Physics Results from FASER – Dark Photon and Collider Neutrino Studies

African Conference on High Energy Physics

Noshin Tarannum on behalf of the FASER Collaboration
The FASER Experiment

- FASER is a new, small experiment at the LHC

**FASER’s target**
1. Light and weakly coupled particles, such as dark photons, axion-like particles, as well as Standard Model neutrinos
2. Exploits high LHC collision rate + forward produced light particles which are highly collimated and highly energetic

**FASER’s installation**
1. Mostly installed in March 2021
2. Fully completed in November 2021, ahead of Run3

**FASER’s positioning**
FASER’s Design \( (\text{https://arxiv.org/abs/2207.11427}) \) present the core picture of the detector (magnet, tracker, calo, veto for muon background rejection)
**FASER and Run3**

- Successfully took data continuously and mostly automatically during 2022 and 2023.
- FASER recorded 97% of the delivered luminosity with 1.3% recording inefficiency due to DAQ deadtime and the rest due to DAQ crashes.

---

**Graph**

- Total Delivered: 70.4 fb⁻¹
- Total Recorded: 68.4 fb⁻¹

---

**Legend**

- LHC P1 Stable (ATLAS)
- FASER Recorded
One of FASER’s Target: Dark Photon
Selection for Dark Photon Search

Example of a signal event; want $e^+e^-$ emerging in the decay volume

The selection criteria we had in place:
1. No signal (40 pC) in all scintillators upstream of decay volume
2. Signal (>40 pC) in all scintillators downstream of decay volume
3. Exactly two good quality tracks in fiducial volume
4. High calorimeter deposit
The total background estimate was: 0.0023±0.0023 events

Neutral hadron background

- The neutral hadron needs to survive 8 interaction lengths before decaying in the decay volume.
- Expected: \((0.8 \pm 1.2) \times 10^{-3}\) events

Veto inefficiency:

- Veto scintillator station (3 layers) (Muon not vetoed)
- Completely negligible: \(10^{-12}\) expected for \(10^8\) muons

Non-collision background

- Both negligible suppressed by high calorimeter energy
- Expected: \((1.5 \pm 2.0) \times 10^{-3}\) events

Neutrino interactions

- Pre-shower scintillator station (2 layers)
The total background estimate was: $0.0023 \pm 0.0023$ events

We do not see any events with calorimeter $E > 500$ GeV

Link to paper
Dark Photon Reach

1. With no events seen with $E>500\text{GeV}$, FASER sets limits on previously unexplored parameter space!
2. The limits are in a region of parameter space motivated by the dark matter relic density.
Collider Neutrinos

1. One of the biggest background we have is from neutrinos
2. Neutrinos produced copiously at hadron colliders, but no direct observation yet!
3. So why not use this to our advantage?

<table>
<thead>
<tr>
<th>150/fb @14TeV</th>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main production source</td>
<td>kaon decay</td>
<td>pion decay</td>
<td>charm decay</td>
</tr>
<tr>
<td># traversing FASERnu 25cm x 25cm</td>
<td>$O(10^{11})$</td>
<td>$O(10^{12})$</td>
<td>$O(10^9)$</td>
</tr>
<tr>
<td># interacting in FASERnu (1 tn Tungsten)</td>
<td>$\sim1000$</td>
<td>$\sim20000$</td>
<td>$\sim10$</td>
</tr>
</tbody>
</table>
Selection for Muon Neutrino in electronic detector

Example of a signal event using spectrometer and scintillators

The selection criteria we had in place:

Essentially, using FASER$\nu$ only as target for neutrino interactions

1. Events in collision crossing, during good physics data period
2. No signal (40 pC) in all scintillators upstream of FASER$\nu$
3. Signal (>40 pC) in all scintillators downstream of FASER$\nu$
4. Exactly 1 good fiducial track
Background Estimate

Estimated from events with just one veto scintillator firing:
- Expect \((3.7 \pm 2.5) \times 10^{-7}\) events

Estimated \(O(300)\) neutral hadrons with \(E > 100\) GeV from simulation:
- Most hadrons absorbed in tungsten (8 int. lengths)
- Estimate \(0.11 \pm 0.06\) events

Estimated from control region (90 < \(r < 95\) mm, \# clusters ≤ 8):
- Expect \(0.08 \pm 1.83\) events

The total background estimate is: \(0.2 \pm 1.8\) events
Collider Neutrino Observation

- Based on GENIE simulation expect 151 ± 41 neutrino events
- Uncertainty from difference between DPMJET and SIBYLL event generators
- No experimental uncertainties → cannot translate to cross section / flux yet
- Observe 153 events with no veto signal with an expected background of 0.2 ± 1.8
- First direct observation of collider neutrinos!
- Signal significance of 16 σ
Neutrino signature in Emulsion Detector (FASERν)

FASERν analysis:
- 730 layers of 1.1 mm thick tungsten plates and emulsion films, 1.1 tones tungsten target
- Excellent position and angular resolution
- Reconstruct tracks and vertices of charged current (CC) and neutral current (NC) interactions of all neutrino flavors
Analysis of emulsion detector data

- 9.5 fb$^{-1}$ of LHC proton collision data
- Observed 3 $\nu_e$ vertices (5$\sigma$), and 4 $\nu_\mu$ vertices (2.5 $\sigma$)
- First direct observation of collider electron neutrinos!

This specific event:
- A very clean high-energy $\nu_e$ candidate
- Energy of electron $\sim$ 200-500 GeV
Conclusion

- FASER successfully took data in Run 3, running at very good efficiency with a fully functional detector!
- Excluded dark photon in region of low mass, low kinetic mixing.
- Observed 153 $\nu \mu$ CC interactions with electronic detectors. First observation of collider neutrinos!
- Observed 3 $\nu e$ vertices (5$\sigma$), and 4 $\nu \mu$ vertices (2.5 $\sigma$) with emulsion detector. First direct observation of collider electron neutrinos!
- Will continue data-taking throughout LHC Run 3 with up to 10 times more data coming in the next years
- Currently ongoing: Faser Preshower upgrade, ALPs analysis, Forward Physics Facility

Simulation made with FORESEE https://arxiv.org/abs/2105.07077

All FASER publications
Thank you for listening!

from FASER Collaboration Meeting #5, 2023
FASER Collaboration

87 members from 24 institutions and 10 countries

FASER Management
Spokespersons: Jonathan Feng (UC Irvine), Jamie Boyd (CERN)
Collaboration Board Chair: Matthias Schott (Mainz)
Executive Board: Akitaka Ariga (Chiba), Carl Gwilliam (Liverpool), Anna Sfyrla (Geneve), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Claire Antel (Geneve), Dave Casper (UC Irvine), Frank Raphael Cadoux (Geneve), Tomoko Ariga (Kyushu), Lorenzo Paolozzi (CERN)

FASER Collaboration Members
Roshan Abraham (UC Irvine), Henso Abreu (Technion), John Anders (CERN), Claire Antel (Geneve), Akitaka Ariga (Chiba/Bern), Tomoko Ariga (Kyushu), Jeremy Atkinson (Bonn), Florian Bernlochner (Bonn), Tobias Boeckh (Bonn), Jamie Boyd (CERN), Lydia Brenner (NIKHEF), Franck Cadoux (Geneve), Roberto Cardella (Geneve), Dave Casper (UC Irvine), Charlotte Cavanagh (Liverpool), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Sergey Dmitrievsky (JINR), Monica D’Onofrio (Liverpool), Yannick Favre (Geneve), Delon Fellers (Oregon), Jonathan Feng (UC Irvine), Carlo Alberto Fegolino (Geneve), Didier Ferrere (Geneve), Max Fieg (UC Irvine), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneve), Yuri Gornushkin (JINR), Yotam Granov (Technion), Carl Gwilliam (Liverpool), Daiki Hayakawa (Chiba), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneve), Tomohiro Inada (Tsinghua), Luca Iodice (Geneve), Sune Jakobsen (CERN), Hans Joos (CERN), Enrique Kajomovitz (Technion), Hiroaki Kawahara (Kyushu), Alex Keykan (Royal Holloway), Felix Kling (DESY), Daniela Kock (Oregon), Umut Kose (CERN), Rafaela Eleftheria Kotisa (Geneve), Susanne Kuehn (CERN), Thanushan Kugathasan (Geneve), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Jack MacDonald (Mainz), Chiara Magliocca (Geneve), Josh McFayden (Sussex), Andrea Pizarro Medina (Geneve), Matteo Milanesio (Geneve), Theo Moretti (Geneve), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Friedemann Neuhaus (Mainz), Laurie Nevay (Royal Holloway), Ken Ohashi (Bern), Hidetoshi Otono (Kyushu), Lorenzo Paolozzi (Geneve), Hao Pang (Tsinghua), Brian Petersen (CERN), Markus Prim (Bonn), Michaela Quellisch-Maltland (Manchester), Hiroki Rukoju (Nagoya), Elisa Ruiz Choliz (Mainz), Jorge Sabater-Iglesias (Geneva), Osamu Sato (Nagoya), Paola Scappoli (Berm), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneve), Savannah Shively (UC Irvine), Yusuke Takubo (KEK), Noshin Tarannum (Geneva), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Svetlana Vassina (JINR), Benedikt Vormwald (CERN), Di Wang (Tsinghua), Eil Welch (UC Irvine), Stefano Zambito (Geneva)

Administrative support for the collaboration is provided by Veronique Wedlake from the CERN, EP Secretariat.
FASER Institutions
Backup
Collider Neutrinos

1. Observed neutrinos from a variety of sources: nuclear reactors, beam dump experiments, cosmic rays, Sun, earth, supernovae, ...
2. Neutrinos produced copiously at hadron colliders, but no direct observation yet!
   - Neutrinos interact extremely weakly
   - Highest energy neutrinos produced in forward direction (parallel to beamline)
3. Energy spectrum complementary to existing neutrino experiments
   - Measurement at highest man-made neutrino energies
**Background estimates**

**Veto inefficiency**

1. Veto layer scintillators efficiency >99.998%
2. Measured layer-by-layer using muon tracks in spectrometer pointing back
3. With five layers, even $10^8$ muons going through veto produces negligible background even before any other selections applied

**Veto layer efficiency**

![Veto layer efficiency graph](image)

Veto Station 2, plane 2
MIP efficiency = 99.99986(1) %
Background from Neutral hadron from muon interactions upstream

1. Even if the above scenario works, deposition of >500GeV in the calorimeter is unlikely
2. Background estimated using lower energy events with two and three tracks reconstructed and different veto conditions
3. The estimated background: $(2.2 \pm 3.1) \times 10^{-4}$
Layout

• Introducing the FASER experiment
• Dark Photon Analysis (Paper Link)
• Direct detection of collider neutrinos with electronic detector (Paper Link)
• Progress on collider neutrinos with emulsion detector (CONF Note)
• Summary and plans
Background estimates

Non-collisions background
1. Studied in non-colliding bunches and runs without any beam
2. We see so events >500GeV and no reconstructed tracks either.

Neutrino background from simulation
1. Using GENIE generator (300 ab⁻¹)
2. With uncertainties for mismodelling and neutrino flux: 0.0018±0.0024 events
3. Background from neutrino induced hadrons upstream found to be negligible
Neutrino Characteristics

Neutrino events match expectations from simulation
- Most events at high momentum ($E_\mu > 200$ GeV)
- More $\nu_\mu$ than $\overline{\nu}_\mu$
- High occupancy in front tracker station
- Large angle $\theta$ with respect to line-of-sight

No experimental uncertainties included in these plots!
Future Plans

• For the HL-LHC, larger versions of FASER and FASERnu with significant gains in physics sensitivity are being studied in the context of the Forward Physics Facility (https://arxiv.org/abs/2203.05090).
FASER 2 and Fasernu2

Technology

<table>
<thead>
<tr>
<th>Feature</th>
<th>FASER2</th>
<th>FASERmu2</th>
<th>Adv-SND</th>
<th>FLArE</th>
<th>FORMOSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large aperture SC magnet</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>High resolution tracking</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large scale emulsion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon tracking</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>High purity noble liquids</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Low noise cold electronics</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Scintillation</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Optical materials</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Cold SiPM</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Picosec synchronization</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Intelligent Trigger</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

17/10/
FASER 2 and Fasernu2 layout
Signal Simulation (FORESEE)

- Signal simulated w. FORESEE: \( \pi^0 \) and \( \eta^0 \) production with EPOS-LHC generator, Dark bremsstrahlung of protons included (sub-dominant), only decays to e+e- in FASER decay volume considered.

- Main signal uncertainties: Generator uncertainty parameterized vs \( A' \) energy as (Based on difference to QGSJET/SIBYLL), calorimeter energy scale (6% uncertainty on energy scale at 500GeV).

\[
\frac{\Delta N}{N} = \frac{0.15 + (E_{A'}/4 \text{ TeV})^3}{1 + (E_{A'}/4 \text{ TeV})^3}
\]
Background estimates

Veto inefficiency
1. Veto layer scintillators efficiency >99.998%
2. Measured layer-by-layer using muon tracks in spectrometer pointing back
3. With five layers, even $10^8$ muons going through veto produces negligible background even before any other selections applied

Veto layer efficiency

Background from Neutral hadron from muon interactions upstream
1. This background is heavily suppressed
   - The neutral hadron needs to survive 8 int lengths before decaying in the decay volume

- **Neutral hadron**
  - Veto
  - FaserNu with 8 interaction lengths
  - Decay Volume
  - Rest of FASER

- **μ**
  - The parent muon needs to miss the detector

1. Even if the above scenario works, deposition of >500GeV in the calorimeter is unlikely
2. Background estimated using lower energy events with two and three tracks reconstructed and different veto conditions
3. The estimated background: $(2.2\pm3.1)\times10^{-4}$
Example Dark Photon simulation
Dark Photon Cut Flow

• Data and example signal efficiency as a function of analysis selections

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data Events</th>
<th>Efficiency</th>
<th>Data Efficiency</th>
<th>Signal Events</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good collision event</td>
<td>151750788</td>
<td></td>
<td></td>
<td>95.3</td>
<td>99.7%</td>
</tr>
<tr>
<td>No Veto Signal</td>
<td>1235830</td>
<td>0.814%</td>
<td></td>
<td>94.0</td>
<td>98.4%</td>
</tr>
<tr>
<td>Timing/Preshower Signal</td>
<td>313988</td>
<td>0.207%</td>
<td></td>
<td>93.0</td>
<td>97.3%</td>
</tr>
<tr>
<td>≥ 1 good track</td>
<td>21329</td>
<td>0.014%</td>
<td></td>
<td>85.2</td>
<td>89.2%</td>
</tr>
<tr>
<td>= 2 good tracks</td>
<td>0</td>
<td>0.000%</td>
<td></td>
<td>52.4</td>
<td>54.8%</td>
</tr>
<tr>
<td>Track radius &lt; 95 mm</td>
<td>0</td>
<td>0.000%</td>
<td></td>
<td>47.6</td>
<td>49.8%</td>
</tr>
<tr>
<td>Calo energy &gt; 500 GeV</td>
<td>0</td>
<td>0.000%</td>
<td></td>
<td>46.7</td>
<td>48.9%</td>
</tr>
</tbody>
</table>
# Dark Photons – Systematic Uncertainties

Complete list of systematic uncertainties and their impact on the signal yield

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Effect on signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theory, Statistics and Luminosity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark photon cross-section</td>
<td>$\frac{0.15 + (E_{\gamma}/4\text{TeV})^3}{1 + (E_{\gamma}/4\text{TeV})^3}$</td>
<td>15-65% (15-45%)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>MC Statistics</td>
<td>$\sqrt{\sum W^2}$</td>
<td>1-3% (1-2%)</td>
</tr>
<tr>
<td><strong>Tracking</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Momentum Scale</td>
<td>5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Momentum Resolution</td>
<td>5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Single Track Efficiency</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Two-track Efficiency</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td><strong>Calorimetry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calo E scale</td>
<td>6%</td>
<td>0-8% (&lt; 1%)</td>
</tr>
</tbody>
</table>
Dark Photon: Timing Scintillator Selection

• Timing cut of 70 pC is ~100% efficiency for signal
One of FASER’s Target: Dark Photon

- Dark Photon can be a feature of hidden sector models where hidden gauge boson can mix with SM photons
- MeV-scale dark photons, $A'$, are produced abundantly in meson decays depending on kinematic mixing, $\varepsilon$
- At small coupling, high energy in forward region, results in long decay lengths, which is ideal for FASER
- For $1 < m_{A'} < 211$ MeV, will decay 100% to $e^+e^-$ pair
Dark Photon: Additional Limits

Limits including recent prelim NA62 results

Alternative limit plot showing individual previous limits available from DarkCast
Dark Photon: Calo Energy Scal

1. Calorimeter energy scale and uncertainty evaluated based on test beam data and in-situ MIP calibration
2. Validated using conversion events ($\mu$ with e$^+$e$^-$ pair)
3. E/p in data and MC agrees within 6%
Dark Photon: Tracking Systematics

• Single track efficiency studies in muons events with track segments found in each station
• Tracking efficiency lower for two close by tracks (~60%)
**FaserNu First Physics**

1. First analysis includes 150 of 730 plates - 68kg target mass for this analysis
2. 9.5 fb$^{-1}$ of LHC proton collision data
3. Preliminary results: [CONF Note](#)
4. Expected 0.6–5.2 (ν e CC) and 3.0–8.6 (ν μ CC) passing selection
5. Observed 3 ν e vertices (5σ), and 4 ν μ vertices (2.5 σ)
6. First direct observation of collider electron neutrinos!
Detector Performance: Timing and Calo

- Calorimeter resolution measured in test beam
- Precision timing of both scintillator and calorimeter

![Graph showing Calo timing for different events](image1)

![Graph showing Test beam calorimeter resolution](image2)

17/10/2023
FASER’s Target: Dark Photon

- Dark Photon can be a feature of hidden sector models where hidden gauge boson can mix with SM photons
- MeV-scale dark photons, $A'$, are produced abundantly in meson decays depending on kinematic mixing, $\varepsilon$
- At small coupling, high energy in forward region, results in long decay lengths, which is ideal for FASER
- For $1 < m_{A'} < 211$ MeV, will decay 100% to $e^+e^-$ pair
Example Event

1. This is a muon traversing the whole detector
2. A very nice way to see that the whole detector is functioning well and timed in for signals from IP1