The FASER experiment

Monica D’Onofrio, University of Liverpool
on behalf of the FASER Collaboration
IPA2022 Vienna, 9/9/2022
The quest for a dark sector

- DM could be just one of the many new particles belonging to a ‘hidden’ dark sector (DS)

- The mechanism of portals as the lowest canonical-dimension operators that mix new dark-sector states with gauge-invariant combinations of SM fields is often considered, with 4 notable examples:

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector (Dark Photon, $A_\mu$)</td>
<td>$\frac{\mu}{2 \cos \theta_W} F^\mu \nu B^{\nu \tau}$</td>
</tr>
<tr>
<td>Scalar (Dark Higgs, $S$)</td>
<td>$(\mu S + \lambda_{HS} S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Fermion (Sterile Neutrino, $N$)</td>
<td>$\gamma_N LHN$</td>
</tr>
<tr>
<td>Pseudo-scalar (Axion, $a$)</td>
<td>$\frac{\mu_a}{f_a} F^\mu \nu \tilde{F}^{\nu \tau}, \frac{\mu_a}{f_a} G_{i, \mu \nu} \tilde{G}_i^{\mu \nu}, \frac{\mu_a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
</tbody>
</table>

- The resulting new particles could be Long-Lived (LLP)

- Targeted searches for these BSM models have been identified as a priority by the European Strategy Update and the Snowmass process

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FASER and the DS: Motivation

- ATLAS, CMS (GPDs) and LHCb devote considerable efforts to searches for LLPs
  - Still, dedicated experiments might complement them in terms of targeted phase space and mitigate issues - notably, large background rates and difficulties in triggering

- Idea of FASER: a Forward Detector for low-mass LLPs
  - Background mitigated by rock/shielding
  - Simpler / no triggering needed

Detector is far from IP → target long lifetimes

LLPs produced in forward-peaked light hadron decays → e.g. $O(10^{14})$ pions within FASER angular acceptance

$$\theta \simeq \tan \theta = \frac{p_T}{p} \sim \frac{m}{E} \ll 1$$

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FASER is located at ~ 480 m downstream of the ATLAS interaction point (IP) in the TI12 - an unused SPS maintenance tunnel intersecting collision axis.

The beam is highly collimated (mrad diameter) → only a small detector needed, with a magnet aperture of 20cm diameter.

Infrastructure & rock catches most collision products.
FASER(ν) Physics reach

- Designed for events of the kind

pp → LLP, LLP travels ~480m, LLP → ee, γγ, μμ, ...

- Probes large range of BSM models in regions favoured according to muon g-2, DM hypotheses and anomalies
  - Dark photons, as well as ALPS, HNL, B-L

- Also sensitive to high-energy neutrinos produced along beamline
  - A dedicated component, FASERν, added in 2020

Expected number of CC interactions (150 fb⁻¹)

<table>
<thead>
<tr>
<th>Generators</th>
<th>FASERν</th>
<th>Light hadrons</th>
<th>Heavy hadrons</th>
<th>νe + ν̄e</th>
<th>νμ + ν̄μ</th>
<th>ντ + ν̄τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIBYLL</td>
<td>SIBYLL</td>
<td>901</td>
<td>4783</td>
<td>14.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPMJET</td>
<td>DPMJET</td>
<td>3457</td>
<td>7088</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPSLHC</td>
<td>PYTHIA8 (Hard)</td>
<td>1513</td>
<td>5905</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QGSJET</td>
<td>PYTHIA8 (Soft)</td>
<td>970</td>
<td>5351</td>
<td>16.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination (all)</td>
<td></td>
<td>1710 ± 1746^{+809}_{-944}</td>
<td>5782^{+1306}_{-1098}</td>
<td>40.5 ± 56.6</td>
<td>40.5 ± 56.6</td>
<td>40.5 ± 56.6</td>
</tr>
<tr>
<td>Combination (w/o DPMJET)</td>
<td></td>
<td>1128^{+335}_{-227}</td>
<td>5346^{+558}_{-503}</td>
<td>21.6 ± 12.5</td>
<td>21.6 ± 12.5</td>
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FASER\(\nu\) Physics reach

- Designed for events of the kind
  \[ pp \rightarrow LLP, \text{LLP travels } \sim 480 \text{m}, \text{LLP } \rightarrow \text{ee, } \gamma \gamma, \mu \mu, \ldots \]

- Probes large range of BSM models in regions favoured according to muon g-2, DM hypotheses and anomalies
  - Dark photons, as well as ALPS, HNL, B-L
  - Also sensitive to high-energy neutrinos produced along beamline
    - A dedicated component, FASER\(\nu\), added in 2020

- Cross-section measurements possible for all neutrino flavours in E range from \sim 100 \text{ GeV to } \sim 1 \text{ TeV}
  - Unconstrained region of phase space
Overview of the FASER detector

- 10 cm radius
- 7 m long, 1.5 m decay volume

Angular acceptance $|\theta| < 0.21$ mrad region, $\eta > 9.2$
FASER$\nu$ extends $|\theta|$ to 0.41 mrad and $\eta \sim 8.5$

FASER$\nu$ emulsion detector
- Emulsion detector for $\nu$'s
- ~750 layers of emulsion films
- Tungsten plates

FASER$\nu$ veto system
- Front Scintillator veto system

Magnets
- 0.57T Dipole
- Charge separation

Trigger / timing scintillator station
- Preshower - veto & 2-$\gamma$ signal
- Trigger/timing - arrival time
- Veto - rejects muon background

Calorimeter
- Donated by LHCb
- Measures total energy of $\gamma, e^+e^-$

Electromagnetic Calorimeter
- Donated by ATLAS
- 8 SCT modules per plane
- 4 Stations, 3 planes each

Tracking spectrometer stations
- 4 Stations, 3 planes each
- 8 SCT modules per plane
- SCTs donated by ATLAS

Decay volume
- 1.5 m decay volume
- 20 cm aperture
- 7 m length

FASER Trigger rate: 650 Hz expected (dominated by muons produced close to the IP)

2021 JINST 16 P12028

Very low radiation levels

Detector paper: https://arxiv.org/abs/2207.11427
Overview of the FASER detector

- 10 cm radius
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FASER signatures for LLPs:
Light, very high momentum, highly collimated decay products

Electromagnetic Calorimeter

Tracking spectrometer stations

Decay volume

Front Scintillator veto system

Trigger / timing scintillator station

Magnets

Energy measurement

Tracking

Decay volume

Scintillator veto

To ATLAS IP

FASERv emulsion detector

Interface Tracker (IFT)

Scintillator veto system

Trigger / pre-shower scintillator system

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Overview of the FASER detector

- 10 cm radius
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FASERν signatures for high energy neutrinos:

- 10 cm radius
- 7 m long, 1.5 m decay volume

- Silicon strip tracker (IFT: InterFace Tracker) is used as the interface for tracking with FASER spectrometer behind it.

- Charge identification of muons is possible with three 0.55 T dipole magnets in the spectrometer (3.5 m length in total).

- Veto scintillator system at the most front part of FASERν rejects charged particles coming from the upstream.

- Allows matching of the signal muon tracks in IFT and spectrometer.
FASER Tracking: components and layout

Composed two distinct parts: the tracking spectrometer (3 tracking stations) and the Interface Tracker (1 tracking station), placed after the FASERV emulsion detector.

Basic component: **SCT Module**

- Strip detector, pitch 80um and stereo-angle of 40mrad.
- 8 modules per tracker plane

**3 Tracker planes per station (12 total)**

Low material central region: 2.1% radiation length

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Number / station</th>
<th>X₀ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon sensor</td>
<td>Si</td>
<td>6</td>
<td>1.8%</td>
</tr>
<tr>
<td>Station Covers</td>
<td>CFRP</td>
<td>2</td>
<td>0.3%</td>
</tr>
<tr>
<td>SCT module support</td>
<td>TPG</td>
<td>3</td>
<td>0.6%</td>
</tr>
<tr>
<td>C-C Hybrid</td>
<td>C (based)</td>
<td>3</td>
<td>2.2%</td>
</tr>
<tr>
<td>ABCD chips</td>
<td>Si</td>
<td>3</td>
<td>6.5%</td>
</tr>
<tr>
<td>Layer frame</td>
<td>Al</td>
<td>3</td>
<td>10.1%</td>
</tr>
<tr>
<td><strong>Total / station</strong></td>
<td></td>
<td>-</td>
<td><strong>2.1%</strong></td>
</tr>
</tbody>
</table>

**Table 2**

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FASER Tracking: tests and performance

Extensive tests have been carried out to evaluate performance, standalone and after installation:

- long-term stability and control checks (temperature, humidity, electronics)
- Quantification of noisy/dead strips
- Alignment and metrology of tracker planes

Commissioning with cosmic rays and LHC pilot run

![Diagram of particle tracking](image)

**Top-view - Run 004458, Event 2061350**

**Side-view - Run 004458, Event 2061350**

purple line: combined track fit to the hits in the tracking stations during 900 GeV pilot beam
**FASER calorimeter, pre-shower and scintillator systems**

- **Four scintillator stations** with multiple scintillator layers in each station
  - (a) FASERν Veto, (b) Interface Veto, (c) Timing, & (d) Preshower
  - >99.98% efficiency, sufficient to veto all incoming muons
  - photo-multiplier tubes to detect the scintillation signals.

Note: Preshower scintillator to be replaced by silicon pixel detector (tech. proposal) in 2023/2024 To detect 2-photon axion-like particle signals

- **Electromagnetic calorimeter** made of spare LHCb modules
  - 66 layers of lead-scintillator plates read by 2x2 array of PMTs
  - calorimeter readout optimised to measure multi-TeV deposits w/o saturation

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\[
\frac{\sigma_E}{E} = 9.2\% \oplus 0.2\% + \text{expected 1\% constant term}
\]

At 1 TeV, about 1.6\% of electrons are expected to leak more than 3\% of their energy
FASER$\nu$ detector

- 700 layers of an emulsion film and 1.1 mm tungsten plate: 25 cm×30 cm×1.1 m, 1.1 tons, 220 $X_0$
- Pilot detector (30 kg) exposed in FASER location for 1 month
  - Observed (2.7$\sigma$) first collider $\nu$ candidates!
- FASER$\nu$ will be exchanged frequently during Run 3
  - First full detector (TS1): 26$^{\text{th}}$ July - 13$^{\text{th}}$ Sept
  - Second detector (TS2): 13$^{\text{th}}$ Sept - 8$^{\text{th}}$ Nov
- Frequently exchanged (~ every 3 months) to keep a manageable detector occupancy. **Procedure:**

**Procedure:**

<table>
<thead>
<tr>
<th>Emulsion Film Production</th>
<th>Detector Assembly</th>
<th>Exposure</th>
<th>Development</th>
<th>Full Area Readout</th>
<th>Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship to CERN</td>
<td>Install in Ti12</td>
<td>Disassemble</td>
<td>Ship to Japan</td>
<td>Full Area Readout</td>
<td>Reconstruction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Replacements: ~ 3 times/yr in technical stops, every 30-50 $fb^{-1}$*
FASER Test Beam

- TB @ CERN H2 beam (summer ‘21)
  - Electrons (5-300 GeV), muons (200 GeV) and pions (200 GeV)
- 6 ECAL modules (inc. spares)
  - Along with IFT and preshower
- Also used for tracking performance studies
  - Tracker cluster efficiency measured: 99.86 ± 0.04 %, agreeing well with MC and ATLAS (99.74 ± 0.04 %)

Goals:
- Calibrate preshower & calorimeter modules
- Develop and validate calibration procedure for TI12
- Operation and performance measurements of IFT tracker station and scintillators in actual beam conditions

Different beams, at various energies
- Electrons: 5-300 GeV; Muons: 150 GeV; Pions: 200 GeV
- Now we could practice particle identification

Tracker cluster efficiency measured: 99.86 ± 0.04 %, agreeing well with MC and ATLAS (99.74 ± 0.04 %)

Correction to gains improves calorimeter resolution by accounting for charges lost to preshower scintillator

Calorimeter response uniform within a few percent across different beam positions

Calo E resolution

Paper in progress!

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FASERν detector commissioning

- ~30% of the full emulsion for commissioning
- MIP efficiency of the veto system was also measured in the test beam
- Better performance than the requirement (>99.98%) obtained.

Charge deposit in veto system

[@Testbeam]

Veto

IFT

Emulsion

Emulsion detector
After further commissioning tests, the detector was ready to see first data on July 5th!
First data!

- Thousands of events were already collected with charged particle tracks traversing the detector even prior to official start on 5\textsuperscript{th} of July
- Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.
- With 13.6 TeV beams, good events seen in the detector consistent with coming from collisions.

Run: 7733  
Event: 214231  
2022-07-05 16:42:03

One of first event displays from collisions

Lessons learned from first 10 fb\textsuperscript{-1} of data taken
- trigger rate broadly consistent with expectation
- beam background level low and easy to remove with timing
- detector working beautifully, no operational issues to date
First data!

Thousands of events were already collected with charged particle tracks traversing the detector prior to official start

- Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.

Tracks from the first FASERν emulsion films

Tracks in 1 mm² are shown.
Data analysis readiness

- On-going tests on full production chain from generation all the way through to analysis
- Representative background and signal processes have been produced
  - Full FASER detector geometry implemented and validated in offline software
  - Calypso software package based on ATLAS framework (Gaudi and Athena)
  - Genie & FLUKA used for neutrinos studies and muon-induced background

Good tests for track reconstruction methods, momentum resolution and calorimeter deposits measurements
Data analysis readiness

- On-going tests on full production chain from generation all the way through to analysis
- Representative background and signal processes have been produced
  - Full FASER detector geometry implemented and validated in offline software
  - **Calypso** software package based on ATLAS framework (Gaudi and Athena)
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Simulated neutrino events in FASERν also fully ready

*Neutrino events simulation also fully ready*
The forward future: FASER(v)2

- We might not see LLPs or NP in Run 3:
  - Extended coverage needs a bigger detector

- Thinking ahead: a scaled-up version of FASER with ~100 x active area
  - Magnets: Superconducting w/ B = 1 T
  - Tracker: much larger using e.g. SiFI/SiPM
  - Calo/Muon: enhanced PID & position resol.

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Substantial increase in sensitivity for LLPs from B, D hadrons decays (e.g. Dark Higgs) thanks to larger radius, Broader scope including QCD physics

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Where: the Forward Physics Facility (FPF)

Proposal to build a new dedicated forward physics facility

Hosting a suite of far-forward experiments at the HL-LHC

Current planned detectors

- **FASER2**
  - FASER scaled to r=1m
  - Light dark sector parts.

- **FASERv2**
  - ~20t emulsion + tungsten detector
  - Mainly $\nu_\tau$

- **AdvSND**
  - Off axis $\nu$ detector
  - Fwd charm + low-x gluon

- **FORMOSA**
  - Scintillating bars
  - Millicharged particles

- **FLArE**
  - ~10t LAr TPC
  - DM + $\nu$ physics

Detailed (429pp) paper submitted as part of Snowmass: [https://arxiv.org/abs/2203.05090](https://arxiv.org/abs/2203.05090)
Summary

- FASER gives access to light, weakly-interacting particles with significant lifetime, providing sensitivity to a wide range of BSM physics models (dark $\gamma$, ALPS and more) complementary to GPDs; FASER$\nu$ can measure high energy neutrinos in a previously unconstrained region of phase space

- FASER and FASER$\nu$ are now installed and fully operational
  - Test beam results show excellent tracker cluster efficiency and uniform calorimeter response within a few percent across different beam positions
  - Data collection has started with Run 3! More than 10/fb of data collected so far...
  - Detector working beautifully, no operational issues to date

- Development of analysis and software tools ongoing
  - First results expected for Spring 2023 - stay tuned!

- A forward look: proposal for FPF, a dedicated forward physics facility @ CERN, to take advantage of HL-LHC and build a FASER2
  - Would give a rich and broad physics programme
Trigger and DAQ

FASER Trigger rate: 650 Hz expected (dominated by muons)

- PMTs from scintillators and calorimeter provide trigger signals
- Trigger system run synchronously to the 40.08 MHz LHC clock
- Data Acquisition (DAQ): Configuration & readout
- Monitoring: checking data flow, detector conditions, and data quality to spot/resolve problems

Data Control & Safety (DCS): powers detector and protects it from unusual conditions

Paper published: 2021 JINST 16 P12028
### Comparison of neutrino rates

<table>
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<th>Generators</th>
<th>FASERν</th>
<th>SND@LHC</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\nu_e + \bar{\nu}_e$</td>
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