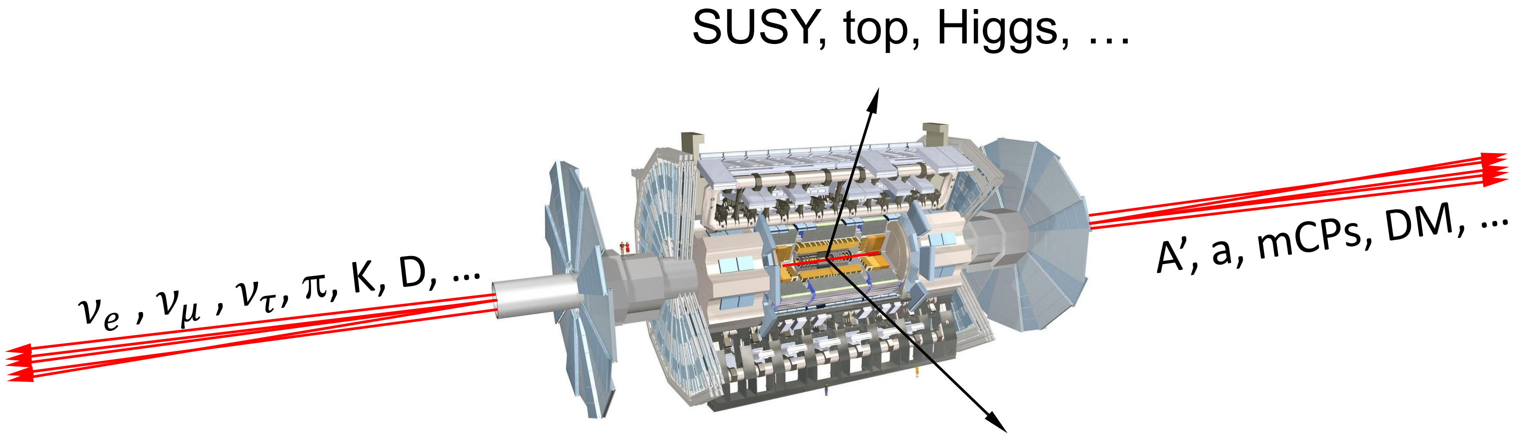
Looking Forward to New Physics:
The FASER Experiment,

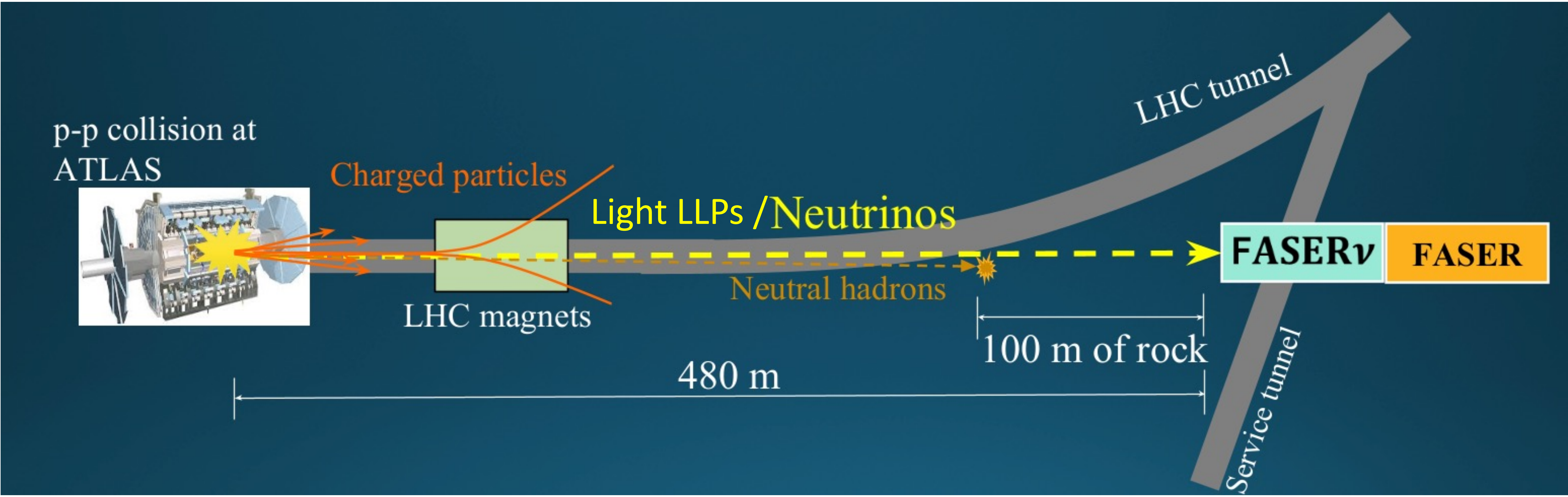
Jamie Boyd (CERN), on behalf of the FASER Collaboration

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 ($\eta > 9.2$)



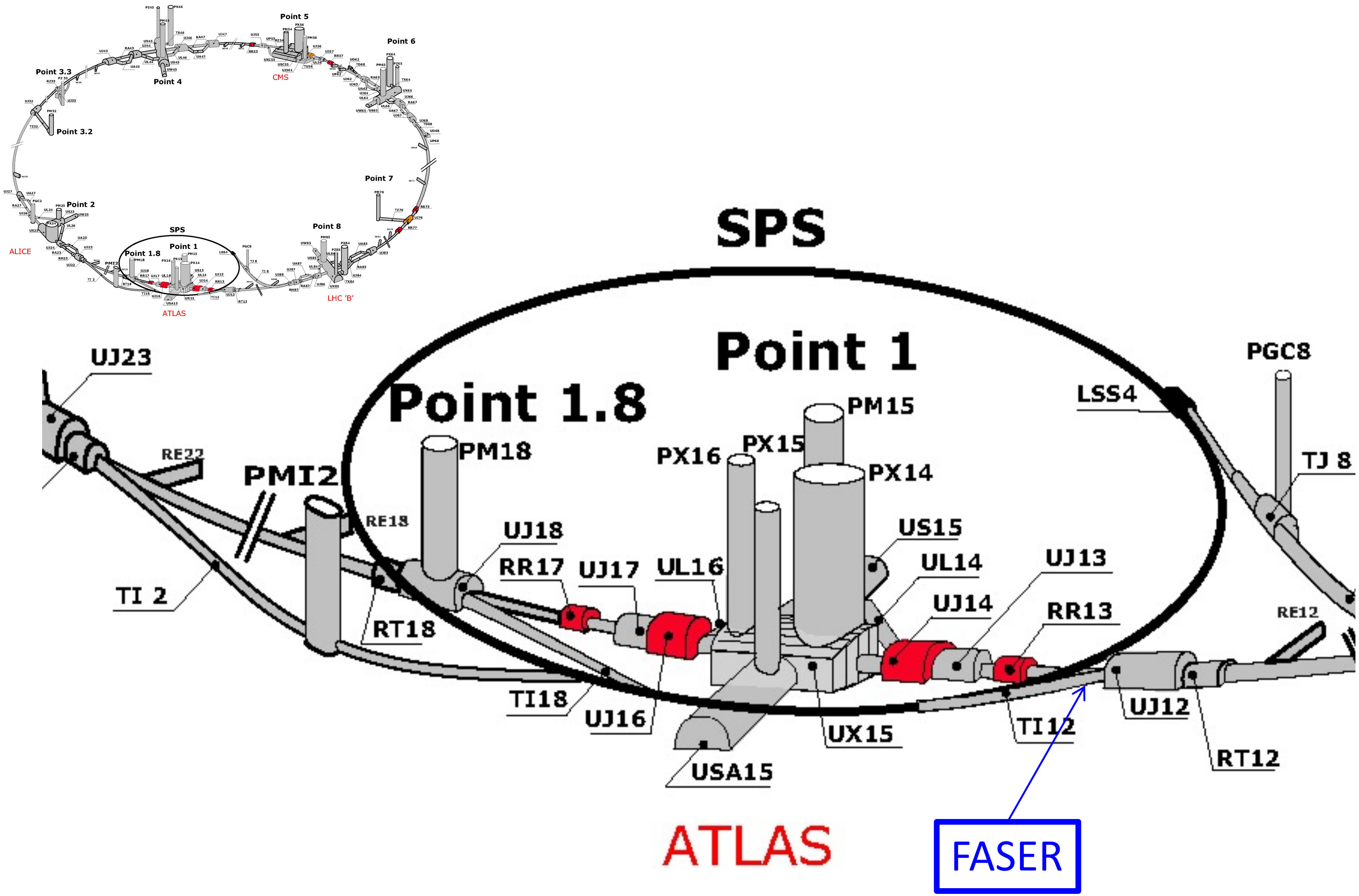
The FASER Experiment



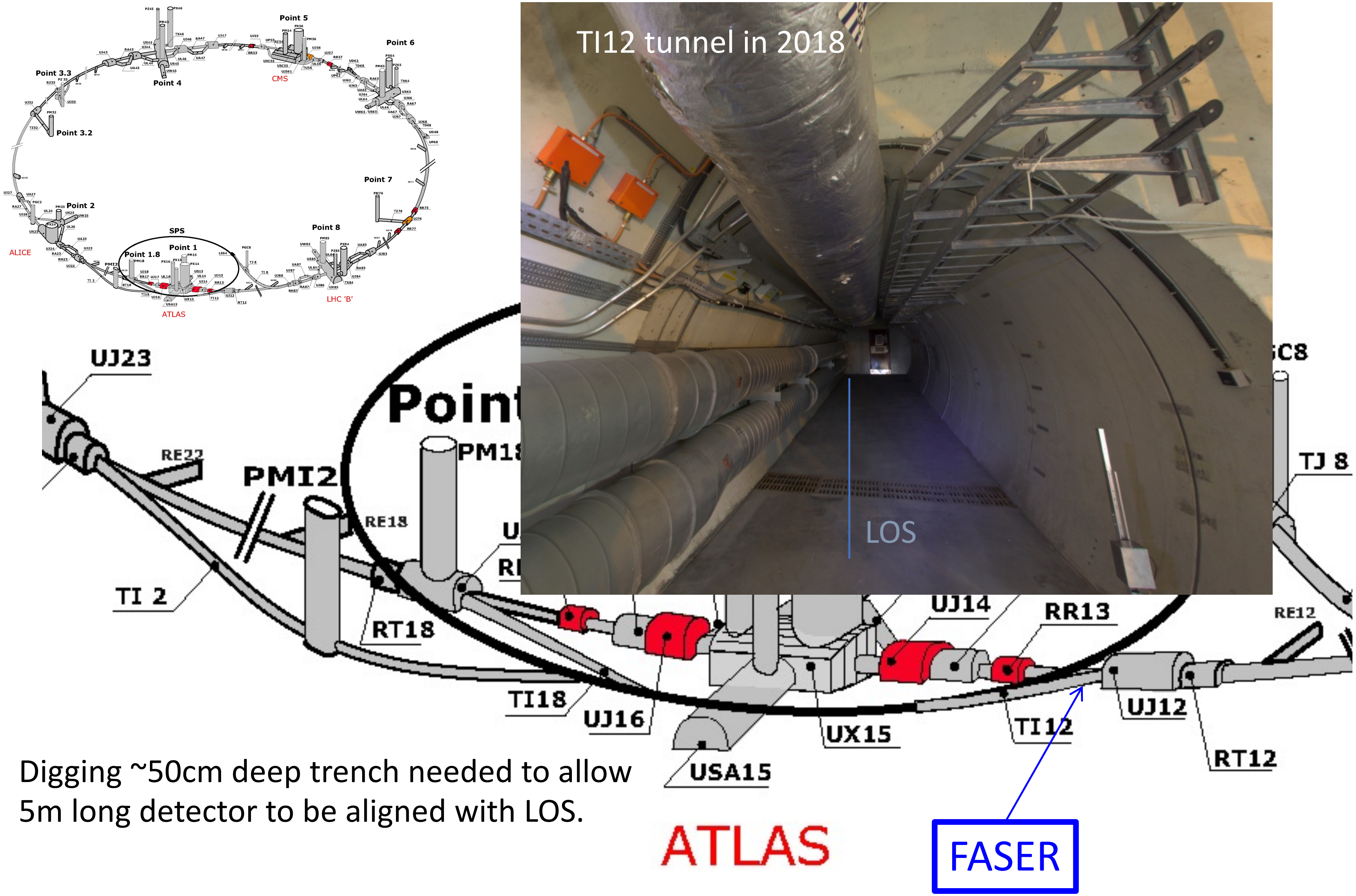
FASER is a new, small experiment at the LHC designed to take advatage of this and to search for new, light, long-lived particles (LLPs), and study neutrinos. The experiment is situated ~500m from the ATLAS collision point, on the beam collision axis line-of-sight (LOS), and started taking physics data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

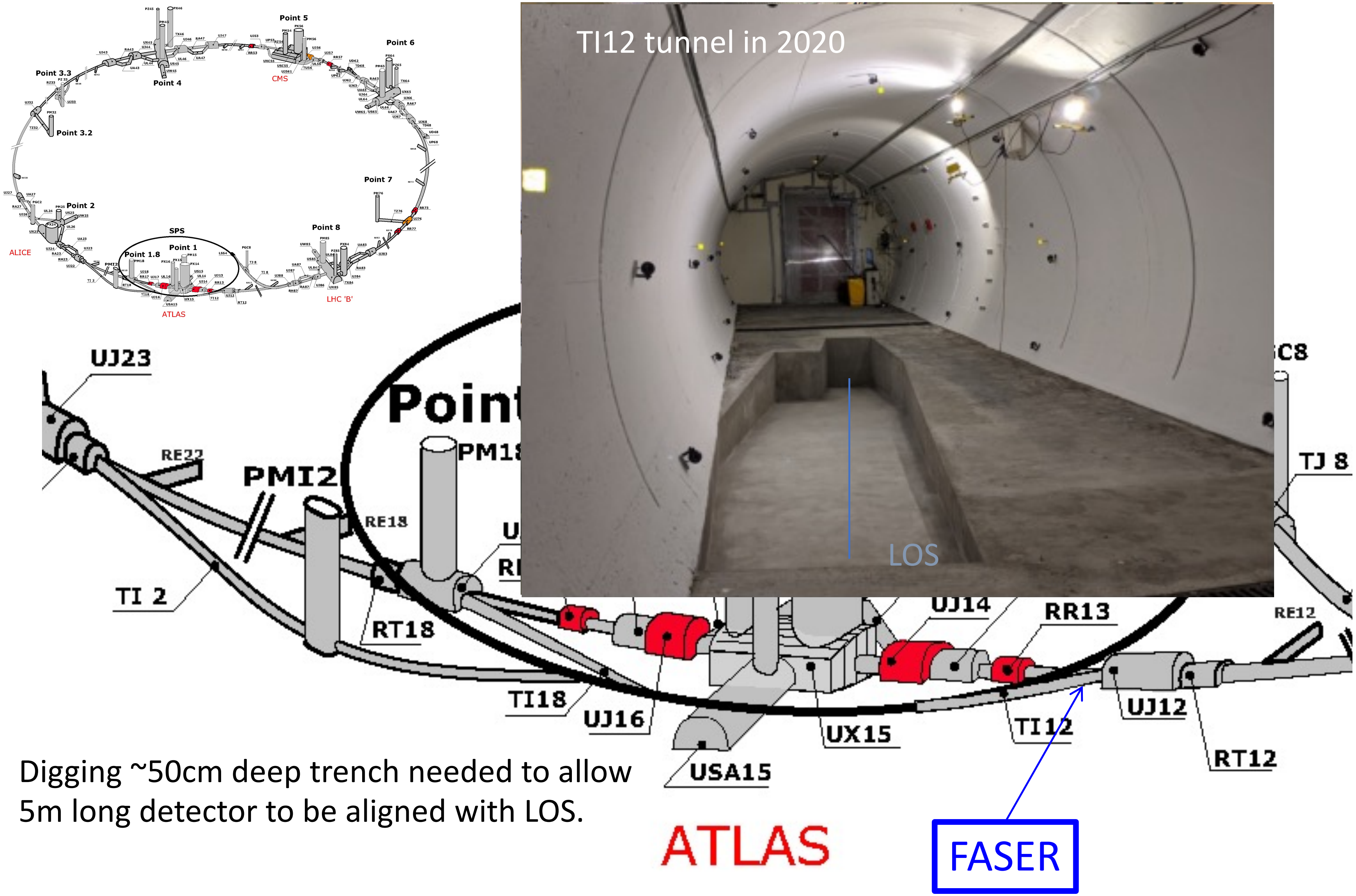


FASER Location: TI12 tunnel



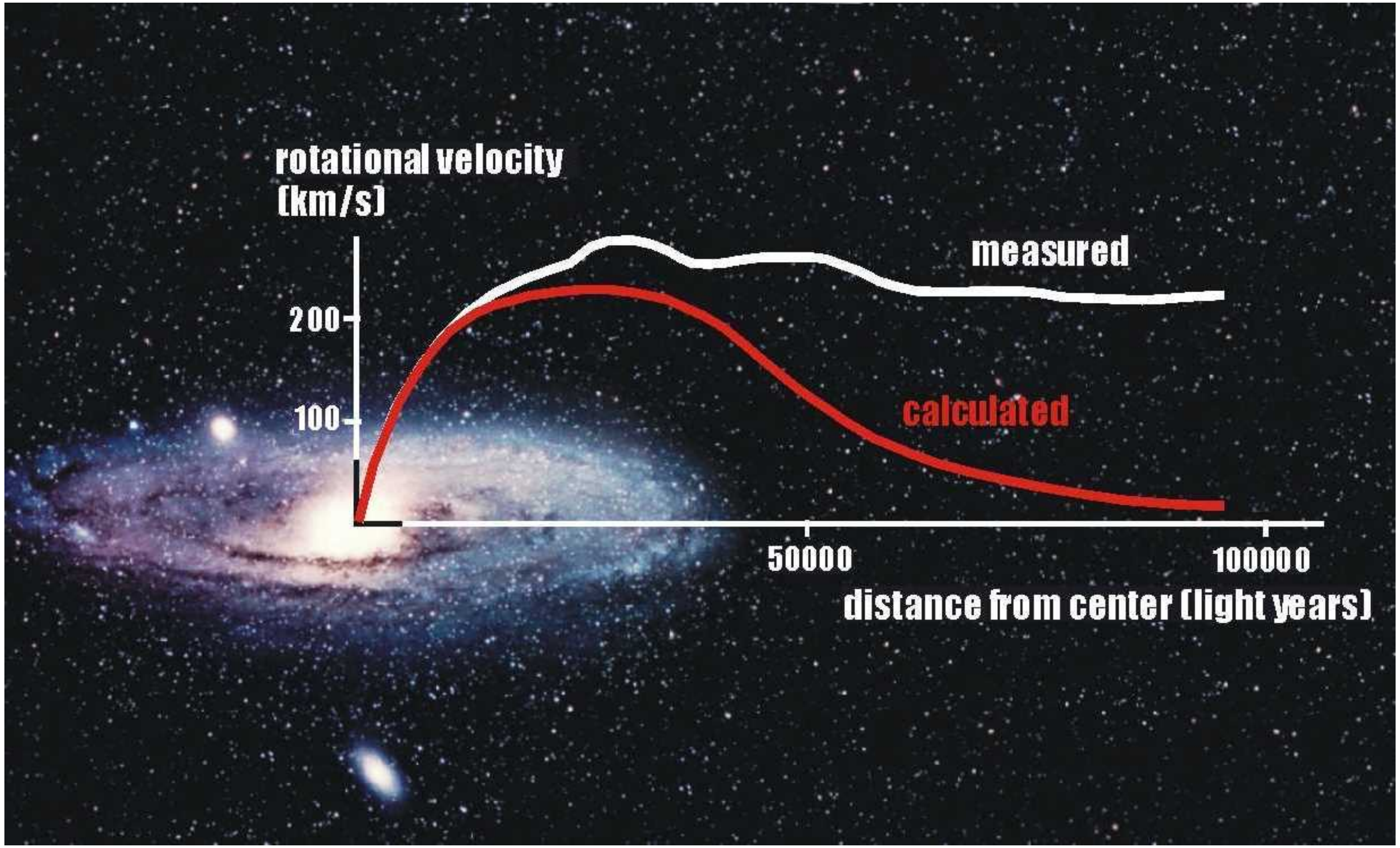
Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS.

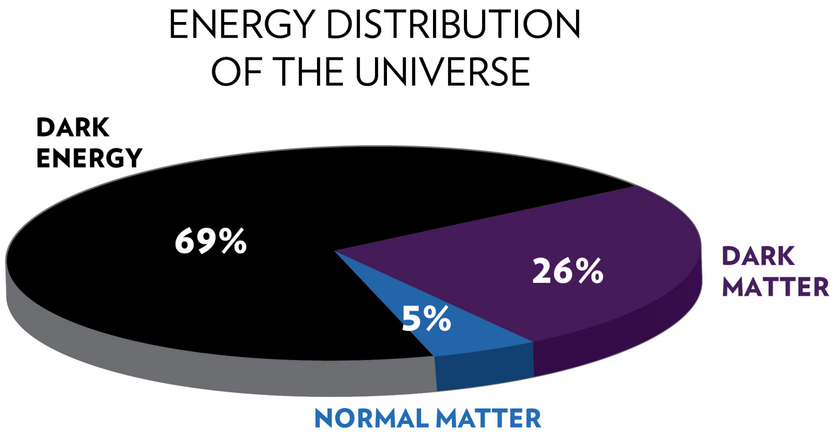
FASER Location: TI12 tunnel



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

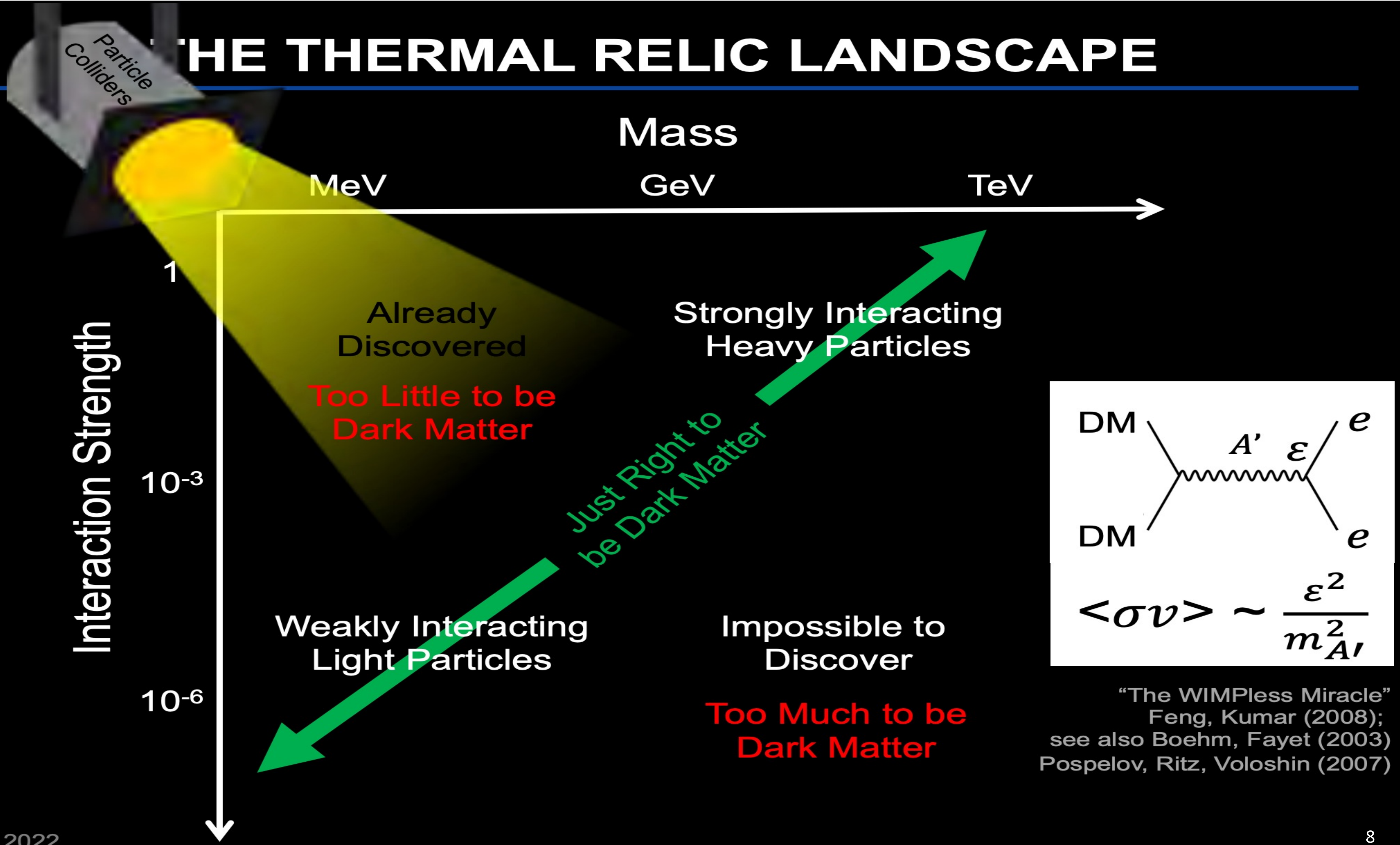
Dark Matter





Clear evidence for dark matter from astrophysics (galaxy rotation curves, gravitational lensing, cosmic microwave background, etc..). The understanding the (particle?) nature of dark matter is a key question in particle physics today.

THE THERMAL RELIC LANDSCAPE



Already Discovered

Too Little to be Dark Matter

Strongly Interacting Heavy Particles

Just Right to be Dark Matter

Weakly Interacting Light Particles

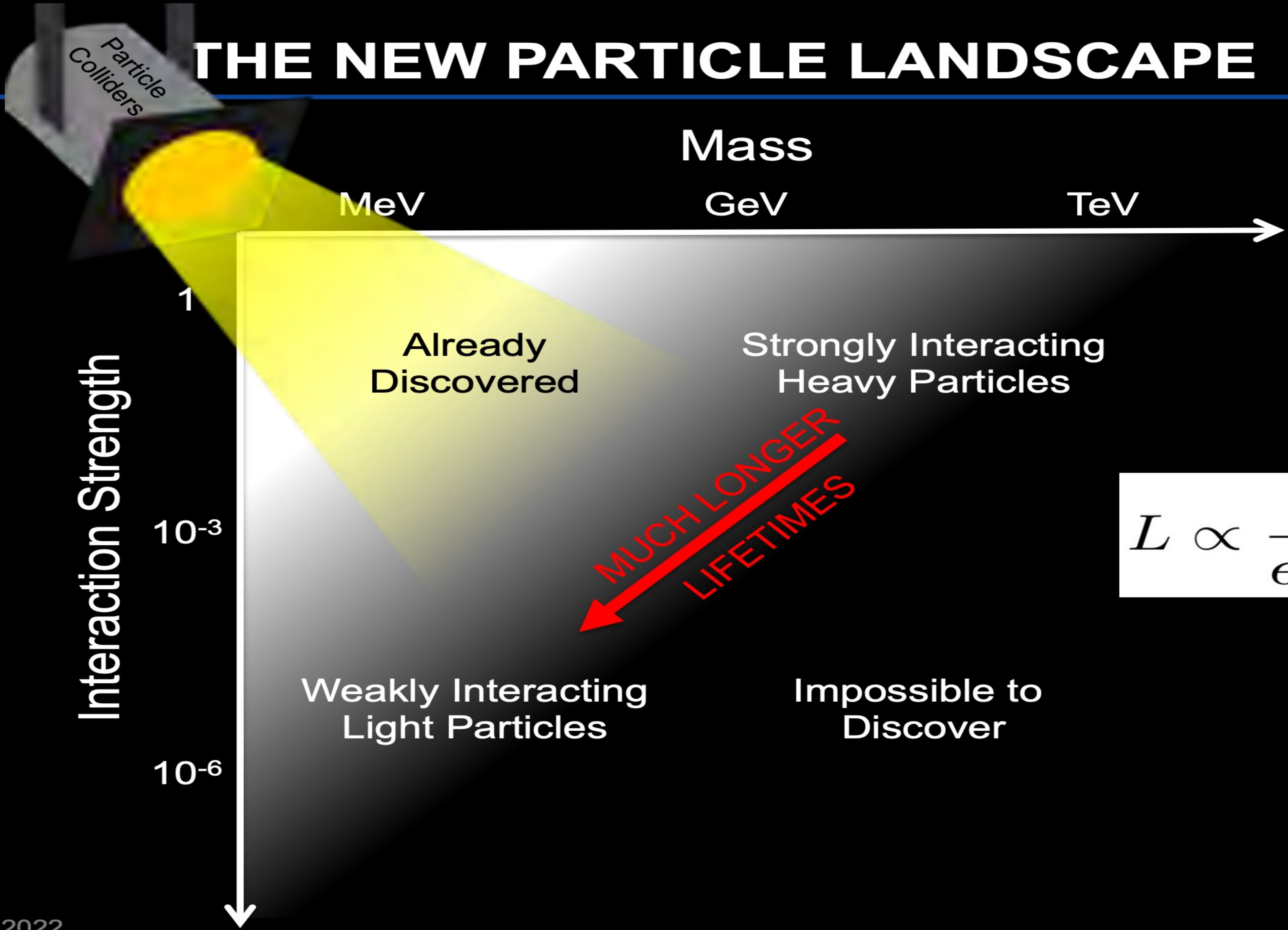
Impossible to Discover

Too Much to be Dark Matter

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

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

THE NEW PARTICLE LANDSCAPE



Particle Colliders

Mass

MeV

GeV

TeV

Interaction Strength

1

10^{-3}

10^{-6}

Already
Discovered

Strongly Interacting
Heavy Particles

MUCH LONGER
LIFETIMES

Weakly Interacting
Light Particles

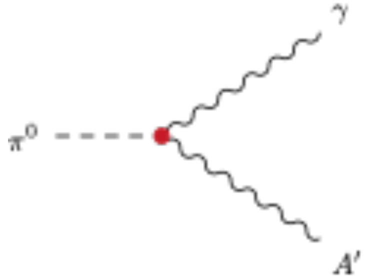
Impossible to
Discover

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

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.,



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

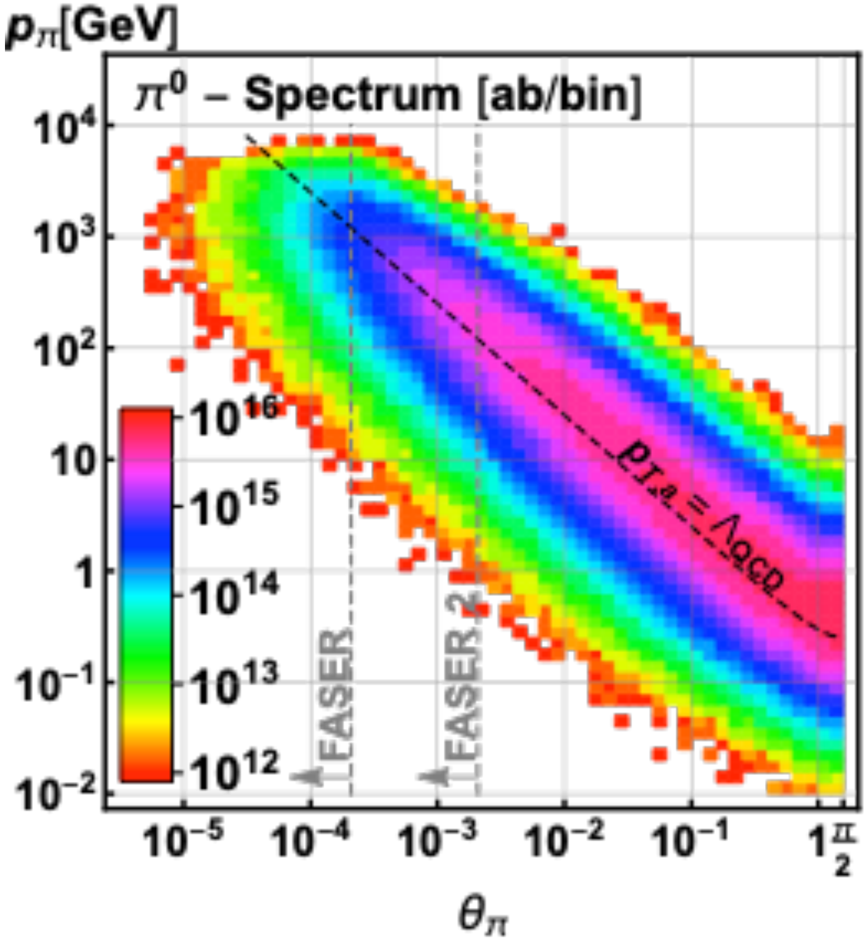
and also through other processes

- 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,

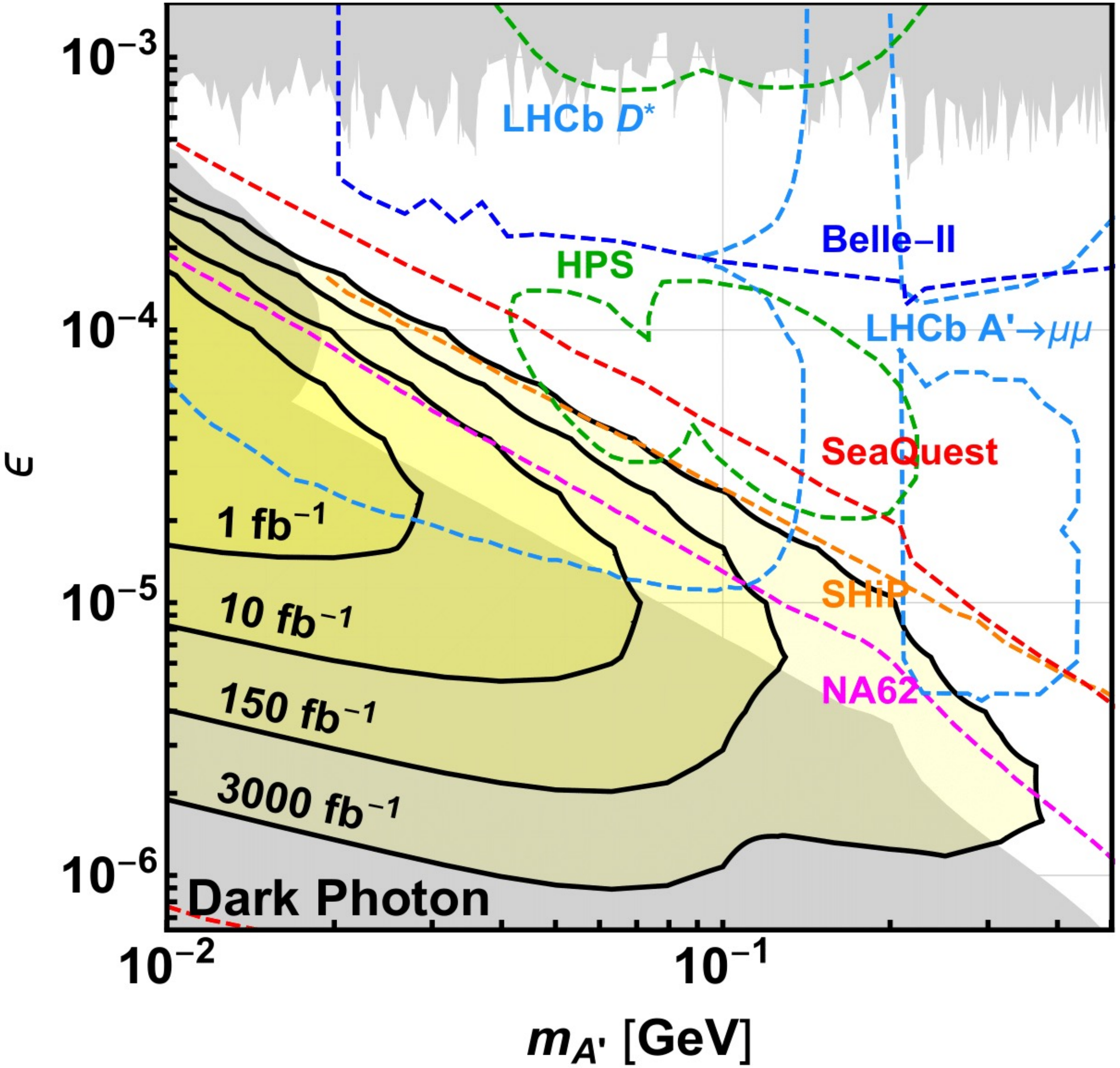
- $\mathcal{O}$(1%) of π^0s fall in FASER acceptance;
- whereas the FASER acceptance covers just $\mathcal{O}$(10^{-6} %) of the solid angle.

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)



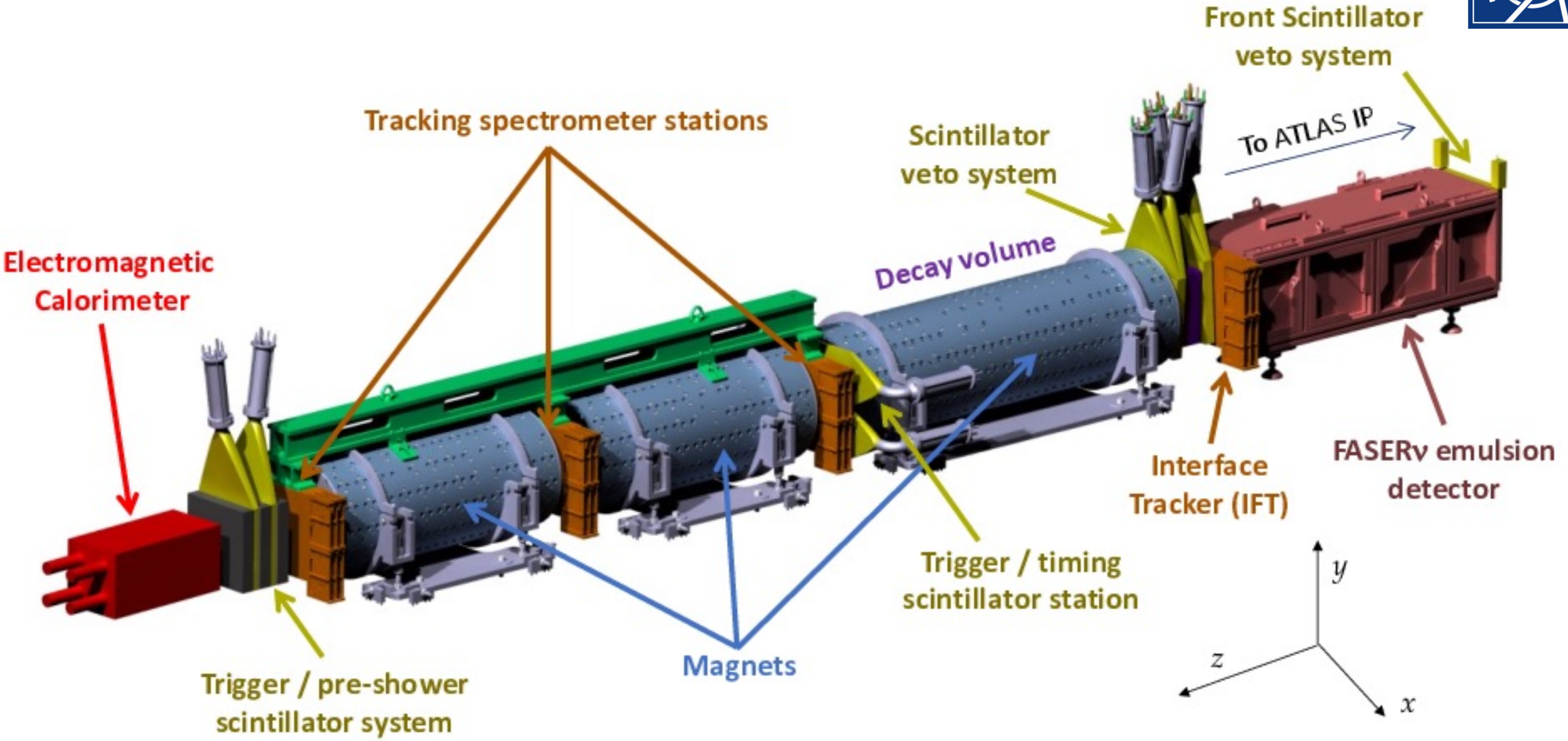
- Start to explore unconstrained space even with 1/fb
- Significant discovery potential with 150/fb (expected lower limit on total Run-3 dataset)

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

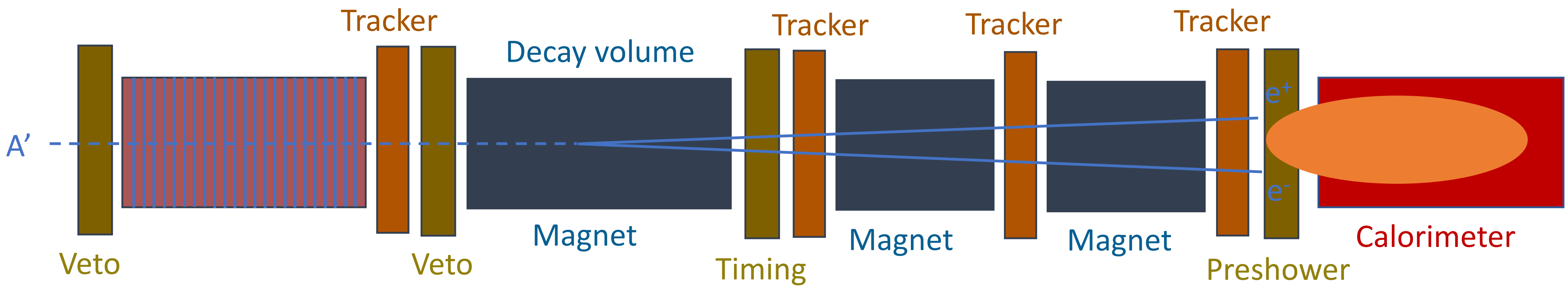
arxiv: 2207.11427



FASER Detector

arXiv: 2207.11427

Signal signature

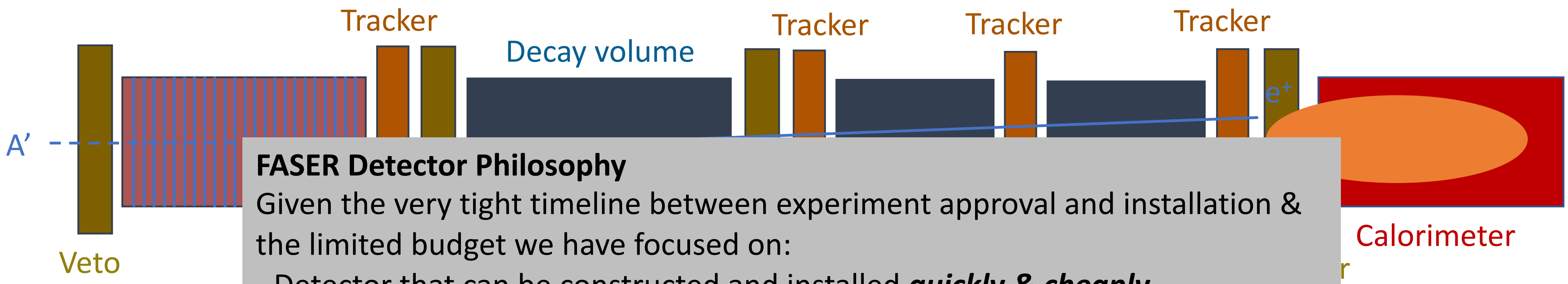


1. No signal in the veto scintillator;
2. Two high energy oppositely charged tracks, consistent with originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP;
3. For A'->e^+e^- decay: Large EM energy in calorimeter. EM showers too close to be resolved.

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

FASER Detector

Signal signature



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

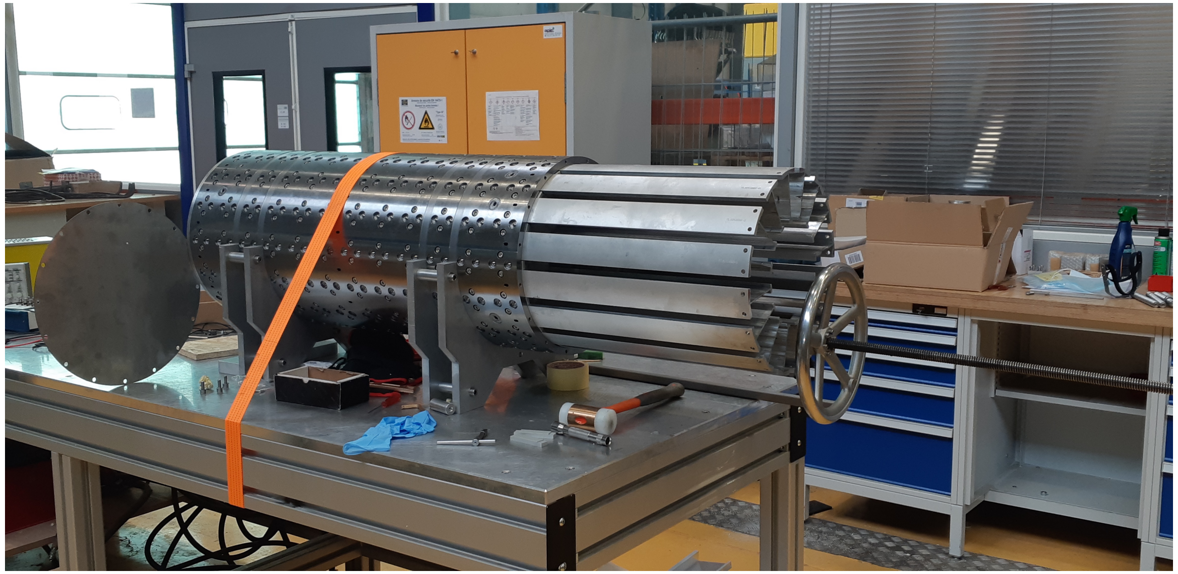
Many challenges of the large LHC experiments not there for FASER:

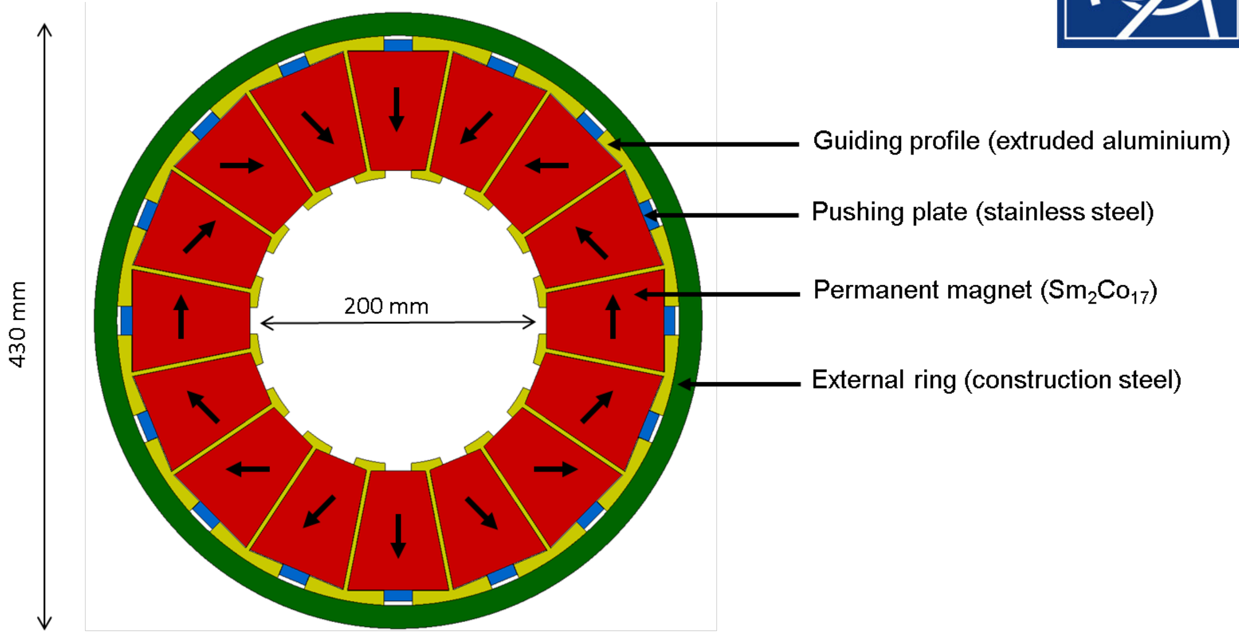
- trigger rate $\mathcal{O}$(1 kHz) (mostly single muon events)
- low radiation
- low occupancy / event size

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

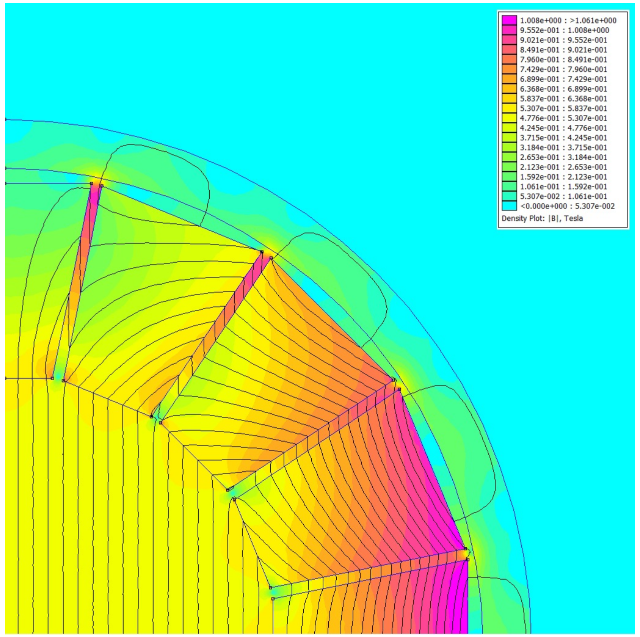
to be able to be resolved in tracker

FASER Magnets





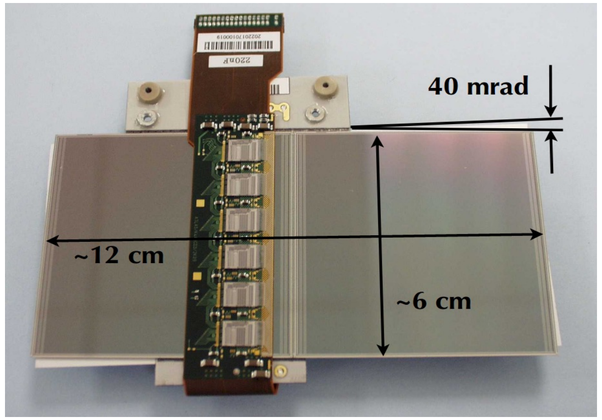
- The FASER magnets are 0.57T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed, constructed and measured by the magnet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



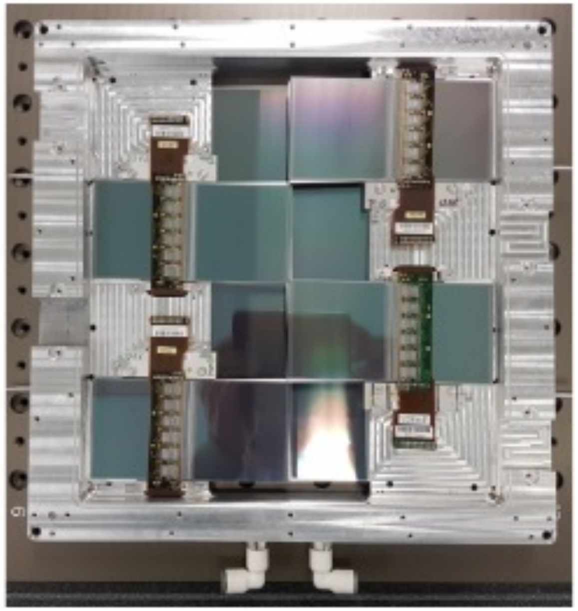
FASER Tracker

NIMA 166825 (2022)

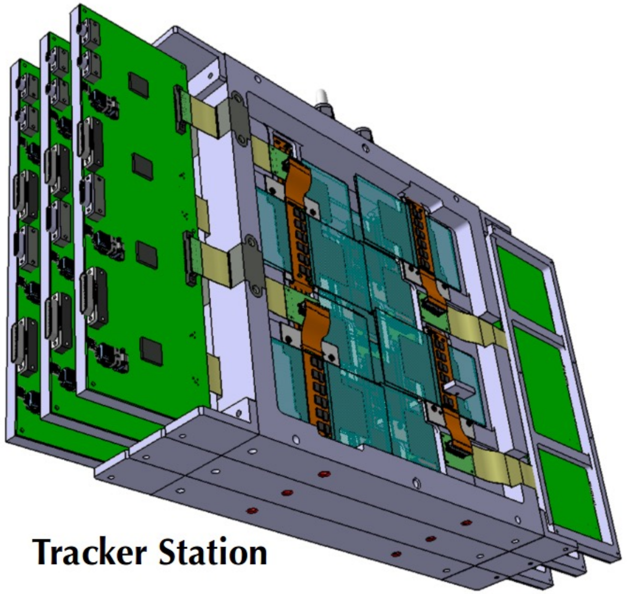
- FASER Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 4 tracking stations
- Each containing 3 layers of double-sided silicon micro-strip sensors
  - Spare ATLAS SCT modules are used
    - 80µm strip pitch, 40mrad stereo angle (17µm / 580µm 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

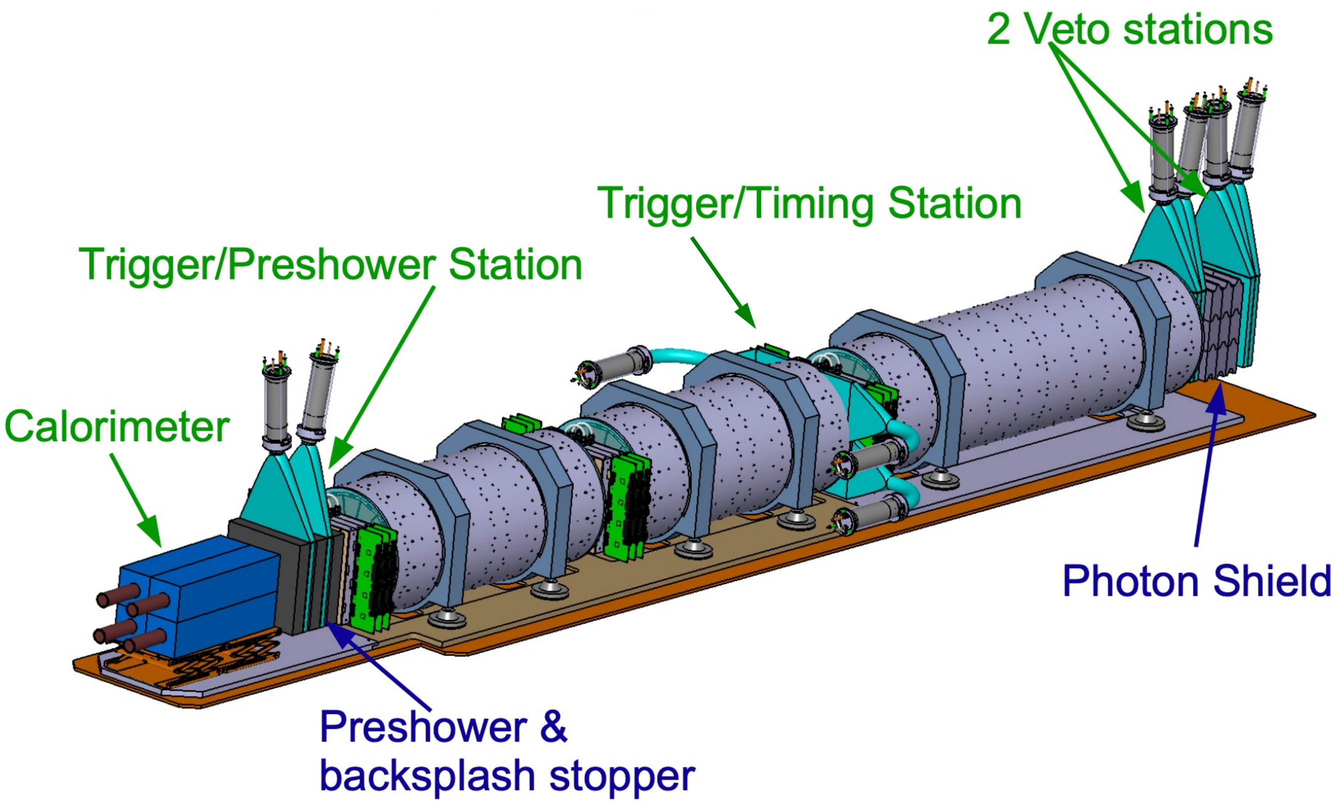


Tracking layer



FASER Scintilators

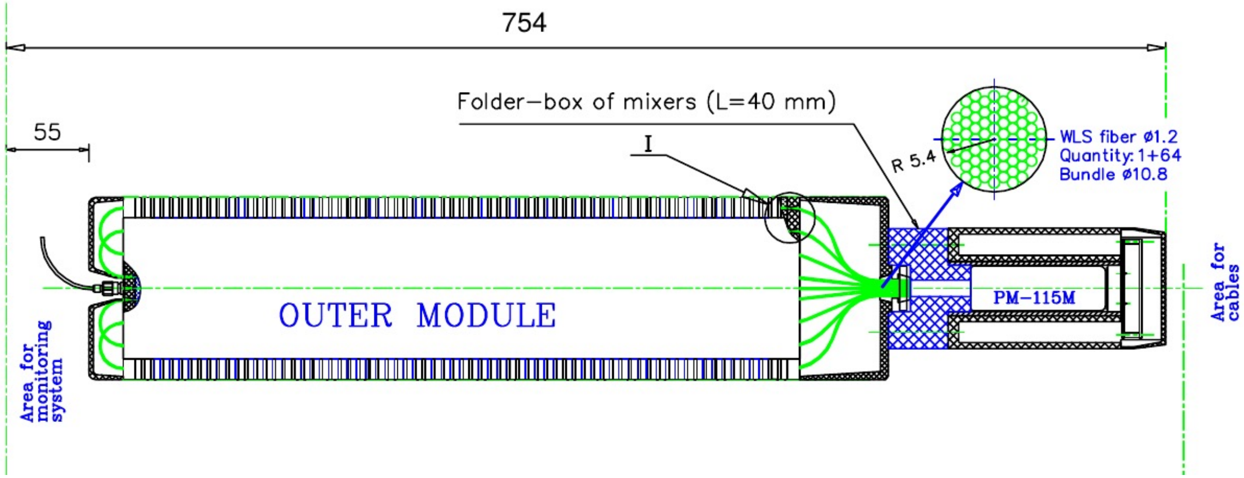
Scintillators used for:
- Vetoing incoming charged particles
  - Very high efficiency needed ($\mathcal{O}(10^8)$ incoming muons in 150/fb)
- Triggering
- Timing measurement
  - ~0.5 ns resolution
- Simple pre-shower for Calorimeter

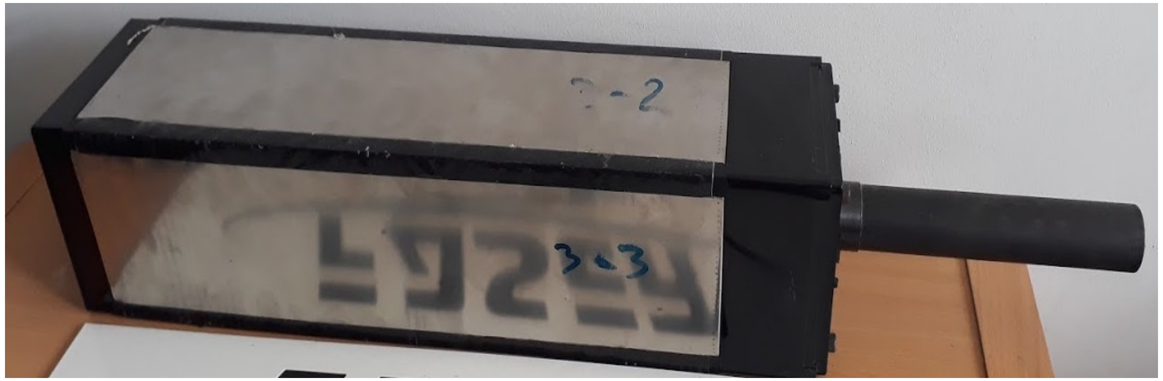


Scintillators, light guides and PMT housing constructed at CERN scintillator lab (EP-DT).

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

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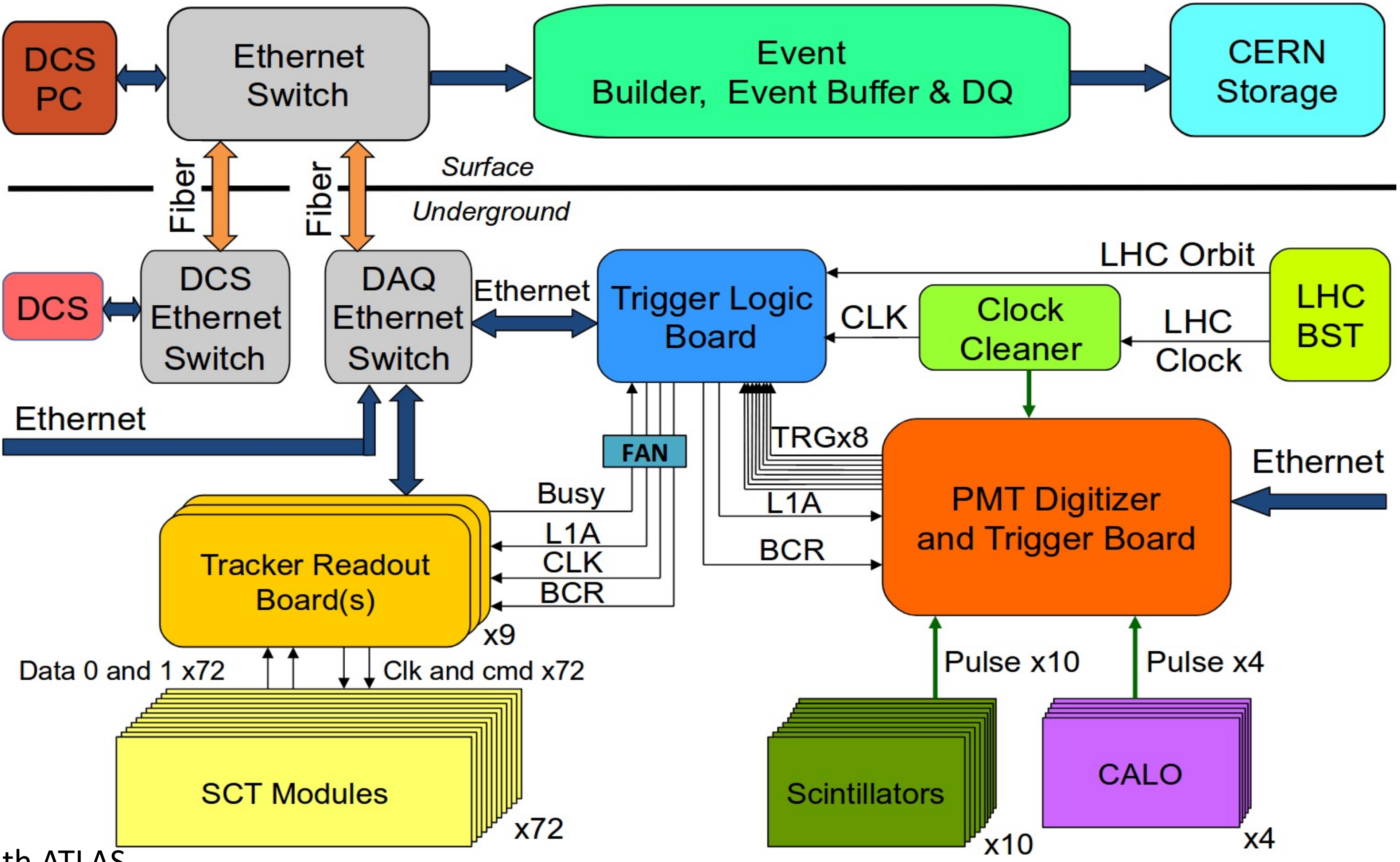
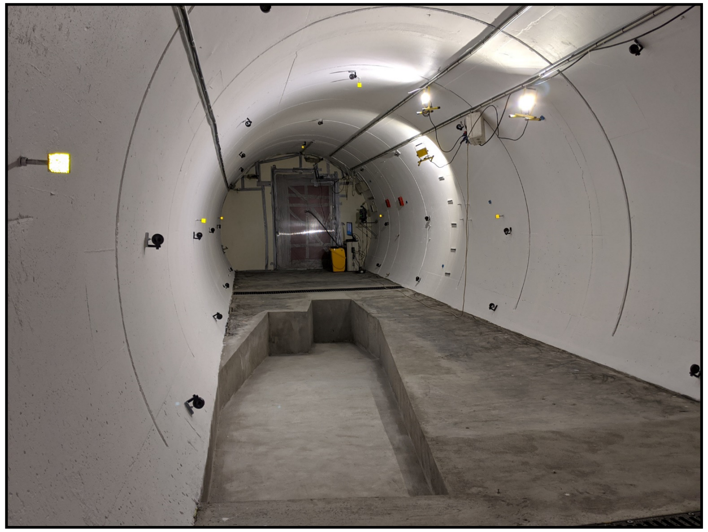


Trigger rate $\mathcal{O}$(1 kHz)
Event size (~25KB)
No triggers shared with ATLAS
FASER DAQ software based on DAQling framework from EP-DT

FASER Detector Installation

8/18



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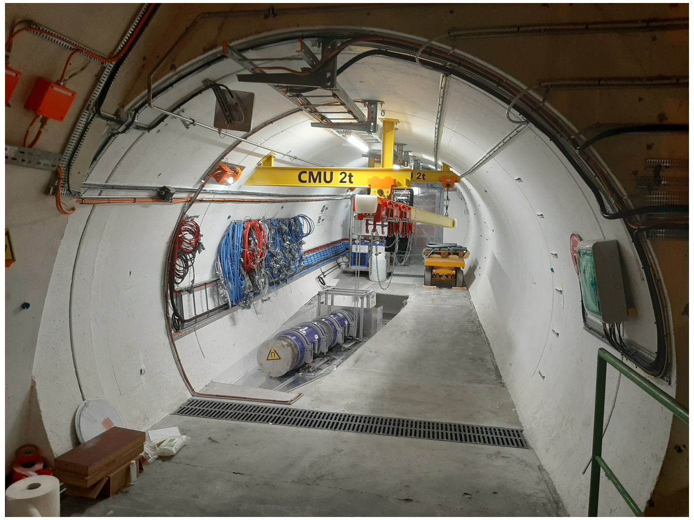

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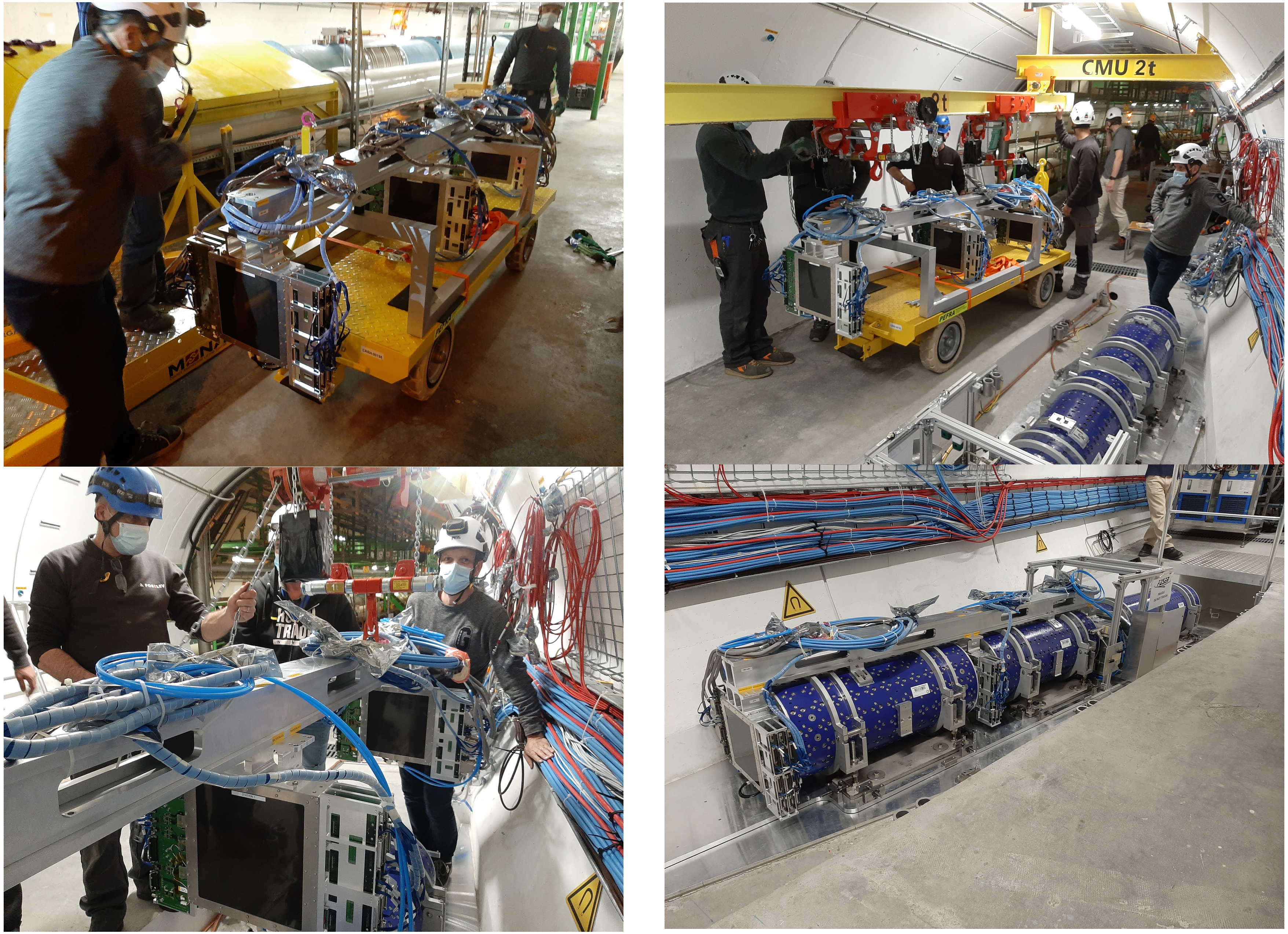
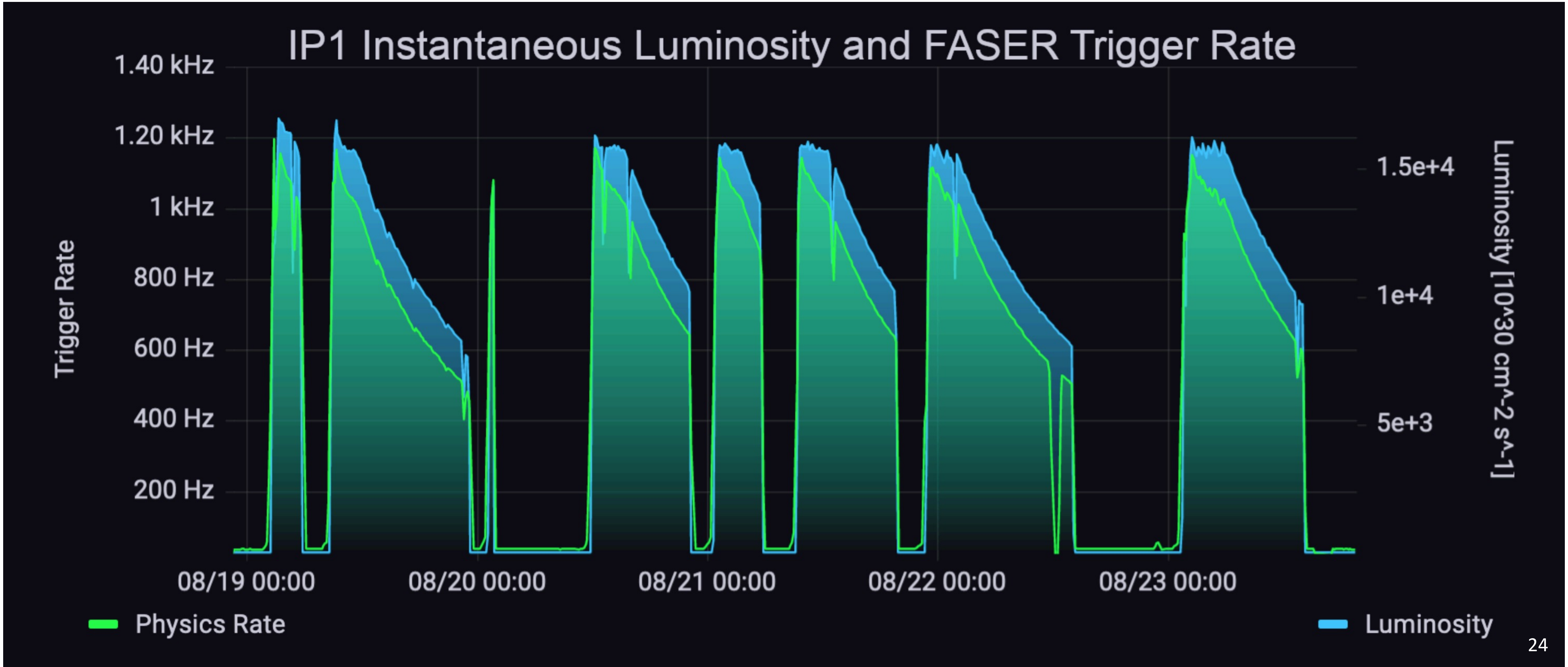
Tracker Installation



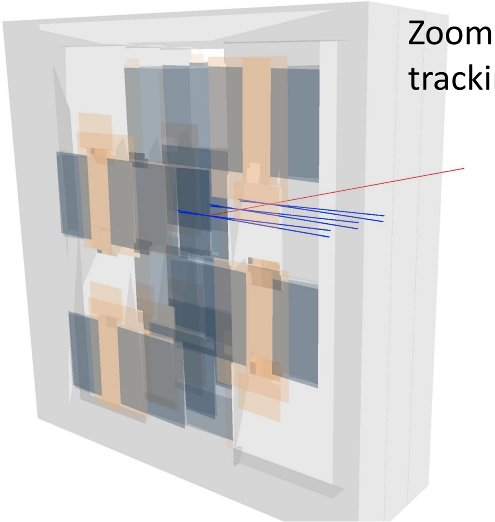
FASER was installed into TI12 in March 2021. Physics data taking started in July 2022, after >1 year of in situ cosmic ray datataking.

FASER Operations

FASER has been succesfully collected 13.6 TeV collision data from July-Nov 2022, with no big problems observed.
The maximum trigger rate was ~1.2kHz, nearly 2x the expectation, but not a problem for physics (physics deadtime <2%).



Collision Muon Event

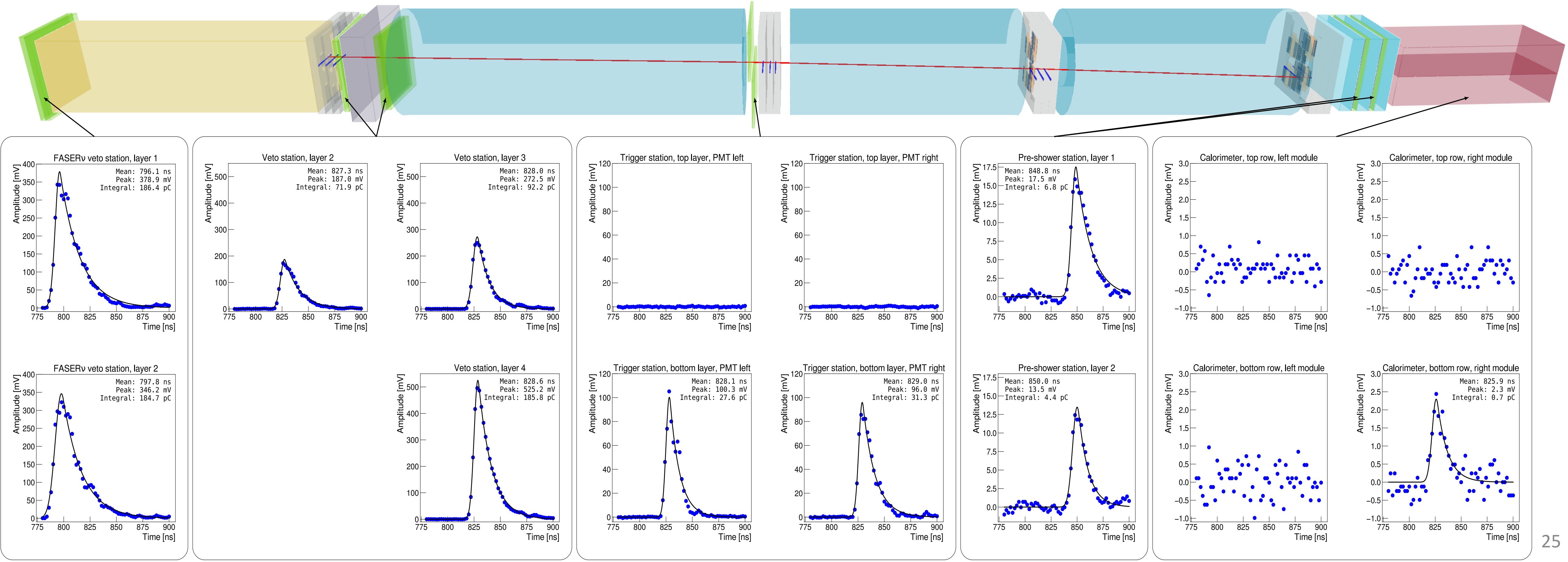


Zoom in of 1st tracking station

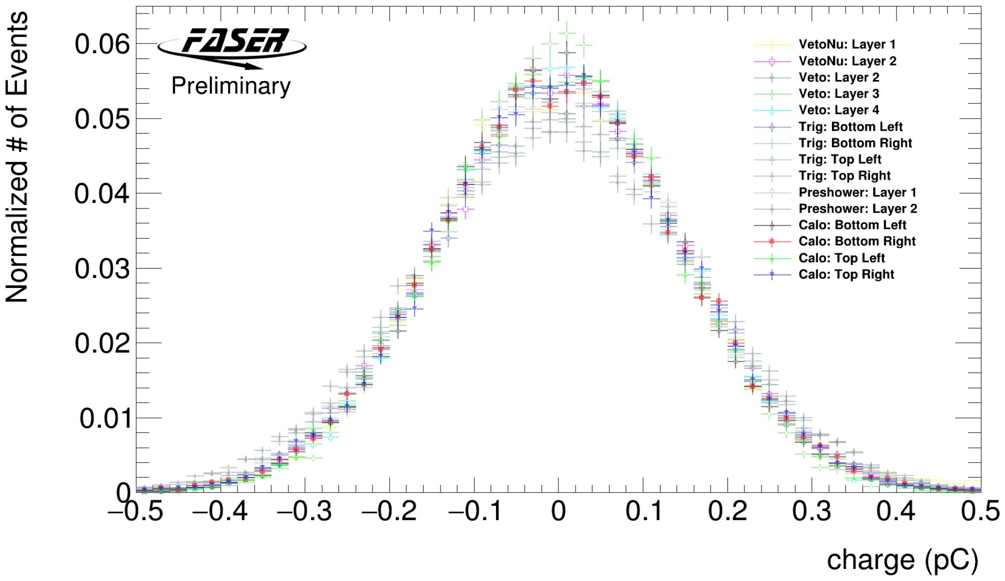
Run 8336
Event 1477982
2022-08-23 01:46:15

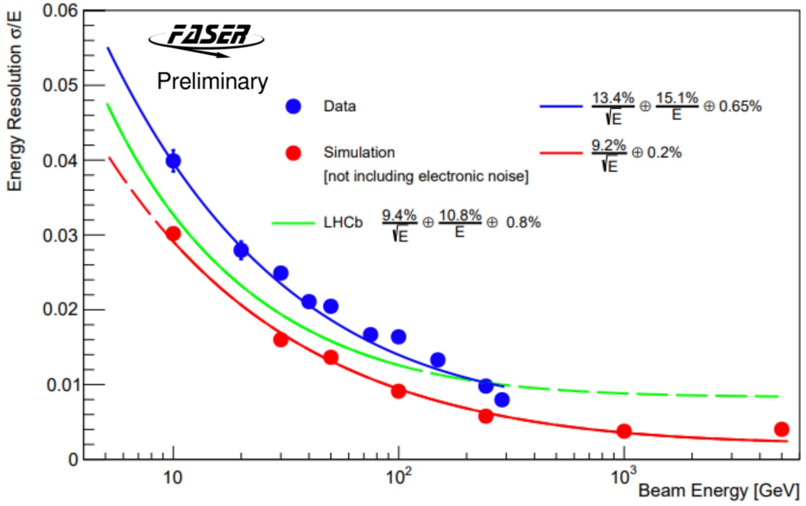
Collision event with a muon traversing FASER
Reconstructed momentum 22 GeV.
Signal consistent with MIP seen in all scintillators and calorimeter.

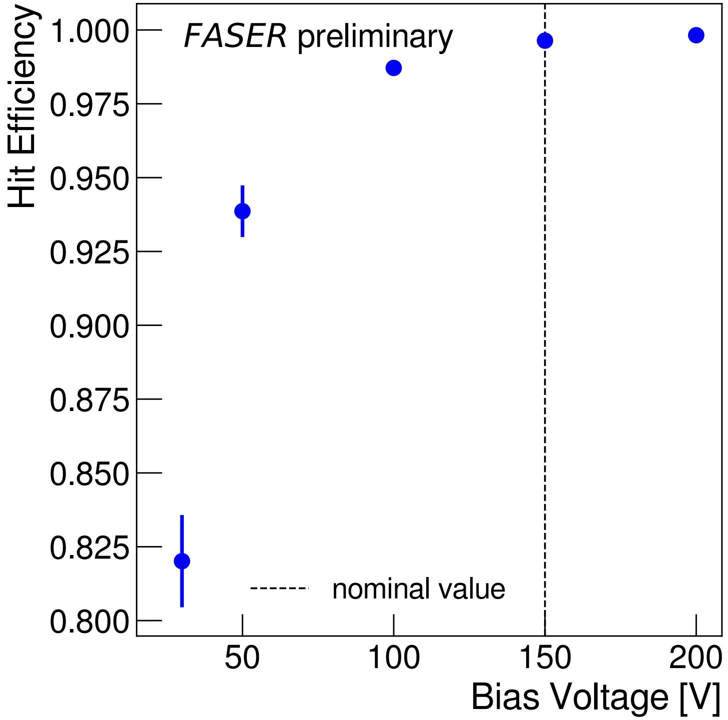
To ATLAS IP



Detector Performance



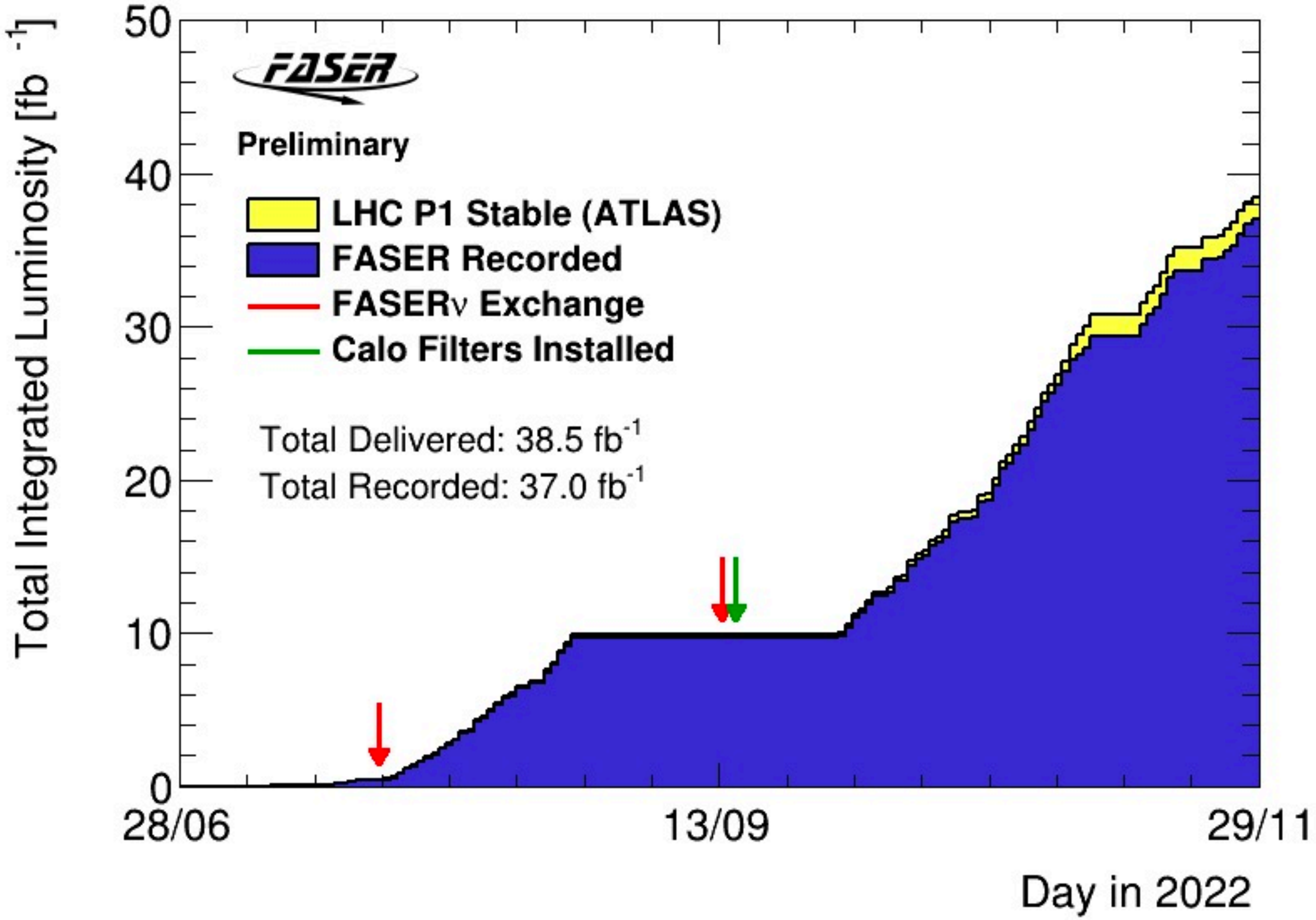




- Scintillators:
  - Efficiency measured with collision data to be very high and within spec
  - Noise ~0.15pC much lower than single MIP signal (~70pC)
- Calorimeter:
  - Energy resolution measured for high energy electrons in a testbeam at the SPS (summer 2021) to be ~1%
- Tracker:
  - Hit efficiency measured in collision data to be >99.9%
  - Noise low (~1500e) and stable through run
  - <0.1% non-operational channels

2022 Data Set

- Detector operated very smoothly during 2022 running
- Recorded 96% of delivered luminosity
  - Losses from 2 DAQ incidents
- Calorimeter optical filters needed for analysis using high energy calorimeter deposits, were installed in Technical Stop (green arrow)

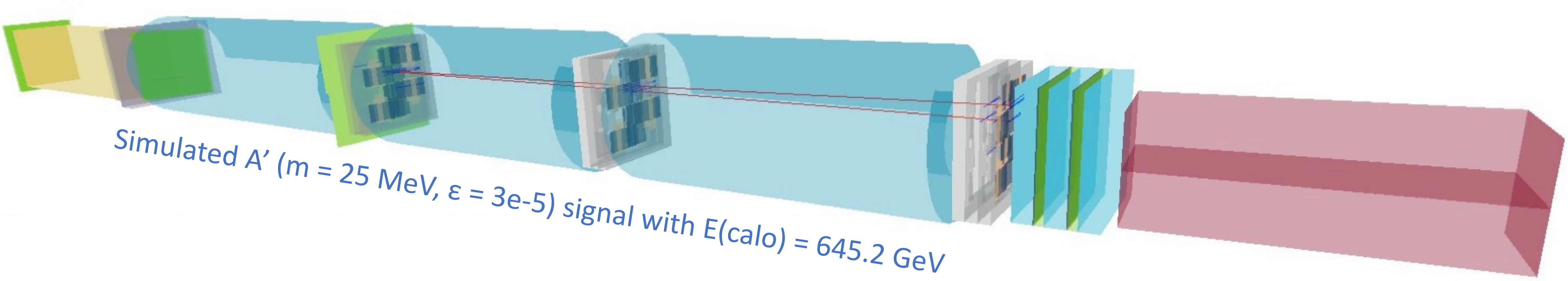


Many thanks to the ATLAS experiment for luminosity information

2022 Dark Photon Selection

- Simple and robust A’ → e^+e^- selection, optimised for discovery

1. Collision event with good data quality
4. Timing and preshower consistent with ≥2 MIPs

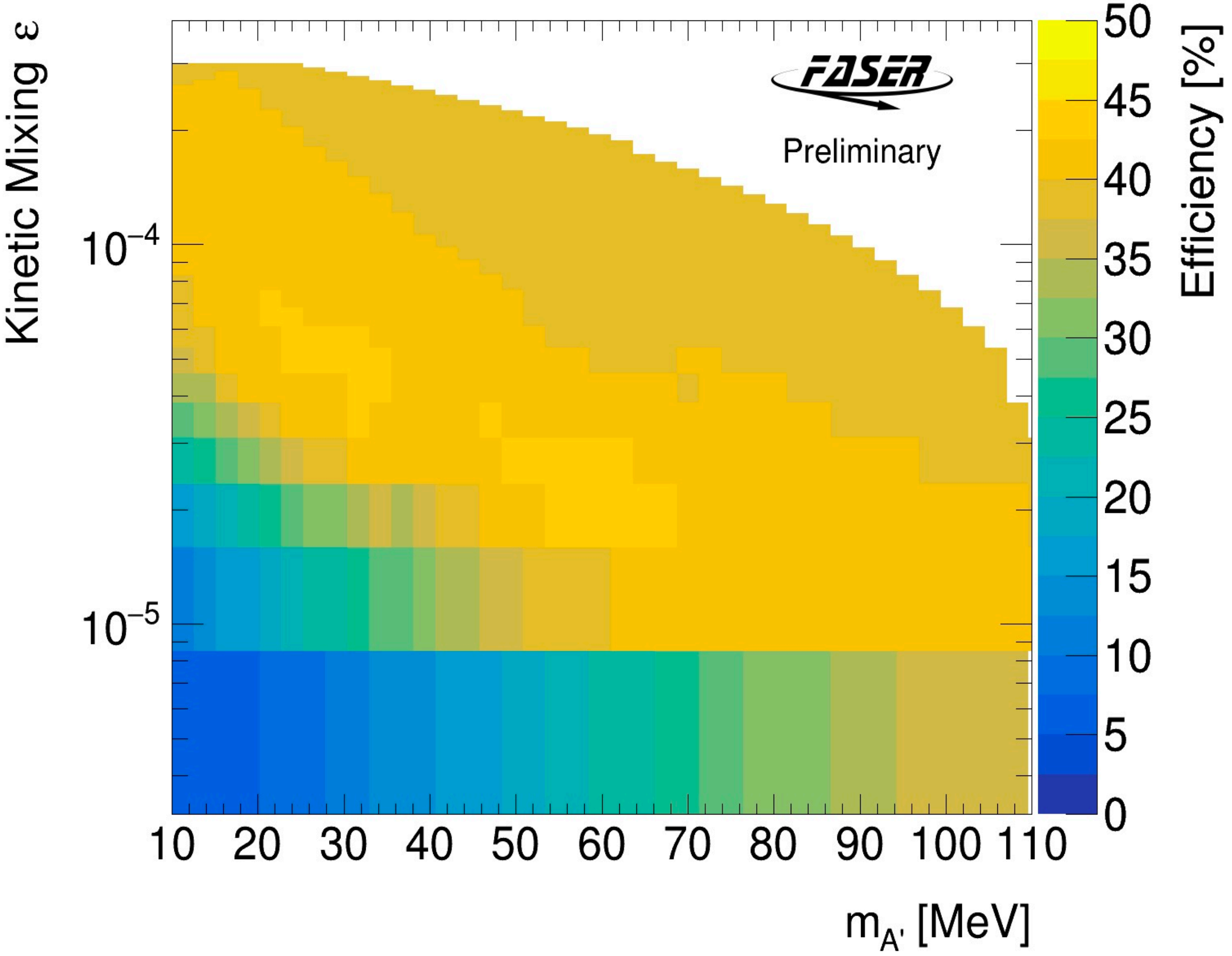


2. No signal (< 40 pC) in any veto scintillator
3. Exactly 2 good fiducial tracks
   - p > 20 GeV and r < 95 mm
   - Extrapolating to r < 95 mm at vetos
5. Calo E > 500 GeV

Blind events with no veto signal and E(calo) > 100 GeV

2022 Dark Photon Selection

- Efficiency of ~40% across region sensitive to
- Largest inefficiency from 2 track requirement (2 very closely spaced tracks in signal)



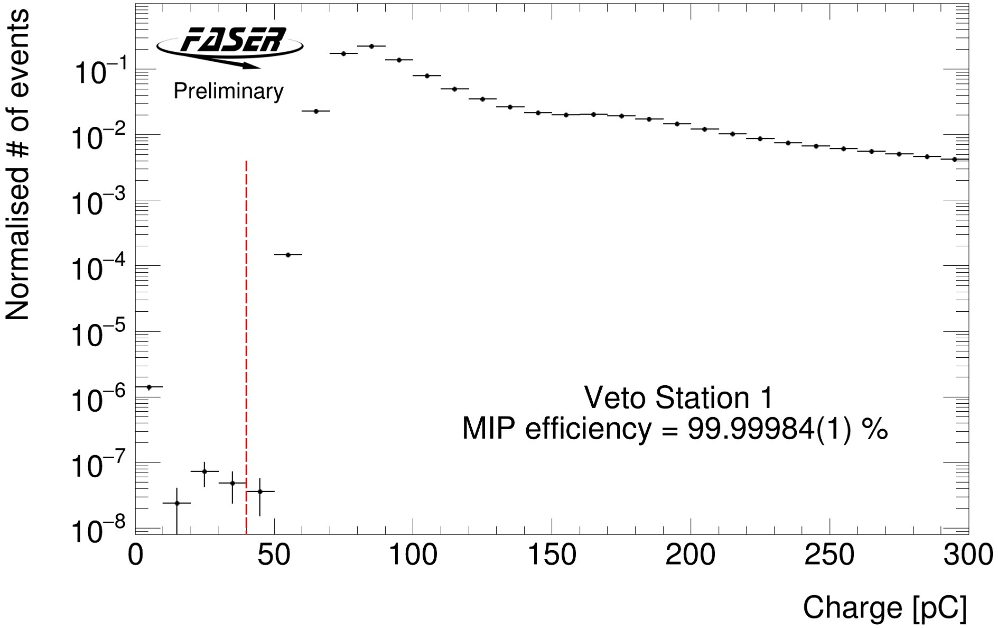
Cut flow for example signal point:

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

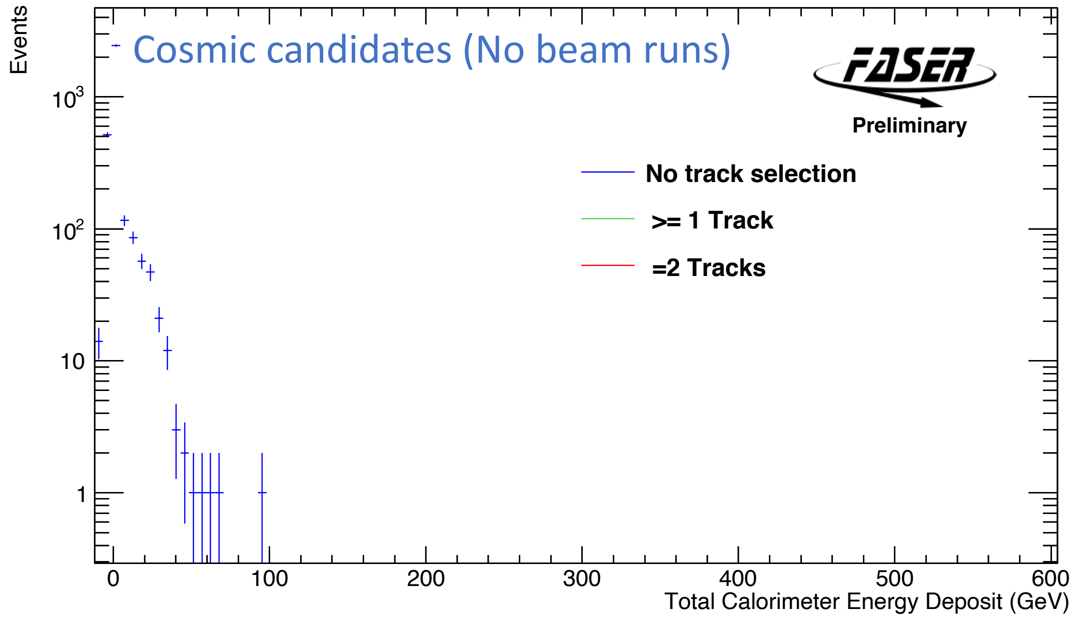
Selection Criteria	**Efficiency**
Good collision event	99.7%
No Veto Signal	98.4%
Timing/Preshower Signal	97.3%
≥ 1 good track	89.2%
$= 2$ good tracks	44.5% *
Track radius $<$ 95 mm	42.3% *
Calo energy $>$ 500 GeV	41.6% *

2022 Dark Photon Backgrounds - 1

- Veto inefficiency
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. 10^8 muons to negligible level (even before other cuts)



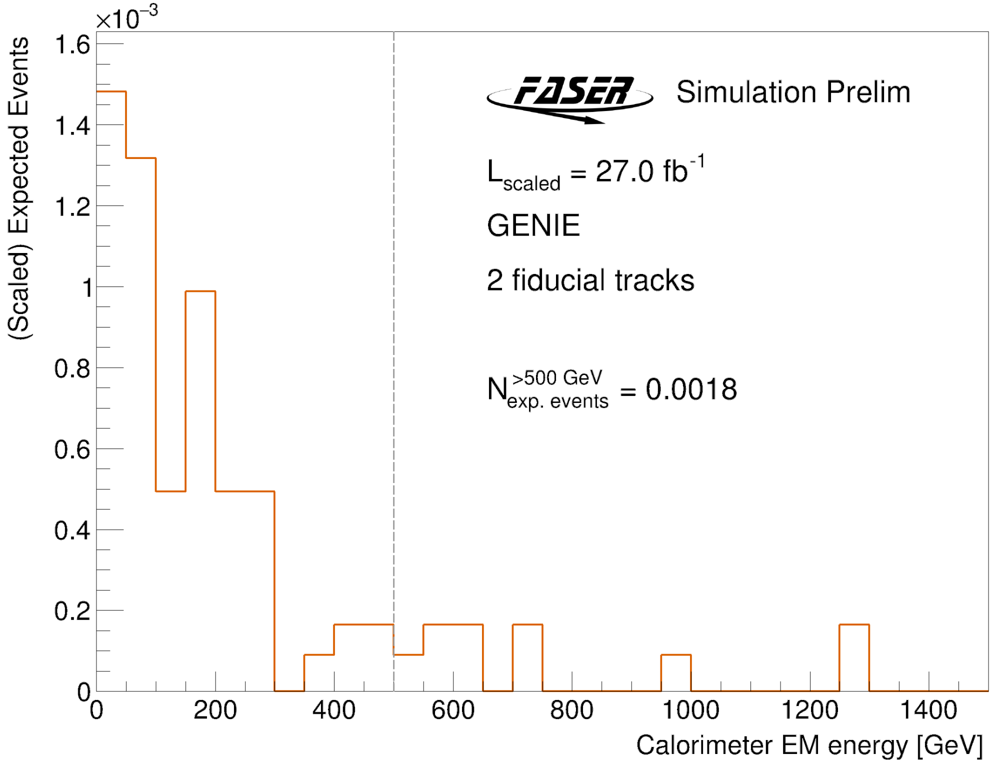
- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually



2022 Dark Photon Backgrounds - 2

- Main background is from neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab^{-1})
    - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

$$N = (1.8 \pm 2.4) \times 10^{-3}$$



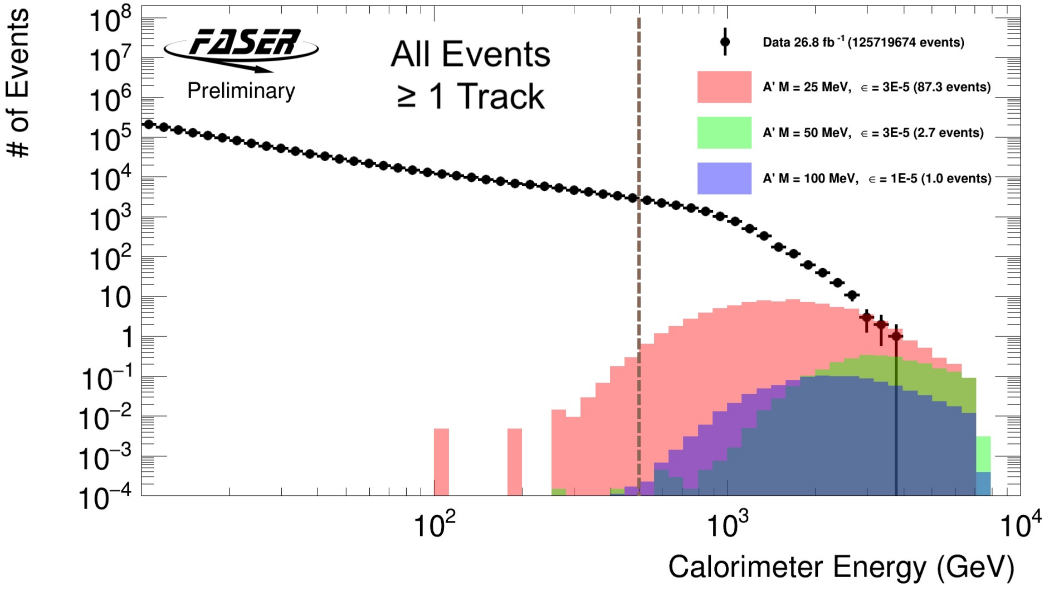
- Neutral hadrons (e.g. K_s) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed since:
    - Muon nearly always continues after interaction
    - Has to pass through 8 interaction lengths (FASERν)
    - Decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2 or 3 tracks and different veto conditions

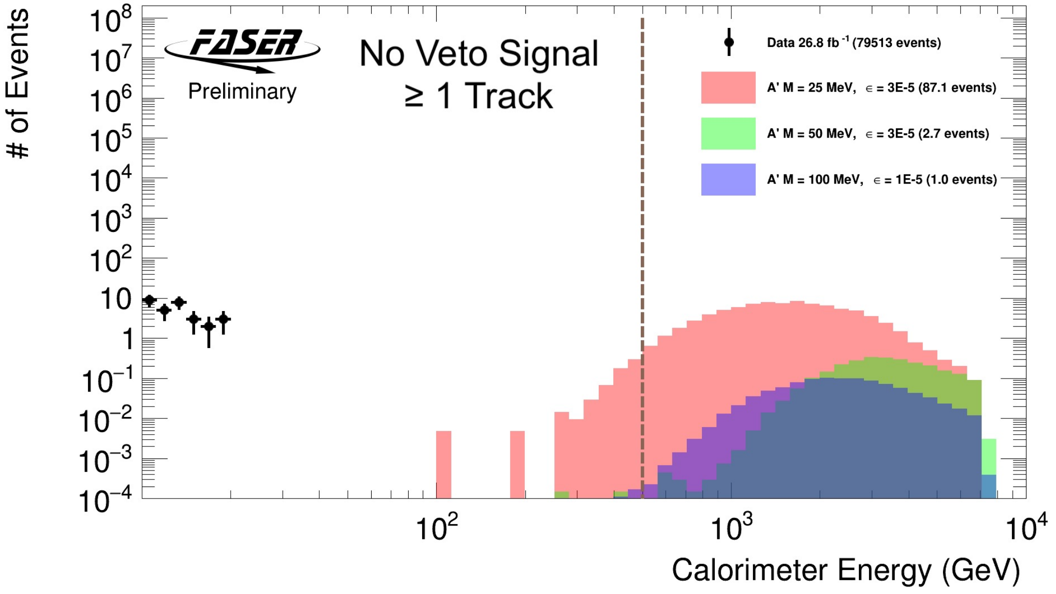
$$N = (2.2 \pm 3.1) \times 10^{-4}$$

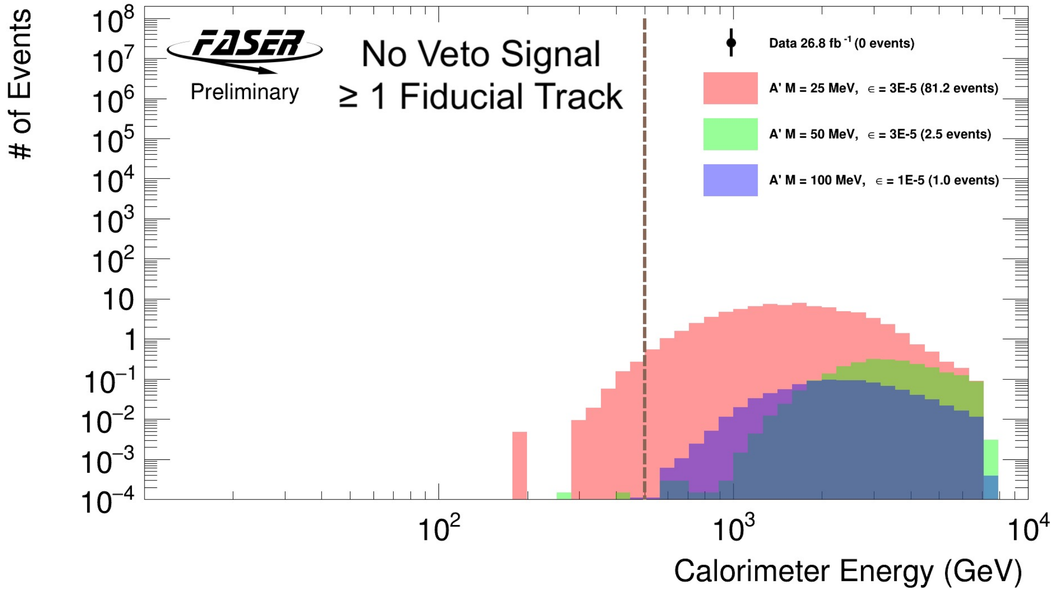
- Total background prediction

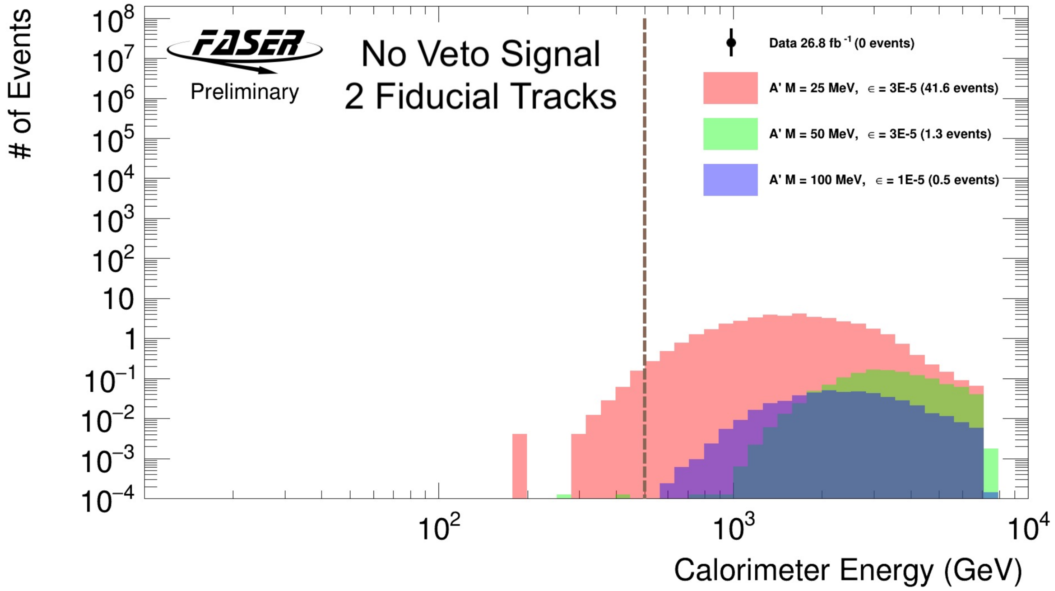
$$N = (2.02 \pm 2.4) \times 10^{-3}$$

2022 Dark Photon Results

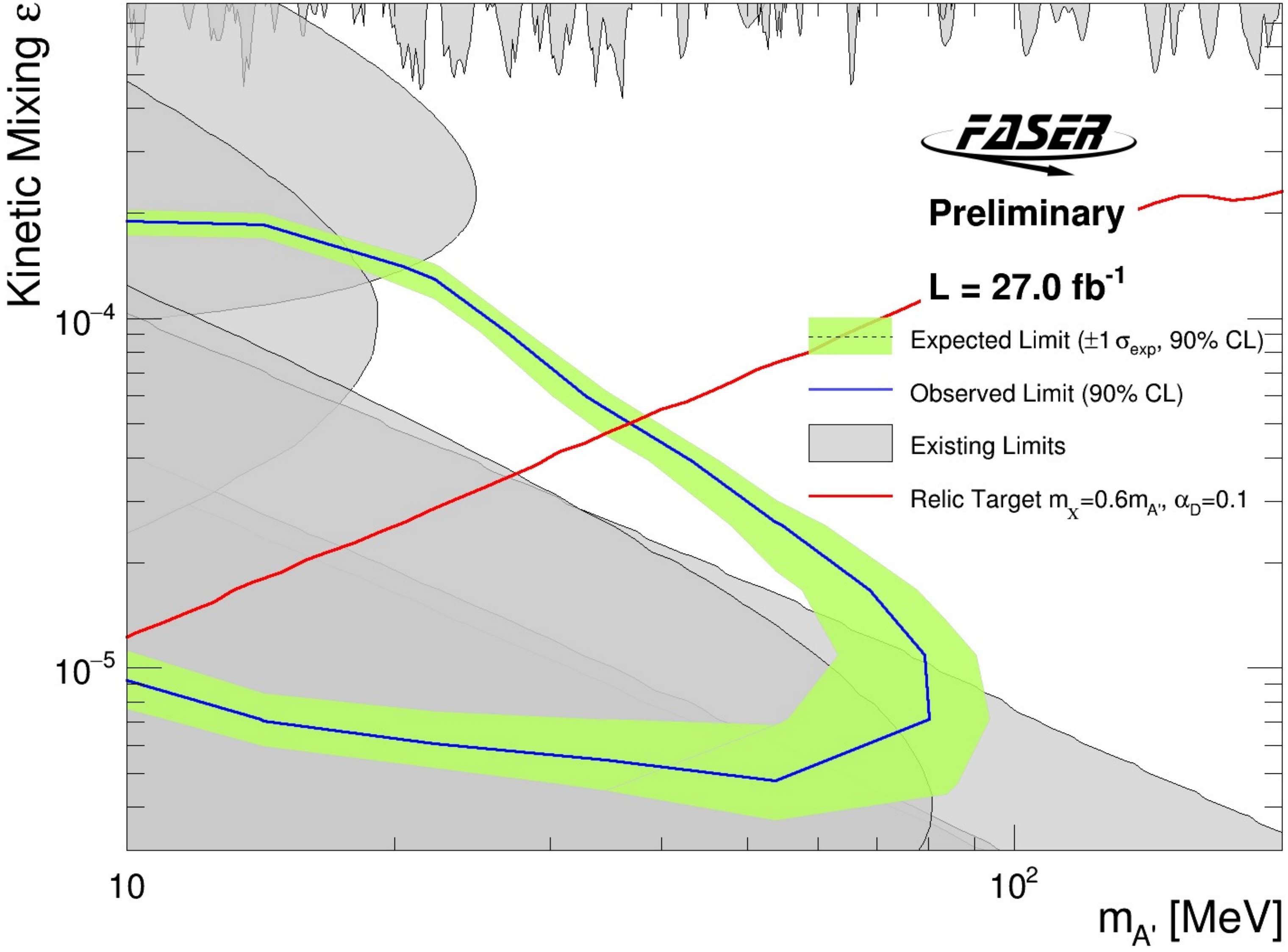








2022 Dark Photon Results



- No events in unblinded signal region
  - Not even any with ≥1 fiducial track
- Based on this null results, FASER sets limits in previously unexplored parameter space!
  - Probing region interesting from thermal relic target
  - Also taking into account new preliminary NA62 result (see backup)

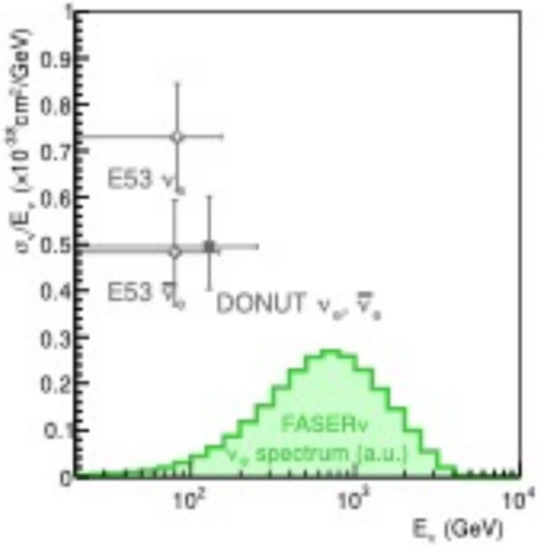
CERN-FASER-CONF-2023-001

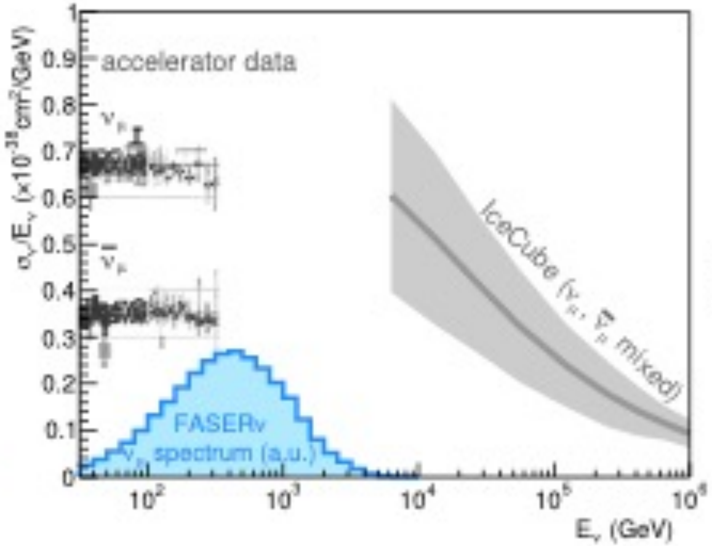
FASER Neutrino Measurements

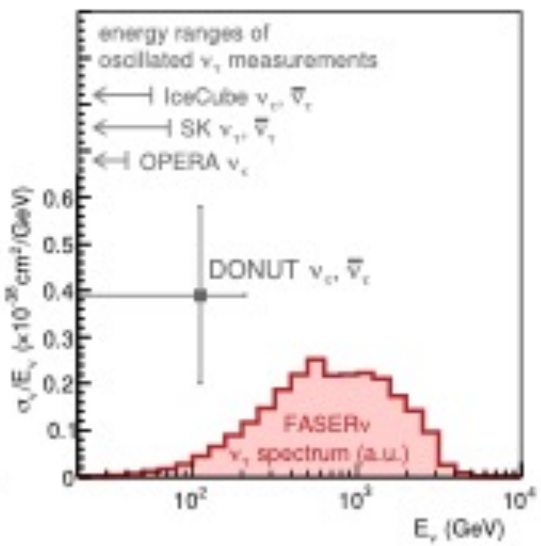
A huge number of neutrinos produced in the LHC collisions (hadron decay) traverse the FASER location covering an unexplored neutrino energy regime.

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







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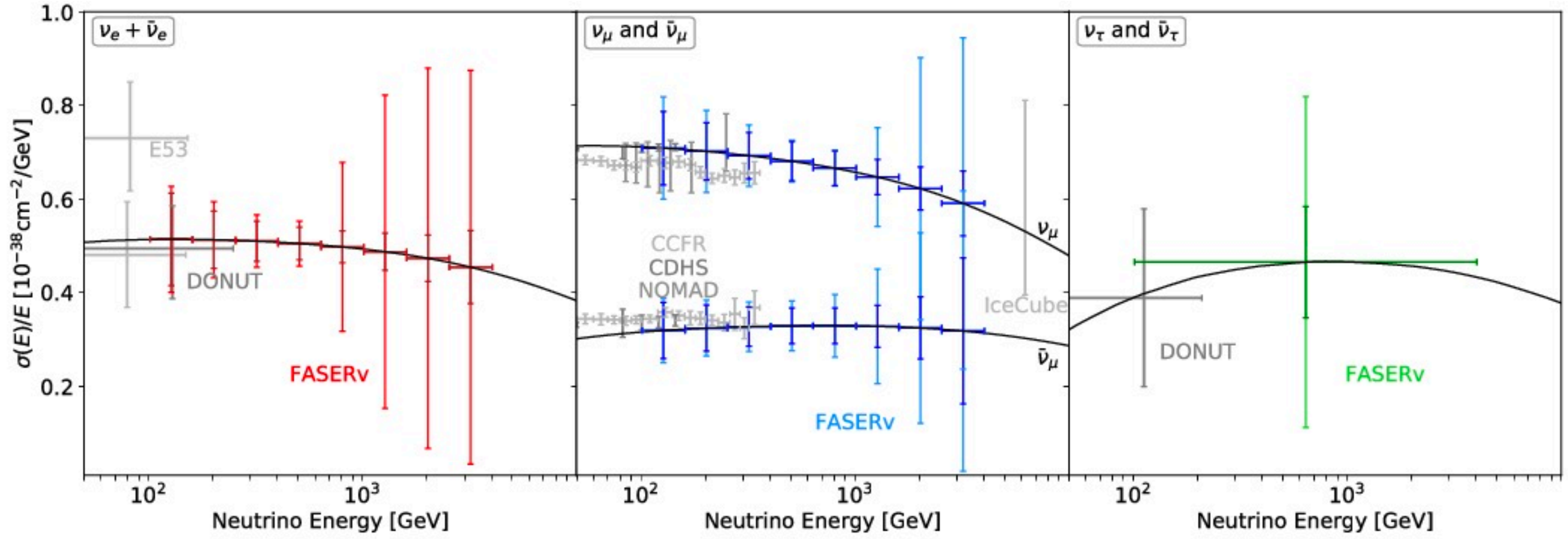
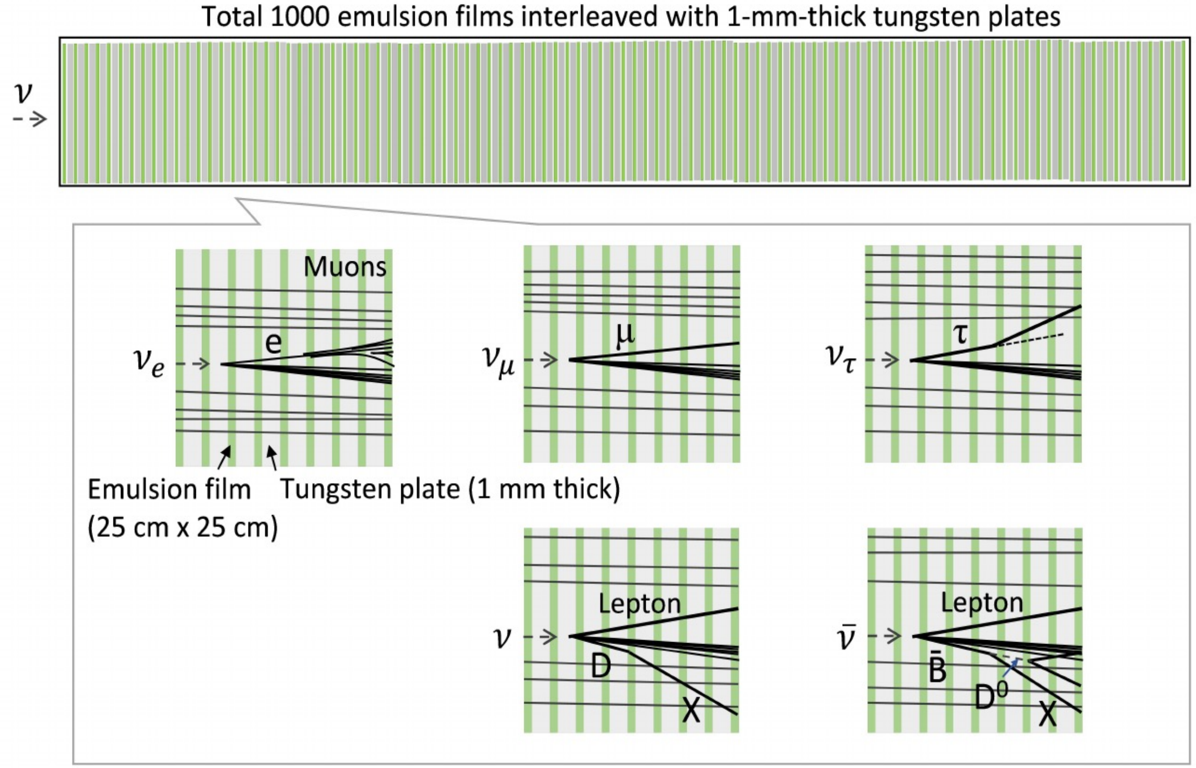
Primary physics goal – cross section measurements at high energy.
Projected results (150/fb):



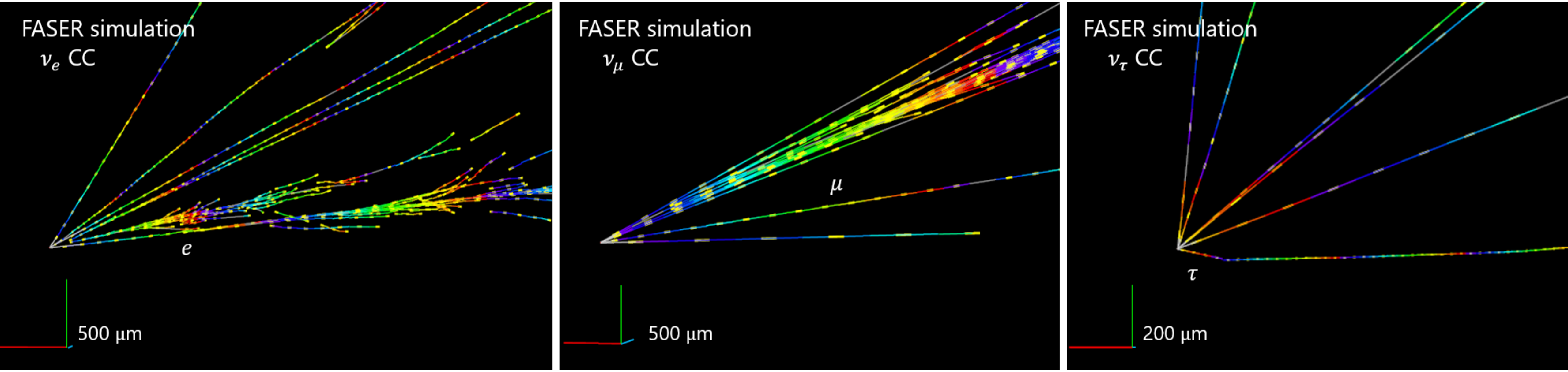
Matching muon track associated with vertex in emulsion detector with spectrometer will allow to measure ν_μ / $\overline{\nu}_\mu$ separately.
Uncertainty from neutrino production important
Neutrino energy reconstruction with resolution ~30% expected from simulation studies

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



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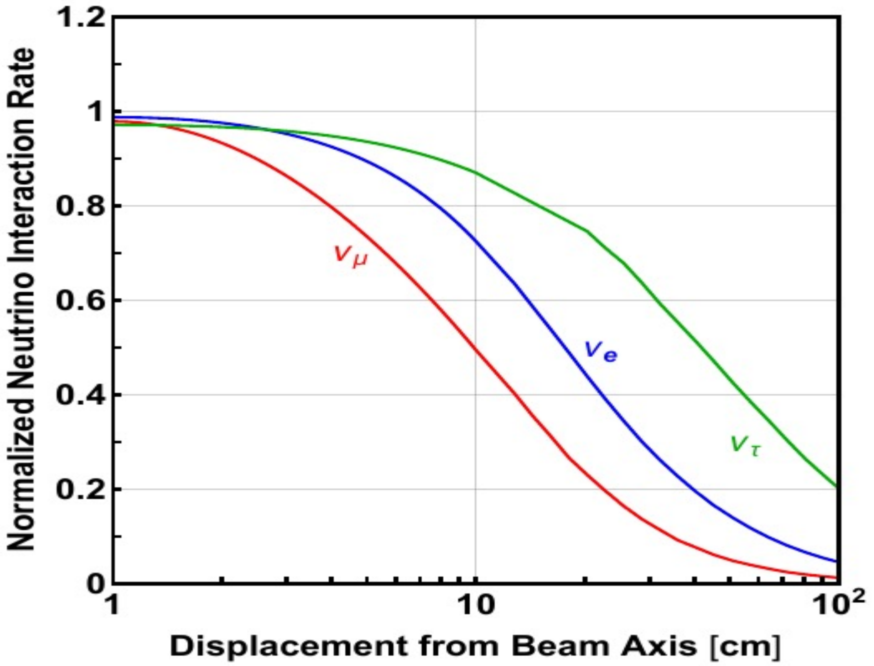
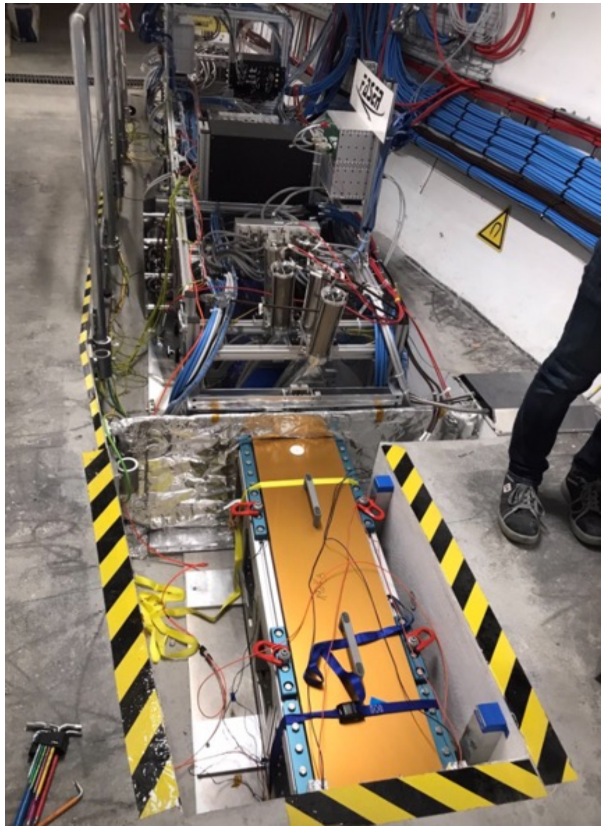
- Replaced during Technical Stops during LHC running (usually 3 times / year)
  - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER
- FASERν is centered on the LOS (in the FASER trench)
  - Maximizes flux of all neutrino flavours

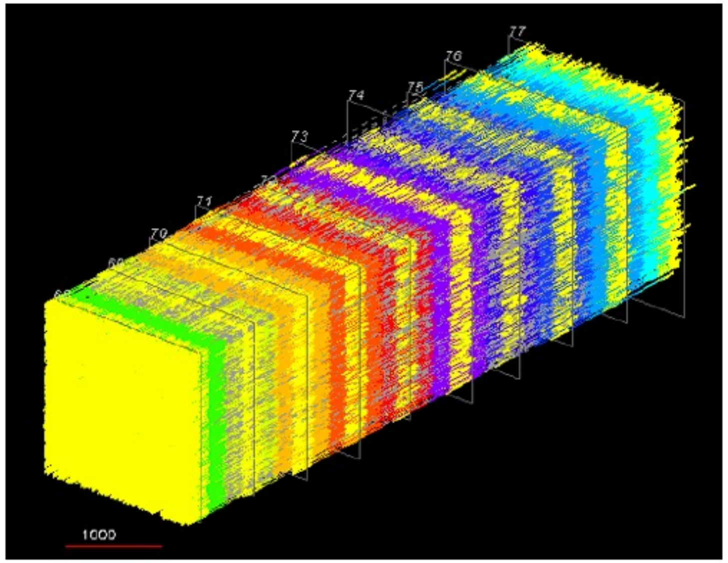




FASERν Pilot Run

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



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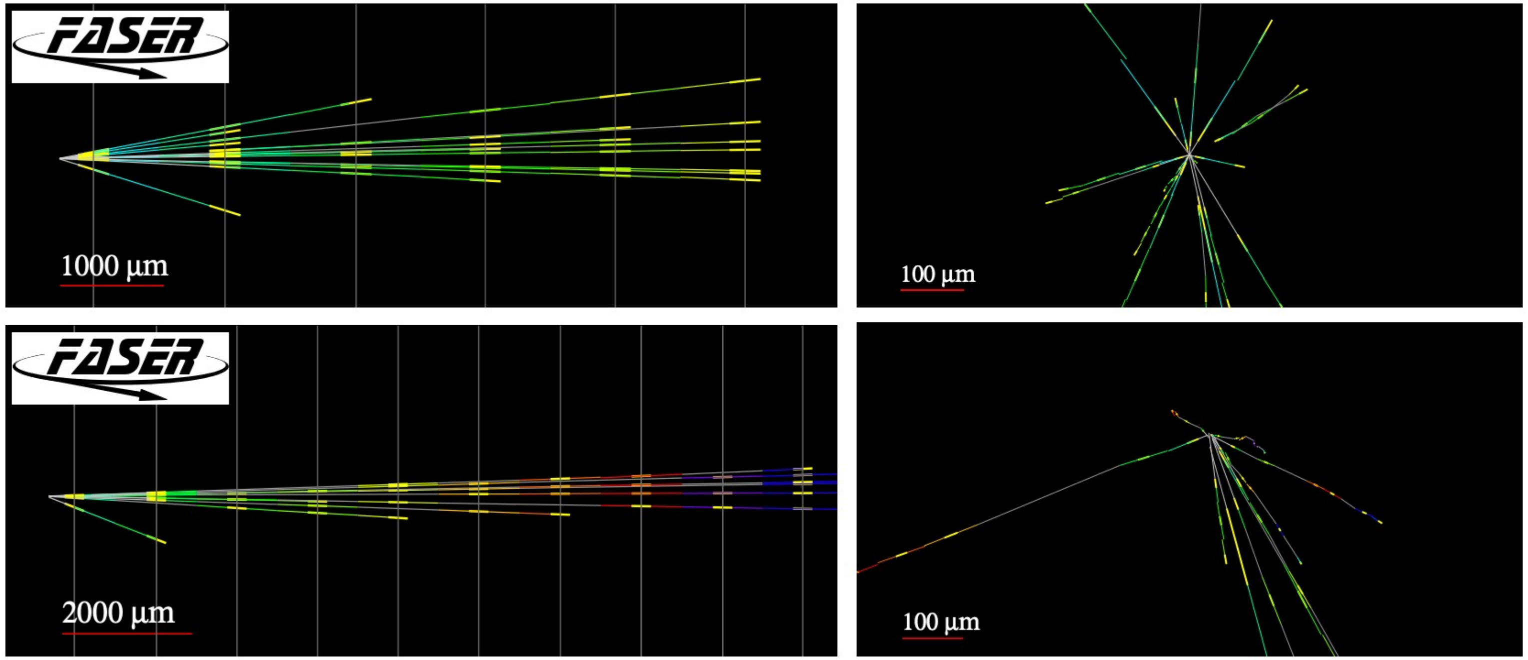
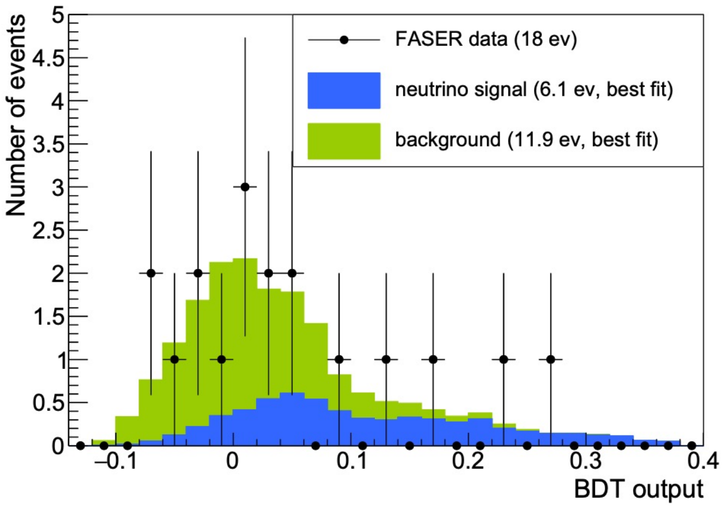
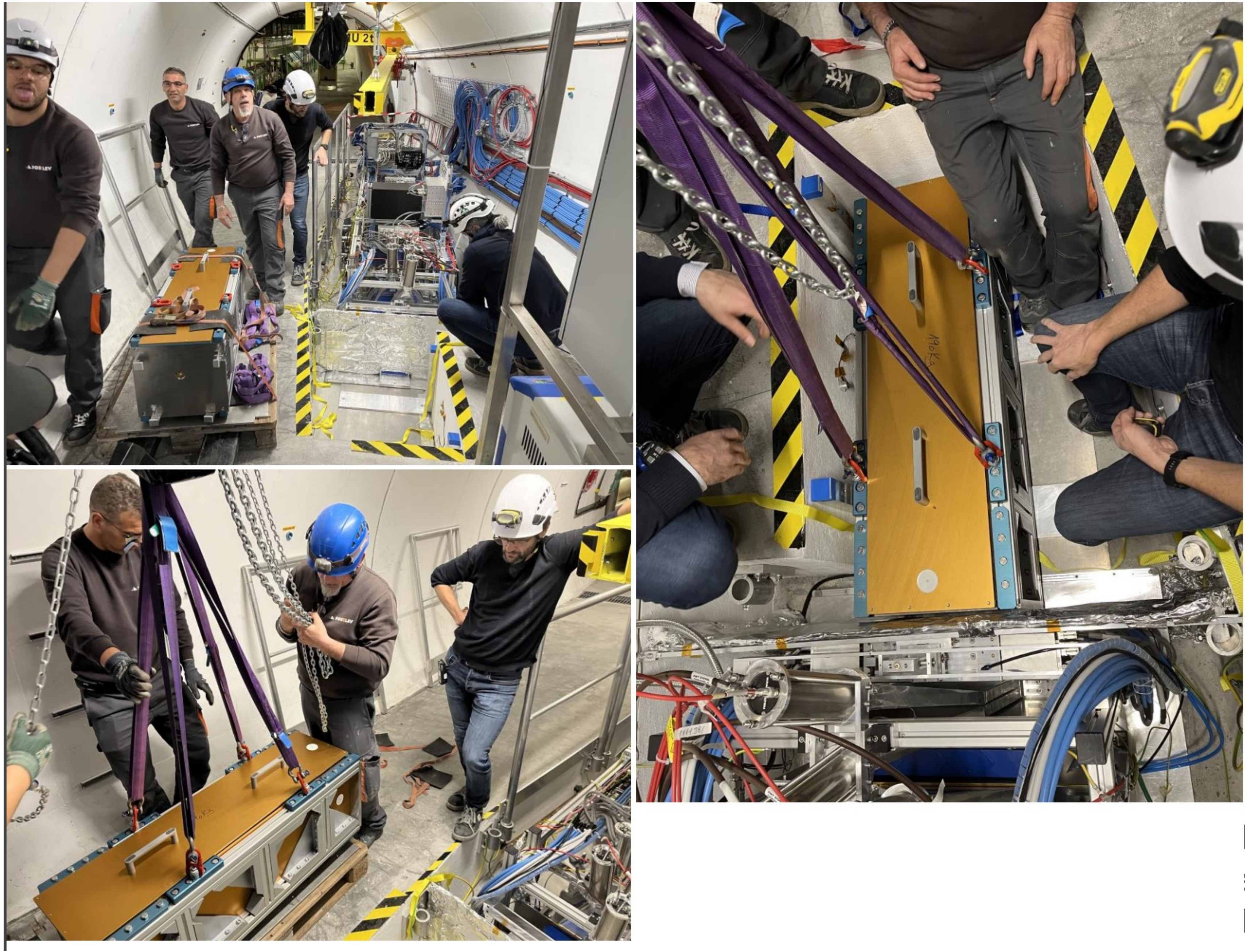
First candidate collider neutrino interactions!





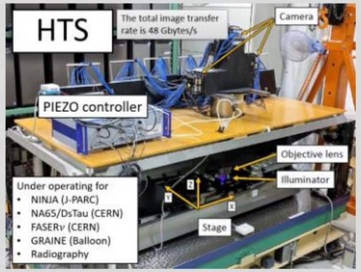
FASERν Installation



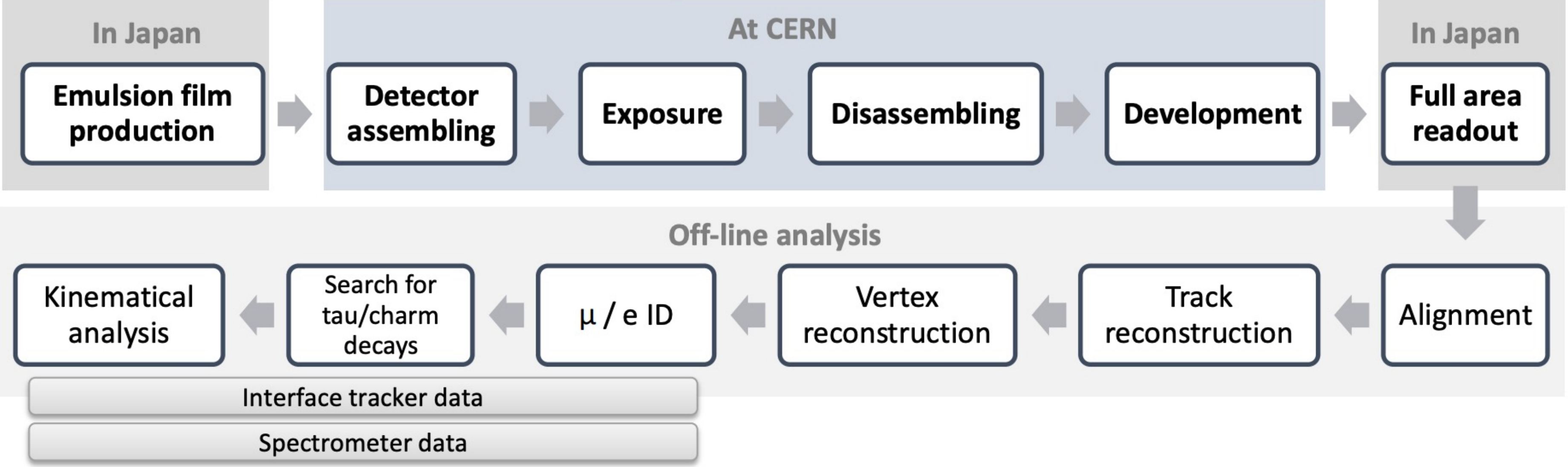
FASERν
Workflow







Under operating for
- NINJA (J-PARC)
- NA65/DsTau (CERN)
- FASERν (CERN)
- GRAINE (Balloon)
- Radiography



In Japan

Emulsion film production

At CERN

Detector assembling → **Exposure** → **Disassembling** → **Development**

In Japan

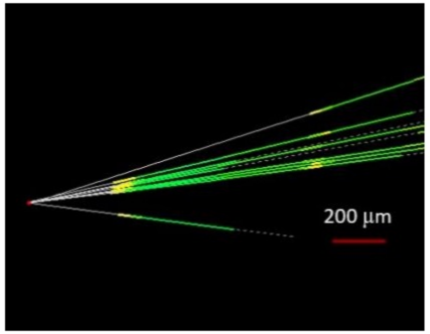
Full area readout

Off-line analysis

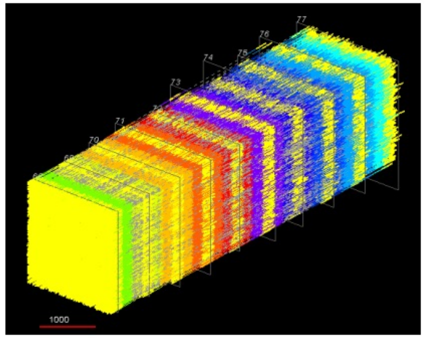
Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

Interface tracker data

Spectrometer data



500-1000 TB/Run3



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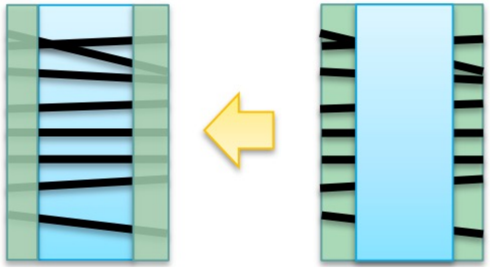
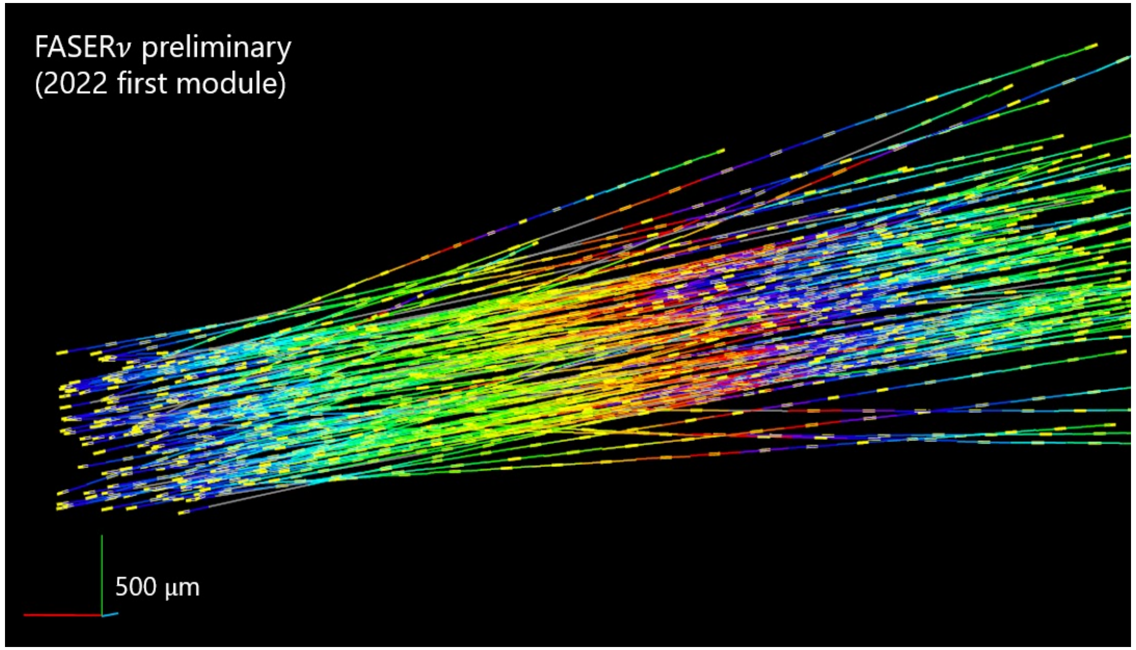
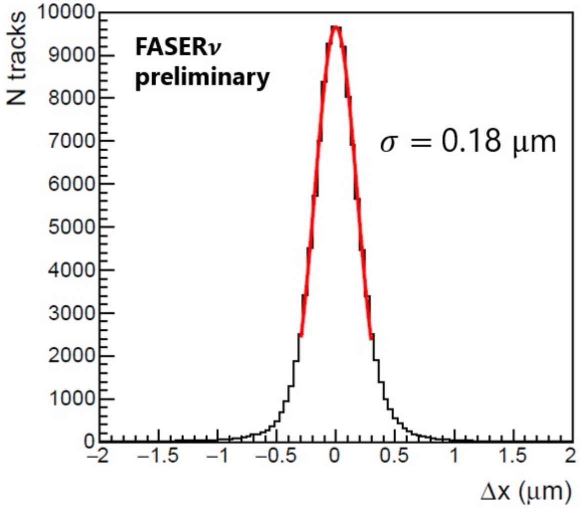
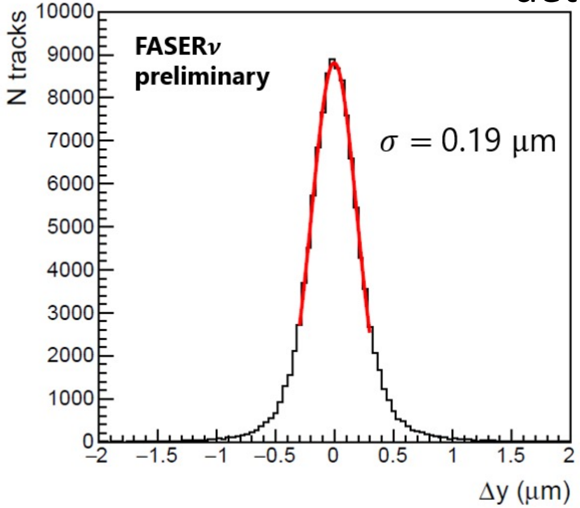


FASERν Detector Performance



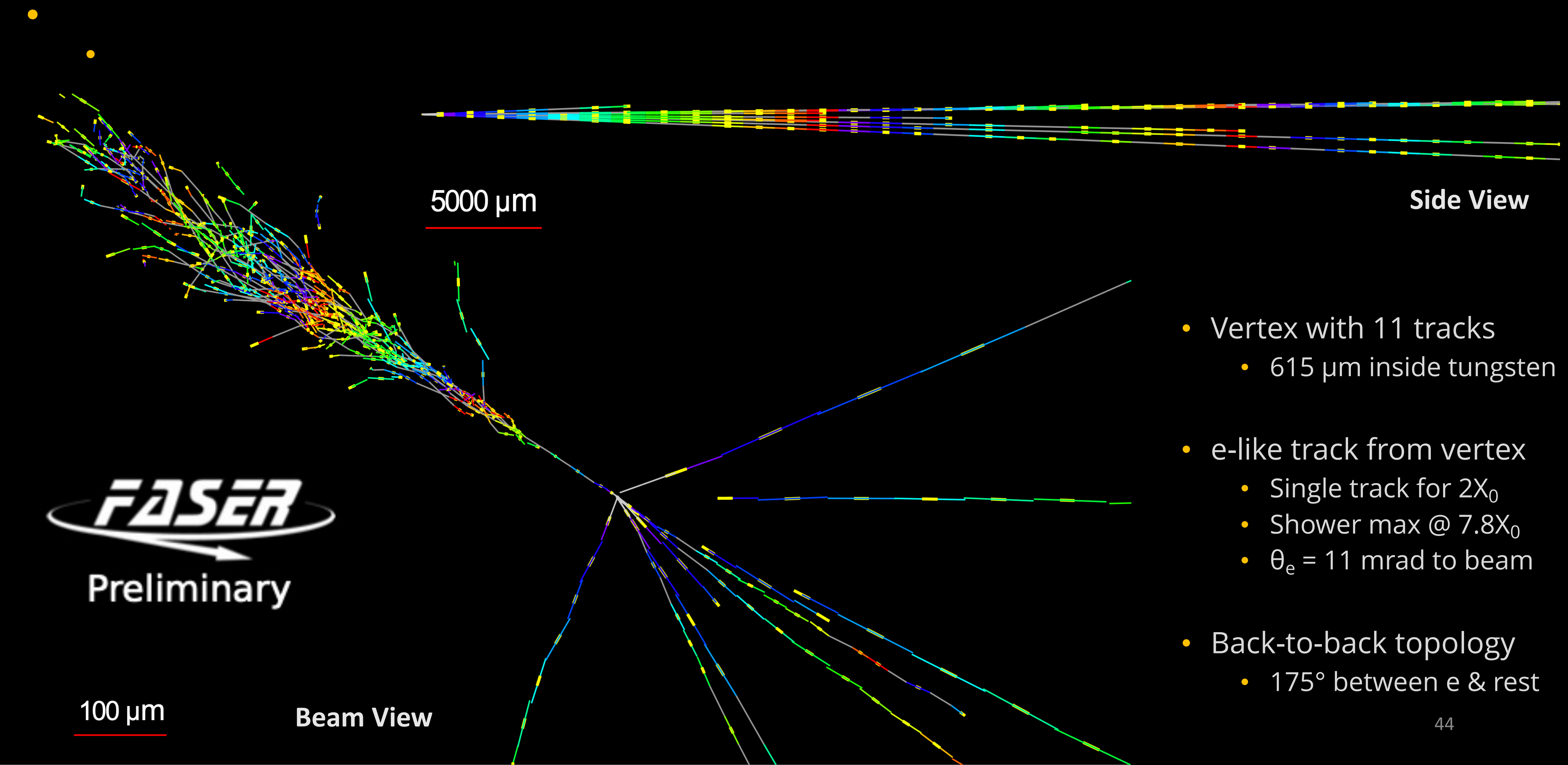
- First FASERν detector installed in FASER for first 4 weeks of data taking, 0.5/fb of data
- Used to commission the assembly, development, scanning, reconstruction, analysis chain
- Measured track multiplicity:
    - ~2×10^4 cm^{-2} / fb^{-1}
    - ~1×10^4 cm^{-2} / fb^{-1} within 10mrad of angular 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 first electron neutrino candidate

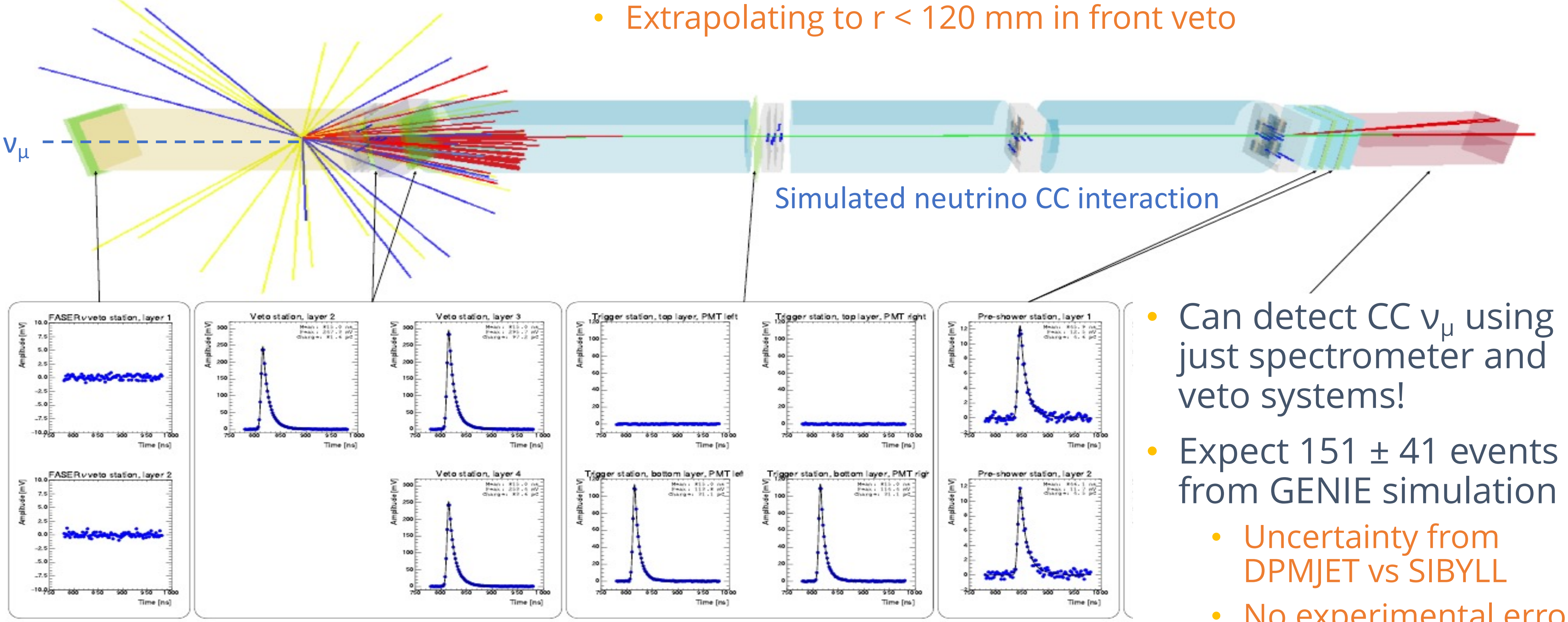


- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Neutrinos with the electronic detector

1. Collision event with good data quality

4. Exactly 1 good fiducial (r < 95 mm) track
   - p > 100 GeV and θ < 25 mrad
   - Extrapolating to r < 120 mm in front veto



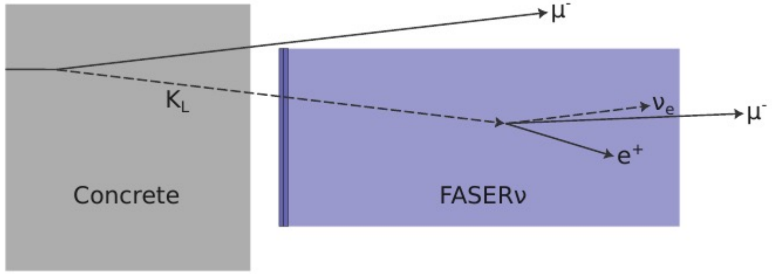
Simulated neutrino CC interaction

2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos
5. Timing and preshower consistent with ≥1 MIP

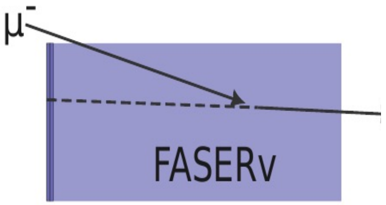
- Can detect CC ν_μ using just spectrometer and veto systems!
- Expect 151 ± 41 events from GENIE simulation
  - Uncertainty from DPMJET vs SIBYLL
  - No experimental errors
    - Currently not trying to measure cross section

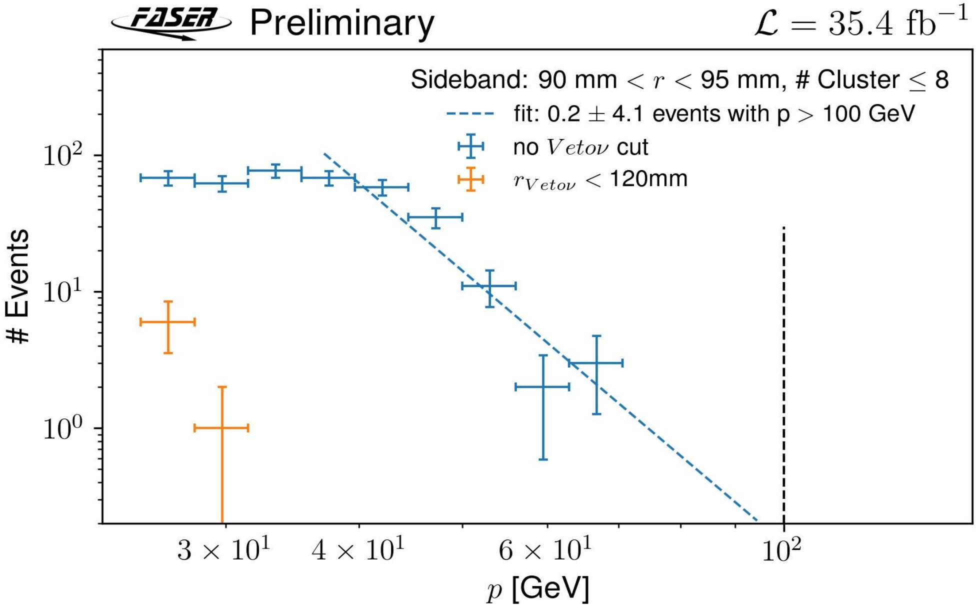
Neutrinos: Backgrounds

- Neutral hadrons estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASER
    - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
    - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events



- Scattered muons estimated from data SB
  - Take events w/o front veto radius requirement and sin
    track segment in first tracker station with 90 < r < 95 m
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
    - Uncertainty from varying selection



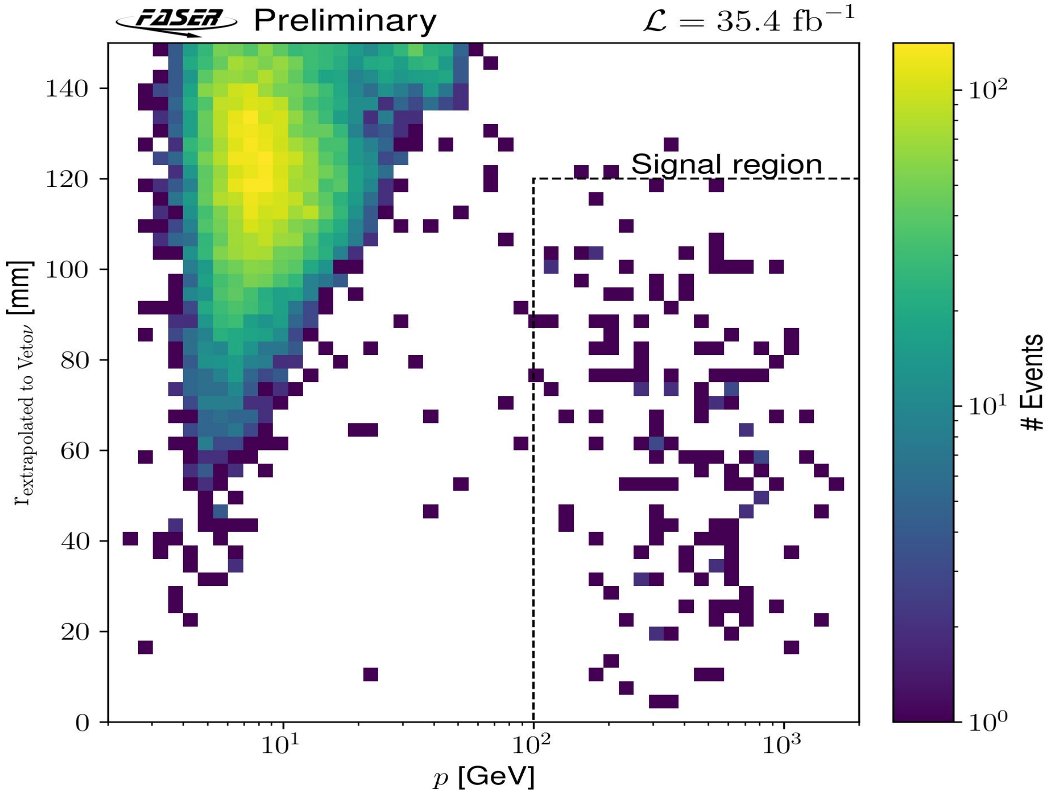


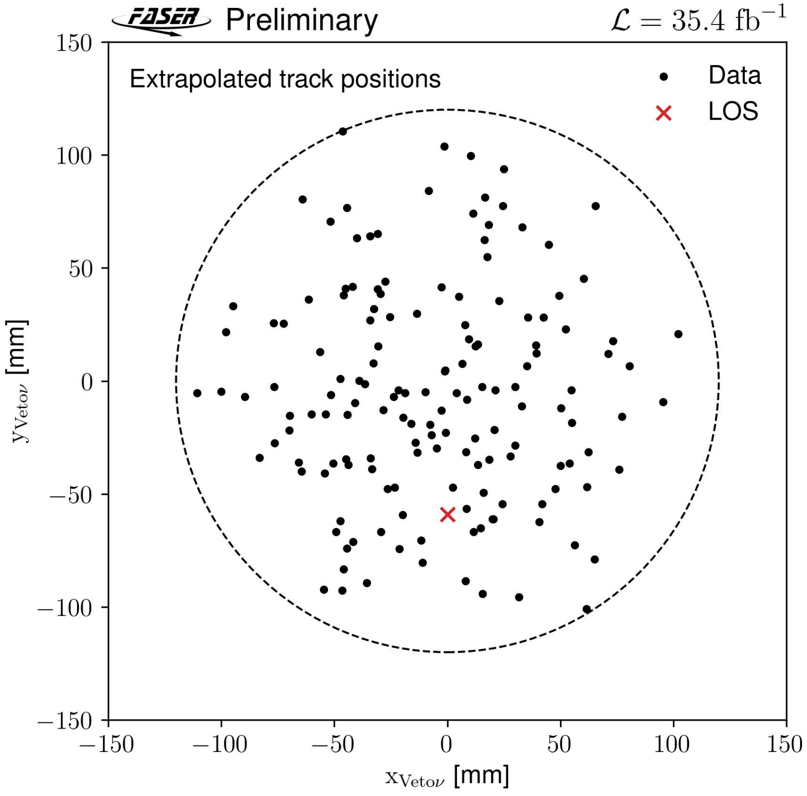
- Veto inefficiency estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Find negligible background due to very high veto efficiency

Neutrinos with the electronic detector

- Upon unblinding find 153 events with no veto signal
  - Just 10 events with one veto signal
- First *direct* detection of collider neutrinos!
  - With signal significance of 16σ
  - Submitted to PRL arXiv:2303.14185

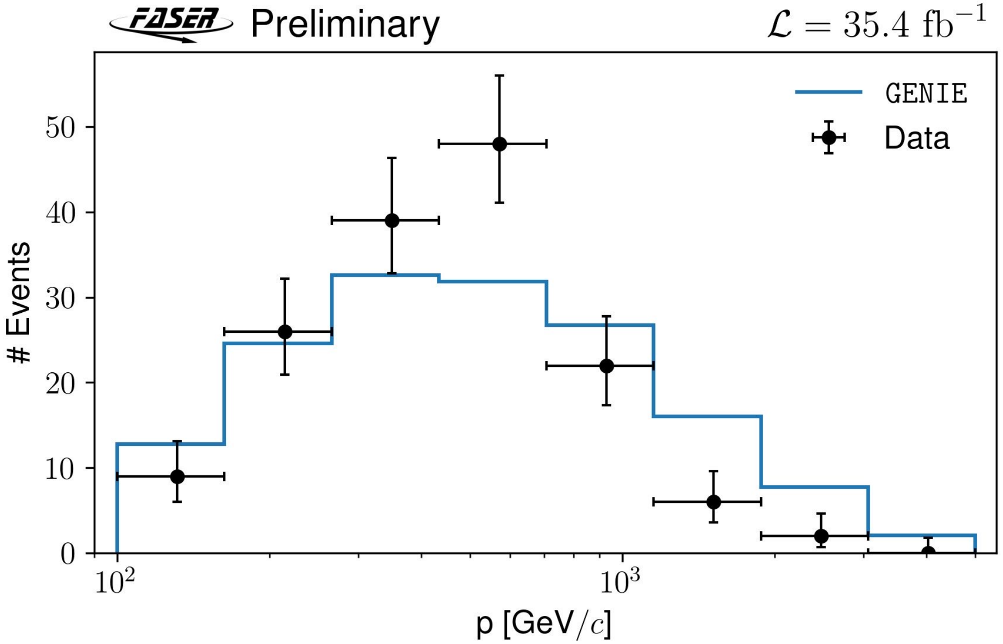
Candidate	Events
n_0	153
n_{10}	4
n_{01}	6
n_2	64014695

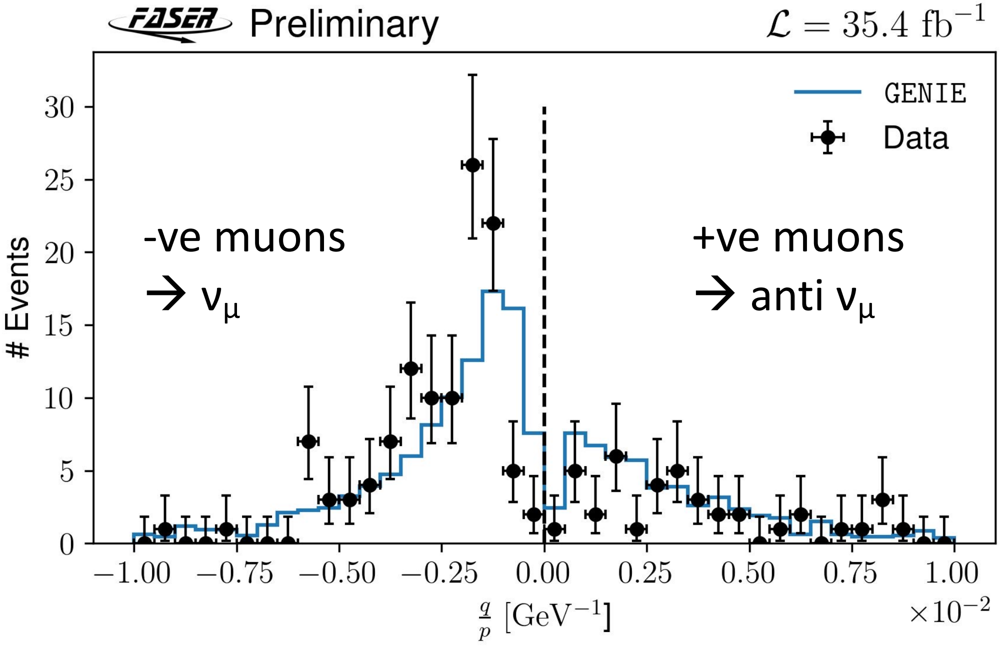




Properties of selected neutrinos

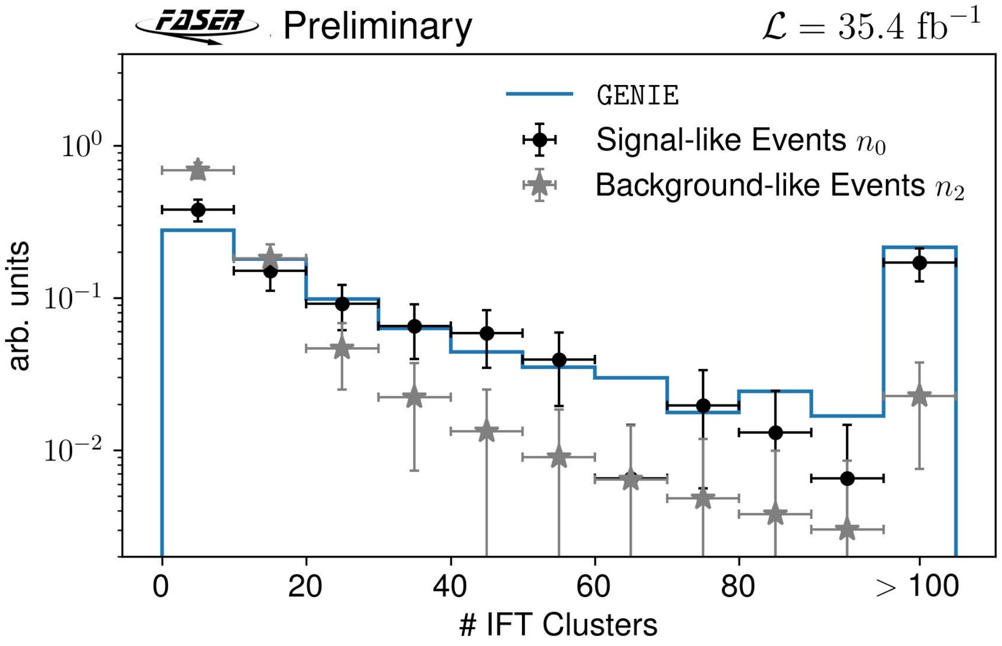
- Data not corrected for detector effects
  - No efficiency uncertainty estimated yet
- (with this caveat) Compare the neutrino event properties with simulation
- Muon momentum and charge distributions look similar between MC and data
- Suggested neutrinos are high energy, with typical energy greater than a few hundred GeV

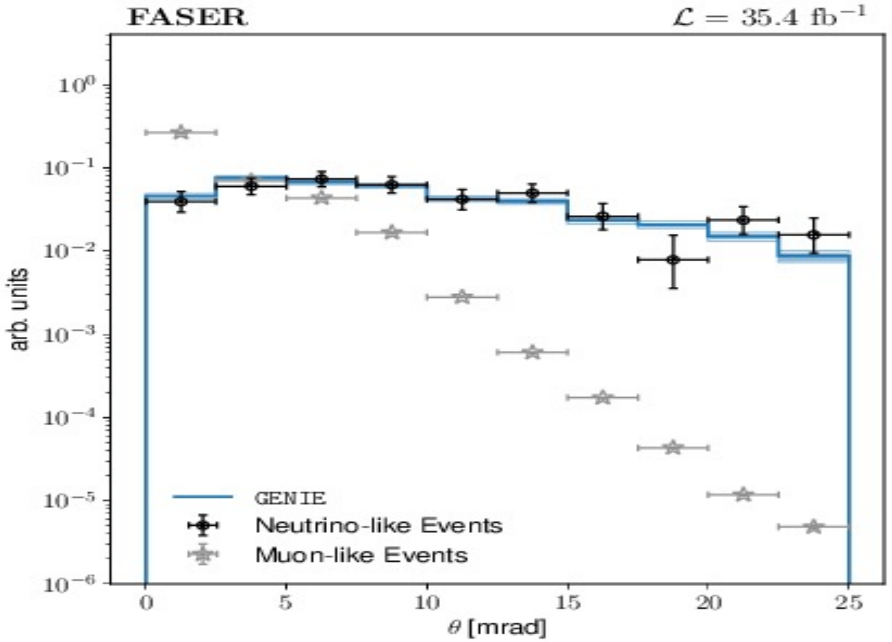




Properties of selected neutrinos

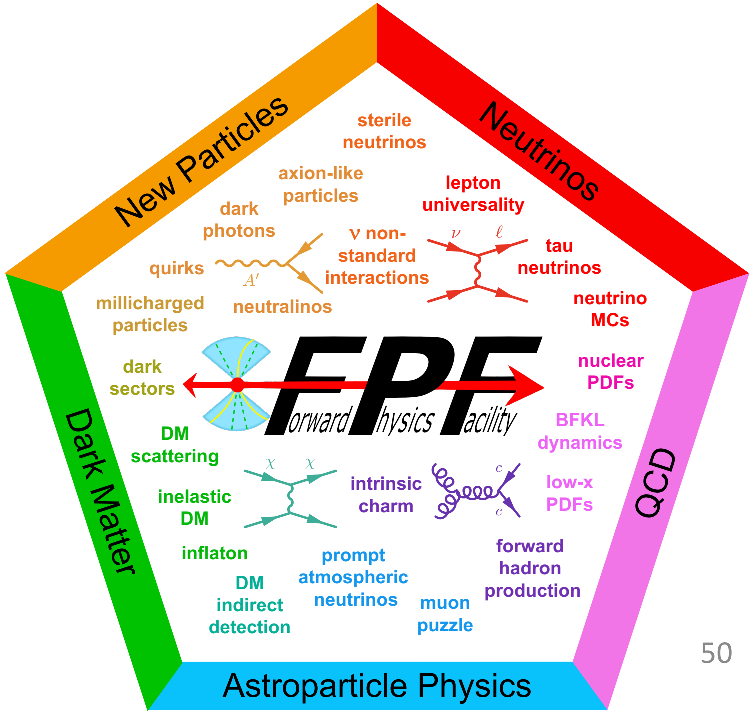
- Data not corrected for detector effects
  - No efficiency uncertainty estimated yet
- (with this caveat) Compare the neutrino event properties with simulation
- Number of clusters in front tracking station (IFT) higher for neutrino events than for muon background (other particles produced in the neutrino interaction)
- Muon angle larger in neutrino events than for muon background
- Both of these are well modelled by GENIE neutrino simulation





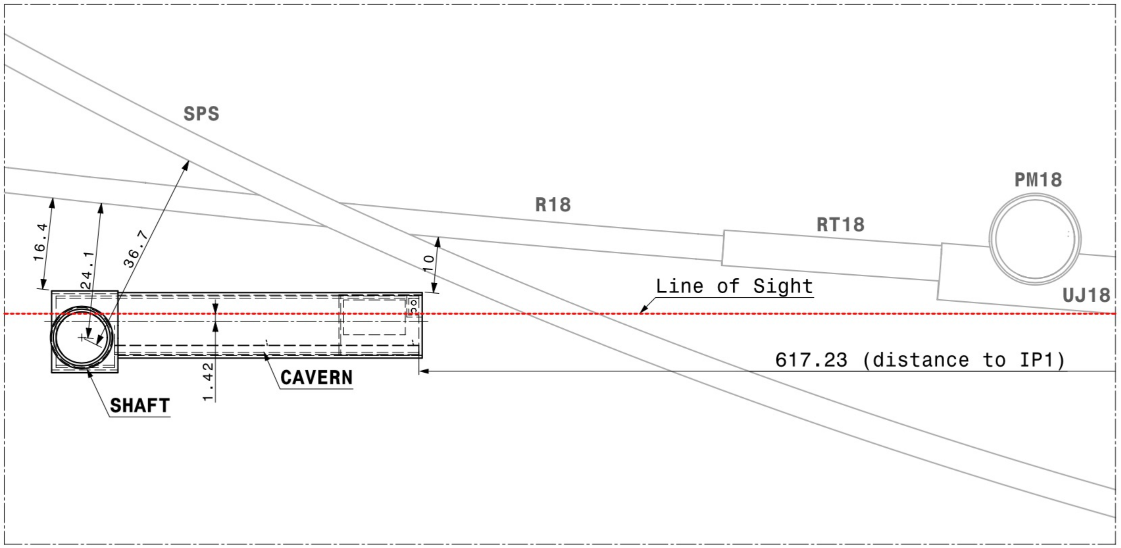
The Forward Physics Facility

- 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



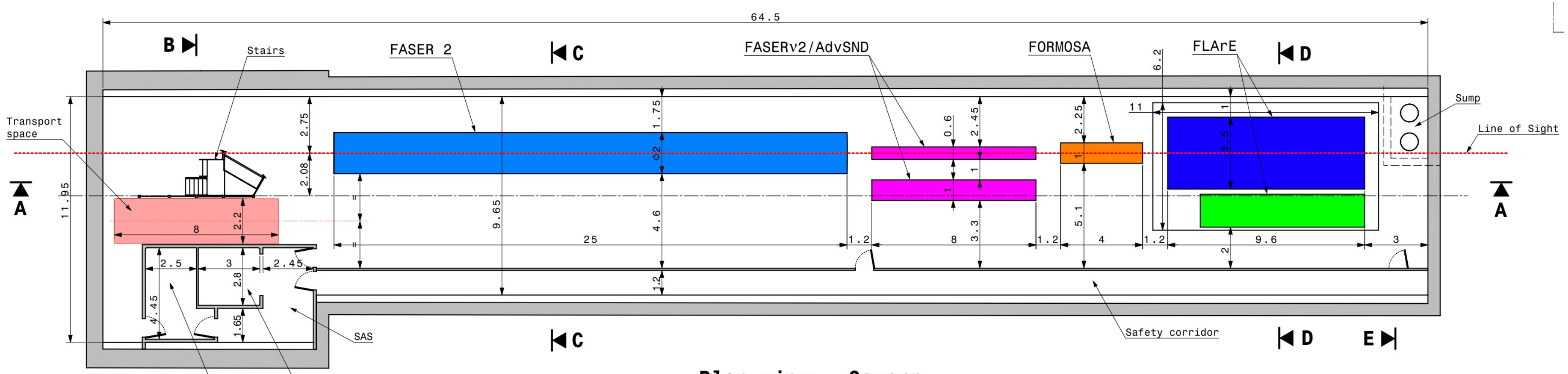
FPF Location

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.

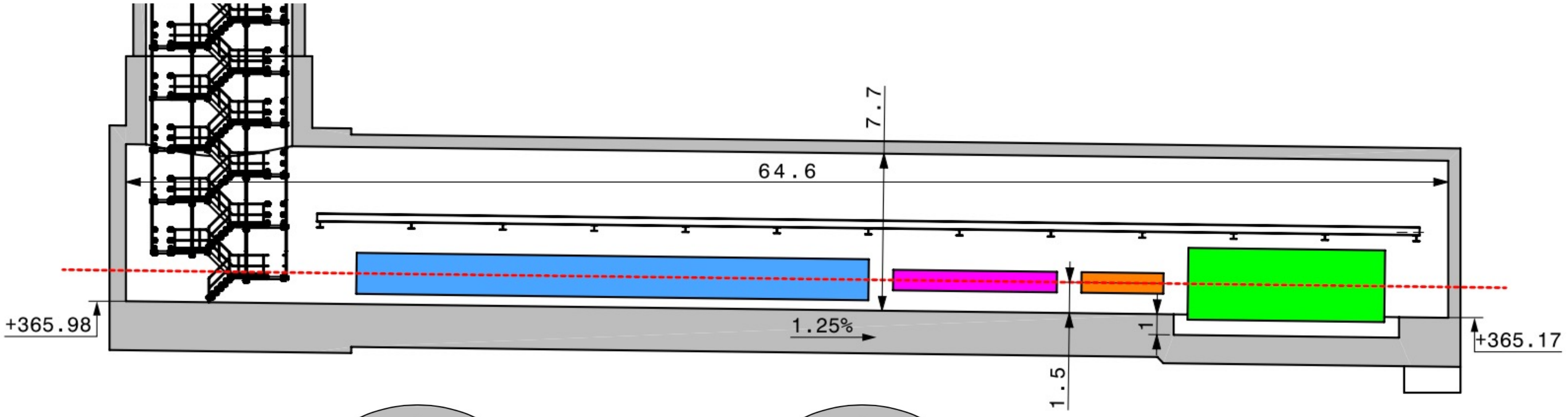


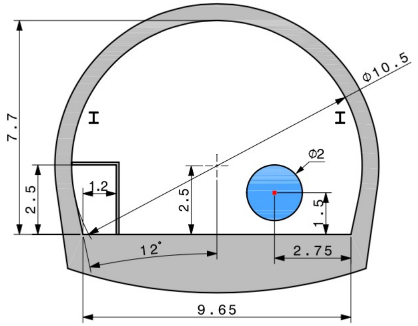
FPF Facility:

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

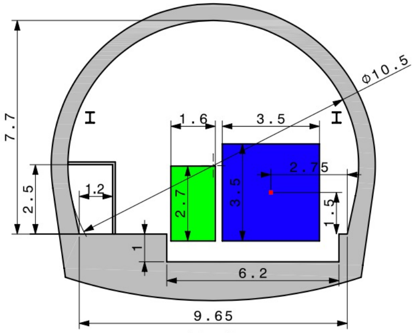


Plan view - Cavern
1:100





C-C
1:100

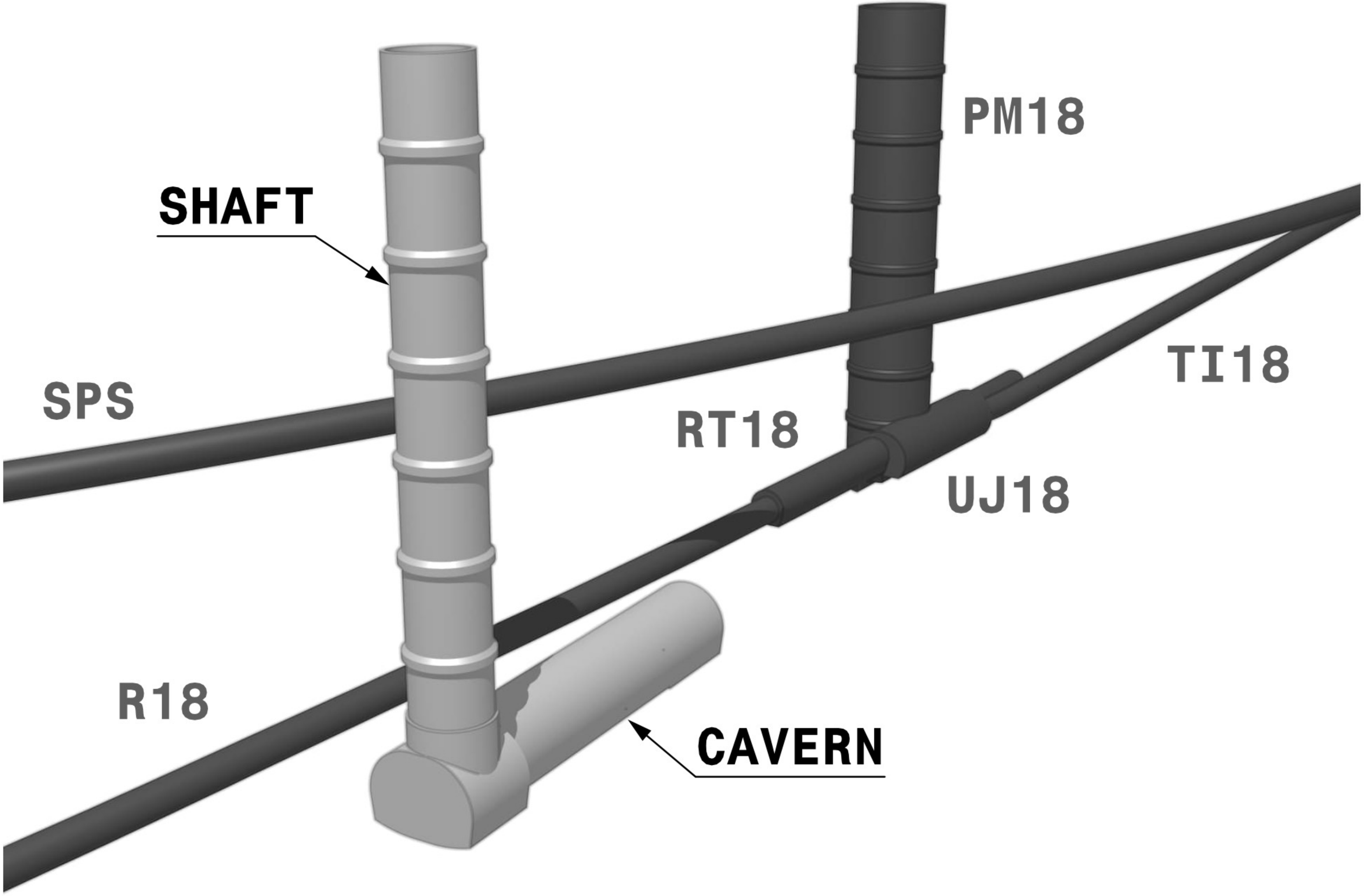


D-D
1:100

More details: [2203.05090](2203.05090)

FPF Facility

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



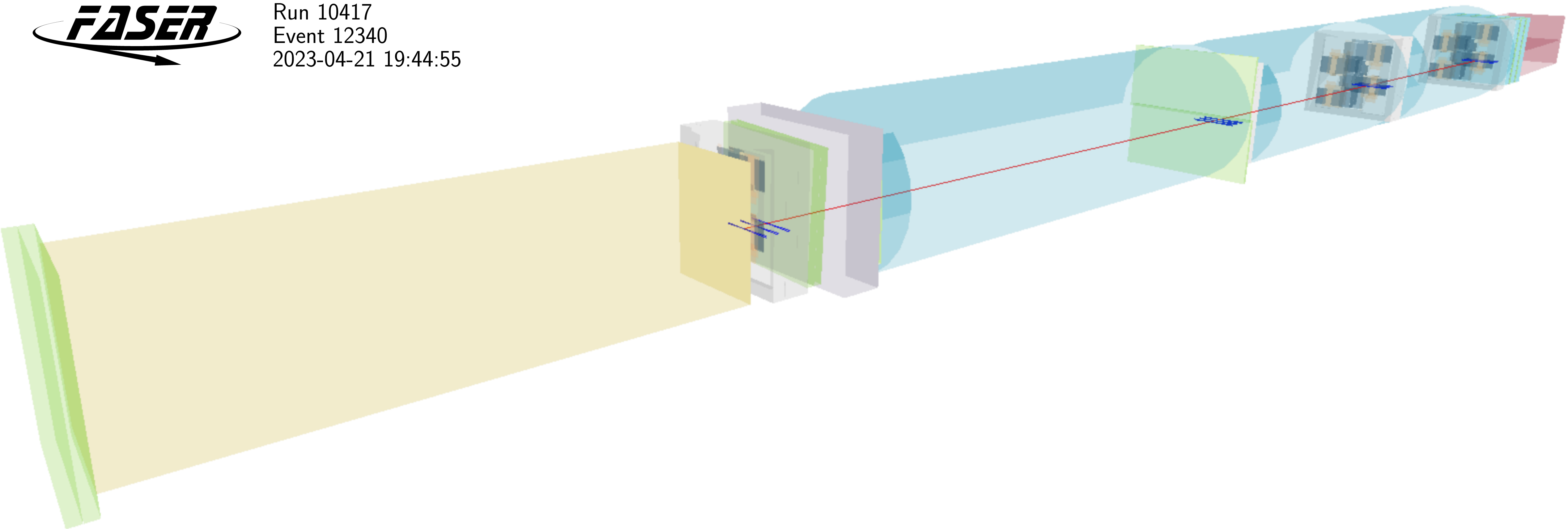
Currently proposed FPF experiments

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
- FASERν2
  - $\mathcal{O}$(20tn) emulsion/tungsten detector (FASERν 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 FASERν2
- 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

2023 Running

2023 physics datataking started this week.
Expect to collect ~80/fb of data, to allow FASER to be more sensitive in searches for light weakly interacting particles to to study collider neutrinos.



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 reported recently
  - Exclusion of new regions of A’ parameter space in the thermal relic region
  - First observation of neutrinos from a collider

- 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…

FASER

The FASER Collaboration

CERN

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

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

u^b 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

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UNIVERSITÄT BONN

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清華大學 Tsinghua University

MANCHESTER 1824 The University of Manchester

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF LIVERPOOL

CHIBA UNIVERSITY

US 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

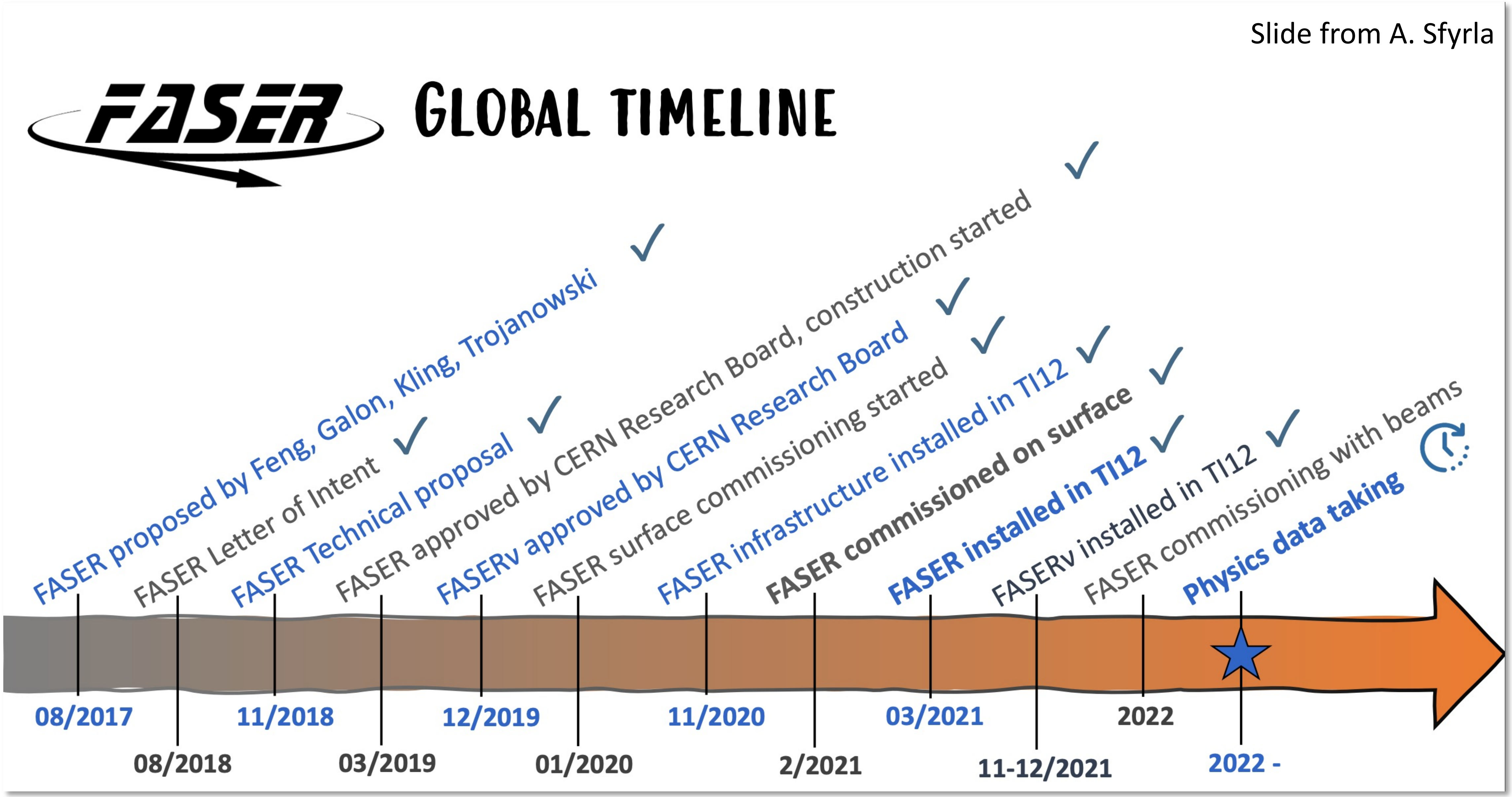
7.Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC
European Physical Journal C and arXiv: 1908.02310

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



Slide from A. Sfyrla

GLOBAL TIMELINE

08/2017 FASER proposed by Feng, Galon, Kling, Trojanowski ✓

08/2018 FASER Letter of Intent ✓

11/2018 FASER Technical proposal ✓

03/2019 FASER approved by CERN Research Board, construction started ✓

12/2019 FASERν approved by CERN Research Board ✓

01/2020 FASER surface commissioning started ✓

11/2020 FASER infrastructure installed in TI12 ✓

2/2021 **FASER commissioned on surface** ✓

03/2021 **FASER installed in TI12** ✓

11-12/2021 FASERν installed in TI12 ✓

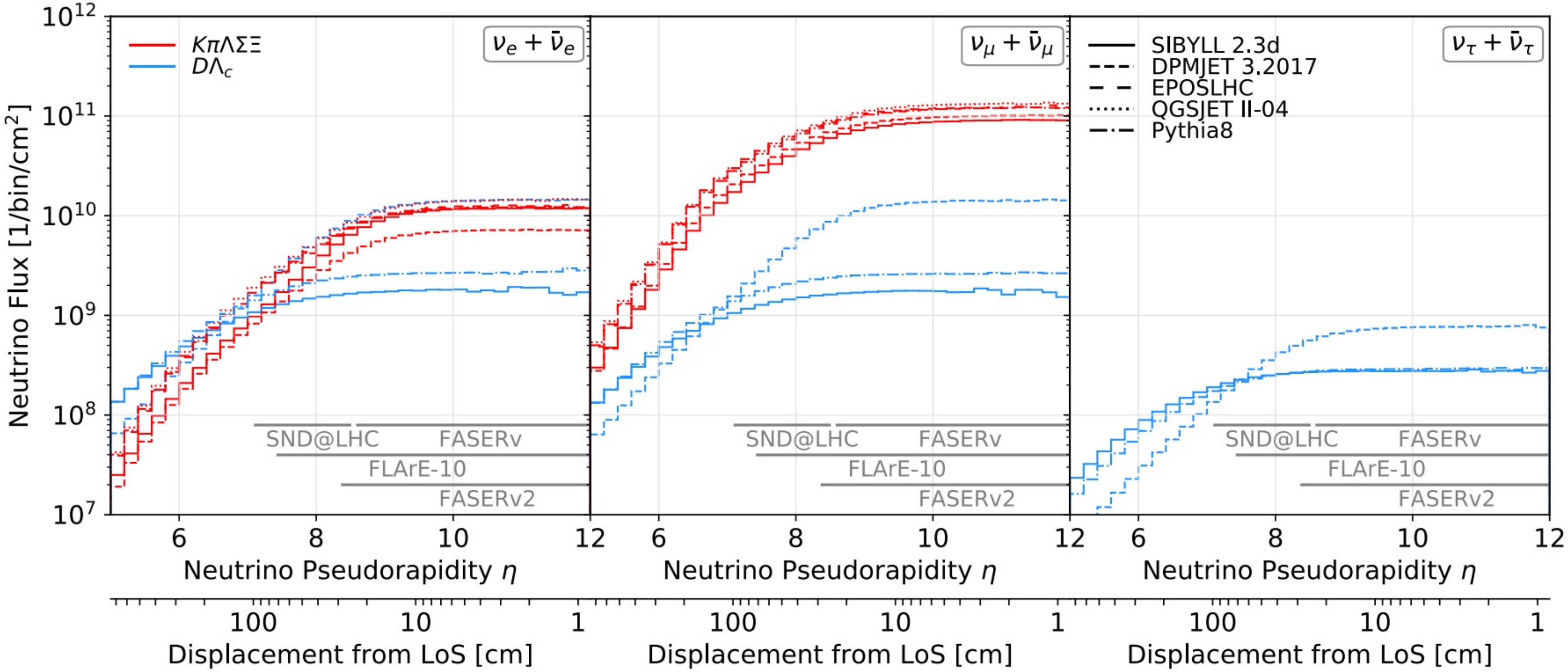
2022 FASER commissioning with beams

2022 - **Physics data taking** ★

And now to the future….

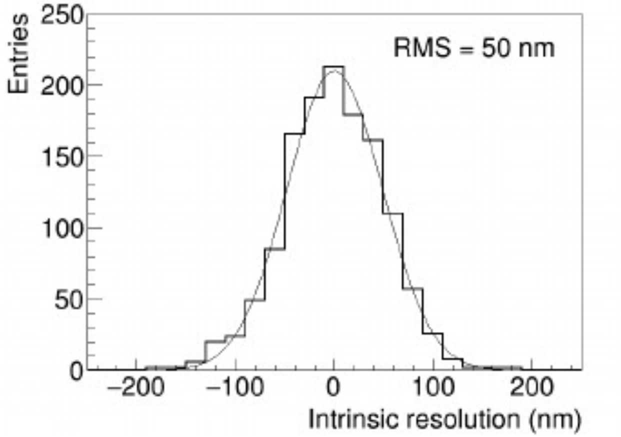
QCD at the FPF

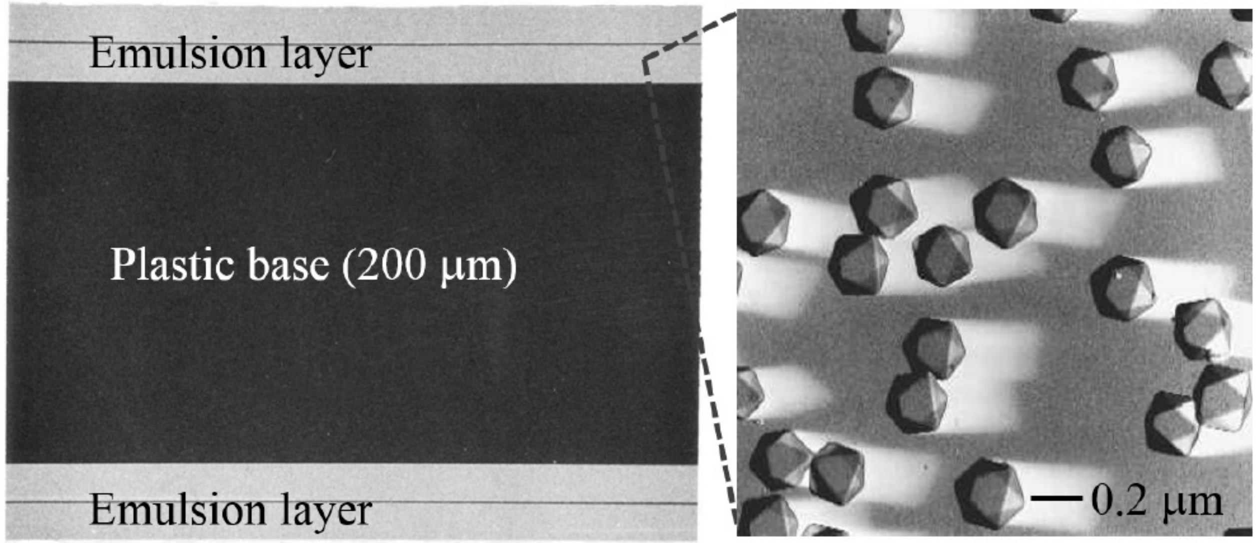
- Neutrinos detected at FPF experiments can also be used to study QCD both in the neutrino production, and in neutrino interaction
- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \rightarrow \nu\mu$, K → ν_e (at high-energy/off-axis D → ν_e), D → $\nu\tau$

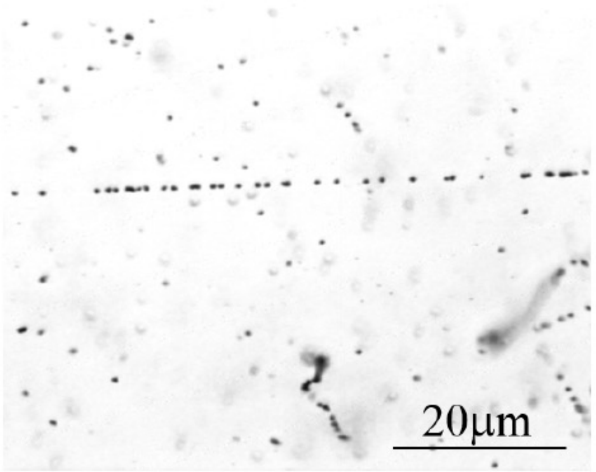


Emulsion Detectors

- 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!

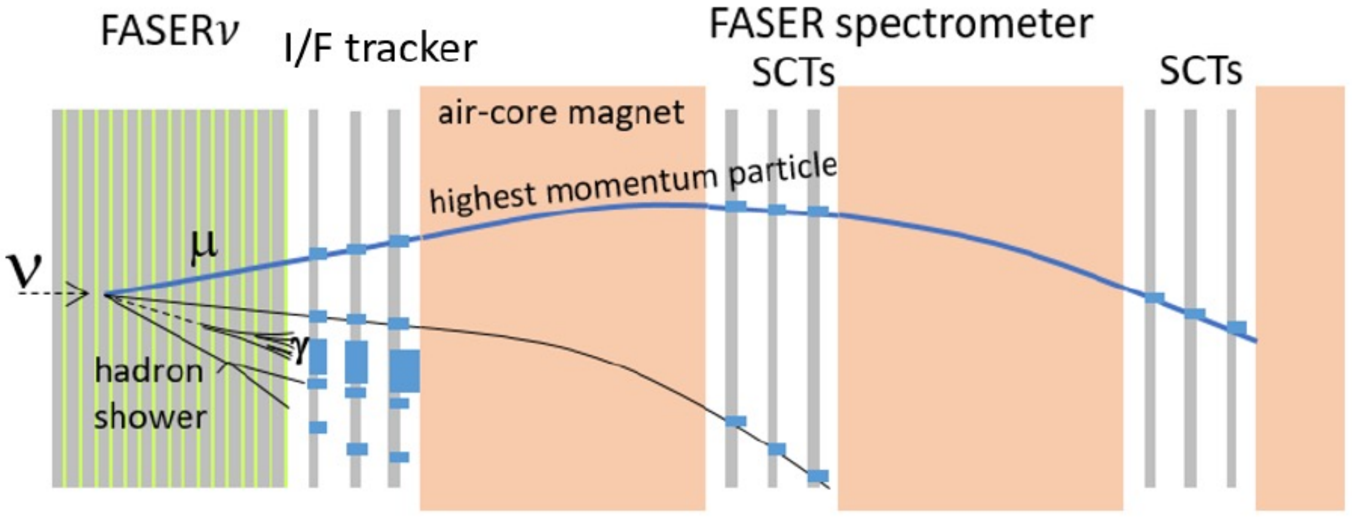




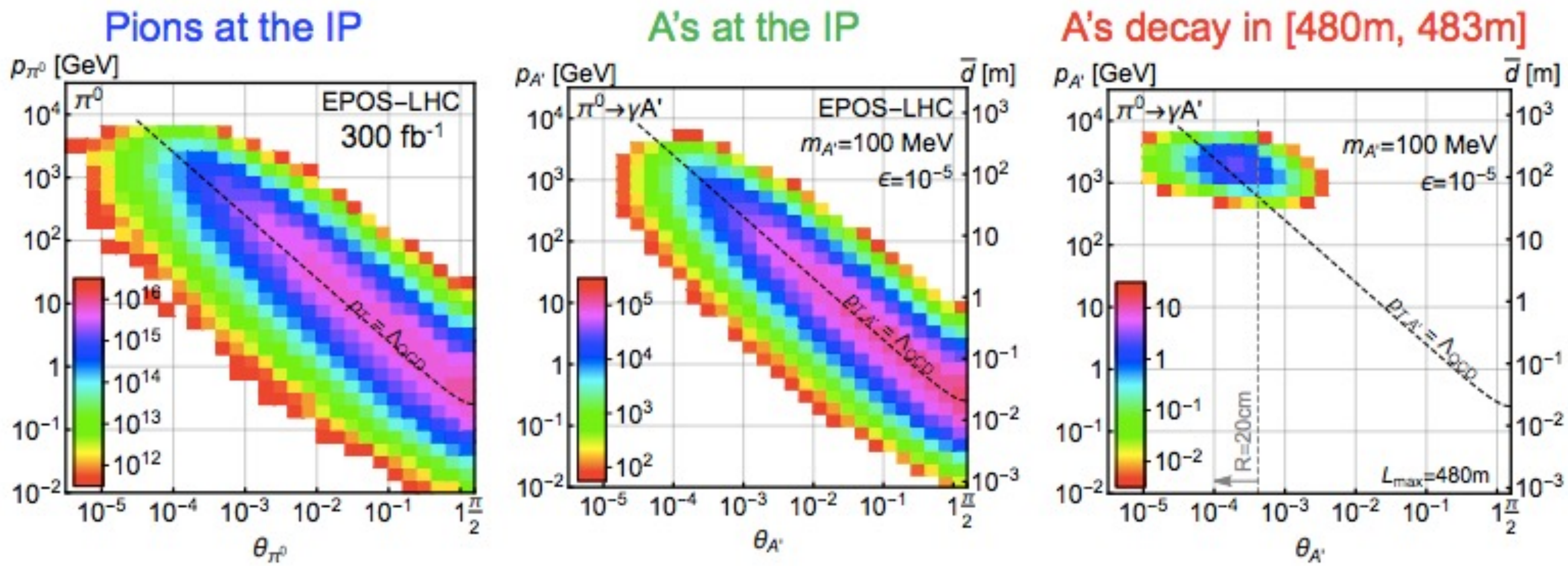


Linking FASERν with FASER

- 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



Dark Photons in FASER



Pions at the IP

A's at the IP

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

- 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

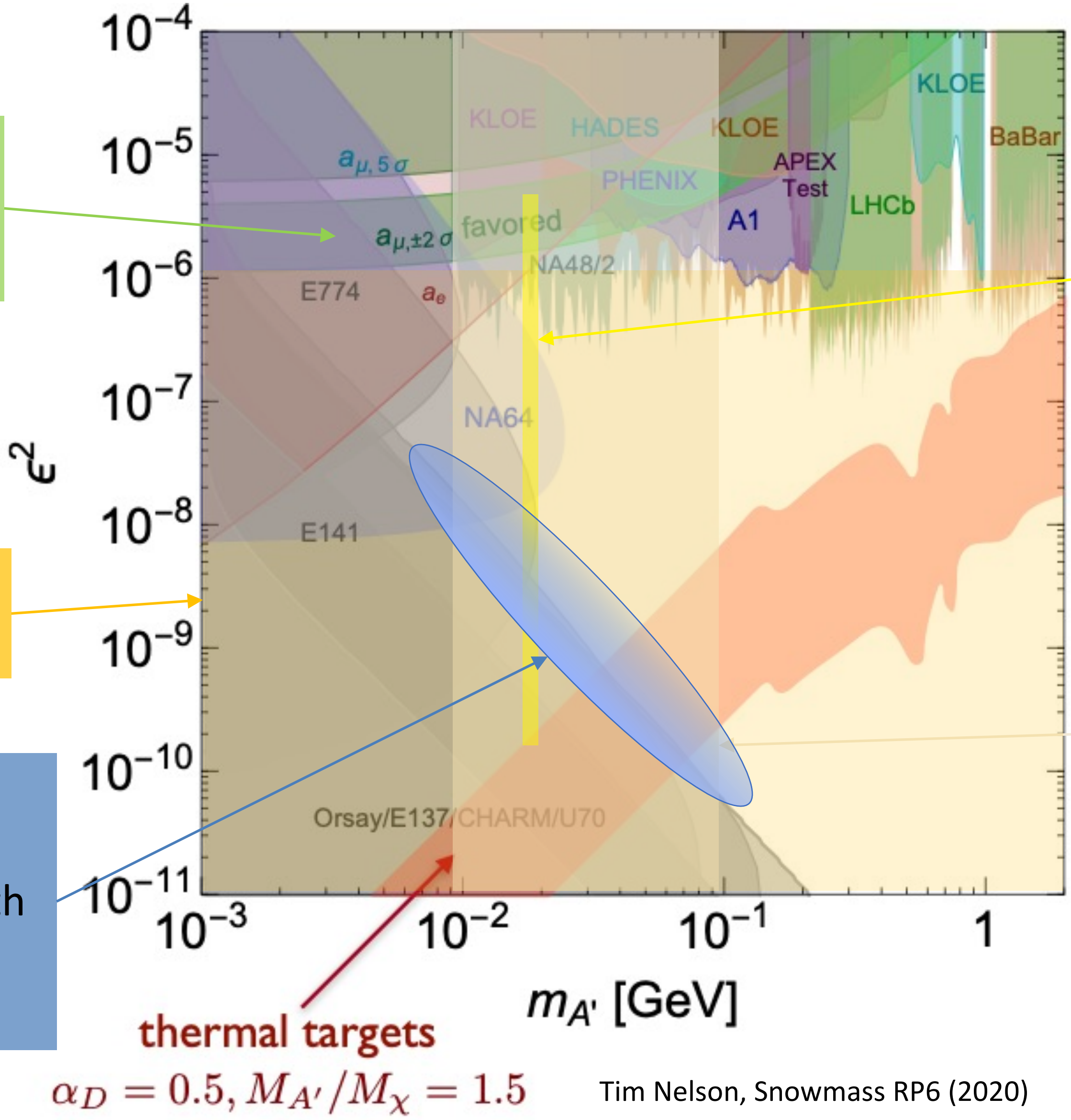
- Production is peaked at $p_T \sim \Lambda_{QCD} \sim 250$ MeV
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin

- 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

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

Loop-induced
Coupling

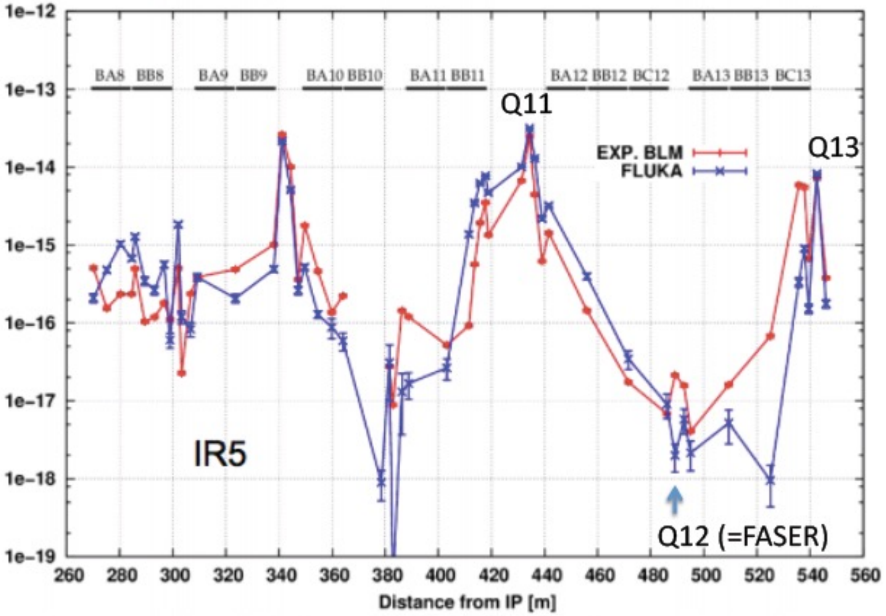
Self-interacting
Dark Matter

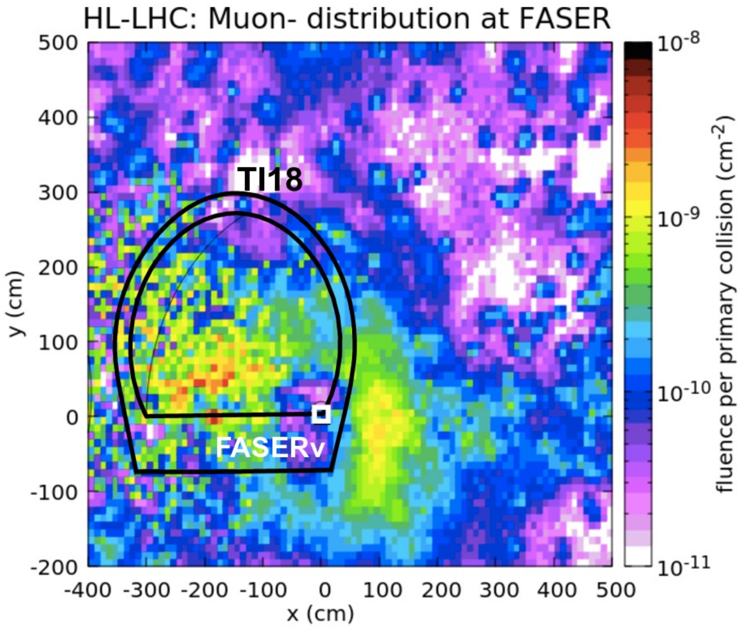
FASER probes
an interesting
region, even with
the 1st fb^{-1}
of Run 3 data

Tim Nelson, Snowmass RP6 (2020)

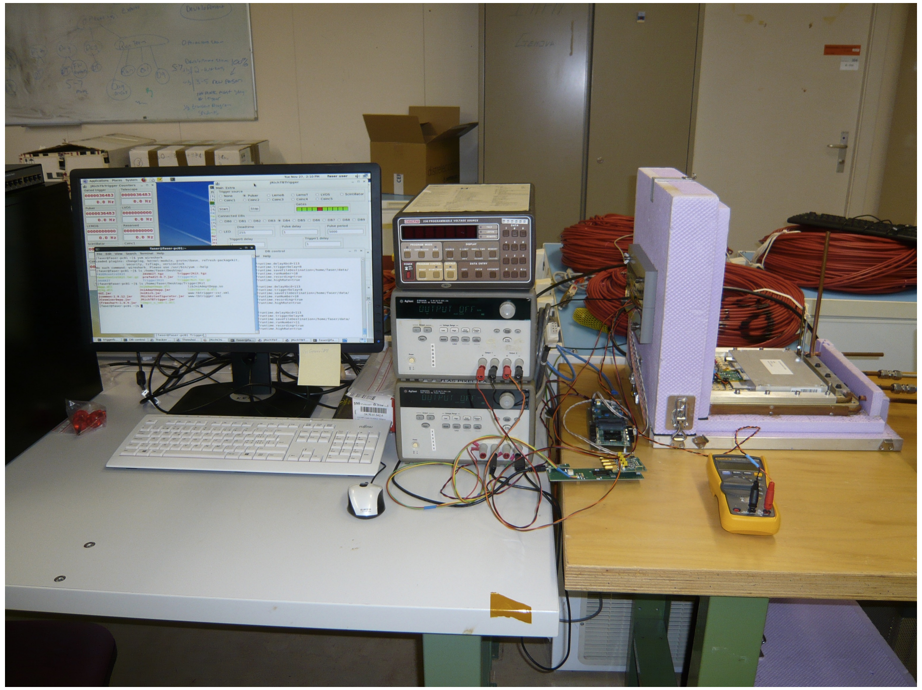
FASER Backgrounds & Radiation

- 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 $0.5 cm^{-2}s^{-1}$ at FASER for $2e34 cm^{-2}s^{-1}$ 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:
  - $<5 \times 10^{-3}$ Gy/year, $<5 \times 10^{7}$ 1 MeV neutron equivalent fluence / year
  - Do not need radiation hard electronics

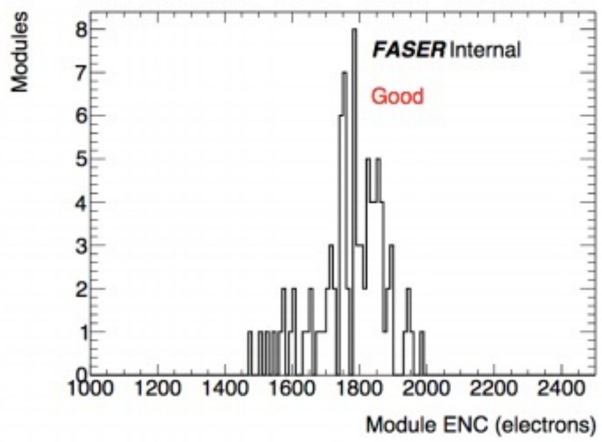


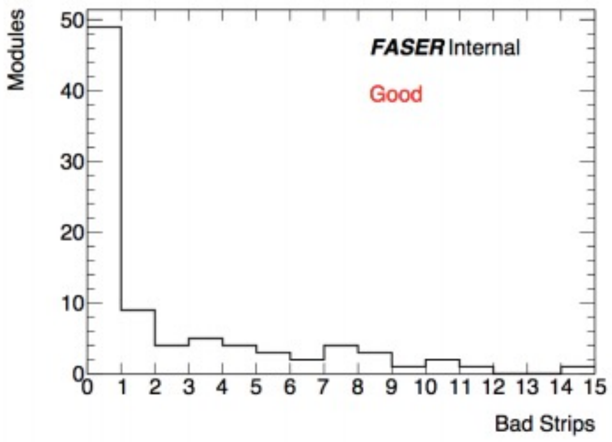


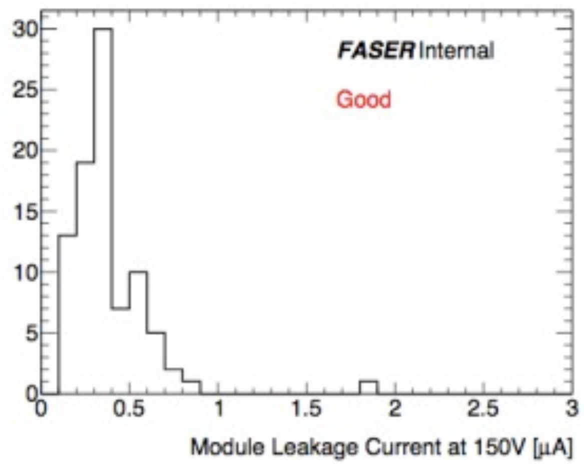
FASER Tracker: Module QA



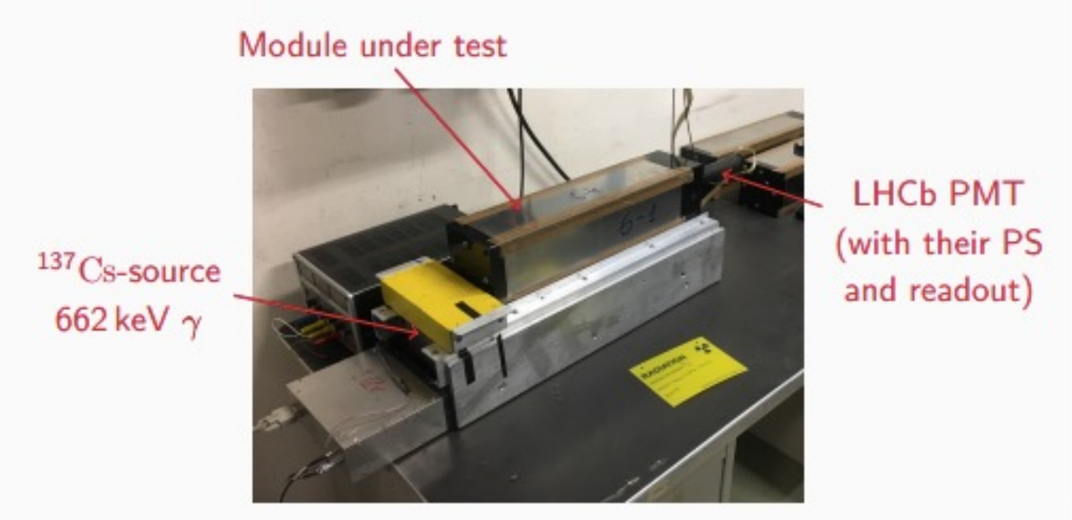
SCT modules used had passed ATLAS QA in ~2005 and then been kept in storage. Important to test their functionality.
SCT module QA at CERN in March 2019. Identified > 80 good spare modules – more than enough for FASER needs.
Performance seems not to be degraded by long term storage/age.



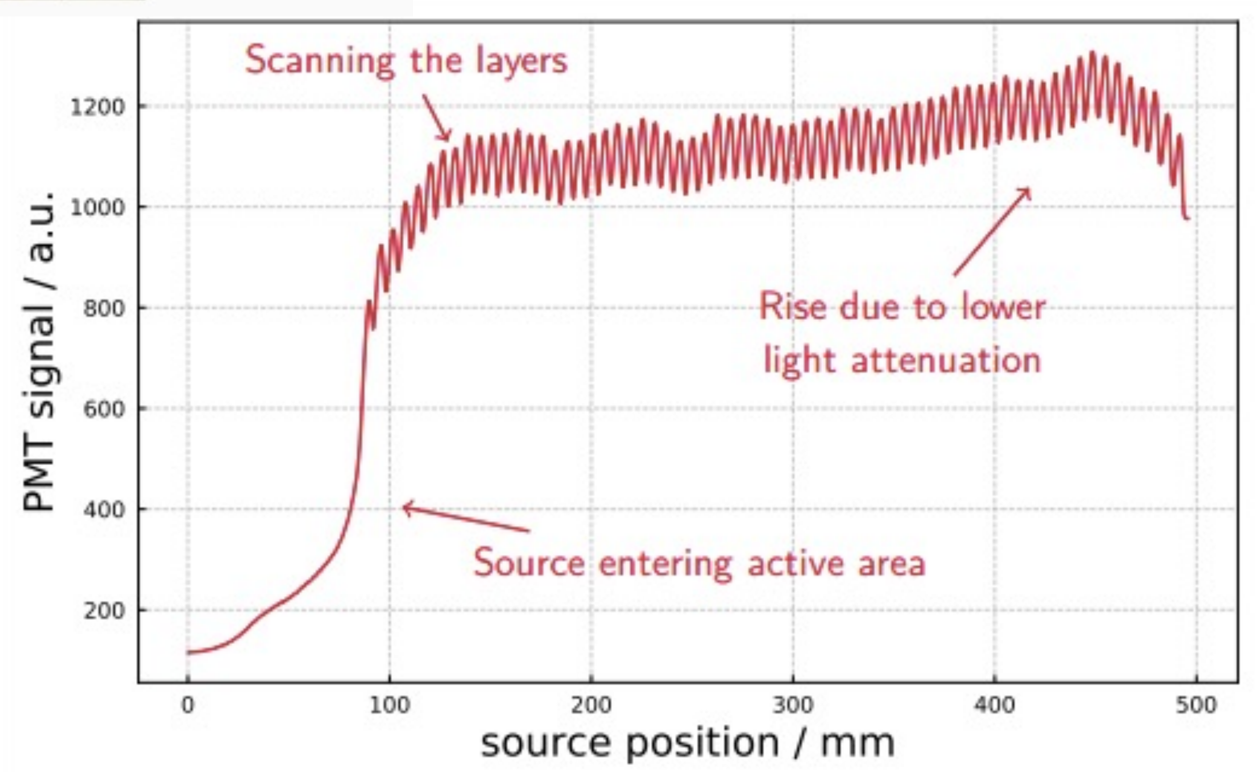




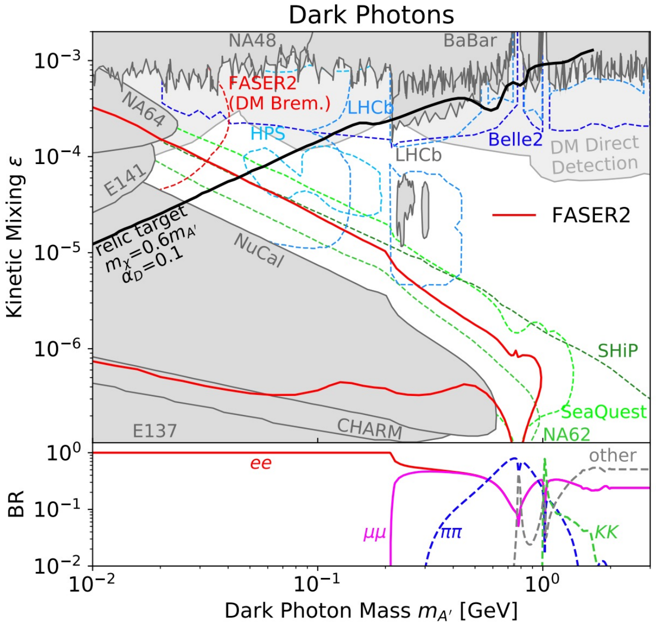
Calorimeter – Initial QA

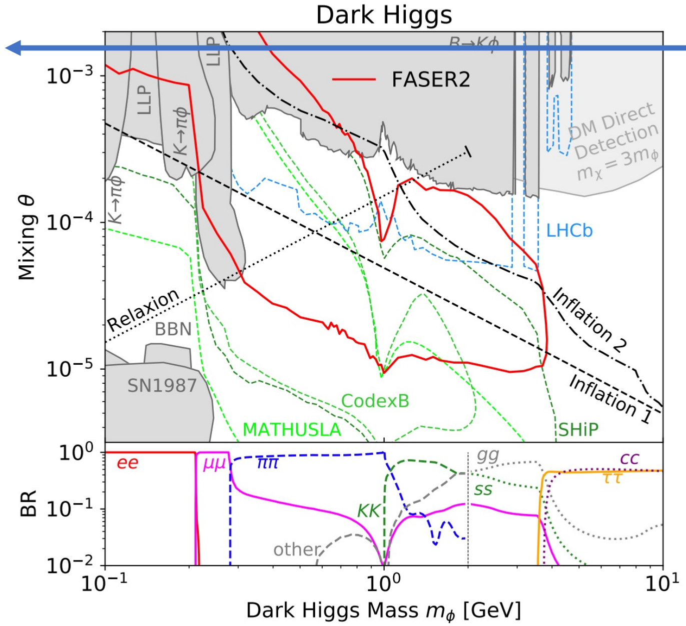


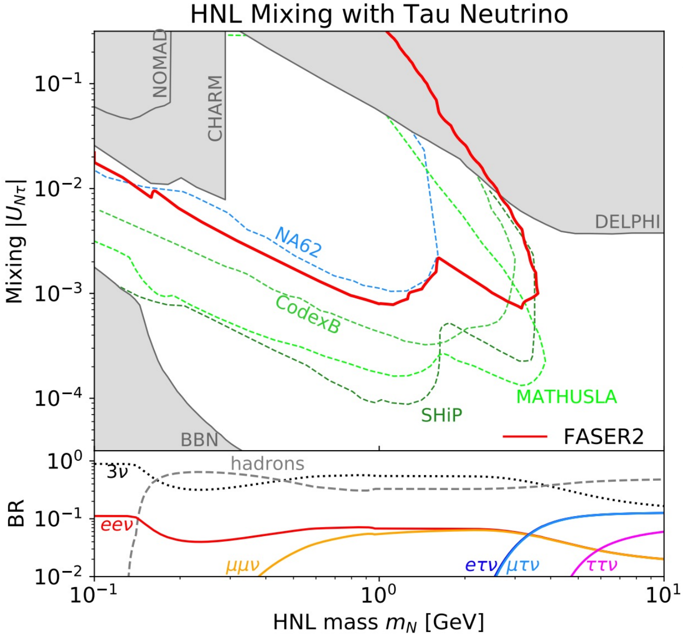
Testing of calorimeter modules at CERN in March 2019 with a source showed expected response in all modules tested.

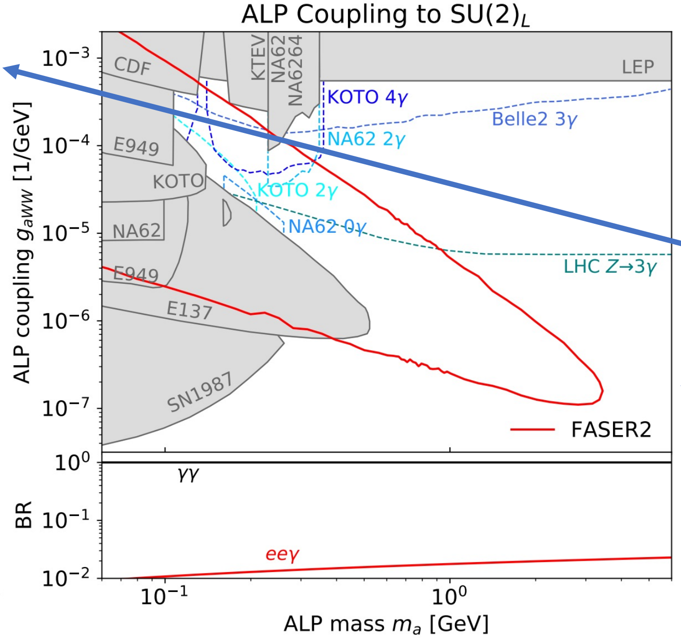


BSM at FPF



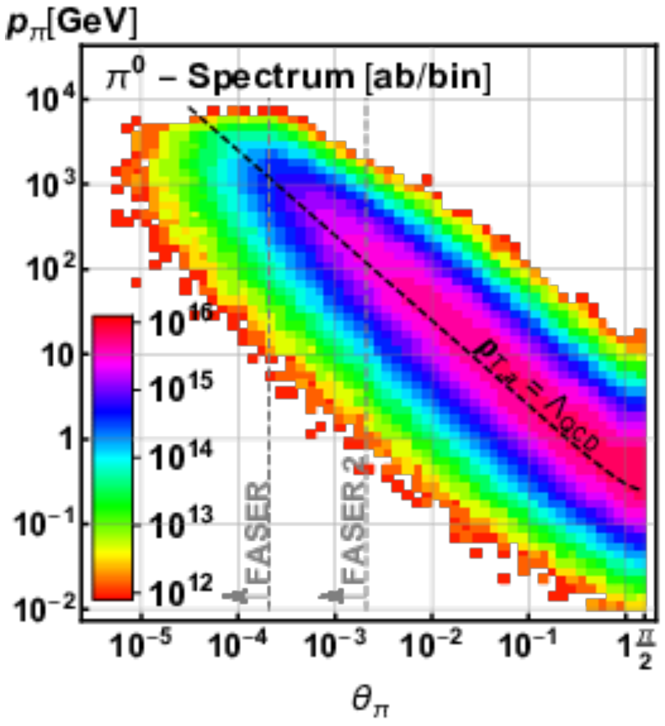


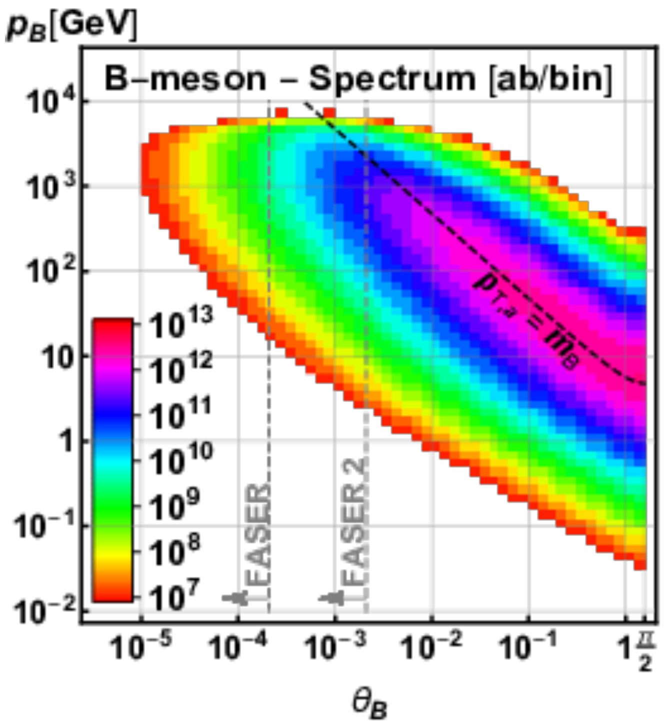


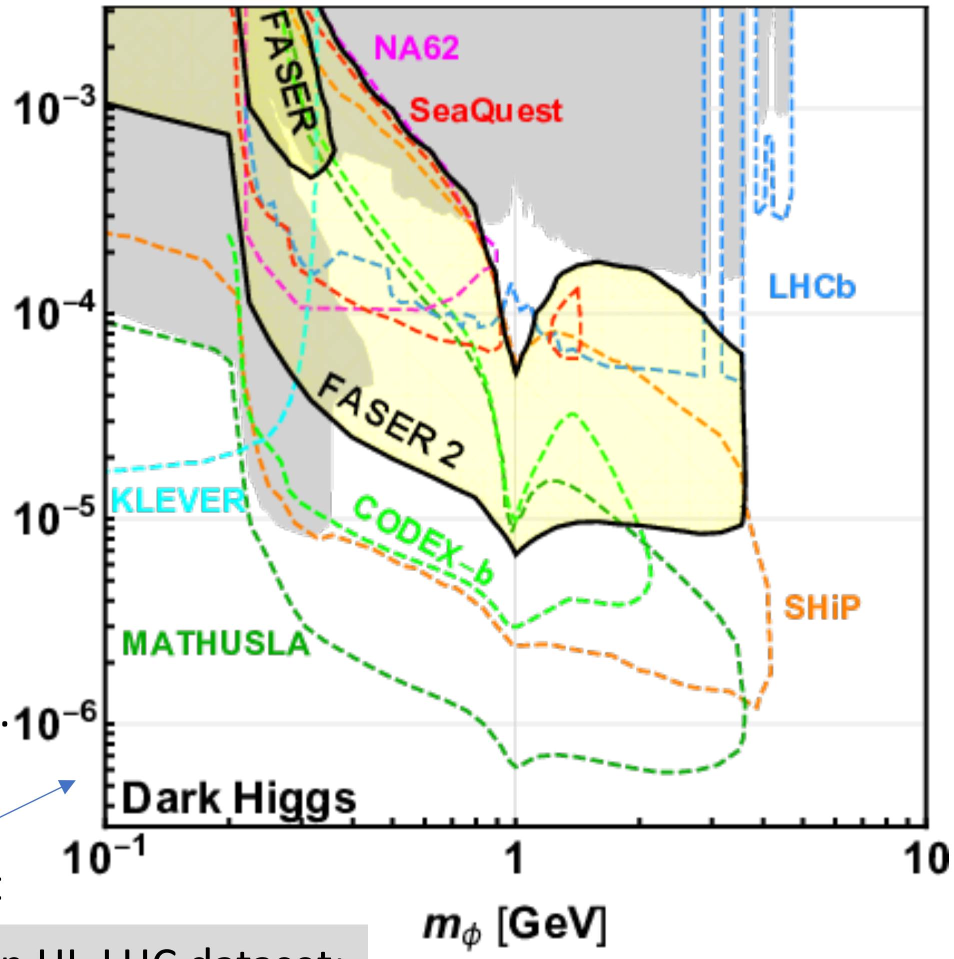


Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': U(1)$_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
BC3: Milli-Charged Particle	FORMOSA
BC4: Dark Higgs Boson	FASER 2
BC5: Dark Higgs with hSS	FASER 2
BC6: HNL with e	FASER 2
BC7: HNL with μ	FASER 2
BC8: HNL with τ	FASER 2
BC9: ALP with photon	FASER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

Aside: Signals from heavy flavour decay





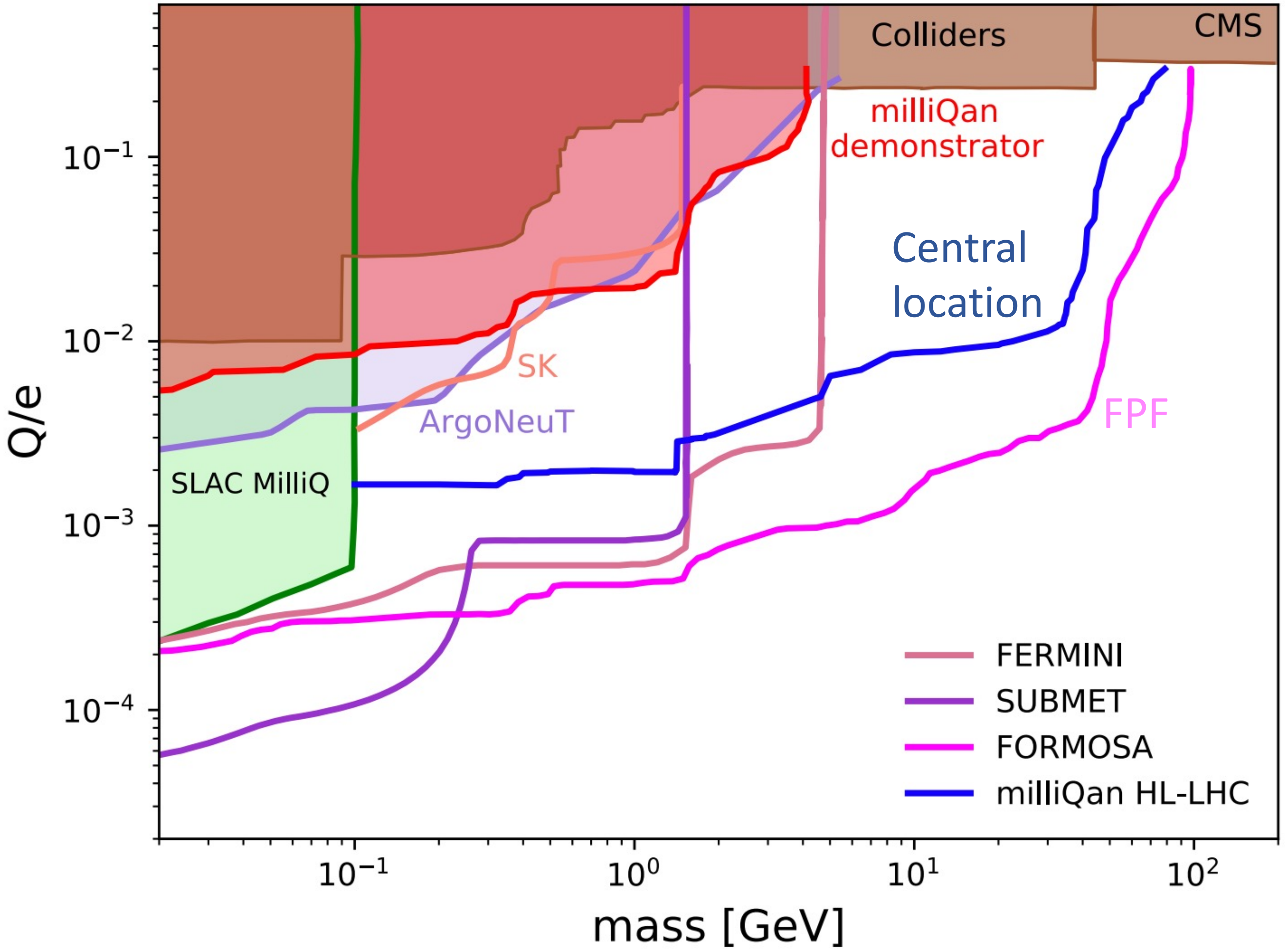


Number of π^0 and B mesons as function of angle wrt LOS and energy (for 150/fb). Heavier B-mesons are more spreadout around the LOS => only small fraction in FASER acceptance, but FASER2 starts to get into the bulk of the distribution. Much better sensitivity for new LLPs produced in B decays (such as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



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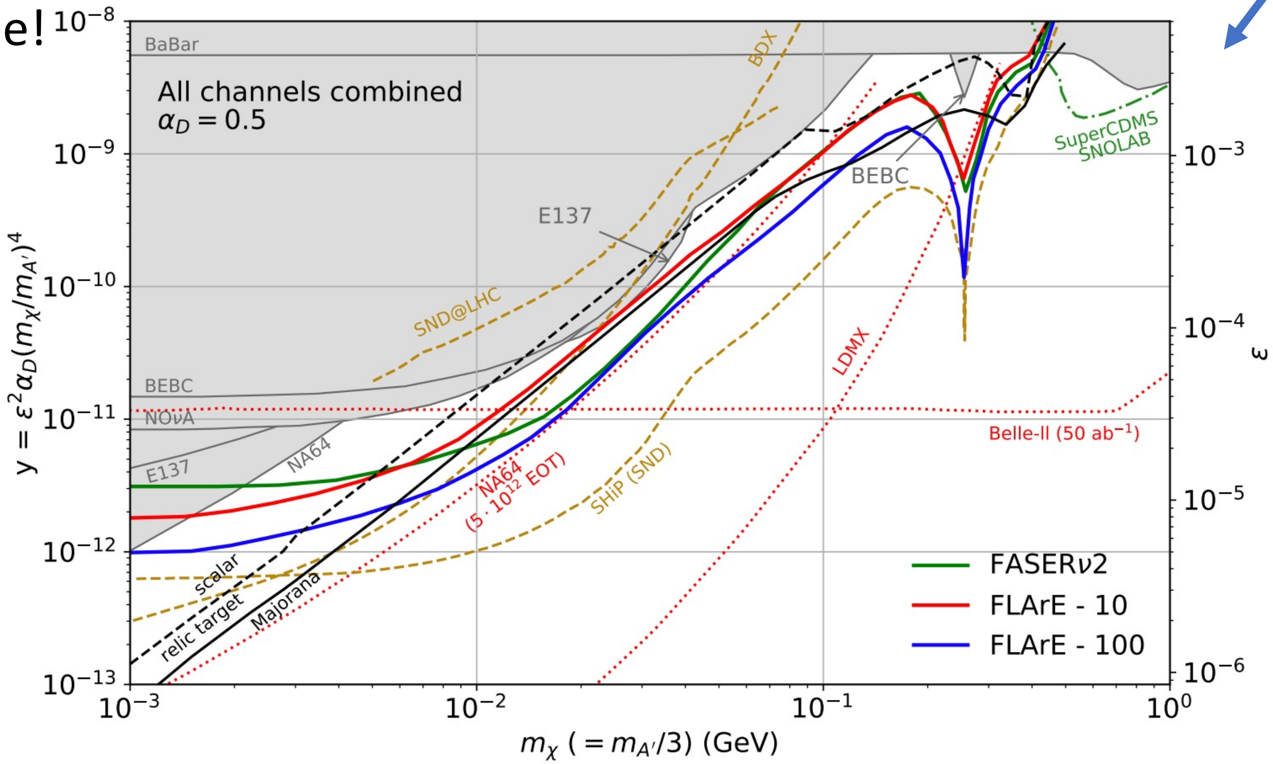
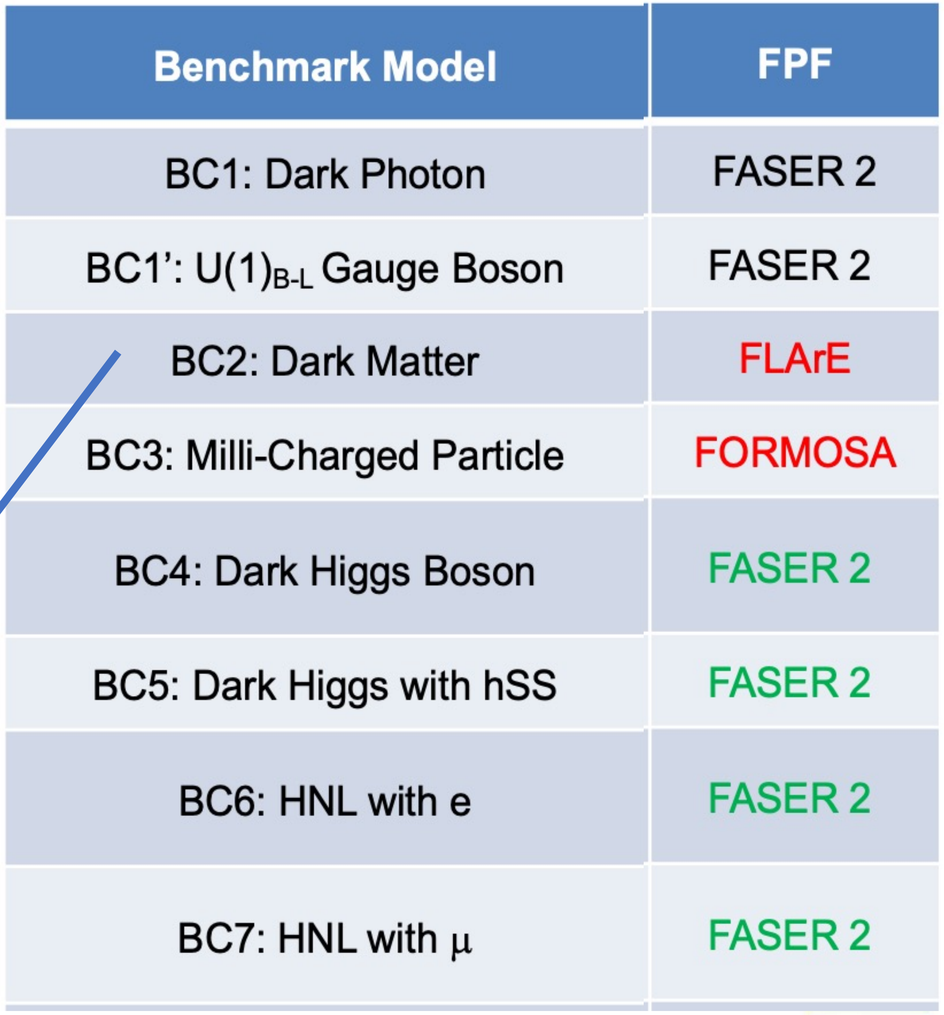
BC8: HNL with τ	FASER 2
BC9: ALP with photon	FASER 2
BC10: ALP with fermion	FASER 2
BC11: ALP with gluon	FASER 2

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!





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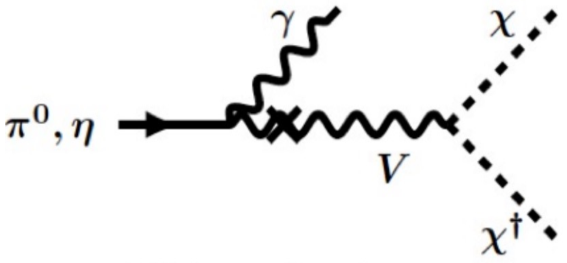
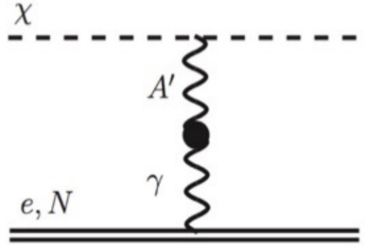
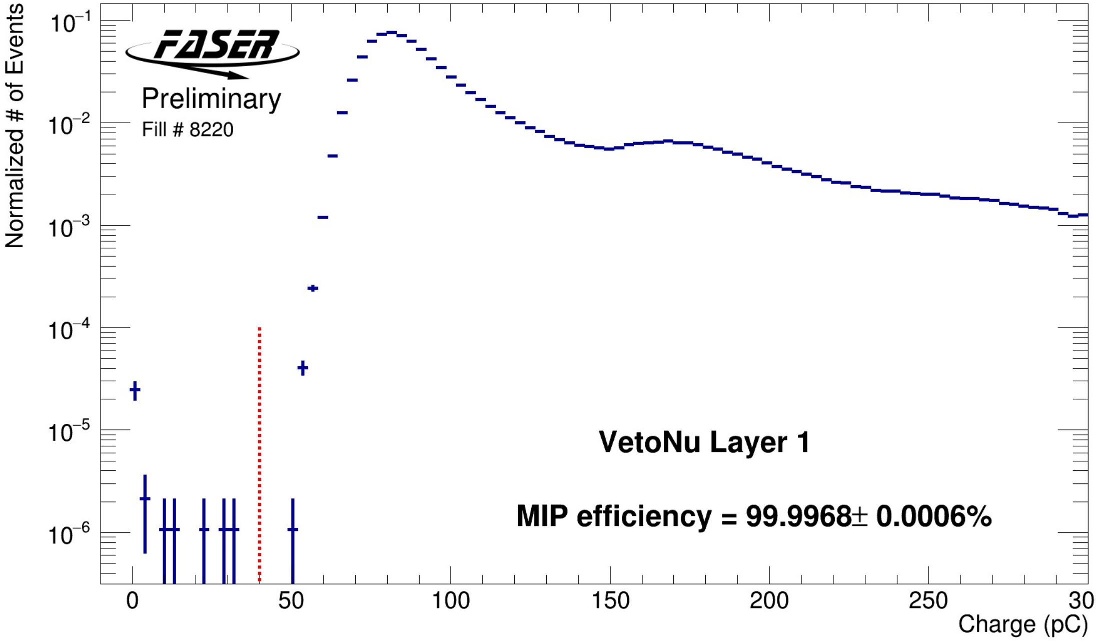


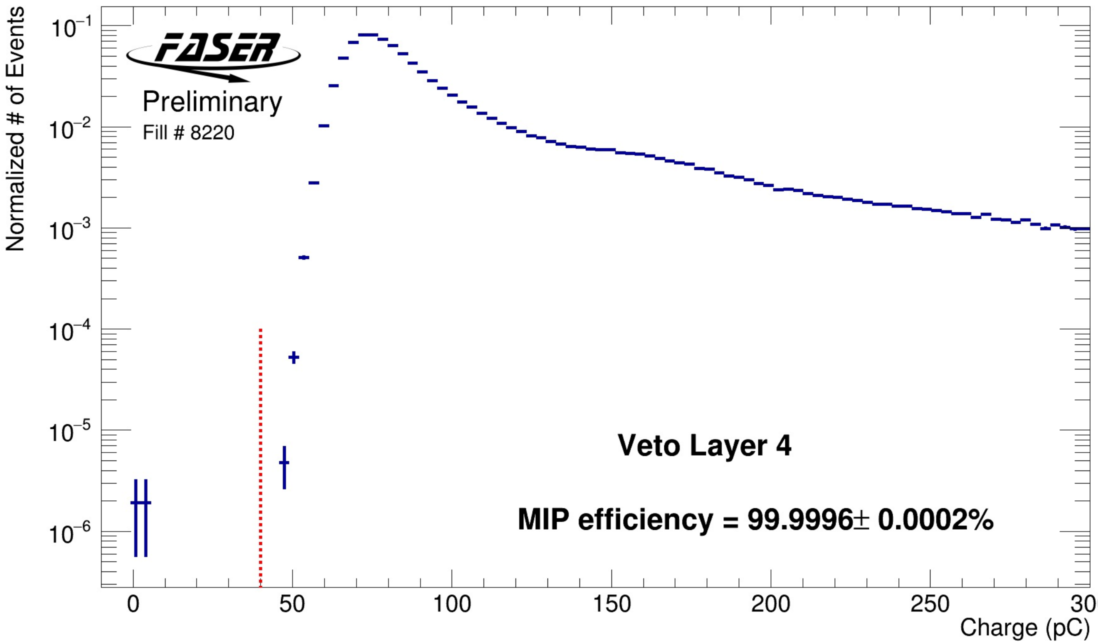
DM production



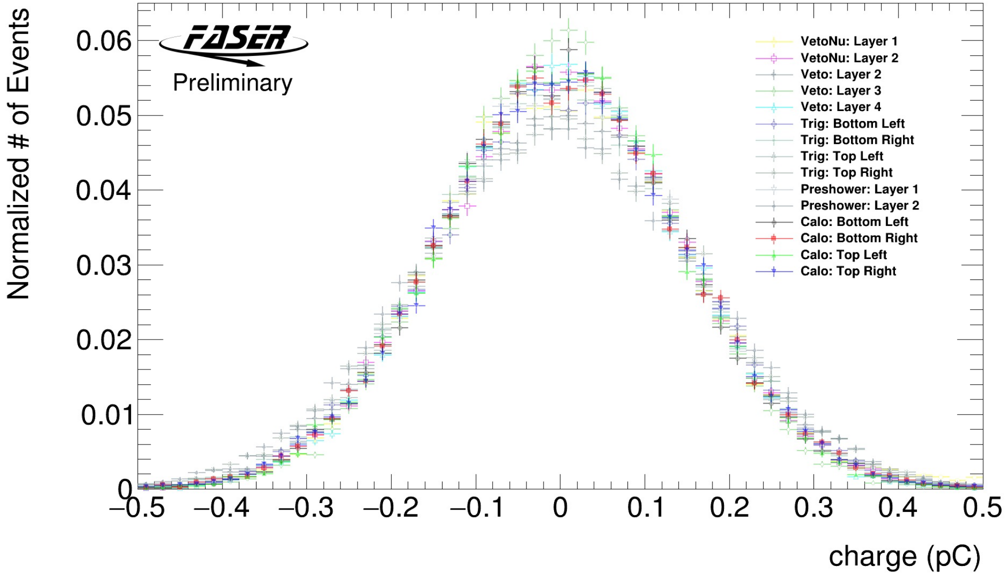
DM scattering

Scintillator Performance

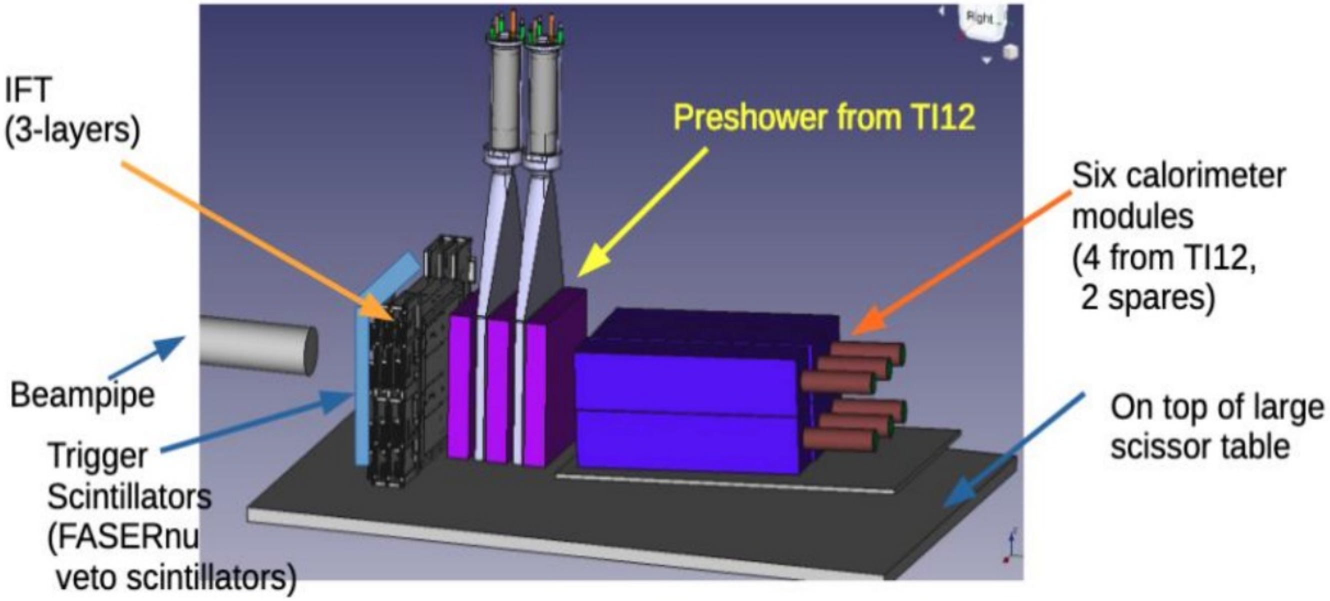


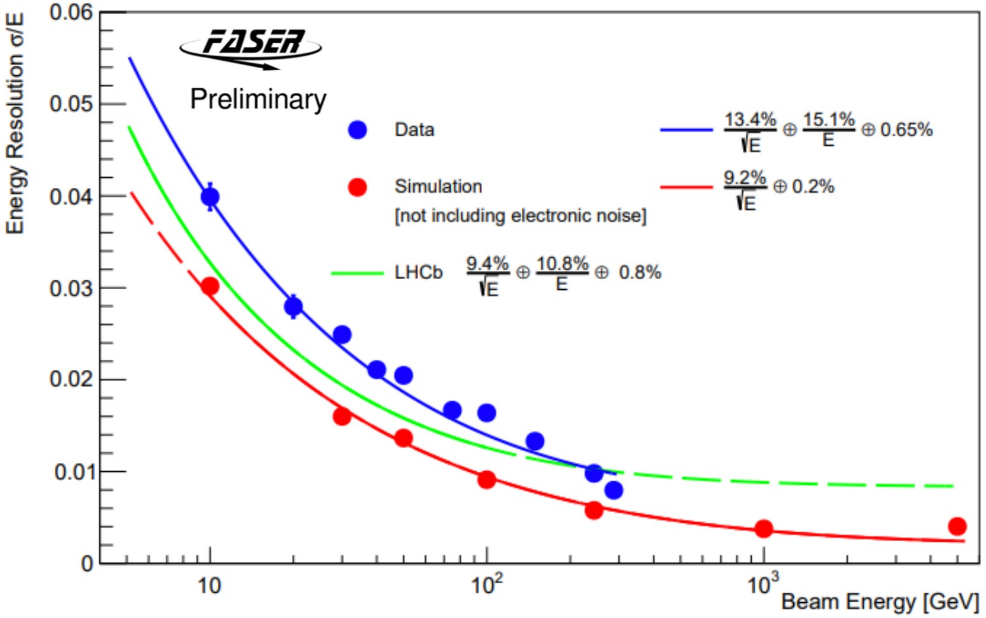


- Veto efficiency measurement in data, for events with track that extrapolates into the scintillator. Each individual scintillator efficiency >99.99%.
- When 4 scintillators combined can veto expected $\mathcal{O}(10^8)$ muons entering the detector in Run 3.
- Scintillator noise measured in random triggered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



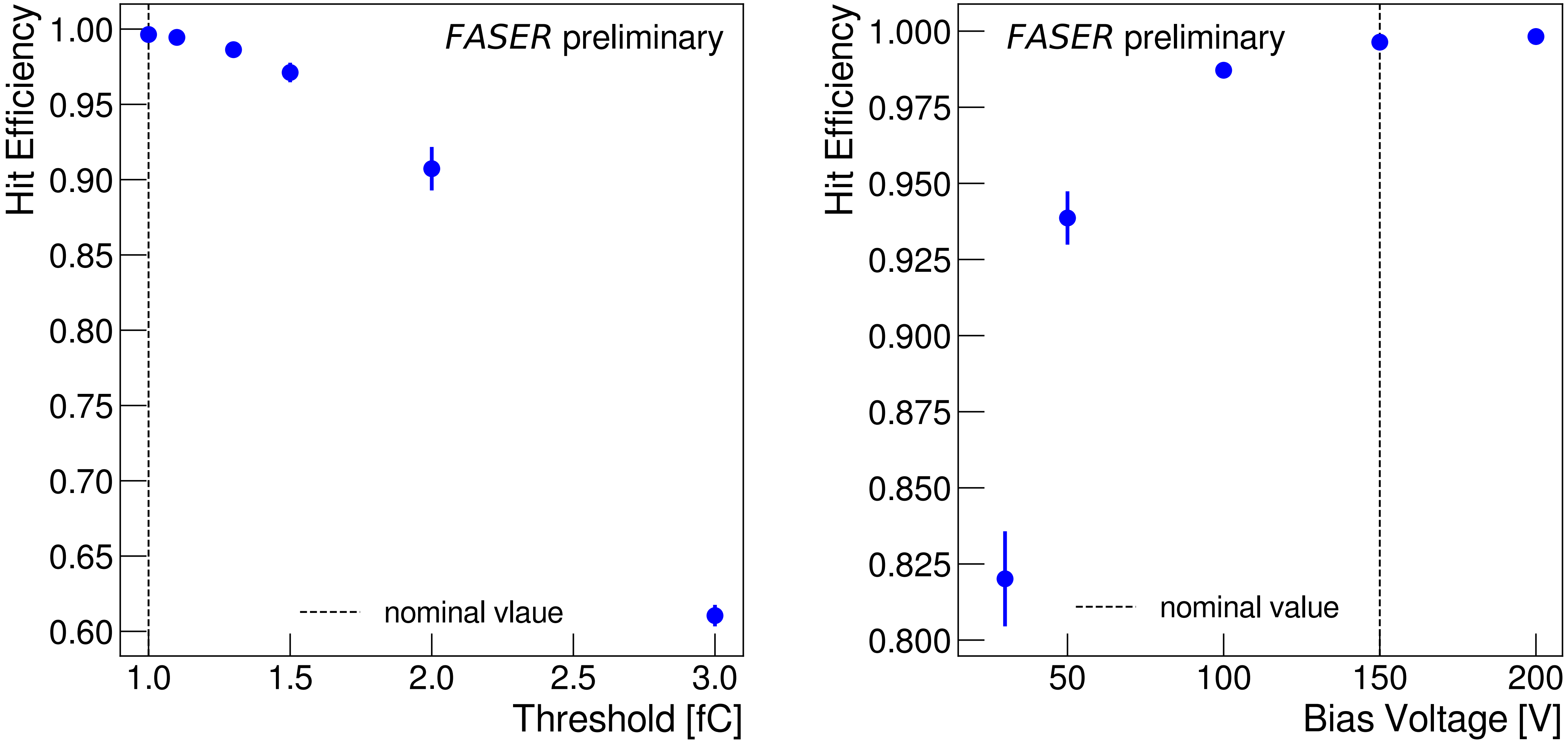
Calorimeter Performance





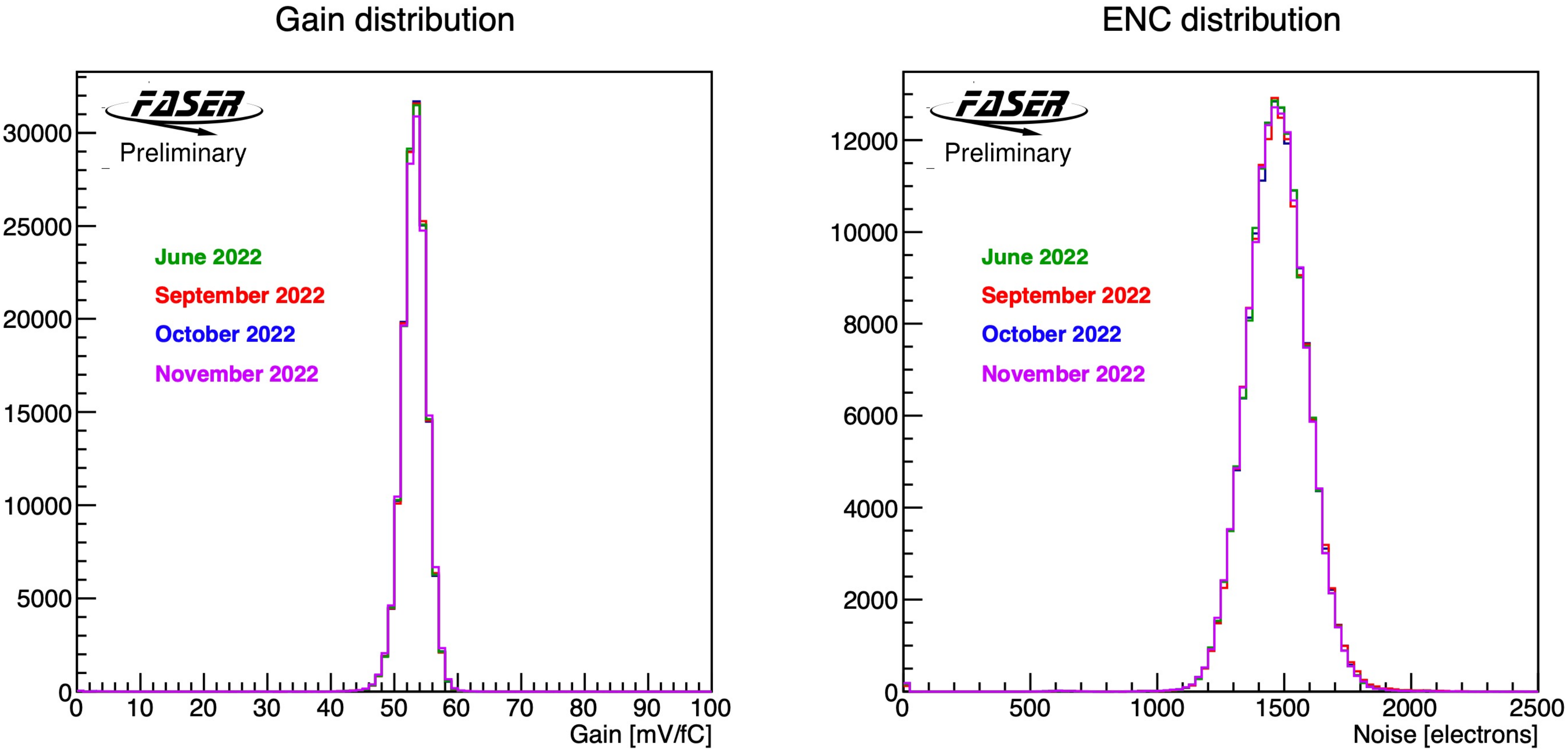
- Calorimeter energy resolution measured with SPS testbeam in summer 2021
- Confirming $\mathcal{O}(1\%)$ resolution for high energy electrons.
- Testbeam also used to demonstrate calibration method using muon MIP peak to set energy scale at low energy, and LED calibration pulses to scale this to high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

Tracker Performance



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

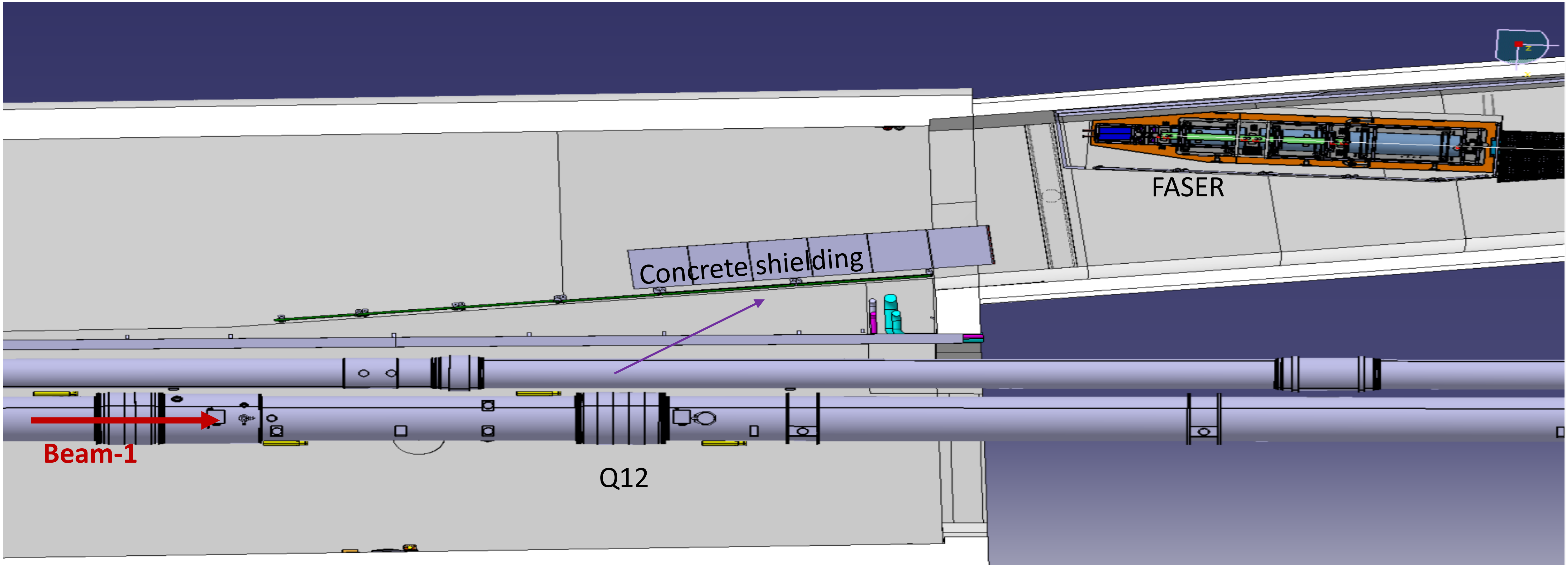
Tracker Performance



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

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

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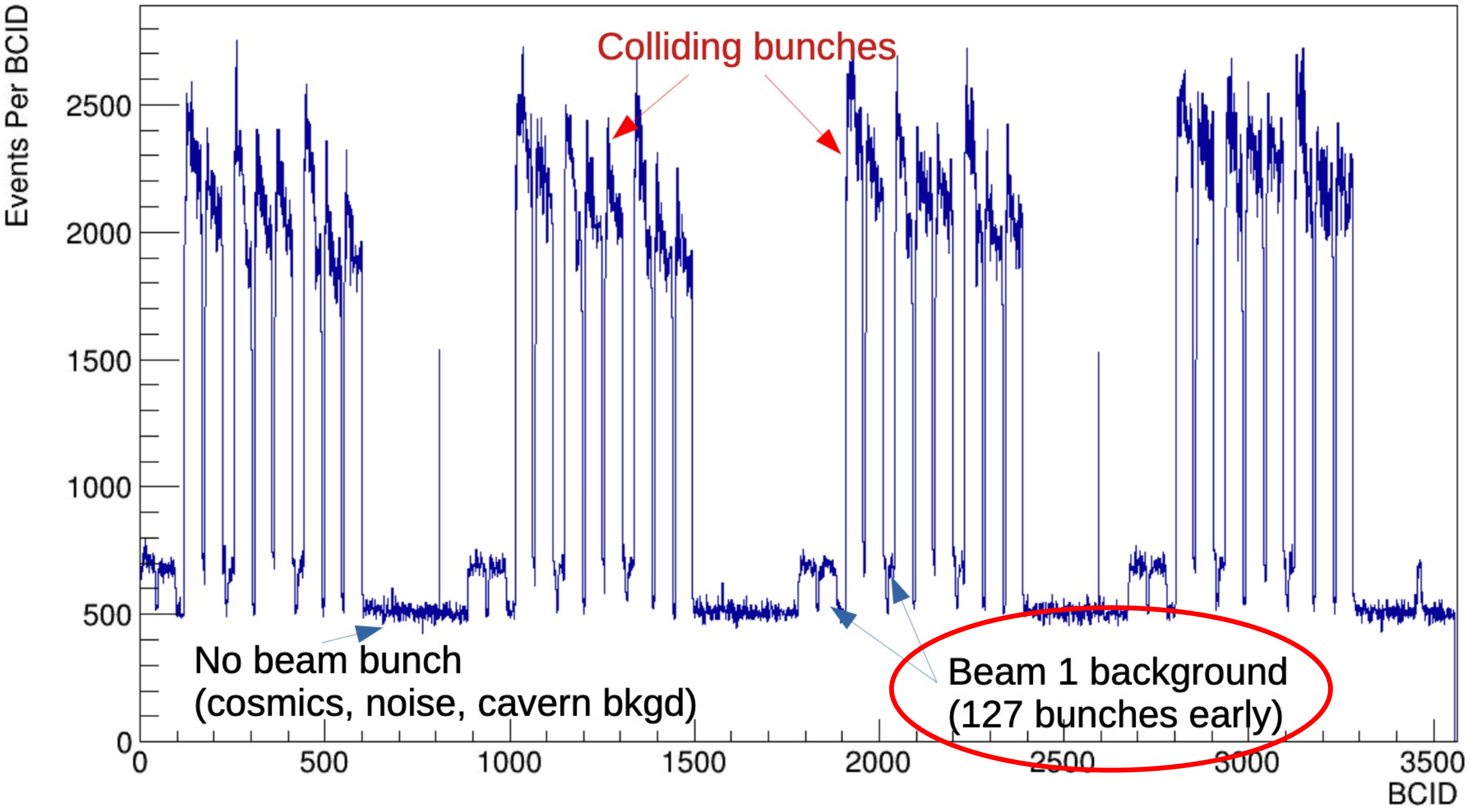
Trigger rate versus BCID in 600b fill



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
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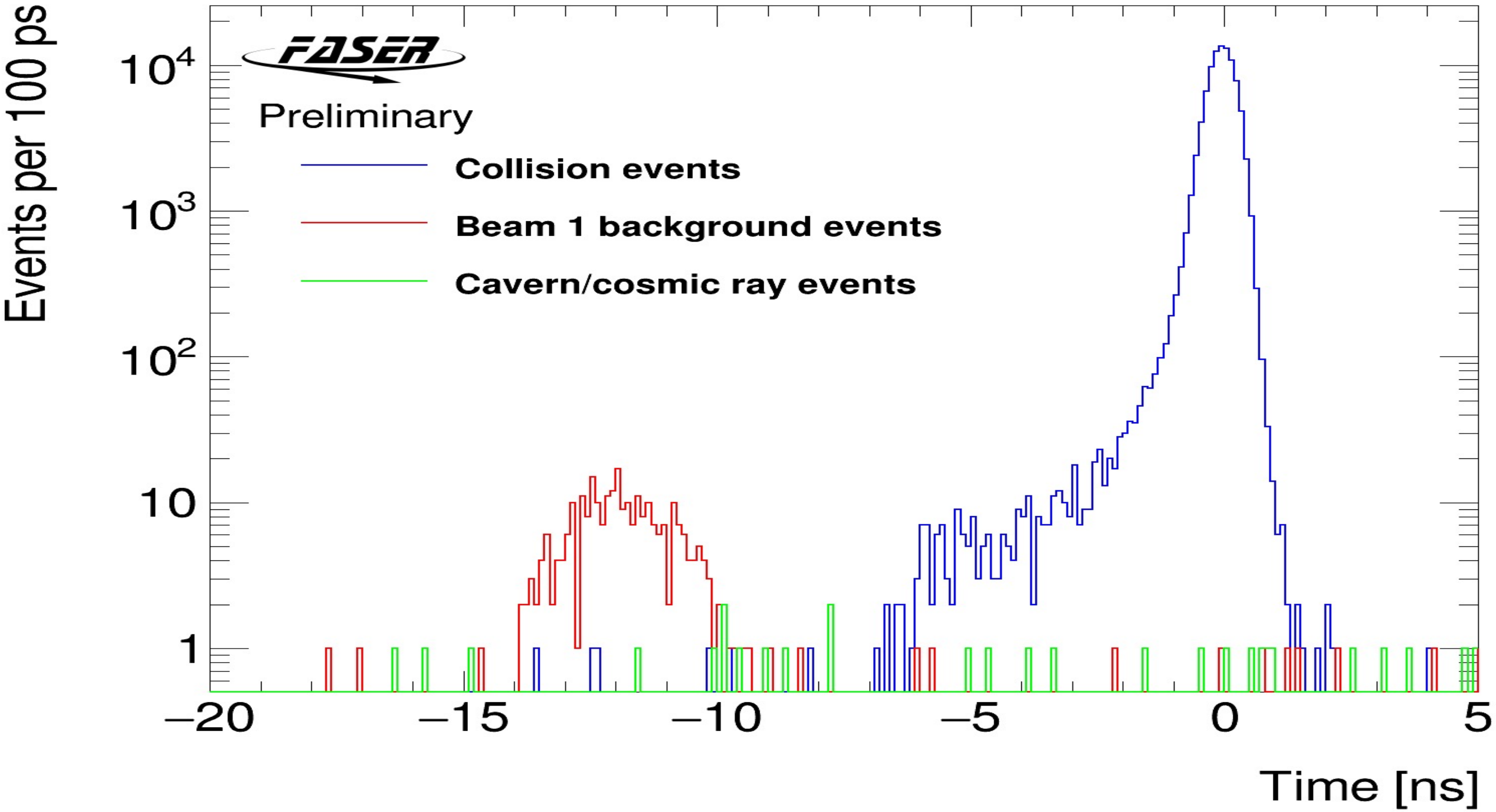
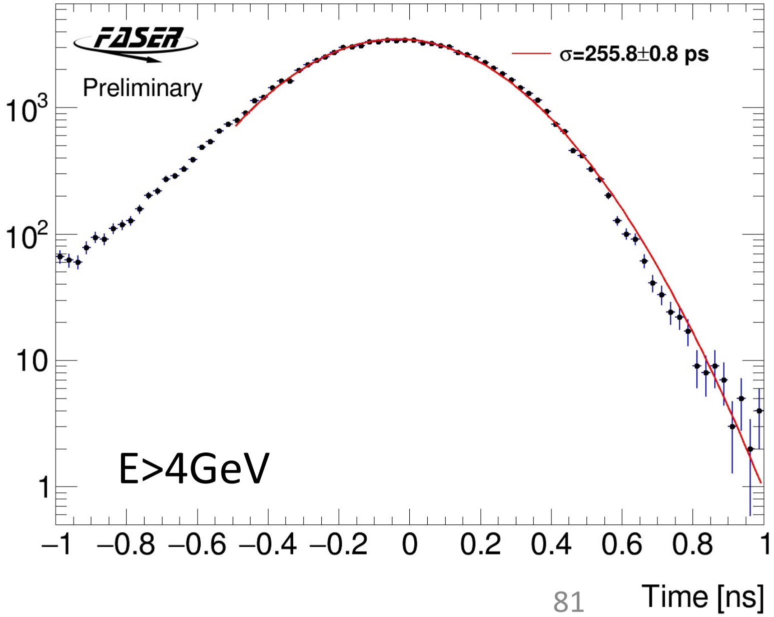
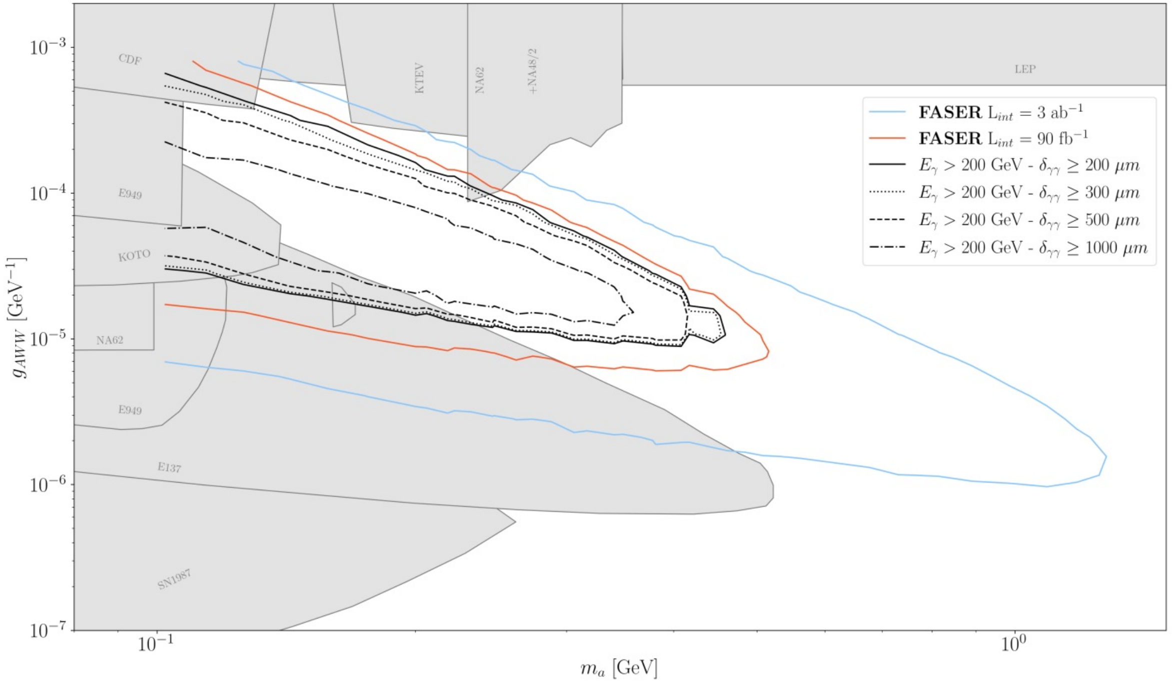


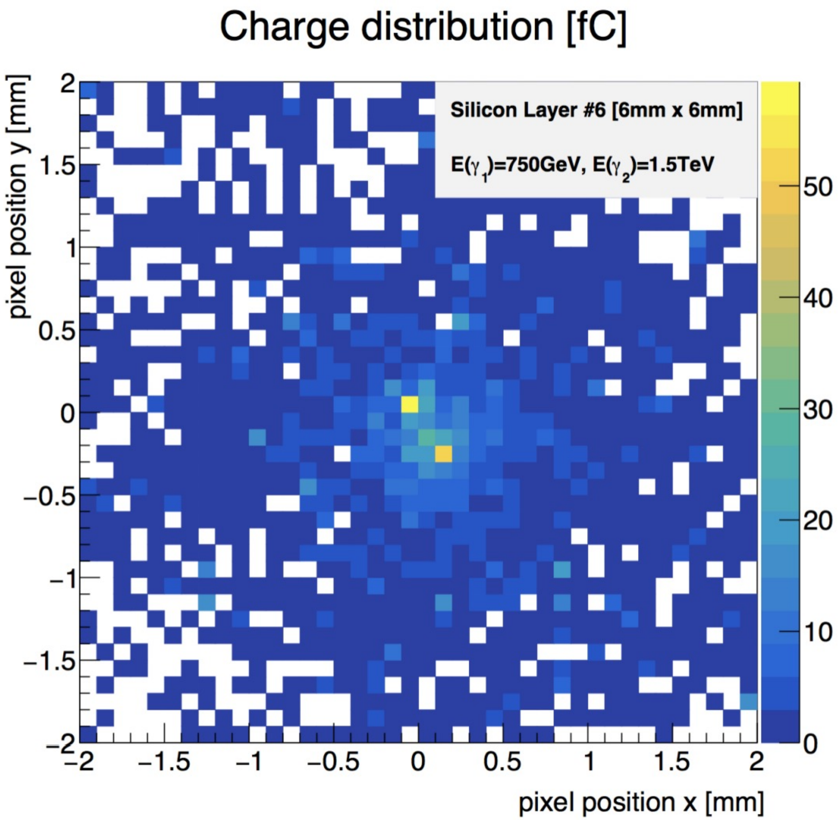
Beam-1 background can be efficiently removed by using calorimeter timing.
Excellent timing resolution for large energy signals (<300ps)



Pre-shower Upgrade

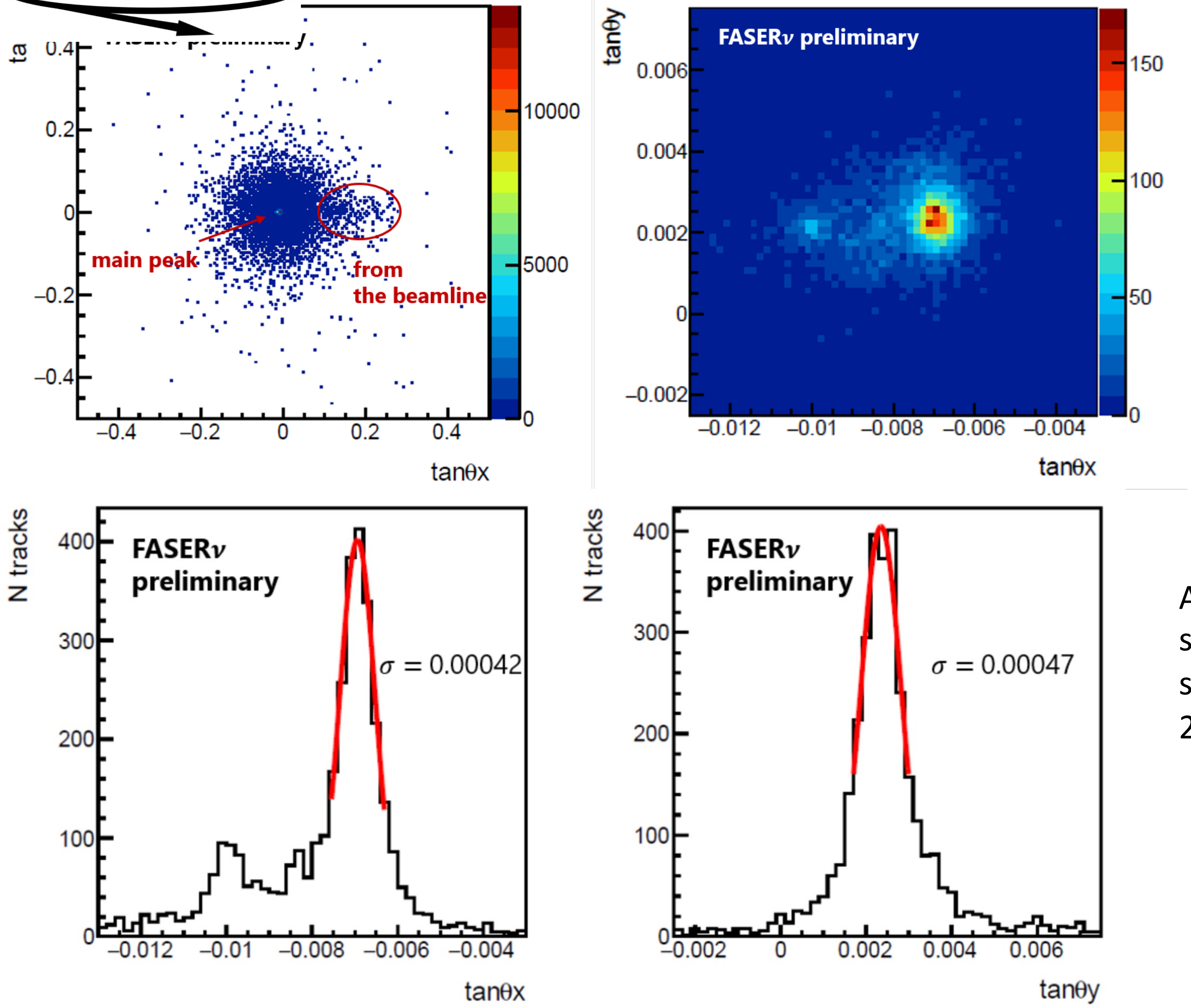
- Current detector problematic for new particles decaying to 2 photons (such as ALPs)
  - Given low mass and large boost resulting photons are very closely spaced (<1mm separation)
- Current detector could detect events with large energy in calorimeter, but this suffers from background from neutrino 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.

FASERν Results



Angular distributions observed from analysis of first FASERnu box.

The angular coordinates (0, 0) roughly corresponds to the LOS .

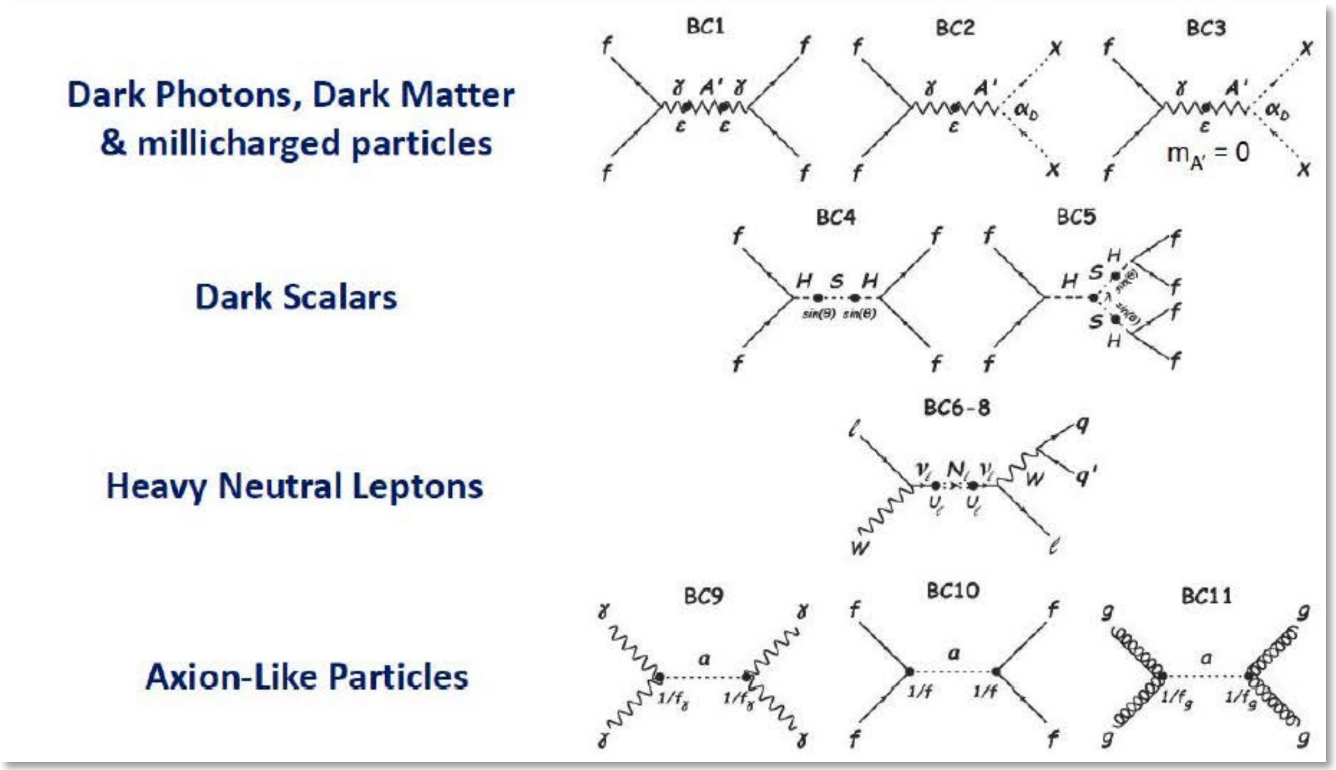
There are two peaks separated by 0.003 rad.

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).

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.

Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1': $U(1)_{B\text{-}L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
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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

No FASER sensitivity

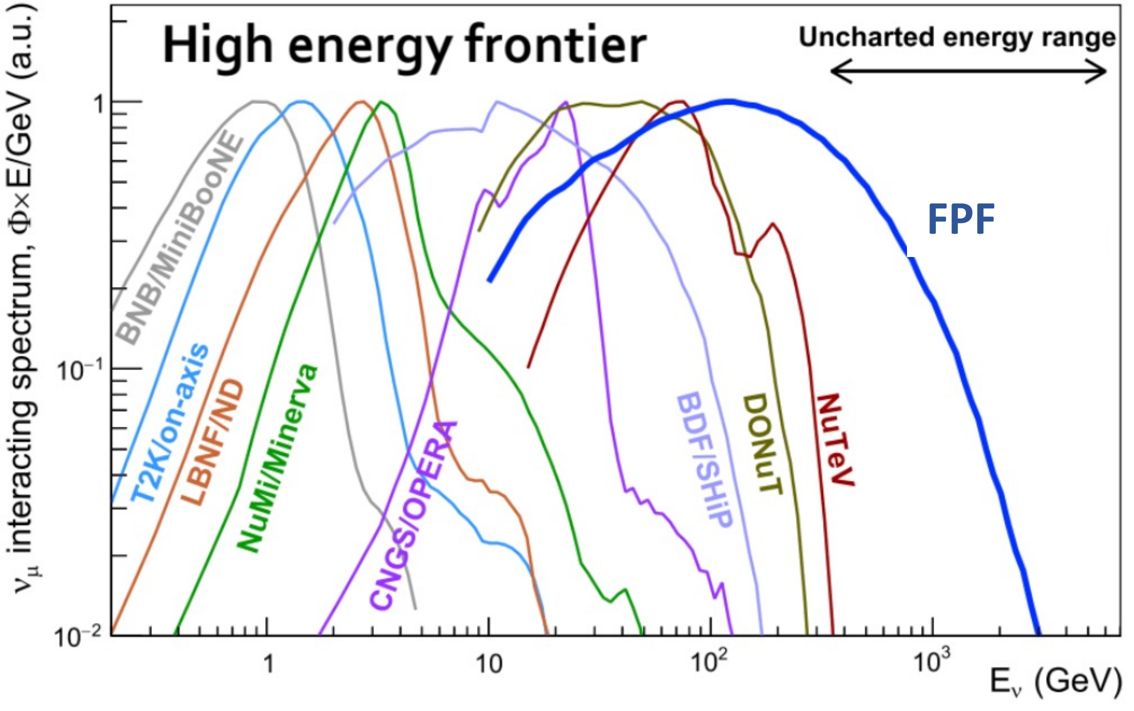
https://arxiv.org/pdf/2105.08270.pdf (F. Kling, DESY)

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.

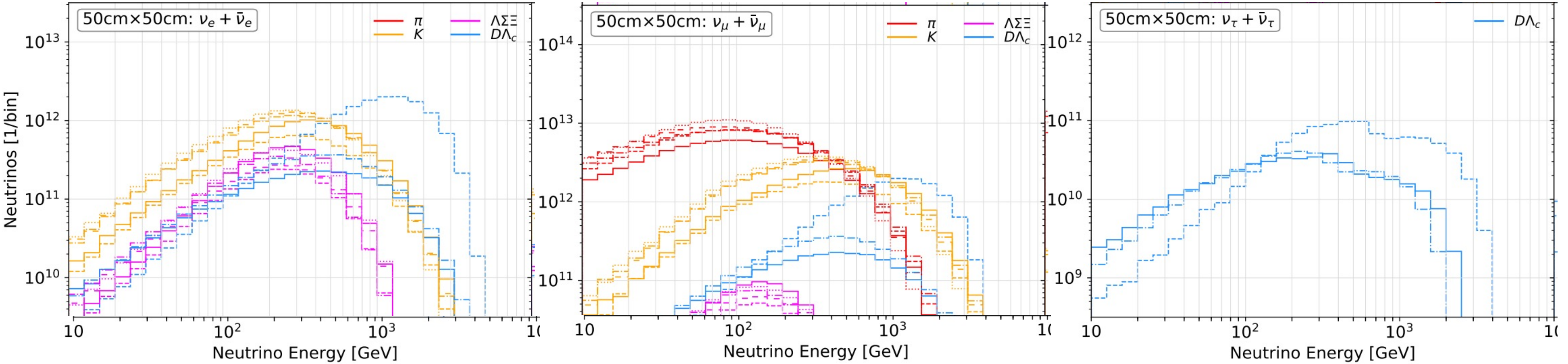


Larger detectors and dataset will allow huge increase in number of neutrino interactions that can be recorded at the FPF experiments compared to FASERν (x20 luminosity, x10 target mass)

- \- large differences in expectations between different generators – numbers shown here the most conservative particularly 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
  - $\pi \rightarrow \nu\mu$, K $\rightarrow \nu_e$ (at high-energy/off-axis D $\rightarrow \nu_e$), D $\rightarrow \nu\tau$

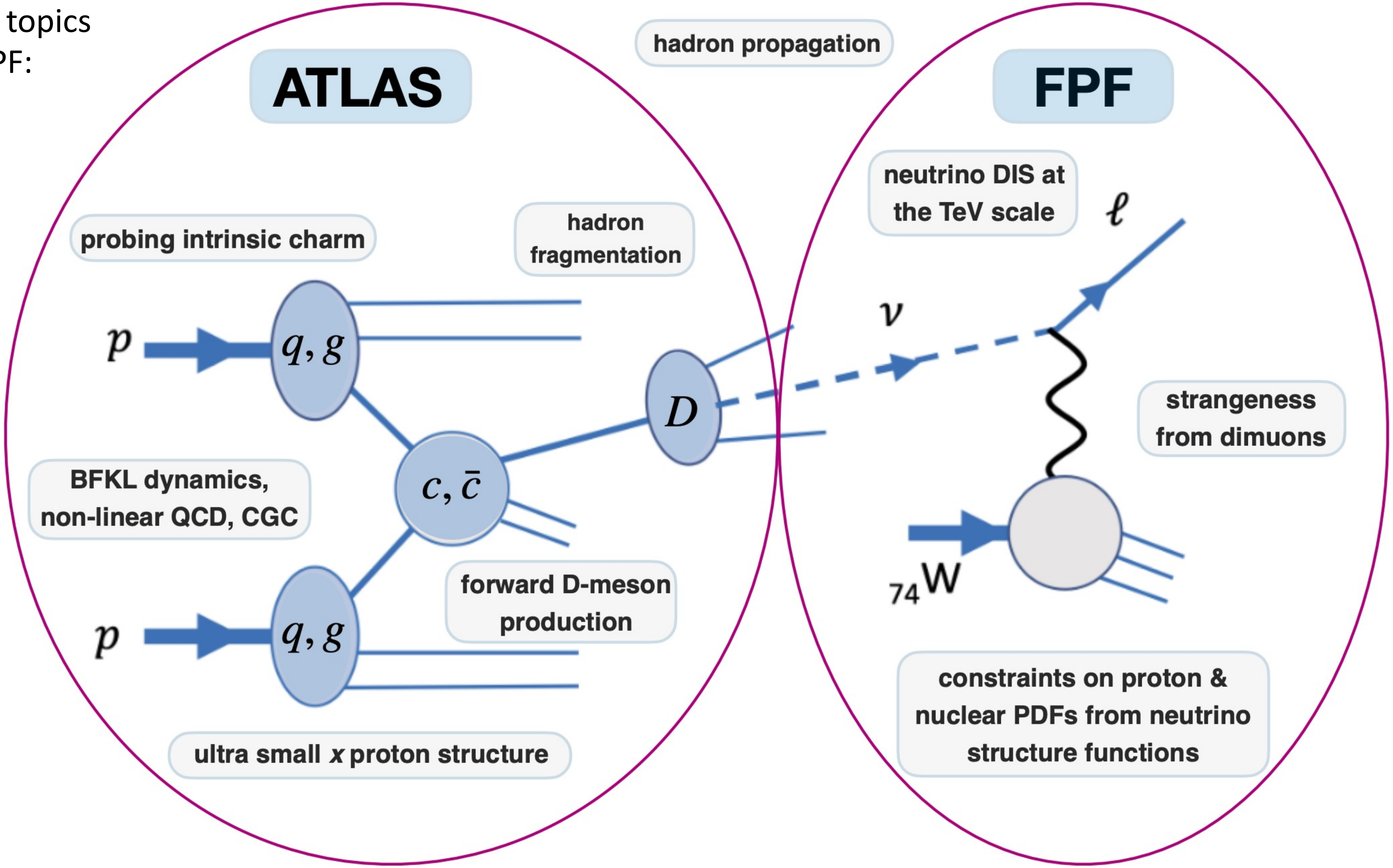


Electron neutrinos at high energy and slightly off-axis, almost exclusively from charm decays.

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