The FASER Experiment,

and the FPF Forward Physics Facility

Looking Forward to New Physics at the LHC and HL-LHC

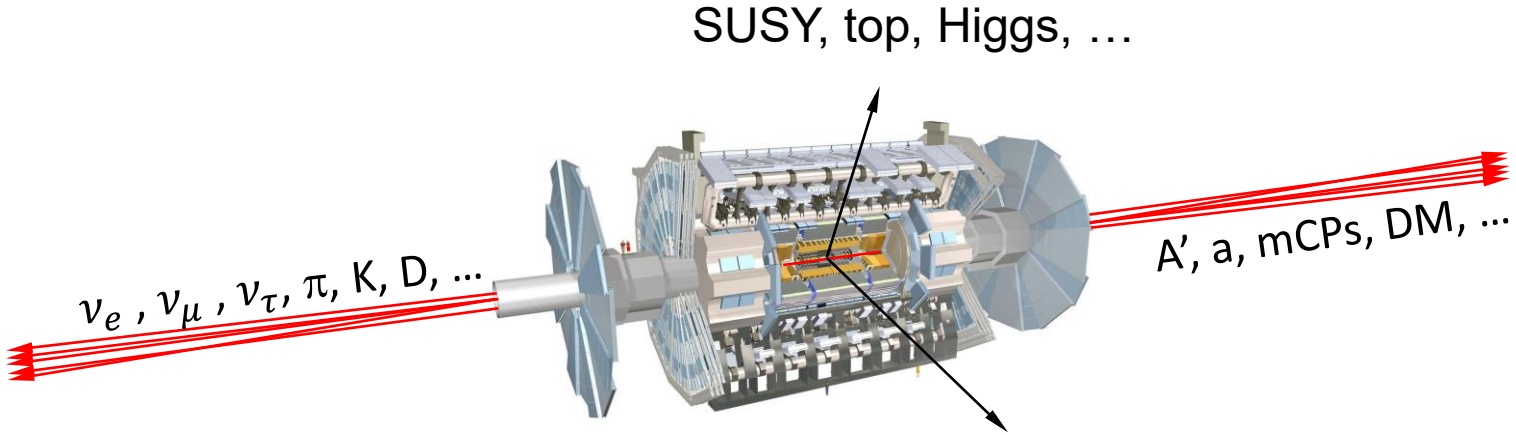
Jamie Boyd (CERN), on behalf of the FASER Collaboration

Covering:

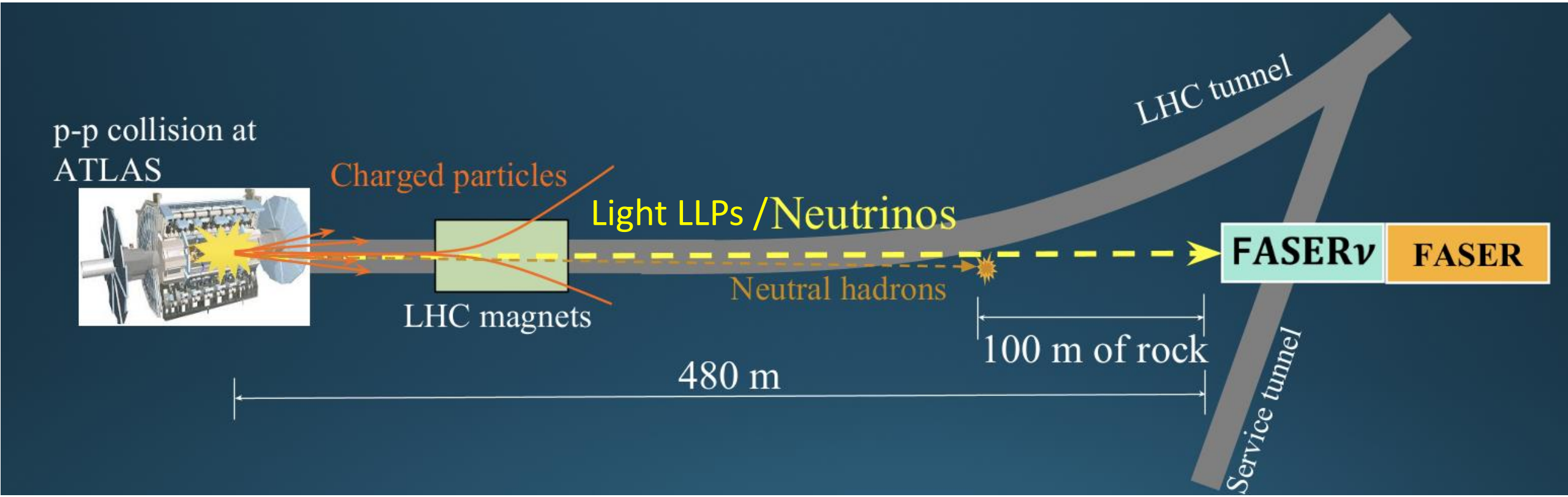
- FASER Motivation
- FASER detector design
- FASER data taking and performance studies
- FASERν neutrino programme
- Future upgrades in the FPF

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 extremely 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 (normally the domain of fixed target experiments):
  - 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)



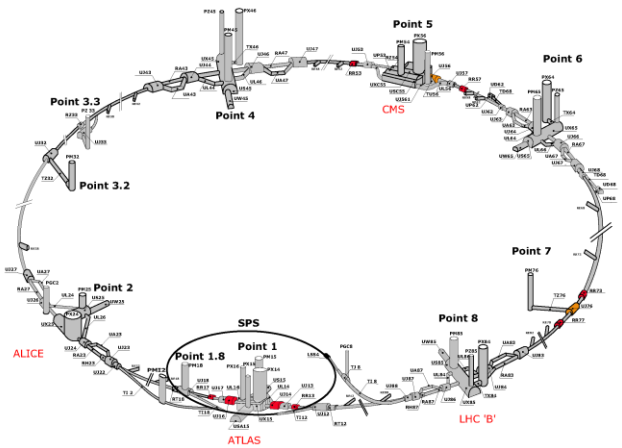
The FASER Experiment

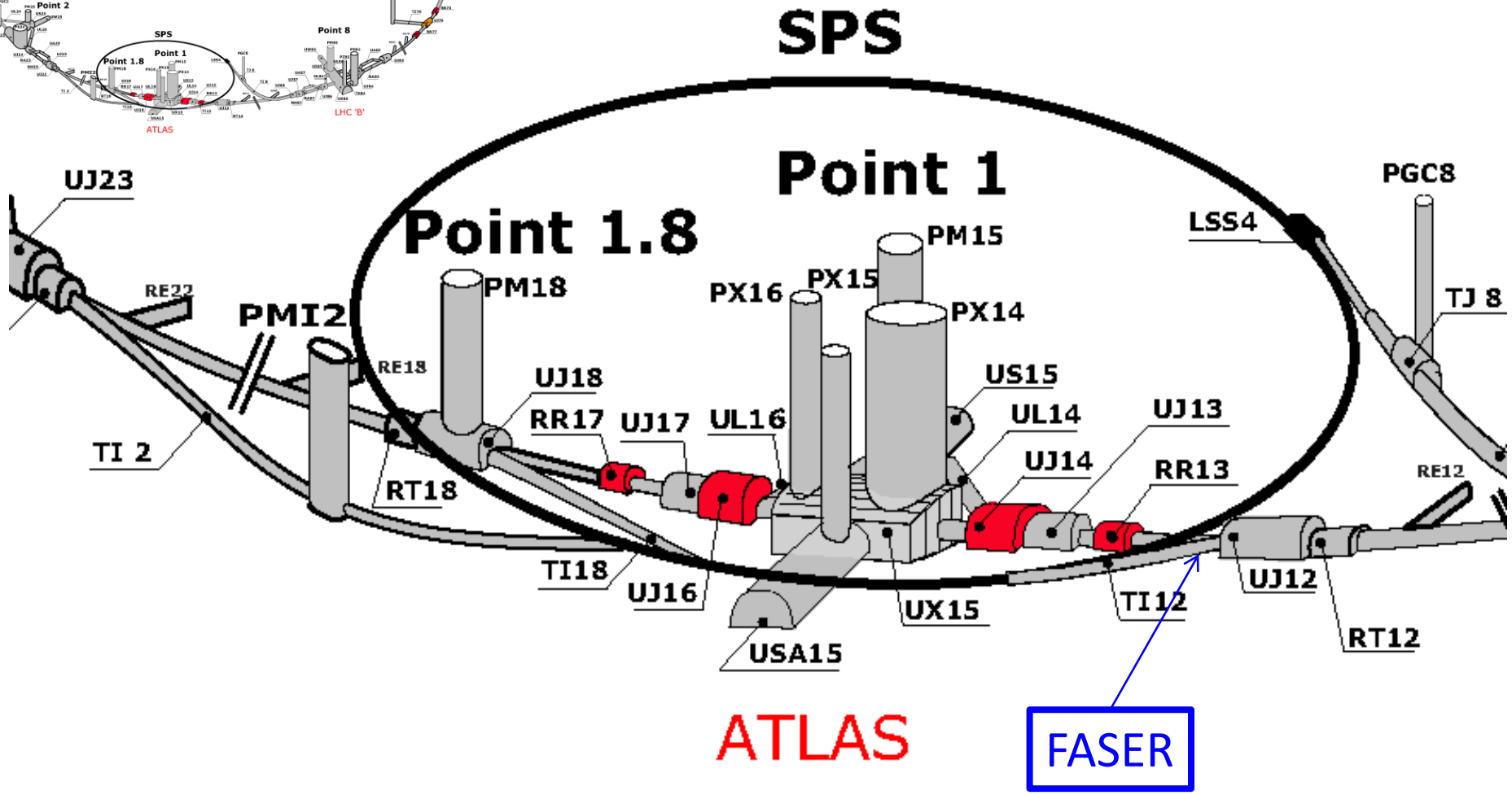


FASER is a new, small experiment at the LHC designed to take advatage of this and to search for new, light, long-lived particles (LLPs), and study neutrinos. The experiment is situated ~500m from the ATLAS collision point, on the beam collision axis line-of-sight (LOS), and started taking physics data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

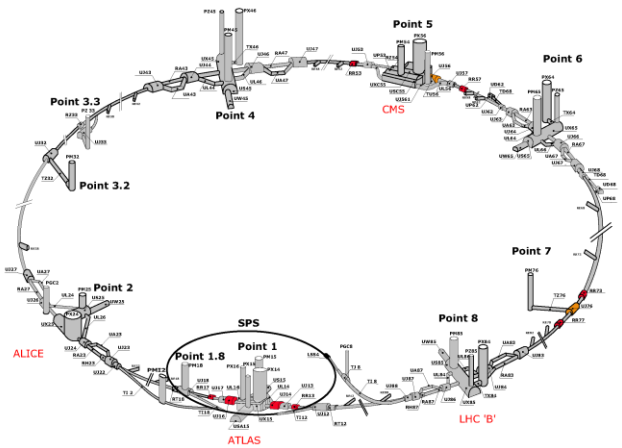
FASER is situated in an unused former injection tunnel which allows the detector to be placed on the LOS, after digging a small trench ~50cm deep.

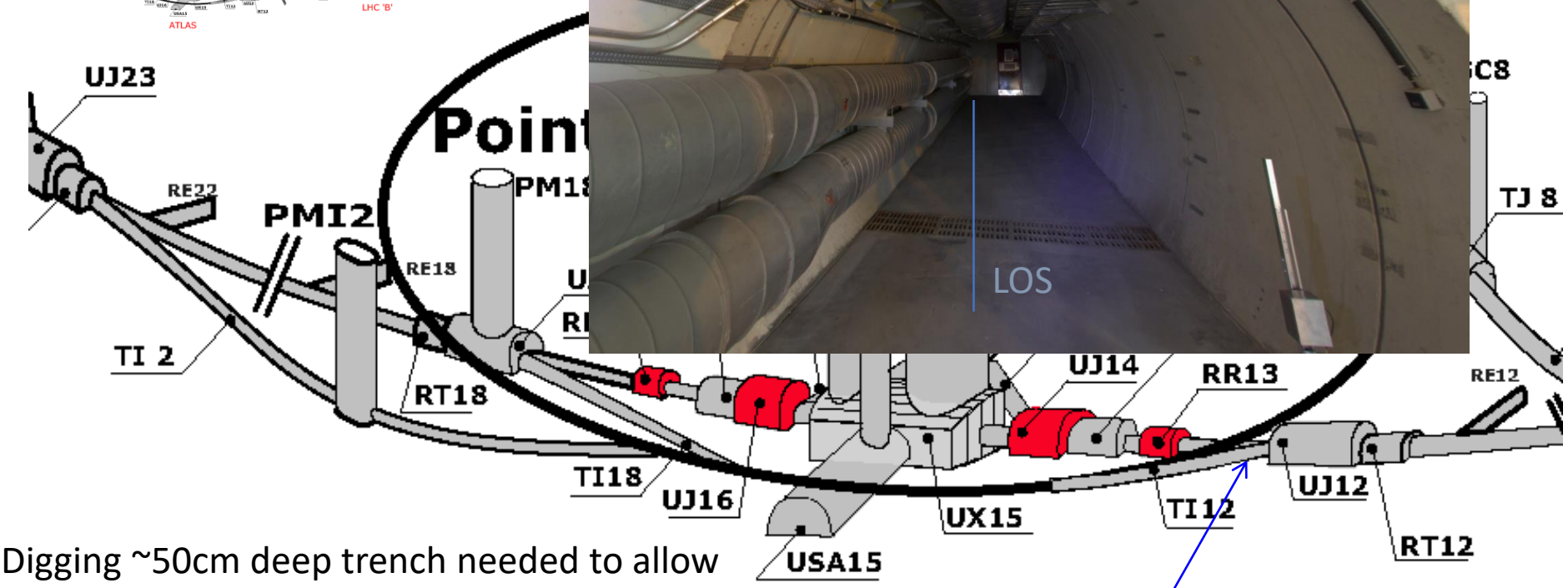
FASER Location: TI12 tunnel





FASER Location: TI12 tunnel



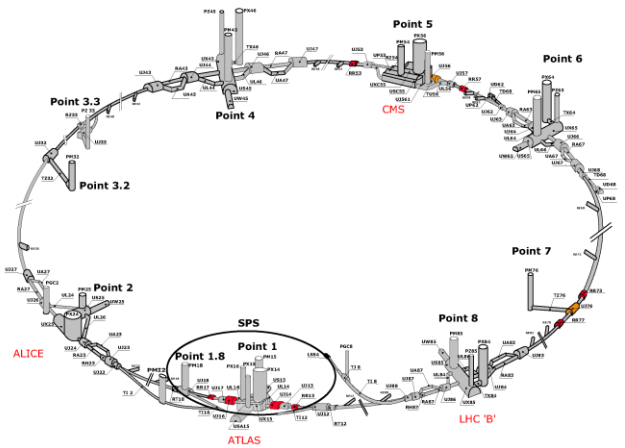


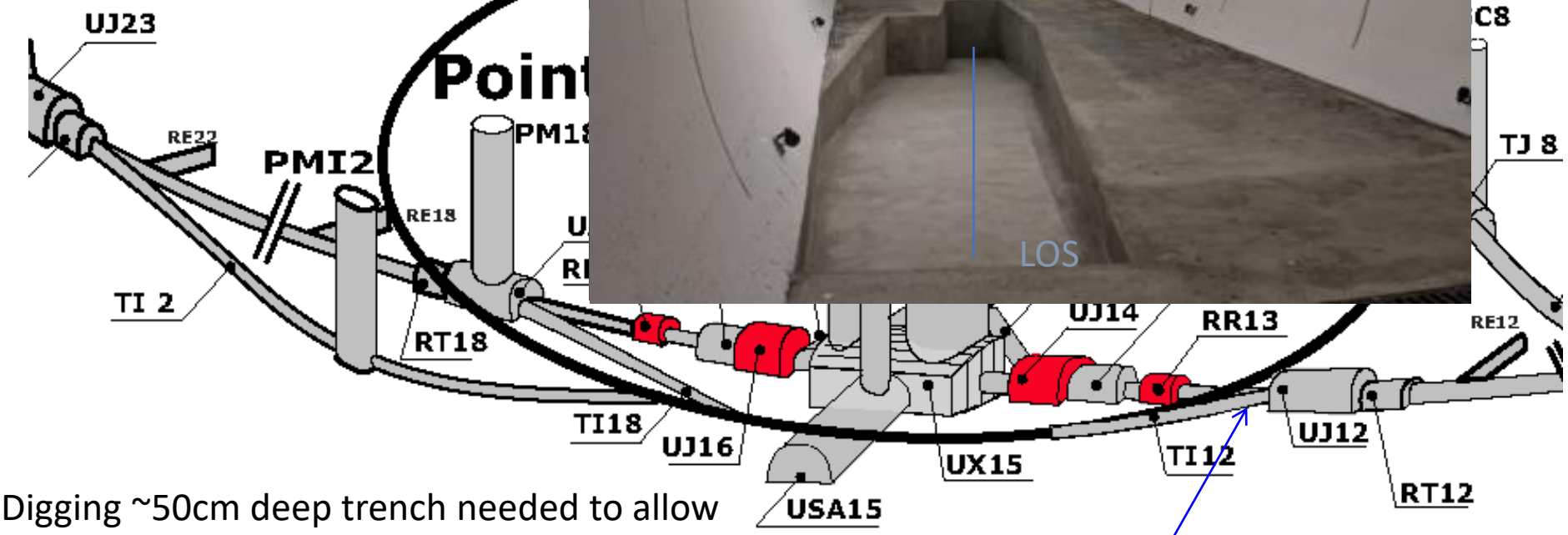
Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS.

ATLAS

FASER

FASER Location: TI12 tunnel



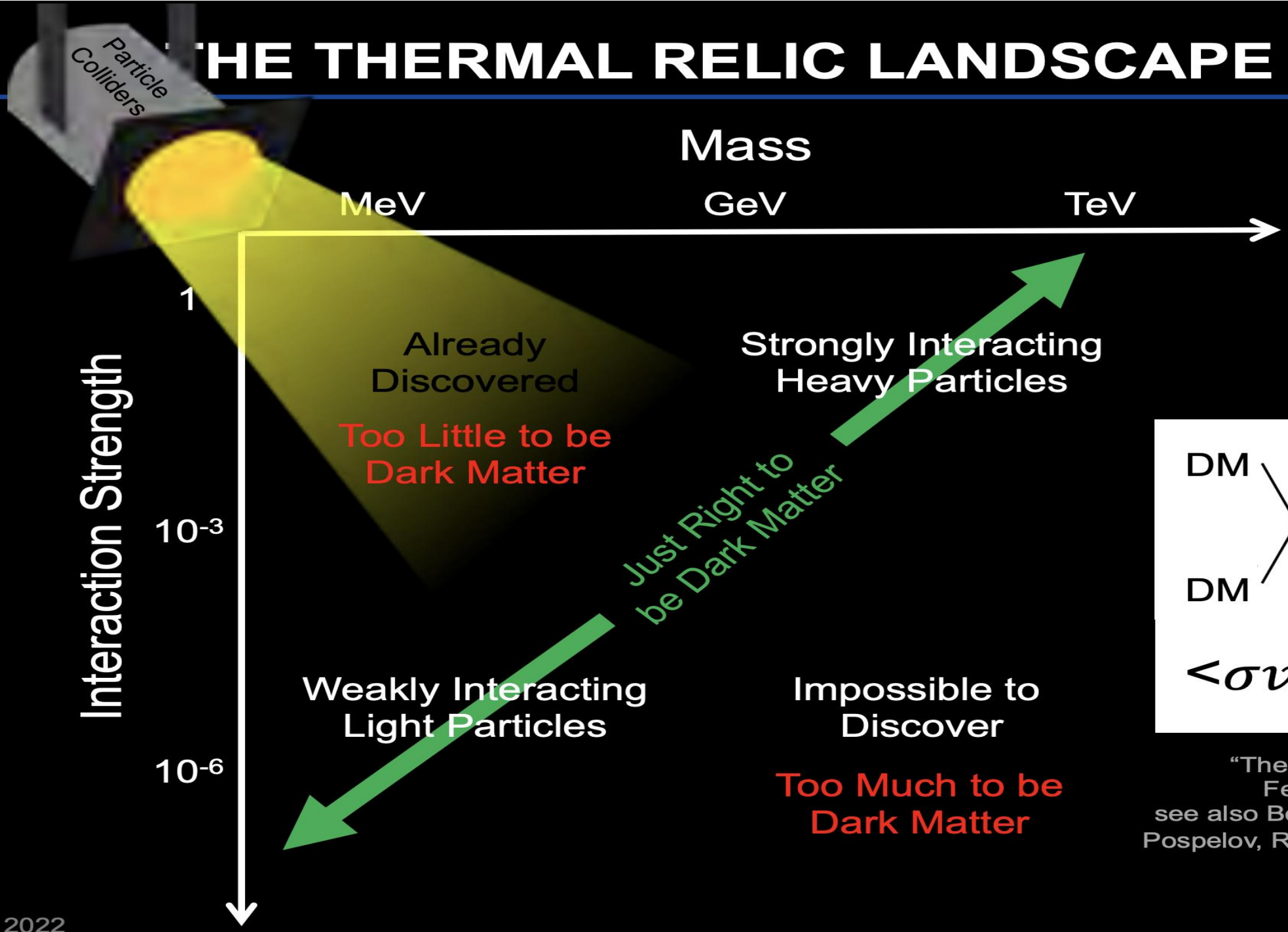


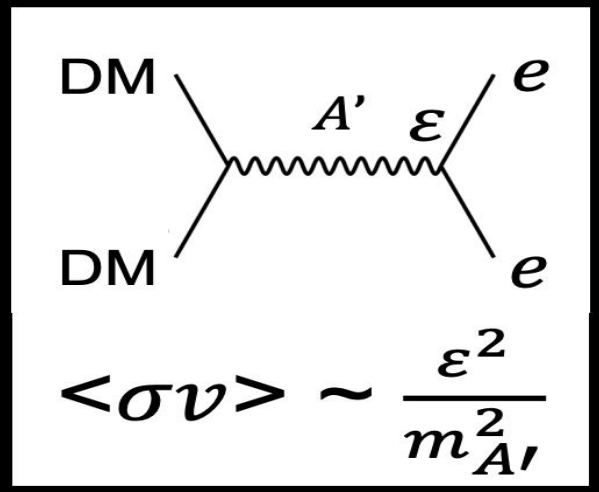
Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS.

ATLAS

FASER

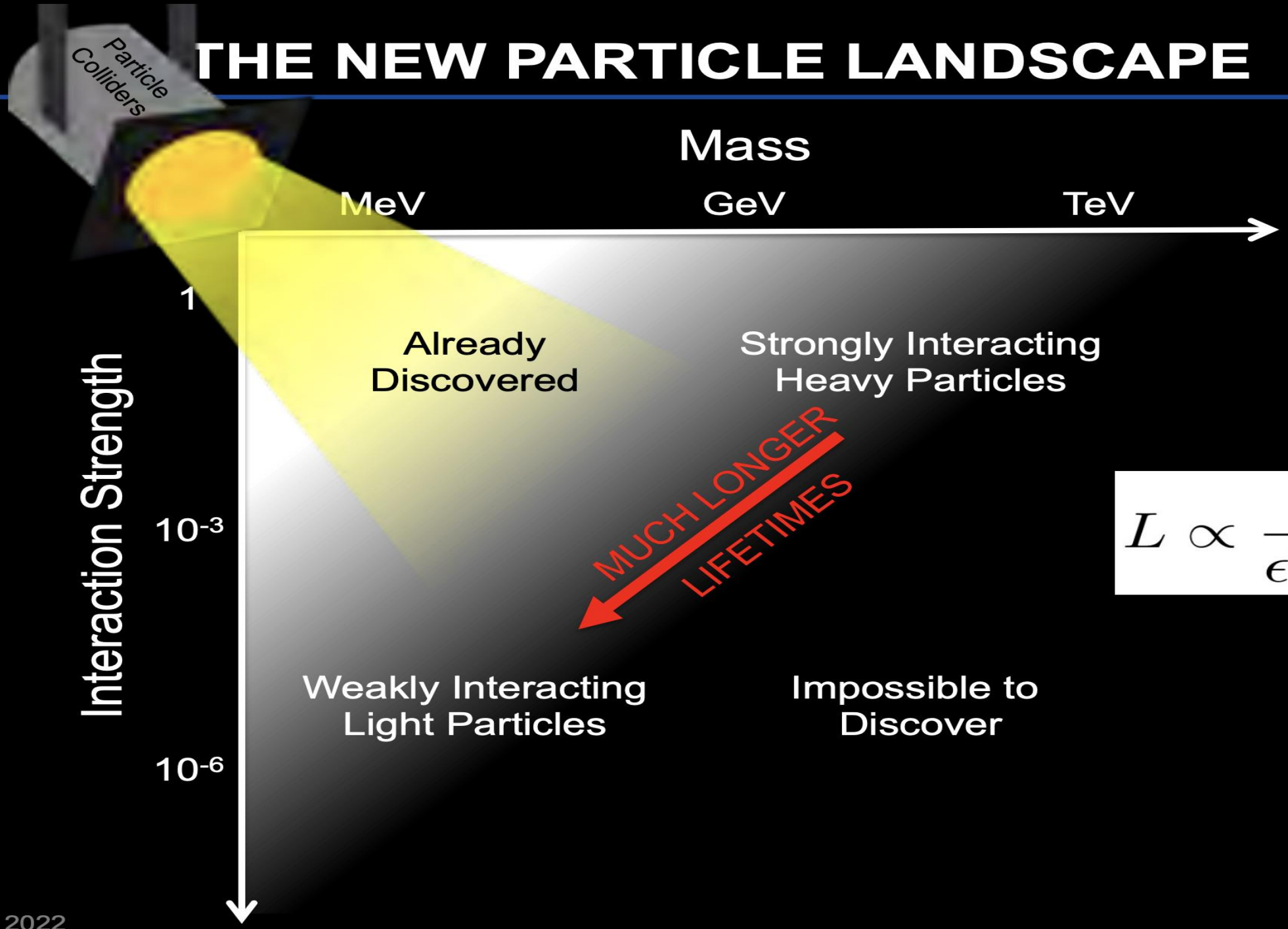
THE THERMAL RELIC LANDSCAPE





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

THE NEW PARTICLE LANDSCAPE



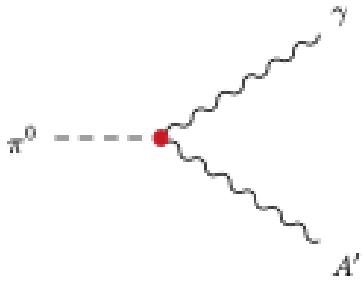
$$L \propto \frac{1}{\epsilon^2 m^2}$$

FASER Physics: Dark Photons

Example:

- 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.,



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

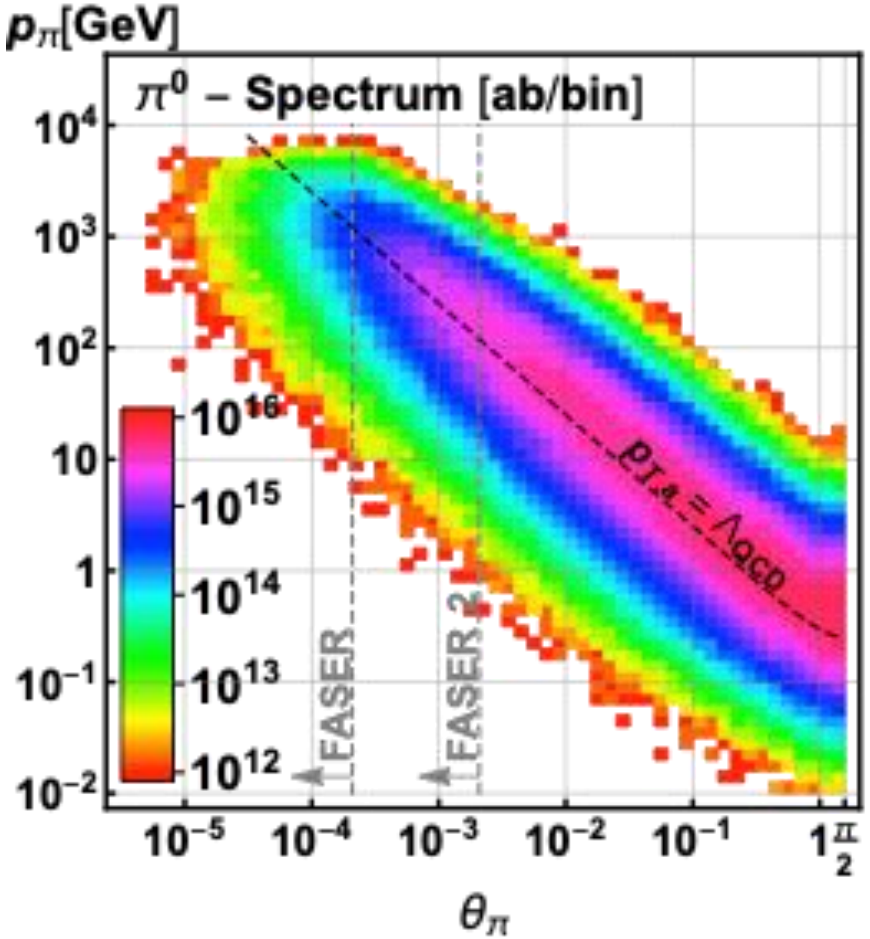
and also through other processes

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

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

- 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.

For example for E(π^0) > 10 GeV,

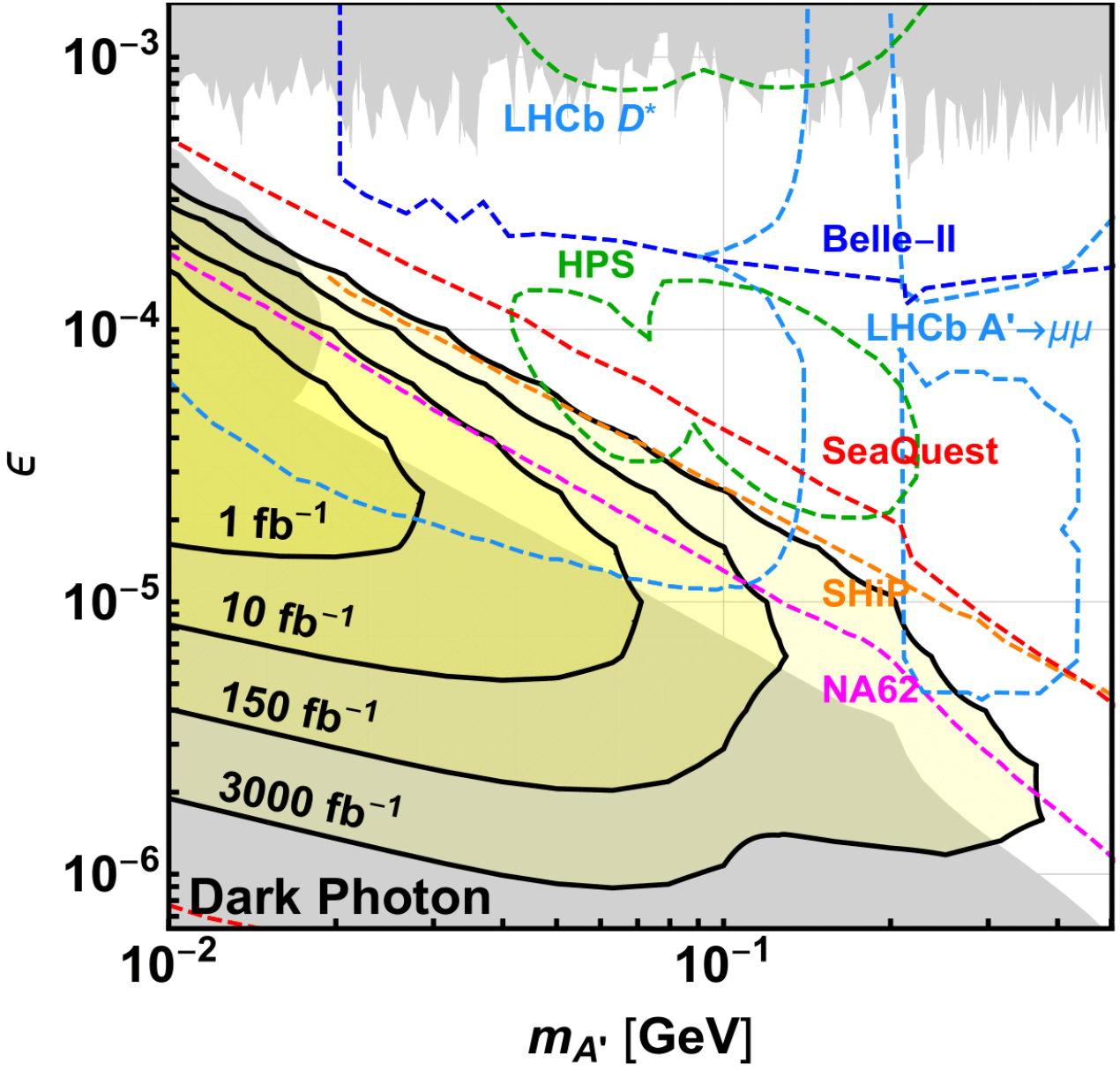
- $\mathcal{O}$(1%) of π^0s fall in FASER acceptance;
- whereas the FASER acceptance covers just $\mathcal{O}(10^{-6}\,\%)$ of the solid angle.

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!

Dark Photons in FASER

Leads to a projected sensitivity (as a function of luminosity)



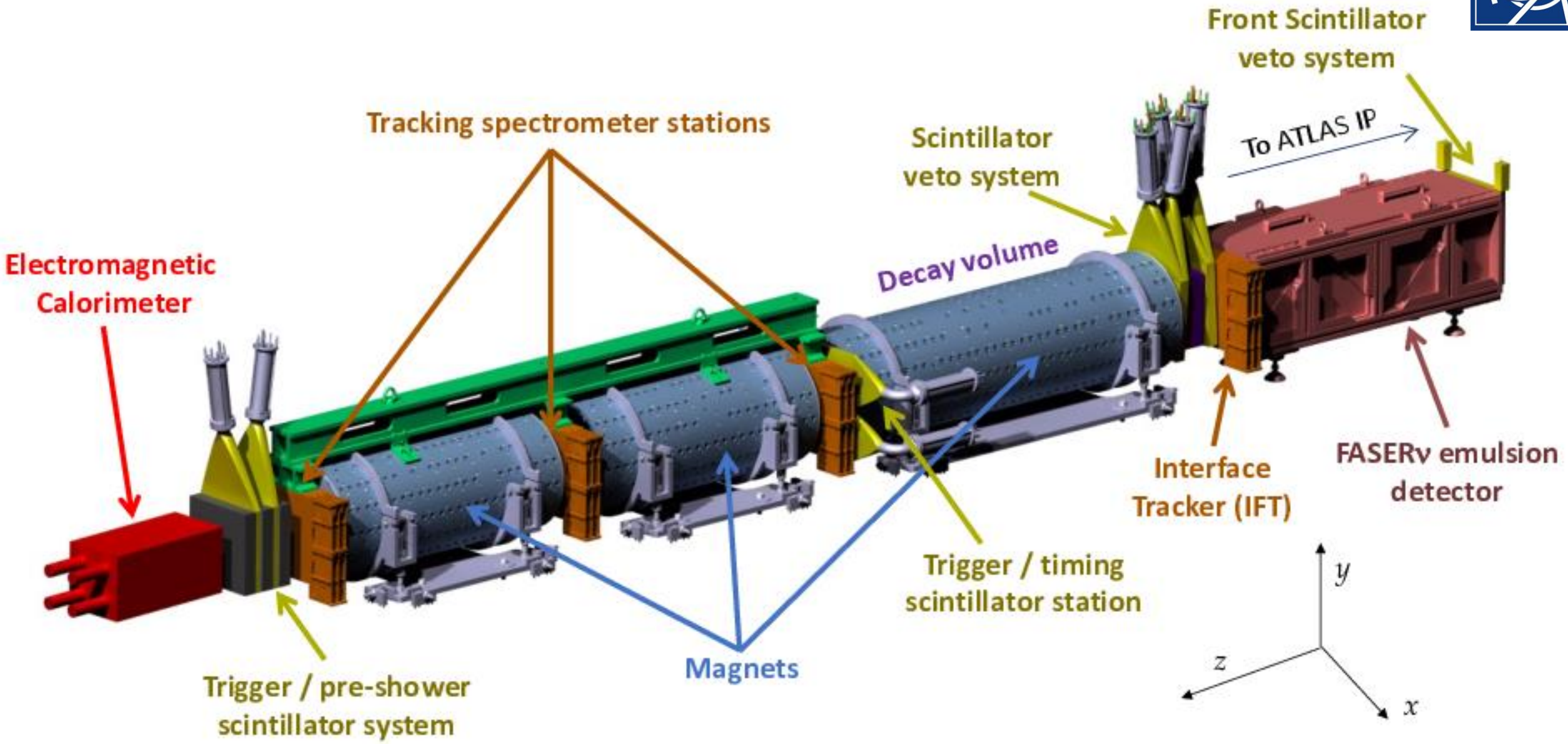
- Start to explore unconstrained space even with 1/fb
- Significant discovery potential with 150/fb (expected lower limit on total Run-3 dataset)

Plot assumes 0 background and 100% efficiency. However contours little effected by $\mathcal{O}(1)$ change in efficiency.
Signal topology striking, so believe that 0-background is reasonable assumption.

FASER will also have sensitivity to several other dark sector scenarios including ALPs, Other gauge bosons, …

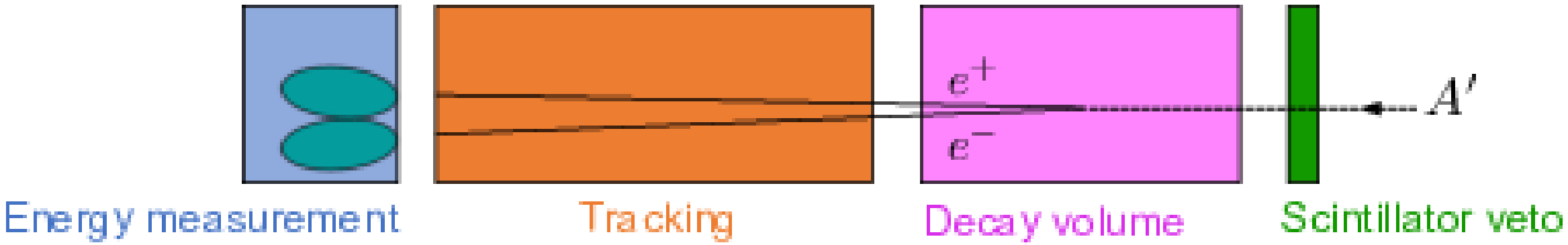
FASER Detector

arxiv: 2207.11427



FASER Detector

Signal signature

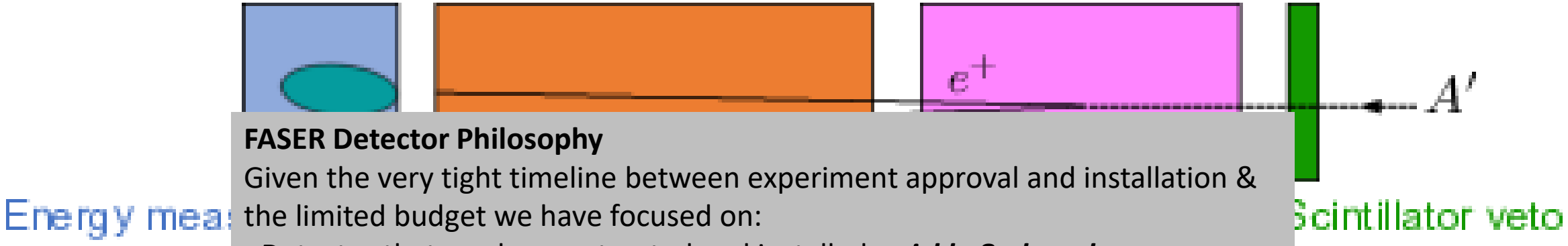


1. No signal in the veto scintillator;
2. Two high energy oppositely charged tracks, consistent with originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP;
3. For A'->e^+e^- decay: Large EM energy in calorimeter. EM showers too close to be resolved.

Magnets needed to separate the A' decay products sufficiently to be able to be resolved in tracker

FASER Detector

Signal signature



1. No signal ir
2. Two high e on vertex in the decay vol
3. For A'->e^+e lved.

FASER Detector Philosophy

Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:

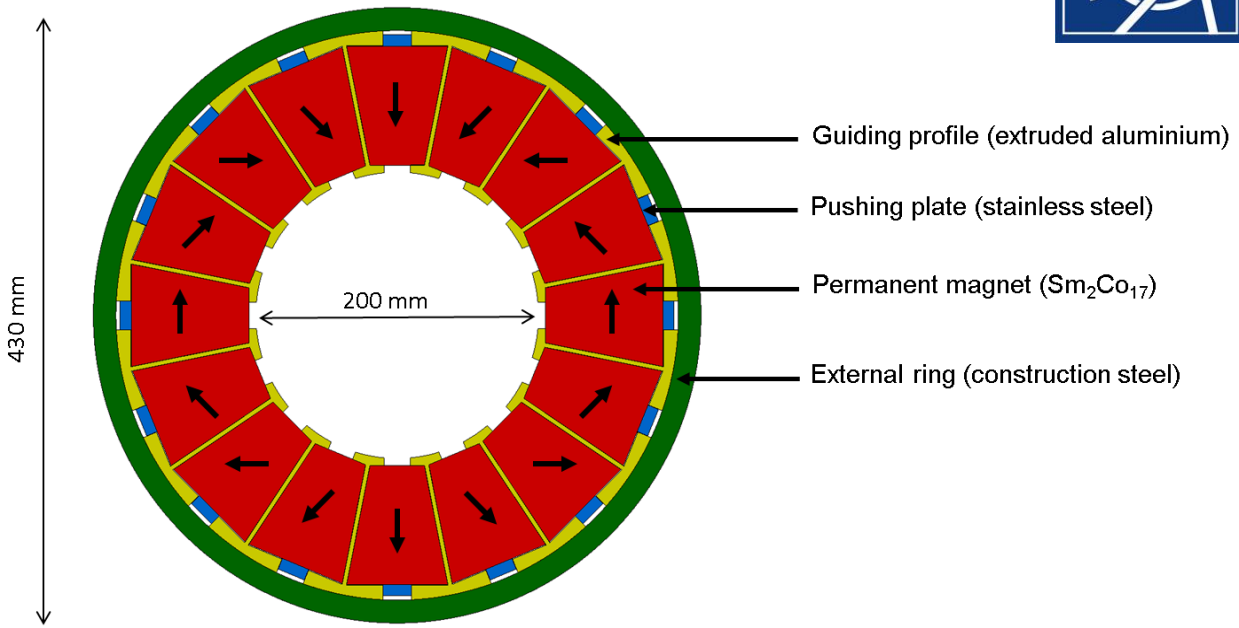
- Detector that can be constructed and installed ***quickly & cheaply***
- Have tried to re-use existing detector components where possible
- Aimed for a simple, robust detector (access difficult)
- Tried to minimize the services to simplify the installation and operations

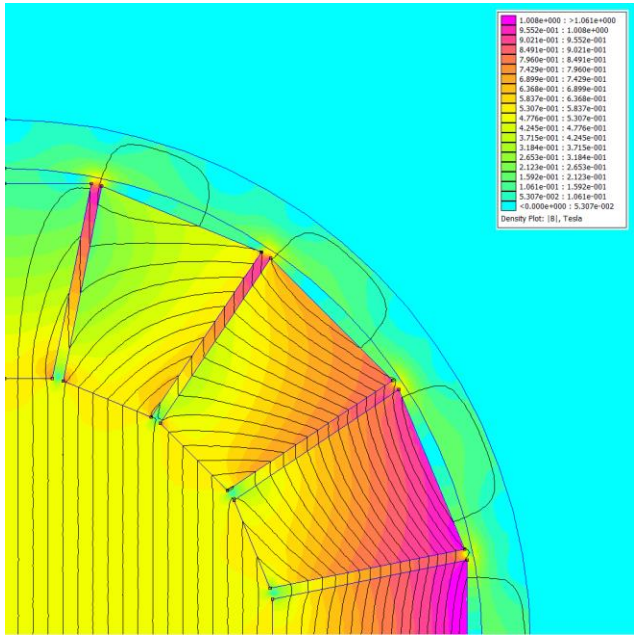
Many challenges of the large LHC experiments not there for FASER:

- trigger rate $\mathcal{O}$(1 kHz) (mostly single muon events)
- low radiation
- low occupancy / event size

to be able to be resolved in tracker

FASER Magnets



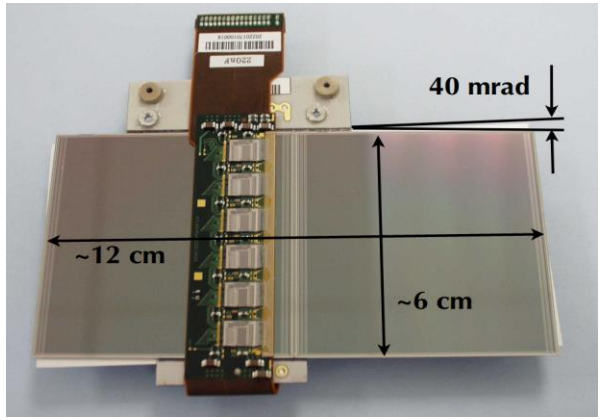


- The FASER magnets are 0.57T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed, constructed and measured by the magnet group at CERN

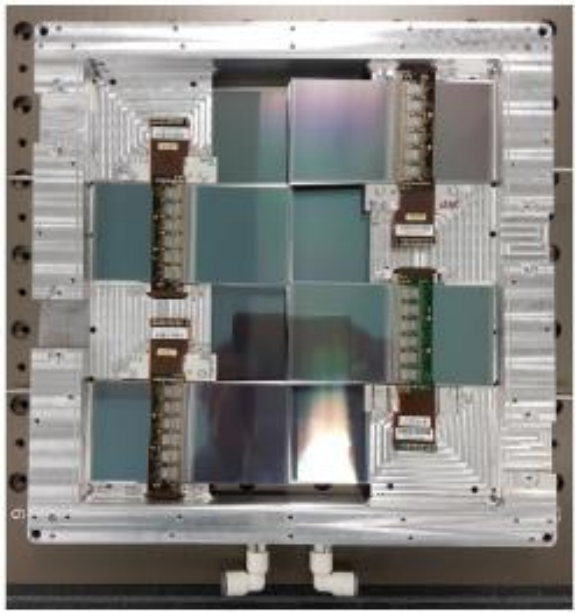
FASER Tracker

NIMA 166825 (2022)

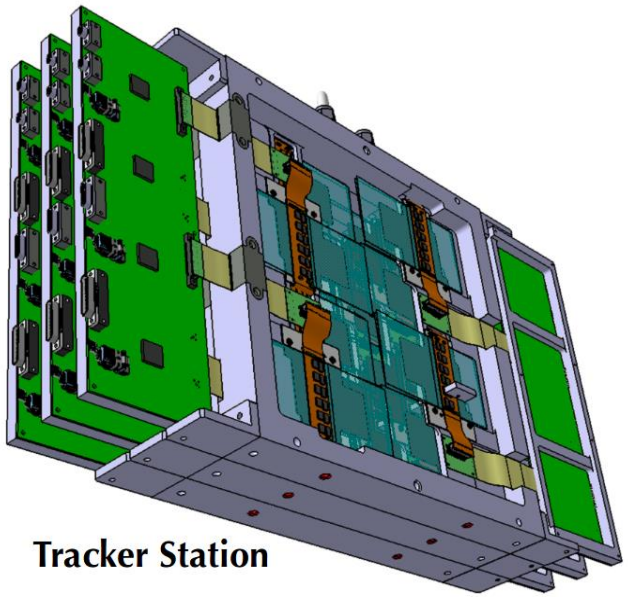
- FASER Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 4 tracking stations
- Each containing 3 layers of double-sided silicon micro-strip sensors
  - Spare ATLAS SCT modules are used
    - 80µm strip pitch, 40mrad stereo angle (17µm / 580µm resolution)
      - precision measurement in bending (vertical) plane
    - ***Many thanks to the ATLAS SCT collaboration!***
- 8 SCT modules give a 24cm x 24cm tracking layer
- 12 layers (3/station, 4 stations) => 96 SCT modules needed for the full tracker



SCT module



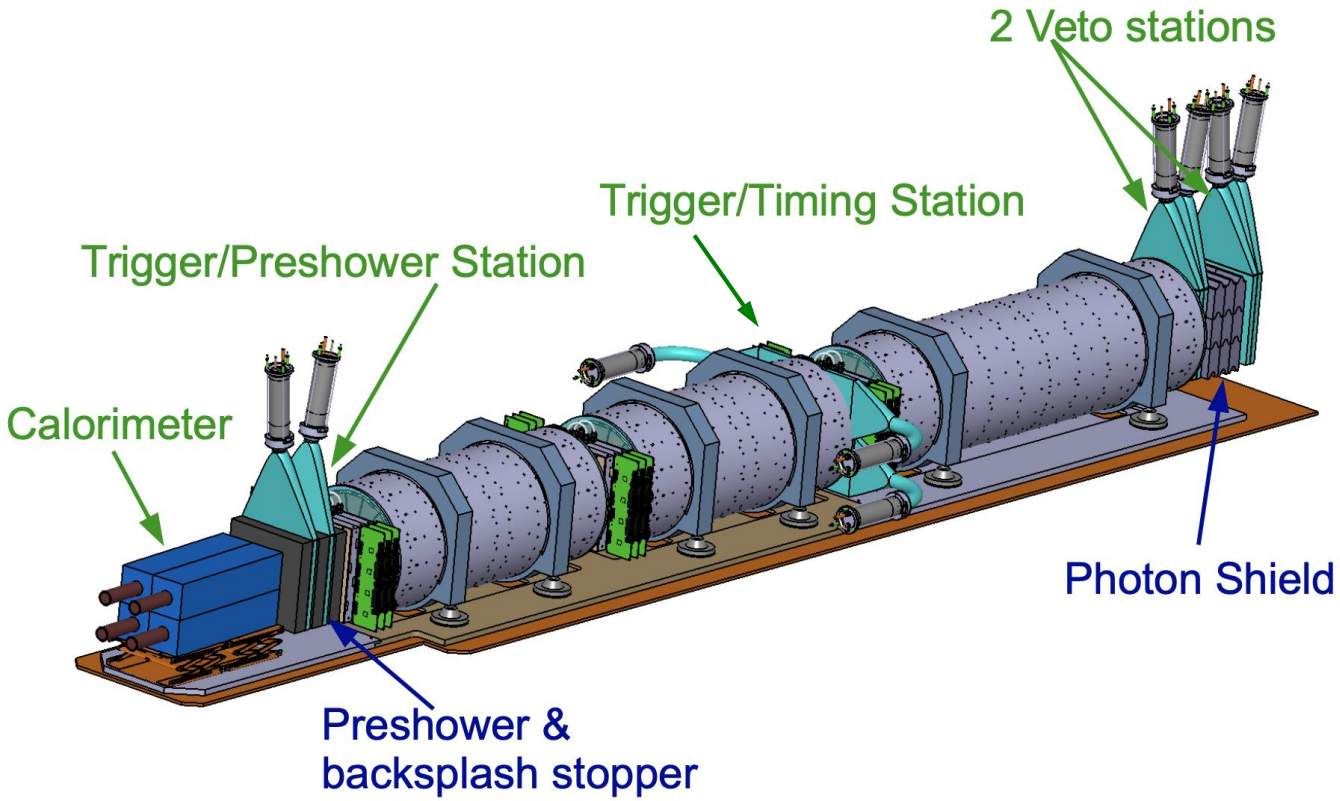
Tracking layer



FASER Scintilators

Scintillators used for:

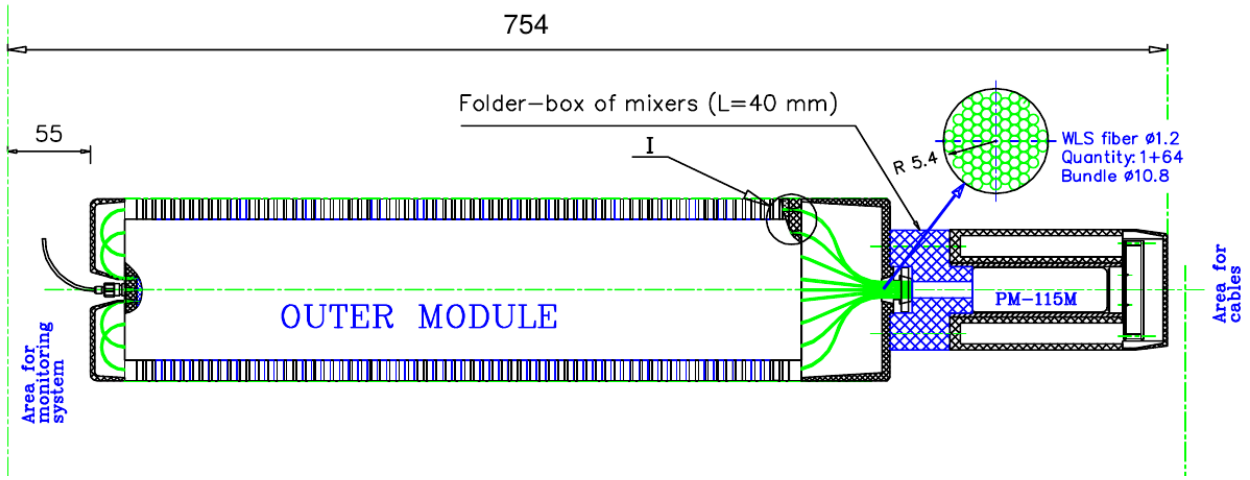
- Vetoing incoming charged particles
  - Very high efficiency needed ($\mathcal{O}(10^8)$ incoming muons in 150/fb)
- Triggering
- Timing measurement
  - ~0.5 ns resolution
- Simple pre-shower for Calorimeter



Scintillators, light guides and PMT housing constructed at CERN scintillator lab (EP-DT).

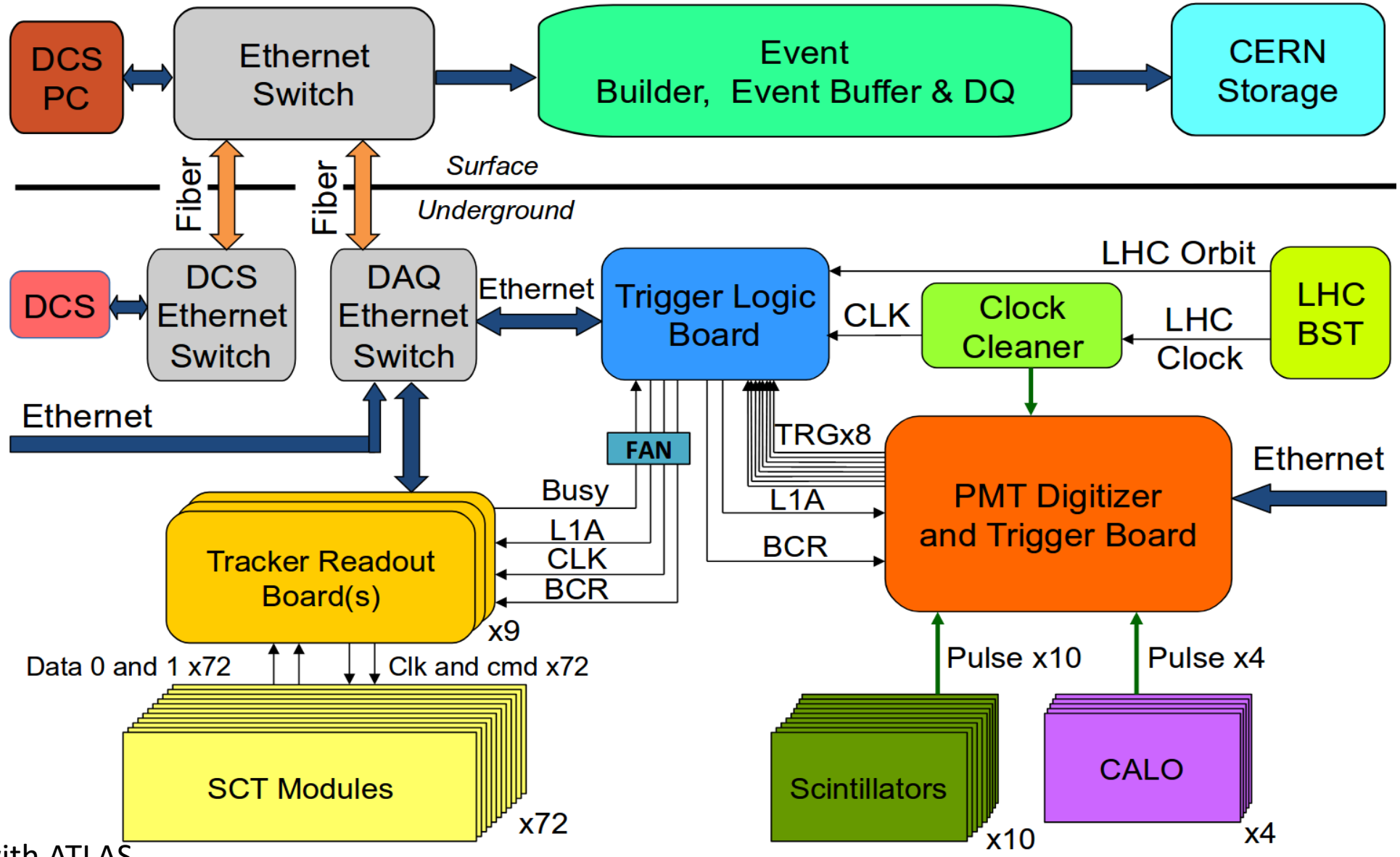
FASER Calorimeter

- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Uses 4 spare LHCb outer ECAL modules
  - ***Many thanks to LHCb*** for allowing us to use these!
  - 66 layers of lead/scintillator, light out by wavelength shifting fibers
    - 25 radiation lengths long
  - Readout by single PMT (no longitudinal shower information)
    - Only 4 channels in full calorimeter
  - Dimensions: 12cm x 12cm – 75cm long (including PMT)
  - Provides ~1% energy resolution for 1 TeV electrons



FASER TDAQ

JINST **16** P12028



Trigger rate $\mathcal{O}$(1 kHz)
Event size (~25KB)
No triggers shared with ATLAS
FASER DAQ software based on DAQling framework from EP-DT

FASER Detector Installation

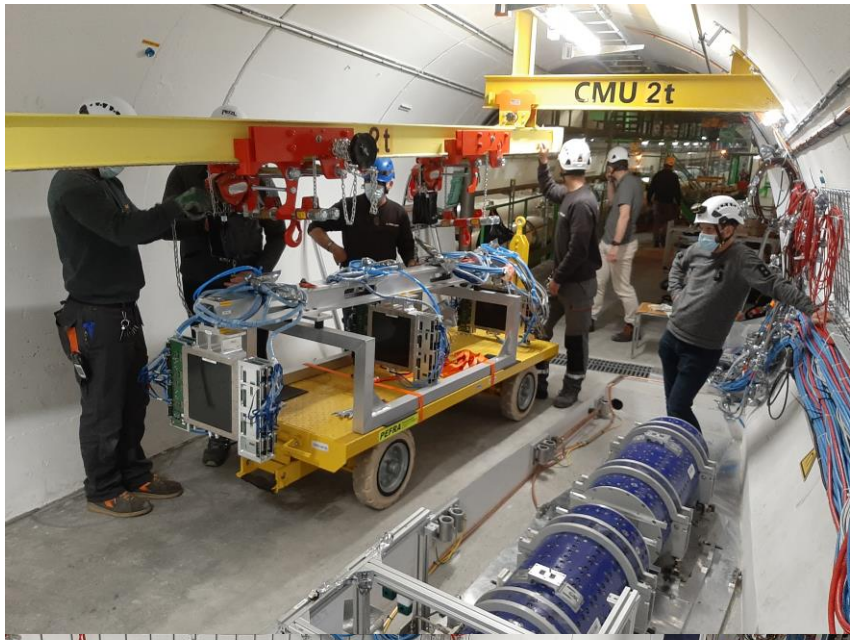
8/18

4/20

11/20

4/21

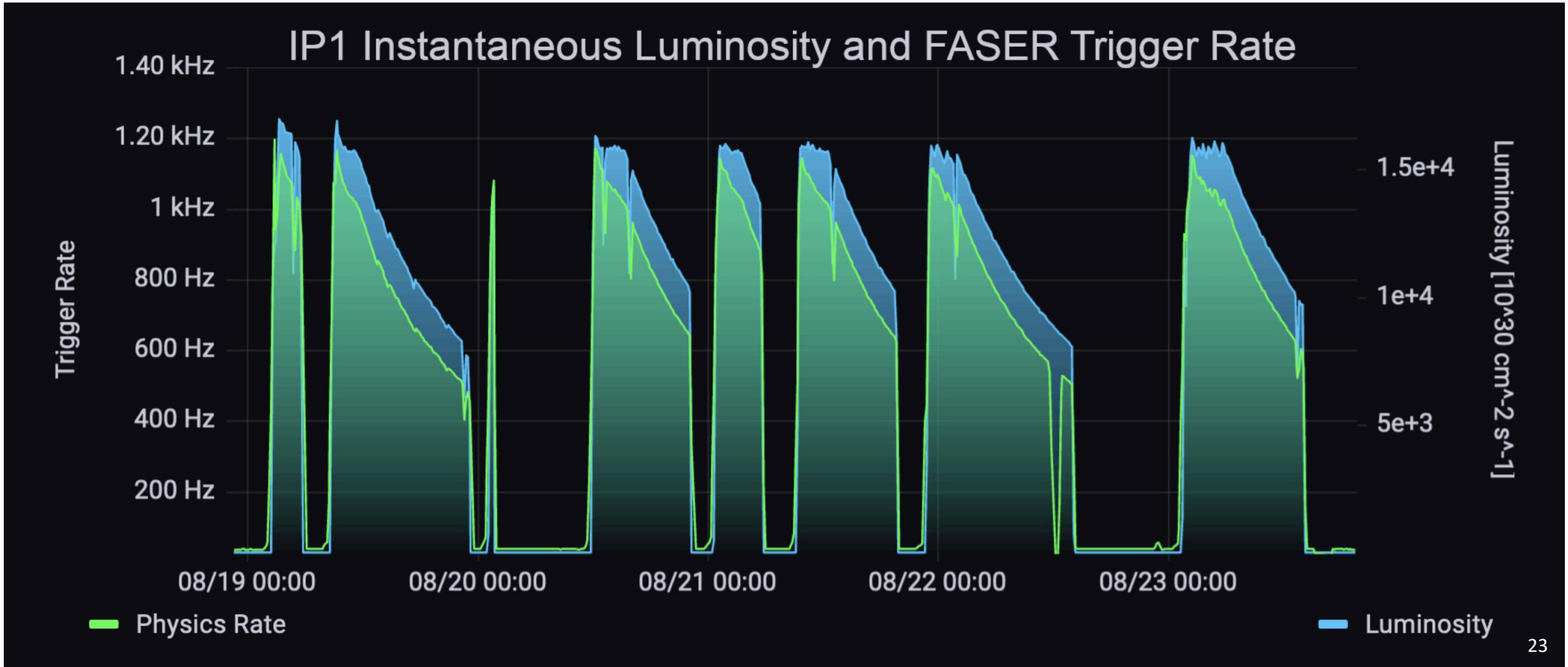
Tracker Installation



FASER was installed into TI12 in March 2021. Physics data taking started in July 2022, after >1 year of in situ cosmic ray datataking.

FASER Operations

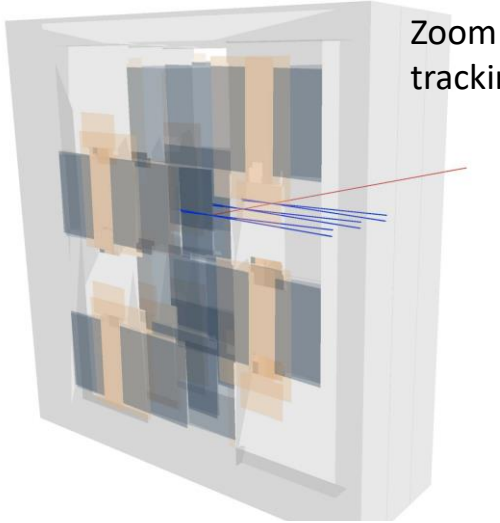
FASER has been succesfully collecting 13.6 TeV collision data since July 2022, with no big problems observed.
Detector timed in with first collision data. Over 35/fb of data have been recorded, and many performance studies are ongoing.
The maximum trigger rate is ~1.2kHz, nearly 2x the expectation, but this is not a problem for physics (physics deadtime <2%).
Currently only 850/pb (<2.5% of full dataset) data lost due to operational issues.



Collision Muon Event

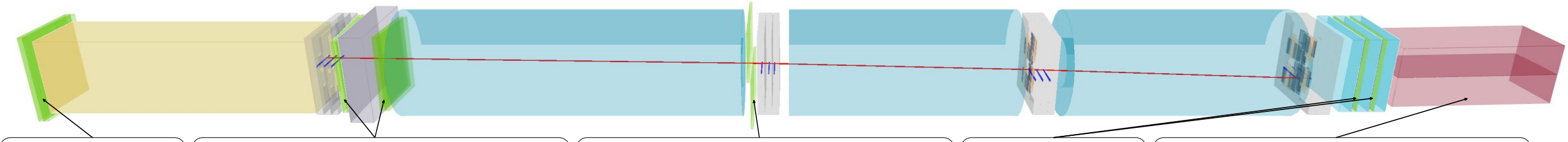
Run 8336
Event 1477982
2022-08-23 01:46:15

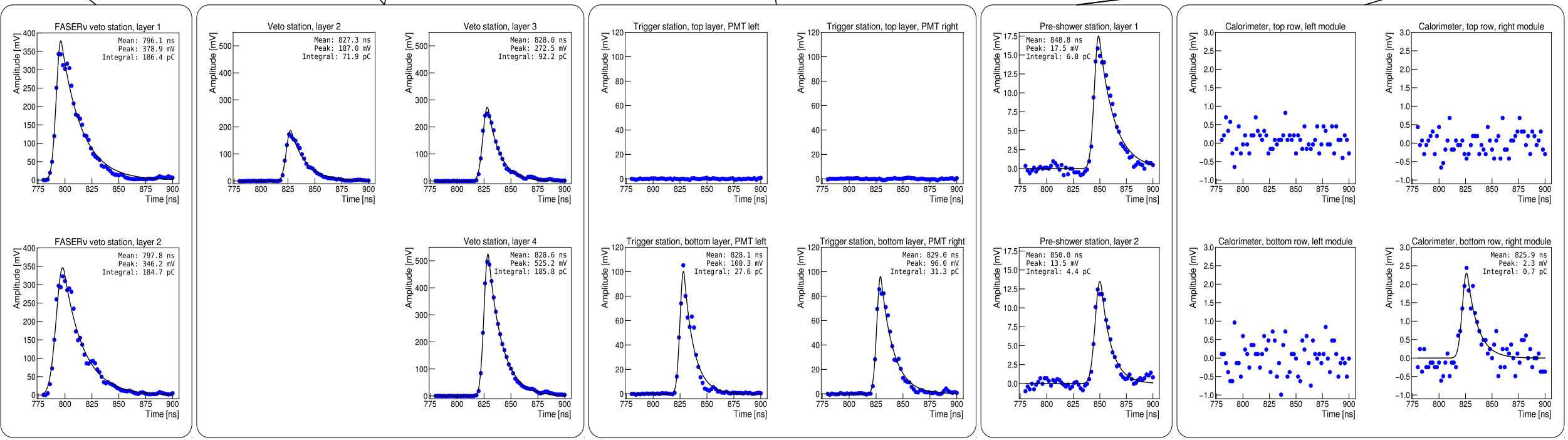
Collision event with a muon traversing FASER
Reconstructed momentum 22 GeV.
Signal consistent with MIP seen in all scintillators and calorimeter.



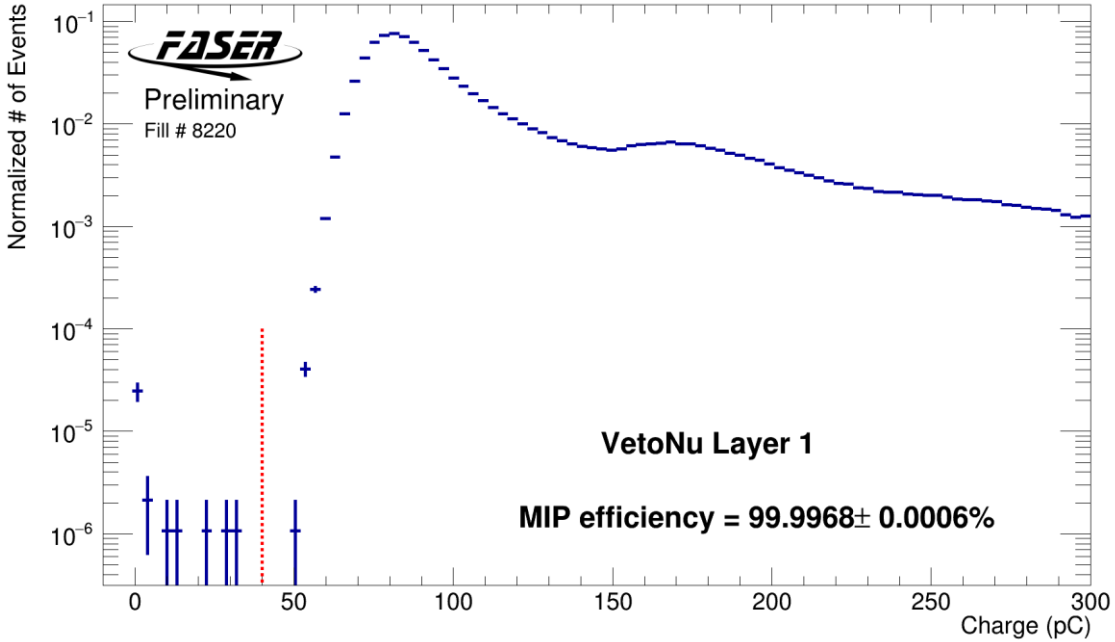
Zoom in of 1st tracking station

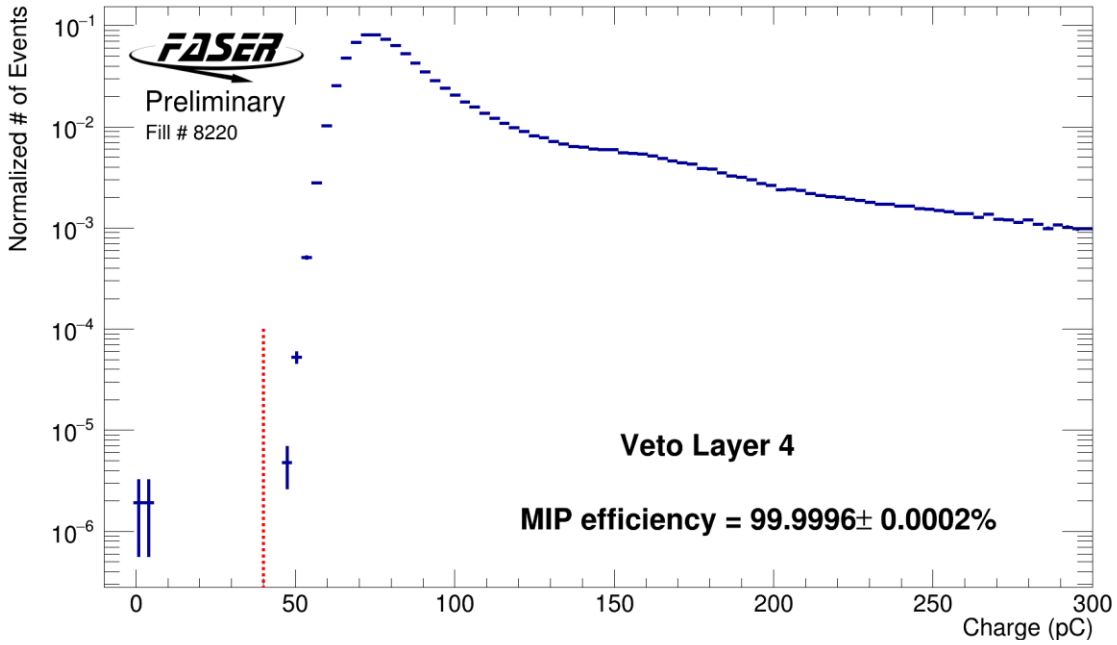
To ATLAS IP



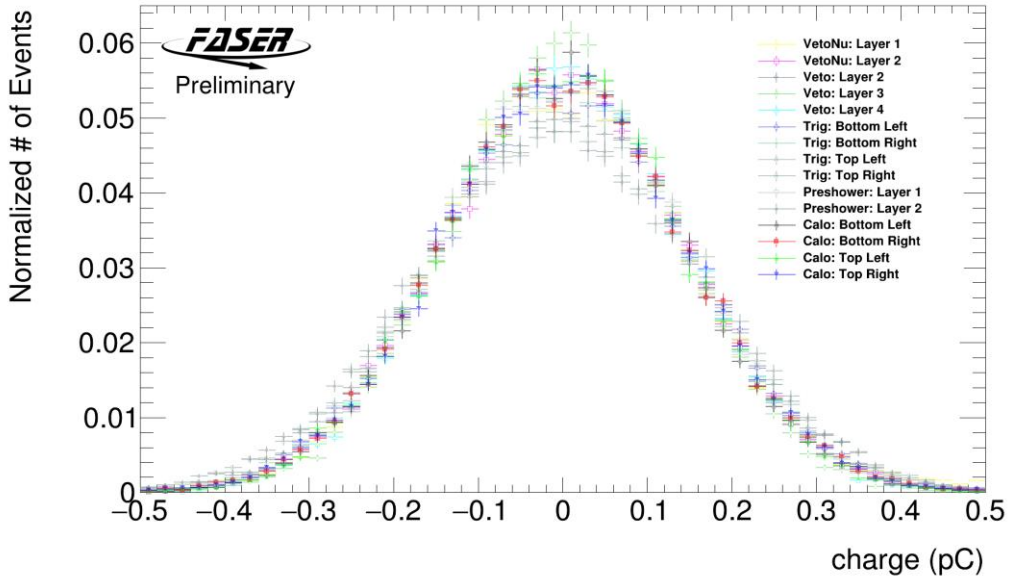


Scintillator Performance

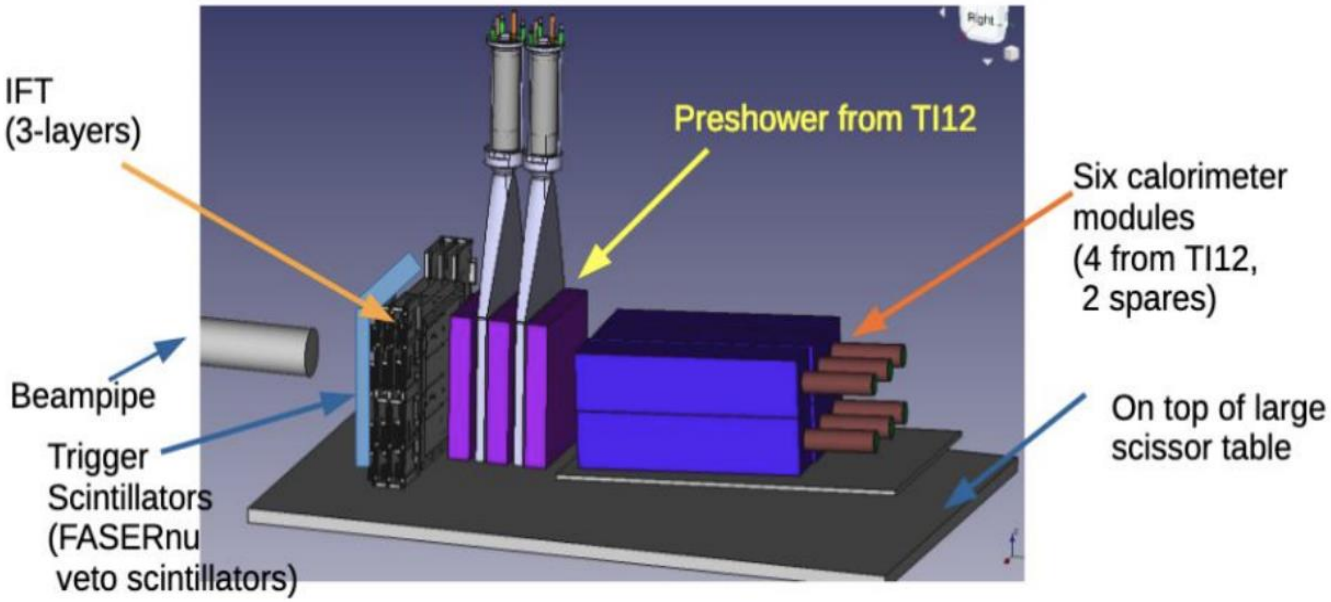


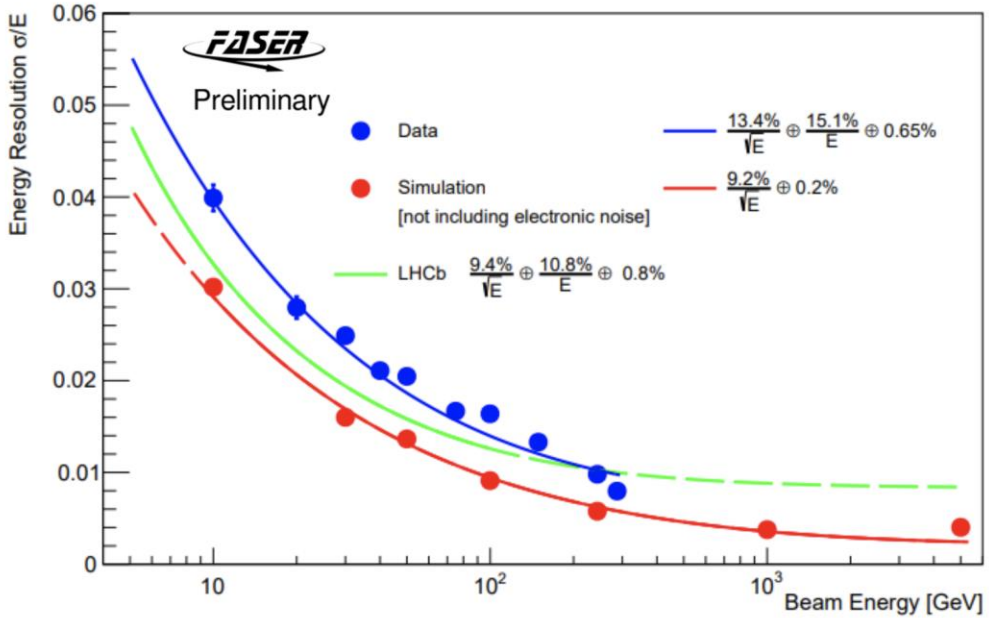


- Veto efficiency measurement in data, for events with track that extrapolates into the scintillator. Each individual scintillator efficiency >99.99%.
- When 4 scintillators combined can veto expected $\mathcal{O}(10^8)$ muons entering the detector in Run 3.
- Scintillator noise measured in random triggered events, observed noise ~0.15pC and dominated by digitizer noise
  - Noise much less than MIP signal (~70pC)



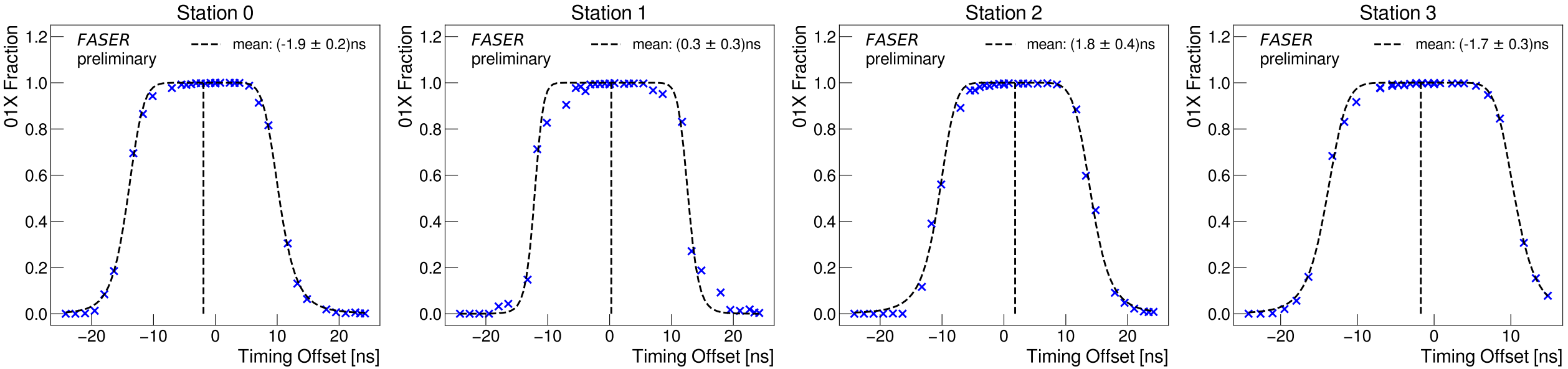
Calorimeter Performance





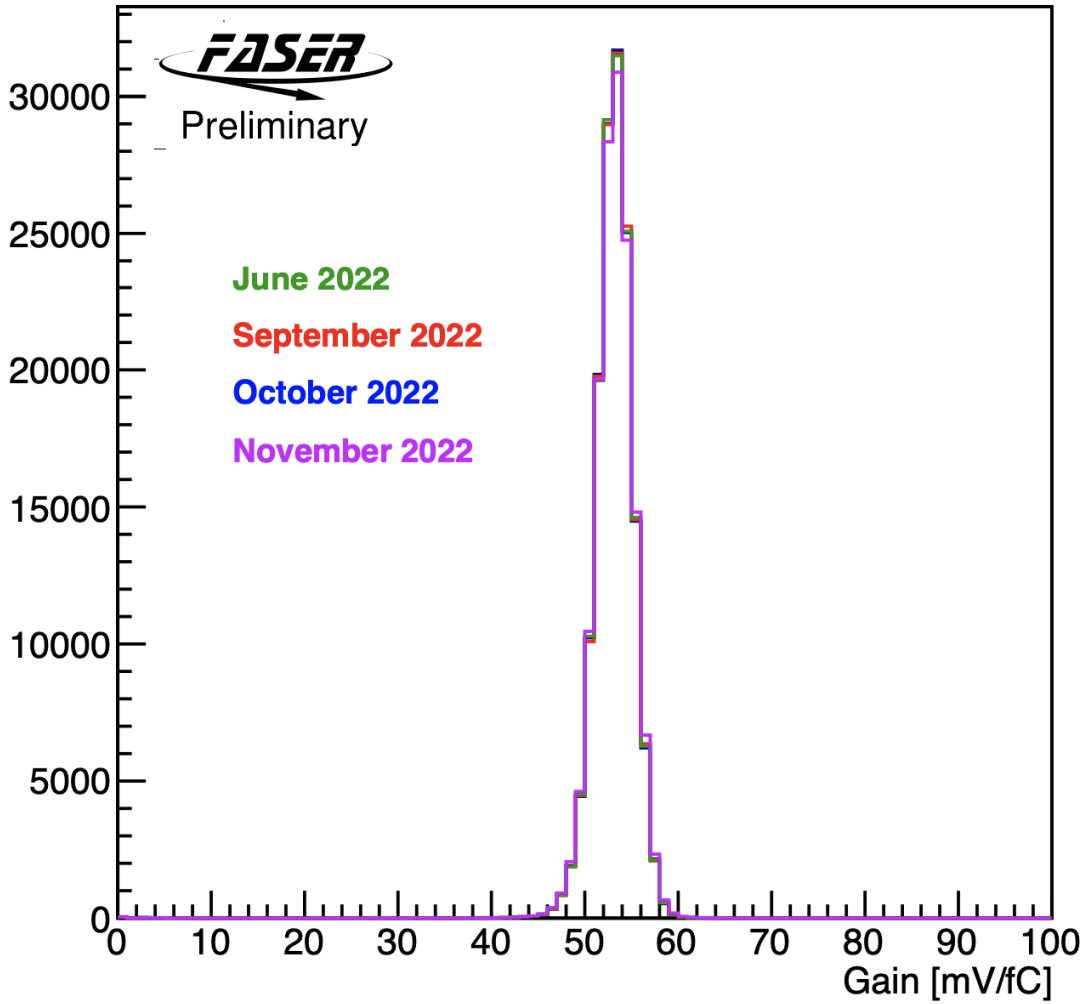
- Calorimeter energy resolution measured with SPS testbeam in summer 2021
- Confirming $\mathcal{O}(1\%)$ resolution for high energy electrons.
- Testbeam also used to demonstrate calibration method using muon MIP peak to set energy scale at low energy, and LED calibration pulses to scale this to high energy as PMT gain changed.

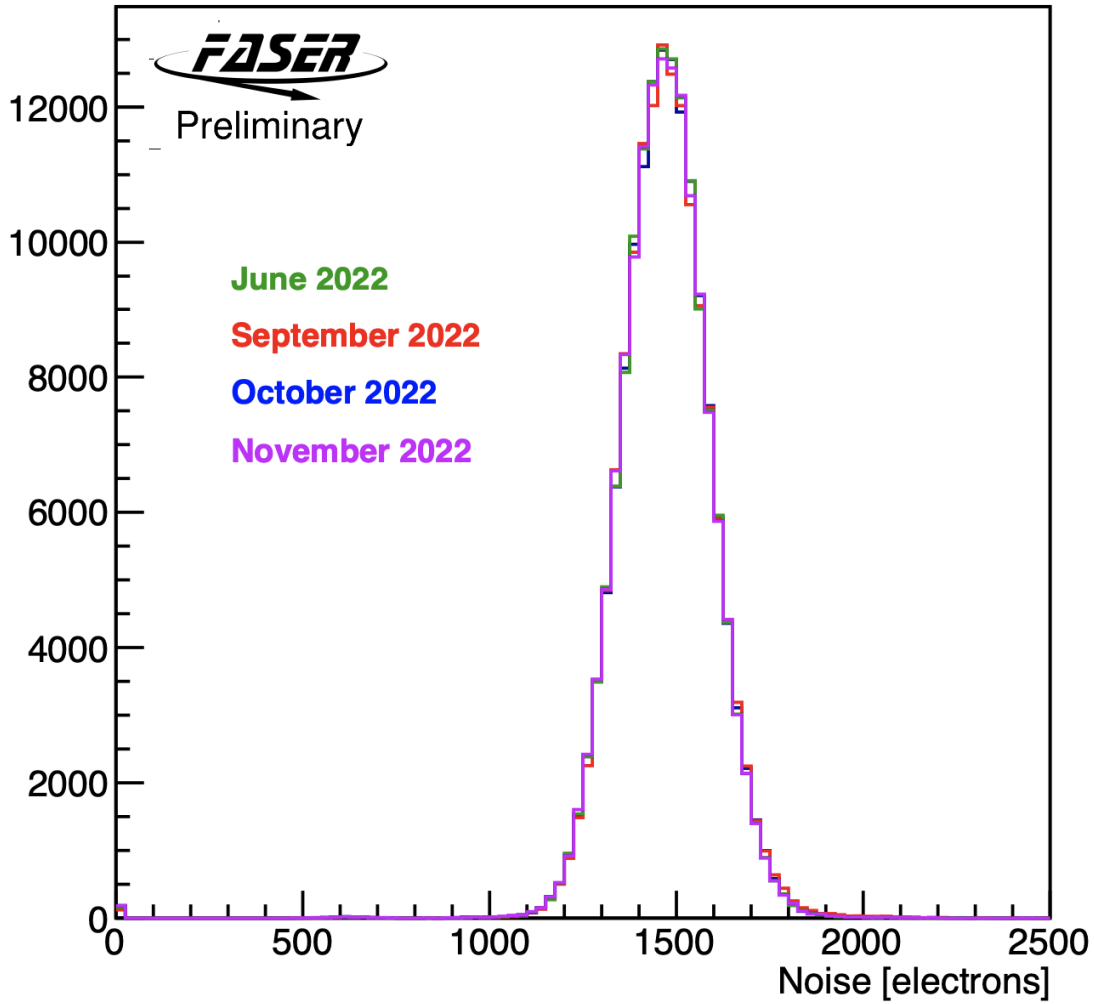
Tracker Timing-in…



Used early collision data tracks to set fine timing delay in the readout of each SCT module, in order to optimize fraction of hits on track in middle of three 25ns time bins read out.

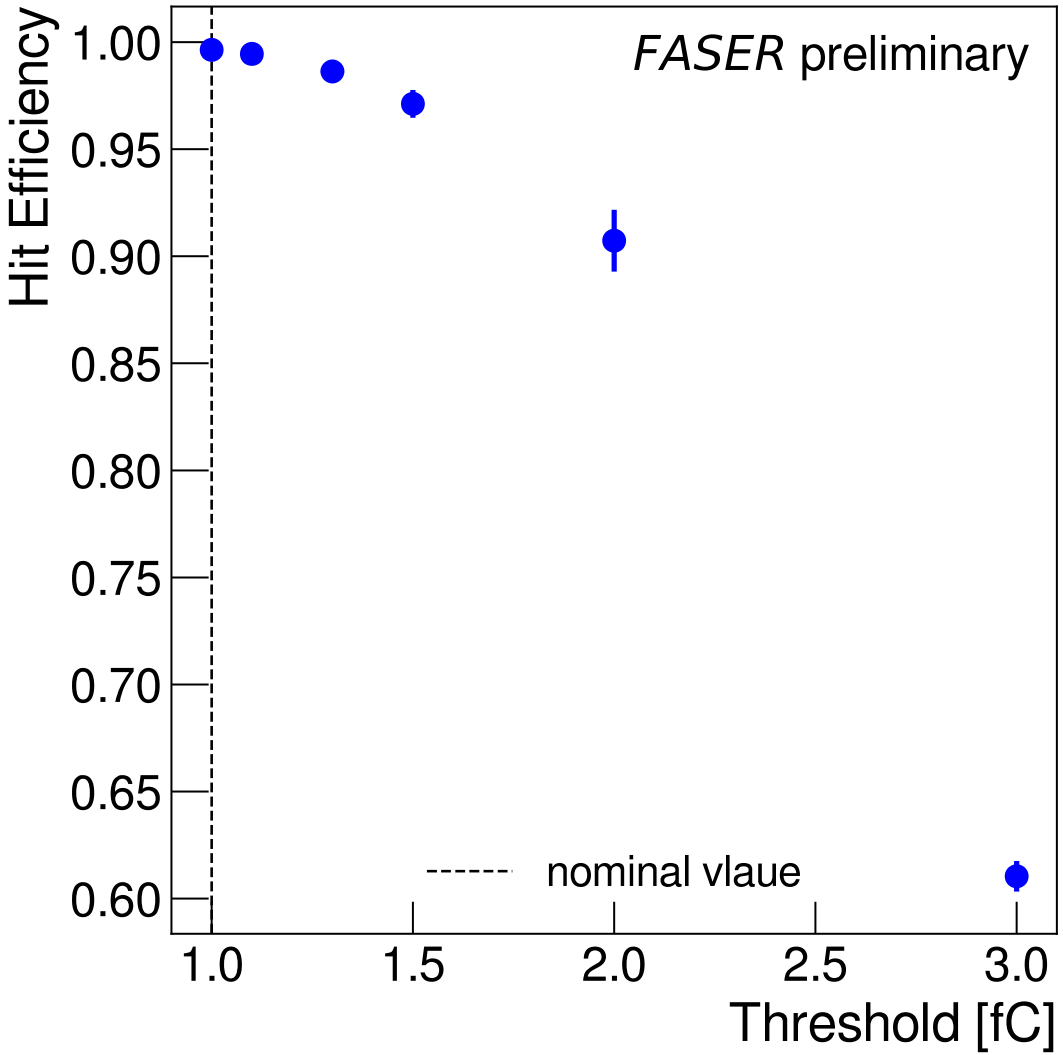
Tracker Performance

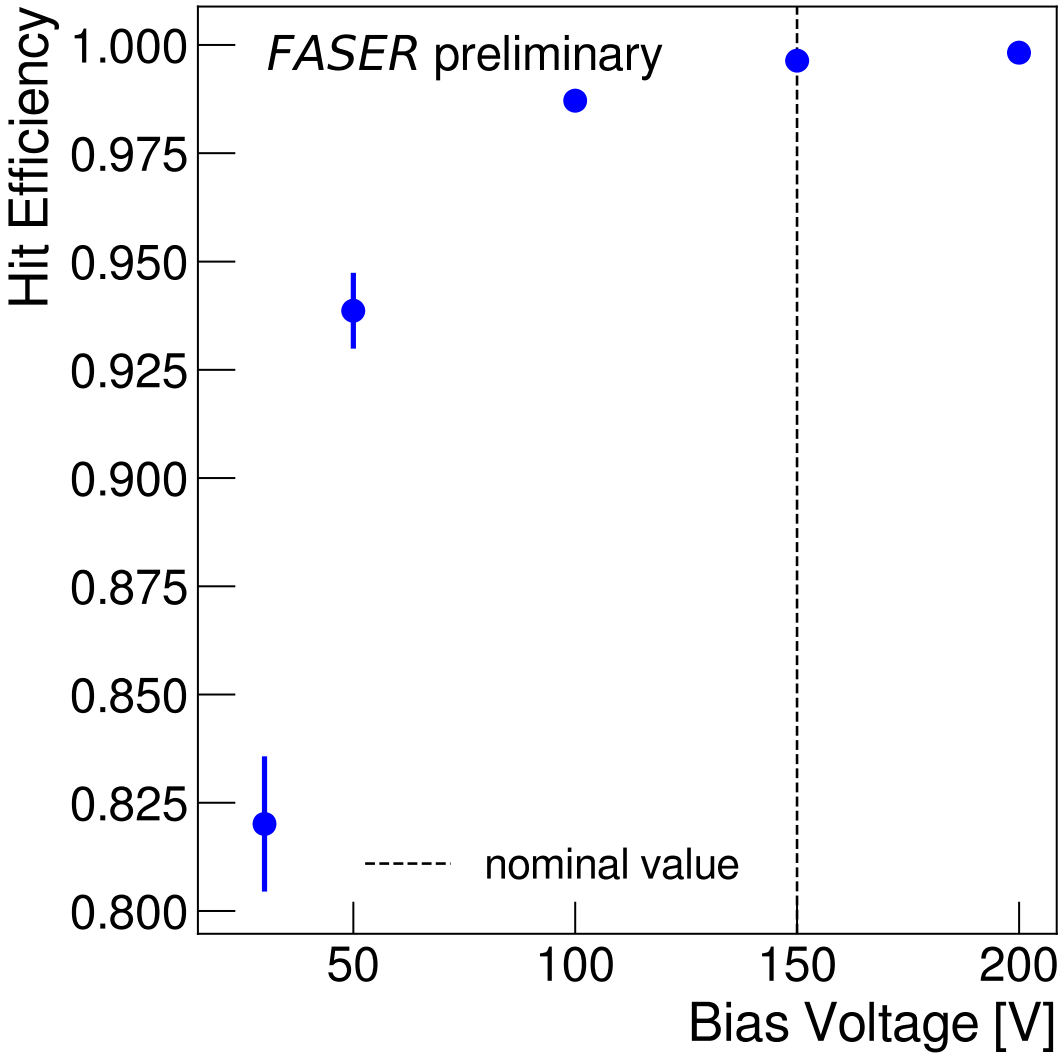




Tracker calibrations run periodically. Show excellent stability of tracker performance throughout the year.
Number of dead/noisy strips constant and <0.1%.

Tracker Performance

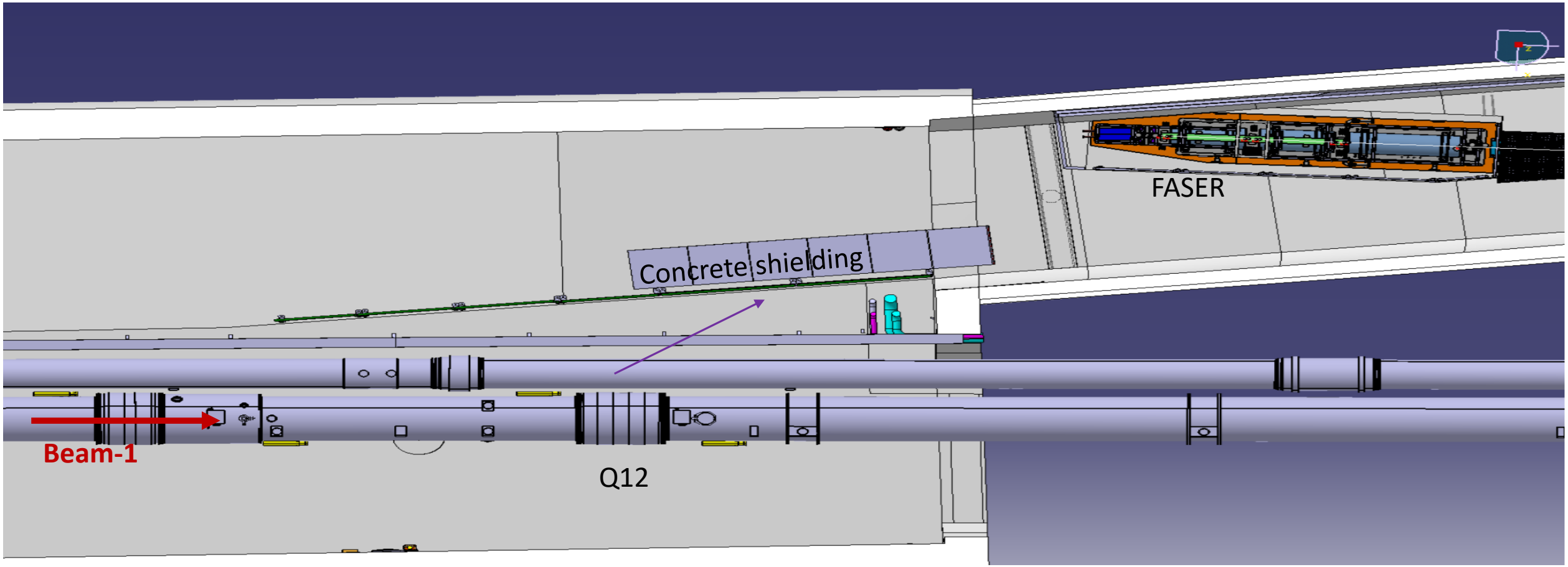




Tracker hit efficiency as a function of threshold and bias voltage, measured in collision data.
Observe as expected very high efficiency >99.6%.

Beam-1 background

- When beam-1 bunches pass the back of FASER (on way to ATLAS) they can lead to background in the detector. This background is ~3.2µs (127 BCs) too early compared to particles coming from IP1 to FASER
- After observing this in the pilot beam test in Nov 2021, concrete shielding installed at back of FASER to reduce this background



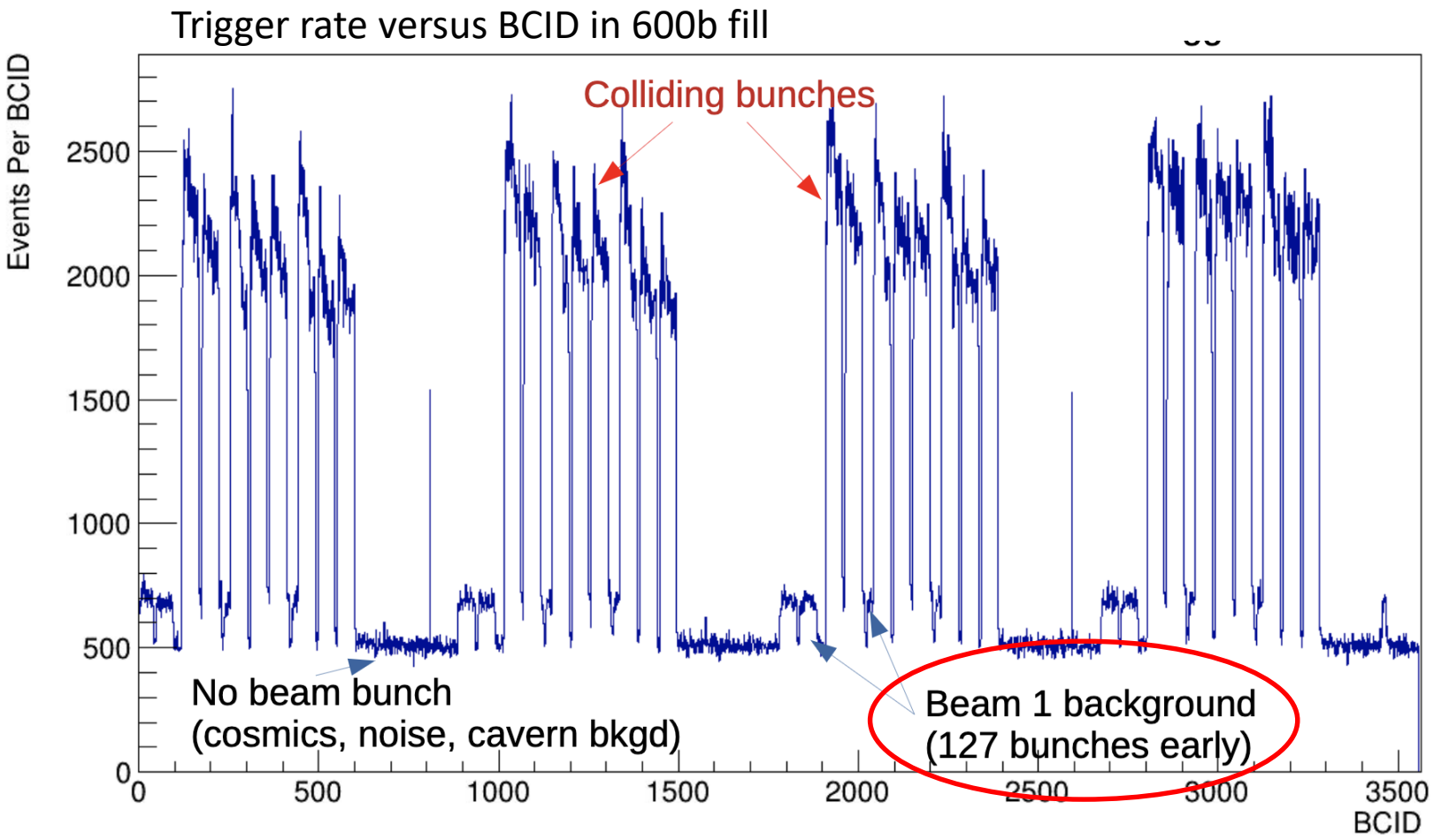
Beam-1 interactions in Q12 magnet can lead to background particles in FASER

Beam-1 background

- When beam-1 bunches pass the back of FASER (on way to ATLAS) they can lead to background in the detector. This background is ~3.2µs (127 BCs) too early compared to particles coming from IP1 to FASER
- After observing this in the pilot beam test in Nov 2021, concrete shielding installed at back of FASER to reduce this background

Beam-1 background

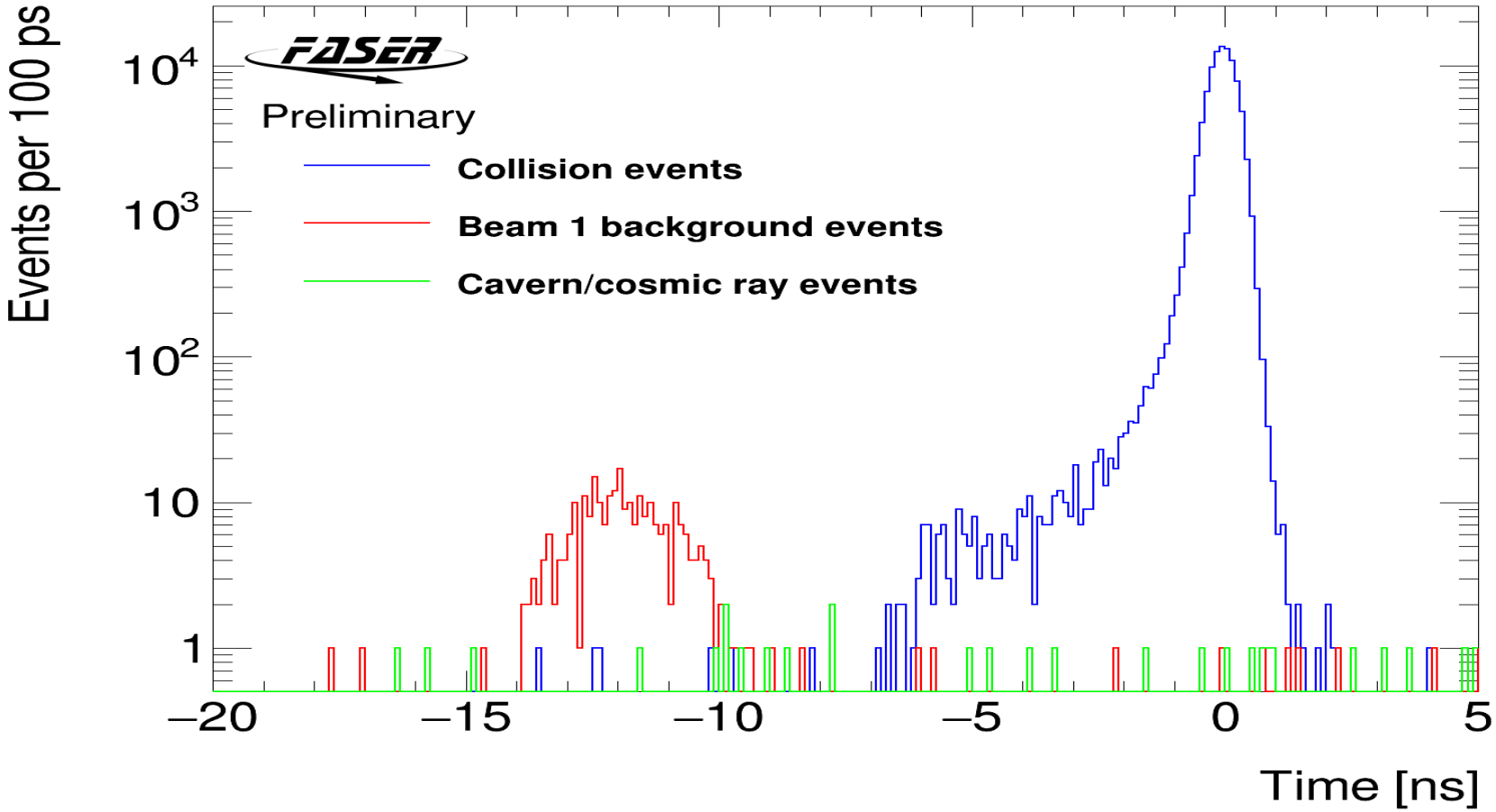
- When beam-1 bunches pass the back of FASER (on way to ATLAS) they can lead to background in the detector. This background is ~3.2µs (127 BCs) too early compared to particles coming from IP1 to FASER
- After observing this in the pilot beam test in Nov 2021, concrete shielding installed at back of FASER to reduce this background



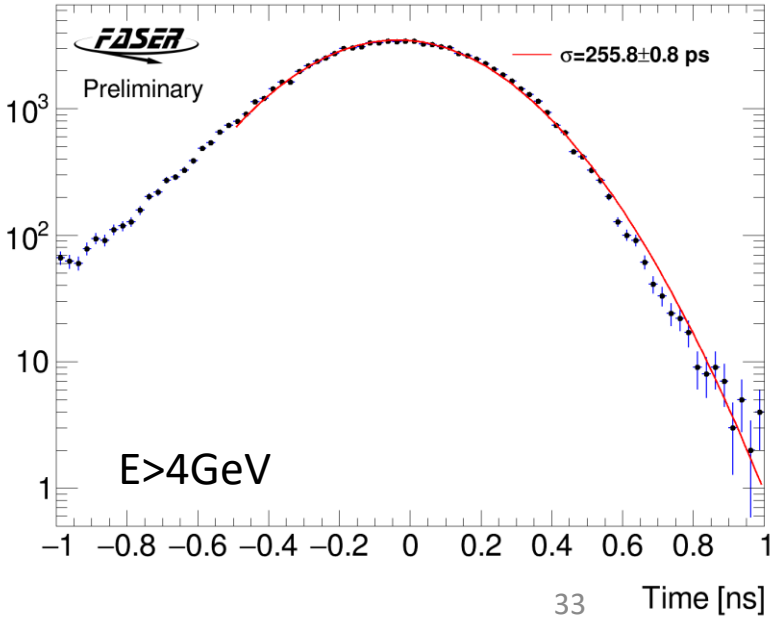
When LHC running with small number of bunches (600b in this plot), can identify specific BCs corresponding to beam-1 background and with no colliding bunch in IP1.

Beam-1 background

- When beam-1 bunches pass the back of FASER (on way to ATLAS) they can lead to background in the detector. This background is ~3.2µs (127 BCs) too early compared to particles coming from IP1 to FASER
- After observing this in the pilot beam test in Nov 2021, concrete shielding installed at back of FASER to reduce this background

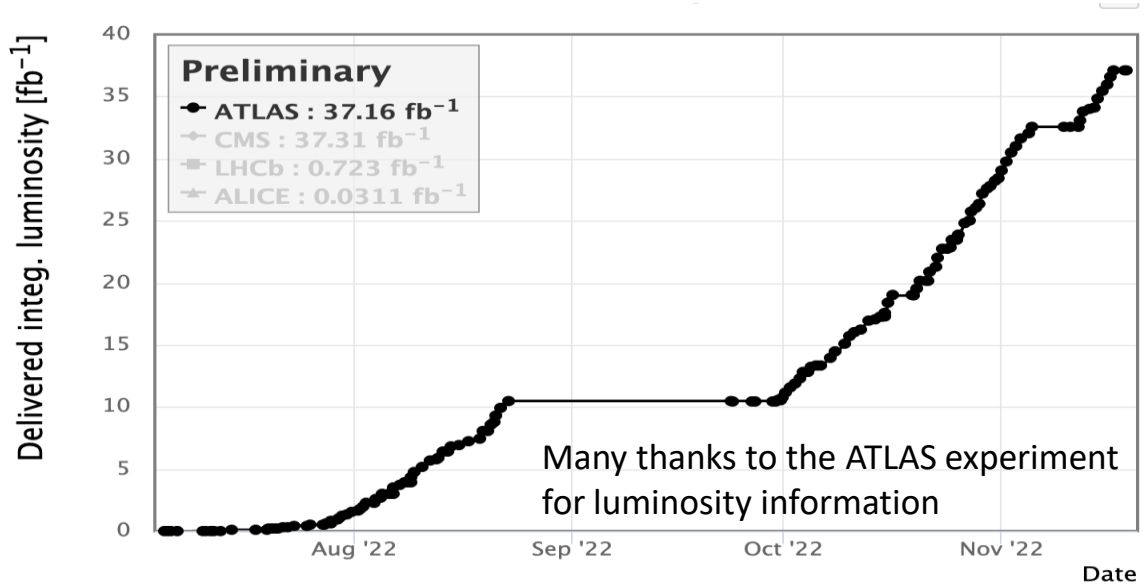


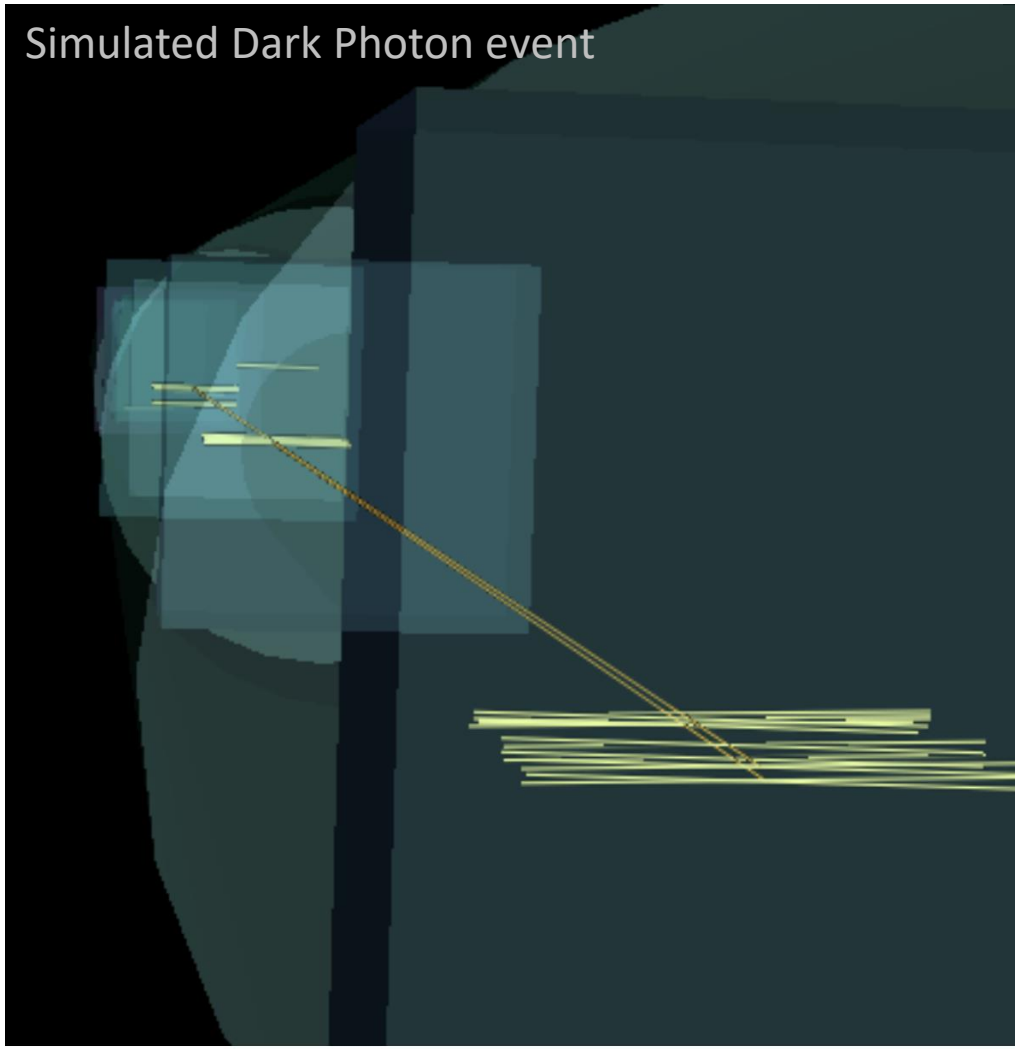
Beam-1 background can be efficiently removed by using calorimeter timing.
Excellent timing resolution for large energy signals (<300ps)



Current Status

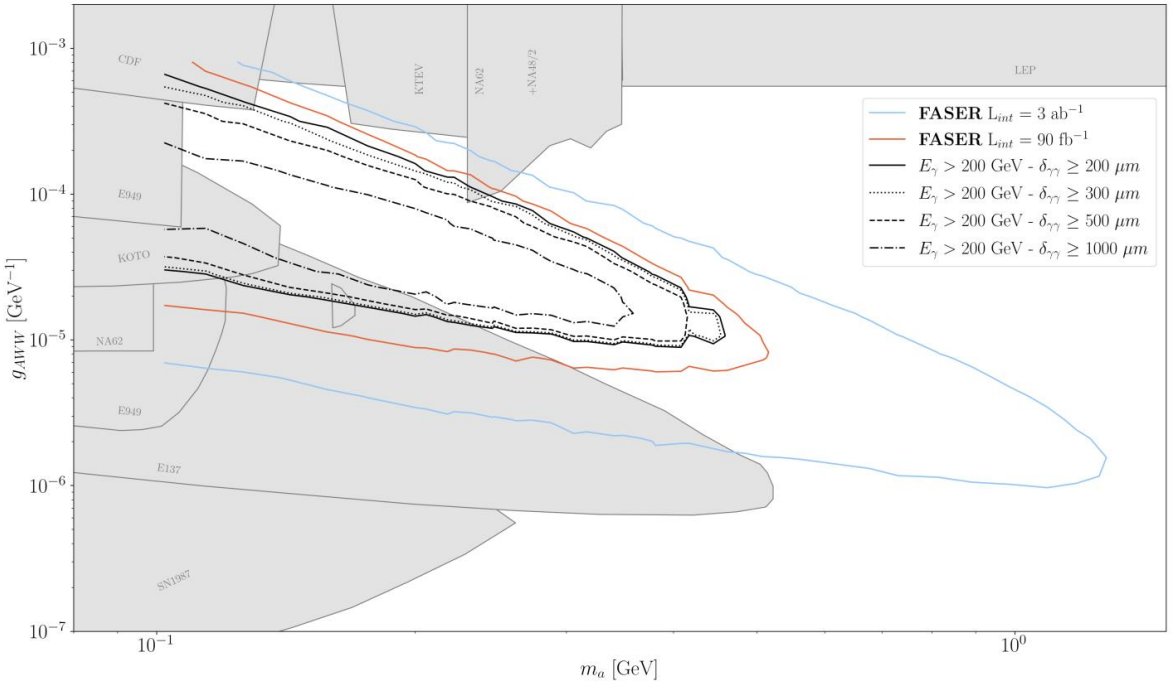
- Detector operations proceedings very well
- Detector performance studies with collision data ongoing, so far showing excellent performance
- Full simulation/analysis chain up and running and validated
- Physics studies ongoing, hoping for first results in Q1 next year

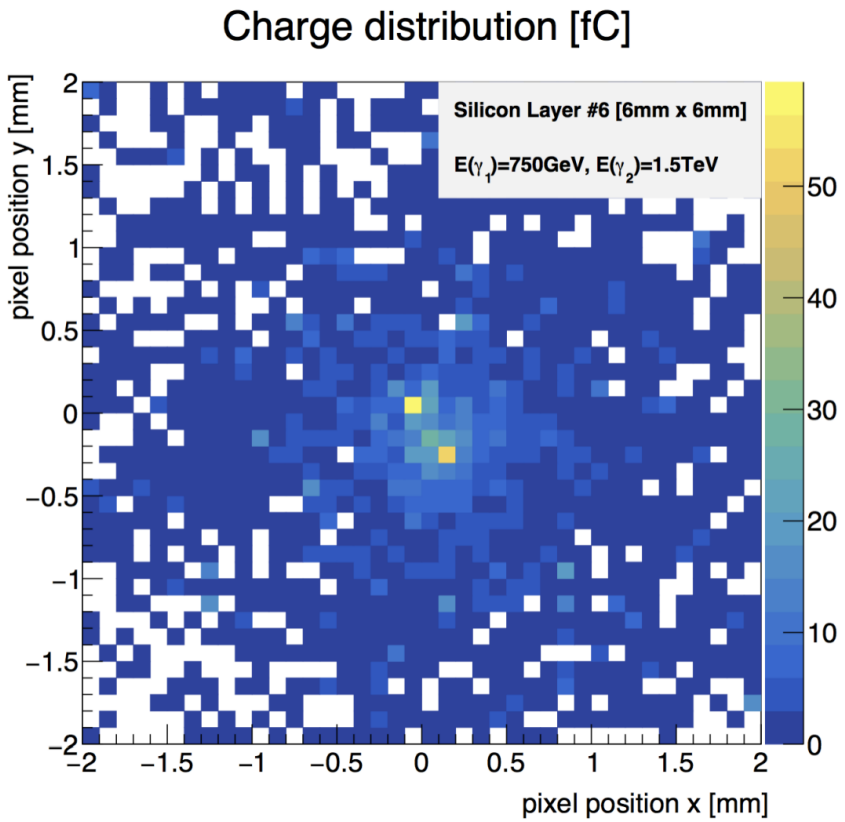




Pre-shower Upgrade

- Current detector problematic for new particles decaying to 2 photons (such as ALPs)
  - Given low mass and large boost resulting photons are very closely spaced (<1mm separation)
- Current detector could detect events with large energy in calorimeter, but this suffers from background from neutrino interactions inside the calorimeter
  - First case of neutrino interactions as a background for collider searches?
- New high granularity silicon pixel / tungsten preshower under development to be able to identify 2 closely spaced photon signature
  - Sensitivity to photon spacing down to 200µm!
- Project approved by CERN in April 2022
  - Technical Proposal: CERN-LHCC-2022-006



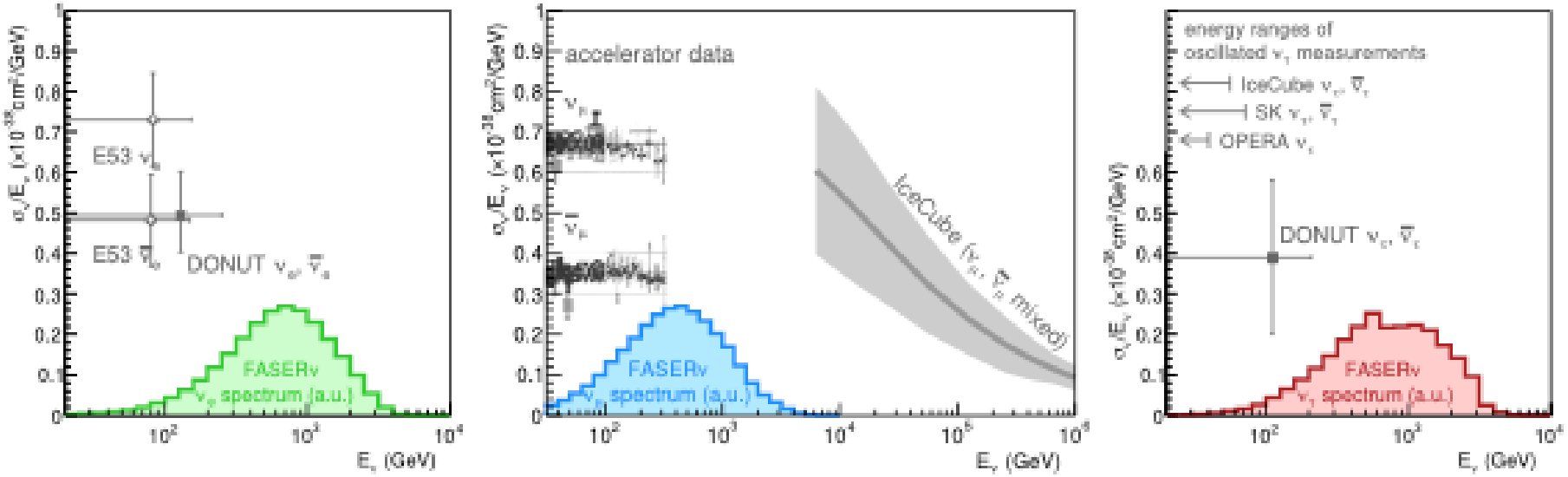


Simulated charge seen in preshower 6th layer, from 2 photons (1 TeV, 750 GeV) separated by 0.2mm.

FASER Neutrino Measurements

A huge number of neutrinos produced in the LHC collisions (hadron decay) traverse the FASER location covering an unexplored neutrino energy regime.
FASERν is an emulsion/tungsten detector placed in front of the main FASER detector to detect neutrino's of all flavours.

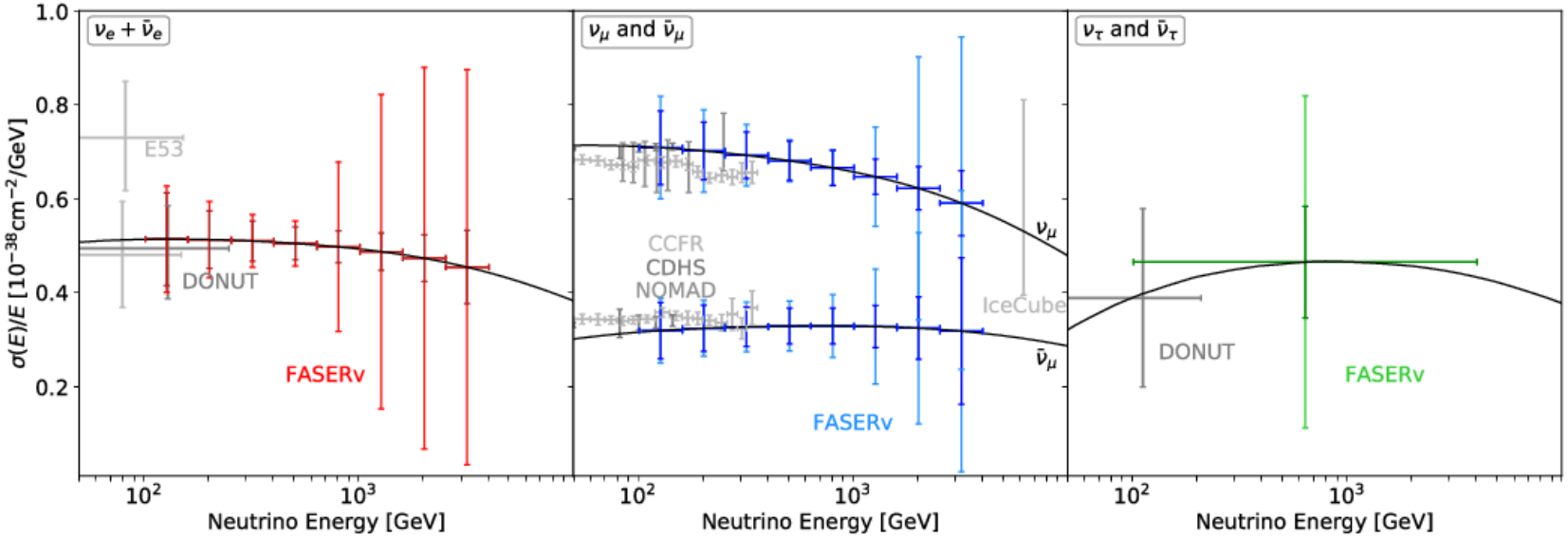
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERν 25cm x 30cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERν (1.1tn Tungsten)	~1300	~20000	~20



FASER Neutrino Measurements

A huge number of neutrinos produced in the LHC collisions (hadron decay) traverse the FASER location covering an unexplored neutrino energy regime.
FASERν is an emulsion/tungsten detector placed in front of the main FASER detector to detect neutrino's of all flavours.

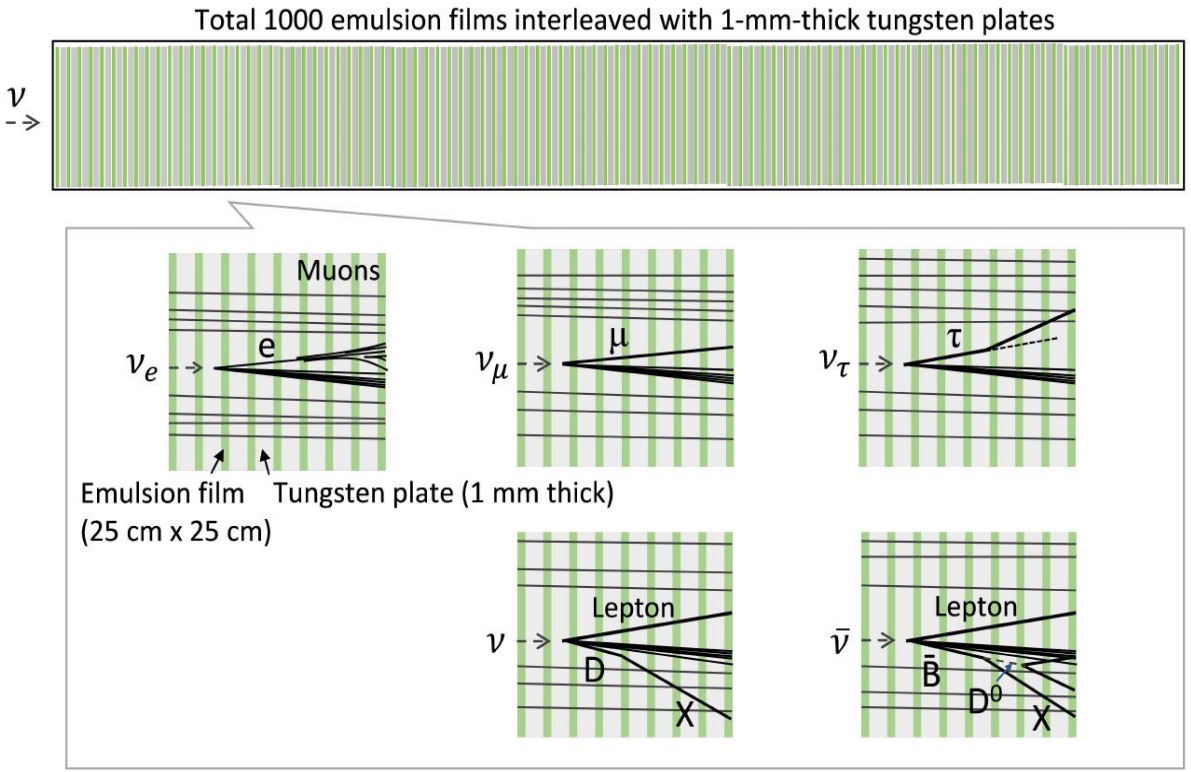
Primary physics goal – cross section measurements at high energy.
Projected results (150/fb):



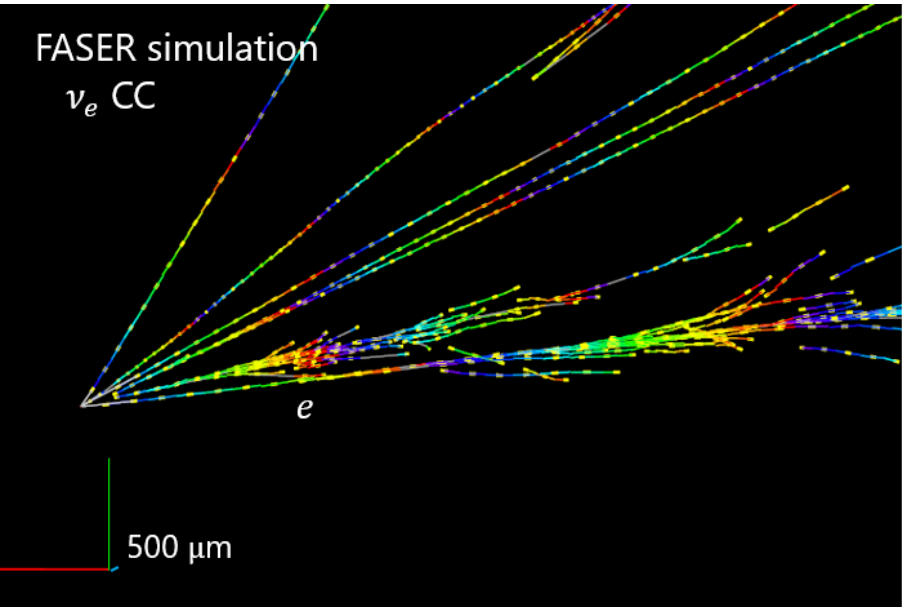
Matching muon track associated with vertex in emulsion detector with spectrometer will allow to measure ν_μ / $\bar{\nu}_\mu$ separately.
Uncertainty from neutrino production important
Neutrino energy reconstruction with resolution ~30% expected from simulation studies

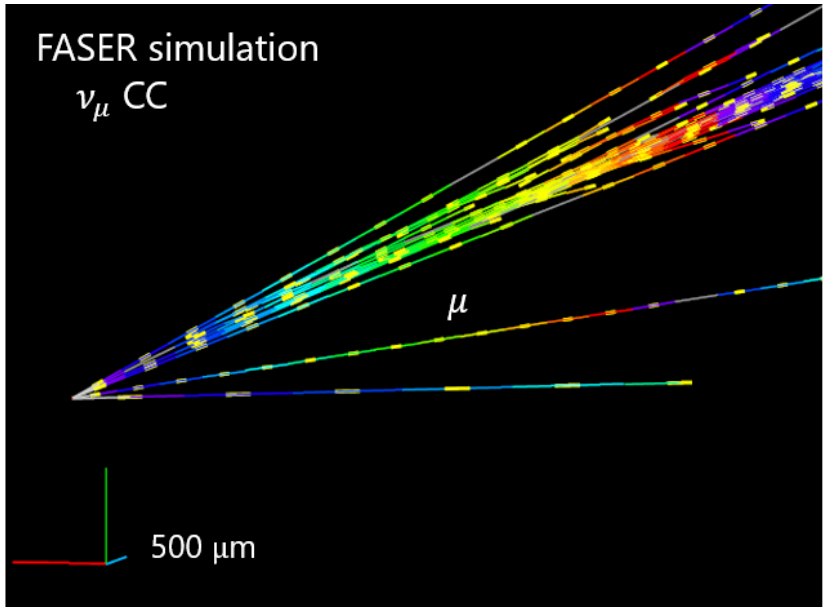
FASERν Detector

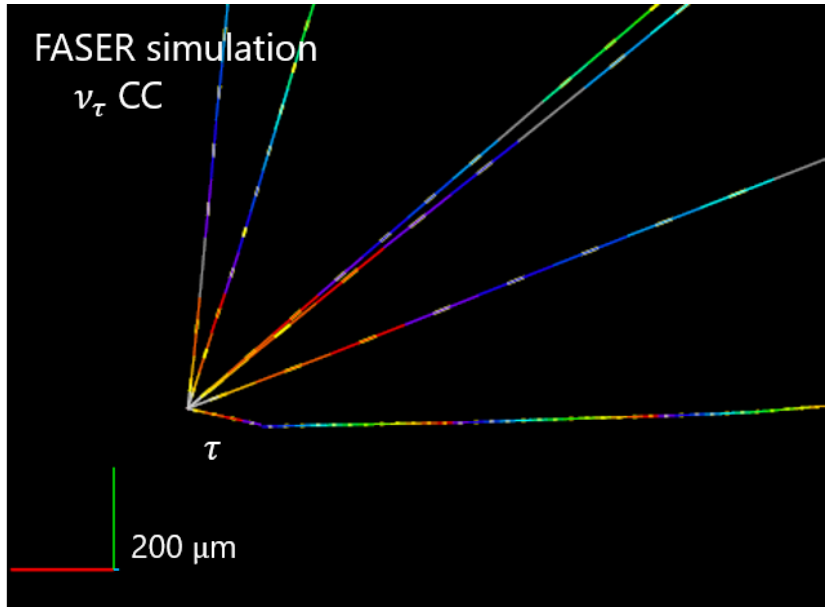
- FASERν detector is 1m long, 30x25cm 1.1tn detector
- Made from 730 x 1.1mm tick tungsten plates, interleaved with emulsion films
- Allows to distinguish all flavour of neutrino interactions and neutral hadron vertices
- Emulsion film has excellent position/angular resolution for charged particle tracks
- But no time resolution…
- Detector needs to be replaced every 30-50/fb to keep the track multiplicity manageable
- Replaced during Technical Stops during LHC running (usually 3 times / year)
    - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER



FASERν Simulated Signal Events

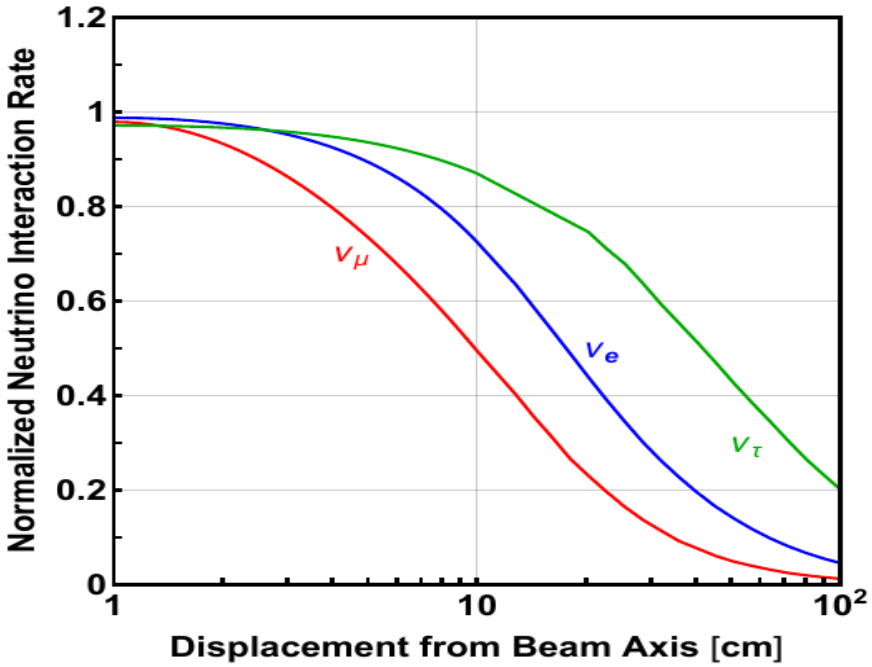


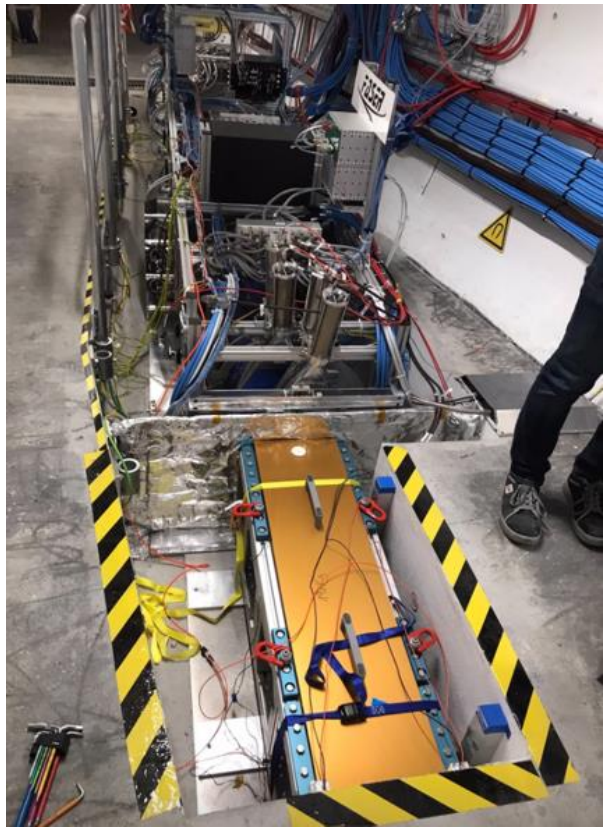




FASERν Detector

- FASERν detector is 1m long, 30x25cm 1.1tn detector
- Made from 730 x 1.1mm tick tungsten plates, interleaved with emulsion films
- Allows to distinguish all flavour of neutrino interactions and neutral hadron vertices
- Emulsion film has excellent position/angular resolution for charged particle tracks
- But no time resolution…
- Detector needs to be replaced every 30-50/fb to keep the track multiplicity manageable
- Replaced during Technical Stops during LHC running (usually 3 times / year)
    - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER
- FASERν is centered on the LOS (in the FASER trench)
    - Maximizes flux of all neutrino flavours

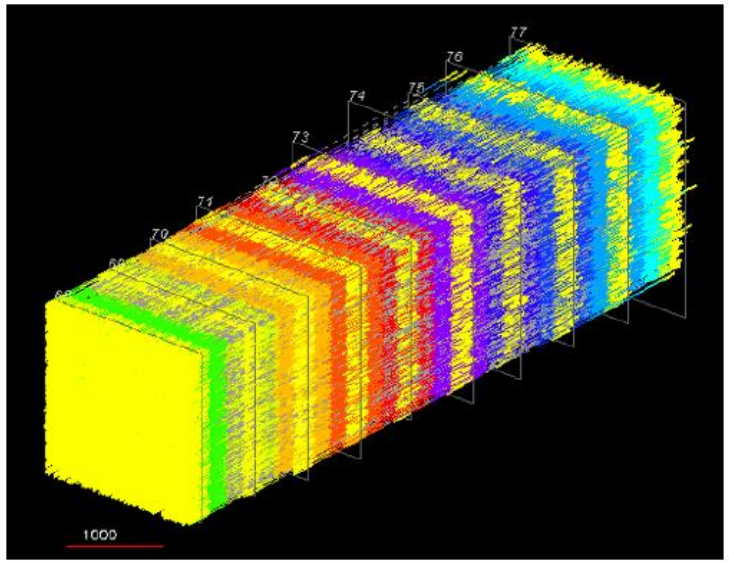




FASERν Pilot Run

PRD.104.L091101

- A small emulsion detector was installed in the FASER location during 2018 LHC running
  - 10 kg target mass after DQ /fiducial selections
  - Used to validate FLUKA simulation of background particle flux
- 12.2/fb data collected (~1 month)
- 18 neutral vertices identified
- Neutrino signal separated from muon induced neutral hadron background using a BDT
  - Exploiting the fact that neutrinos are much more energetic than neutral hadrons
  - Modelling of neutral hadron background validated using reconstructed charged vertices
- Best fit value of 6.1 neutrino interactions (3.3 expected)
  - 2.7sigma significance

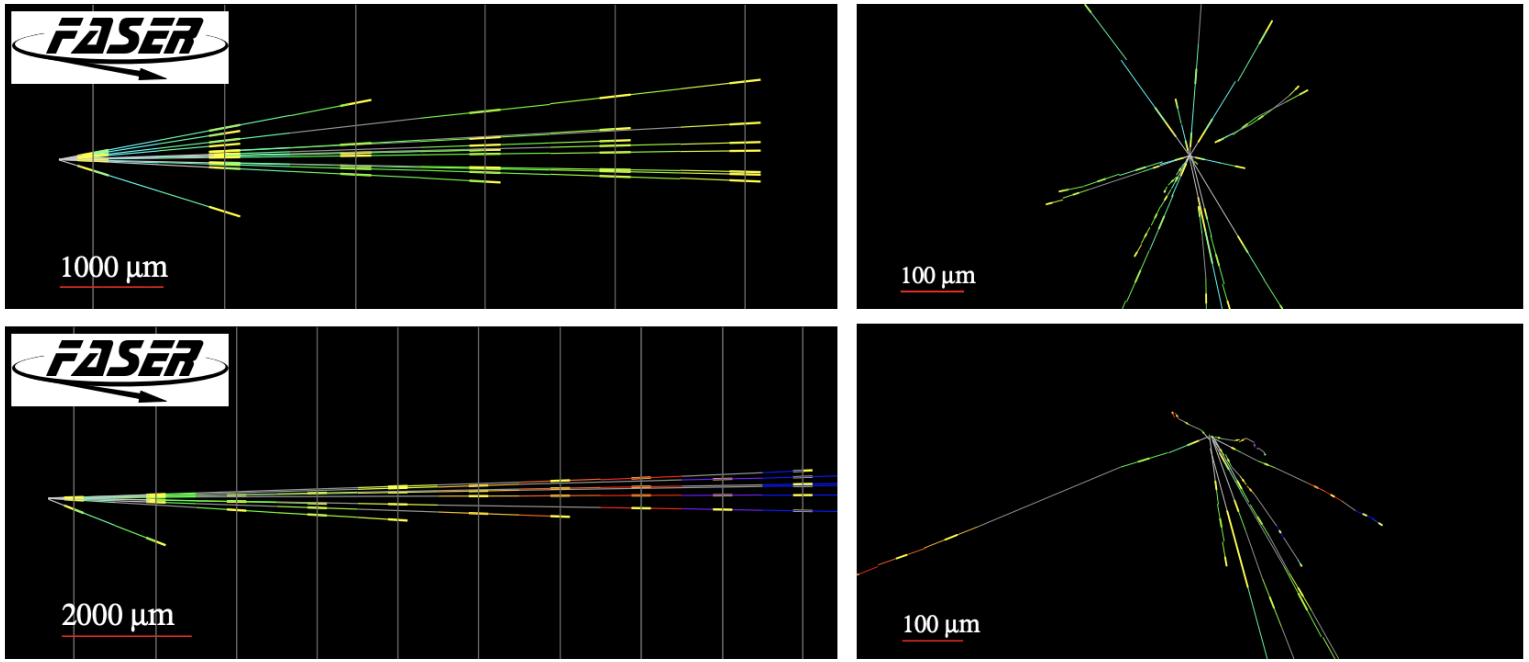


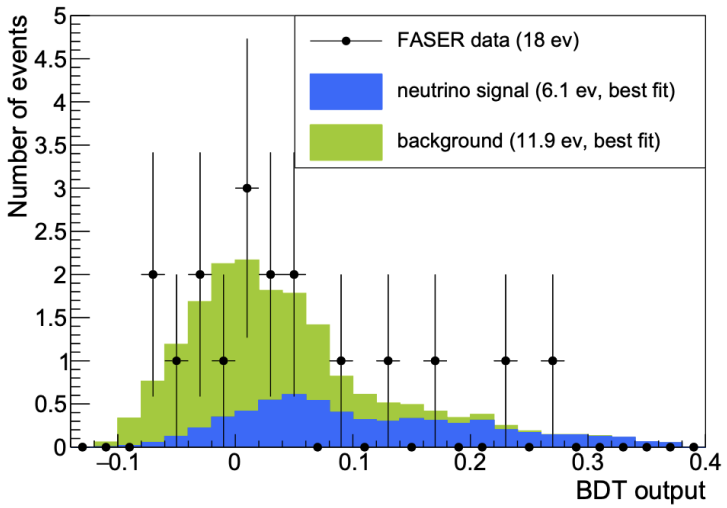
FASERν Pilot Run

PRD.104.L091101

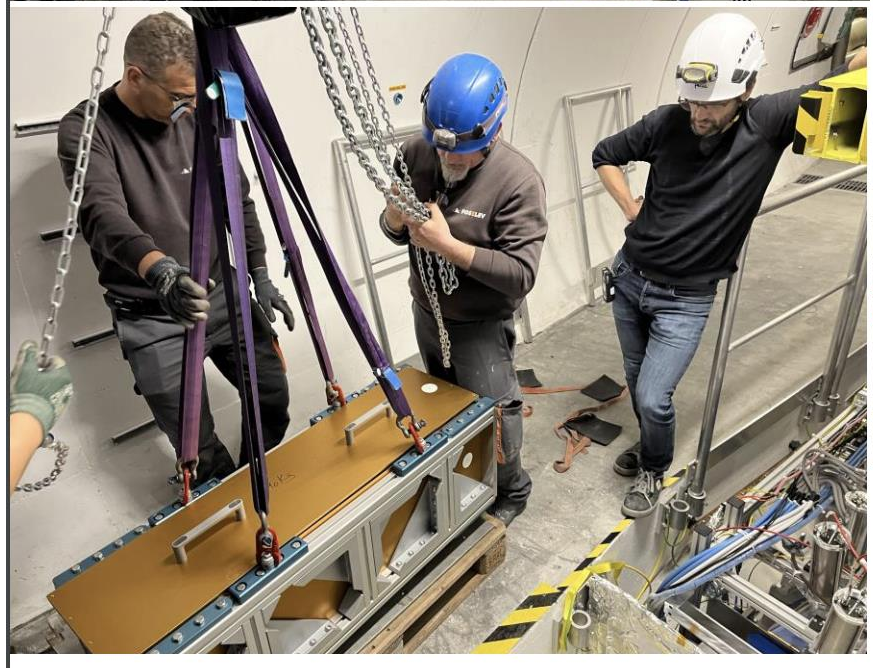
- A small emulsion detector was installed in the FASER location during 2018 LHC running
  - 10 kg target mass after DQ /fiducial selections
  - Used to validate FLUKA simulation of background particle flux
- 12.2/fb data collected (~1 month)
- 18 neutral vertices identified
- Neutrino signal separated from muon induced neutral hadron background using a BDT
  - Exploiting the fact that neutrinos are much more energetic than neutral hadrons
  - Modelling of neutral hadron background validated using reconstructed charged vertices
- Best fit value of 6.1 neutrino interactions (3.3 expected)
  - 2.7sigma significance

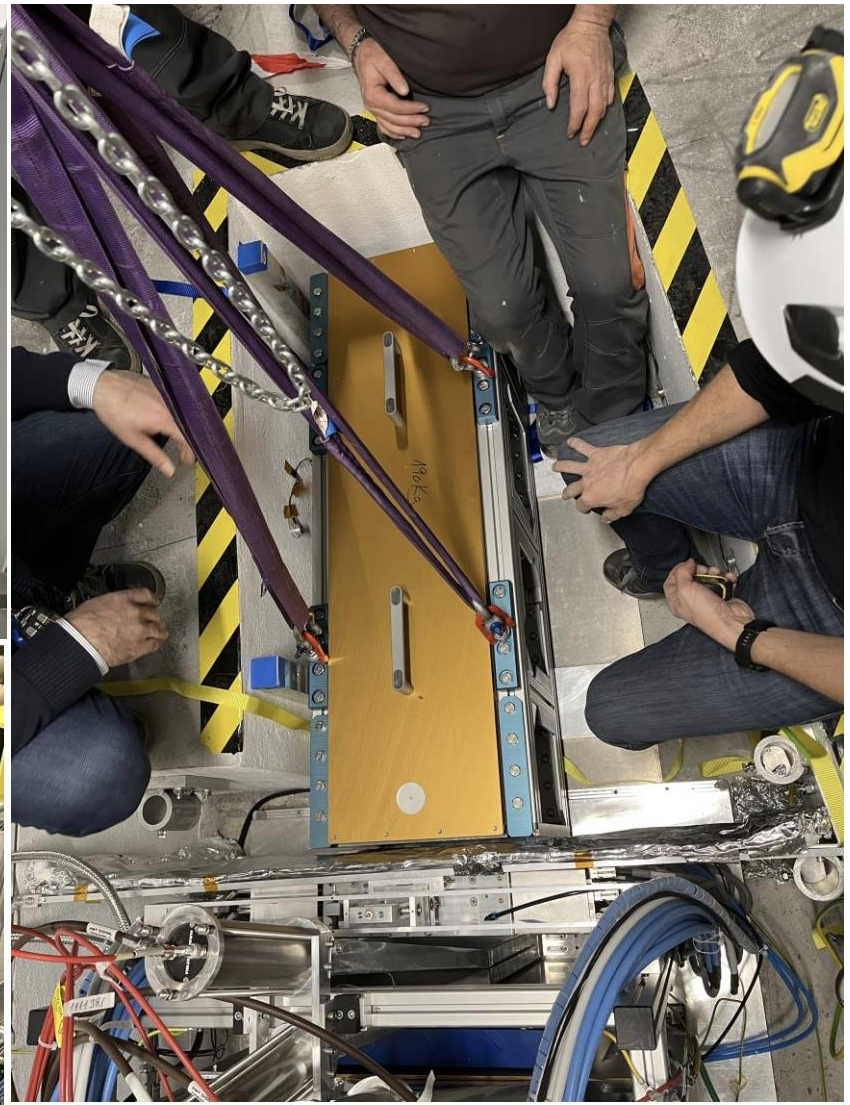
First candidate collider neutrino interactions!





FASERν Installation





FASERν

Workflow

In Japan

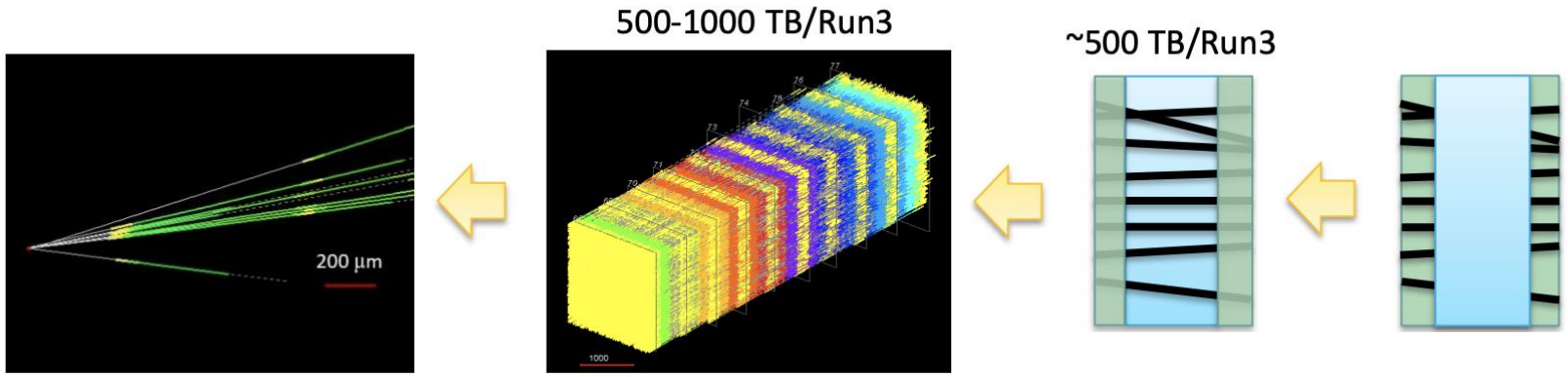
Emulsion film production → **At CERN**: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → **In Japan**: **Full area readout**

Off-line analysis

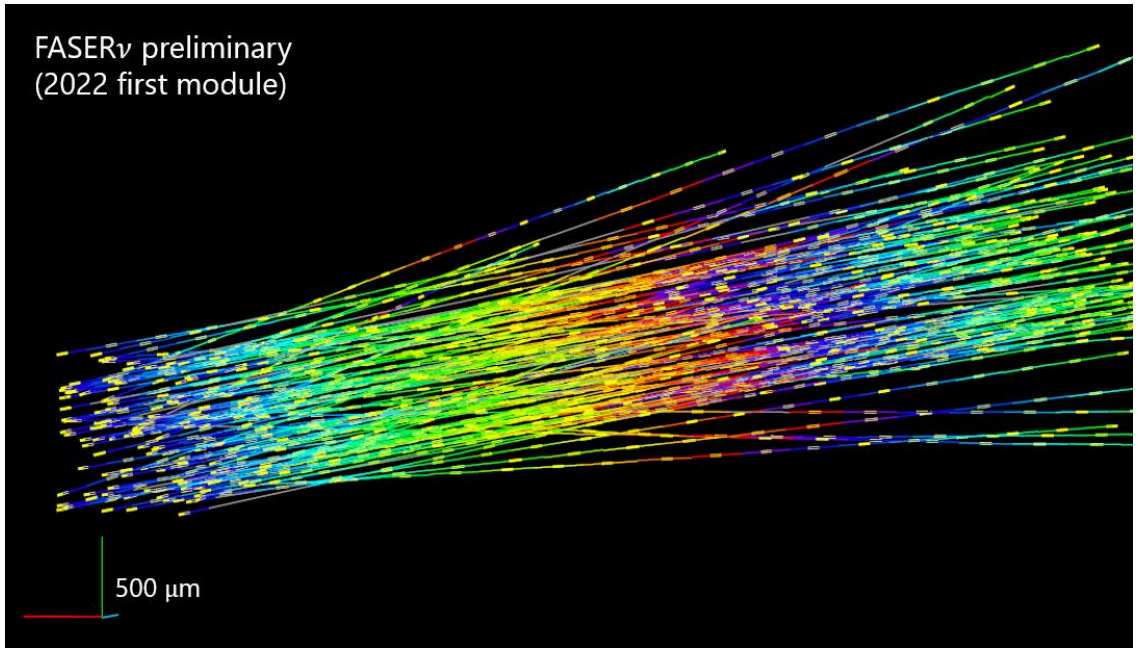
Alignment → **Track reconstruction** → **Vertex reconstruction** → **μ / e ID** → **Search for tau/charm decays** → **Kinematical analysis**

Interface tracker data

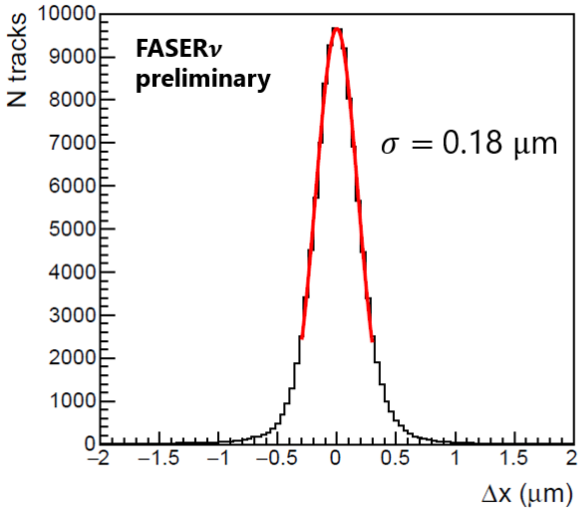
Spectrometer data

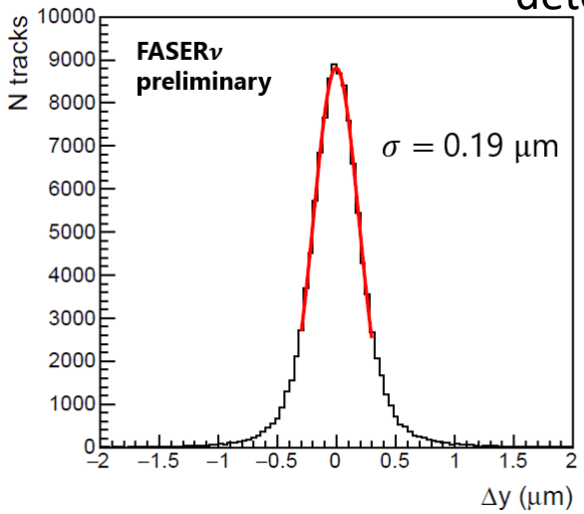


FASERν Detector Performance



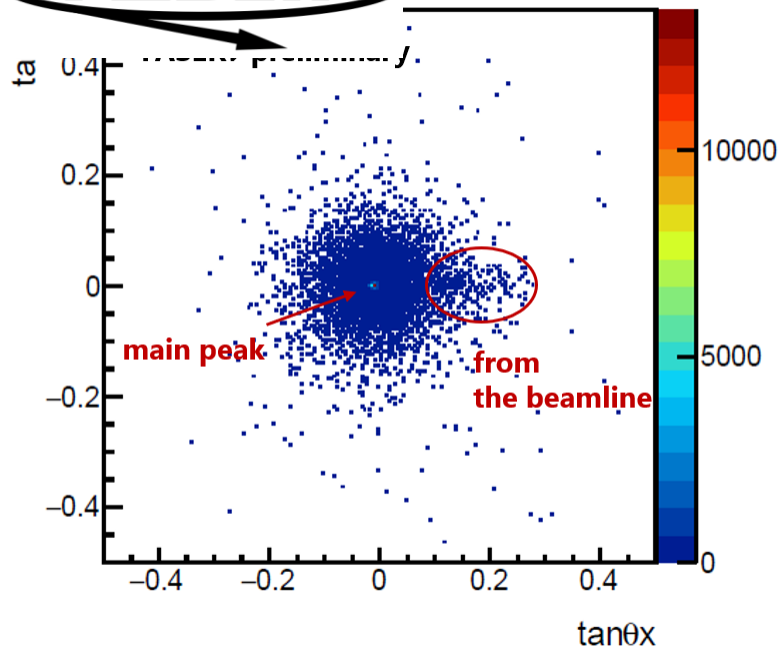
- First FASERν detector installed in FASER for first 4 weeks of data taking, 0.5/fb of data
- Used to commission the assembly, development, scanning, reconstruction, analysis chain
- Measured track multiplicity:
  - ~2×10^4 cm^{-2} / fb^{-1}
  - ~1×10^4 cm^{-2} / fb^{-1} within 10mrad of angular peak
- Consistent with expectation (from FLUKA simulation and 2018 in situ measurements)
- Very good tracking performance (residual <0.5μm)
- Second detector exposed to 10/fb of data, and third detector still in place with >25/fb of exposure so far…

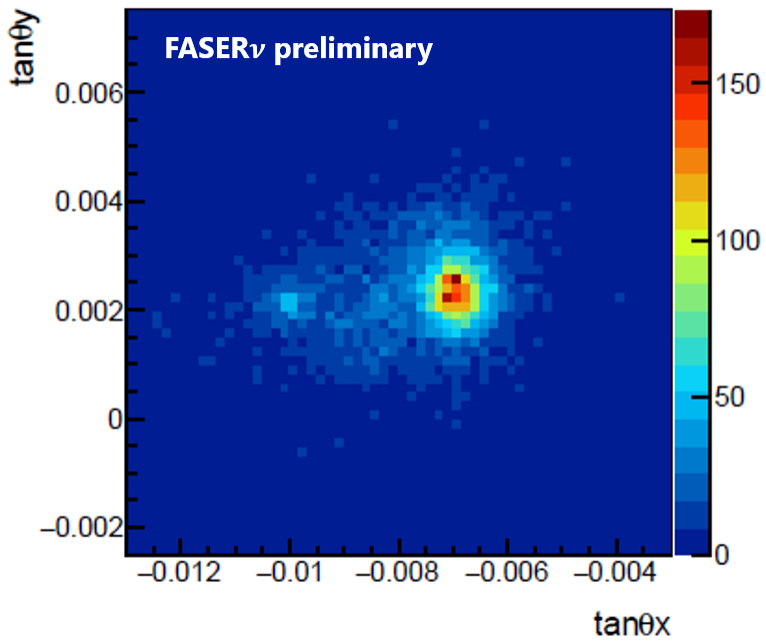




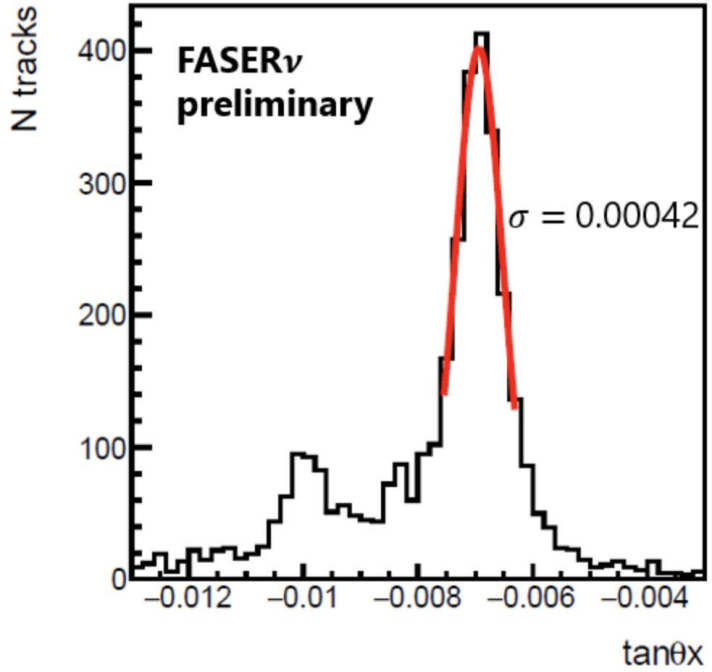
		Integrated luminosity per module (fb^{-1})	N ν int. expected
2022 1st module	Mar 15 – Jul 26	0.5	~7
2022 2nd module	Jul 26 – Sep 13	10.6	~530
2022 3rd module	Sep 13 – Nov 29	(~20)	(~1000)

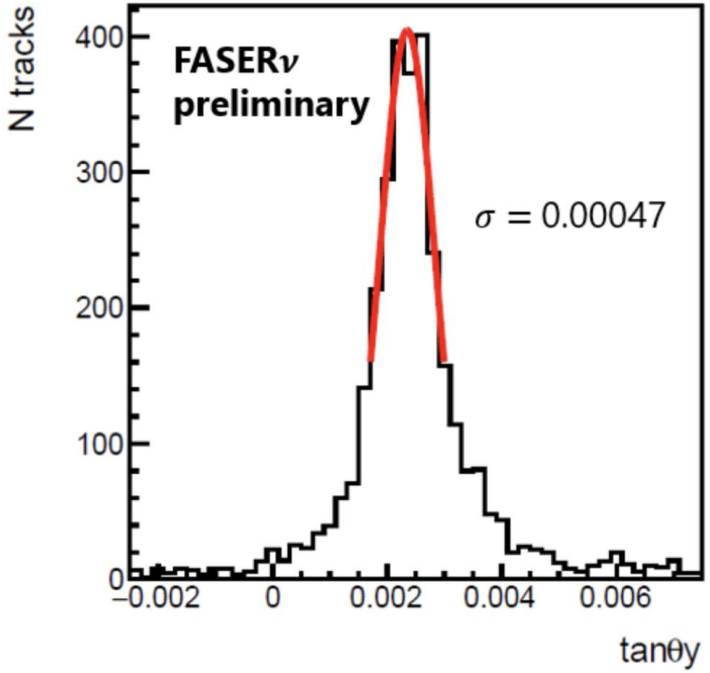
FASERν Results





Angular distributions observed from analysis of first FASERnu box.
The angular coordinates (0, 0) roughly corresponds to the LOS .
There are two peaks separated by 0.003 rad. Both peaks are consistent with particles arriving from the beam line in the vertical plane. The origin of the two-peak structure is under investigation with simulation studies.

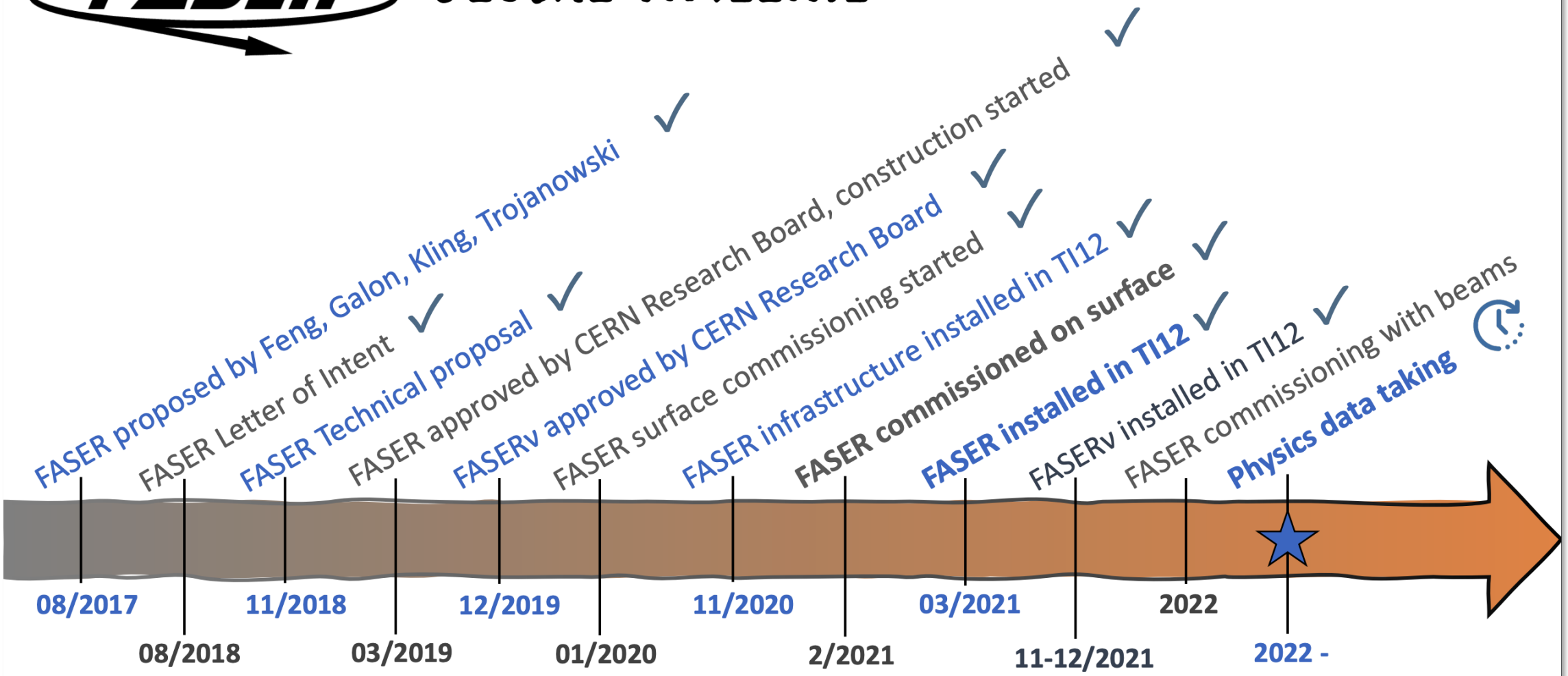




Angular spread consistent with mulitple scattering in ~100m of rock for particle of several hundred GeV. (2mrad corresponds to 270GeV).

Slide from A. Sfyrla

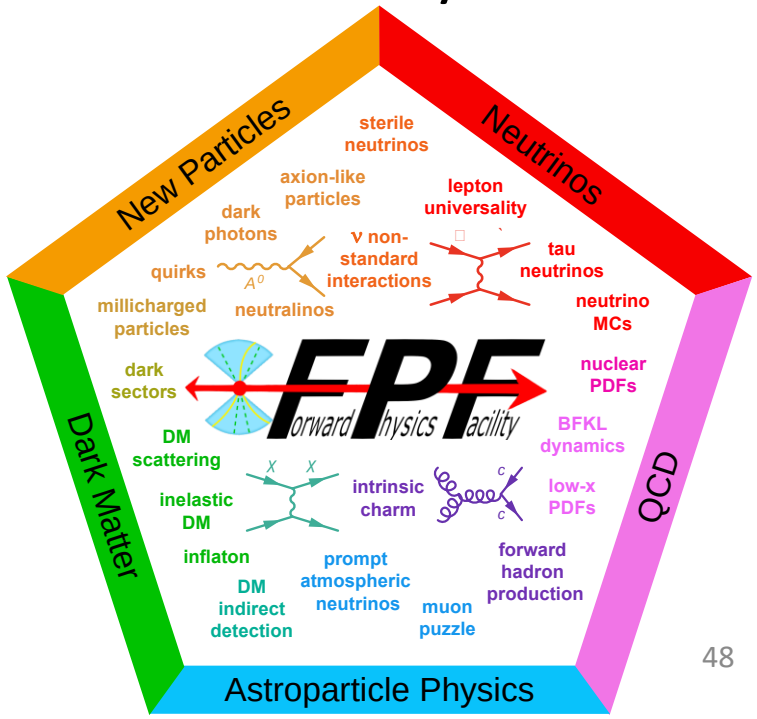
FASER Global Timeline



And now to the future….

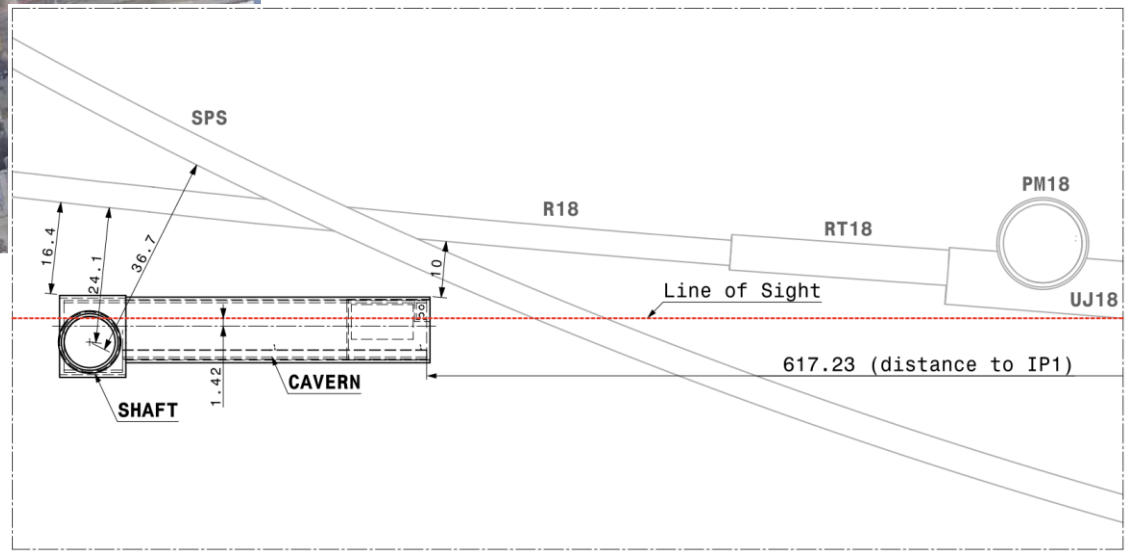
The Forward Physics Facility

- FASER has exciting physic prospects for LHC Run 3
- However, it has become clear that in order to take maximum advantage of the physics in the very forward region of the LHC collisions in the HL-LHC era we need to increase the experimental capabilities
- Unfortunately the FASER location does not allow room for new or larger detectors to be installed on the LOS
- The Forward Physics Facility (FPF) is a proposal to create a new facility to enable a suite of new experiments to be situated on the LOS
  - The FPF has a rich and broad physics programme
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Neutrino physics
  - QCD physics



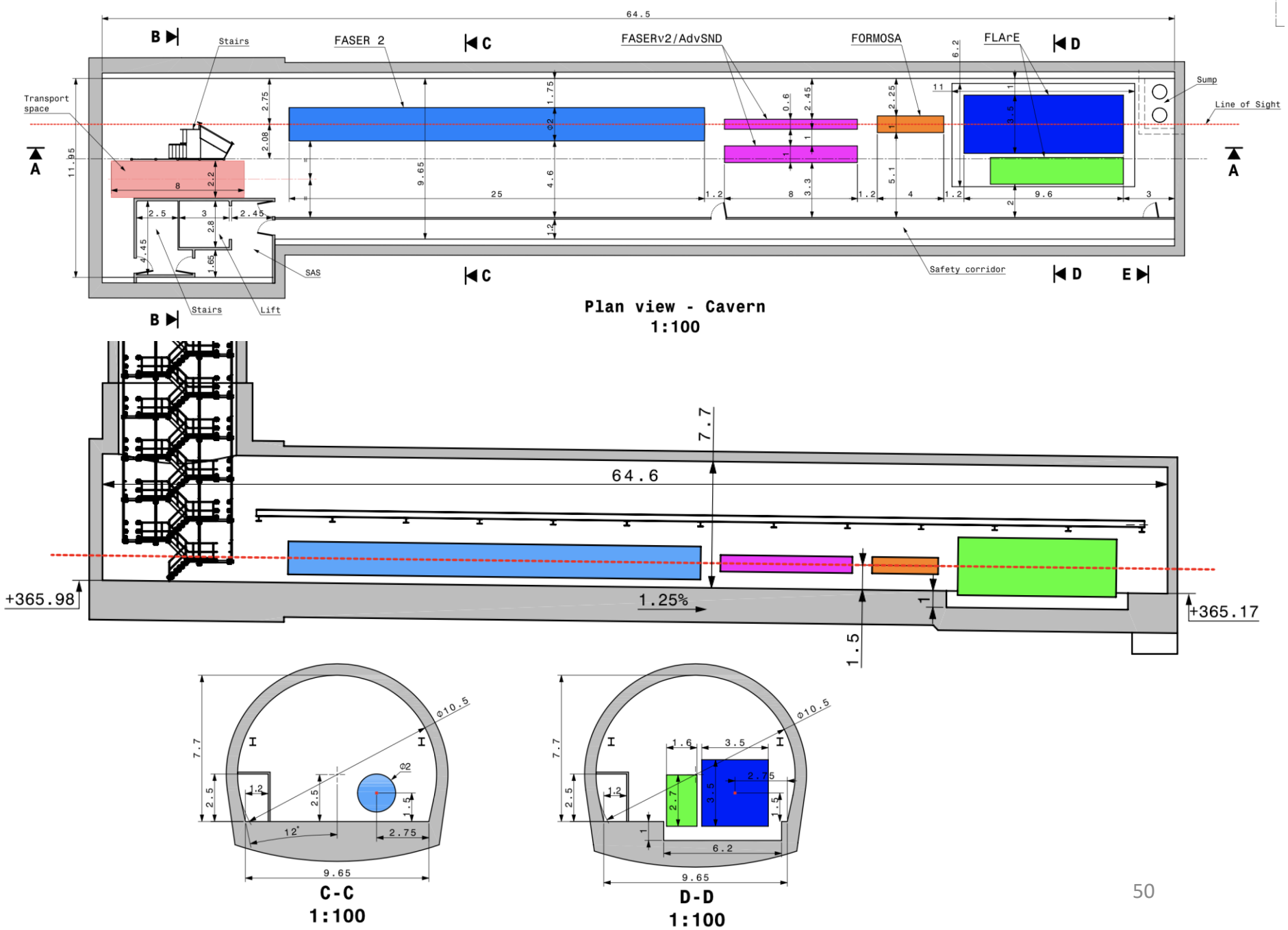
FPF Location

After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points have now converged on the dedicated new facility in the SM18 area as the baseline proposal. This is ~600m from the ATLAS IP (to the west), and is situated on CERN land.



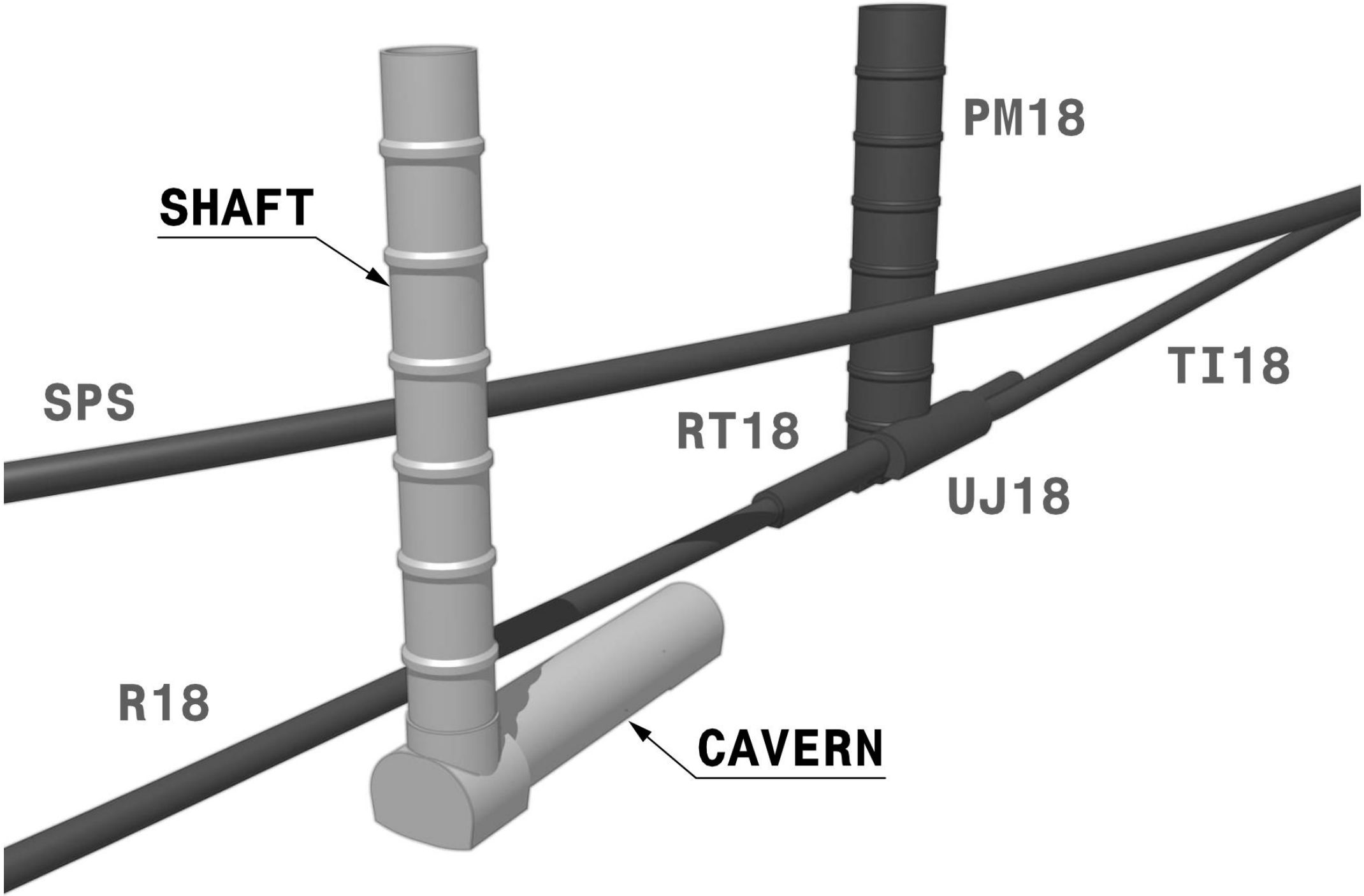
FPF Facility:

65m long, 9.7m wide, 7.7m high cavern.
Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.



FPF Facility

65m long,
cavern.
Connected
88m high s
617m from



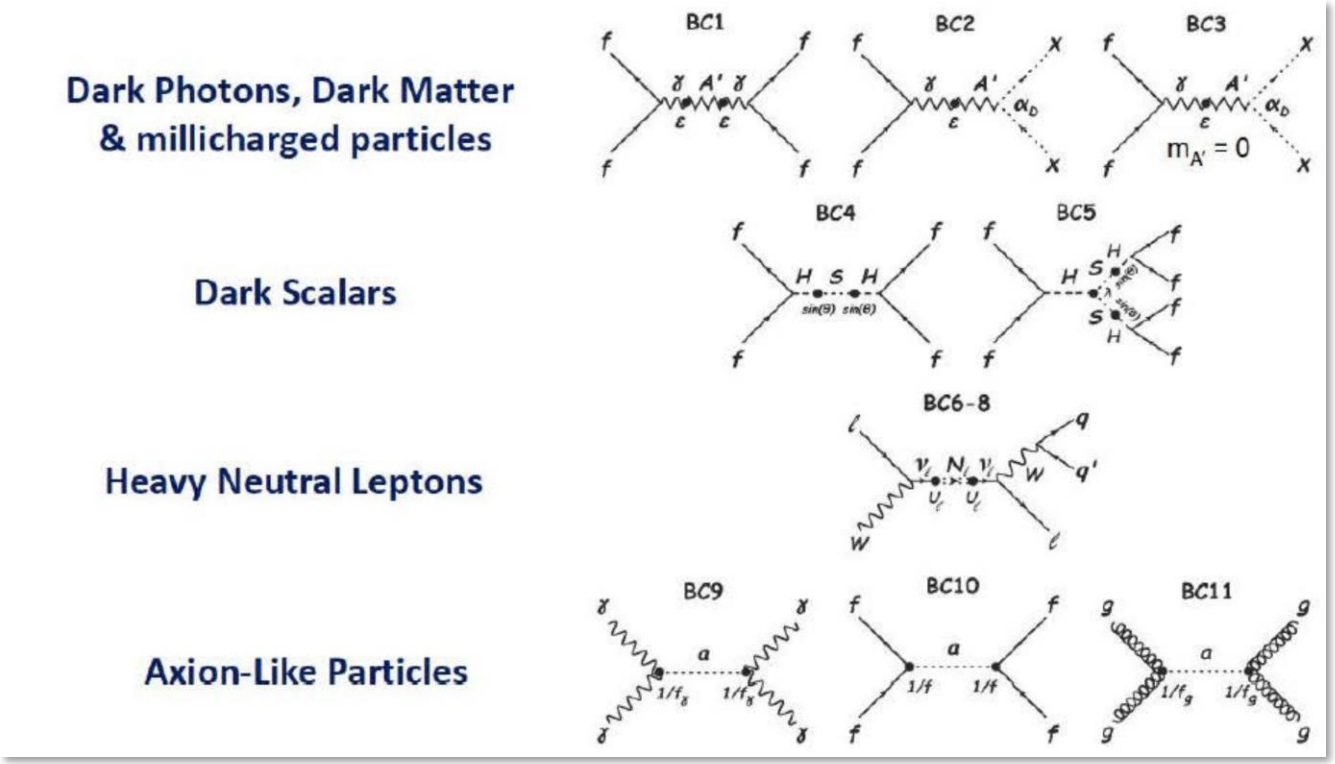
Currently proposed FPF experiments

At the moment there are 5 proposed experiments to be situated in the FPF.
With different capabilities and covering different rapiditiy regions:

- FLArE
  - $\mathcal{O}$(10tn) LAr TPC detector
  - DM scattering
  - Neutrino physics (ν_μ/ν_e , capabilitty for ν_τ under study)
    - Full view of neutrino interaction event
- FASERv2
  - $\mathcal{O}$(20tn) emulsion/tungsten detector (FASERv x20)
    - Mostly for tau neutrino physics
  - Interfaced to FASER2 spectrometer for muon charge ID ($\nu_\tau/\overline{\nu}_\tau$ separation)
- AdvSND
  - Neutrino detector slightly off-axis
    - Provides complementary sensitvity for PDFs from covering different rapidity to FASERv2
- FASER2
  - Detector for observing decays of light dark-sector particles
  - Similar to scaled up version of FASER (1m radius vs 0.1m)
    - Increases sensitivity to particles produced in heavy flavour decay
  - Larger size requires change in detector and magnet technology: Superconducting magnet
- FORMOSA
  - Milicharged particle detector
  - Scintillator based, similar to current miliQan experiment

BSM at FPF

The set of most popular dark-sector models compiled as benchmarks by CERN Physics Beyond Colliders (PBC) group:



FPF experiments would give significant new sensitivity in all of these models.

Proposed dedicated new experiments for milicharged particles and scattering of dark matter particles.

No FASER sensitivity

Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	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 2
BC10: ALP with fermion	FASER 2
BC11: ALP with gluon	FASER 2

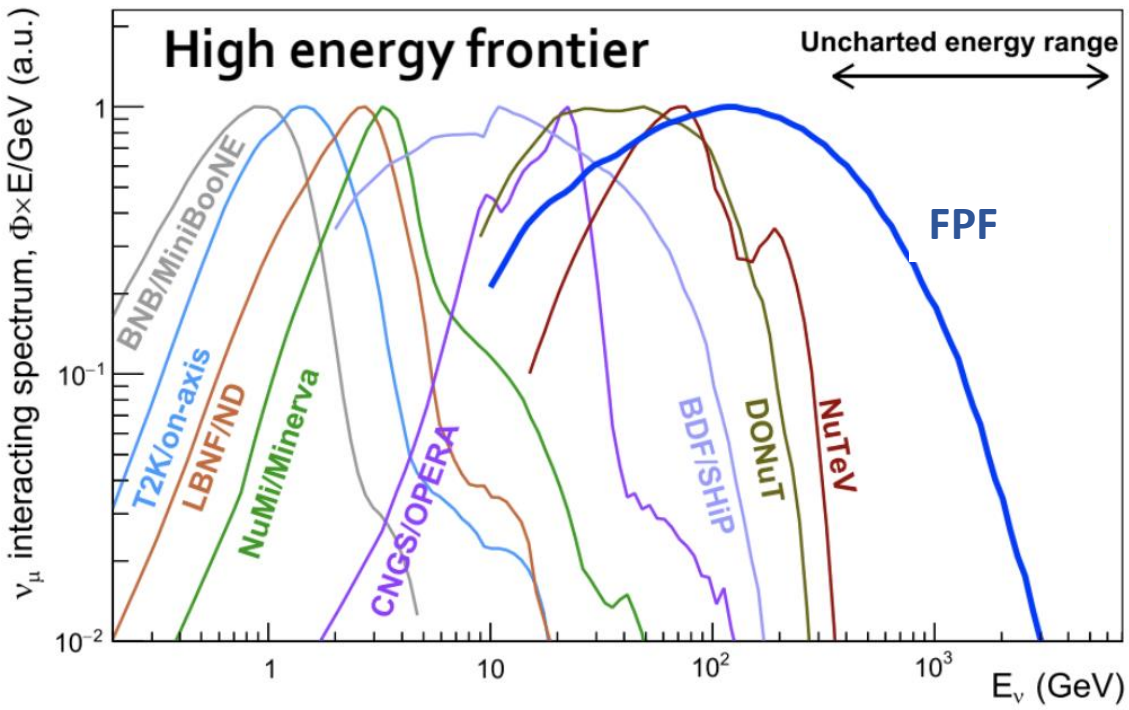
https://arxiv.org/pdf/2105.08270.pdf (F. Kling, DESY)

Neutrinos at the FPF

A ***huge number of high-energy neutrinos of all flavours*** will be detected by experiments at the FPF.

Species	#evts* (20tn, 3/ab)	
ν_e	115k	~180k
$\bar{\nu}_e$	65k	
ν_μ	875k	~1M
$\bar{\nu}_\mu$	225k	
ν_τ	1.7k	~2.5k
$\bar{\nu}_\tau$	0.7k	

Highest energy neutrinos from a terrestrial source.
Typical energy of interacting neutrinos on LOS ~900 GeV.

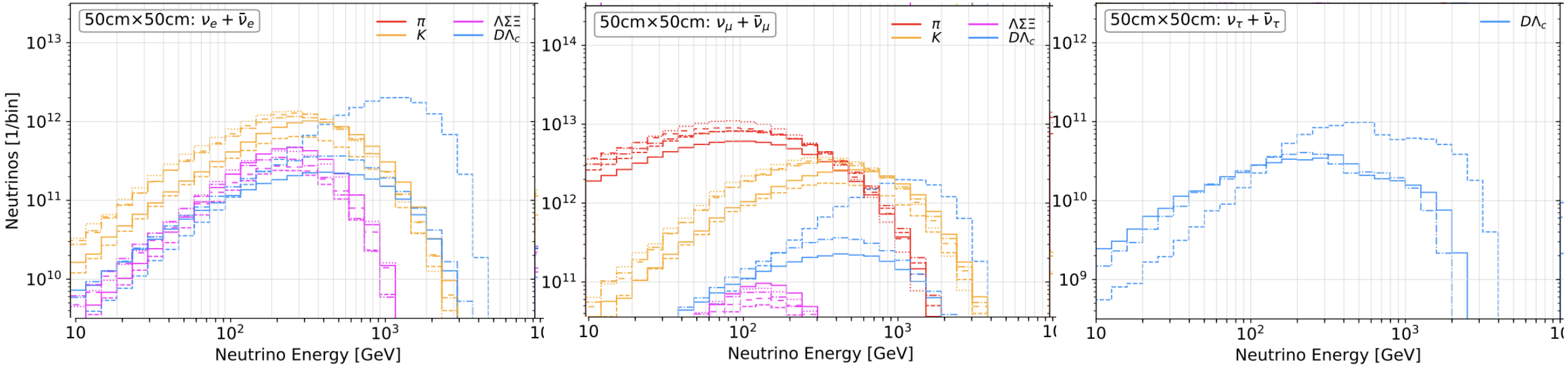


Larger detectors and dataset will allow huge increase in number of neutrino interactions that can be recorded at the FPF experiments compared to FASERν (x20 luminosity, x10 target mass)

- - large differences in expectations between different generators – numbers shown here the most conservative particuarly for ν_τ where some generators predict more than a factor of two larger numbers

QCD at the FPF

- Neutrinos detected at FPF experiments can also be used to study QCD both in the neutrino production, and in neutrino interaction
- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \to \nu\mu$, K $\to \nu_e$ (at high-energy/off-axis D $\to \nu_e$), D $\to \nu\tau$

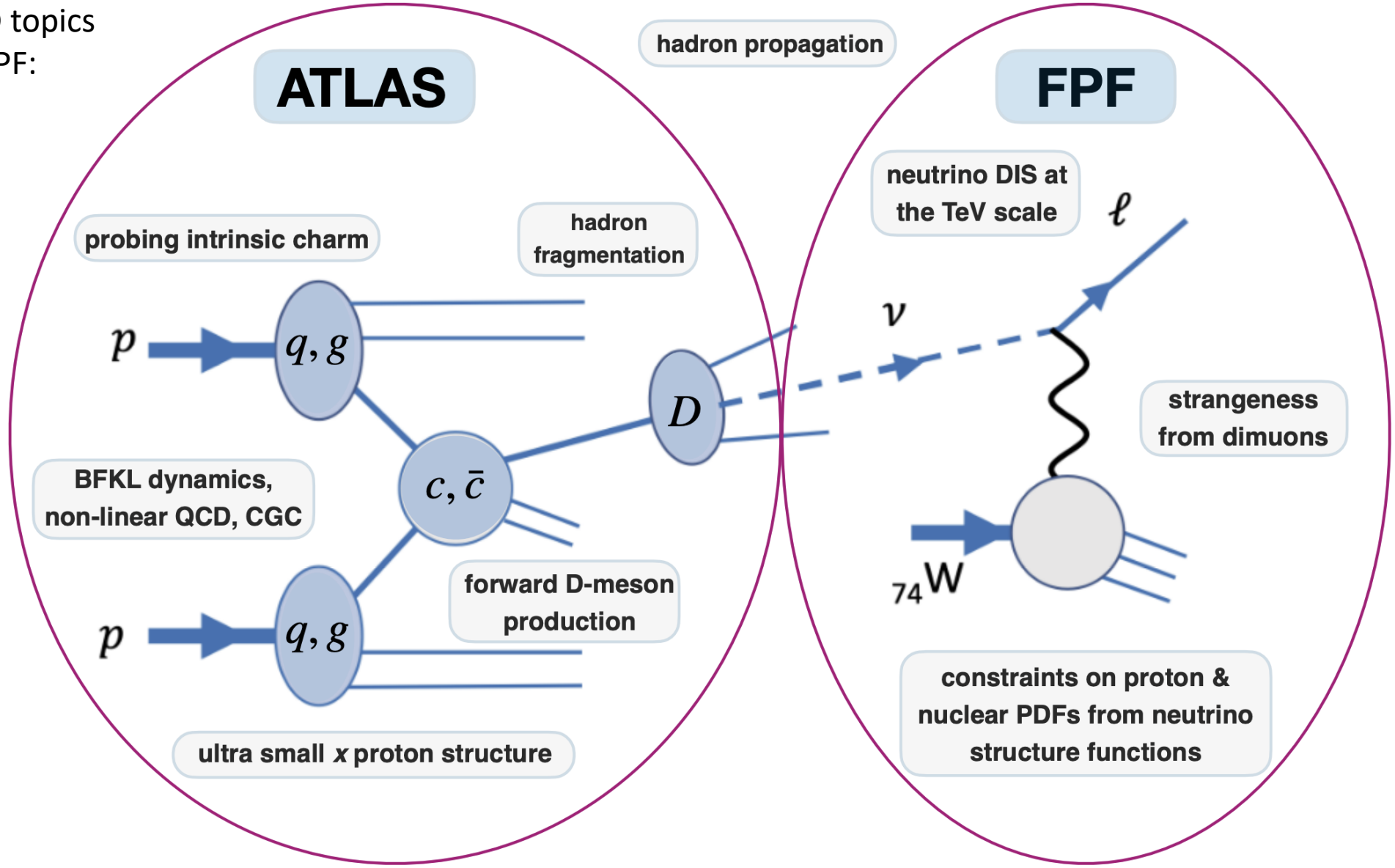


Electron neutrinos at high energy and slightly off-axis, almost exclusively from charm decays.

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)

QCD at the FPF

Many interesting QCD topics to be studied at the FPF:



FPF Studies

A very preliminary first costing of the facility civil engineering works + services gives a cost estimate of 40 MCHF.
Recent studies:

- FLUKA simulation of expected muon flux at the FPF is ~0.5Hz/cm^2 at L=5x10^{34}cm^{-2}s^{-1} (for the region within 1m of the LOS)
- Radioprotection study suggests that the cavern should be accessible during HL-LHC operations (with limited time (<20% occupancy), and some local restrictions)

To further civil engineering design / cost, a core to the cavern depth will be taken early next year.

Facility studies and physics case documented in White paper for Snowmass: 2203.05090 (to appear in J Phys G)

Possible schedule for implementation of FPF:

- CE works done in LS3
- Installation of services and experiments – first years of Run 4
- Physics from mid-Run 4

Summary

- FASER is a new experiment at the LHC designed to
  - Search for light, weakly interacting new particles
  - Study high energy collider neutrinos for the first time
- Detector designed, constructed, installed and commissioned during LS2
- Physics data taking since the start of Run 3
  - Smooth operations
  - Excellent detector performance
- First physics results expected in Q1 2023

- The FPF is a proposed facility to house several BSM and neutrino experiments on the ATLAS collision axis line of sight
  - **Strong and broad physics motivation** with **significant interest from the community**:
    - BSM, neutrino physics, QCD
  - Studies on physics case, facility design and requirements of experiments progressing well

FASER Acknowledgements

FASER is supported by:

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

CERN

Swiss National Science Foundation

In addition, FASERν is supported by:

erc

科研費 KAKENHI

FPF studies supported by:

Physics Beyond Colliders

Backup…

The FASER Collaboration

The FASER Collaboration consists of 85 members from 22 institutions and 9 countries

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大学 Tsinghua University
MANCHESTER 1824 The University of Manchester
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX
DESY.
JINR

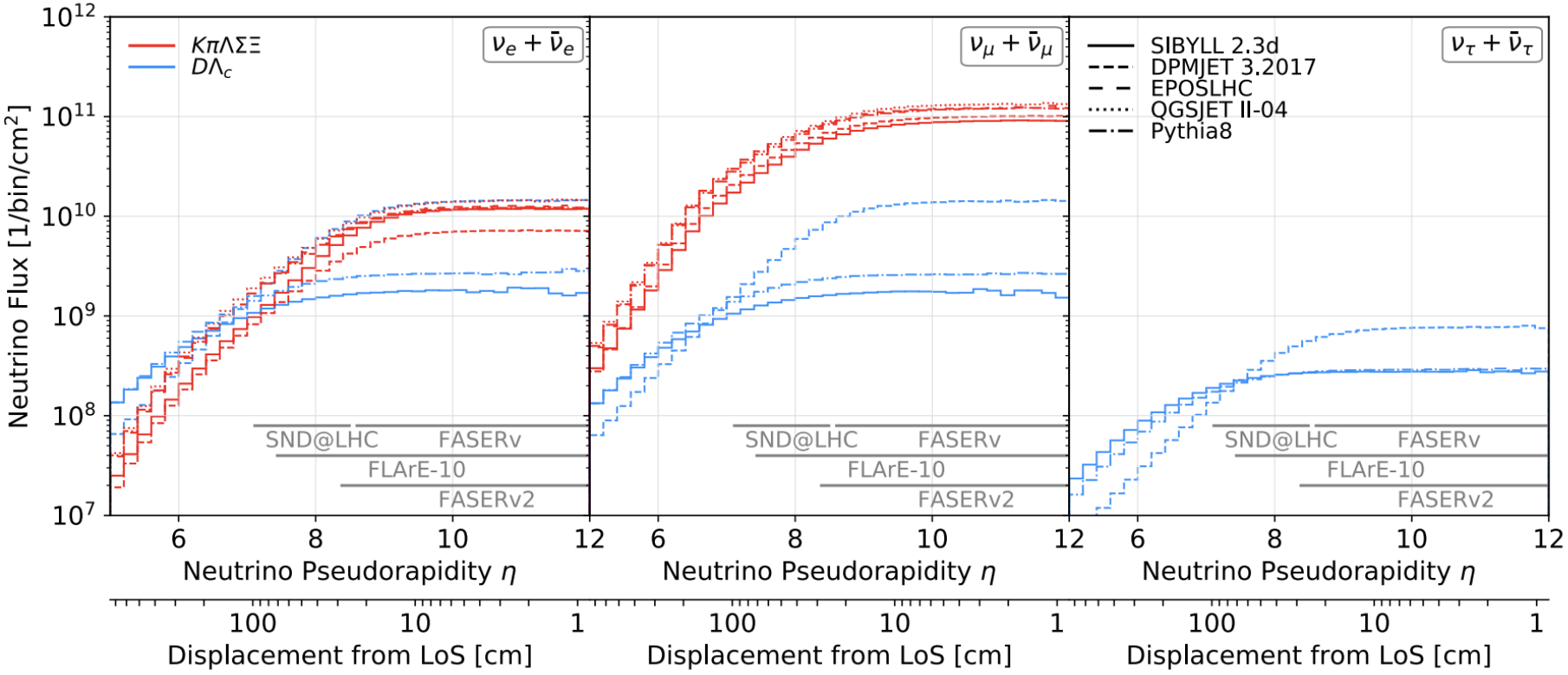
References…

1.The FASER Detector
arxiv: 2207.11427
2.The FASER W-Si High Precision Preshower Technical Proposal
CERN document server
3.The tracking detector of the FASER experiment
NIMA 166825 (2022) and arXiv: 2112.01116
4.The trigger and data acquisition system of the FASER experiment
Journal of Instrumentation and arXiv: 2110.15186
5.First neutrino interaction candidates at the LHC
Physical Review D and arXiv: 2105.06197
6.Technical Proposal of FASERν neutrino detector
CERN document server and arXiv: 2001.03073
7.Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC
European Physical Journal C and arXiv: 1908.02310
8. FASER's Physics Reach for Long-Lived Particles
Physical Review D and arXiv: 1811.12522
9.Technical Proposal
CERN document server and arXiv: 1812.09139
10.Letter of Intent
CERN document server and arXiv: 1811.10243

Further FPF references: https://pbc.web.cern.ch/fpf-resources

QCD at the FPF

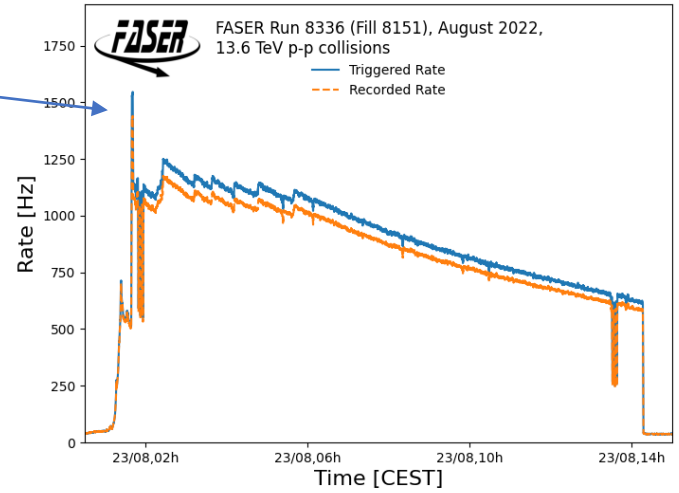
- Neutrinos detected at FPF experiments can also be used to study QCD both in the neutrino production, and in neutrino interaction
- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \to \nu\mu$, K $\to \nu_e$ (at high-energy/off-axis D $\to \nu_e$), D $\to \nu\tau$

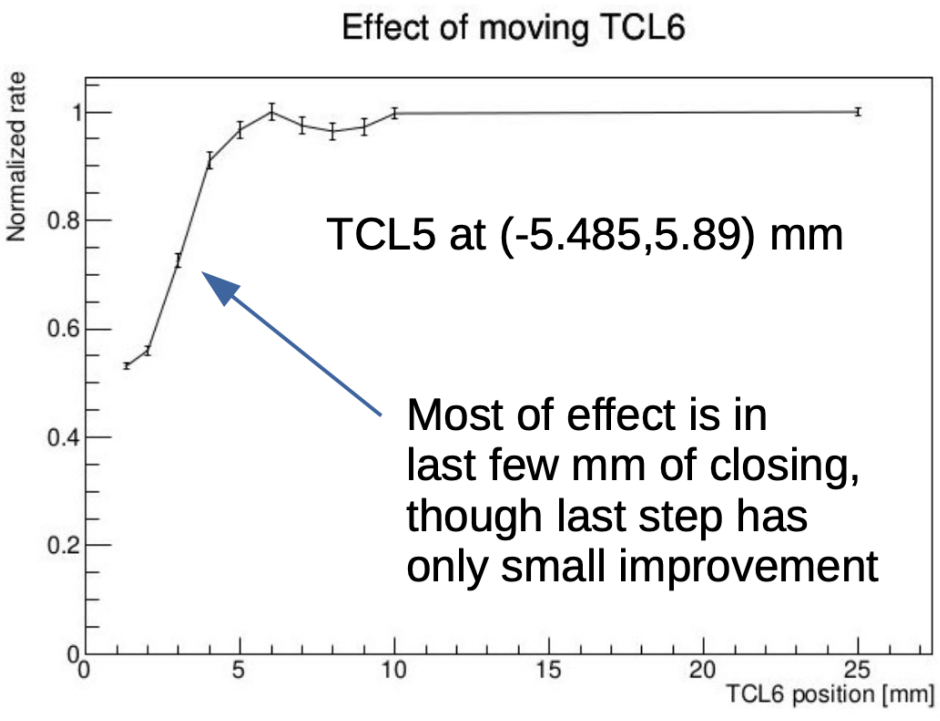


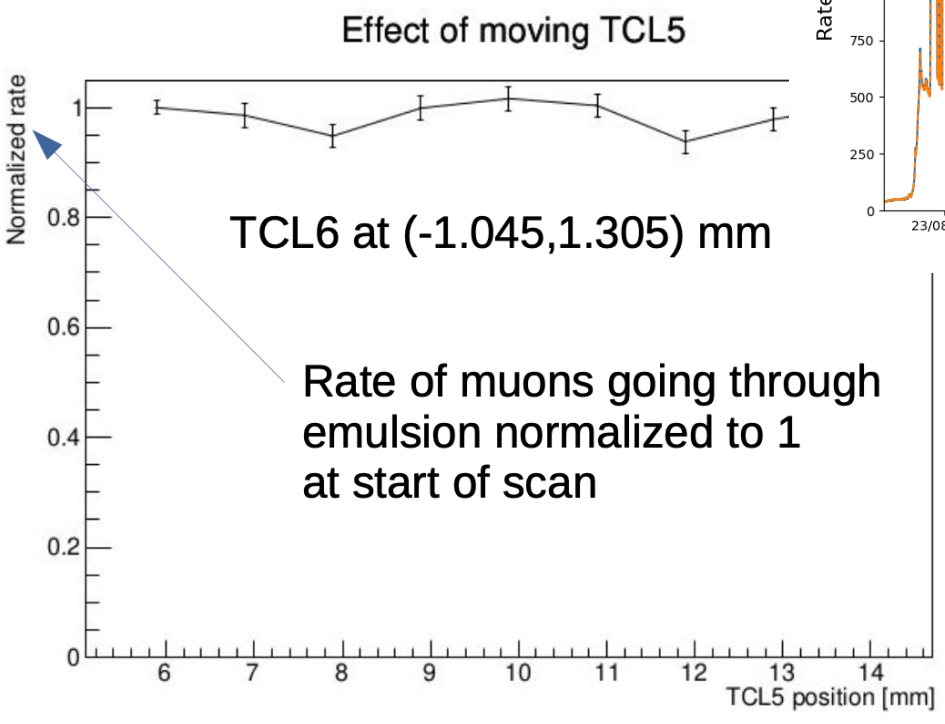
Collimator dependence at FASER Trigger Rate

At start of Run 3 noticed FASER trigger rate was significantly higher for first ~10mins of fill. Rate drop correlated with movement of the TCL collimators (which are changed when the AFP Roman Pot detectors are inserted a few minutes into the fill). In order to understand this we did a dedicated scan of the TCL5 and TCL6 collimator settings to see how they effect the FASER trigger rate.

Before collimator movement



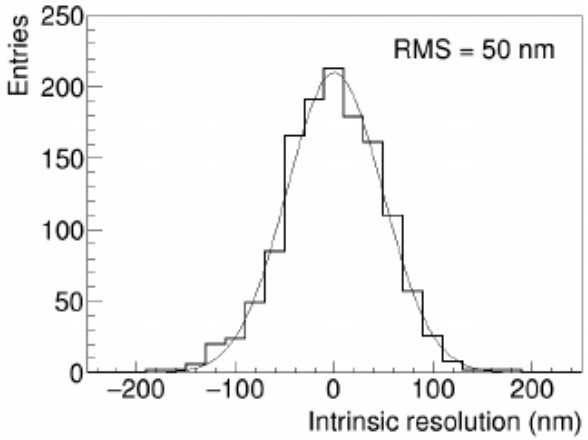


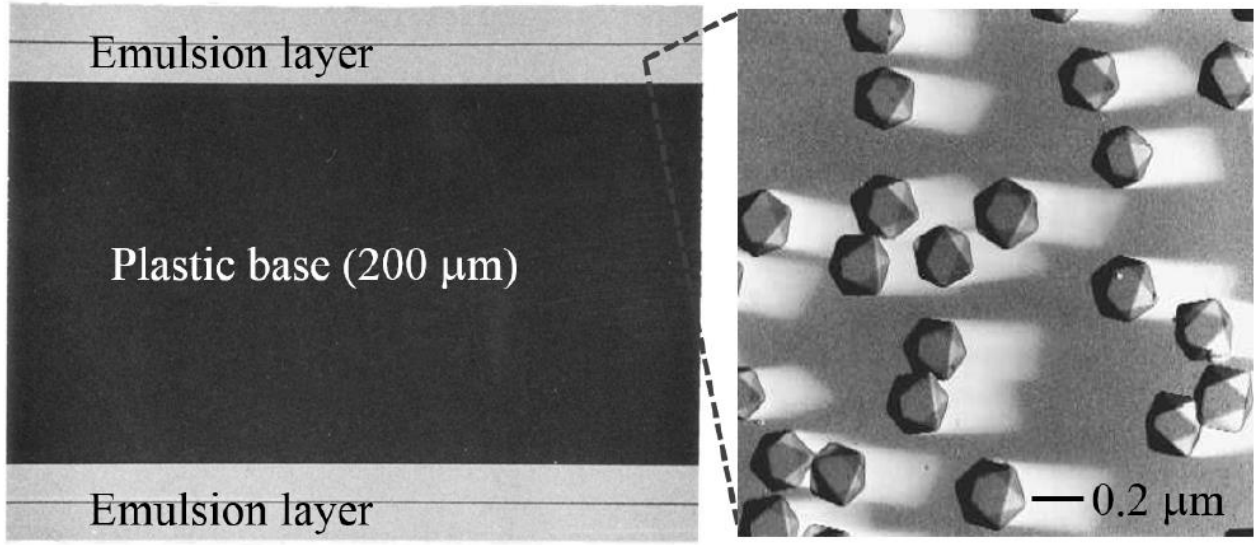


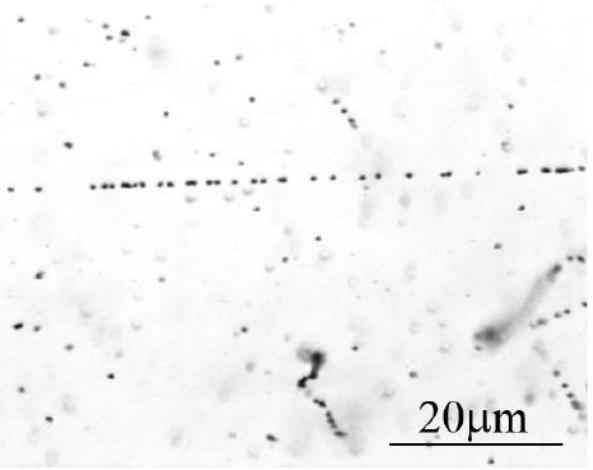
Following this, LHC changed the sequence so tight TCL6 collimator settings implemented at start of Stable Beams.

Emulsion Detectors

- Emulsion film made up of ~80µm emulsion layer on either side of 200µm thick plastic
- Emulsion gel active unit silver bromide crystals (diameter 200nm)
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~50nm, and angular resolution ~0.35mrad
    - But no time resolution!

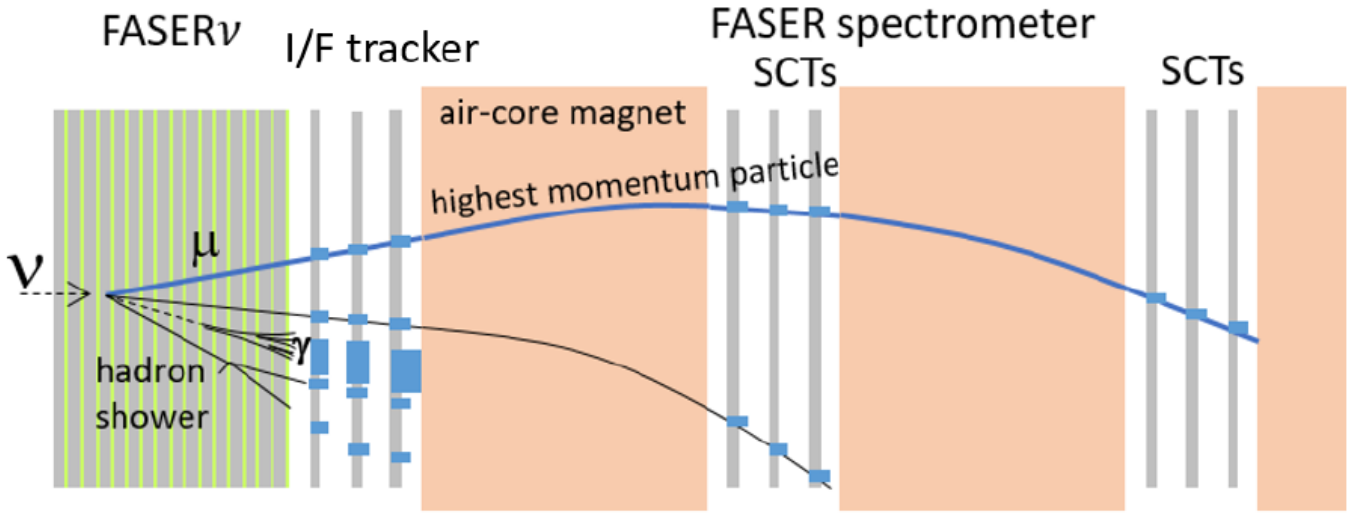




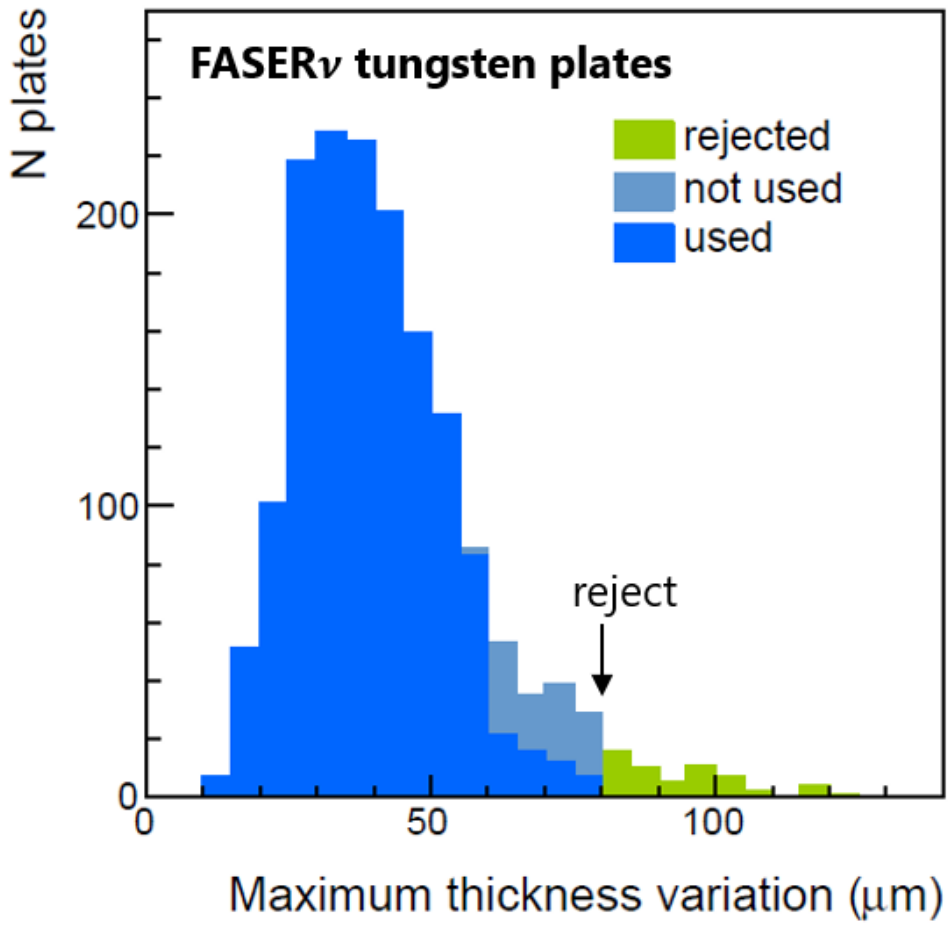


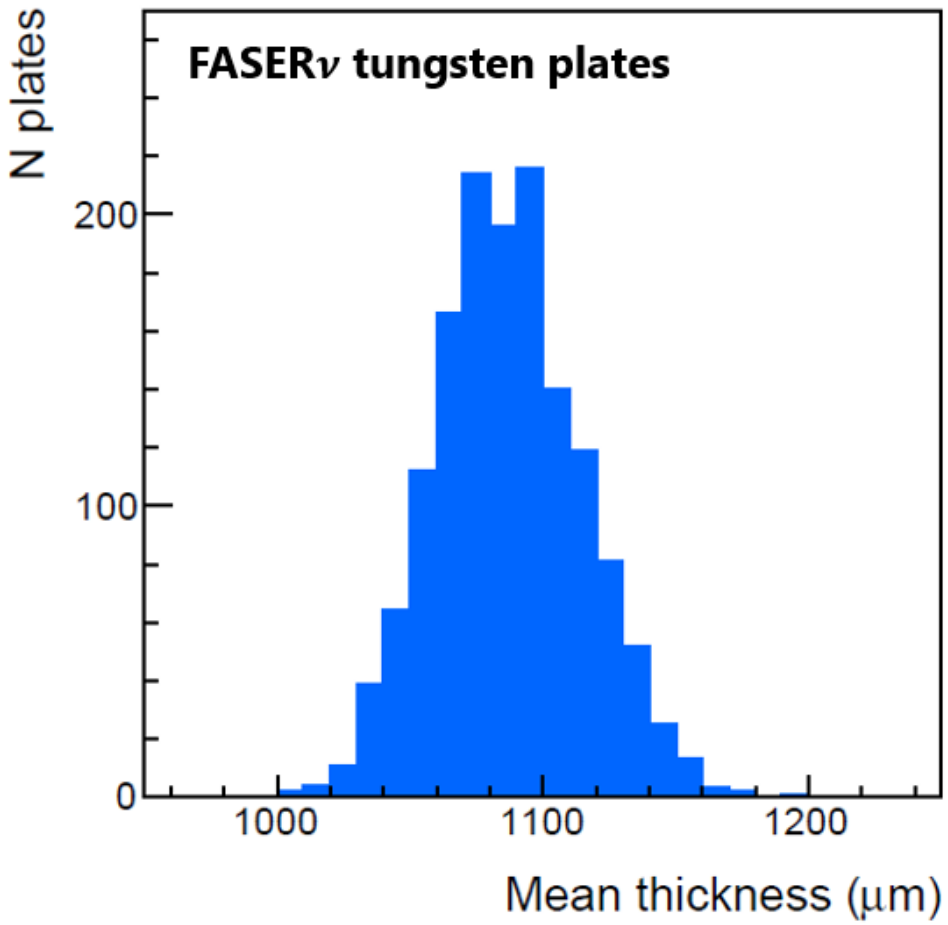
Linking FASERν with FASER

- Possibility to connect FASERν with rest of FASER for:
  - Charge identification
  - Improved energy resolution
  - Better background rejection
- Requires interface detector in front of FASER
  - Precision tracker to link FASERν and FASER tracks
  - Most likely a fourth station of spare ATLAS SCT modules
- Interface detector identical to other FASER tracking stations installed in December 2021



FASERν Tungsten Plates QA

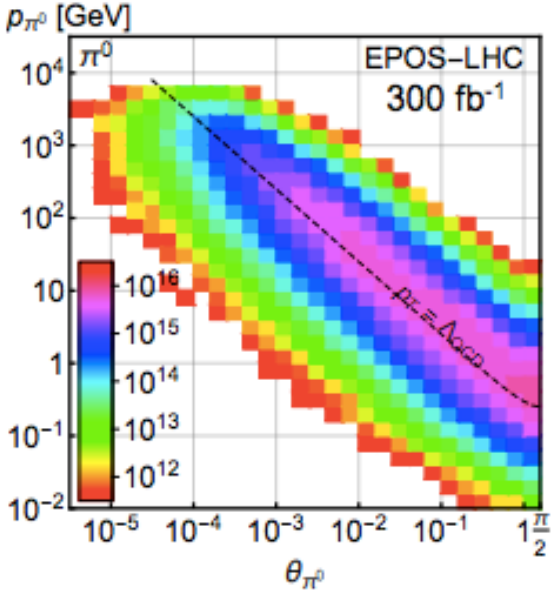




Thickness uniformity of the tungsten plates used for the FASERnu detector was checked with a dedicated device developed by the Collaboration. The thickness was measured semi-automatically at 24 points on each plate, and the maximum difference among the 24 points was checked. A total of 1622 plates were measured, and 1562 plates with a difference smaller than 80 microns were selected as good quality, corresponding to 90% of the measured plates (left). Among them, 1460 plates are used to construct the emulsion detector. The mean thickness of the used plates is 1087 microns, with an RMS of 27 microns (right).

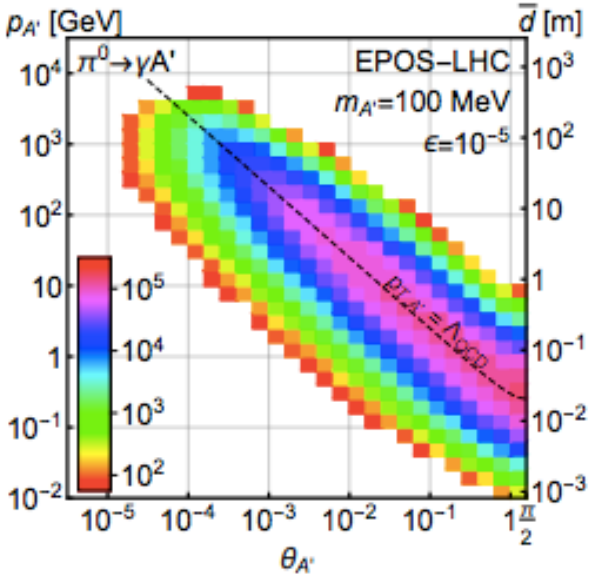
Dark Photons in FASER

Pions at the IP



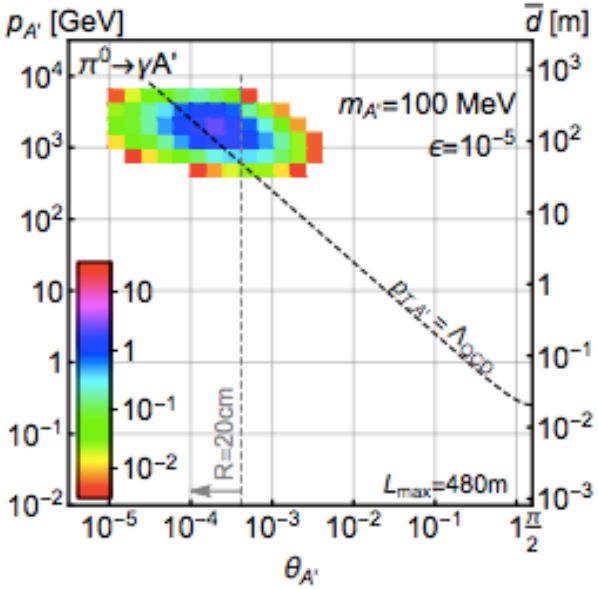
- Simulations greatly refined by LHC data
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin

A's at the IP



- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

A's decay in [480m, 483m]



- Only highly boosted ~TeV A's decay in FASER
- Rates again suppressed by decay requirement
- But still $N_{A'} \sim 100$ signal events, and almost all are within 20 cm of "on axis"

note this is an old slide, and FASER volume R=10cm now!

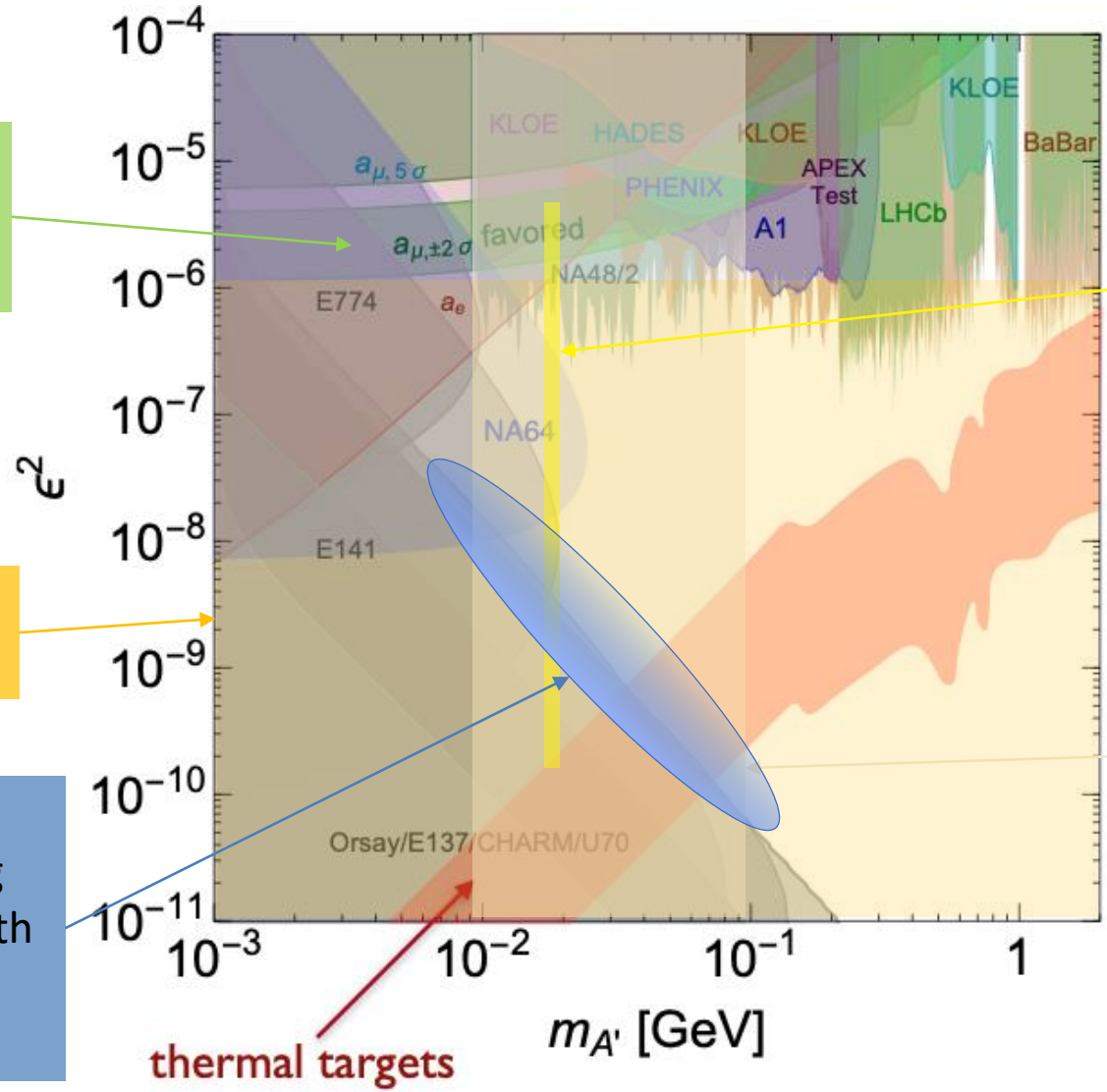
Targets in A' parameter space

Slide from J. Feng

Muon g-2 Anomaly

Loop-induced Coupling

FASER probes an interesting region, even with the 1st fb^{-1} of Run 3 data



thermal targets

$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

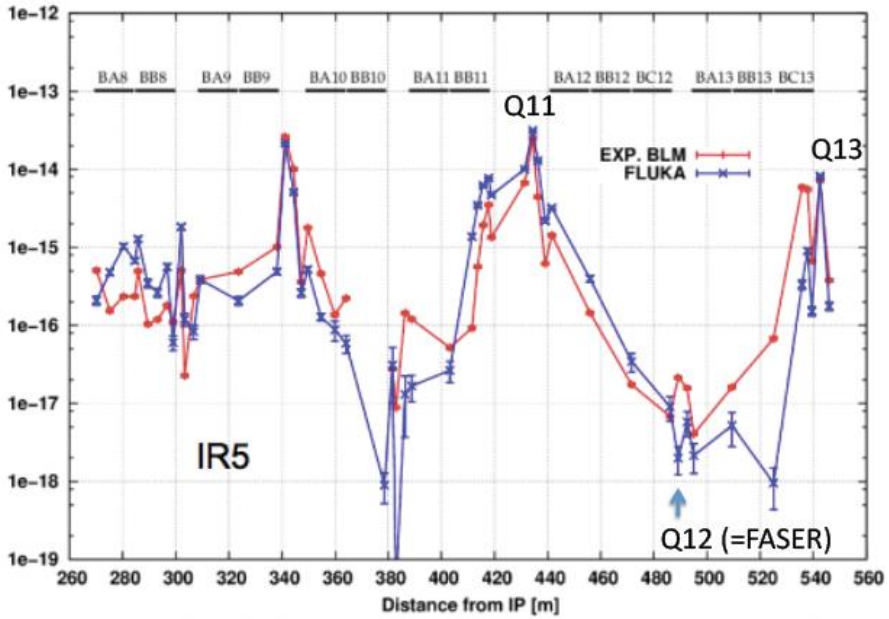
Tim Nelson, Snowmass RP6 (2020)

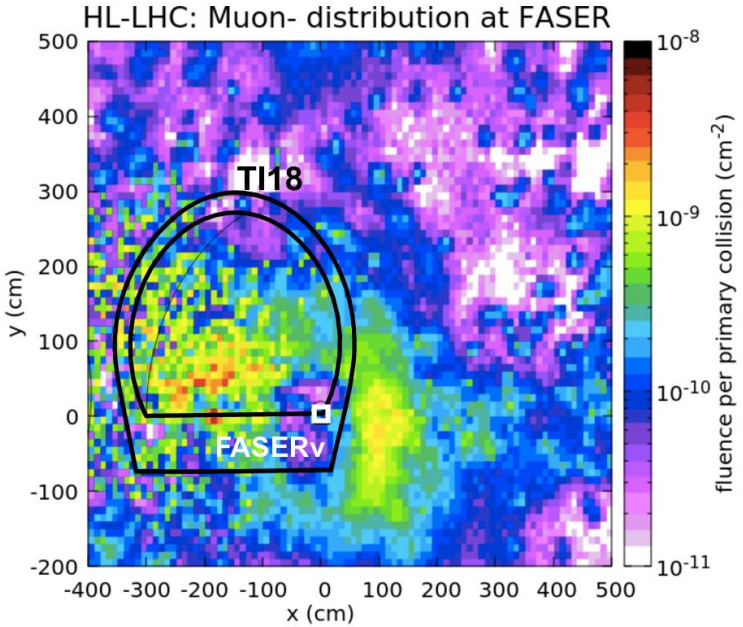
^{8}Be and ^{4}He ATOMKI Anomalies

Self-interacting Dark Matter

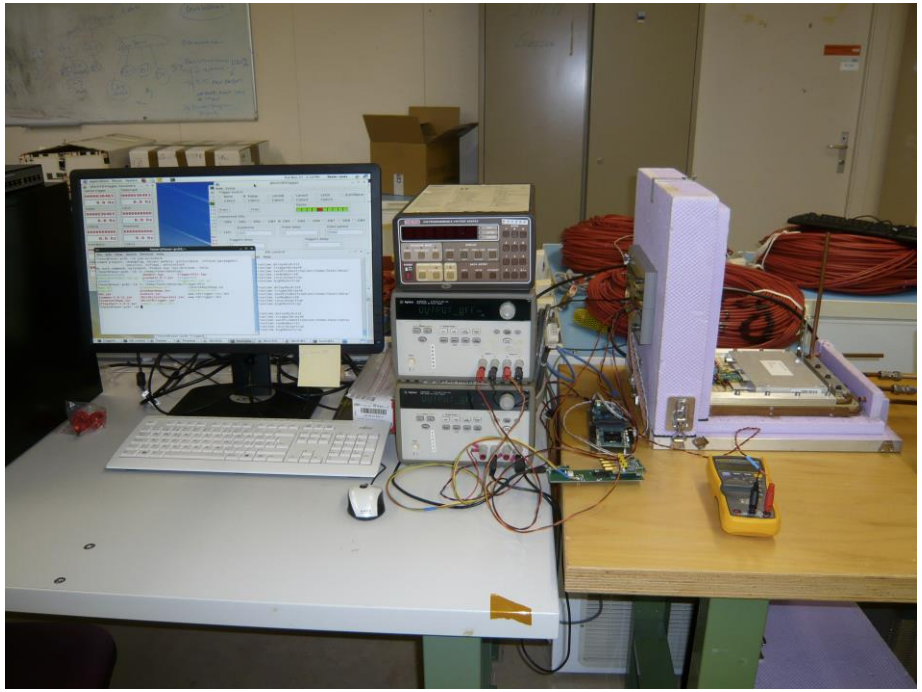
FASER Backgrounds & Radiation

- FLUKA simulations and *in situ* measurements in 2018 have been used to assess the backgrounds and radiation level expected in FASER
- FLUKA simulations studied particles entering FASER from:
  - IP1 collisions (shielded by 100m of rock)
  - off-orbit protons hitting beam pipe aperture in dispersion suppressor (close to FASER) (following diffractive interactions in IP1)
  - beam-gas interactions
- Expect a flux of high energy muons (E>10 GeV) of 0.5cm^{-2}s^{-1} at FASER for 2e34cm^{-2}s^{-1} luminosity from IP1 collisions
  - Confirmed by *in situ* measurements in 2018 running (emulsion detector and TimePix BLM)
- Radiation level low due to dispersion function of LHC at the FASER location:
  - <5 x 10^{-3} Gy/year, <5 x 10^{7} 1 MeV neutron equivalent fluence / year
  - Do not need radiation hard electronics

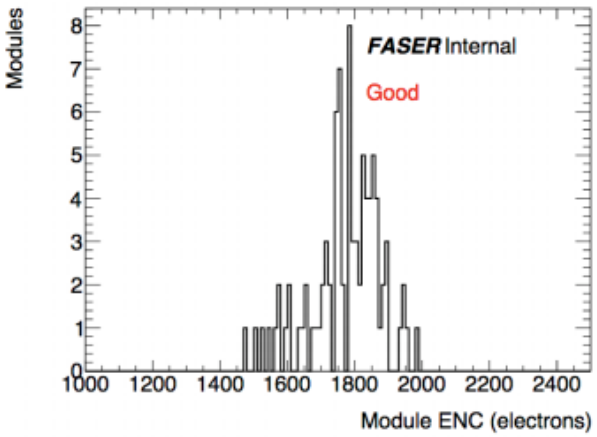


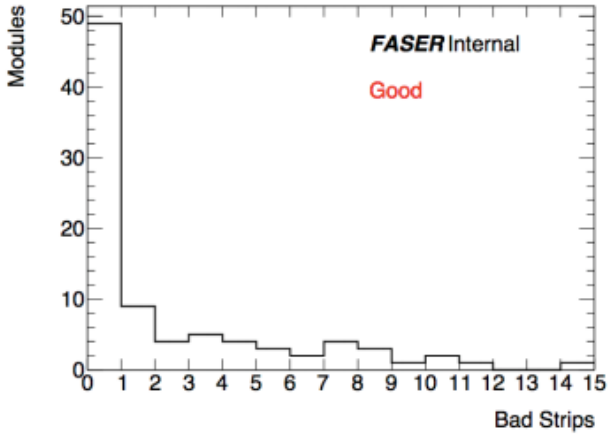


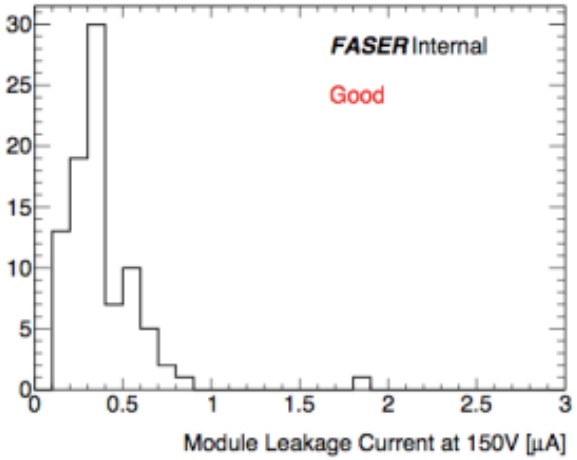
FASER Tracker: Module QA



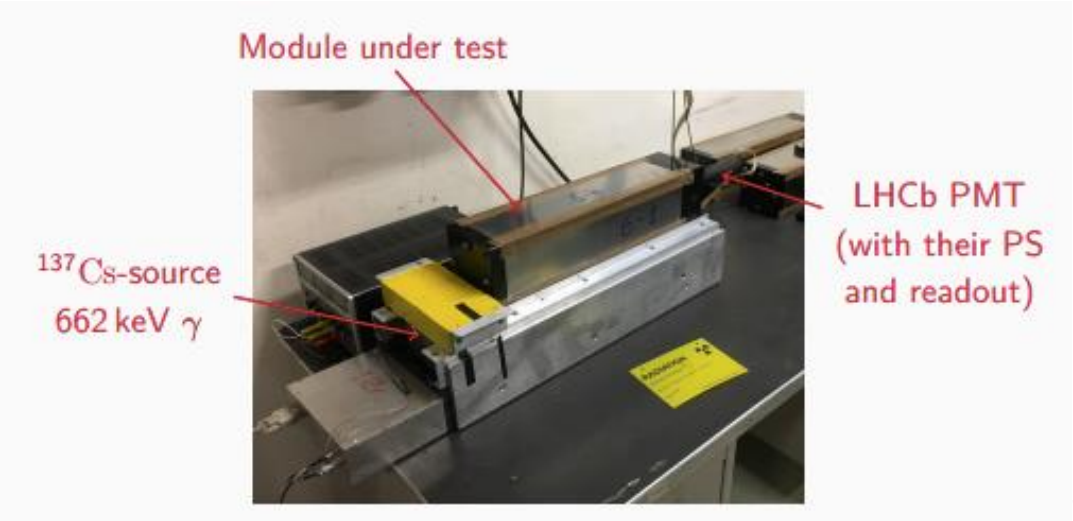
SCT modules used had passed ATLAS QA in ~2005 and then been kept in storage. Important to test their functionality.
SCT module QA at CERN in March 2019.
Identified > 80 good spare modules – more than enough for FASER needs.
Performance seems not to be degraded by long term storage/age.



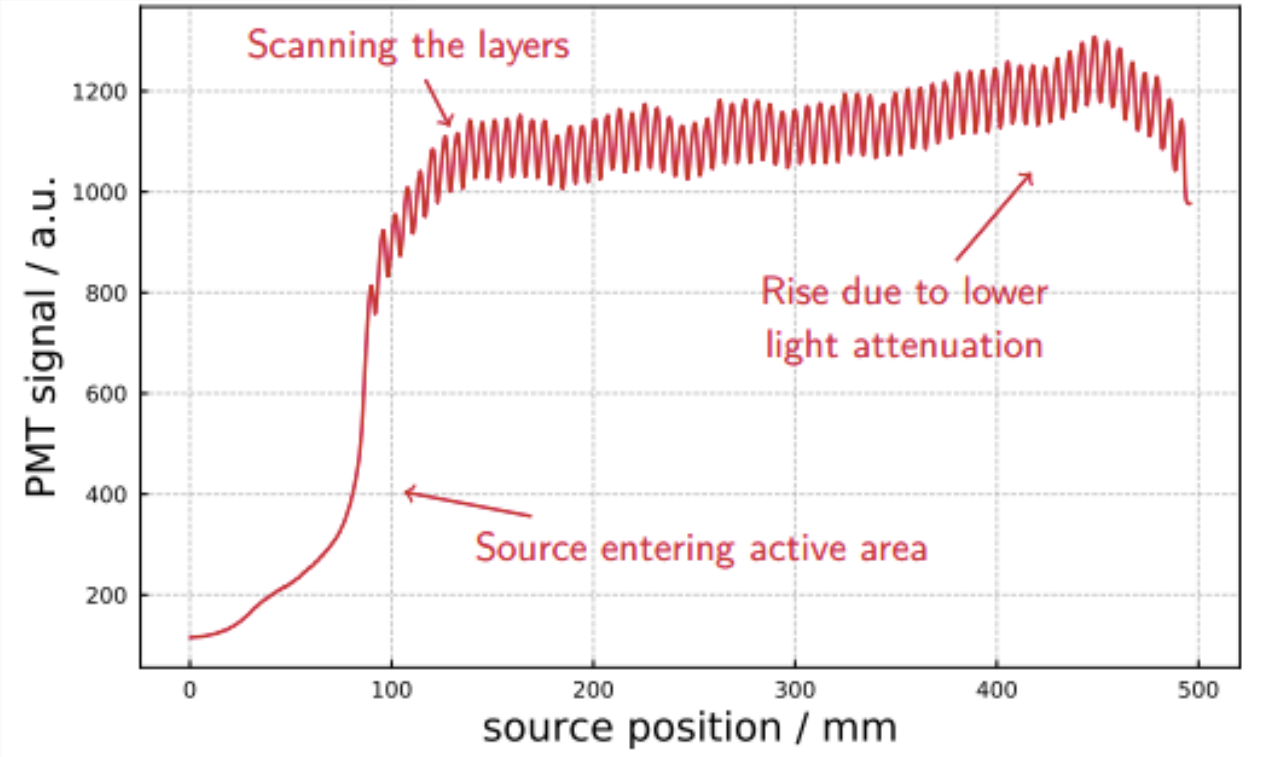




Calorimeter – Initial QA



Testing of calorimeter modules at CERN in March 2019 with a source showed expected response in all modules tested.

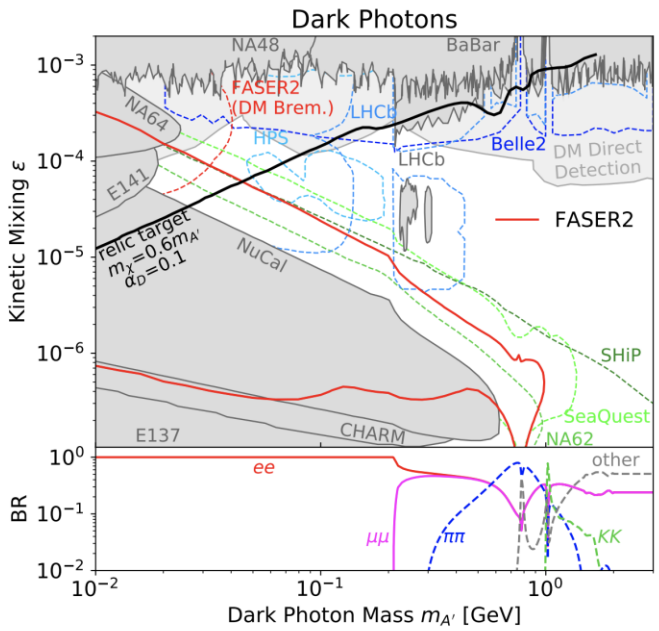


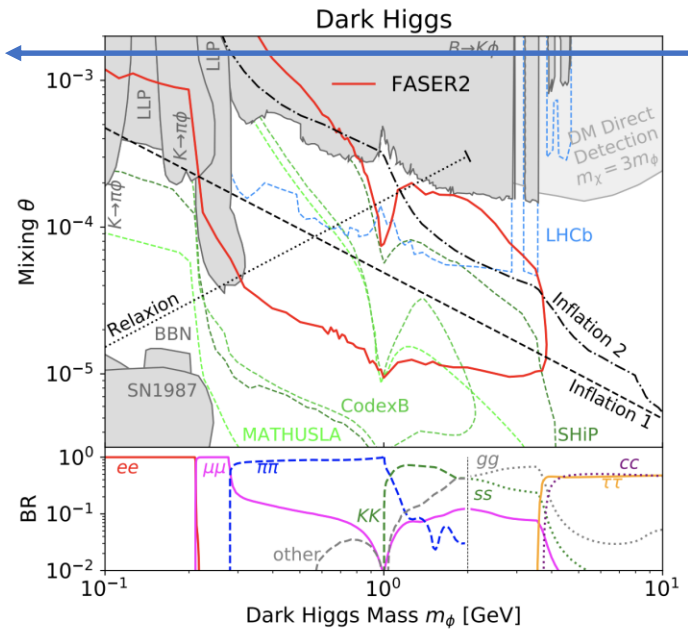
Snowmass statements on FPF

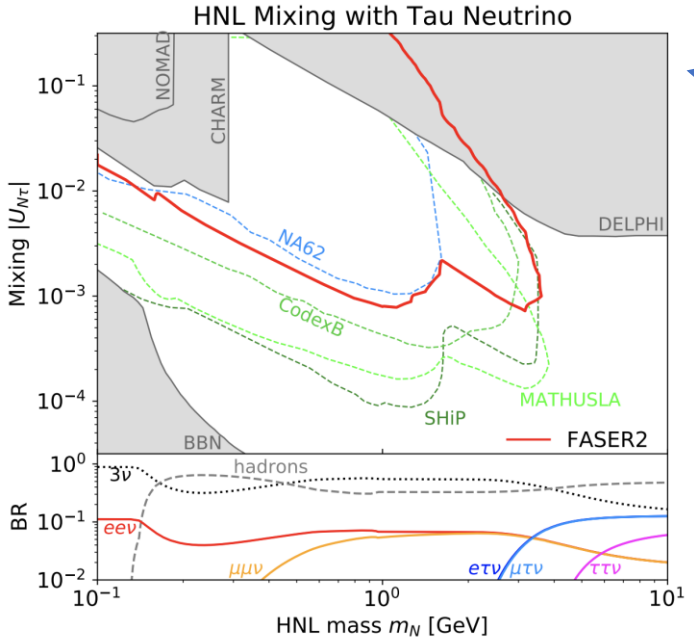
Energy Frontier Report document:
https://snowmass21.org/_media/energy/snowmass-energy_frontier_report-sep7-2022.pdf
The executive summary states (including the emphasis):
"The EF currently has a top-notch program with the LHC and the High Luminosity LHC (HL-LHC) at CERN, which sets the basis for the EF vision. **The EF supports continued strong US participation in the success of the LHC, and the HL-LHC construction and physics programs, including auxiliary experiments."**
In section 2.7.1 Vision (immediate program) it is stated (all in emphasis)
"Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades. "

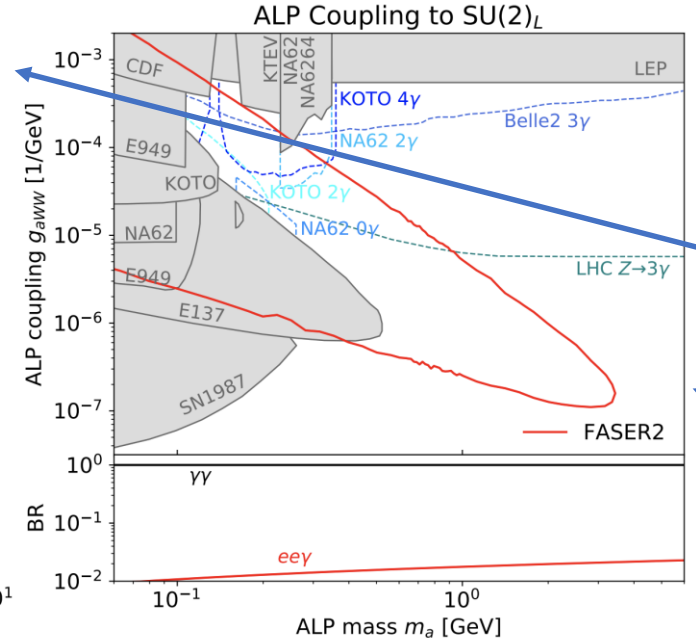
Neutrino Frontier Report (draft):
"Cross-pollination between Frontiers and other fields of science offers further opportunities. Physics topics within the Neutrino Frontier overlap strongly with each other, and also with other Frontiers. Potentially constructive interference at places of overlap between programs traditionally stewarded by different entities merits careful attention. Examples include instrumentation for dark matter and neutrinoless double beta decay searches, the study of neutrino-nucleus interactions, the detection of high-energy neutrinos with far-forward experiments at the LHC, and the connection between Cosmic Frontier programs and the study of neutrino properties. Also meriting attention are opportunities to make optimal use of national and international facilities for particle physics and other sciences.**"**

BSM at FPF



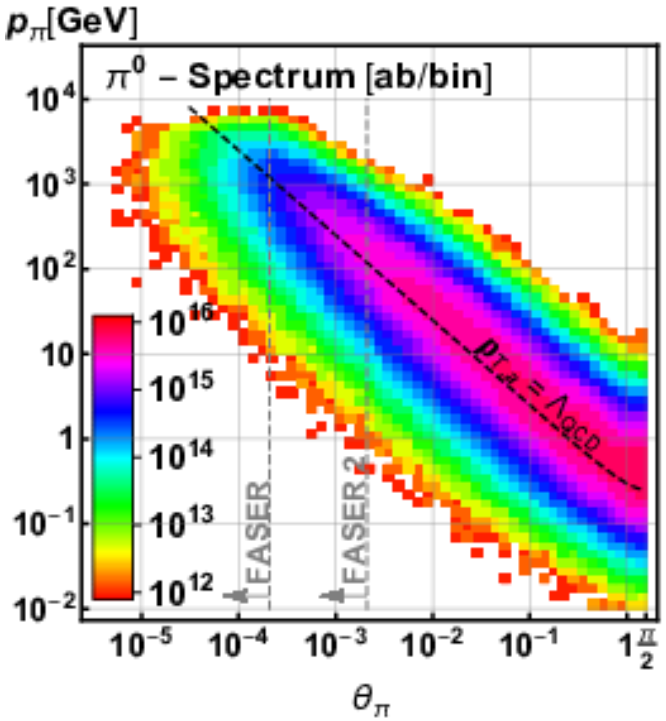


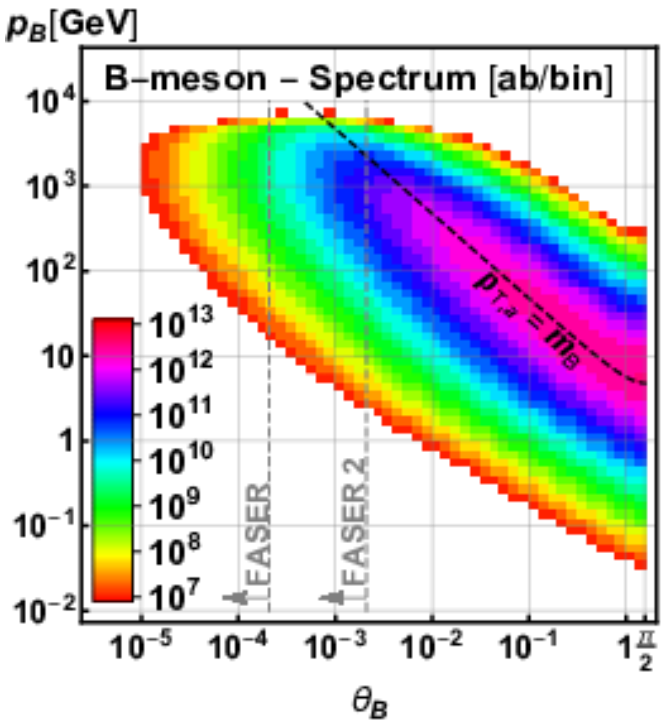


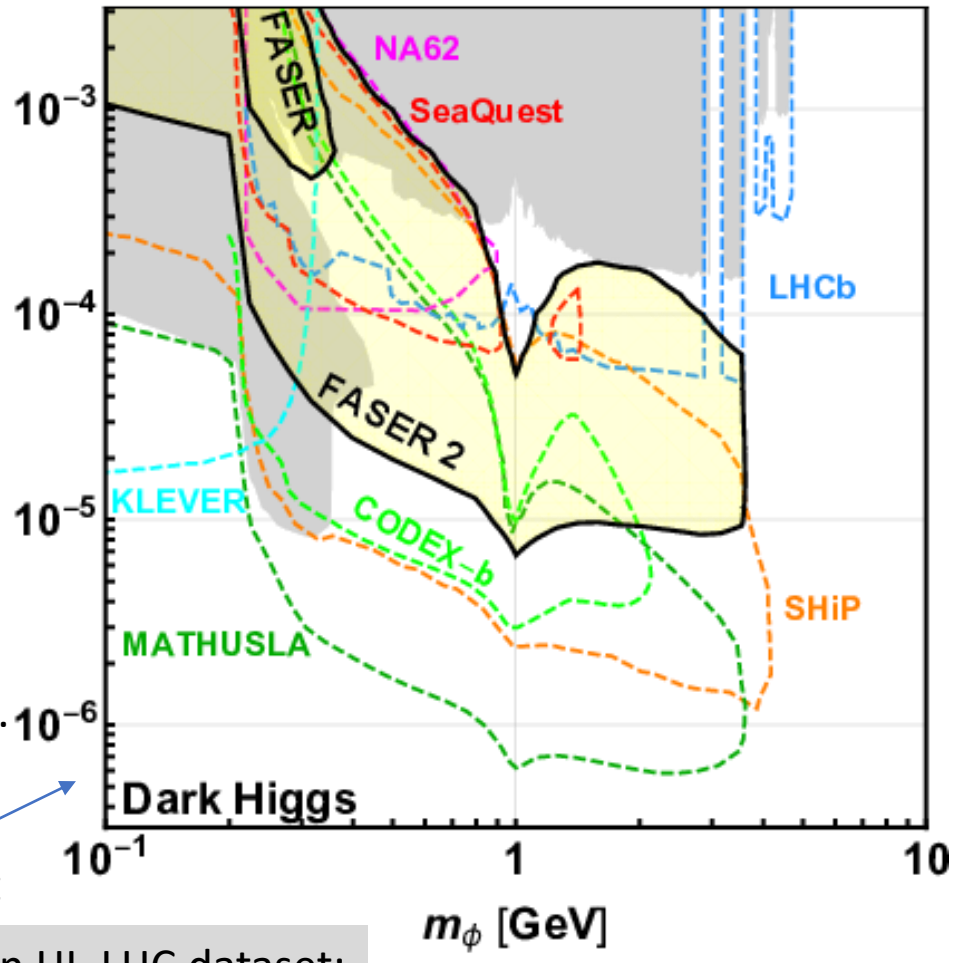


Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
BC3: Milli-Charged Particle	FORMOSA
BC4: Dark Higgs Boson	FASER 2
BC5: Dark Higgs with hSS	FASER 2
BC6: HNL with e	FASER 2
BC7: HNL with μ	FASER 2
BC8: HNL with τ	FASER 2
BC9: ALP with photon	FASER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

Aside: Signals from heavy flavour decay





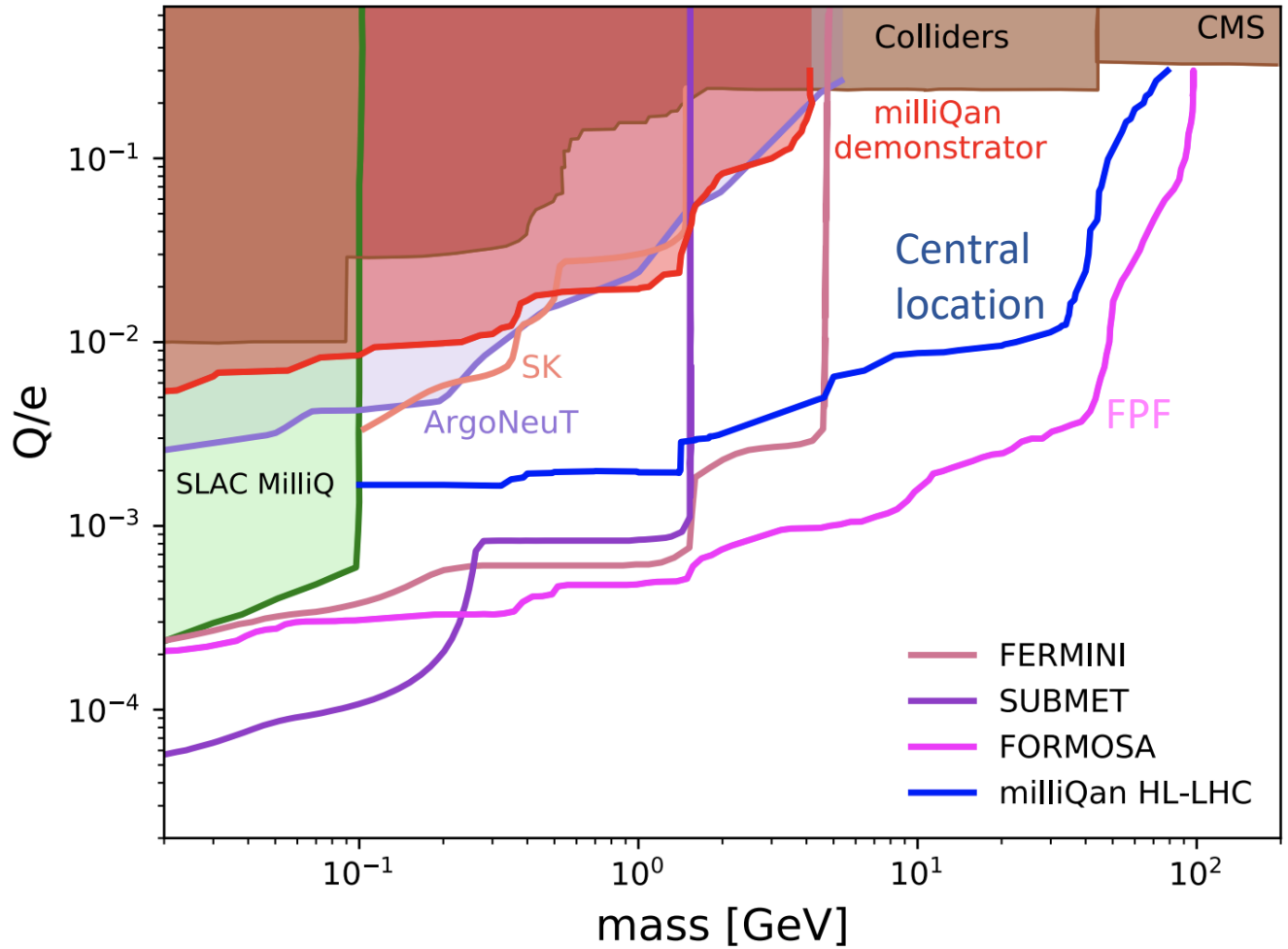


Number of π^0 and B mesons as function of angle wrt LOS and energy (for 150/fb). Heavier B-mesons are more spreadout around the LOS => only small fraction in FASER acceptance, but FASER2 starts to get into the bulk of the distribution. Much better sensitivity for new LLPs produced in B decays (such as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

Expect in FASER2 angular acceptance in HL-LHC dataset:
$\mathcal{O}(10^{17})$ π^0
$\mathcal{O}(10^{17})$ η
$\mathcal{O}(10^{15})$ D mesons
$\mathcal{O}(10^{13})$ B mesons

BSM at FPF

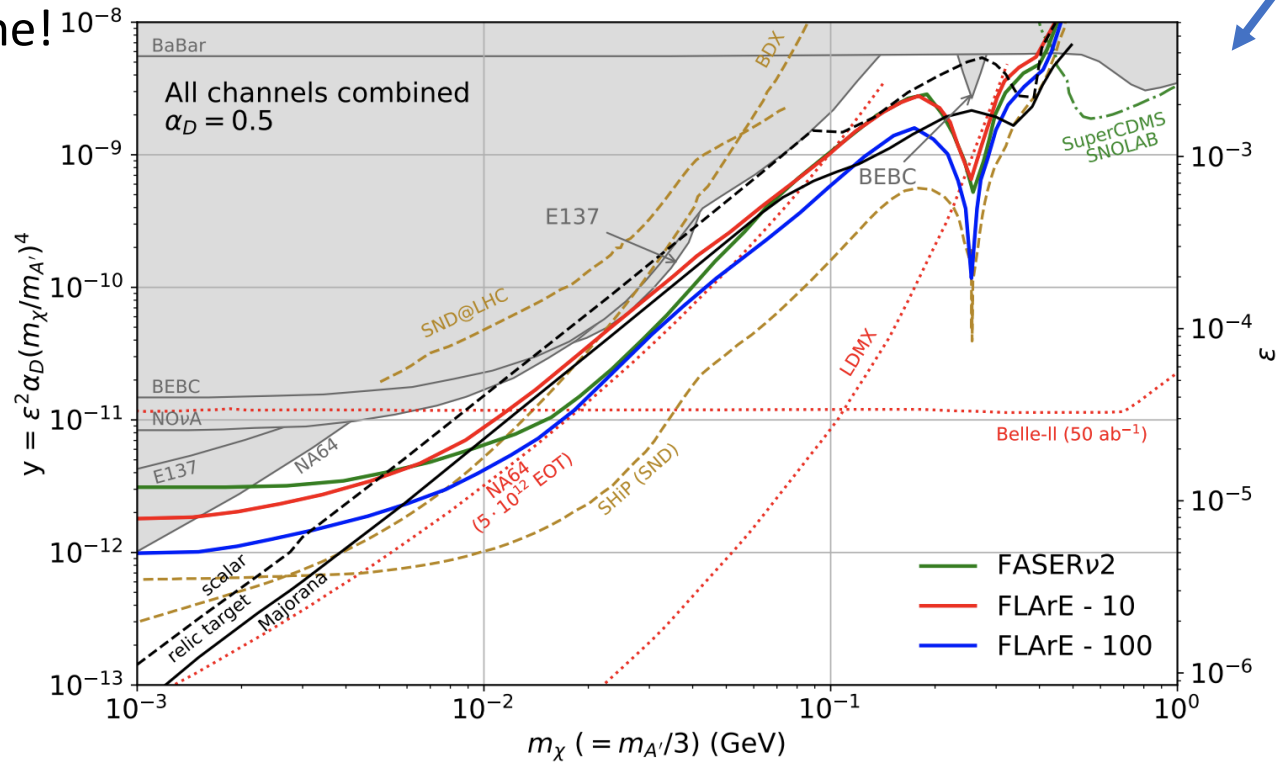
Milicharged particles appear in models with massless dark photons. Improvement in sensitivity for this scenario by FORMOSA at the FPF, compared to milliQan detector installed as a central detector. FORMOSA sees up to ~250x signal rate compared to central detector location.



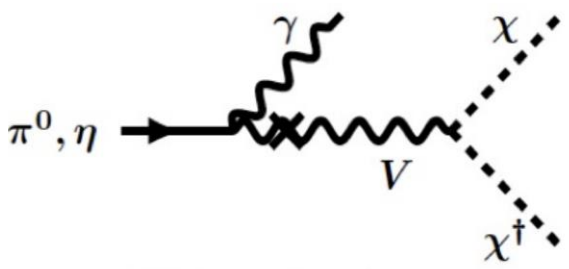
Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
BC3: Milli-Charged Particle	FORMOSA
BC4: Dark Higgs Boson	FASER 2
BC5: Dark Higgs with hSS	FASER 2
BC6: HNL with e	FASER 2
BC7: HNL with μ	FASER 2
BC8: HNL with τ	FASER 2
BC9: ALP with photon	FASER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

BSM at FPF

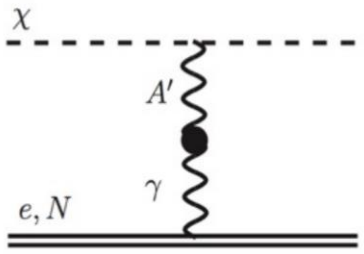
- Recent theory level studies on sensitivity to DM scattering in a LArTPC at the FPF (FLArE)
  - Consider both DM-electron and DM-nucleus scattering
- Very interesting sensitivity, probing the thermal relic region with the "right amount" of Dark Matter
  - Direct scattering, complementary method to "missing energy" (NA64/LDMX) signatures
- Opens door to direct-detection type DM search at a collider for the first time!



Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B-L}$ Gauge Boson	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



DM production



DM scattering