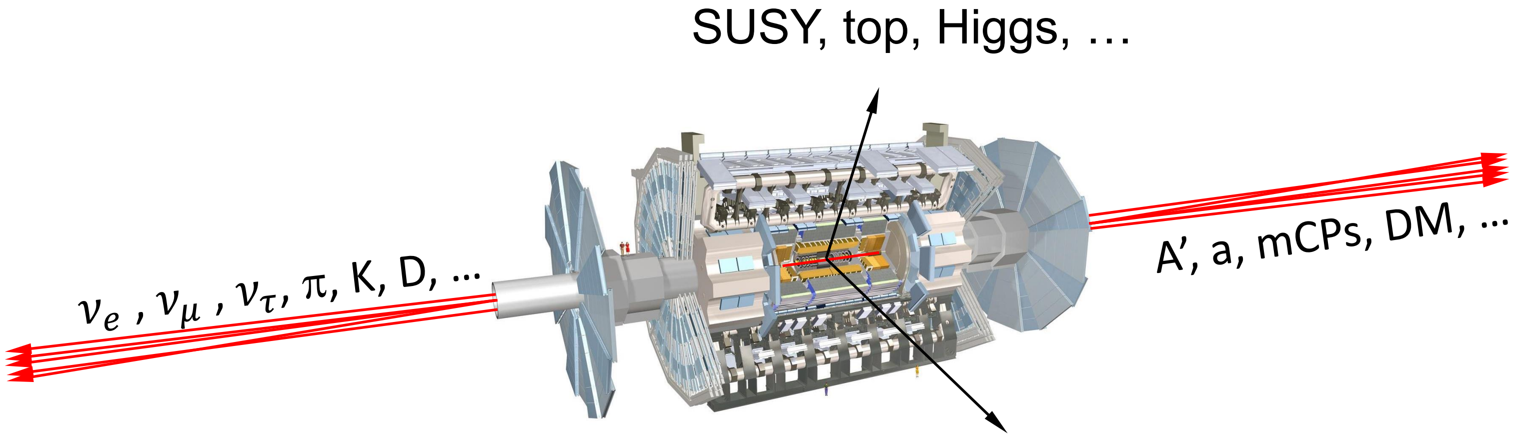
FASER

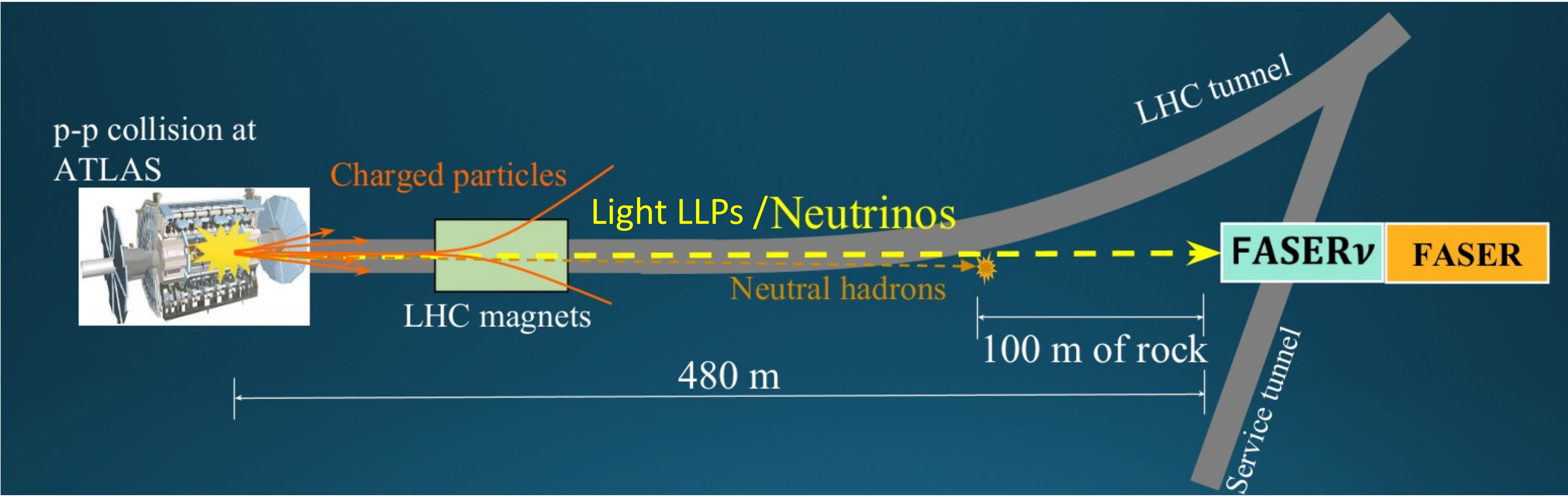
Jamie Boyd (CERN)

Intro: The intensity frontier at the LHC

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



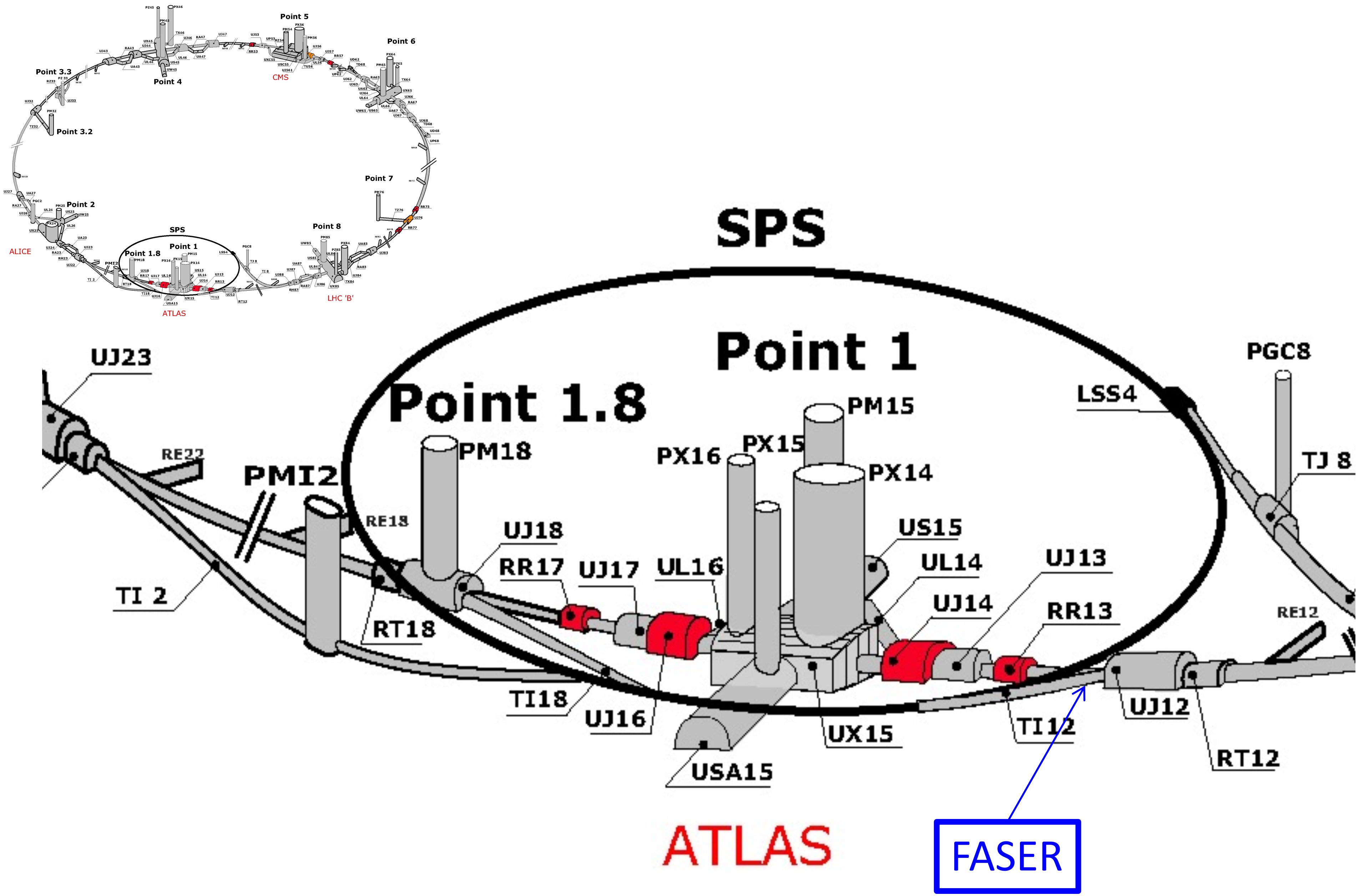
The FASER Experiment



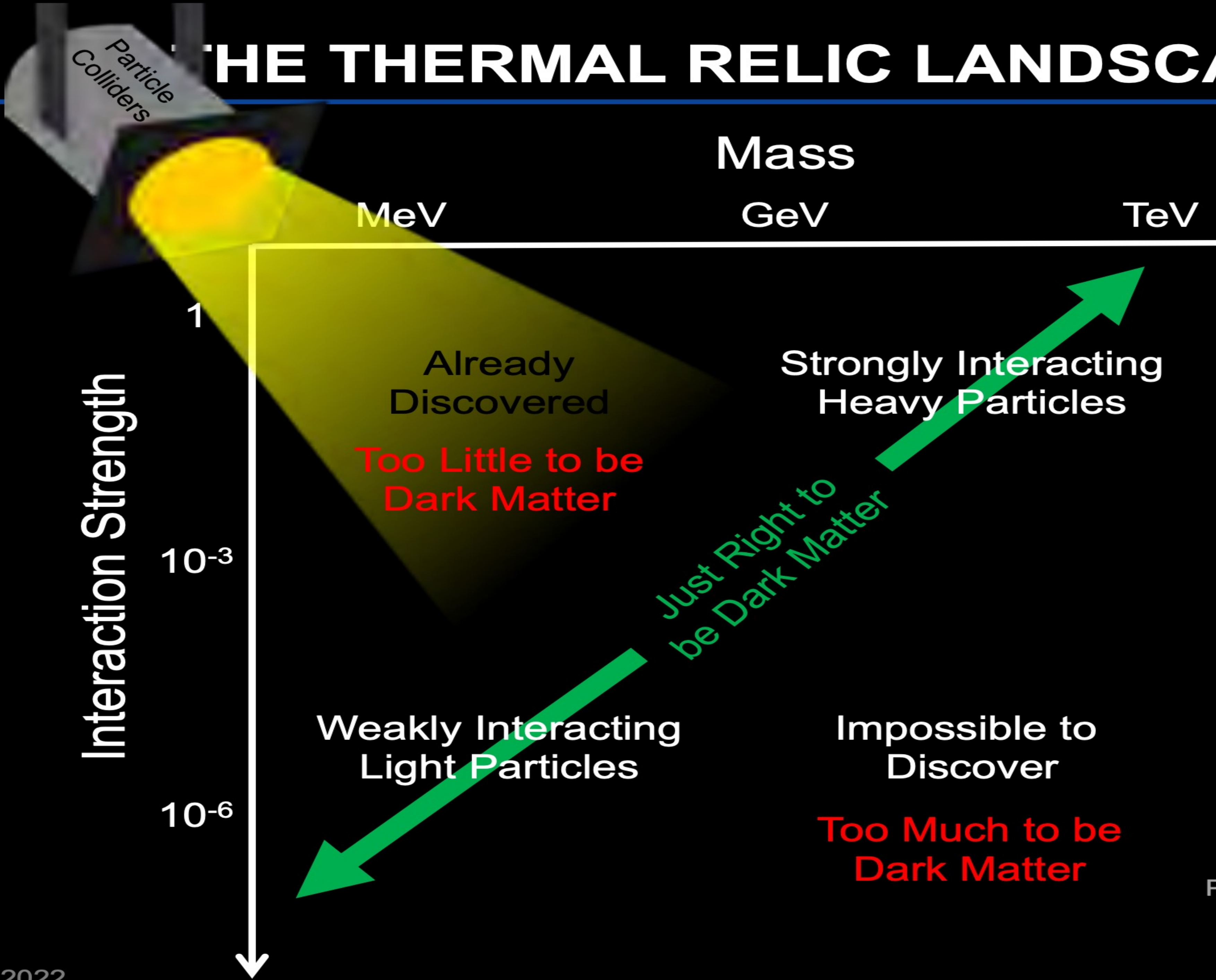
FASER is a new, small experiment at the LHC designed to take advatage of this and to search for new, light, long-lived particles (LLPs), and study neutrinos. The experiment is situated ~500m from the ATLAS collision point, on the beam collision axis line-of-sight (LOS), and started taking physics data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



THE THERMAL RELIC LANDSCAPE



Already Discovered

Too Little to be Dark Matter

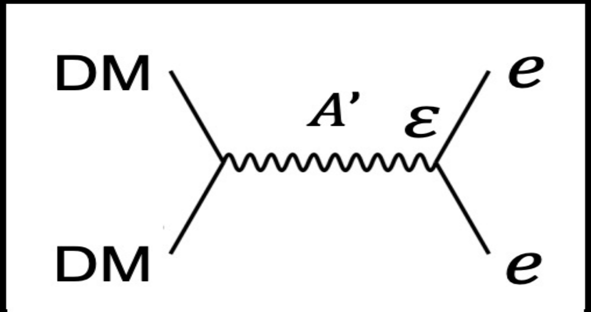
Strongly Interacting Heavy Particles

Just Right to be Dark Matter

Weakly Interacting Light Particles

Impossible to Discover

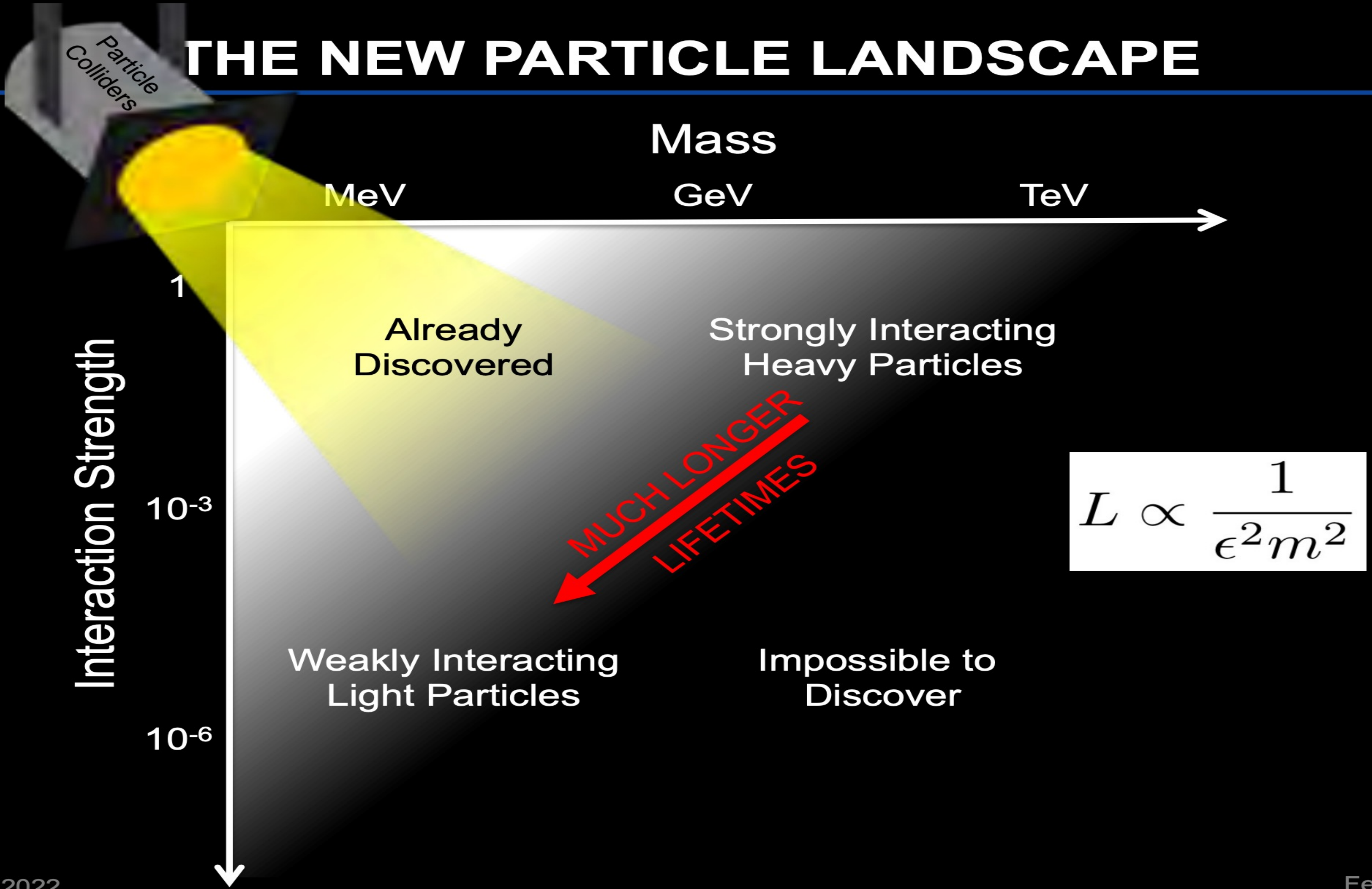
Too Much to be Dark Matter



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

"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

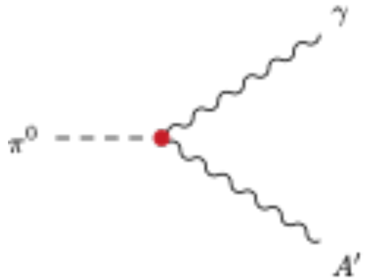
$$L \propto \frac{1}{\epsilon^2 m^2}$$

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.,



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

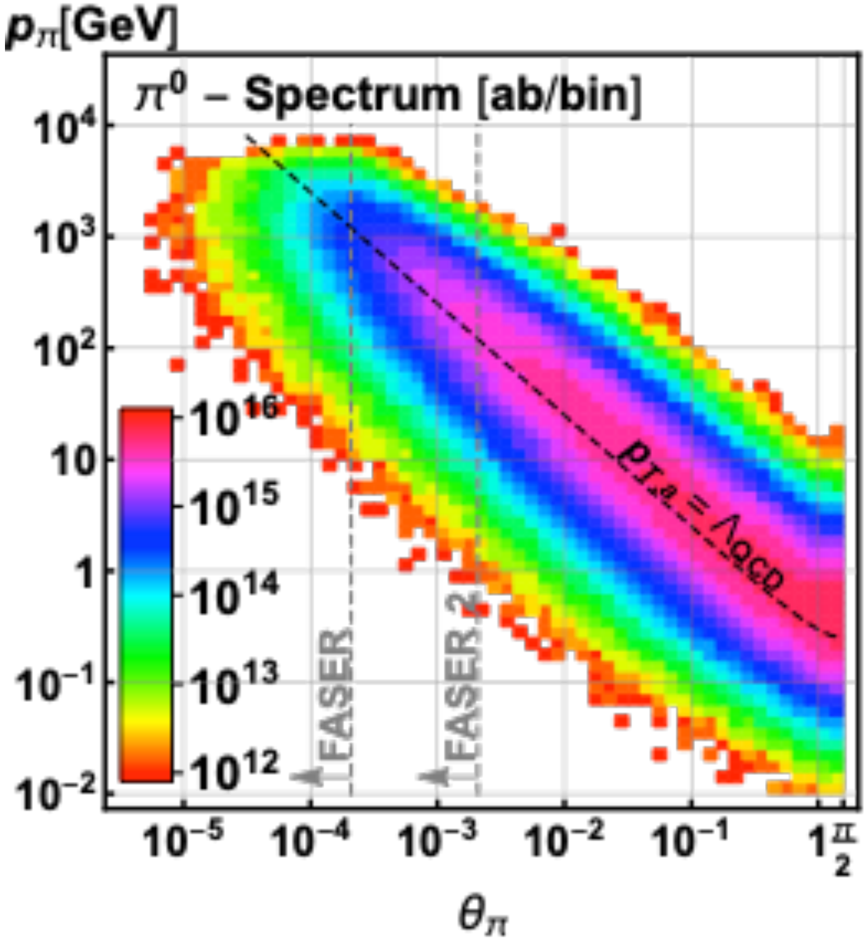
and also through other processes

- 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.

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

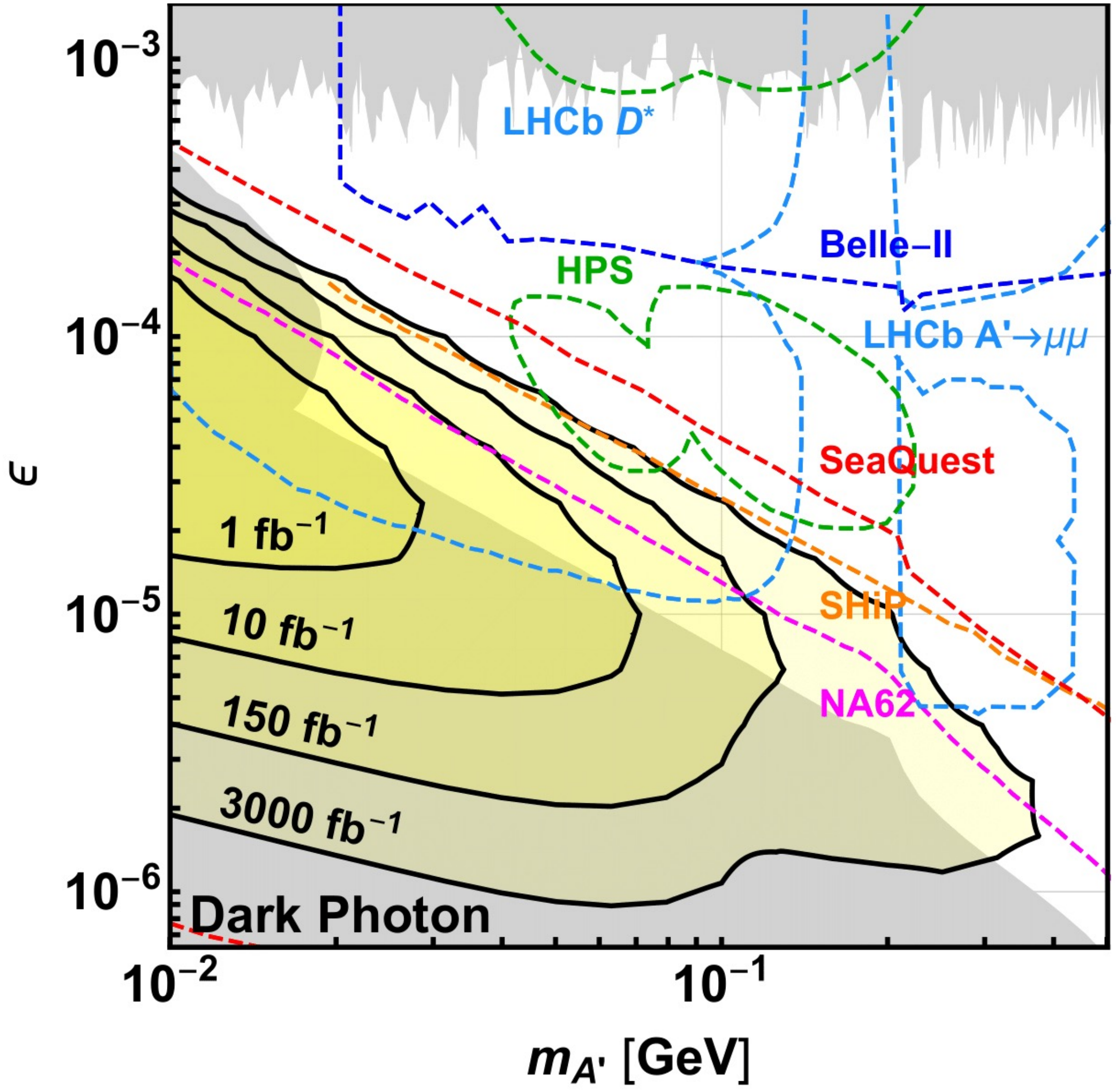
Run-3 (0.15/ab) will produce a huge number of π^0s in FASER angular acceptance $\mathcal{O}(10^{15})$. Even with large suppression ($\varepsilon^2 \sim 10^{-8} – 10^{-10}$ for relevant region of parameter space) can still have very large number of dark photons produced.

LHC can be a dark photon factory!

Dark Photons in FASER

arxiv:1811.12522

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



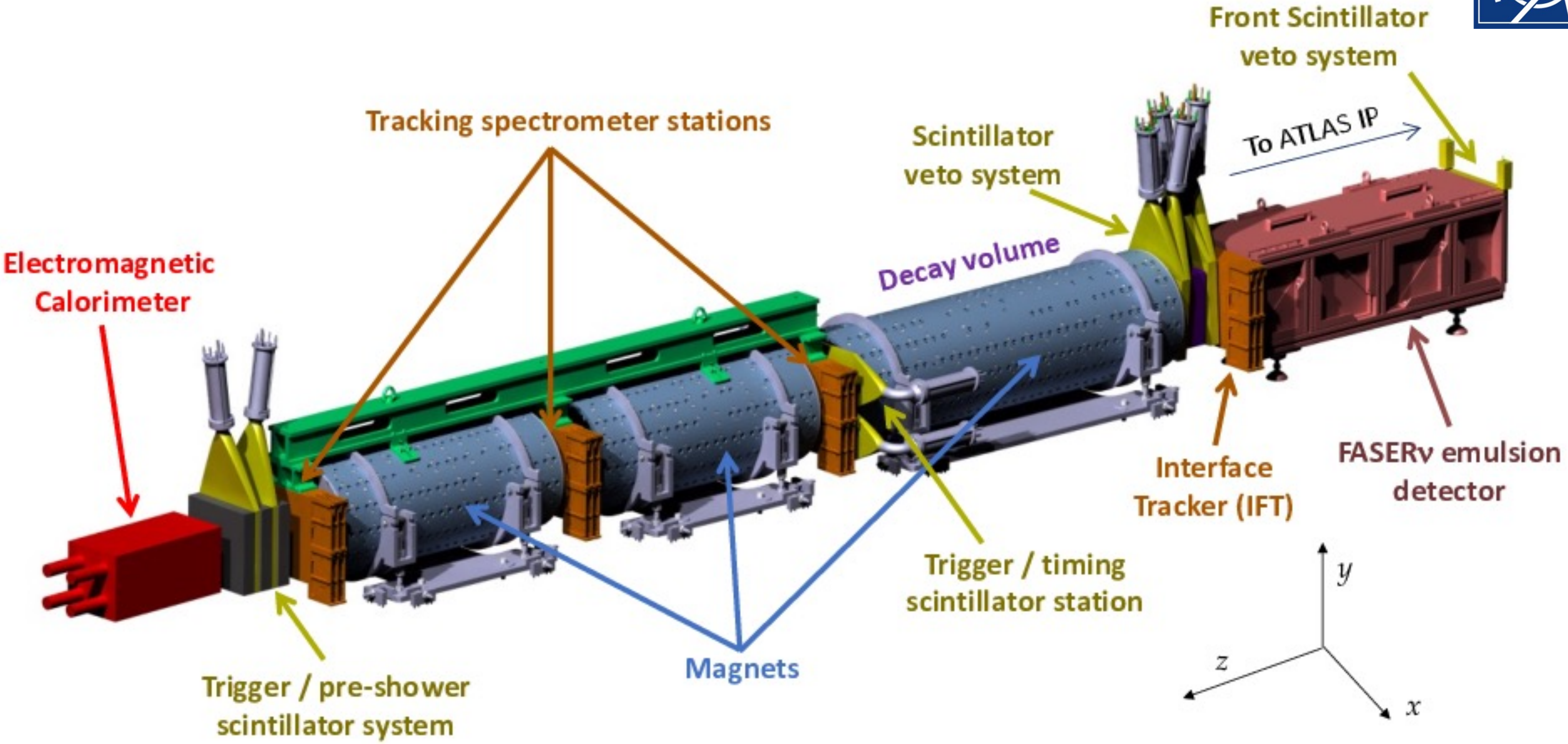
- Start to explore unconstrained space even with 1/fb
- Already recorded 30/fb of data
- Significant discovery potential with 150/fb (expected Run-3 dataset, actually likely to be more)

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, HNLs, …

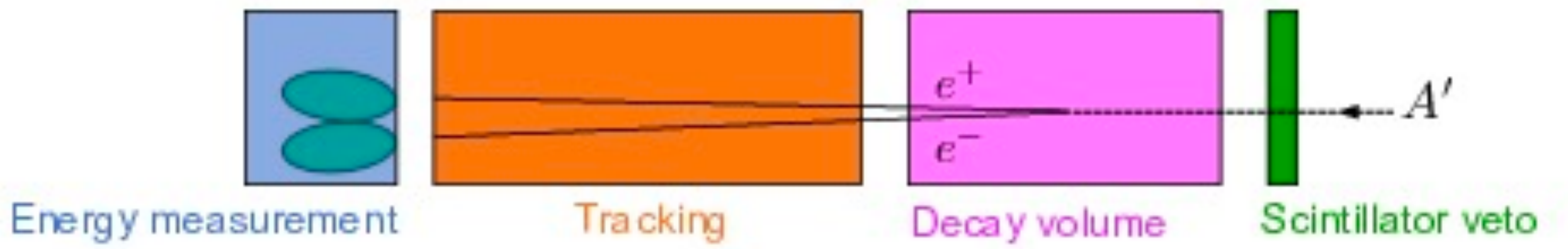
FASER Detector

arxiv: 2207.11427



FASER Detector

Signal signature

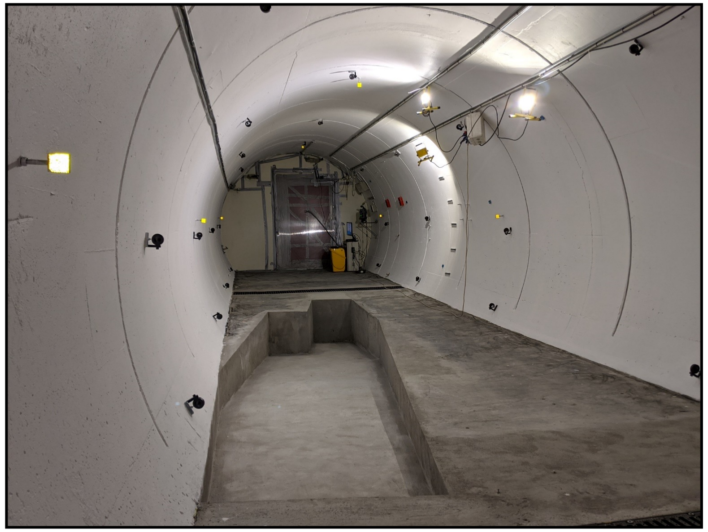


1. No signal in the veto scintillator;
2. Two high energy oppositely charged tracks, consistent with originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP;
3. For A'->e^+e^- decay: Large EM energy in calorimeter. EM showers too close to be resolved.

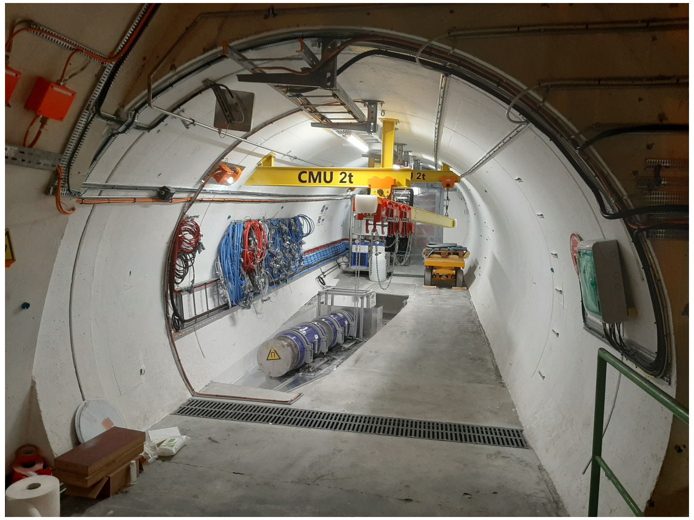
Magnets needed to separate the A' decay products sufficiently to be able to be resolved in tracker

FASER Detector Installation

8/18



4/20



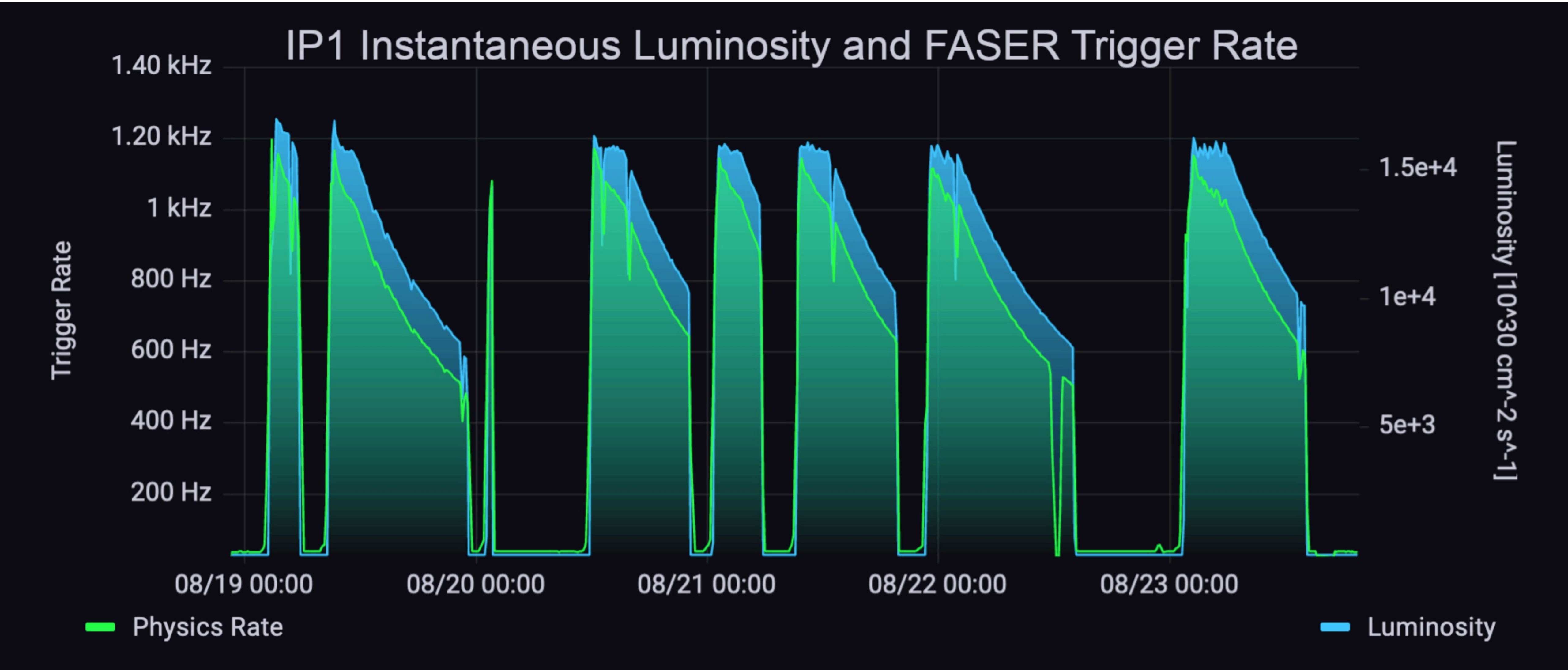
11/20

4/21

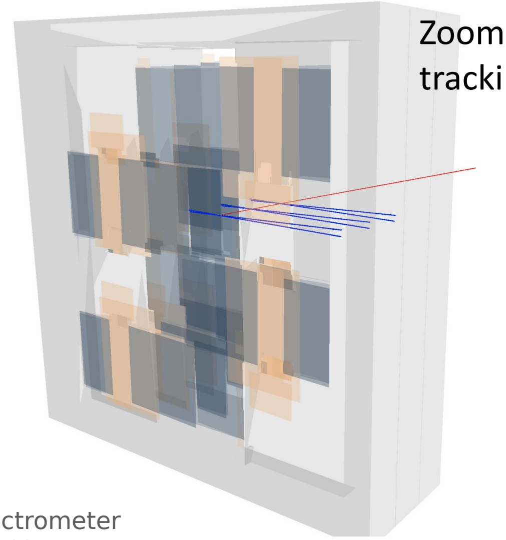
FASER was installed into TI12 in March 2021.
We ran for more than a year with cosmic data taking in situ before, physics data taking started in July 2022.

FASER Operations

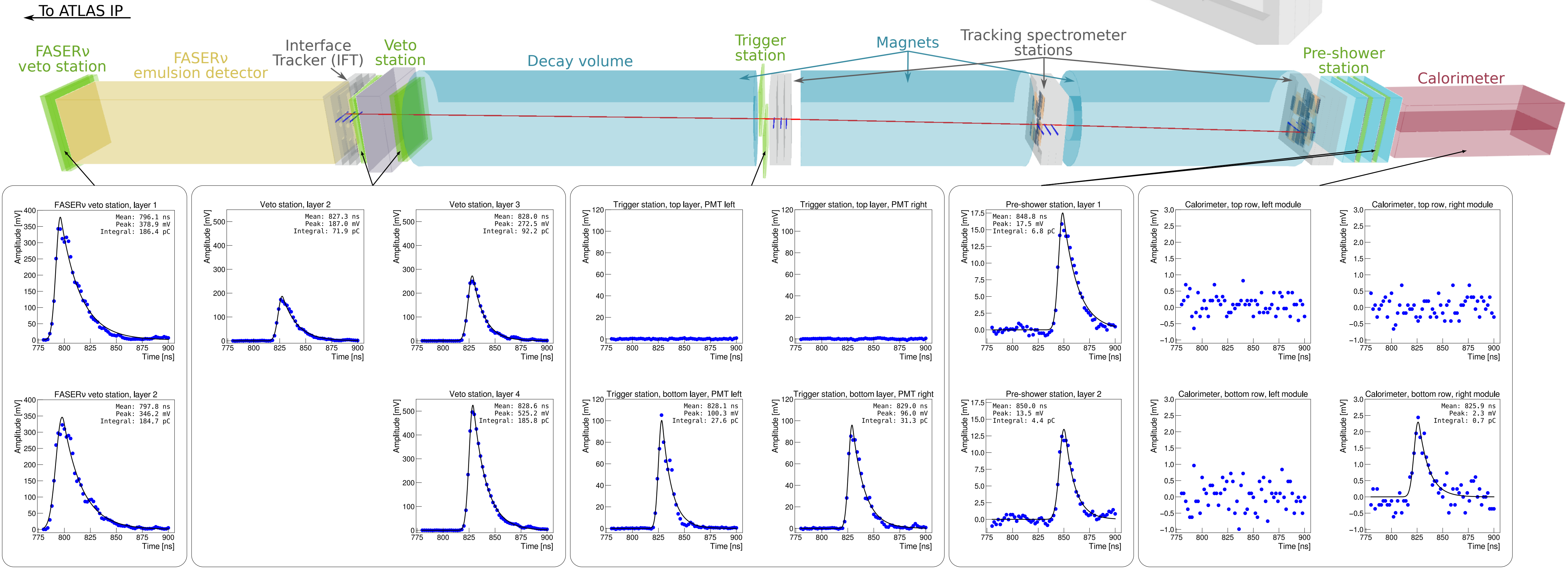
FASER has been succesfully collecting 13.6 TeV collision data since July 2022, with no problems observed.
Over 30/fb of data have been recorded, and many performance and background are ongoing.
The maximum trigger rate is ~1.2kHz (nearly 2x the expectation), but this is not a problem for physics.



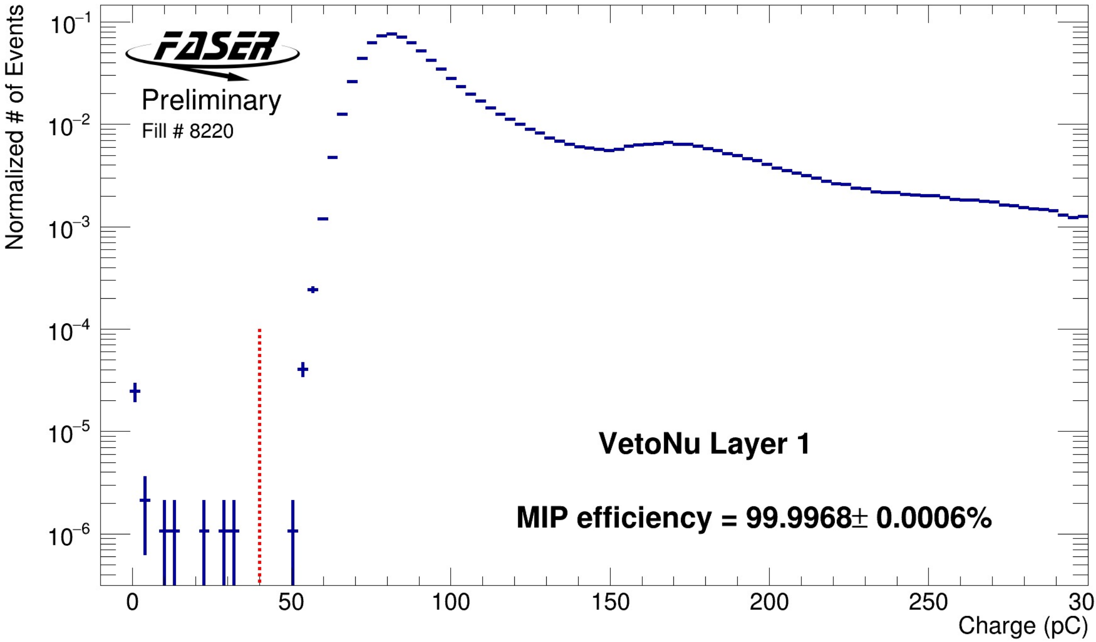
Event display of a muon traversing the full detector.
All parts of the detector performing as expected.

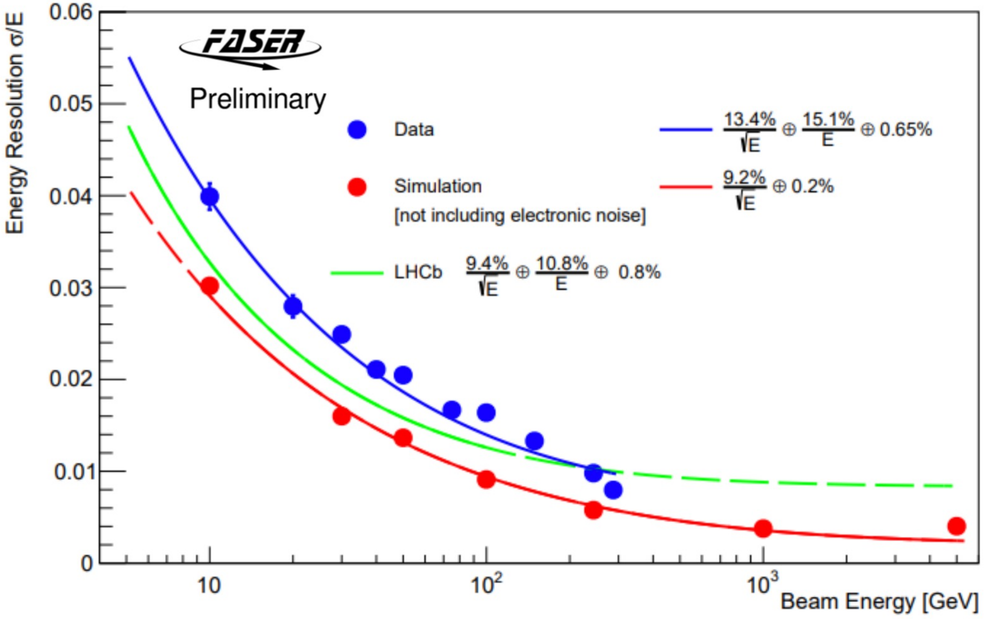


Run 8336
Event 1477982
2022-08-23 01:46:15

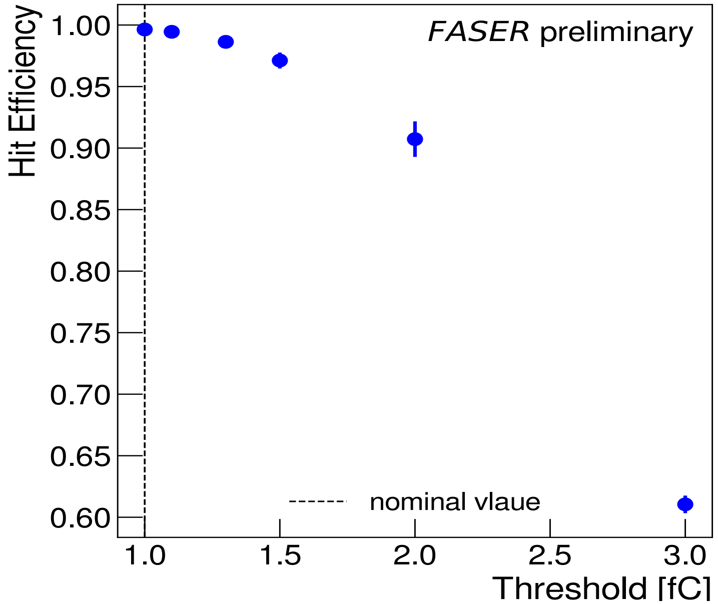


FASER Detector Performance





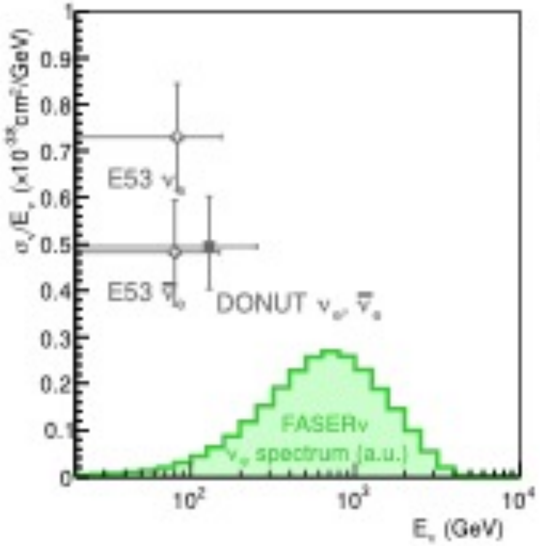
- Veto efficiency measurement in data. Each scintillator efficiency >99.99%. When 4 scintillators combined can veto expected O(10^8) muons entering the detector in Run 3.
- Calorimeter energy resolution measured with electrons in test beam – as expected resolution $\mathcal{O}$(1%) at high energy.
- Tracker hit efficiency measured in data to be >99.6% as expected

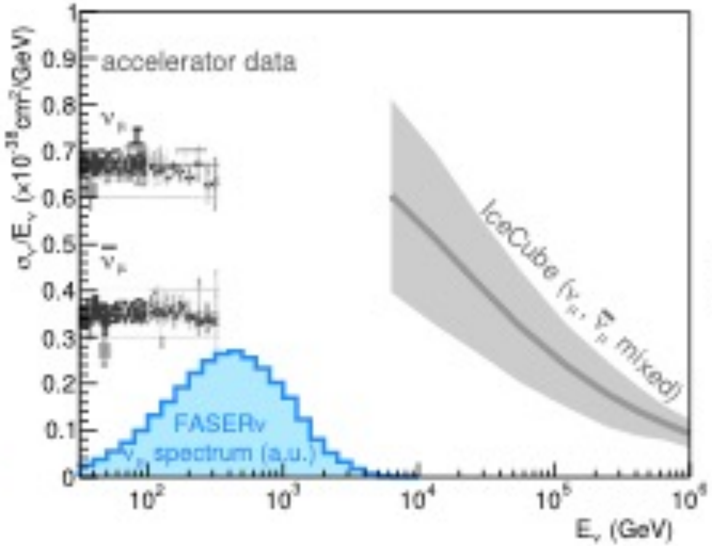


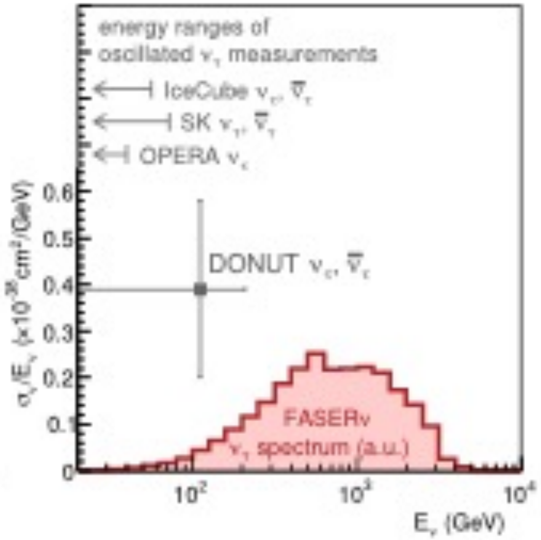
FASER Neutrino Measurements

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 to be 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







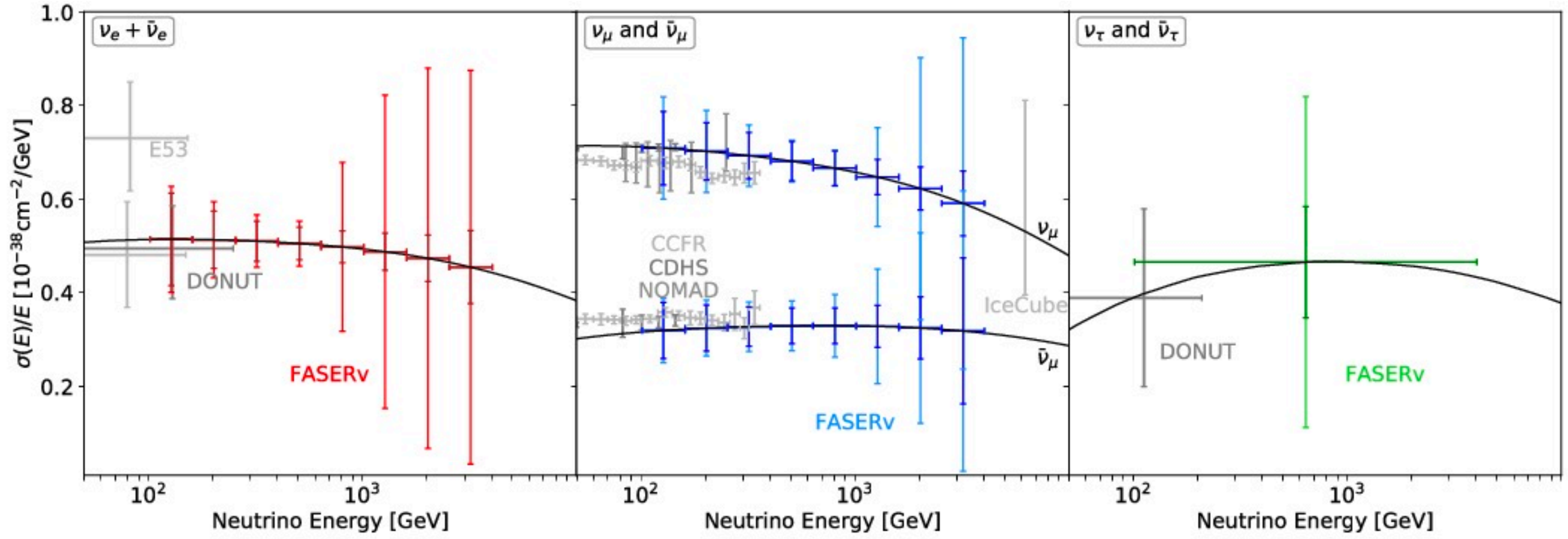
FASER Neutrino Measurements

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 to be 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):

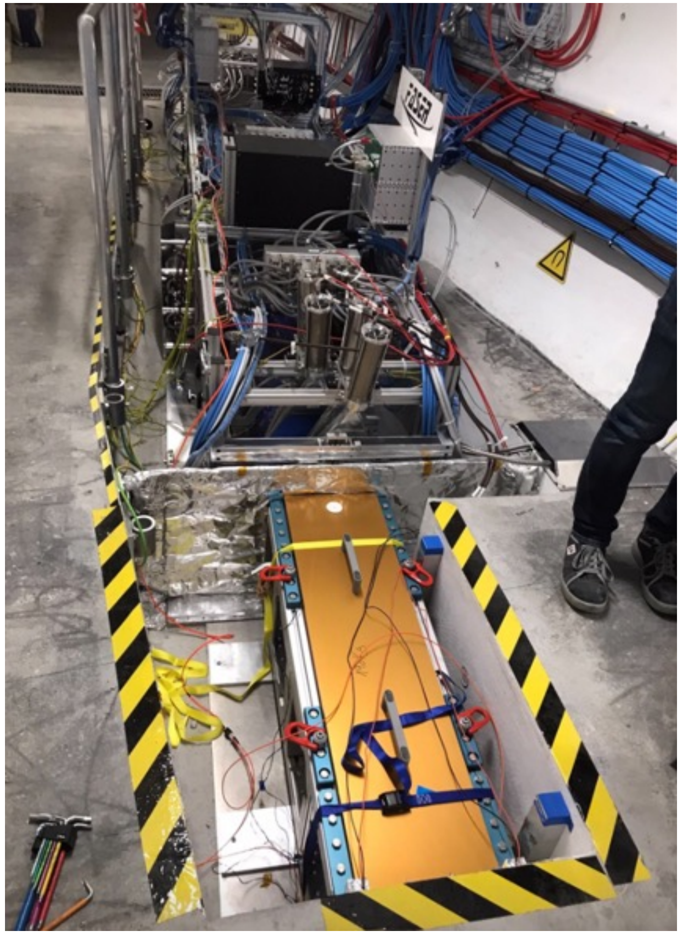


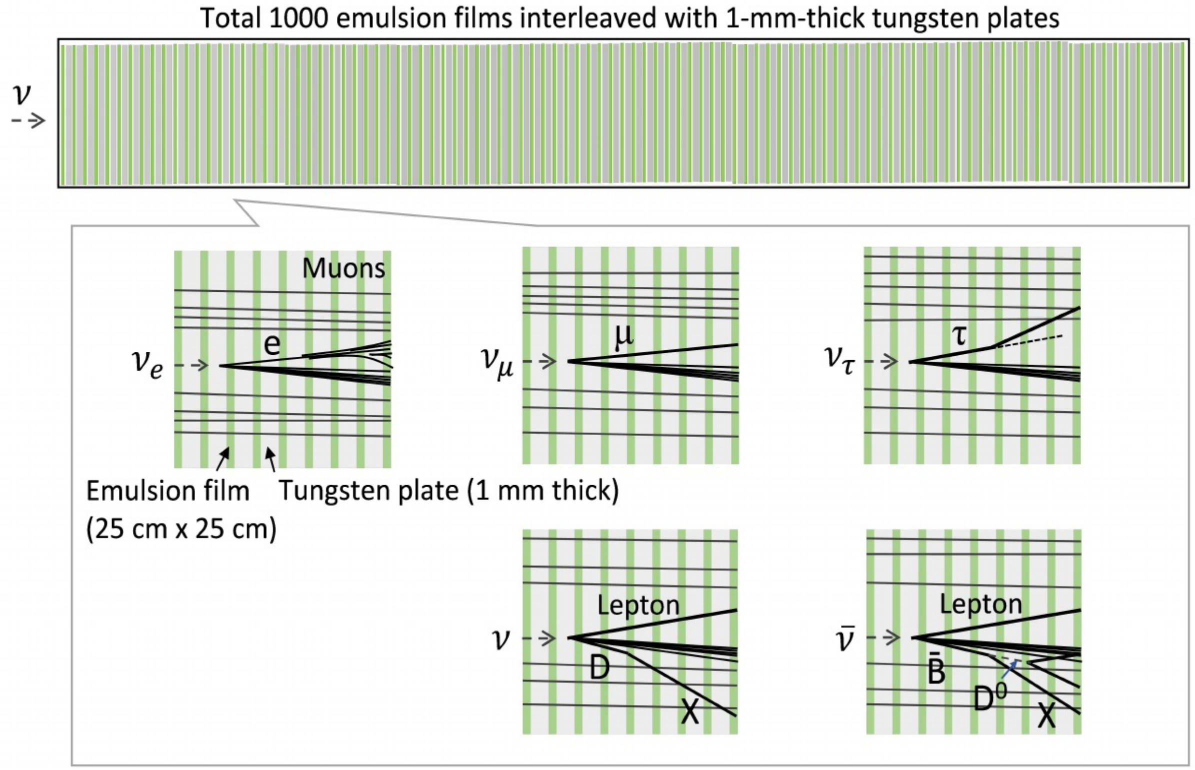
Uncertainty from neutrino production important

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
- Will be replaced during Technical Stops during LHC running
  - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER



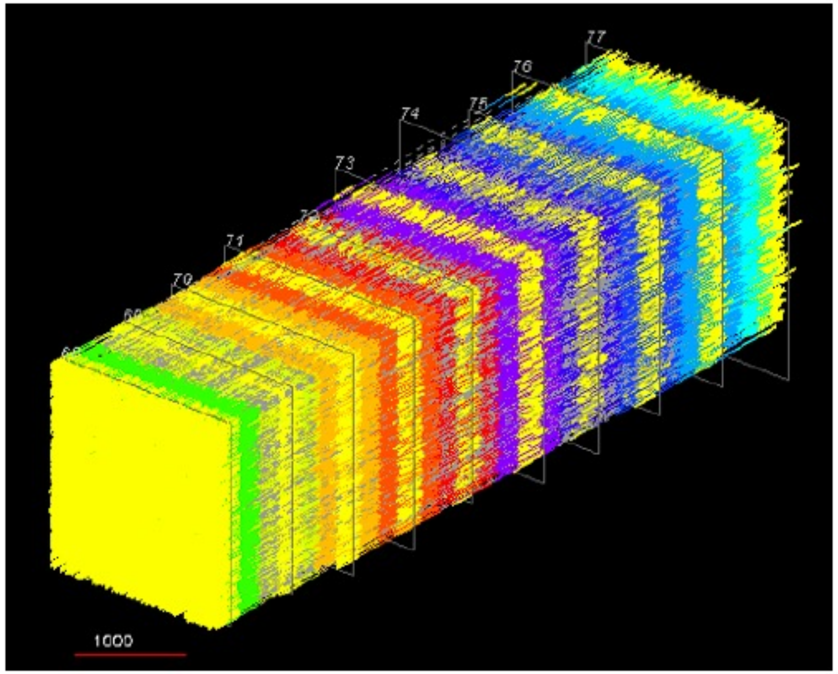


Another neutrino experiment at the LHC: SND@LHC started taking data in Run 3. https://snd-lhc.web.cern.ch/

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
- Best fit value of 6.1 neutrino interactions (3.3 expected)
  - 2.7sigma significance

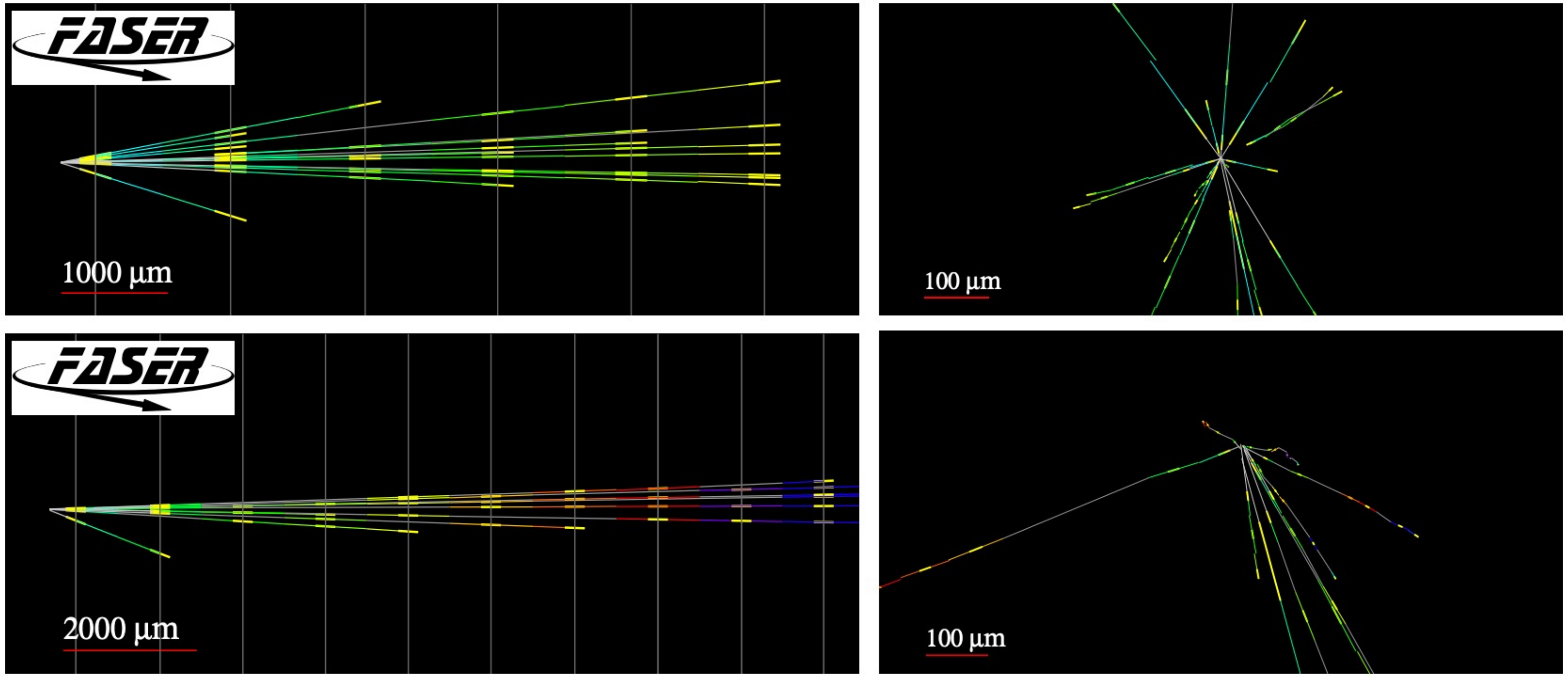


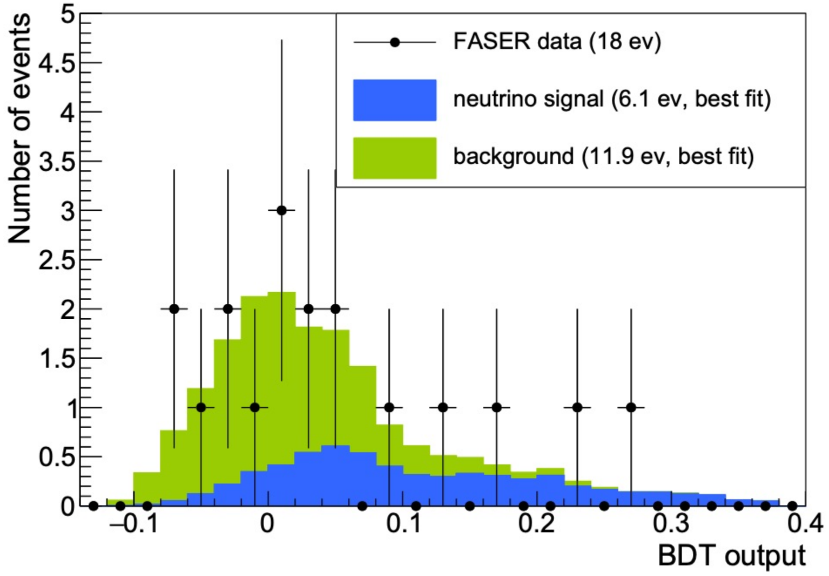
FASERν Pilot Run

PRD.104.L091101

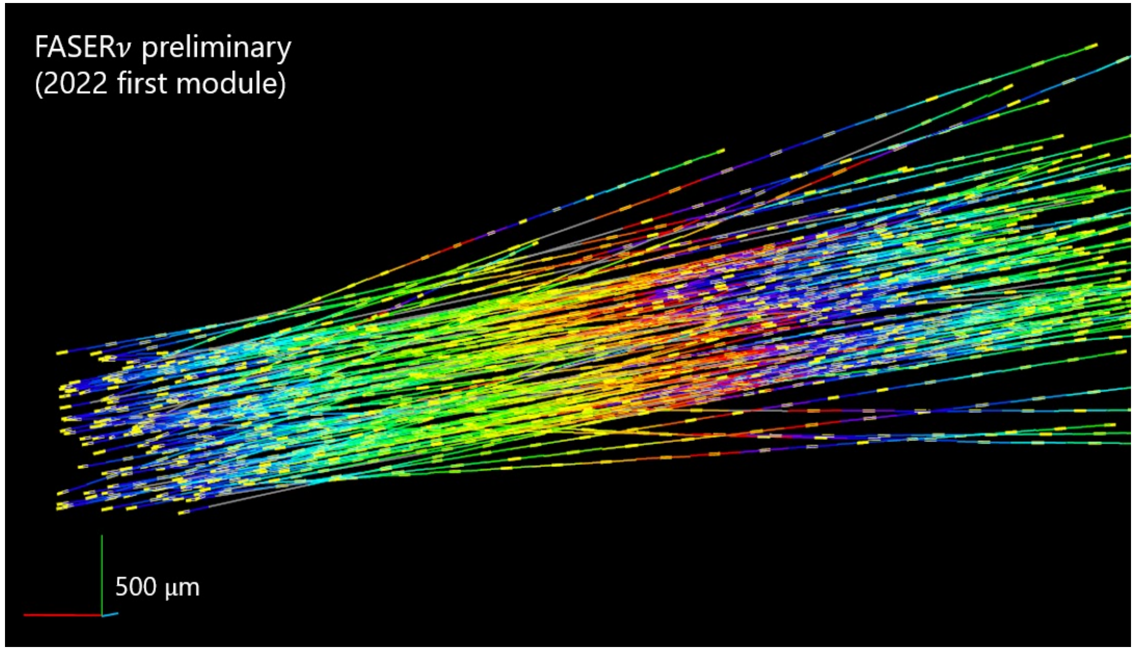
- A small emulsion detector was installed in the FASER location during 2018 LHC running
  - 10 kg target mass after DQ /fiducial selections
  - Used to validate FLUKA simulation of background particle flux
- 12.2/fb data collected (~1 month)
- 18 neutral vertices identified
- Neutrino signal separated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

First candidate collider neutrino interactions!

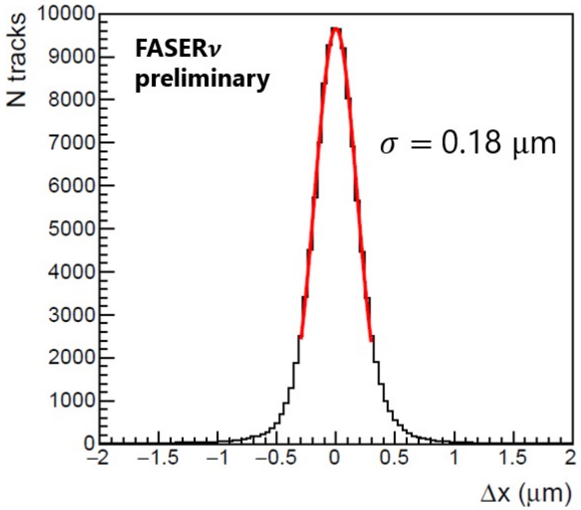


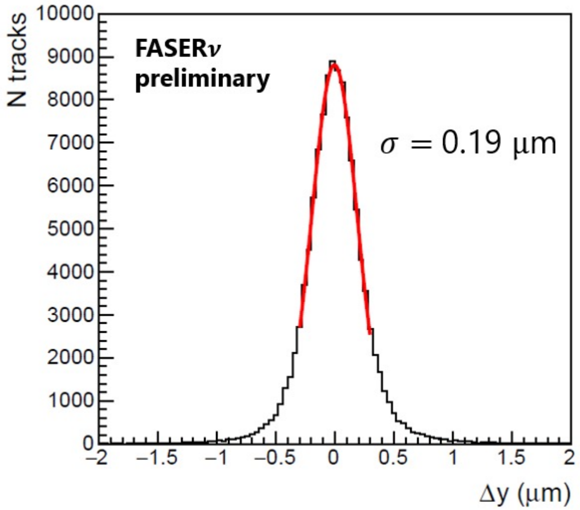


FASERν Detector Performance



- 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 2.3×10^4 cm^{-2} / fb^{-1} consistent with expectation (from FLUKA simulation and 2018 in situ measurements)
- Very good tracking performance (residual <1μm)
- Second detector exposed to 10/fb of data, and third detector still in place with >20/fb of exposure so far…





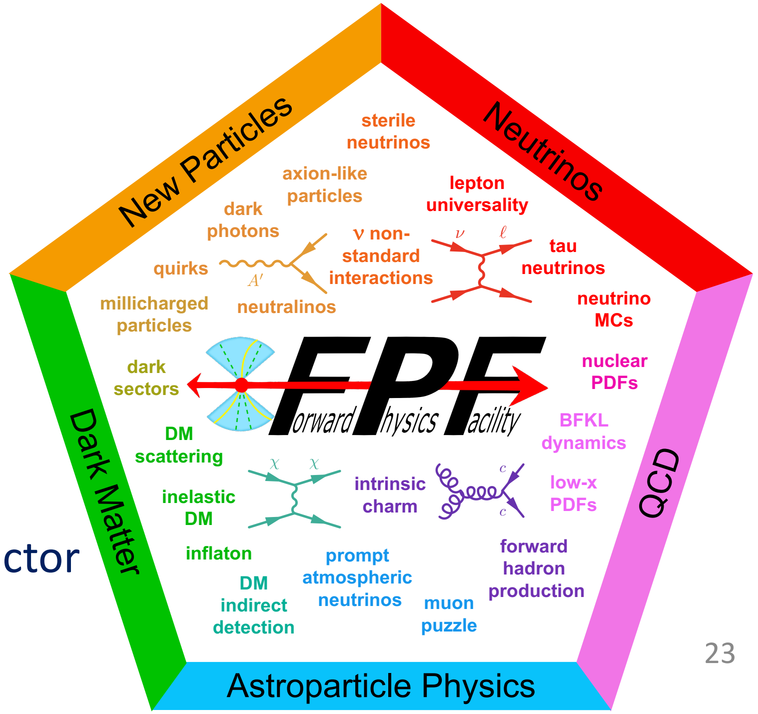
		Integrated luminosity per module (fb^{-1})	**N ν int. expected**
2022 1st module	Mar 15 – Jul 26	0.5	~7
2022 2nd module	Jul 26 – Sep 13	10.6	~530
2022 3rd module	Sep 13 – Nov 29	(~20)	(~1000)

arxiv:2203.05090

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

$\mathcal{O}(10^6)$ mu, $\mathcal{O}(10^5)$ el, $\mathcal{O}(10^3)$ tau neutrino interactions expected in $\mathcal{O}$(10tn) detector



Summary

- FASER is a new experiment that just started running at the LHC
- Targeting discovery (exclusion) of light, weakly-coupled, new-particles such as dark photons
- FASERν detector has a complementary neutrino programme
  - First observation of collider neutrino candidates with small pilot detector in 2018!
- Detector operating well so far with more than 30/fb of data recorded and detector performance looking good
  - Aiming for first physics in Q2 2023
- Possible upgrade programme with the Forward Physics Facility for the HL-LHC with broad physics motivations

FASER Acknowledgements

FASER is supported by:

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

CERN

In addition, FASERν is supported by:

erc

科研費
KAKENHI

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

清華大學
Tsinghua University

MANCHESTER 1824
The University of Manchester

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF LIVERPOOL

CHIBA UNIVERSITY

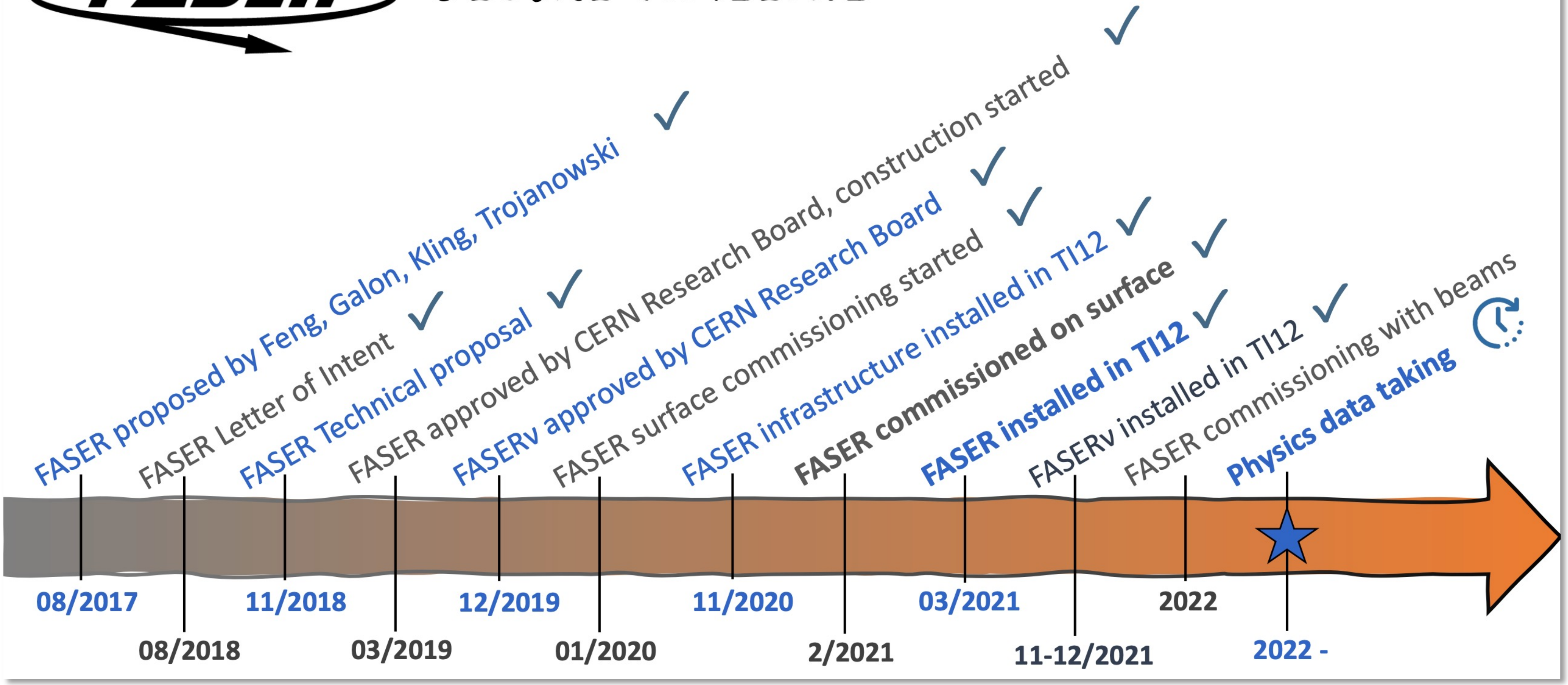
UNIVERSITY OF SUSSEX

DESY.

JINR

Slide from A. Sfyrla

FASER 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 FASERv 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** ✓

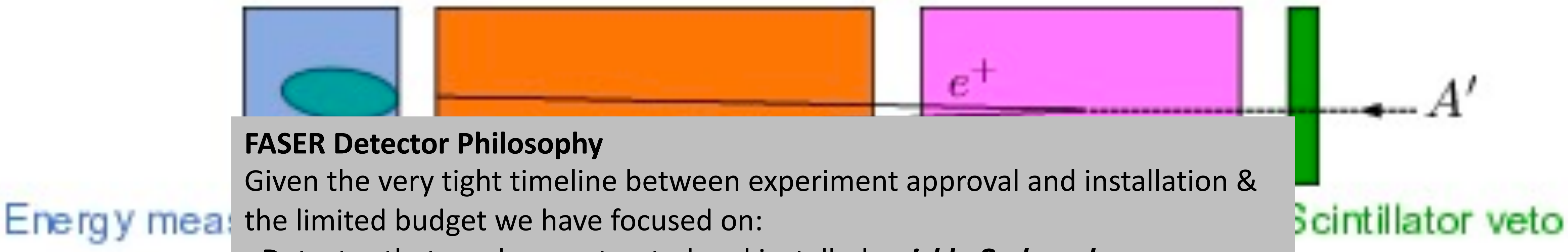
11-12/2021 FASERv installed in TI12 ✓

2022 FASER commissioning with beams ✓

2022 - **Physics data taking**

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

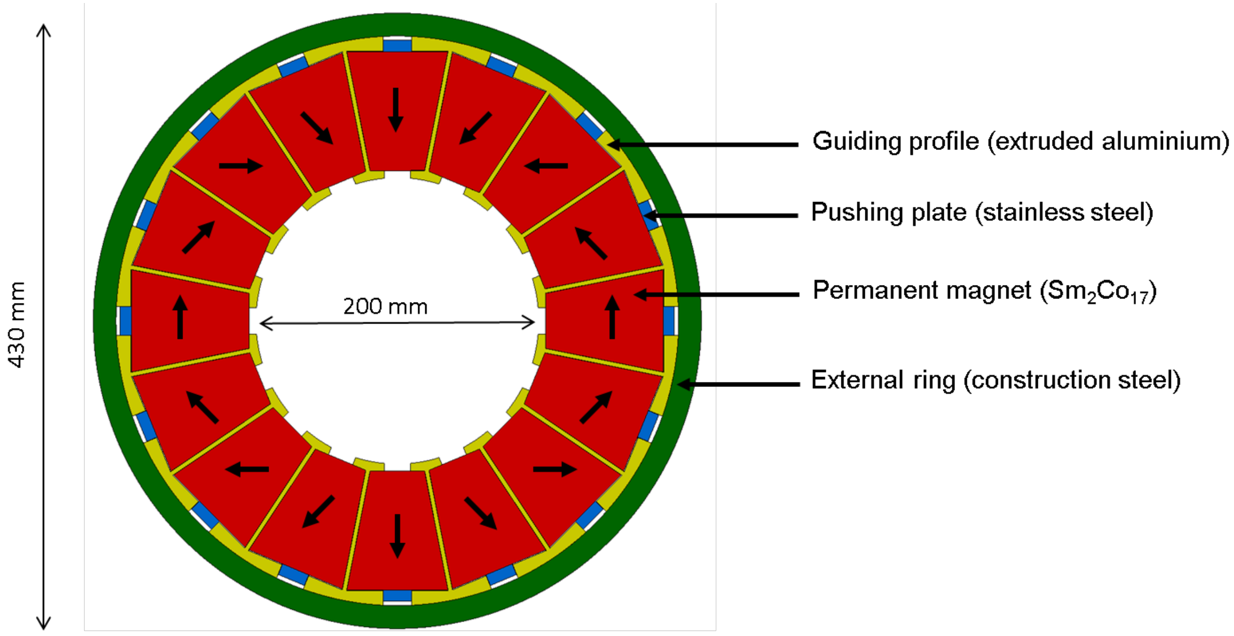
Many challenges of the large LHC experiments not there for FASER:

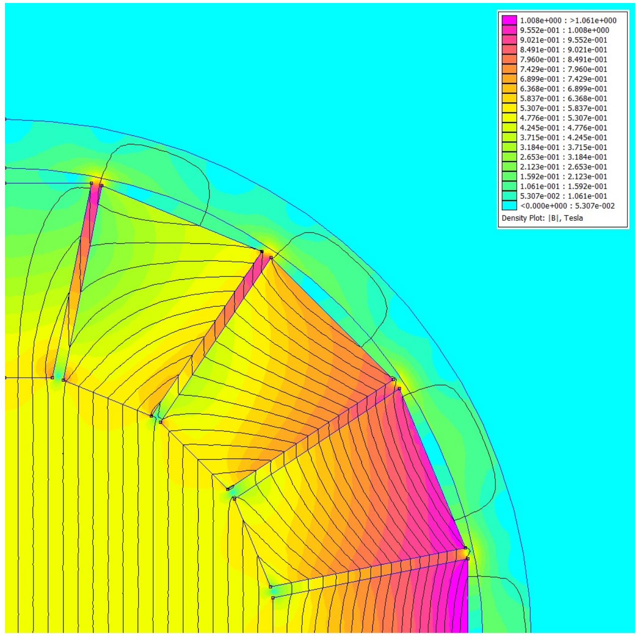
- trigger rate $\mathcal{O}$(1 kHz) (mostly single muon events)
- low radiation
- low occupancy / event size

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



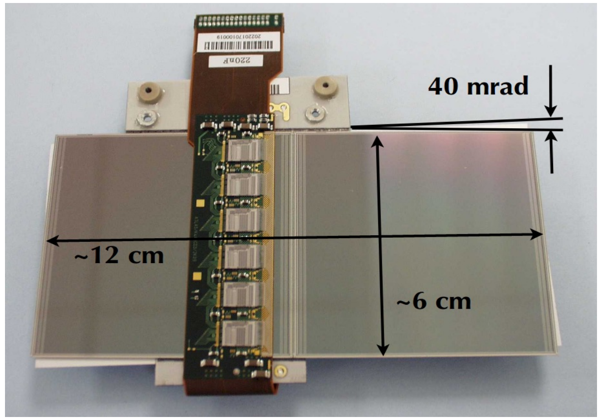


- The FASER magnets are 0.57T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed, constructed and measured by the magnet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

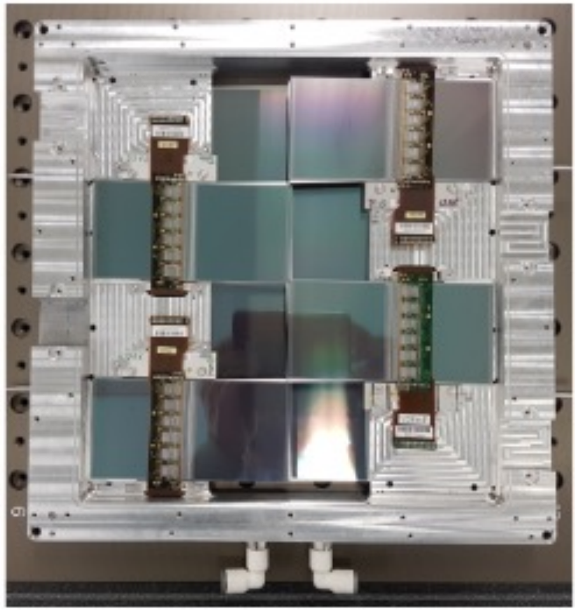
FASER Tracker

NIMA 166825 (2022)

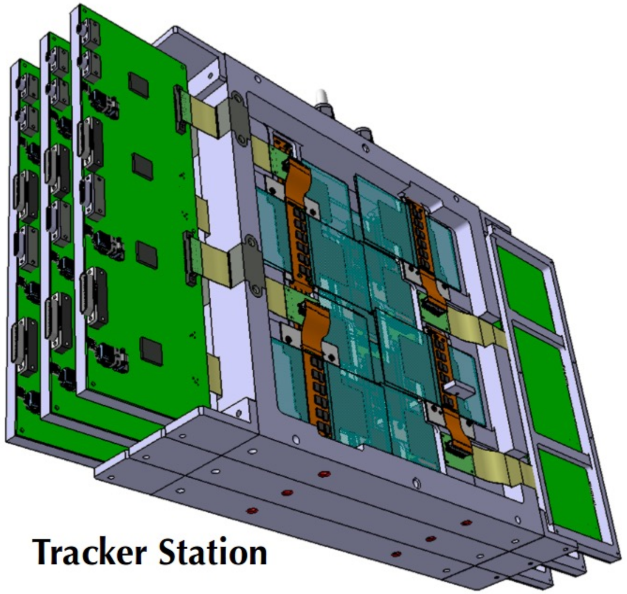
- FASER Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 3 tracking stations
- Each containing 3 layers of double-sided silicon micro-strip sensors
  - Spare ATLAS SCT modules are used
    - 80μm strip pitch, 40mrad stereo angle (17μm / 580μm resolution)
      - precision measurement in bending (vertical) plane
    - ***Many thanks to the ATLAS SCT collaboration!***
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) => 72 SCT modules needed for the full tracker



SCT module



Tracking layer



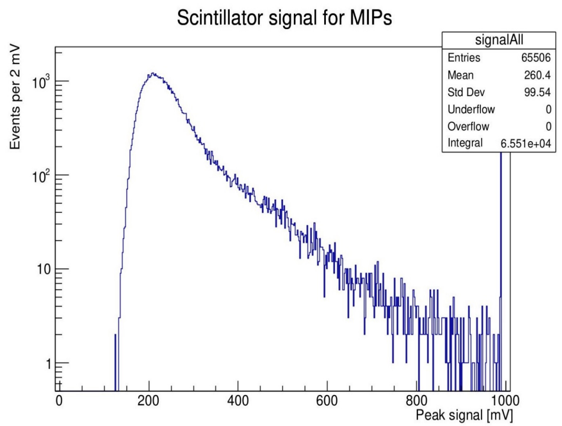
Tracker Station

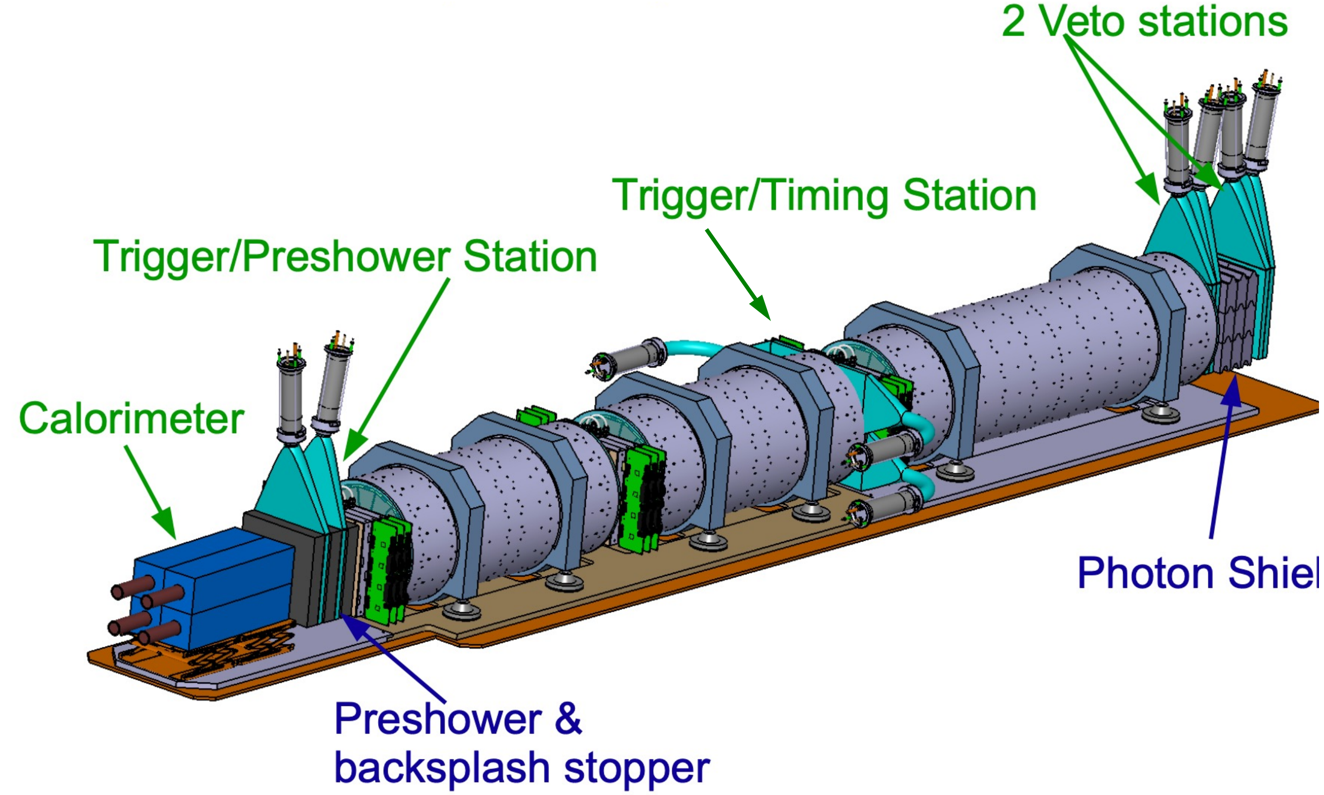
FASER Scintilators

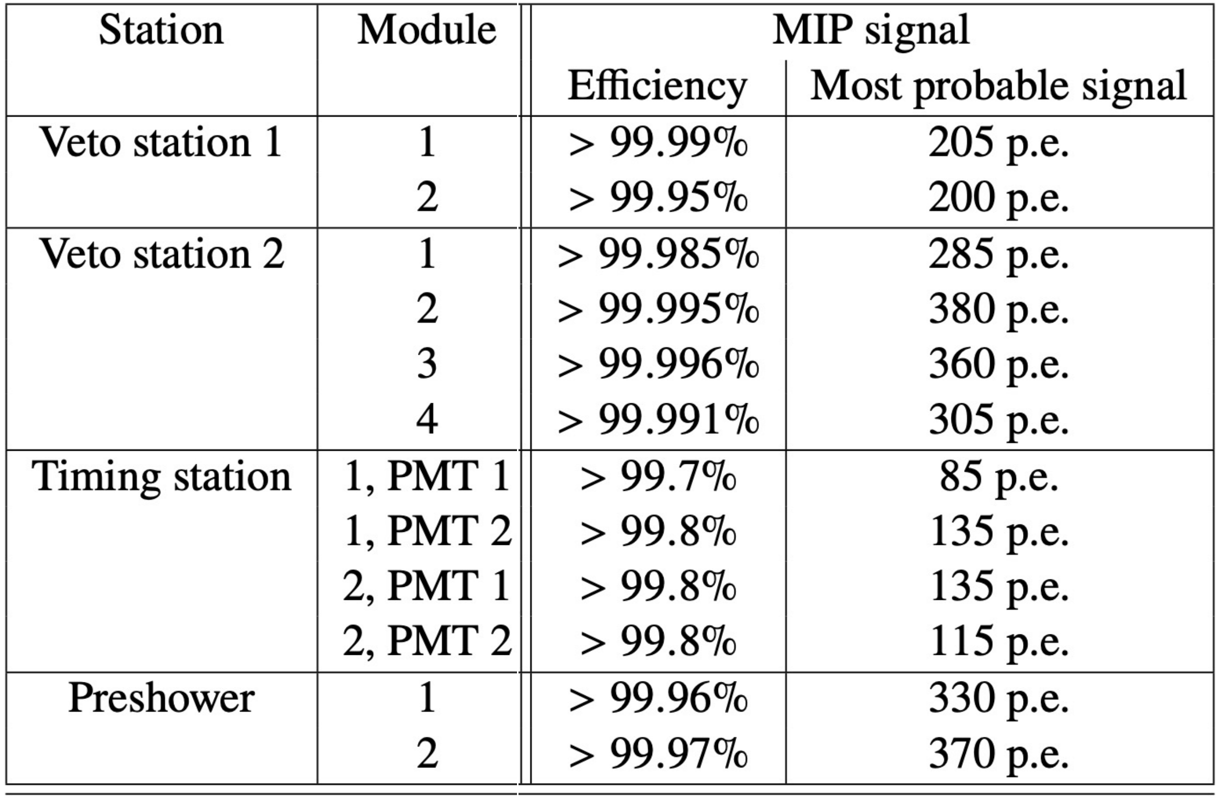
Scintillators used for:

- 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

Scintillator efficiencies measured with cosmic rays on surface, and with collision data and well within spec for required veto efficiency.

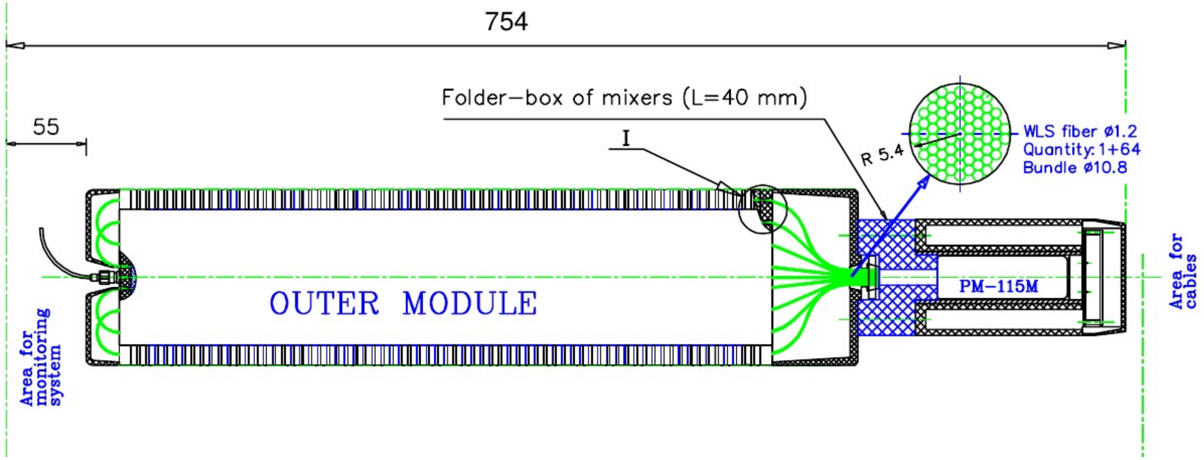


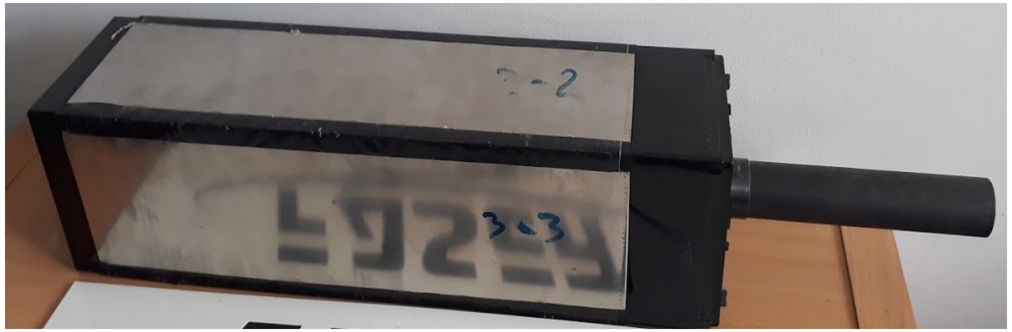


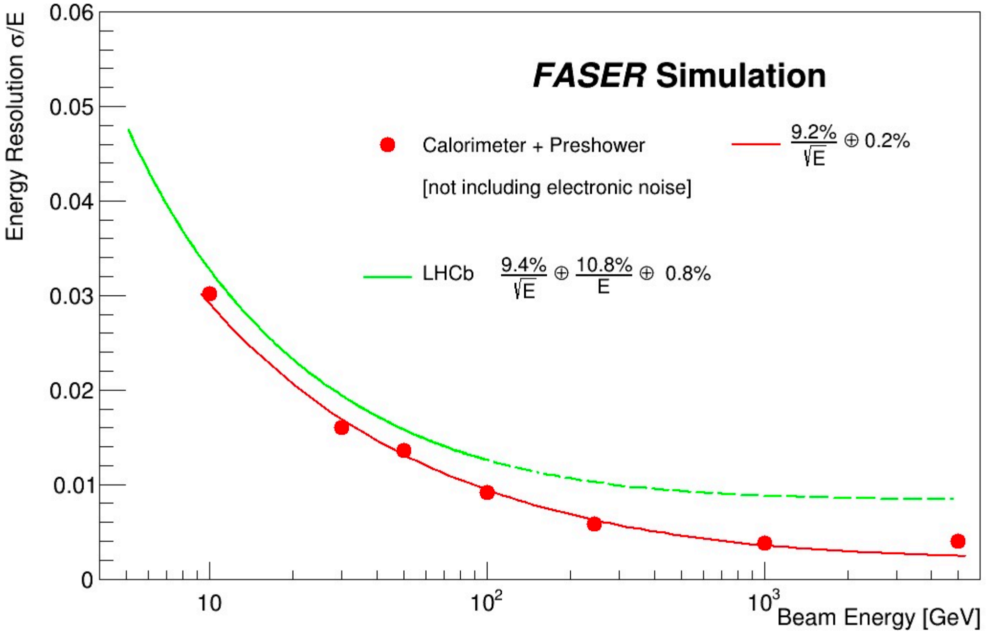


Station	Module	MIP signal	
		Efficiency	Most probable signal
Veto station 1	1	> 99.99%	205 p.e.
	2	> 99.95%	200 p.e.
Veto station 2	1	> 99.985%	285 p.e.
	2	> 99.995%	380 p.e.
	3	> 99.996%	360 p.e.
	4	> 99.991%	305 p.e.
Timing station	1, PMT 1	> 99.7%	85 p.e.
	1, PMT 2	> 99.8%	135 p.e.
	2, PMT 1	> 99.8%	135 p.e.
	2, PMT 2	> 99.8%	115 p.e.
Preshower	1	> 99.96%	330 p.e.
	2	> 99.97%	370 p.e.

FASER Calorimeter



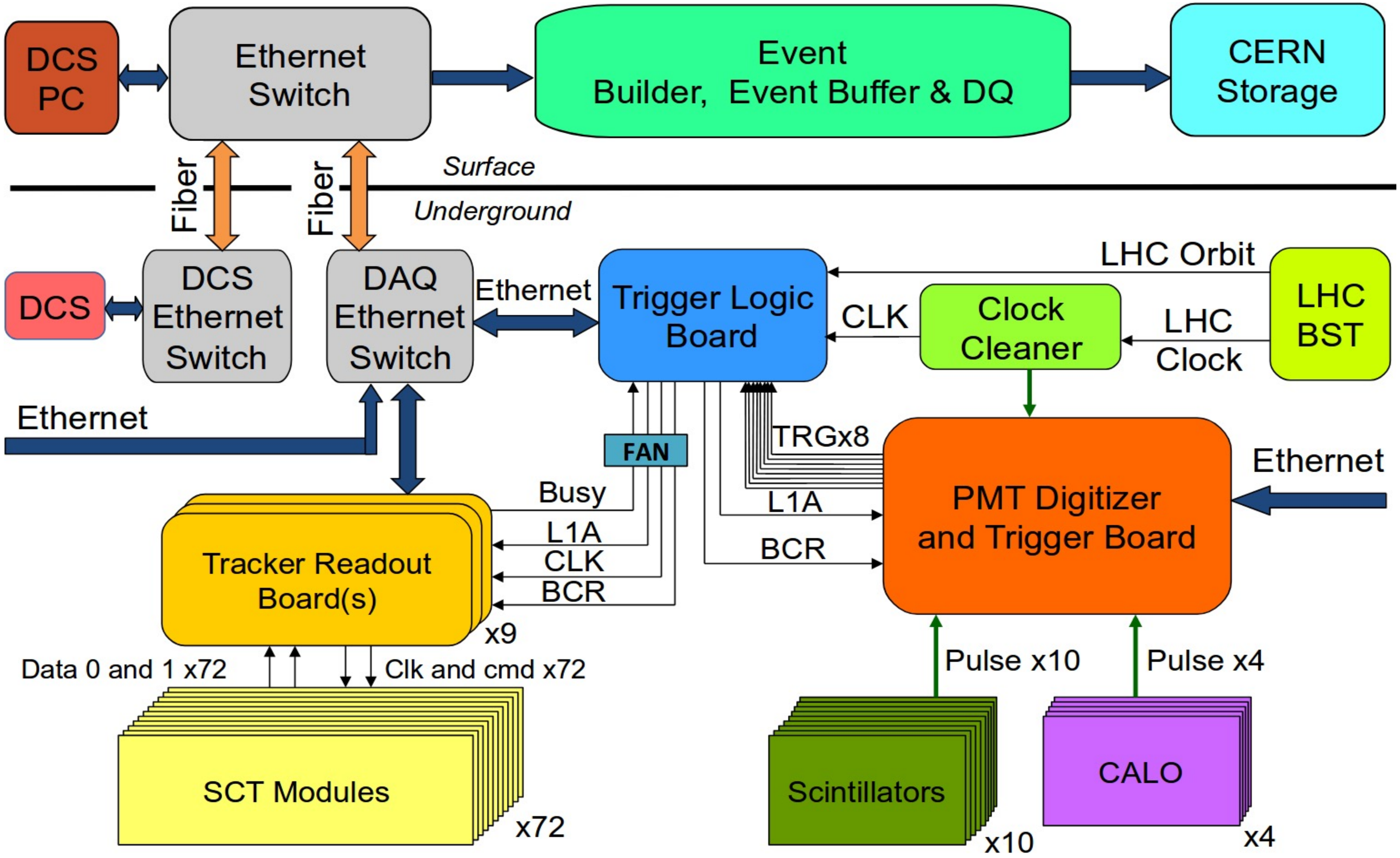




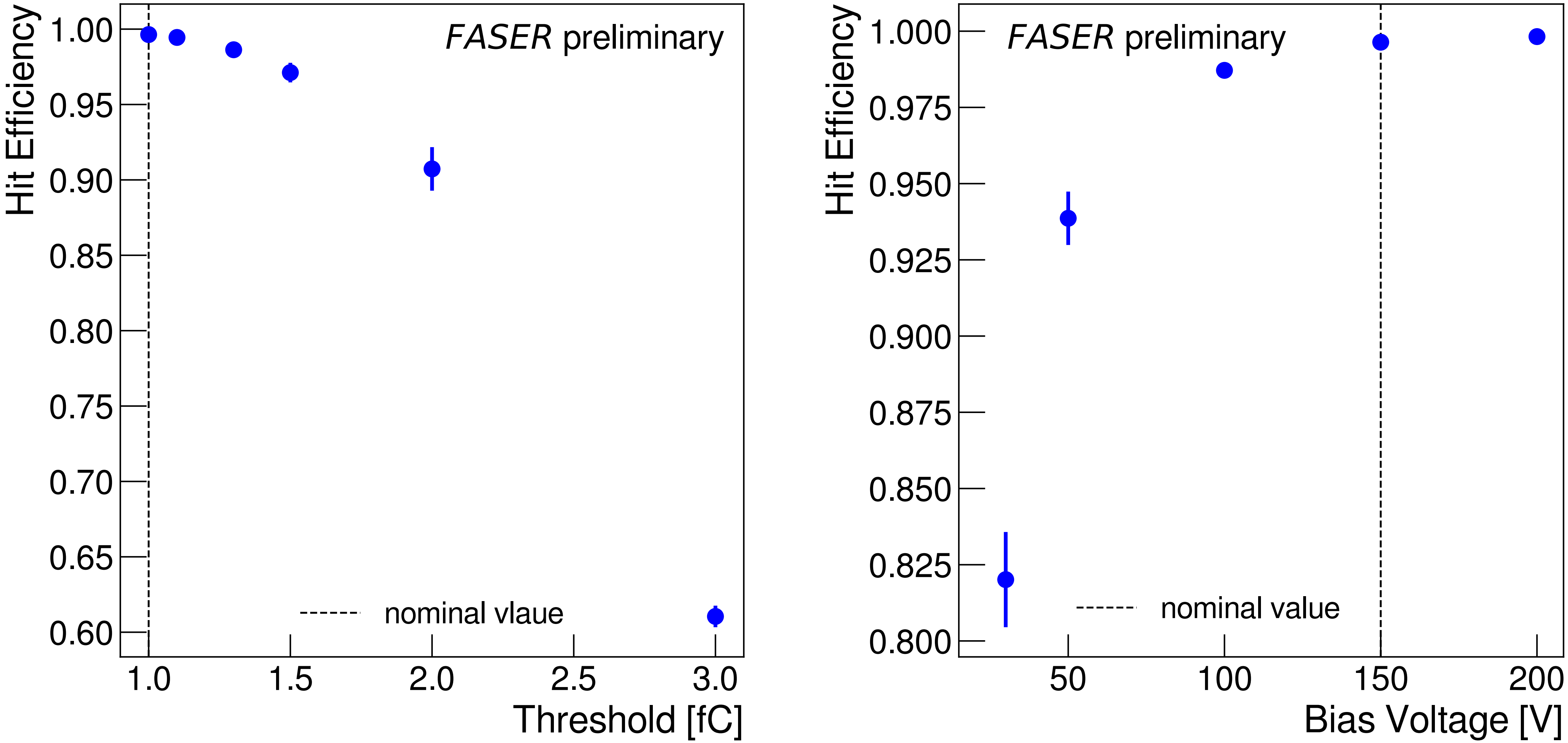
- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Uses 4 spare LHCb outer ECAL modules
  - ***Many thanks to LHCb*** for allowing us to use these!
  - 66 layers of lead/scintillator, light out by wavelength shifting fibers
    - 25 radiation lengths long
  - Readout by 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
    - Resolution will degrade at higher energy due to not containing full shower in calorimeter; Energy scale will depend on the calibration

FASER TDAQ

JINST **16** P12028

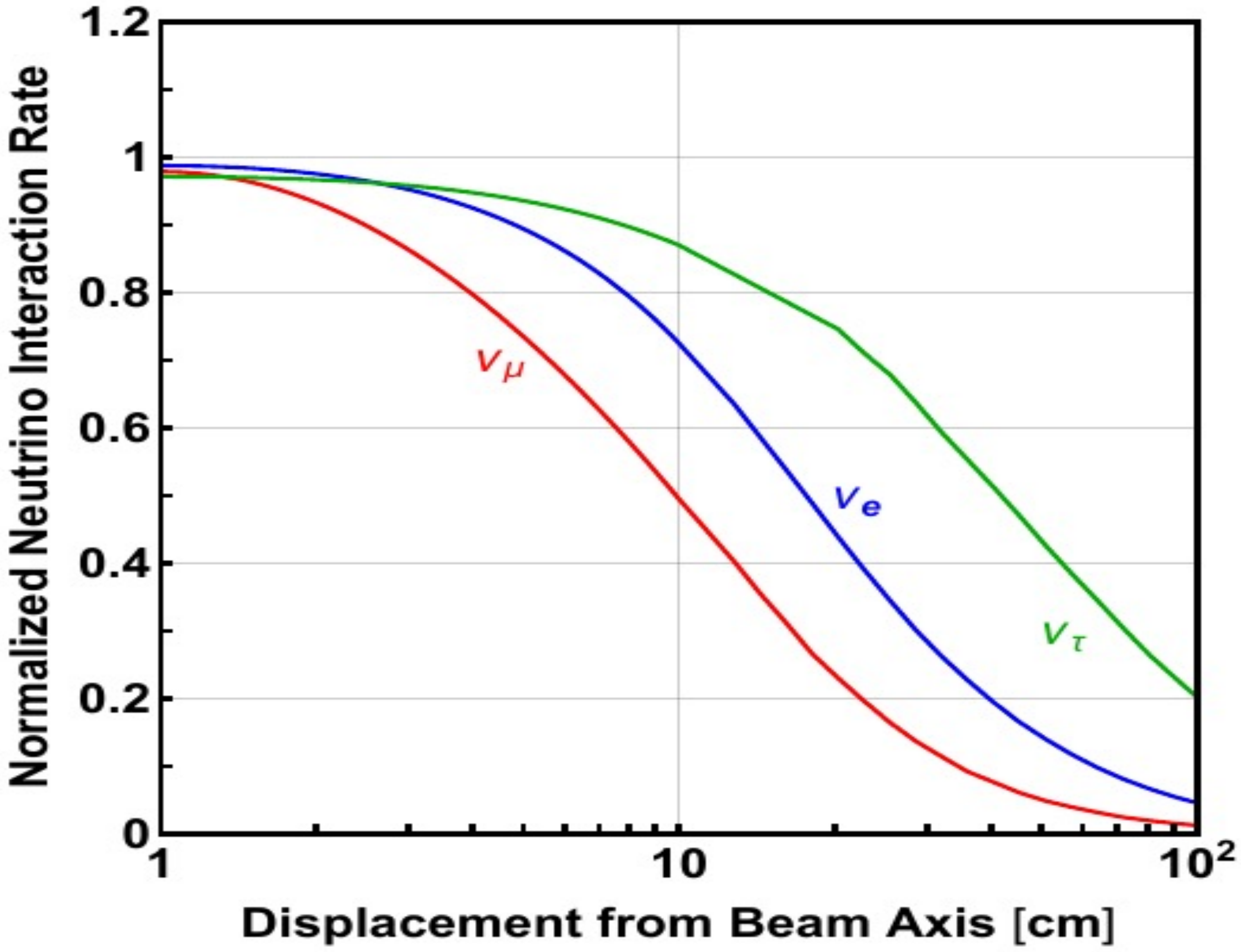


FASER Detector Performance



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

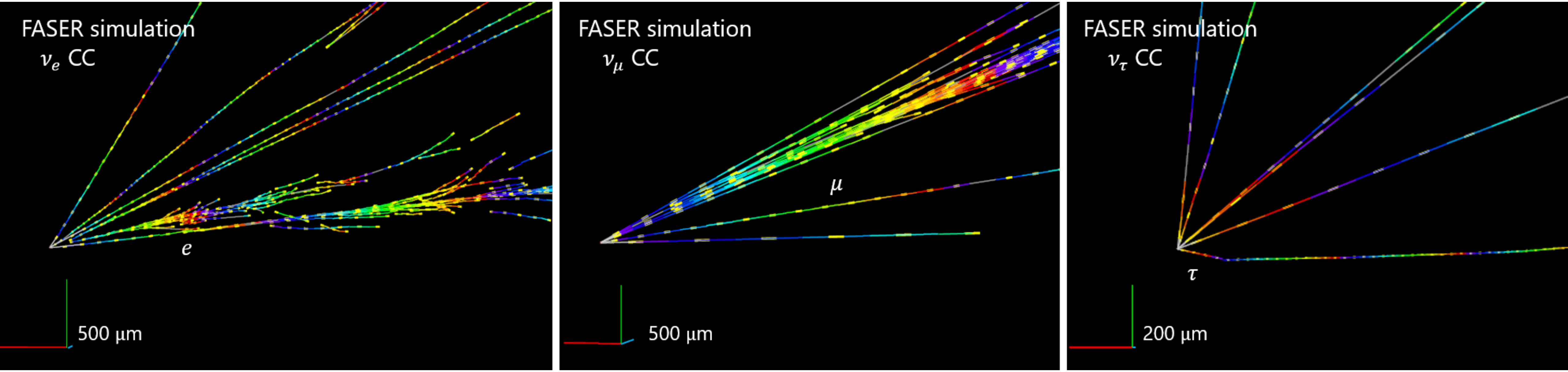
Neutrino production at LHC



Neutrino flux maximized on the collision axis line of sight.

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

FASERν Simulated Signal Events



FASERν

Workflow

In Japan

Emulsion film production →

At CERN

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

In Japan

Full area readout

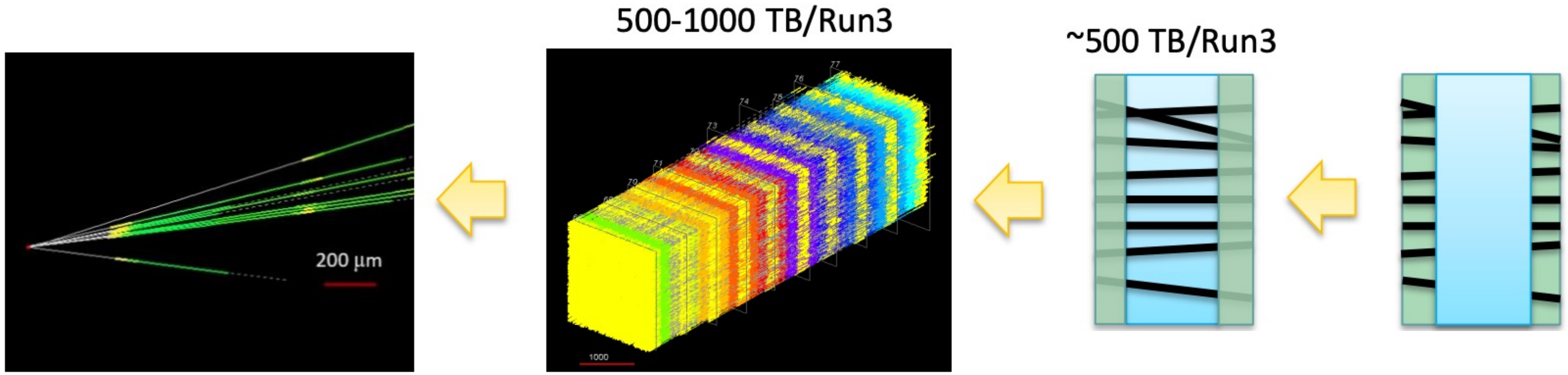
↓

Off-line analysis

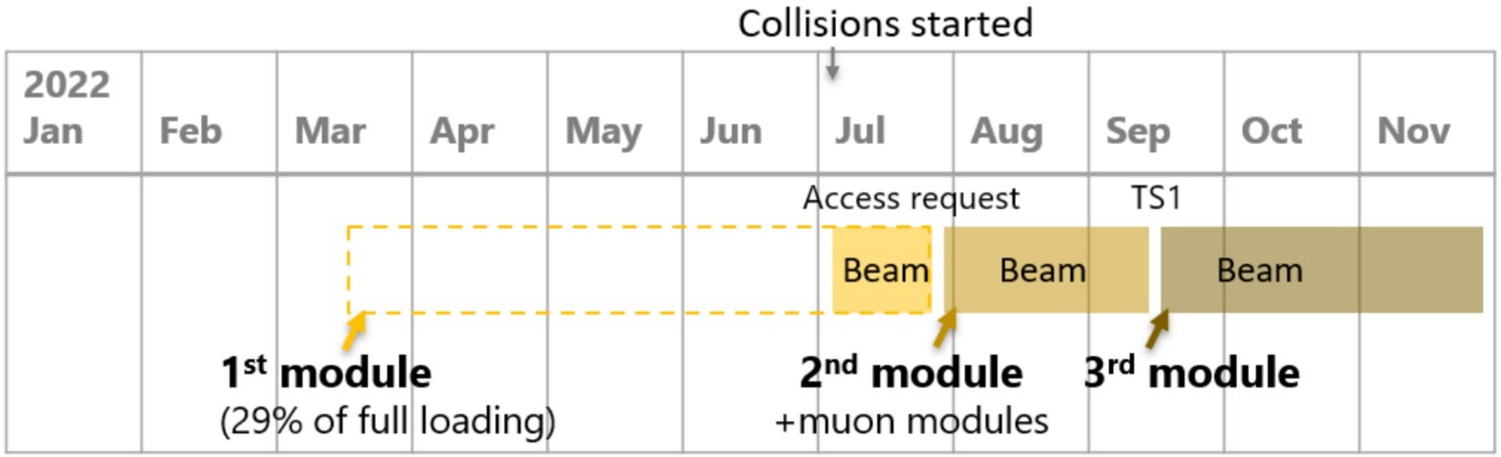
Alignment ← Track reconstruction ← Vertex reconstruction ← μ / e ID ← Search for tau/charm decays ← Kinematical analysis

Interface tracker data

Spectrometer data



FASERν Schedule of the 2022 runs



Collisions started

2022 Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov

Access request

TS1

Beam

Beam

Beam

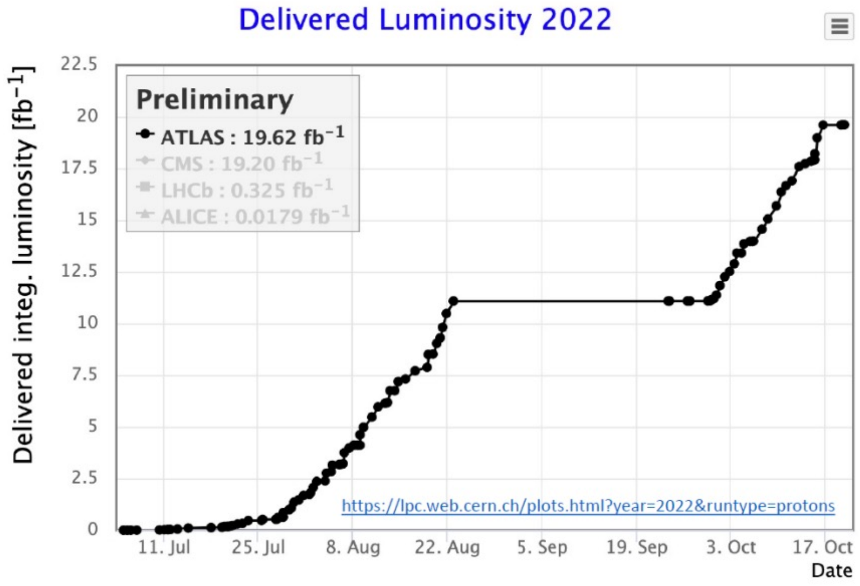
1^{st} module

(29% of full loading)

2^{nd} module

+muon modules

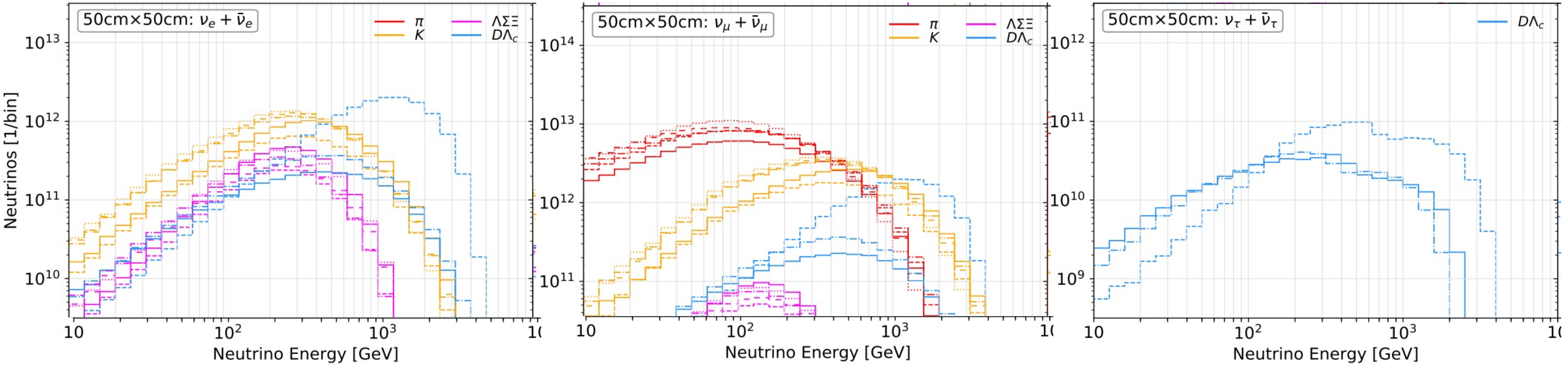
3^{rd} module



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

QCD at the FPF

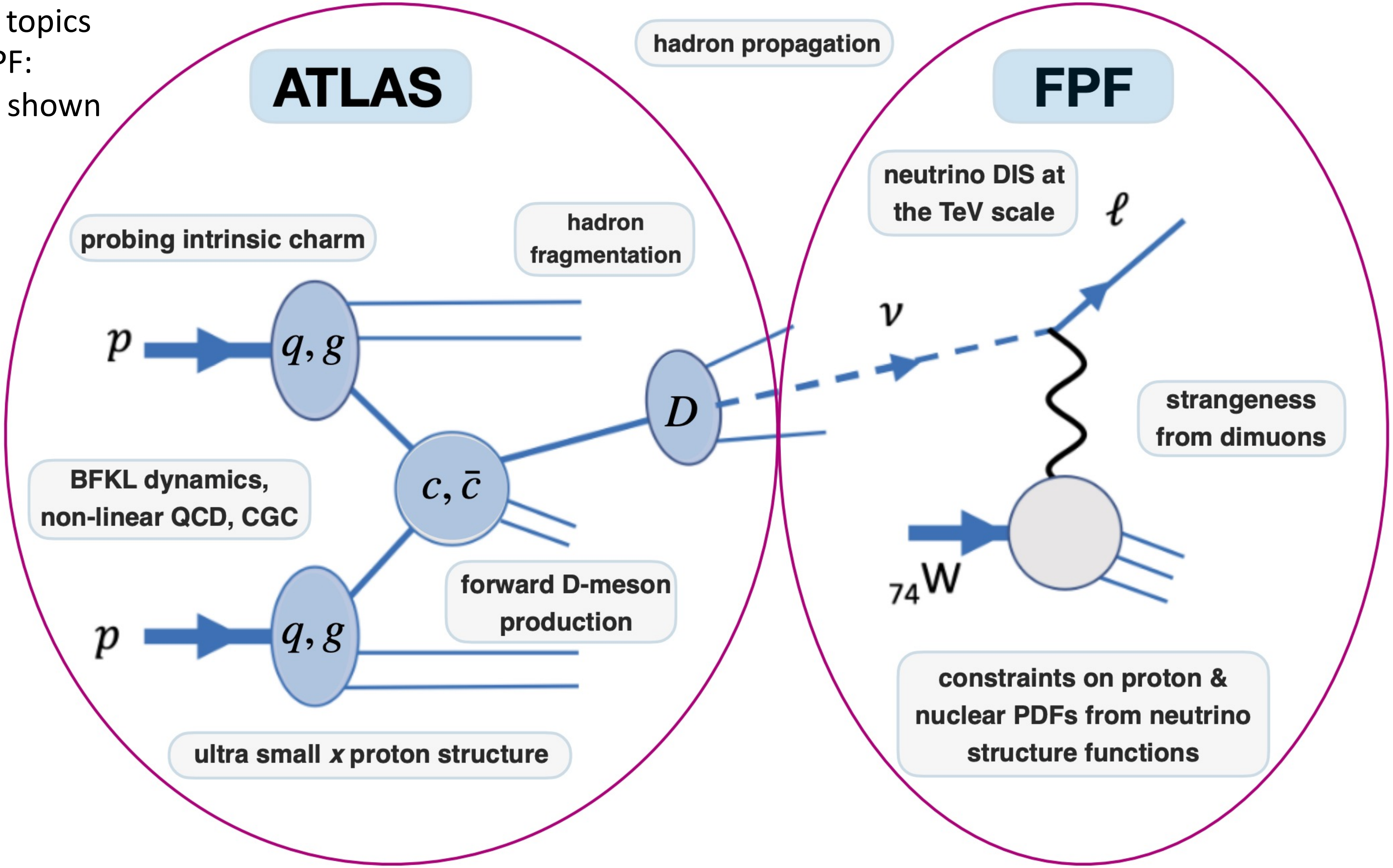
- Neutrinos detected at FPF experiments can also be used to study QCD both in the neutrino production, and in neutrino interaction
- Production mechanism, depends on neutrino flavour, rapidity and energy
  - $\pi \rightarrow \nu\mu$, K → ν_e (at high-energy/off-axis D → ν_e), D → $\nu\tau$



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:
(A couple of examples shown on next slides)



ATLAS

FPF

hadron propagation

probing intrinsic charm

hadron fragmentation

BFKL dynamics, non-linear QCD, CGC

forward D-meson production

ultra small *x* proton structure

neutrino DIS at the TeV scale

strangeness from dimuons

constraints on proton & nuclear PDFs from neutrino structure functions

Input for astroparticle experiments

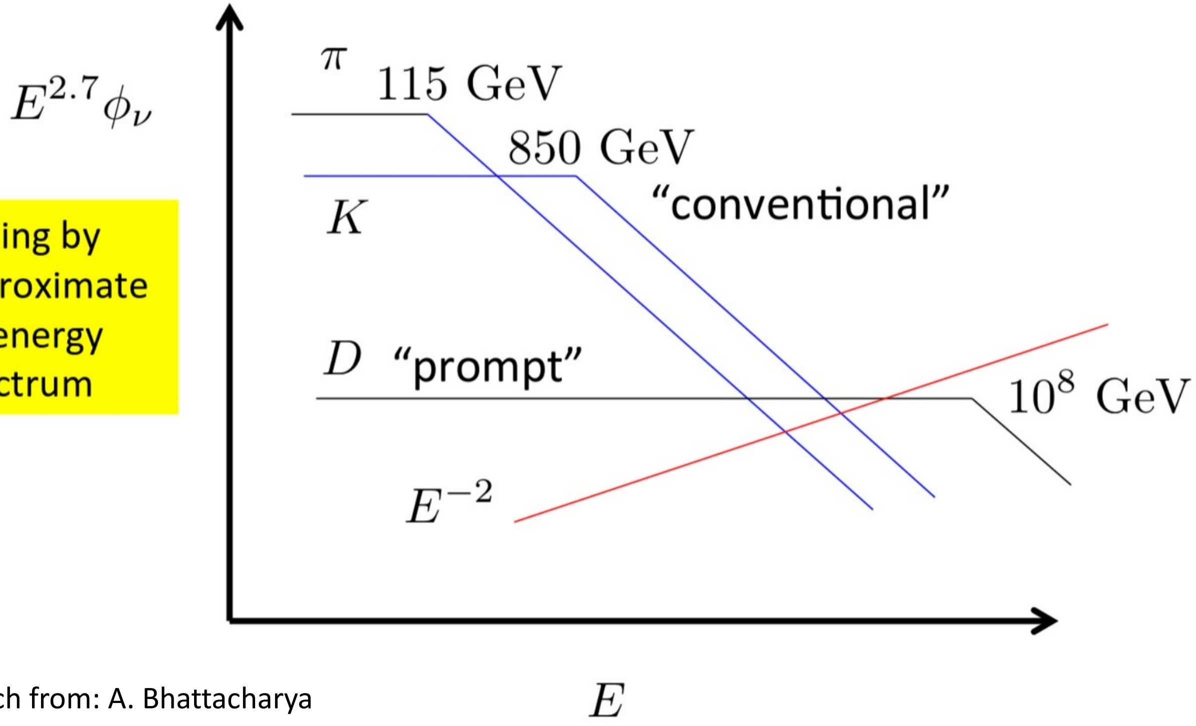
Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).

At ultra high-energy light hadrons travel far through the atmosphere, losing energy, and hence produce lower energy neutrinos. Neutrinos produced in charm decay ("prompt neutrinos") are therefore the key background at high energy.

This prompt background has a large associated uncertainty which limits the study of astrophysical neutrinos.

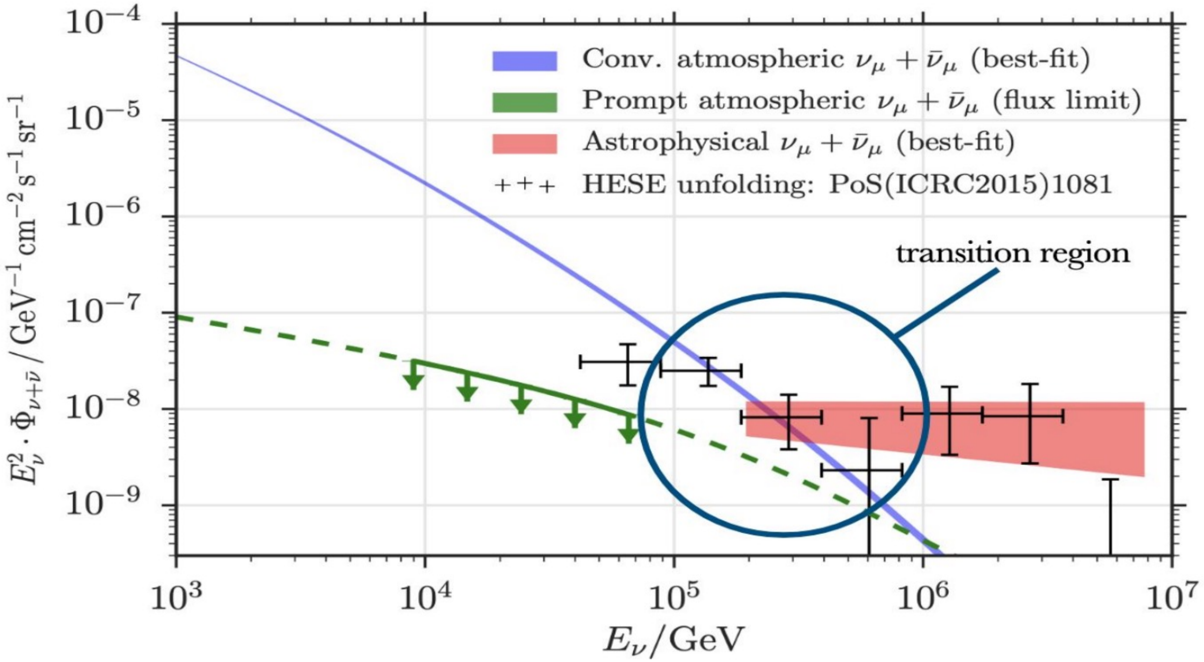
Measurements of neutrinos from charm at the FPF can provide important information to constrain this background.

Scaling by approximate CR energy spectrum



Sketch from: A. Bhattacharya

IceCube, PoS (ICRC2017) 1005



Input for astroparticle experiments

Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).

At ultra high-energy light hadrons travel far through the atmosphere, losing energy, and hence produce lower energy neutrinos. Neutrinos produced in charm decay ("prompt neutrinos") are therefore the key background at high energy. This prompt background has a large associated uncertainty which limits the study of astrophysical neutrinos. Measurements of neutrinos from charm at the FPF can provide important information to constrain this background.

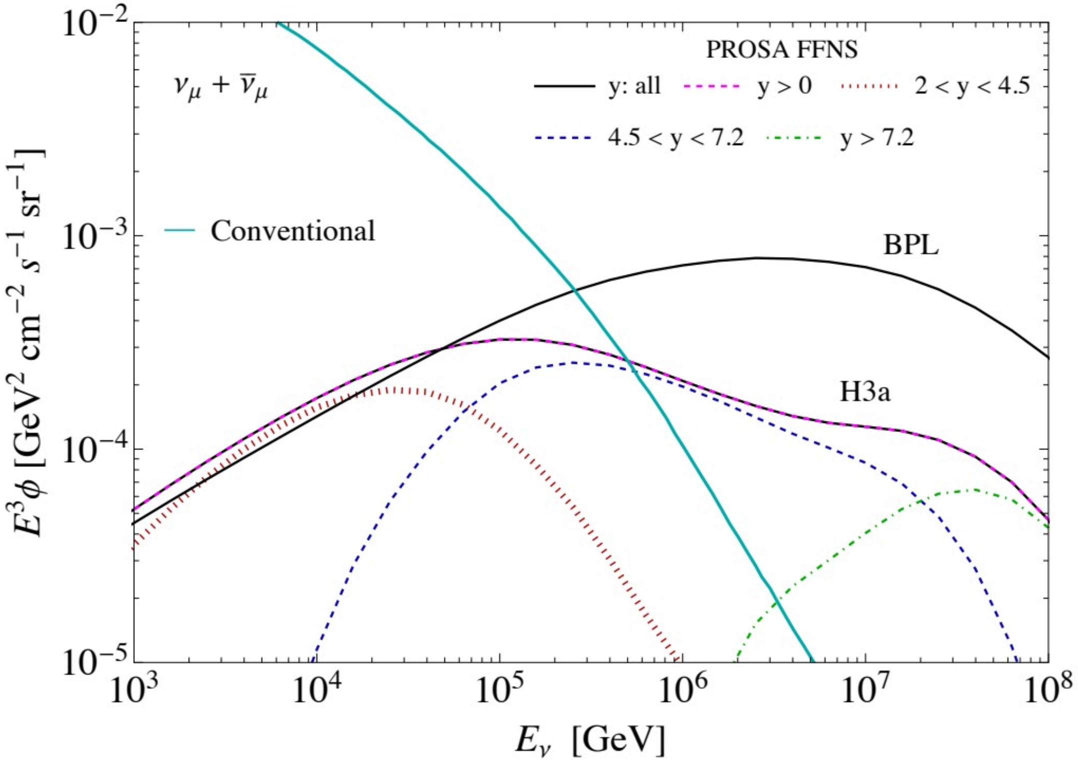
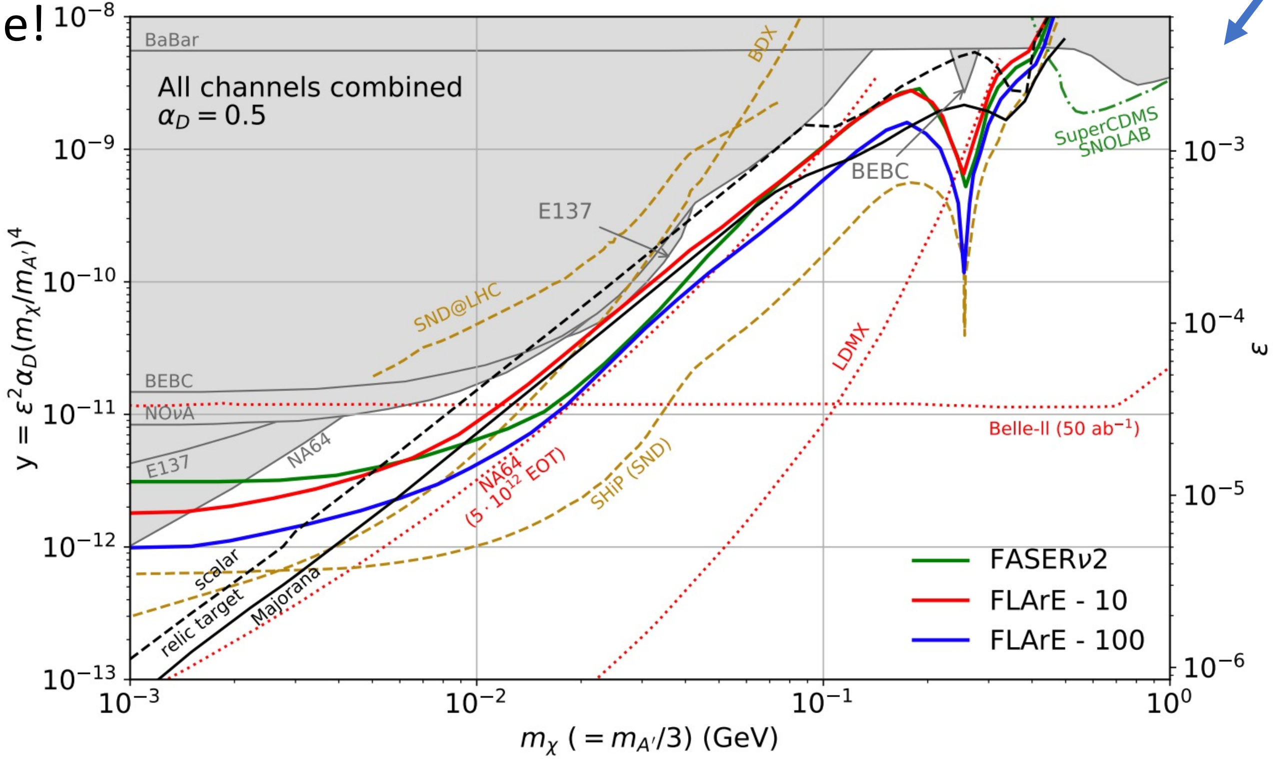


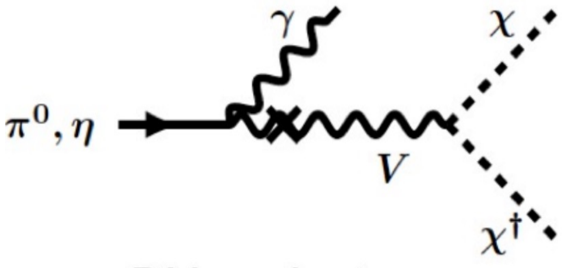
Figure shows what is the relevant rapidity range of LHC charm measurements to correspond to the IceCube neutrino energy:
Rapidity regions 4.5<y<7.2 and y>7.2 both (currently unexplored) in relevant energy range.

BSM at FPF

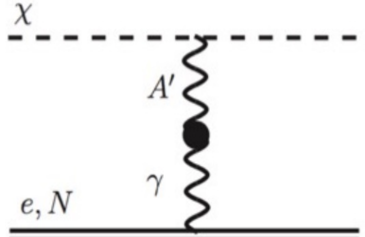
- Recent theory level studies on sensitivity to DM scattering in a LArTPC at the FPF (FLArE)
  - Consider both DM-electron and DM-nucleus scattering
- Very interesting sensitivity, probing the thermal relic region with the “right amount” of Dark Matter
  - Direct scattering, complementary method to “missing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



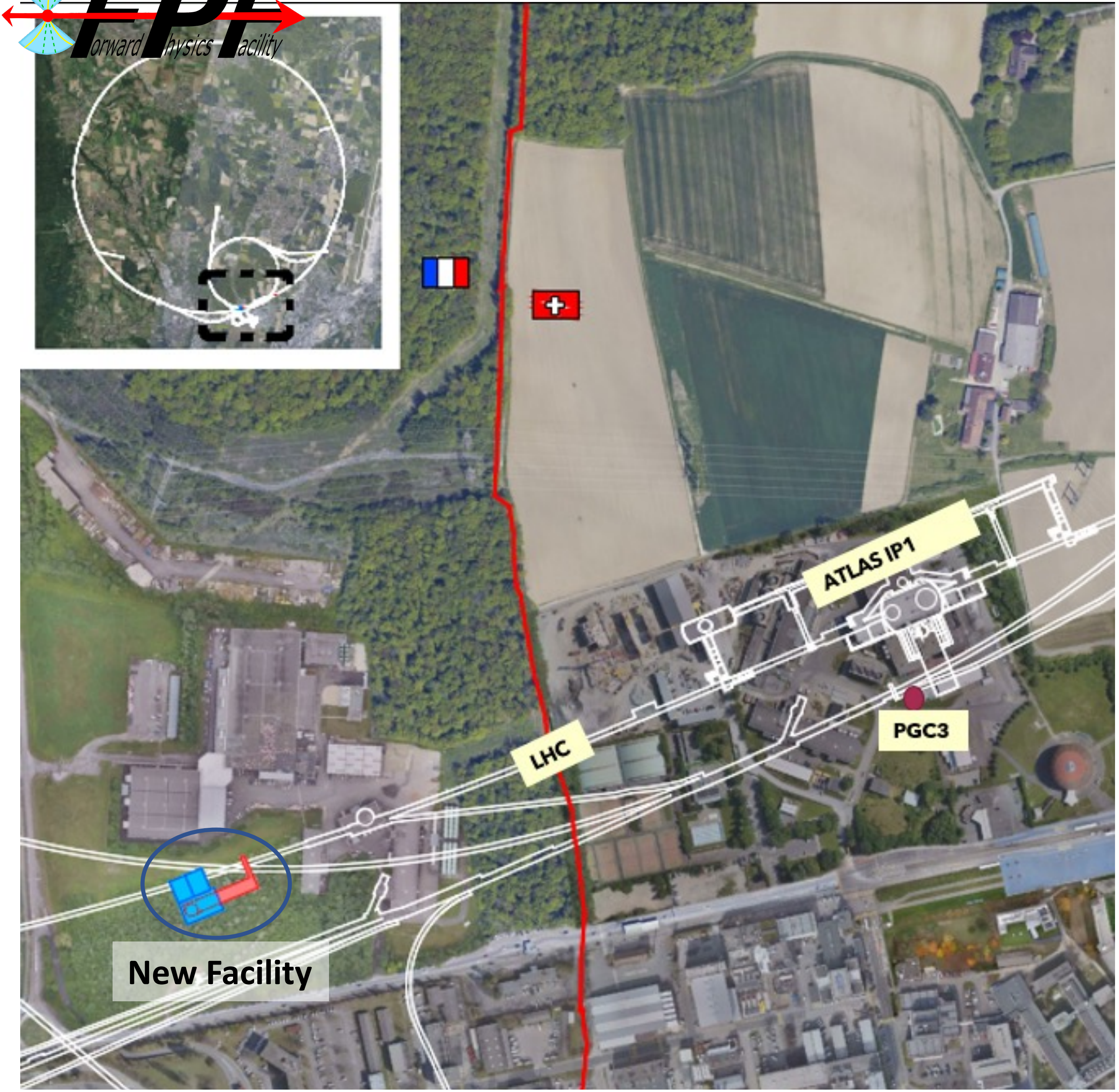
Benchmark Model	FPF
BC1: Dark Photon	FASER 2
BC1’: U(1)$_{B-L}$ Gauge Boson	FASER 2
BC2: Dark Matter	FLArE
BC3: Milli-Charged Particle	FORMOSA
BC4: Dark Higgs Boson	FASER 2
BC5: Dark Higgs with hSS	FASER 2
BC6: HNL with e	FASER 2
BC7: HNL with μ	FASER 2



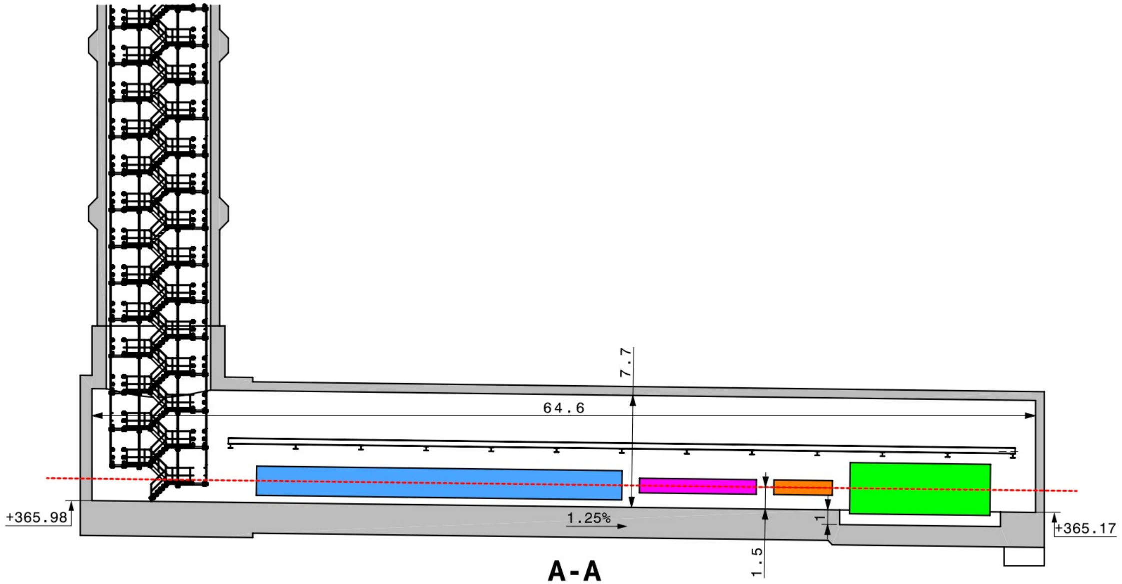
DM production



DM scattering



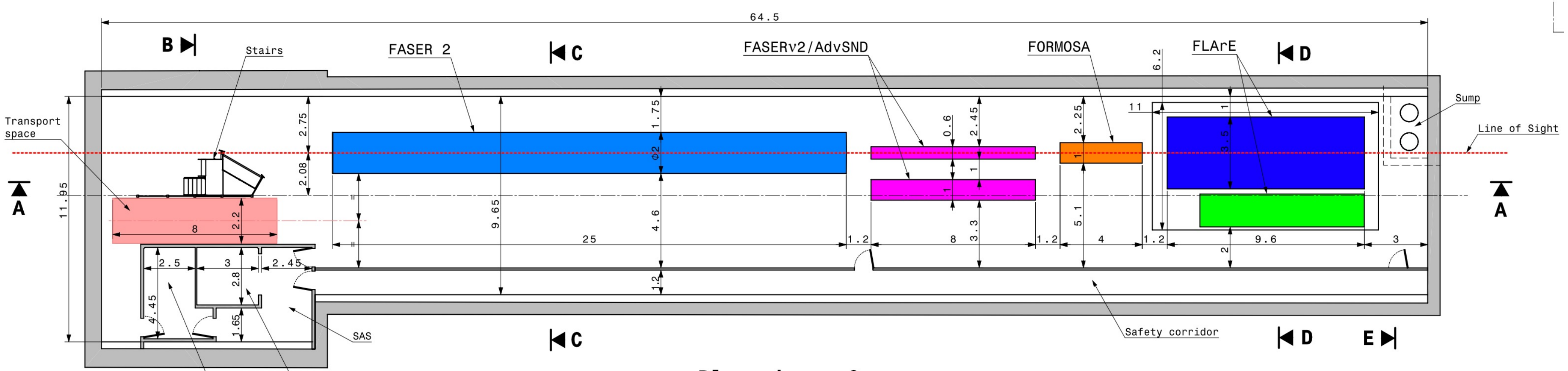
After several studies by CERN civil engineering team, looking at options around both the ATLAS and CMS interaction points, the best option for the FPF facility is chosen as a dedicated new facility ~600m from the ATLAS IP (to the west). On CERN land.



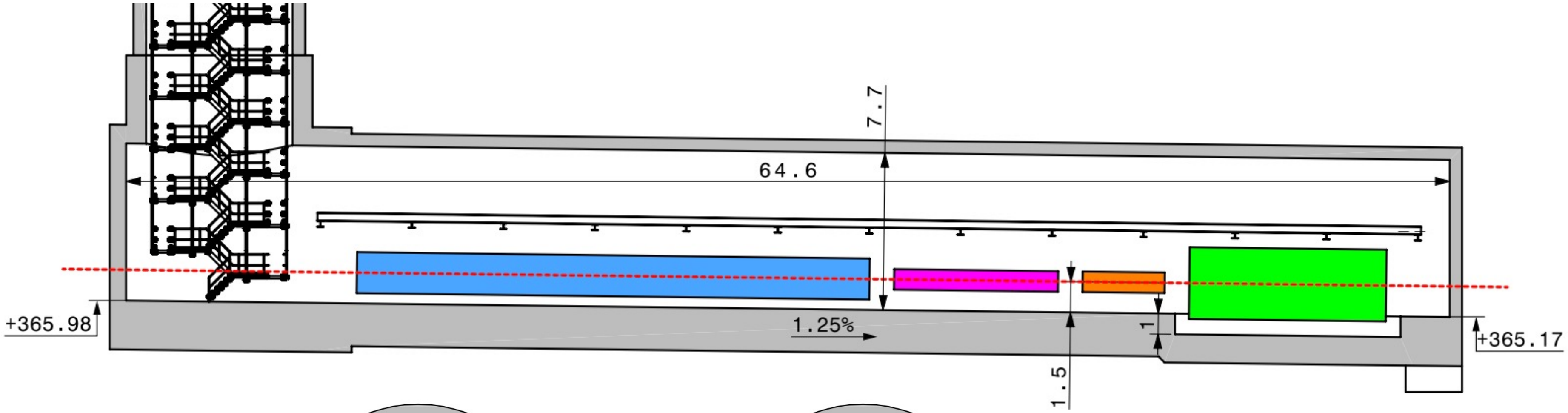
A-A
1:200

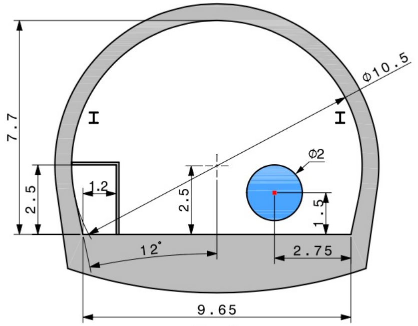
FPF Facility:

65m long, 8m wide/high cavern
Connected to surface through
88m high shaft (9.1m diameter):
617m from IP1.

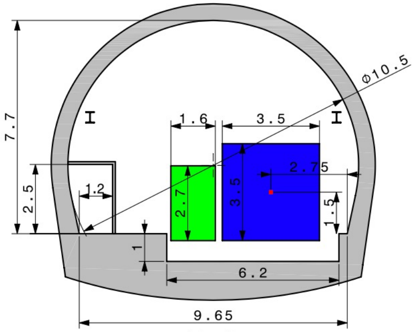


Plan view - Cavern
1:100





C-C
1:100



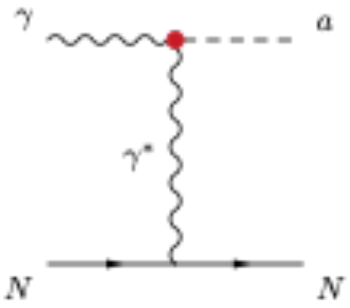
D-D
1:100

K. Balazs, J. Osborne
CERN SCE

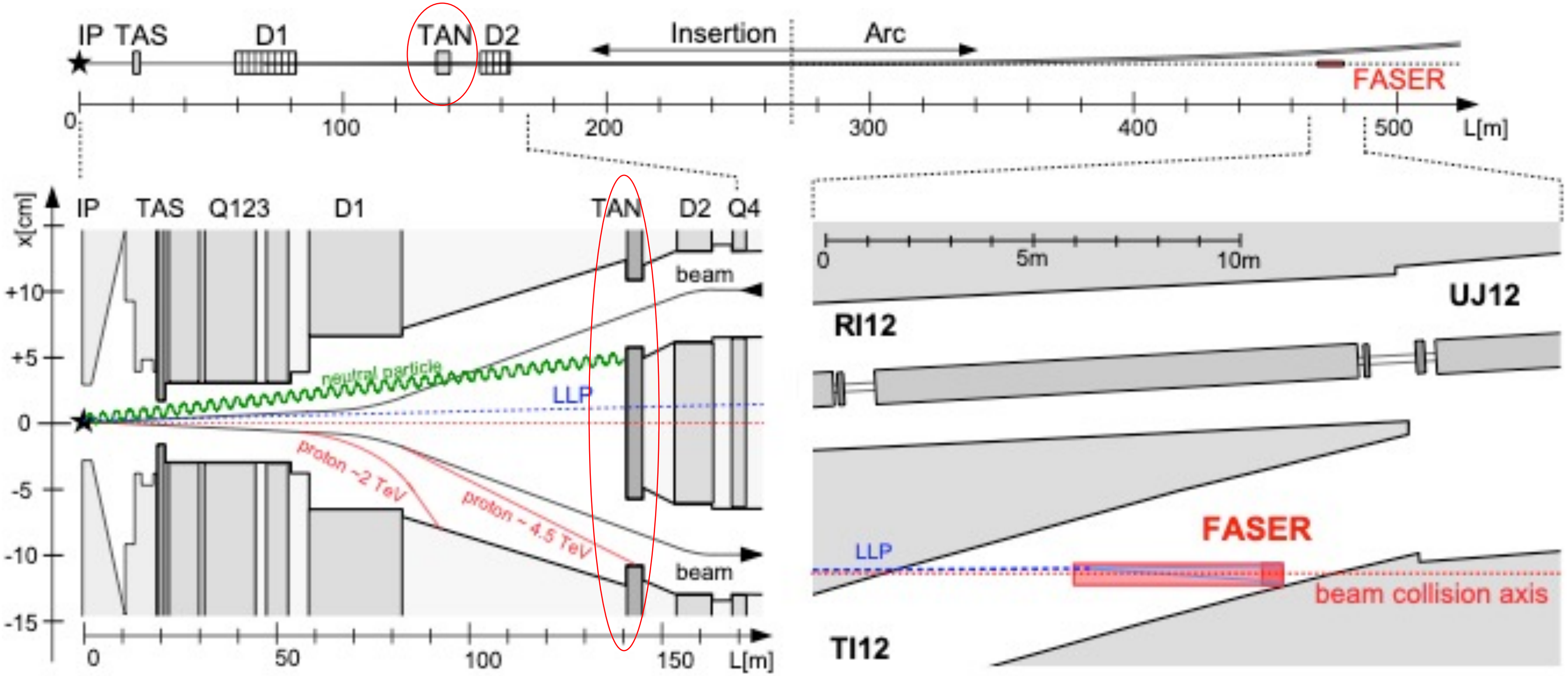
Axion-Like-Particles (ALPs)

1806.02348

ALP production using the LHC as a beam-dump experiment.
Very high energy photons produced in LHC collisions, interacting with material in the TAN can produce ALPs.
The ALPs (with ~TeV energy) then propagate in a straight line, and can decay inside FASER (480-140 = 340m from their production point).

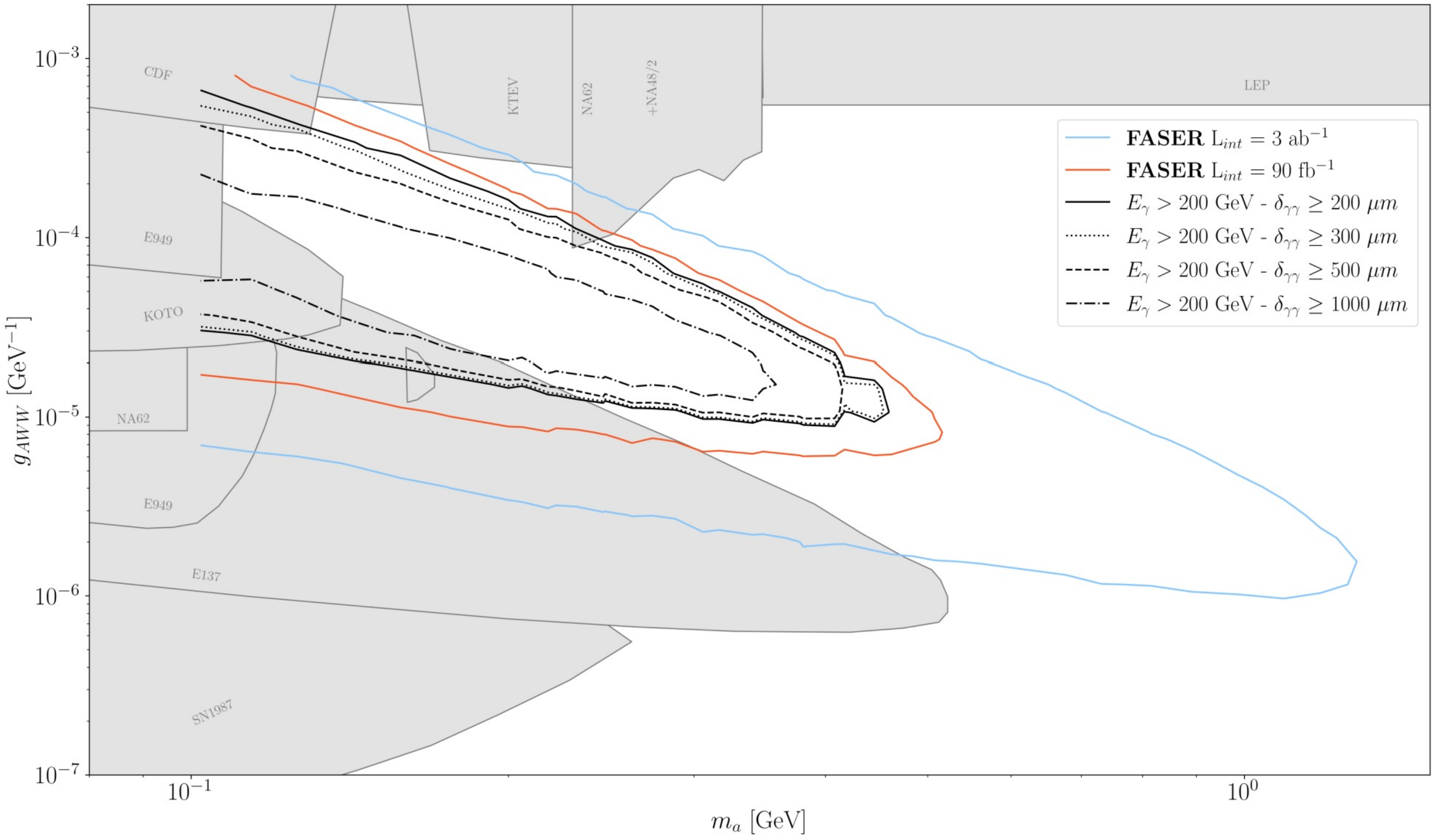


ALP production via the Primakoff process from photons scattering in the TAN



ALP Sensitivity

- Assuming background free single-photon like search for ALPs sensitivity for 10/fb and 150/fb



Detector signature two very closely spaced high energy photons. Unable to be resolved by current FASER calorimeter. Large energy signature may allow to search for this, but complicated background from neutrino interactions in calorimeter.

Ongoing upgrade project to introduce a high granularity silicon/tungsten preshower to be able to resolve closely spaced high energy photons down to 0.2mm separation. To be installed at end of 2023.

More details in: https://cds.cern.ch/record/2803084/