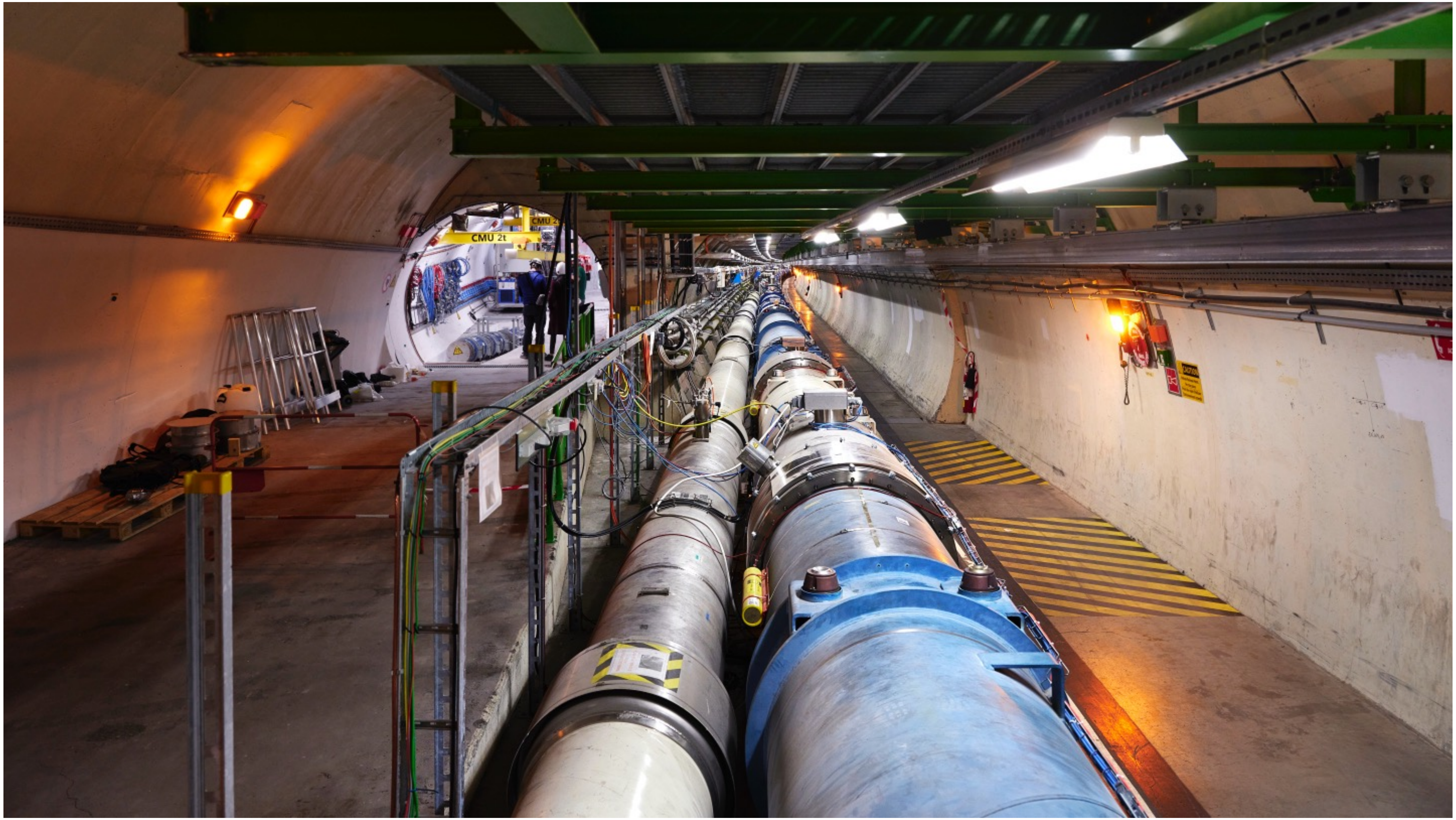
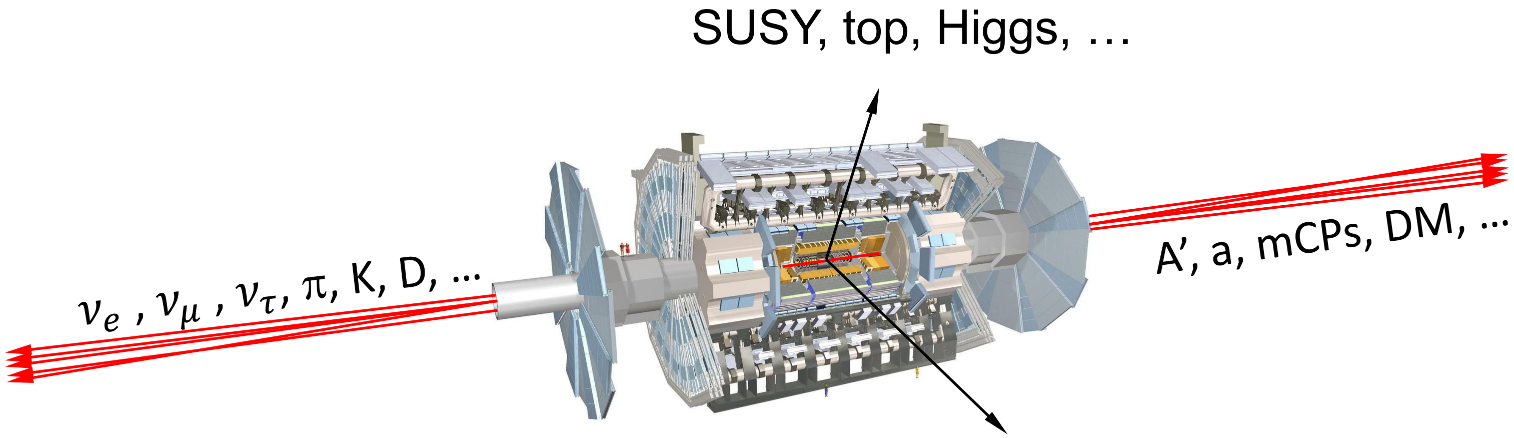
FASER and the FPF Forward Physics Facility

Jamie Boyd (CERN) @ Light Dark Worlds, KIT, Sept. 20th

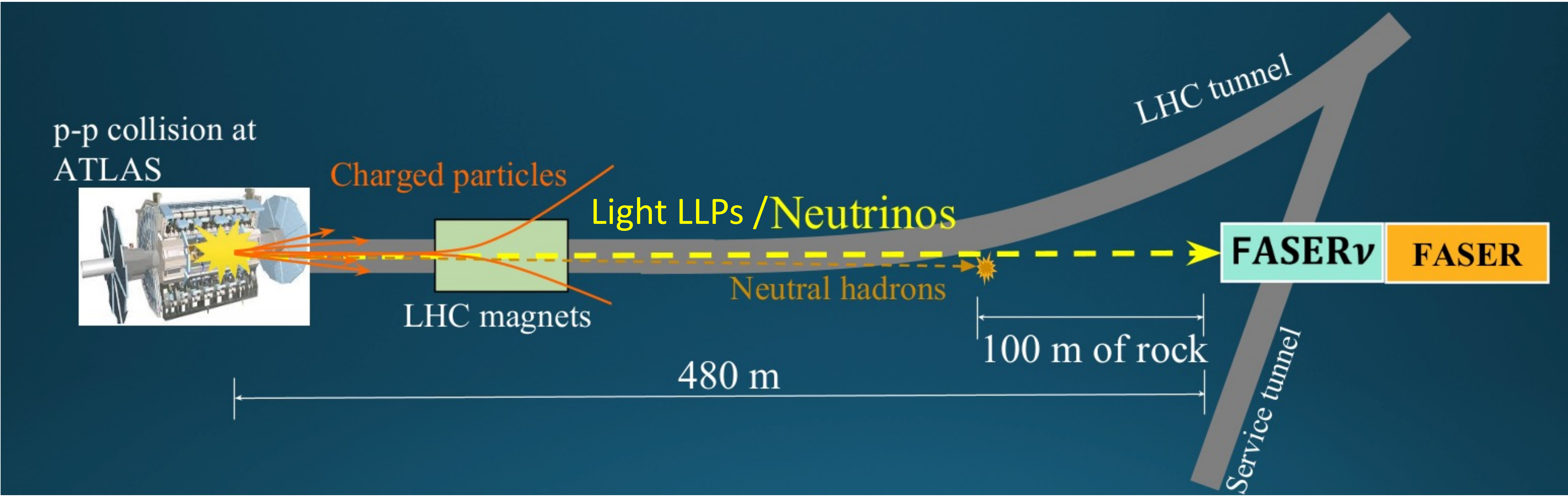


Intro: The intensity frontier at the LHC

- The LHC is the highest energy collider in the world with a very high luminosity
- It was designed to search for heavy strongly produced new particles, and to study heavy Standard Model physics
  - Existing experiments well suited for this, and performing well
- However, given the huge number of light SM hadrons that are produced in the LHC collisions it can also be used to study intensity frontier physics:
  - Weakly coupled, light new particles (dark sector)
    - Weak coupling means very rarely produced, and long-lived
  - Neutrinos produced in hadron decay
    - Weak coupling means rarely interacting
- Given that the flux of light hadrons produced in the LHC collisions is very collimated around the beam collision axis, even a small detector situated in this region can have important sensitivity to both dark sector particles and neutrino interactions
  - e.g. 1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle (η > 9.2)



The FASER Experiment



FASER is a new, small experiment at the LHC designed to take advatage of this and to search for new, light, long-lived particles (LLPs), and study neutrinos. The experiment is situated ~500m from the ATLAS collision point, on the beam collision axis line-of-sight (LOS), and started taking physics data in July 2022 with the start of LHC Run 3.

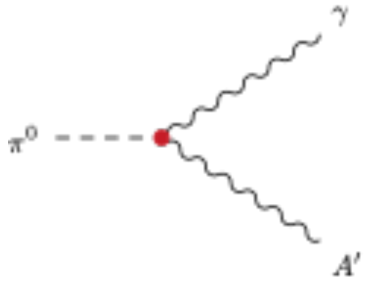
FASER is situated in an unused former injection tunnel which allows the detector to be placed on the LOS, after digging a small trench ~50cm deep.

Example:

FASER Physics: Dark Photons

- Vector portal, contains a new gauge boson, the dark photon (A') with mass $m_{A'}$ and εQ_f couplings to SM fermions f

- Produced (very rarely) in meson decays, e.g.,



$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

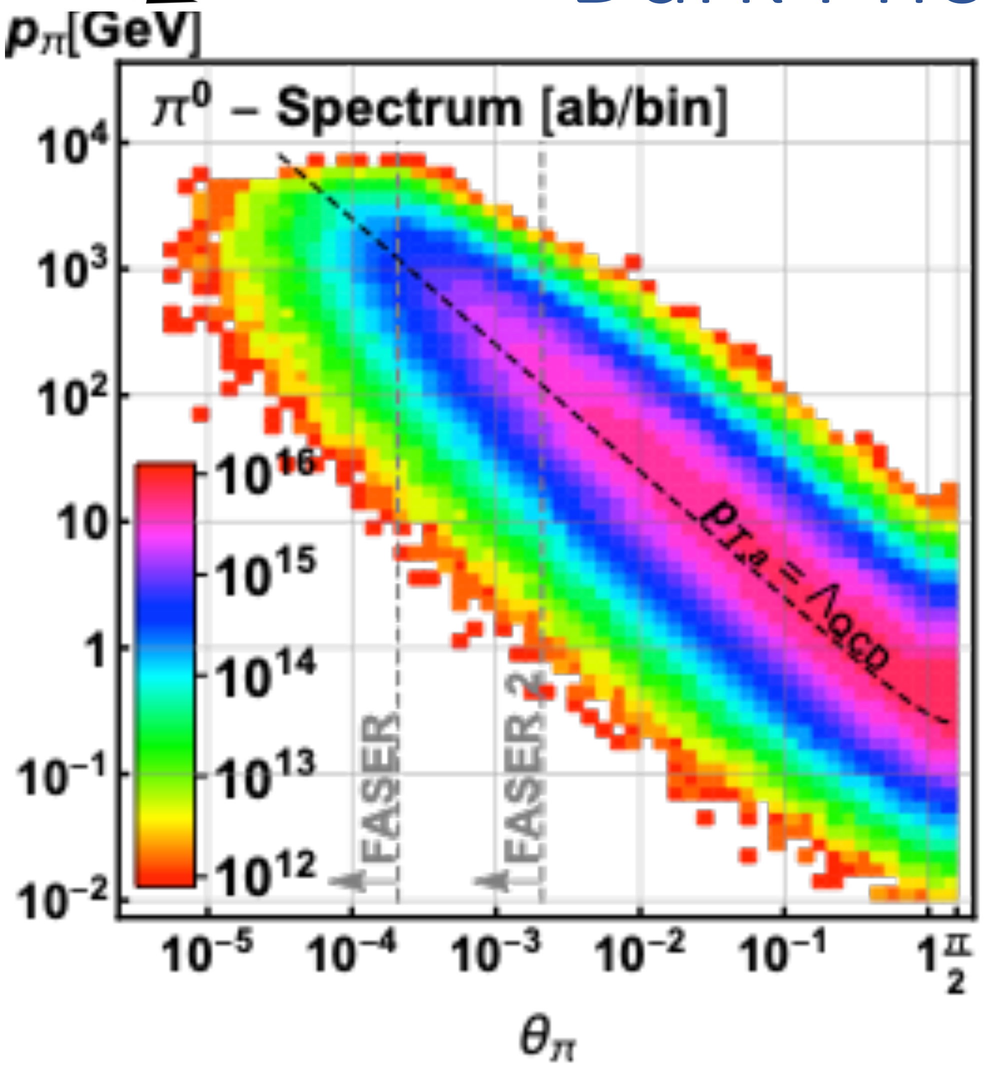
and also through other processes

- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2\, m_\mu$, other charged pairs

$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80\text{ m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \qquad E_{A'} \gg m_{A'} \gg m_e$$

- TeV energies at the LHC → huge boost, decay lengths of ~100 m are possible for viable and interesting parameters

Dark Photon Production



FASER takes advantage of the the huge number of light mesons (π^0,η,..) that are produced at the LHC, predominantly in the very forward direction.

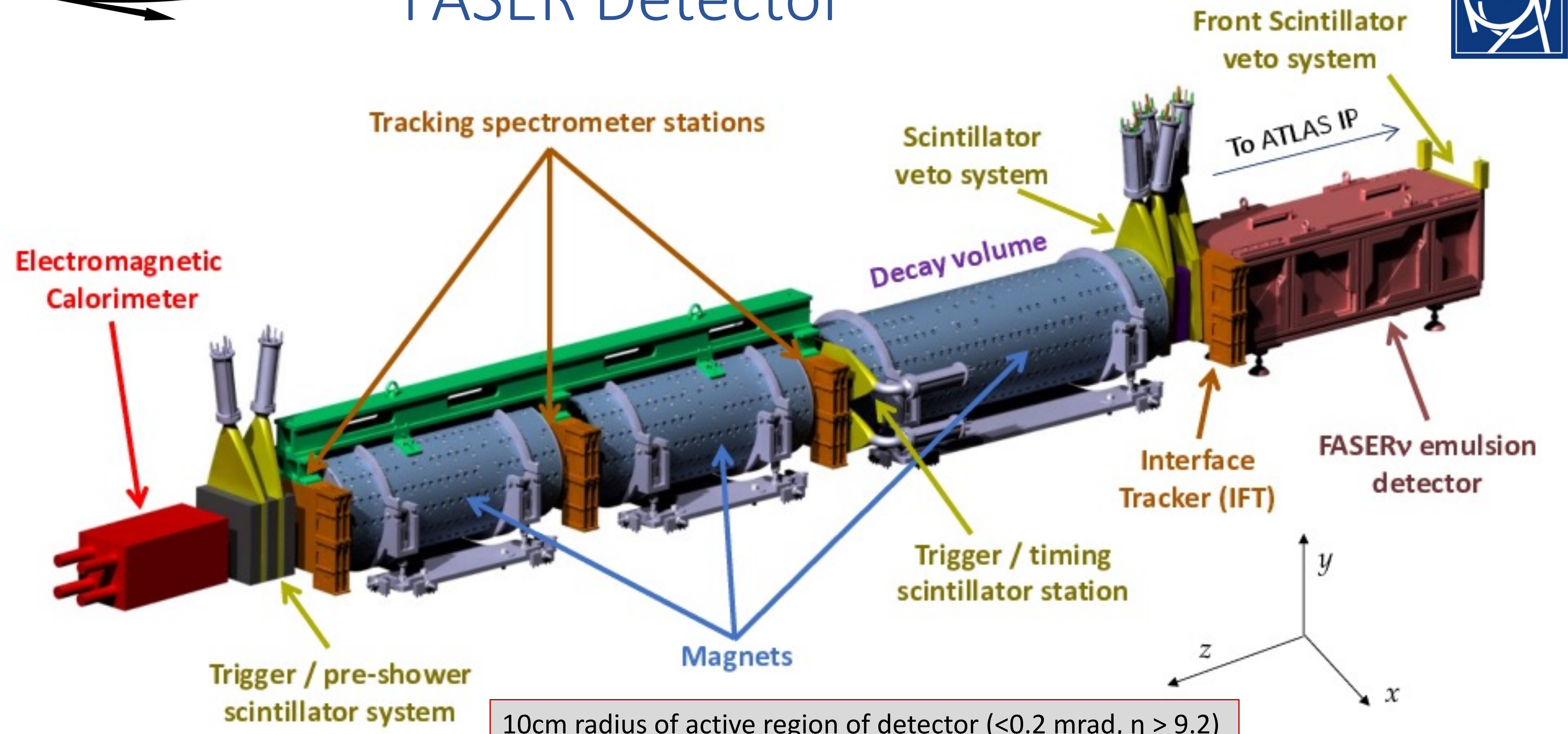
Mesons in FASER acceptance very boosted $\mathcal{O}$(TeV), allows shorter lifetimes to reach FASER before decaying.

Run-3 (0.15/ab) will produce a huge number of π^0s in FASER angular acceptance $\mathcal{O}(10^{15})$. Even with large suppression ($\varepsilon^2 \sim 10^{-8} – 10^{-10}$ for relevant region of parameter space) can still have very large number of dark photons produced.

LHC can be a dark photon factory!

FASER Detector

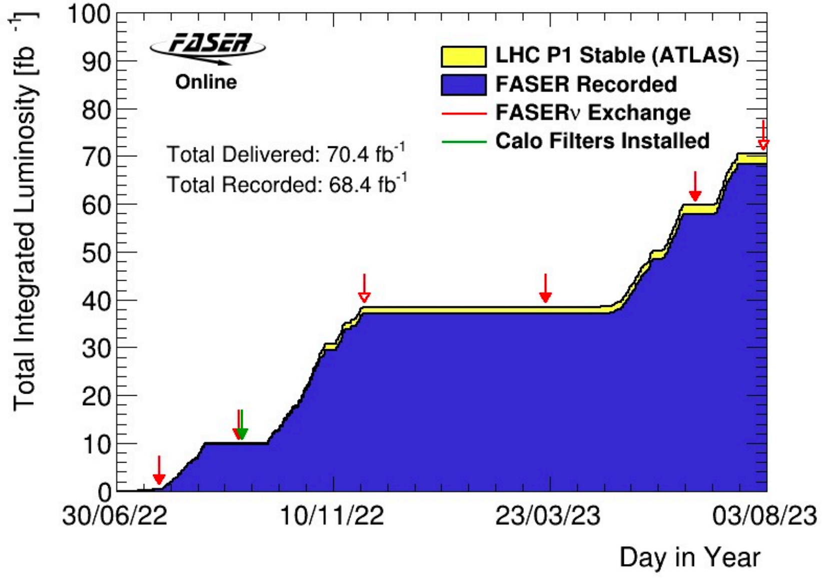
arxiv: 2207.11427



10cm radius of active region of detector (<0.2 mrad, η > 9.2)
1.5m long decay volume
2.5m long tracking spectrometer (0.6T dipole field)

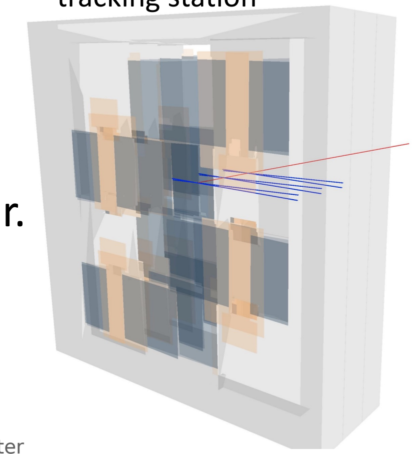
FASER was installed into TI12 in March 2021.
We ran for more than a year with cosmic data taking in situ before, physics data taking started in July 2022.

FASER Operations

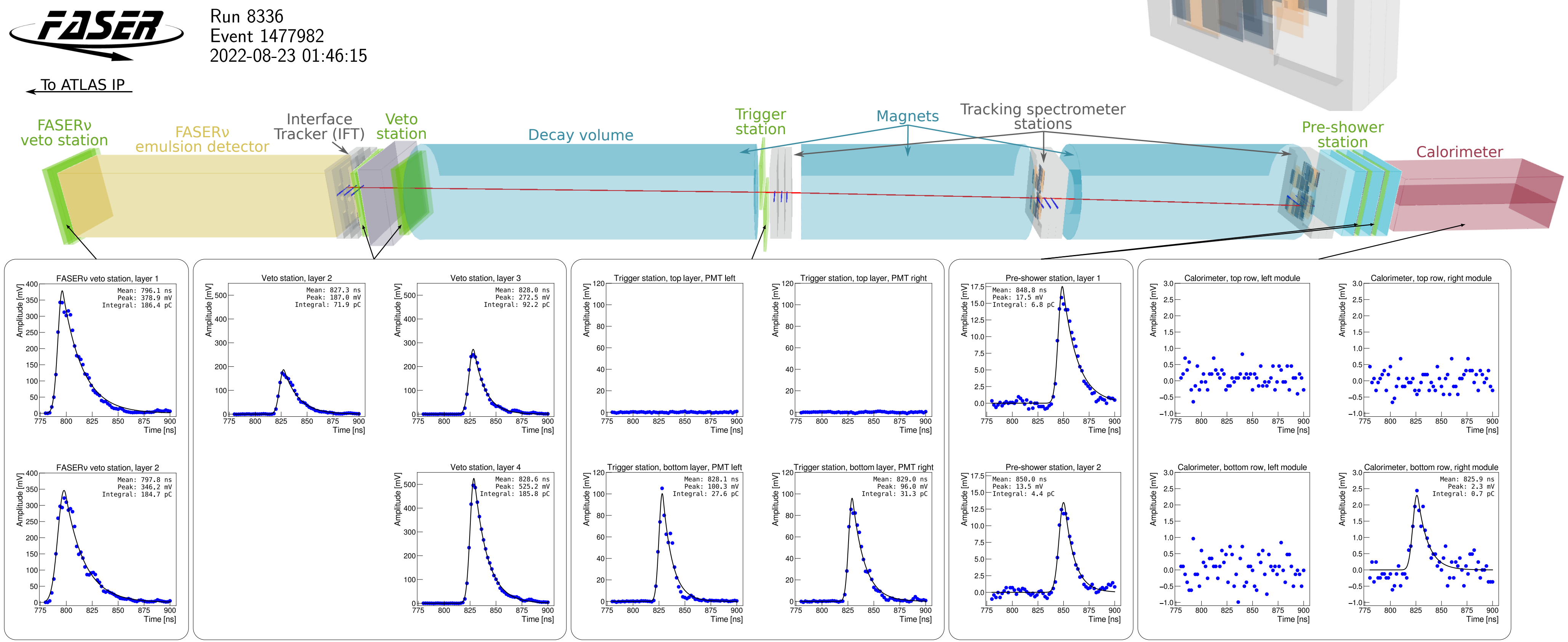


Detector operated very smoothly since July 2022.
Collected 97% of delivered data.
All components working as expected!

Zoom in of 1st tracking station

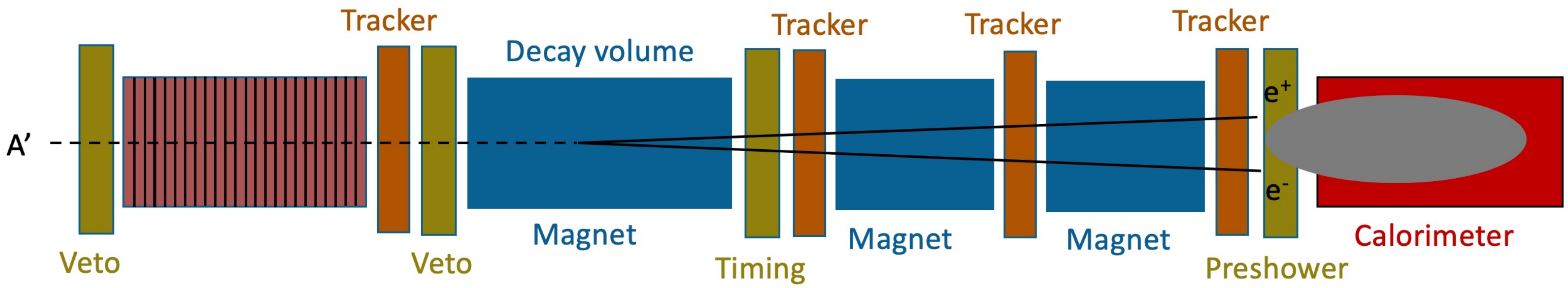


Event display showing a muon traversing the full detector.
All parts of the detector performing as expected.



Dark Photon Search

arxiv:2308.05587
(submitted to PLB)



- First FASER analysis, designed to be simple and robust (blind analysis to avoid unconscious bias)
  - Using 27/fb of 2022 data
  - Event selection:
    - No signal in any of 5 veto scintillators
    - 2 reconstructed tracks (extrapolate into veto scintillators)
    - >500 GeV energy in calorimeter
  - ~50% signal efficiency in relevant region of signal parameter space

Dark Photon Search

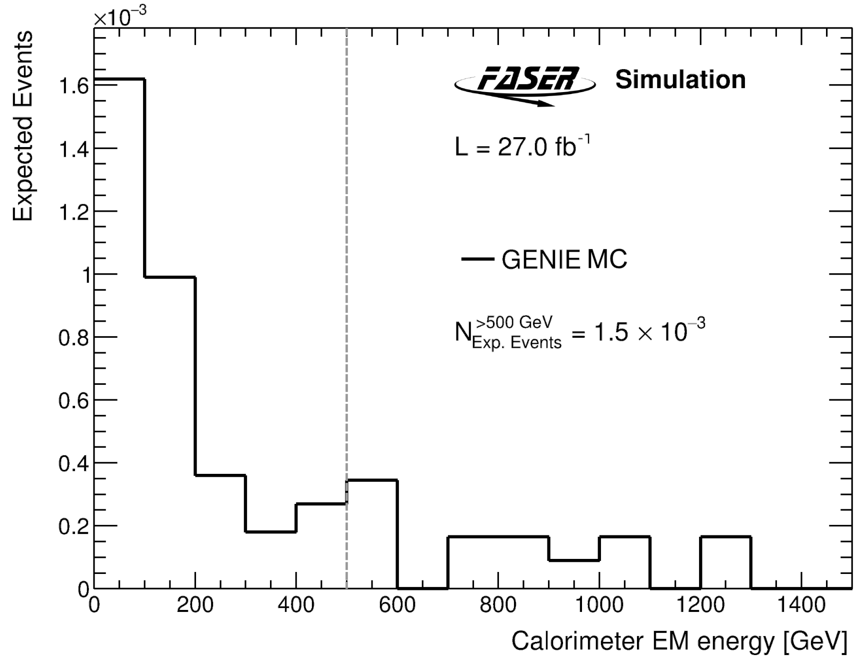
arxiv:2308.05587
(submitted to PLB)

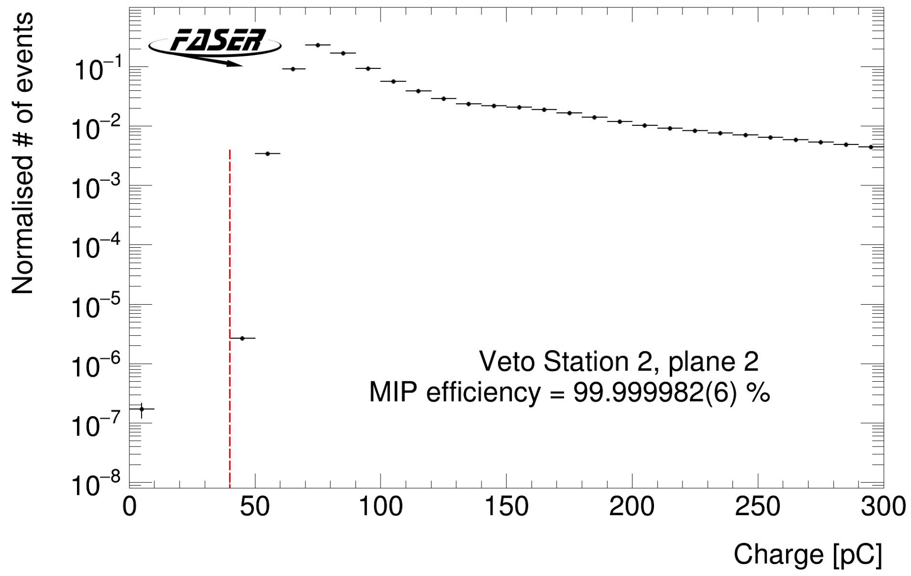
Studied backgrounds from:

- Scintillator inefficiencies
- Neutral hadrons produced by upstream muon interactions
- Neutrino interactions inside main detector volume
- Non-collision backgrounds

Background	Central Value	Error (%)
Veto inefficiency	-	-
Non-collision	-	-
Neutral hadrons	0.8×10^{-3}	1.2×10^{-3} (140%)
Neutrinos	1.5×10^{-3}	2.0×10^{-3} (130%)
Total	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{2.3 \times 10^{-3}}$ **(100%)**

Detector design and excellent performance leads to an essentially background free analysis

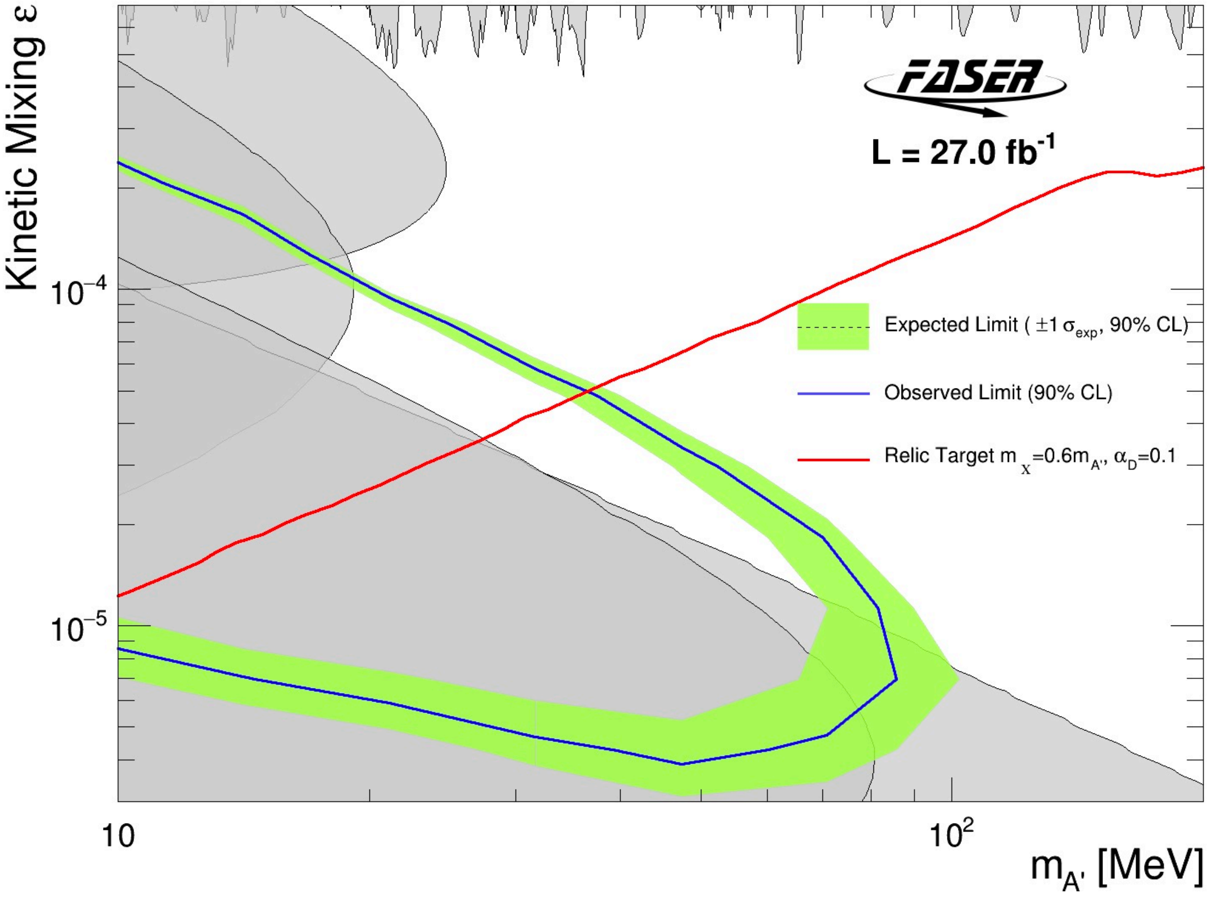


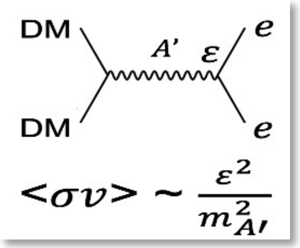


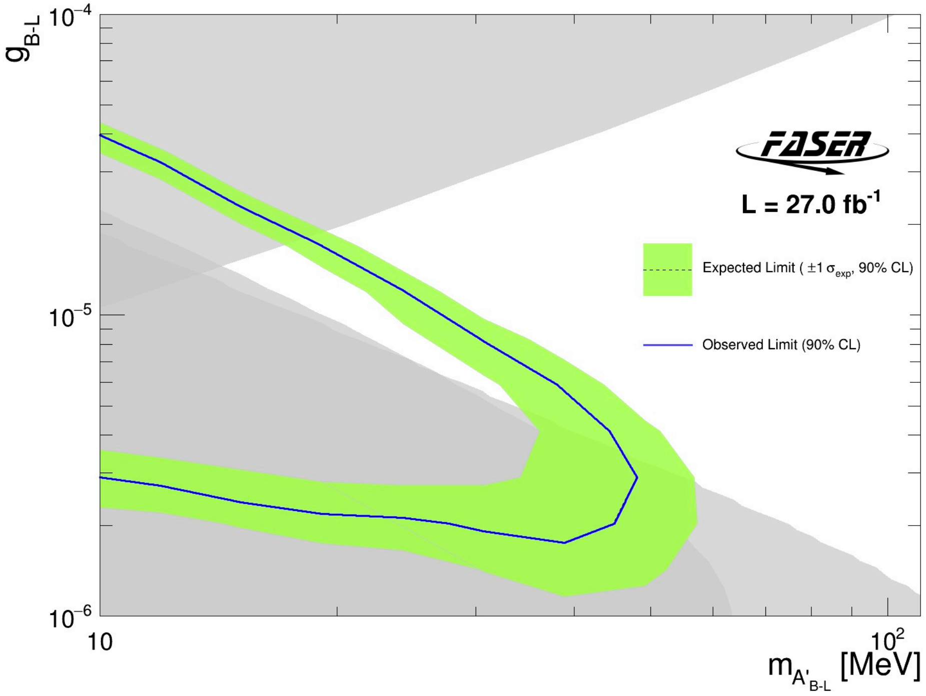
Dark Photon Search

[arxiv:2308.05587](https://arxiv.org/abs/2308.05587)
(submitted to PLB)

- Zero events observed
  - Set limits in unconstrained regions of parameter space
  - First improvement of sensitivity into the thermal relic region from weak coupling since the 1990's
  - Result also interpretted in B-L gauge boson model







Note: Preliminary result from NA62 (partially overlapping with FASER excluded region) not shown.

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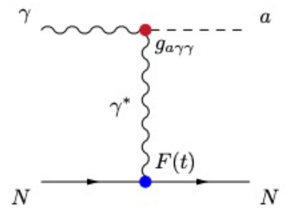
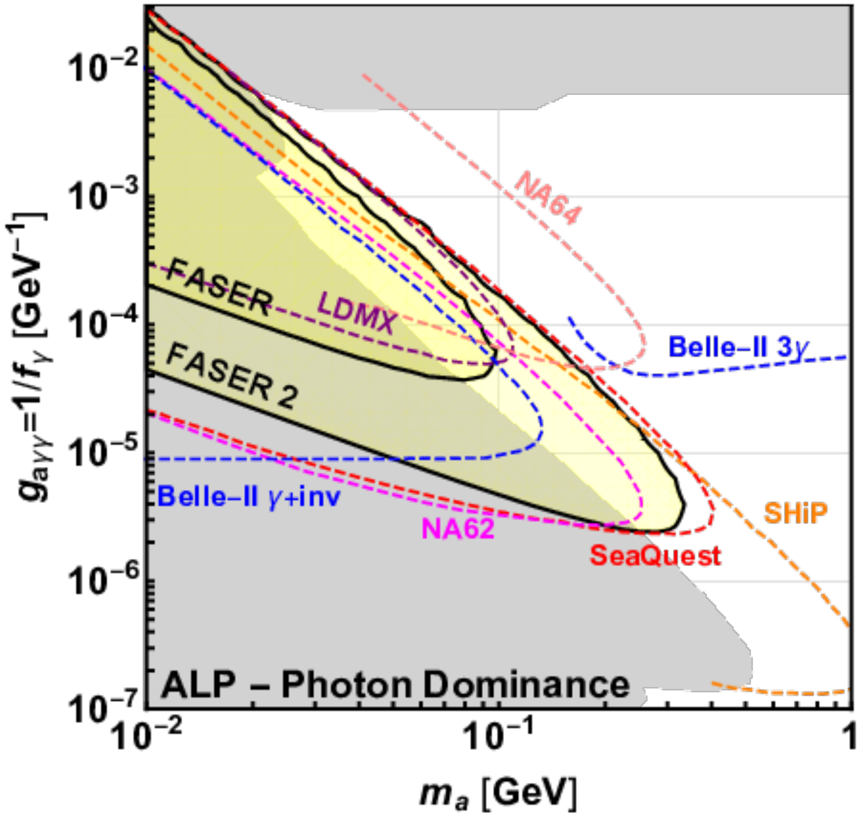
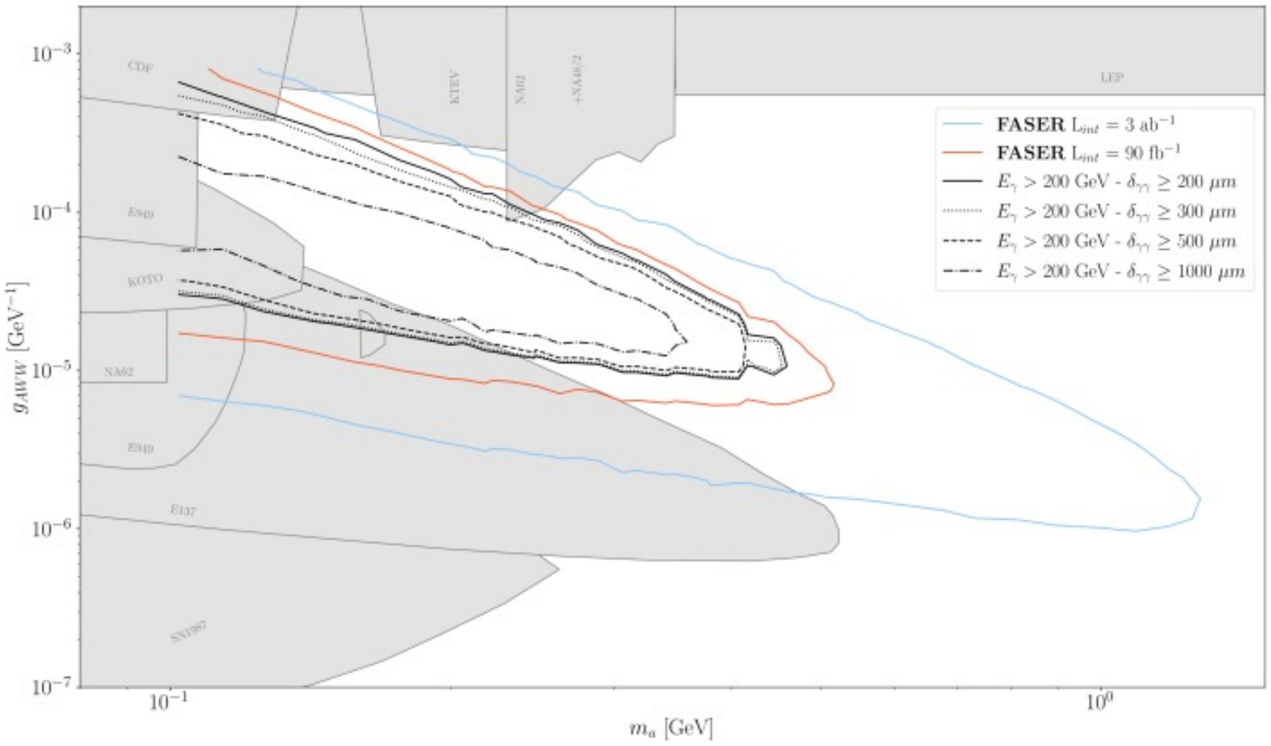
Axion Like Particles

- ALPs with photon-like couplings can be produced by high energy photons in the forward direction interacting with LHC material (the TAN absorber) via the Primakoff process. "LHC as a photon beam dump". The ALP can then decay to 2 photons in FASER: [Phys. Rev. D98 no. 5, (2018) 055021]



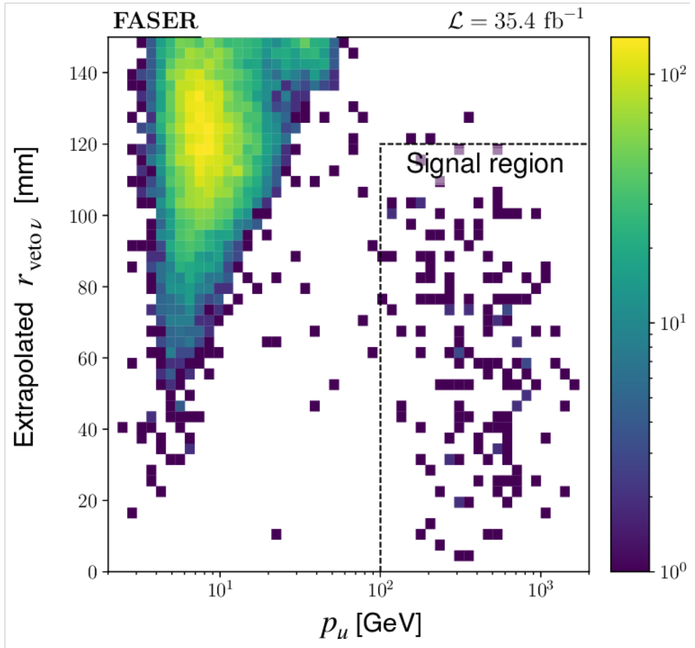
- ALPs with W-like couplings can be produced in b hadron decays, and decay to 2 photons in FASER
  - FASER sensitivity nicely fits between existing collider and fixed target

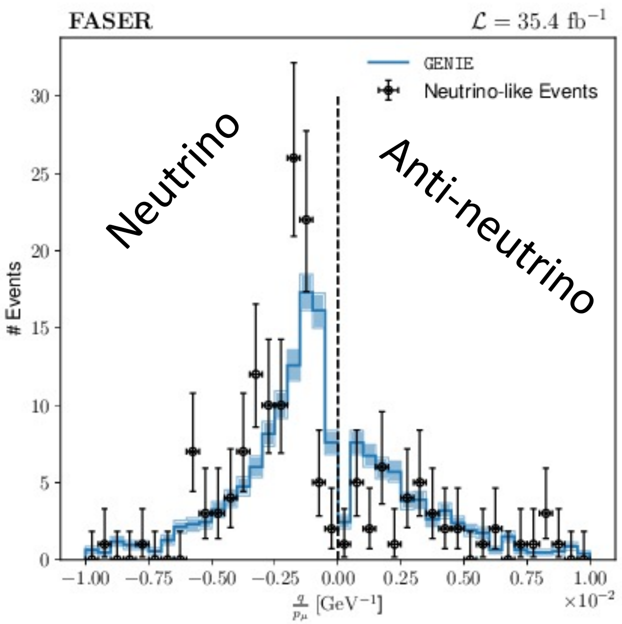




FASER Neutrino Results

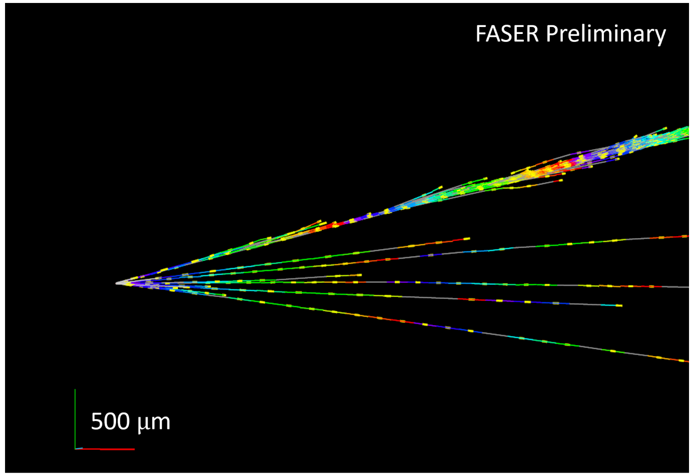
In addition to dark sector searches FASER has a strong neutrino programme

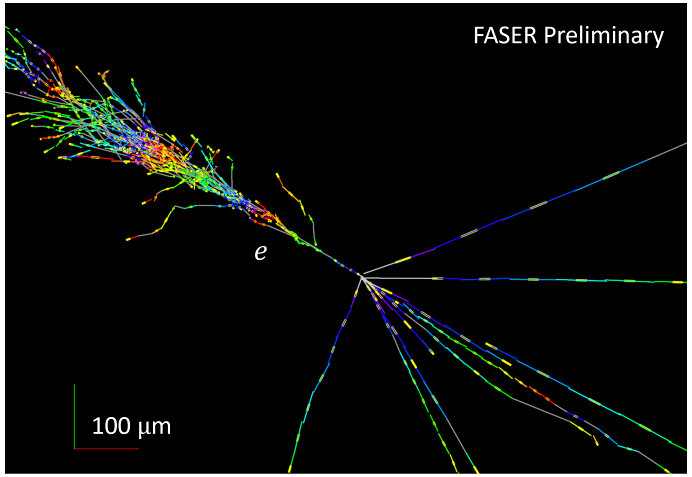




First direct observation of collider neutrinos!
Using electronic detector components to search for ν_μ charged current (CC) interaction in 1.1tonne tungsten target.
Expected: 151+/-40 events
Observed: 153 events (expected background 0.2+/-1.8)
Selected neutrino characteristics consistent with expectations (ν, $\bar{\nu}$). Selected ν of high energy E>200 GeV

Phys. Rev. Lett. 131 no. 3, (2023) 031801





Highest energy selected vertex. Reconstructed electron energy 1.5 TeV.

First direct observation of electron neutrinos!
Using FASERν emulsion detector. Only 70 kg target mass analyzed (1% of data collected). Selection requires reconstructed electron candidate with E>200GeV.
Expected: 0.6–5.2 (ν_e CC) vertices
Observed: 3 vertices (exp bkg 0.002+/-0.003)
CERN-FASER-CONF-2023-002

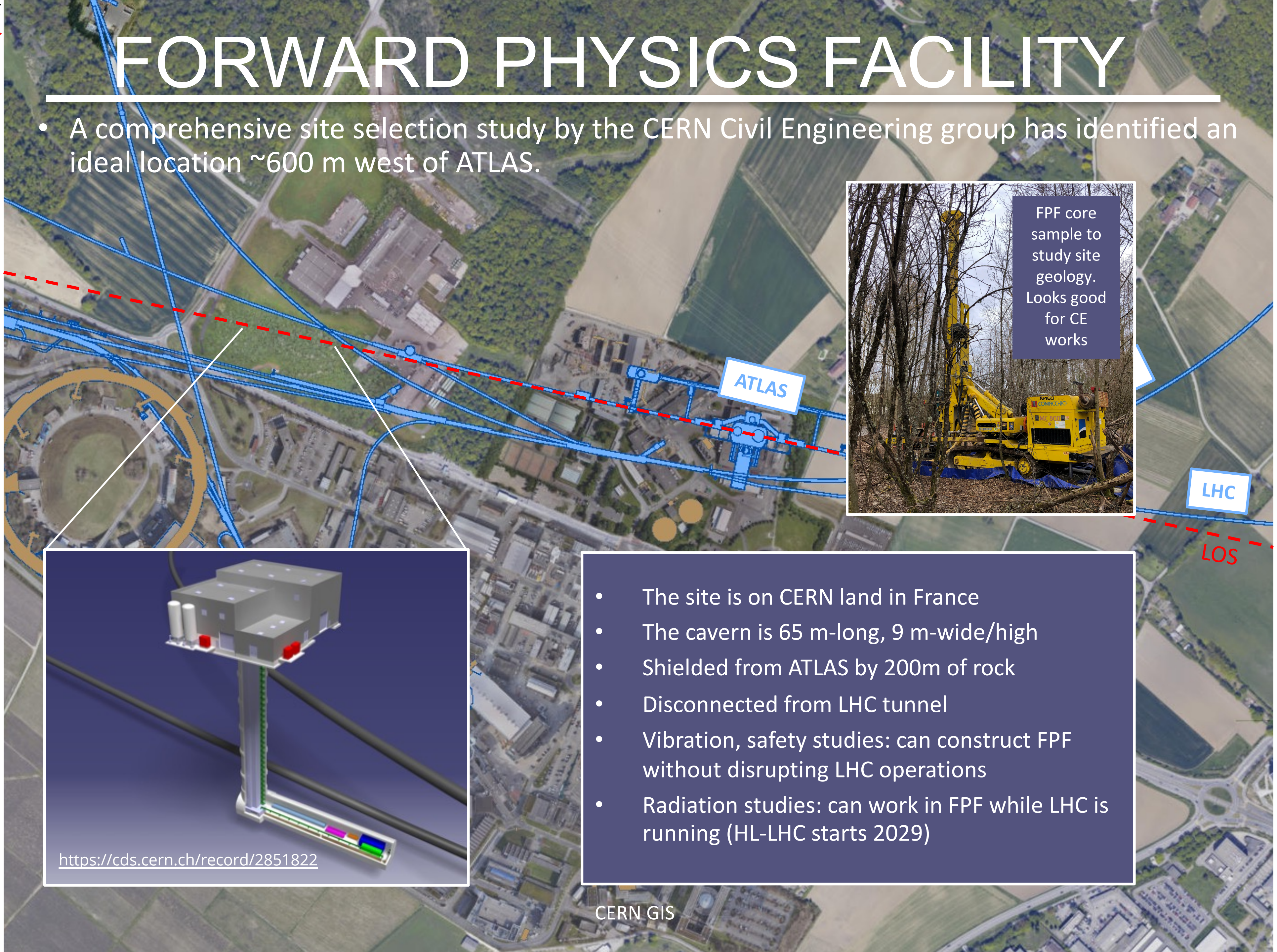
Now to the future…

- Studies for FASER have highlighted the broad and strong case for physics in the far forward region of the LHC collisions
- To maximally exploit this, we need to enhance the experimental capabilities in this region:
  - Larger detectors:
    - In the transverse plane increase acceptance for particles from heavy flavour decay
    - In the longitudinal plane increased target mass for neutrino experiments and decay volume length for BSM searches
  - Add new detectors with different technologies to allow different signatures to be explored
    - mCPs, dark matter scattering etc…
- To realize this, we can no longer rely on the small side tunnel that "happens to be in the right place"
  - No room for larger/additional experiments
  - Access for detector installation very limited
  - Required services missing

=> Build a dedicated facility to house several new experiments in this interesting region!

FORWARD PHYSICS FACILITY

- A comprehensive site selection study by the CERN Civil Engineering group has identified an ideal location ~600 m west of ATLAS.



FPF core sample to study site geology. Looks good for CE works

https://cds.cern.ch/record/2851822

- The site is on CERN land in France
- The cavern is 65 m-long, 9 m-wide/high
- Shielded from ATLAS by 200m of rock
- Disconnected from LHC tunnel
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

J. Phys. G 50 (2023) 030501, 1-410
https://cds.cern.ch/record/2851822/

FPF Experiments

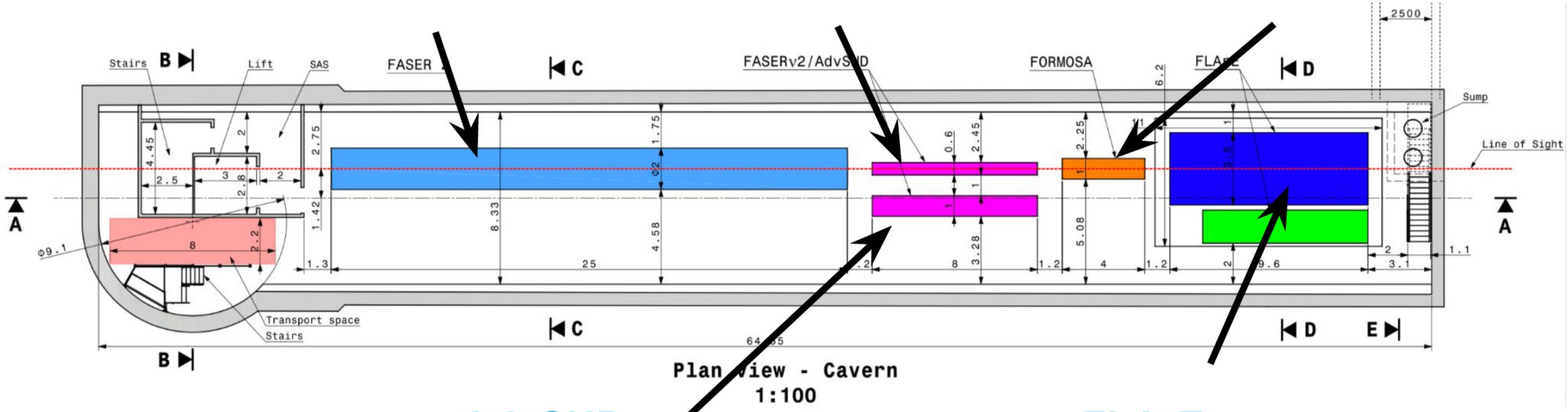
J. Phys. G 50 (2023) 030501, 1-410

- At present there are 5 experiments being designed for the FPF.
- Diverse technologies optimized for particular SM and BSM topics.
- FPF covers η > 5.5, experiments on LOS cover η ≳ 7.

FASER2
magnetized spectrometer for BSM searches

FASERν2
emulsion-based neutrino detector

FORMOSA
plastic scintillator array for BSM searches



AdvSND
electronic neutrino detector

FLArE
LAr based neutrino detector

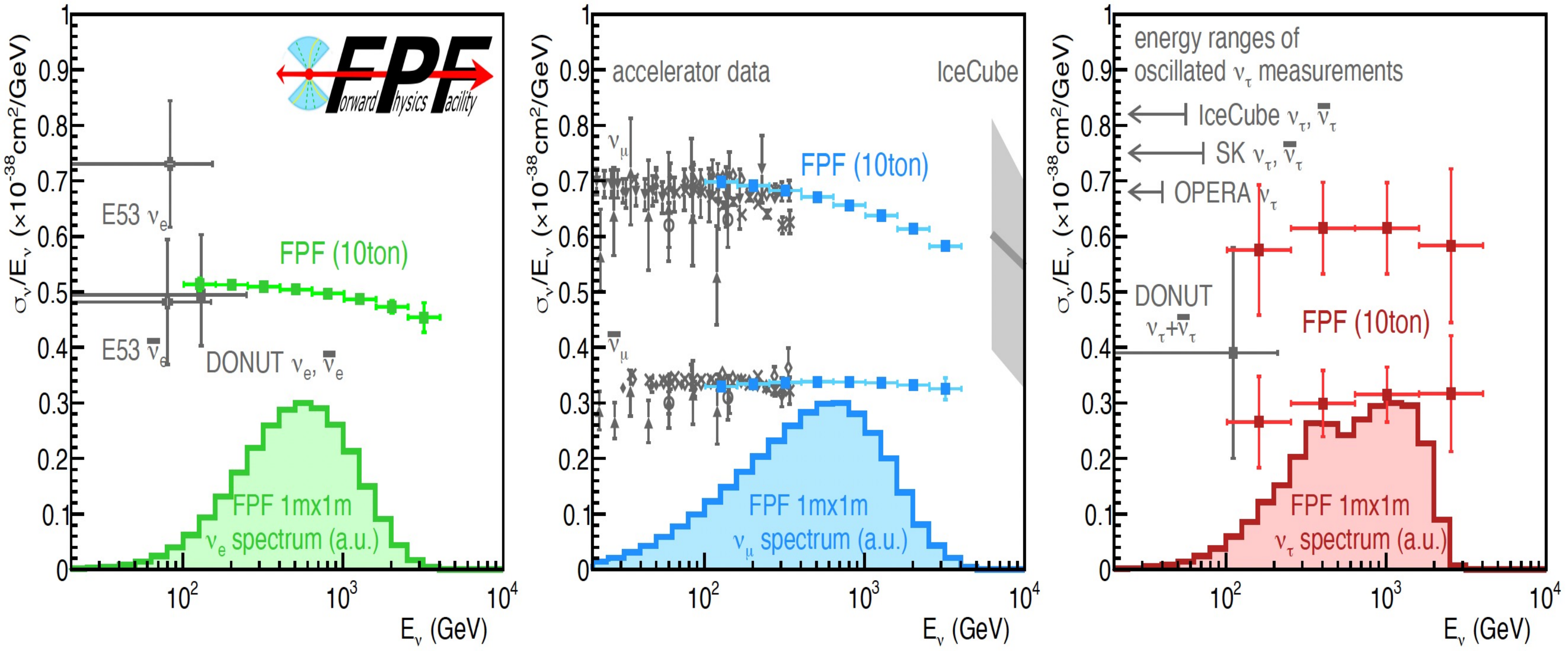
FASER2
10m decay volume
1m transverse radius
$\mathcal{O}(10^{17})\ \pi^0$
$\mathcal{O}(10^{17})\ \eta$
$\mathcal{O}(10^{15})\ D-$mesons
$\mathcal{O}(10^{13})\ B-$mesons
in FASER2 angular acceptance in HL-LHC

J. Phys. G 50 (2023) 030501, 1-410

The FPF Neutrino Programme

- FPF experiments FLArE, FASERν2, and AdvSND will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ interactions at ~TeV energies.

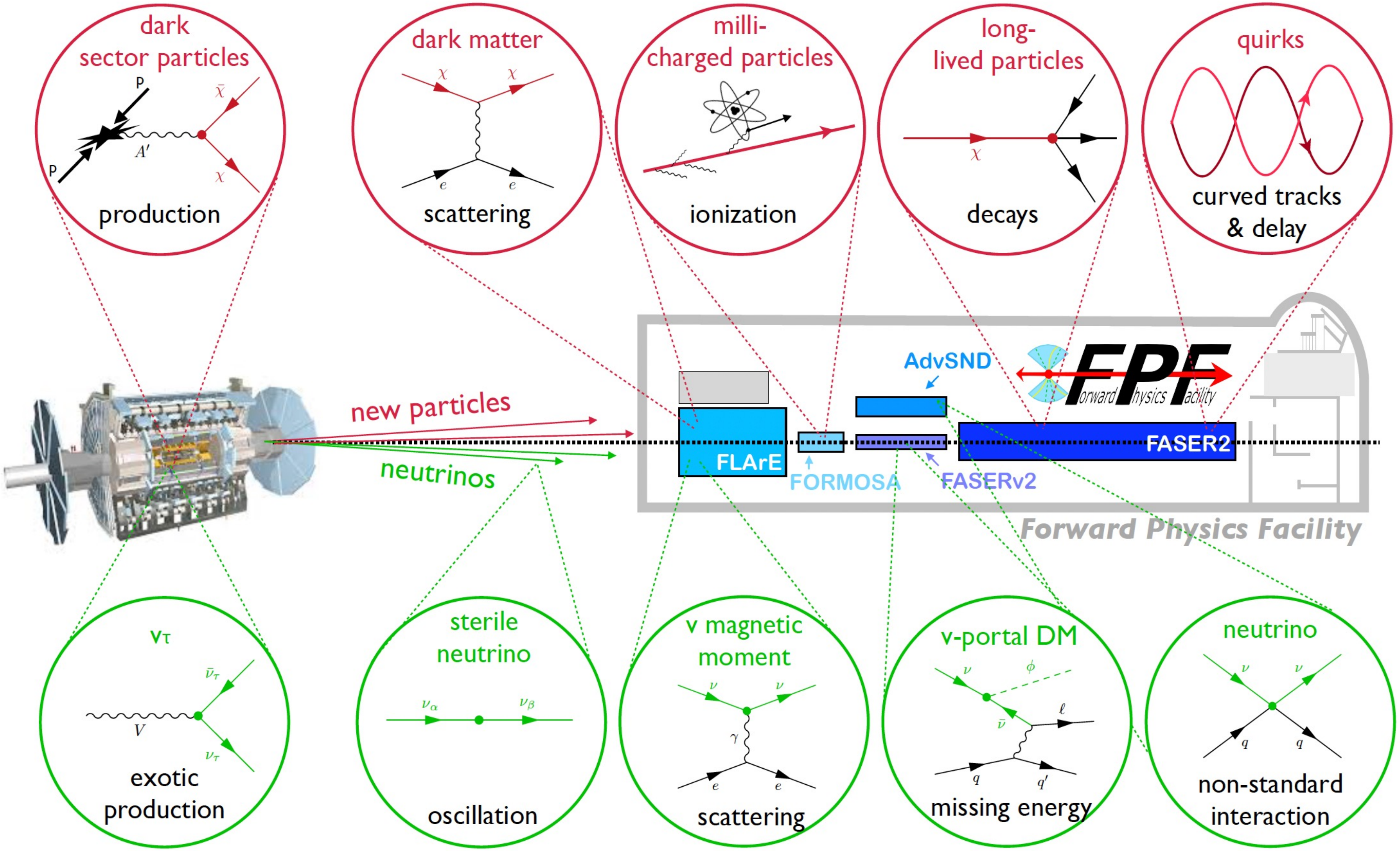
- Implications for
  - neutrino properties
  - QCD ($x \sim 10^{-7} - 0.1$, DIS)
  - astroparticle physics



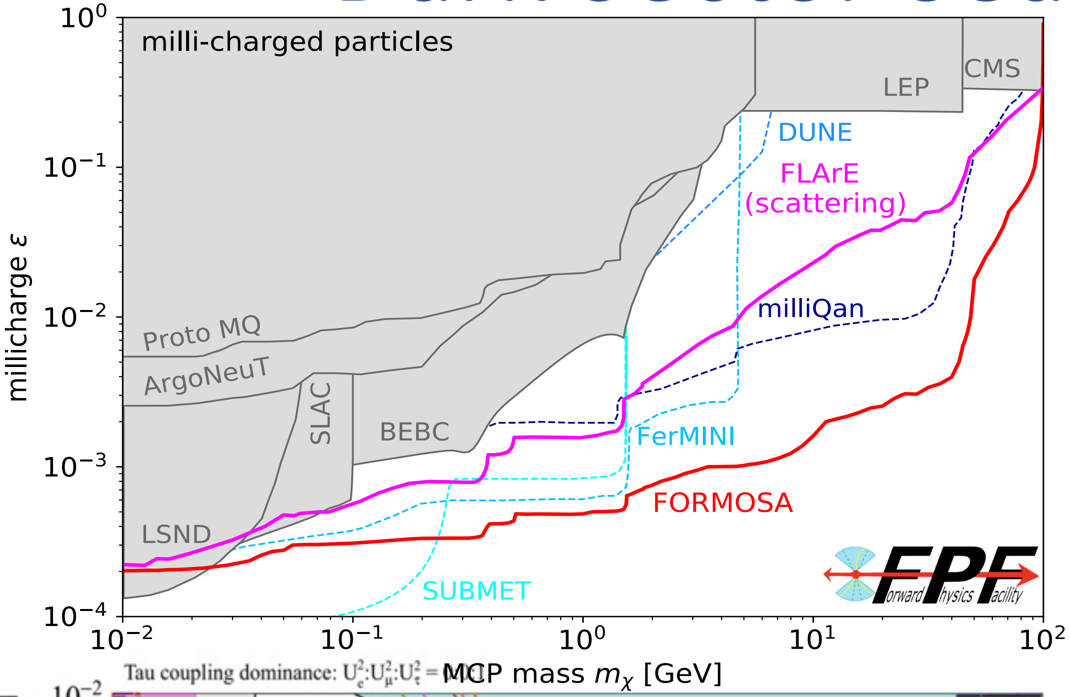
J. Phys. G 50 (2023) 030501, 1-410

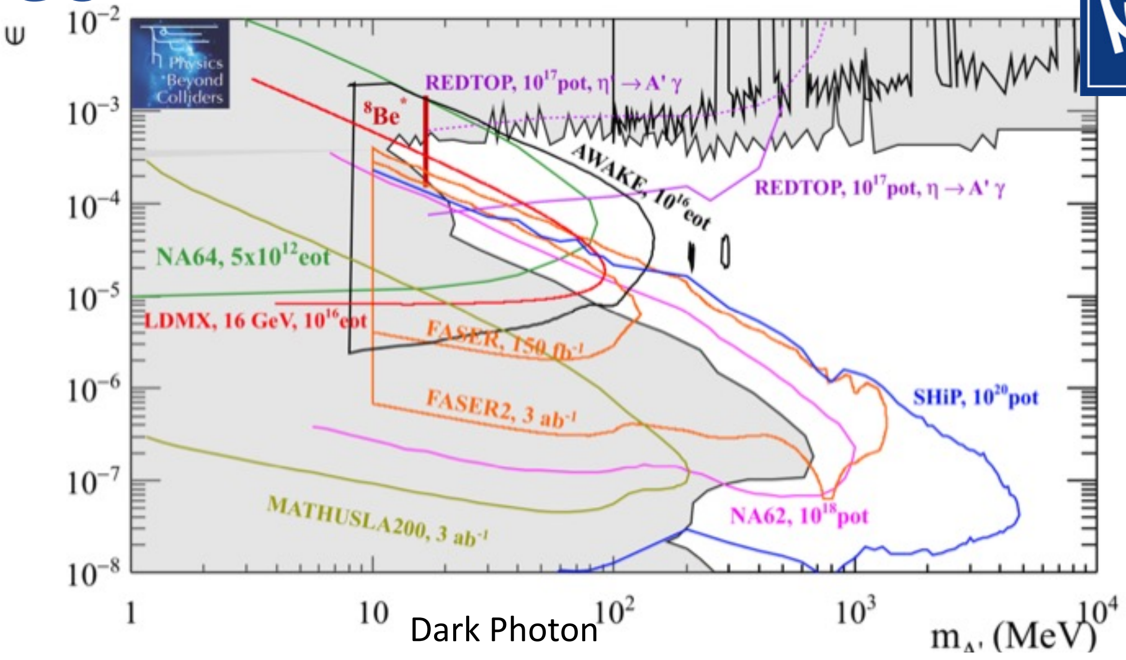
The FPF BSM Programme

- Wide variety of BSM probes: new physics in neutrino production, propagation, and interaction, FIPs, LLPs, DM scattering, inelastic DM, and dark sectors.

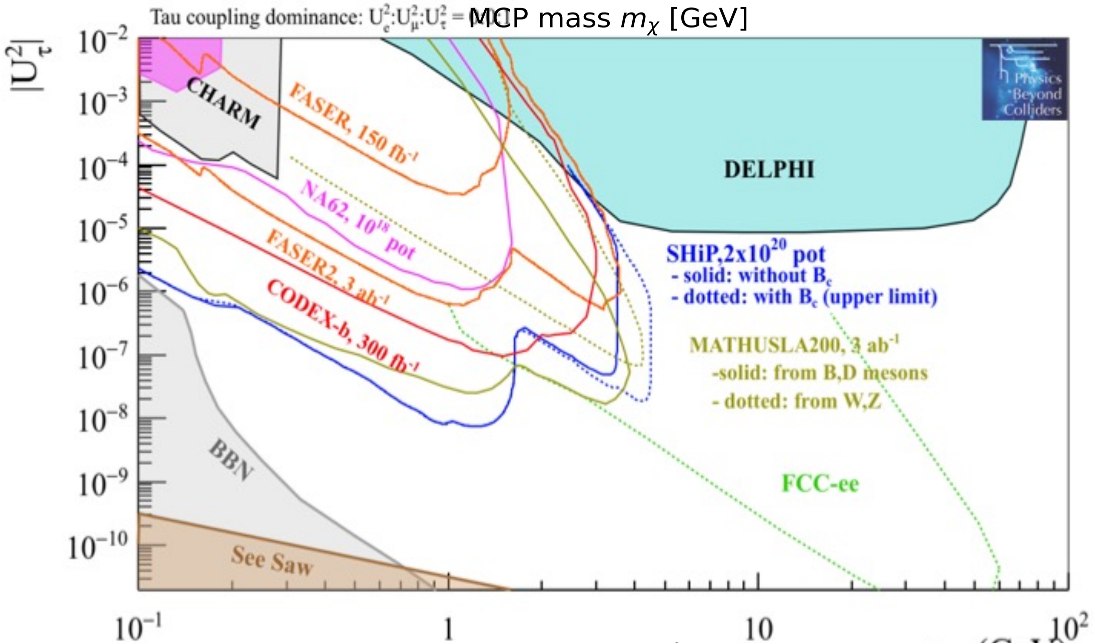


Dark Sector Searches

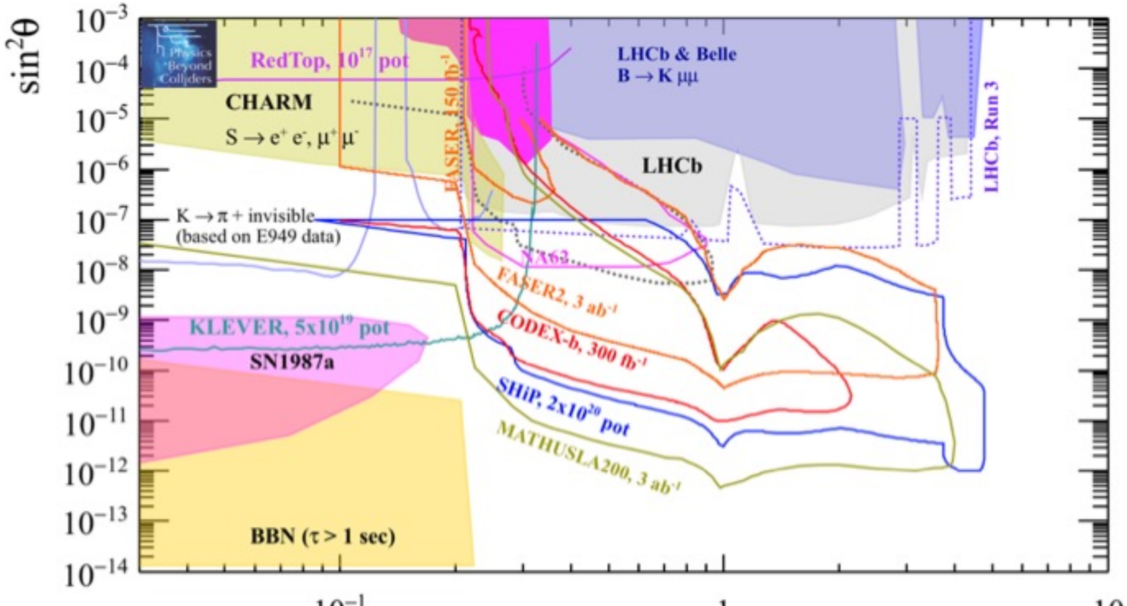




Dark Photon



Dark Fermion

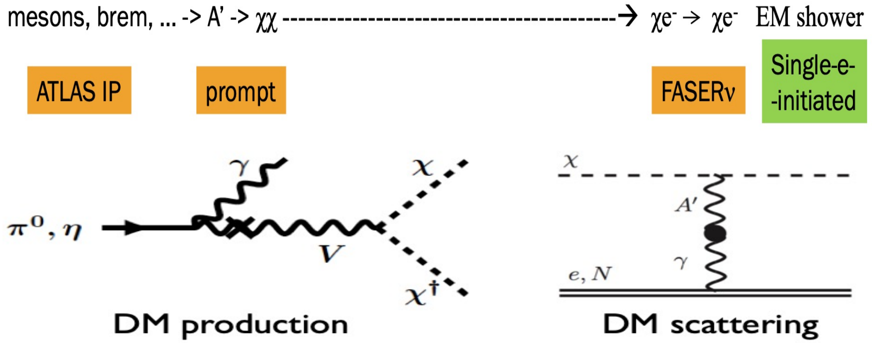


Dark Scalar

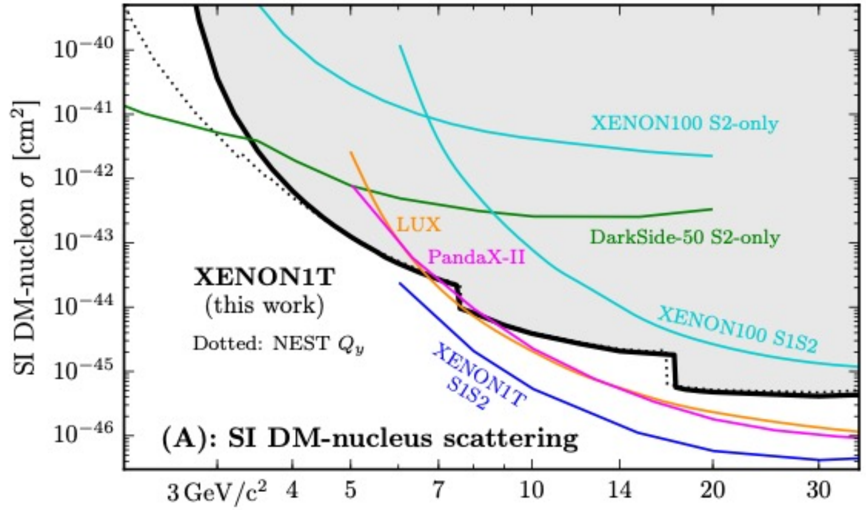
Dark Matter Direct Detection

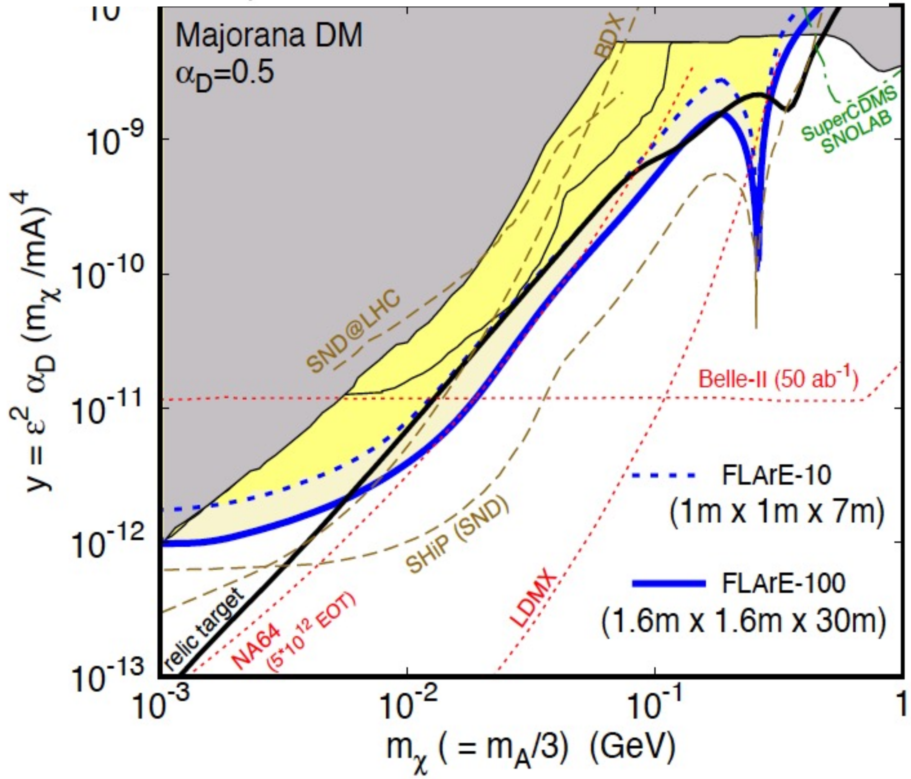
- Light DM with masses at the GeV scale and below is famously hard to detect.
  - Galactic halo velocity ~ 10^{-3} c, so kinetic energy ~ keV or below.

- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.



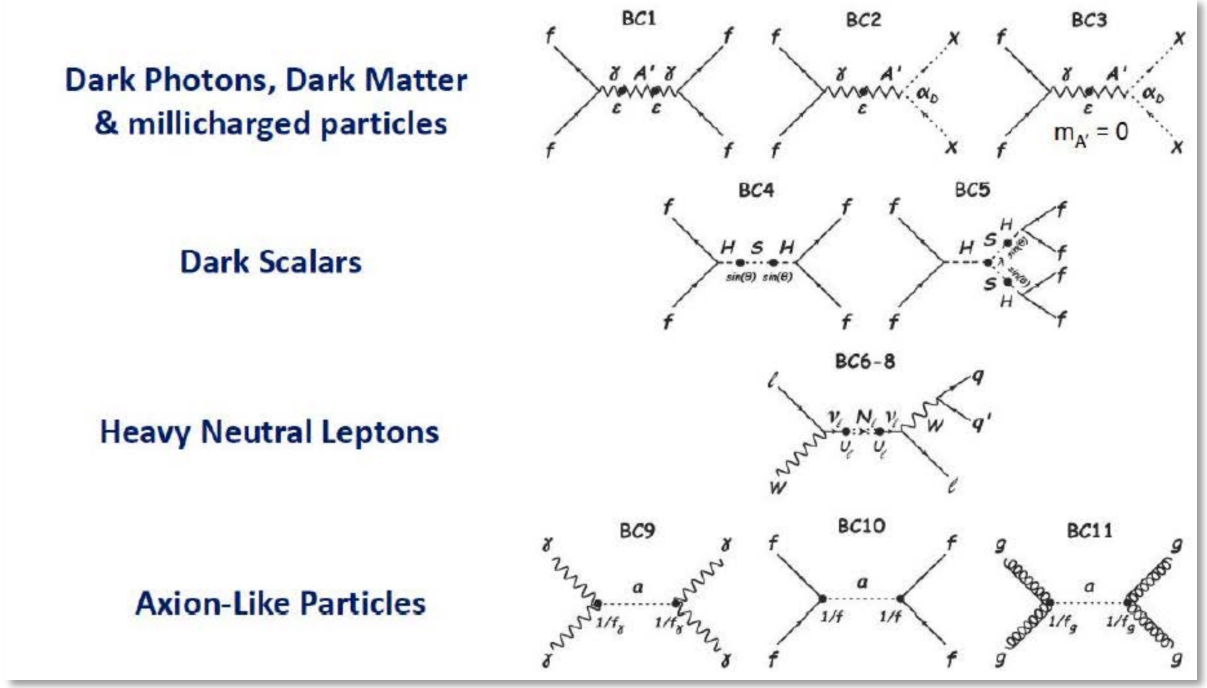
- FLArE is powerful in the region favored/allowed by thermal freezeout.





DS @ FASER/FPF

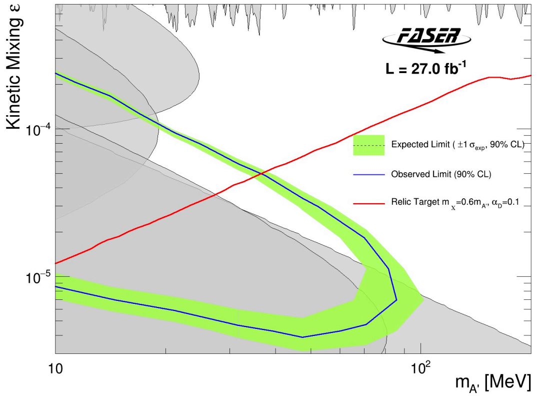
FPF experiments would give significant new sensitivity in all of the dark sector PBC benchmark models



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

https://faser.web.cern.ch/index.php/physics/publications

Summary



- FASER Experiment
  - Operating since the start of LHC Run 3
  - 70/fb of data recorded
- First search for dark photons:
  - Exclude interesting parameter space motivated by dark matter
  - Almost background free search validates detector design/performance; bodes well for future searches with up to 10x more data in Run 3
- FASER has opened the door to neutrino studies at the LHC
  - First direct observation of collider muon and electron neutrinos
- Forward Physics Facility (FPF)
  - Maximise the physics output in the far forward region of the LHC collisions in the HL era
  - Strong physics case:
    - Dark sector searches
    - Neutrino physics
    - QCD with strong connection to astroparticle physics
- Technical studies on the feasibility of the FPF
  - Site investigation shows geology good for proposed civil engineering works
  - Studies on muon background, radiation level, vibrations with positive results
  - Design studies for the propsoed detectors ongoing…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SEARCHES FOR NEW PHYSICS | MEETING REPORT

Looking forward at the LHC

1 September 2023

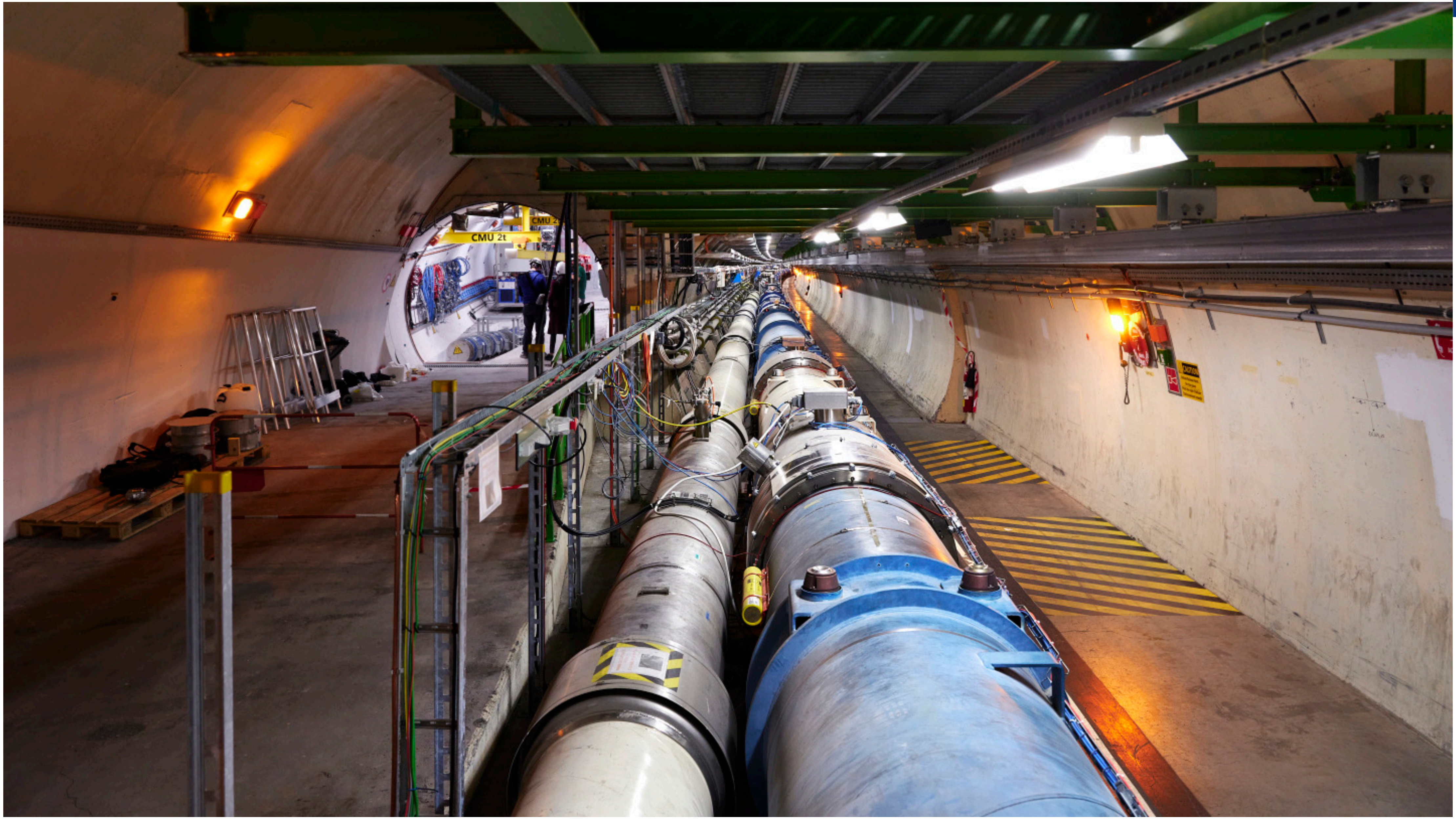
The Forward Physics Facility (FPF) is a proposed new facility to operate concurrently with the High-Luminosity LHC, housing several new experiments on the ATLAS collision axis. The FPF offers a broad, far-reaching physics programme ranging from neutrino, QCD and hadron-structure studies to beyond-the-Standard Model (BSM) searches. The project, which is being studied within the Physics Beyond Colliders initiative, would exploit the pre-existing HL-LHC beams and thus have minimal energy-consumption requirements.

New territory 3D rendering of the proposed Forward Physics Facility and its experiments. Credit: A Navascues Cornago

On 8 and 9 June, the 6th workshop on the Forward Physics Facility was held at CERN and online. Attracting about 160 participants, the workshop was organised in sessions focusing on the facility design, the proposed experiments and physics studies, leaving plenty of time for discussion about the next steps.

https://cerncourier.com/a/looking-forward-at-the-lhc

Backup



FASER Collaboration

The FASER collaboration consists of 84 members from 24 institutions and 10 countries:

International laboratory covered by a cooperation agreement with CERN

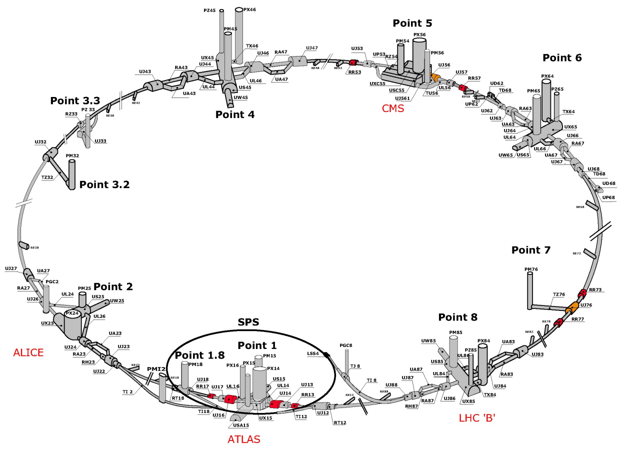
FASER Acknowledgements

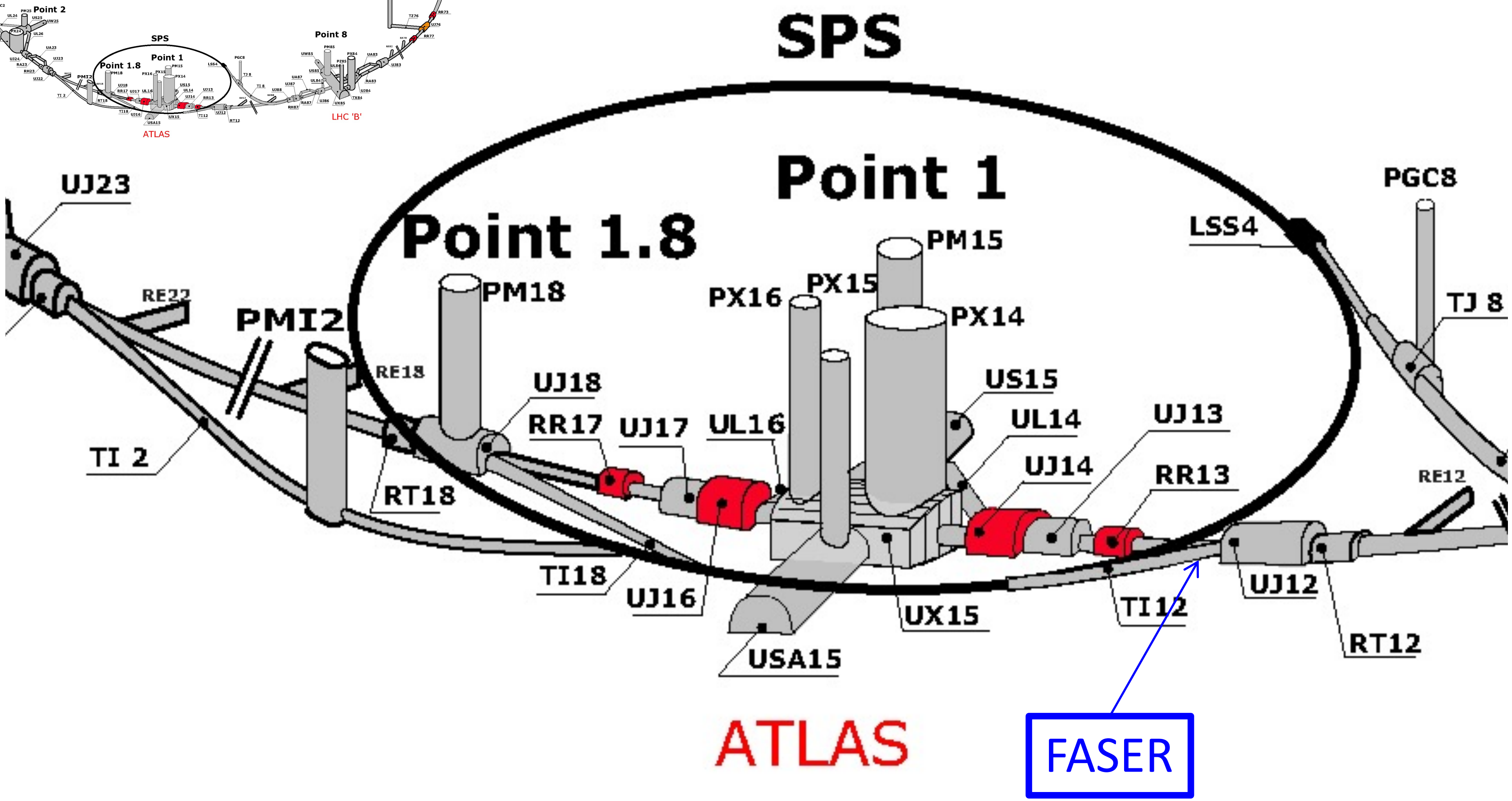
- FASER is supported by:

- We also thank:
  - LHC for the excellent performance
  - ATLAS Collaboration for providing luminosity information
  - ATLAS SCT Collaboration for spare tracker modules
  - ATLAS for the use of their ATHENA software framework
  - LHCb Collaboration for spare ECAL modules
  - CERN FLUKA team for the background simulation
  - CERN PBC and technical infrastructure groups for the excellent support

Visit of Jim Simons and Mark Heising to FASER in 1/23

FASER Location: TI12 tunnel





FASER Detector Installation

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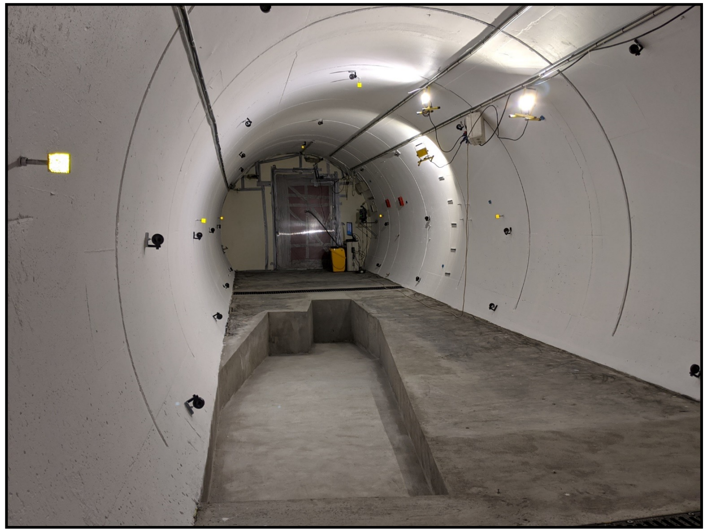

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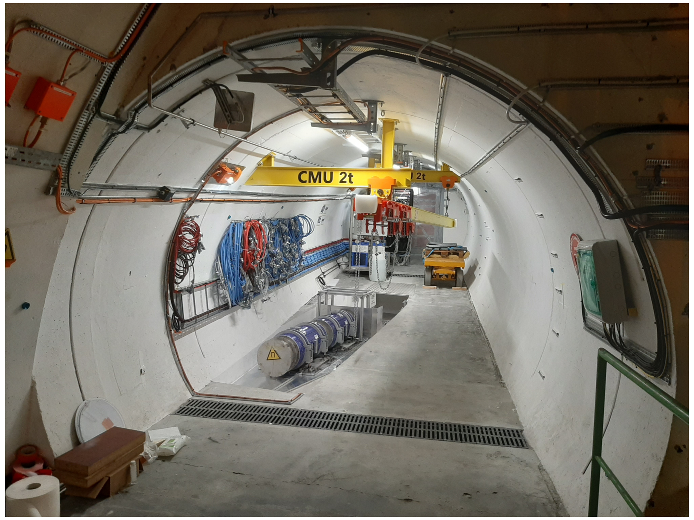

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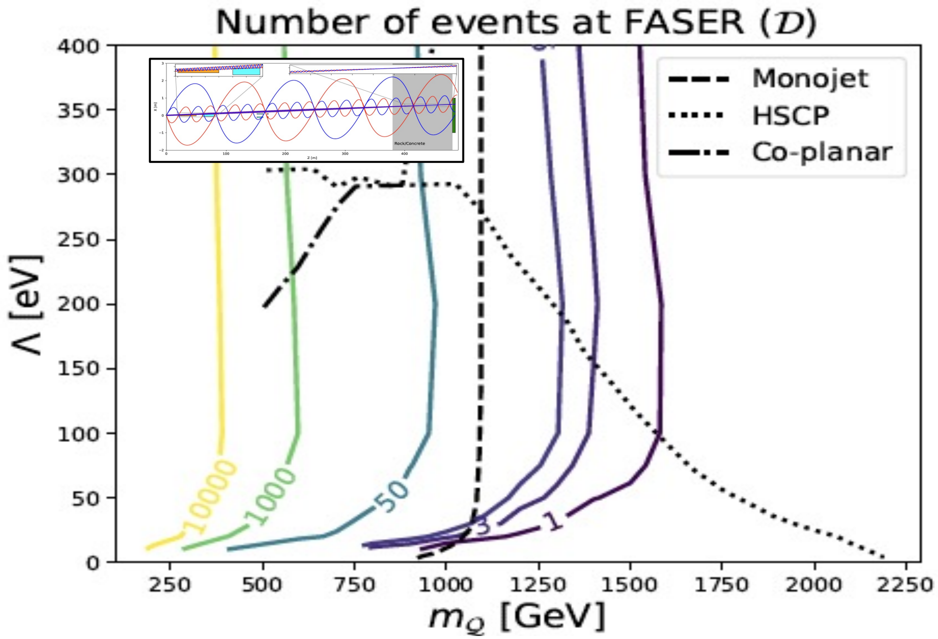
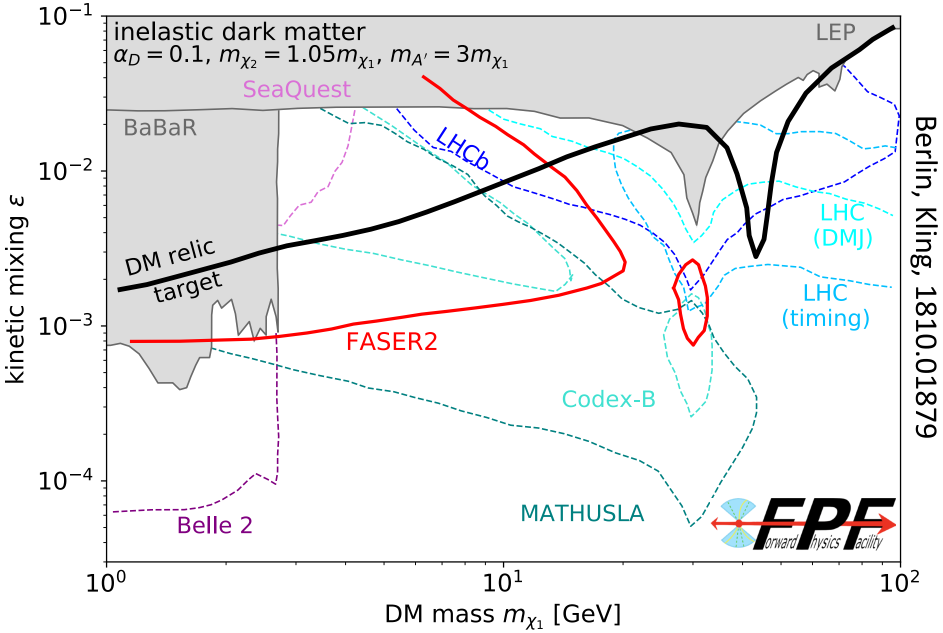
FPF BSM Searches

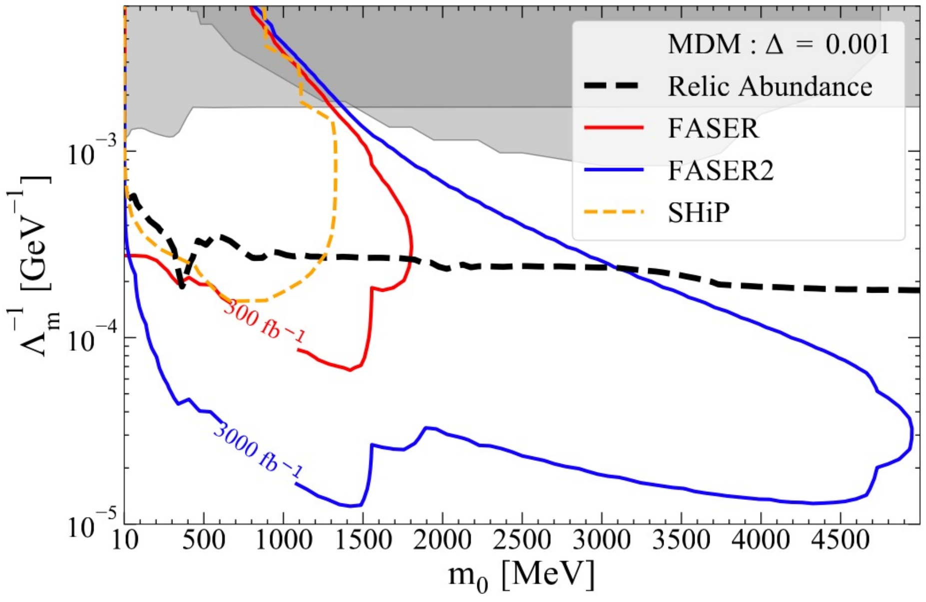
- Complementarity of high energy and fixed target experiments. High energy experiments probe
  - High mass states (e.g., quirks)
  - High mass mediators
  - Compressed spectra by boosting soft decay products to high energy



Li, Pei, Ran, Zhang, 2108.06748

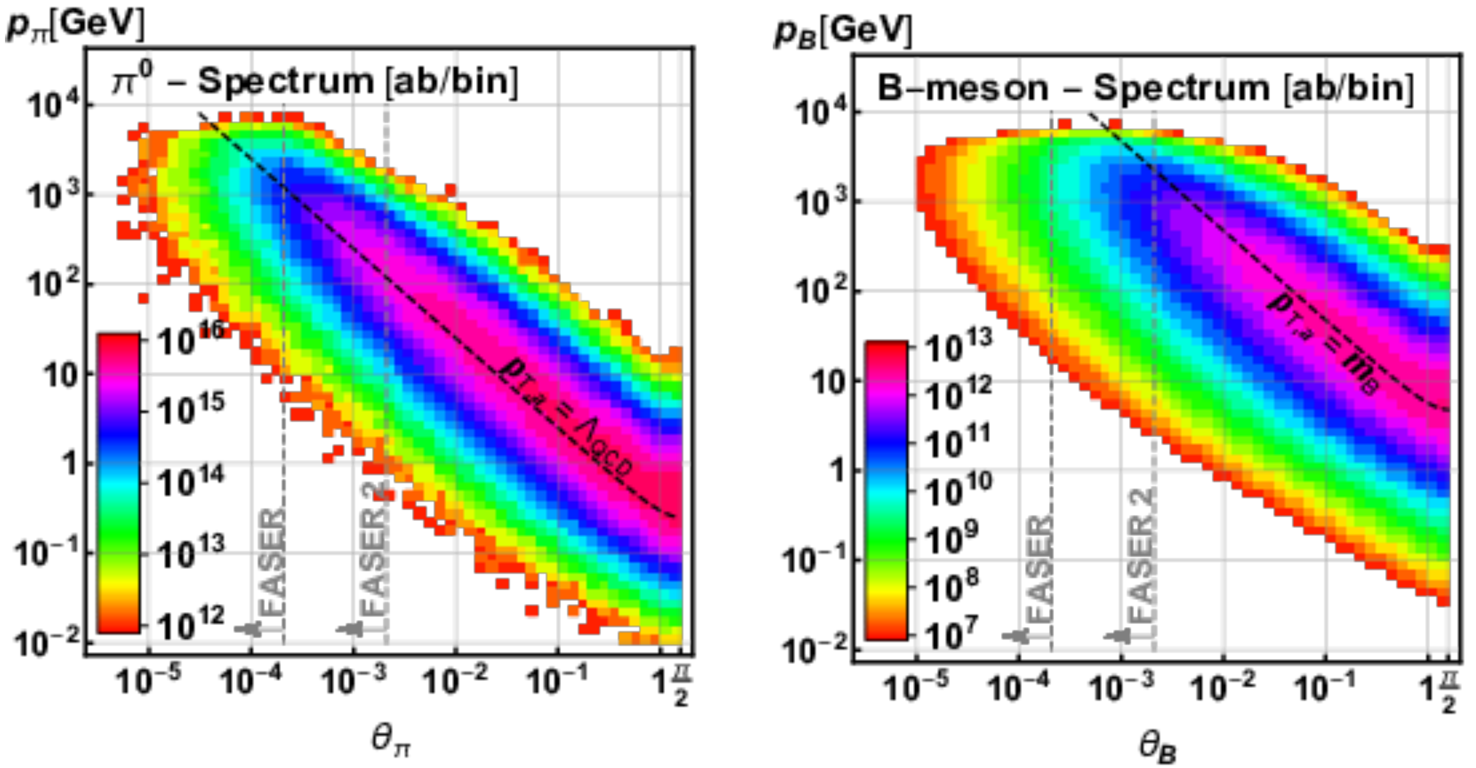


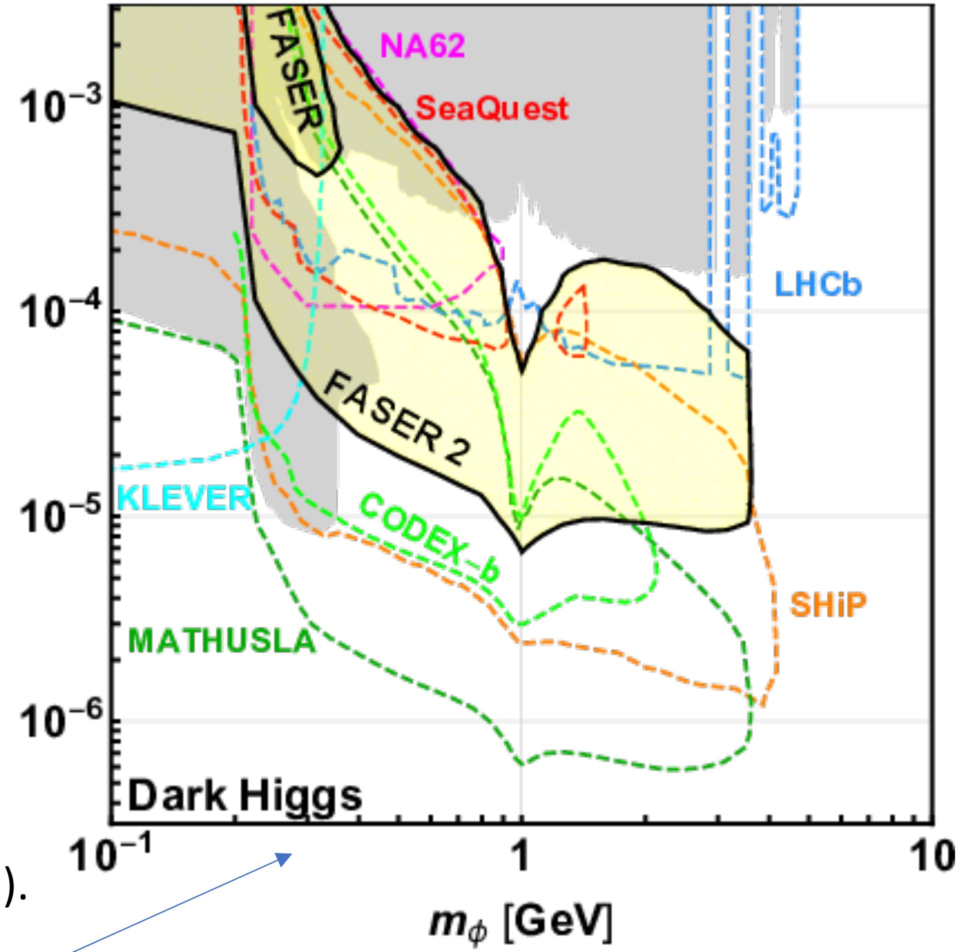
Berlin, Kling, 1810.01879



Dienes et al., 2301.05252

Aside: Signals from heavy flavour decay

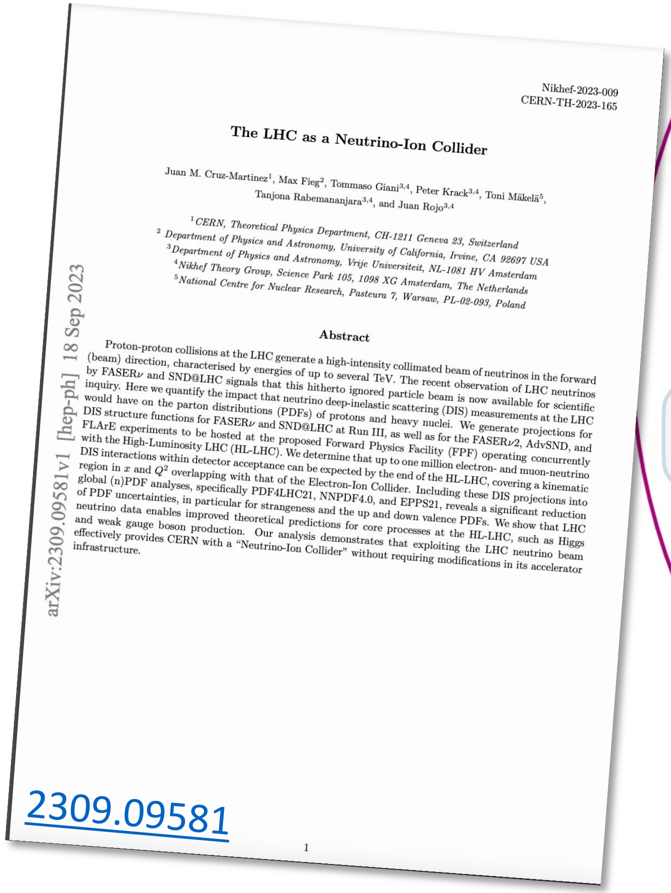




Number of π^0 and B mesons as function of angle wrt LOS and energy (for 150/fb). Heavier B-mesons are more spreadout around the LOS => only small fraction in FASER acceptance, but FASER2 starts to get into the bulk of the distribution.
Much better sensitivity for new LLPs produced in B decays (such as Dark Higgs) at FASER2 than FASER.

QCD at the FPF

Many interesting QCD topics to be studied at the FPF:



arXiv:2309.09581v1 [hep-ph] 18 Sep 2023

Nikhef-2023-009
CERN-TH-2023-165

The LHC as a Neutrino-Ion Collider

Juan M. Cruz-Martinez[1], Max Fieg[2], Tommaso Giani[3,4], Peter Krack[3,4], Toni Mäkelä[5], Tanjona Rabemananjara[3,4], and Juan Rojo[3,4]

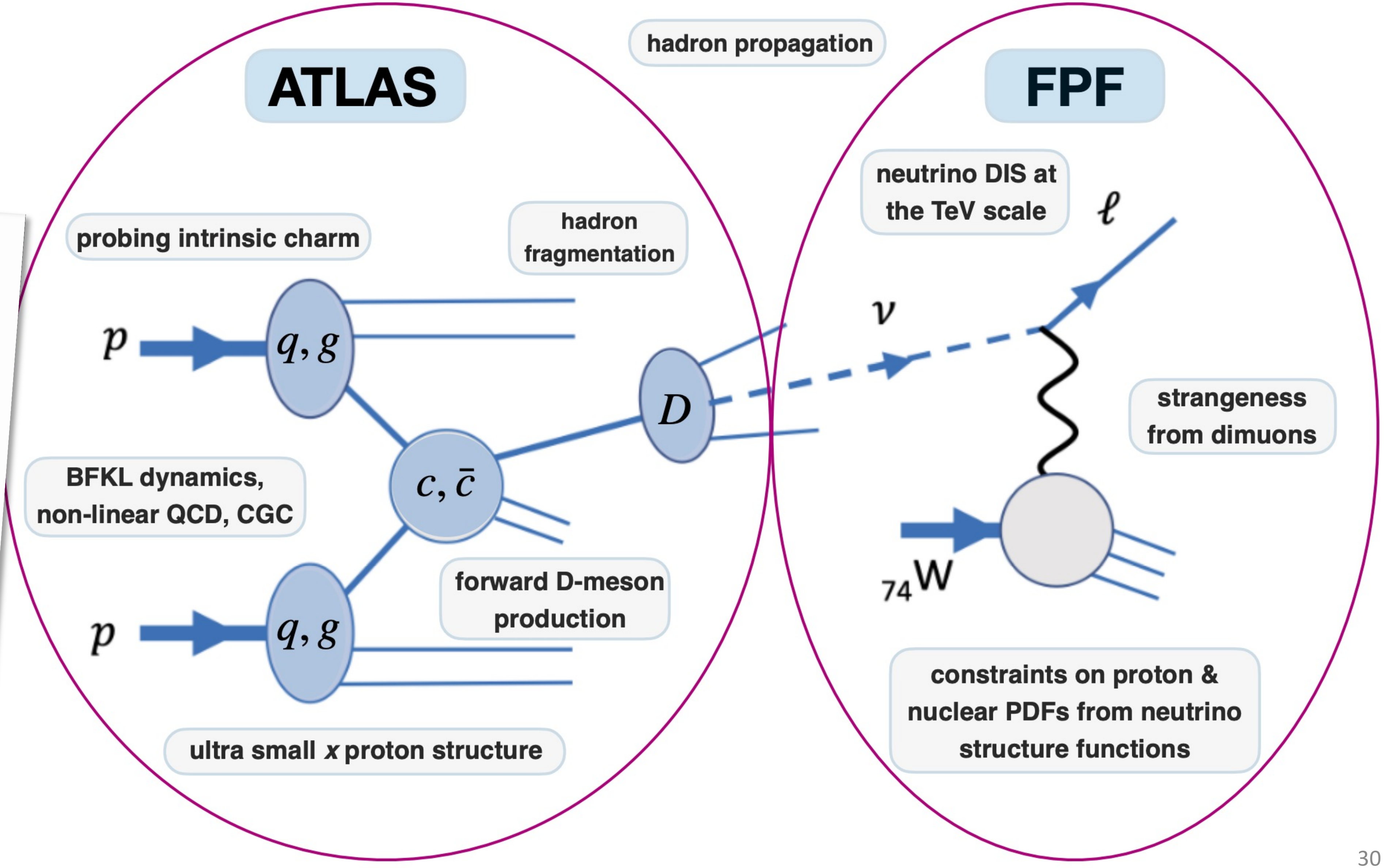
[1] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[2] *Department of Physics and Astronomy, University of California, Irvine, CA 92697 USA*
[3] *Department of Physics and Astronomy, Vrije Universiteit, NL-1081 HV Amsterdam*
[4] *Nikhef Theory Group, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[5] *National Centre for Nuclear Research, Pasteura 7, Warsaw, PL-02-093, Poland*

Abstract

Proton-proton collisions at the LHC generate a high-intensity collimated beam of neutrinos in the forward (beam) direction, characterised by energies of up to several TeV. The recent observation of LHC neutrinos by FASERν and SND@LHC signals that this hitherto ignored particle beam is now available for scientific inquiry. Here we quantify the impact that neutrino deep-inelastic scattering (DIS) measurements at the LHC would have on the parton distributions (PDFs) of protons and heavy nuclei. We generate projections for DIS structure functions for FASERν and SND@LHC at Run III, as well as for the FASERν2, AdvSND, and FLArE experiments to be hosted at the proposed Forward Physics Facility (FPF) operating concurrently with the High-Luminosity LHC (HL-LHC). We determine that up to one million electron- and muon-neutrino DIS interactions within detector acceptance can be expected by the end of the HL-LHC, covering a kinematic region in x and Q^2 overlapping with that of the Electron-Ion Collider. Including these DIS projections into global (n)PDF analyses, specifically PDF4LHC21, NNPDF4.0, and EPPS21, reveals a significant reduction of PDF uncertainties, in particular for strangeness and the up and down valence PDFs. We show that LHC neutrino data enables improved theoretical predictions for core processes at the HL-LHC, such as Higgs and weak gauge boson production. Our analysis demonstrates that exploiting the LHC neutrino beam effectively provides CERN with a "Neutrino-Ion Collider" without requiring modifications in its accelerator infrastructure.

1

2309.09581

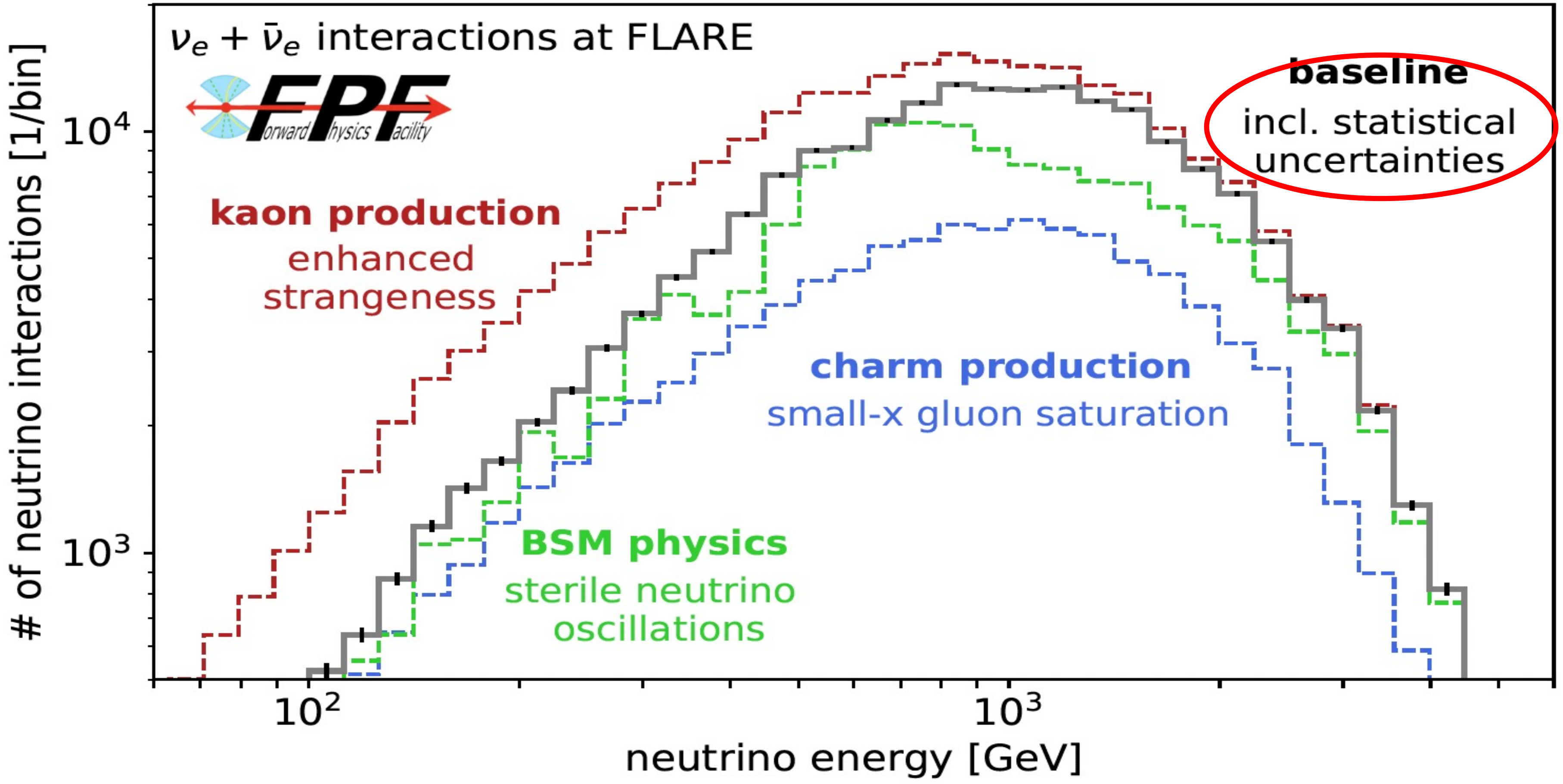


The FPF Neutrino Programme

J. Phys. G 50 (2023) 030501, 1-410

- FPF experiments FLArE, FASERν2, and AdvSND will see $10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ interactions at ~TeV energies.

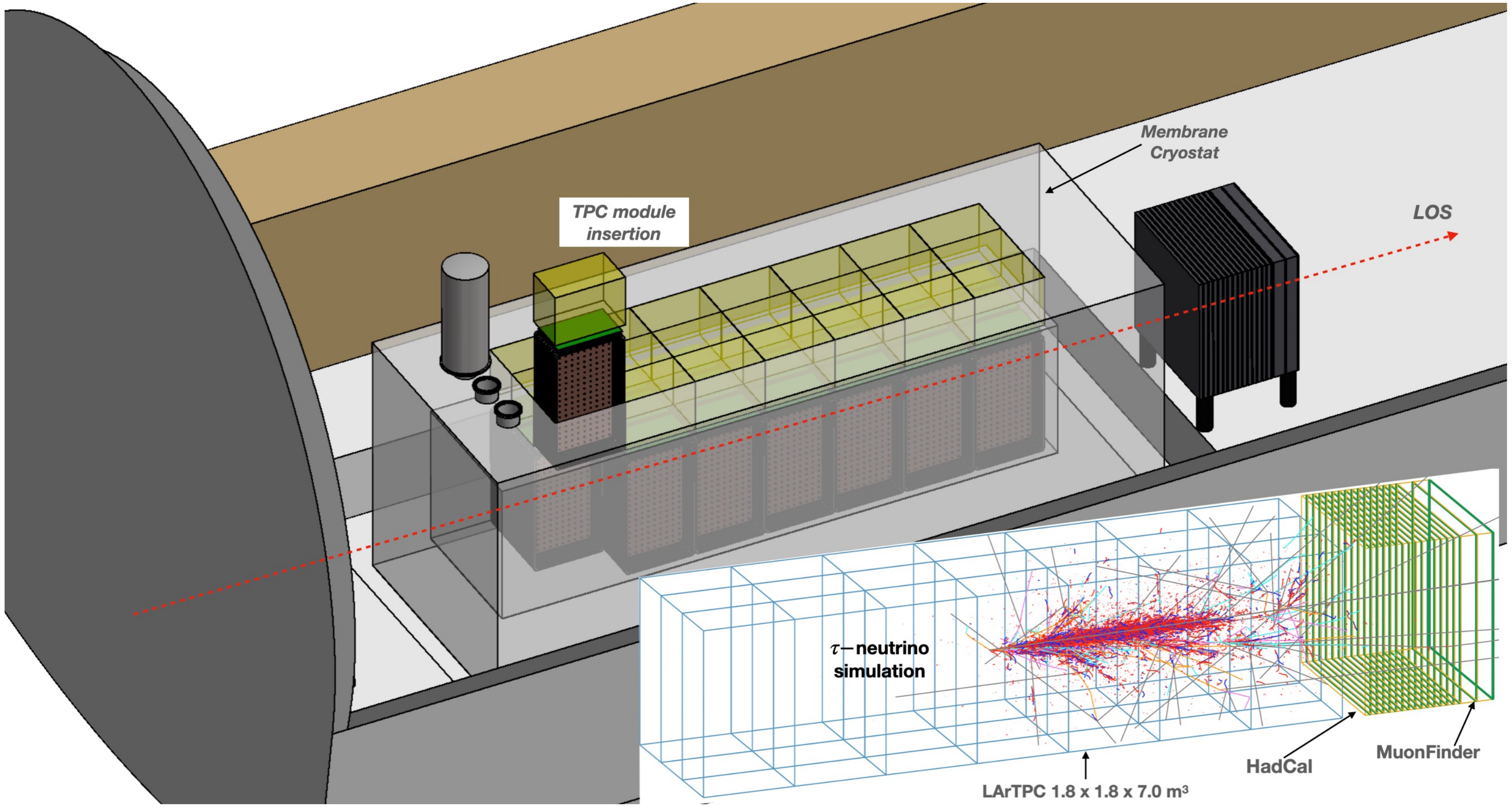
- Implications for
  - neutrino properties
  - QCD ($x \sim 10^{-7} - 0.1$, DIS)
  - astroparticle physics



FLArE

- On-axis LArTPC neutrino and light DM detector
- 1.8 m x 1.8 m x 7 m, ~10 ton LAr mass

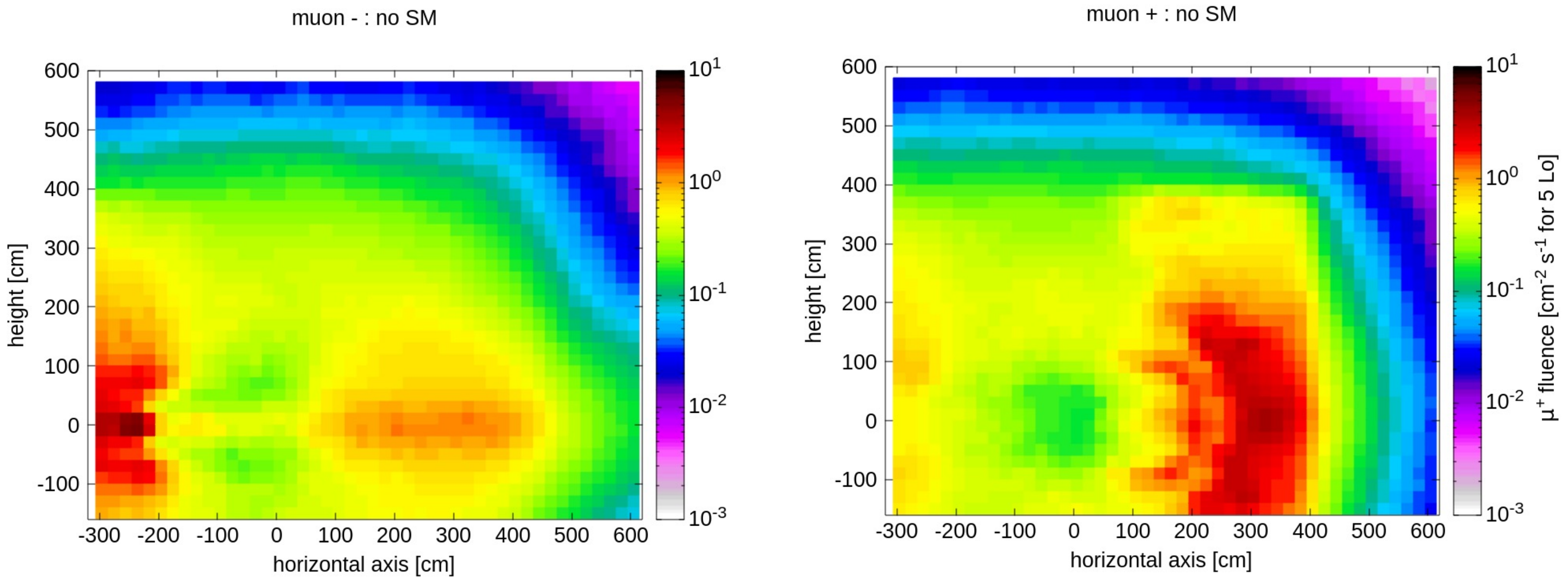
	Value	Remarks
LAr detector fiducial mass	>10 tons	
Active dimensions	1.8 m $\times$ 1.8 m $\times$ 7 m	not including cryostat
Cryostat dimensions	3.5 m $\times$ 3.5 m $\times$ 9.6 m	membrane type
TPC modules/drift length	3 $\times$ 7 (gap: $\sim$30 cm)	short gap TPC
TPC height	1.8 m	
Spatial resolution	<1 mm	in drift and tranverse dimension
Charge readout	pixels	pixel/wire hybrid approach possible
Trigger and light readout	SiPMs/WLS-plates	needed for neutrino trigger and time
Background muon rate	$\sim 1/\text{cm}^2/\text{s}$	at luminosity $5 \times 10^{34}/\text{cm}^2/\text{s}$
Neutrino event rate	$\sim 50/\text{ton/fb}^{-1}$	for all flavors of neutrinos
Hadronic calorimeter (hadmu)	$\sim 6 - 10\lambda$	interactions lengths
Dimensions	1.8 m $\times$ 1.8 m $\times$ 1.05 m (depth)	Fe/scint sandwich
Muon tagger and momentum	1 Tesla magnetized Fe/scint	same as the hadmu



FLArE with simulated 500 GeV tau neutrino

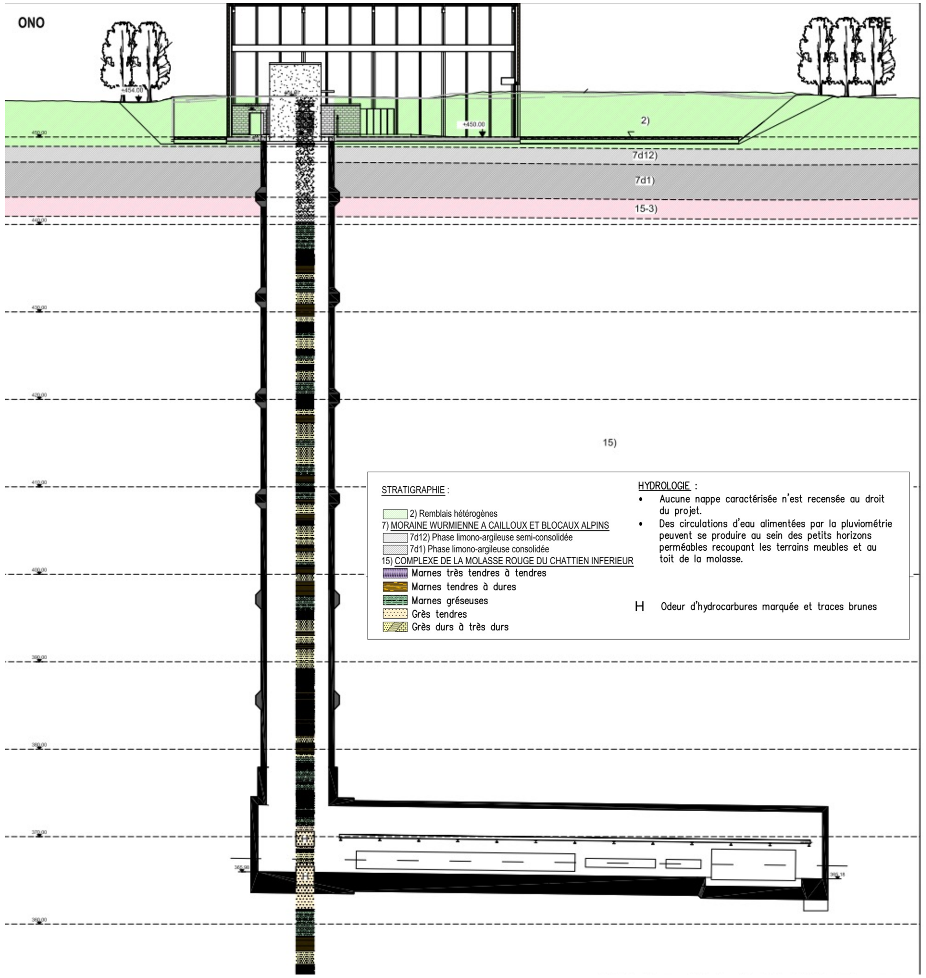
Muon Flux at the FPF

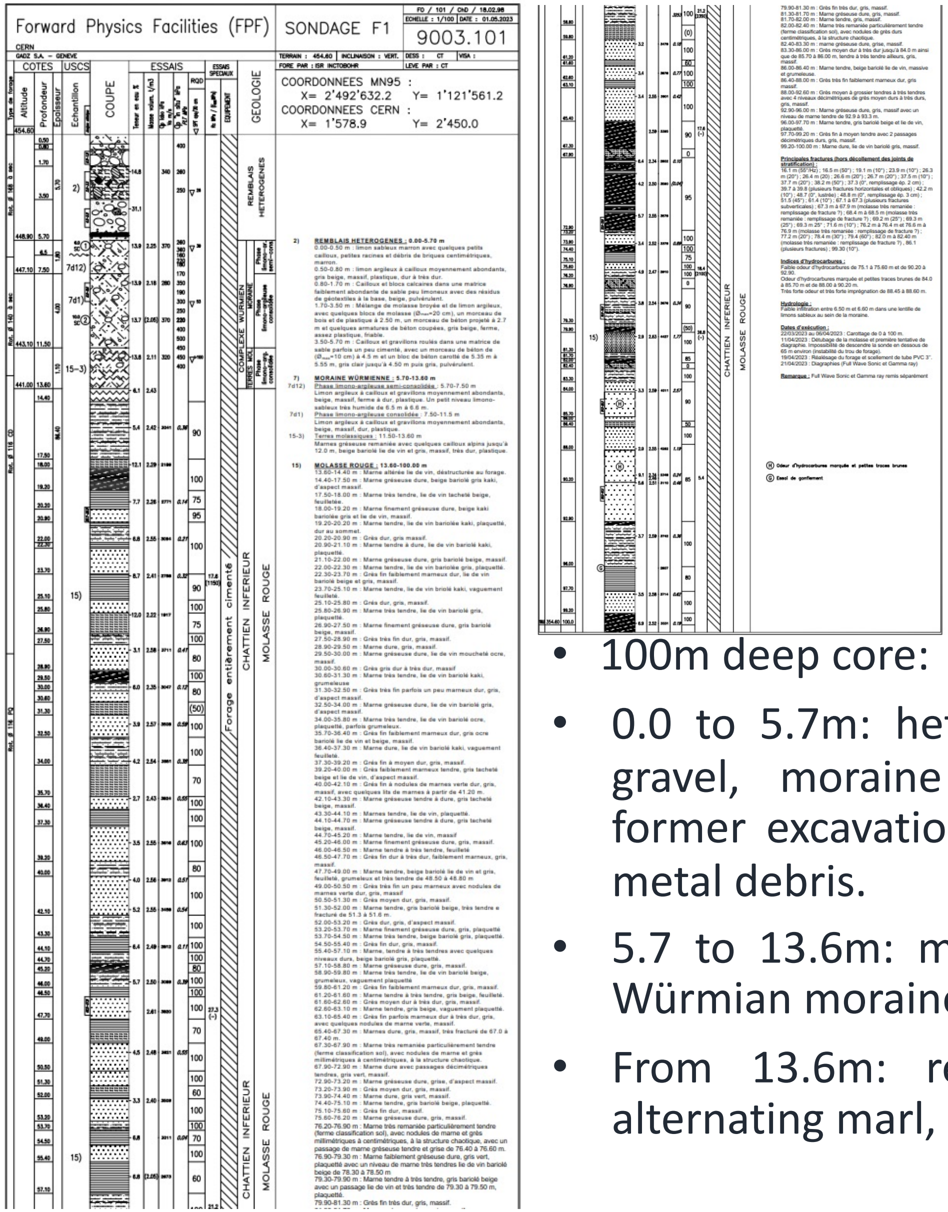
- Muons from ATLAS IP are the main background for most FPF signals.
- FLUKA results for the LHC have been validated to ~30% in Run 3 by FASER and SND@LHC.
- FLUKA results for the HL-LHC are 0.6 Hz/cm^2 at LOS, much larger at some locations ~1 m from the LOS; easy to veto for most FPF signals.



FPF Site Investigation Works

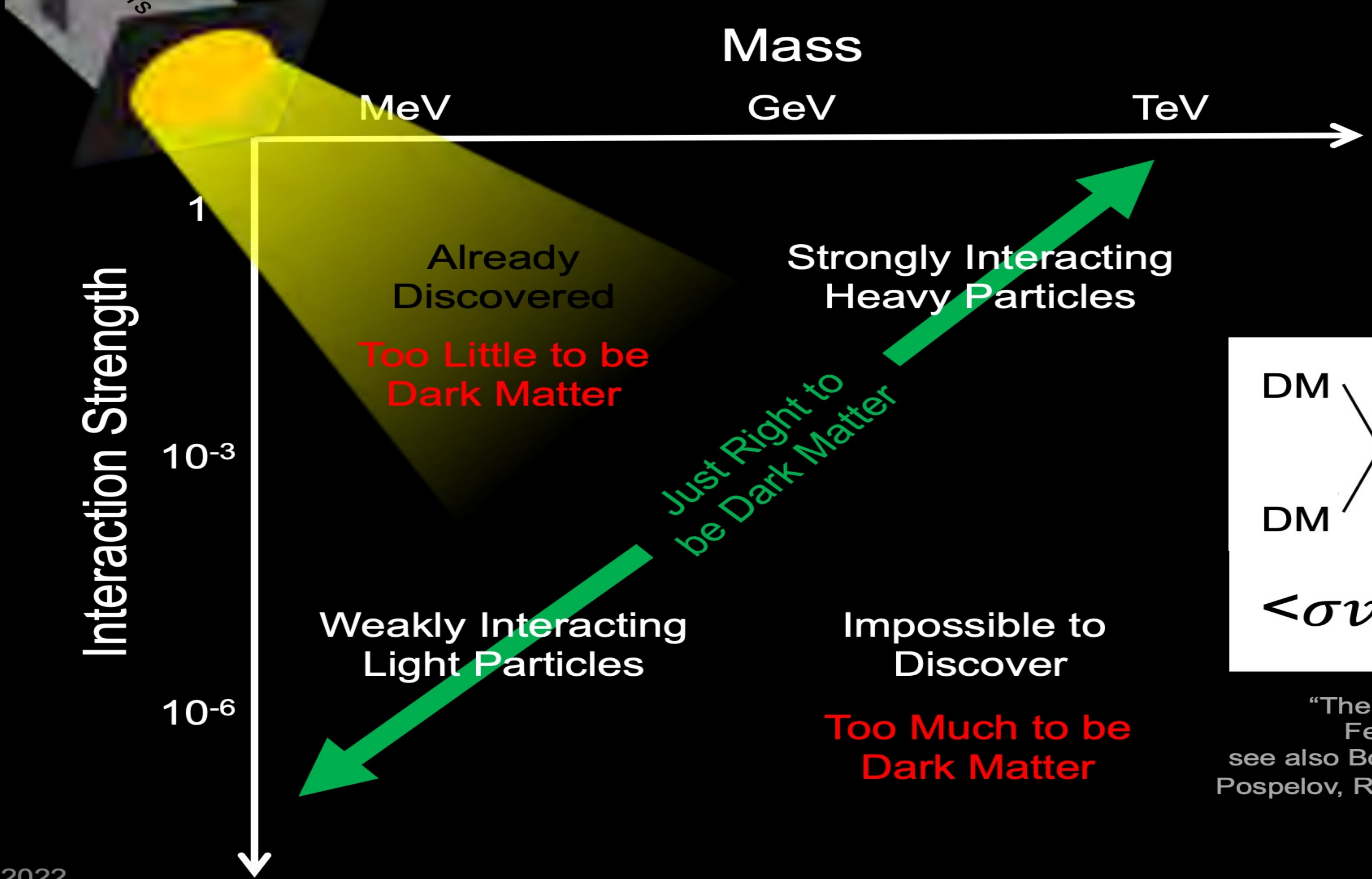
First results

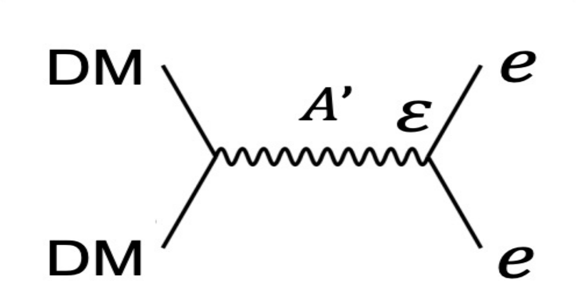




- 100m deep core:
- 0.0 to 5.7m: heterogeneous fill comprising gravel, moraine and molasse rock from former excavations, as well as concrete and metal debris.
- 5.7 to 13.6m: mainly consolidated silty-clay Würmian moraine.
- From 13.6m: red molasse, consisting of alternating marl, sandstone and sandy marl.

THE THERMAL RELIC LANDSCAPE

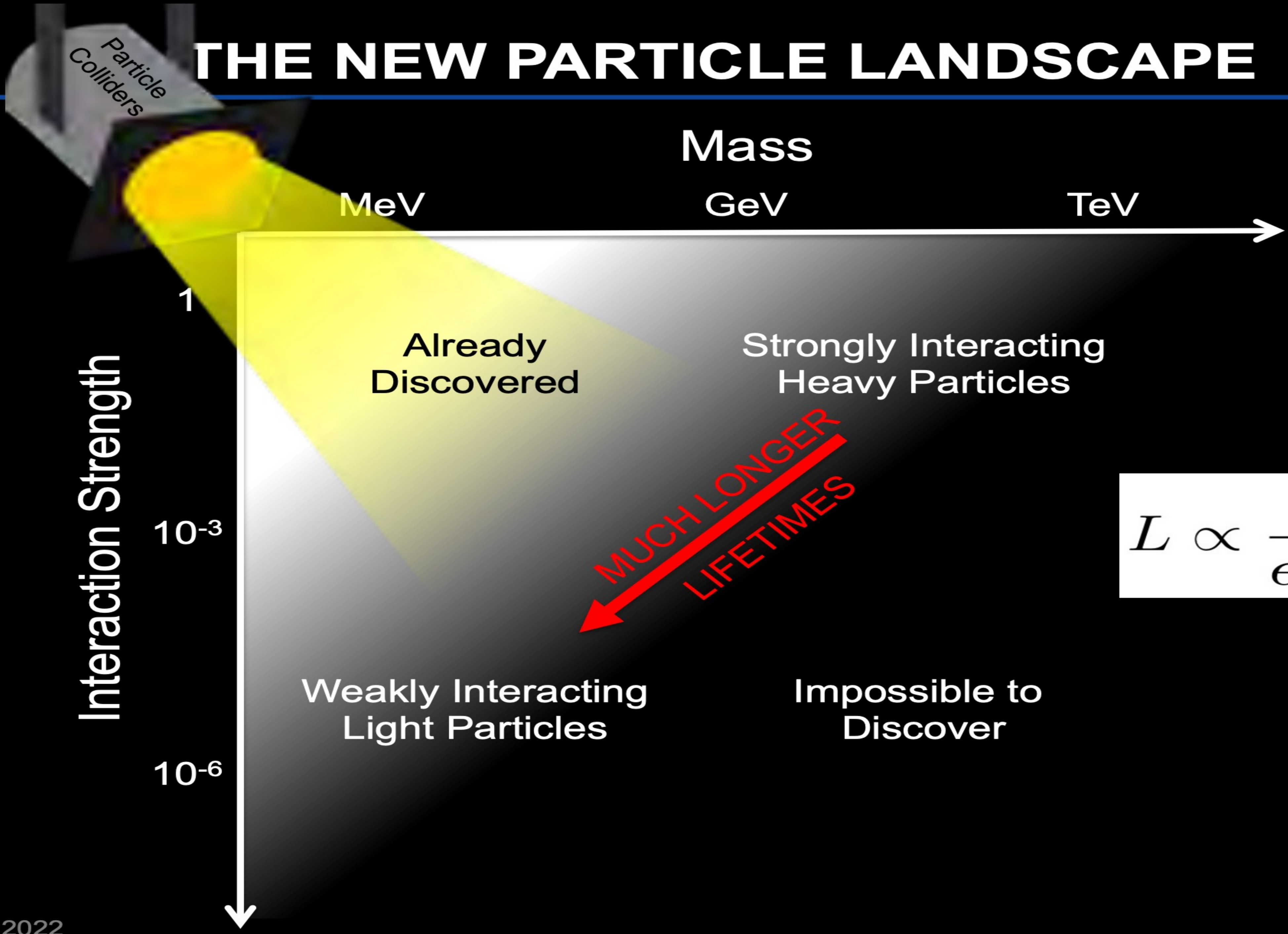




$$<\sigma v> \sim \frac{\varepsilon^2}{m_{A'}^2}$$

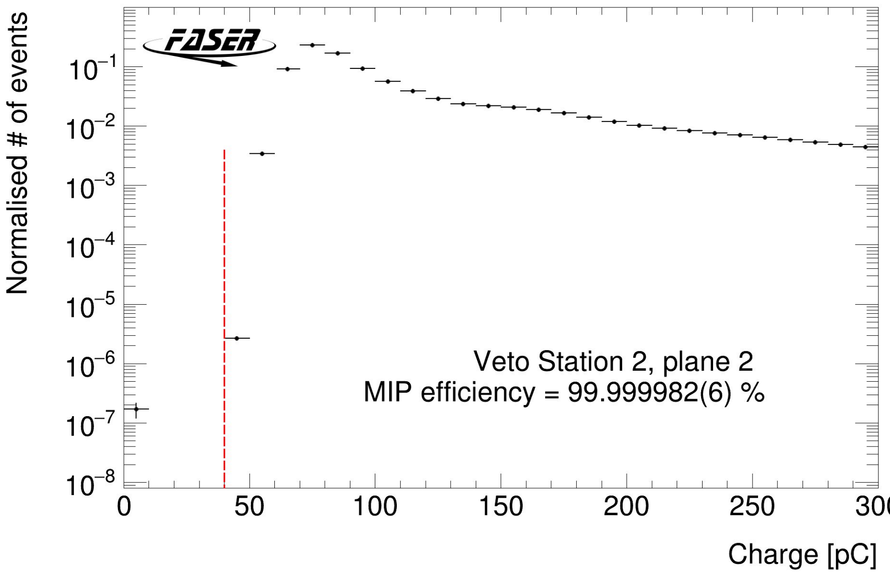
"The WIMPless Miracle"
Feng, Kumar (2008);
see also Boehm, Fayet (2003)
Pospelov, Ritz, Voloshin (2007)

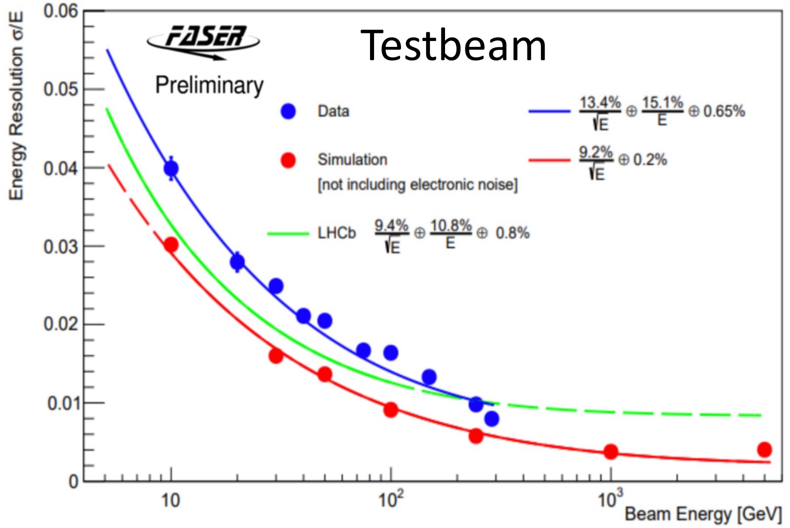
THE NEW PARTICLE LANDSCAPE

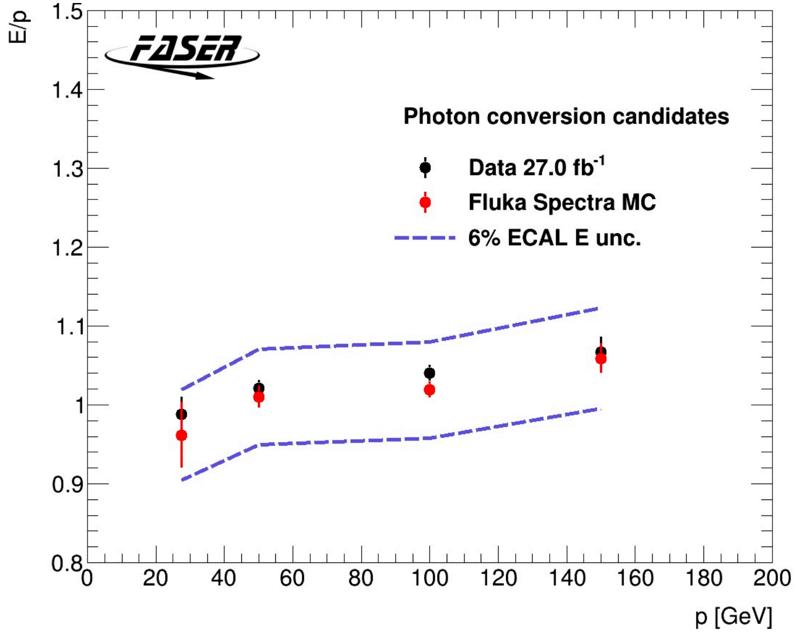


$$L \propto \frac{1}{\epsilon^2 m^2}$$

Scintillator/Calorimeter Performance

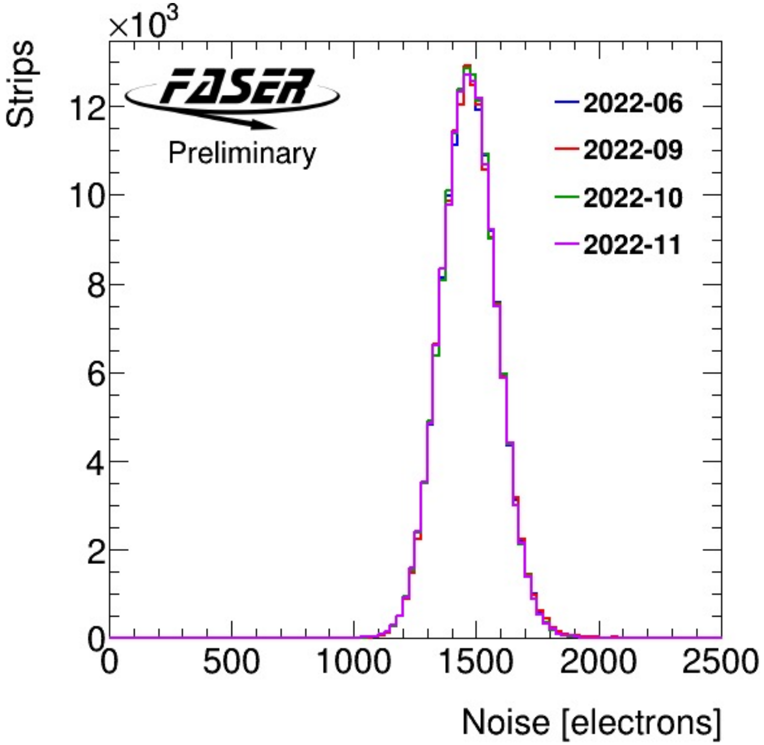


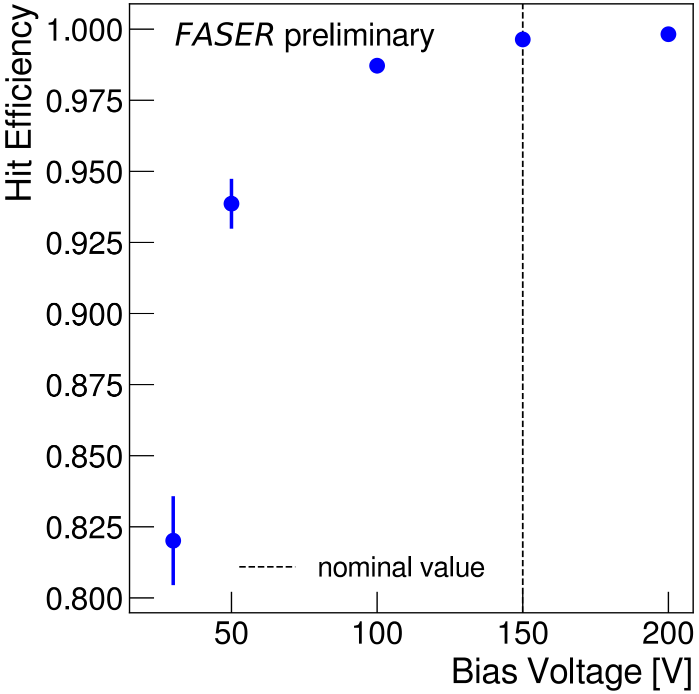


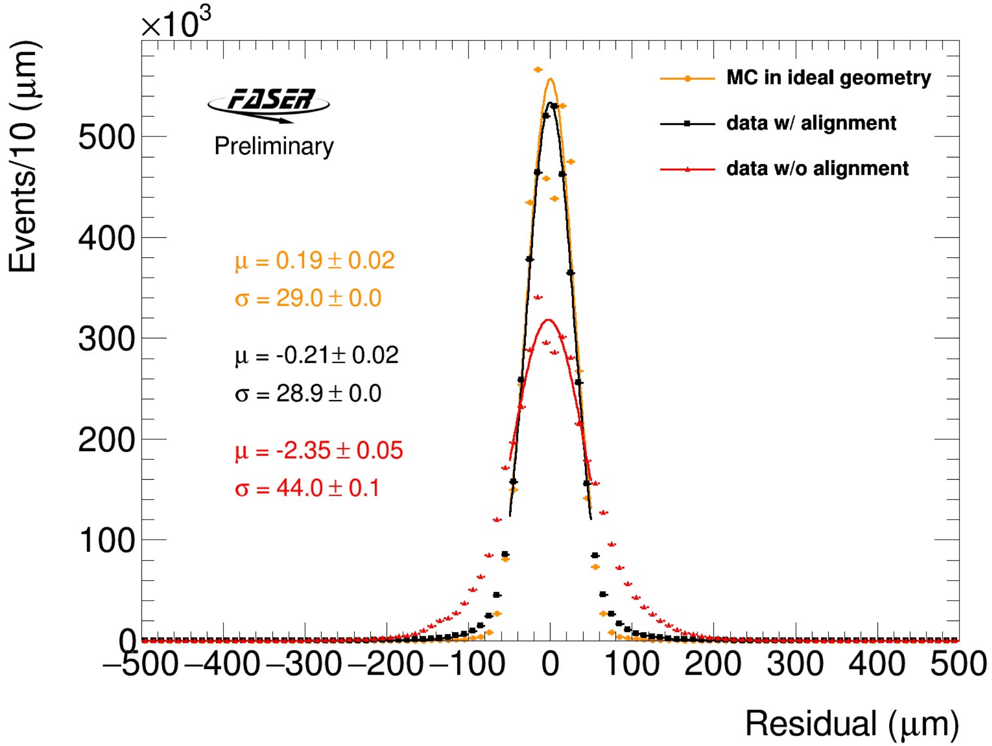


- 5 veto scintillators plane. Per plane inefficiency measured with data to be $\mathcal{O}(10^{-5})$
- Calorimeter energy resolution measured to be ~1% for high energy electrons in SPS testbeam
- Calorimeter energy scale uncertainty of 6% derived from testbeam. Checked using E/p in collision data photon conversion events

Tracker Performance



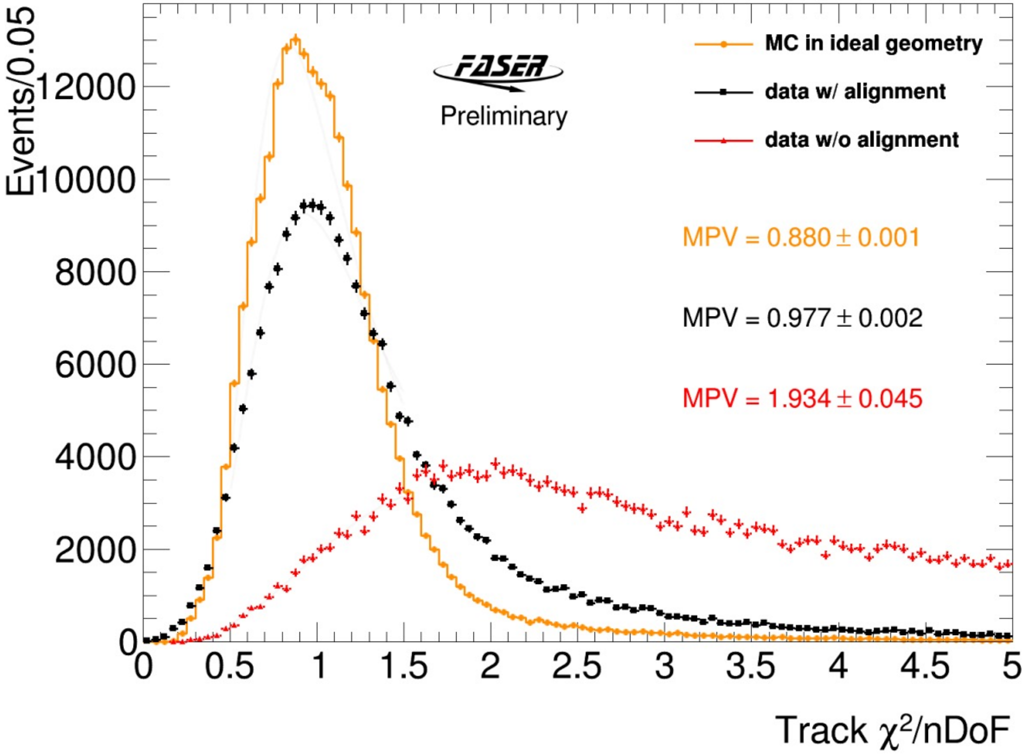


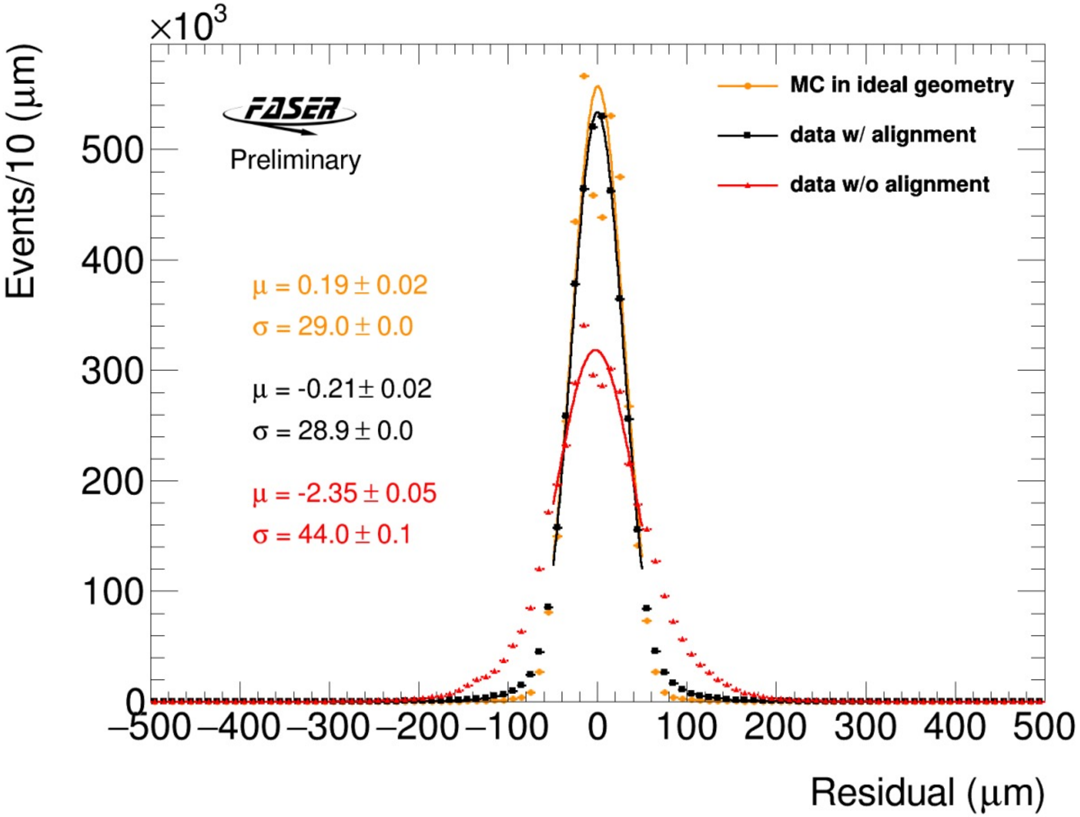


- Noise measured in regular calibrations, stable versus time. Corresponds to noise occupancy <5x10^{-4}
- <0.5% bad channels
- High hit efficiency 99.6+/-0.1% at nominal bias voltage of 150V
- Unbiased track hit residuals of <30µm in precision coordinate after first detector alignment

Tracker Alignment

Current tracker alignment of 2 most sensitive degrees of freedom at module level:





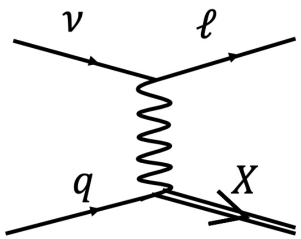
Work ongoing to improve alignment with 6 DOF.

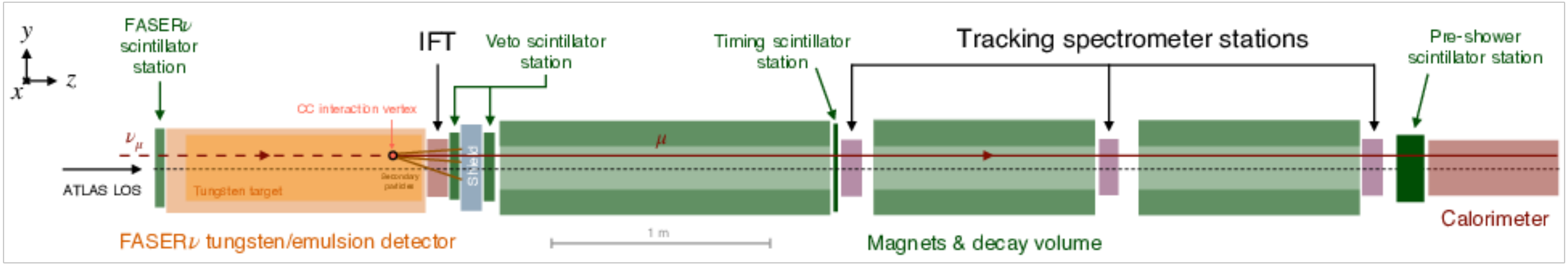
Observation of collider neutrinos

Phys. Rev. Lett. 131 no. 3, (2023) 031801

A huge number of high energy neutrinos traverse the FASER location.
Allows to detect neutrino interactions at a collider for the first time, using the electronic detector components (not using the FASERν emulsion, which has a slower data processing workflow).

Search for events with no signal in veto scintillators in front of FASERν, and a reconstructed track with p>100GeV (extrapolated track must pass through central region of front veto's).
Topology consistent with a ν_μ charged current interaction in 1.1tonne FASERν tungsten target.
Expect 151+/-40 neutrino interactions to pass the events selection
(error envelope from generators SIBYLL/DPMJET – no experimental uncertainties included)





Phys. Rev. Lett. 131 no. 3, (2023) 031801

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Expect 151+/-40 neutrino interactions to pass the events selection
(error envelope from generators SIBYLL/DPMJET – no experimental uncertainties included)

Background studied from:

- Veto inefficiency
    - measured in situ
- Neutral hadrons from upstream muon interactions
    - estimated using high statistics MC samples
- Muon passing veto and scattering to pass analysis selection
    - estimated using data control regions, extrapolated to signal region using MC

Total background estimate 0.2+/-1.8 events

Phys. Rev. Lett. 131 no. 3, (2023) 031801

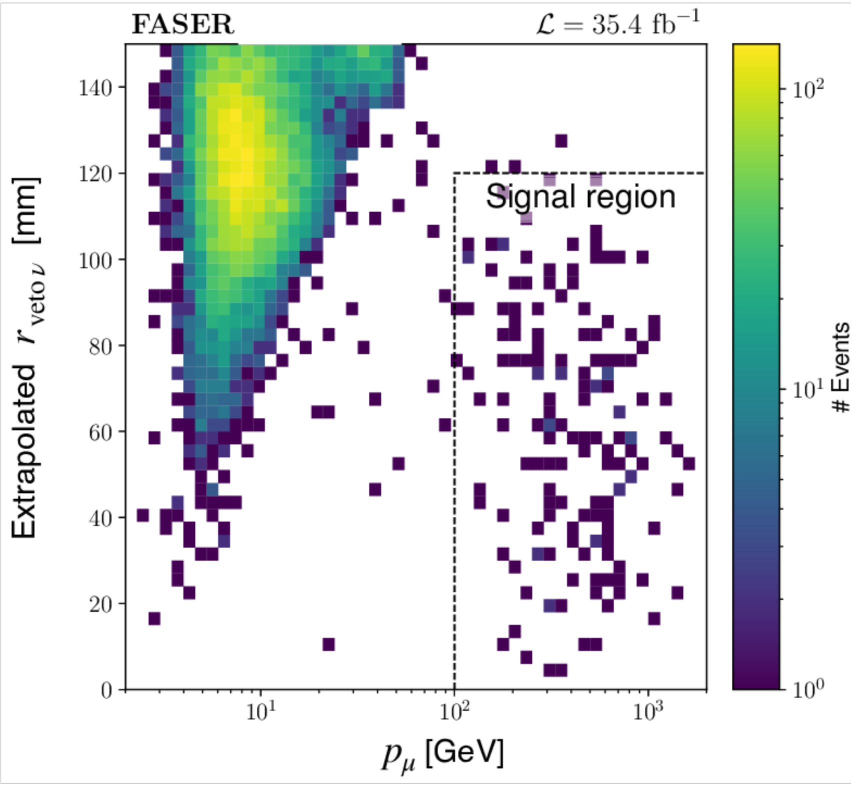
Observation of collider neutrinos

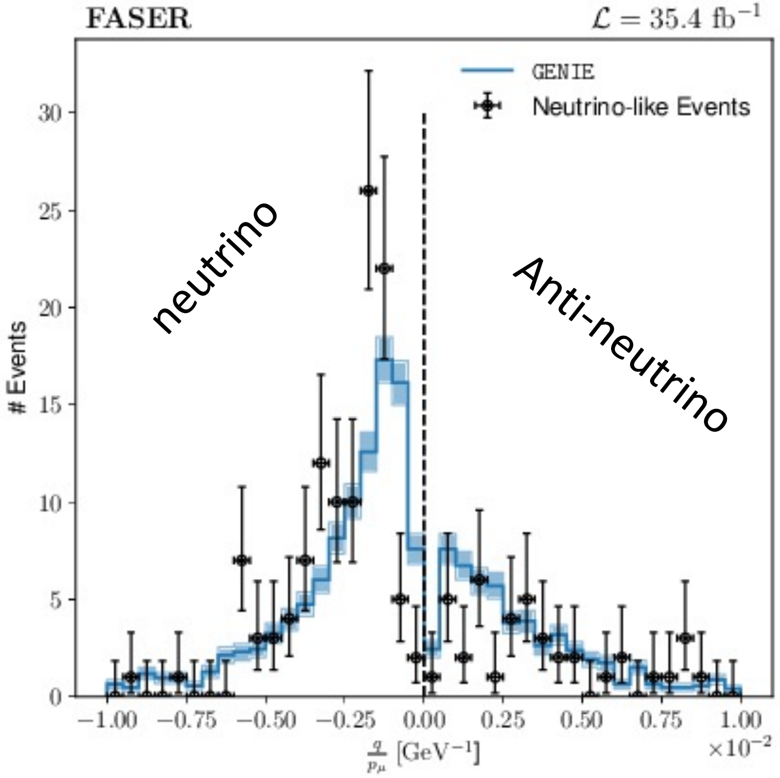
After unblinding, observe 153 neutrino candidates (statistical significance ~16sigma)

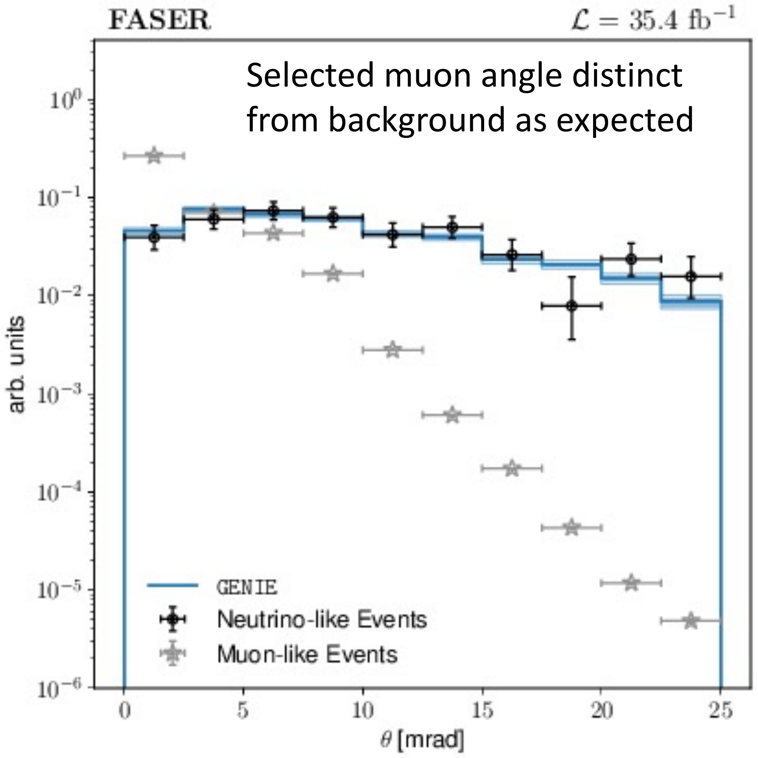
First direct observation of collider neutrinos.

Characterization of candidates consisent with expectation:

- Observe both neutrino/anti-neutrinos with rates consistent with expectation,
- Selected neutrinos are of high energy (>200GeV)







In above plots experimental systematic uncertainties are not included on the GENIE MC histograms

Observation of collider neutrinos

Phys. Rev. Lett. 131 no. 3, (2023) 031801

Final analysis presented at Moriond 2023

Paper Timeline:
Submitted: 24 March 2023
Accepted: 8 May 2023
Published: 19 July 2023

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First Direct Observation of Collider Neutrinos with FASER at the LHC

Henso Abreu *et al.* (FASER Collaboration)
Phys. Rev. Lett. **131**, 031801 – Published 19 July 2023

Physics See Viewpoint: The Dawn of Collider Neutrino Physics

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of $35.4\,\mathrm{fb}^{-1}$ using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

Accompanied by nice APS Viewpoint article
https://physics.aps.org/articles/v16/113

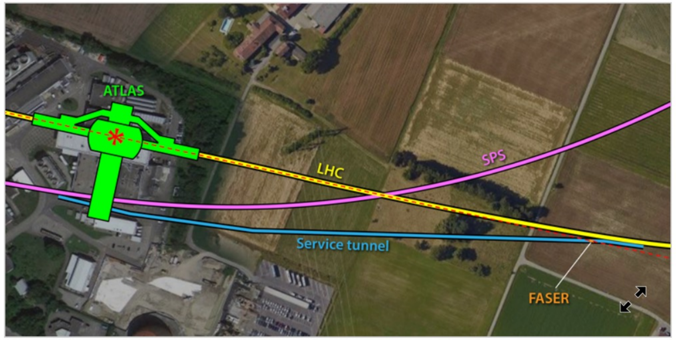
VIEWPOINT

The Dawn of Collider Neutrino Physics

Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



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

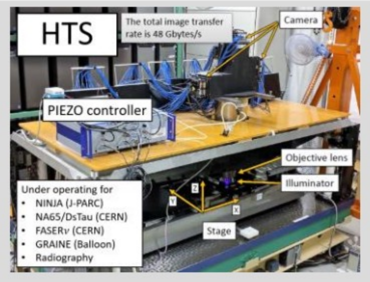
Figure 1: The Forward Search Experiment (FASER) is installed in a service tunnel that connects the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS). Proton collisions at the ATLAS experiment's interaction point (red star) generate beams of ne... **Show more**

Neutrinos are among the most abundant particles in the Universe, but they rarely interact with matter: trillions pass through us every second, but most of us will never have even a single one interact with the matter in our bodies. Nonetheless, scientists can study these particles using high-intensity neutrino sources and detectors that are large enough to overcome the rarity of neutrino interactions. In this way, neutrinos have been observed from the Sun, FASERν

Workflow





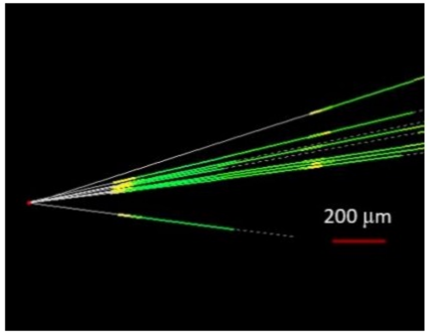


In Japan: **Emulsion film production** → **At CERN**: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → **In Japan**: **Full area readout**

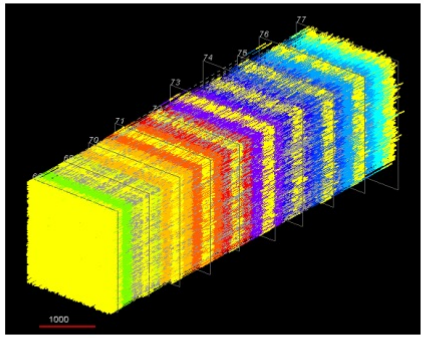
Off-line analysis: Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

Interface tracker data

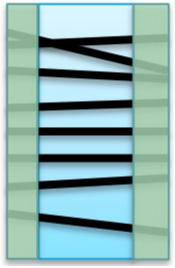
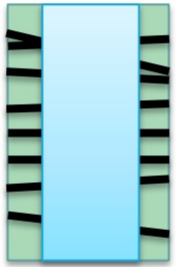
Spectrometer data



500-1000 TB/Run3



~500 TB/Run3

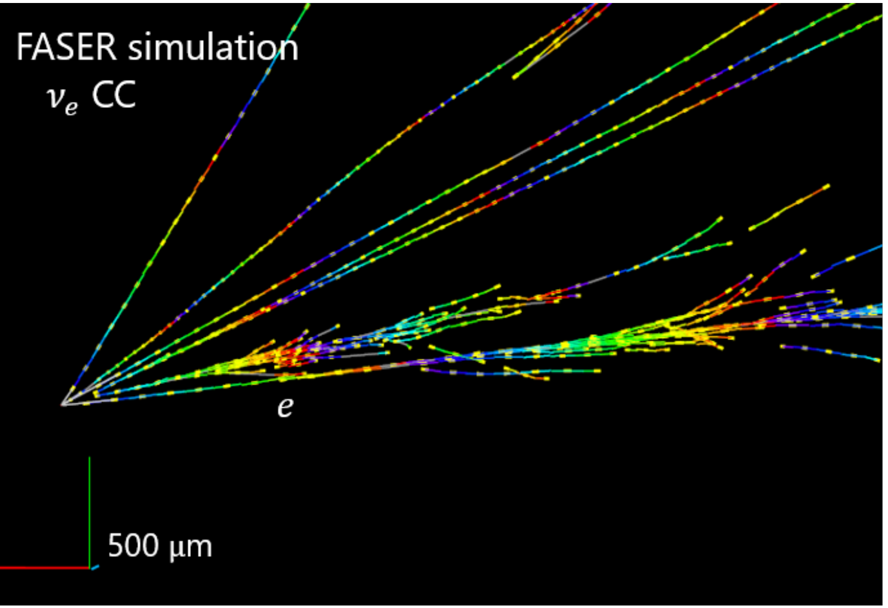



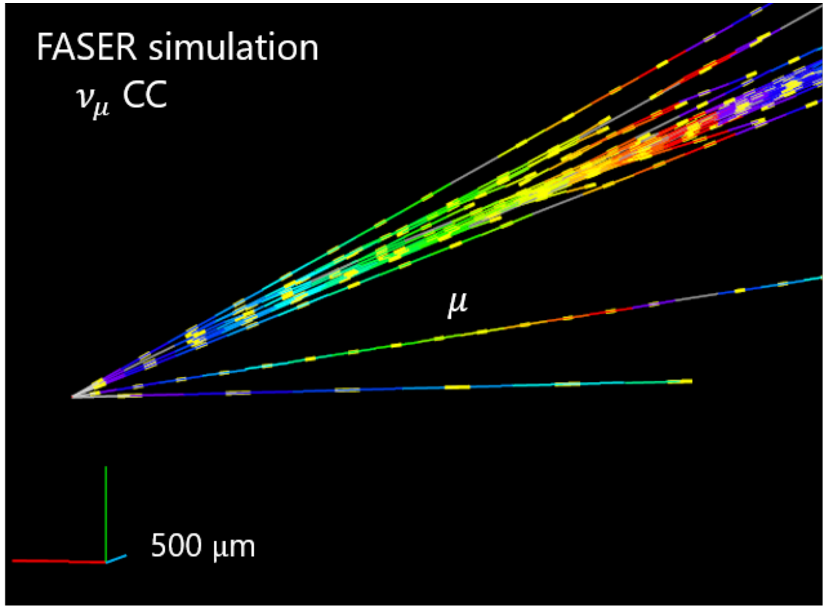
FASERν expected signal rate

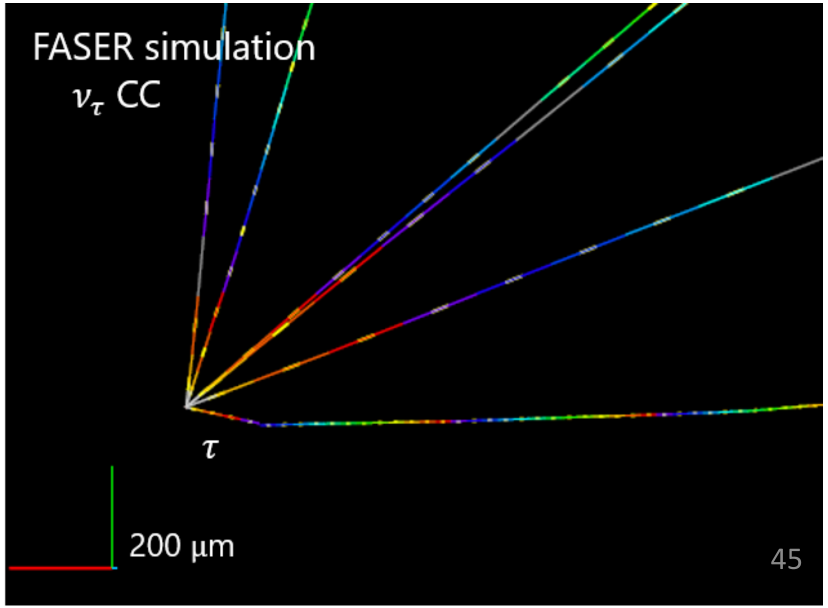
Based on
F. Kling and L. J. Nevay,
"Forward Neutrino Fluxes at the LHC",
Phys. Rev. D 104, 113008

Expected number of CC interactions (250 fb^{-1})

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$

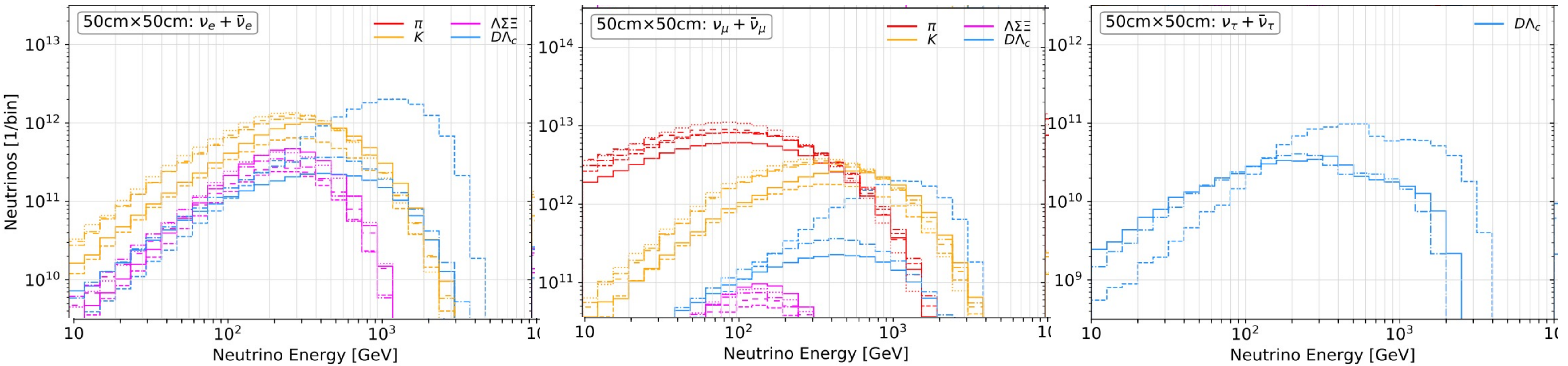






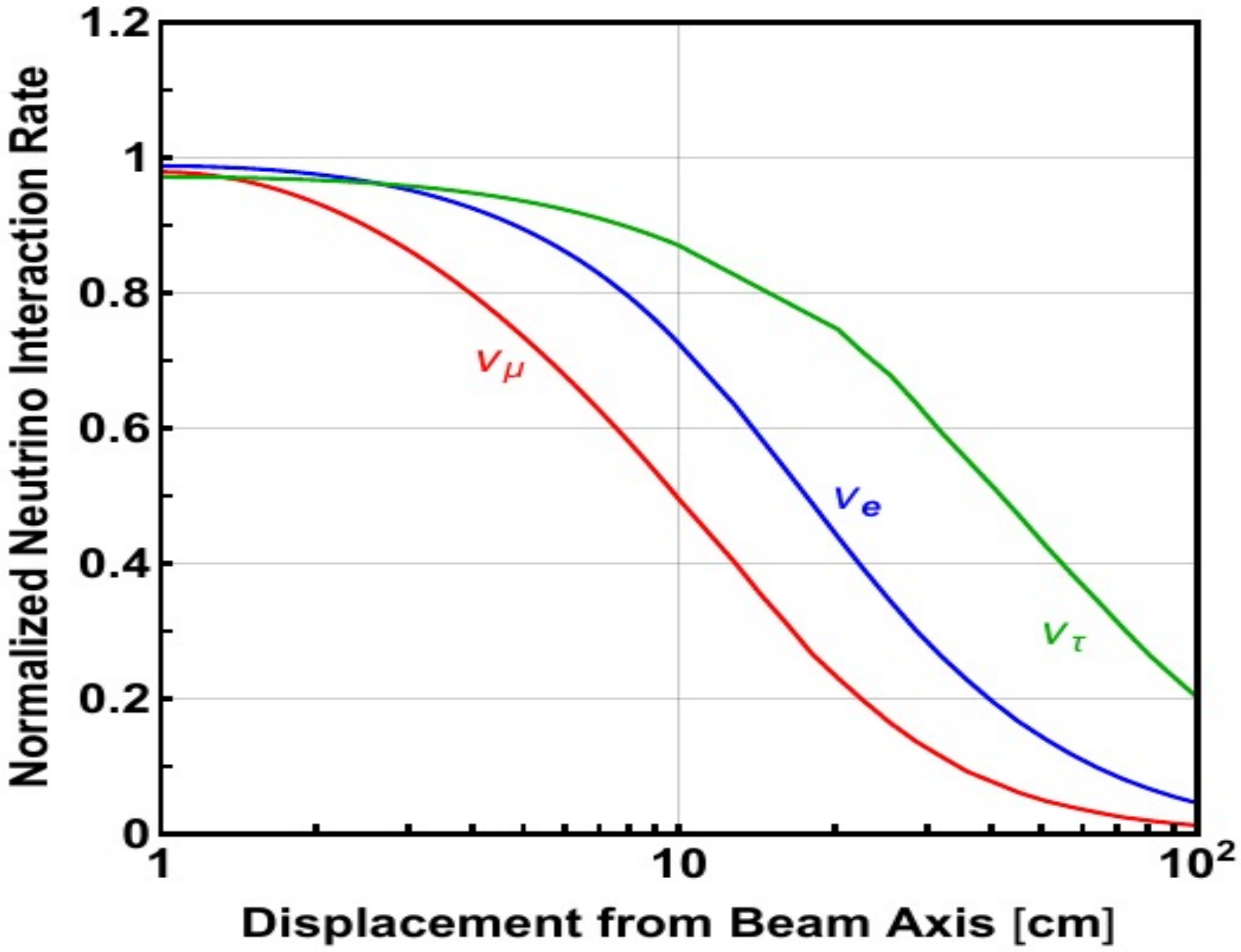
Neutrino production at LHC

- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \rightarrow \nu\mu$, K → ν_e (at high-energy/off-axis D → ν_e), D → $\nu\tau$



Large differences between generators on rate of forward hadron production, especially for charm:
SIBYLL 2.3d (solid), DPMJet 3.2017 (short dashed), EPOS-LHC (long dashed), QGSJet II-04(dotted), and Pythia 8.2 (dot-dashed)

Neutrino production at LHC

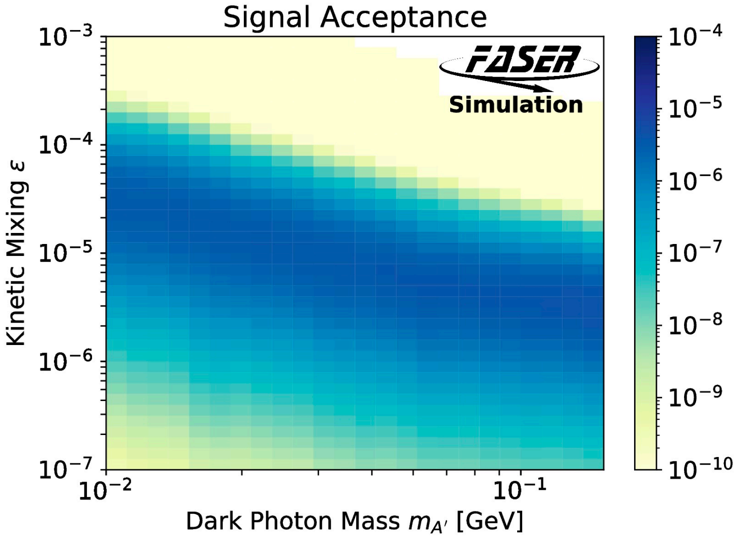


Neutrino flux for all flavours maximized on the collision axis line of sight.

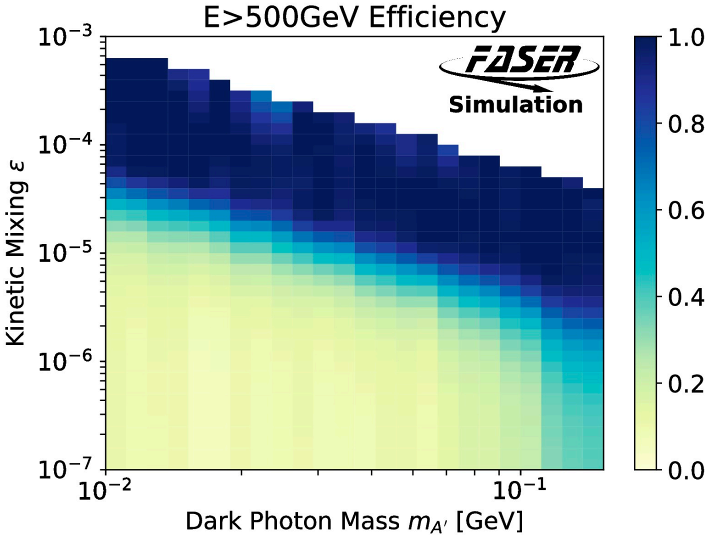
- Muon neutrinos (mostly from pion decay) are very collimated (~50% flux 10cm from LOS)
- Electrons neutrinos (mostluy from kaon decay) are more spread out (~50% at 20cm)
- Tau neutrinos (from charm decay) are much more spread out (~50% at 50cm)

Dark Photon Search

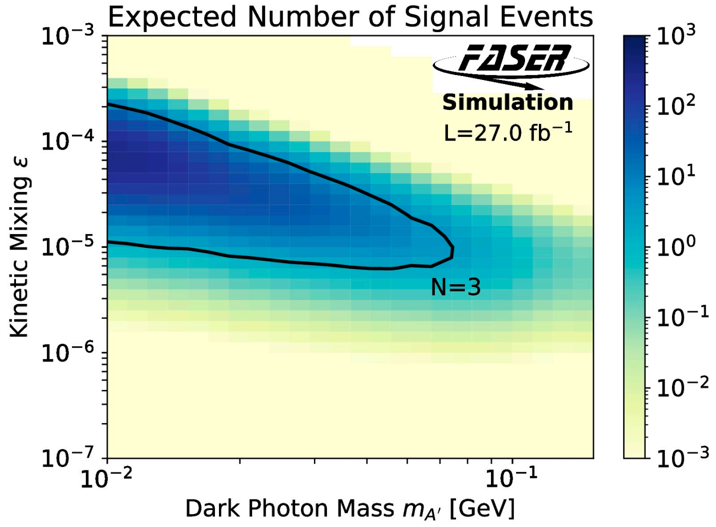
[arxiv:2308.05587](https://arxiv.org/abs/2308.05587)
(submitted to PLB)



Acceptance for dark photon to decay inside FASER

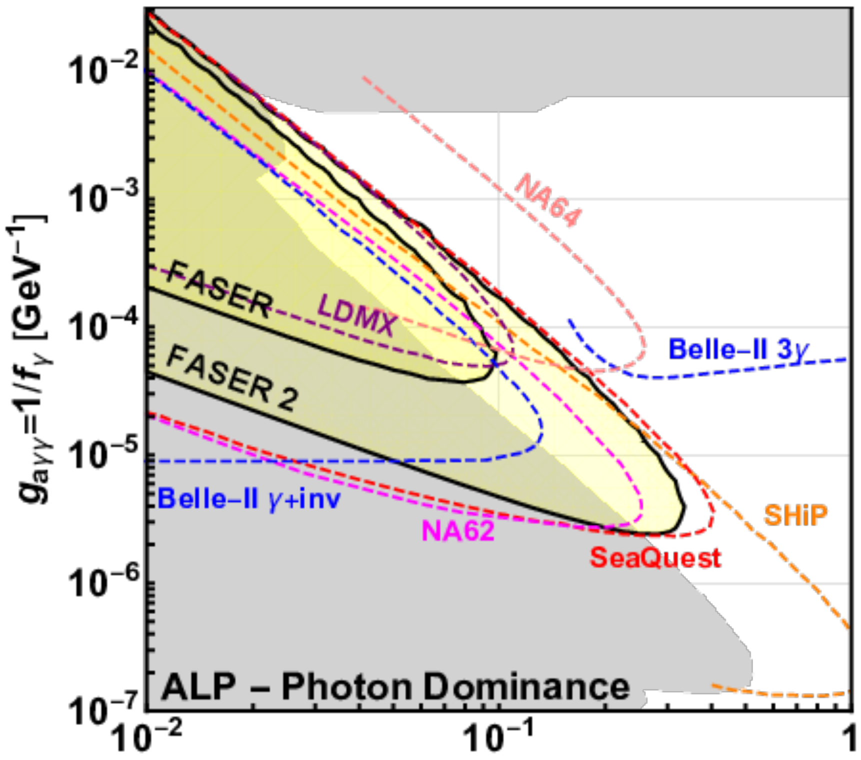


Fraction of these with E>500 GeV



Truth level expected number of signal events with E>500GeV and 50% efficiency

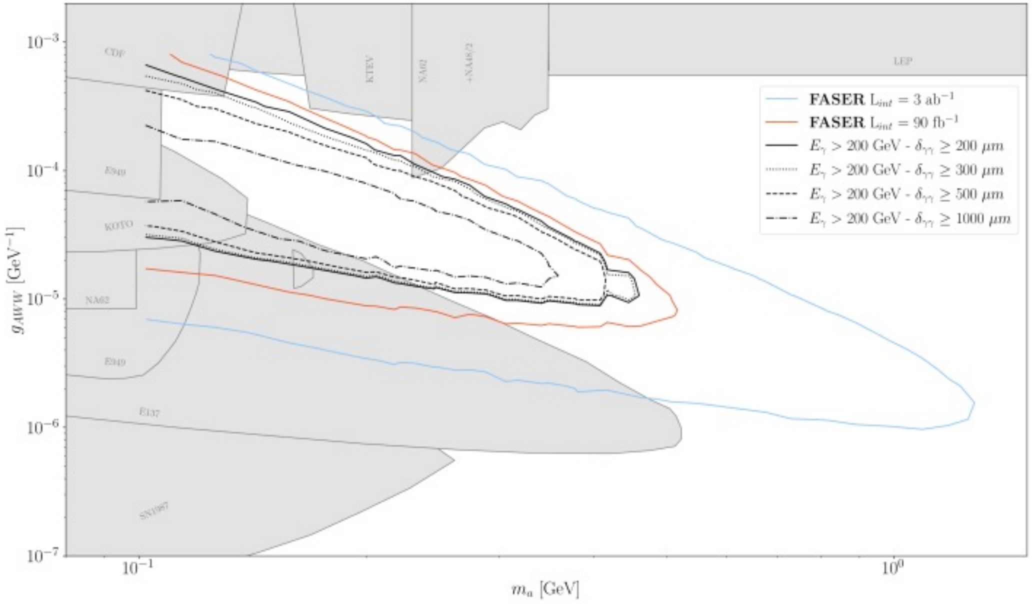
Axion Like Particles



ALPs with photon-like couplings can be produced by high energy photons in the forward direction interacting with LHC material (the TAN absorber) via the Primakof process. The ALP can then decay to 2 photons in FASER.

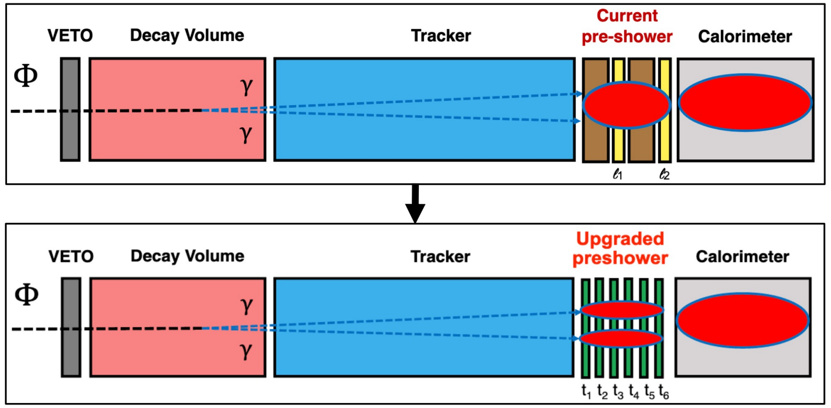
[Phys. Rev. D98 no. 5, (2018) 055021]

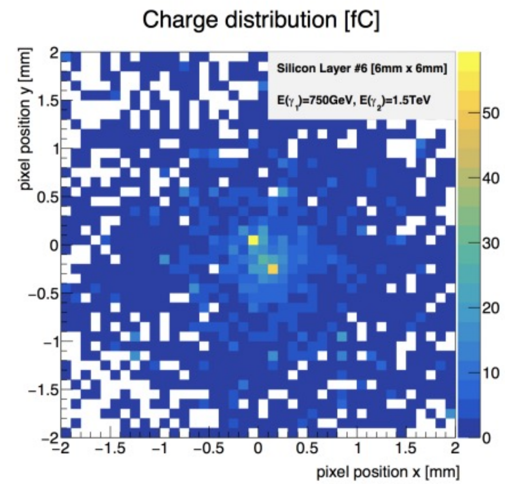
ALPs with W-like couplings can be produced in b hadron decays, and decay to 2 photons in FASER.



Experimentally we can not seperate 2 closely spaced high energy photons in the FASER calorimeter. We can still carrry out ALP searches with the current detector, but will have an irreducible background from neutrino interactions in the calorimeter.

We are planning to install a high granularity silicon/tungsten preshower which will allow to separate 2 photons separated by more than 0.2mm: [CERN-LHCC-2022-006]

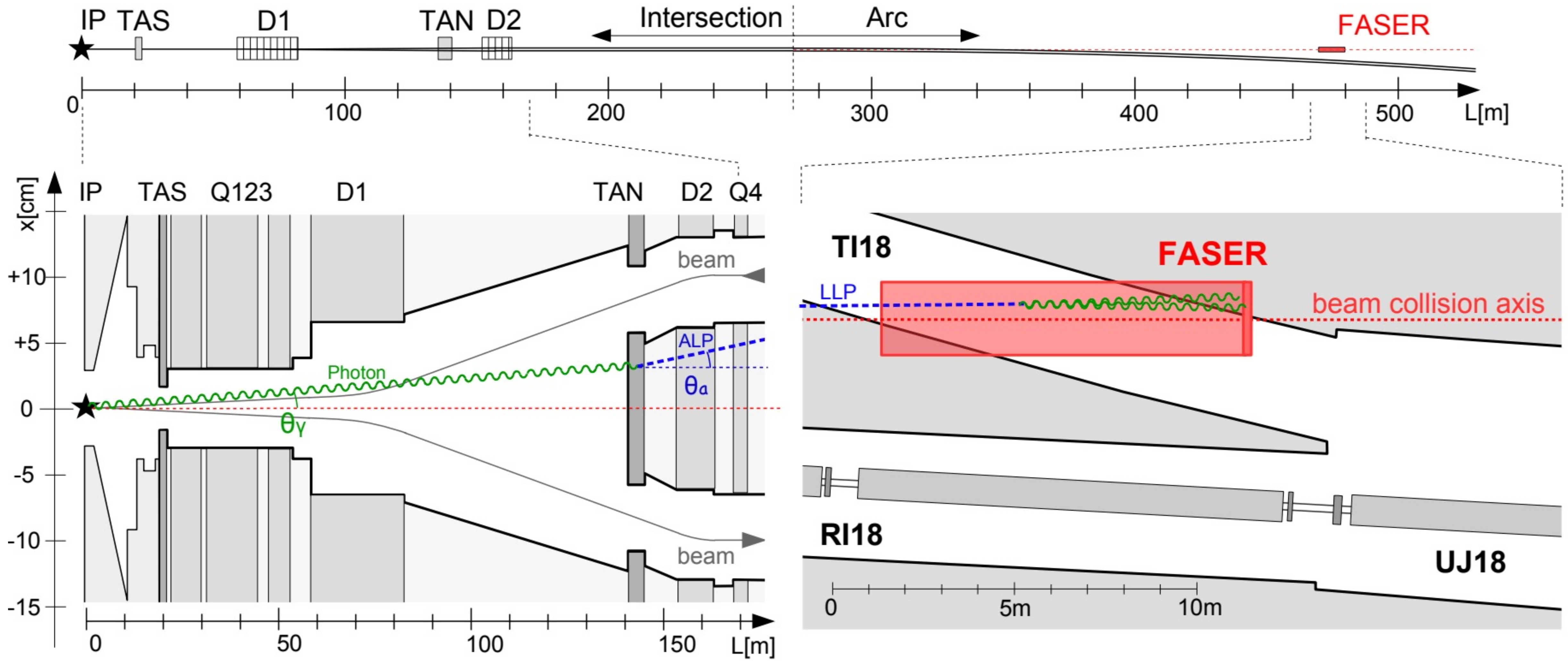




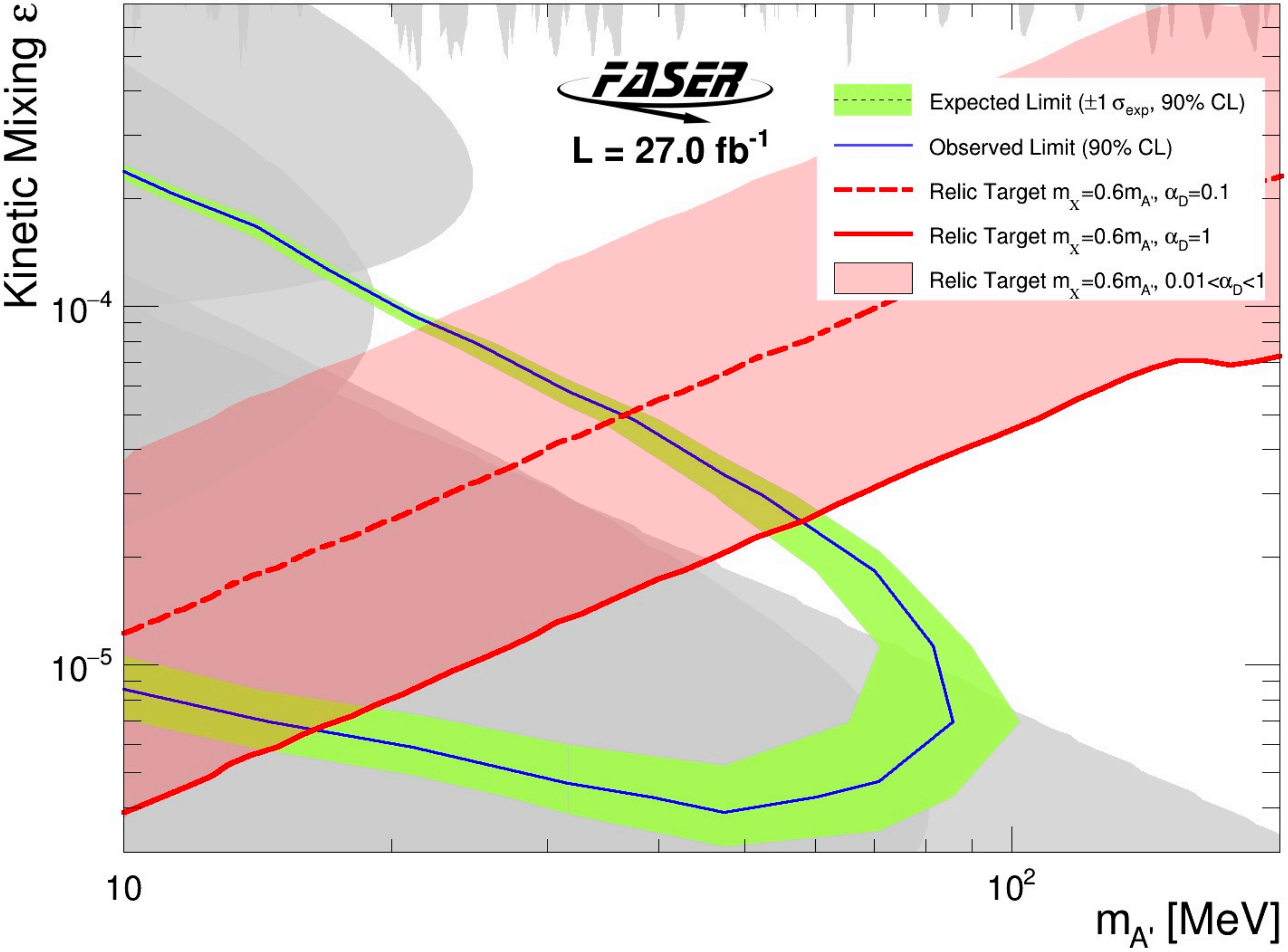
Simulation of 6th pixel layer in preshower for 2x 750 GeV photons separetd by 0.2mm

Axion Like Particles

The LHC as a Photon Beam Dump



Phys. Rev. D98 no. 5, (2018) 055021



FASER
L = 27.0 fb^{-1}
Expected Limit ($\pm1\ \sigma_{exp}$, 90% CL)
Observed Limit (90% CL)
Relic Target m_χ=0.6$m_{A'}$, α_D=0.1
Relic Target m_χ=0.6$m_{A'}$, α_D=1
Relic Target m_χ=0.6$m_{A'}$, 0.01<α_D<1
Kinetic Mixing ε
10^{-4}
10^{-5}
10
10^2
$m_{A'}$ [MeV]

Dark Photon Search

arxiv:2308.05587
(submitted to PLB)

Systematic uncertainties on expected signal yield:

Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
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% ($< 1\%$)