The FASER detector: from concept to operation

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FASER experiment

FASER is a new forward experiment of LHC, located 480 m downstream from the ATLAS IP. Successfully started data taking in Run 3 from July 2022 for:

- Search for new weakly-coupled particles in the MeV-GeV range
  - proposed in 2018, approved by CERN in 2019
- Study of all flavors of neutrinos at the TeV-energy frontier
  - proposed in 2019, approved by CERN in 2020

Favorable location, except that refurbishment is needed to be an experimental site.

- Background from collision point is only high-energy muon at about $1 \text{ cm}^{-2} \text{ sec}^{-1}$, thanks to ~100-m rock
- Radiation level from LHC is quite low, around $4 \times 10^{-3} \text{ Gy/year} (= 4 \times 10^7 \text{ 1-MeV neutron/cm}^2/\text{year}$)
More detail about FASER location
Searching for new particles in MeV-GeV range

Motivated by dark matter
• Example is a dark photon ($A'$) – vector portal to dark sector
• Could be produced very rarely in decay of a $\pi^0$
• Could be long-lived due to small coupling constant

Huge flux of $\pi^0$ produced in LHC collision provides strong opportunity
• $\mathcal{O}(10^{15})$ of $\pi^0$ in FASER acceptance ($r = 10$ cm) in Run 3
  • corresponding to $10^{-8}$ solid angle
• Very energetic - typically $E > 1$ TeV

Dark photon ($A'$) decays into a collimated pair of charged particle
• $m_{A'} = 200$ MeV and $E = 2$ TeV, the separation is $\mathcal{O}(200)$ um at the first tracker
• $e^+ e^-$ for most of the $m_{A'}$ range relevant for FASER
Searching for new particles in MeV-GeV range

FASER is the first far collider experiment for new particle searches
• Unique approach provides sensitivity to unexplored region with the first $1 \, \text{fb}^{-1}$ of the LHC collision

LHC finished the 2022 operation end of November
• More than $40 \, \text{fb}^{-1}$ delivered at the ATLAS interaction point
• FASER successfully collected the data, the first result expected in Q1 2023

FASER will also have sensitivity to other dark sector scenarios including ALPs, other gauge bosons, ...
Exploring neutrinos at the TeV-energy frontier

The LHC collisions also produce a copious number of neutrinos at uncharted energies

- FASER is the first experiment to probe collider neutrinos

In 2018, a 29 kg emulsion detector had been installed
- the fiducial mass used for the pilot analysis was only 12 kg
- exposed to 12.2 fb\(^{-1}\) data
- best fit value of 6.1 neutrino interactions (3.3 expected) - 2.7\(\sigma\)

In Run3, 1.1 ton emulsion detector is installed
- the first result expected in Q1 2023
Exploring neutrinos at the TeV-energy frontier

Sensitive to new physics by measuring scattering cross sections and studying the final states

• Expected number of CC neutrino interaction with 250 fb$^{-1}$ in Run 3

• Emulsion detector provides great ID for all leptons and heavy flavor hadrons from neutrino interaction

based on PhysRevD.104.113008
In-situ background measurement in 2018

No infrastructure in 2018 (last year of Run 2) – quick/reliable measurement needed

• an emulsion detector exposed to 7 fb\(^{-1}\) in TI12
  • Good agreement with FLUKA simulation, accelerating FASER detector design

<table>
<thead>
<tr>
<th>beam</th>
<th>observed tracks/cm(^2)</th>
<th>efficiency</th>
<th>normalized flux, all fb cm(^{-2})</th>
<th>normalized flux, main peak fb cm(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH18</td>
<td>2.86</td>
<td>18407</td>
<td>0.25</td>
<td>(2.0 \pm 0.7) \times 10^4</td>
</tr>
<tr>
<td>TH12</td>
<td>7.07</td>
<td>174208</td>
<td>0.80</td>
<td>(3.0 \pm 0.3) \times 10^4</td>
</tr>
<tr>
<td>FLUKA simulation, E&gt;100 GeV</td>
<td></td>
<td></td>
<td>1 \times 10^4</td>
<td></td>
</tr>
</tbody>
</table>

• a TimePix BLM to confirm that the muon rate was correlated with luminosity at IP1
FASER detector

- Target for neutrino: Installation completed 2022 March
- Decay volume of new particles
- For neutrino physics: Installation completed 2022 March
- For new particle search: Installation completed 2021 March
Civil engineering work

The floor in TI12 excavated by ~50 cm to have the FASER detector on beam axis
FASER detector installation

FASER spectrometer (magnets and tracker), scintillators and calorimeter

April 2021

Emulsion/Tungsten detector, IFT and scintillator

March 2022
Emulsion/Tungsten detector

All flavors of neutrino interactions can be identified

• Heavy quark production also can be distinguished
• 730 x 1-mm-thick tungsten plates, interleaved with emulsion films
• 25 x 30 cm², 1.1 m long, 1.1 ton detector (220 $X_0 / 8 \lambda_{int}$)
  • ~10000 $\nu_\mu$, ~1000 $\nu_e$ and ~10 $\nu_\tau$ expected in Run 3
• 3 replacements each year
  • emulsion will be produced a few months before installation
Thickness uniformity of the tungsten plates

A total of 1622 plates were semi-automatically measured using a custom made apparatus

- the maximum difference among the 24 points on each plate was checked.
- 1562 plates with a difference smaller than 80 microns were selected as good quality
  - corresponding to 90% of the measured plates
- 1460 plates are used to construct the emulsion detector

![Histogram of tungsten plates thickness variation](image1)

1087 ± 27 μm
The first result from the emulsion films

Three installations done in 2022

- The last removal on 29th Nov right after the LHC operation

<table>
<thead>
<tr>
<th></th>
<th>Integrated luminosity per module (fb⁻¹)</th>
<th>N x int. expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022 1st module</td>
<td>Mar 15 – Jul 26</td>
<td>0.5</td>
</tr>
<tr>
<td>2022 2nd module</td>
<td>Jul 26 – Sep 13</td>
<td>10.6</td>
</tr>
<tr>
<td>2022 3rd module</td>
<td>Sep 13 – Nov 29</td>
<td>(~30)</td>
</tr>
</tbody>
</table>

1st module is used to commission the workflow

- The track density measured in the data sample is $1.2 \times 10^4 /\text{cm}^2$ – consistent to the expectation
Very good position resolution

The position deviation of 0.2μm between the track hits and the straight-line fits to reconstructed tracks.
The angular spreads of the peaks are $\sim 0.5$ mrad, mainly due to the multiple Coulomb scattering through 100 m of rock. Small peak at tan$\theta$x is under investigation with simulation studies.
Three 0.57 T permanent dipole magnets (1.5m-long x 1 and 1m-long x 2)

- Sufficient magnetic field to separate a pair of charged particles, assuming tracking detectors with good resolution
- Compact and robust design adapted to cope with limited space in the tunnel and limited access during Run3

The magnets were designed and constructed by the CERN magnet group
Magnetic measurements

The assembled dipoles were measured with single-stretched wire (SSW) and 3D Hall probe mapper

- Measured integrated field and field orthogonality for the three dipoles within specified value

- Stray field in the central axis of the magnet
  - less than 10 mT (100 Gauss) about 250 mm from the magnet apparatus

- Zero stray field outside the side of the magnet
Tracker station

Four stations total; one station as interface tracker to emulsion detector and three stations for spectrometer

• Based on ATLAS SCT modules - 4 station x 3 layers x 8 modules = 96 modules

ATLAS SCT module:
• 6cm x 12cm x 2 sides (40 mrad)
• 80 um pitch/ 768 strips per side
• Resolution: 17 um x 580 um
• 6 ASICs per side
Tracker cooling system

**Two air-cooled water chiller used, whose coolant temperature at 15 °C**
- one is running to cool the detector and the other acts as a hot spare
- If both chillers are not operating correctly, the power supply system is forced to be turned off by the hardware interlock system
- Module temperature is kept well below 30 °C

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DCS warning</th>
<th>DCS automatic actions</th>
<th>Hardware interlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module temperature</td>
<td>&gt;30°C</td>
<td>&gt;31°C</td>
<td>-</td>
</tr>
<tr>
<td>Plane humidity</td>
<td>&gt;10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Frame temperature</td>
<td>&gt;23.0°C</td>
<td>-</td>
<td>&lt;5°C or &gt;25°C</td>
</tr>
</tbody>
</table>

glass-transition temperature of the glue: 35°C
Tracker plane/station metrology and survey

Each plane/station is measured with a mechanical touch-probe and an optical camera

- All frames satisfied the required tolerances ($\pm 20 \, \mu m$) with respect to the CAD manufacturing drawings
- The maximum deviation was $100 \, \mu m$ in positioning the SCT module

Before and after installation TI12, 3D laser scanning was performed by the CERN survey group

- measured the position of the survey points on the tracker station with $O(16 \, \mu m)$ accuracy.
FASER spectrometer assembled in March 2021

After commissioning in EHN1, three tracker stations are integrated with the magnets.
IFT installed in Nov 2022

Track matching between the emulsion and IFT enable us to reconstruct with the spectrometer, enabling:
- charge identification, improved energy resolution and better background rejection.

![Diagram of particle detection setup](image-url)
Tracker alignment in progress

Track based alignment clearly improves residual and track chi2 for the three tracker station

- These three tracker stations are connected to the backbone, mechanically decoupled from fourth tracker station (IFT)
- 35.8 um (w/o alignment) -> 24.8 um (w/ alignment)
Early collision data in July/Aug 2022 was used to

• set proper fine timing delay (390 ps step), and
• evaluate hit efficiency as a function of threshold and HV
  • Hit efficiency of $99.64 \pm 0.10\%$ at 1.0 fC and 150V
Stable performance in 2022

More than **99.5%** strips are active:
- The number of defective strips (dead, low-gain, low ENC and noisy strips) are stable

**Calibration periodically performed, showing good stability on gain and electric noise charge (ENC)**
- Consistent to the measurement by ATLAS SCT group
Hits on track on each tracker plane

Uniform distribution inside magnet aperture except for gaps between SCT modules

- Staggered planes (± 5 mm in vertical axis) inside the station mitigate the gap
Scintillation detectors

Four scintillator stations are commissioned and installed

• Veto incoming charged particle, precise timing, and pre-shower for calorimeter
• Scintillators, light guides and PMT housing constructed at CERN scintillator lab (EP-DT)
Scintillator performance

More than 99.99% efficiency achieved for each scintillator

- $O(10^8)$ muon expected in Run3 would be rejected; sufficient for zero background in new particle search

Trigger scintillator provides timing resolution of 423 ps

- Average time of two PMTs on both ends of the trigger scintillator to correct for timewalk
Electromagnetic calorimeter

Calorimeter utilizes spare LHCb ECAL module x 4 is also installed

- one module has:
  - 12 cm x 12 cm x 75 cm (25 $X_0$)
  - 66 layers of (2mm lead and 4mm scintillator)
EM Calorimeter – test beam at SPS

Testbeam at SPS in 2021 summer

- Tracker + preshower scintillator + Calorimeter
- Reasonable resolution compared to the LHCb result and simulation for high energy electrons
EM Calorimeter – First collision data

LHC collision data shows calorimeter provides timing resolution of 256 ps, requiring:

• EM energy is above 4 GeV
• only events with unsaturated PMT signals
• BCID to be consistent with a colliding bunch ID

Close to the intrinsic 239 ps timing resolution of the LHC
FASER detector material

The amount of material inside the magnet aperture is minimized to reduce physics backgrounds

• The largest fraction of material is in the tracking stations
  • No Layer frame and electronics in the central region ( |x| < 4 cm )

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Number / station</th>
<th>$X_0$ (%)</th>
<th>Central region</th>
<th>Edge region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon sensor</td>
<td>Si</td>
<td>6</td>
<td>1.8%</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>Station Covers</td>
<td>CFRP</td>
<td>2</td>
<td>0.3%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>SCT module support</td>
<td>TPG</td>
<td>3</td>
<td>-</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>C-C Hybrid</td>
<td>C (based)</td>
<td>3</td>
<td>-</td>
<td>2.2%</td>
<td></td>
</tr>
<tr>
<td>ABCD chips</td>
<td>Si</td>
<td>3</td>
<td>-</td>
<td>6.5%</td>
<td></td>
</tr>
<tr>
<td>Layer frame</td>
<td>Al</td>
<td>3</td>
<td>-</td>
<td>10.1%</td>
<td></td>
</tr>
<tr>
<td><strong>Total / station</strong></td>
<td>-</td>
<td>-</td>
<td>2.1%</td>
<td>21.5%</td>
<td></td>
</tr>
</tbody>
</table>

• 0.1 $X_0$ for the central region and 0.7 $X_0$ for the edge region

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>$X_0$ (%)</th>
<th>Central region</th>
<th>Edge region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator timing station - scintillator</td>
<td>1 cm polyvinyltoluene</td>
<td>2.4%</td>
<td>2.4%</td>
<td></td>
</tr>
<tr>
<td>Scintillator timing station - foil wrapping</td>
<td>1 mm Al</td>
<td>1.1%</td>
<td>1.1%</td>
<td></td>
</tr>
<tr>
<td>3 Tracking stations</td>
<td>See Table 2</td>
<td>6.3%</td>
<td>64.5%</td>
<td></td>
</tr>
<tr>
<td>Decay volume magnet cover - front</td>
<td>0.4 mm CFRP</td>
<td>0.15%</td>
<td>0.15%</td>
<td></td>
</tr>
<tr>
<td>Decay volume magnet cover - back</td>
<td>3 mm plastic</td>
<td>0.75%</td>
<td>0.75%</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td>10.7%</td>
<td>68.9%</td>
<td></td>
</tr>
</tbody>
</table>
Trigger and DAQ system

Readout electronics in TI12
- Tracker: Custom GPIO board
- Scintillator and Calorimeter: CAEN digitizer
- Trigger: Custom GPIO board
  - Clock and bunch taken from LHC
- Ethernet switch → Servers on surface

DAQ Software implemented on DAQling
- open-source framework developed at CERN

Paper is published: 2021 JINST 16 P12028
Stable data taking throughout 2022

The number of bunches in LHC has reached 2400 since August 2022

- Maximum trigger rate around 1.2 kHz, giving dead time less than 2%
- Physics coincidence trigger (foremost veto and the preshower scintillator station) around 200Hz
  - our main triggered background is not muons passing through from IP1 but particles triggering individual trigger stations
- only 850 pb\(^{-1}\) (< 2.5% of full dataset) data lost due to operational issues
Trigger rate v.s. luminosity

The total trigger rate (green) falls off faster than luminosity at the start of fill
- higher beam-induced background apparent at the beginning of the fill

The coincidence trigger rate (red) almost correlated with luminosity
Muon event from LHC collision

Reconstructed momentum 21.9 GeV
FASER detector operation

No control room for FASER operation – two people remotely have responsibility on safe operation

• Live monitoring via Grafana for DAQ, DCS, trigger and LHC status
• Alarms sent to Mattermost, shared with experts

This operation model works very well in 2022
Upgrade planned for 2025

The preshower scintillator will be replaced by silicon pixel detector

- Installation is planned at the end of 2024, aiming to take data in 2025 (the last year of Run3)
- Separation of 2 close-by gammas down to 200 um enables us to get strong sensitivity for ALP -> 2 gamma
- Monolithic Active Pixel Sensors (MAPS) with SiGe BiCMOS technology developed by University of Geneve

CERN research board formally approved this preshower project in April 2022

- Technical proposal is public: [https://cds.cern.ch/record/2803084/](https://cds.cern.ch/record/2803084/)
Toward HL-LHC

A new facility called the Forward Physics Facility (FPF) under intensive discussion

- FASER progressing well, however TI12 is too small to exploit full physics potential in the forward region of the LHC
- Discussion started since 2020, summarizing white paper in March 2022 for snowmass
  - 5th FPF Meeting, Nov 2022: https://indico.cern.ch/event/1196506/
- 617 m from ATLAS interaction point (opposite side of FASER) near SM18
- 65m long, 9.7m wide, 7.7m high cavern; 88m high shaft and surface building

CERN civil engineering team provides a preliminary cost estimation of 40 MCHF including services
Currently proposed FPF experiments

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

- **FLArE**
  - $\mathcal{O}(10\text{tn})$ LAr TPC detector
  - DM scattering
  - Neutrino physics ($\nu_\mu/\nu_e$, capability for $\nu_\tau$ under study)
    - Full view of neutrino interaction event

- **FASERv2**
  - $\mathcal{O}(20\text{tn})$ emulsion/tungsten detector (FASERv x20)
    - Mostly for tau neutrino physics
    - Interfaced to FASER2 spectrometer for muon charge ID ($\nu_\tau/\bar{\nu}_\tau$ separation)

- **AdvSND**
  - Neutrino detector slightly off-axis
    - Provides complementary sensitivity for PDFs from covering different rapidity to FASERv2

- **FASER2**
  - Detector for observing decays of light dark-sector particles
  - Similar to scaled up version of FASER (1m radius vs 0.1m)
    - Increases sensitivity to particles produced in heavy flavour decay
  - Larger size requires change in detector and magnet technology: Superconducting magnet

- **FORMOSA**
  - Millicharged particle detector
  - Scintillator based, similar to current miliQan experiment

Jamie Boyd
Conclusion

FASER is a new forward experiment at the LHC in the unused tunnel, TI12 for:

• discovery of a light weakly-coupled particle in MeV-GeV range
  • Spectrometer (Tracker and magnets), scintillators and calorimeter installed in March 2021
  • preshower scintillator will be replaced by silicon pixel detector at the end of 2024
• probe all flavors of neutrinos at the TeV-energy frontier
  • Emulsion/Tungsten detector, veto scintillator and interface tracker installed in March 2022
  • Emulsion/Tungsten detector replaced every Technical Shutdown (~3 times in one year)

Successful data taking from the beginning of LHC Run3 in 2022

• smooth operations and excellent detector performance
• first physics results from FASER expected in Q1 2023

Towards HL-LHC, Forward Physics Facility is proposed to host several experiments

• Workshop organized every half year for intensive discussion toward conceptual design
  • The last one (FPF5) was held Oct 2022 - https://indico.cern.ch/event/1196506/
FASER Acknowledgements

FASER is supported by:

- HEISING-SIMONS FOUNDATION
- SIMONS FOUNDATION
- CERN
- Swiss National Science Foundation

In addition, FASERν is supported by:

- ERC
- KAKENHI

FPF studies supported by:

- Physics Beyond Colliders
Background simulation

Simulation implied that FASER would be located in very lucky place

- $10^{-3}$ less flux compared to just 1m away since LHC magnets seem to sweep charged particles
- No neutral particle by 100m thick rock

should be confirmed by measurement
DAQ - deadtime

Rate limiter: in order to avoid uncontrolled high rates from an input channel suddenly becoming noisy, a rate limiter limits the L1A rate to 3 L1As per 15 orbits (or 2.2 kHz).
Further measurement from end of July in 2022
Search for new light weakly-coupled particles.

LHC collisions produce an enormous flux of light mesons in the forward direction.

\[ \sim 10^{14} \pi^0 \] in the FASER angular acceptance in LHC Run-3, which could decay into a new long-lived particle (LLP).

These LLPs are supposed to be decaying into a pair of collimated SM particles, for example:

- Dark photon (A') \[ A' \rightarrow e^+ + e^- \] appears with a new U(1) symmetry.

- Axion-like particle, heavy neutral leptons, (Phys. Rev. D 99, 095011 (2019)).

FASER detector is designed to separately detect the two highly collimated tracks.

Assuming LLP with \( m = 200 \text{ MeV} \) and \( E = 2 \text{ TeV} \), the separation is \( O(200) \text{ um} \) at the first tracker station.

No background event expected, which gives strong sensitivity for many new physics.

FASER is the first dedicated far-detector collider experiment for new long-lived particle searches.

Installed 26th July
Neutrino-induced DIS could probe strangeness puzzle

- Provide new information by measuring branch of $D \rightarrow \mu$
- Constrain proton PDF, and nuclear PDFs

Neutrino is generated from low $x$ & high $x$ regions of the colliding protons

- Low-$x$ Gluon PDF affecting Higgs production $x$-sec in FCC, intrinsic charm, and so on
QCD in the forward region

**QCD@FPF**

- Wide range of QCD studies relating to:
  - **Forward particle production** mechanisms in and/or the central detector.
  - **Neutrino induced DIS** scattering at FPF.

- Both aspects can provide new understanding of QCD physics, complementary to ongoing LHC (...) programme.

Lucian Harland-Lang, 4th FPF workshop:
https://indico.cern.ch/event/1110746/contributions/4701724/attachments/2382412/4071581/lhl_FPF_QCD.pdf
Astroparticle physics

13 TeV center-of-mass pp collision corresponds to 100 PeV proton in lab frame

Better understanding of atmospheric neutrino could improve the IceCube experiment
FASER/FASER 2 physics reach for various model

Dark photon

Dark higgs

Heavy neutral lepton