Recent results from the FASER experiment

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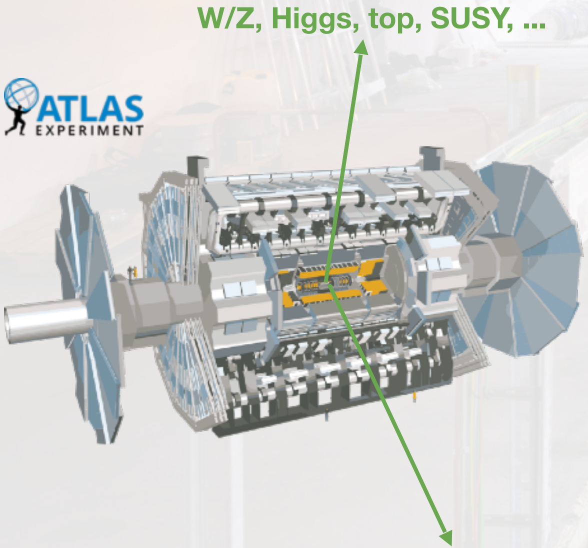
Oxford particle physics seminar
12th November 2024

FASER

MANCHESTER 1824
The University of Manchester

Forward at the LHC

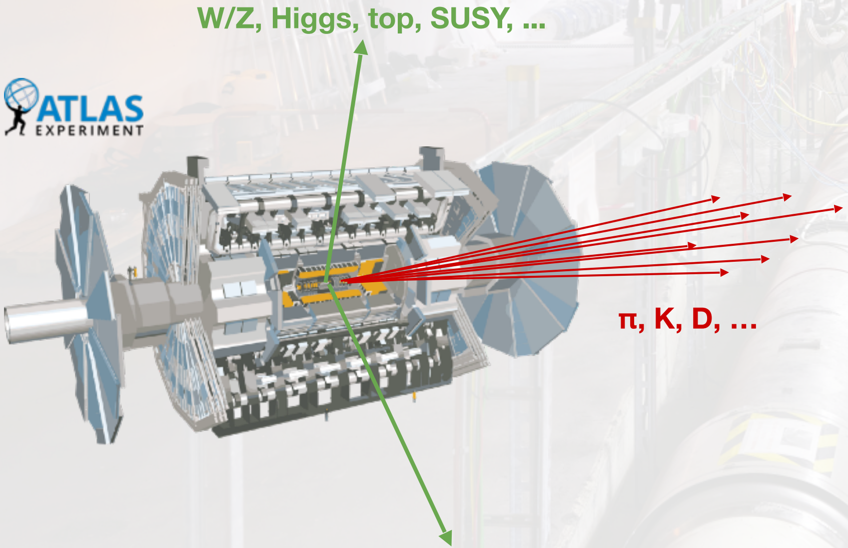
Experiments at the LHC designed to search for **heavy** and **strongly coupled** particles



Produced **isotropically** at **high p_T**

Forward at the LHC

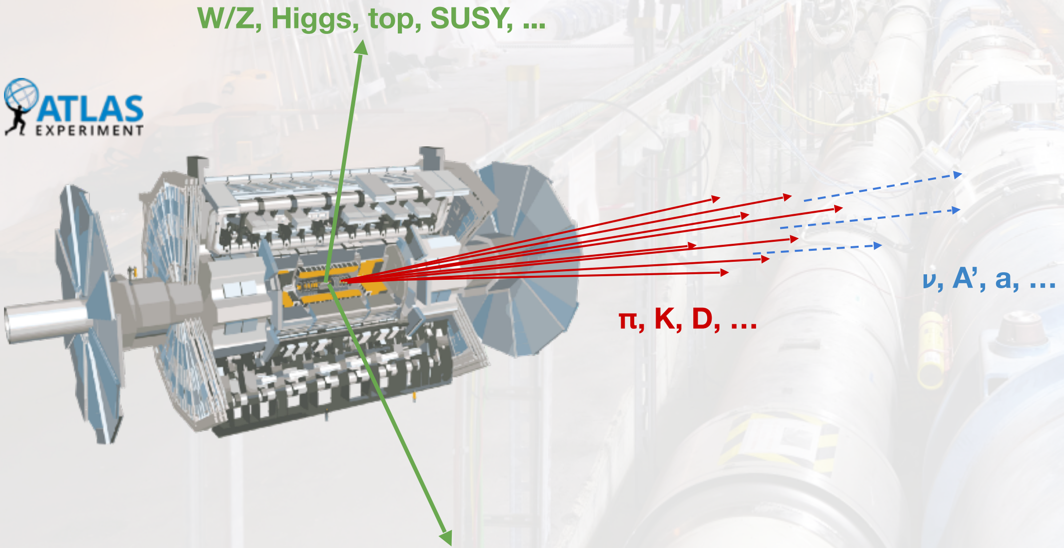
High rate of **light hadrons** also produced in *non-instrumented* **far-forward (low p_T)** region



1% of **pions** produced in forward ~10^{-6}% of solid angle

Forward at the LHC

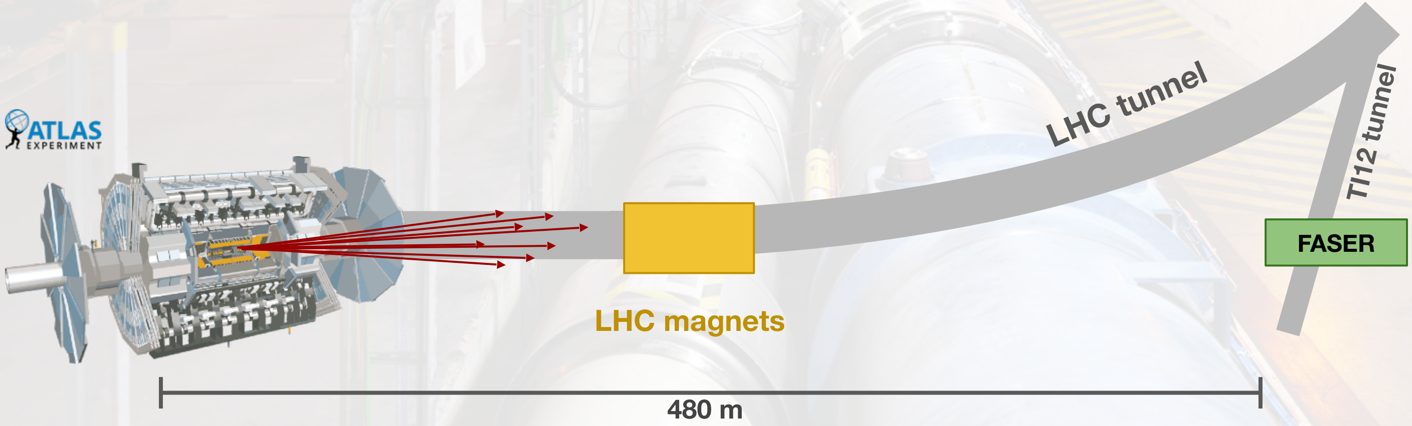
Light, **weakly coupled** particles produced in proliferation in forward region.



Neutrinos of all flavours, and **BSM** particles

ForwArd Search ExpeRiment (FASER)

- FASER is a new, small, experiment at the LHC:
    - In TI12 located **480 m** from the ATLAS interaction point
      Aligned with the ATLAS collision **Line of Sight**
    - **Low background** environment: LHC magnets deflect charged particles (e.g. muons); shielded by 100 m of rock/concrete
    - **Maximal neutrino flux**



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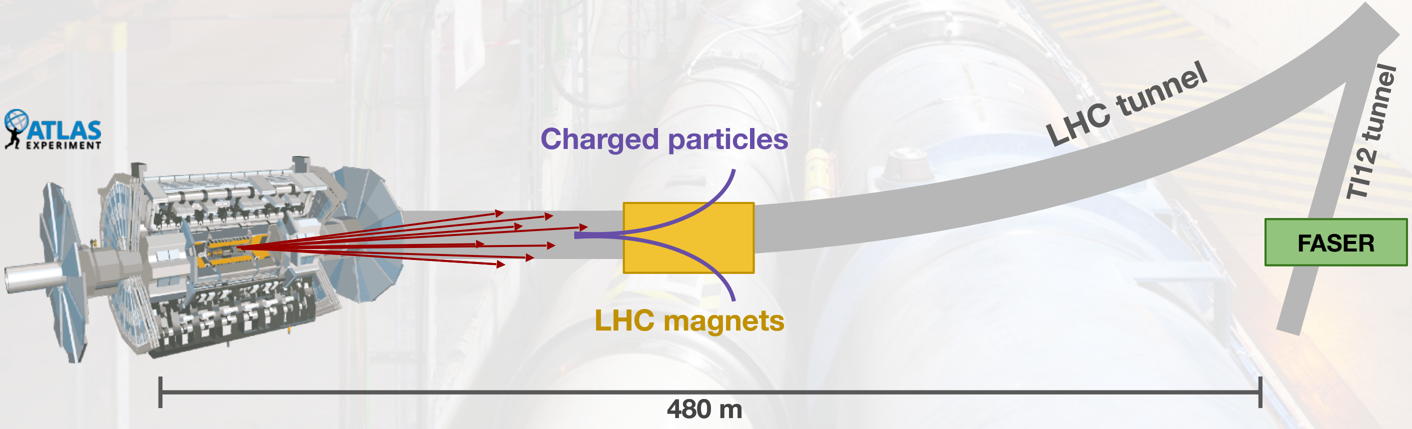

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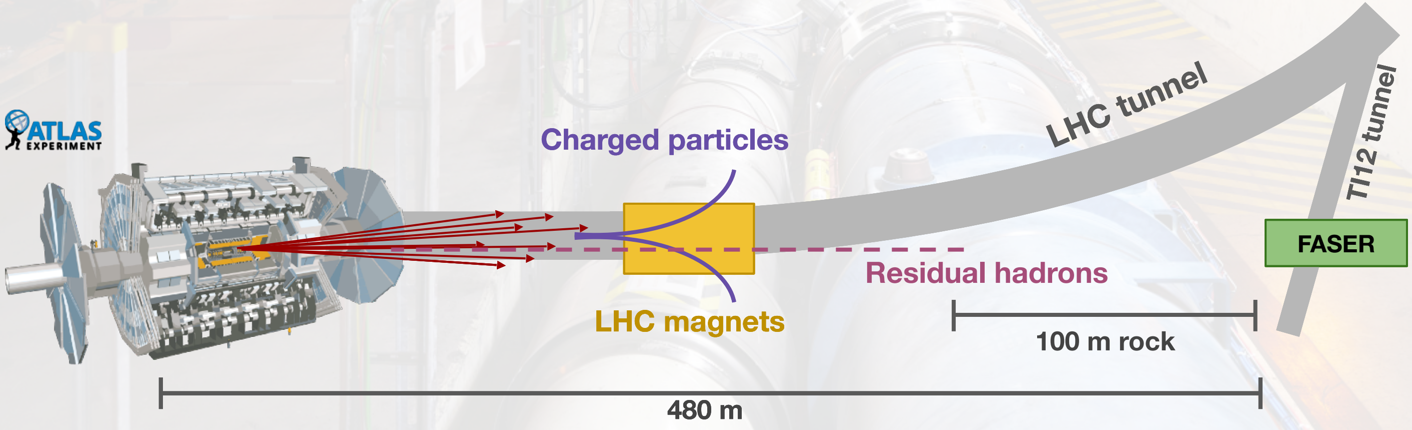

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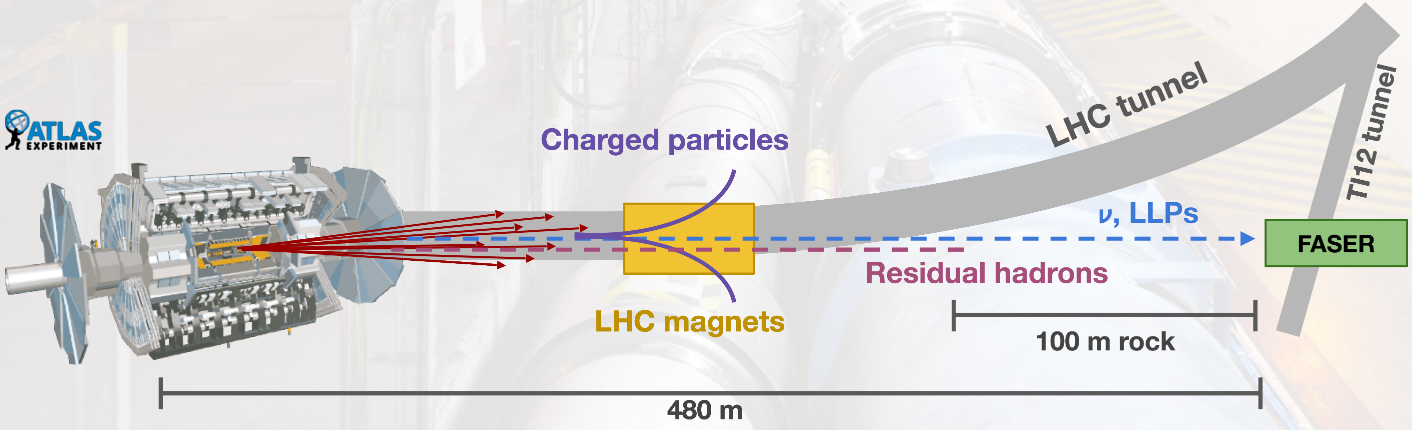
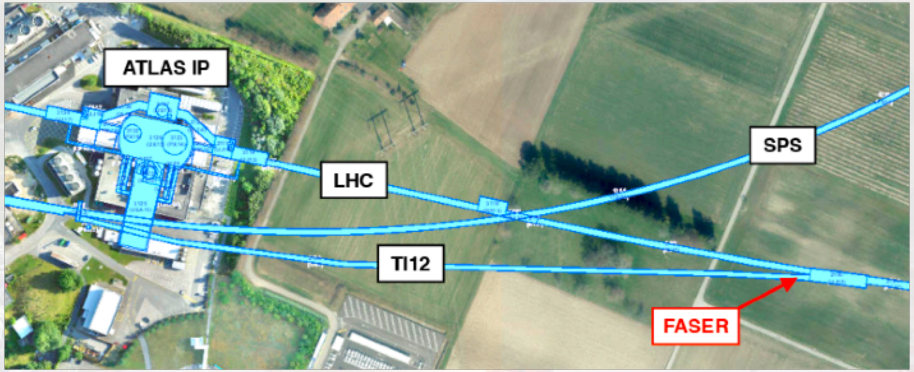
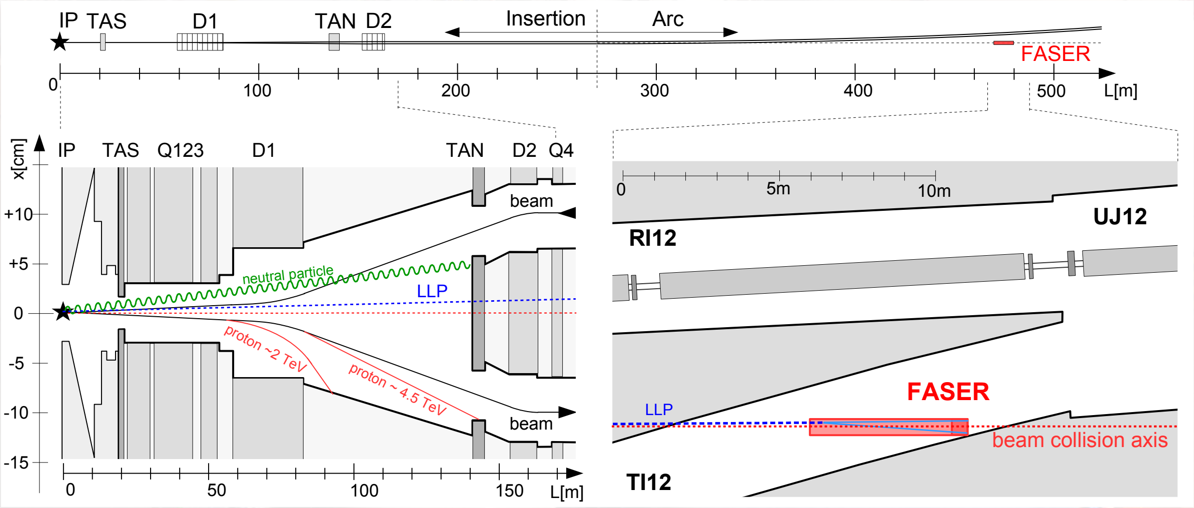


FASER Location

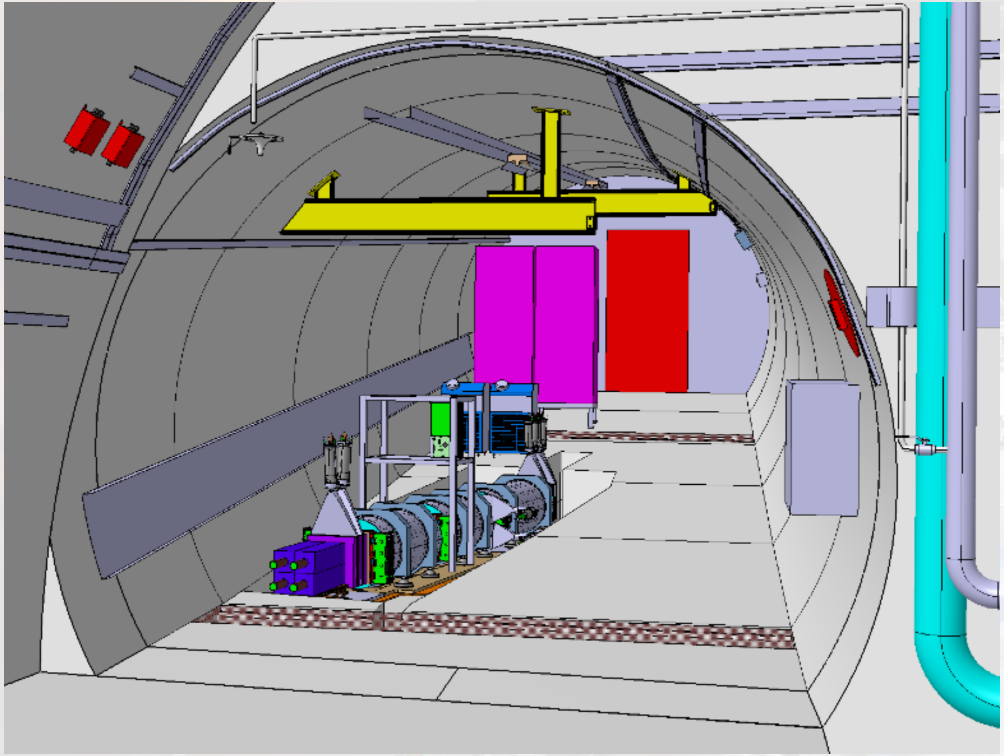
FASER location

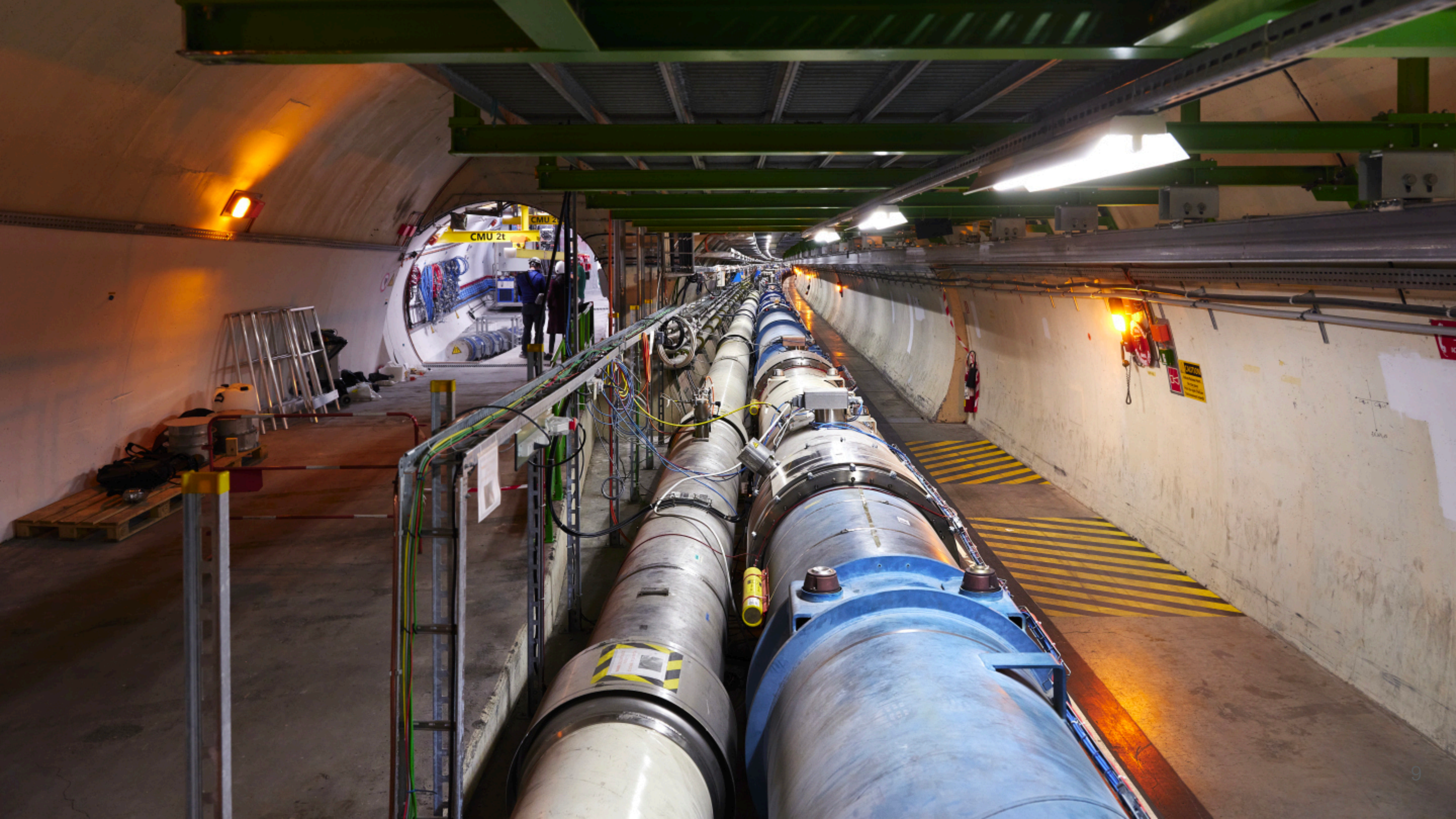
- Old SPS → LEP tunnel ideal location:
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds





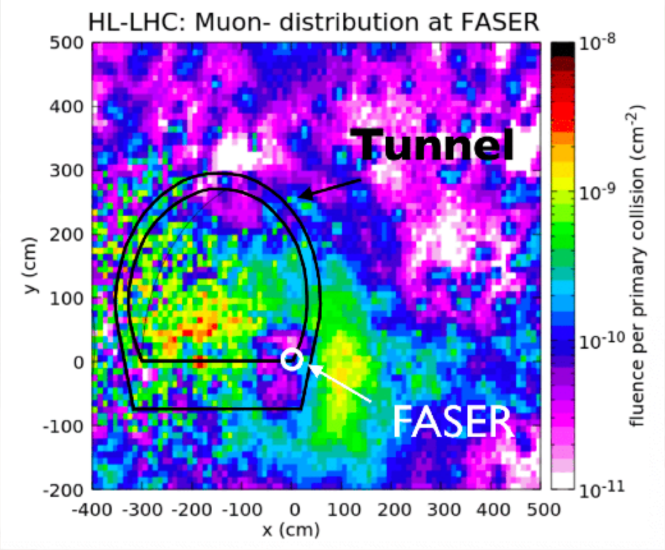
FASER location: TI12

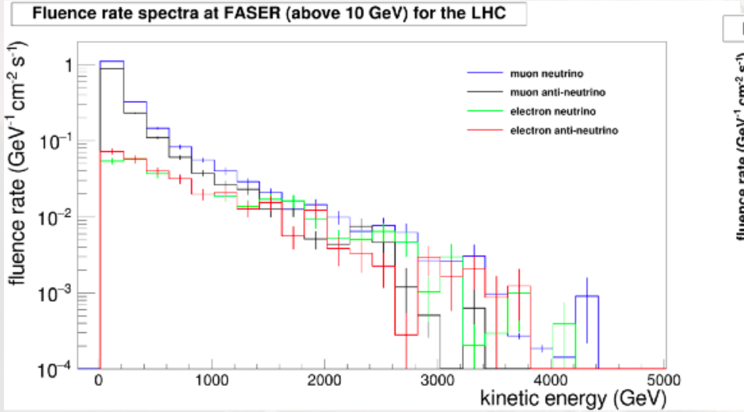


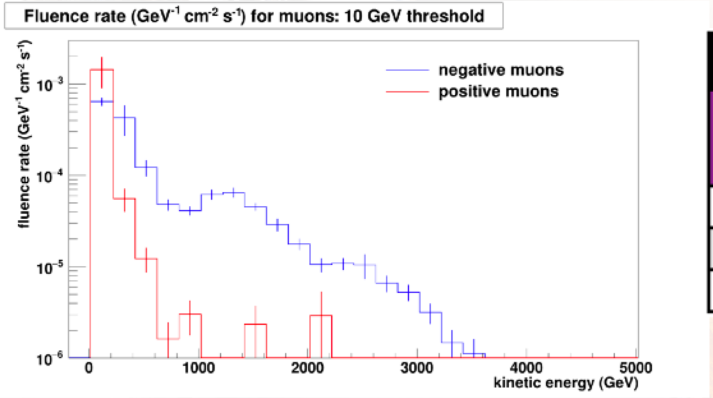

CMU 2t

Beam backgrounds

- FLUKA simulations and *in situ* measurements used to assess expected backgrounds.
  - IP1 collisions (shielded by 100m rock)
  - Off-orbit protons hitting beam pipe aperture near TI12
  - Beam-gas interactions
- Low particle flux along beam axis due to LHC optics.







Muon charge asymmetry due to LHC magnets

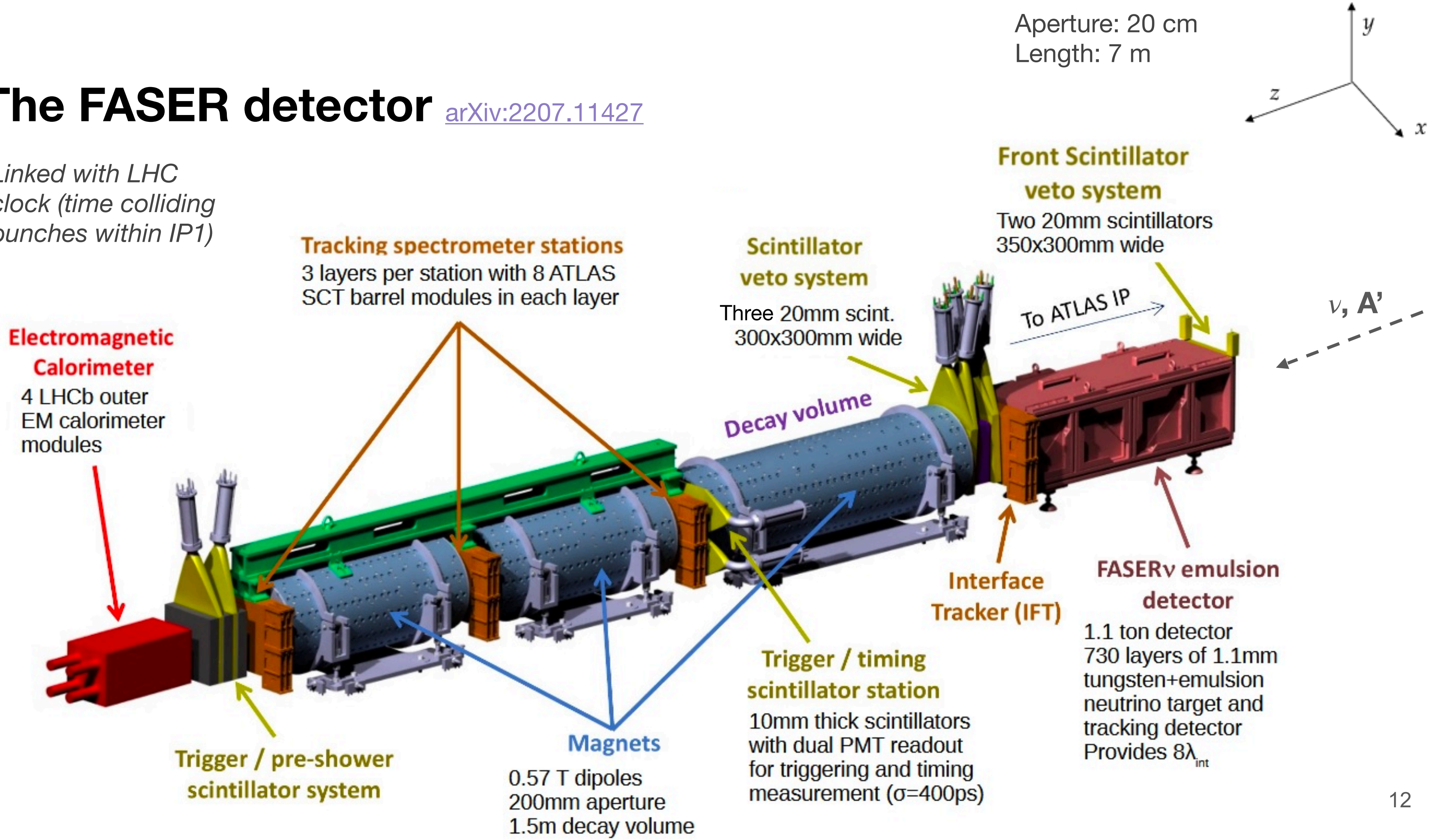
Muons (@L=2x10^{-34} cm^{-2} s^{-1})	
Energy threshold [GeV]	Charged Particle Flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

FASER detector & installation

The FASER detector [arXiv:2207.11427]

Aperture: 20 cm
Length: 7 m

Linked with LHC clock (time colliding bunches within IP1)

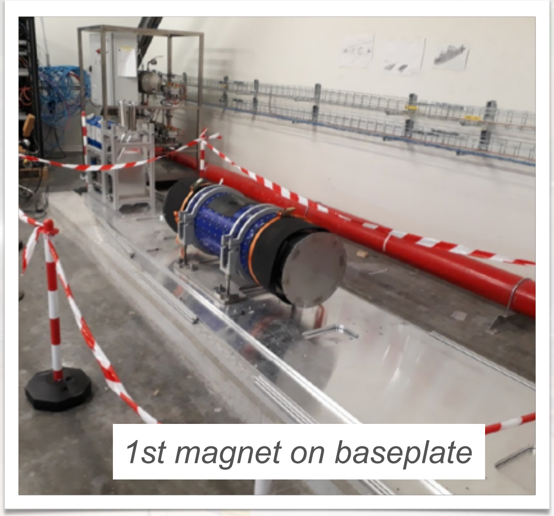


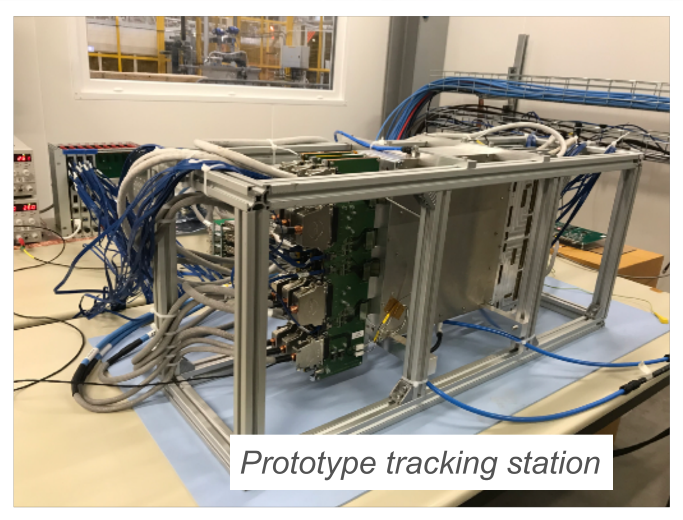
EHN1 - 2020

- Area in CERN’s Prevessin site (“EHN1”, neutrino platform) used for full detector commissioning.
- Baseplate mock-up on cement including 1% slope (simulate slope of LHC).

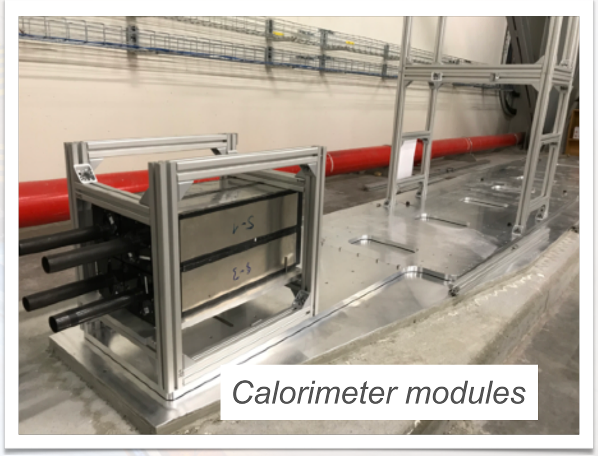
Commissioning & Surface dry run - 2020

- Surface dry run, before disassembly and installation in LHC tunnel.


1st magnet on baseplate

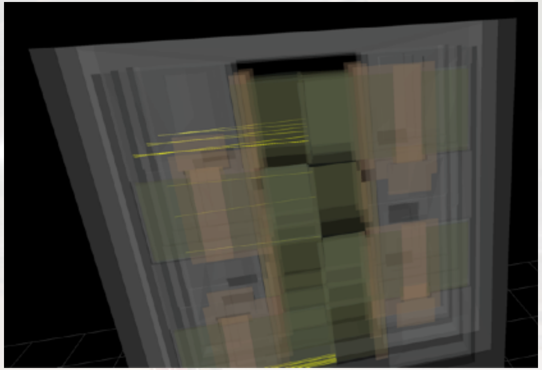

Prototype tracking station

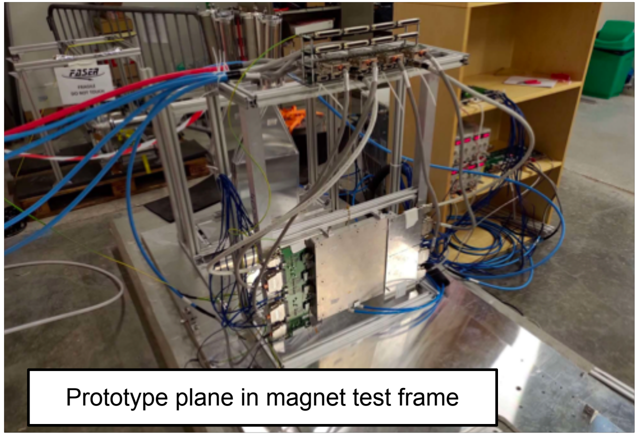

Scintillator station


Calorimeter modules

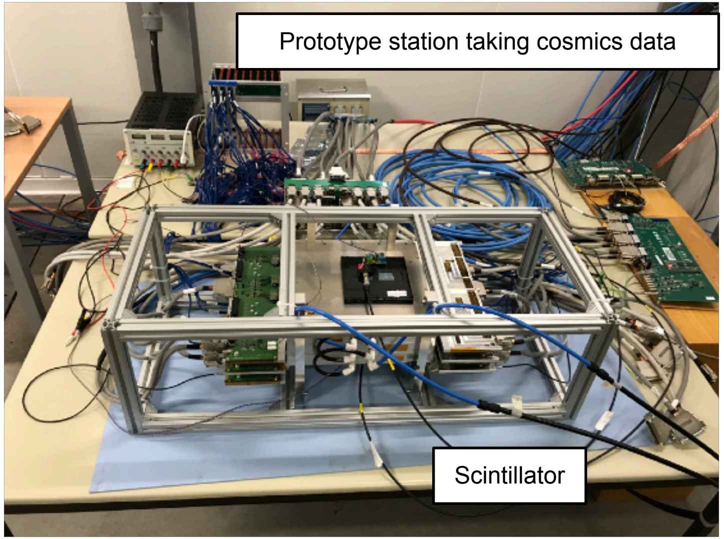
Commissioning & Surface dry run - 2020

- First tests of operating tracker plane next to magnet (including tests lowering next to magnetic field).
- Combined tests of TDAQ and tracker systems in cosmic data taking, reconstructed in offline software.





Prototype plane in magnet test frame

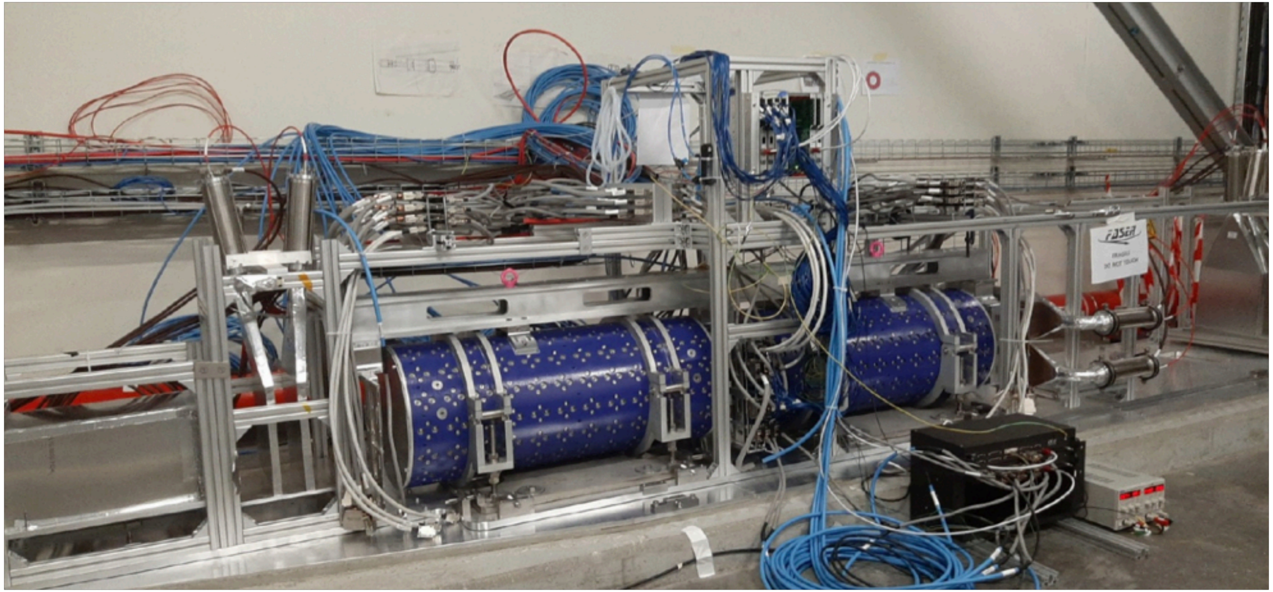


Prototype station taking cosmics data

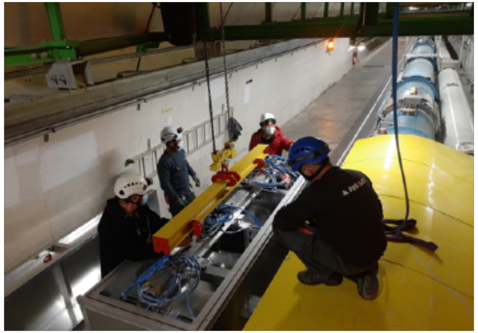
Scintillator

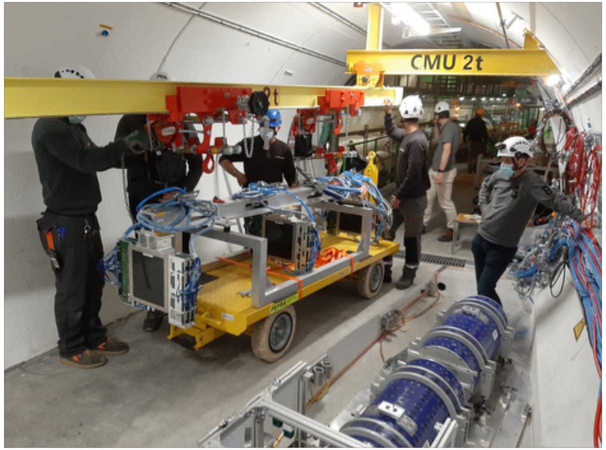
Commissioning & Surface dry run - 2020

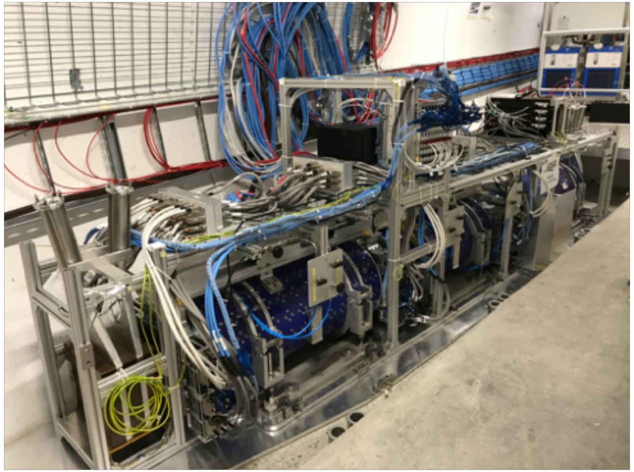
- First assembly of upper frame with one tracker station, calorimeter, all scintillators, and two magnets and combined run.
- Some “horizontal cosmics” events recorded.



Installation in TI12 - March 2021







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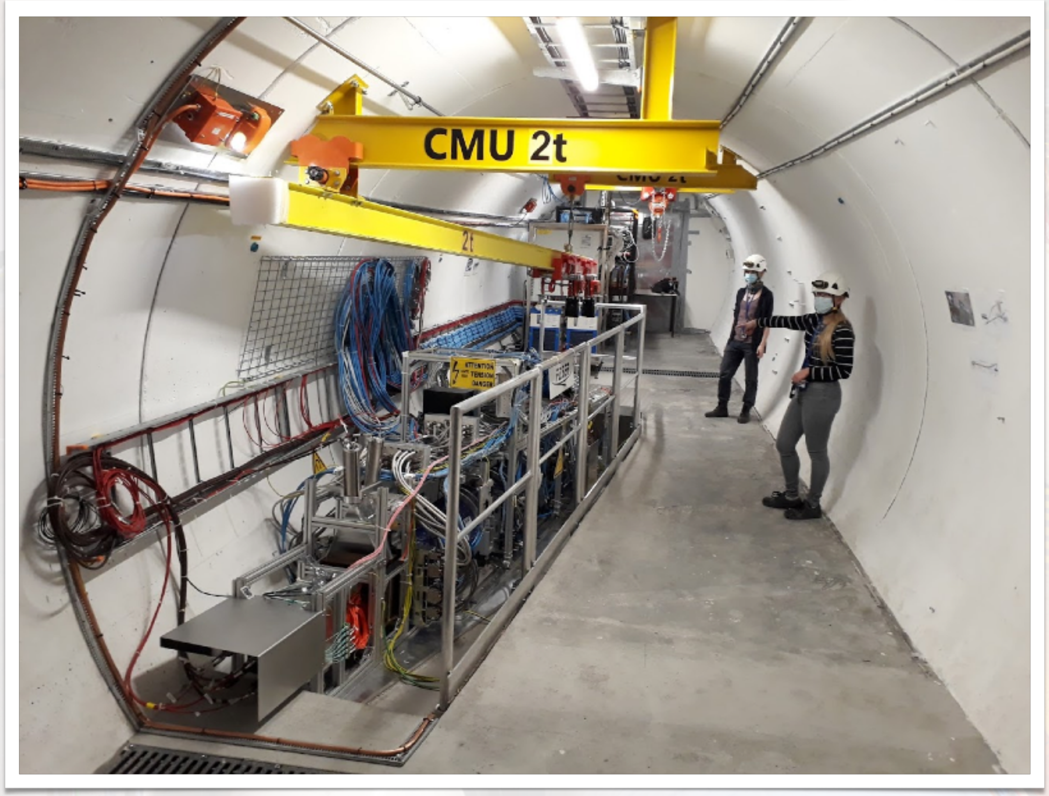
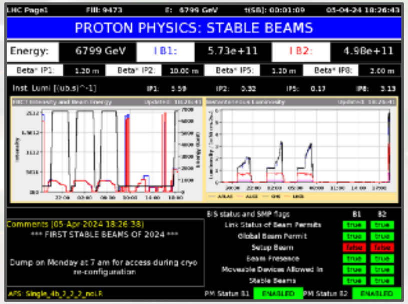
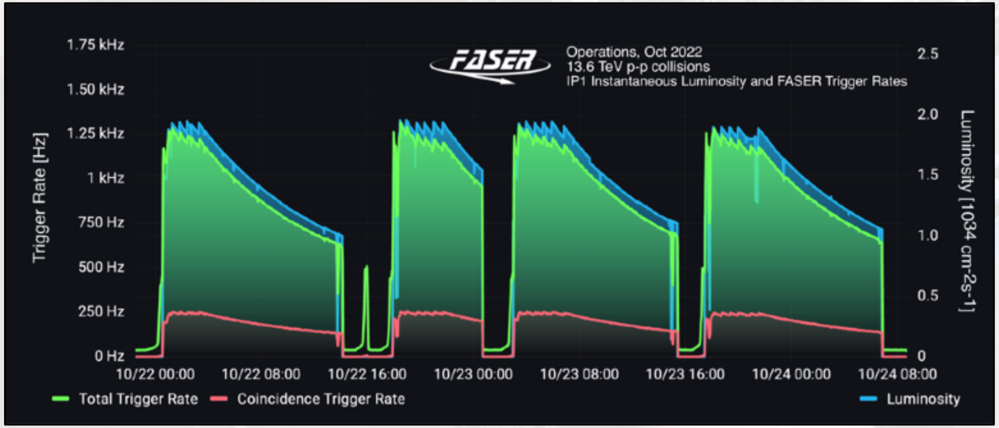
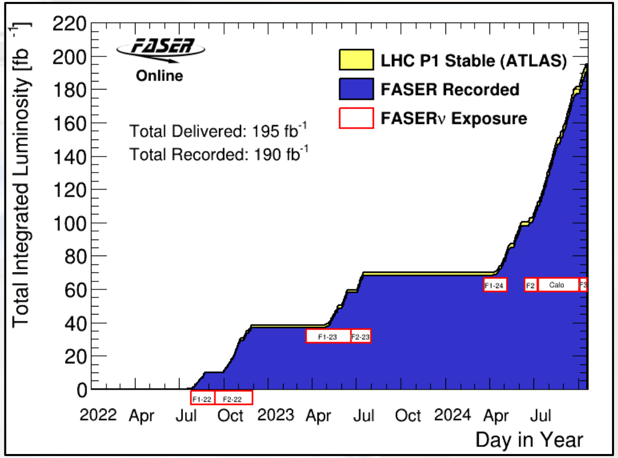


FASER operations - 2022-2024

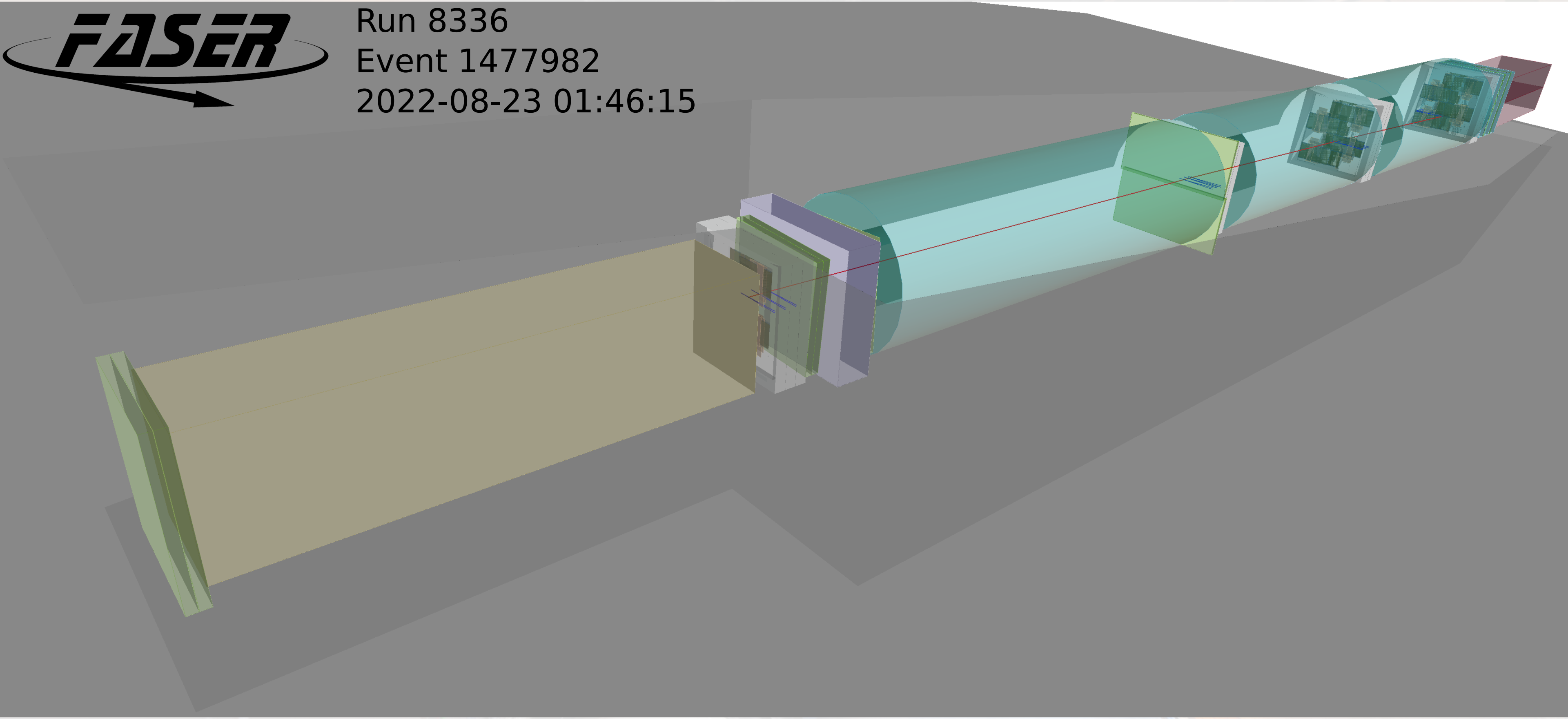


- Successfully collected 35 fb^{-1} in 2022, 33 fb^{-1} in 2023, and 120 fb^{-1} in 2024.
- Data taking efficiency > 97%.
- Due to change in LHC beam setup, muon background ~2x higher in 2024 data.
  - Issue for FASER (will see why later), hopefully move to more optimal nominal horizontal crossing angle for 2025.



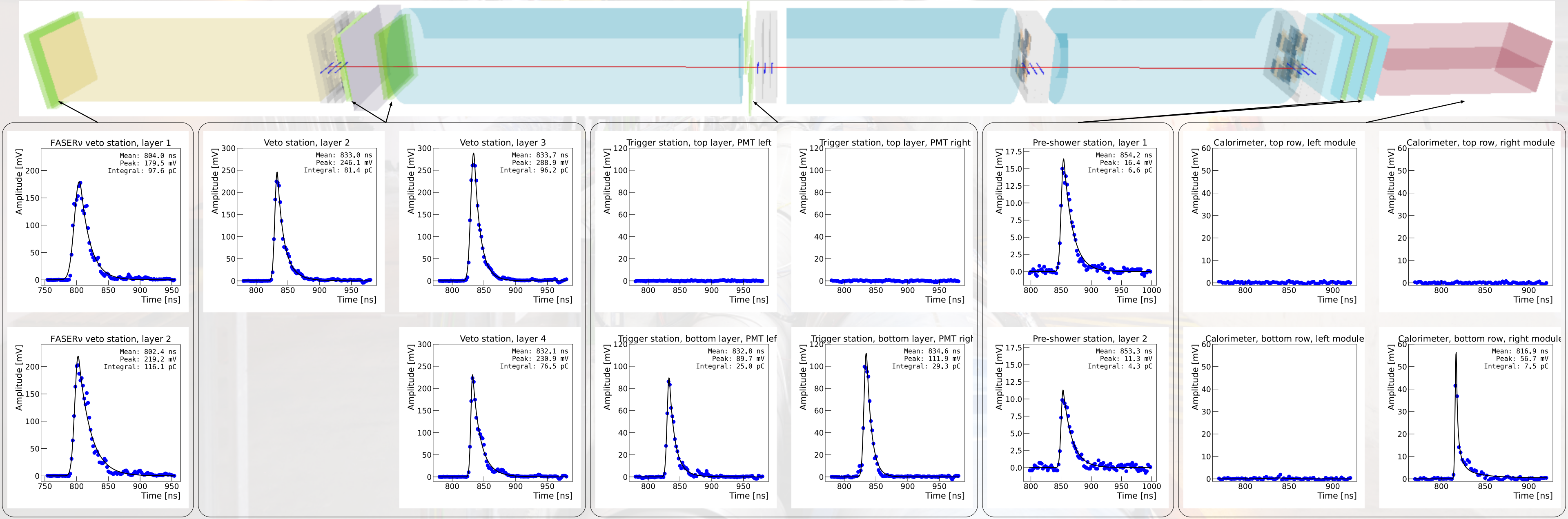


Event from 2022 with 21.9 GeV muon traversing FASER spectrometer



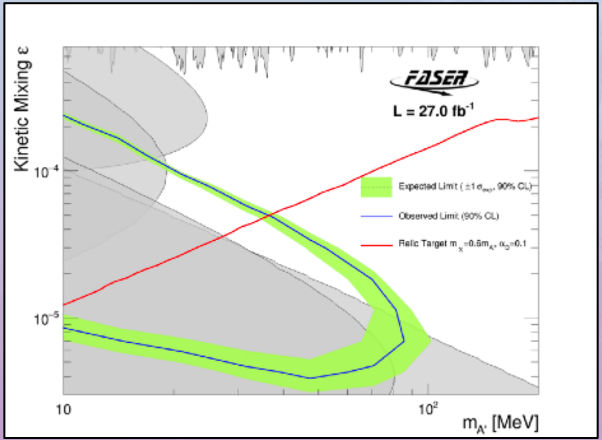
Event from 2023 with 1.3 TeV muon traversing FASER spectrometer

Run 10417
Event 12340
2023-04-21 19:44:55



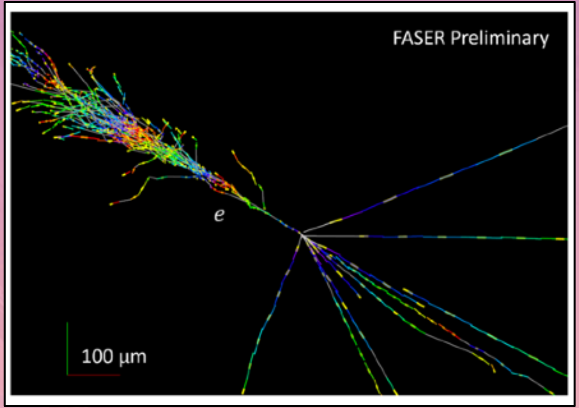
Recent results from FASER

BSM searches (LLPs)



FASER physics

Neutrino measurements

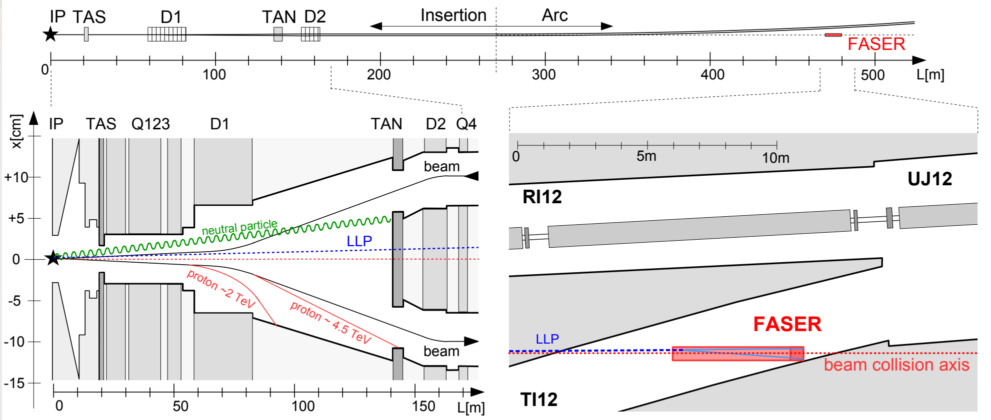


BSM searches at FASER

FASER physics

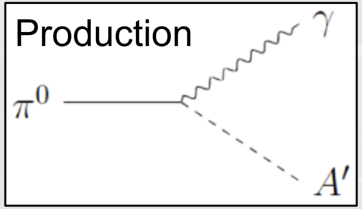
- FASER is sensitive to new light (MeV-GeV mass) weakly interacting long-lived particles (LLPs).
- Long-lived particles at FASER:

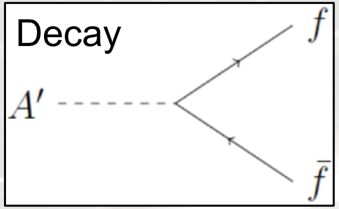
pp → LLP + X, LLP travels ~ 480m, LLP → $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$



LLPs could also be produced by interactions in neutral beam absorbers (TAN) then travel ~ 350 m to FASER

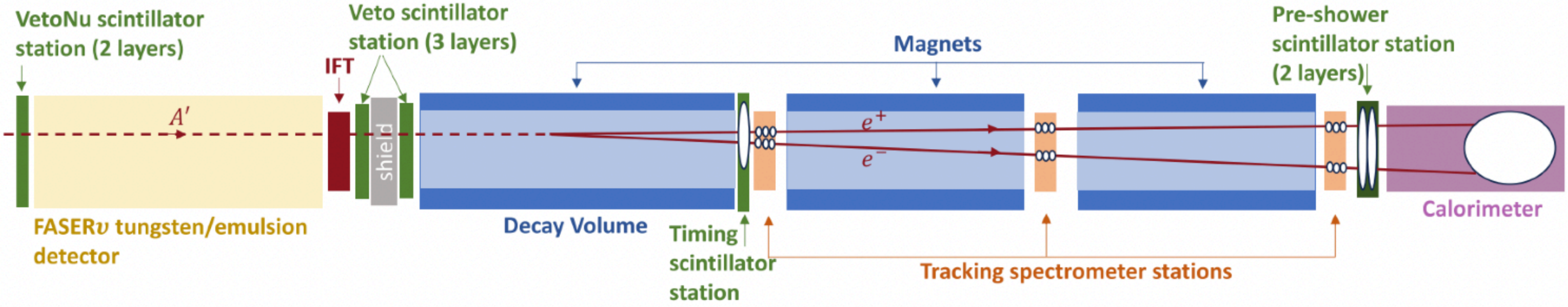
Dark photon search





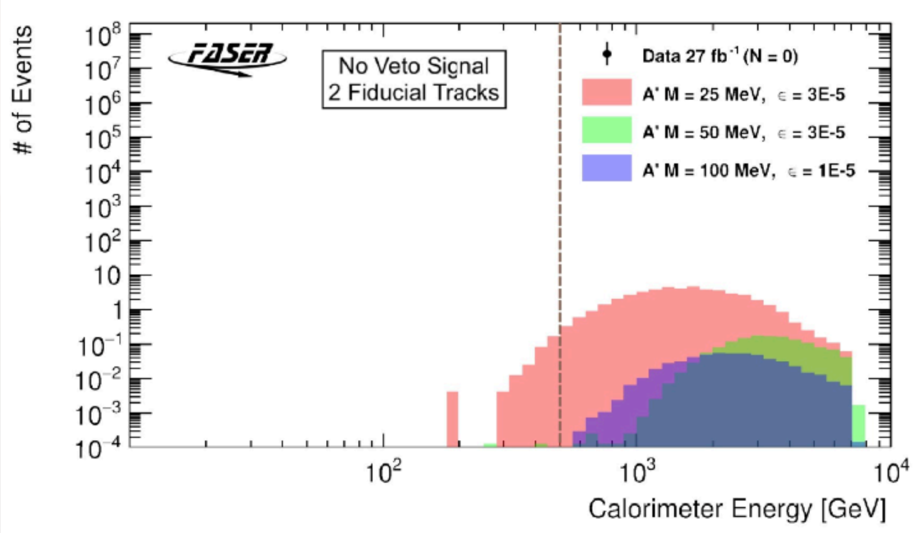
PLB 848 (2024) 138378

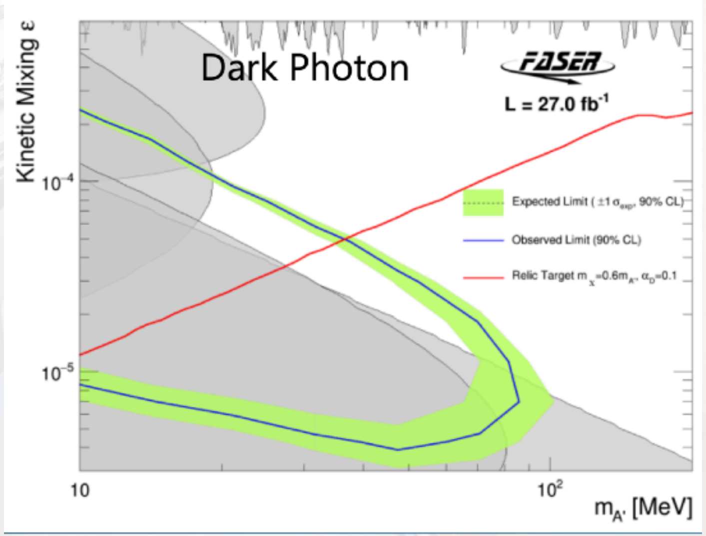
- Search for dark photons decaying into e^+e^- using 27 fb^{-1} of 2022 data.
- No veto signal, two tracks and E(calo) > 500 GeV.



Dark photon search

- Total background prediction (dominated by neutrinos) = $(2.3 \pm 2.3) \times 10^{-3}$
- **No events** in unblinded signal region
- Set world-leading constraints in new region of parameter space



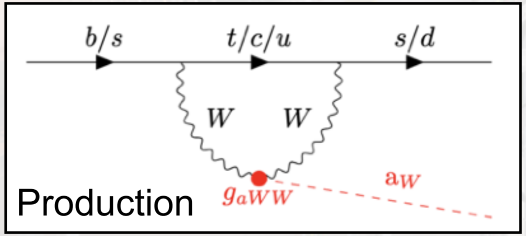


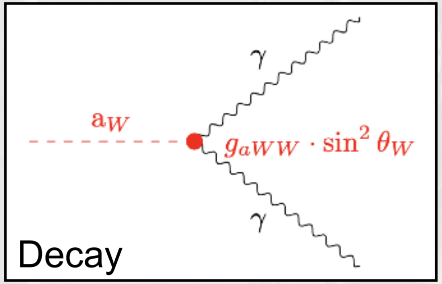
arXiv:2410.10363

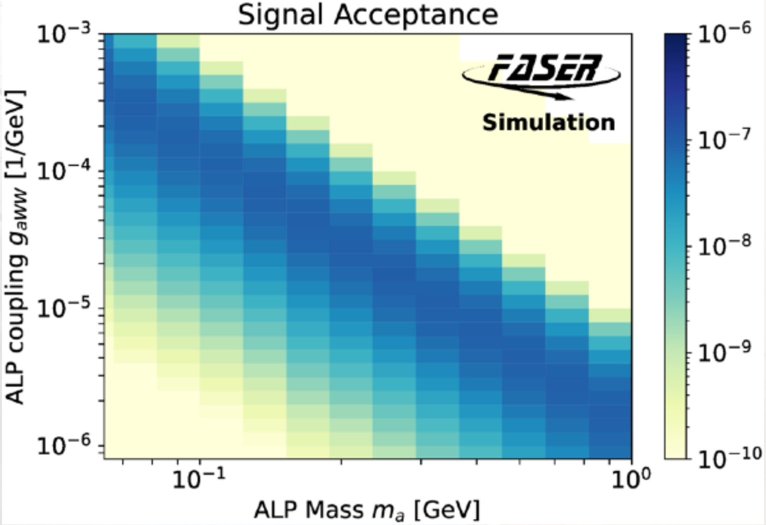
NEW!

Axion Like Particles (ALPs)

- Search for a light pseudoscalar particle decaying to a pair of photons.
- ALPs reaching FASER have momentum up to TeVs.
- Using 58 fb^{-1} of 2022 + 2023 data.



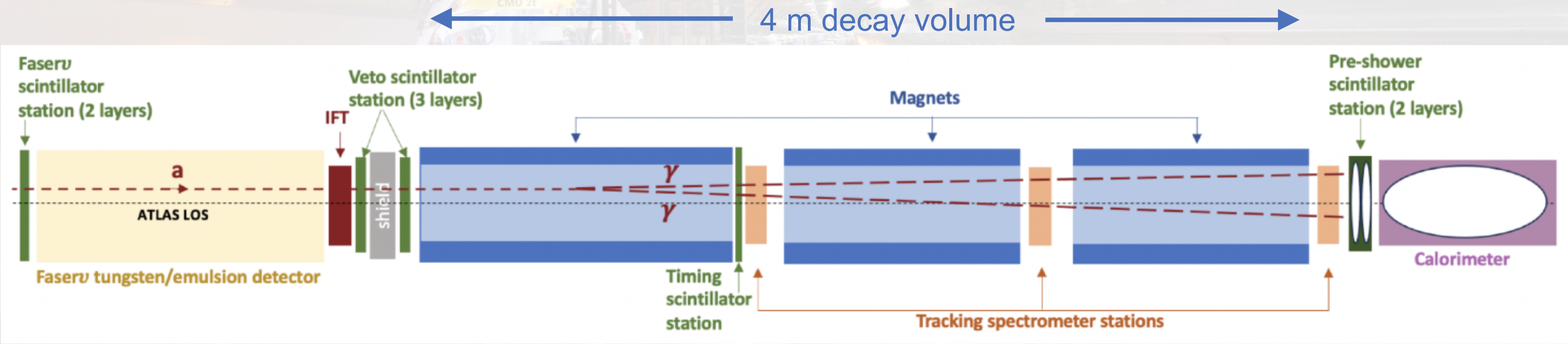




arXiv:2410.10363

NEW!

ALPs signature



No charge deposited in scintillators

Decays to pair of photons

Preshower charge > 10 MIPs, ratio > 4.5

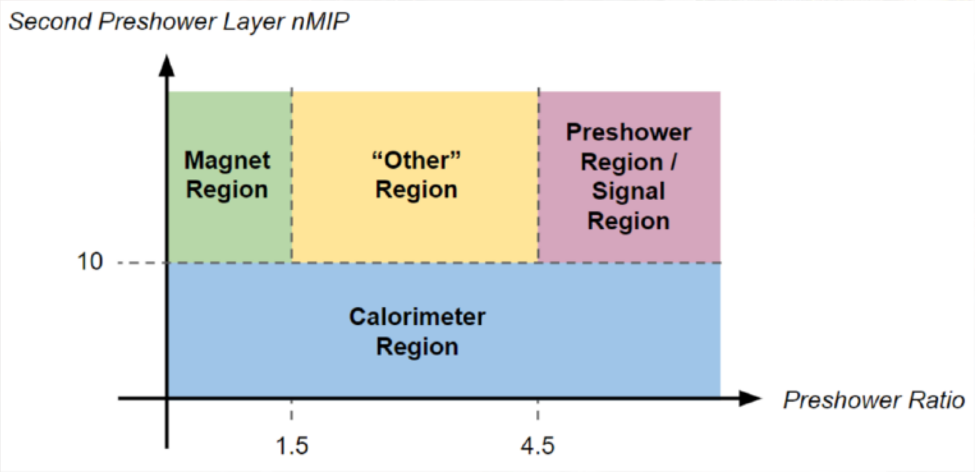
Calorimeter energy > 1.5 TeV

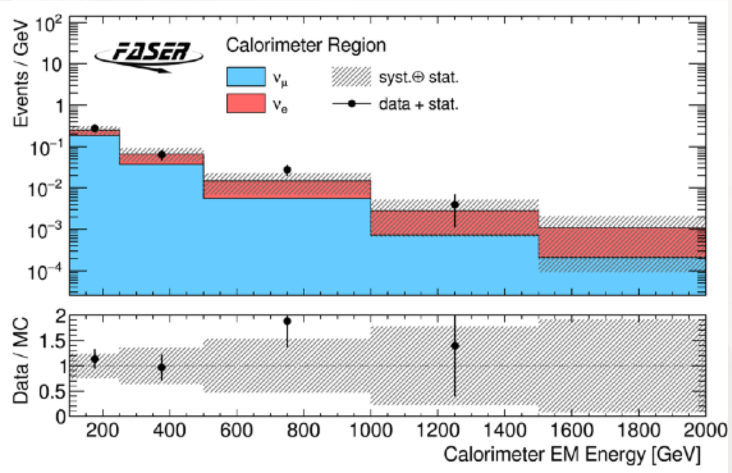
arXiv:2410.10363

NEW!

ALPs backgrounds

- Dominant background: neutrino interactions → 0.4 ± 0.4 events
- Negligible backgrounds from other sources:
  neutral hadrons, large-angle muons, non-collision/cosmic
- Backgrounds validated in control regions



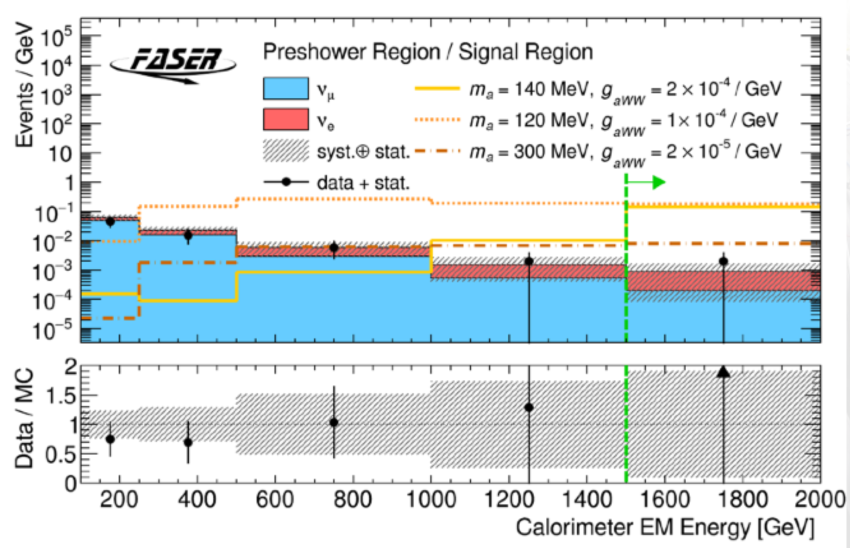


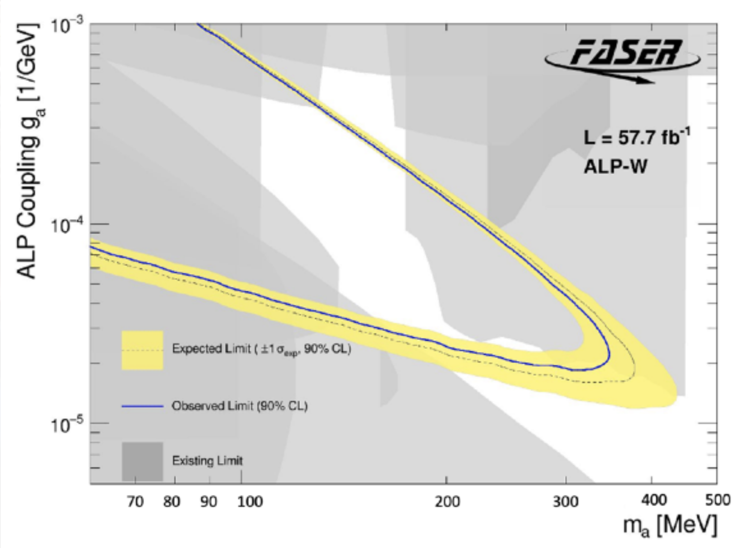
arXiv:2410.10363

NEW!

ALPs results

- Expect 0.4 ± 0.4 from ν interactions
- 1 observed event
- Exclude uncovered parameter space significantly

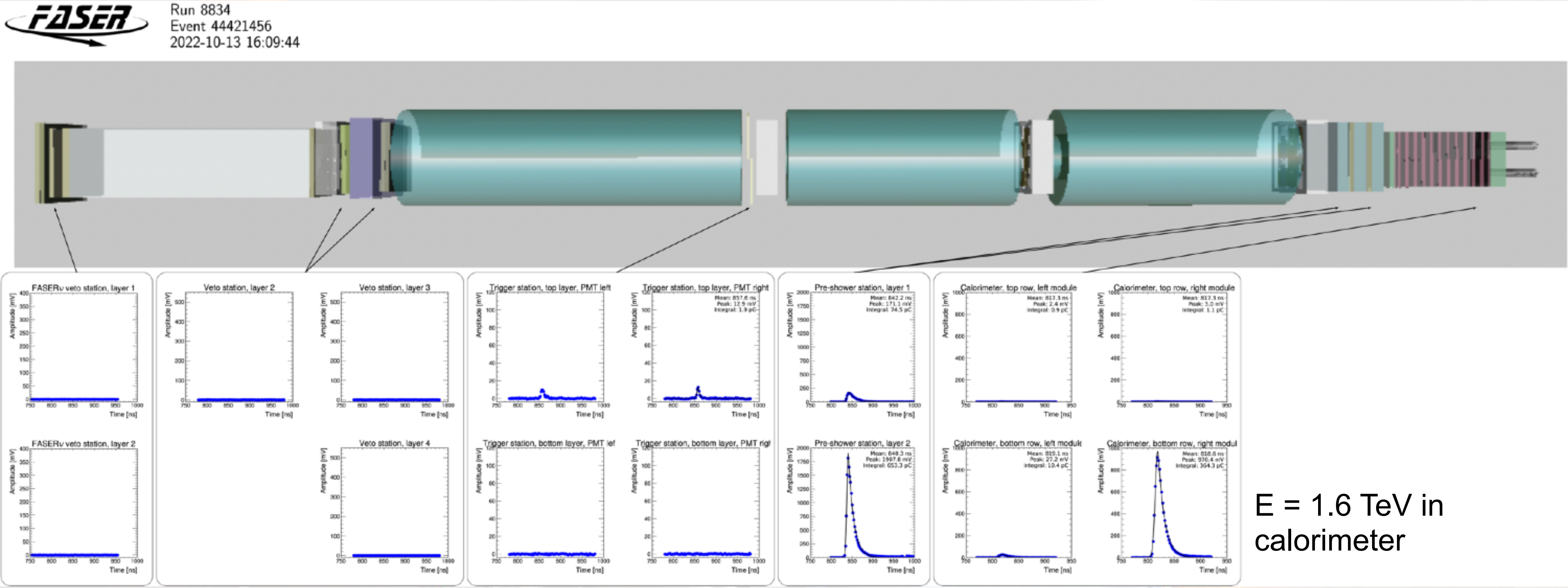




arXiv:2410.10363

NEW!

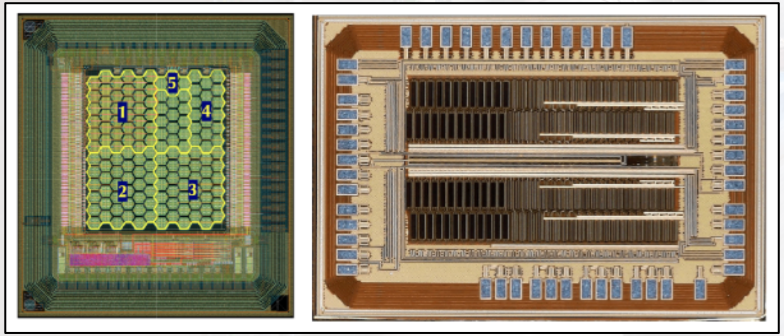
"ALPtrino" event display

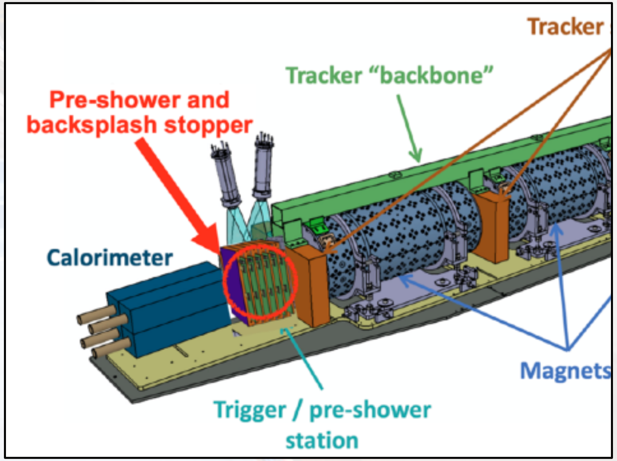


E = 1.6 TeV in calorimeter

Preshower upgrade

- ALPs decays to 2 photons generally separated by < 1 mm
  → cannot be resolved in current detector.
- **Preshower upgrade:**
  - Layers of monolithic silicon pixel detectors (high-granularity hexagonal pixels) with tungsten absorber
  - Identify photons separated by ~200 μm
  - Installation by 2025

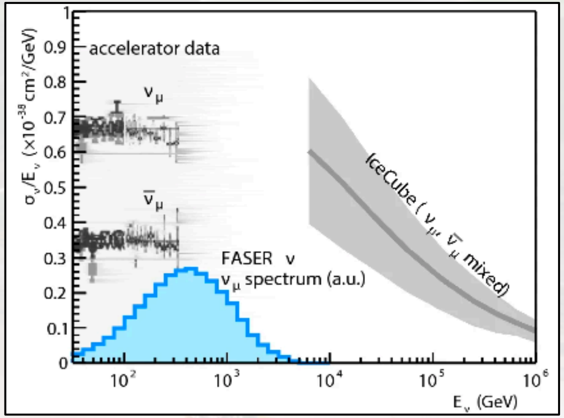


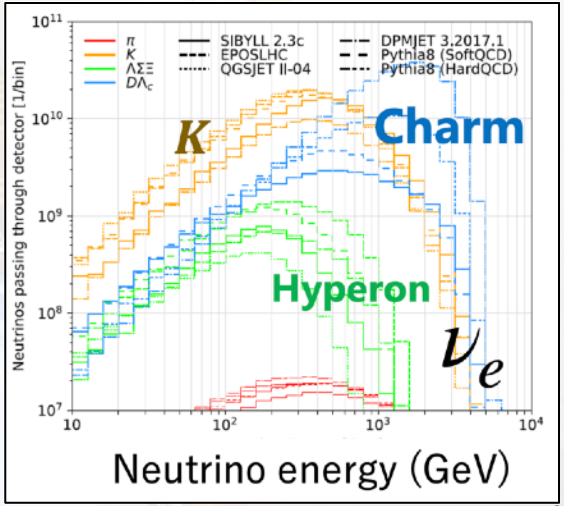


Neutrinos at FASER

Why study collider neutrinos?

1. Neutrino interactions (all flavours) at **unexplored TeV energies**
2. Probe of **forward hadron production**, novel inputs for:
   - QCD (gluon PDFs at low-x, intrinsic charm)
   - Astroparticle physics (collider counterpart of high-energy cosmic rays interactions: cosmic ray muon puzzle)
3. Probe of **hadron structure** (proton/nuclear PDFs)
4. Background to BSM searches





Forward hadron production and nuclear PDFs

Neutrino **production** at the ATLAS IP probes **forward hadron production**

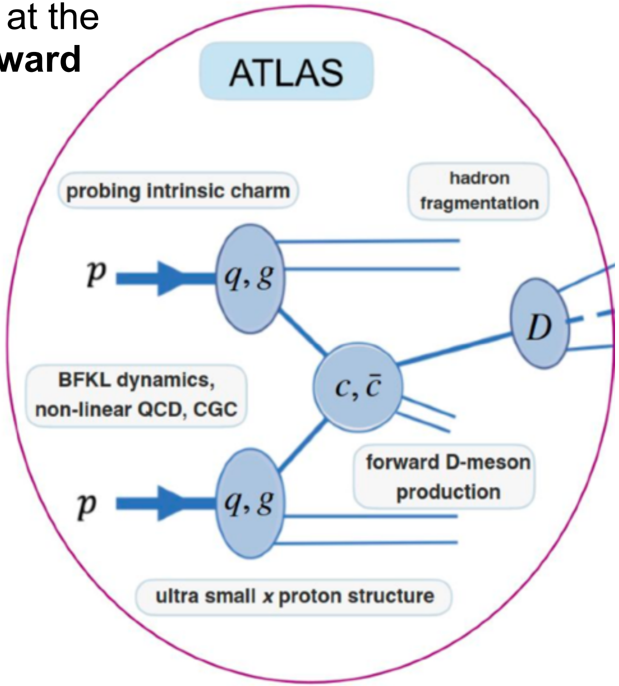


Figure adapted from: [J. Phys. G 50 (2023) 3, 030501]

Forward hadron production and nuclear PDFs

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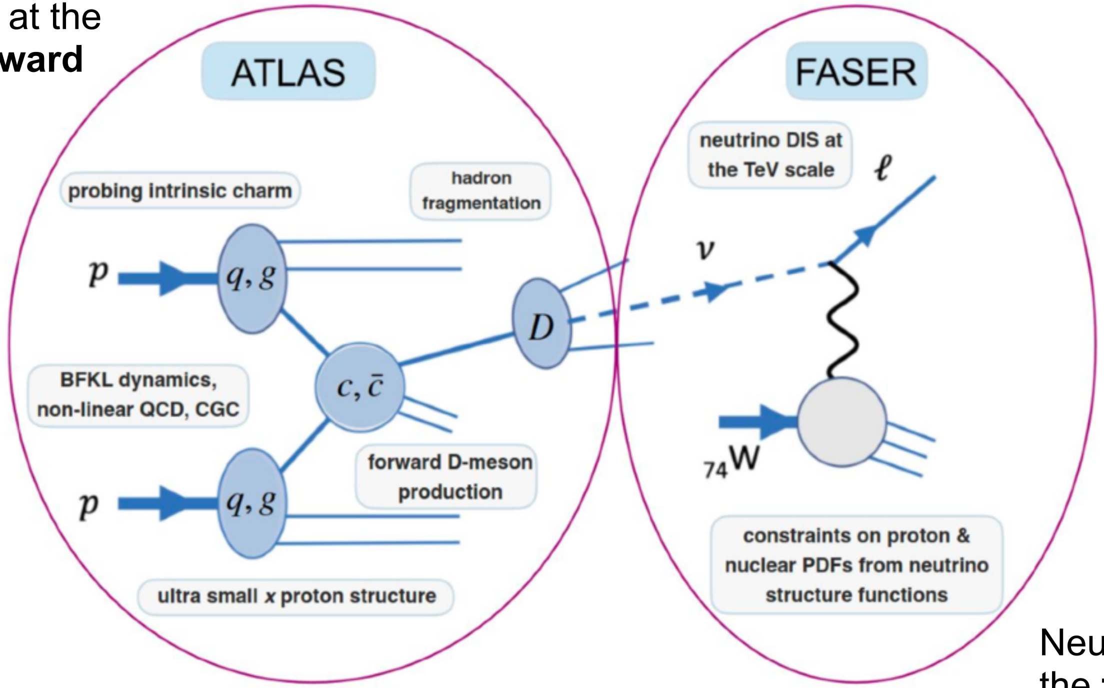


Figure adapted from: J. Phys. G 50 (2023) 3, 030501

Neutrino **interaction** with the **target** (Deep Inelastic Scattering) probes the **proton/nuclear PDF**

Neutrinos at FASER

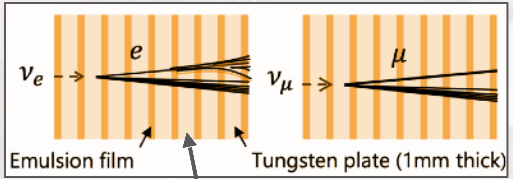
Two methods of detecting collider neutrinos with FASER:

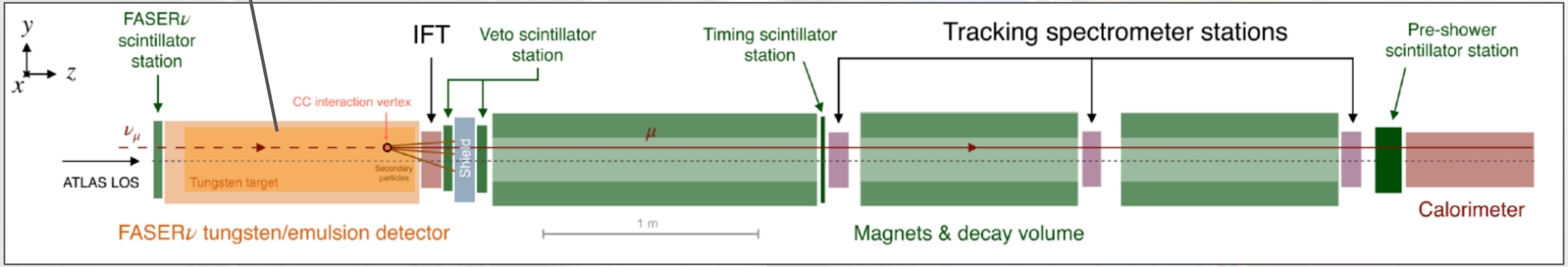
1) Emulsion detector:

- detect **all neutrino flavours**
- excellent spatial resolution
- slow (each film must be scanned, digitised, and processed)

2) Electronic spectrometer:

- fast analysis (only using electronic components of detector)
- separate anti-neutrino/neutrino (muon charge)
- can study only **CC muon neutrino** interactions (so far)



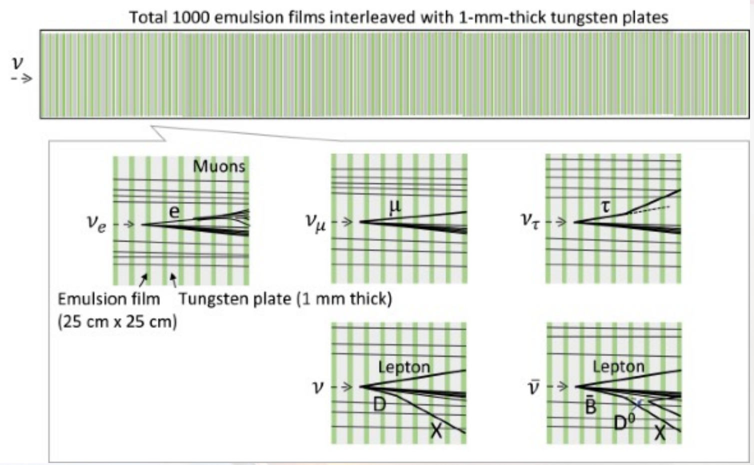


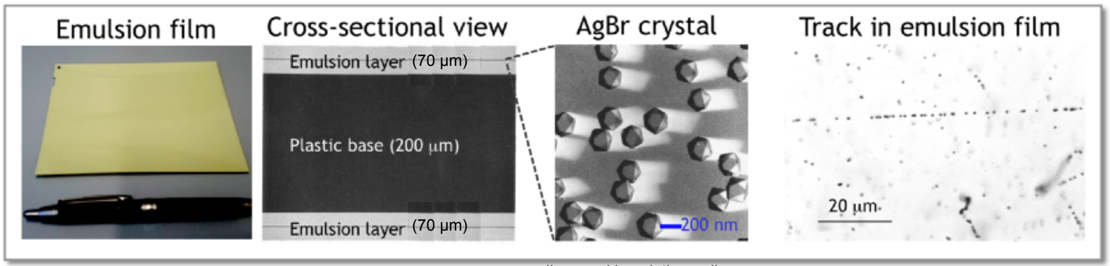
FASERν detector

- FASERν: tungsten emulsion detector
  - 3D tracking detector, 50 nm precision, no timing
  - Total mass 1.2 tons, 285 X_0, 10.1 λ_{int}
- Needs to be exchanged every ~3 months (during technical stops) to control track density $\lesssim 1 \times 10^6$ tracks/cm^3
  - 10 emulsion detectors in total needed for 2021-2024 data

	Interactions	Mean energy
$\nu_e + \bar{\nu}_e$	~1300	~830 GeV
$\nu_\mu + \bar{\nu}_\mu$	~20400	~630 GeV
$\nu_\tau + \bar{\nu}_\tau$	21	965 GeV

Assumptions: tungsten emulsion detector (25 cm x 25 cm x 100 cm), 14 TeV, 150 fb^{-1}, E_ν > 100 GeV



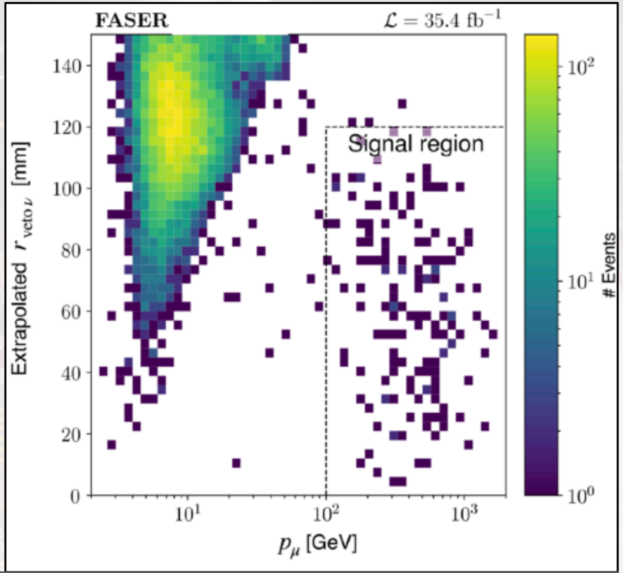


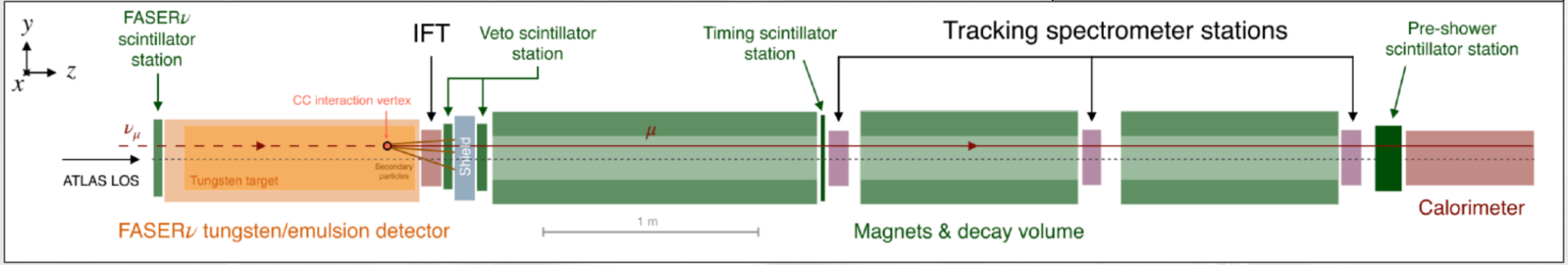
dispersed in gelatin media

PhysRevLett.131.031801

First direct observation of collider neutrinos

- Measure CC muon (anti-)neutrino interactions using electronic components of detector
- Signature selection:
    - No hits in **FASERν scintillator** station
    - Track in spectrometer with **p > 100 GeV**
    - Track within **r < 120 mm** when extrapolated back to FASERν scintillator

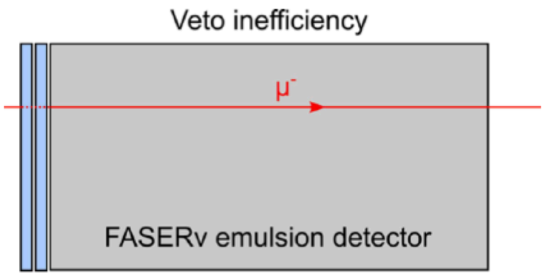




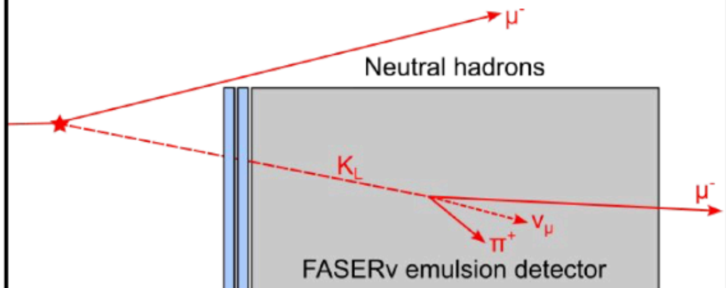
PhysRevLett.131.031801

First direct observation of collider neutrinos

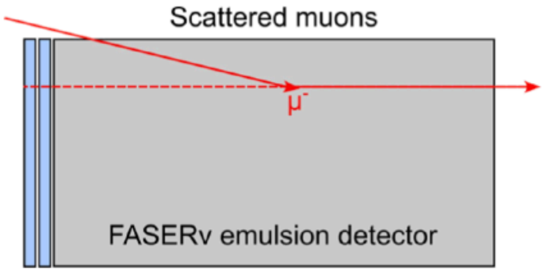
3 background sources:



1) Front-veto inefficiency



2) Background from neutral hadrons



3) Geometric muons

Estimated in **data** comparing hit difference in 1st/2nd layer

Inefficiency is ~10^{-7}, so expect to be **negligible**

Estimated in simulations. Majority of hadrons absorbed in tungsten or parent muon hits veto.

Expect **0.11 ± 0.06 events**

Estimated from control region

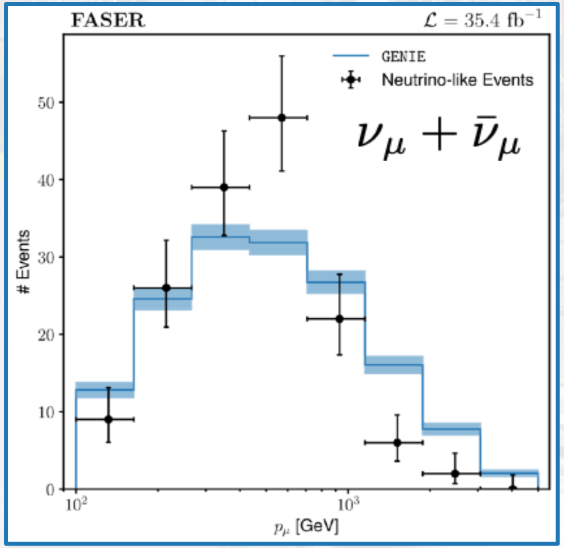
Expect **0.08 ± 1.83 events**

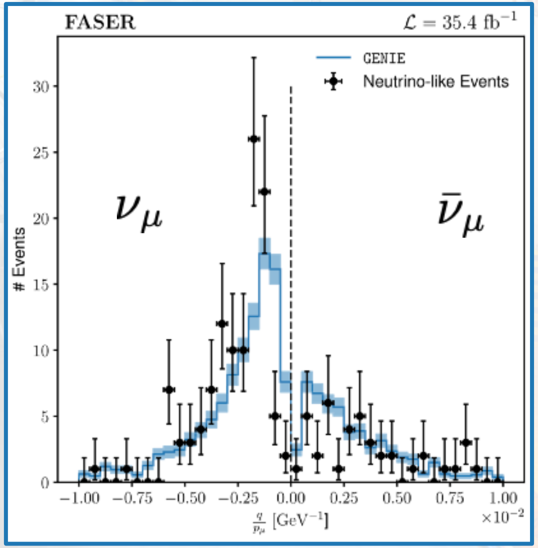
First observation of collider electron neutrinos

Observation with more than **16 sigma significance:**

$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$

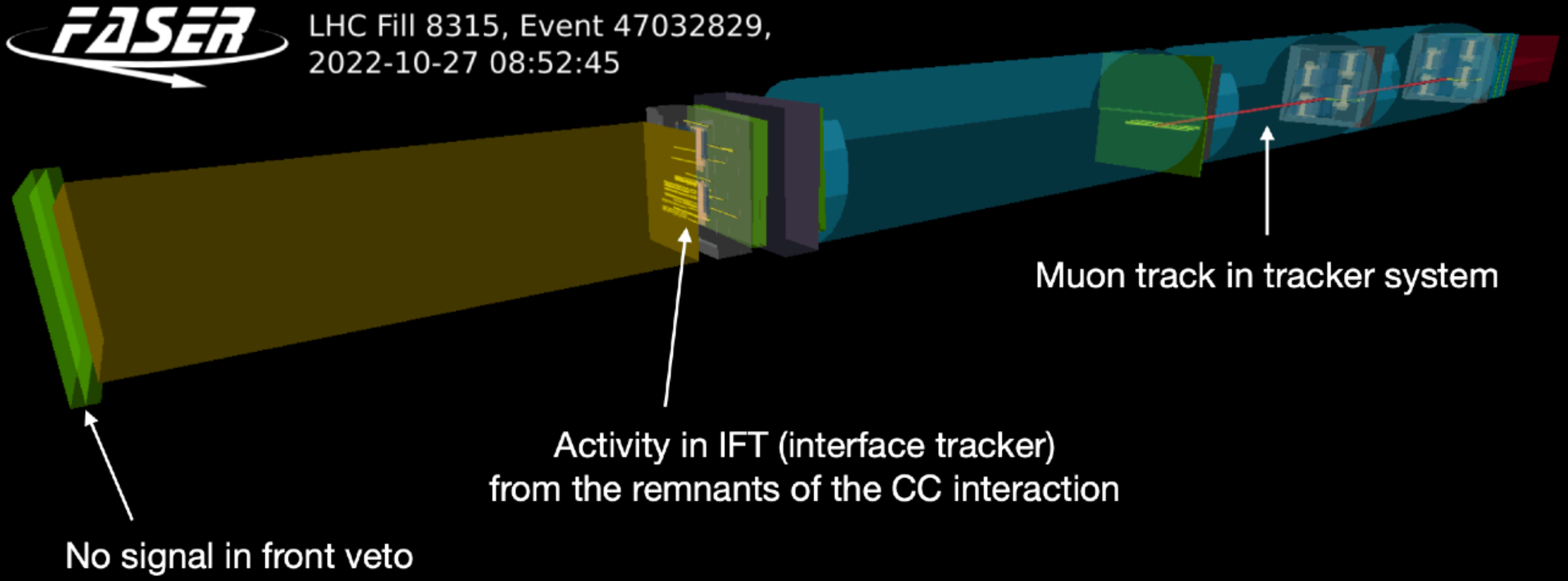
Compatible with **expectation: 151 ± 41**
(from mean/envelope of DPMJET and SIBYLL predictions)





NB: GENIE errors do not include systematic uncertainties on detector effects

Muon neutrino candidate event

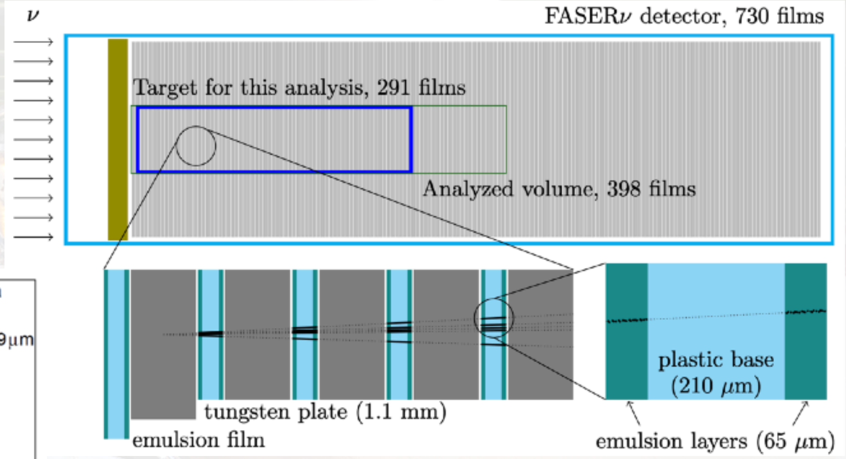


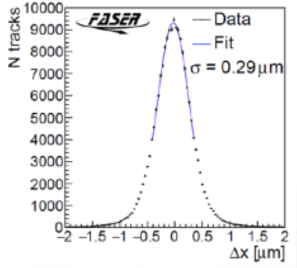
arXiv:2403.12520

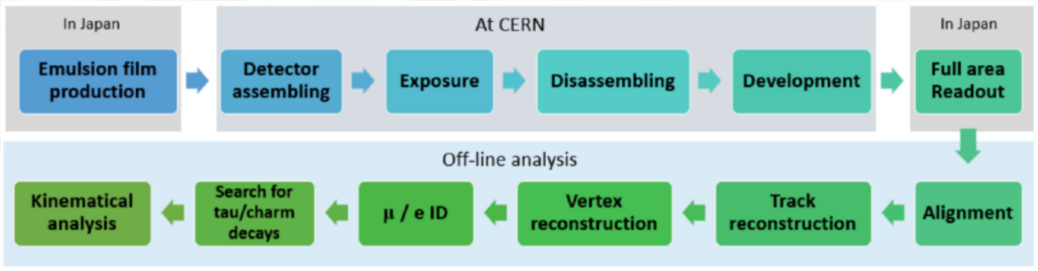
NEW!

First observation of collider ν_e and ν_μ with FASERν

- Analysis of first 9.5 fb^{-1} of data from 2022.
  - Target mass of 128.6 kg
  - ~ 1.7% of data so far





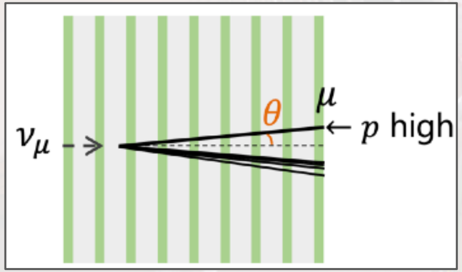


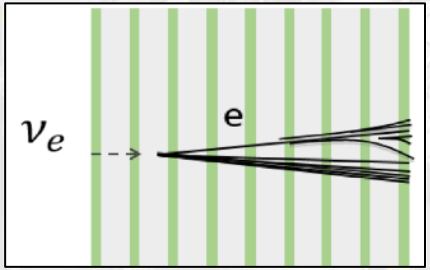
arXiv:2403.12520

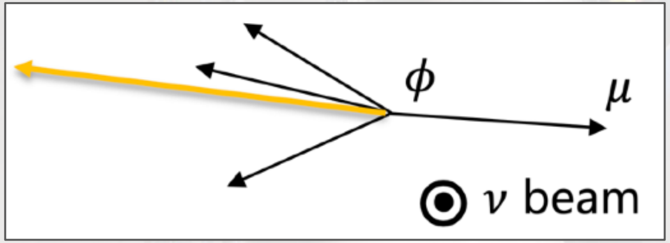
NEW!

First observation of collider ν_e and ν_μ with FASERν

- CC neutrino candidates selected from vertices with at least 5 tracks:
  - **Electrons:** short track, EM shower
  - **Muons**: long track, no secondary particles
- Large angular separation between lepton and CC remnants.

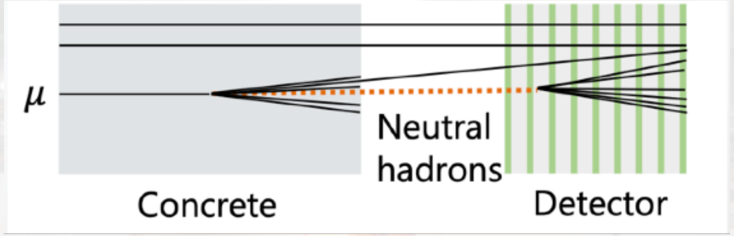






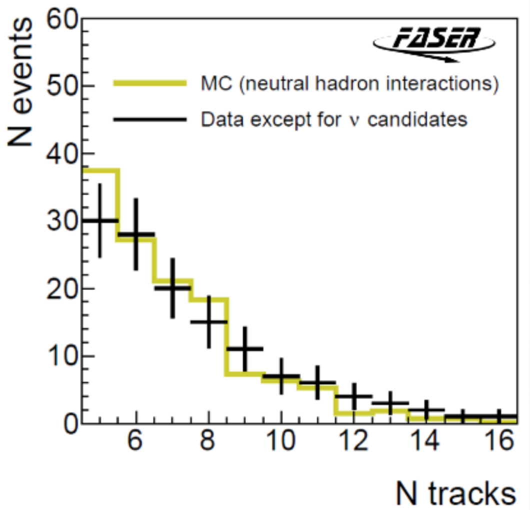
High purity selection
Vertex reconstruction ($N_{\text{track}} \geq 5$, $N_{\text{track}}(\tan\theta \leq 0.1) \geq 4$)
E_e or p_μ >200 GeV
$\tan\theta_e$ or $\tan\theta_\mu$ >0.005
ϕ>90°

First observation of collider ν_e and ν_μ with FASERν



Backgrounds:

- **Neutral hadron** interactions estimated from simulations, validated with data
- **Neutral current** (NC) muon neutrino interactions, estimated in simulation



Total background expectation:

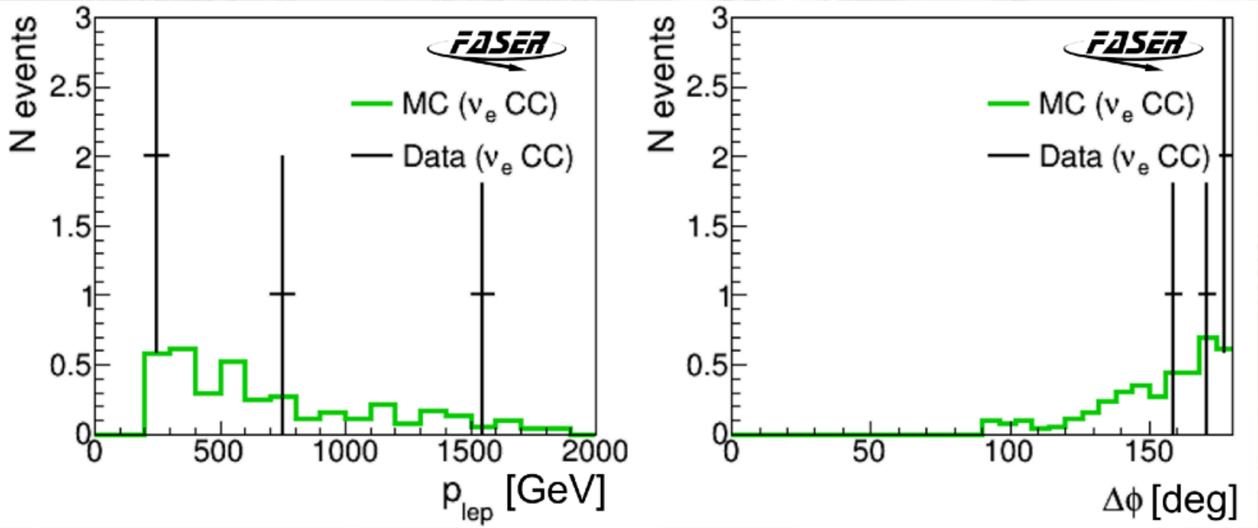
- Electron: 0.025 ± 0.015
- Muon: 0.22 ± 0.09

NEW!

First observation of collider ν_e and ν_μ with FASERν

First observation of collider ν_e

	Expected background	Expected signal	**Observed**	**Significance**
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	**4**	**5.2σ**
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	**8**	**5.7σ**

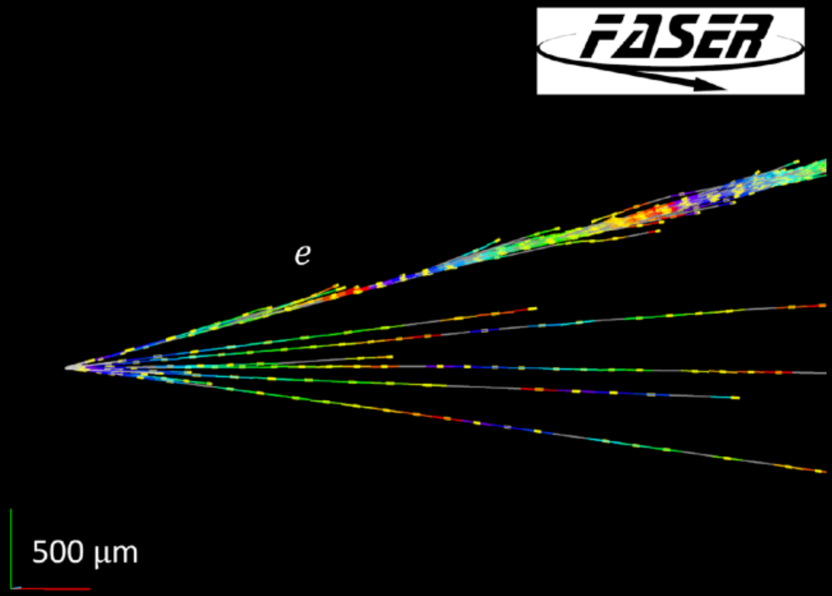


arXiv:2403.12520

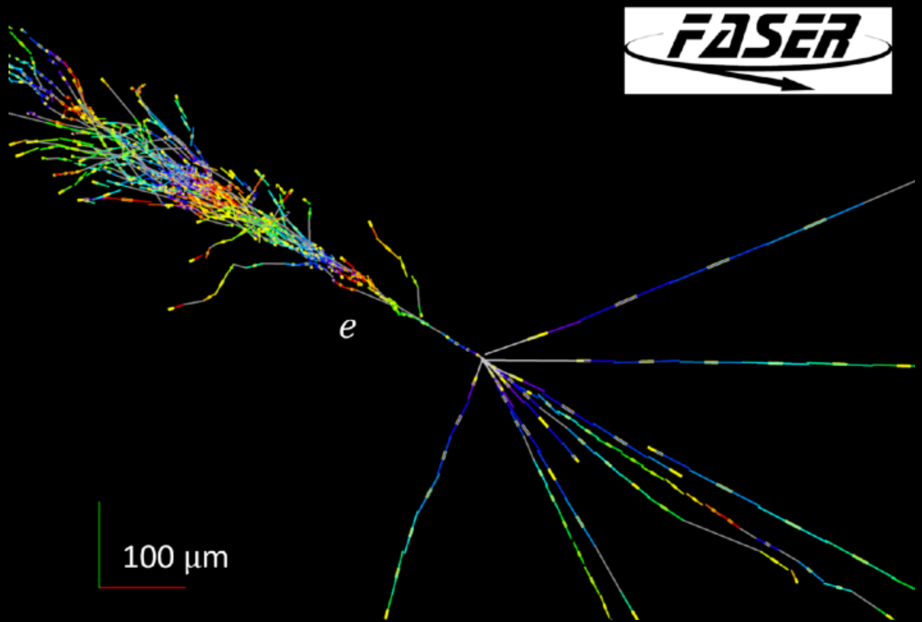
NEW!

Electron neutrino candidate event

Lab view



Transverse plane

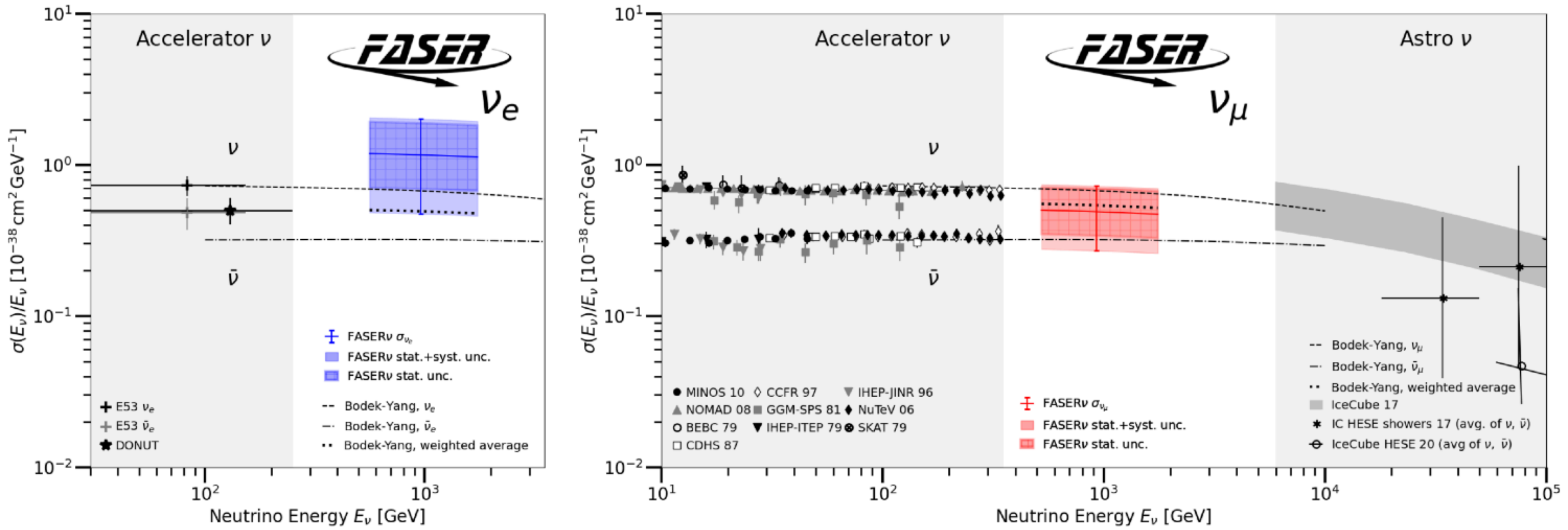


arXiv:2403.12520

NEW!

First observation of collider ν_e and ν_μ with FASERν

First cross section measurements at TeV energies:

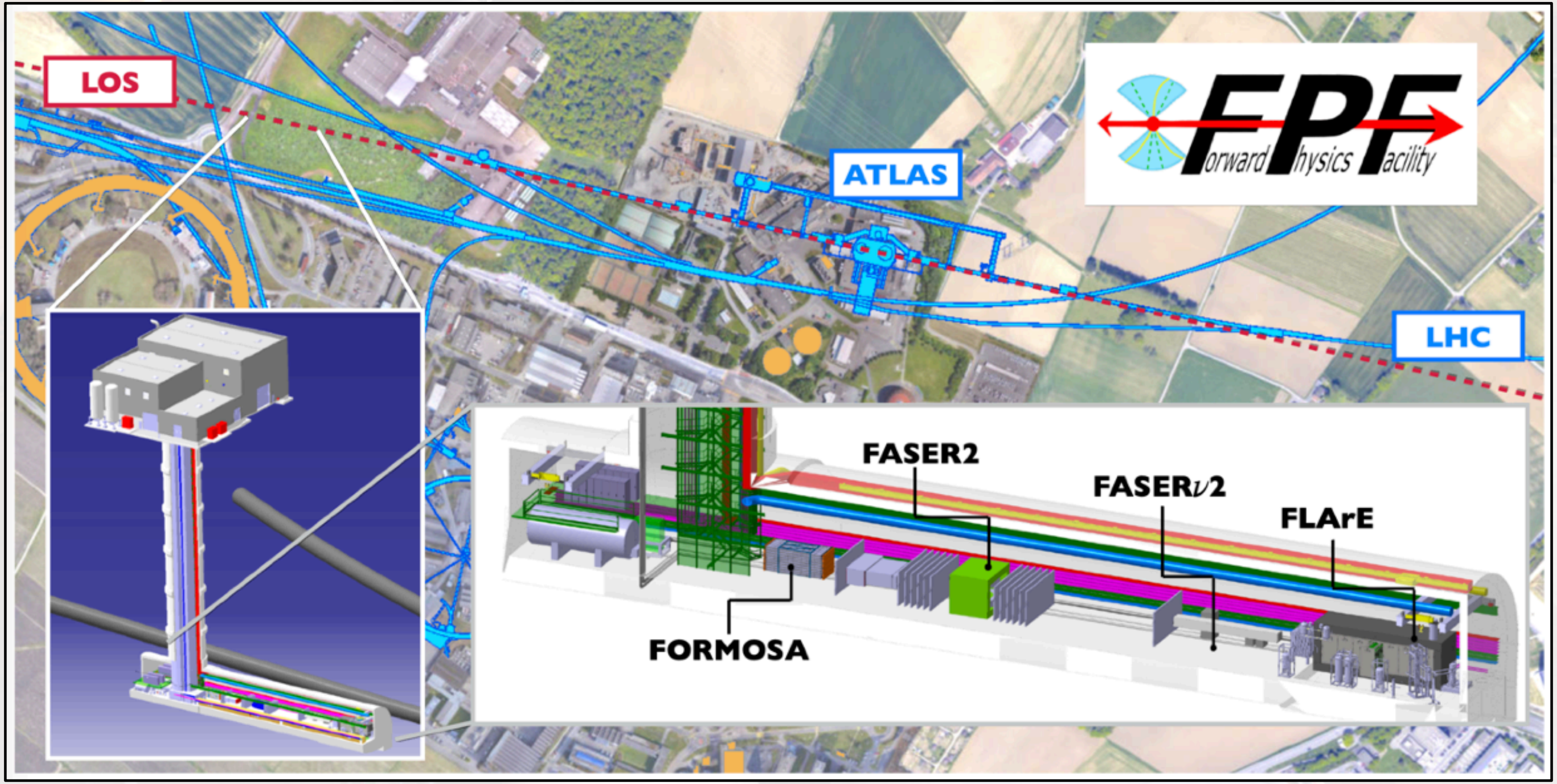


FASER2 and the FPF

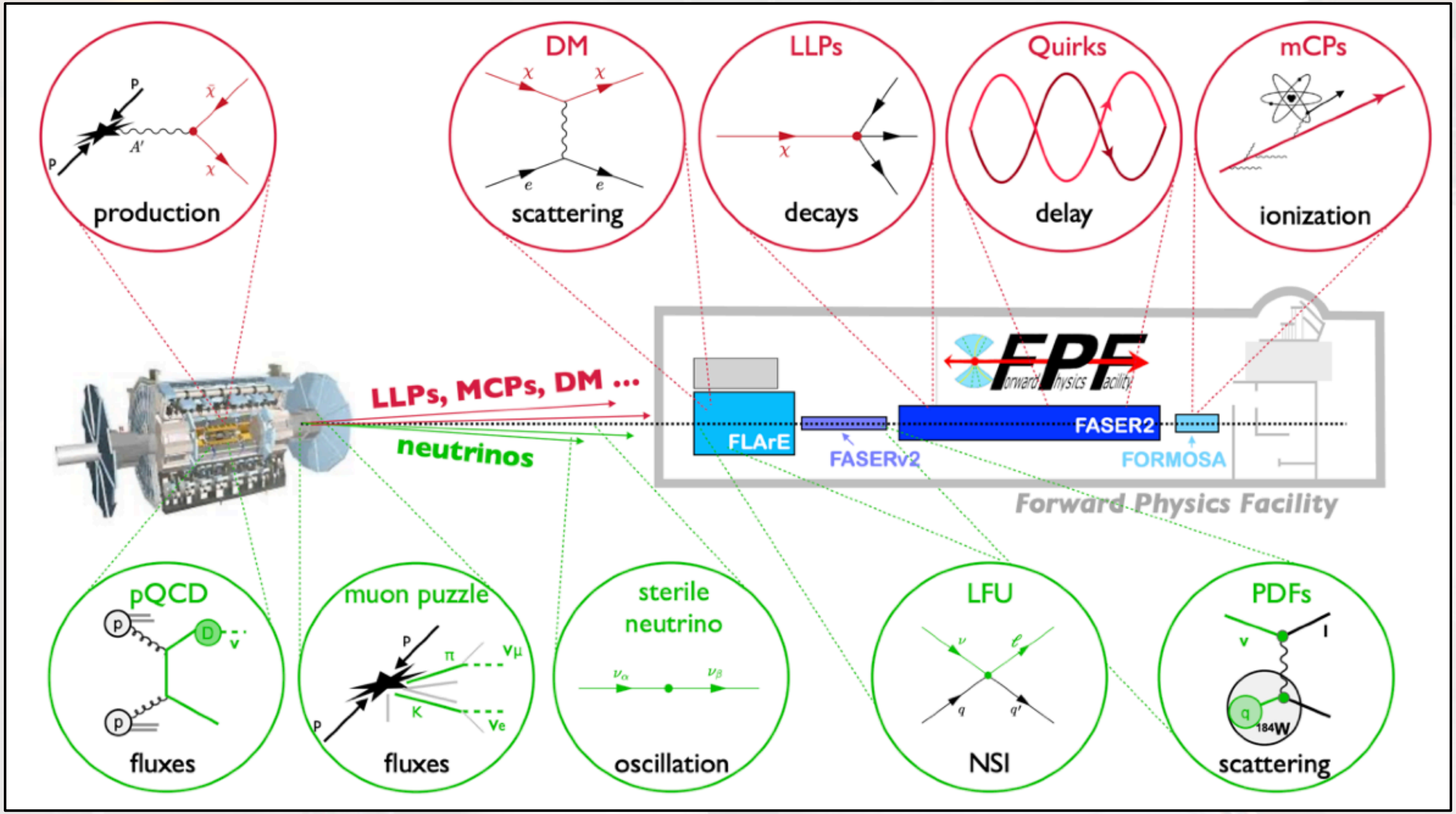
FPF Short Paper: Phys. Rept. 968, 1 (2022)
FPF White Paper: J. Phys. G (2022)
EPPSU contribution

Further forward (to the future): Forward Physics Facility

Proposed dedicated facility for the HL-LHC that could house a suite of experiments.

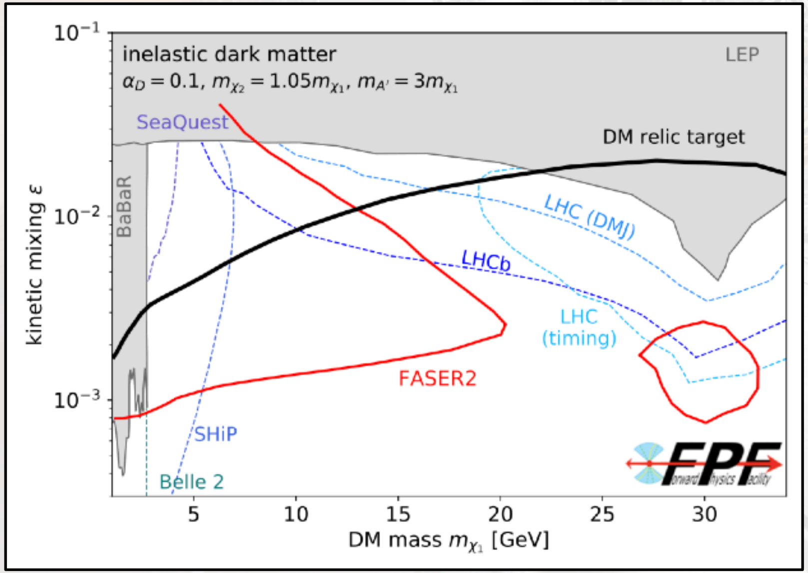


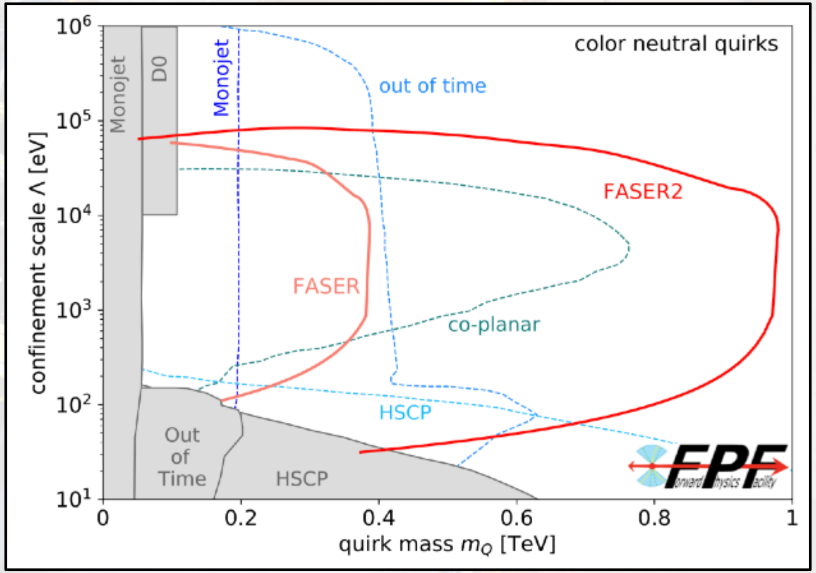
FPF physics overview



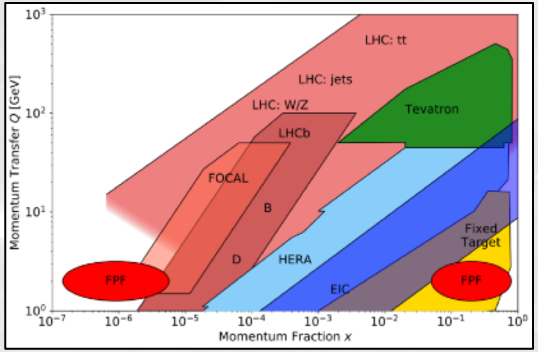
FPF physics: new particles

- FASER2 will be complementary to existing/proposed experiments and uniquely sensitive to certain DM/BSM models e.g. inelastic DM, quirks.

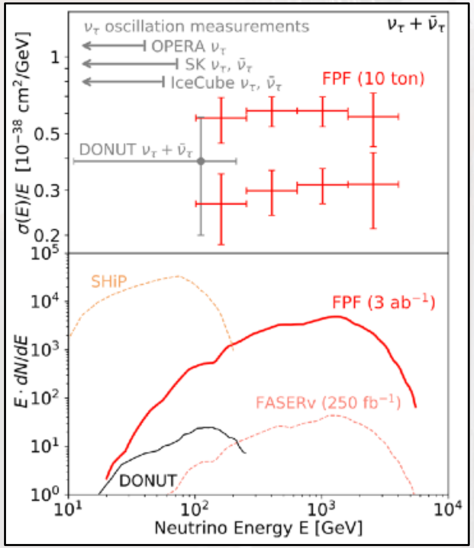


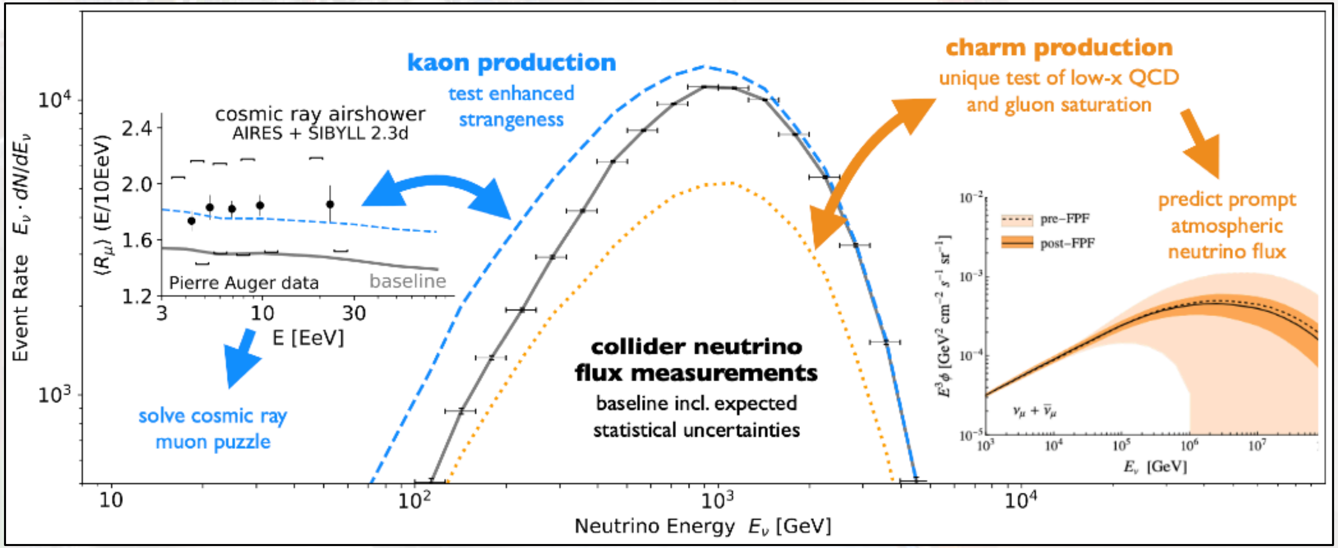


FPF physics: neutrinos

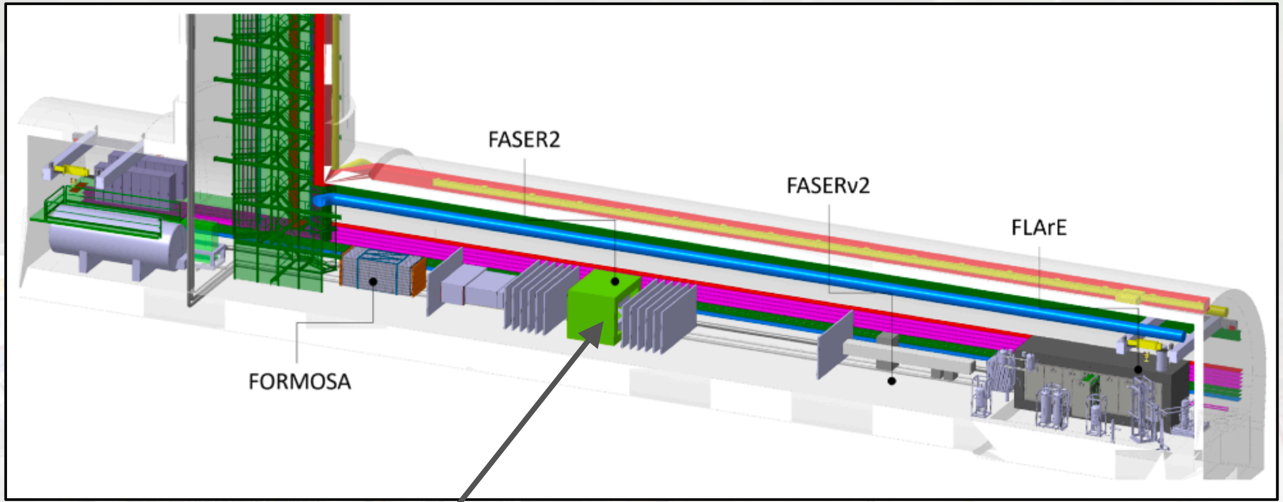


- Study neutrino interactions at TeV energies (including $\bar{\nu}_\tau/\nu_\tau$)
- Study PDFs by neutrino DIS
- Study forward hadron production via neutrino flux measurements

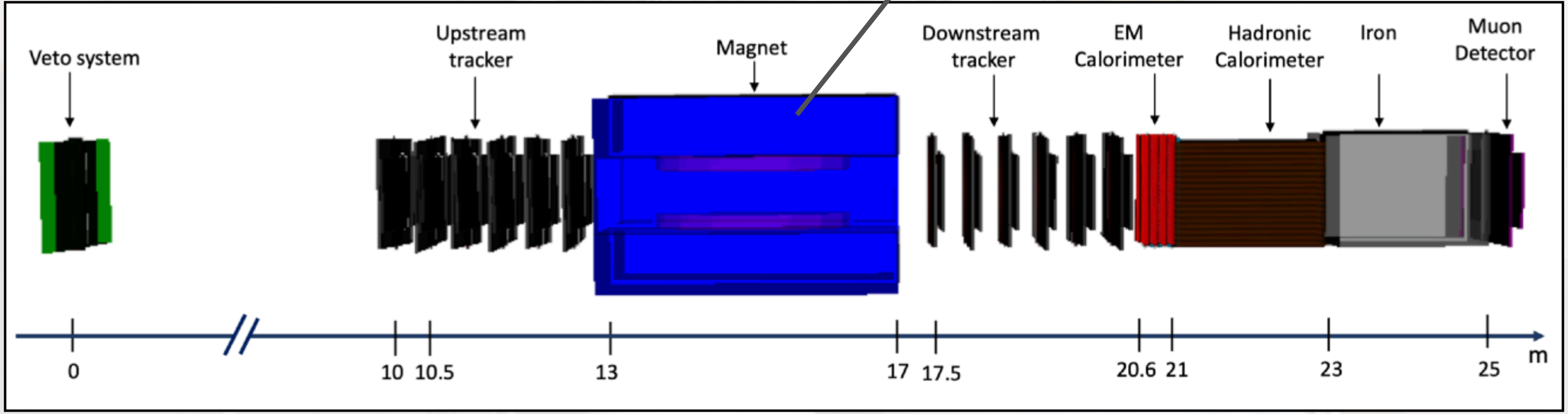


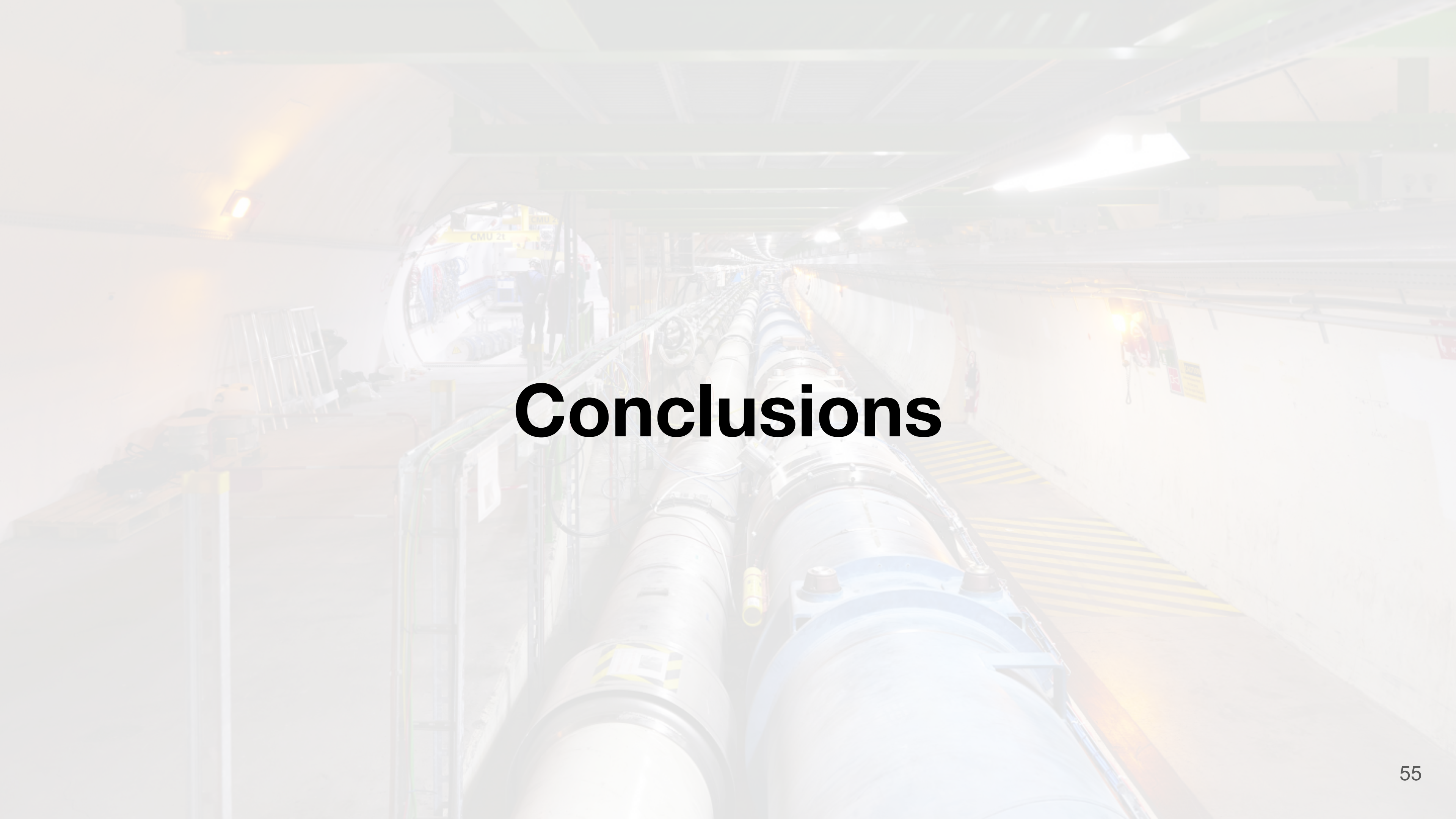


FASER2



FASER2 baseline design





Conclusions

Looking forward to more physics

- Successful operation of FASER in Run-3 (190 fb^{-1} recorded so far)
- First physics results coming out:
  - First ν_e , ν_μ cross sections
  - BSM searches (ALPs and dark photon limits)

- **Prospects**
  - Additional data be collected in 2025 (~100-125 fb^{-1}) & 2026 (~30 fb^{-1})
  - Pre-shower detector upgrade in 2025 to enhance ALPs sensitivity
  - FASER in Run-4 approved
  - Proposed dedicated Forward Physics Facility (2031-) in HL-LHC era that would extend and complement existing/proposed physics programme

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

CERN

erc

Swiss National Science Foundation

科研費 KAKENHI

NSF

Acknowledgements

FASER is supported by:

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

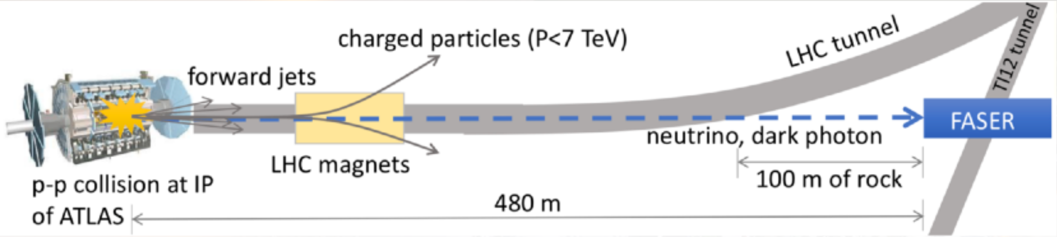
Additional slides

FASER Collaboration

89 collaborators, 25 institutions, 10 countries

International laboratory covered by a cooperation agreement with CERN

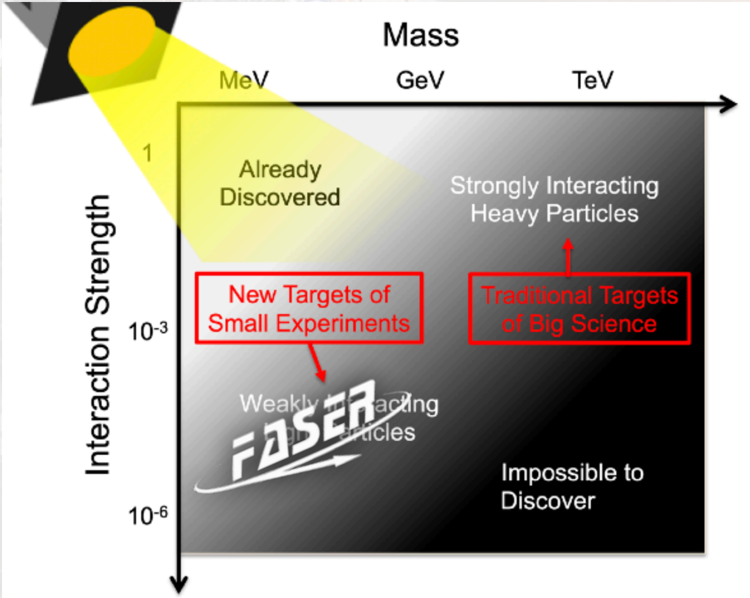
ForwArd Search ExpeRiment



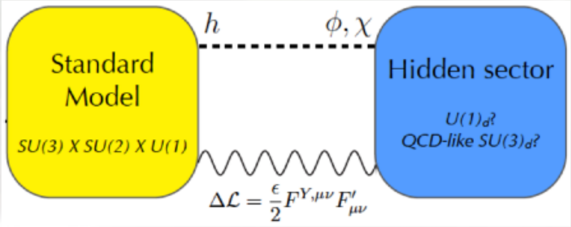
- A **new small experiment** in an old LEP injector tunnel to search for **long-lived particles** produced in Interaction Point 1 (IP1/ATLAS) at the **LHC** in Run-3 and beyond (2021+).
- First concept in **2017** (Feng, Galon, Kling, Trojanowski), approved by CERN in **March 2019** (limited budget ~ 2M$).
- To be fully built & installed in the current **Long Shutdown** (2020).
  - Detector concept: constructed and installed quickly & cheaply (reuse detector components), simple and robust design (limited tunnel access), minimise services (ease for installation).
- 65 collaborators, 19 institutions, 8 countries.

The light, weakly interacting frontier

- Light, weakly interacting particles can travel macroscopic distances before decaying.



Light and weakly coupled



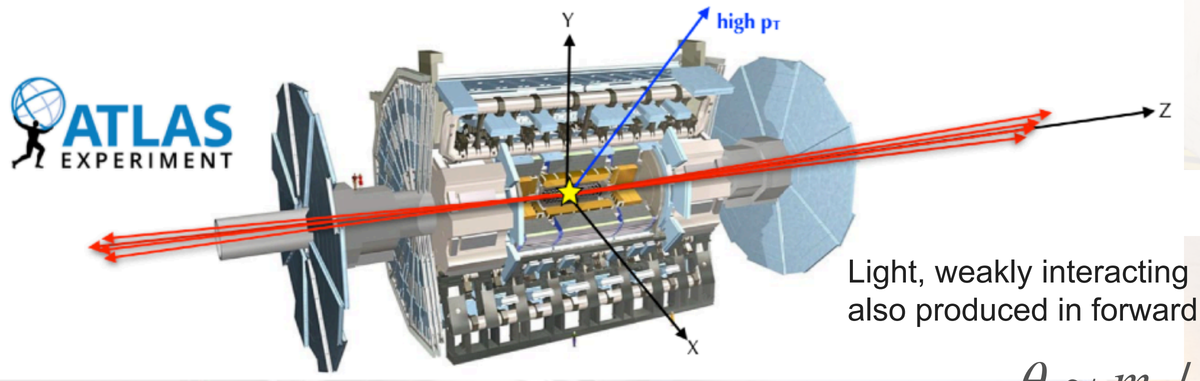
$$\boxed{\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}}$$

- **Hidden sector** physics:
  - New mediating particles, couplings to SM via mixing with SM “portal” operator
  - Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations…
  - Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)
- Typically long-lived particles (**LLPs**) that travel macroscopic distances before decaying to SM particles.

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

Looking forward

- ATLAS/CMS searches for heavy, strongly interacting new particles (high p_T, isotropic)
- If new particles light and weakly coupled, cross sections in acceptance of ATLAS too low
  - **Light**: produced in pi, K, D, B decays
  - **Weakly-interacting**: need extremely large SM event rate to see them
- Benefit from high rate of of hadrons produced in ATLAS in forward region.



Light, weakly interacting particle from e.g. π decay also produced in forward region:

$$\theta \sim m_\pi / E \sim \text{mrad}$$

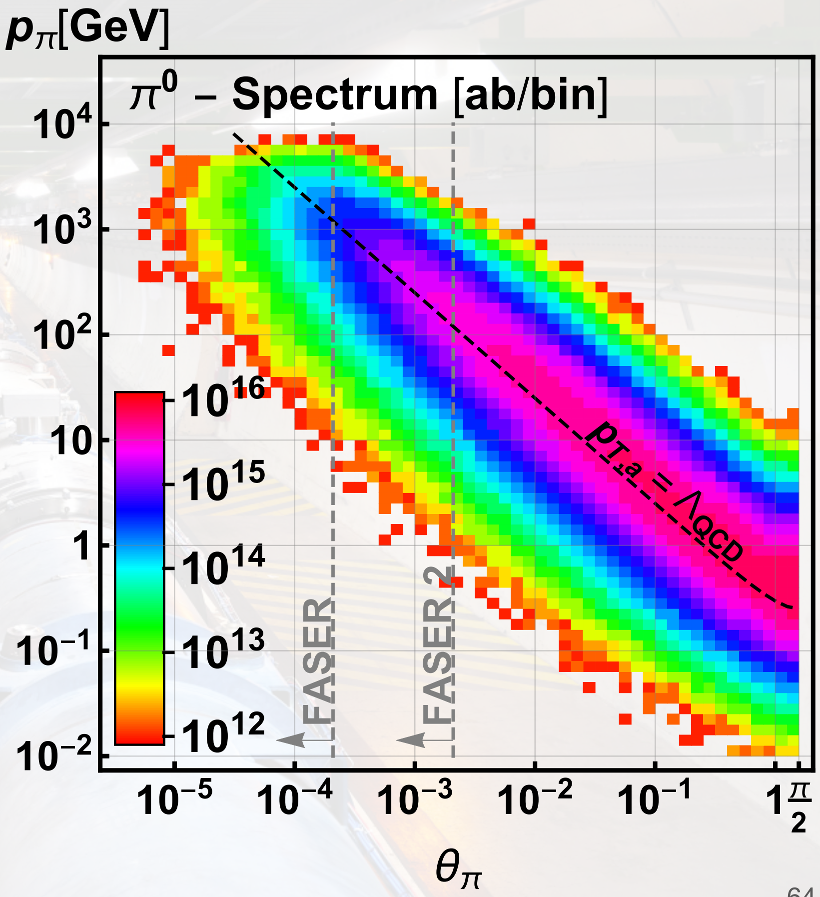
(for E ~ TeV)

σ_{inel}(13 TeV) ~ 75 mb, N_{inel} (Run3, 150 fb^{-1}) ~10^{16}

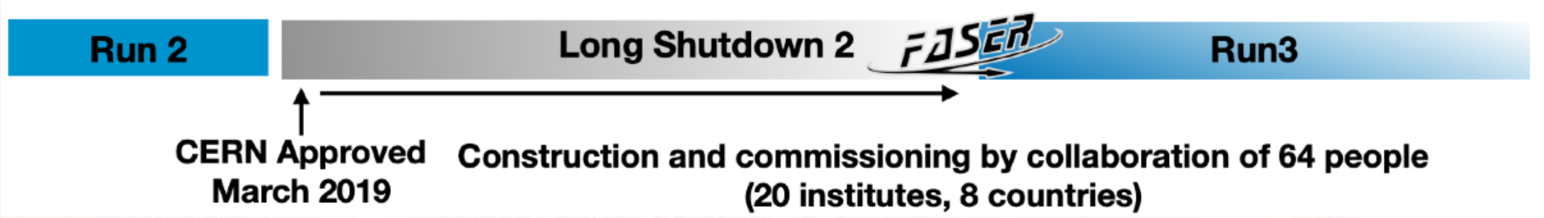
(mostly in forward region)

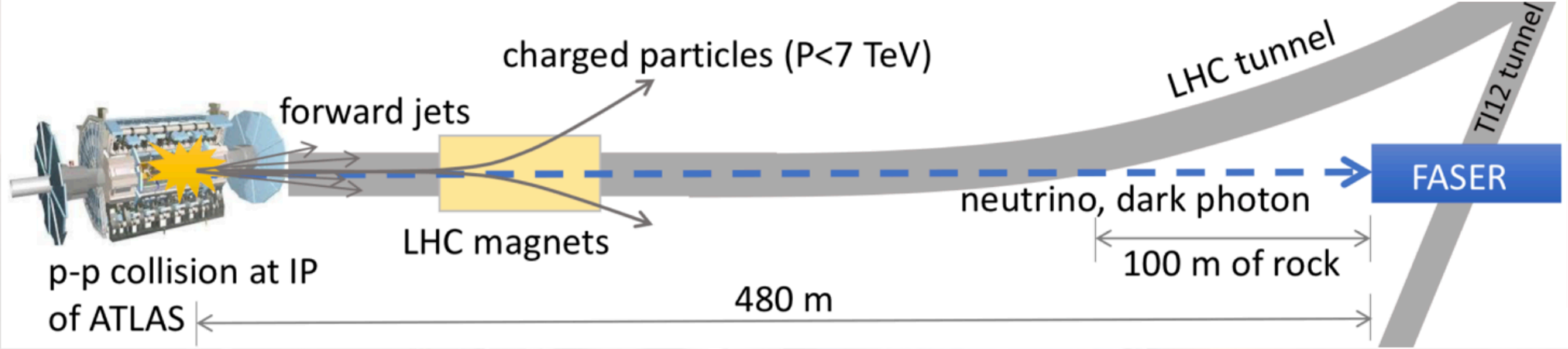
Looking forward

- Expect in forward region during Run-3 (150 fb^{-1})
  $\sim 2.3 \times 10^{17}\ \pi^0$, $\sim 2.5 \times 10^{16}\ \eta$, $\sim 1.1 \times 10^{15}\ D$, $\sim 7.1 \times 10^{13}\ B$
- For E(π^0) > 10 GeV, 2% of π^0 within 10 cm of line-of-sight of beam after ~500 m, despite only covering (2x10^{-6})% of solid angle



FASER: ForwArd Search ExpeRiment



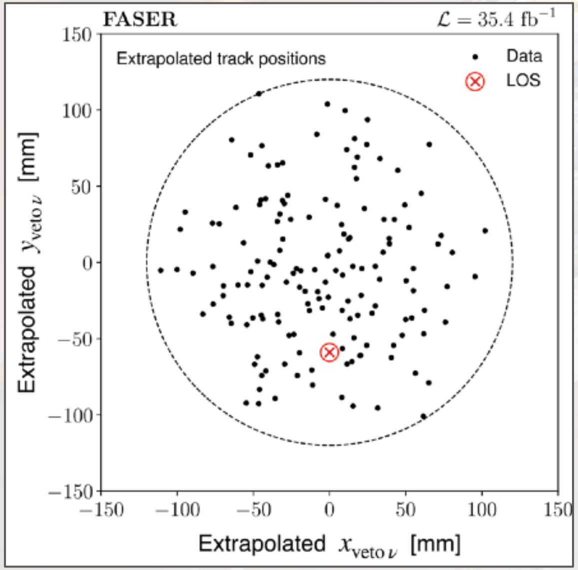


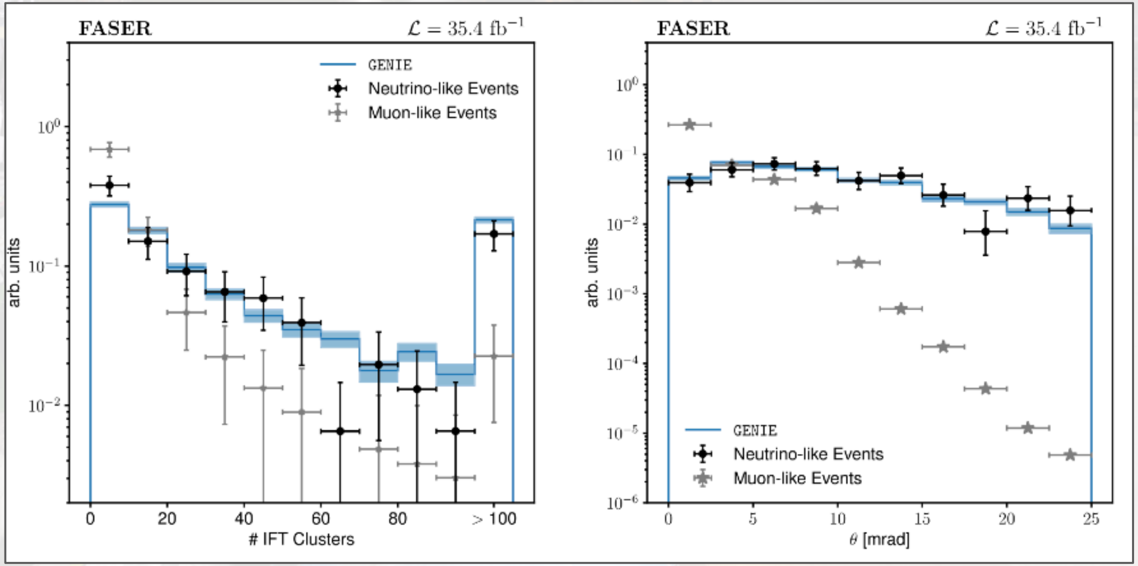
Neutrinos passing through FASER

For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERν	$\sim 10^{10}$	$\sim 10^{11}$	$\sim 10^{8}$
# interacting in FASERν	≈200	≈1200	≈4

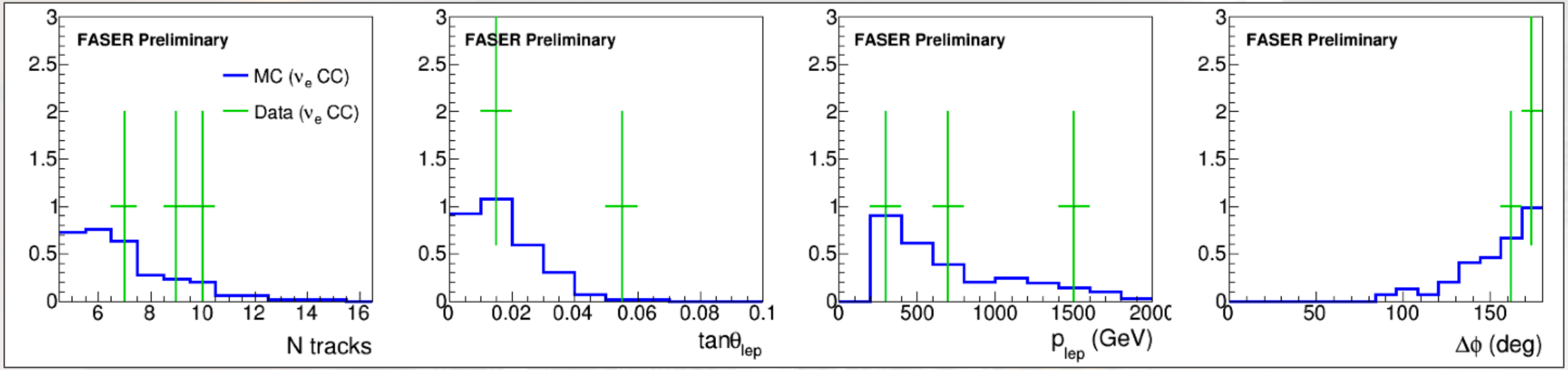
[PRD 104, 113008]

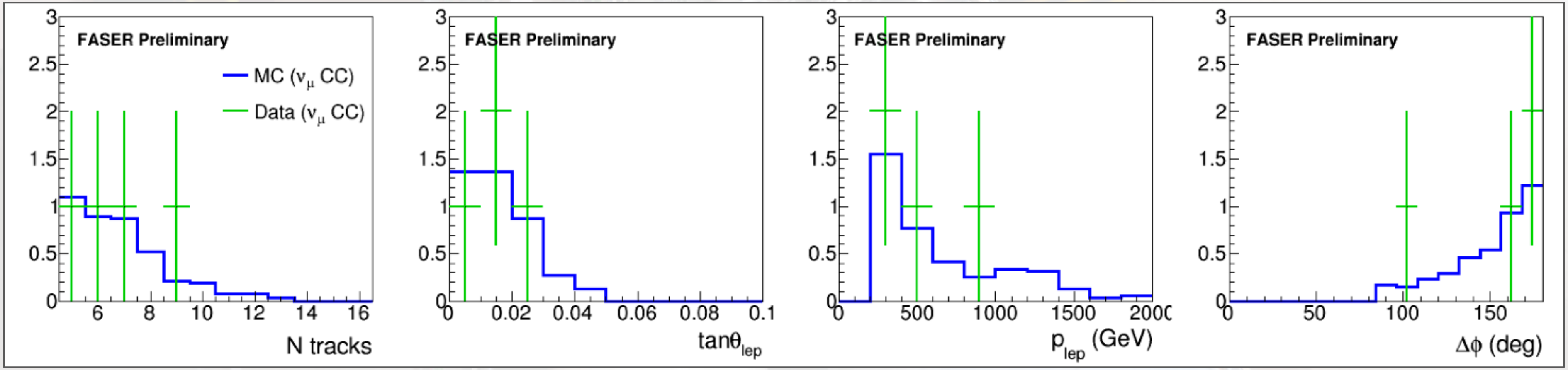
Electronic neutrino analysis distributions





FASERν selected CC candidate events

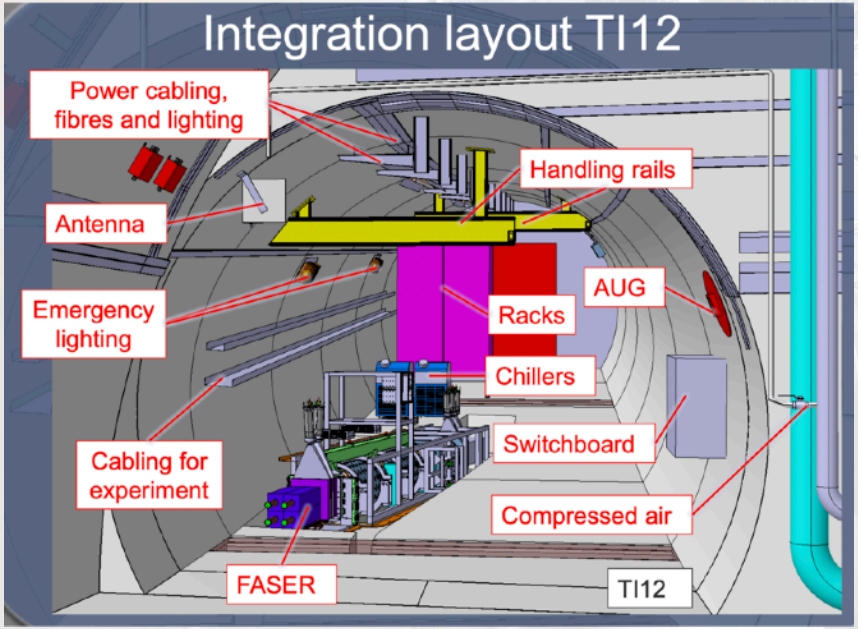


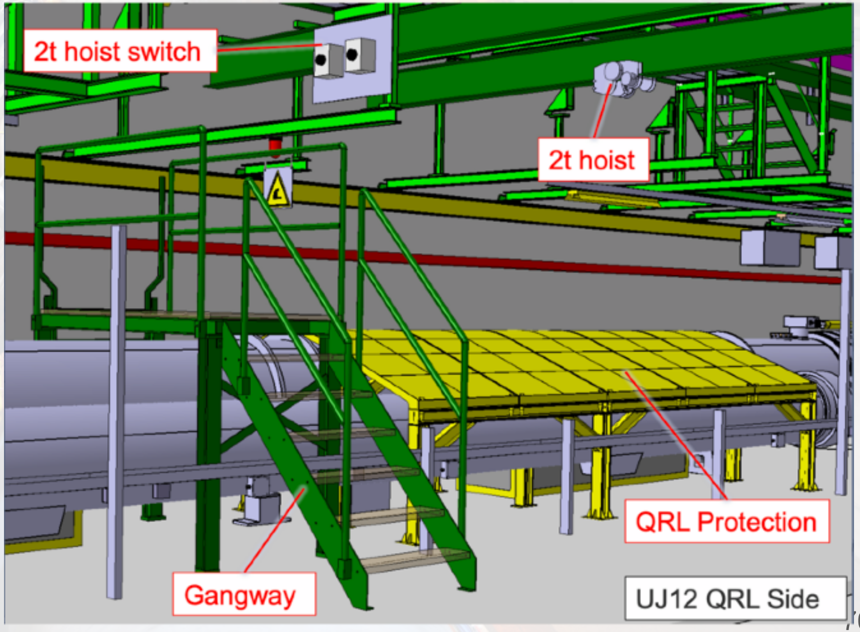



CMU 2t
CMU 2t
2t
To ATLAS
FASERnu
IFT
Veto
Decay volume
Tracking spectrometer
Calorimeter
Preshower

Preparation of TI12/UJ12

- Significant work to prepare TI12 for FASER, including lowering of floor by ~50 cm and installation of gangway/protective shield.





Preparing TI12

- Unused ventilation and cable trays removed.
- TI12 sealed off with dust-proof tent.

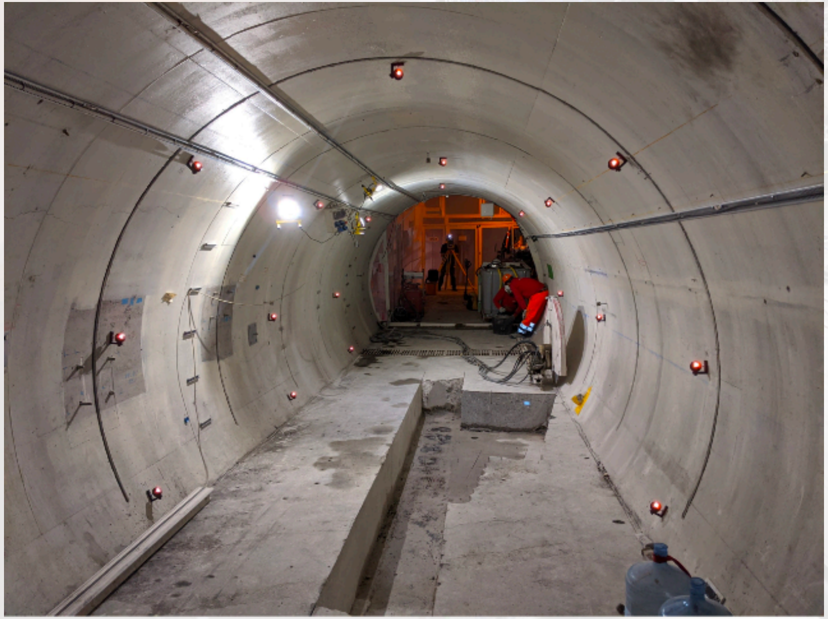
Visit to TI12 Dec 2019

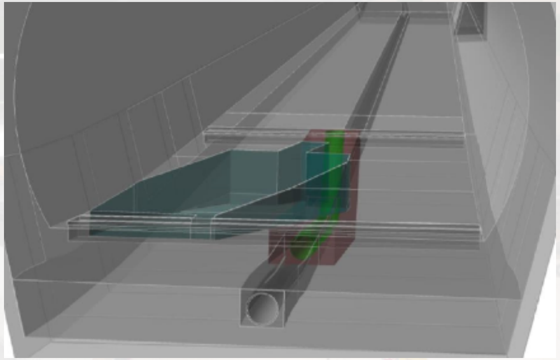
Some of the FASER Collaboration in TI12

TI12

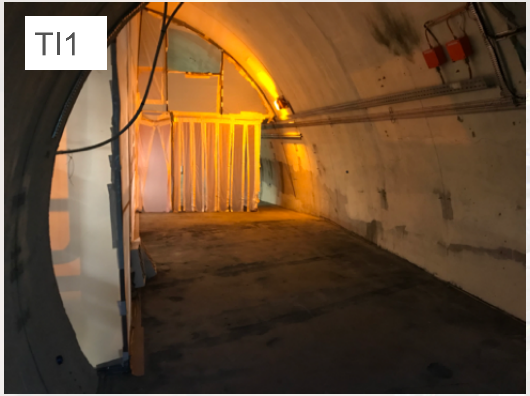
UJ12

Digging the trench



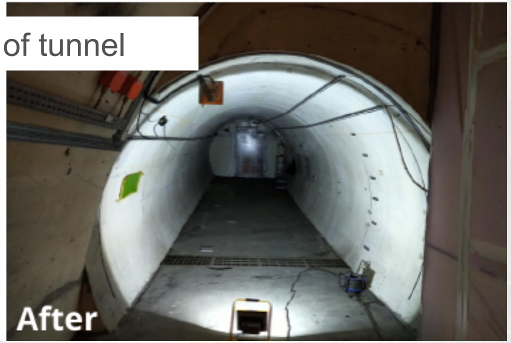


Civil engineering


TI1


UJ1

Preparation of tunnel



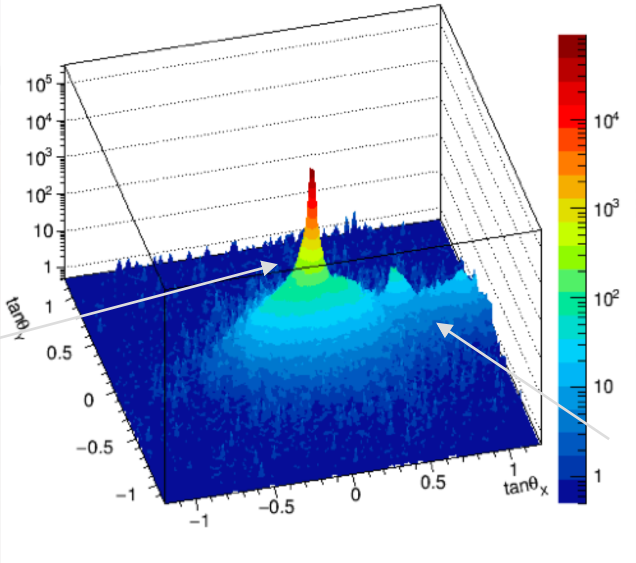
Handling rails


Baseplate

Beam backgrounds

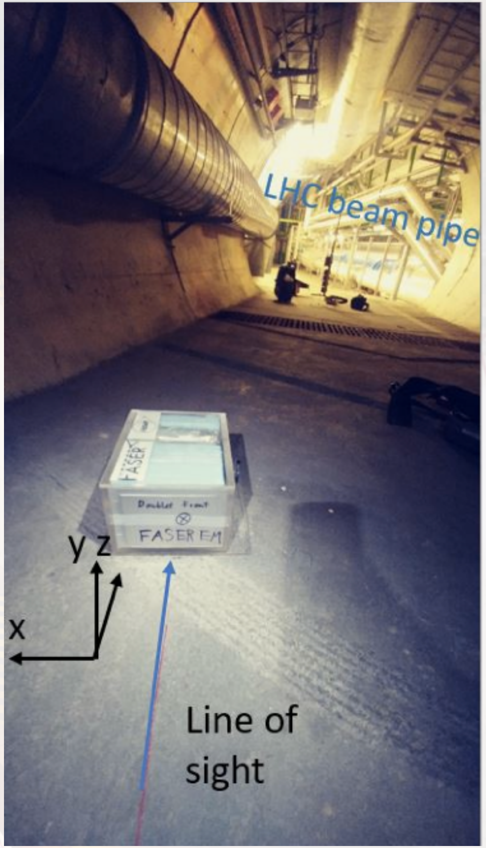
- *In situ* measurements using emulsion detectors and TimePix BLM in TI12 in 2018 confirm expected particle flux, and correlation with IP1 luminosity.

Angular distribution of particles in emulsion detector



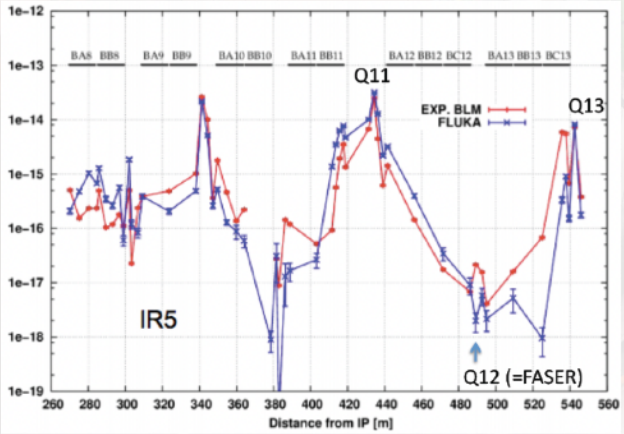
Particles from IP1

Particles from beam background

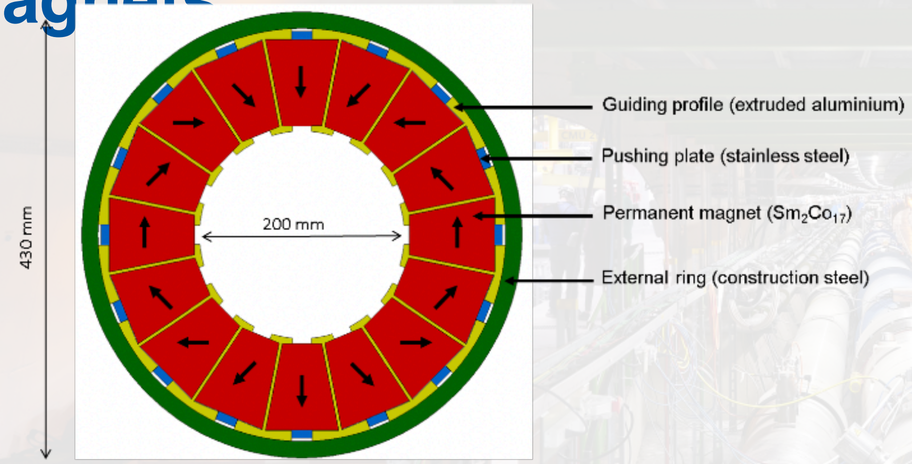


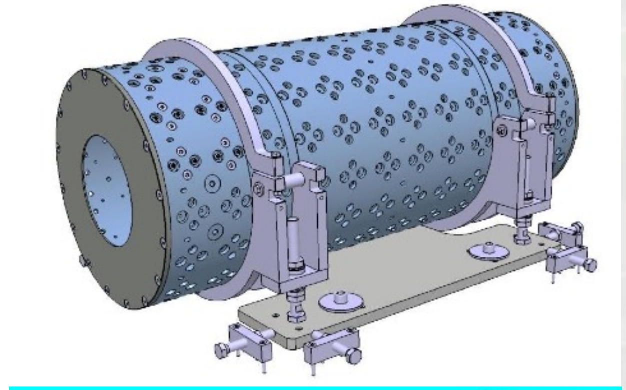
Radiation levels

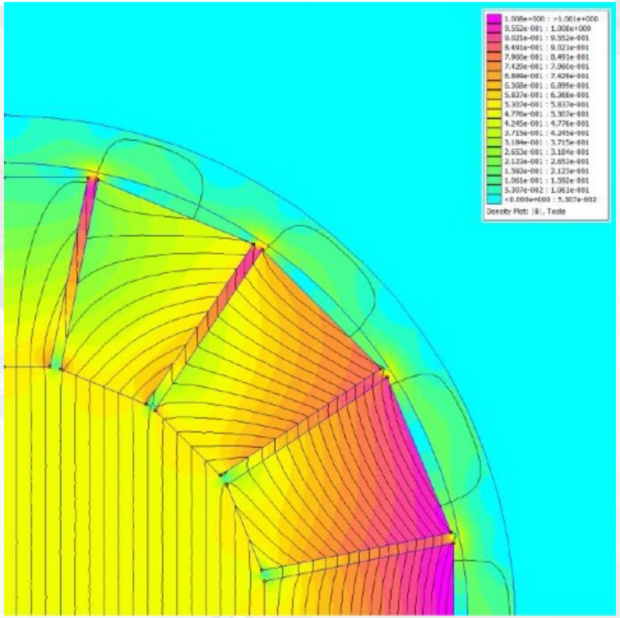
- Radiation level predicted to be very low in TI12 due to dispersion function of LHC at TI12.
- Measurements using BatMon radiation monitor in 2018 confirm FLUKA expectations:
  - less than 5 x 10^{-3} Gy/year
  - less than 5 x 10^{7} 1 MeV neutron equivalent fluence/year
- **FASER detector does not need radiation hard electronics**



Magnets



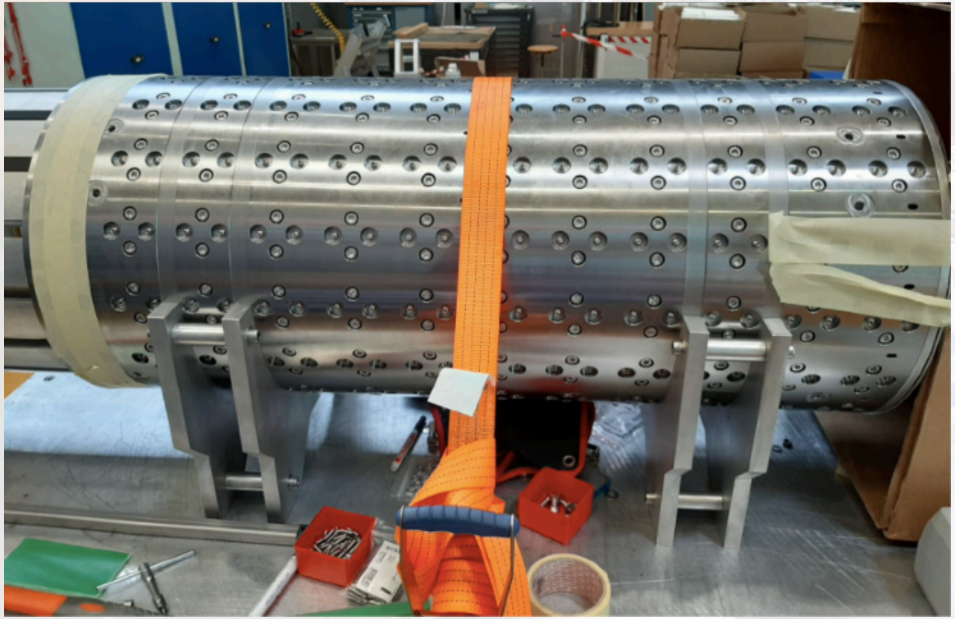




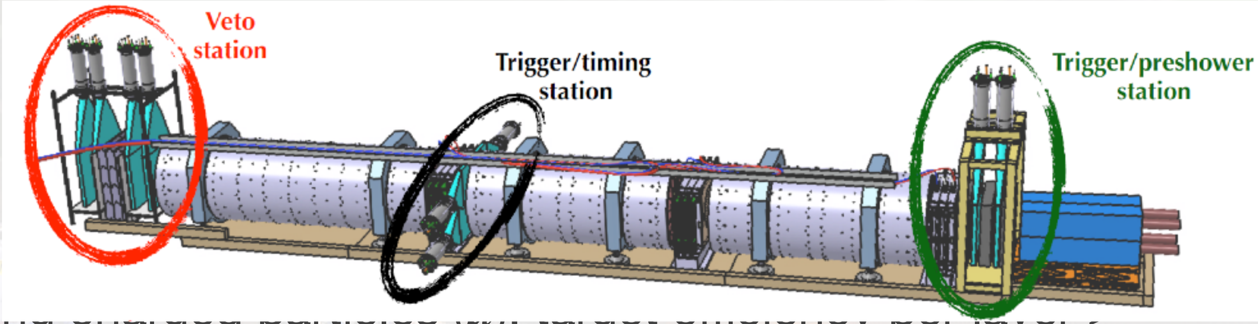
- The FASER magnets are **0.55T** permanent dipole magnets based on the **Halbach array design**
    - 1x magnet 1.5 m (decay volume)
    - 2x magnets 1.0 m for spectrometer
- Thin to minimise digging in tunnel floor
- Minimise services (power, cooling, etc.)

Magnets

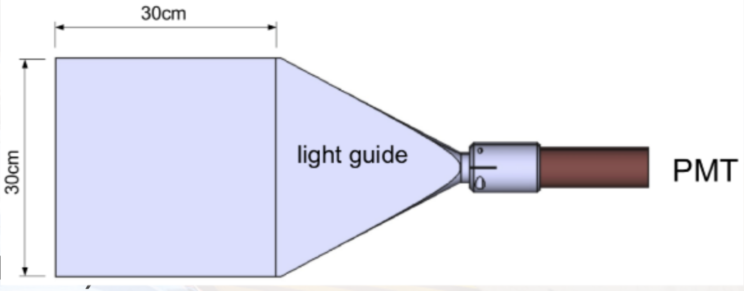
- First two magnets (1m) assembled. Third 1.5m decay volume magnet expected by the end of October.



Scintillators

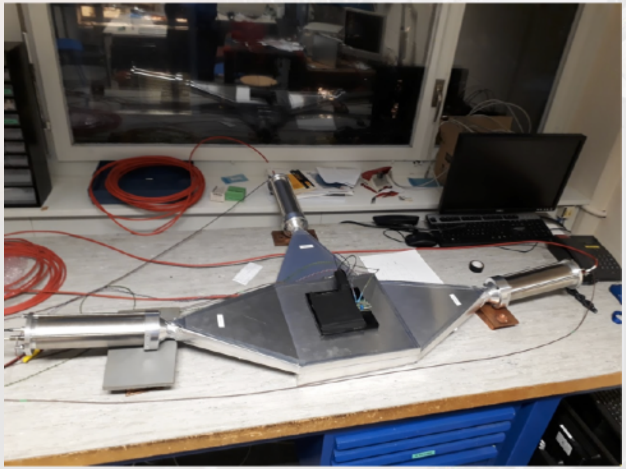


- **Veto station:**
  - Suppress incoming charged particles (μ), target efficiency per layer > 99%
  - Pb absorber (20 X_0) for γ conversion to be vetoed by scintillator
- **Trigger/timing:**
  - Target timing resolution < 1 ns
  - Light guides bent 90° to reduce width
- **Trigger/preshower:**
  - Trigger (coincidence with other trigger sta
  - Pb preshower layer (conversion + ID of γ) + low-Z absorber to reduce calorimeter backsplash

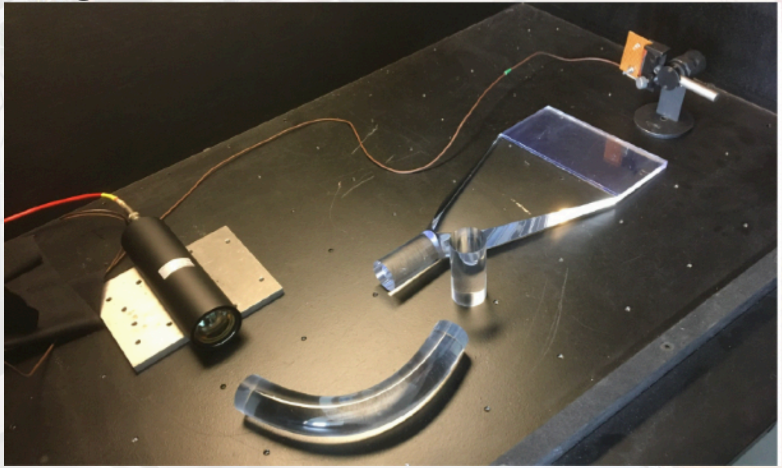


Scintillators

- Scintillator planes produced at CERN
- Characterisation of scintillator, light guides, and PMTs ongoing.
  - Scintillator layers tested with cosmic measured > 99.8% efficiency.
  - Readout through CAEN digitiser validated.



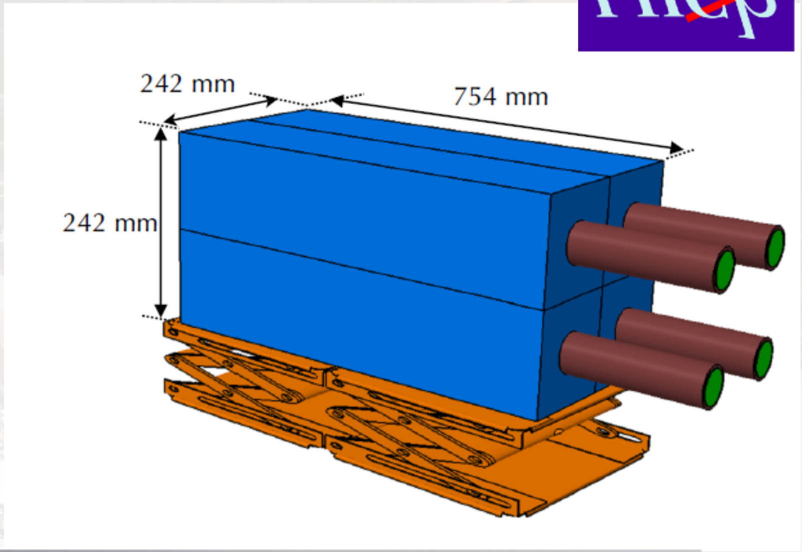
Cosmic tests

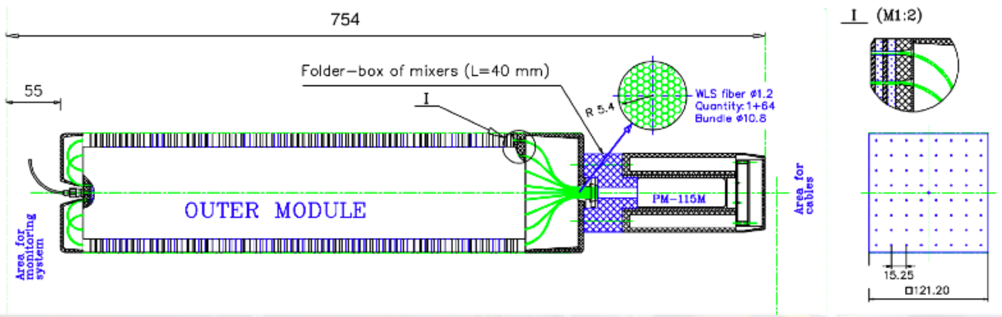


Scintillator with curved light guide

Calorimeter

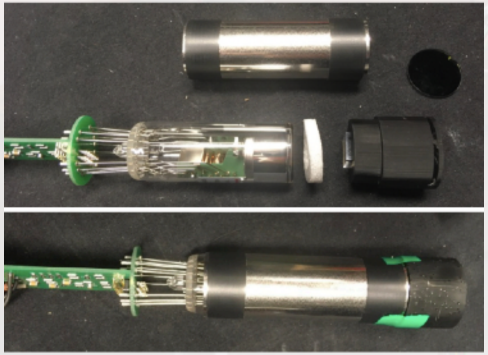
- EM calorimeter for energy, electron/γ ID, triggering
  - Build from 4 spare LHCb outer ECAL modules
  - Thanks to the LHCb Collaboration!
  - 66 layers x (2mm Pb + 4mm plastic scintillator), **25 X_0**
  - ~1% energy resolution, light read by single PMT

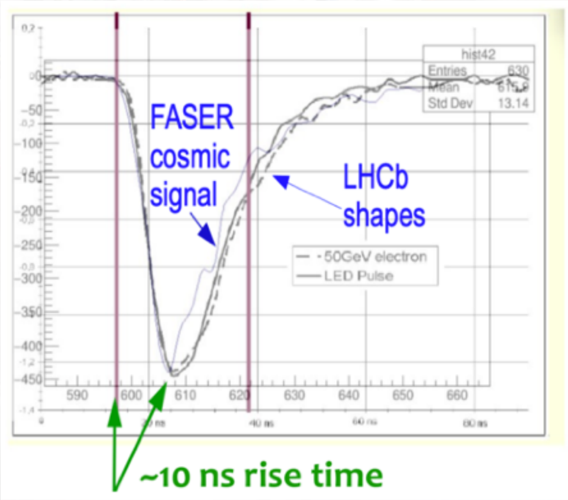


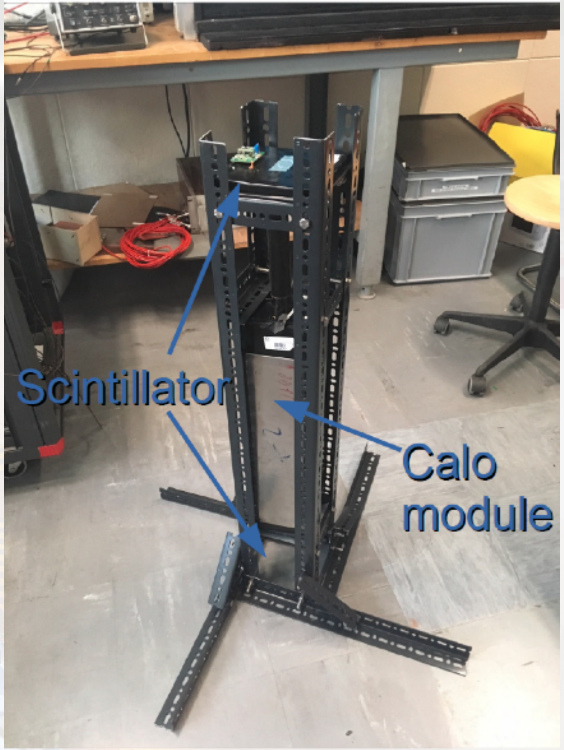


Calorimeter

- Calibration/tests using both ^{137}**Cs** source and **cosmics setup and running**
- Cosmic-ray test stand to allow combined testing of scintillator stations and calorimeter
    - Calorimeter performing as expected



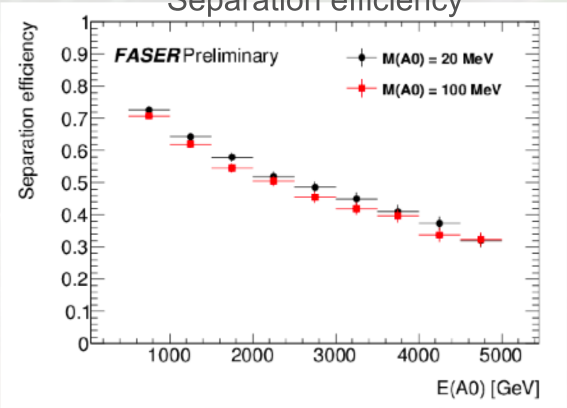


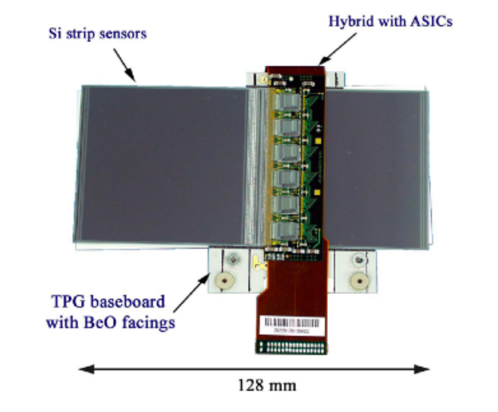


Tracker overview

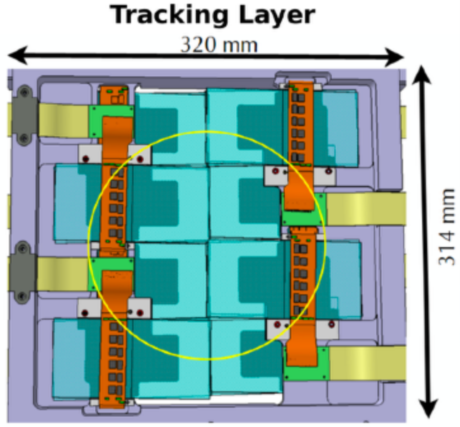
- 3 tracking stations, each containing 3 layers
  - Each layer uses 8 spare ATLAS SCT barrel modules
    - Thanks to the ATLAS Collaboration!
  - 80 μm strip-pitch, 40 mrad stereo angle, 1536 channels/module
- 80 SCT modules tested and confirmed as good for FASER

Separation efficiency



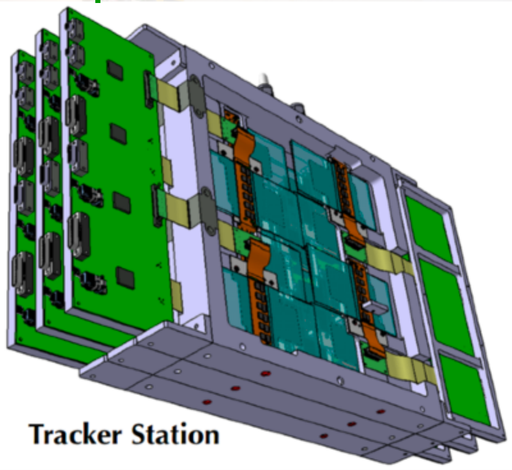


ATLAS SCT barrel module

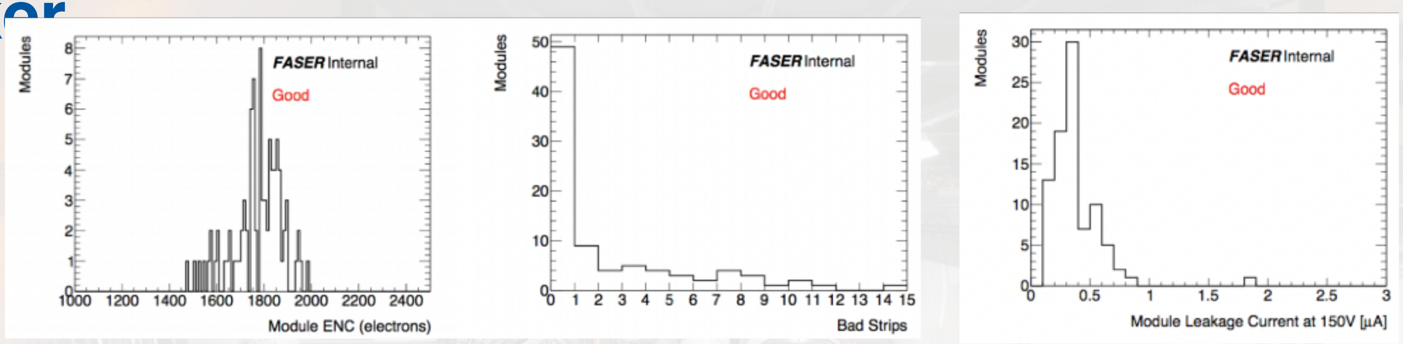


Flex cables

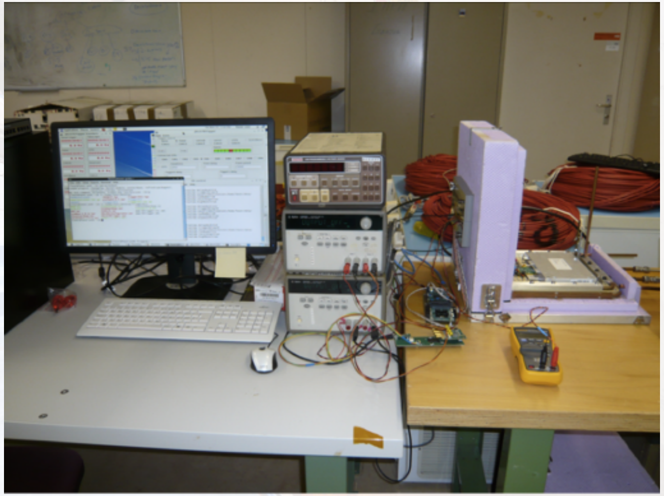
Patch panels



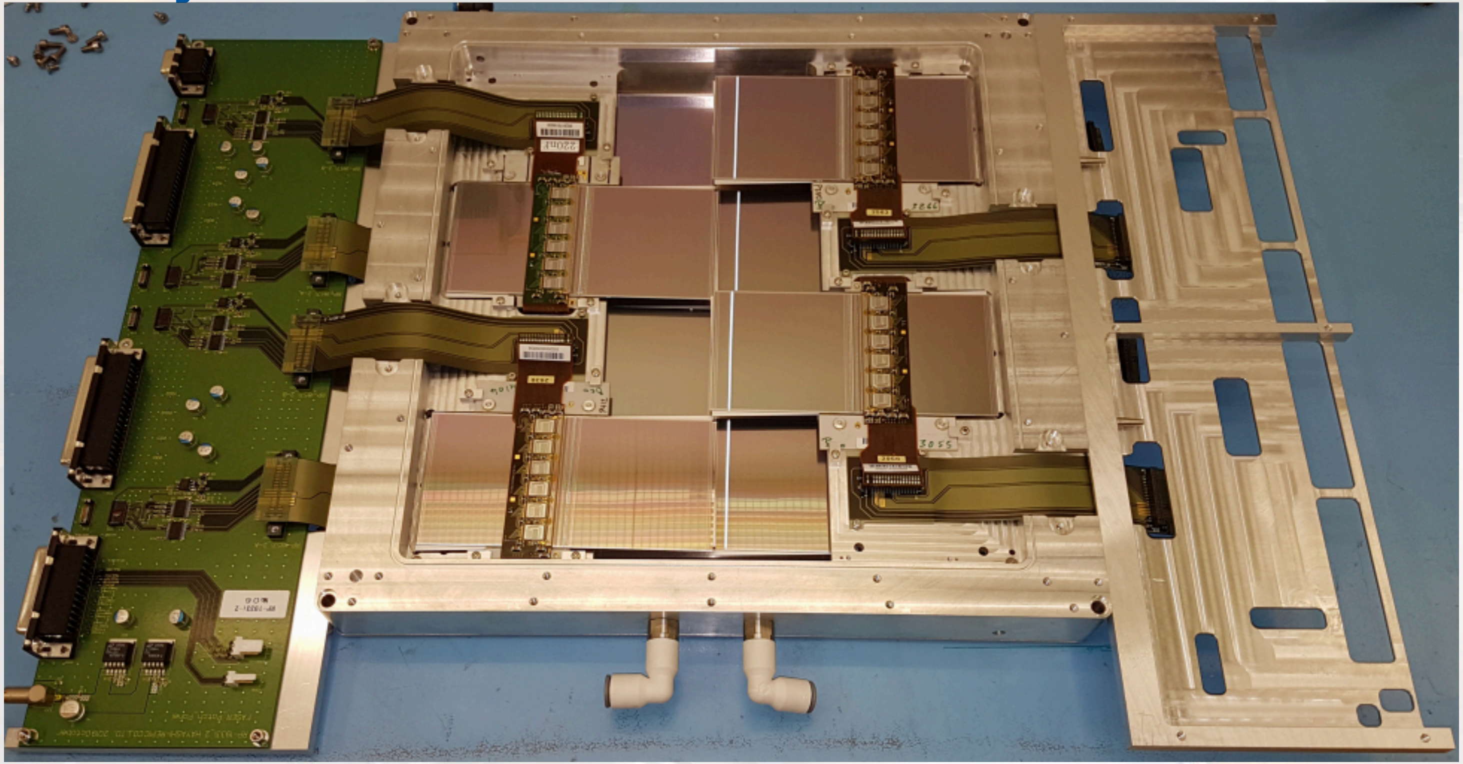
Tracker



- Quality Assurance (QA) of SCT modules (after long time in storage)
- 80 modules tested and found good for use in FASER.

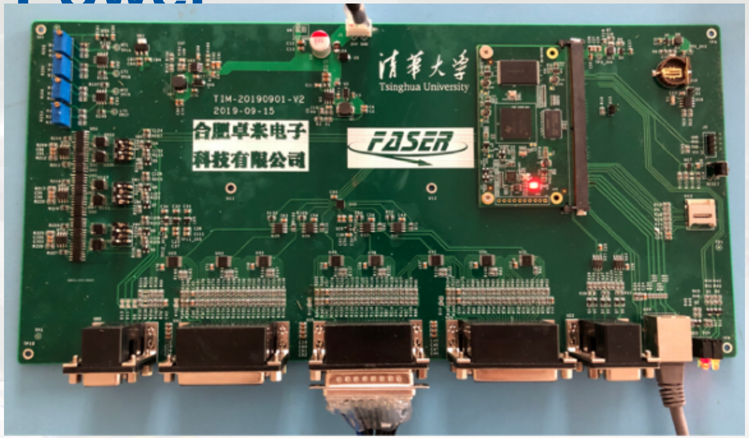


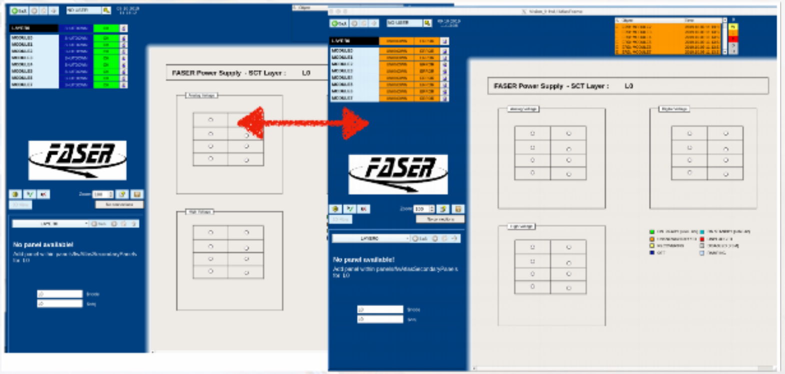
Tracker layer



Tracker Monitoring, Cooling, and Power

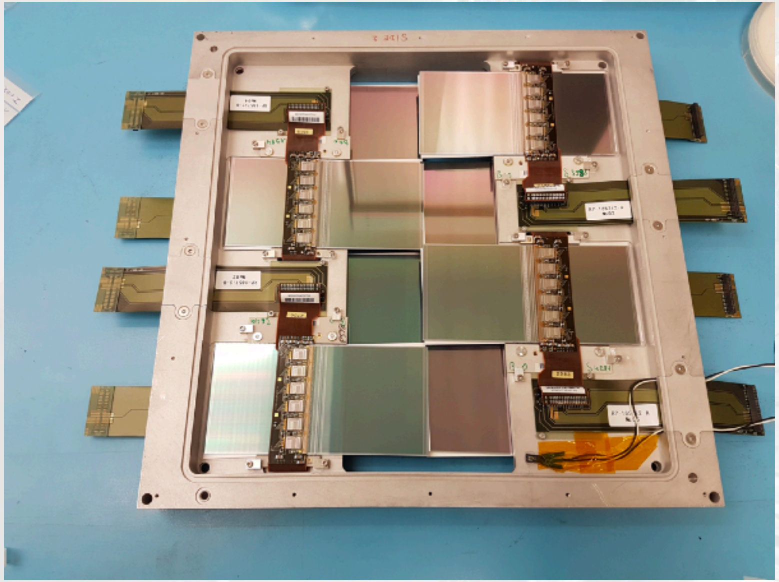
- Low radiation environment → simple water chiller at ~ 15 °C sufficient to cool ASICs
- Dry air in tracking stations (avoid condensation)
- WIENER system for power supply
- Custom board for tracker interlock & monitoring (TIM)
- Detector Control System (DCS) under development.

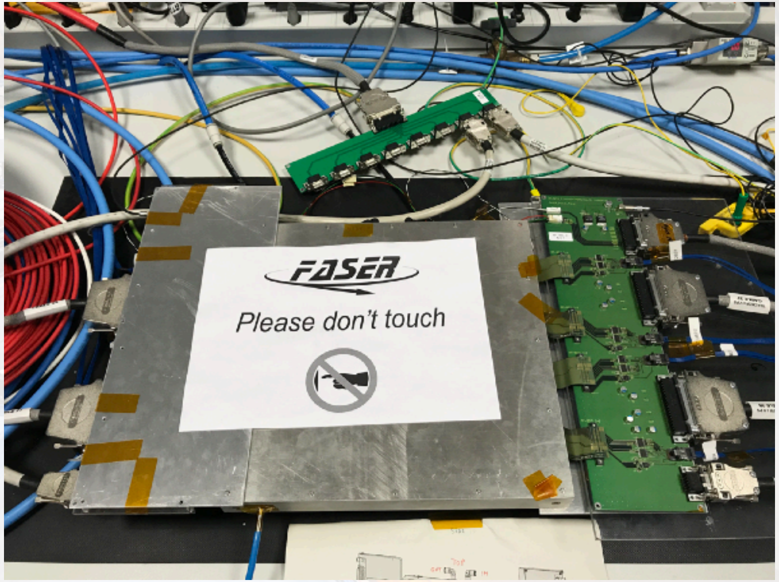




Tracker prototype layer

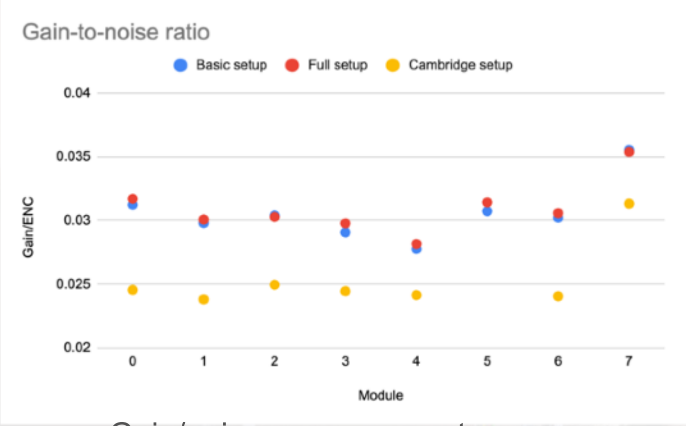
- First prototype layer produced and mounted in September 2019.
    - Undergone extensive tests to characterise mechanical and electrical tracker components.



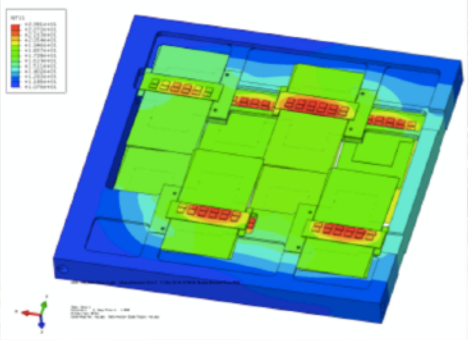


Tracker prototype layer

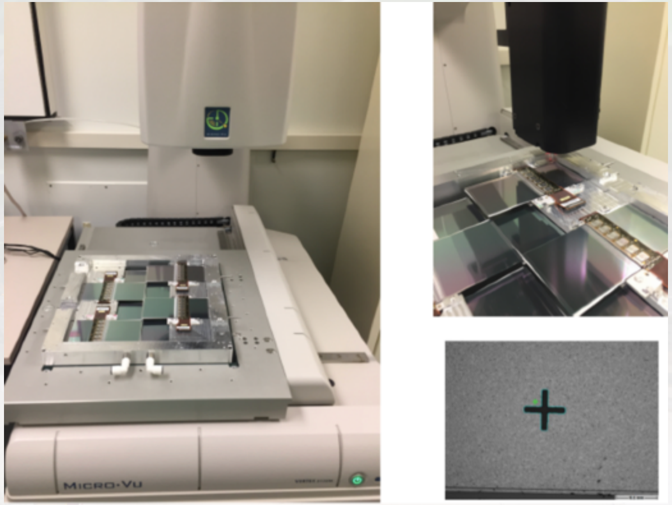
- Thermal measurements
- Readout tests (calibrations/scans) and noise measurements
- Metrology for pre-alignment (~ few microns precision)



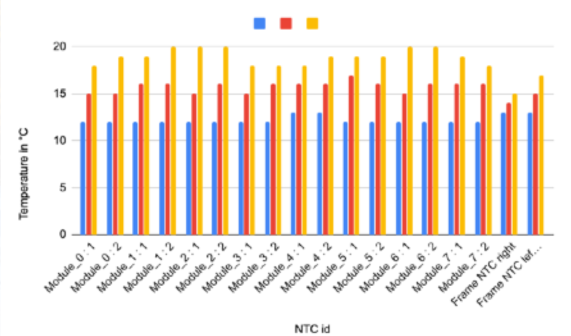
Gain/noise measurements



FEA simulation



Metrology studies

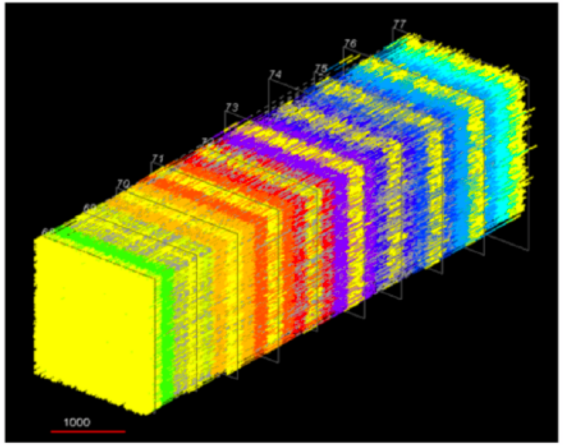


Thermal measurements

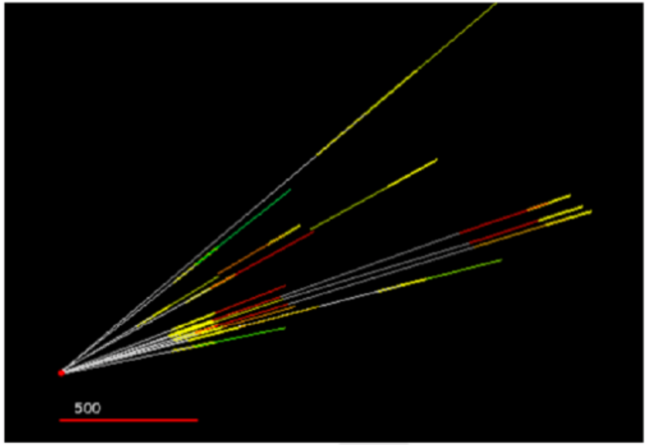
Pilot neutrino detector

- Pilot neutrino detector (two modules, 15 kg each) installed in TI18 tunnel in 2018:
  - 12.5 cm x 10 cm/module: 100 layers of 1 mm Pb plates, 120 layers of 0.5 mmW plates
  - Collected 12.5 fb^{-1} of data (~30 neutrino interactions expected)

Pilot neutrino detector



All reconstructed tracks



Reconstructed neutral vertex