BSM Searches with FASER

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The FASER Collaboration

- FASER is a forward LHC experiment designed to detect light and weakly interacting particles
  - Situated 480m downstream of the ATLAS IP
  - Utilises the large LHC collision rate (and increased light particle production rate in the forward region) to:
    - Search for long-lived BSM particles such as Dark Photons (A')
    - Measure collider-produced neutrinos

- Further FASER related talks:
  - Tomohiro: FASER Neutrino results, Jamie: Forward Physics Facility
The FASER Detector

A (relatively) small detector composed of:

- An emulsion based neutrino detector (FASERv)
- Multiple scintillator systems (used for either triggering, timing, or vetoing)
- A calorimeter system (LHCb outer Calo modules)
- 4 tracking stations (IFT and 3 spectrometer stations composed of 3x3 layers of ATLAS SCT strip modules with 0.5 B-field applied)
- 1 decay volume (1.5m) with 0.5T B-field applied
FASER 2022 Operations

- Installed and successfully commissioned during 2021/22
  - More than 350M single-muon events recorded
  - All detector components working as expected
- Recorded 37 fb\(^{-1}\) of data
  - Generally automated, continuous data-taking
  - Trigger rate of up to 1.3 kHz
  - Dead-time of 1.3%
- Dark Photon analysis luminosity: 27 fb\(^{-1}\)
  - Lower luminosity used than the full dataset as only events where the optical fibres were installed
  - Allowing for a calorimeter gain optimised up to 3 TeV
Dark photons ($A'$) are predicted in many hidden sector models

- Weakly coupled to the SM via kinetic mixing ($\epsilon$) to the SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f ,$$

At the LHC, low mass $A'$ will mainly be produced in the decays of light mesons (e.g., the pion), with a branching ratio:

$$B(\pi^0 \to A'\gamma) = 2\epsilon^2(1 - m_{A'}/m_{\pi^0})^3 B(\pi^0 \to \gamma\gamma)$$

As the lifetime is dependent upon the kinetic mixing, FASER targets long decay lengths, (therefore weak mixing) due to the distance of the detector from the IP

$$L = c\beta\tau\gamma \approx (80 \text{ m}) \left[ \frac{10^{-5}}{\epsilon} \right]^2 \left[ \frac{E_{A'}}{\text{TeV}} \right] \left[ \frac{100 \text{ MeV}}{m_{A'}} \right]^2$$
Provided $m(A') < 2m(\mu)$, the dark photon decay will always decay to an $e^+e^-$ pair

- Dark photon signal simulated using FORESEE
- Generated $\pi^0$ & $\eta$ using EPOS-LHC
- Subdominant contributions from "dark"-bremsstrahlung
- Systematic uncertainties on the signal generation are considered (and are found to be the dominant uncertainty)
- A parameterised (based on E($A'$)) difference between the nominal and QGSJET/SIBYLL is applied
- All generators are tuned on LHCf forward pion data, and these generators bracket the LHCf data

For the phase space that FASER is sensitive to, high electron energies are expected, hence a relatively high calorimeter energy requirements
Dark Photon Search - Event Selection

- For the first result a simple analysis strategy is implemented
  - A blind analysis is performed, with a blinding criteria of no-veto signal in the veto scintillator and Ecalo > 100GeV

- Robust selection:
  - Collision event passing FASER data-quality requirements
  - No signal (< 40pC) in any veto scintillator
  - Exactly two good tracks:
    - p > 20GeV
    - r < 95mm (tracks are then extrapolated back to the veto stations and are also required to be within r <95mm)
  - Timing & preshower scintilators are consistent with 2 MIPs
  - Calo energy deposit of E > 500GeV

![Diagram of energy measurement, tracking, decay volume, and scintillator veto]
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Momentum: 420.4 GeV, 21.5 GeV
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- Veto inefficiency
- Non-collision backgrounds (Cosmics, Beam debris)
- Neutrino background
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The inefficiency is measured (layer-by-layer in the scintillators) with muons with tracks which point back to the veto layers.

5-layer veto reduces $10^8$ muon sample to a negligible level before applying selections: 0 expected events.
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• Cosmics: measured in runs without beam (left), beam debris measured in non-colliding bunches
  • No events observed with ≥1 track or ECalo > 500 GeV
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The neutrino background is the main background in the analysis

- Estimated using GENIE simulation ($300\text{ab}^{-1}$, with uncertainties from neutrino flux and mismodelling included)
- $1.8 \times 10^{-3}$ expected events
Dark Photon Search - Background Sources

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  - Veto inefficiency
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  - Neutrino background
  - Neutral Hadron background

- Neutral hadron background arises from upstream muons interacting in the rock in front of FASER
  - Estimated with FLUKA SIM of muons interacting in the final 10m of rock in front of FASER
  - This background is heavily suppressed:
    - The muon generally always continues and passes through FASER (hence is vetoed in the veto scintillator)
    - The hadron must pass through 8 interactions lengths before decaying
    - The decay products must have a high energy
  - From the generated sample, a negligible amount of neutral hadrons pass the full selection, hence an extrapolation is performed using events with 2/3 tracks and differing veto conditions. **Expectation = $2.2 \times 10^{-4}$**
  - An ABCD method is also used to validate this (with consistent results)
After considering all backgrounds the total expected number of background events are found to be $2.02 \times 10^{-3}$.

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TABLE V. Summary of the different background estimates.

After the background predictions were finalised, the unblinding was performed, with 0 events found passing the selections (0 events were found passing the ≥ 1 track requirement!)
After considering all backgrounds the total expected number of background events are found to be $2.02 \times 10^{-3}$.

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### Graphs

- **No Veto Signal ≥ 1 Fiducial Track**
- **No Veto Signal 2 Fiducial Tracks**

Event counts as a function of calorimeter energy for different dark photon masses and $\xi$ values.
From this null result, FASER can place (90% CL) limits in previously unprobed phase space. Probing region relevant for thermal relic target & region uncovered by the recent NA62 result (overlay in backup).
Dark Photon Search - Outlook

- Presented the results of the first BSM search performed by FASER
  - Limits placed in interesting (and uncovered) regions of parameter space with respect to the thermal relic target

- Currently presented results are from our preliminary CONF note, with the final results (including small analysis improvements) to be finished in the next months
  - Will also include an interpretation in a B-L model
  - Final paper documenting this search is expected by the end of July

- We are already planning on the reinterpretation of our results and we plan to implement RECAST (not just for this result but generally for our BSM searches)
  - We will also obviously provide the standard HEPDATA
    - Limit results
    - Acceptance x efficiency
    - Cutflow examples
  - We will also put the result into DarkCast
• We expect x10 more data for the full Run 3 dataset
  • We will search for several other models including ALPs → \psi \psi
  • 2023 data taking is proceeding well, with 20 fb\(^{-1}\) of data already collected

• Proposed large upgrade to FASER is being discussed in the context of the Forward Physics Facility

With many thanks to:
Appendices

Preliminary

$L = 27.0 \text{ fb}^{-1}$

- Expected Limit (±1σ, 90% CL)
- Observed Limit (90% CL)
- BaBar Limit
- KLOE Limit
- LHCb Limit
- NA48 Limit
- NA64 Limit
- E141 Limit
- Orsay Limit
- NuCal Limit
- E137 Limit
- CHARM Limit

Relic Target $m_\chi = 0.6 m_{A'}$, $\alpha_0 = 0.1$
Preliminary

$L = 27.0 \text{ fb}^{-1}$

- Expected Limit ($\pm 1\sigma_{\text{exp}}, 90\% \text{ CL}$)
- Observed Limit (90\% CL)
- Existing Limits
- NA62 (ee) Limit (Preliminary)
- Relic Target $m_x = 0.6m_A$, $\alpha_0 = 0.1$