Recent results from the FASER experiment

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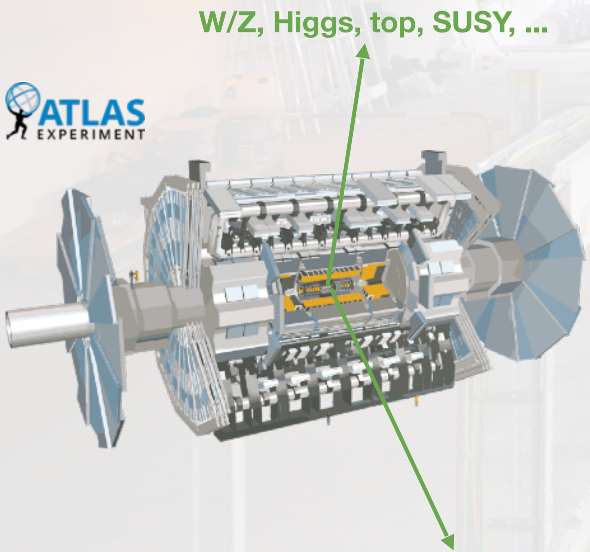
RAL PPD seminar
24th April 2024

FASER

MANCHESTER 1824
The University of Manchester

Forward at the LHC

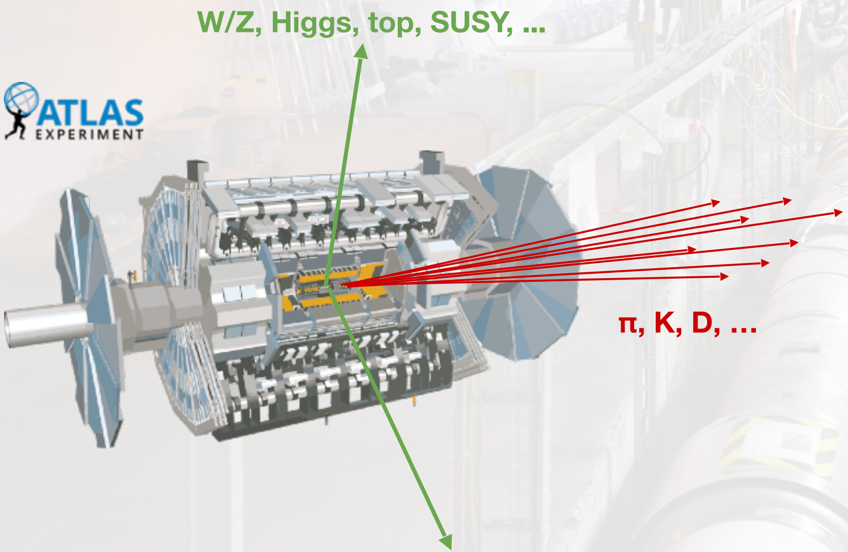
Experiments at the LHC designed to search for **heavy** and **strongly coupled** particles



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

Forward at the LHC

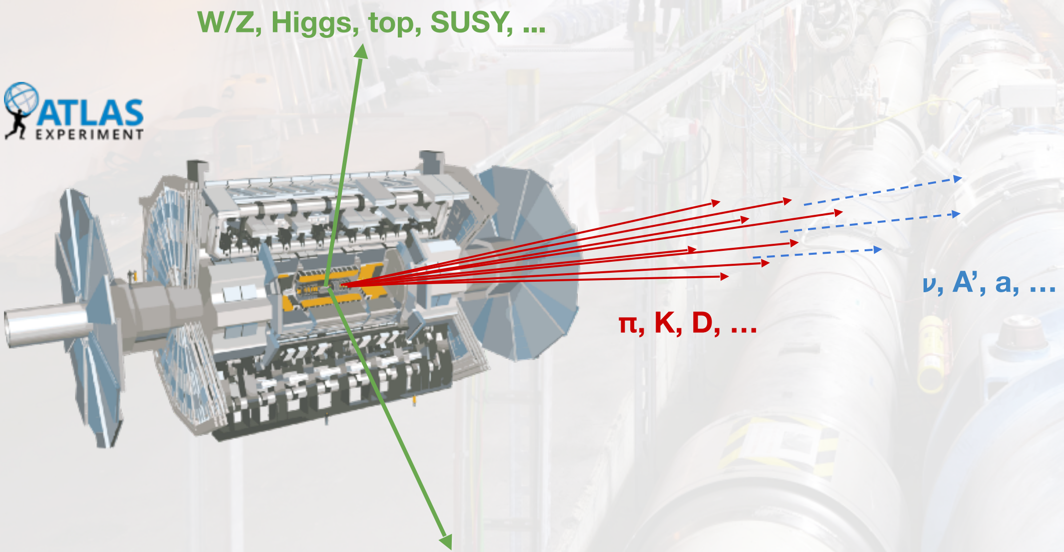
High rate of **light hadrons** also produced in *non-instrumented* **far-forward (low p_T)** region



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.

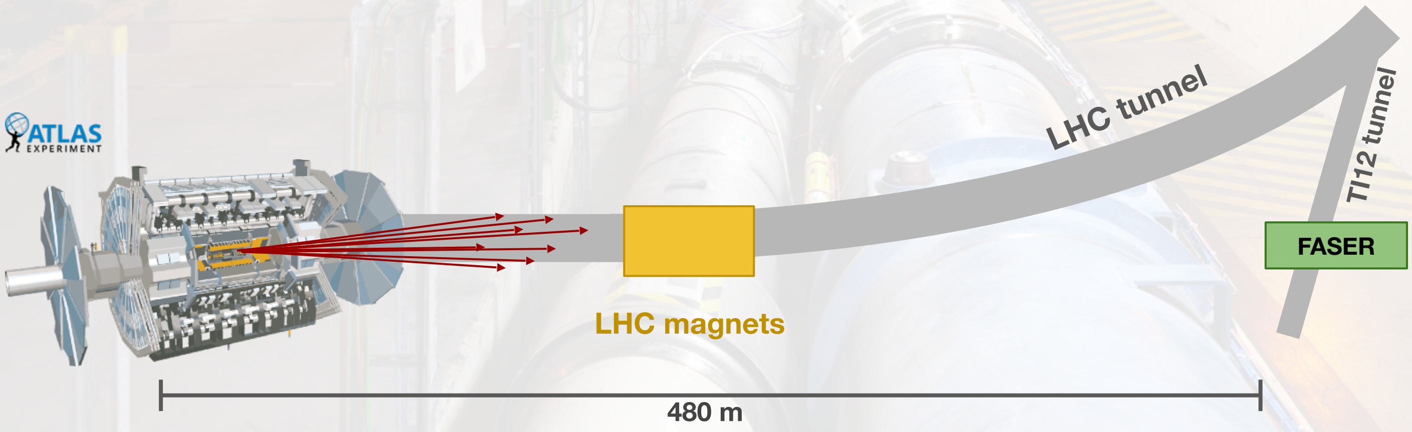


Neutrinos of all flavours, and **BSM** particles

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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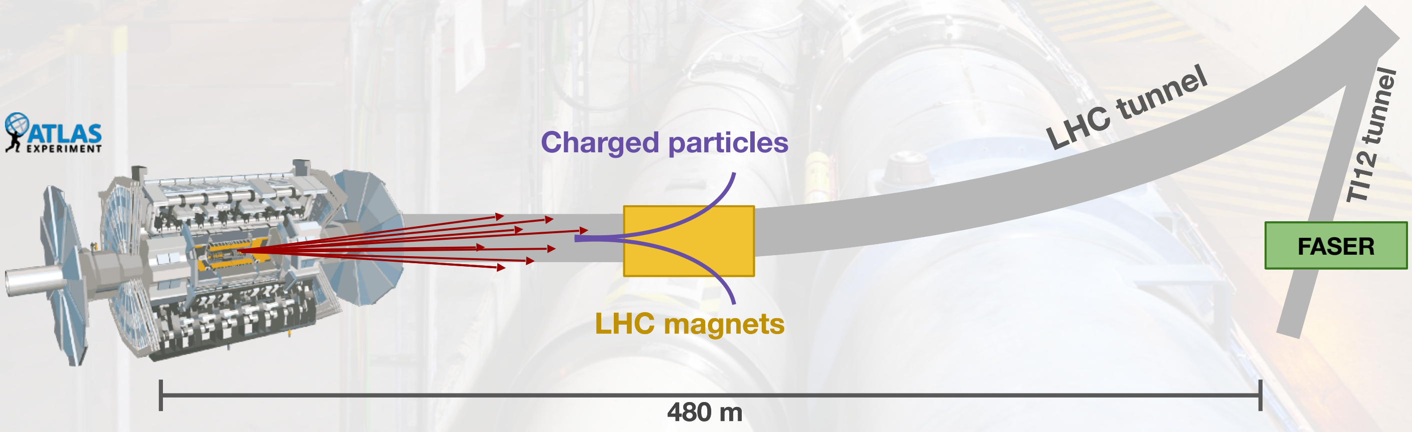

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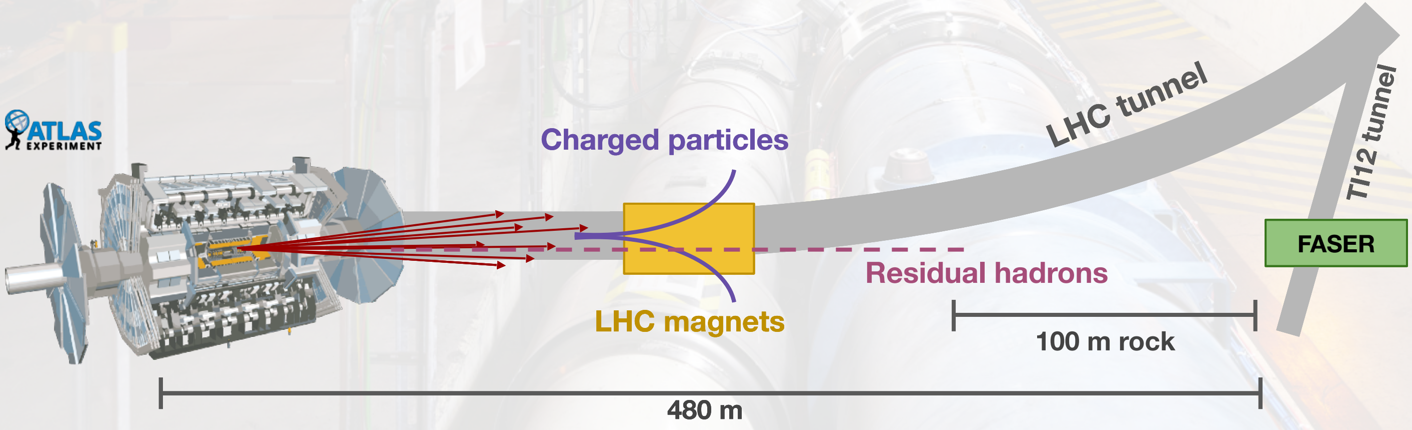

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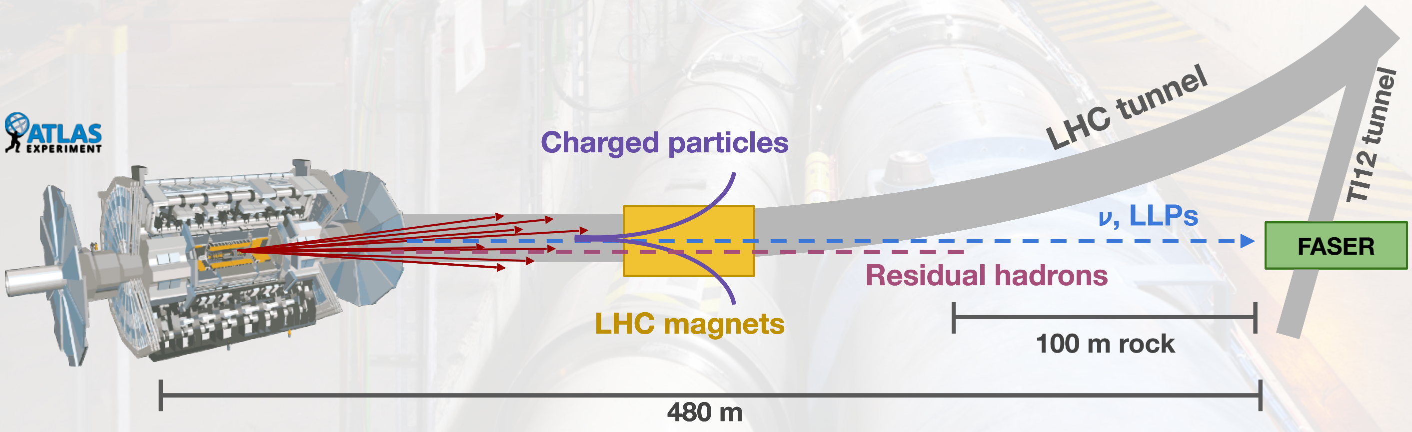
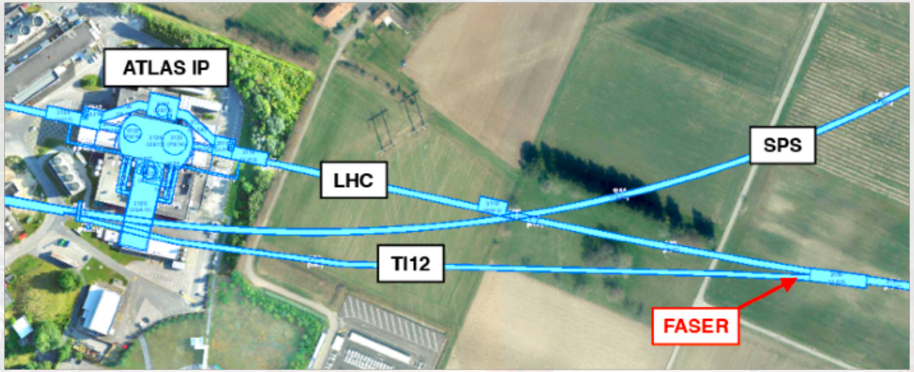
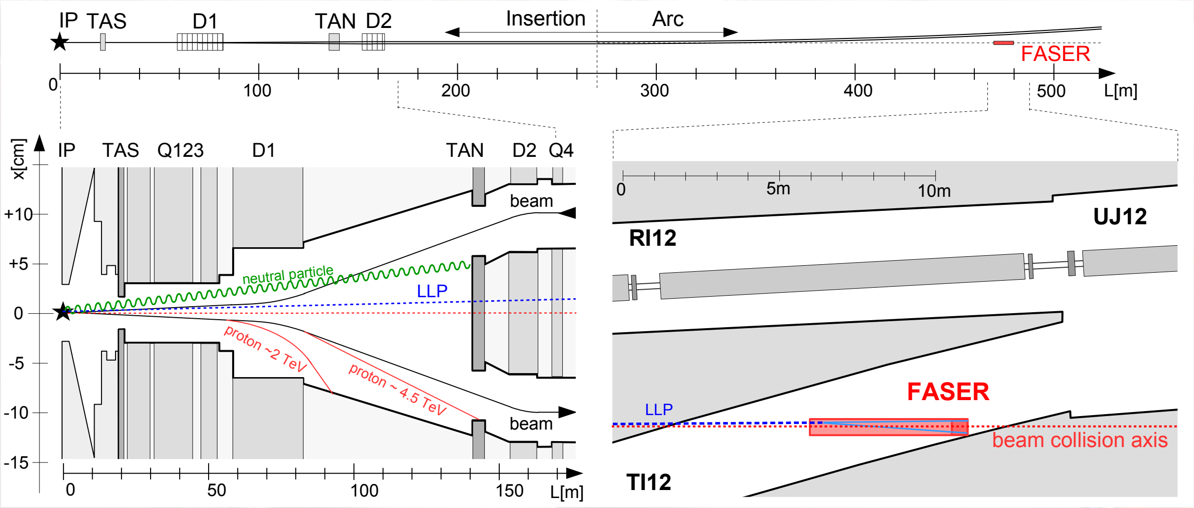


FASER Location

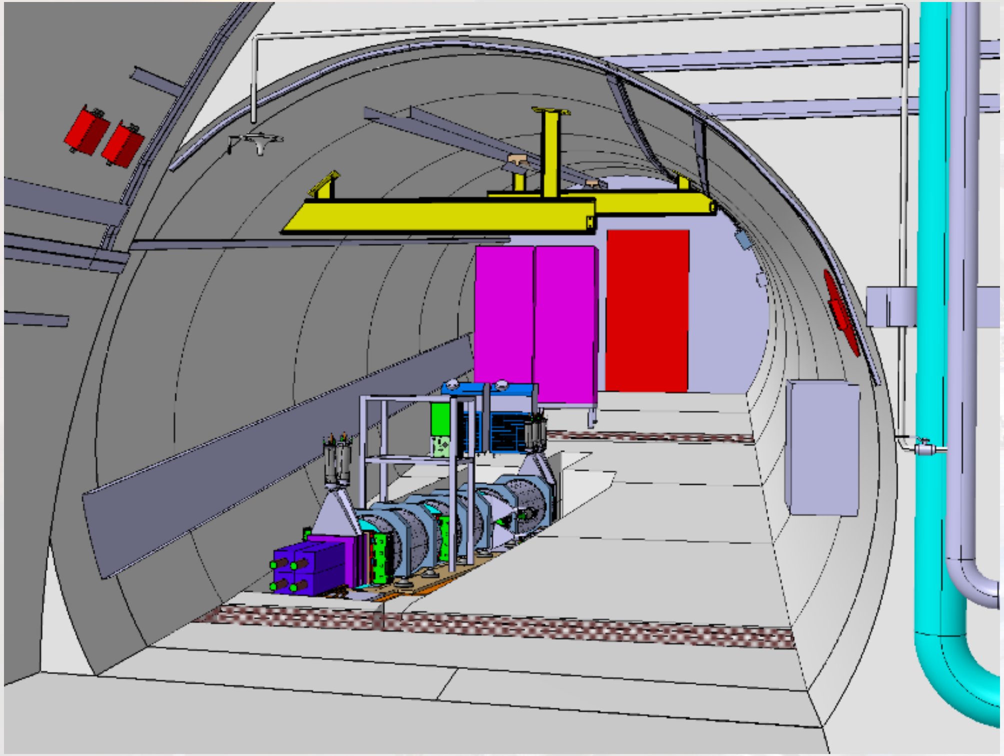
FASER location

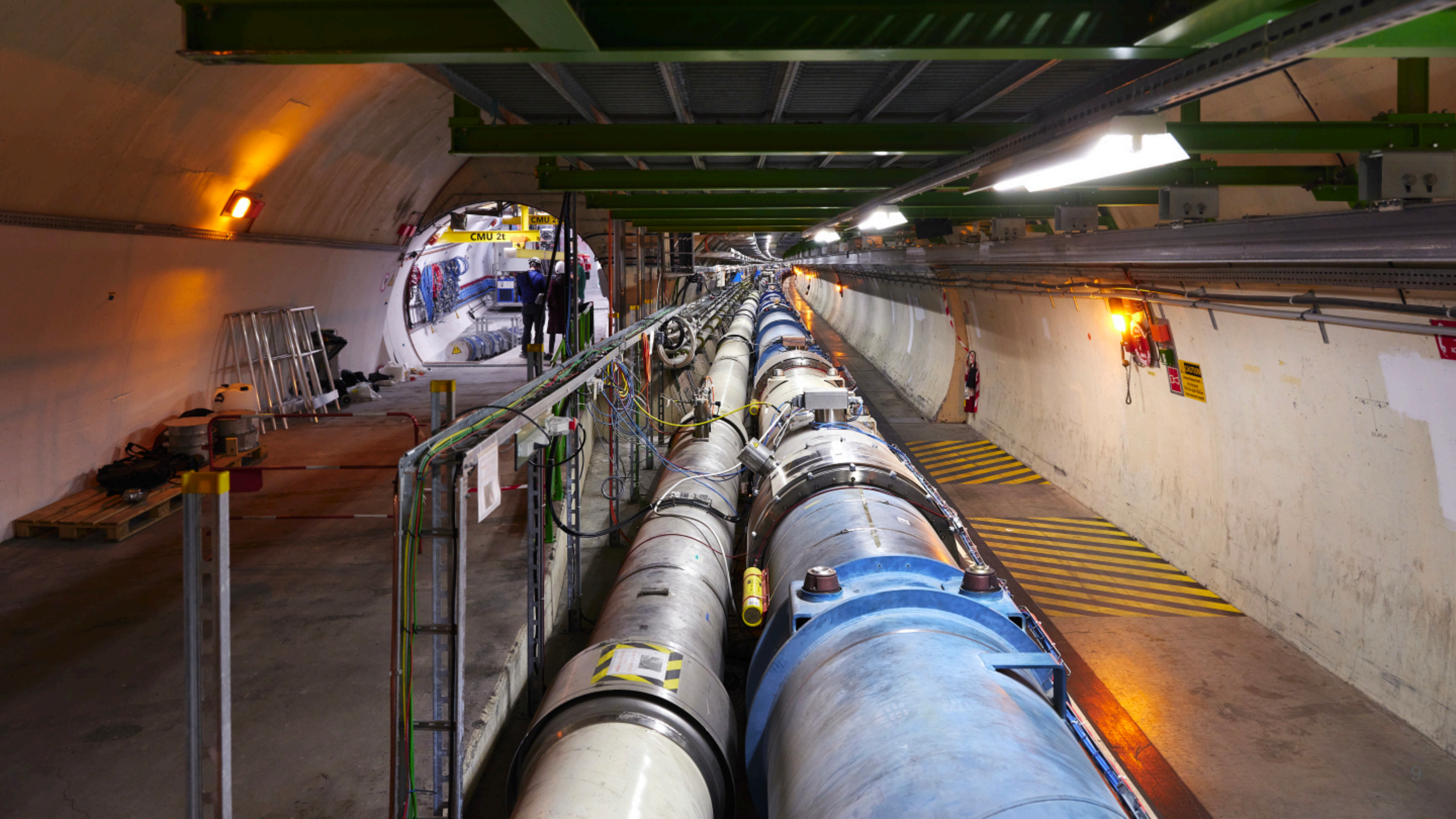
- Old SPS → LEP tunnel ideal location:
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds





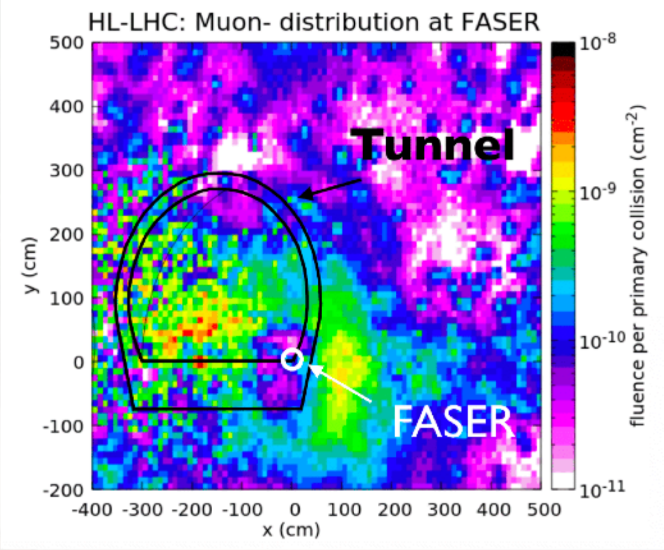
FASER location: TI12

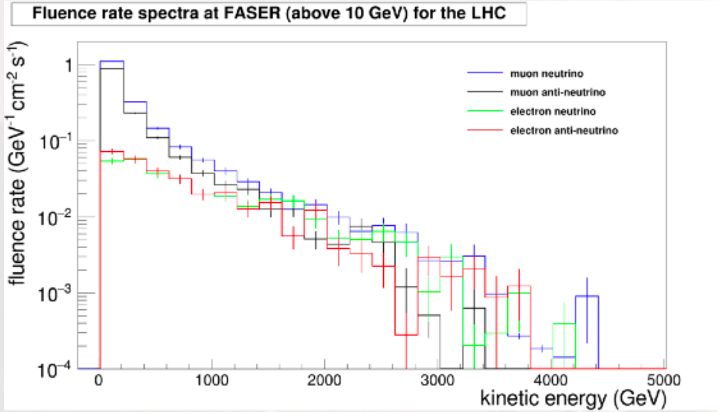


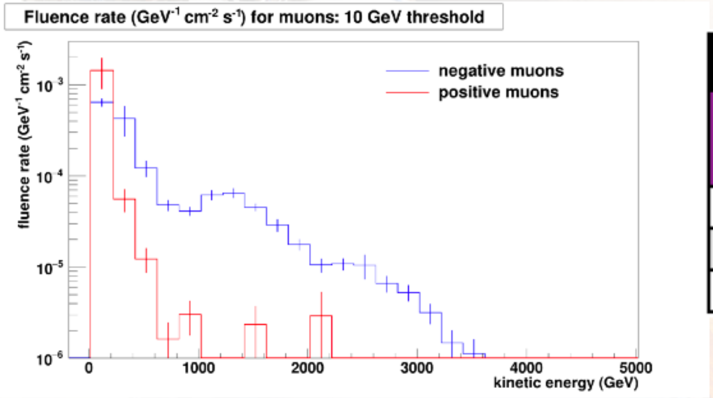

CMU 2t

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.







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

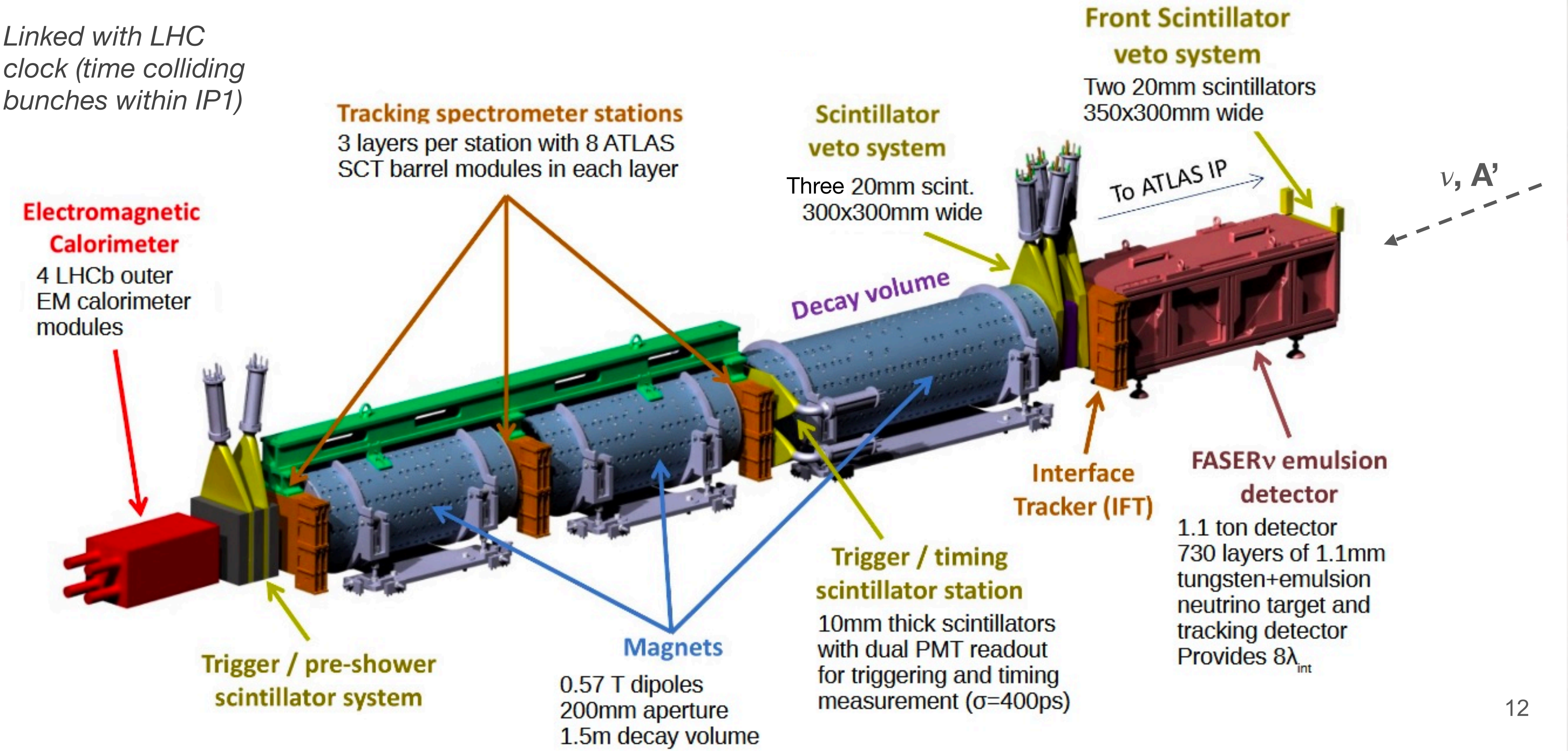
Muon charge asymmetry due to LHC magnets

FASER detector & installation

The FASER detector [arXiv:2207.11427]

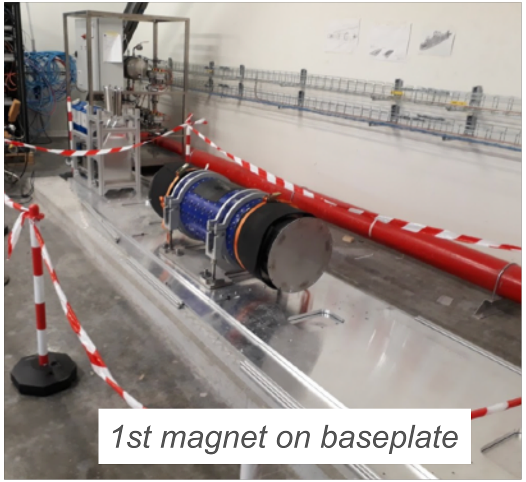
Aperture: 20 cm
Length: 7 m

Linked with LHC clock (time colliding bunches within IP1)

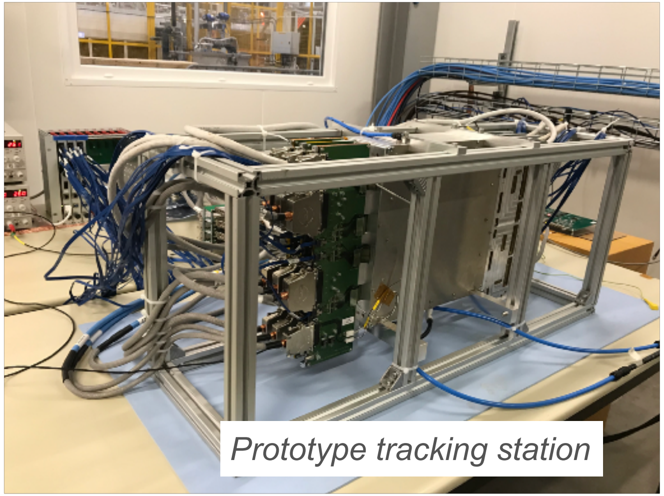


Commissioning & Surface dry run - 2020

- Area in CERN's Prevessin site ("EHN1", neutrino platform) used for full detector commissioning.
- Surface dry run, before disassembly and installation in LHC tunnel.

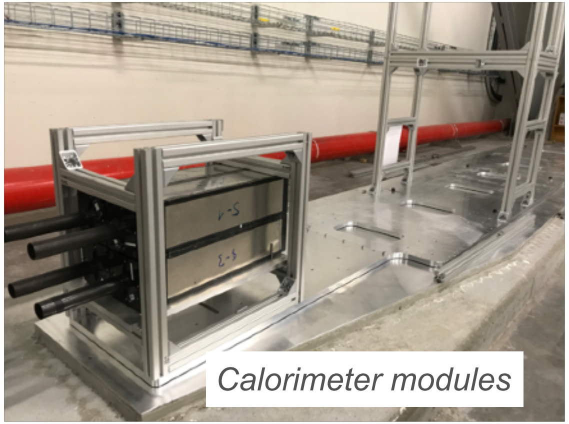


1st magnet on baseplate



Prototype tracking station

Scintillator station

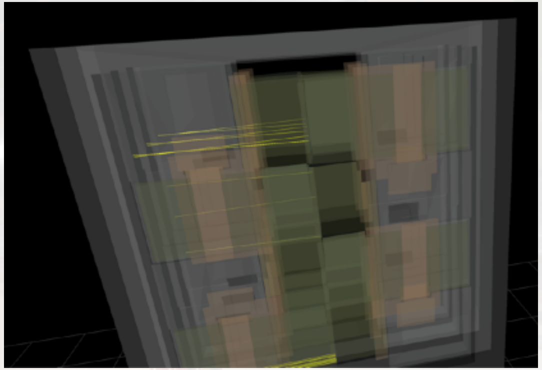


Calorimeter modules

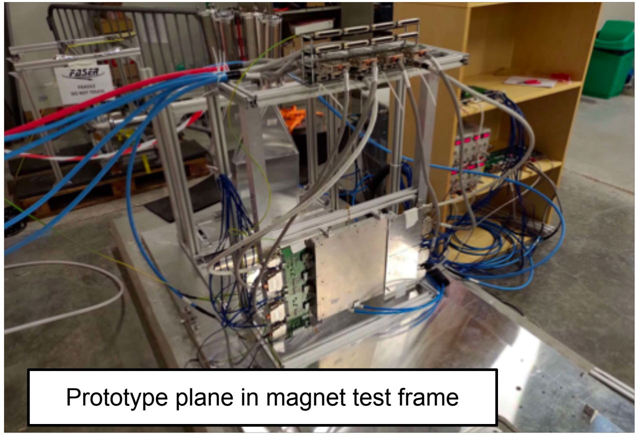
EHN1 - 2020

- Baseplate mock-up on cement including 1% slope (simulate slope of LHC).

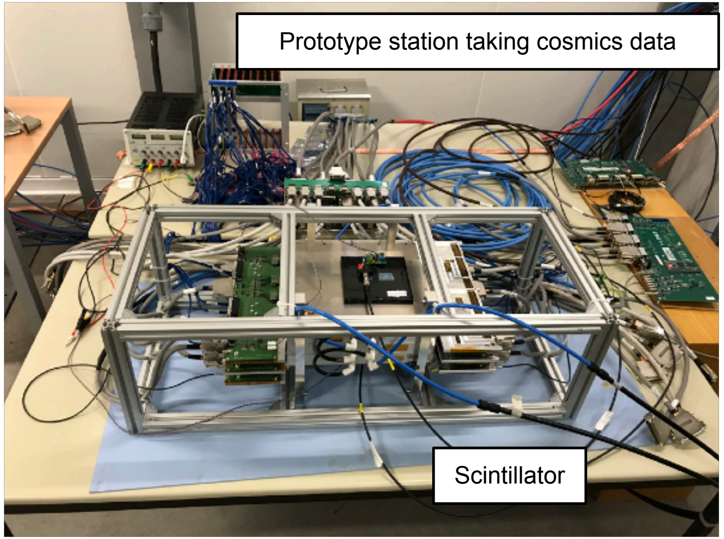
Commissioning & Surface dry run - 2020



- 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

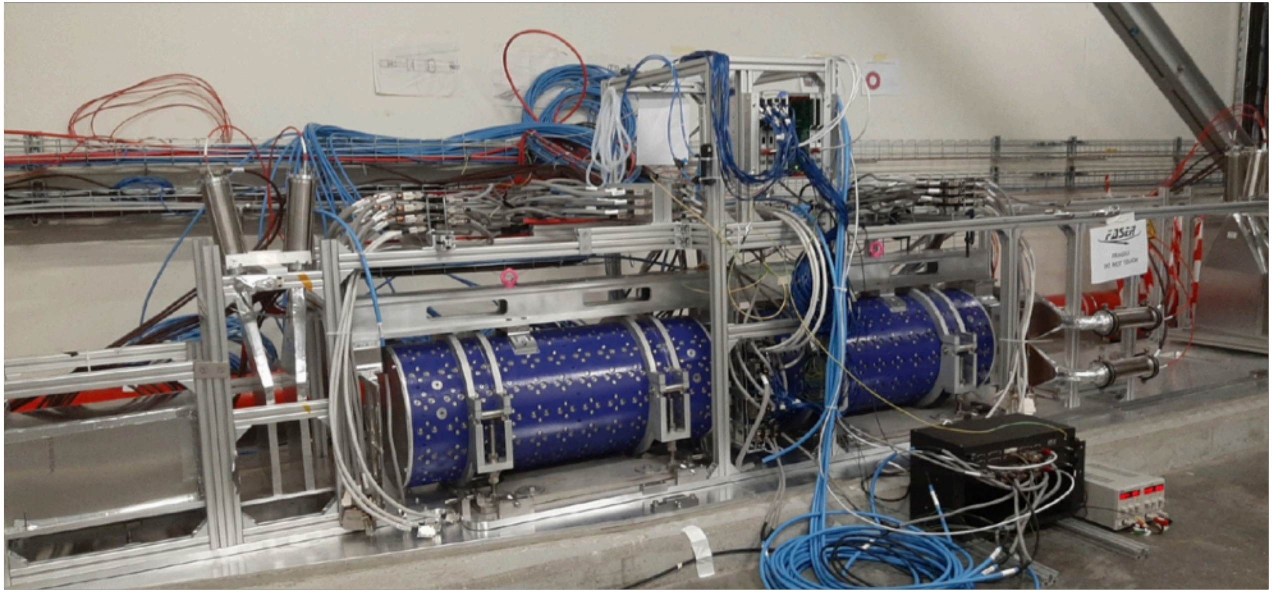


Prototype station taking cosmics data

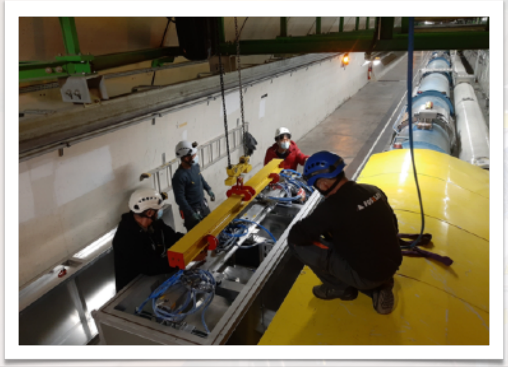
Scintillator

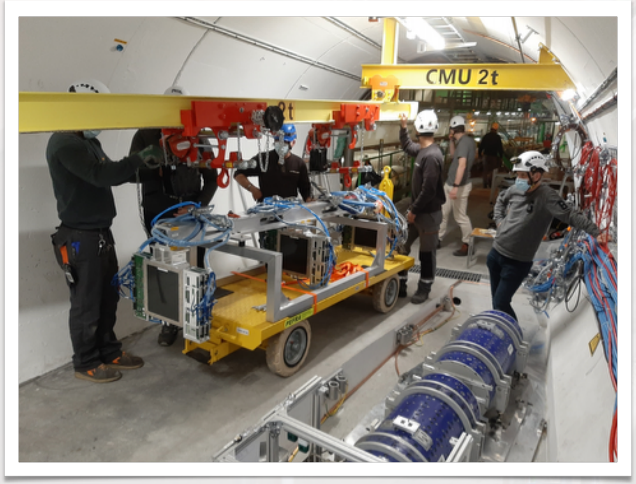
Commissioning & Surface dry run - 2020

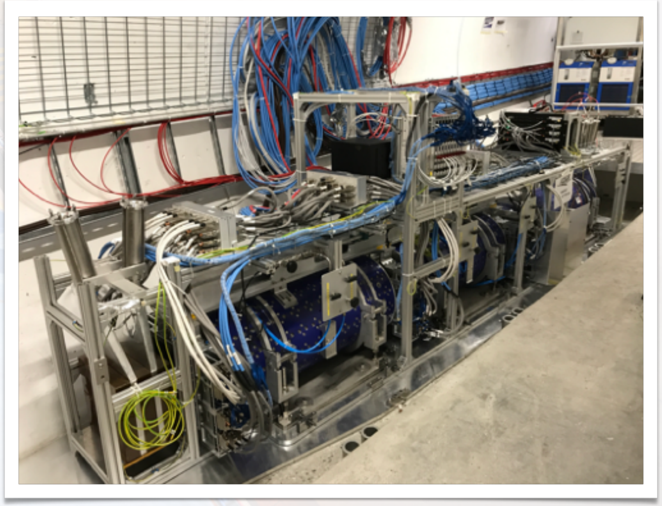
- First assembly of upper frame with one tracker station, calorimeter, all scintillators, and two magnets and combined run.
- Some “horizontal cosmics” events recorded.



Installation in TI12 - March 2021







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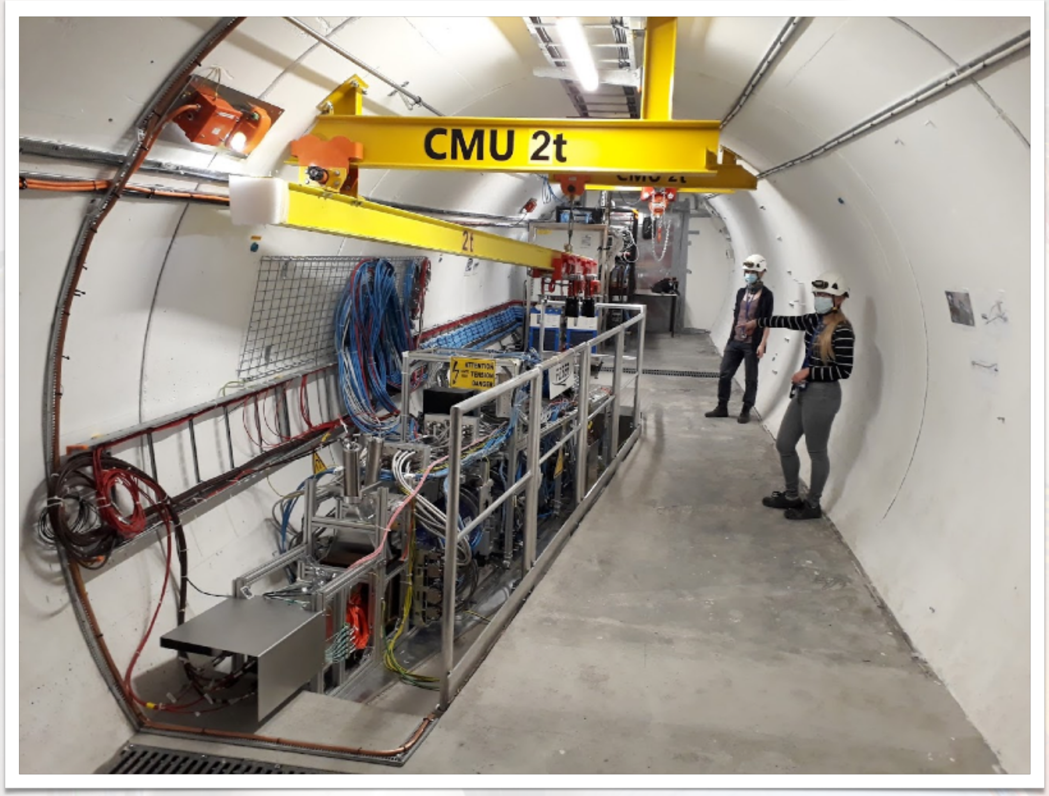
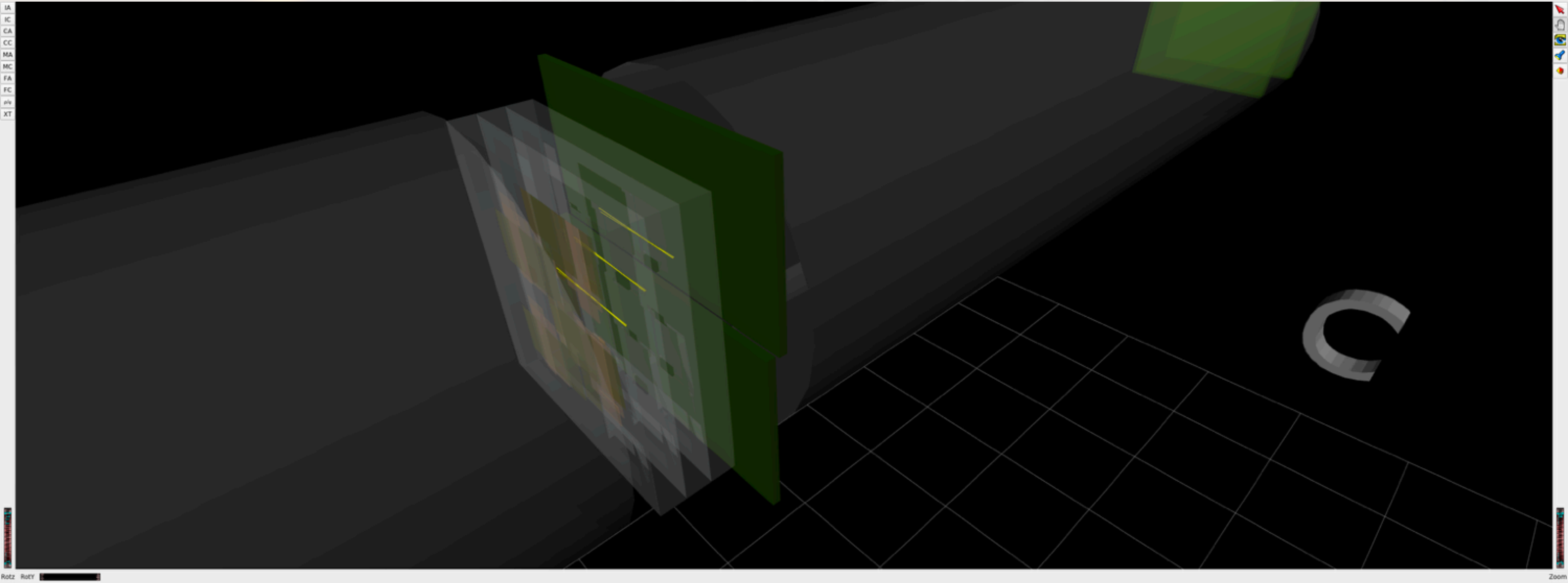
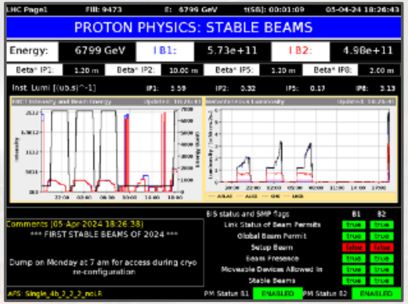


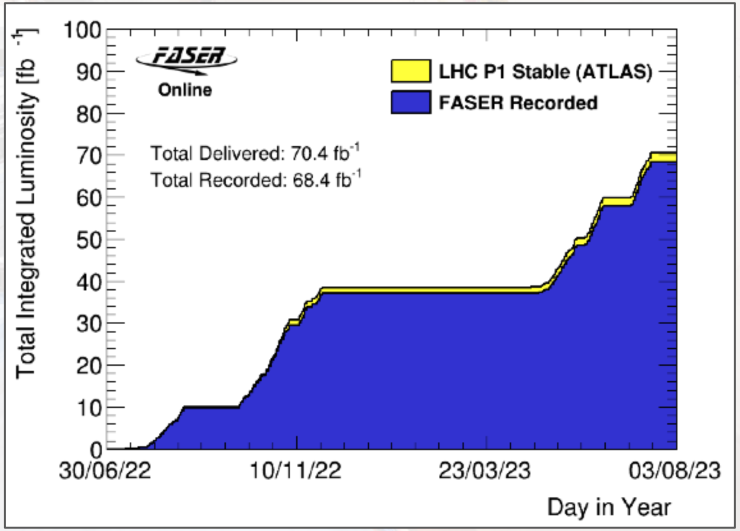
First display of Cosmic Ray event in TI12!



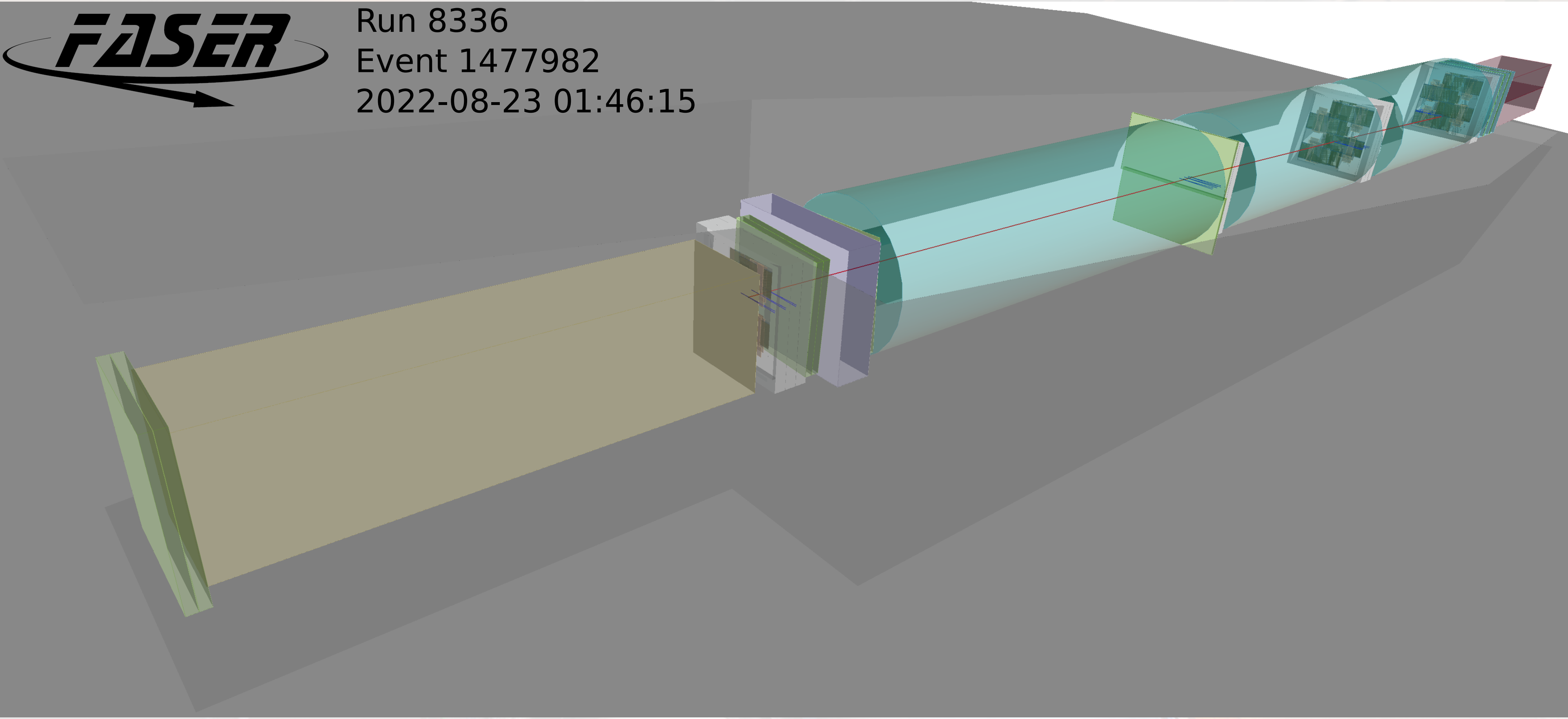
FASER operations - 2022-2024



- Successfully collected 35 fb^{-1} in 2022 and 33 fb^{-1} in 2023.
- Data taking efficiency > 97%.
- Smooth restart to data taking in 2024.

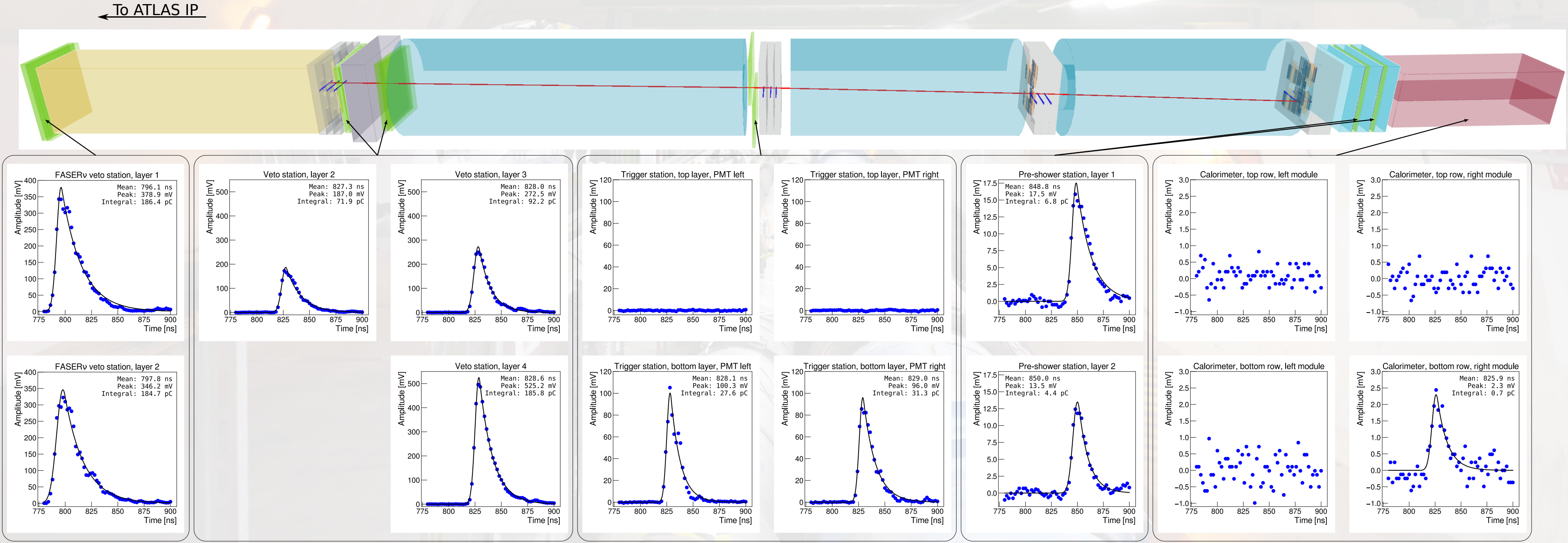


Event from 2022 with 21.9 GeV muon traversing FASER spectrometer



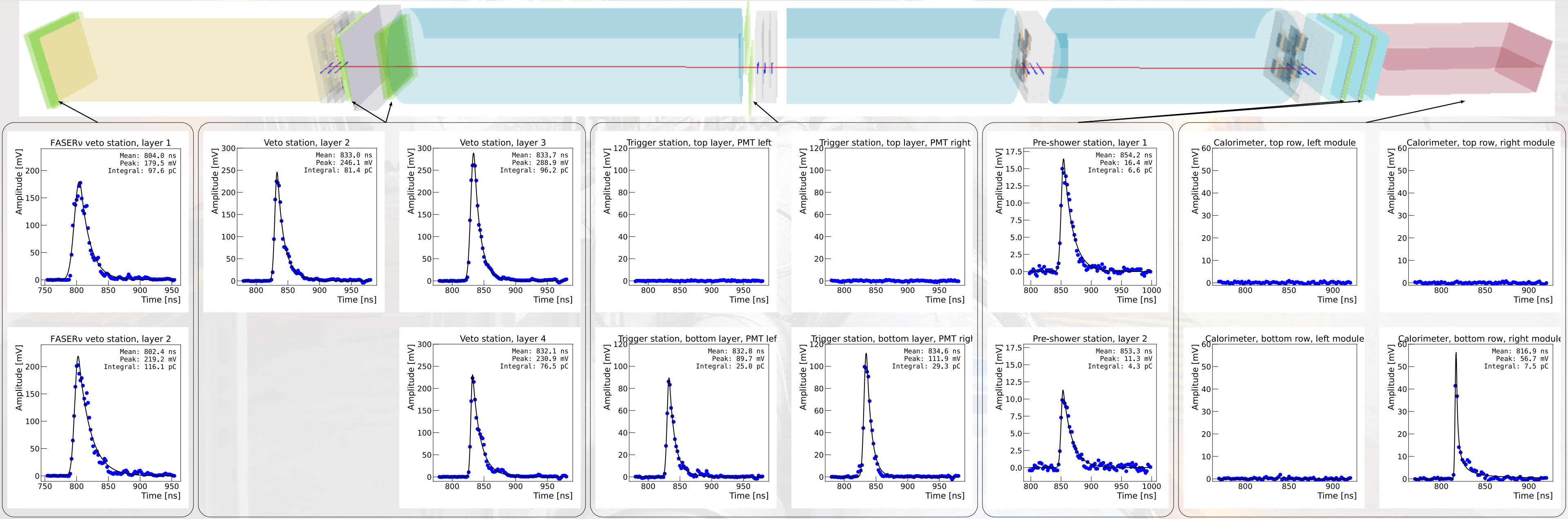
Run 8336
Event 1477982
2022-08-23 01:46:15

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

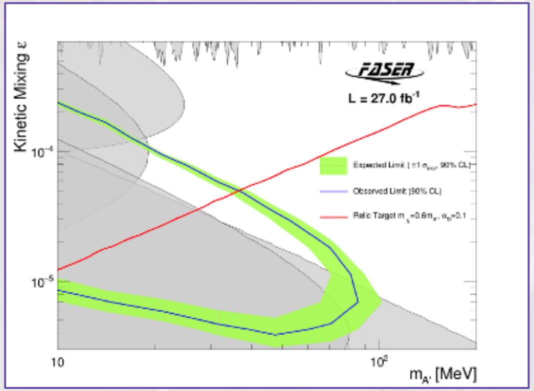


Recent results from FASER

FASER physics

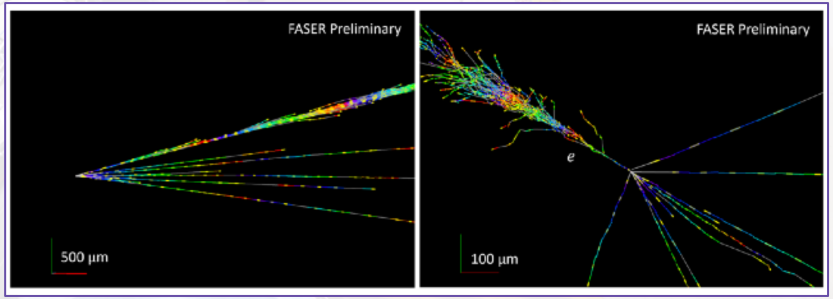
BSM searches

- Dark photons
- ALPs
- Dark Higgs



arXiv:2308.05587

Neutrino measurements

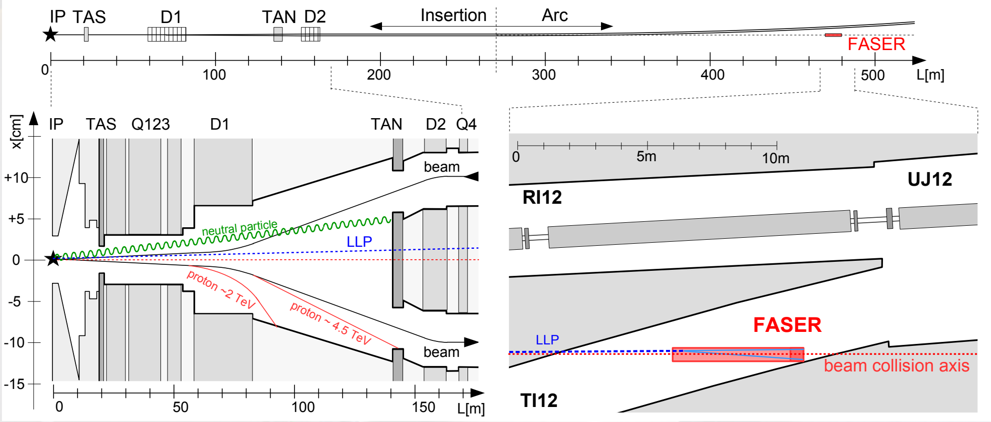


BSM searches at FASER

FASER physics

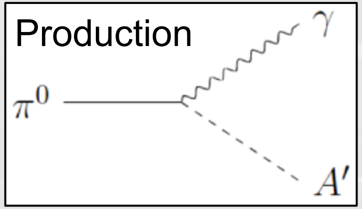
- FASER is sensitive to new light (MeV-GeV mass) weakly interacting long-lived particles (LLPs).
- Long-lived particles at FASER:

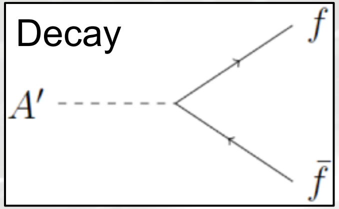
pp → LLP + X, LLP travels ~ 480m, LLP → $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$



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

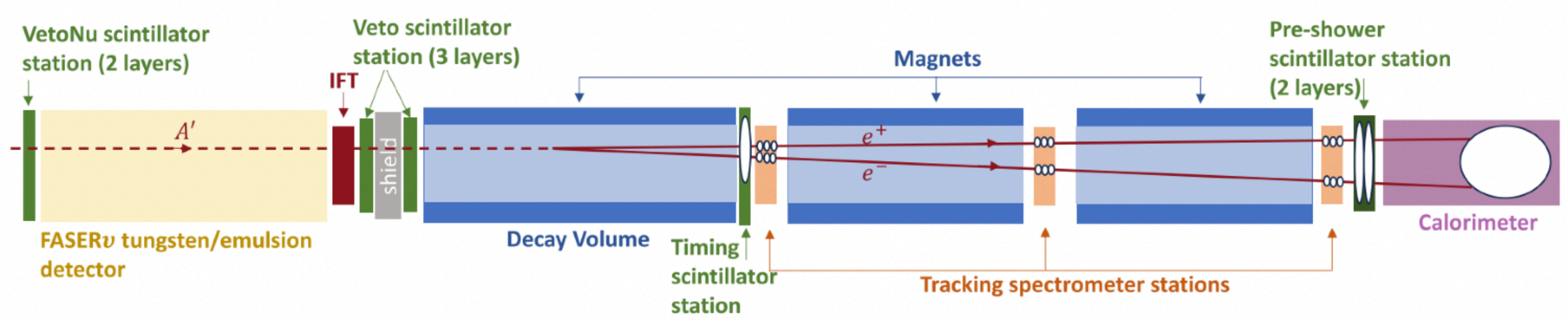
Dark photon search





PLB 848 (2024) 138378

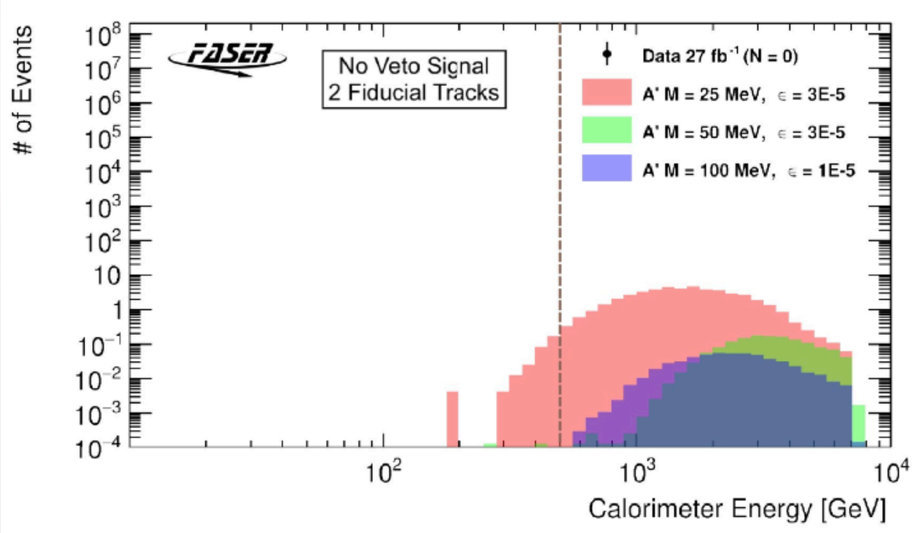
- Search for dark photons decaying into e^+e^- using 27 fb^{-1} of 2022 data.
- No veto signal, two tracks and E(calo) > 500 GeV.

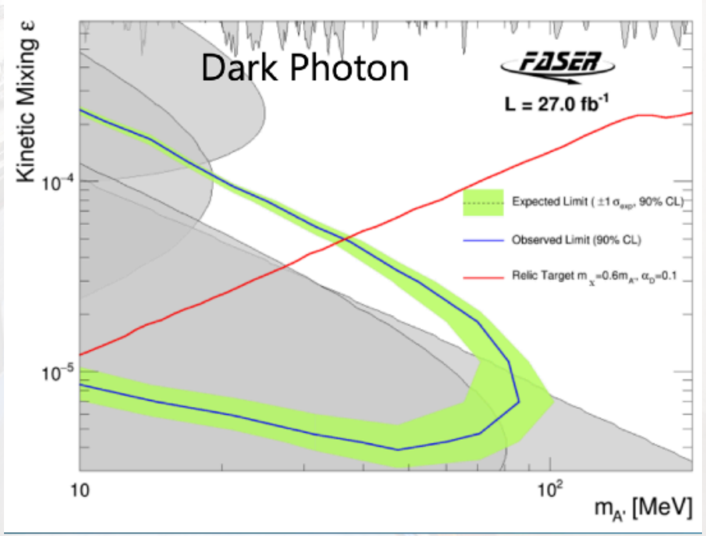


PLB 848 (2024) 138378

Dark photon search

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



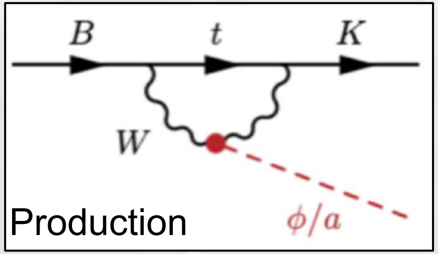


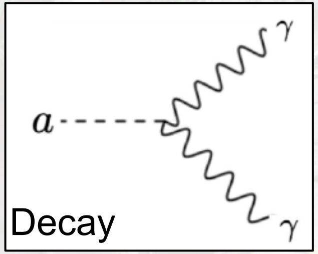
CERN-FASER-CONF-2024-001

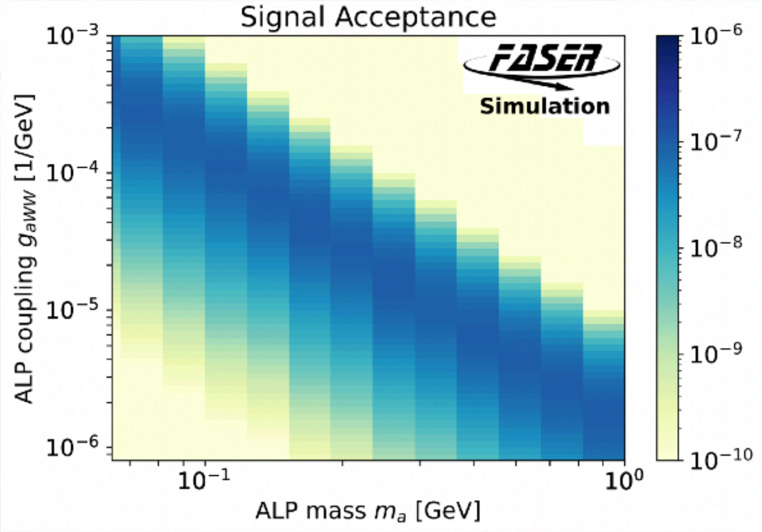
NEW!

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.





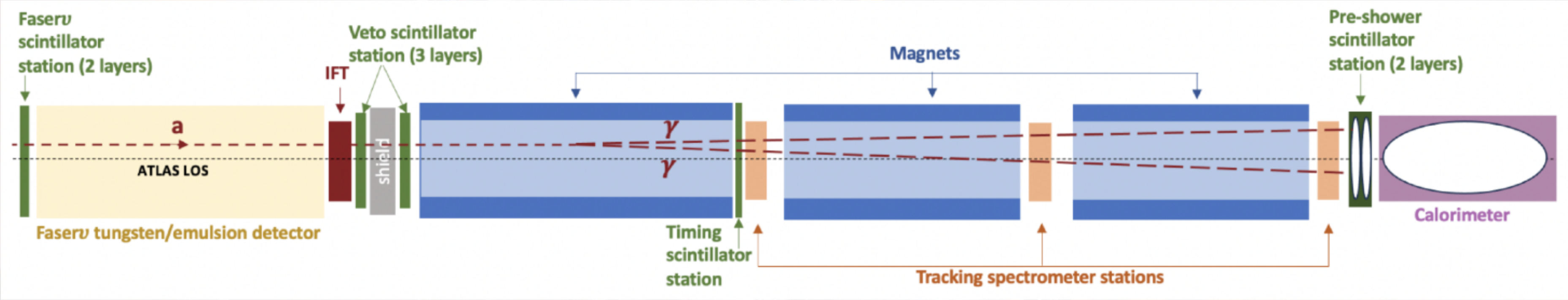


CERN-FASER-CONF-2024-001

NEW!

ALPs signature

4 m decay volume



No charge deposited in scintillators

Decays to pair of photons

Preshower charge > 10 MIPs, ratio > 4.5

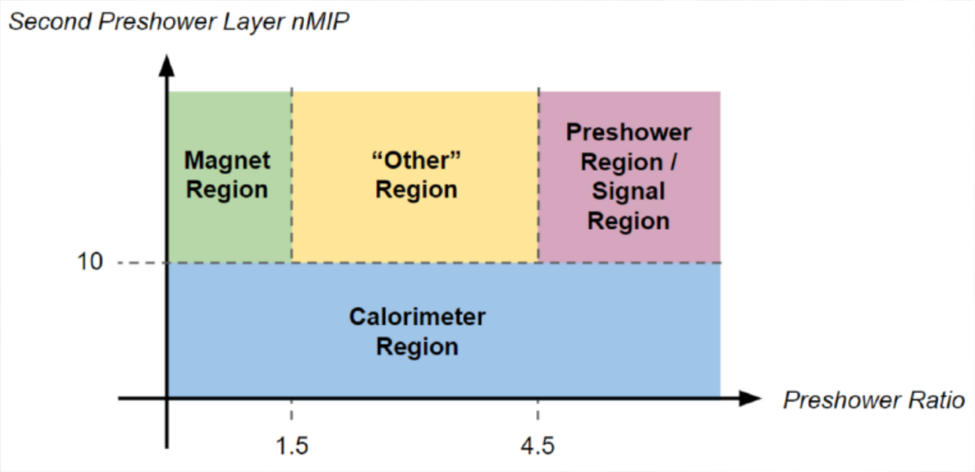
Calorimeter energy > 1.5 TeV

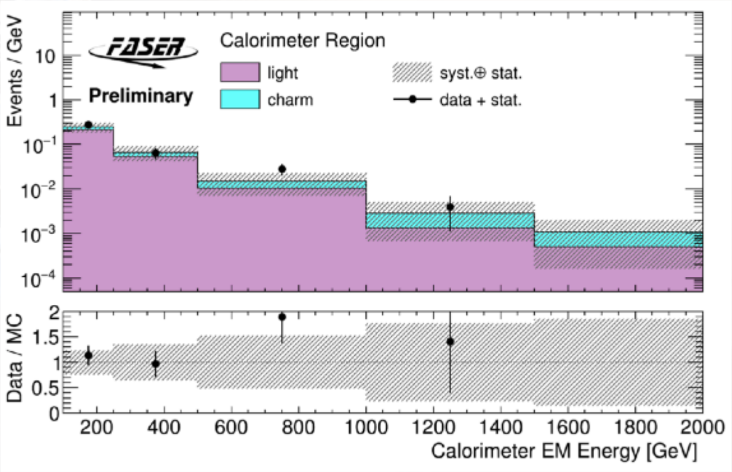
CERN-FASER-CONF-2024-001

NEW!

ALPs backgrounds

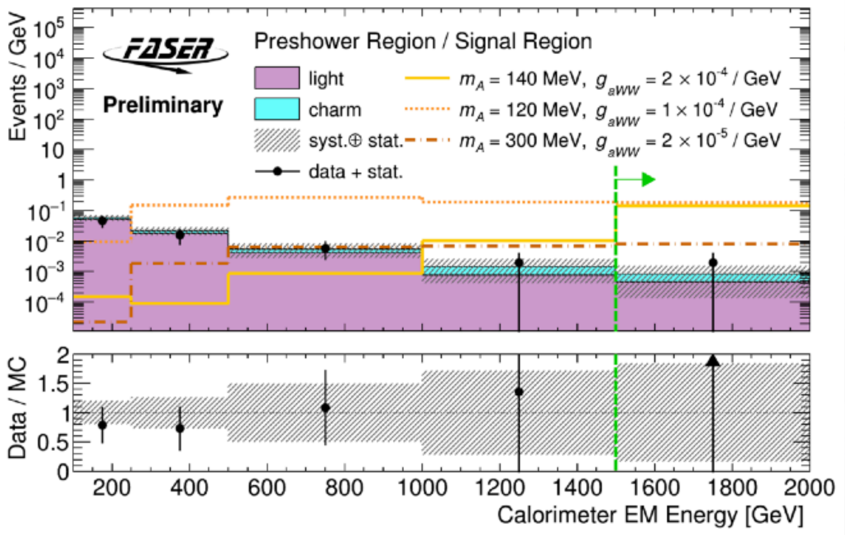
- Dominant background: neutrino interactions → 0.4 ± 0.4 events
- Negligible backgrounds from other sources:
  neutral hadrons, large-angle muons, non-collision/cosmic
- Backgrounds validated in control regions

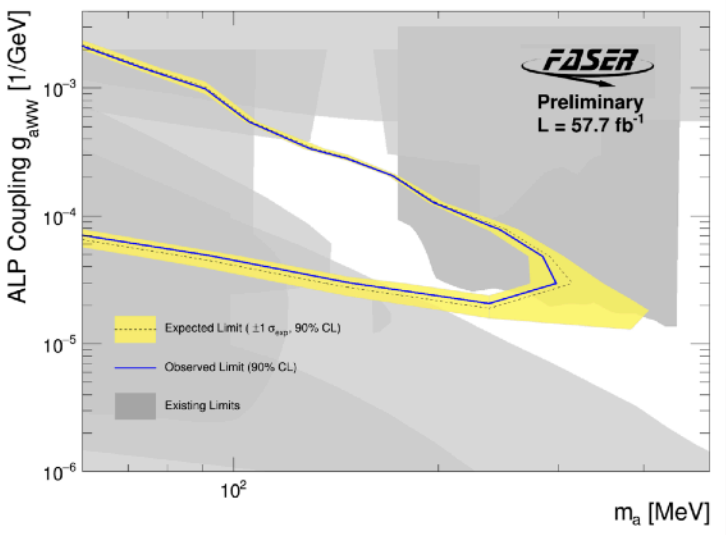




ALPs results

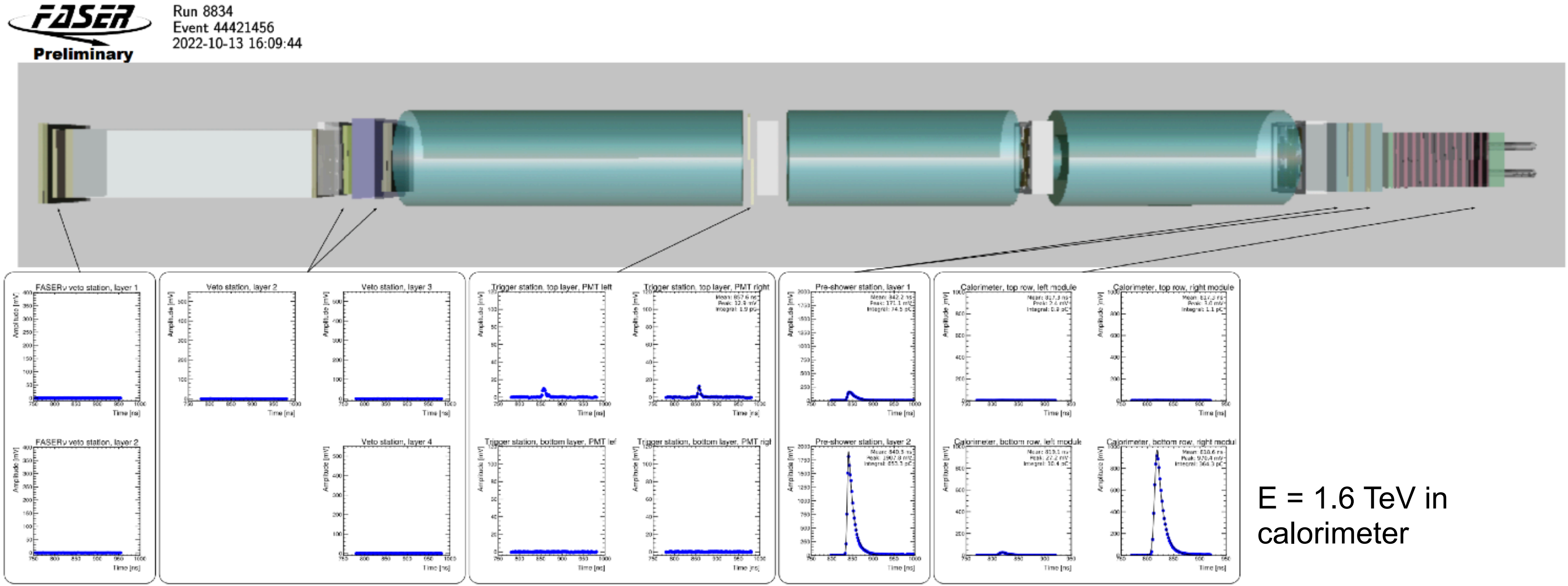
- Expect 0.4 ± 0.4 from ν interactions
- 1 observed event
- Exclude uncovered parameter space significantly





NEW!

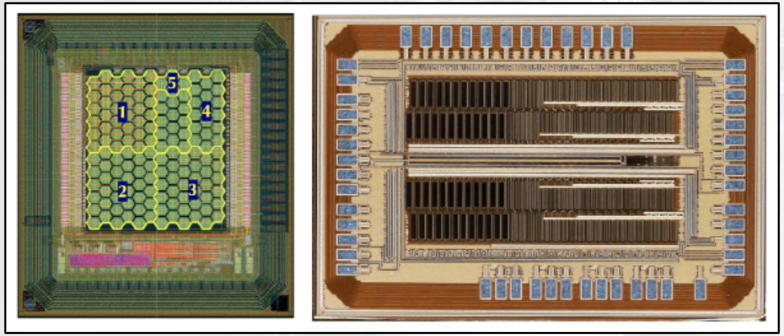
“ALPtrino” event display

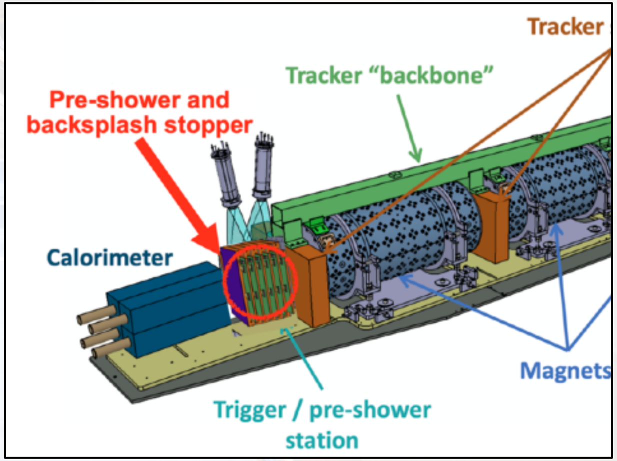


E = 1.6 TeV in calorimeter

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

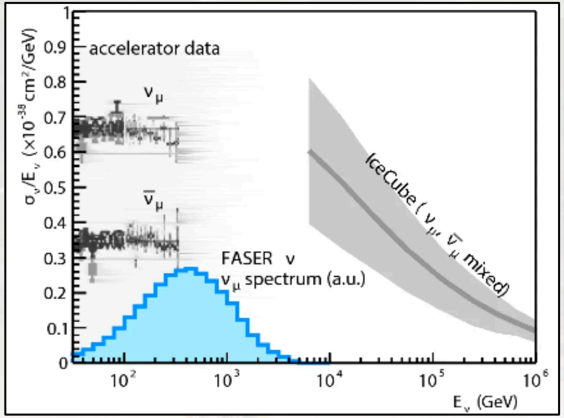
Why study collider neutrinos?

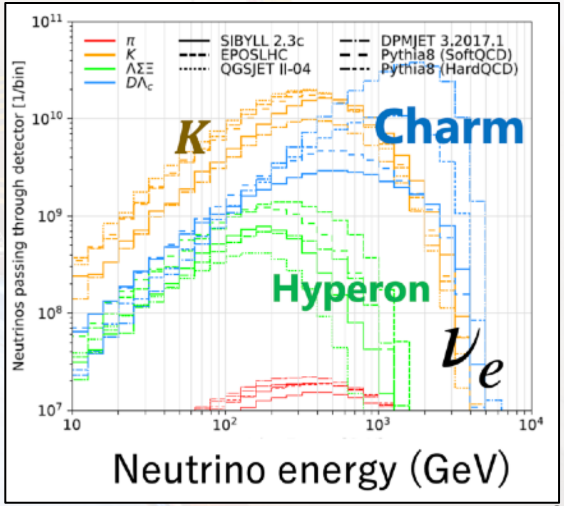
1. Neutrino interactions (all flavours) at **unexplored TeV energies**

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**

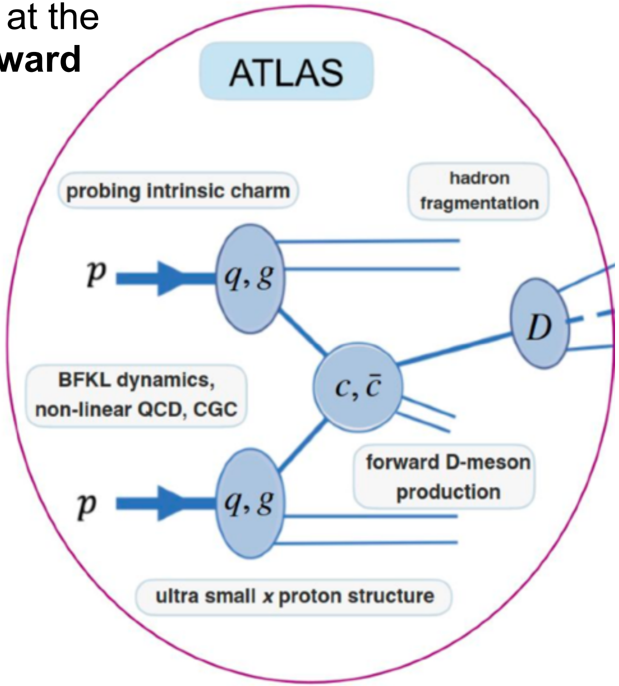


Figure adapted from: [J. Phys. G 50 (2023) 3, 030501]

Forward hadron production and nuclear PDFs

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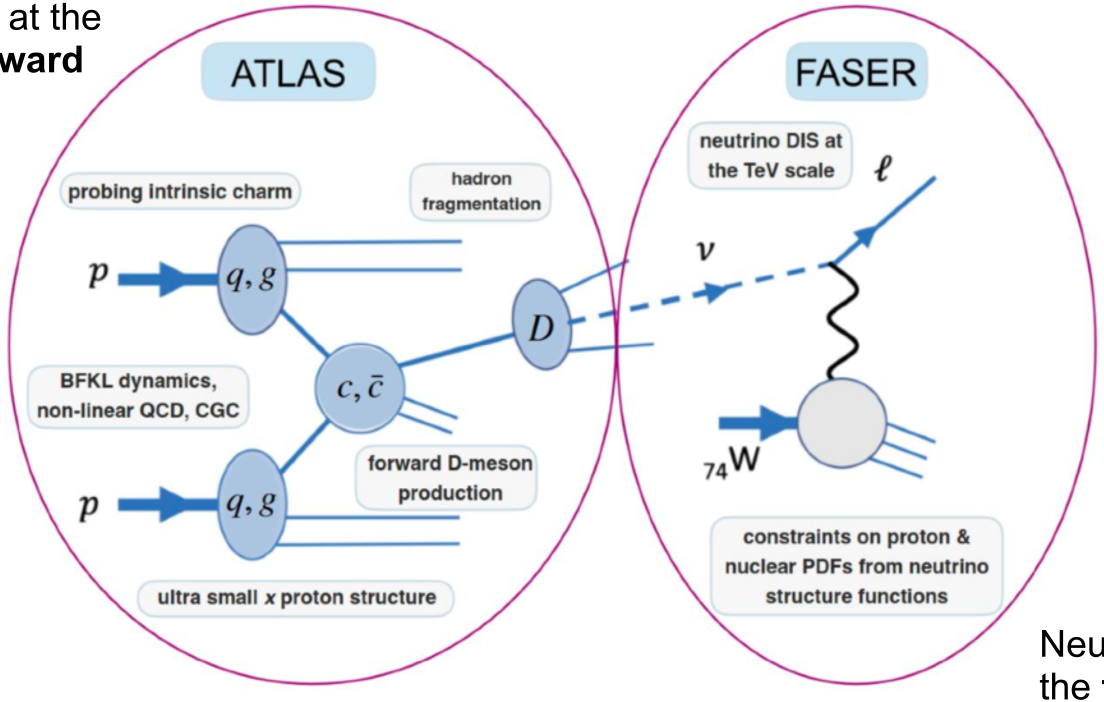


Figure adapted from: J. Phys. G 50 (2023) 3, 030501

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

Neutrinos at FASER

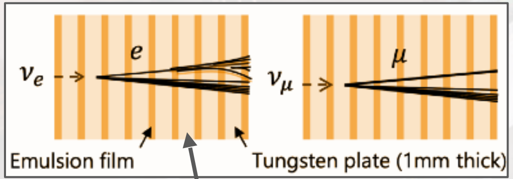
Two methods of detecting collider neutrinos with FASER:

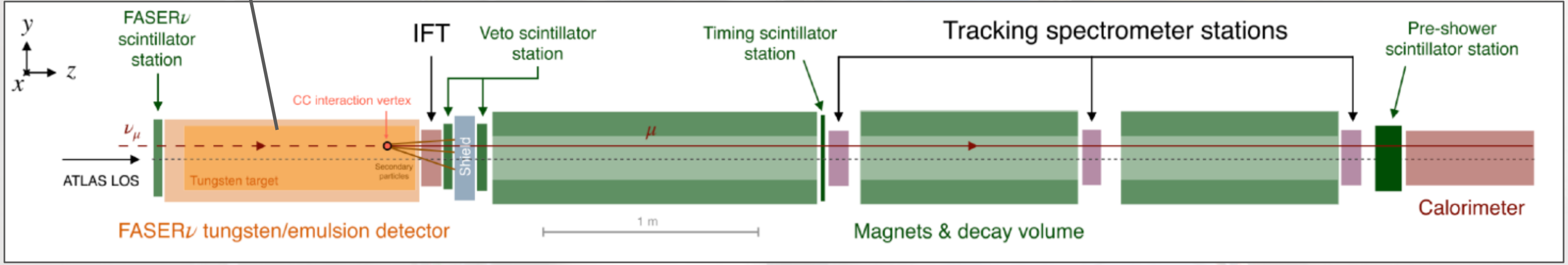
1) Emulsion detector:

- 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)



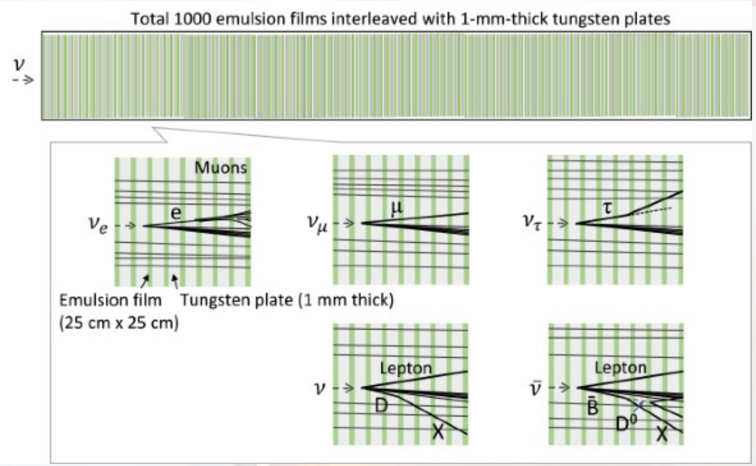


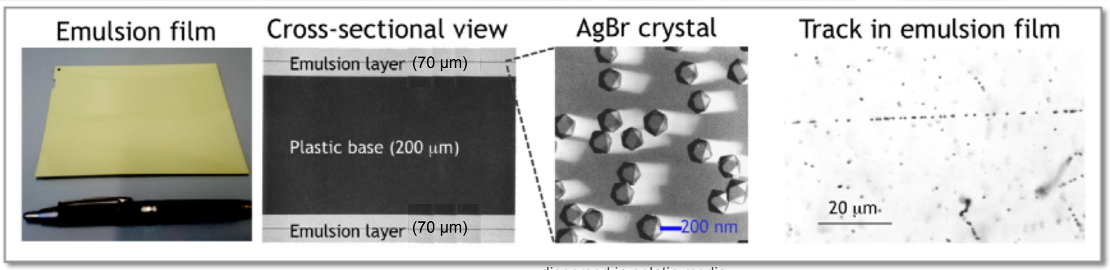
FASERν detector

- 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



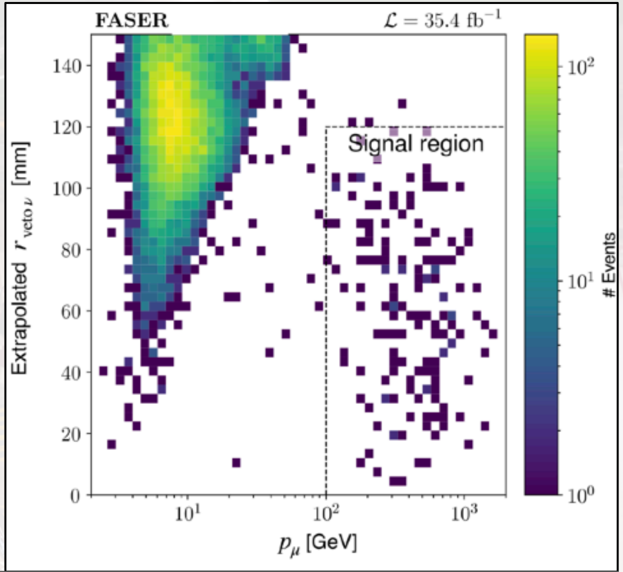


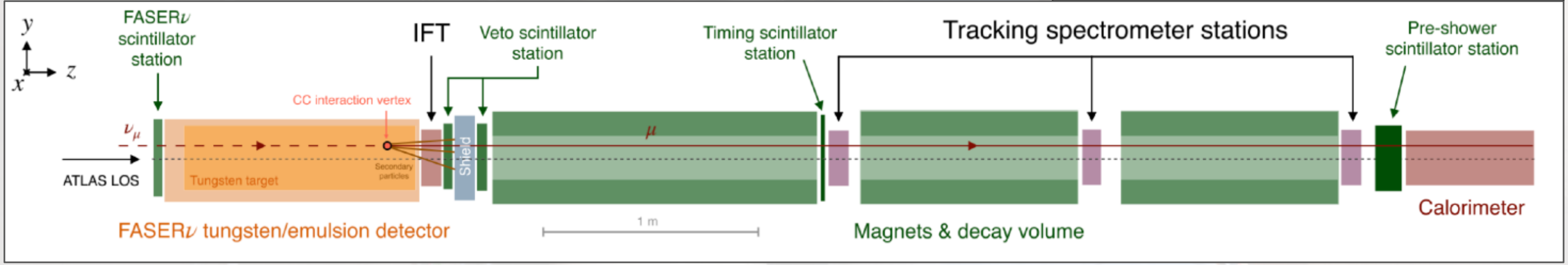
dispersed in gelatin media

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

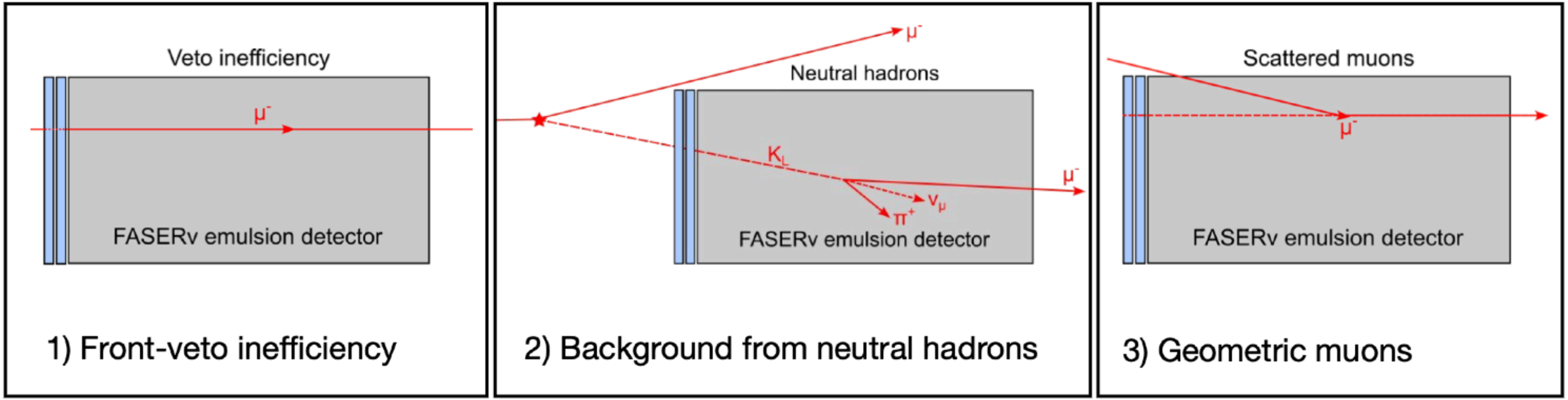




PhysRevLett.131.031801

First direct observation of collider neutrinos

3 background sources:



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**

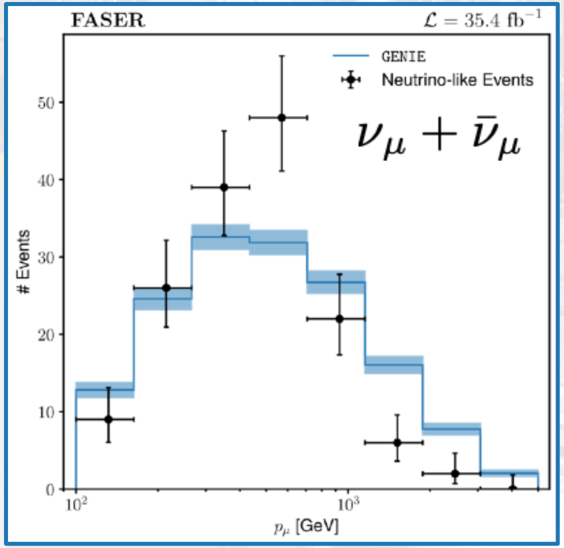
PhysRevLett.131.031801

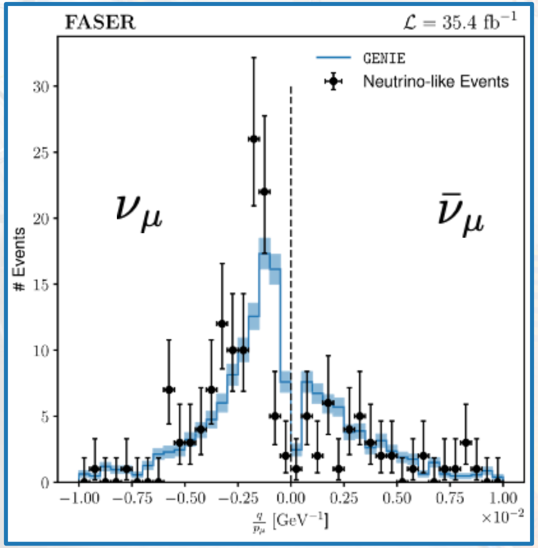
First observation of collider electron neutrinos

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

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

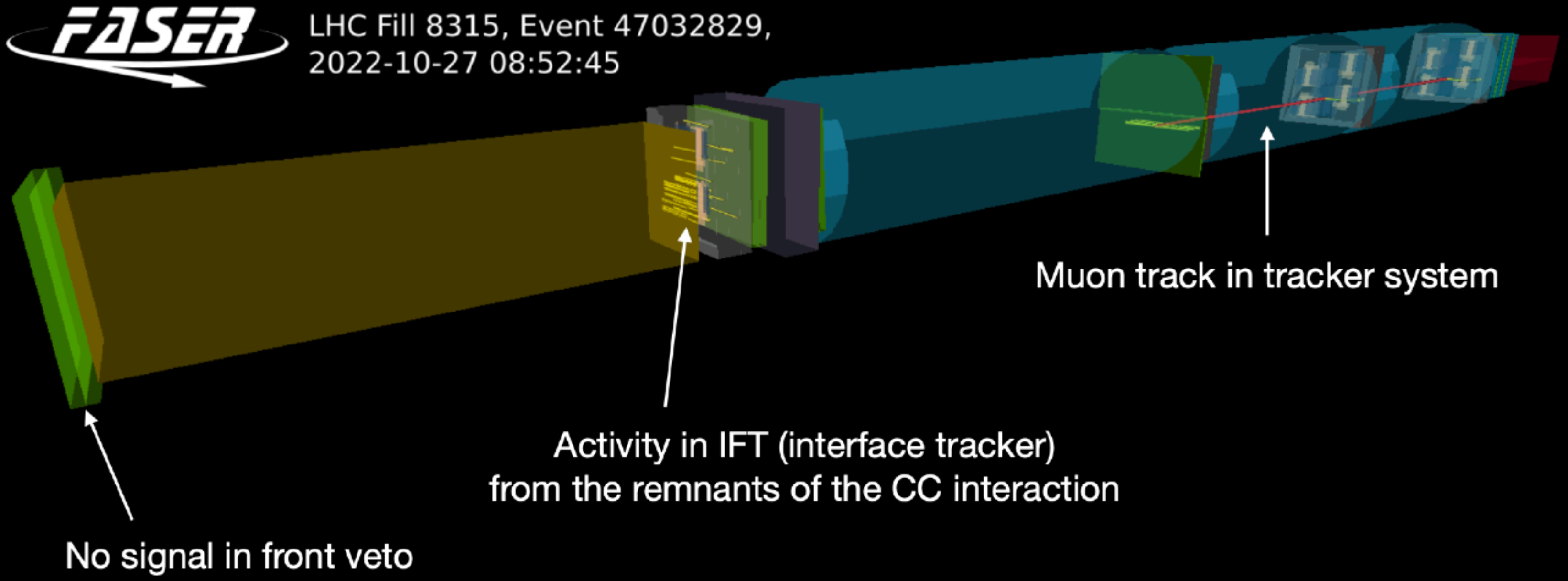
Compatible with **expectation: 151 ± 41**
(from mean/envelope of DPMJET and SIBYLL predictions)





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

Muon neutrino candidate event

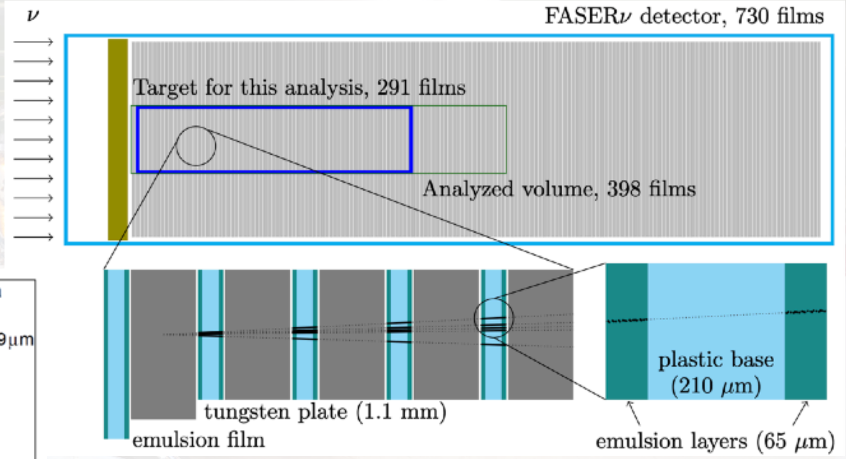


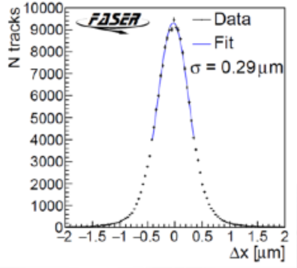
arXiv:2403.12520

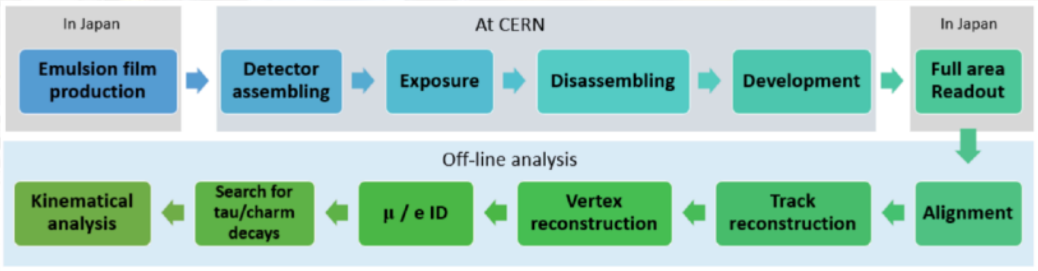
NEW!

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

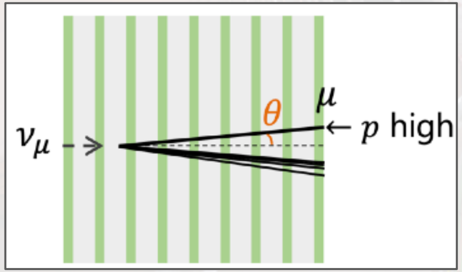


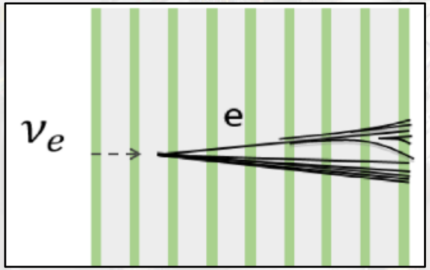


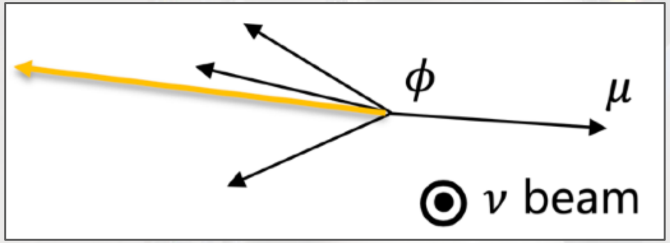


First observation of collider ν_e and ν_μ with FASERν

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

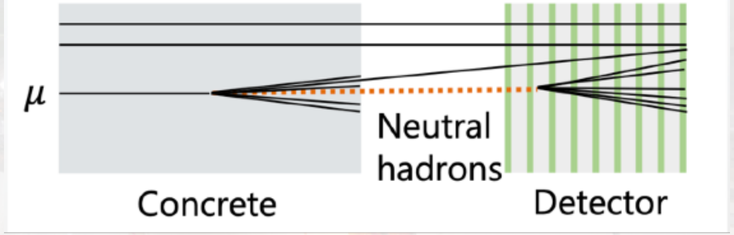
arXiv:2403.12520

NEW!

First observation of collider ν_e and ν_μ with FASERν

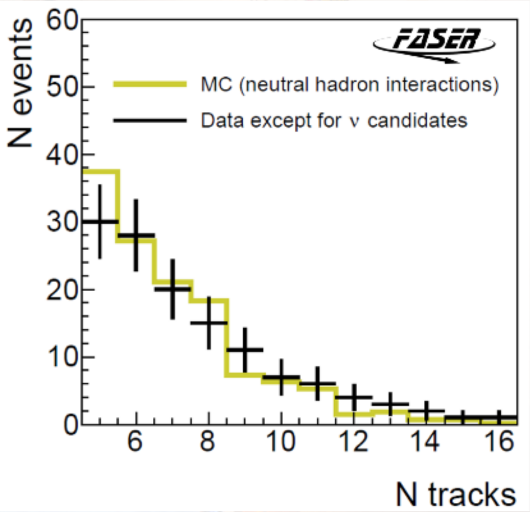
Backgrounds:

- **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



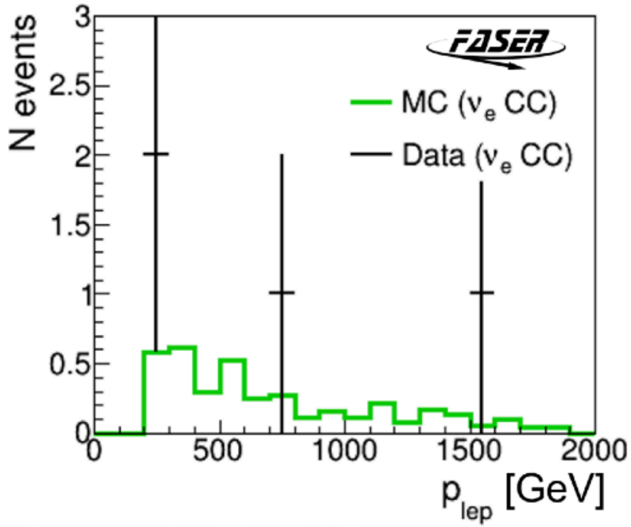
arXiv:2403.12520

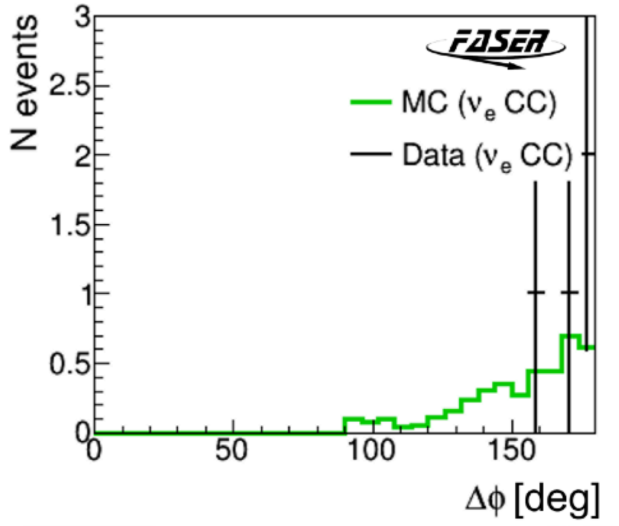
NEW!

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**

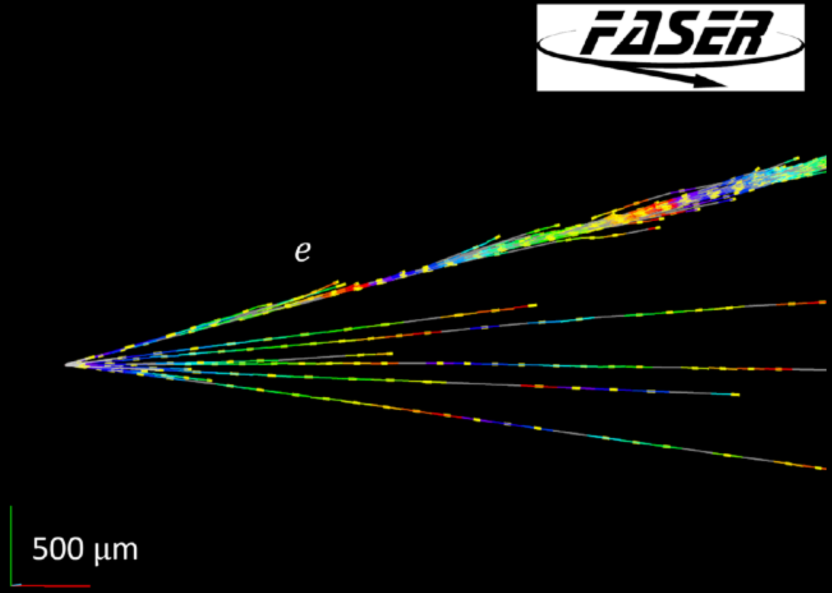




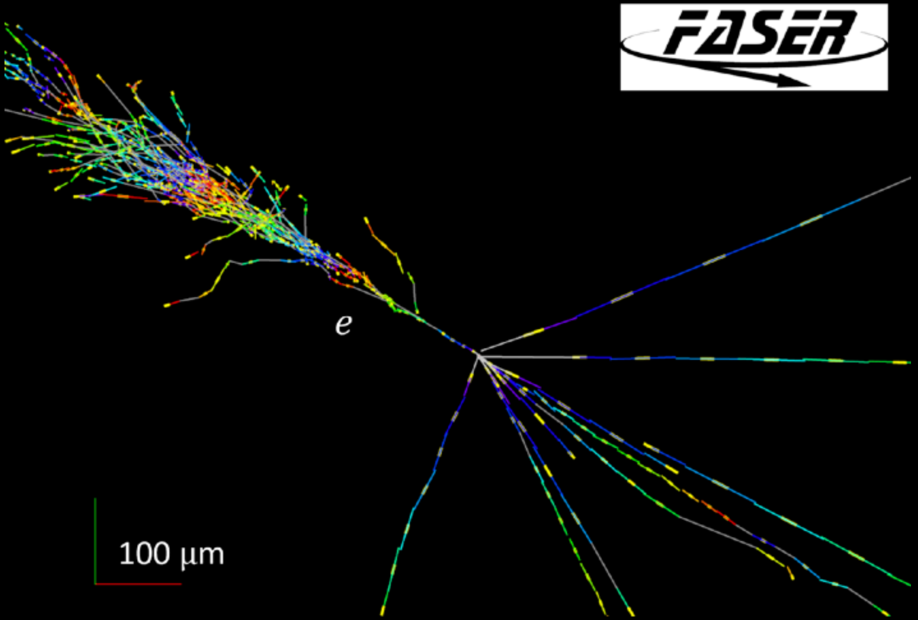
NEW!

Electron neutrino candidate event

Lab view



Transverse plane

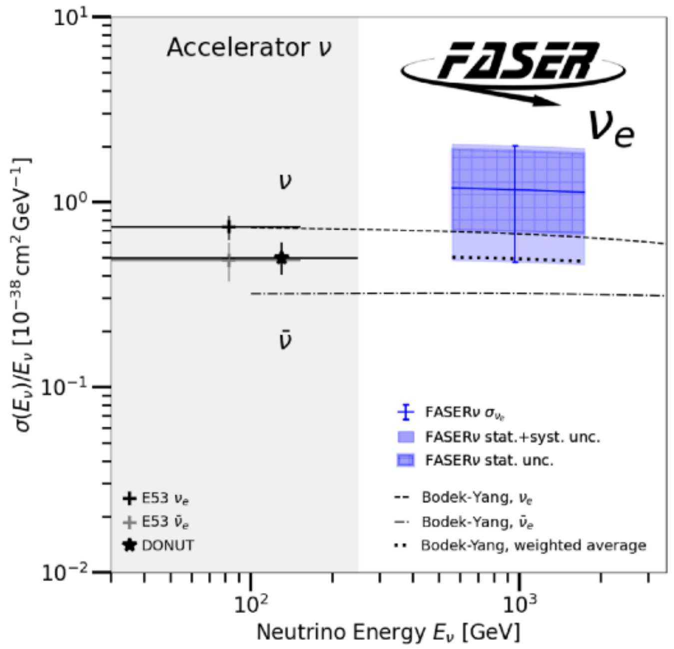


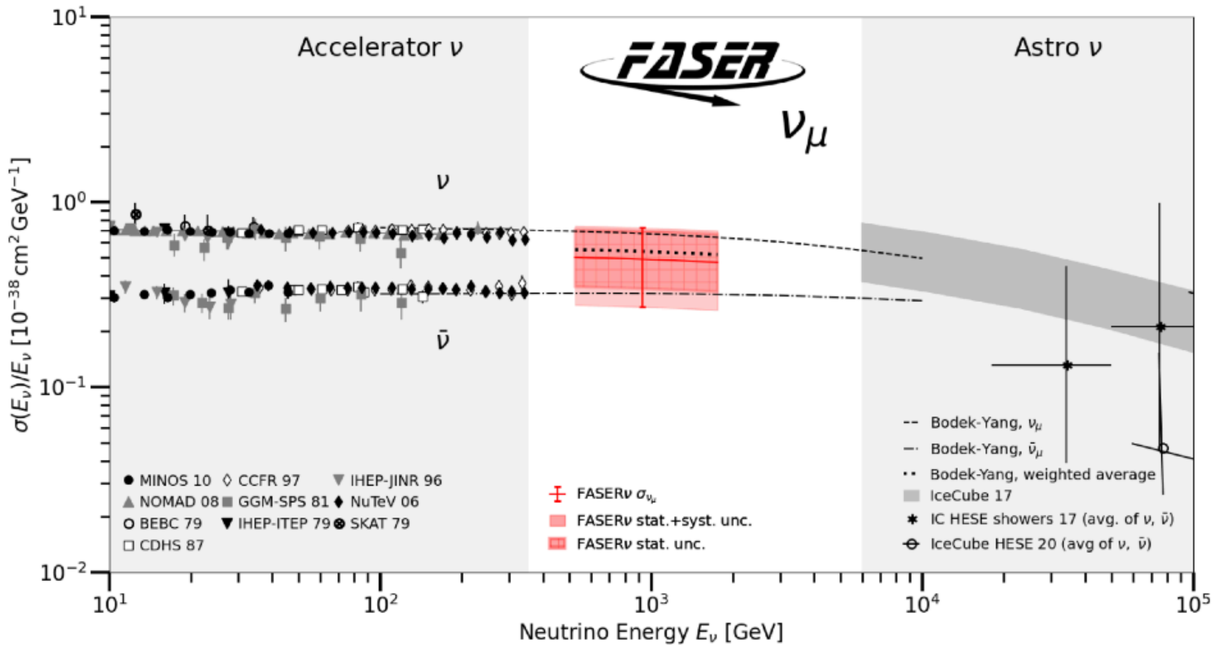
arXiv:2403.12520

NEW!

First observation of collider ν_e and ν_μ with FASERν

First cross section measurements at TeV energies:



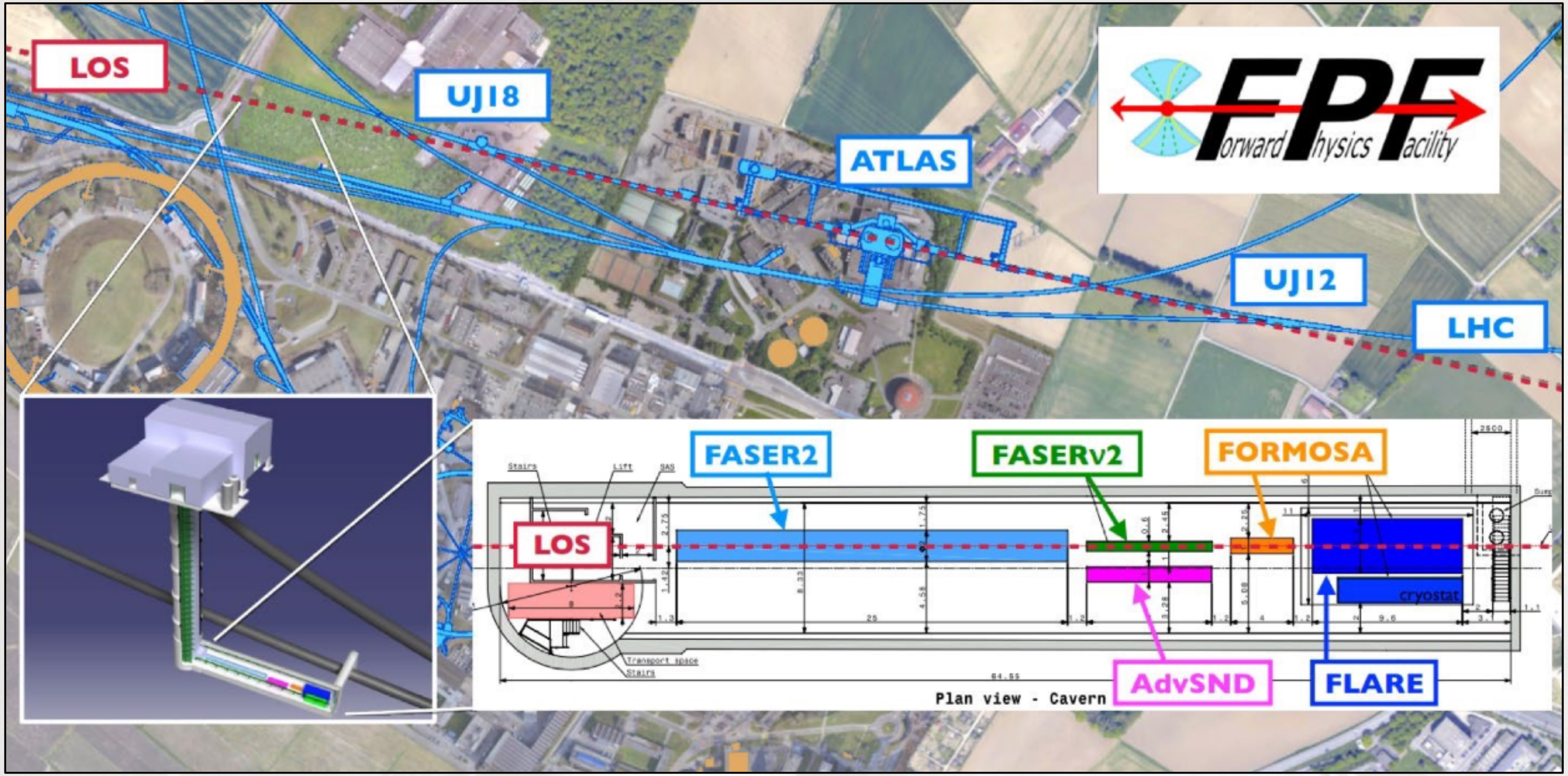


FASER2 and the FPF

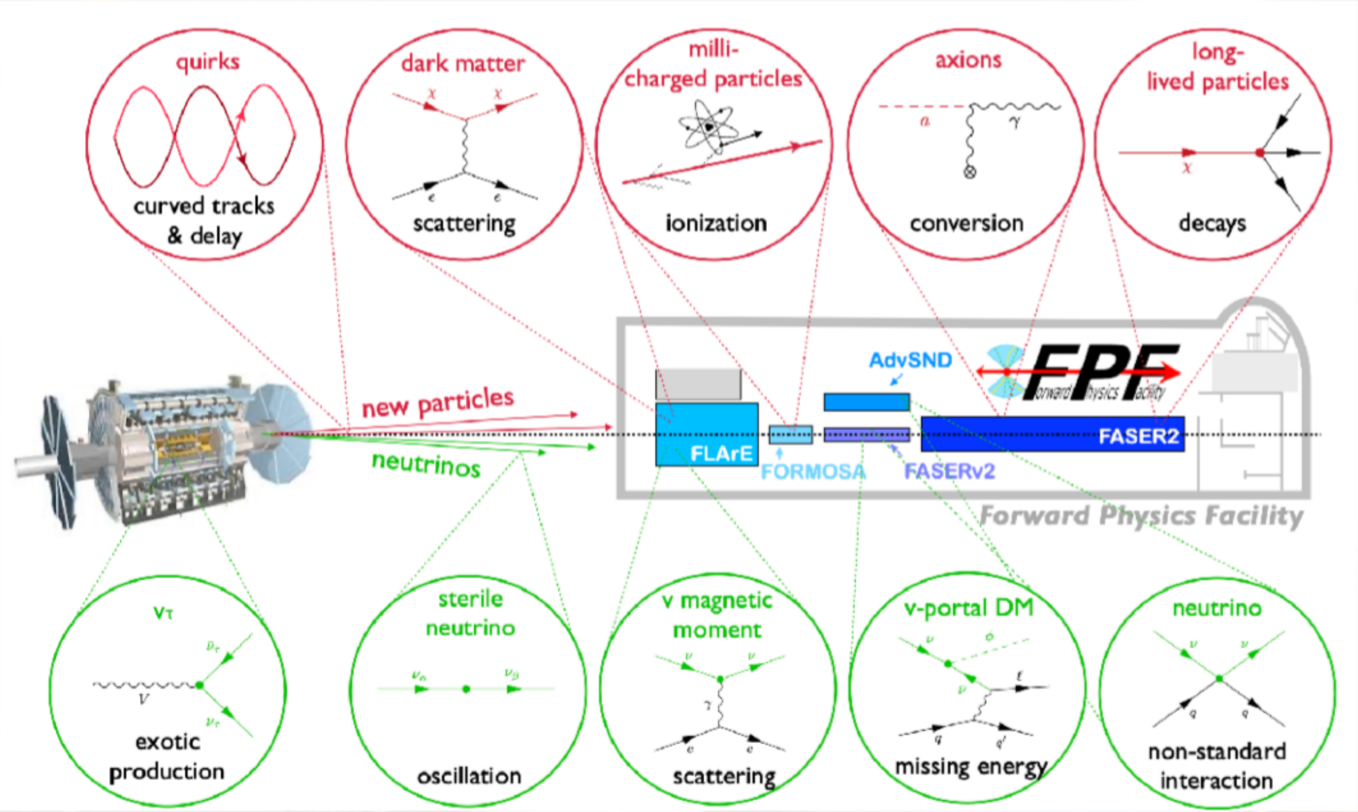
FPF Short Paper: Phys. Rept. 968, 1 (2022)
FPF White Paper: J. Phys. G (2022)

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

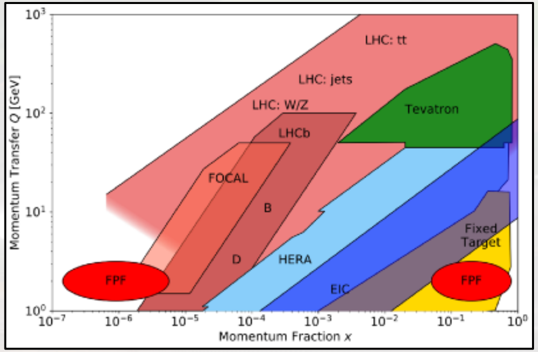


FPF physics: BSM

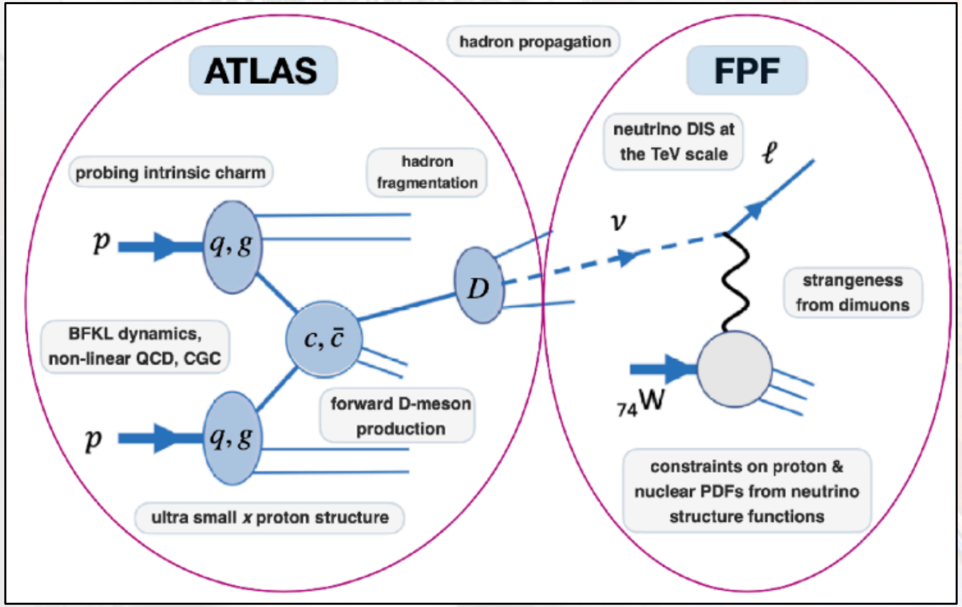
- Broad sensitivity to new physics models
- FASER2 (R = 1 m, L = 5-20 m) can discover:
    - dark photons, dark Higgs, HNL
    - ALPs with all types of couplings (ɣ, f, g)
    - many other particles
- Discovery potential covers most PBC benchmark scenarios

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

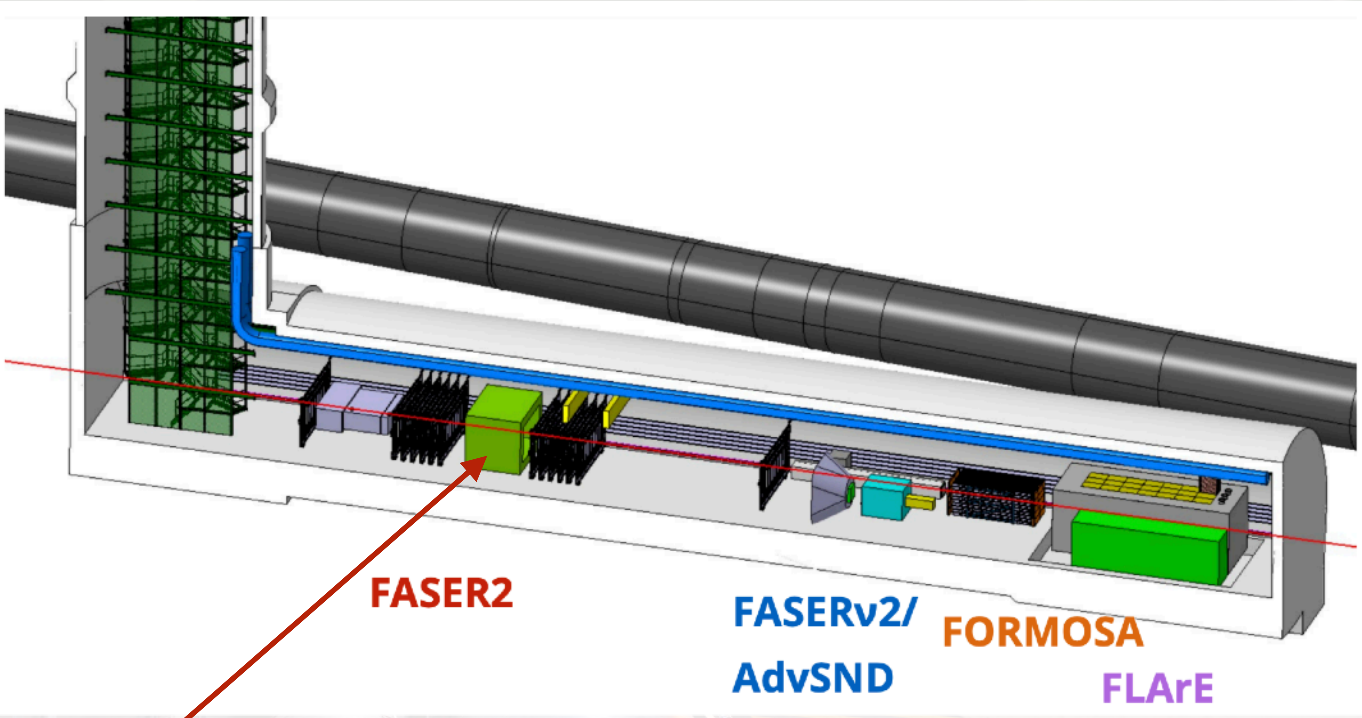
FPF physics: neutrinos



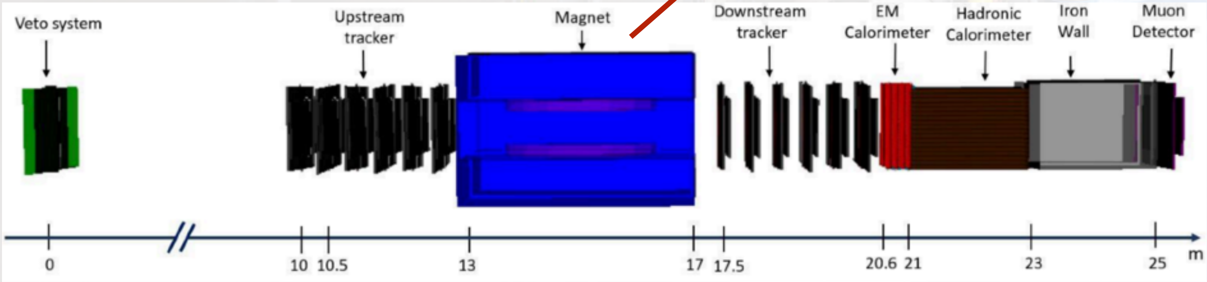
- Study neutrino interactions at high energy
- Study PDFs by DIS of neutrino in the target
- Study forward hadron production via neutrino flux measurements

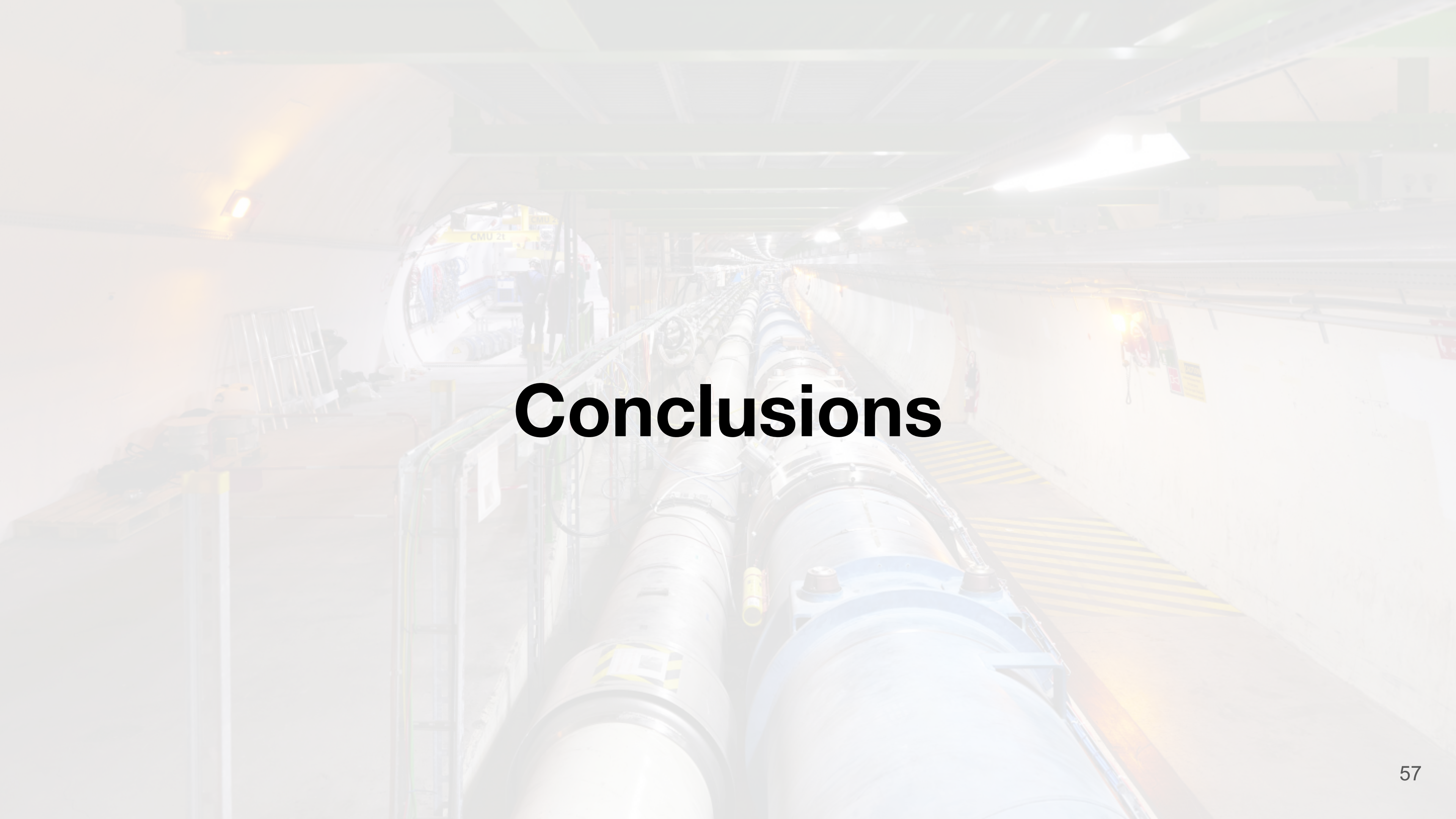


FPF experiments



FASER2 proof-of-principle design





Conclusions

Looking forward to more physics

- Successful operation of FASER in Run-3 (~70 fb^{-1} collected so far)
- First physics results coming out:
    - First ν_e , ν_μ cross sections
    - BSM searches (ALPs and dark photon limits)

- **Prospects**
    - Additional 180 fb^{-1} to be collected in 2024, 2025
    - Pre-shower detector upgrade in 2025 to enhance ALPs sensitivity
    - FASER in Run-4 approved
    - Discussing extended physics programs in Forward Physics Facility (2031-) in HL-LHC era

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

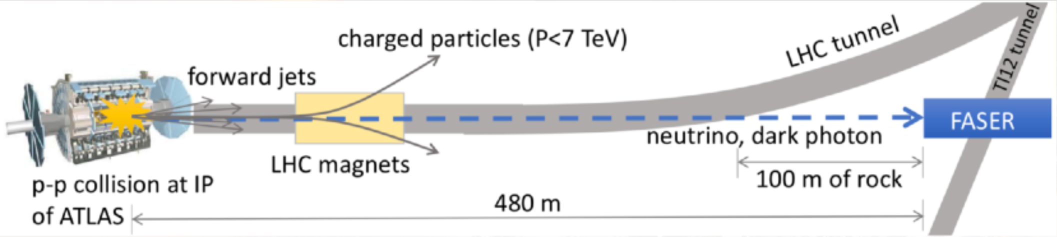
Additional slides

FASER Collaboration

89 collaborators, 25 institutions, 10 countries

- CERN
- Université de Genève
- Kyushu University
- UC Irvine
- Universität Bern
- Technion – Israel Institute of Technology
- Nagoya University
- University of Washington
- Johannes Gutenberg Universität Mainz (JGU)
- מכון ויצמן למדע – Weizmann Institute of Science
- KEK
- University of Oregon
- DESY.
- INFN
- International laboratory covered by a cooperation agreement with CERN
- 清華大學 – Tsinghua University
- Royal Holloway University of London
- Università degli Studi di Napoli Federico II
- University of Liverpool
- Chiba University
- University of Sussex
- Nikhef
- Universität Bonn
- ETH zürich
- Manchester 1824 – The University of Manchester

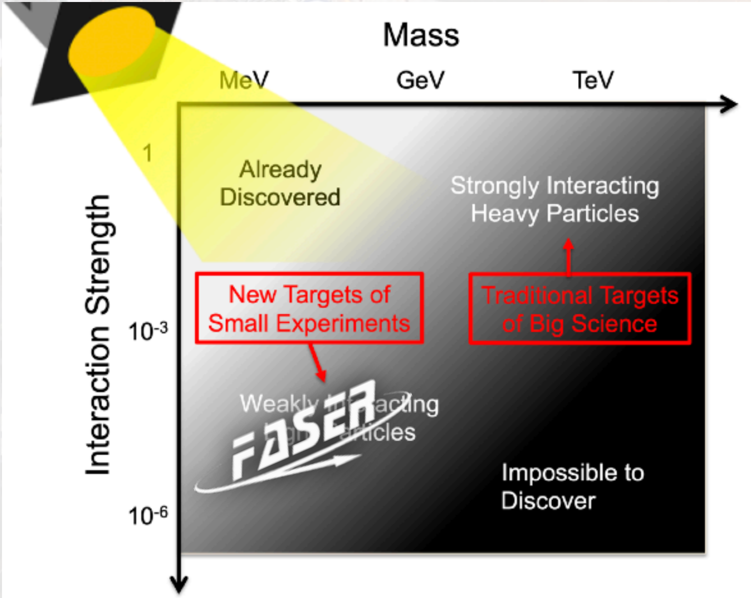
Forw**A**rd **S**earch **E**xpe**R**iment



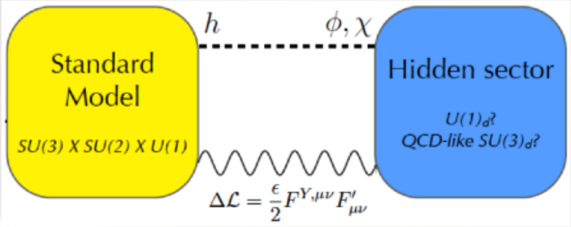
- A **new small experiment** in an old LEP injector tunnel to search for **long-lived particles** produced in Interaction Point 1 (IP1/ATLAS) at the **LHC** in Run-3 and beyond (2021+).
- First concept in **2017** (Feng, Galon, Kling, Trojanowski), approved by CERN in **March 2019** (limited budget ~ 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



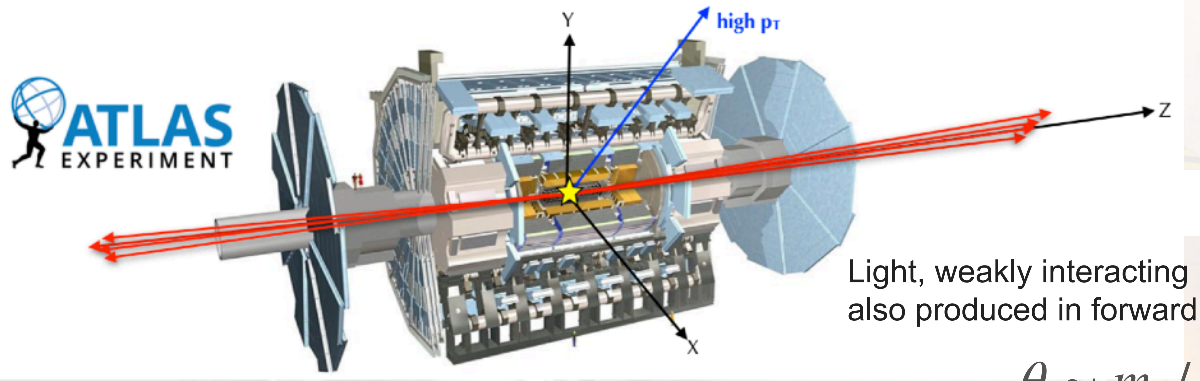
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

- **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	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}^{\mu\nu}_i$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
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:

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

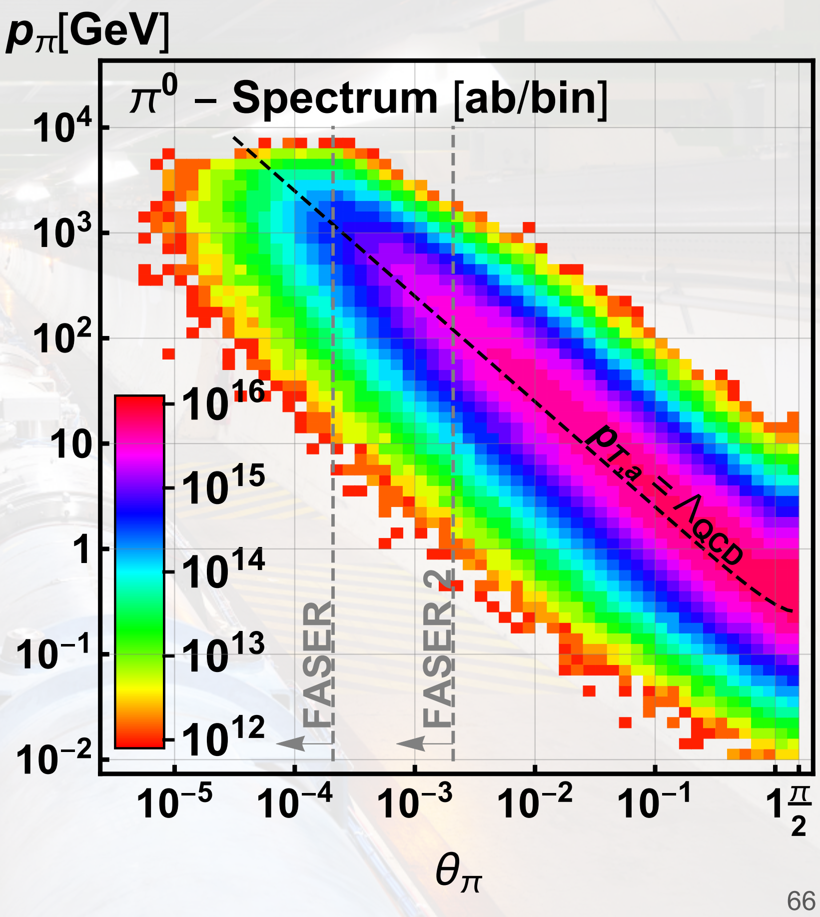
(for E ~ TeV)

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

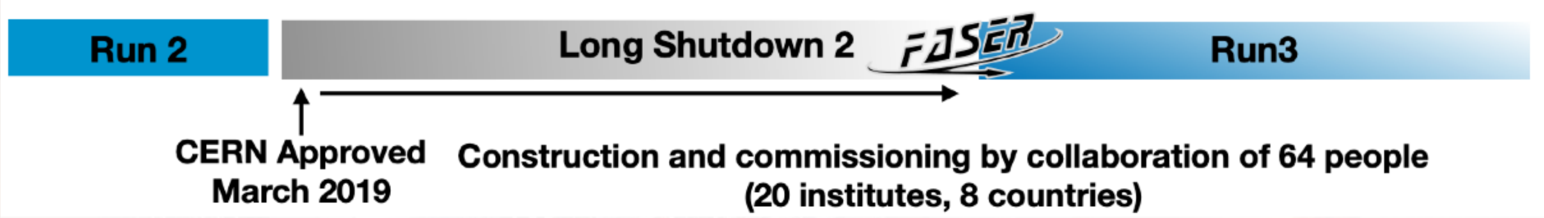
(mostly in forward region)

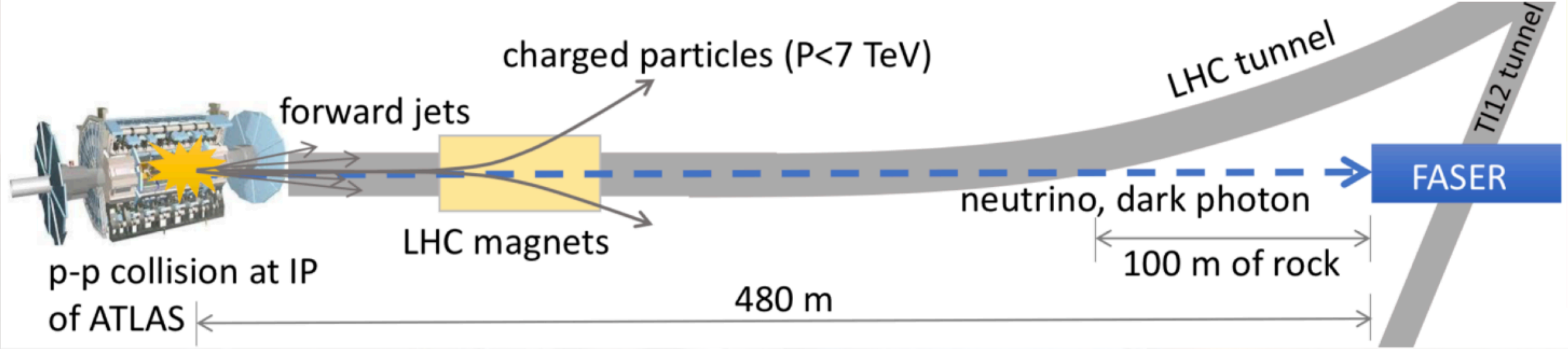
Looking forward

- 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 $E(\pi^0) > 10$ GeV, 2% of π^0 within 10 cm of line-of-sight of beam after ~500 m, despite only covering (2×10^{-6})% of solid angle



FASER: ForwArd Search ExpeRiment



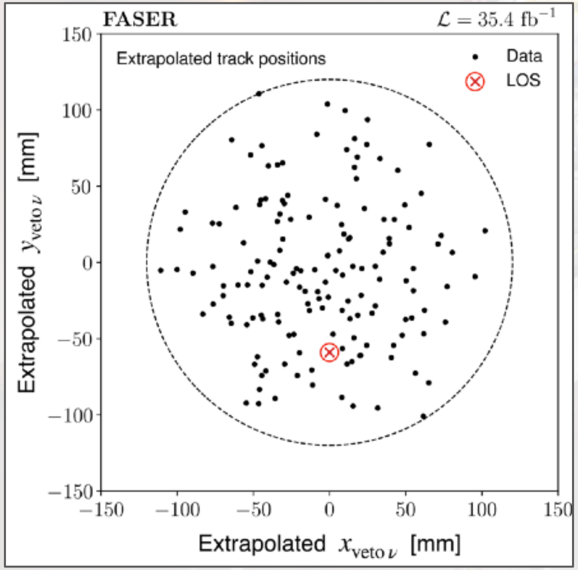


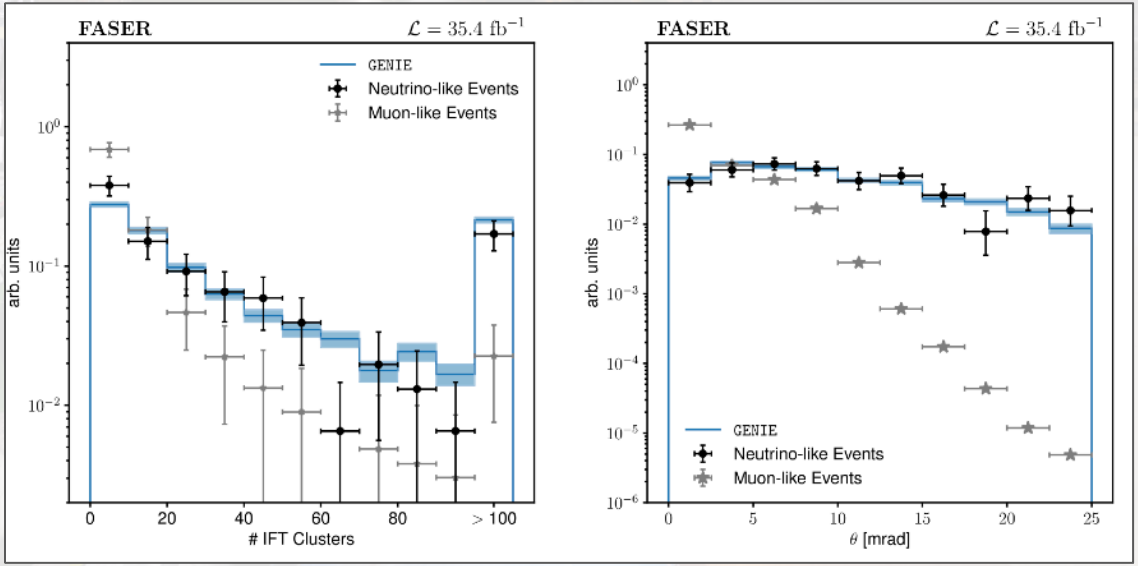
Neutrinos passing through FASER

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

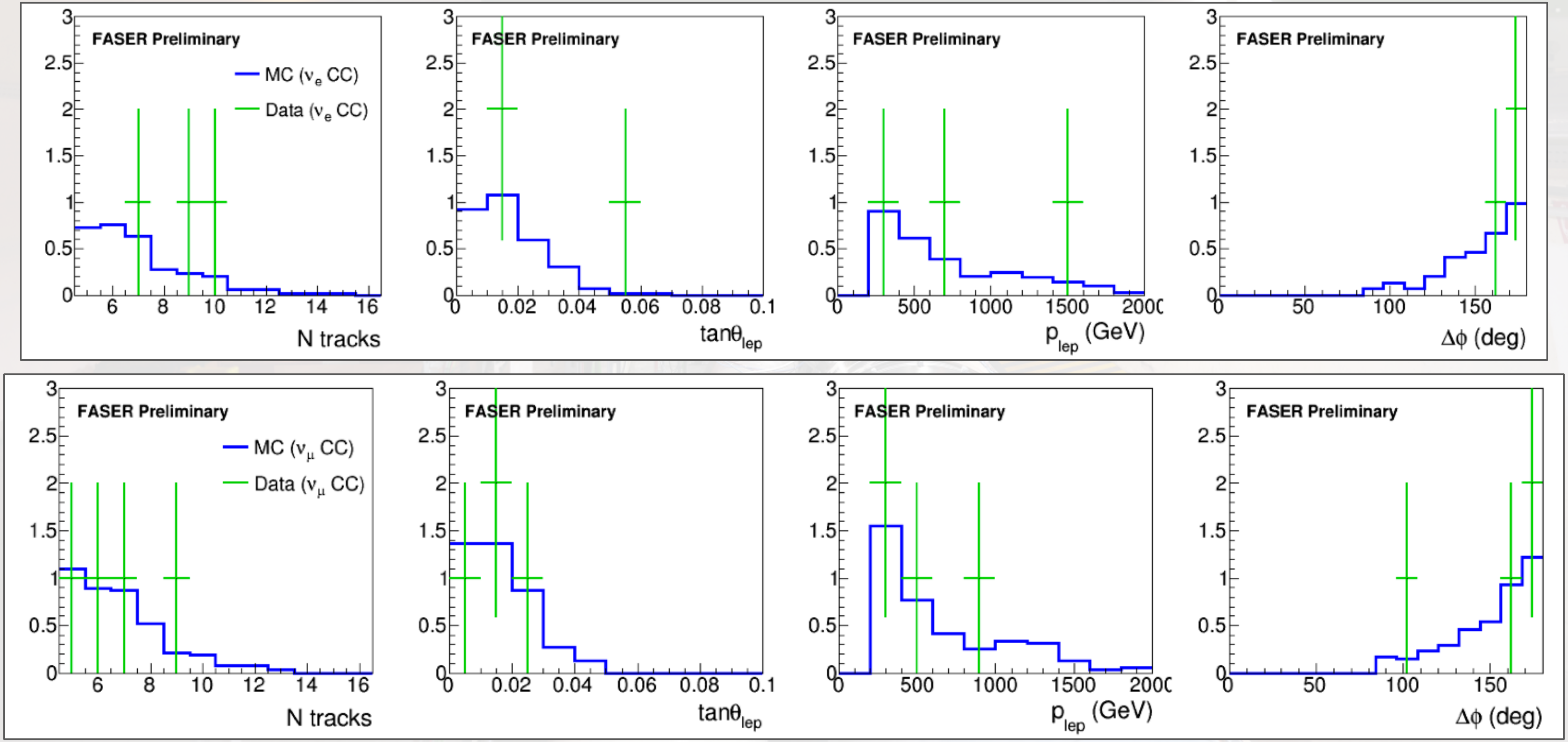
[PRD 104, 113008]

Electronic neutrino analysis distributions





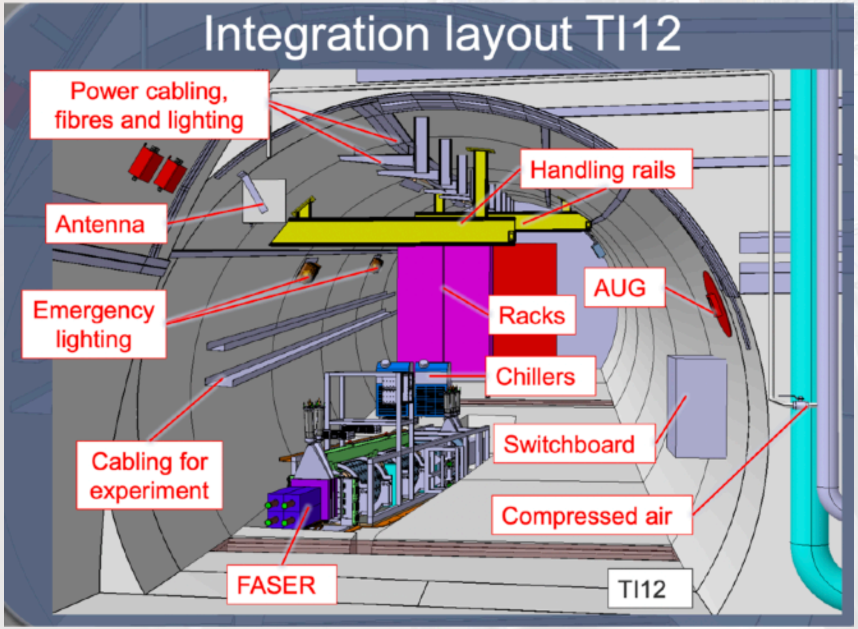
FASERν selected CC candidate events

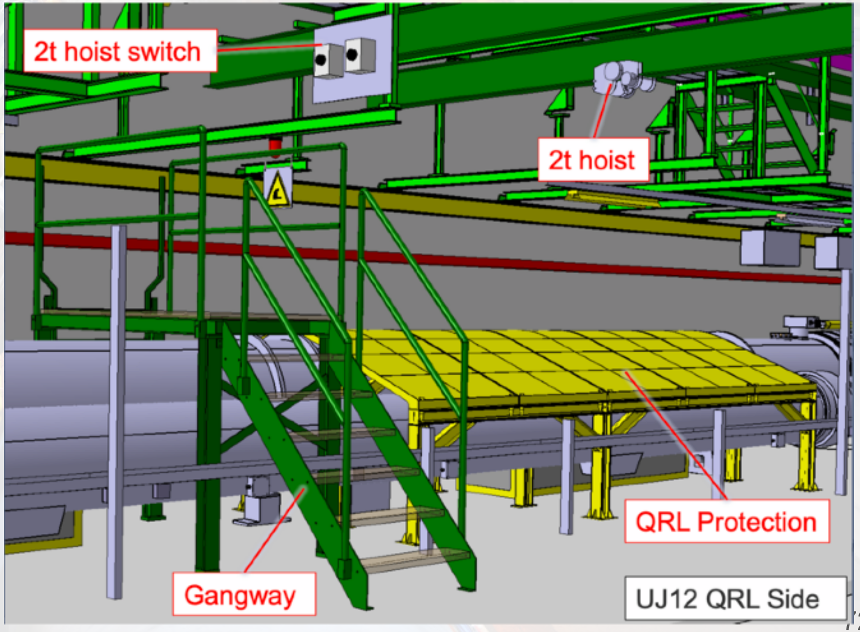



CMU 2t
CMU 2t
2t
To ATLAS
FASERnu
IFT
Veto
Decay volume
Tracking spectrometer
Preshower
Calorimeter

Preparation of TI12/UJ12

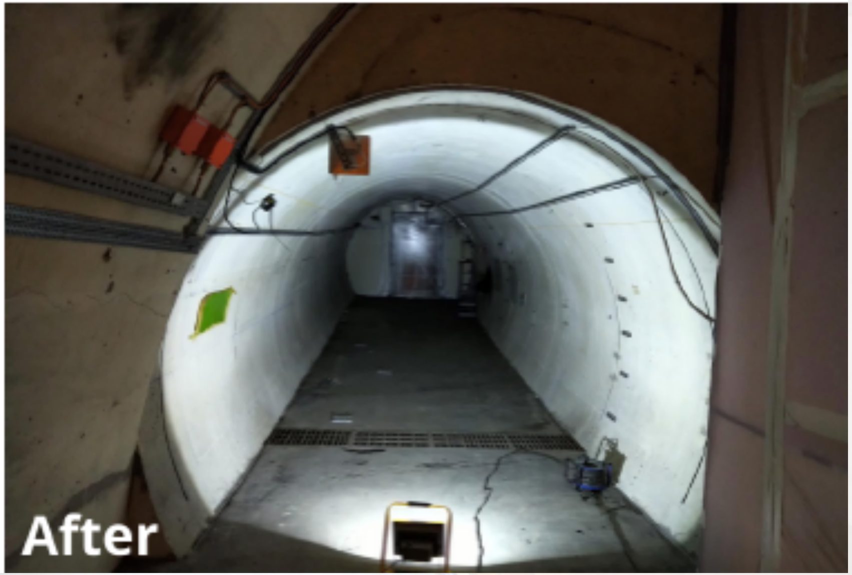
- Significant work to prepare TI12 for FASER, including lowering of floor by ~50 cm and installation of gangway/protective shield.





Preparing TI12

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



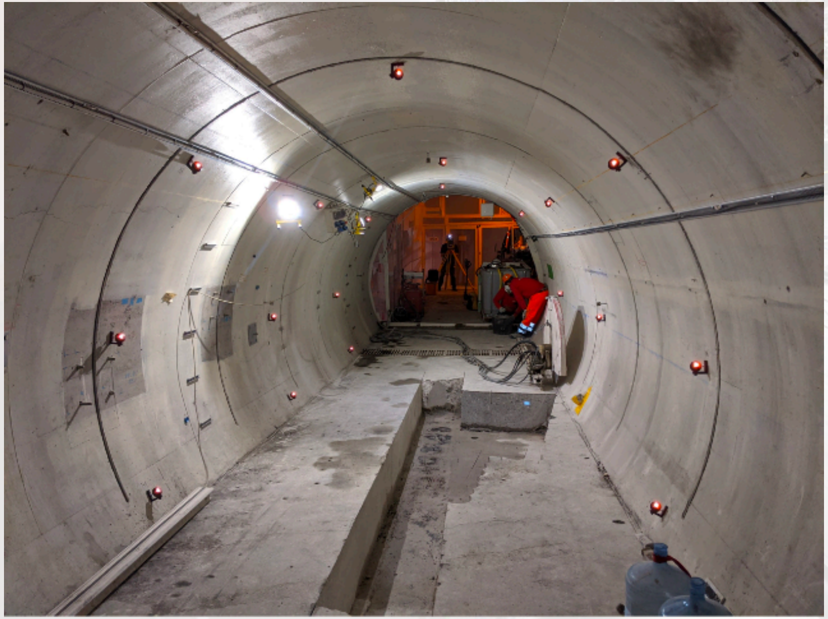
Visit to TI12 Dec 2019

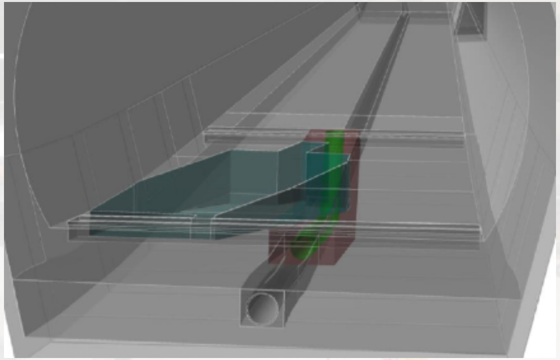
Some of the FASER Collaboration in TI12

TI12

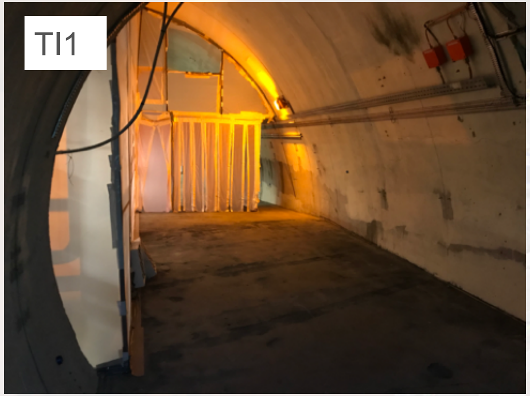
UJ12

Digging the trench





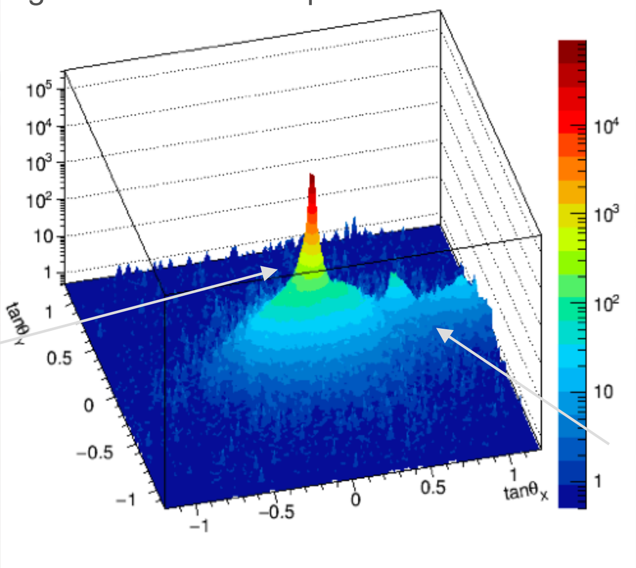
Civil engineering

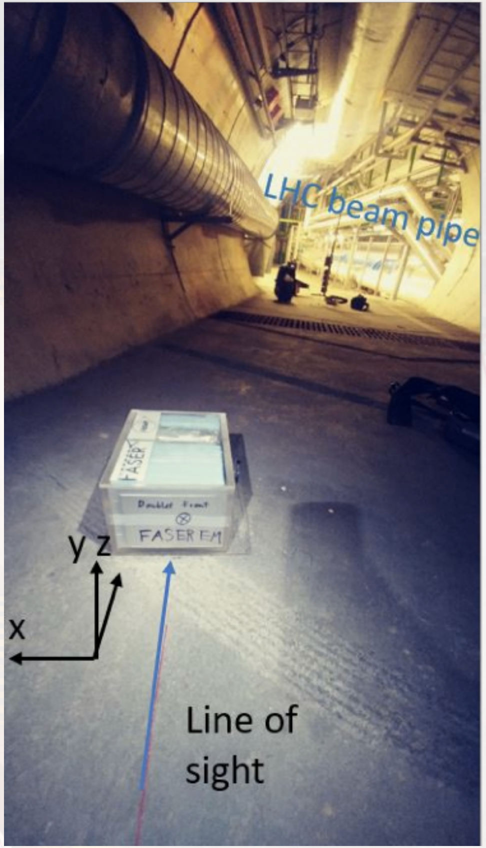


Beam backgrounds

- *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





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**