FASER

Dark Photon Analysis – BSM Studies at FASER

LHCP 2023

Large Hadron Collider Physics Conference

Belgrade, 22-26 May 2023

Noshin Tarannum on behalf of the FASER Collaboration

Swiss National Science Foundation

HEISING-SIMONS FOUNDATION

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The FASER Experiment

- FASER is a new, small experiment at the LHC

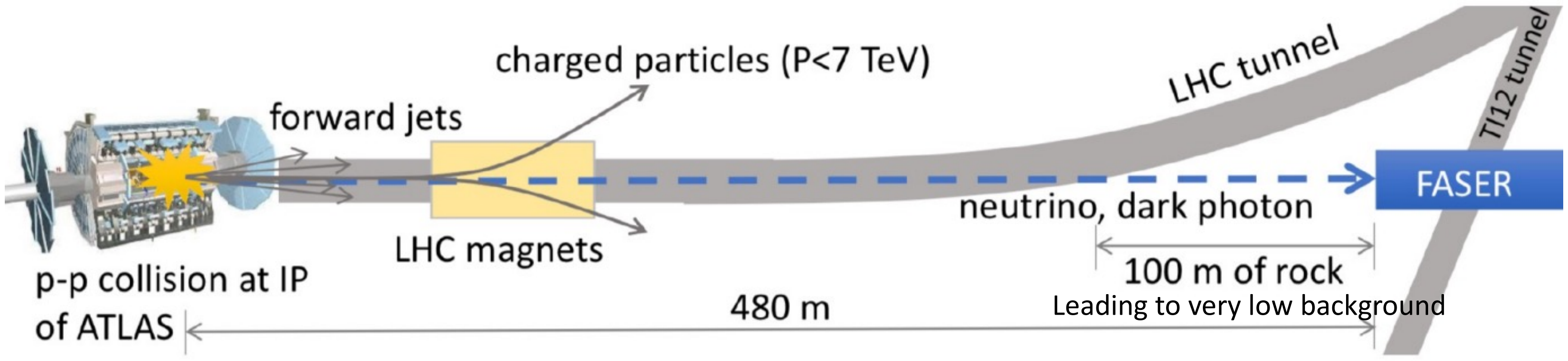
FASER's target

1. Light and weakly coupled particles
2. Exploits high LHC collision rate + forward produced light particles which are highly collimated
3. Particles in question are dark photons, axion like particles and neutrinos

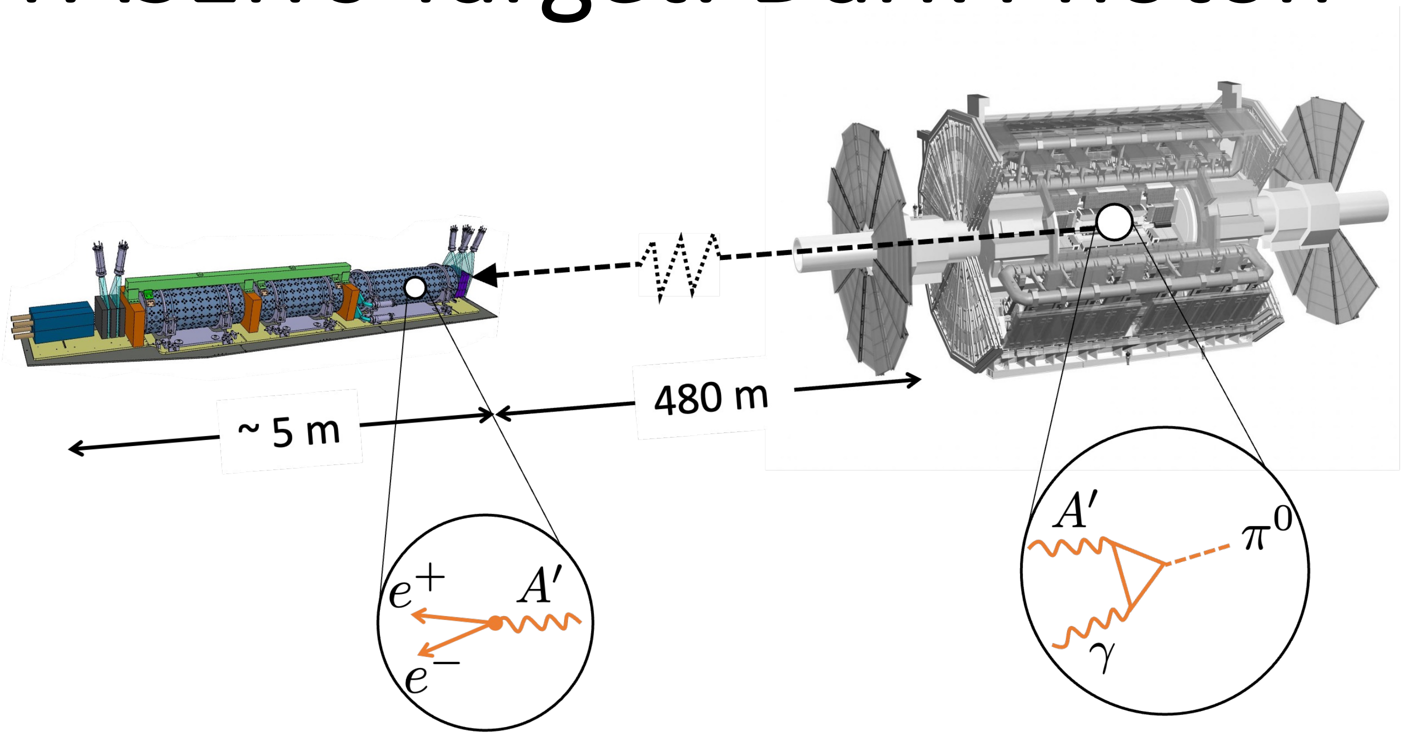
FASER's Installation

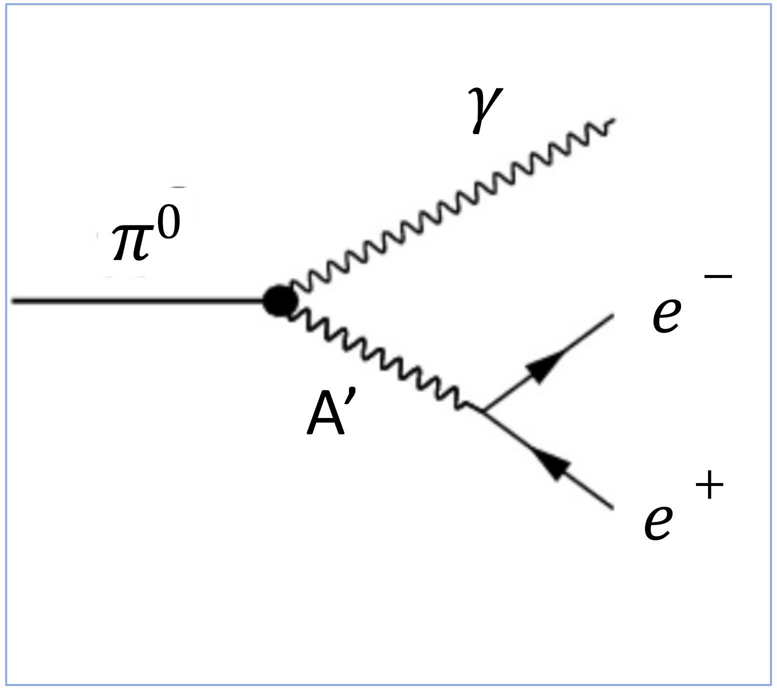
1. Mostly installed in March 2021
2. Fully completed in November 2021, ahead of Run3

FASER's positioning



FASER’s Target: Dark Photon

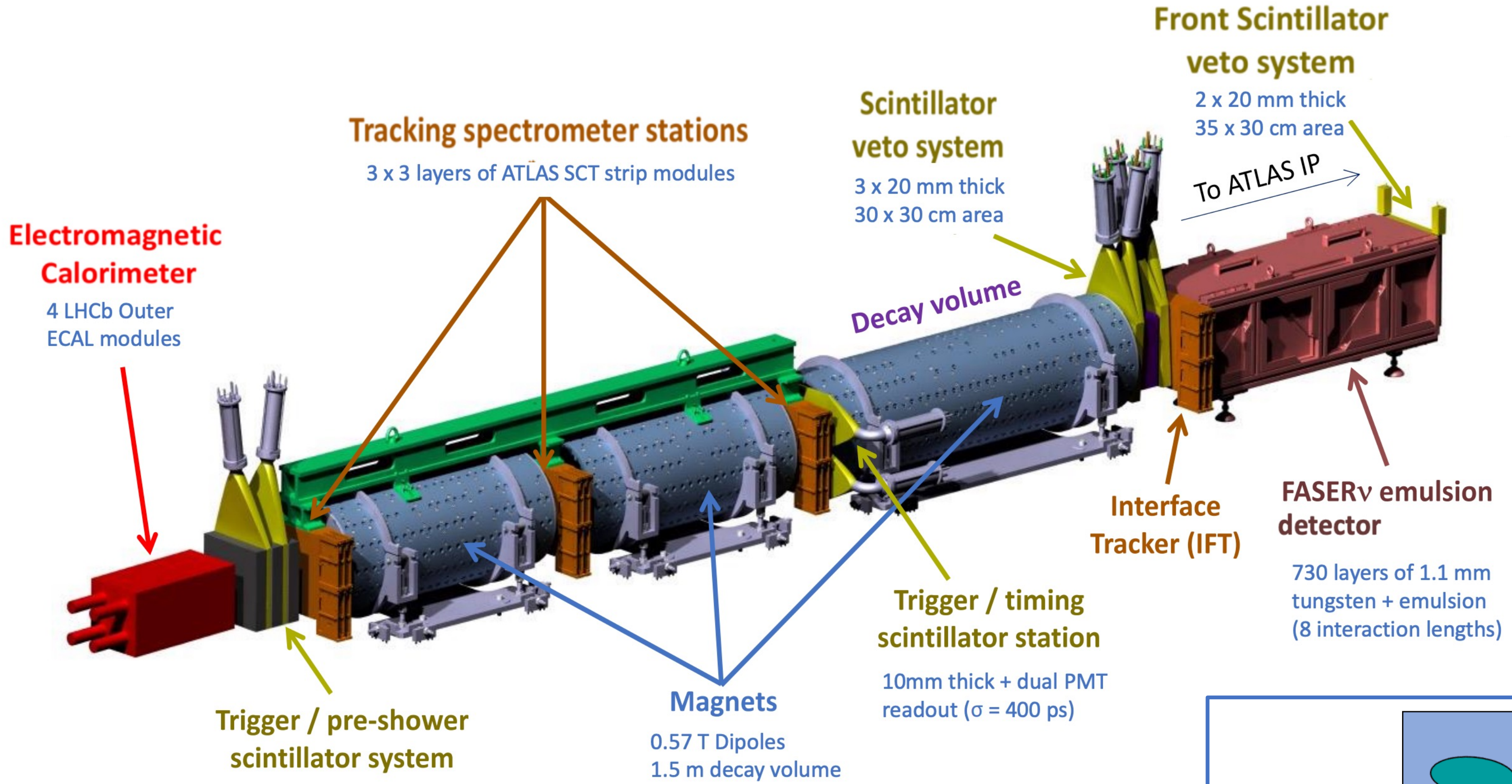


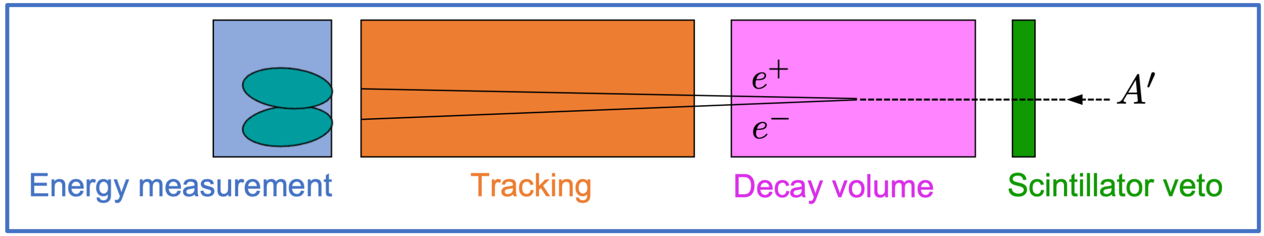


- Dark Photon can be a feature of hidden sector models where hidden gauge boson can mix with SM photons
- MeV-scale dark photons, A’, are produced abundantly in meson decays depending on kinematic mixing, ε
- At small coupling, high energy in forward region, results in long decay lengths, which is ideal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

FASER’s Design

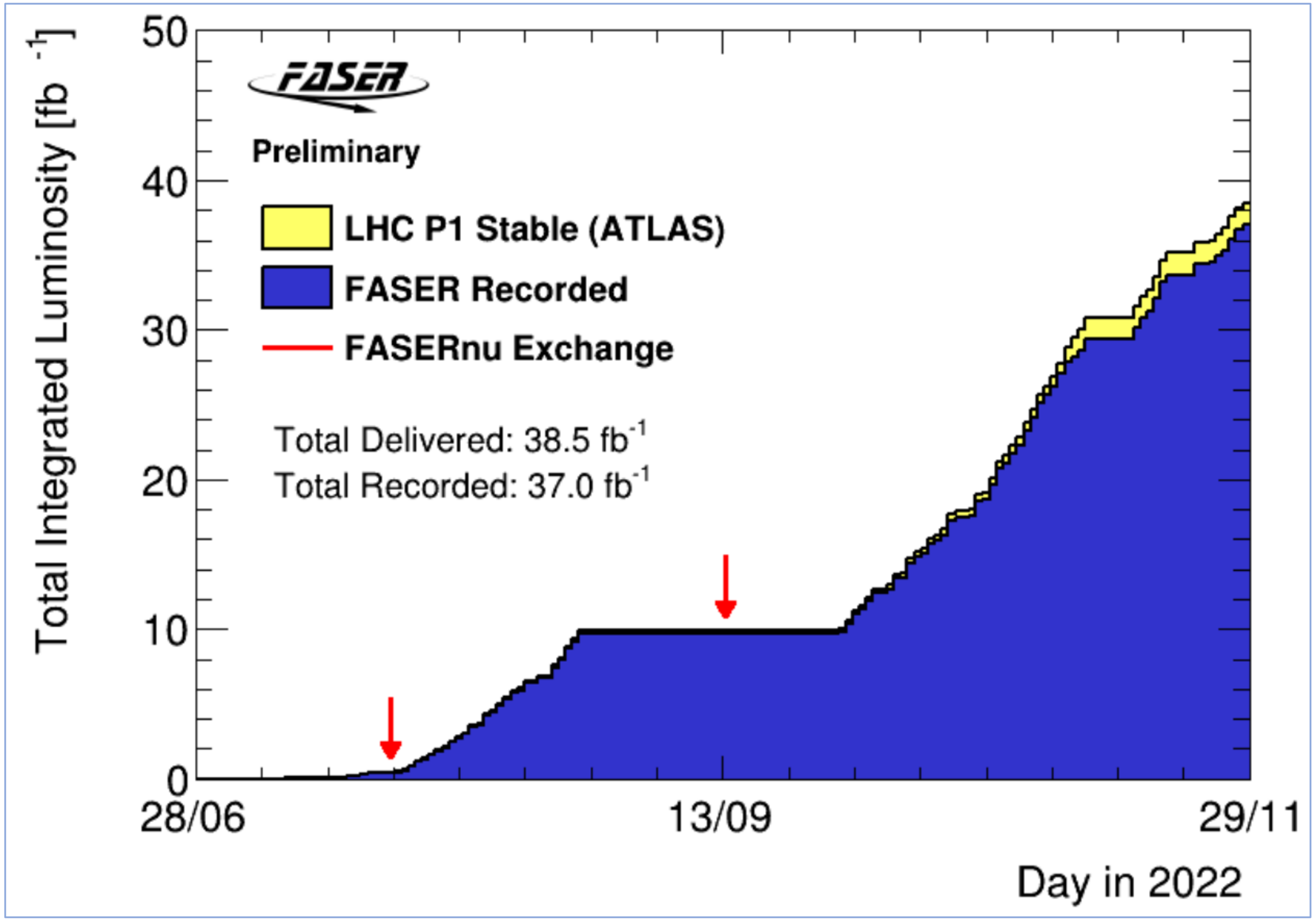
(https://arxiv.org/abs/2207.11427) present the core picture of the detector (magnet, tracker, calo, veto for muon background rejection)





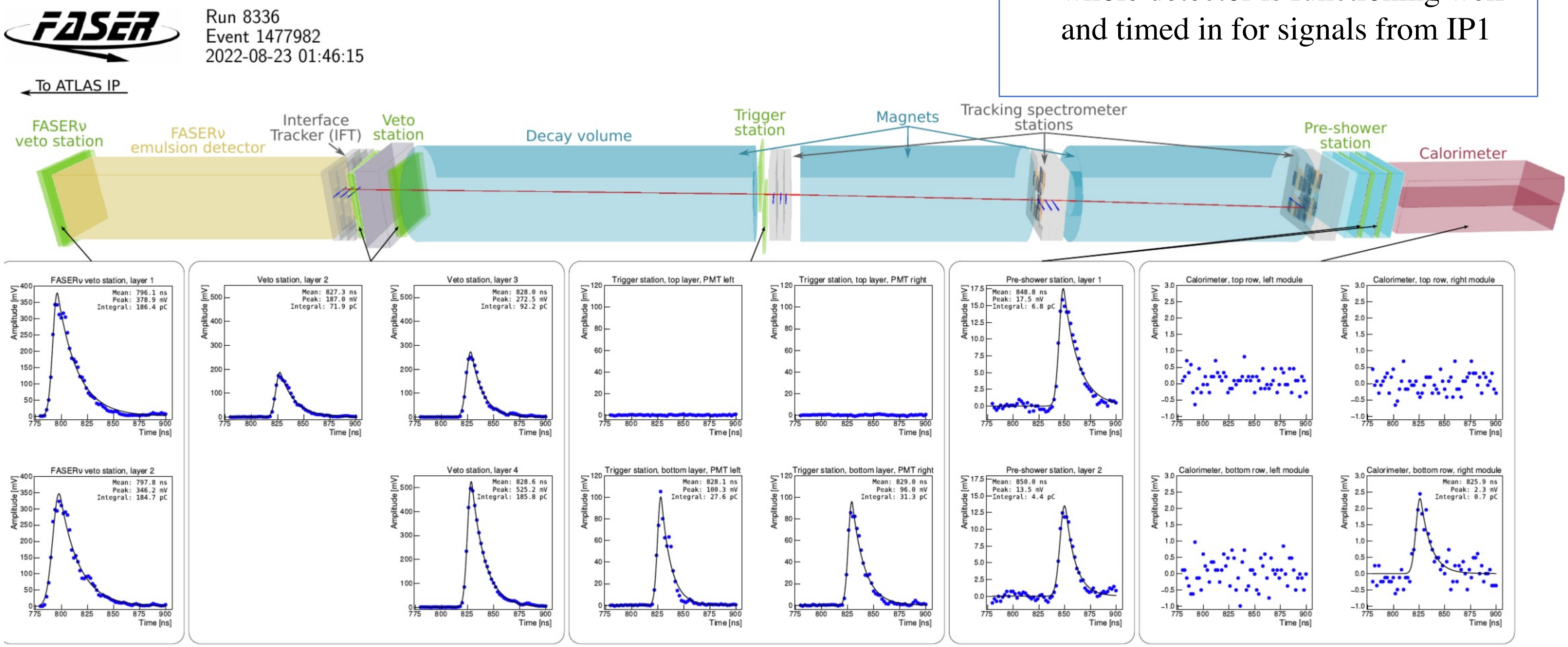
FASER and Run3

- Successfully took data continuously and mostly automatically during 2022.
- FASER recorded 96.1% of the delivered luminosity with 1.3% due to DAQ dead time and rest for some DAQ crashes.
- Calorimeter gain was optimized for low energy (<300GeV) until second emulsion detector exchange. Optimized for high E (up to 3 TeV) after that for our Dark Photon studies.



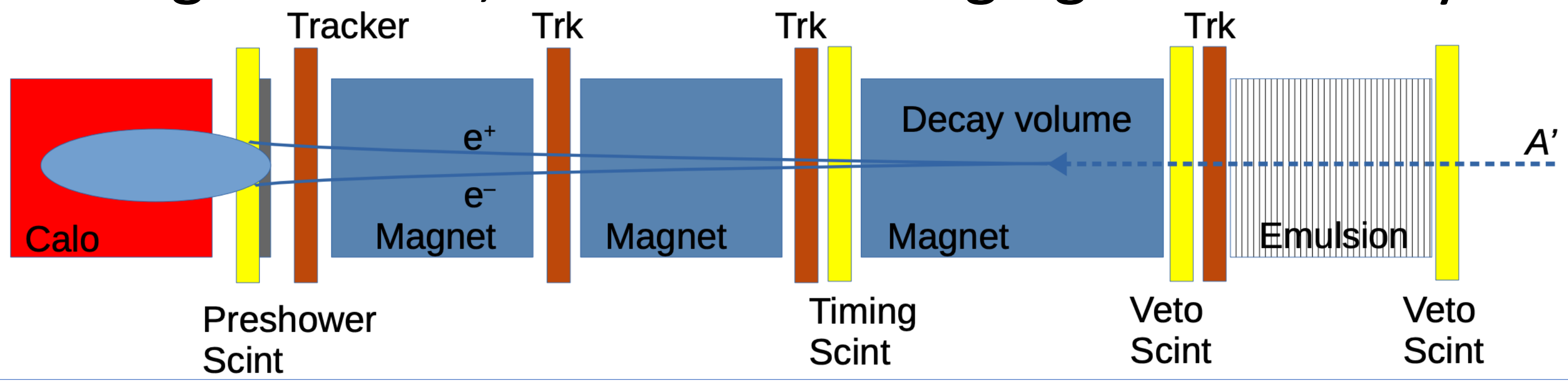
Example Event

1. This is a muon traversing the whole detector
2. A very nice way to see that the whole detector is functioning well and timed in for signals from IP1



Selection for Dark Photon Search

Example of a signal event; want e^+e^- emerging in the decay volume



The selection criteria we had in place:

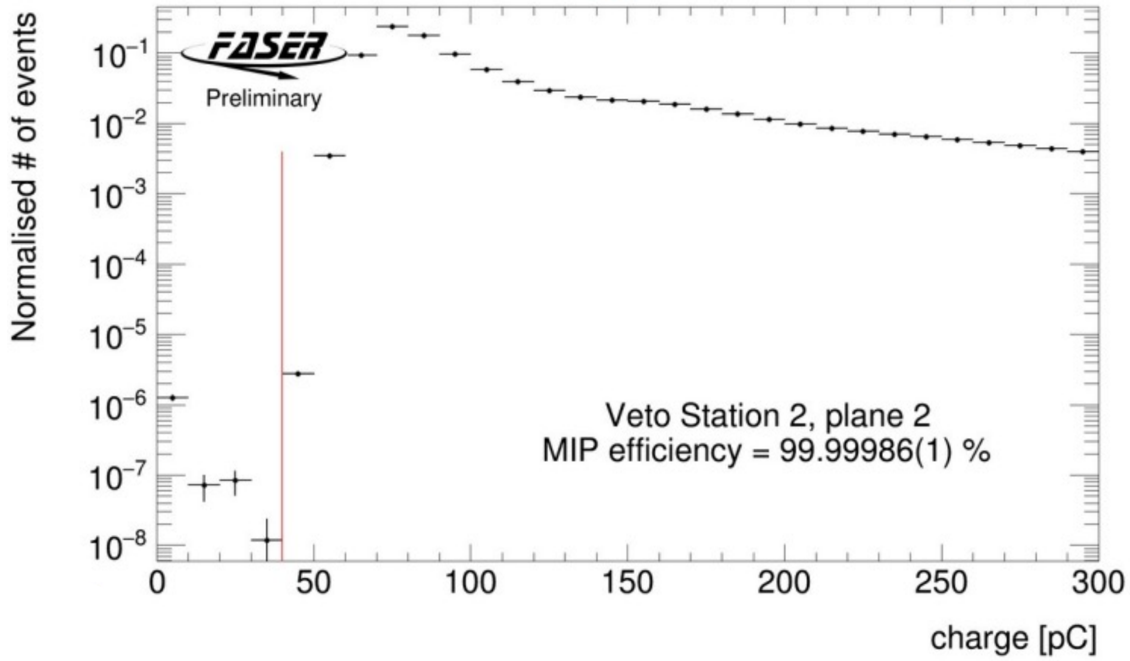
1. Events in collision crossing, during good physics data period
2. No signal in any of five veto scintillators
3. Timing and preshower scintillators consistent with ≥2 minimum ionising particles
4. Exactly two good quality tracks with p>20 GeV and r < 95 mm
5. Both tracks extrapolate to r<95mm in veto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

Background estimates

Veto inefficiency

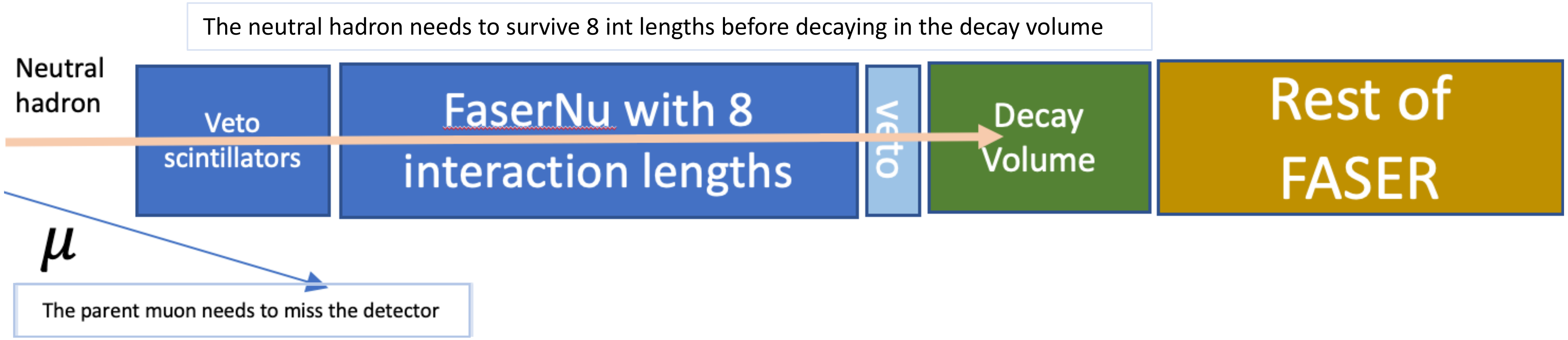
1. Veto layer scintillators efficiency >99.998%
2. Measured layer-by-layer using muon tracks in spectrometer pointing back
3. With five layers, even 10^8 muons going through veto produces negligible background even before any other selections applied

Veto layer efficiency



Background from Neutral hadron from muon interactions upstream

Heavily suppressed background



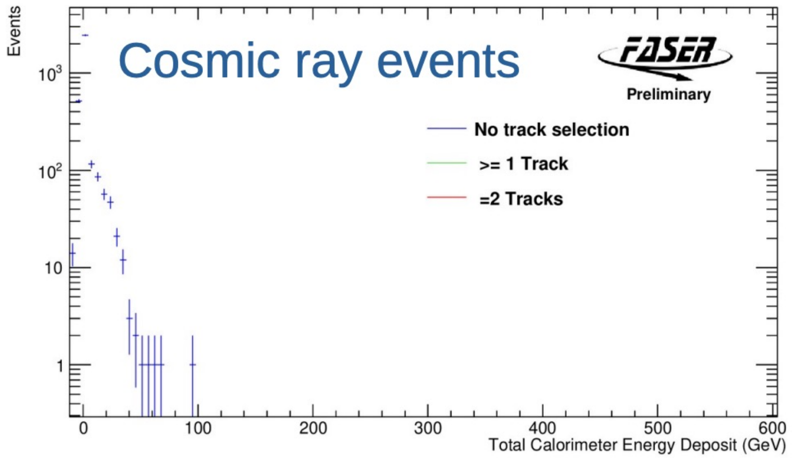
1. Even if the above scenario works, deposition of >500GeV in the calorimeter is unlikely
2. Background estimated using lower energy events with two and three tracks reconstructed and different veto conditions
3. The estimated background: $(2.2 \pm 3.1) \times 10^{-4}$

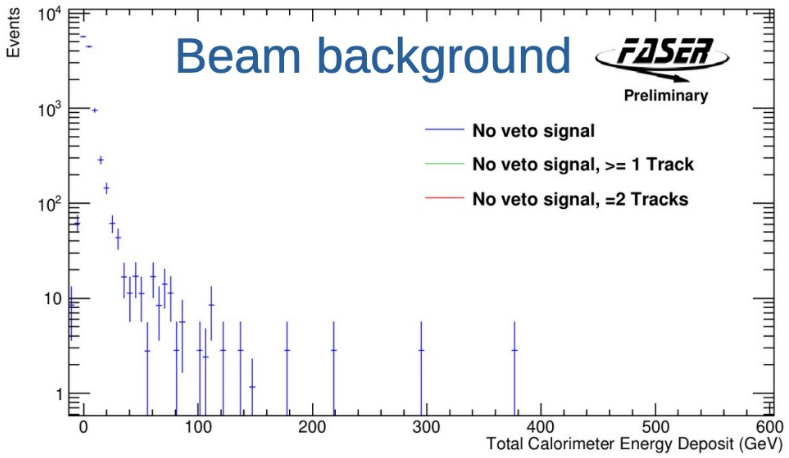
Background estimates

Biggest expected background

Non-collisions background

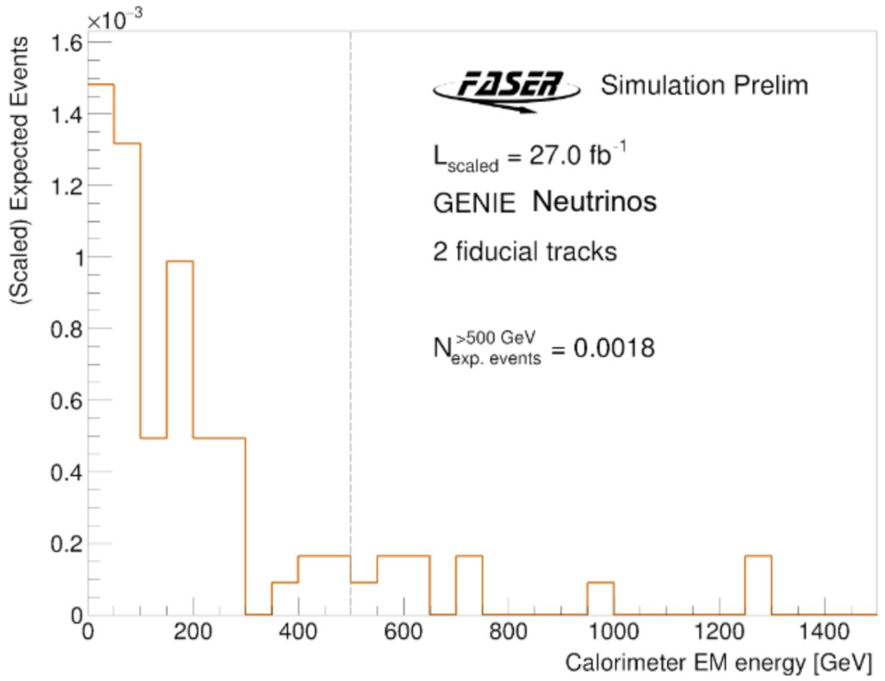
1. Studied in non-colliding bunches and runs without any beam
2. We see so events >500GeV and no reconstructed tracks either.





Neutrino background from simulation

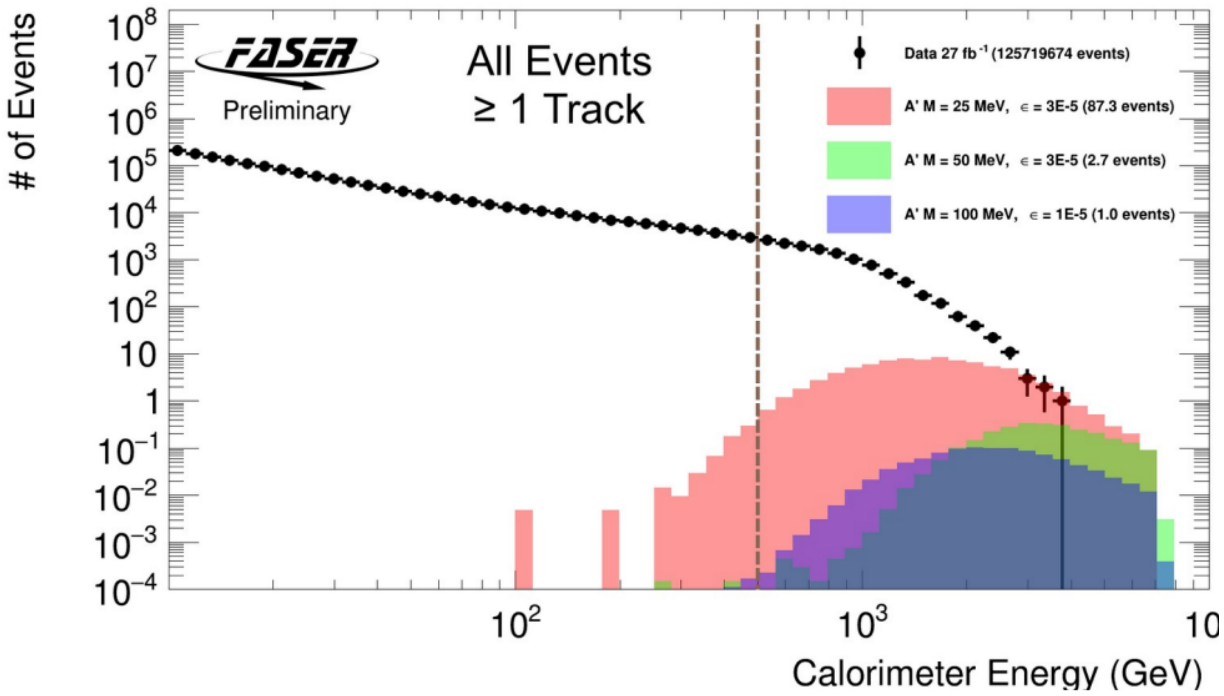
1. Using GENIE generator (300 ab^{-1})
2. With uncertainties for mismodelling and neutrino flux: 0.0018±0.0024 events
3. Background from neutrino induced hadrons upstream found to be negligible

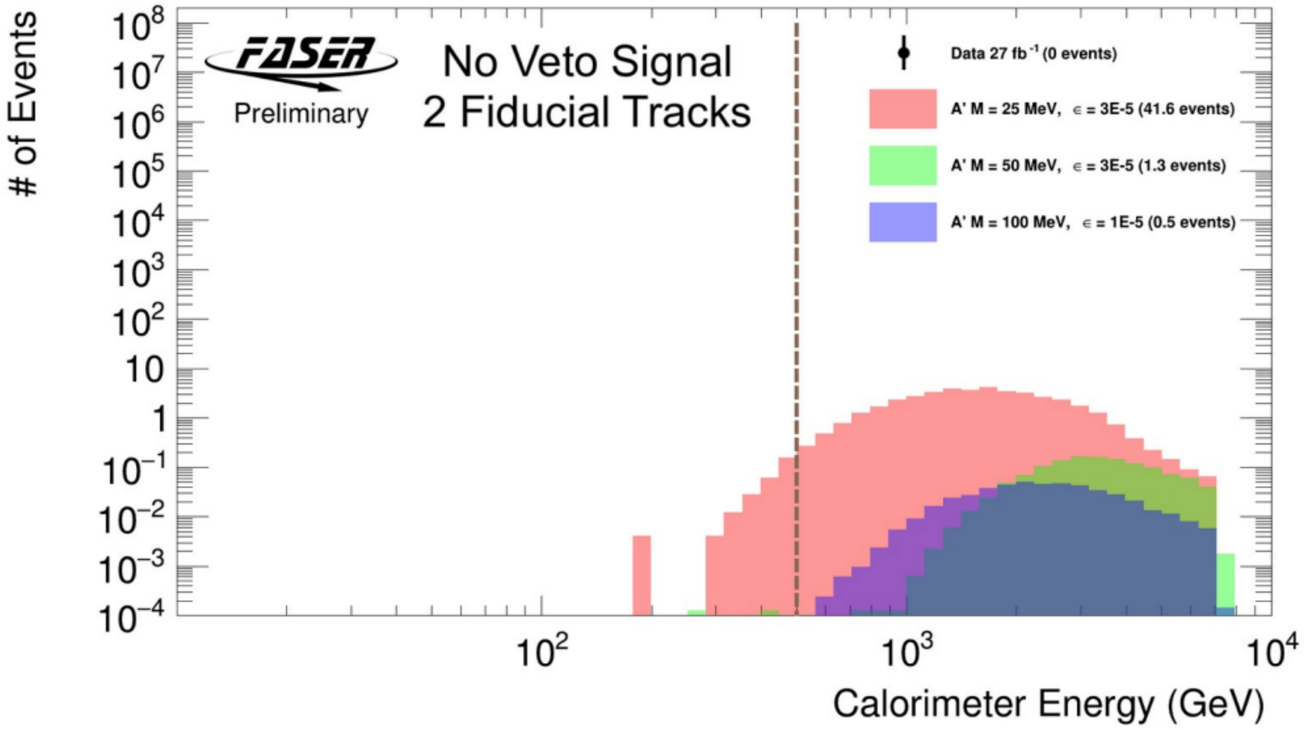


Dark Photon - Data

The total background estimate was: 0.0020±0.0024 events

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

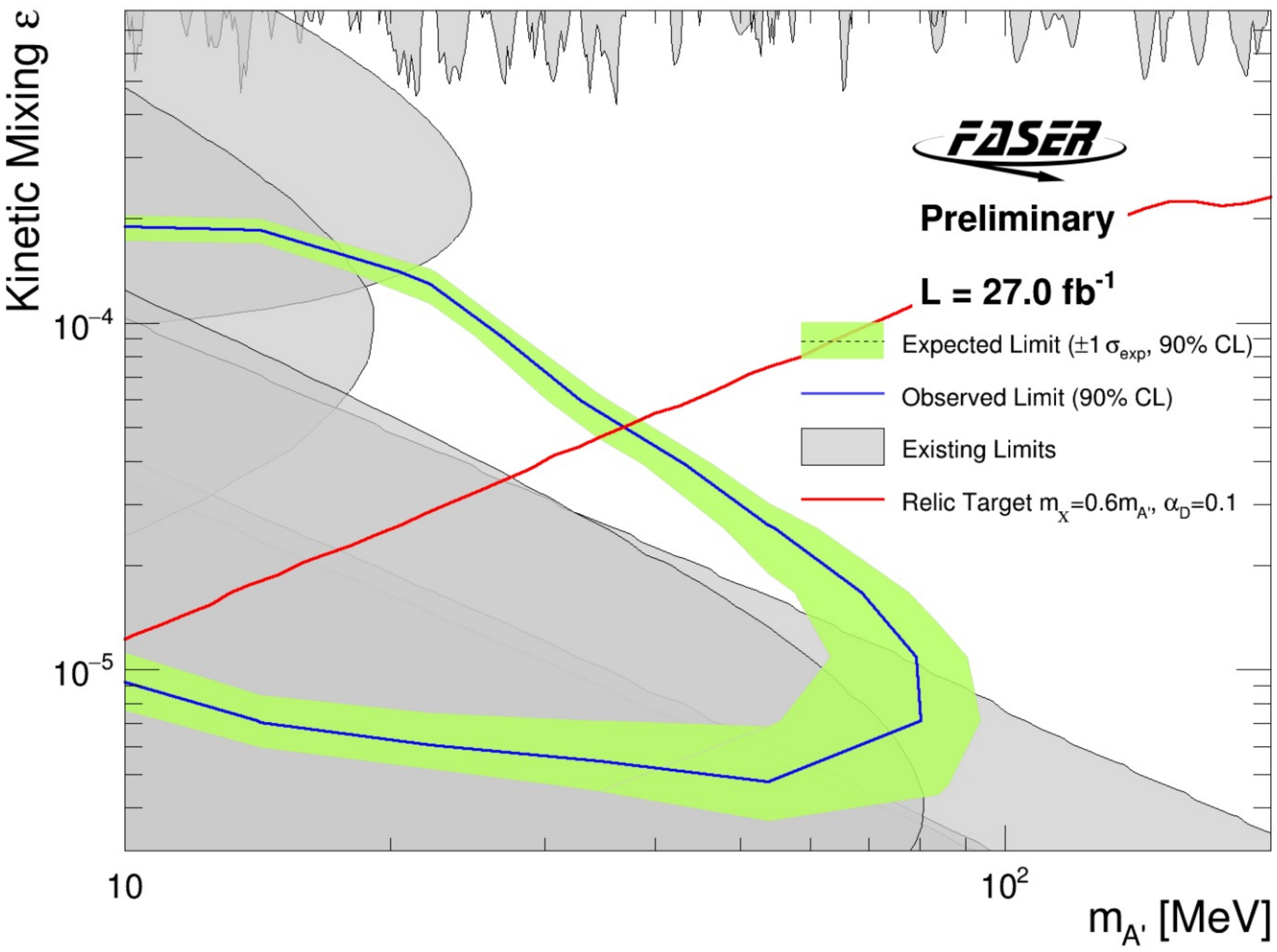




Public conf note: https://cds.cern.ch/record/2853210?ln=en. CERN-FASER-CONF-2023-001

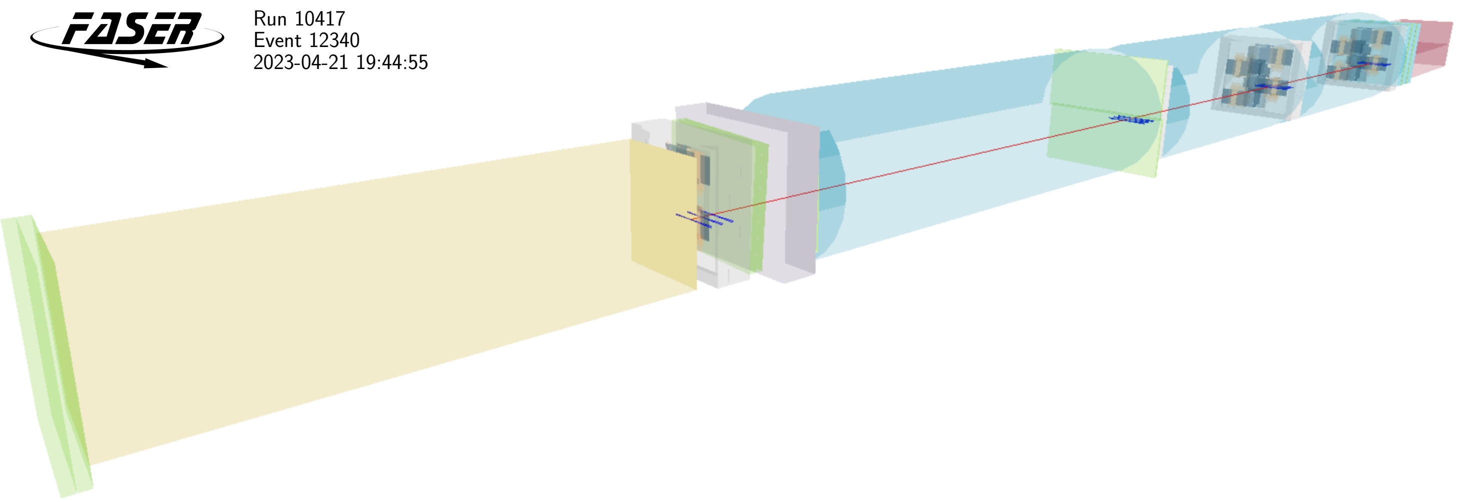
Dark Photon Reach

1. With no events seen with E>500GeV, 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.

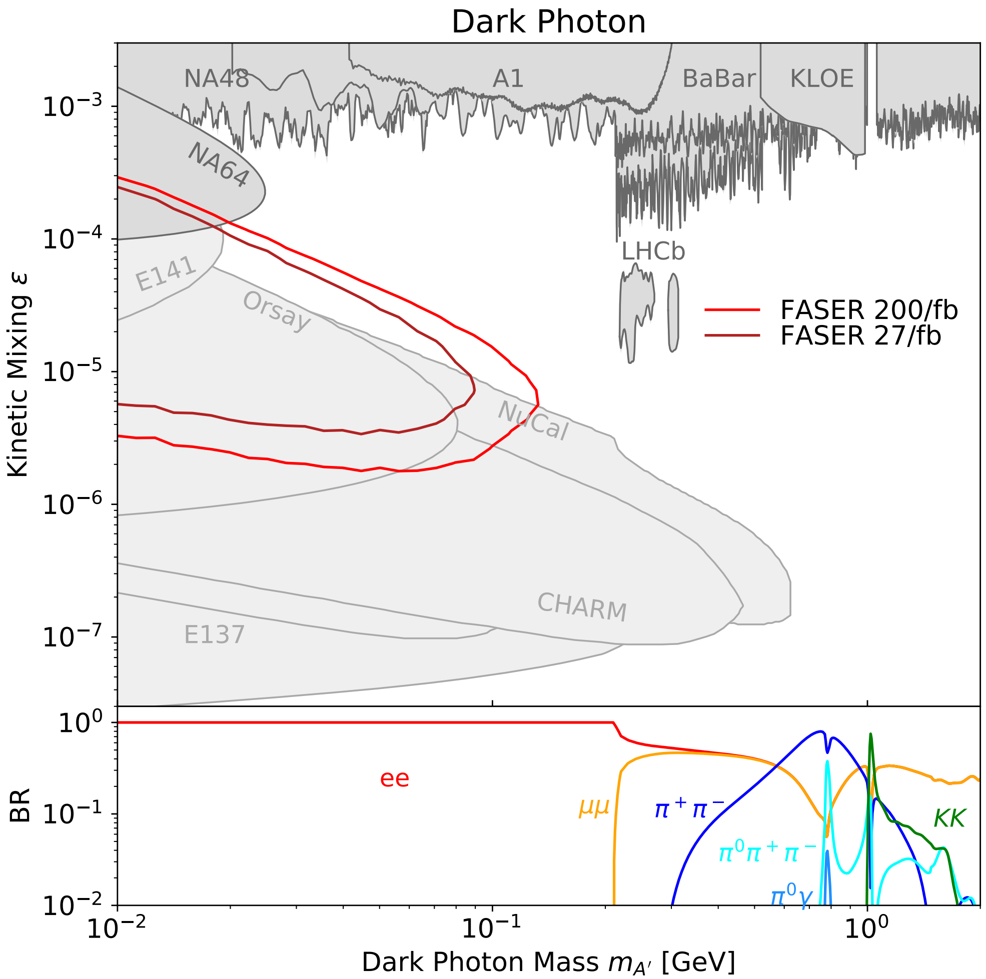


Conclusion

- 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.
- 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!



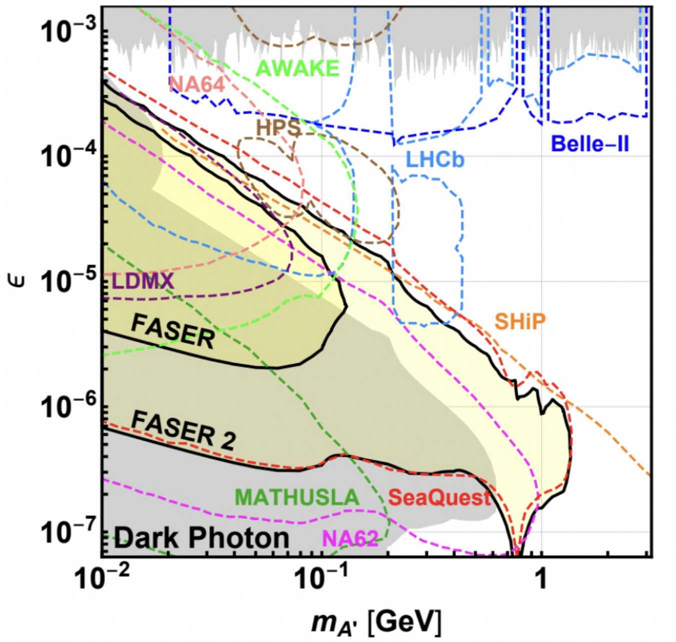
Simulation made with FORESEE https://arxiv.org/abs/2105.07077

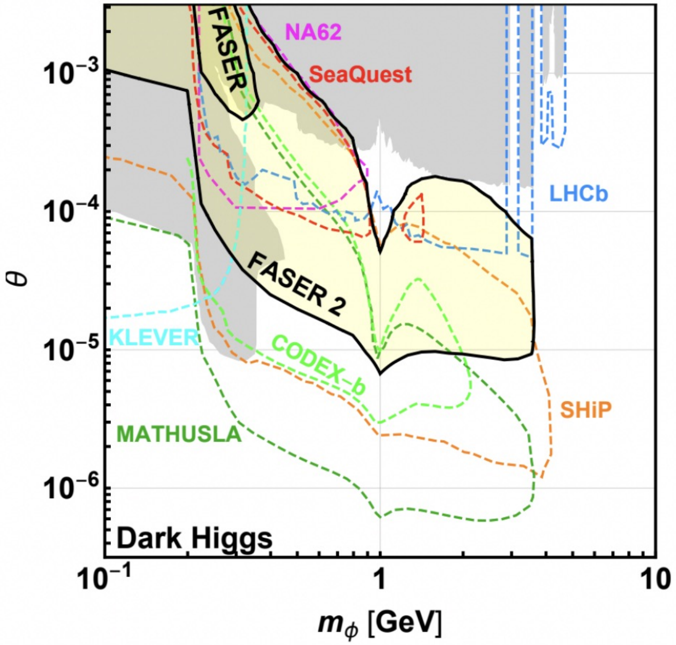
Future Plans

- 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).

Further details here: BSM2 session: Overview of New physics searches at the Forward Physics Facility - Rosham Mammen Abraham (Oklahoma State University) https://indico.cern.ch/event/1198609/timetable/?view=standard#143-overview-of-new-physics-se

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





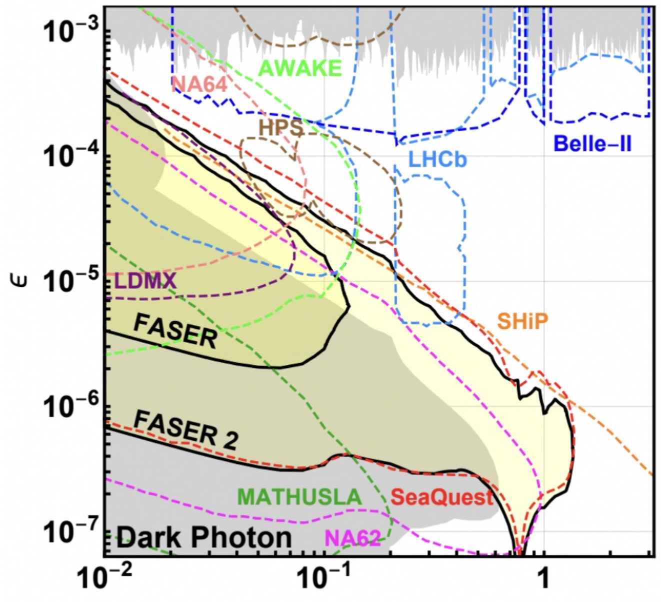
Some Other Talks on FASER this week

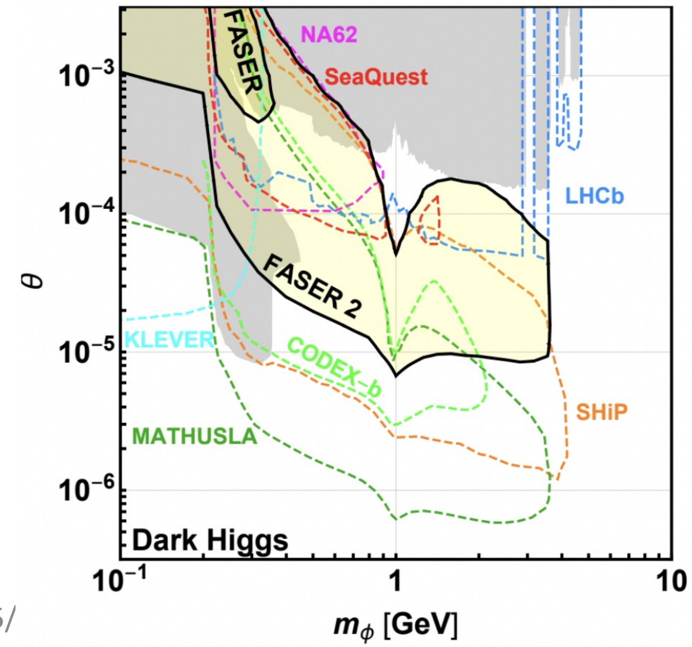
- QCD/Forward physics session: Neutrinos in the forward region (FASER) - Tobias Boeckh (Bonn) https://indico.cern.ch/event/1198609/timetable/?view=standard#265-faser-neutrino-results
- BSM2 session: Overview of New physics searches at the Forward Physics Facility - Rosham Mammen Abraham (Oklahoma State University) https://indico.cern.ch/event/1198609/timetable/?view=standard#143-overview-of-new-physics-se
- Upgrade and future projects session: FASER Upgrades - Stefano Zambito (Geneva) https://indico.cern.ch/event/1198609/timetable/?view=standard#315-faser-upgrades

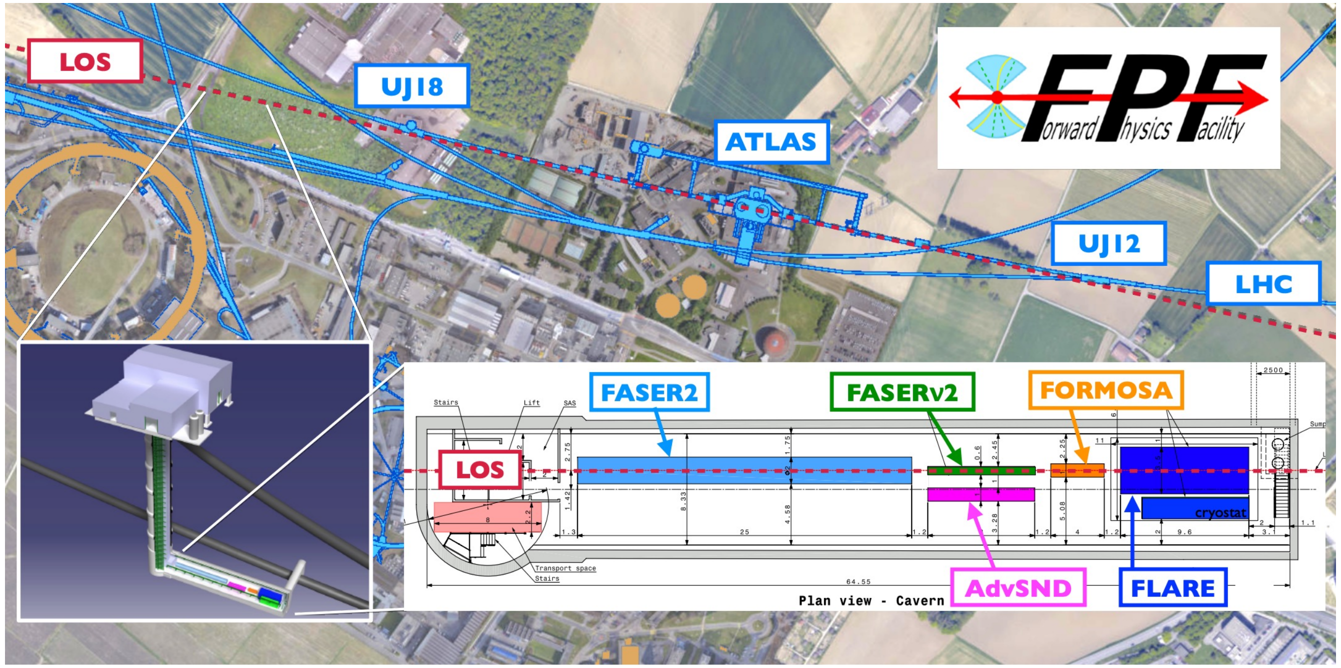
Thank you for listening!

Backup

FASER 2 and Fasernu2

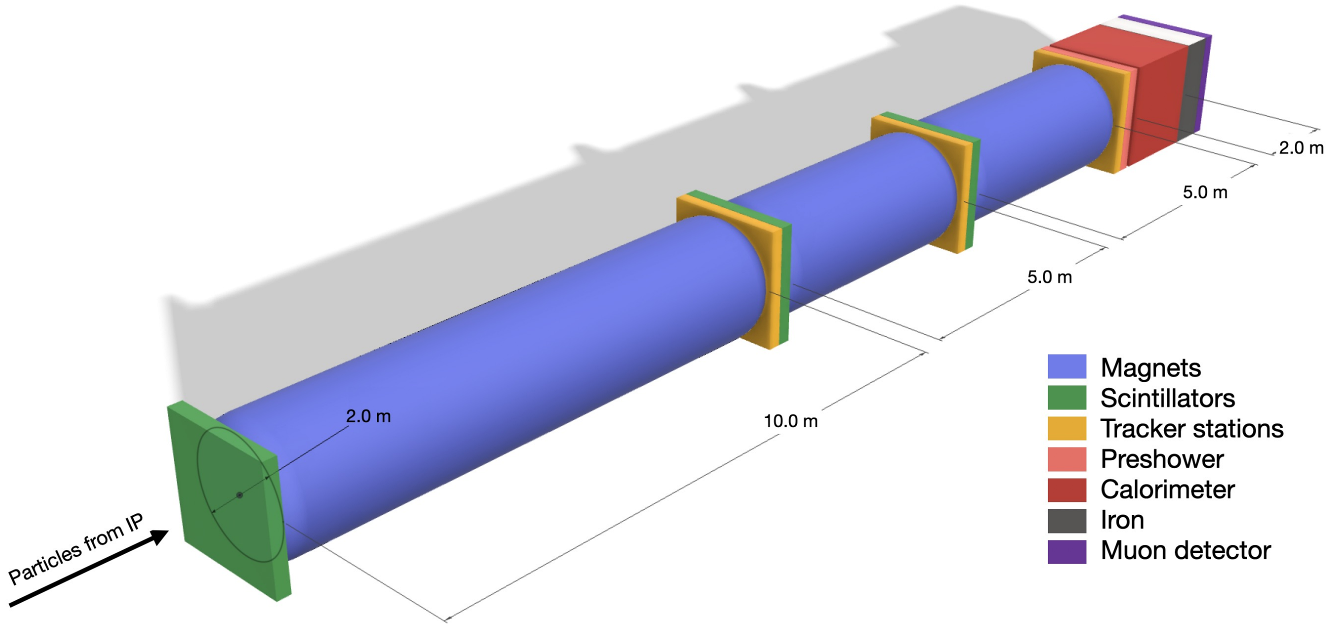


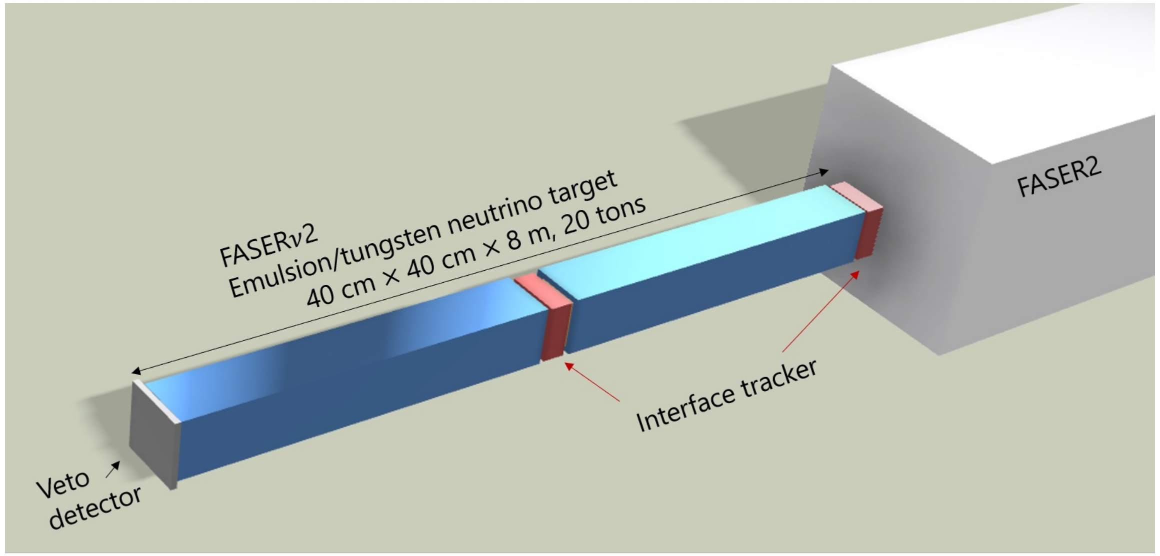




Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization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

FASER 2 and Fasernu2 layout

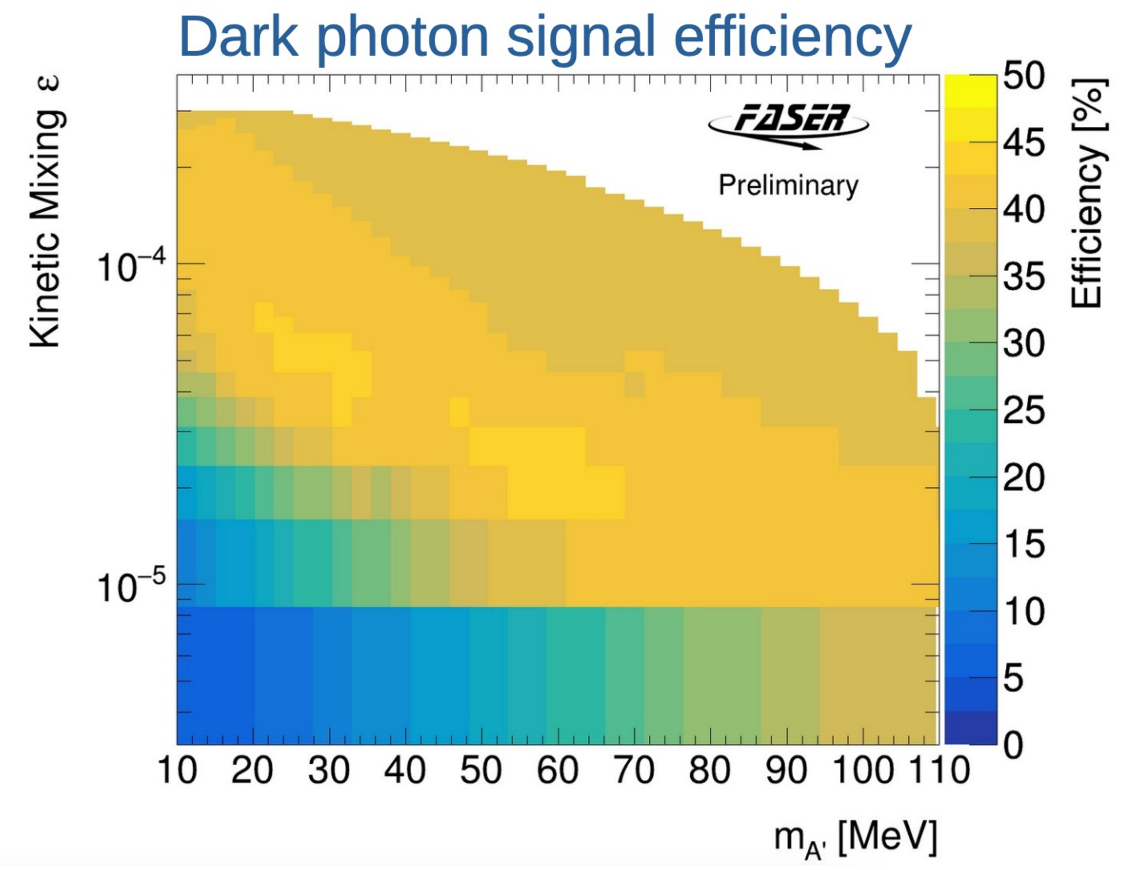




Signal Simulation (FORESEE)

- 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).

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



Background estimates

Veto inefficiency

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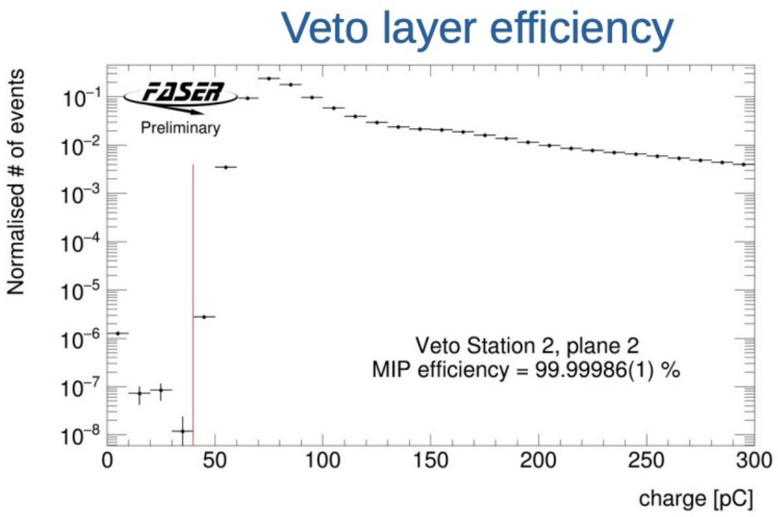
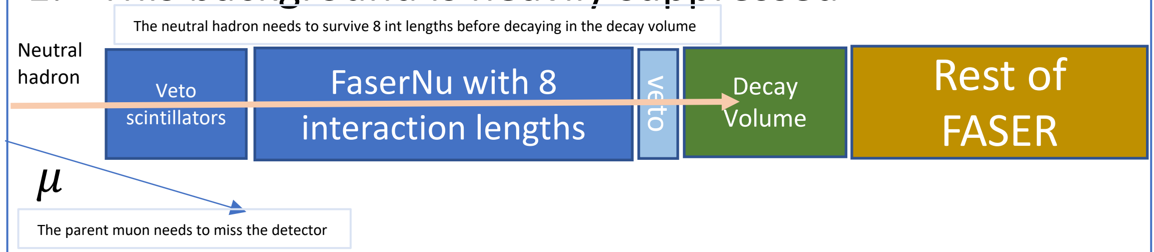


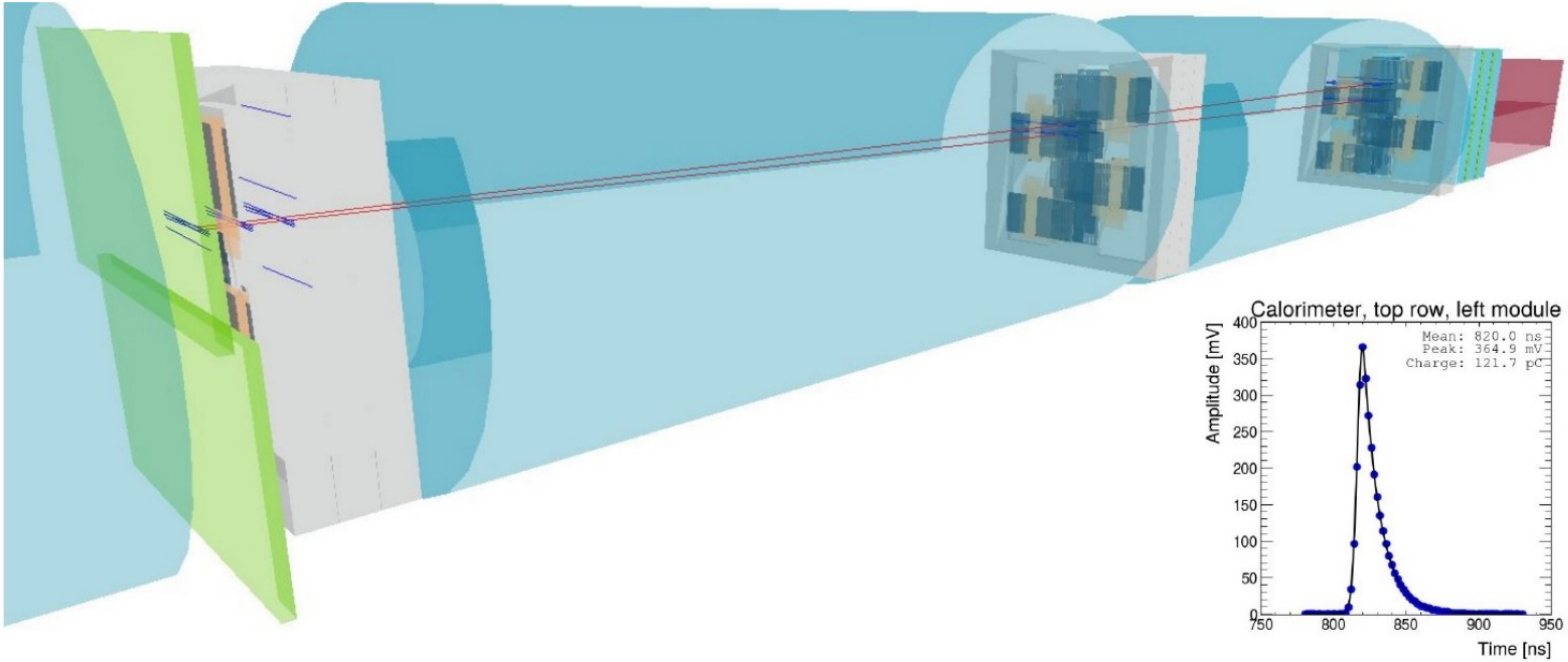
Background from Neutral hadron from muon interactions upstream

1. This background is heavily suppressed



1. Even if the above scenario works, deposition of >500GeV in the calorimeter is unlikely
2. Background estimated using lower energy events with two and three tracks reconstructed and different veto conditions
3. The estimated background: $(2.2\pm3.1)\times10^{-4}$

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%
$\geq$ 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%

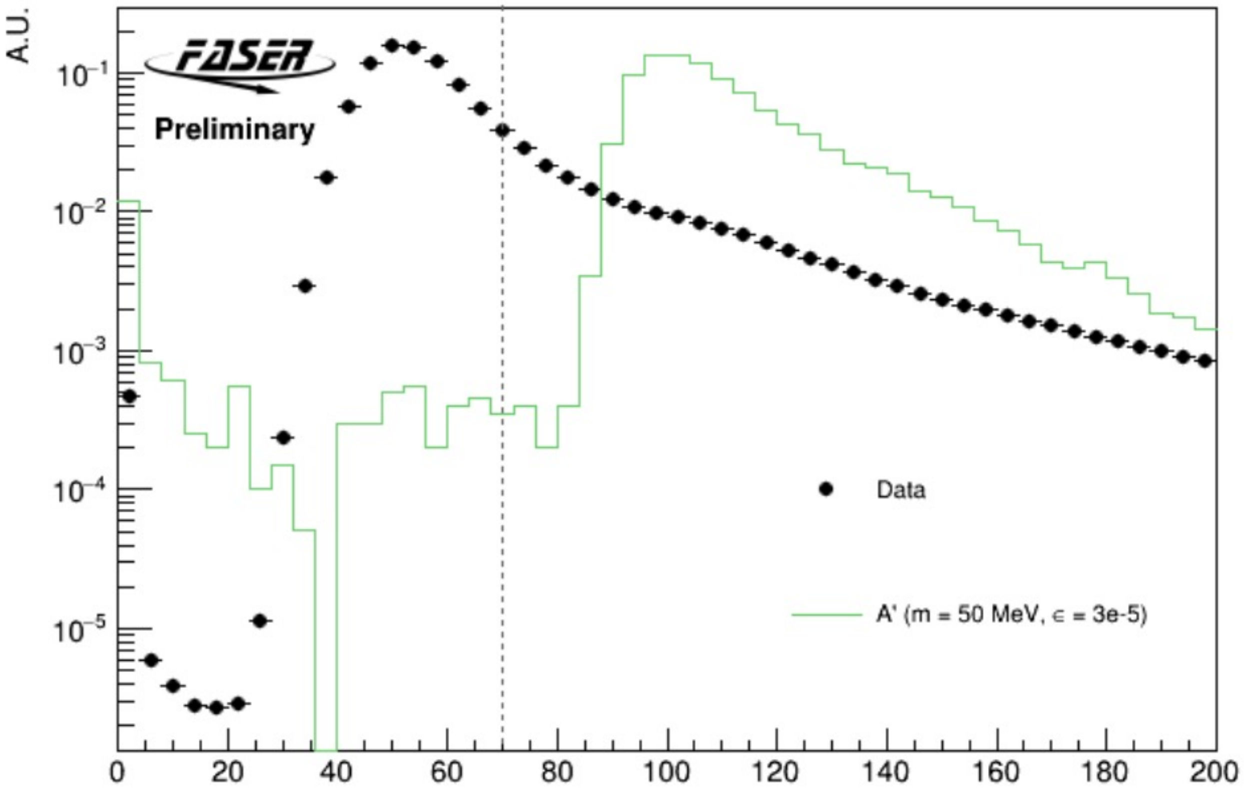
Dark Photons – Systematic Uncertainties

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% ($< 1\%$)

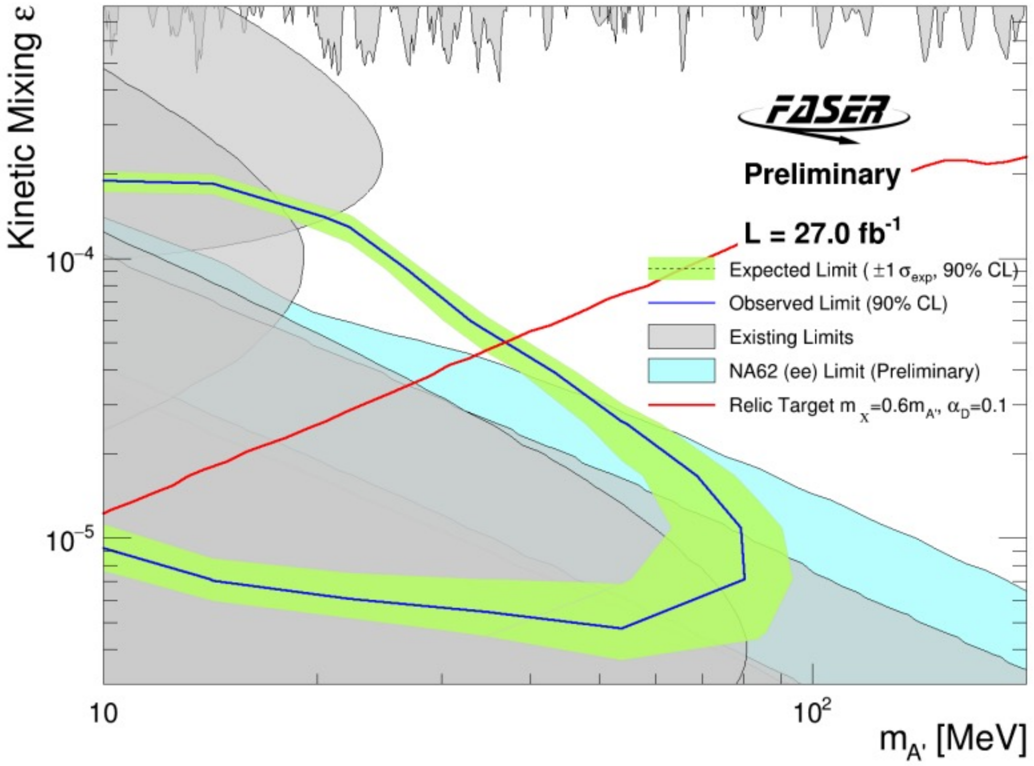
Dark Photon: Timing Scintillator Selection

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

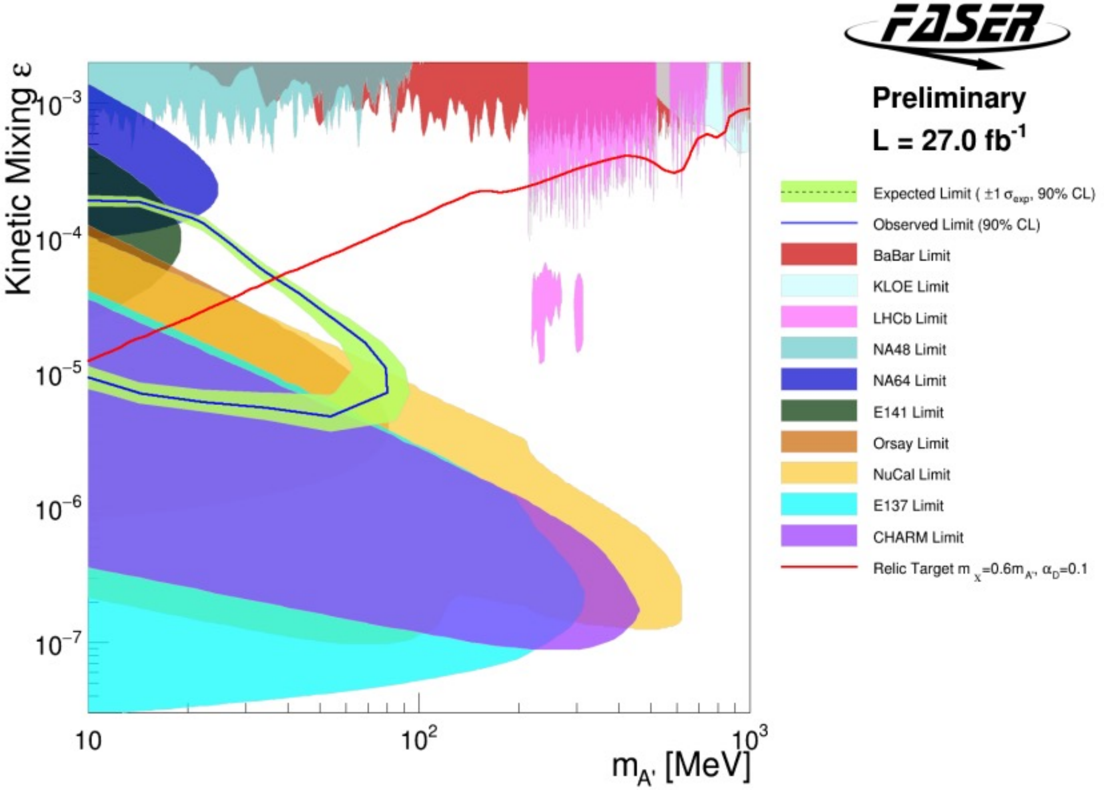


Dark Photon: Additional Limits

Limits including recent prelim NA62 results

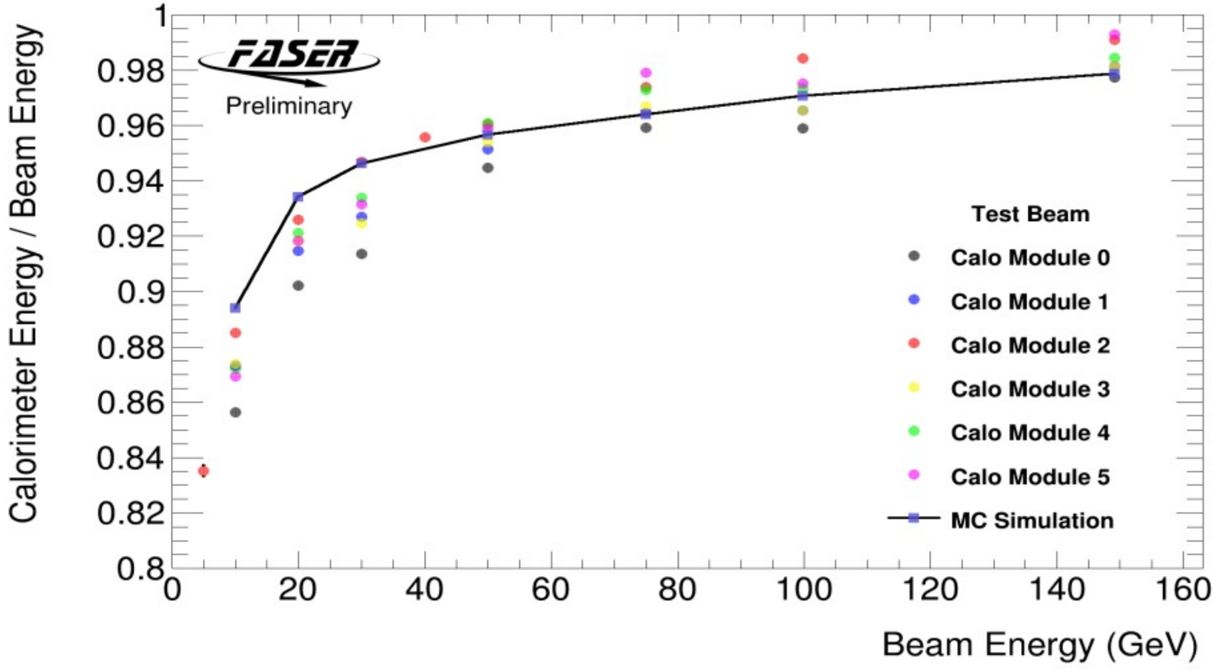


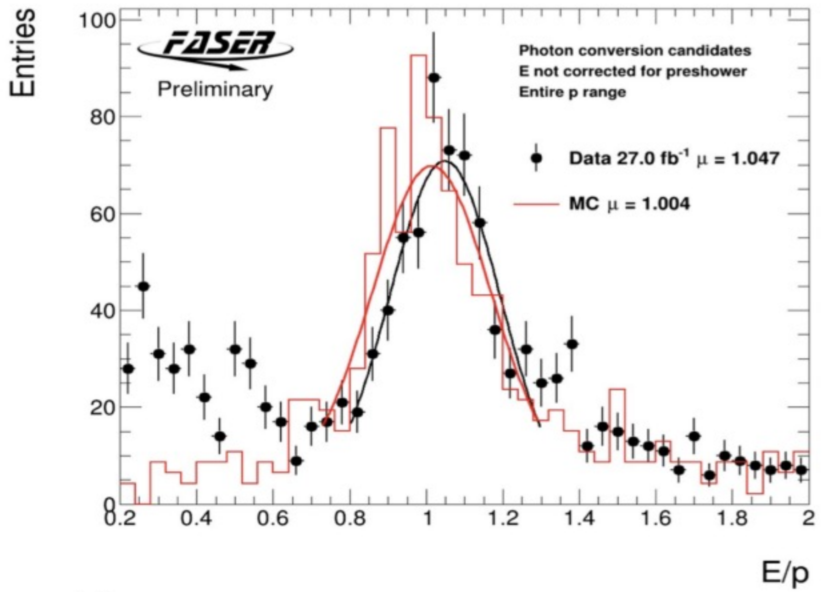
Alternative limit plot showing individual previous limits available from DarkCast

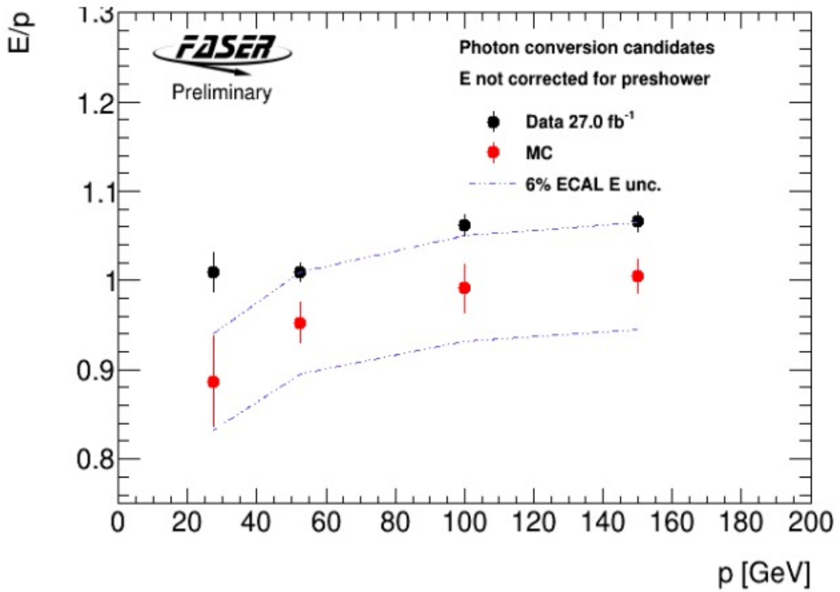


Dark Photon: Calo Energy Scale

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%

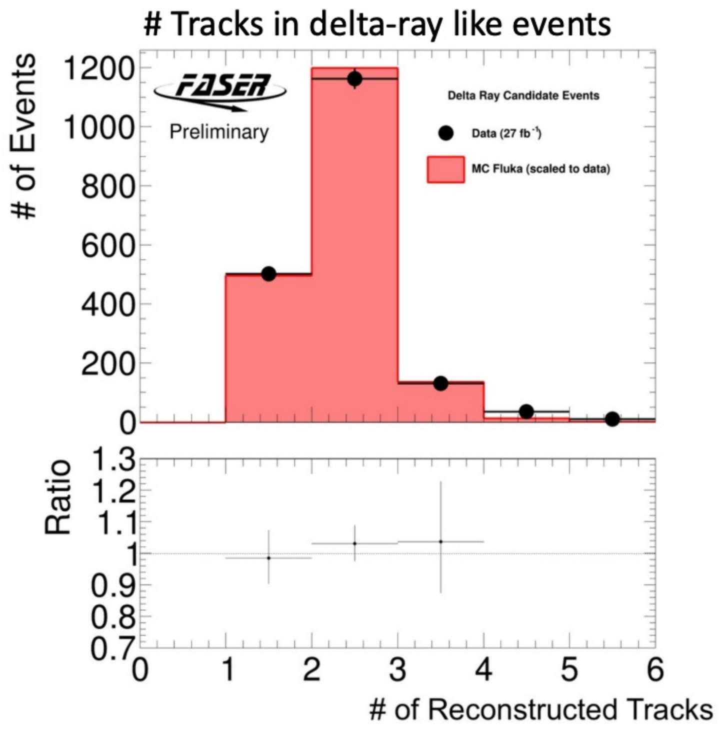


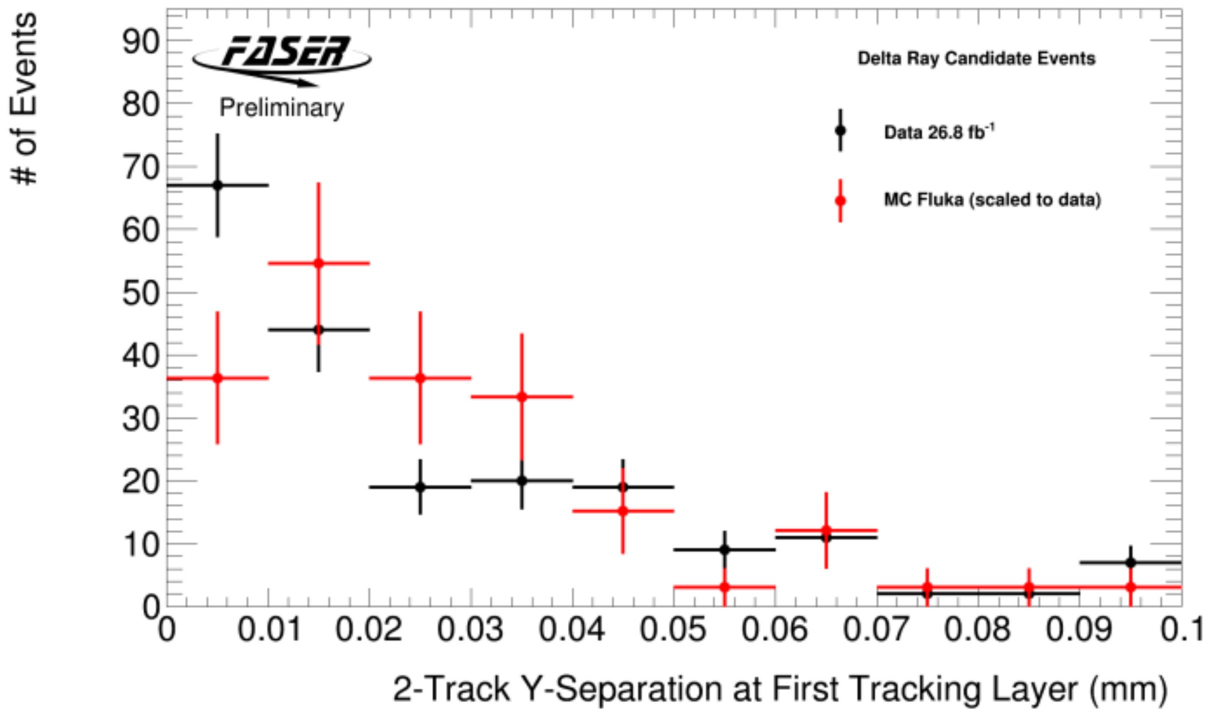




Dark Photon: Tracking Systematics

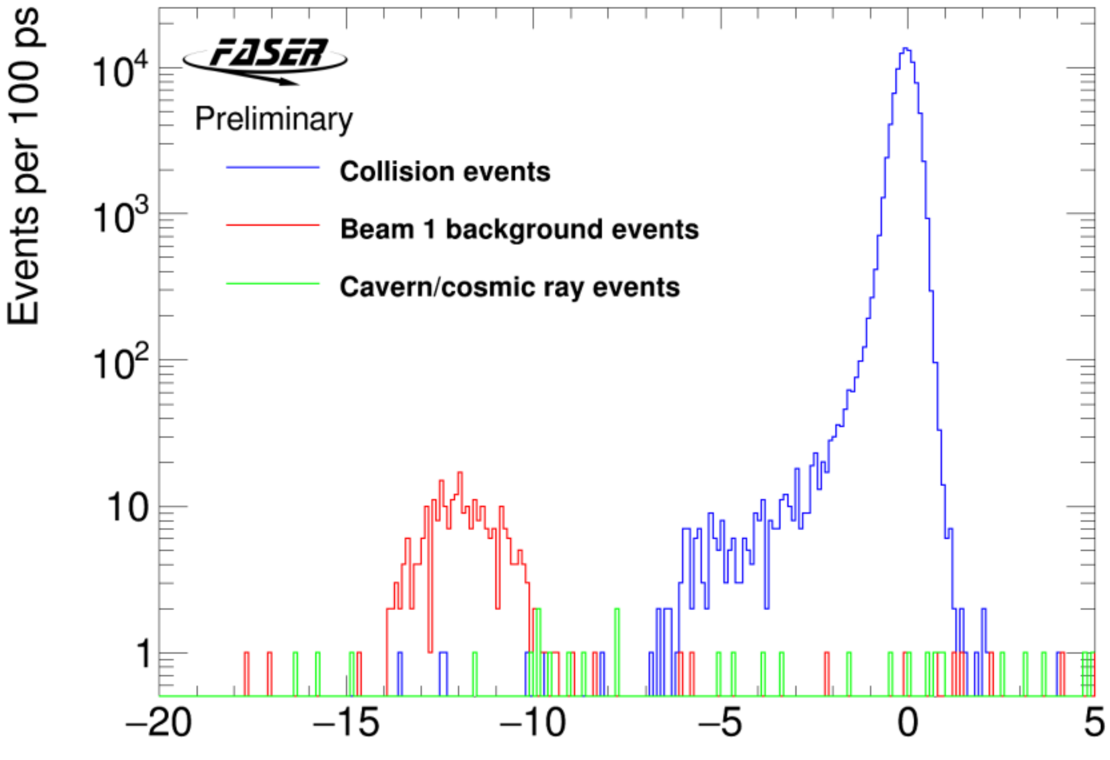
- Single track efficiency studies in muons events with track segments found in each station
- Tracking efficiency lower for two close by tracks (~60%)



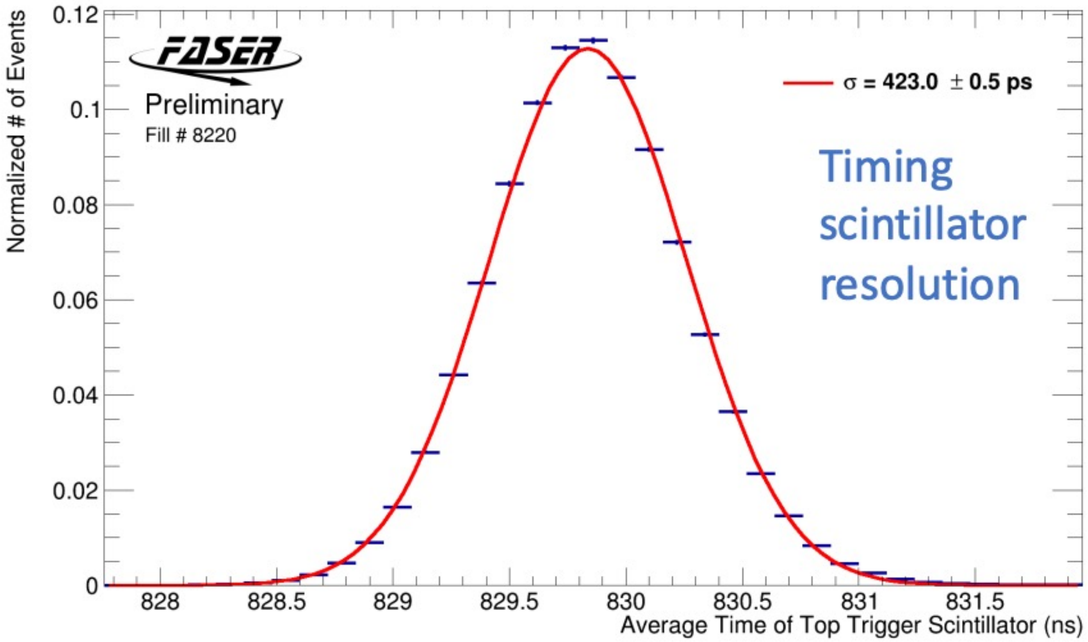


Detector Performance: Timing and Calo

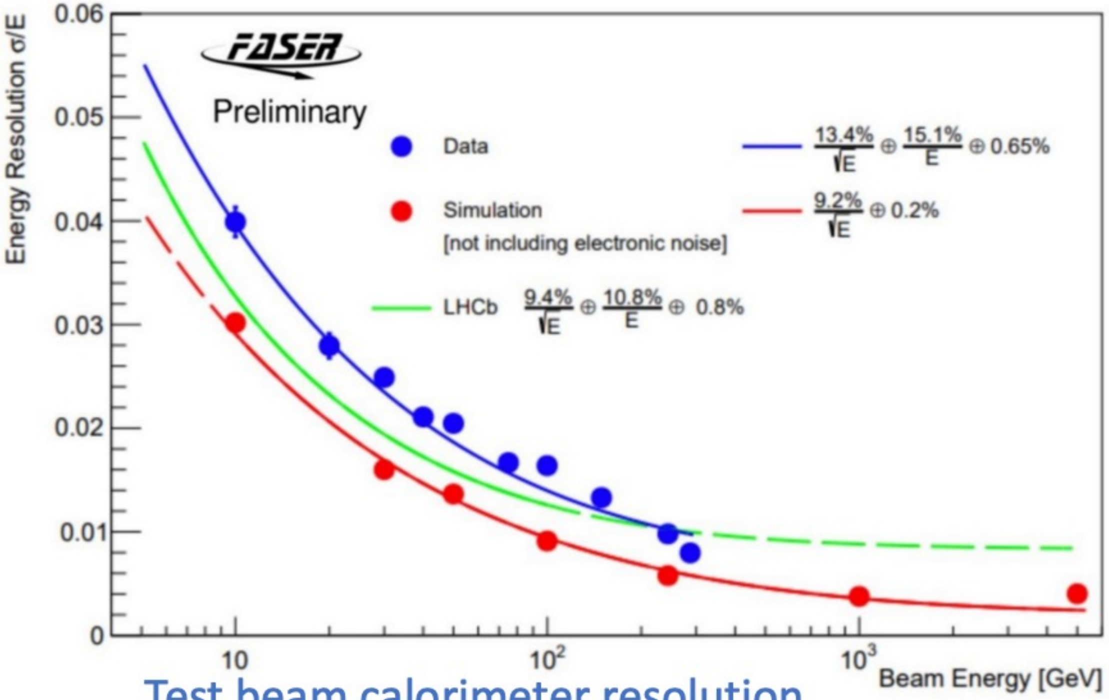
- Calorimeter resolution measured in test beam
- Precision timing of both scintillator and calorimeter



Calo timing for different events



Timing scintillator resolution



Test beam calorimeter resolution