ForwArd Search ExpeRiment

ICHEP 2022 - Savannah Shively
The Far Forward Region

- Last new particle detection - Higgs Boson - 10 years ago 🎂
- Dark Matter & Dark Energy still unexplained (among other things)
- Standard Model not enough; no interactions with DM or DE known
- Most experiments measure particles emitted transverse to the beamline (ATLAS, CMS...)
- Long Lived Particles (LLPs) - low mass, long life → High pseudorapidity
- Need complementary experiments like FASER
Location

8.5km (5.4 mi) diameter

ALICE

ATLAS

SPS

Point 1.8

Point 1

Point 2

Point 3.2

Point 3.3

Point 4

Point 5

Point 6

Point 7

Point 8

CMS

LHC 'B'

Projects Overview link
Location

- TI12 - unused SPS maintenance tunnel intersecting collision axis
- ~480m from IP
- Highly Collimated beam (mrad diameter) → only small detector needed
  - Magnet aperture 20cm diameter
- Infrastructure & rock catches most collision products
Physics reach

- **Dark Photon**
  - Run 3 has integrated luminosity of 290 fb$^{-1}$
    - 13.6 TeV center-of-mass energy
  - Plot assumes no background for dark photon search
    - Probes regions favored by many considerations, such as muon g-2, dark matter, and ATOMKI anomalies
    - FASER starts probing LLP candidates with the first few fb$^{-1}$

- **Neutrinos**
  - Highest energy neutrinos produced along beamline - blindspot strikes again!
  - All lepton variations to be studied with distinction of $\nu_\mu$ from $\nu_\mu$
  - FASER$\nu$ **dedicated talk** by Yosuke Takubo
Calorimeter
- Donated by LHCb
- Measures total energy of $\gamma$, $e^\pm$

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

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

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

Magnets
- 0.57T Dipole
- Charge separation

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

Physics Signal
- Dark photons (LLP) and neutrinos from meson decay
  $$pp \rightarrow LLP + X, \ LLP \rightarrow e^+e^-, \mu^+\mu^-...$$

INSTALLED March 2021
Background/noise

- Emulsion detector Particle flux tests
  - Installed during 2018 LHC Technical stops
  - Measured muon flux agrees with FLUKA simulation
  - Mostly $\mu$- and neutrinos expected & measured
  - First neutrino interaction candidates at a particle collider! (Paper here)

- Neutrinos produced primarily at IP
  - Neutrino-rock interactions negligible (<0.01Hz)

- Non-radiation-hard electronics ok

- Cosmics accounted for by direction and timing

<table>
<thead>
<tr>
<th>Energy threshold [GeV]</th>
<th>Charged particle flux $[\text{cm}^{-2} \text{s}^{-1}]$</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>0.40</td>
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<tr>
<td>100</td>
<td>0.20</td>
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<tr>
<td>1000</td>
<td>0.06</td>
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Muon flux (FLUKA)
The FASER Tracker

Stages of Commissioning

1. SCT Module - 8 per tracker plane
2. Plane - 3 per station (12 total)
3. Station - 4 stations in the detector
4. Detector - Final configuration

- Long term stability and control
  - Temperature, humidity, electric...
- Quantifying noisy/dead strips
- Electronics stability
  - IV Scans, ENC, Gain...

Paper released [here](#)!

(A) EHN1 Single station cosmosics setup
(B) EHN1 Test Beam setup
(C) TI12 LHC Pilot beam event reconstruction (900 GeV, Oct 2021)
Calorimeter & Scintillators

- 4 Scintillator stations commissioned & installed, including for FASER$_\nu$
  - (a) FASER$_\nu$ Veto, (b) Interface Veto, (c) Timing, & (d) Preshower
  - >99.9% efficiency, enough to trigger when an LLP decays inside FASER
  - Installed muon metal shield to reduce noise, light leaks, and discharge
- 4 LHCb ECAL modules selected & tested
  - Energy resolution of ~1%, dependent on calibration
- Both tested with light and cosmic sources; acceptable, expected rates found
  - To be detailed in upcoming detector paper
  - All channels working well
- SPS Test beam - Summer 2021
  - Along with tracker (see previous slide for setup)
  - Analysis nearing completion
  - Few-% energy resolution confirmed

Preshower scintillator to be replaced by silicon pixel detector (tech. proposal) To detect 2-photon axion-like particle signals
Trigger & Data Acquisition

- PMTs from scintillators and calorimeter provide trigger signals
  - Trigger system run synchronously to the 40.08 MHz LHC clock
- Data Acquisition (DAQ): Configuration & readout
- Data Control & Safety (DCS): powers detector and protects it from unusual conditions
- Monitoring: checking data flow, detector conditions, and data quality to spot/resolve problems
- FASER Trigger rate: 650 Hz expected (dominated by muons)
- Paper published: 2021 JINST 16 P12028
Offline Software

- **Calypso** software package based on ATLAS framework (Gaudi and Athena)
  - Uses Geant4, ROOT, etc
  - Borrows much from ATLAS, now open-source
- Reconstruction, simulation, event display
- Includes Tracker, Scintillators, ECAL, magnetic field, FASERv, and non-active material in detector
- Physics generators - Dark Photons, Cosmic Rays, neutrino interactions, single muons
  - More robust far-forward simulation than ATLAS’ models
  - Work ongoing to refine the event generator description of far forward hadron production (mostly relevant for FASER neutrino programme)

Reconstructed two-station cosmic ray in FASER data
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

Paper in progress!
First Beam Data

- Continual data taking during beam commissioning since late-April.
- Thousands of events collected with charged particle tracks traversing the detector.
  - Great for performance studies, optimizing operation procedures, & commissioning reconstruction software.
- First 13.6 TeV collisions on July 5th. Saw good events in the detector consistent with coming from collisions.
- Ideally all hits have 010 or 011 timing; after timing corrections, large improvement in the fraction with these hit patterns.

![Hit Pattern Graph](image-url)
Run 3 Officially Begins!

Fresh event displays from first collisions after official high energy beams this week.
Mock Data Challenge

- Exercise to generate, reconstruct, and analyze specific signal and background samples
- Springboard for development of analysis protocols and procedures
- Samples generated for a variety of signals:
  - Dark photons/ALPs, neutrinos, photons, charged pions...
  - Genie & FLUKA
- Sample generation began in May; improved after collaborators begin to use them and regenerated as needed
- Good exercise of MC production

- Validation of samples produced for single particle and physics signal carried out at different levels, things look good
- Tests with track reconstruction allow studies of momentum resolution
- Can also study & improve upon Track finding and fitting

An ongoing exercise!
Summary & FASER Looking Forward

- **All FASER Publications** - 3 published this year, with two more planned! (Detector & Test Beam)
- **FASER and FASER$_\nu$ installed and operational**
  - Preshower upgrade approved March 2022 for installation in 2023/2024
  - Data collection has started with Run 3!
  - FASER$_\nu$: guaranteed neutrino physics results
  - At the end of Run 3 (~2026): dark photon evidence or model constraints
- **Development of analysis tools ongoing**
  - Begun with earliest commissioning phases & cosmics
  - Assisted & focused by the ongoing Mock Data Challenge
EXTRAS
FASER INSTITUTIONS

75 collaborators, 22 institutions, 9 countries

Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Chiba/Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (NIKHEF), Franck Cadoux (Geneva), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Sergey Dmitrievsky (JINR), Monica D’Onofrio (Liverpool), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Yuri Gornushkin (JINR), Carl Gwilliam (Liverpool), Daiki Hayakawa (Chiba), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Tomohiro Inada (Tsinghua), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (DESY), Umut Kose (CERN), Raifella Kotitsa (Geneva), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (Sussex), Matteo Milanesio (Geneva), Dimitar Mladenov (CERN), Theo Moretti (Geneva), Magdalena Munker (Geneva), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Laurie Nevy (Royal Holloway), Hidetoshi Otono (Kyushu), Hao Pang (Tsinghua), Lorenzo Paolozzi (Geneva), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Markus Prim (Bonn), Michaela Queitsch-Maitland (Manchester), Filippo Resnati (CERN), Hiroki Rukujo (Nagoya), Elisa Ruiz Choliz (Mainz), Jorge Sabater-Iglesias (Geneva), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyria (Geneva), Savannah Shively (UC Irvine), Yosuke Takubo (KEK), Noshin Tarannum (Geneva), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Serhan Tufanli (CERN), Svetlana Vasina (JINR), Benedikt Vormwald (CERN), Di Wang (Tsinghua), Eli Welch (UC Irvine)
The Signal \[ pp \rightarrow LLP + X, \ LLP \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^- \ldots \]

- 2 oppositely charged tracks. \( E \sim 1 \text{ TeV} \)
- Combined momentum points back to IP

- Production is peaked at \( p_T \sim m_\pi, \Lambda_{QCD} \sim 250 \text{ MeV} \)
- Enormous event rates: \( N_\pi \sim 10^{15} \) per bin
- Rates highly suppressed by \( \epsilon^2 \sim 10^{-10} \)
- But still \( N_{A'} \sim 10^5 \) per bin
- Only highly boosted \( \sim \text{TeV} \) \( A' \)’s decay in FASER
- \( N_{A'} \sim 100 \ e^+e^- \) events, within 20 cm of “on axis”

Feng, Galon, Kling, Trojanowski (2017)
Other production modes - LLPs

- **Dark Bremsstrahlung**
  - For LLPs heavier than thresholds for the decays of the lightest mesons
  - Fermi-Weizsacker-Williams approximation
  - Dominant for \( m > m_\pi \)

- **LLPs from Hard Scattering**
  - Technically possible, but large uncertainties from:
    - determination of PDFs at low momentum transfer
    - low parton momentum fraction
  - Becomes relevant: \( m > 2 \text{ GeV} \) with Drell-Yan process

- **Beam dump from TAN**
  - Sort of fixed target experiment
  - Also could produce dark gauge boson via dark compton