pdf/1811.12522.pdf
[2] https://arxiv.org/pdf/1812.09139.pdf

FASER and Run3

- Successfully took data continuously and mostly automatically during 2022.
- Recorded **96.1%** of the delivered luminosity
  - DAQ dead time of 1.3%, rest lost to a couple of DAQ crashes
- Calorimeter gain was optimized:
  - For low energy (<300GeV) until 2nd FASERnu exchange.
  - For high E (up to 3 TeV) after that for A' studies.

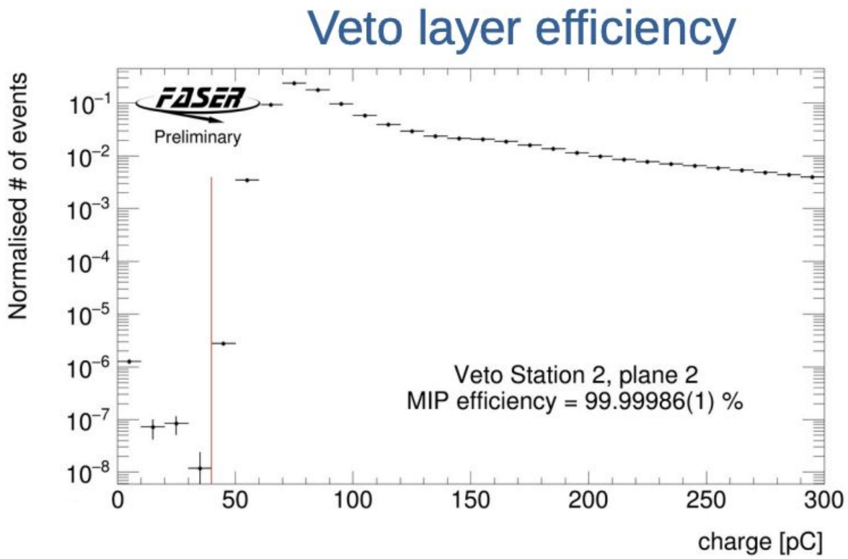


Example Event - Complete Muon Track



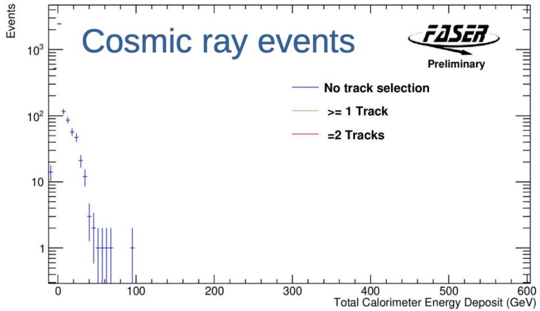
Veto Efficiency

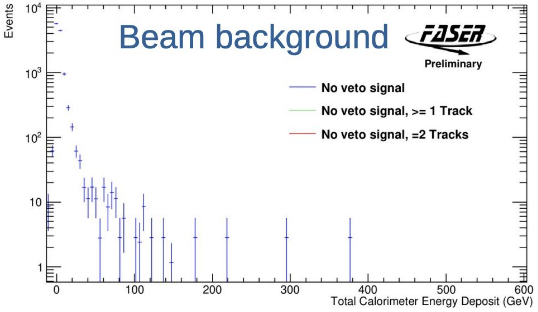
- Veto *single*-layer scintillator efficiency >**99.998%**
- Measured layer-by-layer using muon tracks in spectrometer pointing back
- With five Veto layers, 10^8 muons produce negligible background before other selections.

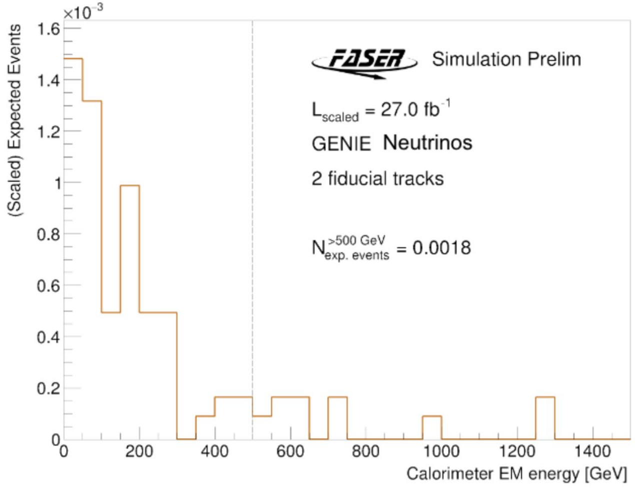


Background Sources & Estimates

1. Neutral hadron from upstream muon interaction
   a. Estimate: (2.2±3.1)x10-4
   b. Heavily suppressed
2. Non-collision background
   a. **Cosmics** measured in runs with no beam
   b. **Nearby beam debris** measured in non-colliding bunches
   c. Gone with track selection; all below 500GeV
3. Neutrino interactions
   a. *Largest background in analysis*
   b. Predicted events (Genie) with >500GeV:
      N = **(1.8 ± 2.4) x 10 -3**

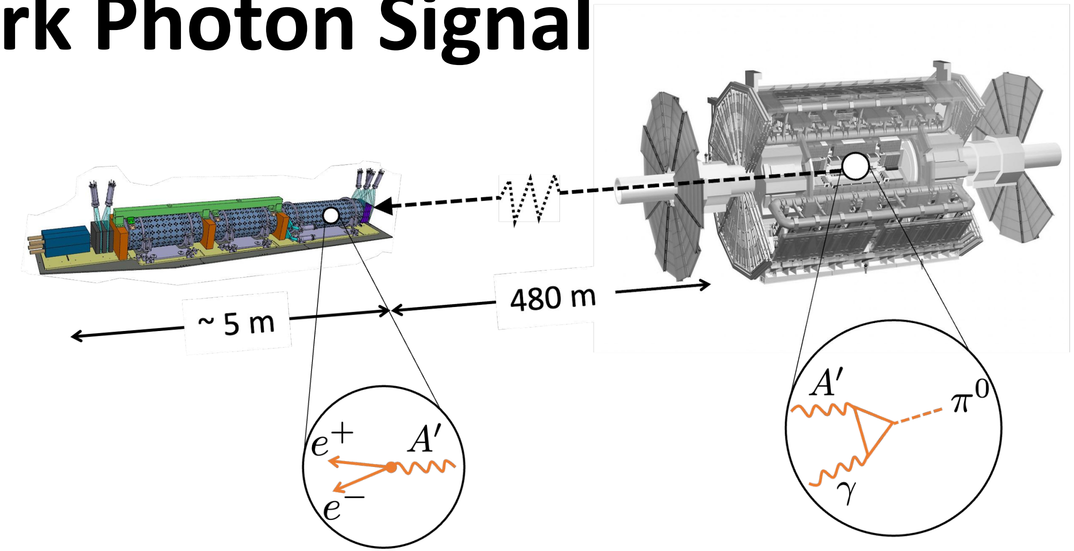


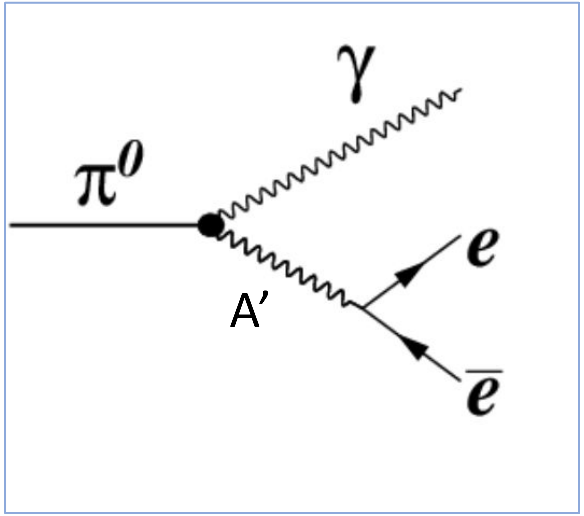




Total Background Estimate: 0.0020±0.0024 events

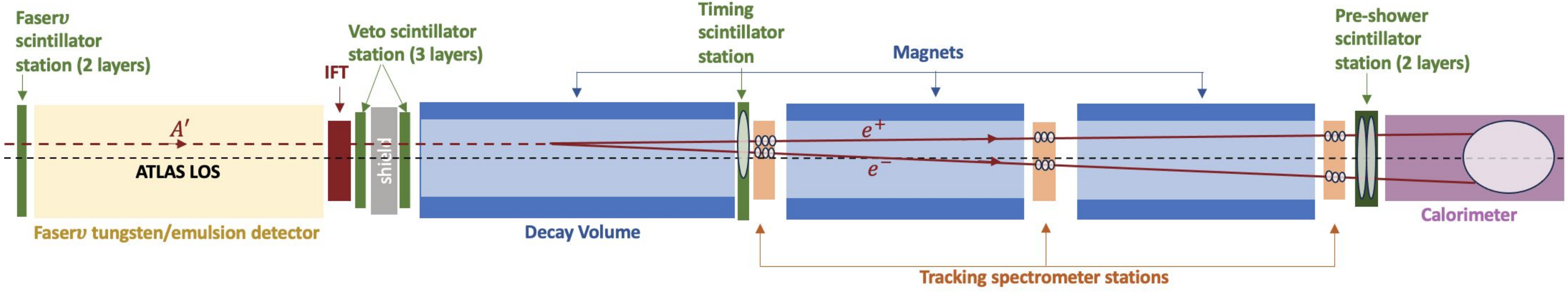
Dark Photon Signal





- Dark Photon, A', can be a feature of hidden sector models where hidden gauge boson can mix with SM photons
- MeV-scale A' produced abundantly in meson decays depending on kinematic mixing, ε
- At small coupling, high energy in forward region, results in long decay lengths, which is ideal for FASER
- For $1<m_{A'}<211$ MeV, will decay 100% to e^+e^- pair

Selection for Dark Photon Search

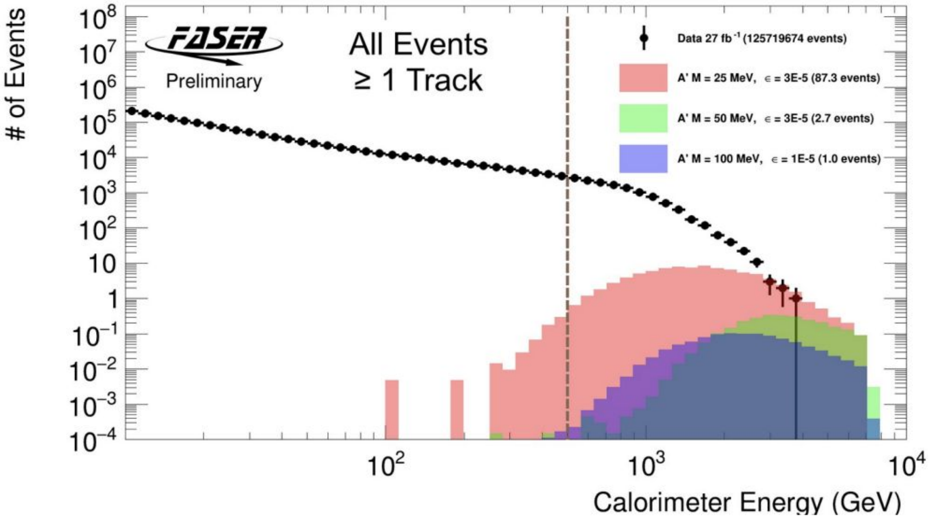


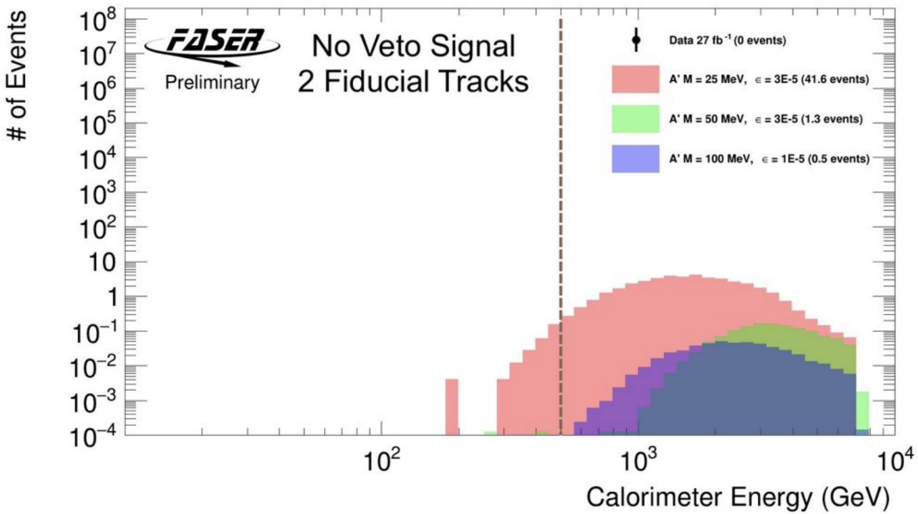
Selection Criteria:

1. Events in collision crossing, during good physics data period
2. No signal in any of five veto scintillators
3. Timing and preshower scintillators consistent with ≥2 minimum ionising particles
4. Exactly two good quality tracks with p>20 GeV and r < 95 mm
5. Both tracks extrapolate to r<95mm in veto scintillators
6. Calorimeter energy above 500 GeV

Dark Photon - Data

We do not see any events with calorimeter E>500GeV

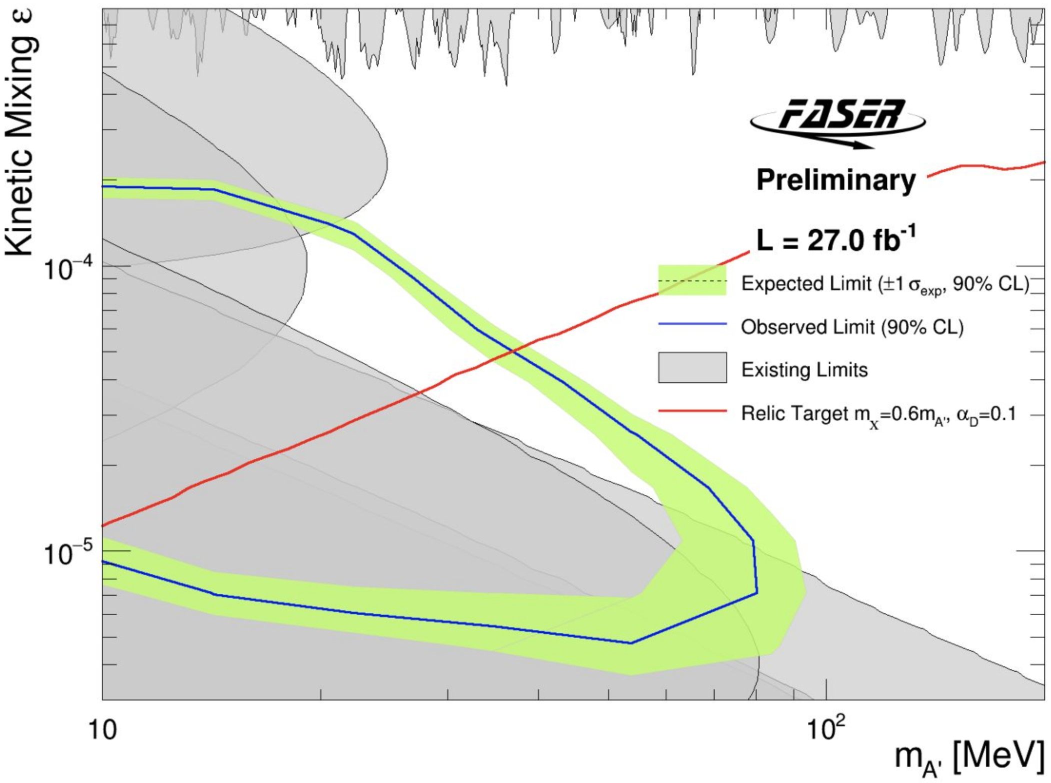




Public conf note: *https://cds.cern.ch/record/2853210?ln=en*
CERN-FASER-CONF-2023-001

Dark Photon Reach

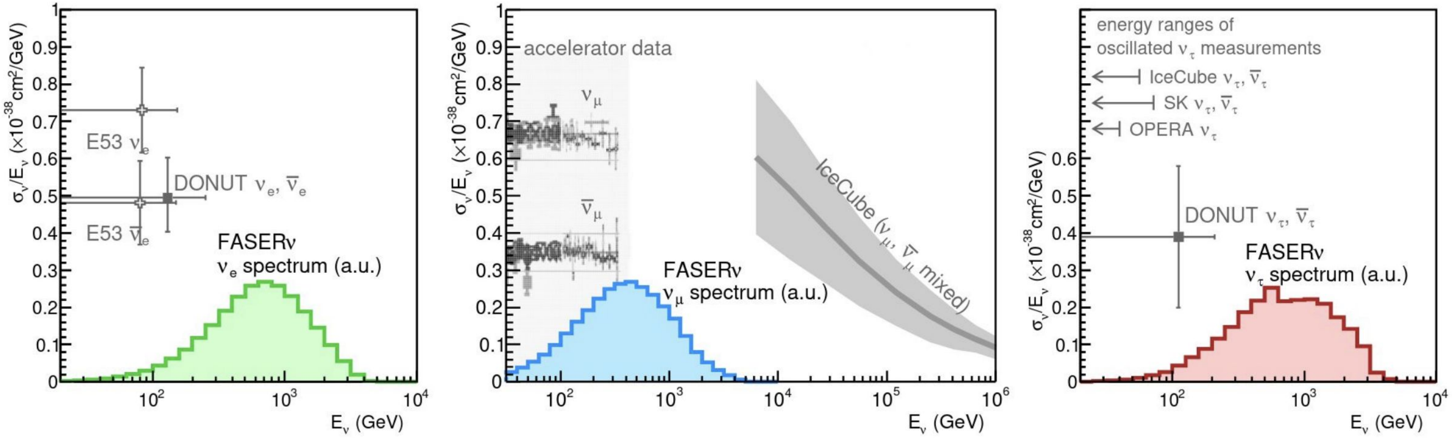
1. With null result, FASER sets limits on previously unexplored parameter space!
2. The limits are in a region of parameter space motivated by the dark matter relic density.



Collider Neutrinos

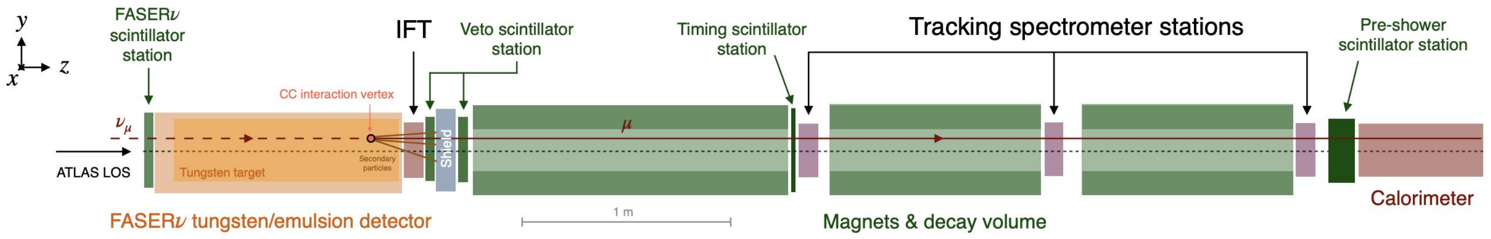
- 1. Observed neutrinos from a variety of sources
    - Nuclear reactors, beam dump experiments, cosmic rays, Sun, earth, supernovae, …
- 2. Neutrinos produced copiously at hadron colliders, but no direct observation yet!
    - Neutrinos interact extremely weakly
    - Highest energy neutrinos produced in forward direction (parallel to beamline)
- 3. Energy spectrum complementary to existing neutrino experiments
    - Measurement at highest man-made neutrino energies

https://arxiv.org/pdf/1908.02310.pdf



Selection for Electronic Neutrino

Example of a signal event using spectrometer and scintillators

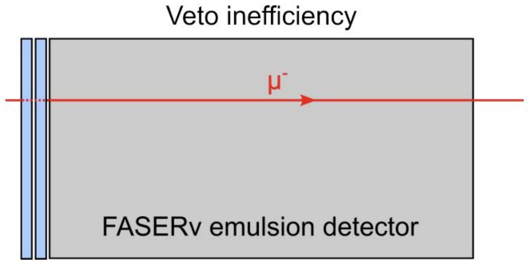


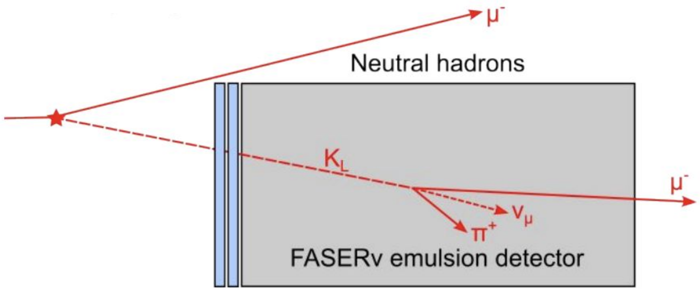
The selection criteria we had in place:

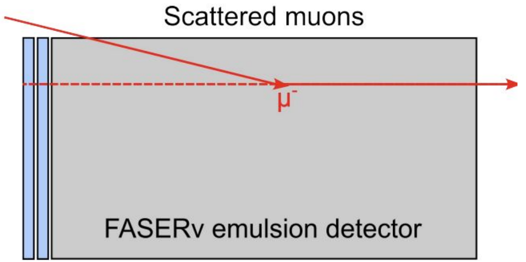
Essentially, using FASERν only as target for neutrino interactions

1. Collision event timing and good data quality
2. No signal (40 pC) in all scintillators downstream of decay volume
3. Signal (>40 pC) in all scintillators downstream of decay volume
4. Exactly 1 good fiducial track (p > 100 GeV, r < 120 mm at front veto, …)

Background Estimate

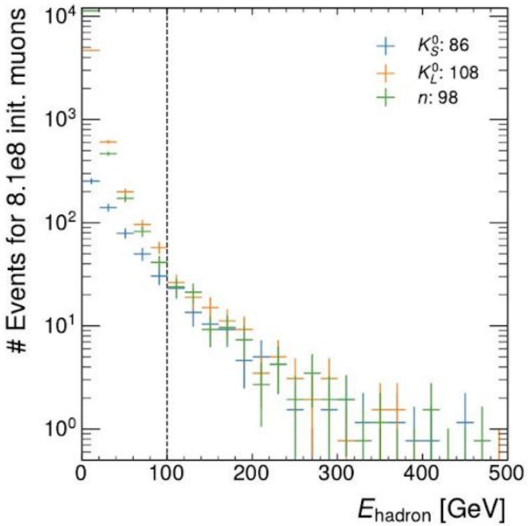


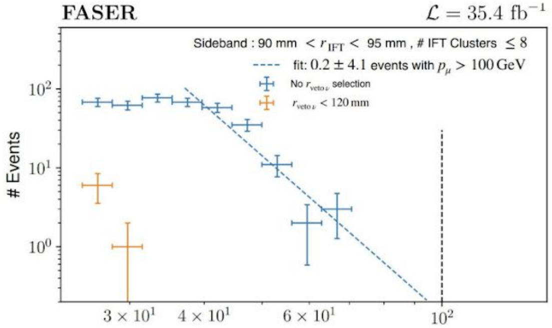




Estimated from events with just one veto scintillator firing
-**Expect (3.7±2.5) x 10-7 events**

Expect O(300) neutral hadrons with E > 100 GeV
- Most hadrons absorbed in tungsten (8 int. lengths) - **Estimate 0.11 ±0.06 events**

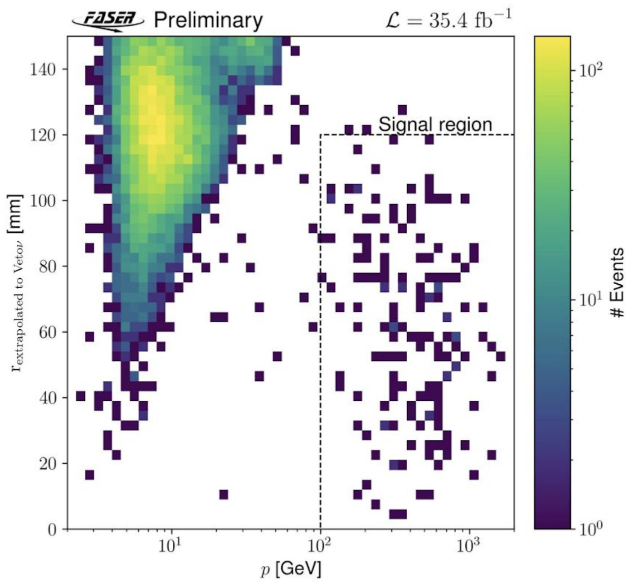


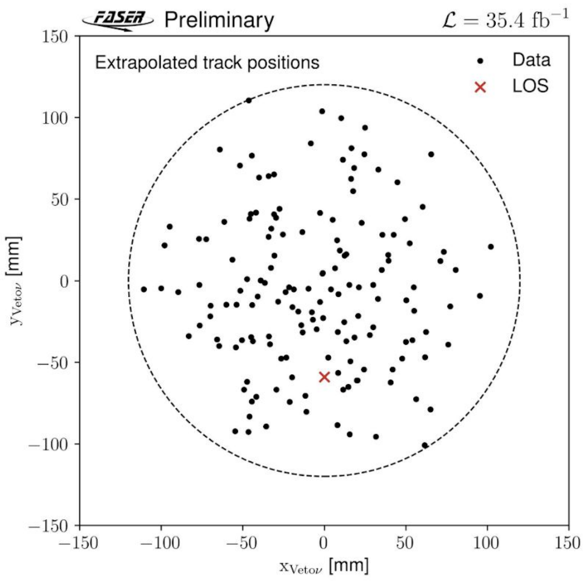


Estimated from control region (90 < r < 95 mm, # clusters ≤ 8)
- Expect 0.08 ± 1.83 events

Neutrino Observation

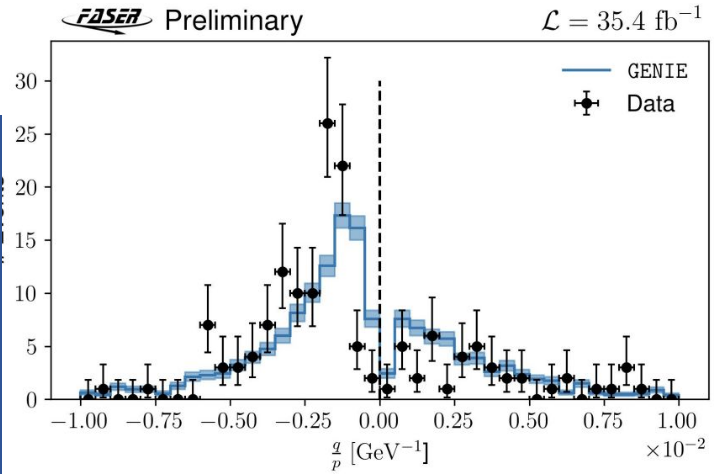
- Based on GENIE simulation *expect 151 ± 41* neutrino events
  - Uncertainty from difference between DPMJET and SIBYLL event generators
- No experimental uncertainties → cannot translate to cross section / flux yet
- **Observe 153 events** with no veto signal with an expected background of 0.2 ± 1.8
- **First direct observation of collider neutrinos!**
- Signal significance of **16 σ**
- Recently accepted by PRL https://arxiv.org/abs/2303.14185

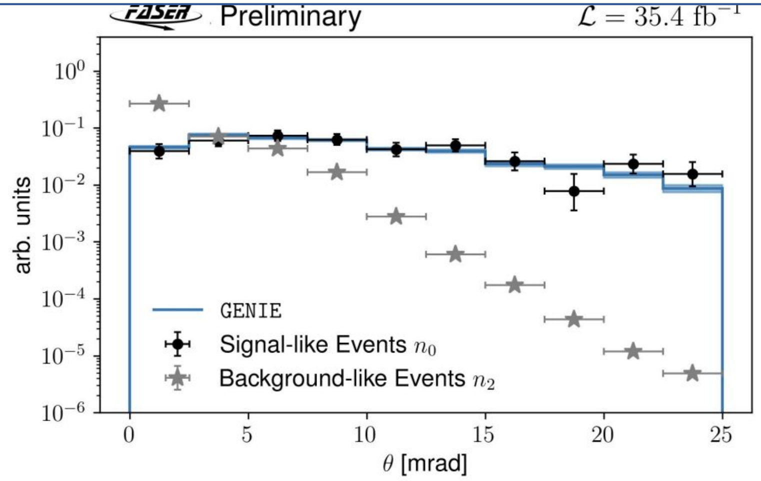


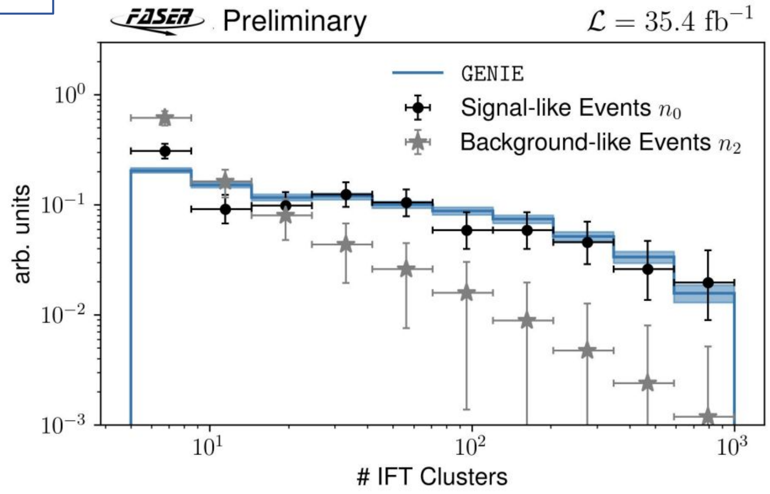


Neutrino Characteristics

Neutrino events match expectations from simulation
-Most events at high momentum (Eμ > 200 GeV)
-More ν_μ than $\bar{\nu}_\mu$
-High occupancy in front tracker station
-Large angle θ with respect to line-of-sight
**No experimental uncertainties included in these plots!*

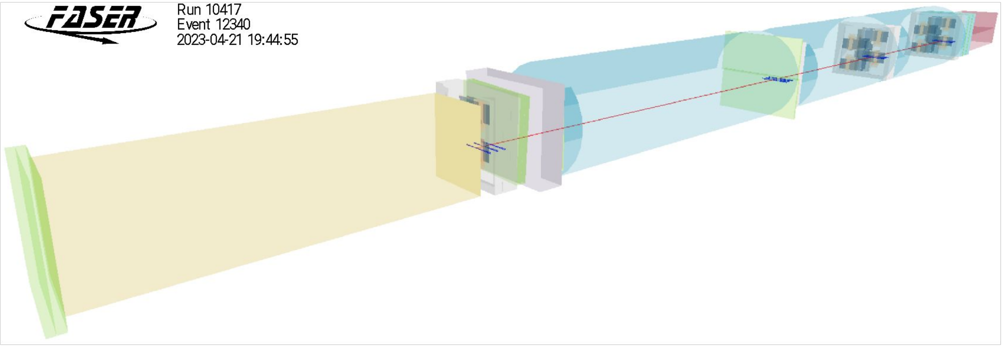




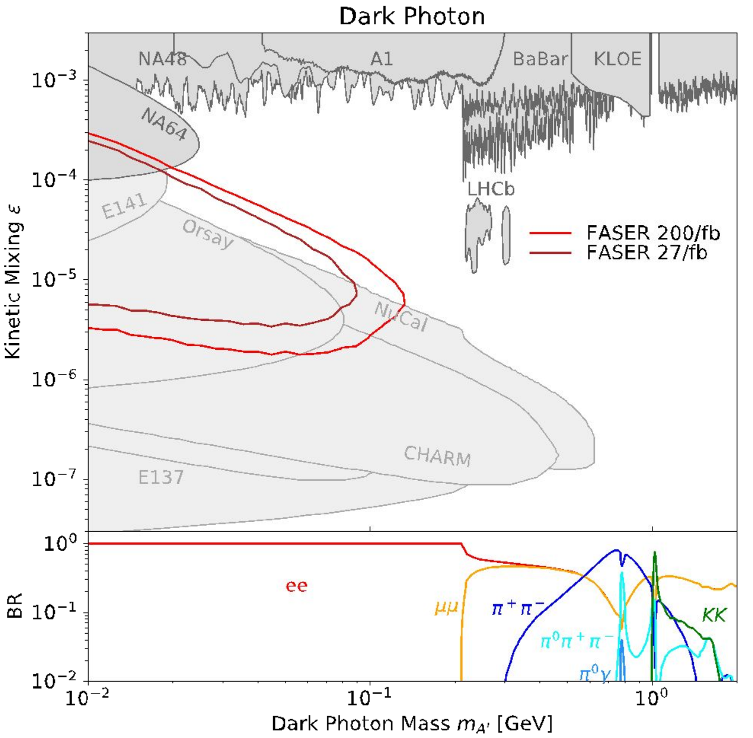


Conclusion

- FASER successfully took data in first year of Run 3, running at very good efficiency with a fully functional detector!
- Excluded dark photon in region of low mass, low kinetic mixing.
- Observed 153 ν μ CC interactions with electronic detectors. First observation of collider neutrinos!
- Will continue data-taking throughout LHC Run 3 with up to 10 times more data coming in the next years



An event display taken from a run in 2023. FASER is operating successfully in 2023 as well!



Simulation made with FORESEE https://arxiv.org/abs/2105.07077

Thank you for listening!

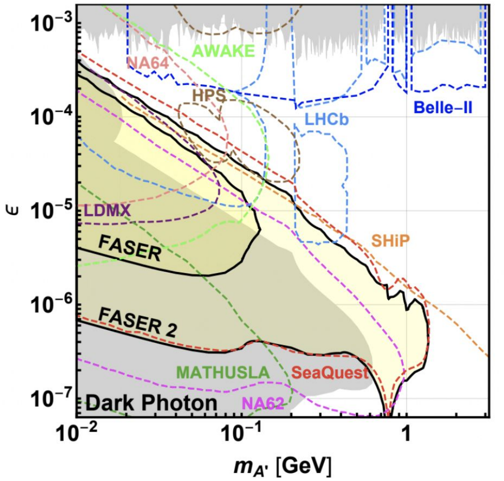
from FASER Collaboration Meeting #5!

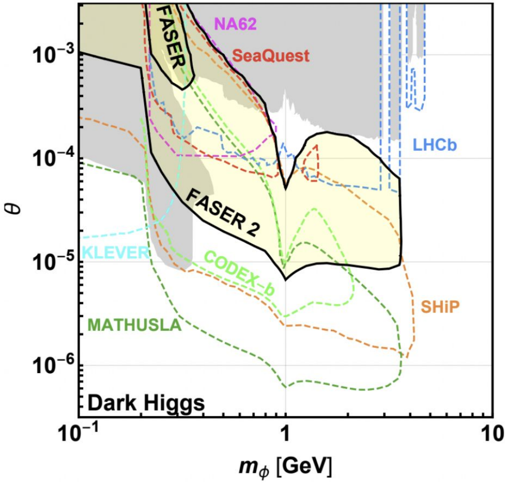
Backup

Future Plans

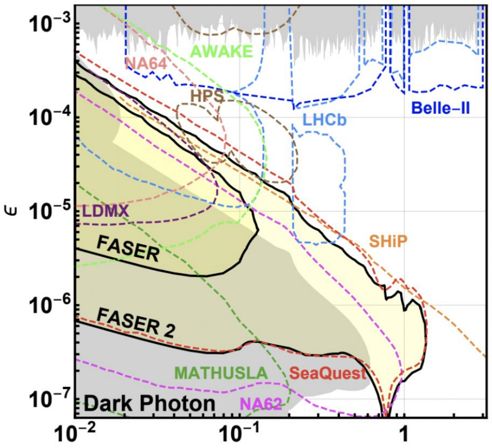
- For the HL-LHC, larger versions of FASER and FASERnu with significant gains in physics sensitivity are being studied in the context of the Forward Physics Facility (https://arxiv.org/abs/2203.05090).

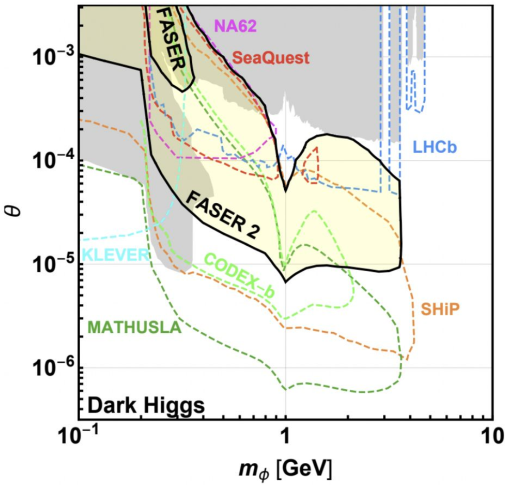
Benchmark Model	Underway	FPF
BC1: Dark Photon	FASER	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2
BC2: Dark Matter	–	FLArE
BC3: Milli-Charged Particle	–	FORMOSA
BC4: Dark Higgs Boson	–	FASER 2
BC5: Dark Higgs with hSS	–	FASER 2
BC6: HNL with e	–	FASER 2
BC7: HNL with μ	–	FASER 2
BC8: HNL with τ	–	FASER 2
BC9: ALP with photon	FASER	FASER 2
BC10: ALP with fermion	FASER	FASER 2
BC11: ALP with gluon	FASER	FASER 2

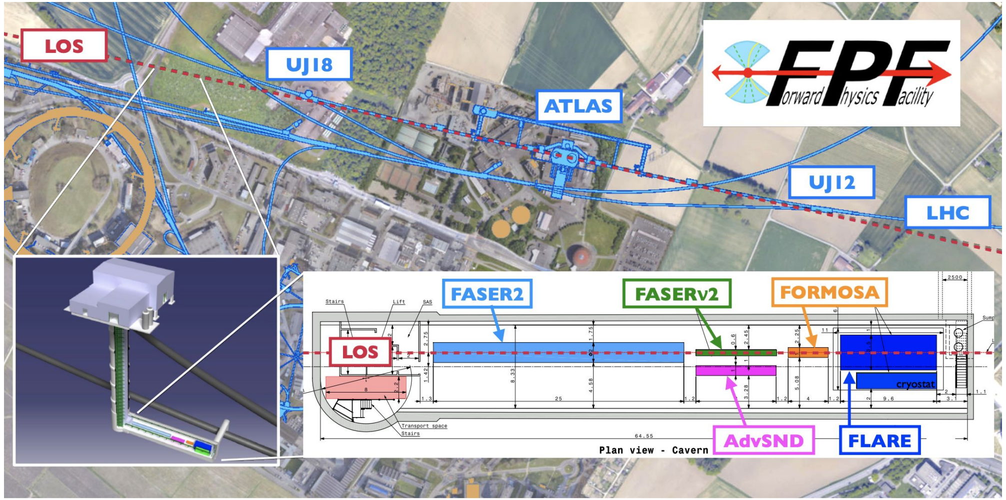




FASER 2 and Fasernu2

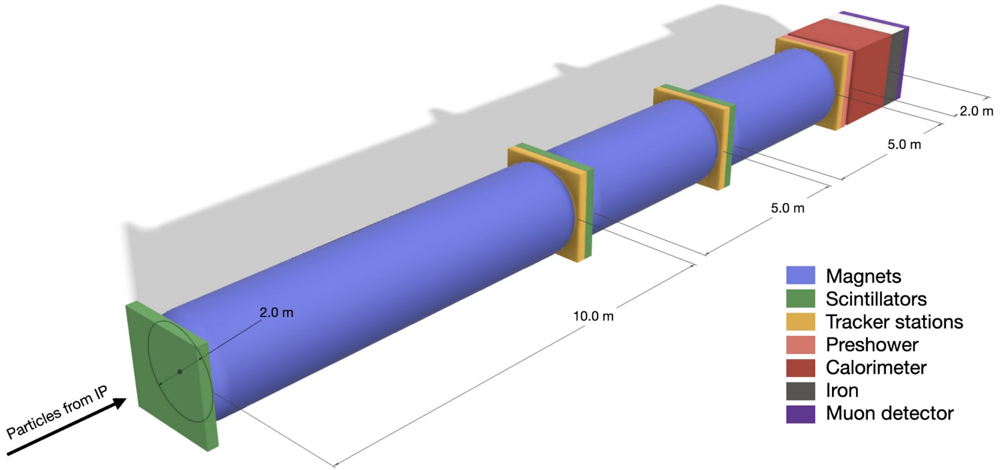


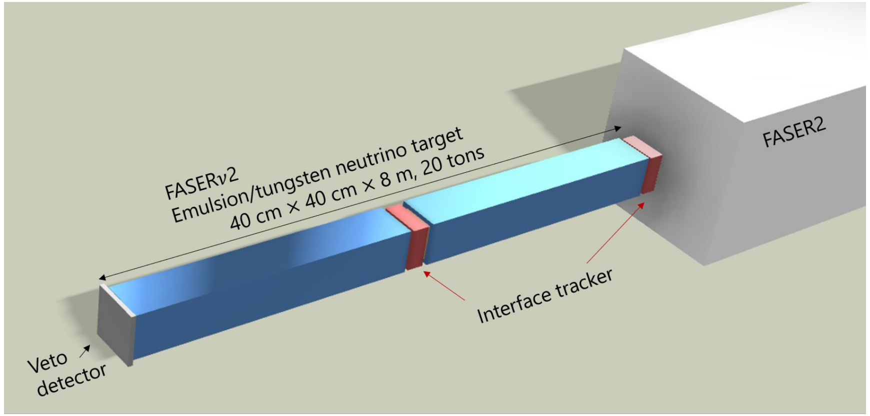




Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x

FASER 2 and Fasernu2 layout

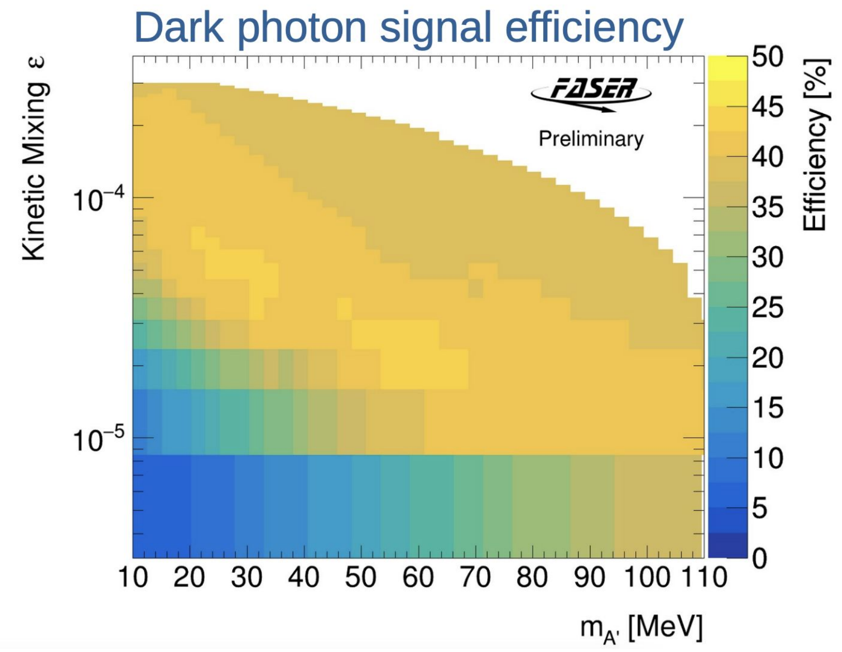




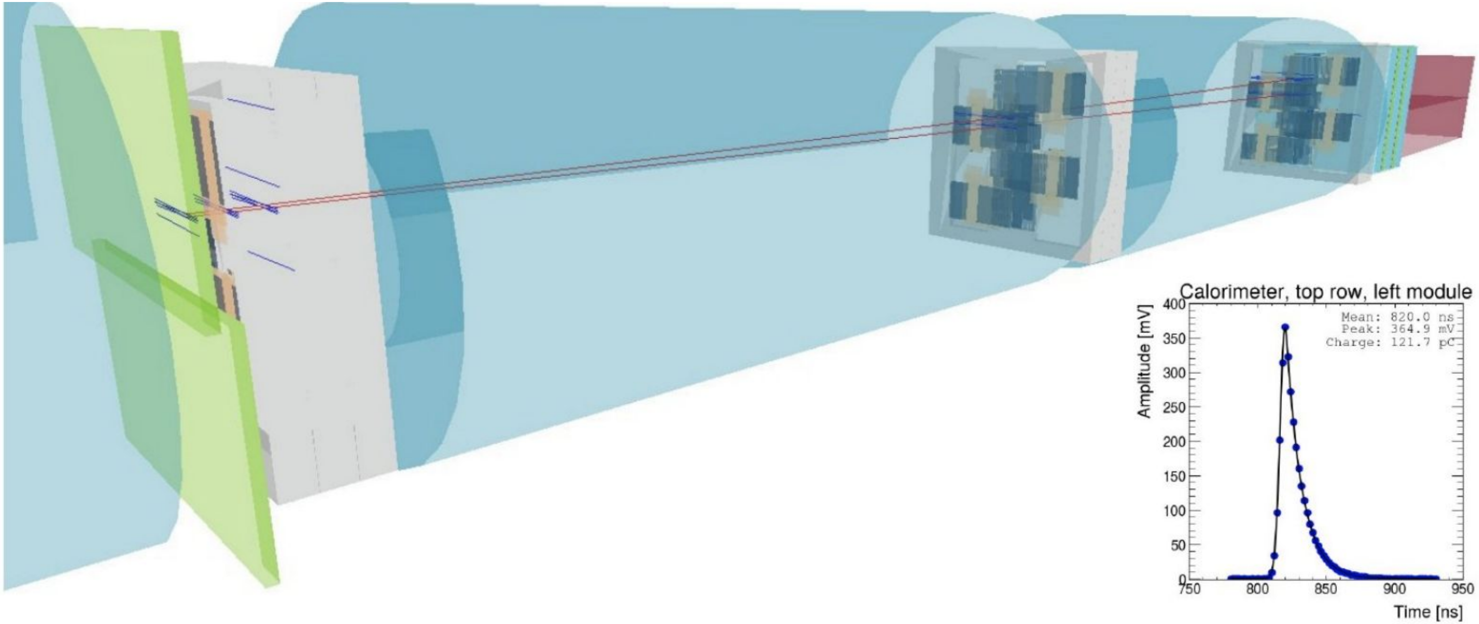
Signal Simulation (FORESEE)

- Signal simulated w. FORESEE: π0 and η0 production with EPOS-LHC generator, Dark bremsstrahlung of protons included (sub-dominant), only decays to e+e- in FASER decay volume considered.
- Main signal uncertainties: Generator uncertainty parameterized vs A’ energy as (Based on difference to QGSJET/SIBYLL), calorimeter energy scale (6% uncertainty on energy scale at 500GeV).

$$\frac{\Delta N}{N} = \frac{0.15 + (E_{A'}/4\ \text{TeV})^3}{1 + (E_{A'}/4\ \text{TeV})^3}$$



Example Dark Photon simulation



Dark Photon Cut Flow

- Data and example signal efficiency as a function of analysis selections

Cut	Data		Signal ($\varepsilon = 3 \times 10^{-5}$, $m_{A'} = 25.1\,\text{MeV}$)	
	Events	Efficiency	Events	Efficiency
Good collision event	151750788	—	95.3	99.7%
No Veto Signal	1235830	0.814%	94.0	98.4%
Timing/Preshower Signal	313988	0.207%	93.0	97.3%
≥ 1 good track	21329	0.014%	85.2	89.2%
$= 2$ good tracks	0	0.000%	52.4	54.8%
Track radius < 95 mm	0	0.000%	47.6	49.8%
Calo energy > 500 GeV	0	0.000%	46.7	48.9%

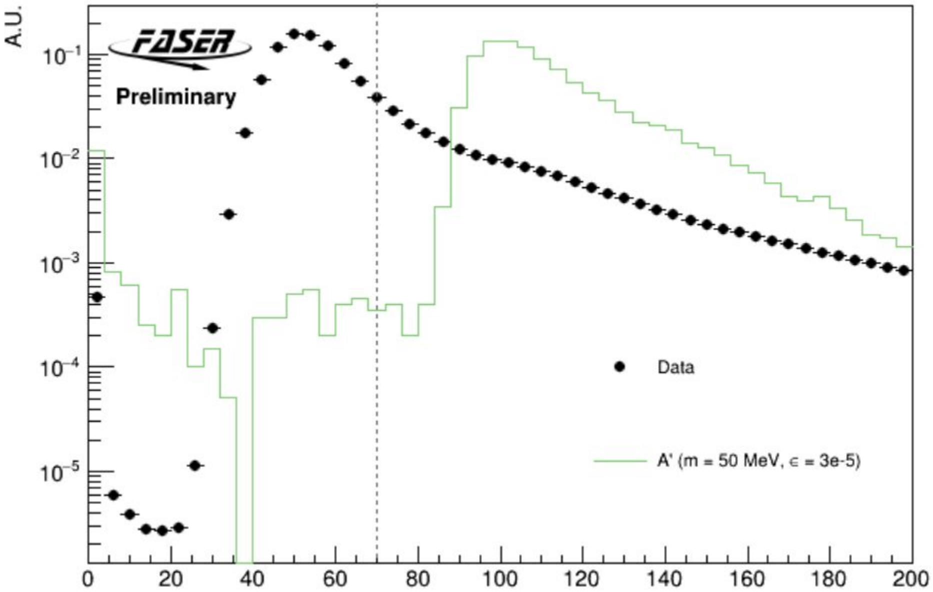
Dark Photons – Systematic Uncertainties

Complete list of systematic uncertainties and their impact on the signal yield

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

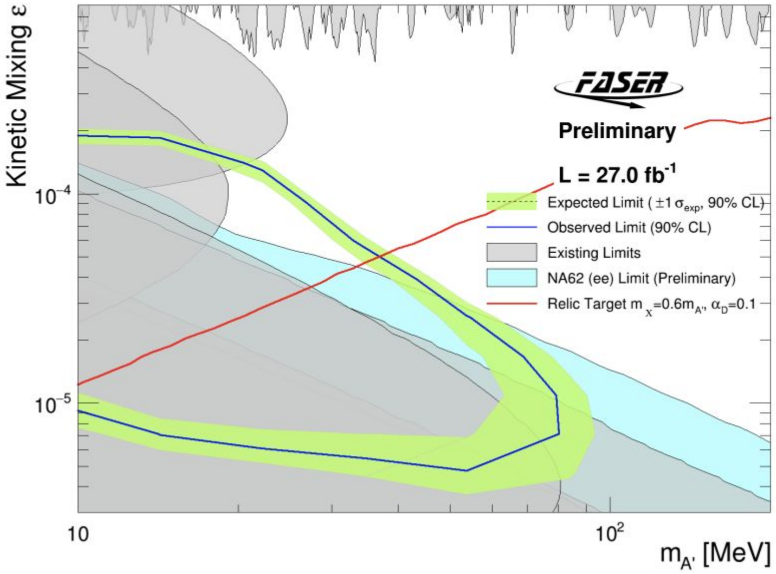
Dark Photon: Timing Scintillator Selection

- Timing cut of 70 pC is ~100% efficiency for signal

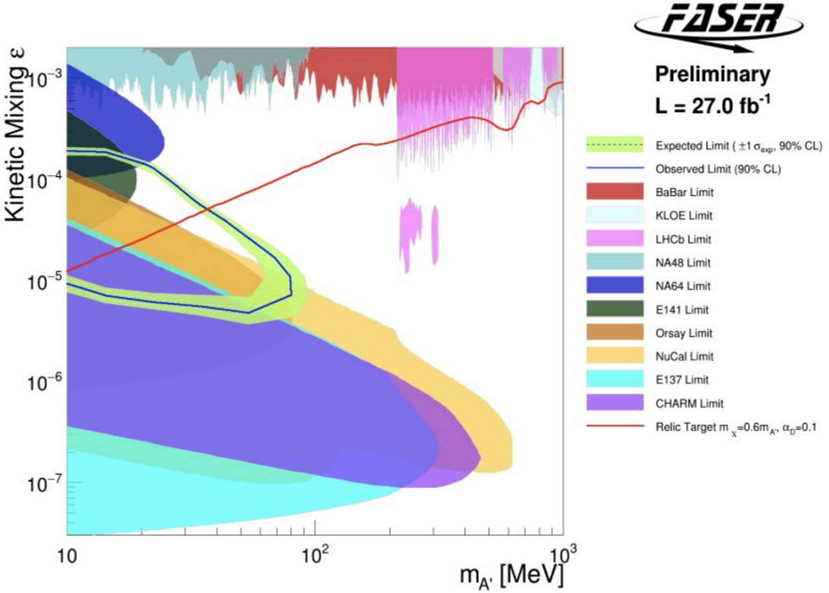


Dark Photon: Additional Limits

Limits including recent prelim NA62 results

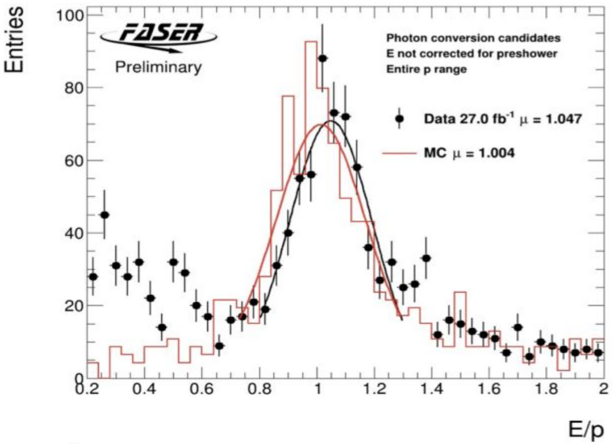


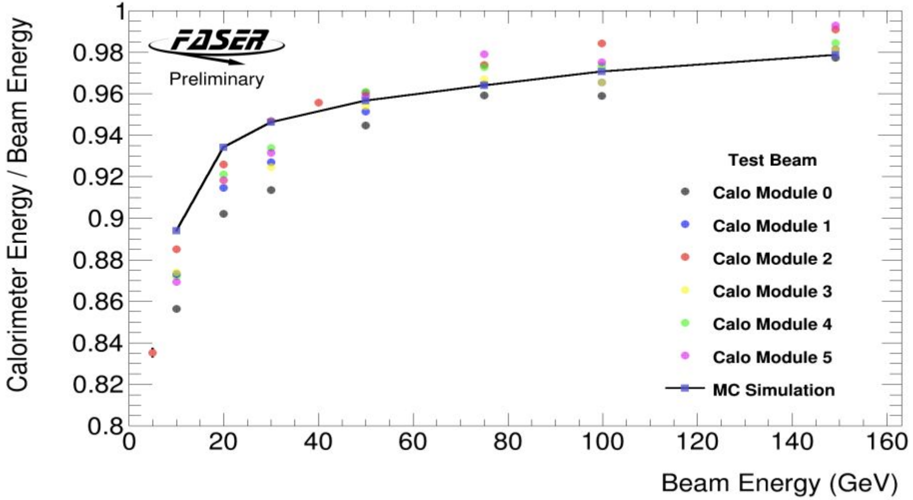
Alternative limit plot showing individual previous limits available from DarkCast

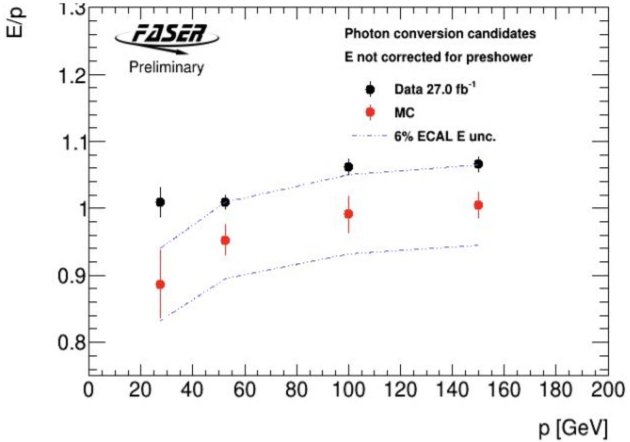


Dark Photon: Calo Energy Scal

1. Calorimeter energy scale and uncertainty evaluated based on test beam data and in-situ MIP calibration
2, Validated using conversion events (μ with e+e- pair)
3. E/p in data and MC agrees within 6%

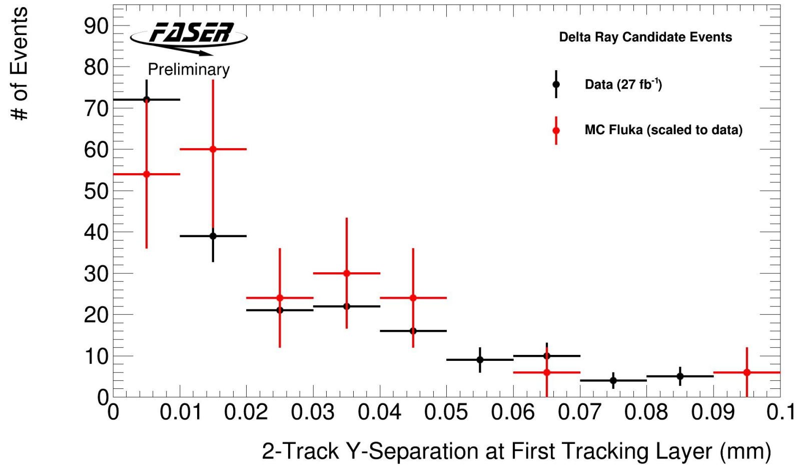


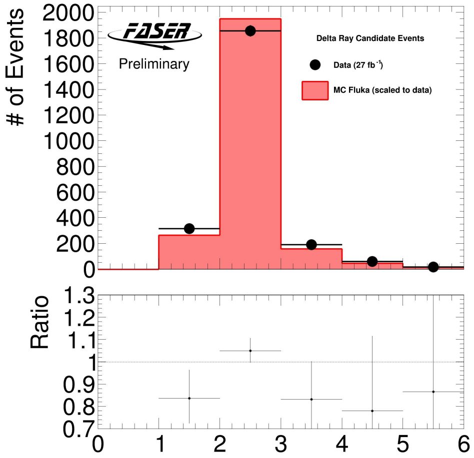




Dark Photon: Tracking Systematics

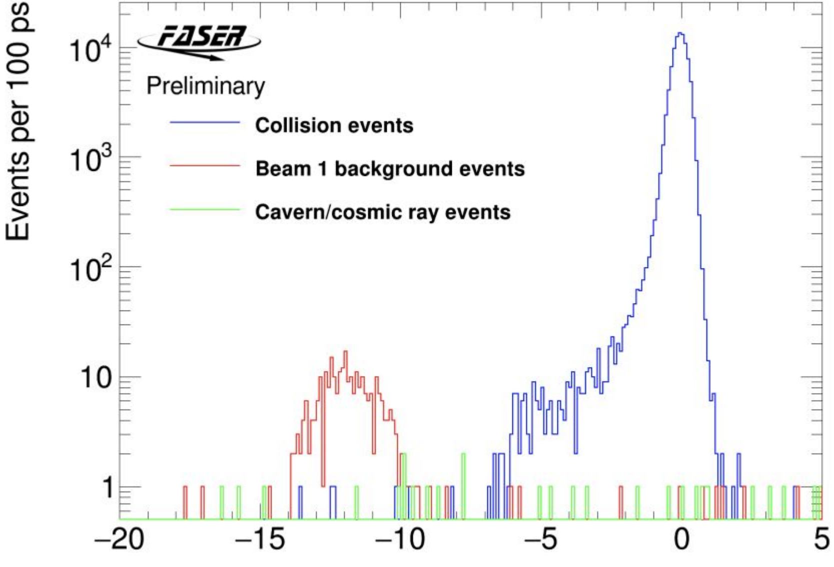
- Single track efficiency studies in muons events with track segments found in each station
- Tracking efficiency lower for two close by tracks (~60%)



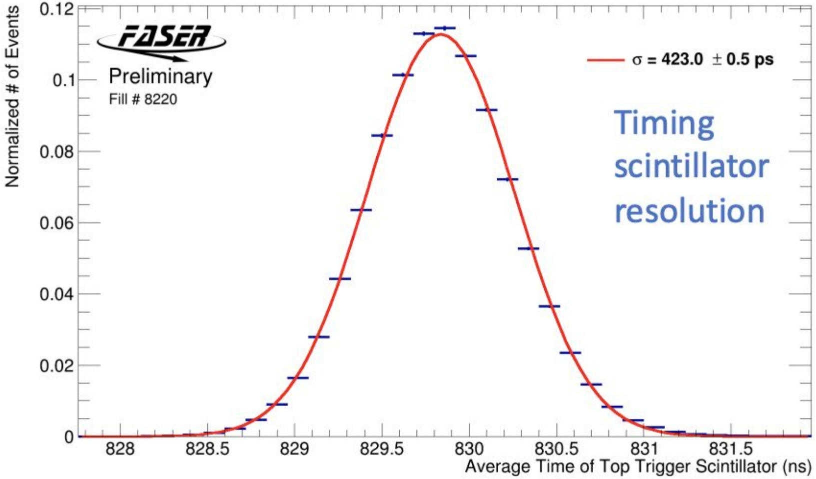


Detector Performance: Timing and Calo

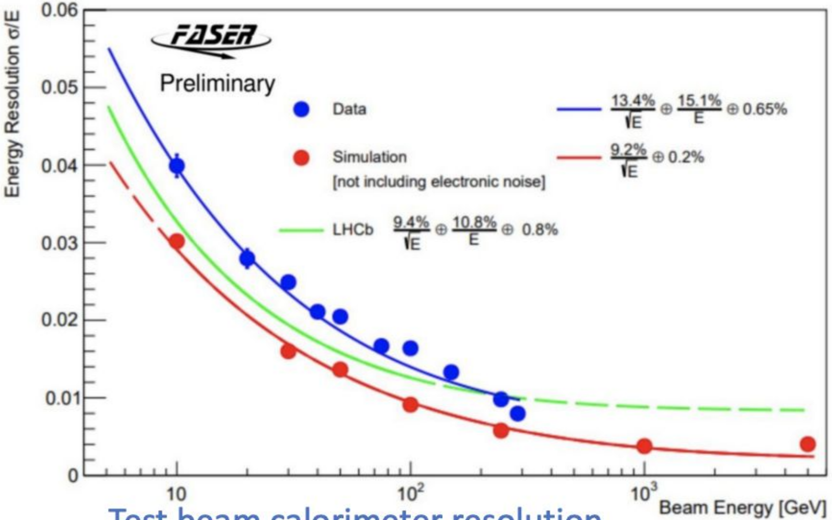
- Calorimeter resolution measured in test beam
- Precision timing of both scintillator and calorimeter



Calo timing for different events



Timing scintillator resolution



Test beam calorimeter resolution