The FASER experiment and detector performance from the first data

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ForwArd Search ExpeRiment

> Faser is designed to search for long lived particles (LLP) and neutrinos produced in pp collision in ATLAS IP:
  – The LLP is produced in the decay of SM meson which are predominantly produced very collimated with the beam direction
  – Even small detectors on (or close to) the LOS can have good sensitivity in these scenarios
    > e.g. 1% of pions with $E > 10 \text{ GeV}$ are produced in the forward $0.000001\%$ of the solid angle ($\eta > 9.2$)
  – 480m from ATLAS IP in the forward regions
  – 100m rock to shield most of the background
FASER detector

**3 Tracker stations:**
- Each has 3 layers of 8 silicon strip modules
- Measure track trajectory
- More details in [NIMA166825(2022)]

**Scintillator:**
- Veto charged particles

**EM Calorimeter:**
- 66 scintillator + lead planes
- ~25 $X_0$

**Scintillator:**
- Trigger/preshower

**ATLAS IP**

**Decay volume:**
1.5 m

**Interface tracker:**
- 3 layers of 8 silicon strip modules (SCT)

**Scintillator station:**
- Trigger/timing
- More details in [INST16.P12028 (2021)]

**Magnets:**
0.55 T

**Scintillator:**
- 770 emulsion + tungsten plate
- ~$8\lambda$
- Measure track trajectory, neutrino flavor

arXiv:2207.11427
Long-lived particles

> Searches for new weakly interacting light particles, coupling to SM in forward region \( pp \rightarrow LLP + X, \) LLP travels \( \sim 480 \text{ m} \), LLP \( \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots \),
  - Produced in decays of light mesons (e.g. \( \pi^0, K \))
  - Light SM particles abundantly present in pp collisions, primarily in large pseudorapidity
  - Dark photon, axion-like particle (ALP) ...

- By being on the LOS maximises the acceptance for potential signals
- In Run-3 of the LHC we expect \( O(10^{14}) \pi^0 \) to be produced in the FASER acceptance.

FASER operations

- FASER successfully collected ~40/fb of 13.6 TeV collision data in 2022 running (July - Dec)
- Average trigger rate: ~700 Hz
- Detector operations went very smoothly
First collision data

Event display of a muon traversing the full detector, all parts of the detector performing as expected.
Detector performance - tracker

- Build of same silicon strip module (SCT) as ATLAS, module fine time tuned with 390 ps precision
- Hit efficiency of $99.64\pm0.10\%$ at threshold of 1.0 fC and sensor bias 150V

- Total number of dead/noisy strips < 0.5%
- Inefficiency from module edges are expected
Detector performance - alignment

- Iterative local chi2 alignment
- Validated with MC simulation
- Only consider 2 of 6 degree of freedoms, Y translation and Z rotation
  - Silicon strip detector, precision on Y is much better than X
  - Track parameters and residuals are improved significantly
  - Remaining discrepancy will be taken as systematic uncertainty
Detector performance - scintillator/calorimeter

- Veto scintillator efficiency from data:
  - $>99.99\%$ for each veto scintillator
  - Veto $O(10^{10})$ muons by combining 5 scintillators
- Calorimeter energy resolution measured with electrons in test beam
  - Resolution at $O(1\%)$ at high energy as expected
- Timing resolution $\sim 250\text{ps}$
  - Reject the beam-1 background efficiently
Dark photon

- Even with 1/fb of data FASER will have sensitivity to unconstrained parameter space
- Production:
  - mainly from decays of light mesons, $\pi$, $\eta$ and dark bremsstrahlung.
- Decays: two charged particles
  - $e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$

More details in PRD.99.095011 (2019)
Axion-like particles (ALPs)

In the case of ALPs only couple to photons

\[ \mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a \gamma \gamma} a F^{\mu \nu} \tilde{F}_{\mu \nu}, \]

- Mainly produced via Primakoff process \((\gamma N \rightarrow aN)\) in forward region of pp collision
- \(a \rightarrow \gamma \gamma\) or \(\gamma e^+e^-\)

More details in PRD.99.095011 (2019)
Pre-shower upgrade

- Current pre-shower unable to separate closely spaced high energy photons (e.g. from ALP decay)
- Upgrade to enable detecting $\gamma\gamma$ searches
  - Able to reconstruct 2 high energy photons separately by $\sim 200\mu m$
- New pre-shower: high-resolution silicon pre-shower detector using monolithic pixel ASICs
  - Hexagonal pixels of 65$\mu m$ side
  - Planned to be ready for 2024 data taking

More details in CERN-LHCC-2022-006
Neutrinos from LHC

- A huge number of neutrinos produced in the LHC collisions traverse the FASER location covering an unexplored neutrino energy regime
  - Originate from hadron decays, mainly pion, kaon and charm mesons
- FASERν is an emulsion/tungsten detector placed in front of the main FASER detector to detect all flavor of neutrino interactions

<table>
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<th>Generators</th>
<th>FASERν (GeV)</th>
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| light hadrons | heavy hadrons | $\nu_e + \bar{\nu}_e$ | $\nu_\mu + \bar{\nu}_\mu$ | $\nu_\tau + \bar{\nu}_\tau$
| SIBYLL      | SIBYLL       | 901                      | 4783                     | 14.7                      |
| DPMJET      | DPMJET       | 3457                     | 7088                     | 97                        |
| EPOS/LHC    | Pythia8 (Hard) | 1513                    | 5905                     | 34.2                      |
| QGSJET      | Pythia8 (Soft) | 970                      | 5351                     | 16.1                      |
| Combination (all) |           | $1710^{+1746}_{-809}$ | $5782^{+1306}_{-998}$ | $40.5^{+56.6}_{-25.8}$ |
| Combination (w/o DPMJET) |           | $1128^{+385}_{-227}$ | $5346^{+558}_{-563}$ | $21.6^{+12.5}_{-6.9}$ |
FASER$\nu$ detector

- 730 x 1.1mm thick tungsten plates, interleaved with emulsion films
- 1m long, 1.1 ton detector
- Capable to distinguish all flavours of neutrino
- Emulsion films has excellent position/angular resolution but no time information
- Need to be replaced every ~3 months

Neutrino reconstruction efficiency: >80% with a energy resolution ~30%
FASER$\nu$ pilot run

- A small emulsion detector (10kg target mass) to validate simulation of background particle flux
- 12.2/fb data collected in ~1 month
- 18 neutral vertices detected
- Main background from muon induced neutral hadron
- Best fit on BDT score shows 6.1 neutrino candidates (3.3 expected) with a significance of 2.7$\sigma$

First candidate collider neutrino!
Detector performance - FASERν

- 3 emulsion detectors installed in 2022 running
  - First emulsion detector collected 0.5/fb collision data and used for commissioning and validation of data acquisition and processing
- Measured track multiplicity $2.3 \times 10^4 \, \text{cm}^2/\text{fb}^{-1}$ consist with FLUKA simulation and in-situ measurement in 2018
- Very good spatial resolution (0.2μm)
- Across all modules collected 40/fb data

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<th>Integrated luminosity (fb)</th>
<th># neutrino interaction expected</th>
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<tr>
<td>2022 1st module</td>
<td>Mar 15 - Jul 26</td>
<td>0.5</td>
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<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>
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Across all modules collected 40/fb data
FPF and FASER2

- FASER2 for HL-LHC
  - Radius increased to 1m (FASER is 10cm)
  - Acceptance ($\pi^0$) increased to 10% (FASER is 0.6%)

The FPF is proposal to create a new facility to house a suite of experiments on LOS
- FASER2
- FASERnu2
- AdvSND
- FLArE
- FORMOSA

$O(10^5)\nu_e, O(10^6)\nu_\mu, O(10^3)\nu_\tau$ expected in $O(10\text{tons})$ detector

40cmx40cmx8m, 20 tons
Summary and outlook

> FASER is well constructed and started to collect collision data at July 2022
  – Detector operated well in 2022 running, and collected >40/fb data
  – Will increase the sensitivity for light weakly interacting new particles at the LHC, complementing the other LHC experiments
  – Will make first collider neutrino measurements

> **Aiming to have first results in few weeks**

> Strong physics case emerging for large upgraded FASER2 detectors beyond Run 3, to be housed in the proposed **Forward Physics Facility (FPF)**
back-up
FASER detector

- A veto scintillator to veto charged particles
- A 1.5-meter magnetized decay volume
- A 2-meter magnetic spectrometer with three tracking stations
- An electromagnetic calorimeter
- Three scintillator stations for triggering, veto and precise timing
Key features for BSM search

> Trigger rate $O(700 \text{ Hz})$ - dominated by muons
> Muon flux is $1 \text{ Hz/cm}^2$ for $L=2\times10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  – Confirmed by in situ measurements in 2018.
> Tracking detector strip pitch 80 µm with 40 mrad stereo angle
  – $\sim 20$ µm resolution in precision coordinate
  – $\sim 550$ µm in the other coordinate
> Good separation for two collimated tracks
> EM shower energy resolution: $\sim 1\%$ for TeV deposits
Detector performance - alignment

> Mean and std of the residuals for each module