First Physics Results

Supported by: HEISING-SIMONS FOUNDATION, CERN, SIMONS FOUNDATION

Deion Fellers (University of Oregon)
on behalf of the FASER collaboration

Mitchell Conference
May 16th, 2023
FASER Overview

• FASER is a new experiment at the LHC
  • Built in 2019-2021

• Located along the longitudinal beam axis, 480m from the ATLAS interaction point
  • LHC magnets and 100m of rock stop most particles
  • Sensitive to light and weakly interacting particles

• Our first physics results were announced this past March
  • Probed dark photon phase space that was previously unconstrained
  • First direct observation of collider neutrinos
FASER Detector

- Small, inexpensive detector [arXiv:2207.11427]
  - 10 cm radius of active volume
  - 7 m long

Tracking spectrometer stations
3 x 3 layers of ATLAS SCT strip modules

Electromagnetic Calorimeter
4 LHCb Outer ECAL modules

Trigger / pre-shower scintillator system

FASERv emulsion detector (1.1 ton)
730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)

Front Scintillator veto system
2 x 20 mm thick
35 x 30 cm area

To ATLAS IP

Decay volume
3 x 20 mm thick
30 x 30 cm area

Interface Tracker (IFT)

Scintillator veto system
3 x 20 mm thick
10mm thick + dual PMT readout (σ = 400 ps)

Magnets
0.57 T Dipoles
1.5 m decay volume
Detector installed between March – Nov 2021, ready for LHC run 3
FASER Operations

• Successfully operated throughout 2022
  • Continuous data taking
  • Largely automated
  • Up to 1.3 kHz

• Recorded 96.1% of delivered lumi
  • DAQ dead-time of 1.3%
  • A couple of DAQ crashes

• Emulsion detector exchanged twice
  • Needed to manage occupancy
  • First box only partially filled

• Calorimeter gain optimised for:
  • Low E (<300 GeV) before 2nd exchange
  • High E (up to 3 TeV) after this exchange

Analyses presented use 27.0 fb⁻¹ or 35.4 fb⁻¹
Example Collision Event

- More than 350M single-muon events recorded
- Example: muon leaving track passing through full detector + scintillator/calorimeter deposits consistent with MIP
Search for Dark Photons

• Dark photon (A’) is a common feature of hidden sector models
  • Weakly coupled to SM via kinetic mixing (ε) with SM photon

\[ \mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} A' f \]

• MeV-scale dark photons are produced mainly in meson decays at LHC

\[ B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma) \]

• FASER targets small ε, highly boosted, MeV-scale massive dark photons which have decay lengths ideal for FASER

\[ L = c\beta\tau\gamma \approx (80 \text{ m}) \left[ \frac{10^{-5}}{\epsilon} \right]^2 \left[ \frac{E_{A'}}{\text{TeV}} \right] \left[ \frac{100 \text{ MeV}}{m_{A'}} \right]^2 \]

• Will decay 100% to e+e- pair for 1 < m_{A'} < 211 \text{ MeV}
Dark Photon Event Selection

• Signal: $\pi/\eta \rightarrow A'\gamma$, $A'$ travels hundreds of meters through LHC magnets and rock/concrete, then decays $A' \rightarrow e^+e^-$ inside FASER

• Event selection: simple and robust, optimized for discovery
  • LHC collision event with good data quality
  • No signal in any of the 5 veto scintillators
  • Timing and preshower scintillators consistent with $\geq 2$ MIPs
  • Exactly 2 good tracks ($p > 20$ GeV and $r < 95$ mm, extrapolating to $r < 95$ mm at vetos)
  • Calorimeter energy $> 500$ GeV

• Signal efficiency $\approx 40\%$ across parameter space that FASER is sensitive to

• Blinded events with no veto signal and calorimeter energy $> 100$ GeV
Dark Photon Backgrounds

1. Veto inefficiency
   • Measured layer-by-layer via muons with tracks pointing back to vetos
   • Layer efficiency > 99.998%
   • 5 layers reduce exp. $10^8$ muons to negligible level (even before cuts)

2. Non-collision backgrounds
   • Cosmics measured with no beam
   • Near-by beam debris measured in non-colliding bunches
   • No events observed with ≥1 track or $E_{\text{calo}} > 500$ GeV

![Graph showing vetos and efficiency](image)

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3. Neutrino interactions (main background)
   • Primarily coming from vicinity of timing detector
   • Estimated from GENIE simulation (300 ab⁻¹)
     • Uncertainties from neutrino flux & mismodelling
   • Predicted signal-like events in 27 fb⁻¹ = (1.8 ± 2.4) x 10⁻³

4. Neutral hadrons from upstream muons interacting in rock in front of FASER
   • Heavily suppressed since:
     • Muon nearly always continues after interaction
     • Has to pass through 8 interaction lengths (FASERv tungsten)
     • Decay products must leave E(calo) > 500 GeV
   • Data-driven estimate from lower energy events with 2 or 3 tracks and different veto conditions
   • Predicted signal-like events = (2.2 ± 3.1) x 10⁻⁴

• Total background prediction = (2.02 ± 2.4) x 10⁻³ events
Dark Photon Unblinded Data

• No events seen in unblinded signal region (not even any with ≥1 fiducial track)
Dark Photon Exclusion

• With null-result, FASER sets limits on previously unexplored parameter space
  • Extends exclusion into region motivated by thermal relic dark matter
  • Public conf note: CERN-FASER-CONF-2023-001
Collider Neutrinos

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → larger interaction cross section
- FASER is sensitive to an exciting neutrino program
  - Collider neutrinos have never been directly observed before
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments

<table>
<thead>
<tr>
<th>For 35 fb⁻¹</th>
<th>( \nu_e )</th>
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PRD 104, 113008

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- Our first ever $\nu$ analysis only strives to claim observation
- The FASERν emulsion is not used for this analysis
  - processing the emulsion films takes a long time
- Analysis is done using FASERν 1.1-ton target for $\nu_\mu$ CC interactions ($\nu_\mu N \rightarrow \mu X$), then detecting the high energy $\mu$ in rest of FASER
FASTER Neutrino Event Selection

1. LHC collision event and good data quality
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos after FASERν
4. Timing and preshower consistent with ≥1 MIP
5. Exactly 1 good track
   • $p > 100 \text{ GeV} \text{ and } \theta < 25 \text{ mrad}$
   • $r < 95 \text{ mm in tracking stations}$
   • $r < 120 \text{ mm when extrapolating to front veto}$

Simulated neutrino CC interaction

- Expect $151 \pm 41$ events from GENIE simulation
  - Estimated from average of DPMJET and SIBYLL generators, with the error being the envelope of the two

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Neutrino Backgrounds

• **Neutral hadrons estimated from 2-step simulation**
  • Expect ~300 neutral hadrons with E>100 GeV reaching FASER
    • Most accompanied by μ but conservatively assume missed
  • Estimate fraction of these passing event selection
    • Most are absorbed in tungsten with no high-momentum track
  • Predict $N = 0.11 \pm 0.06$ events

• **Scattered muons estimated from data sideband**
  • Take events w/o front veto radius requirement and single track segment in first tracker station with $90 < r < 95$ mm
    • Fit to extrapolate to higher momentum
  • Scale by # events with front veto cut
    • Use MC to extrapolate to signal region
  • Predict $N = 0.08 \pm 1.83$ events
    • Uncertainty from varying selection

• **Veto inefficiency estimated in final likelihood fit**
  • Fit events with 0 (SR) and also 1 or 2 front veto layers firing
  • Find negligible background due to very high veto efficiency
Neutrino Results

• Upon unblinding find 153 events with no veto signal
  • With signal significance of $16\sigma$
  • First direct detection of collider neutrinos!
  • Accepted for publication in PRL: arXiv:2303.14185

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<td>6</td>
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<td>$n_{11}$</td>
<td>64014695</td>
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Neutrino Characteristics

• Candidate neutrino events match expectation from signal
  1. High occupancy in front tracker station
  2. Most events have high $\mu$ momentum
  3. More $\nu_\mu$ than anti-$\nu_\mu$
• Note: no experimental uncertainties included in these plots
Neutrinos in FASER

- Analysis of FAESRv emulsion detector underway
  - Have multiple candidates including highly $\nu_e$ like CC event

- Vertex with 11 tracks
  - 615 $\mu$m inside tungsten

- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ 7.8$X_0$
  - $\theta_e = 11$ mrad to beam

- Back-to-back topology
  - 175° between e & rest
Summary

- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency

- Excluded A' in region of low mass and kinetic mixing
  - Probes new territory in interesting thermal-relic region

- Reconstructed ~150 $\nu_\mu$ CC interactions in spectrometer
  - First *direct* detection of collider neutrinos!

- More searches and neutrino measurements to come
  - Including first results from emulsion detector

- Looking forward to up to 10x more LHC run-3 data
  - FASER is operating well for the startup of 2023 LHC running