HEPHY

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# The Kalman Alignment Algorithm

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# Outline

- Motivation
- The Kalman Alignment Algorithm (KAA)
  - basic functionality and formulae
  - application to big systems: restricted updates
- Alignment studies
  - Monte Carlo studies with the full CMS Tracker
  - cosmic ray studies at the Tracker Integration Facility
- Current status and outlook

# Motivation

- When people started thinking about aligning the CMS Tracker it became obvious that this was not a trivial task.
- People realized that conventional approaches might face serious problems:
  - computing times
  - memory
  - stability
- The KAA was specifically designed to circumvent these problems.
- Starting from a basic idea, overcoming problems arising from conceptual details, the algorithm is now working properly and is well understood.

# Basic functionality

- The particle tracks are processed one-by-one using a specialized Kalman filter:
  - use a global track-model that parameterizes all measurements
  - track-model depends not only on the (ideal) track parameters but also the alignment constants
  - estimate and update alignment parameters and their full variance-covariance matrix at every step (Kalman filter update)
- Method accounts for all statistical correlations between the individual measurements (hits) due to multiple scattering
  - off-diagonal terms in the variance-covariance matrix of the measurements
- Method accounts for the geometrical (statistical) correlations between all detector modules
  - update is not restricted to detector modules hit by current track

# Basic formulae

- The vector of all measurements $m$ depends via the track-model $f$ on the track parameters $q$ and the alignment constants $p$:

$$\vec{m} = \vec{f}\left(\vec{q},\vec{p}\right) + \vec{\varepsilon}, \quad \mathrm{cov}\left(\vec{\varepsilon}\right) = V$$

- The intrinsic detector resolution and multiple-scattering effects are accounted for in $V$, energy-loss effects (for high momentum muons) can be included into $f$.
- Using the Kalman filter formalism, update equations at step $k$ for the estimate on the alignment parameters $p_{k+1}$ can be derived:

$$\vec{p}_{k+1} = \vec{p}_k + K\left(\vec{m}_k - D_p\vec{p}_k - D_q\vec{q}_k + \vec{c}\right)$$

$$D_p = \partial\vec{f} \big/ \partial\vec{p}, \quad D_q = \partial\vec{f} \big/ \partial\vec{q}$$

- The matrix $K$ is the *gain matrix* of the Kalman filter.
- Formula for the variance-covariance matrix of $p_{k+1}$ follows from error propagation.
- By design, no inversions of large matrices required!

# Introduce new concept: restricted updates

- Problems for large systems (like the CMS Tracker):
  - Non negligible IO overhead due to reading and writing of the alignment parameters and their full variance-covariance matrix at every step.
  - Potentially large amount of virtual memory needed for storing the geometrical (statistical) correlations
- Proposed solution:
  - Update only those alignment parameters at each step that are significantly correlated
- Difficulties:
  - Need a-priori knowledge of which alignables should be included
  - Incomplete update can corrupt the full variance-covariance matrix, i.e. it might not be positive definite anymore

# Making the concept work …

- No general recipe available as how to deal with these two difficulties
- However, in the case of a track-based alignment it is possible to adapt the algorithm such that these issues pose no problem
  - by bookkeeping which alignables were hit by which tracks, one can make a good guess which alignables are significantly correlated
  - storing the statistical correlations instead of the covariance entries avoids inconsistencies
  - some more minor *tricks* …
- Needs tuning of a few *internal parameters* for a given geometrical setup
  - trade-off between precision and used memory and computing time

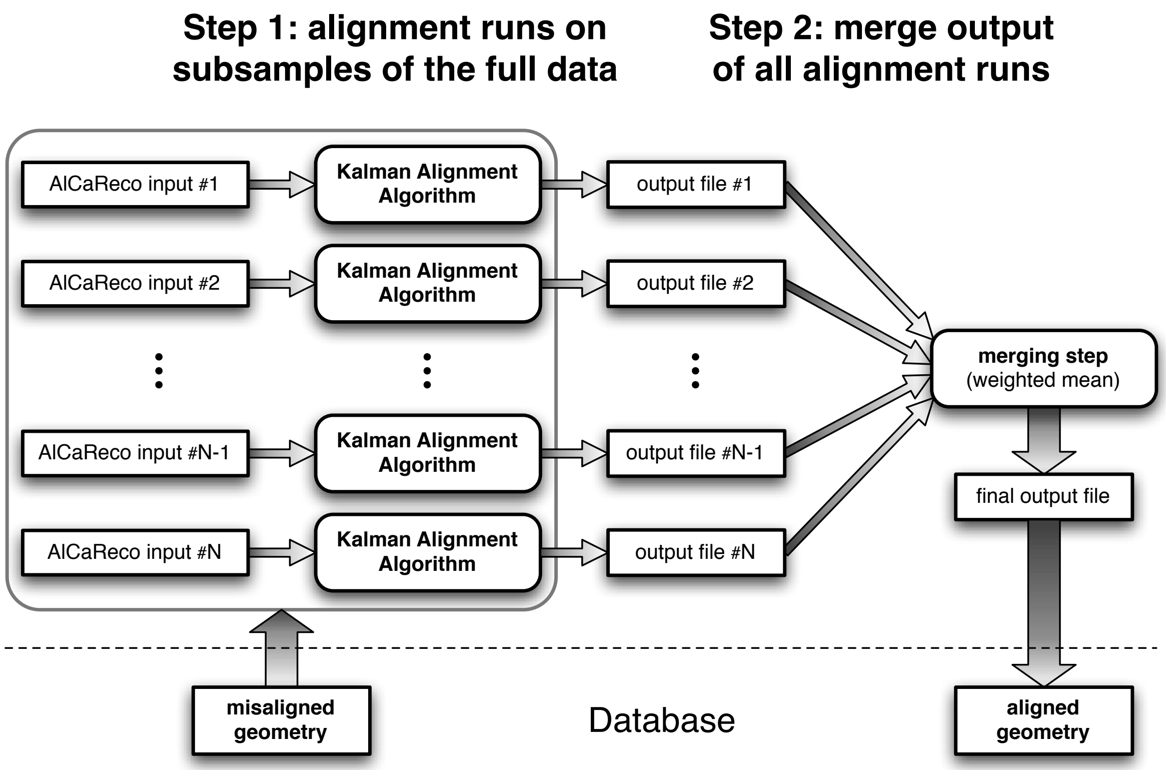
# Monte Carlo Alignment Studies

- Monte Carlo studies have been performed to prove that the algorithm is able to align the full CMS Tracker
- Realistic startup scenario:
  - realistic start-up conditions (initial misalignment, calibration, etc.)
  - skimmed data-samples from the *CMS Computing, Software and Analysis Challenge 2008* (CSA08)
  - using the resources from the *CERN Analysis Facility* (CAF)
    - limited amount of RAM (2GB per core)
    - used max. 10 cores parallel (*fair use*)
  - automated using a specialized production system (modified version of the *CMS MillePede Production System*)
- Results were computed within reasonable amounts of time and look good

# Alignment Strategy

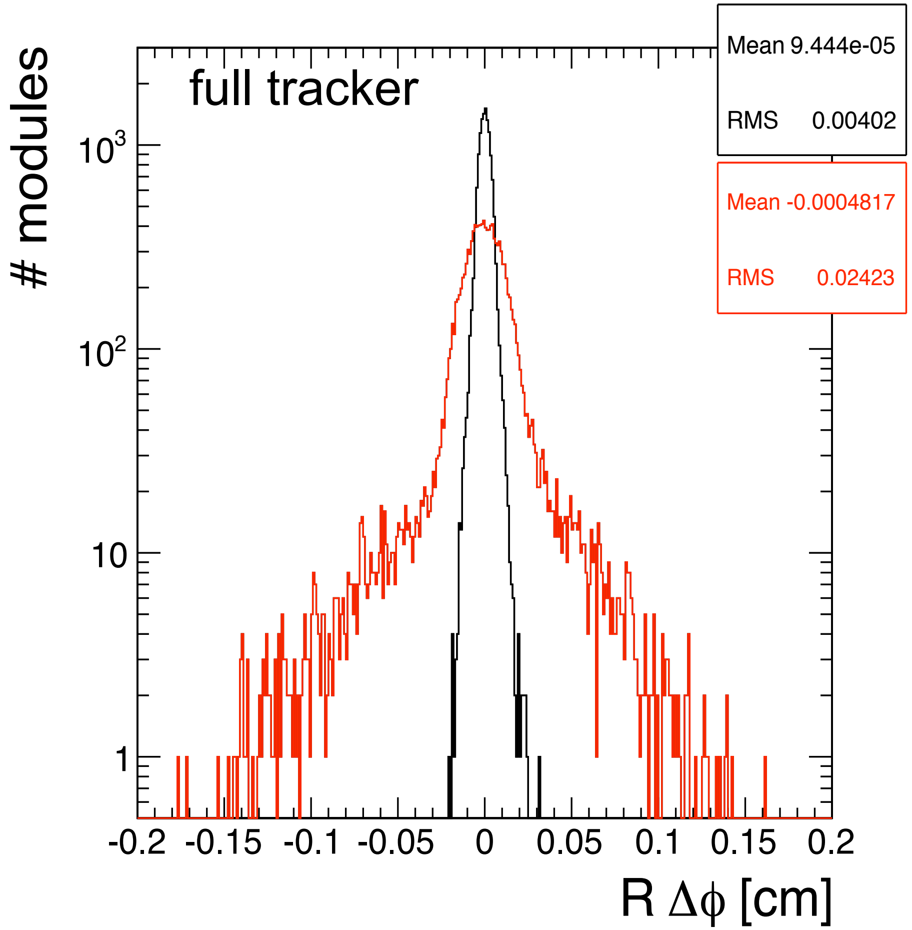
- Due to the constraint on virtual memory the CMS Tracker was aligned in three steps:
  - start with the outer silicon micro-strip tracker (*Tracker Outer Barrel*, *Tracker Endcaps*)
  - continue with the inner silicon micro-strip tracker (*Tracker Inner Barrel*, *Tracker Inner Disks*)
  - finish with the pixel tracker
- The first two steps were done using collision data and cosmic ray data
- The final step was done using additional $Z \to \mu^+\mu^-$ events
- Tuning of *internal parameters* was based on constraints regarding memory and computing time only
  - no feedback from comparison between the results and the MC-truth (which will obviously not be possible with real data)

# Workflow for a single alignment step




- KAA is completely implemented within the reconstruction and analysis software framework of CMS (*CMSSW*)
- Use CMS-specific data-skims for alignment and calibration tasks (*AlCaReco* format)

# Alignment with CMS Monte Carlo collision data (corresponding to the first 1 $pb^{-1}$)

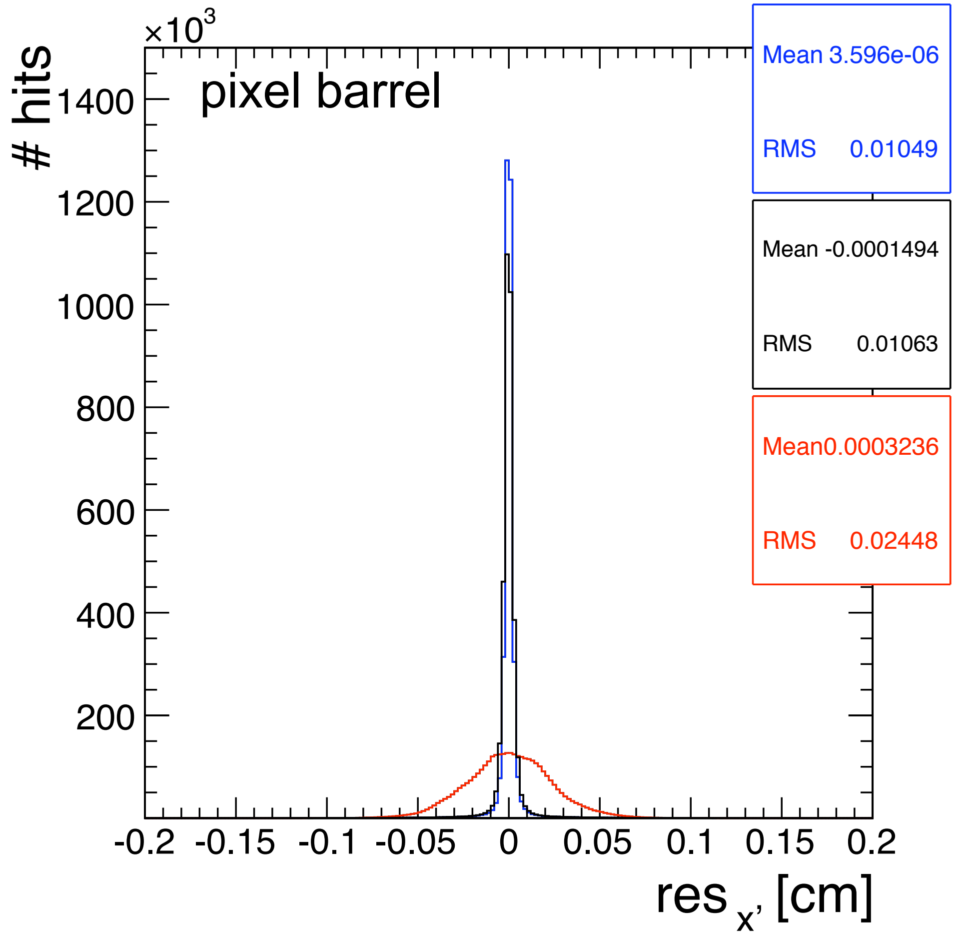



Red: misaligned geometry (startup)

Black: aligned geometry (1 $pb^{-1}$)

Overall precision of all detector modules in global $R\Delta\phi$ is 40 $\mu$m!

# Alignment with CMS Monte Carlo collision data (corresponding to the first 1 $pb^{-1}$)



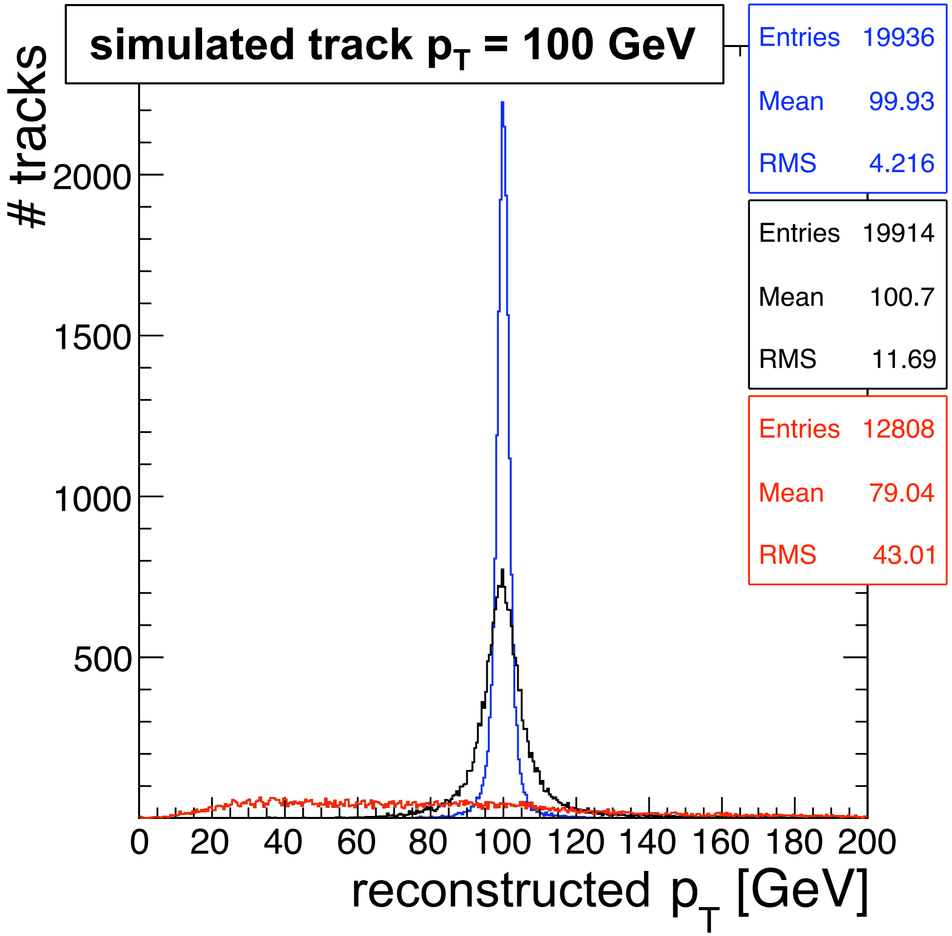

Red: misaligned geometry (startup)

Black: aligned geometry (1 $pb^{-1}$)

Blue: ideal geometry

Distinct improvement in the tracking residuals.

# Impact on track reconstruction



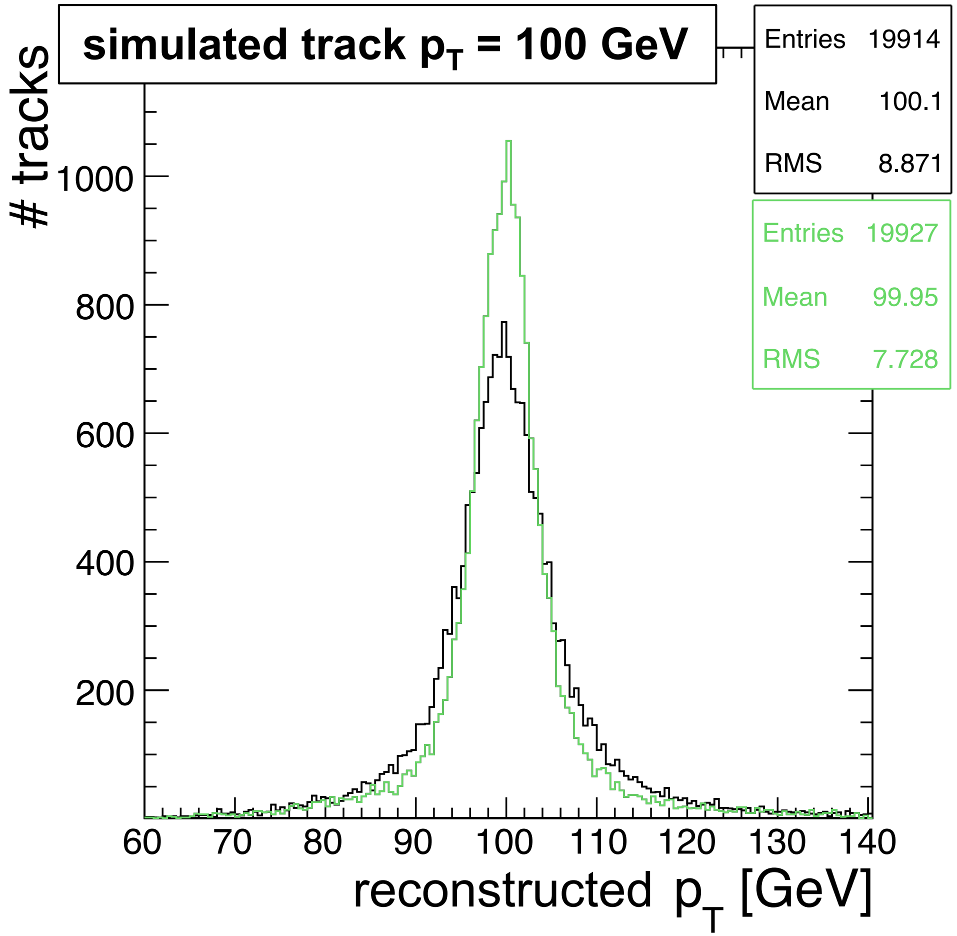

Red: misaligned geometry (startup)

Black: aligned geometry (1 $pb^{-1}$)

Blue: ideal geometry

Recovers the reconstruction performance to a great extent.

# Alignment with CMS Monte Carlo collision data (corresponding to the first 10 $pb^{-1}$)




Black: aligned geometry (1 $pb^{-1}$)

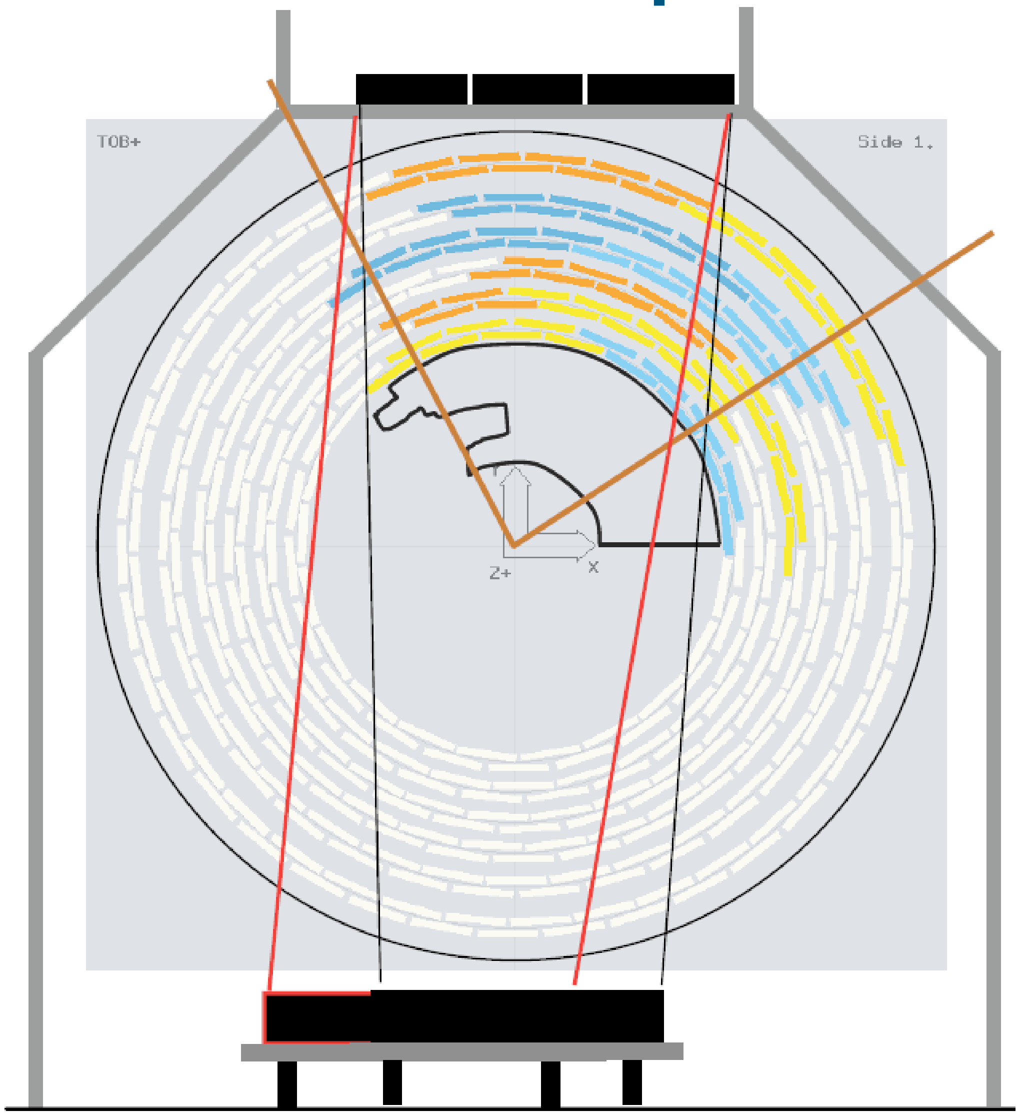
Green: aligned geometry (10 $pb^{-1}$)

Processing more high momentum tracks gives further improvements.

# Tracker Integration Facility

- The final assembly of the CMS silicon micro-strip tracker took place at a dedicated facility, referred to as the *Tracker Integration Facility*.
- The tracker has been operated at different temperatures, powering and reading out about 15% of all modules.
- Cosmic ray data has been recorded and used for track-based alignment.
- No magnetic field present, therefore no momentum estimate for individual tracks (and hence for effects due to multiple scattering)
- The results for the three different alignment algorithms used for the CMS tracker have been compared (HIP, MillePede, KAA).
- The quality assessment of the alignment objects was done by analyzing tracking residuals.

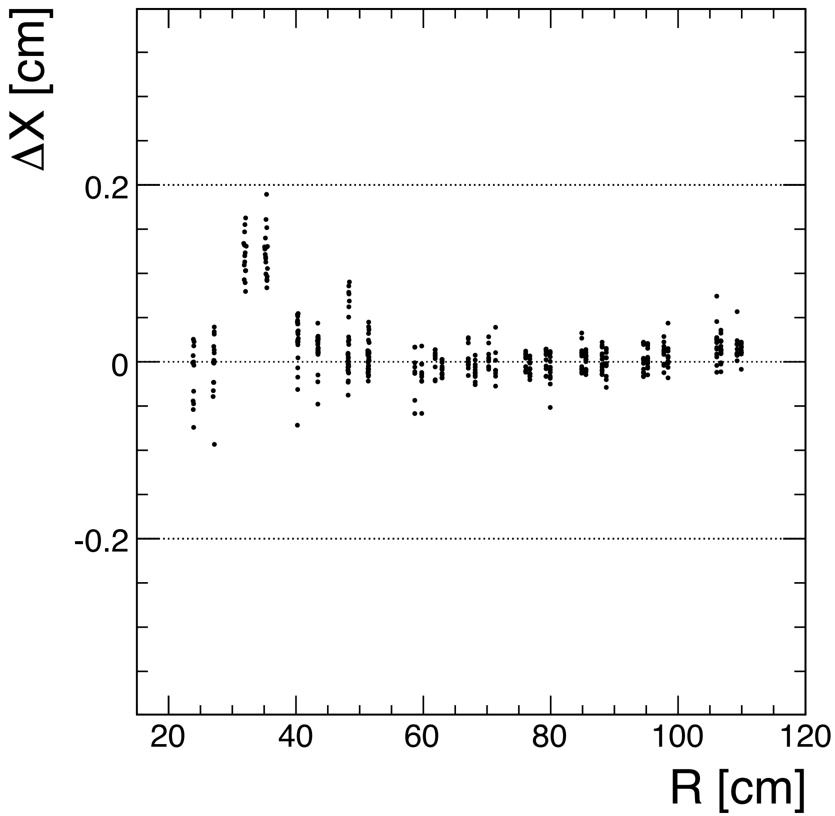
# TIF Setup

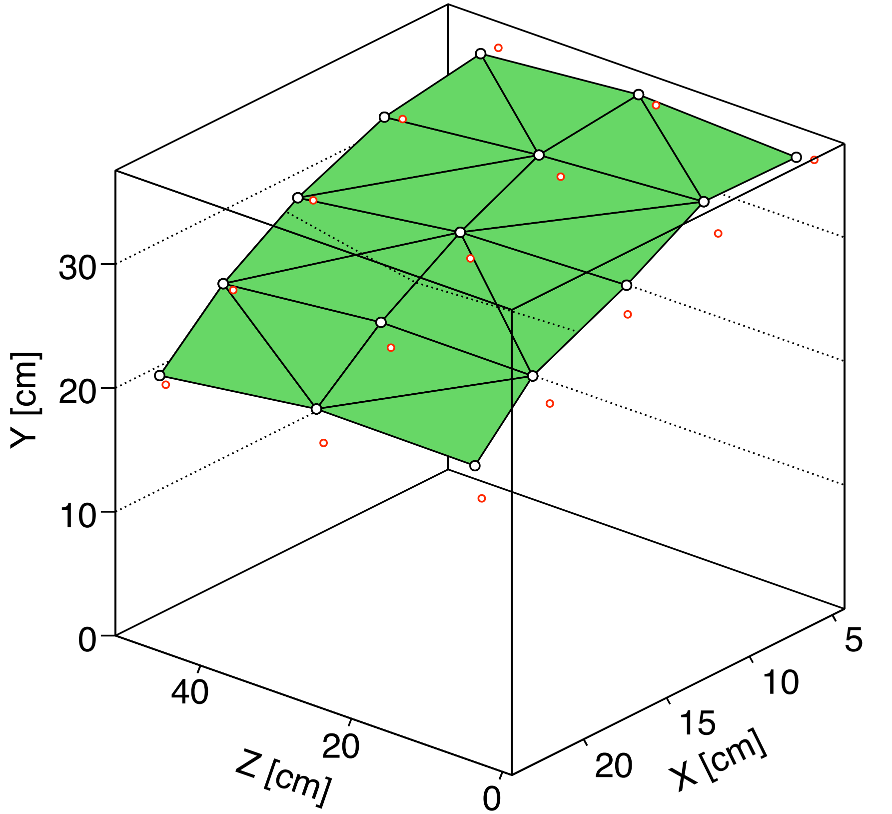


# Alignment Strategy

- A set of 430 detector modules in the barrel region has been chosen for alignment
  - relatively small number, hence the concept of *restricted updates* was not applied
  - same set for all three algorithms (comparability)
- Biggest data sample recorded at a single temperature has been processed
  - rules out possible effects due to different thermal expansion at different temperatures
  - approximately 70.000 well isolated cosmic particle tracks
  - same data sample for all three algorithms (comparability)

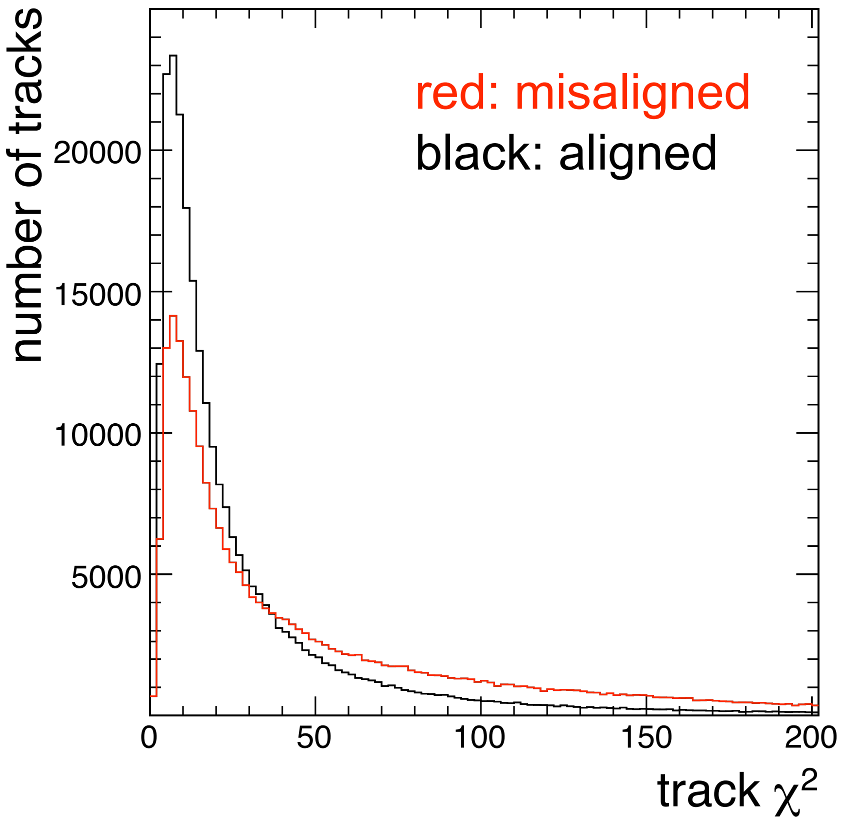
# Computed constants



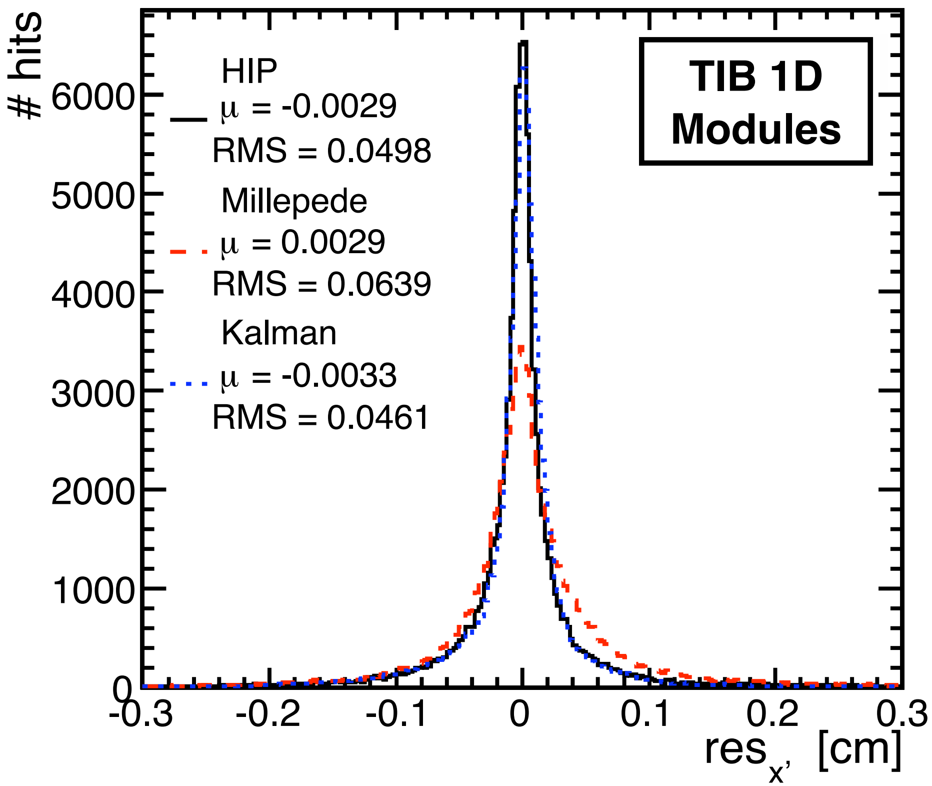

- Observed large deviations from the ideal geometry
- Due to deformations of the mechanical support structure on a larger scale

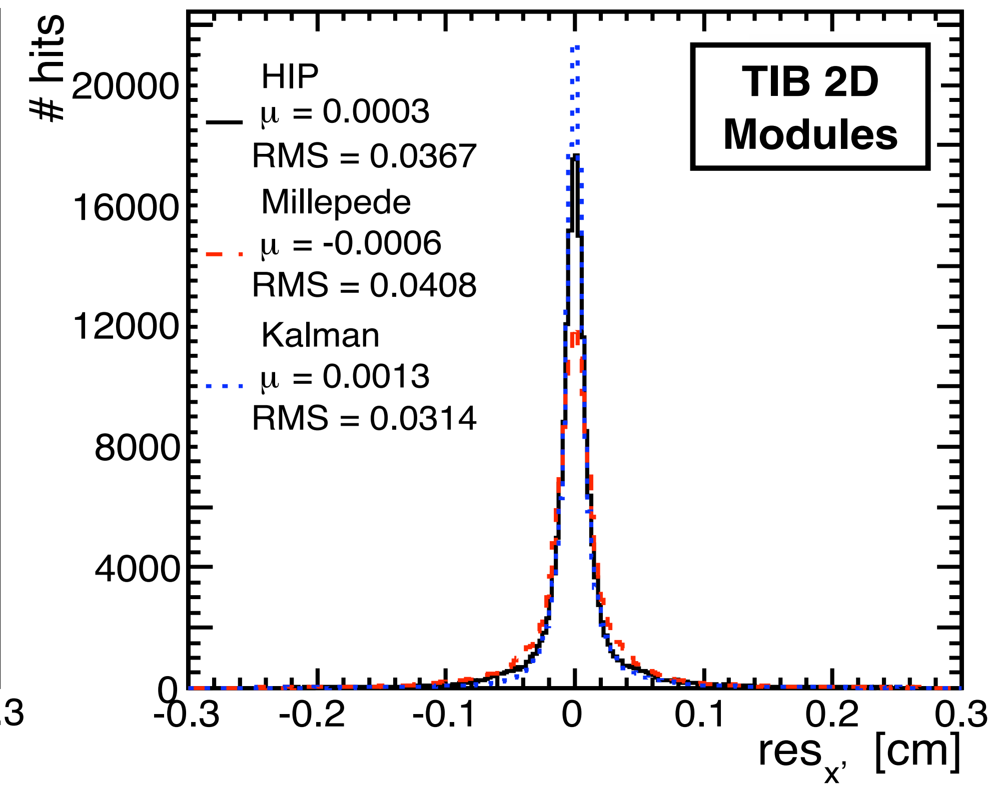
# Improvement of the tracking residuals




- Improved distribution of the track $\chi^2$
  - sum of the squared residuals, each normalized by the detector resolution (no uncertainties due to misalignment included)

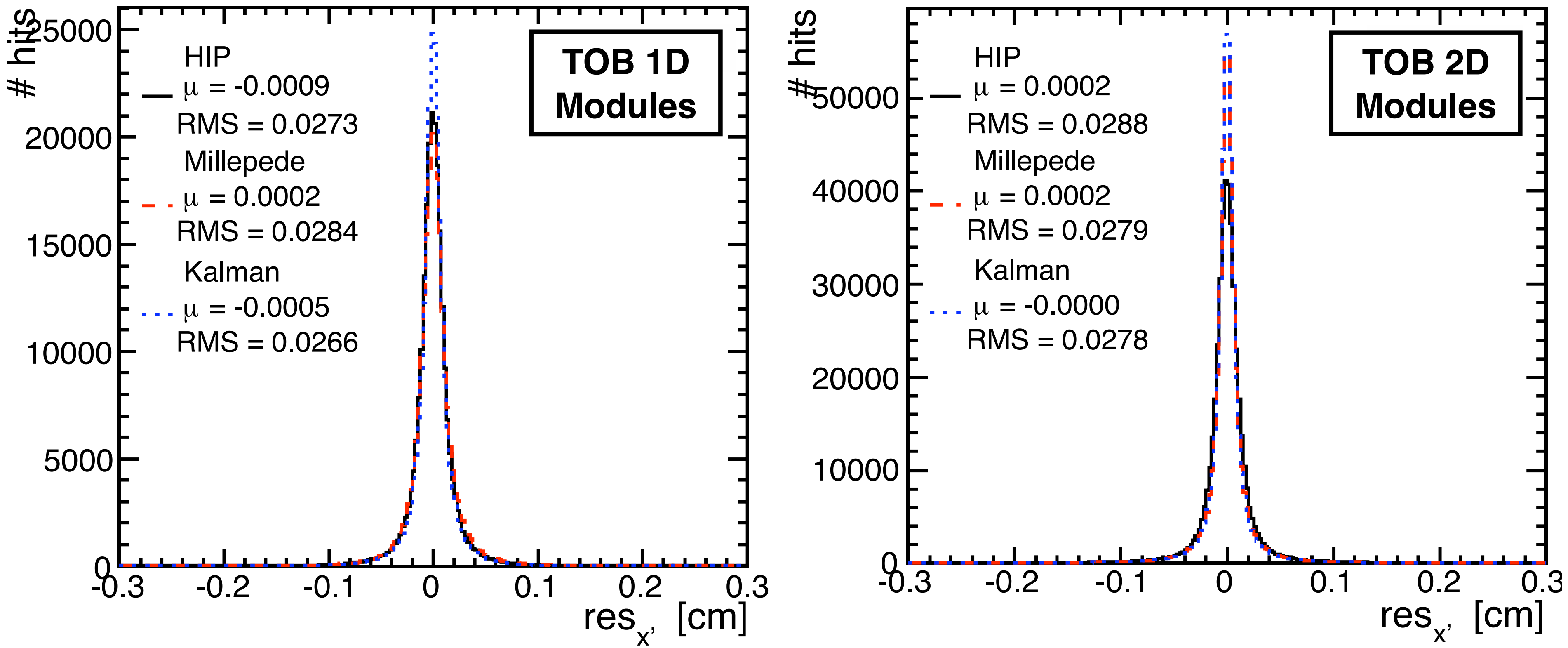
# Comparison of the tracking residuals (Tracker Inner Barrel)




Results of the three algorithms in good agreement

# Comparison of the tracking residuals (Tracker Outer Barrel)




Results of the three algorithms in good agreement

# Current status and outlook

- The KAA is a functional and well understood method.
- Results from detailed simulation studies show that the KAA is able to align the CMS Tracker – even under conditions expected during the LHC start-up phase.
- The associated computational effort can be kept at a reasonable level.
- For production, a dedicated production system is available.
- An analysis of the first experimental data from cosmic particle tracks, recorded at the Tracker Integration Facility, shows that the KAA is competitive to existing algorithms.
- The KAA will be used to analyze collision data in the future.