FASER tracking system and performance

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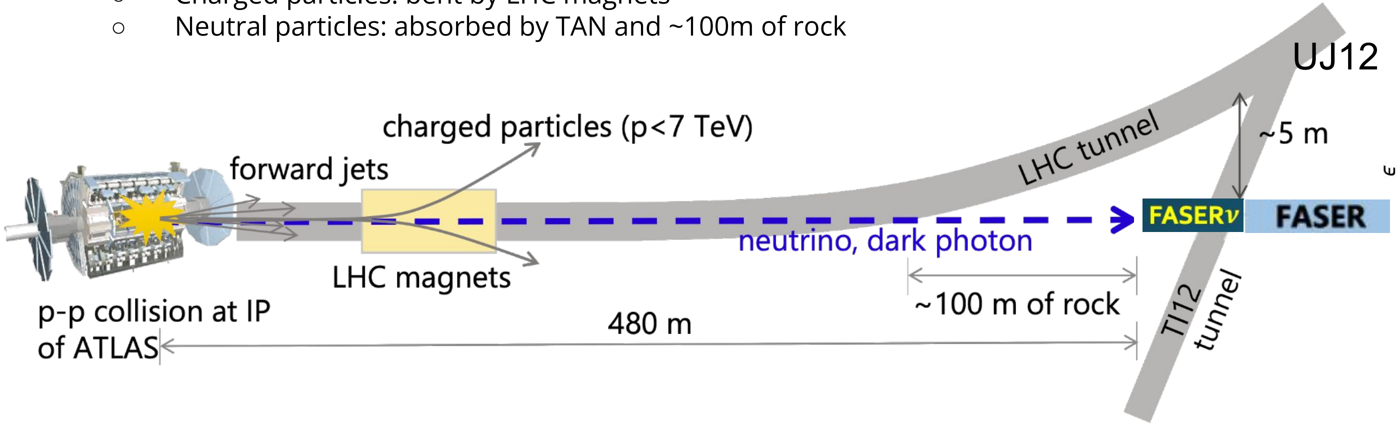
Connecting the dots 2023

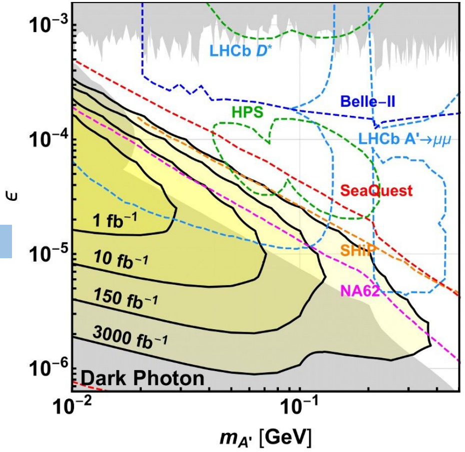
Outline

- Introduction of FASER experiment
- Silicon-strip tracker
- Tracking based on ACTS
- Alignment
- First physics results
- Summary and next todos

ForwArd Search ExpeRiment (FASER) at the LHC

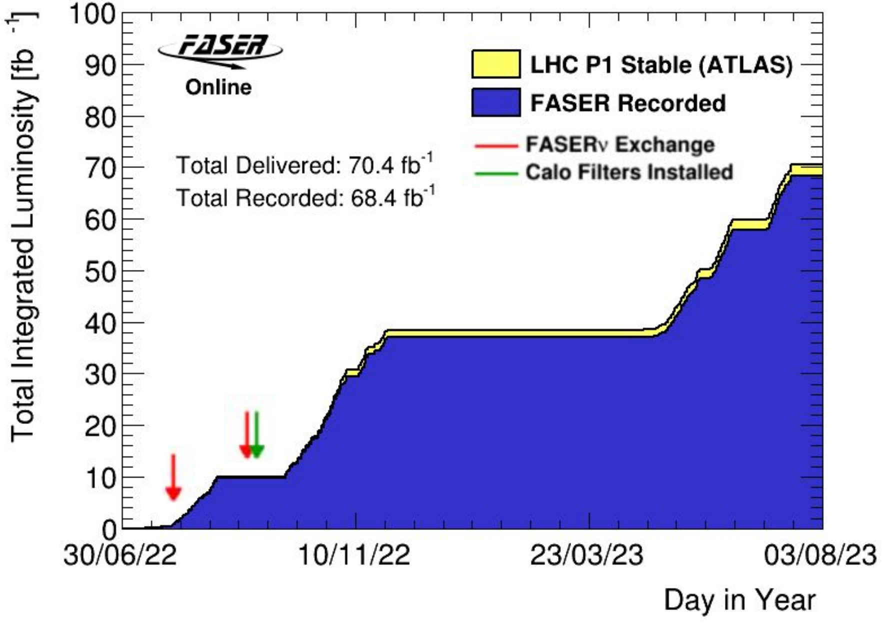
- FASER is designed to search for **LLPs** and **neutrinos** produced in pp collisions at the ATLAS IP
- Light LLPs are produced in the decay of SM mesons, which are predominantly produced very collimated in the beam direction
- Even small detectors on (or close to) the **LOS** can have good sensitivity in these scenarios
  - N~ 10^{16} pions/10^{12} neutrinos in LHC Run 3 (2022-2025)
  - E~ TeV, $\theta_{\text{beam axis}}$ ~ mrad
    - e.g. 1% of pions with E > 10 GeV are produced in the forward 0.000001% of the solid angle (η > 9.2)
  - Even with 1 fb^{-1} of data FASER will have sensitivity to unconstrained parameter space
- Unique opportunities to search for long-lived particles and measure very high energy neutrino interactions
- Almost **background free**
  - Charged particles: bent by LHC magnets
  - Neutral particles: absorbed by TAN and ~100m of rock





FASER operation at Run3

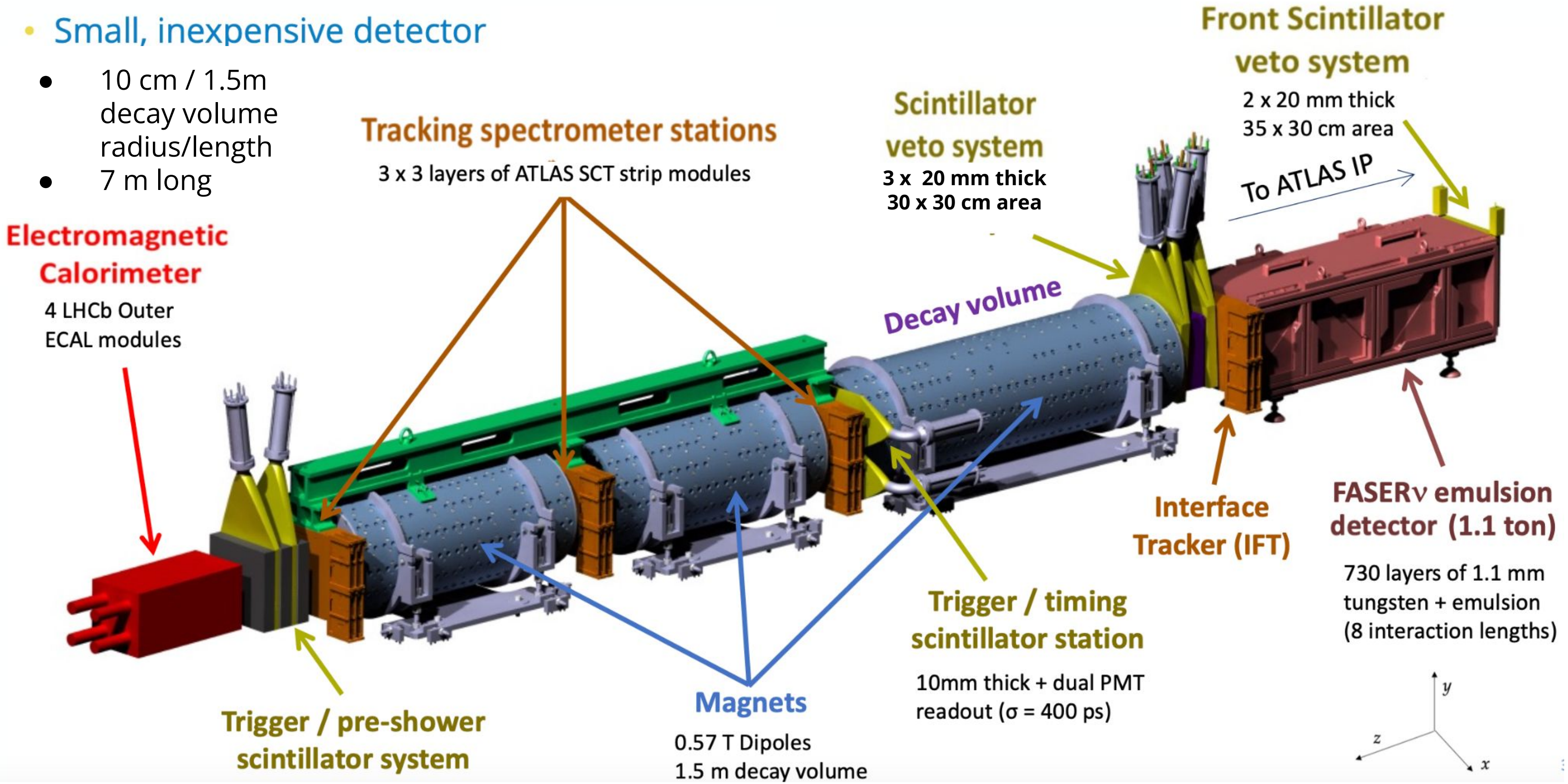
- Successfully constructed, installed and commissioned
- Smoothly operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered luminosity
  - DAQ dead-time of 1.3%
  - A couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage the occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after the exchange
- Smoothly operating at 2023
  - Another ~30 fb^{-1} data



Analyses presented use 27.0 fb^{-1} or 35.4 fb^{-1} collected at 2022

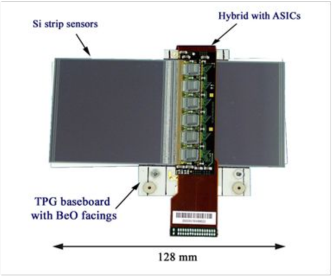
FASER detector

- Small, inexpensive detector
  - 10 cm / 1.5m decay volume radius/length
  - 7 m long



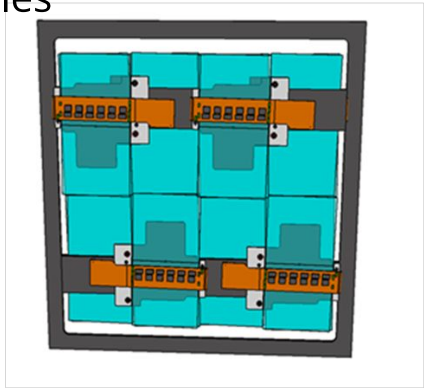
Silicon-strip Tracker

- Made by 4 tracking stations (including interface station)
  - Each containing a 3 layer (24cm x 24cm) of double-sided silicon micro-strip detectors
  - Each layer has 8 SCT modules
    - same SCT modules with ATLAS
    - 80µm strip pitch, 40mrad stereo angle
  - 12 layers => 96 SCT modules

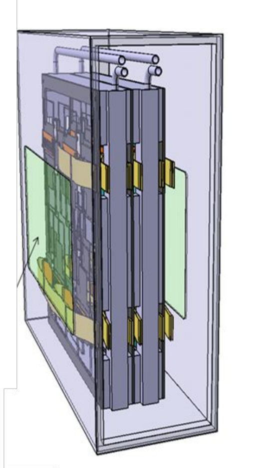


SCT module

Same with SCT in ATLAS



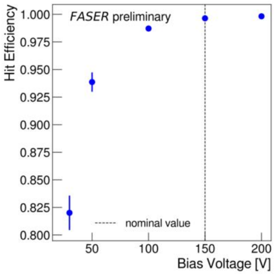
Tracking layer

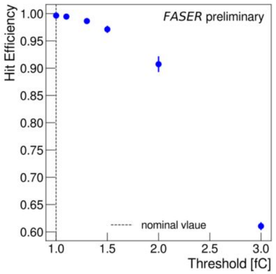


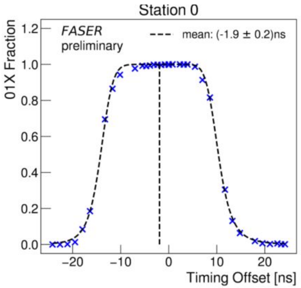
Tracking station

Tracker performance

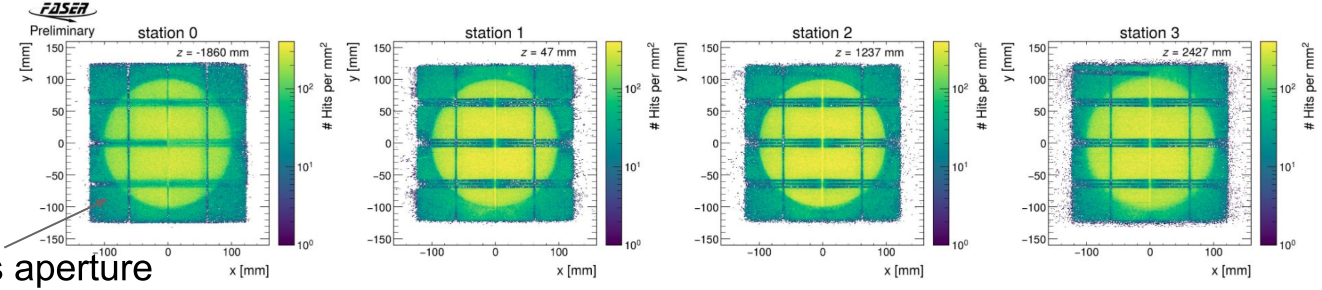
- Build of same silicon strip module (SCT) as ATLAS, module fine time tuned with 390 ps precision
- Hit efficiency of 99.64±0.10% at threshold of 1.0 fC and sensor bias 150V





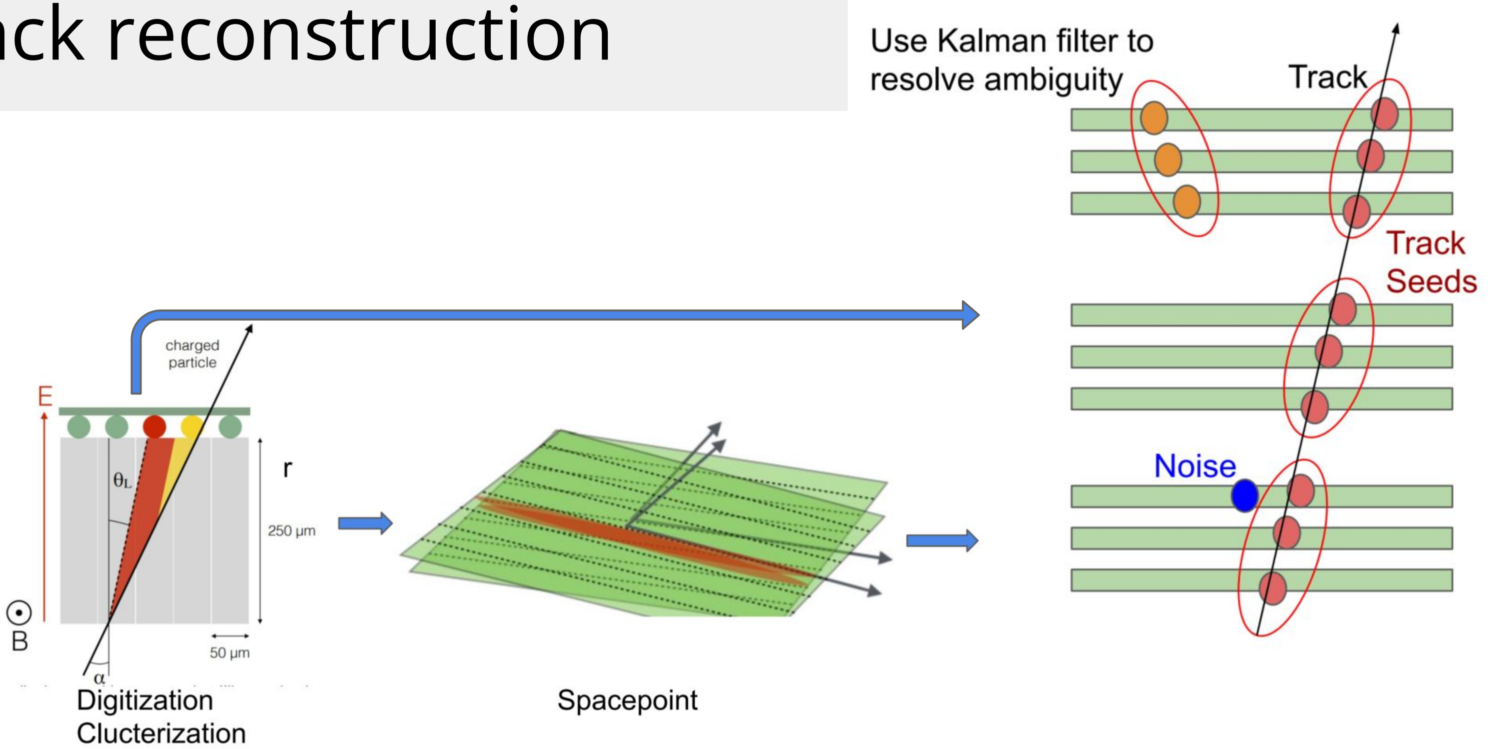


- Total number of dead/noisy strips < 0.5%
- Inefficiency from module edges are expected



Magnets aperture

Track reconstruction

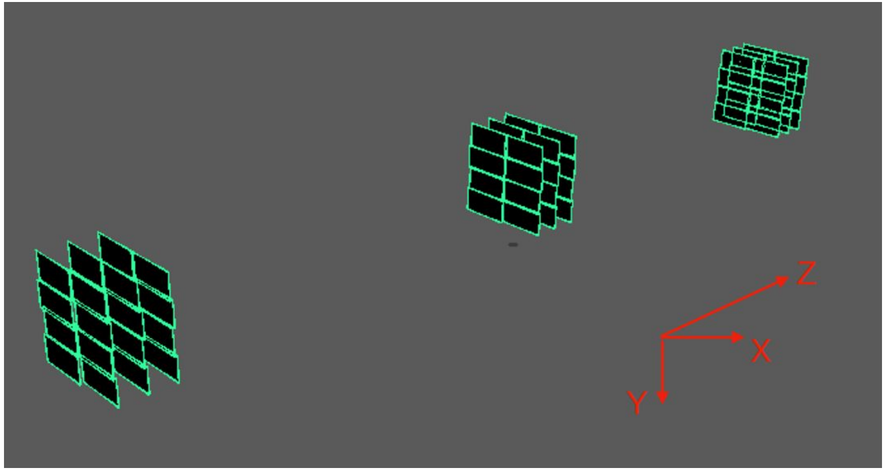


Same with ATLAS (Athena)
- **Same EDM**
- **Similar algorithm**

Acts
- **(Combinatorial) Kalman Filter using cluster or spacepoint**

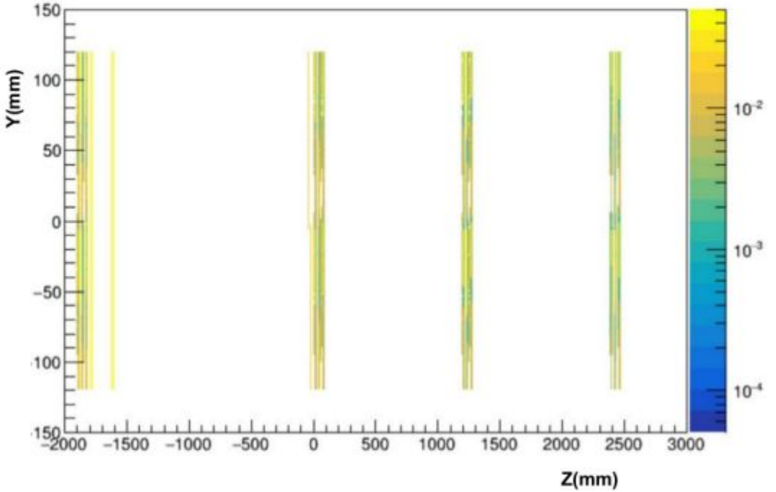
Tracking geometry with ACTS

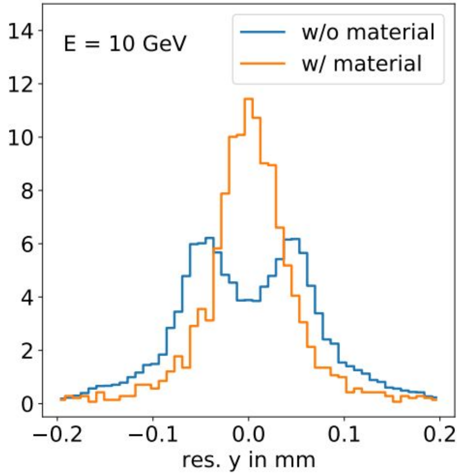
- One cuboid volume for whole detector
  - One sub-volume for each tracker and veto/trigger stations
  - Each module has two plane surfaces and has shift on Z with nearby modules in the same layer
  - One material cylinder surface for magnets

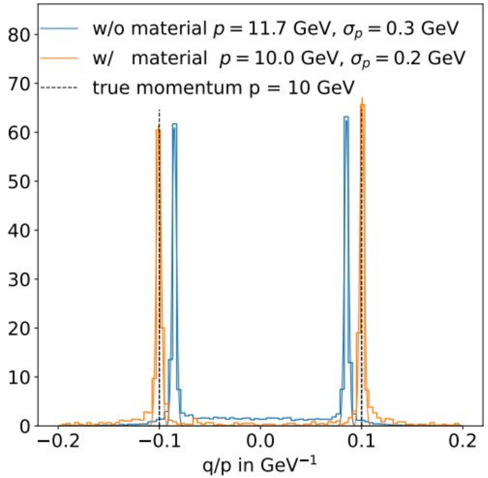


Material mapping

- Shoot geantino particles through whole detector and record the interactions with material
- Map the material to the simplified tracking geometry, i.e. surface, to consider the interactions with material correctly

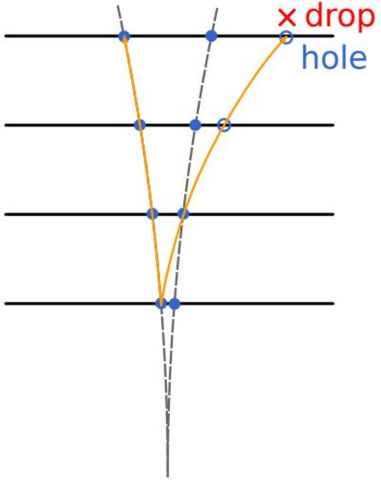






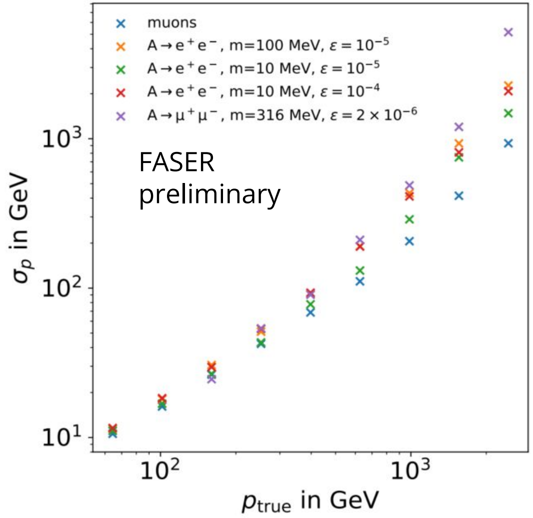
Track reconstruction

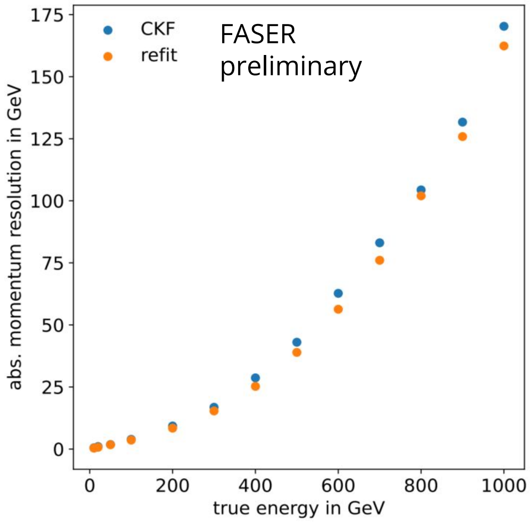
- Three approaches
  - ACTS Kalman Filter (KF)
    - Loop over all the track candidates
  - ACTS Combinatorial Kalman Filter (CKF)
    - Tracking finding + fitting
    - Loop over the initial parameters from all track candidates
    - Solve the ambiguity while propagating
  - Chi2Fitter
    - Loop over all the track candidates
    - Use ACTS to propagate the track parameters to other layers
    - Use TMinuit to minimize $\chi^2 = \sum_i \frac{\left(x_{\mathrm{meas_i}} - x_{\mathrm{pred_i}}\right)^2}{\sigma_x^2} + \frac{\left(y_{\mathrm{meas_i}} - y_{\mathrm{pred_i}}\right)^2}{\sigma_y^2}$
  - Cross check with each other



Combinatorial Kalman Filter

- The momentum resolution is tested with a series of MC simulations in ideal geometry
- Around 10% resolution at 100 GeV, and 17% at 1 TeV
- CKF input: a large covariance for initial parameter and all measurements
  - Refit with the previous results as input can improve the precision



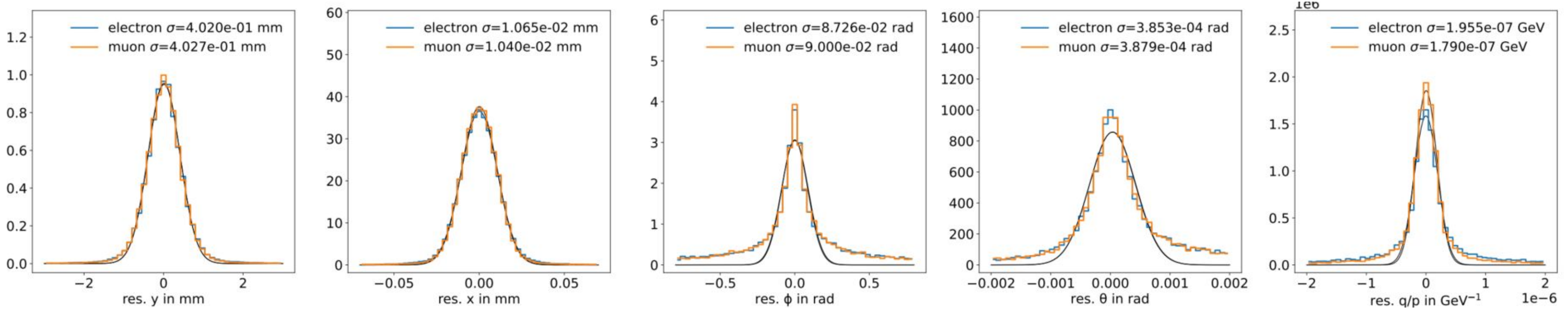


W.I.P.
More study are on going

Track parameters from CKF

- Tested with single particle MC simulation
- Track parameter is defined at a fixed plane surface
- Resolution for track x/y is ~400/10 μm
  - For single measurement (space point), resolution is 816/16 μm

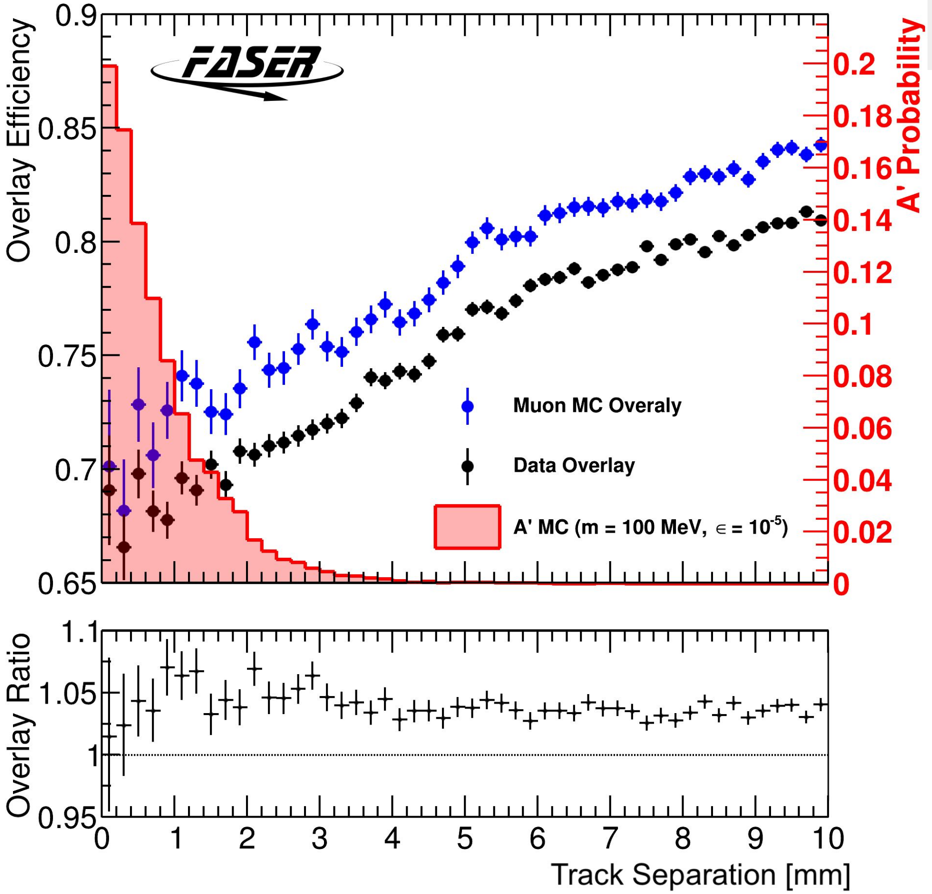
Preliminary study with MC



Track parameters: truth - reco

Reconstruction efficiency

- Reconstruction efficiency for two collimated tracks from MC and data
  - Dark photon is highly boosted
  - Two tracks are close to each other
  - Difficult to model the MC and remaining mis-alignment correctly
- Overlay events
  - Select two 1-track events and overlay the raw data
  - Re-run tracking and compare with 1-track event to get the efficiency
- Efficiency is **~70%**
- Difference between data and MC is taken as a systematic uncertainty
  - Dominant uncertainty, **~7%**

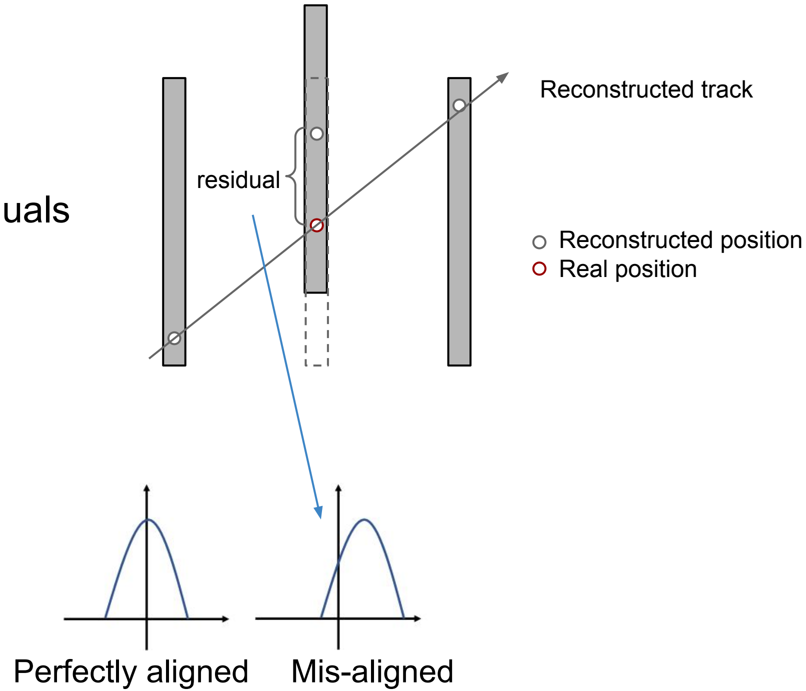


Alignment

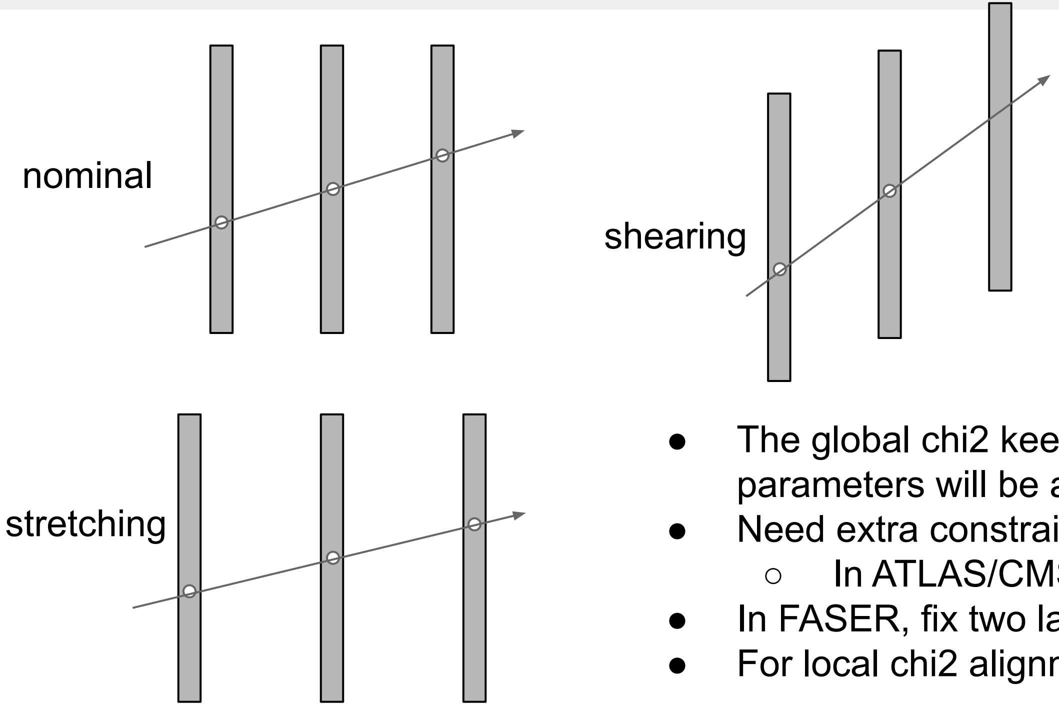
Purpose:
Calibrate the geometry

Method:
Minimize the chi2 defined with residuals

Two approaches in FASER
- Global chi2 using Millepede II
  - W.I.P.
- Iterative local chi2



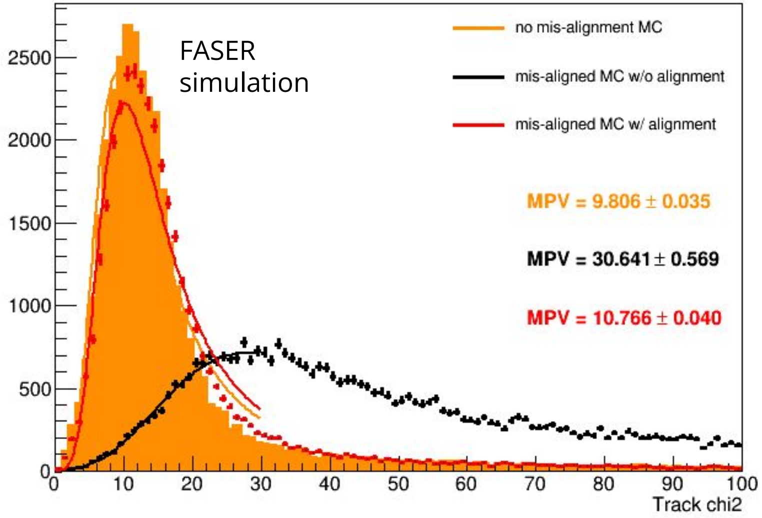
Weak mode and Alignment strategy

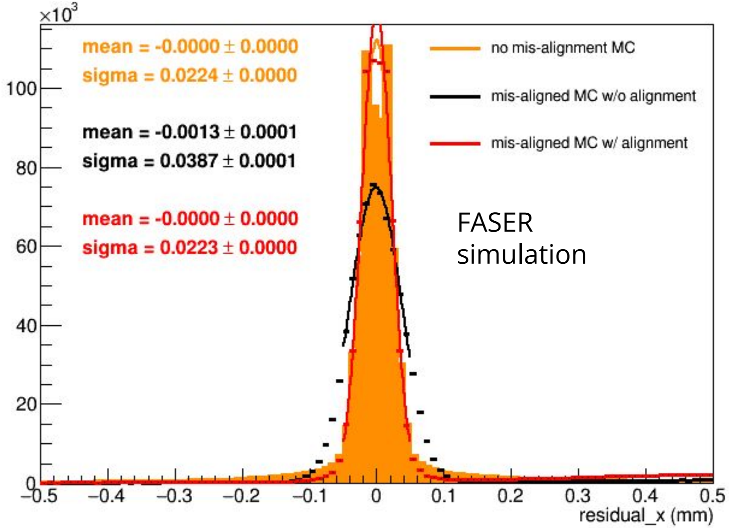


- The global chi2 keeps invariant in weak modes but track parameters will be affected
- Need extra constraints
  - In ATLAS/CMS, good constraints from J/psi or Z mass
- In FASER, fix two layers in order to avoid weak modes
- For local chi2 alignment, converged after ~20 iterations

Validation with mis-aligned MC

- Single muon MC (E = [100, 1000] GeV) with mis-aligned geometry (randomly mis-align all station/layer/module)
- Good tracks: pz>300GeV, nClusters>14, chi2 <200, r<95mm
- ~20 iterations
- Both residual and track chi2 improved significantly and more consistent with the results in ideal geometry





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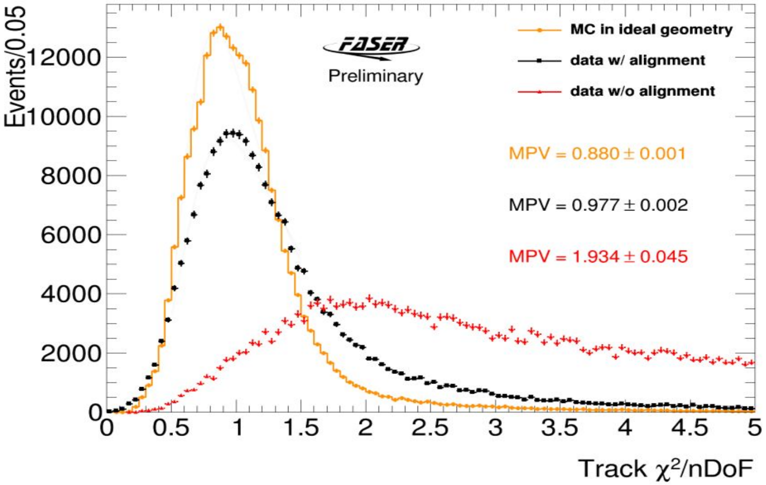
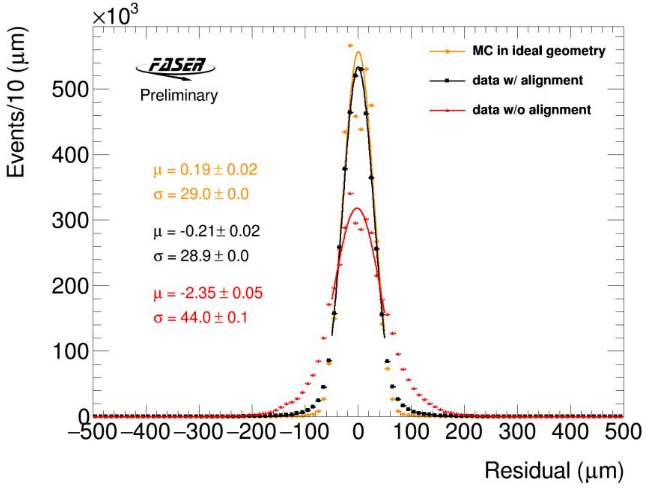
First alignment on collision data

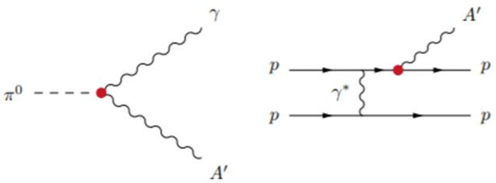
- Main challenge: no good prior knowledge to set constraints
- Iterative local chi2 alignment
- Validated with MC simulation
- Only consider 2 of 6 degree of freedoms, Y translation and Z rotation
  - Silicon strip detector, precision on Y is much better than X
  - Track parameters and residuals are improved significantly
  - Remaining discrepancy will be taken as systematic uncertainty

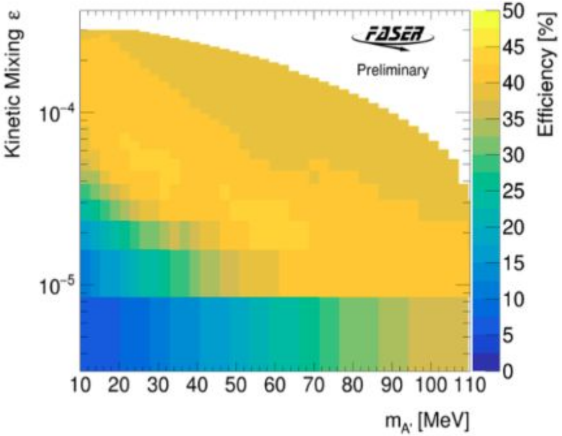




Physics results: dark photon

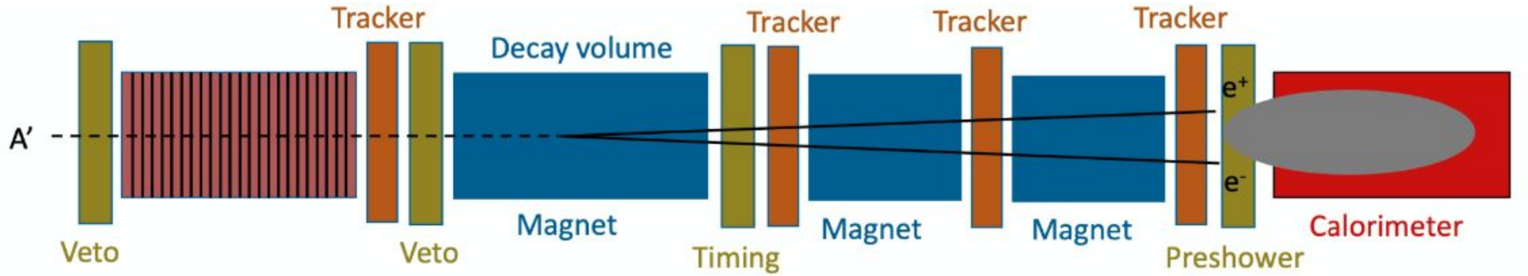
- Mainly produced from decay of light mesons (π^0 and η), and dark bremsstrahlung
- Simple and robust A'->e⁺e⁻ selection, optimised for discovery
  - Blind events with no veto signal and E(calo) >100 GeV
  - Eff. of ~50% across region of sensitivity





1, good quality collision event

4, Timing and preshower consistent with ≥ 2 MIPs



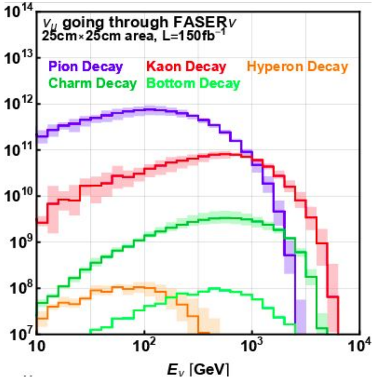
2, No signal (<40pC) in any veto scintillator

3, Exactly 2 good tracks in fiducial volume:
- p > 20 GeV and r <95 mm (r of magnet: 100 mm)
- Extrapolated to r<95 mm at veto scintillators

5, Energy in calorimeter E > 500 GeV

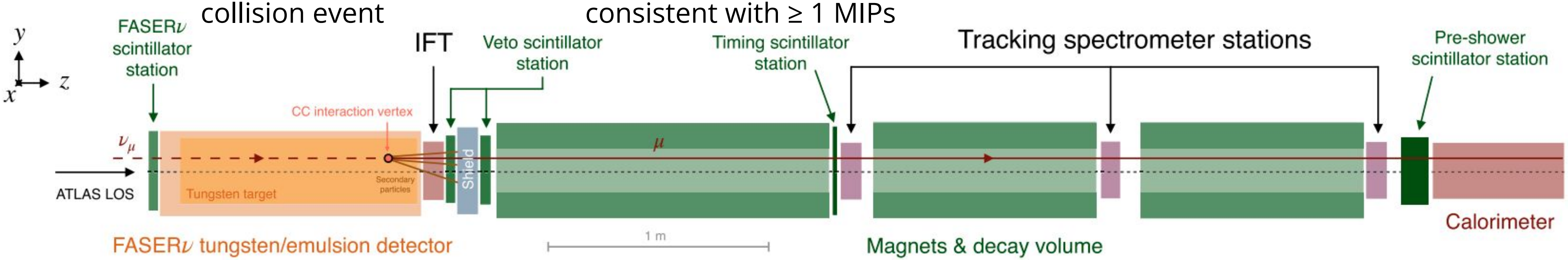
First direct observation of collider neutrinos

- A huge number of neutrinos produced in the LHC collisions traverse the FASER location covering an unexplored neutrino energy regime
  - Originate from hadron decays, mainly pion, kaon and charm mesons
- Expected to record several 1000 of neutrino interactions in Run3
  - **~1000 ν_e, ~10000 ν_μ, ~50 ν_τ**
- For first study, we use silicon tracker to detect neutrino interaction at FASERν
  - Focusing on ν_μ CC interactions



1, good quality collision event

4, Timing and preshower consistent with ≥ 1 MIPs



2, No signal (<40pC) in 2 front vetos, but signal (>40pC) in other 3 vetos

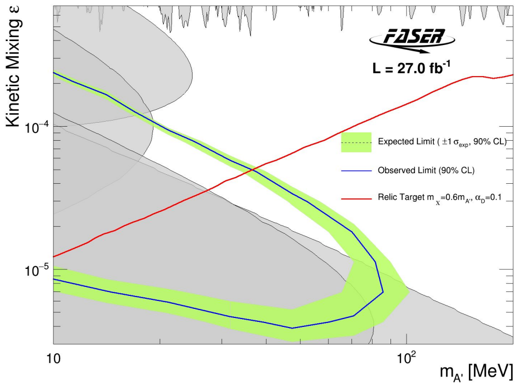
3, Exactly 1 good fiducial track
- p >100 GeV, θ<25 mrad, r<95mm
- Extrapolated to r<95 mm at veto scintillators

First physics results

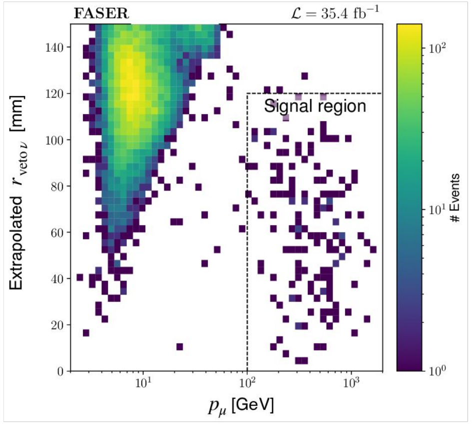
- No event in SR for dark photon is observed
- **FASER sets limits in previously unexplored parameter space !**
    - Probes new territory in the interesting thermal-relic region

- Observed **153 neutrino events** with 0.2 background
    - Consistent with prediction: 151 ± 41
- Significance of **16σ**

$$n_\nu = 153^{+12}_{-13}(\text{stat})\,^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$



- Track reconstruction and alignment are crucial for these two analyses
- **Updating the studies** with a better track finding algorithm and detector alignment
- Possible future improvement:
    - ML track finder for two collimated tracks



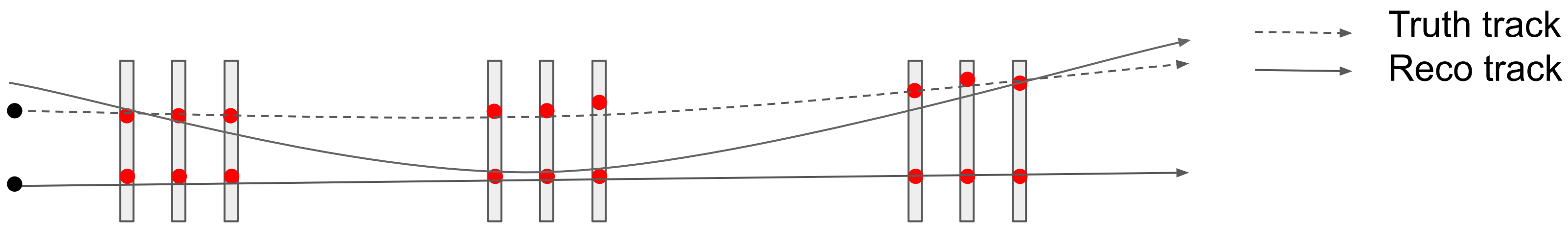
Summary

- FASER successfully constructed and took data in 2022 and 2023 of Run 3
  - Running with fully functional detector and very good efficiency
- Track reconstruction is developed using ACTS, e.g. CKF
  - Good reconstruction efficiency and resolution (10% at 100 GeV)
  - First experimental result using ACTS
- Preliminary alignment with iterative local chi2 approach
  - Better consistency of track chi2 after alignment w.r.t MC in ideal geometry
- Good efficiency for LLP signature, e.g. ~50% for A->ee
- Further improvements
  - Developing new alignment with millepede II
    - Misalignment is the dominant systematic uncertainty, ~7%
  - ML track finder for collimated tracks (<70% efficiency)
  - …

back-up

Inefficiency for overlay tracks

- One of the reasons
  - >=2 segments in each station
  - Due to the geometry, no precise track parameter until fitting with 3 stations
  - There is a possibility to select wrong segment especially at second station



Alignment

- 6 alignment parameters per module (X/Y/Z shift and rotations)
- Residual is defined as: $\vec{r} = \vec{f}(\vec{a}, \vec{\pi}) - \vec{m}$
- Define the total chi2 from all the tracks as:

$$\chi^2 = \sum_{tracks} \vec{r_i}^T \cdot V_i^{-1} \cdot \vec{r_i}$$

- Minimize the chi2 $\frac{d\chi^2(\vec{a})}{d\vec{a}} = \vec{0}$

$\vec{f}(\vec{a}, \vec{\pi})$: Prediction from track fitting

$\vec{m}$: Measurements

V_i^{-1} : Covariance matrix of residuals measurements

⇓

$$\Delta\vec{a} = -\left(\sum_{tracks}\left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right) \cdot V_i^{-1} \cdot \left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right)^T\right)^{-1} \cdot \left(\sum_{tracks}\left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right) \cdot V_i^{-1} \cdot \vec{r}_i(\vec{a}_0)\right)$$

Alignment parameters (← $\Delta\vec{a}$)

Track seeding

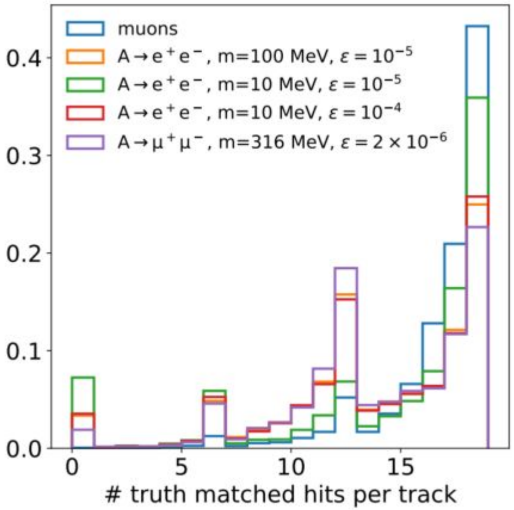
- Start with track segments in each stations
  - 3 layers of SCT modules
    - Each layer is expected to have 2 clusters
  - Linear chi2 fit (no magnet field in stations)
  - Allows for missing hits (can create track segment from only 4 clusters)
- Combine 3 or 4 track segments to build a track candidate

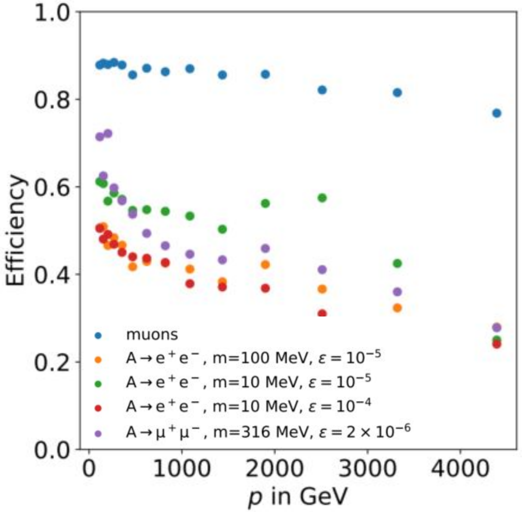
	Efficiency in % $\epsilon = \frac{\text{\# segments with all hits matched to the same particle}}{\text{\# events} \cdot 6}$	Purity in % $p = \frac{\text{\# segments with all hits matched to the same particle}}{\text{\# segments}}$
all segments	93.4	3.5
segment selection	90.0	46.9
remove ghosts	89.6	83.6

W.I.P.
More study are on going

Track finding

- Track finding = find the correct clusters to build a track candidate
- Combine 3 or 4 track segments from different stations
  - Each combination will go to track fitting
- Efficiency = truth-matched tracks / all truth tracks





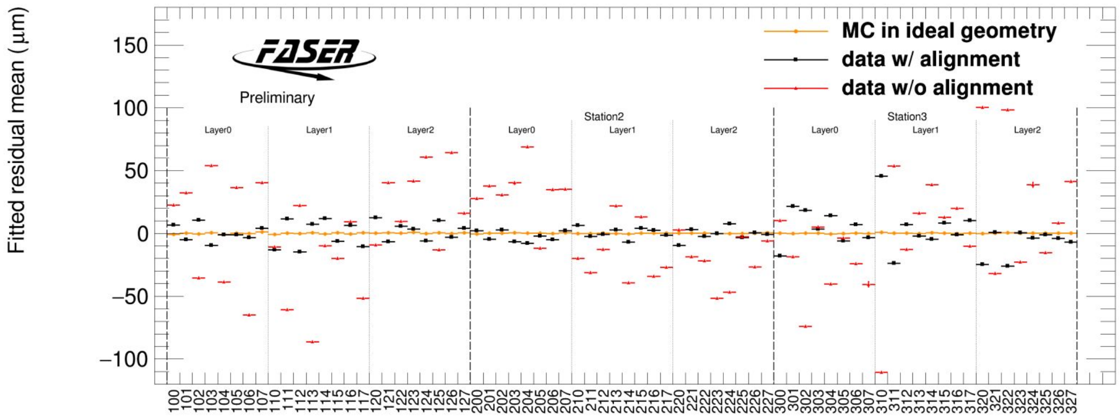
Truth-matched track:

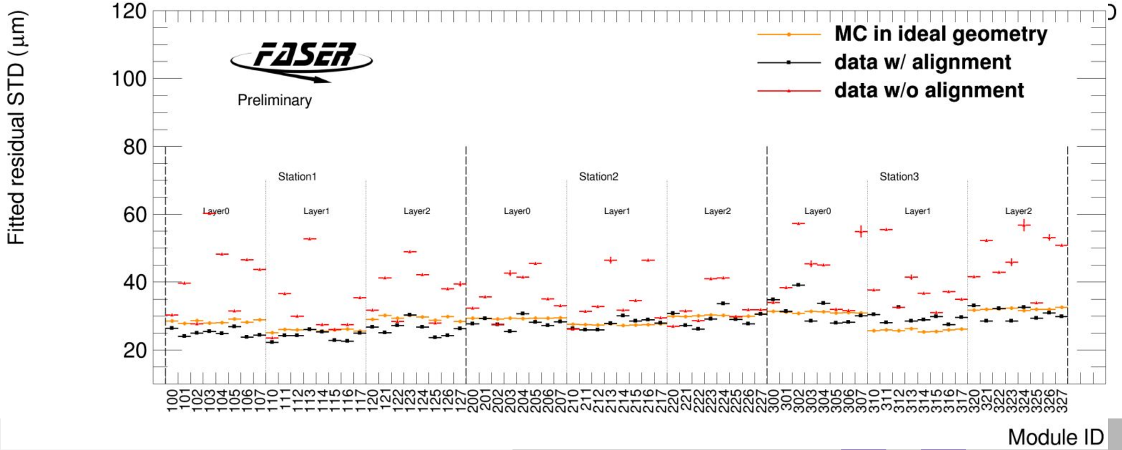
- Momentum is close to truth momentum
- At least 4 Truth-matched clusters per station

W.I.P.
More study are on going

Detector performance - alignment

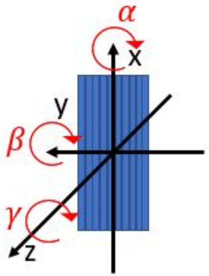
- Mean and std of the residuals for each module

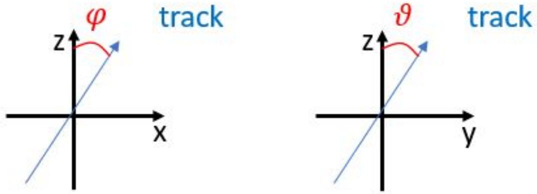




Coordinate systems

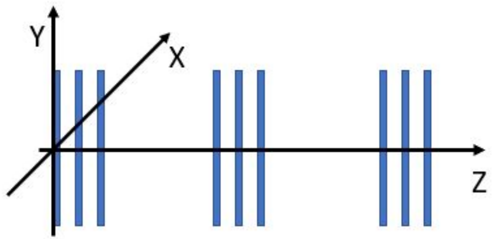
- Local (module)





Same with ATLAS

- Global



Origin point is defined by the center of magnets

- Global chi2 alignment: residuals are defined in local frame
- Local chi2 alignment: residuals are defined in global frame for layer/station and local frame for module alignment

Alignment

- 6 alignment parameters per module (X/Y/Z shift and rotations)
- Residual is defined as: $\vec{r} = \vec{f}(\vec{a}, \vec{\pi}) - \vec{m}$
- Define the total chi2 from all the tracks as:
- Minimize the chi2

$\vec{f}(\vec{a}, \vec{\pi})$: Prediction from track fitting

$\vec{m}$: Measurements

V_i^{-1} : Covariance matrix of residuals measurements

$$\chi^2 = \sum_{tracks} \vec{r_i}^T \cdot V_i^{-1} \cdot \vec{r_i}$$

$$\frac{d\chi^2(\vec{a})}{d\vec{a}} = \vec{0}$$

⇓

$$\Delta\vec{a} = -\left(\sum_{tracks} \left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right) \cdot V_i^{-1} \cdot \left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right)^T\right)^{-1} \cdot \left(\sum_{tracks} \left(\frac{d\vec{r}_i(\vec{a})}{d\vec{a}_0}\right) \cdot V_i^{-1} \cdot \vec{r}_i(\vec{a}_0)\right)$$

Alignment parameters