Usage of ACTS (C)KF in FASER

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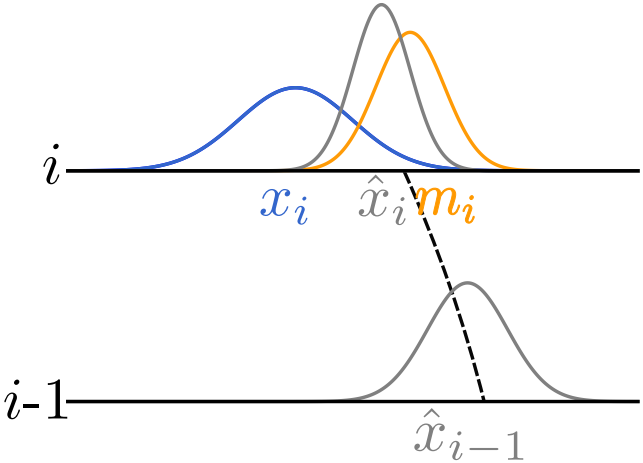
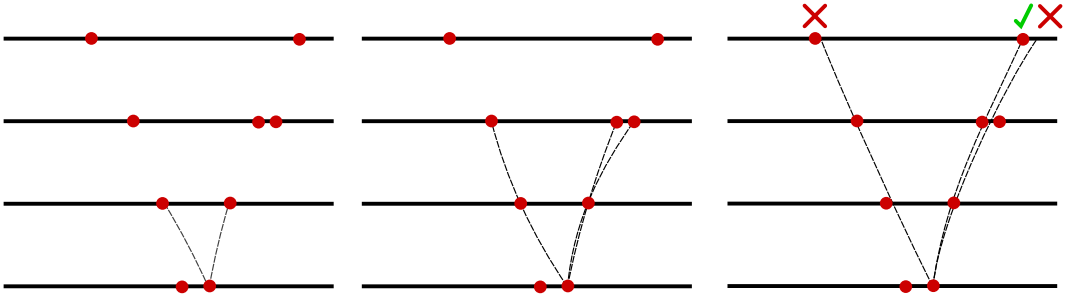
Kalman Filter

- Goal: estimate track $\vec{x} = (x, y, \phi, \theta, q/p, t)^T$ from initial guess and series of measurements
- **Prediction:** extrapolate previous best estimate x_{i-1} to the next layer
- **Update:** weighted average of predicted state x_i and new measurements m_i with more weight being given to estimates with greater certainty



Combinatorial Kalman Filter (CKF)

- combine track finding and track fitting:
  create new trajectory for each possible hit and use χ^2 value from KF to determine if hit is good

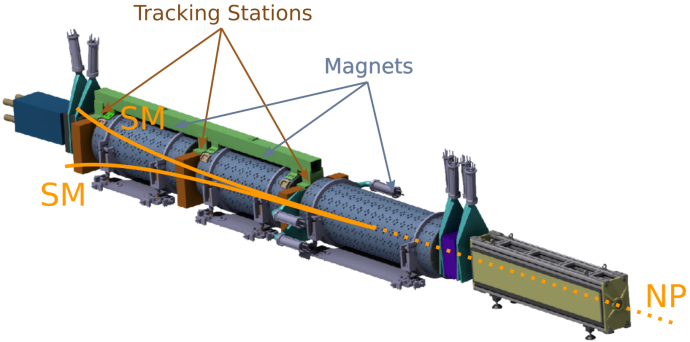


ForwArd Search ExpeRiment (FASER)

- Goal: search for new, long-lived particles, which can decay in two SM particles

Detector:

- 0.55 T permanent dipole magnets
  - separate pair of closely separated, oppositely charged particles
- Three tracker stations, each containing 3 layers
  - use ATLAS semiconductor strip tracker modules (SCT)
    Thanks to the ATLAS Collaboration!
  - reconstruct tracks and measure the position and momentum of charged particles
- Electromagnetic calorimeter, scintillator stations, tungsten/emulsion detector

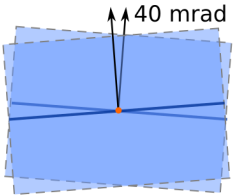


Track Reconstruction

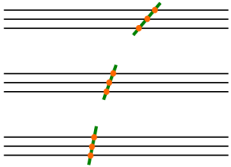
- Software framework based ATLAS software framework "Athena" and ACTS: A Common Tracking Software

Cluster → Space point → Track Seed → Track

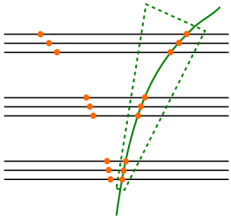
combine adjacent strips
23µm resolution



combine clusters from front and back
16µm resolution in precision direction
816µm resolution in non-precision direction



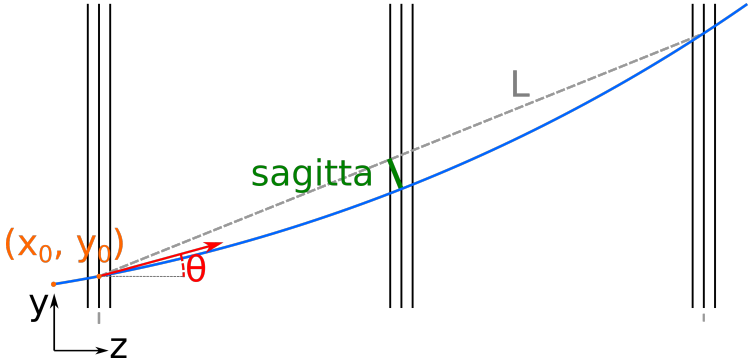
create track seeds
from linear χ^2 fit



track finding and fitting
using combinatorial Kalman filter

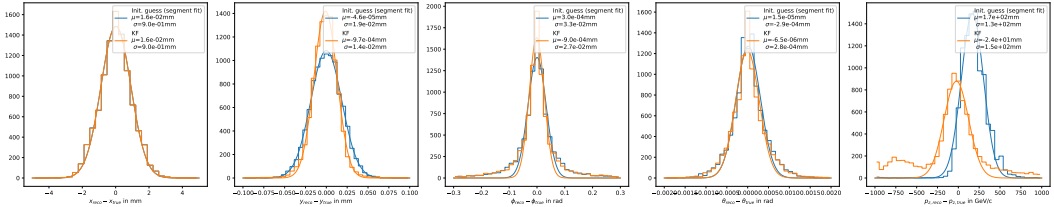
Track Seeds

- linear χ^2 fit of clusters in each station
  - robust against noise and missing hits
  - can handle multiple tracks in the same station
- Estimate initial track parameters $\hat{x}_0 = (x_0, y_0, \phi_0, \theta_0, q_0/p_0, t_0)^T$
  - position (x_0, y_0): extrapolate position in station 1 to origin
  - direction (ϕ_0, θ_0): direction between position in station 1 and 2
  - momentum and charge (q/p): estimated from curvature of track $p = \frac{0.3BL^2}{8s}$



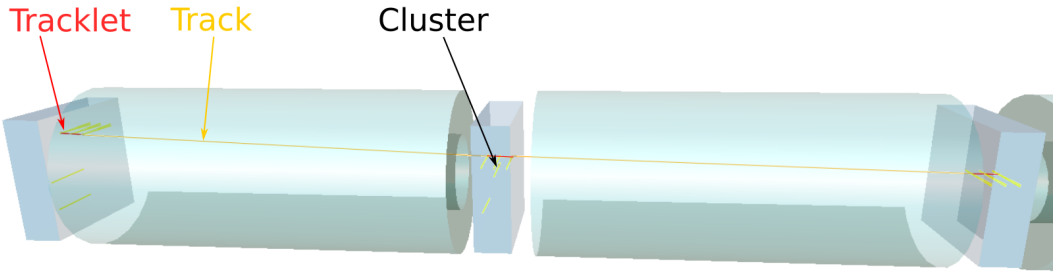
Track Fitting

- reconstruction of 1 TeV muon tracks
- Spatial resolution of 14 µm in the precision direction and 900 µm in the non-precision direction is close to expectation of 16 µm and 816 µm
- Kalman Filter can correct wrong initial momentum and momentum resolution agrees with expectation



Pilot Beam

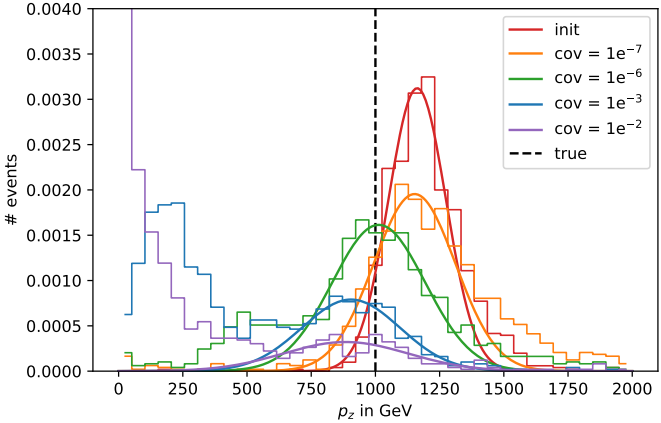
- beam splashes and 450 GeV pilot beam from October 20 - November 1
  → multiple three station tracks
  → test of KF with more realistic conditions



Problem of current Implementation

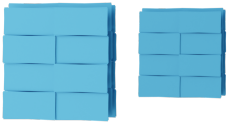
- small initial covariance matrix: KF "trusts" initial estimate more than measurements
  $\rightarrow$ works fine
- large initial covariance matrix: KF "trusts" measurements more than initial estimate
  $\rightarrow$ KF cannot fit track!

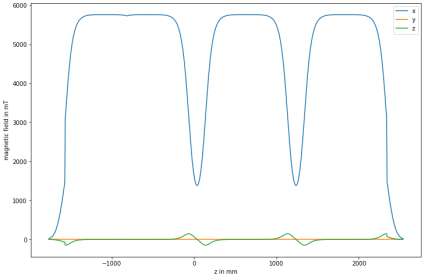
$\Rightarrow$ Kalman filter does not really work but only starts with a good initial guess



Debugging (I)

- tested Kalman filter instead of combinatorial Kalman filter
- tested propagation of track states
- tested constant magnetic field
- checked geometry





Debugging (II)

layer	global $y_{\mathrm{pred}} - y_{\mathrm{meas}}$ in µm	local $y_{\mathrm{pred}} - y_{\mathrm{meas}}$ in µm	$p_{z,KF}$ in GeV
1	−7	−1136	1234
2	15	−1104	1058
3	−7	−1115	13
4	86	−856	6

- track state is propagated in global frame, but Kalman update is calculated in local frame
- predicted and measured positions agree in the global frame, but not in the local frame
  $\rightarrow$ problem with global to local transformation
- currently, we use frame of each SCT sensor for transformations, but these are rotated by 20 mrad!
- still work in progress, next steps:
  - define transformation for module (which is not rotated)
  - use clusters instead of space points for track fitting

Summary

- finished first version of track reconstruction
  - good estimate of initial track parameters
  - reasonable results with CKF for small initial covariance matrix
  - but problem for local coordinates of measurements
    this can explain strong dependence on initial parameters

Next steps:

- fix local to global transformation
- use clusters for track fitting
- reconstruct events with multiple tracks

Additional Slides

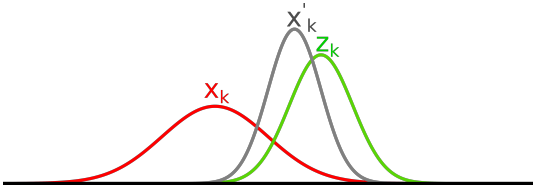
Kalman Filter

- estimate track $\vec{x} = (x, y, \phi, \theta, q/p, t)^T$ from initial guess and series of measurements
- **prediction:** extrapolate previous best estimate x_{k-1} to the next layer

$$\vec{x_k} = F_k \vec{x}_{k-1} + B_k \vec{u}_k, \qquad P_k = F_k P_{k-1} F_k^T + Q_k$$

  where the state-transition model F_k is the solution of the equations of motion,
  and the external influences $\vec{u}_k$ and process noise Q_k include e.g. multiple scattering

- **update:** weighted average of predicted state $(\vec{x_k}, P_k)$ and new measurement $(\vec{z_k}, R_k)$
  with more weight being given to estimates with greater certainty

$$\vec{x_k}' = (1 - K H_k)\, \vec{x_k} + K \vec{z_k}, \qquad P_k' = P_k - K H_k P_k$$

  where the Kalman gain $K = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1}$ is the weight given to measurement/prediction,
  and H_k maps the state vector to the measurement space