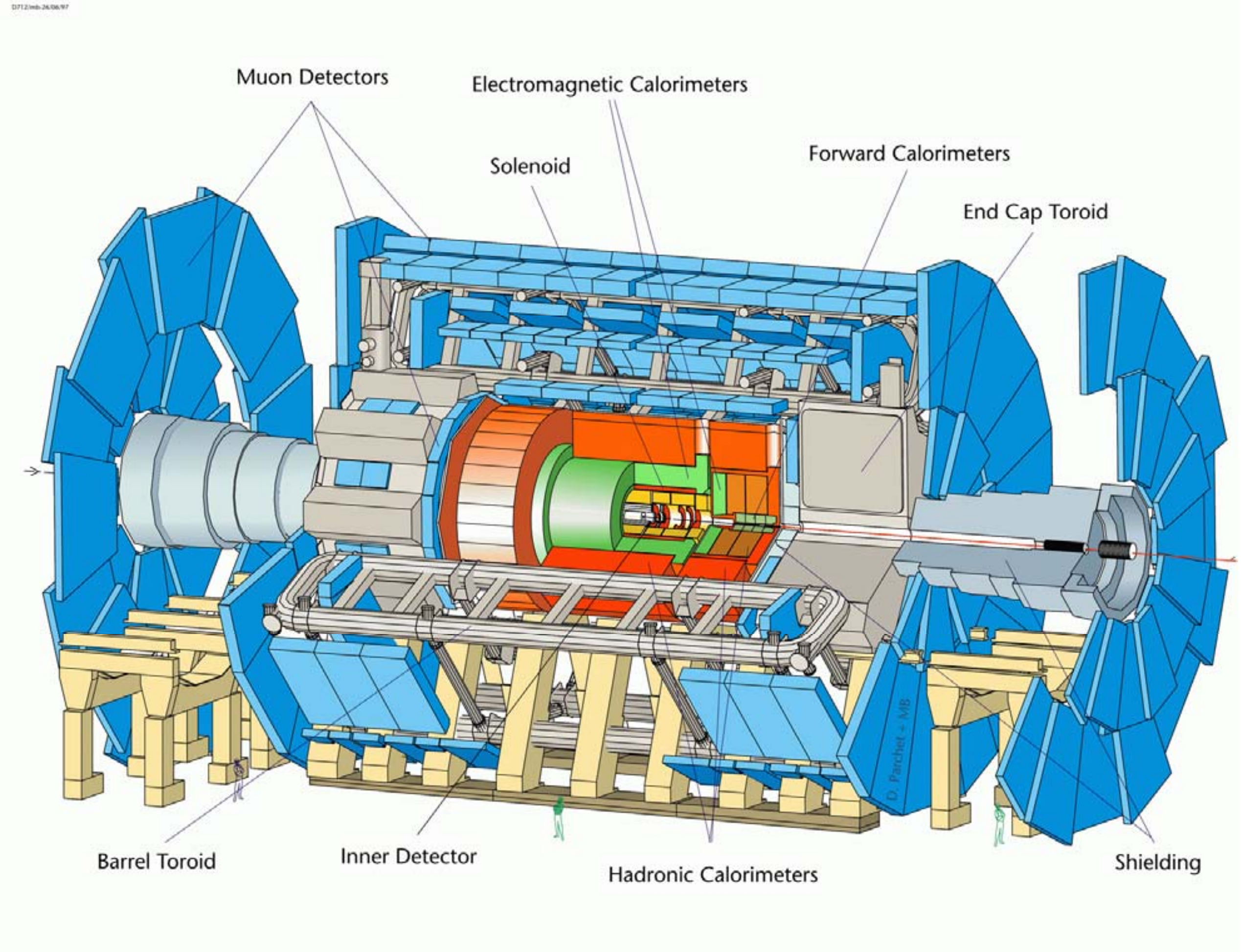
Tracking at ATLAS and an Introduction to STEP

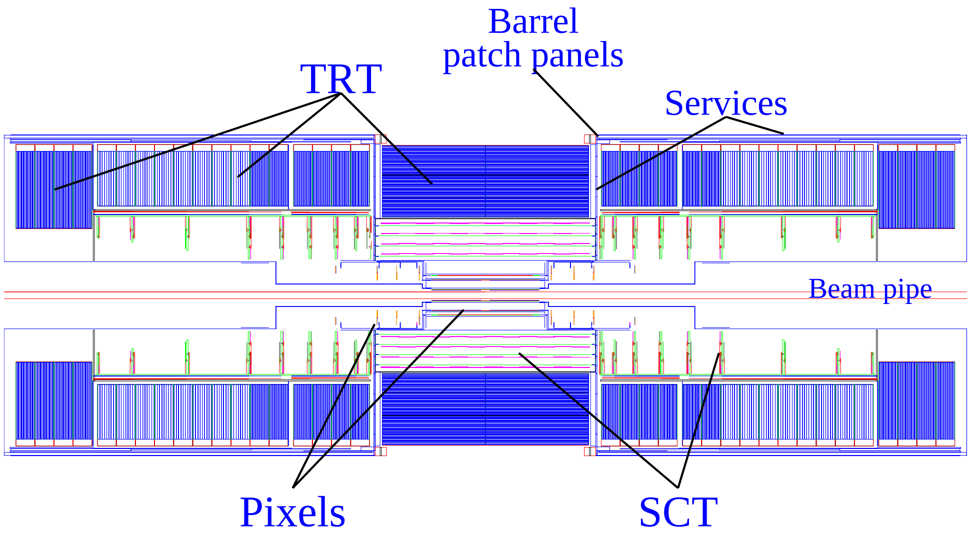
Esben Lund, University of Oslo

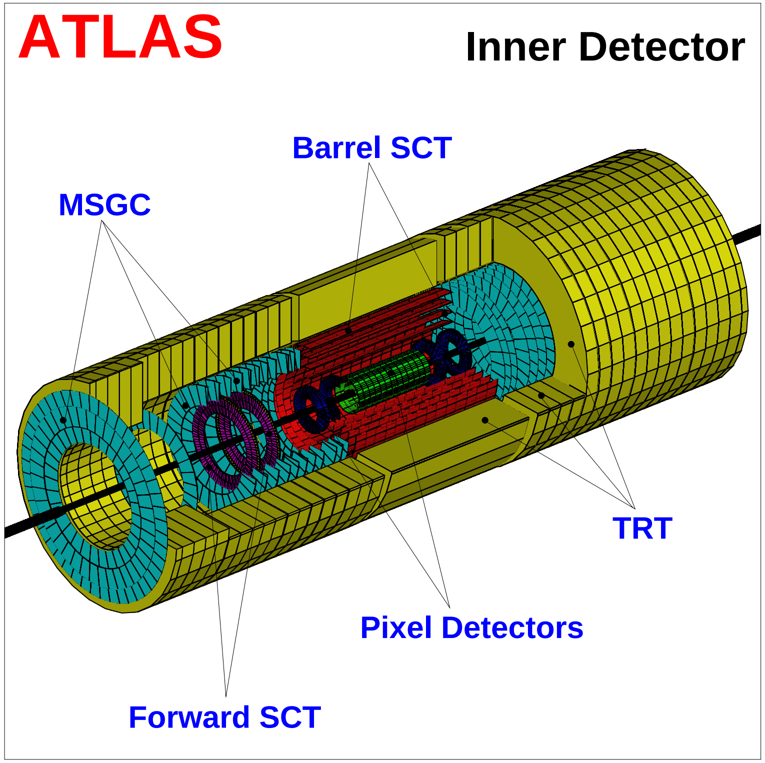
The ATLAS Detector



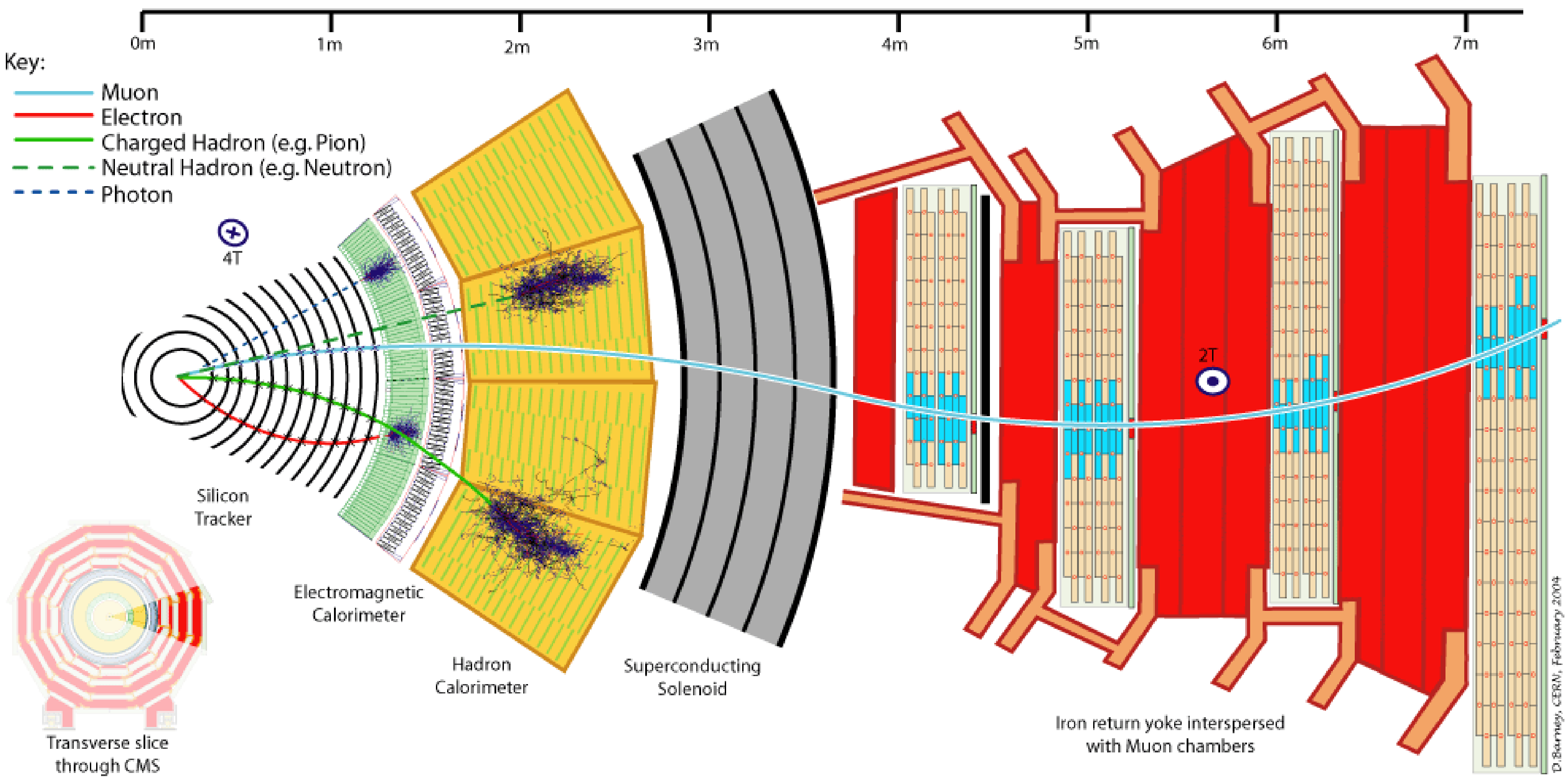
The ATLAS Inner Detector

- This is where most of the tracking happens.
- High resolution is necessary to separate tracks.



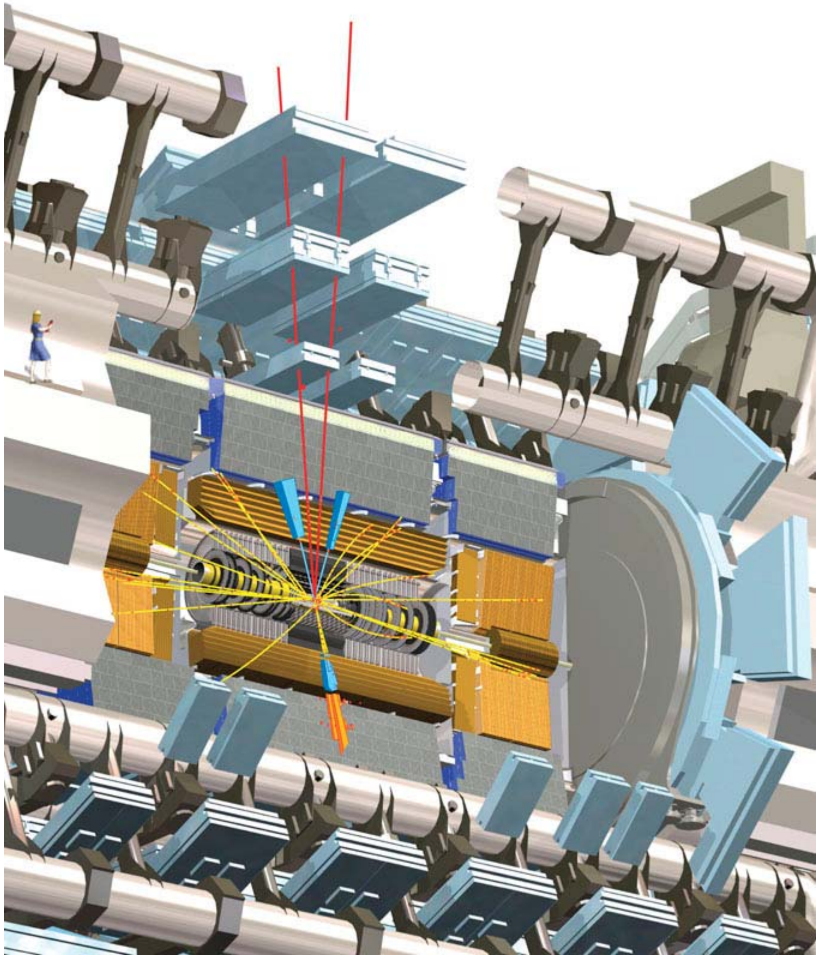


Typical Tracks at CMS (and ATLAS)



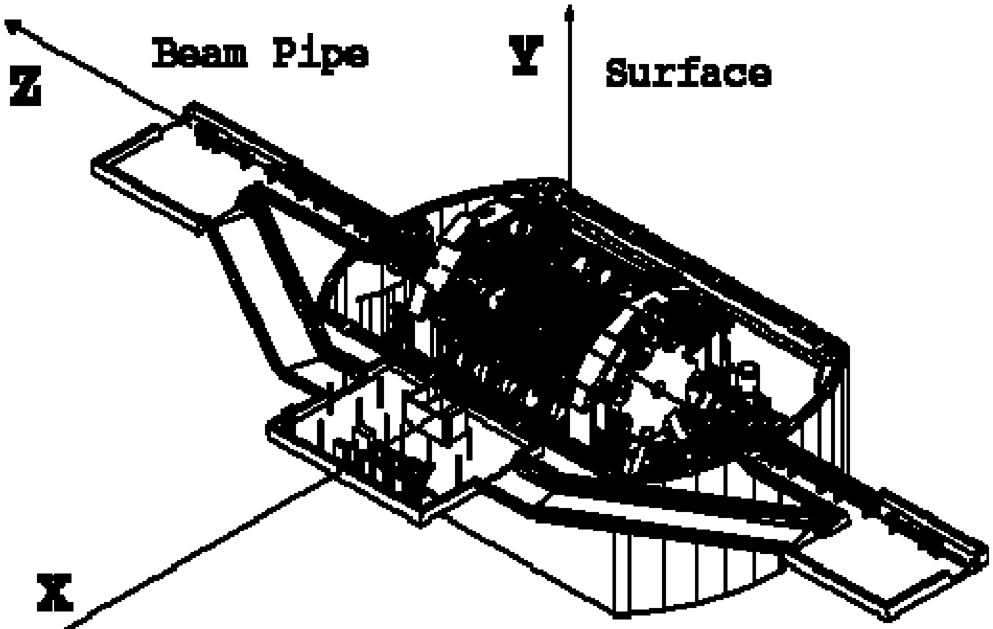
Simulated Higgs Event

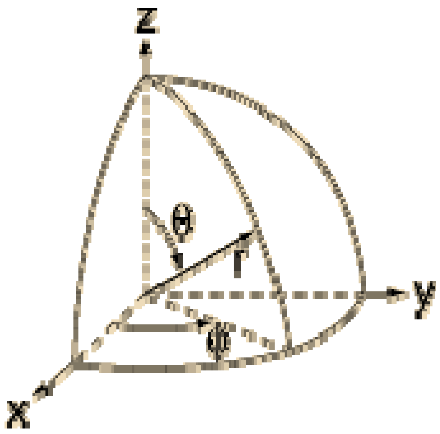
- Simulated Higgs to ZZ event where one Z goes to e+e-, and the other Z goes to μ+μ- and a girl in a blue dress.



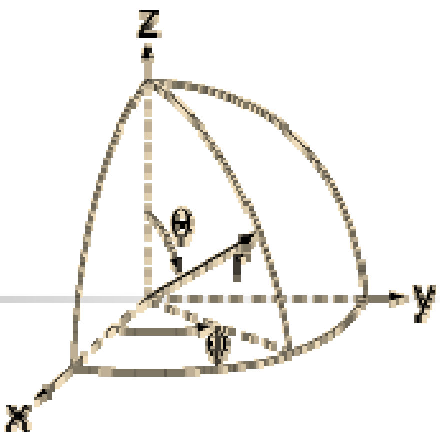
The ATLAS Coordinate System

- This is a right handed XYZ coordinate system defined by the beampipe, the centre of the LHC tunnel and the surface.

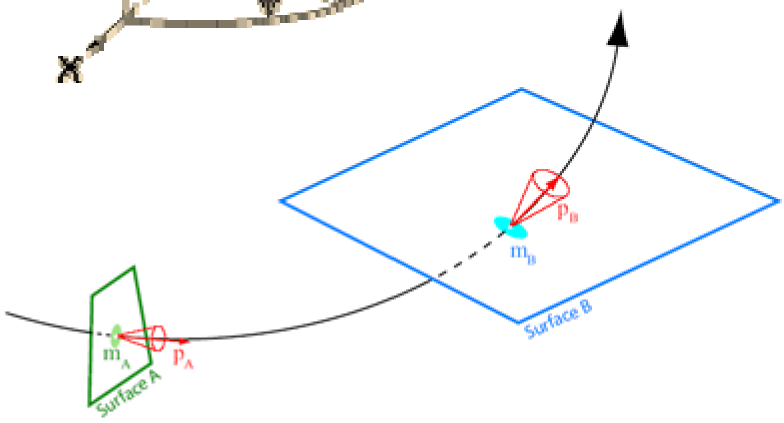




Track Parameters



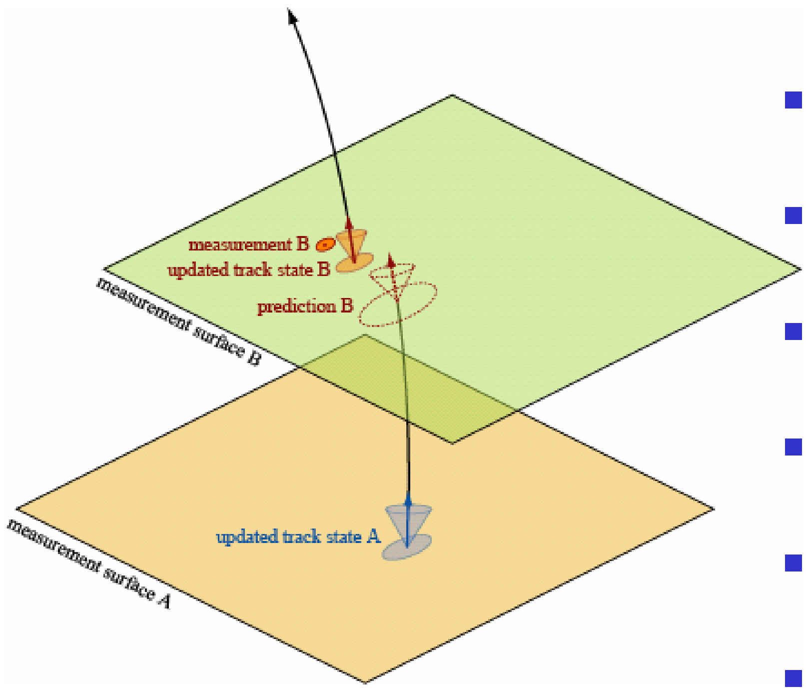
- To reconstruct tracks we need to agree on a common set of track parameters.
- Since our track measurements are always done in some known part of the detector it is useful to recycle this information.
- Tracks are defined by two local positions on a plane or a line, corresponding to some active part of the detector.
- In addition, tracks have two globally defined angles, the azimuthal angle ϕ, and the polar angle θ. ϕ is the projection angle into the x-y plane, and θ is the angle between the track and z-axis (beam).
- Finally, tracks have momentum and charge, q/p.



Full set of track parameters

$$\begin{pmatrix} x_1 \\ x_2 \\ \varphi \\ \theta \\ q/p \end{pmatrix} \quad \begin{pmatrix} \sigma_1 & c_{21} & c_{31} & c_{41} & c_{51} \\ c_{12} & \sigma_2 & c_{32} & c_{42} & c_{52} \\ c_{13} & c_{23} & \sigma_3 & c_{43} & c_{53} \\ c_{14} & c_{24} & c_{34} & \sigma_4 & c_{54} \\ c_{15} & c_{25} & c_{35} & c_{45} & \sigma_5 \end{pmatrix}$$

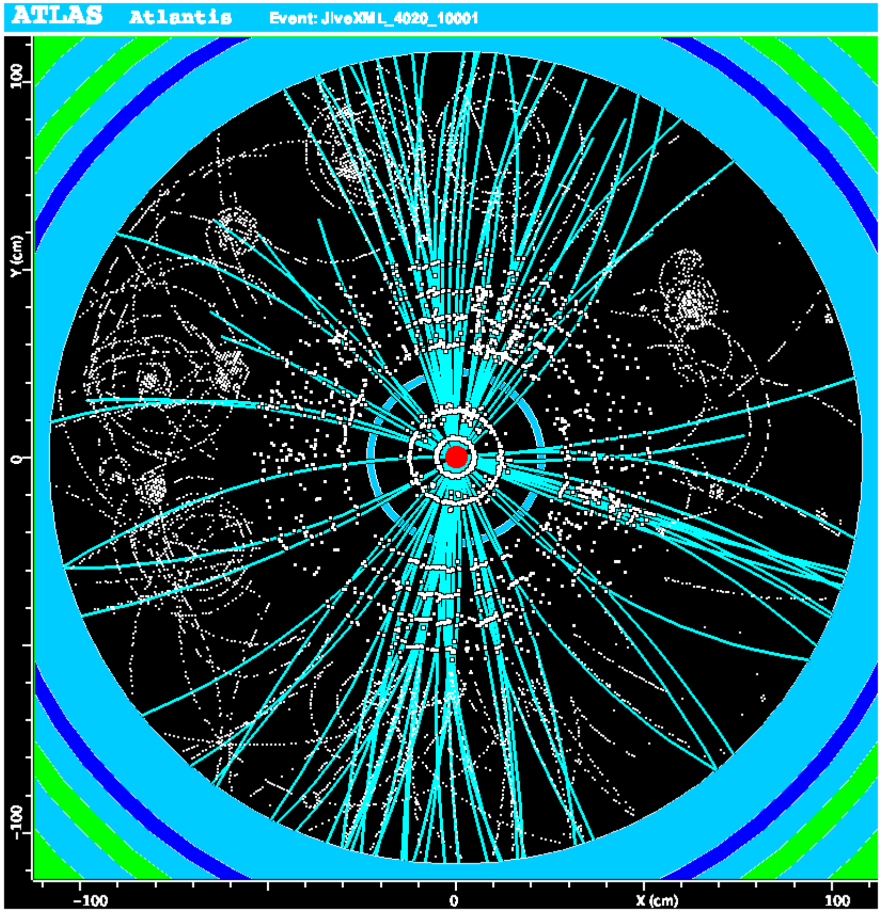
Track Fitting with a Kalman Filter



- This method is the basis for track fitting in much of the ATLAS tracking.
- Track fitting produces a number, the chi-square, indicating the quality of the track.
- The Kalman filter starts with a track state on a measurement surface A.
- It then predicts the intersection with the next measurement surface B along the track.
- The measurement on surface B is used to update the predicted state.
- This method does not involve big matrix inversions, and material effects are easily included.
- Measurements close to the predictions lowers the chi-square of the fit, indicating a well understood track.

Track Finding in Pixel and SCT

- The track finding starts by doing a fast scan to locate the z-vertex.
- Then all linear combinations of detector measurements in the three pixel layers, pointing back to the z-vertex, are created.
- For every of these initial track seeds a road is built through the SCT layers.
- In every SCT layer crossed by this road, the closest measurement is included into the track. In case of no close measurements a hole in the track is registered.



Track Resolving

- The track finding leaves us with a lot of track candidates, many sharing detector hits.
- The track resolver decides which tracks to keep.
- It starts by ranking tracks according to their number of hits, holes and the chi-square of their fit. Tracks with many hits, few holes and a low chi-square are preferred.
- If several tracks contain the same hits only the highest scoring track is kept.
- When tracks are removed, their hits are free to be included in the next round of track finding.
- Track finding and resolving is an iterative procedure repeated until no good tracks are found anymore.

Extending Tracks Beyond the SCT

- After finding and resolving tracks they are extended into the TRT part of the inner detector, and new fits are done.
- Muon tracks are reconstructed separately in the muon spectrometer before being connected to track segments in the inner detector.

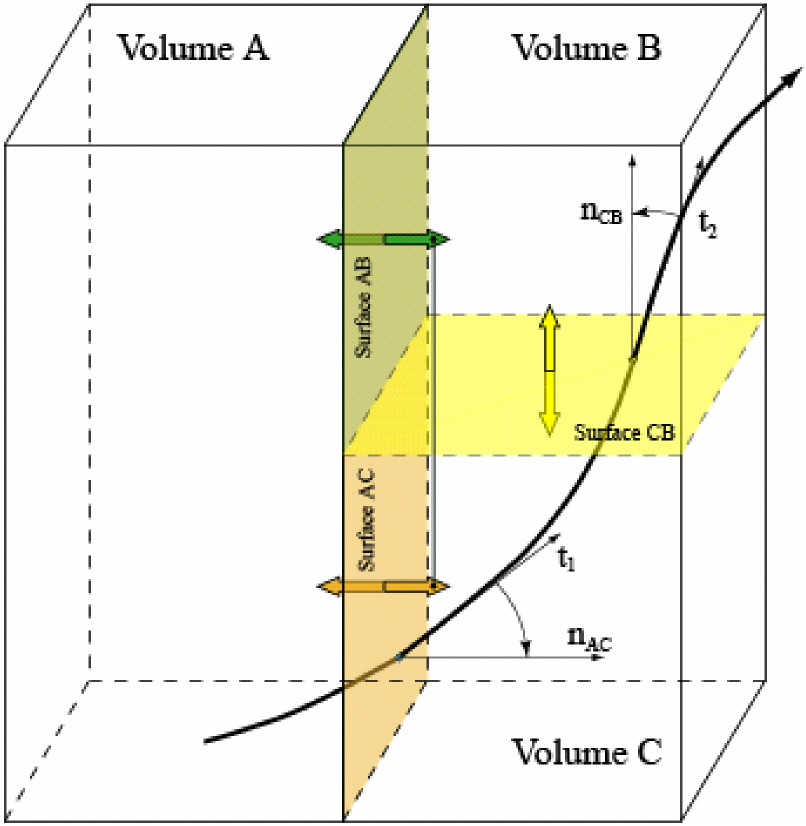
- Many competing tracking algorithms:
  - **Inner detector:** XKalman, iPatRec, NewTracking
  - **Muon spectrometer:** Muonboy, Moore, NewTracking
  - **Combined reconstruction:** STACO, MuID, globalChi2Fitter, NewTracking

Problems with Existing Tracking

- Having many competing methods of tracking is nice for comparing and testing, but it increases the complexity of the event data model, slowing things down and bloating the reconstructed data.
- The current algorithms are limited to parts of the detector, tracking is not done consistently through the whole detector. Segments from the inner detector and muon spectrometer are just fitted in the end.

- NewTracking is a new approach to solve these problems:
  - All algorithms should share a common interface and one event data model to simplify things and save space.
  - Algorithms should be split into smaller parts. This opens the possible to change or fix parts of the reconstruction chain without disturbing the rest.
  - The number of algorithms should be limited to reduce maintainance.

Main Ideas of the NewTracking



- Split the detector into simplified volumes and layers. Similar to Geant4 but less detailed.
- Create a propagator that tranports track parameters and covariance matrices through these volumes, taking material effects into account. This is the STEP propagator.
- Create a navigator to guide the track through the geometry.
- Everything is finished except from parts of the calorimeter and muon geometry.

The STEP Propagator

- Short for Simultaneous Track and Error Propagation.
- Programmed and tested by the EPF group at UiO.
- Used for estimating the most likely path of a particle through the detector given an initial set of track parameters.
- In a Kalman filter STEP is used for predicting the intersection with the next measurement surface.
- The covariance matrix (errors) is propagated together with the track parameters.
- Energy loss (ionization and bremsstrahlung) is included in the track and error propagation.
- Multiple scattering is included in the error propagation.

The Equation of Motion

- The core of the propagator is very simple and well known, this is the Lorentz force:

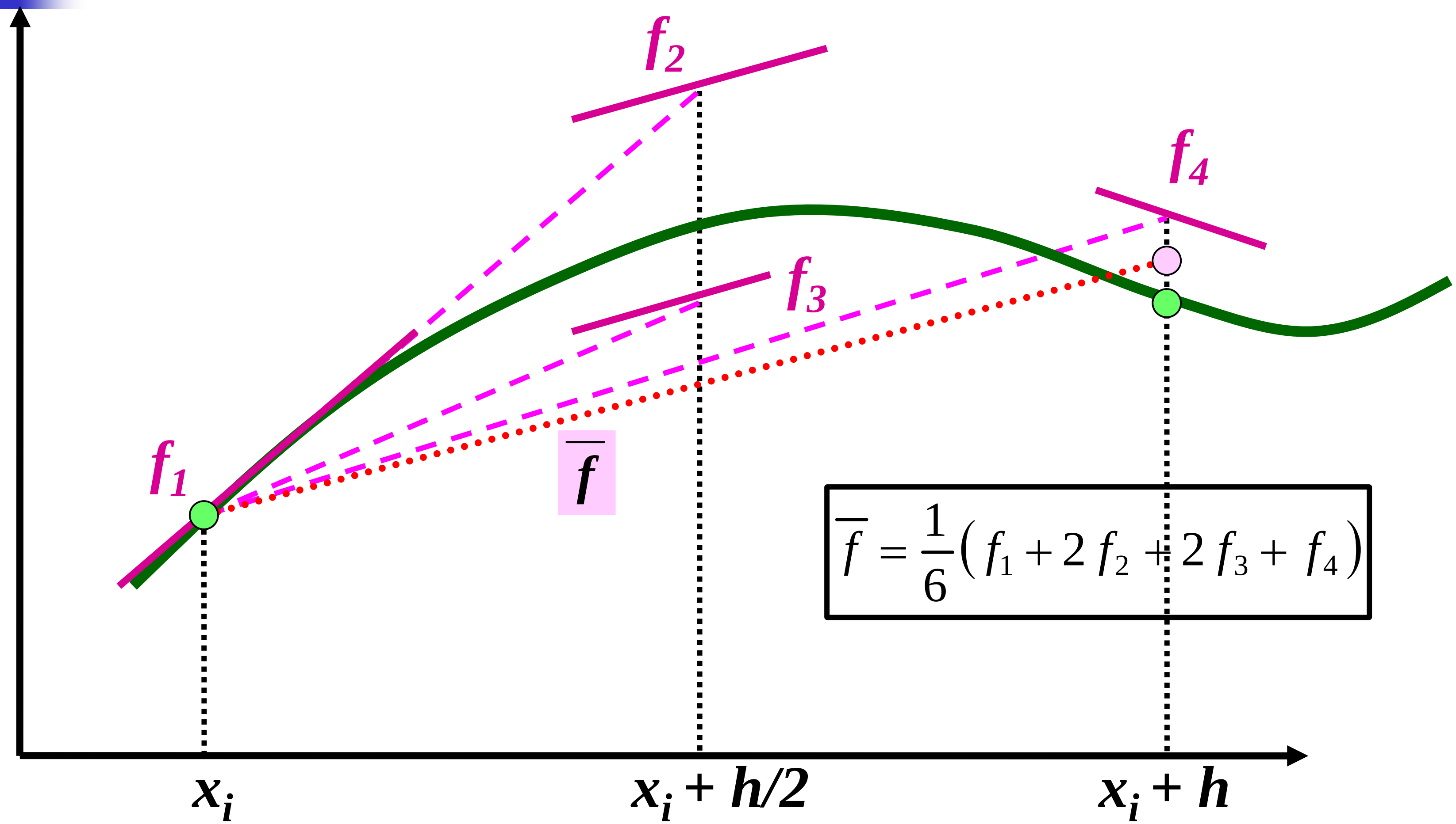
$$\frac{d^2\vec{r}}{ds^2} = \frac{q}{p}\left(\frac{d\vec{r}}{ds} \times \vec{B}\right) = \lambda(\vec{T} \times \vec{B})$$

- Where T is the normalized tangent vector to the track, B is the magnetic field and s is the arc length.
- The bending power of electrical fields is ignorable.
- The above formula is given in the curvilinear coordinate system defined by the direction of the track at all times.
- The curvilinear system allows looping tracks.

Integrating the Equation of Motion

- The equation of motion gives us the acceleration of the particle along the track.
- What we see in the tracker are the positions of the track, so we need to integrate the equation of motion twice to go from acceleration to speed to position.
- In a homogenous magnetic field this integration can be done analytically.
- In an inhomogenous field (like ATLAS) this integration has to be done numerically.
- There are many ways of numerical integration, but the Runge-Kutta-Nystrøm method has proven to be very well suited in this case.

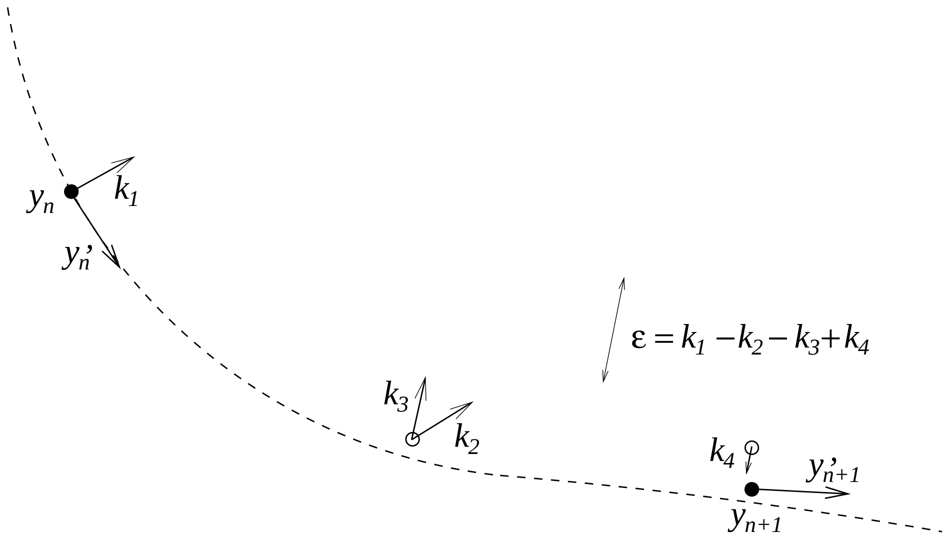
One Runge-Kutta Step



$$\bar{f} = \frac{1}{6}\left(f_1 + 2f_2 + 2f_3 + f_4\right)$$

Adaptive Integration

- The accuracy of the integration is decided by the step length.
- Shorter steps increase the accuracy.
- To guarantee a minimum accuracy we have to adjust the step length during the integration.
- The adjusted step length is decided by the error estimate, ε, and the tolerance, τ.
- The tolerance is the user defined error tolerance of each step. Lower tolerance equals higher accuracy.



Adjusting the Step Length

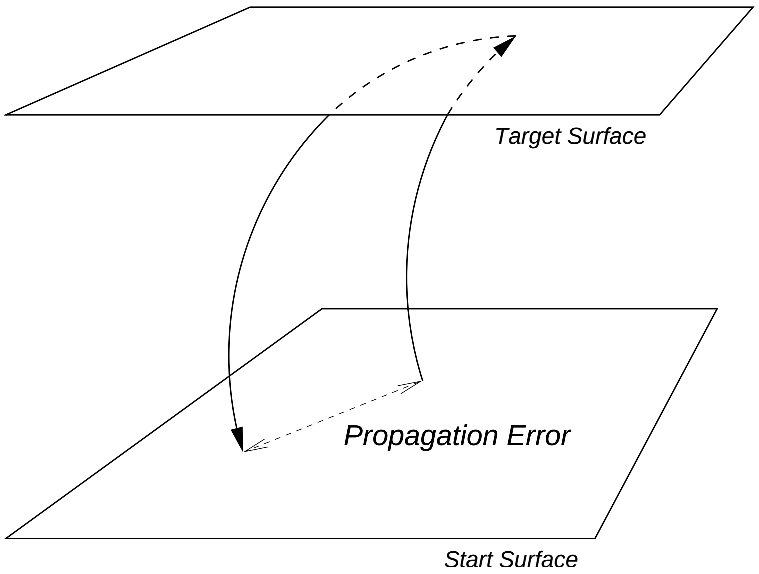
- Given the current step length, h_n, tolerance, τ, and error estimate, ε, the new step length, h_{n+1}, becomes,

$$h_{n+1} = h_n \left(\frac{\tau}{|\epsilon|} \right)^{\frac{1}{4}}$$

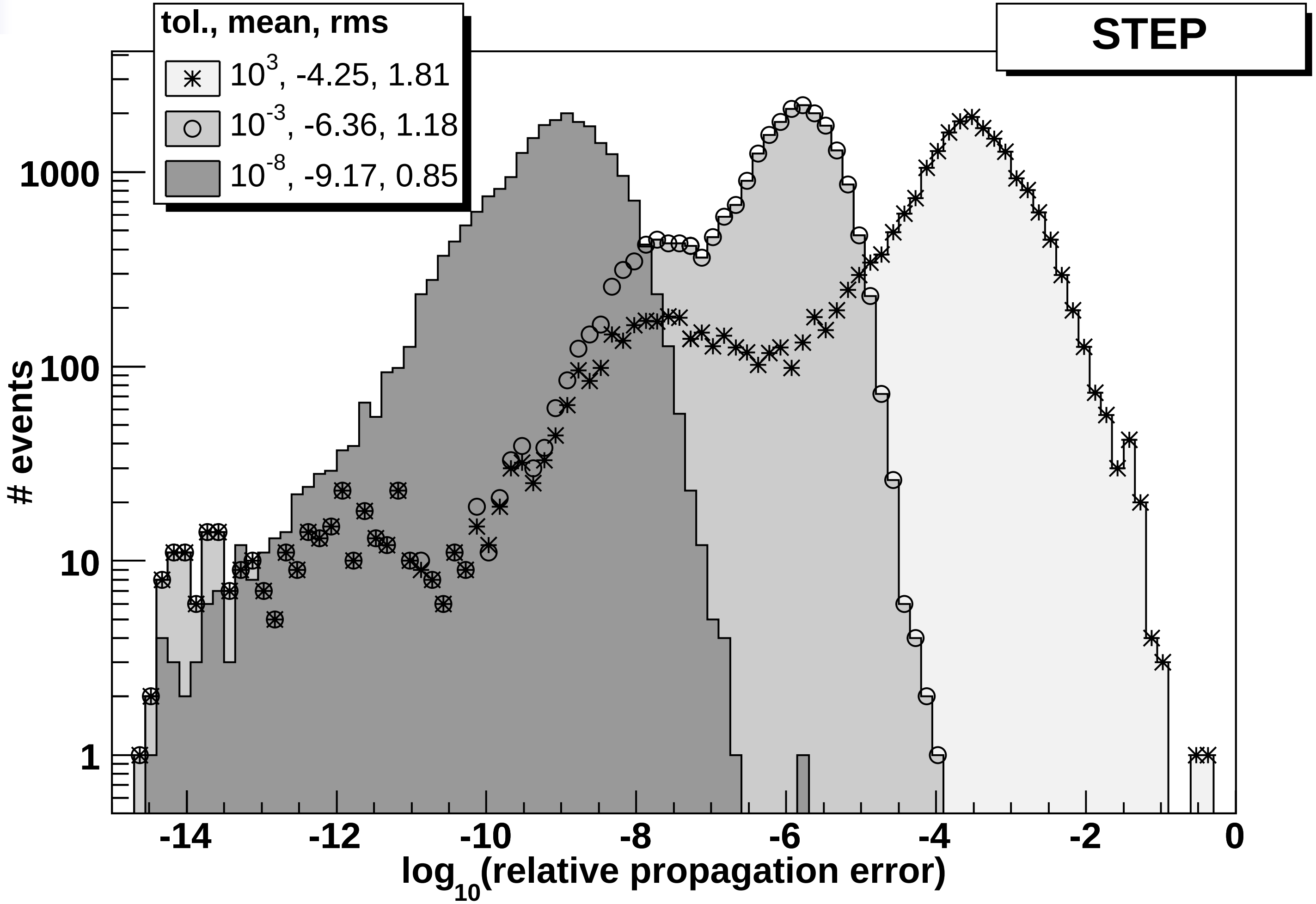
- The core of this expression is the fraction $\tau/|\varepsilon|$.
- If the error is lower than the tolerance, this fraction becomes bigger than one, increasing the step length and lowering the accuracy.
- If the error is bigger than the tolerance, this fraction becomes smaller than one, shortening the step length and increasing the accuracy.
- In this way the accuracy is matched to the tolerance set by the user.

Validating the Parameter Propagation

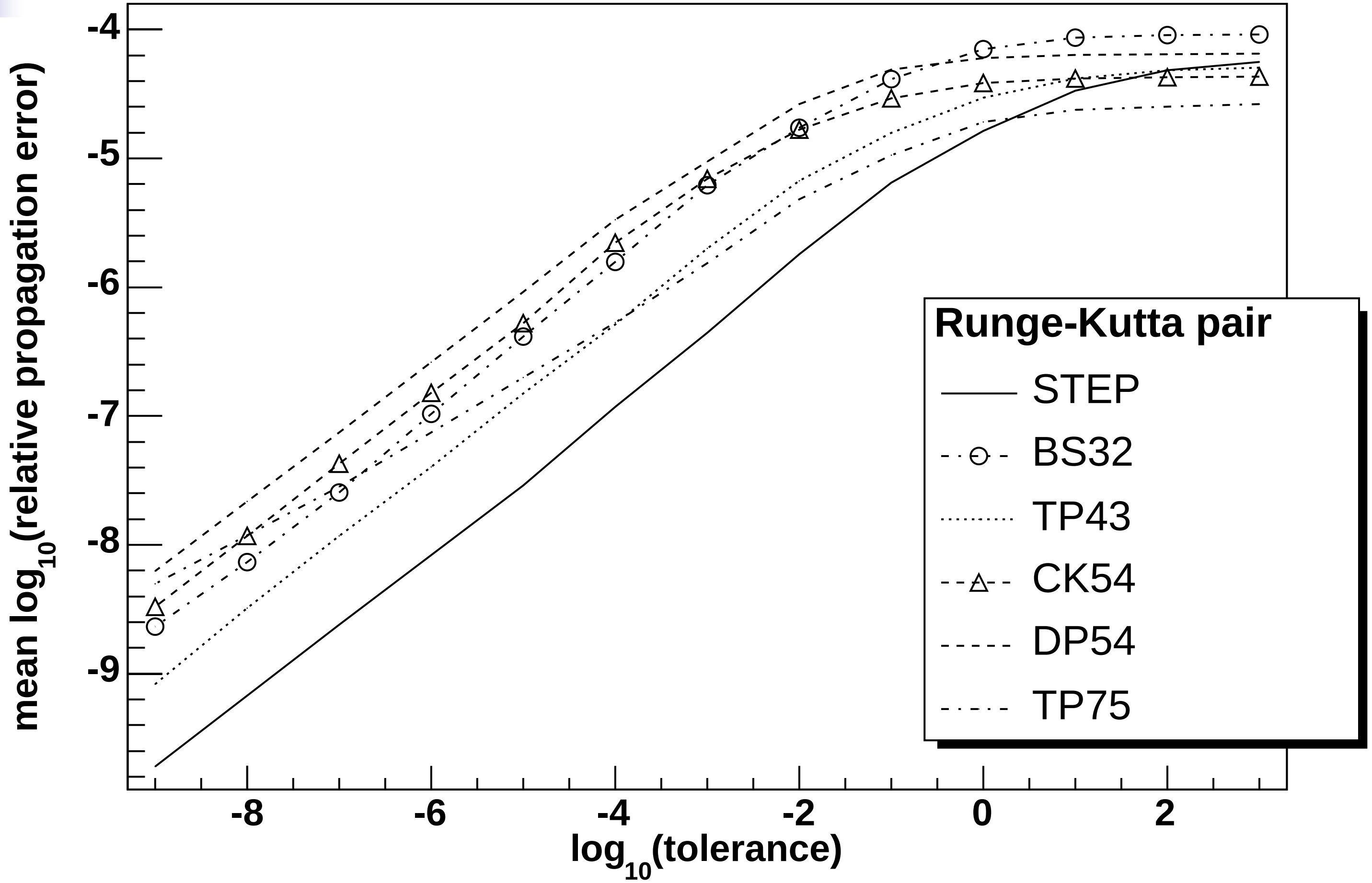
- To test the propagation we set up a randomly placed target surface in the ATLAS magnetic field.
- We then send a track with random charge, direction and momentum (between 0.5 and 500 GeV) from the center of the detector towards the target surface.
- In case of a hit the particle is sent straight back towards the start surface.
- The *relative propagation error* is defined as the distance between the initial track position and the final track position divided by the total path length back and forth.



Error Distributions at Three Tolerances for 50000 Tracks



Mean Relative Propagation Errors



Efficiencies Relative to STEP