Tracking Studies and Two Track Searches with the FASER Detector

Pawan

Supervisors: Prof. Carl Gwilliam, Dr. Monika Weilers, Prof. Monica D'Onofrio

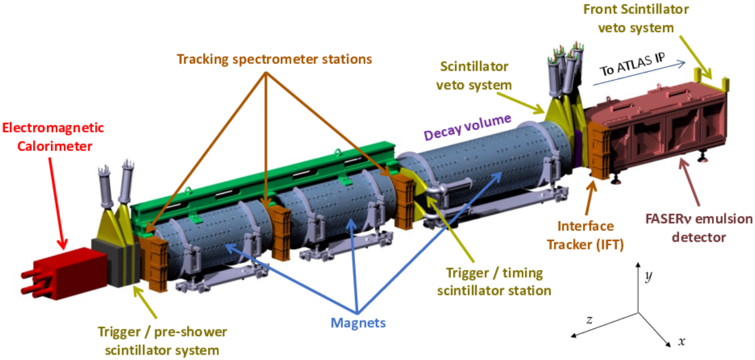
June 24, 2025

Outline

- Introduction to FASER
- Tracking Studies 1 : Data Quality Checks for 2024 Data
- Tracking Studies 2 : Validation Study for Track Reconstruction
- Preliminary Dark Higgs Analysis

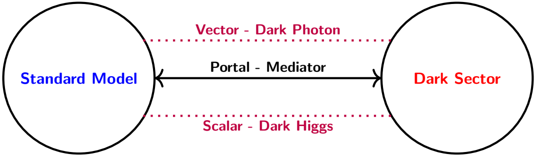
FASER Detector

- FASER is located 480 m downstream of the ATLAS Interaction Point (IP1).
- It is positioned along the Line Of Sight (LoS) and is shielded by various LHC infrastructure and 100 m of rock and concrete.
- Physics analyses at FASER are based on the veto scintillators, the tracking spectrometer, the preshower detector and the electromagnetic calorimeter.

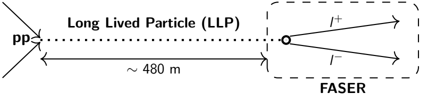


LLPs at FASER

- Dark Matter is theorized to be composed of undiscovered particles and forces, neutral under the Standard Model that make up a Dark Sector (DS).
- These Dark Sectors can couple to the SM only via specific interactions called portals, leading to new mediator-particles that are weakly interacting.



- Mediators can be produced in collider experiments and are usually long-lived (LLP) – allowing them to be detected at FASER through their SM decays.

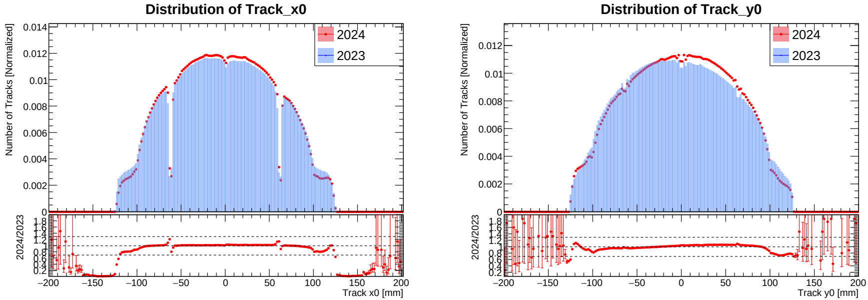


Motivation for Tracking Studies

- Track Studies with the 2024 Data
  - In 2024 FASER collected its largest dataset of 120 fb^{-1}.
  - This data was also collected under a new LHC configuration.
  - The beam crossing angle at IP1 changed from -160 μrad to $+160$ μrad.
  - Large Data + New Configuration made it imperative to understand the differences in the track quality of the newly collected data.
- FASER also underwent a major software upgrades to its track reconstruction
  - On account of the operating system CentOS7 reaching its end of life
  - Entire software stack was migrated to AlmaLinux9.
  - Required major upgrades to the tracking software (Acts [2]).
  - This necessitated a revalidation of the track reconstruction software.

Track Studies with 2024 Data

- The changed crossing angle for 2024 was reflected in the track-y positions.



(a) Track x-positions is consistent with the previous runs.

(b) Track y-positions shows a shift in the positive y-direction.

Figure: Track Positions as measured by the first tracking station

- Other track parameters also showed some differences attributable to the changes in the LHC optics but were otherwise consistent.

Validation of Track Reconstruction

- Validation using the single track dataset was already performed
- This study utilized the simulated Dark Photon samples to evaluate the track reconstruction efficiency for close-by tracks.
- Efficiency $= \frac{\text{NEvents with} \geq 2\text{Tracks}}{\text{NFiducial Events}}$
- The efficiency was observed to be consistent across updated (ALMA9) and the previous (CENTOS7) reconstruction software versions for small track separations.

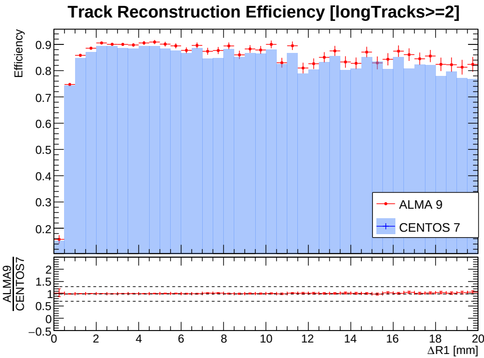
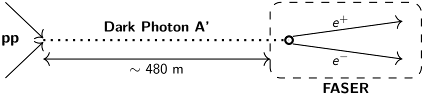


Figure: Efficiency of Track Reconstruction as a function of separation between the two decay products at the final tracking station.

Dark Photon Analysis 2022

- FASER performed a search for Dark Photon in 2022 using 27 fb^{-1} of data [3], focusing on the electron channel.
- The major background was from neutrino interactions in the timing scintillators.
- The large calorimeter energy requirement of 500 GeV supressed this background.



Description	Value
Pre-selecton	
Time consistent with a colliding bunch identifier Timing scintillator trigger	
Scintillator	
Timing station: Top or Bottom Scintillator charge OR Top and Bottom charge	 > 70 pC > 30 pC
Each Preshower scintillator charge Each Veto scintillator charge	>2.5 pC <40 pC
Tracking	
Exactly 2 Good Tracks Momentum χ^2/NDF Number of tracker layers on track Number of tracker hits on track	 > 20 GeV < 25 $>= 7$ $>= 12$
Fiducial selection	
Track extrapolated to all scintillators and tracking stations	 < 95mm
Calorimeter	
Calorimeter energy (sum of four channels)	> 500 GeV

Figure: Dark Photon Analysis Selection Criteria

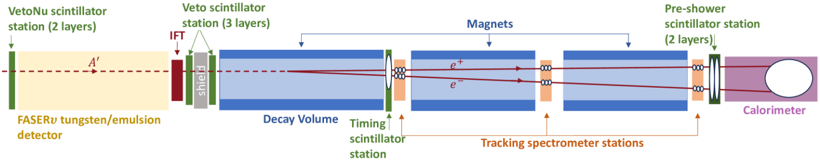


Figure: Dark Photon Signature in the FASER Detector [3]

Preliminary Dark Higgs Analysis

- The seven fold increase in the data collected from 2022 (27 fb^{-1}) to 2024 (190 fb^{-1}) could enable sensitivity to heavier Dark Photons and Dark Higgs
- These have significant branching fractions in the muonic and pionic channels.

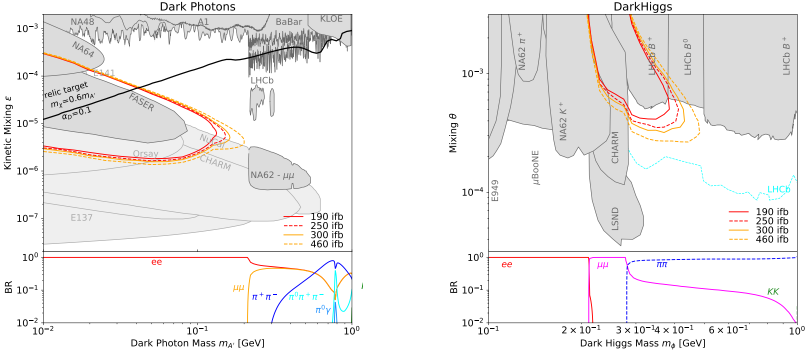


Figure: Projected reach of the Dark Photons (left) and Dark Higgs (right) for various luminosities assuming a zero background and 100% efficiency of the detector [4].

Alternative Final States

- The 2022 analysis primarily focused on the e^+e^- final state.
- Alternative final states such as $\mu^+\mu^-$ and $\pi^+\pi^-$ are incompatible with the 2022-selection due to the high calorimeter energy requirement.

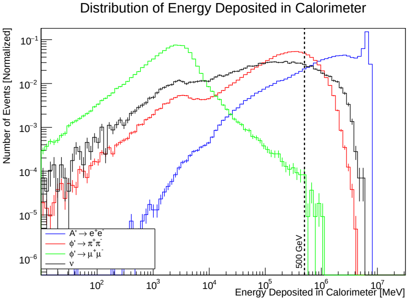
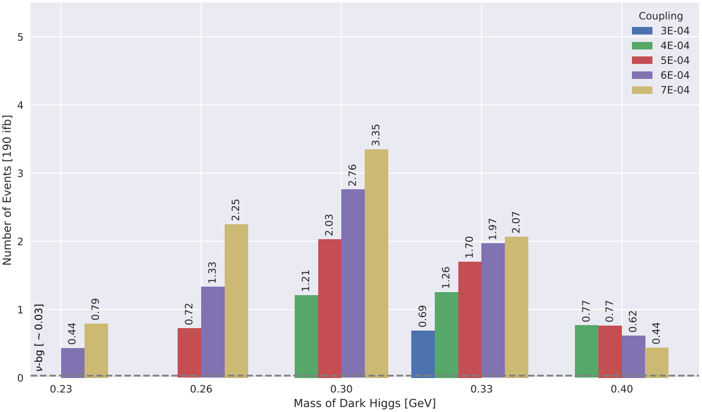


Figure: Calorimeter energy deposition for different final states and neutrinos. Signal samples of different masses are chained.

- In general, muons and pions don't deposit as much energy in the calorimeter as electrons making them hard to distinguish from the neutrino background.

Analysis with Modified Two Track Selection

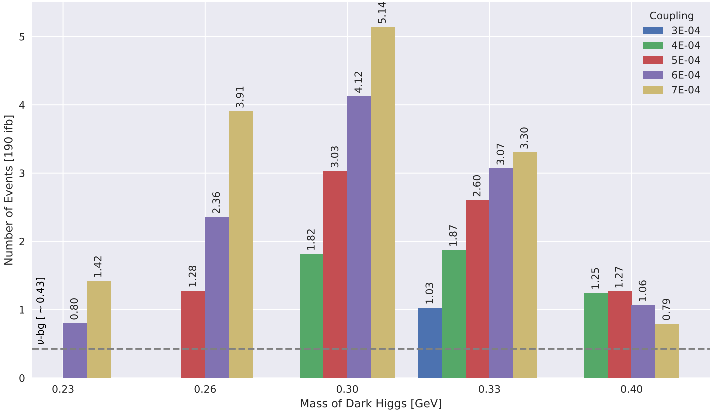
- A trivial modification would be to relax the calorimeter energy requirements.



- The Dark Higgs sensitivity despite the loose selection is quite low, only one mass point has > 3 events needed for a 95% exclusion with 0-background.

Analysis with a One Track Selection

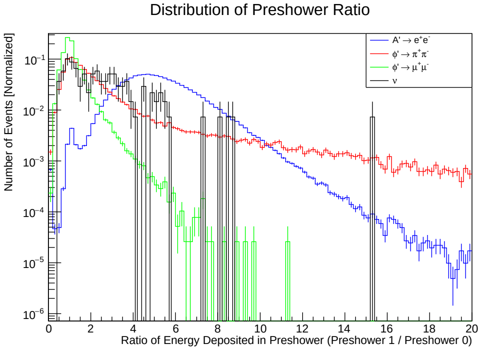
- Such selections are being explored for the 2024 Dark Photon analysis.



- Significantly raises the neutrino background (almost 10-fold) but also increases the signal yield – necessitating further background rejection.

Possible Background / PID using Preshower

- The preshower detector is composed of two layers of scintillating layers interleaved with tungsten radiators and is located before the calorimeter.
- The difference in the showering of various final states in the preshower could be a possible PID tool aiding in the background rejection.



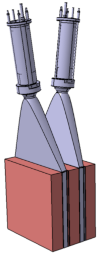


Figure: Preshower Detector Schematic [1]

- While the Preshower Ratio does not definitively separate signal from background, conjunction with other variables could improve this.

Future Directions

- Dark Photon Analysis
  - Contribute to background studies for the 2024 Dark Photon analysis.
  - Perform the statistical analysis for exclusion limits.
- Non Electronic Final States
  - Investigate other possible background discriminators – particularly using track kinematics and other multivariate techniques.
  - Explore other models with higher branching fractions into muons and pions. Eg : Up-philic Scalar [5]
- FASER Operations
  - Handling some of FASER's MC Production for BSM signals.
  - Contribute to monitoring and run manager shifts once on LTA.

Thank You

References

[1] FASER Collaboration. "The FASER Detector". *Journal of Instrumentation* 19.05 (May 2024), P05066. ISSN: 1748-0221. DOI: 10.1088/1748-0221/19/05/P05066. arXiv: 2207.11427 [physics].

[2] Andreas Salzburger et al. *Acts-Project/Acts*. Version v10.0.0. Zenodo, July 28, 2021. DOI: 10.5281/ZENODO.5141419. URL: https://zenodo.org/record/5141419.

[3] FASER Collaboration. "Search for Dark Photons with the FASER Detector at the LHC". *Physics Letters B* 848 (Jan. 2024), p. 138378. ISSN: 03702693. DOI: 10.1016/j.physletb.2023.138378. arXiv: 2308.05587 [hep-ex].

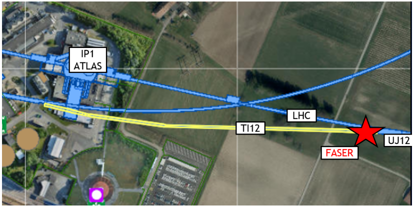
[4] J Boyd and J L Feng. "Request to Run FASER in Run 4". (2023).

[5] FASER collaboration. "Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER". (Dec. 17, 2024). DOI: 10.48550/arXiv.2410.10363. arXiv: 2410.10363 [hep-ex].

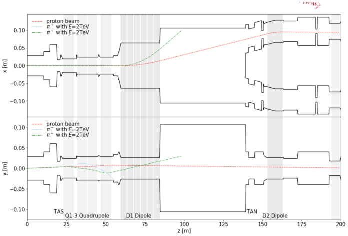
Backup

FASER's Positioning

- FASER's positioning puts it in a low background environment.
- The configuration of the LHC quadrupoles (Q1, Q2, Q3) control the beam crossing angle at IP1 while also affecting the flux of particles that make it to FASER.



(a) Location of the FASER Detector in the LHC



(b) Trajectory of the charged particles through the quadrupoles

Beam Crossing Angle and LoS at FASER

- A beam crossing angle of θ at IP1 shifts the position of the Line of Sight (LoS) at FASER by a distance of $d = 480m \times \tan(\theta/2)$.

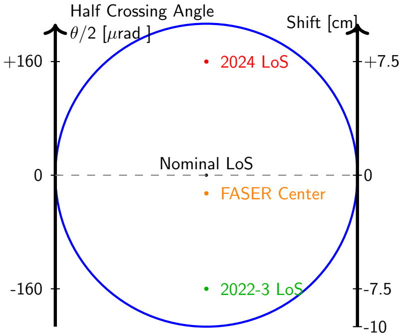
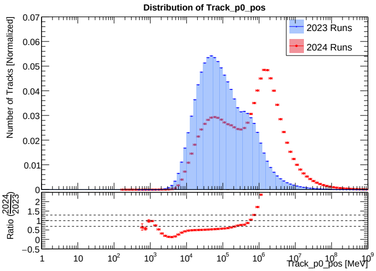


Figure: The LoS at FASER as shifted by the half crossing angle at IP1. The detector itself was moved - 1.2 cm during installation to partially account for the crossing angle in 2022.

Track Momenta in 2024



(a) Positively Charged Tracks

(b) Negatively Charged Tracks

Figure: Track Momenta as measured by the first tracking station split by charge.

- Due to the changed optics in 2024, FASER saw a significant increase in the number positively charged muons.