

Tracking stations alignment with Kalman tracks at LHCb.

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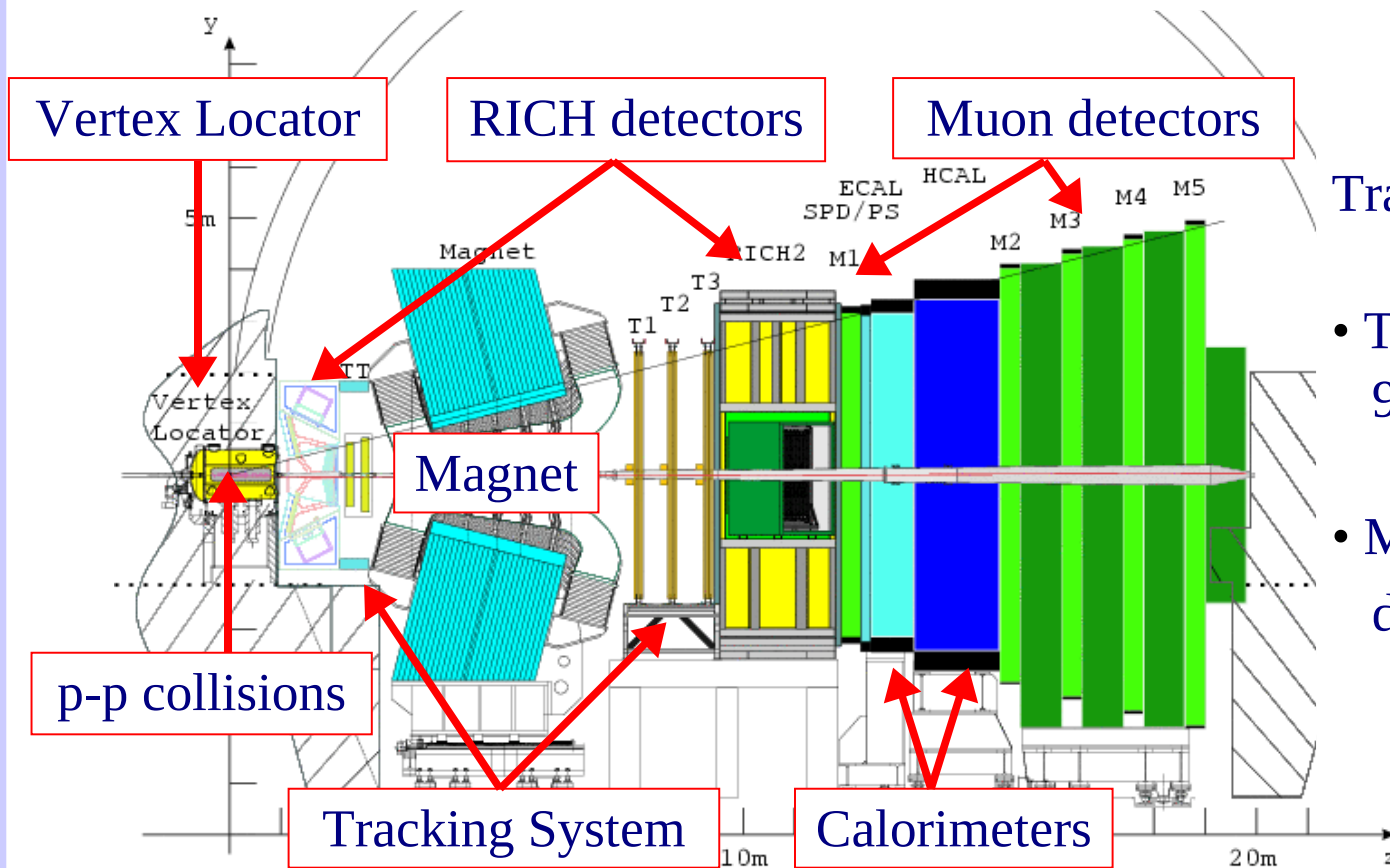
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- The LHCb detector and its tracking system.
- The alignment procedure and its maths.
- Alignment scenario using MC magnet-on data.
- A first glimpse at real data at LHC.
- Conclusions.

Overview of the *L*arge *H*adron *C*ollider *b*eauty detector:

- Forward arm spectrometer operated at the Large Hadron Collider.
- Luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.
- $10^{12} \text{ } b\bar{b}$ pairs / year in acceptance, b-production peaked in forward direction.

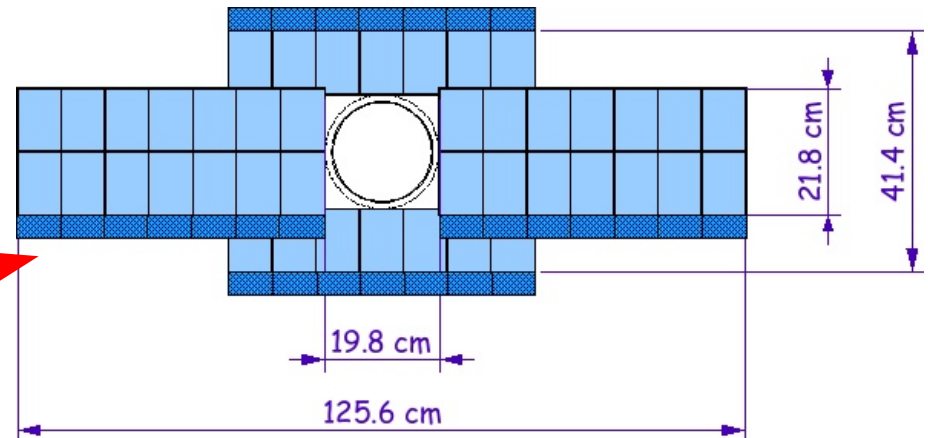
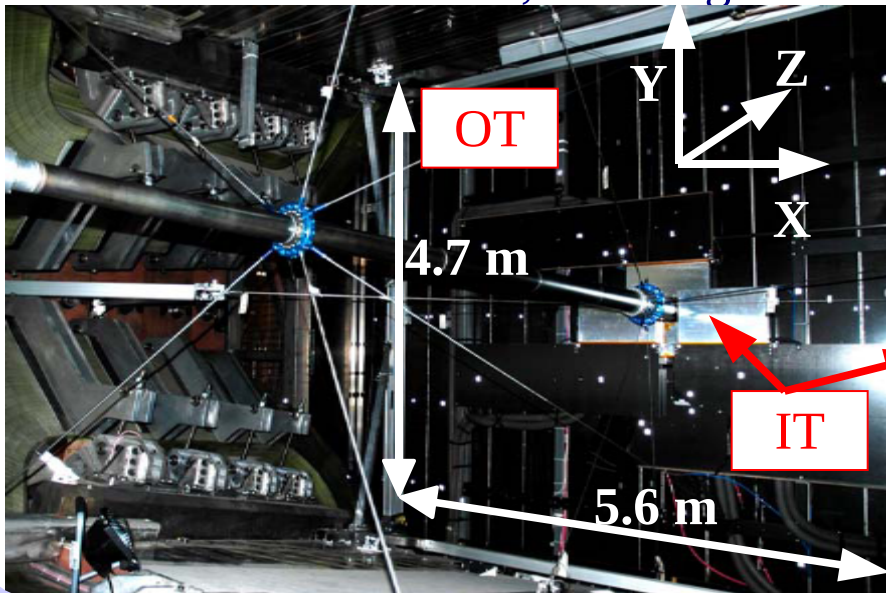
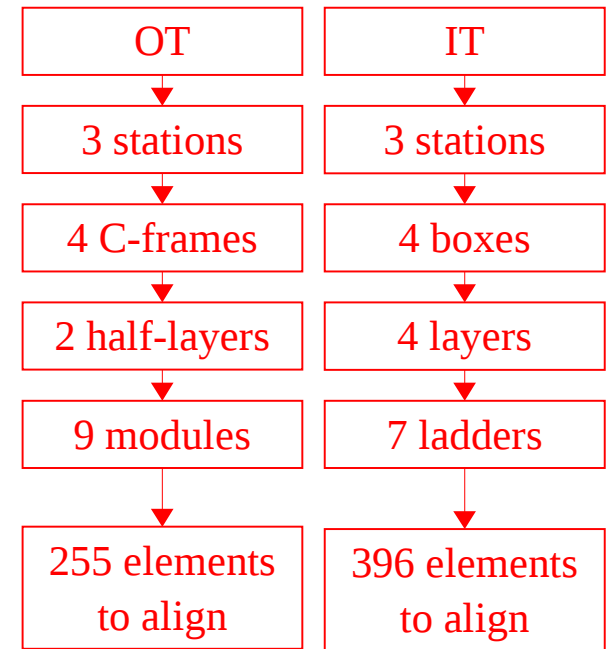


Tracking performances:

- Tracking efficiency: 95 % above 10 GeV
- Momentum resolution: $dp/p \approx 3-4 \text{ } \text{‰}$

The LHCb tracking system is composed of:

- **Trigger Tracker**: large silicon detector before magnet.
- Tracking stations after magnet:
 - **Outer Tracker**: straw tubes covering all the acceptance except for the innermost region.
 - **Inner Tracker**: silicon strips detector in region closest to beam pipe.
- Resolution: 200 μm (OT) / 57 μm (IT).
- Hadronic environment, need high tracking efficiency.



- We use a global χ^2 minimisation (Millepede-like).

- V. Blobel, "Software alignment for tracking detectors", NIM A 566 (2006) 5.
- P. Brückman, A. Hicheur and S. J. Haywood, "Global χ^2 approach to the alignment of the ATLAS silicon tracking detectors", ATL-INDET-PUB-2005-002.
- A. Bocci and W. Hulsbergen, "TRT alignment for SR1 cosmics and beyond", ATL-COM-INDET-2007-011.

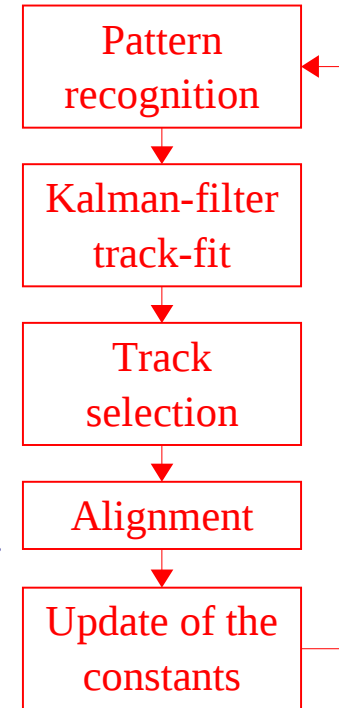
- BUT: we use tracks from the standard Kalman track fit in LHCb.

Advantages:

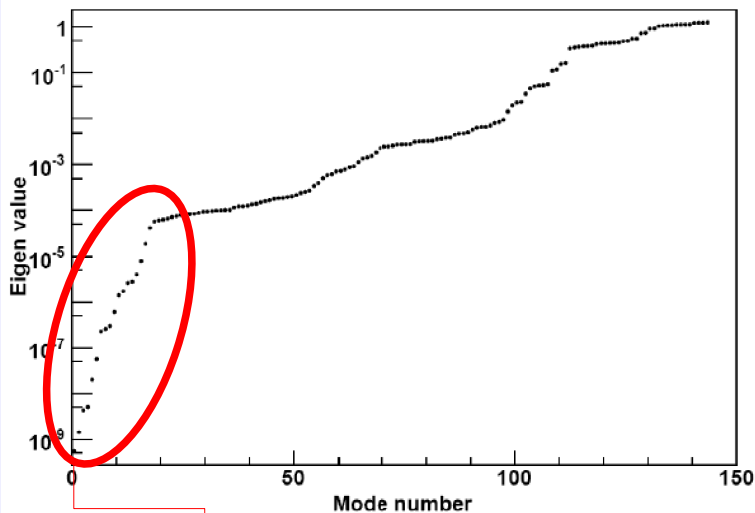
- Use same model for calibration and physics.
- Most complicated model: includes multiple scattering, dE/dx correction, ...
- Problem: in calculation, we need global track covariance matrix. This is not given by Kalman track fit, but it can be calculated afterwards. Details of this novel calculation can be found in:

- W. Hulsbergen, "The global covariance matrix of tracks fitted with a Kalman filter and an application in detector alignment", e-Print: arXiv:0810.2241v1 [physics.ins-det] 13 Oct 2008.

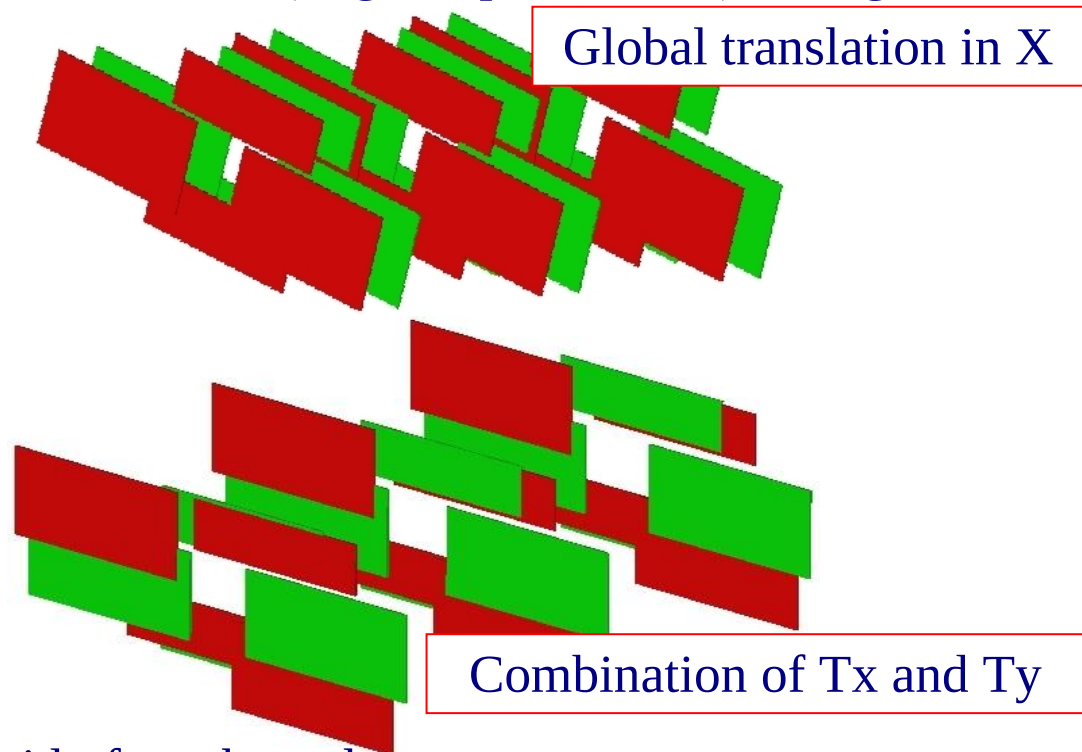
- Use of standard LHCb track fit, magnetic field and geometry framework:
 - No global track model needed.
 - Possibility to use any standard tracking tool.
- Alignment software: core algorithm using a set of tools, e.g. solving final stage in which regularisation, eigenvalues analysis, etc. can be done.
 - Align any detector element. All elements can be aligned simultaneously using long tracks: coherent approach!
 - Align for any degrees of freedom: 3 translations + 3 rotations.
 - Individual degrees of freedom are selected (e.g. translation along 'y' for TT/IT/OT modules are dropped).
- Iterations of pattern recognition and track fit to solve non-linear system.



- Solving the alignment equation leads to a big alignment matrix.
- Without any constraints, the matrix is positive definite \Rightarrow diagonalisable.
- Small eigenvalues correspond to weak modes (large displacements) of alignment.



Weak modes



Global translation in X

Combination of Tx and Ty

- Constraints can be applied to get rid of weak modes:
 - Unconstrained DoFs are constrained with Lagrange multipliers.
 - Vertex constraints: information propagated to residuals, correlations computed.
 - Cut on eigenvalues to remove unwanted weak modes.

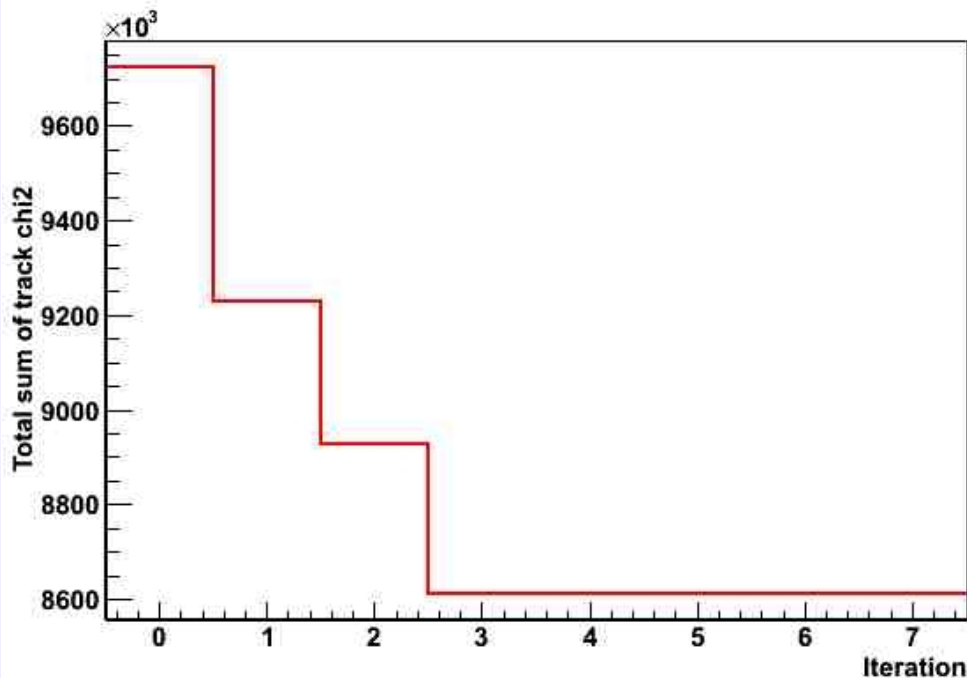
- Run 8 iterations over 50'000 minimum bias, magnet on events with 7 TeV protons.

- Misalignment scenario:

Detector	Element	DoF	Amplitude
IT	Boxes	Tx [mm]	1
	Layers	Tx [mm]	0.1
	Ladders	Tx [mm]	0.05
OT	Layers	Tx [mm]	1
		Rz [urad]	150

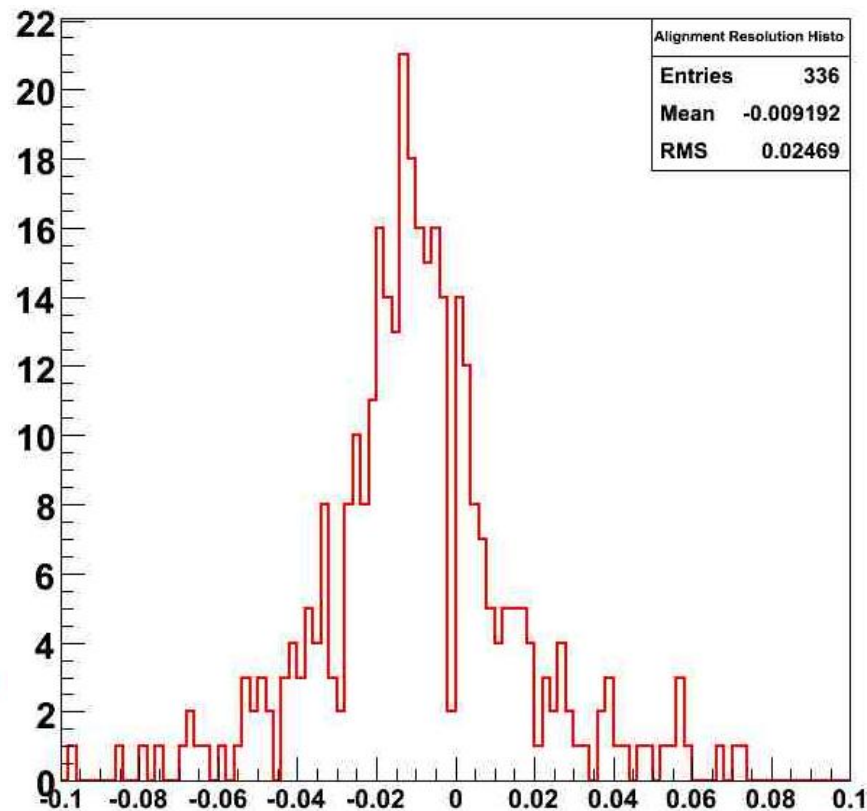
- Alignment of IT and OT constrained to VeLo ideal position (using long tracks).
Additional constraints: Weak degrees of freedom not aligned for.
- Important points for the convergence of the alignment algorithm:
 - Track selection: ==> 1.5 long tracks / event left for the alignment procedure.
 - Select events with low occupancy to reduce ghost rate.
 - Use evolving χ^2 cut to remove ghost tracks and hadronic interactions.
 - Multistep approach:
 - Align first IT boxes, then IT layers (independent of OT).
 - Align OT layers (independent of IT).
 - Align IT+OT layers, then IT ladders + OT layers together.

- χ^2 convergence plot for the 5th step (IT ladders + OT layers alignment):
Convergence in 3 iterations.



hits / element ranges between:
1'000 and 10'000

- Alignment resolution for IT ladders:
(distribution of residual misalignment)

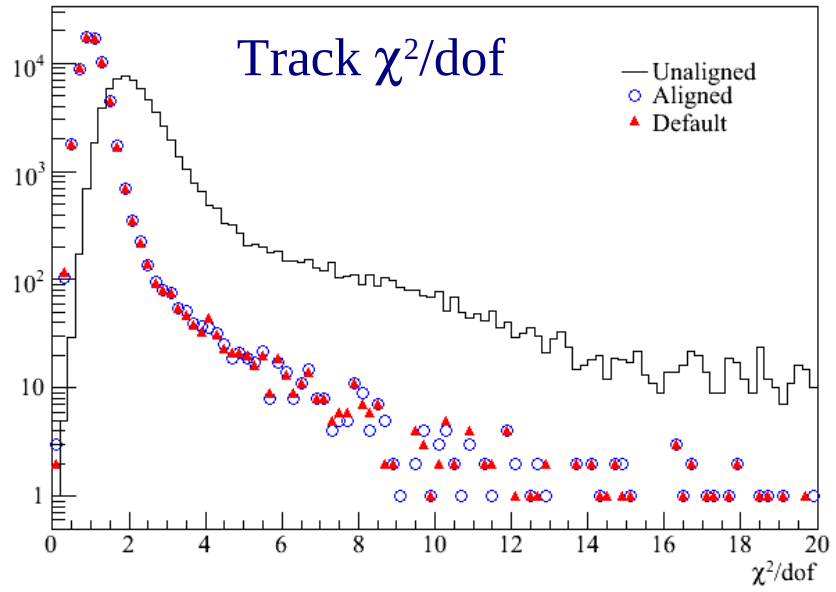
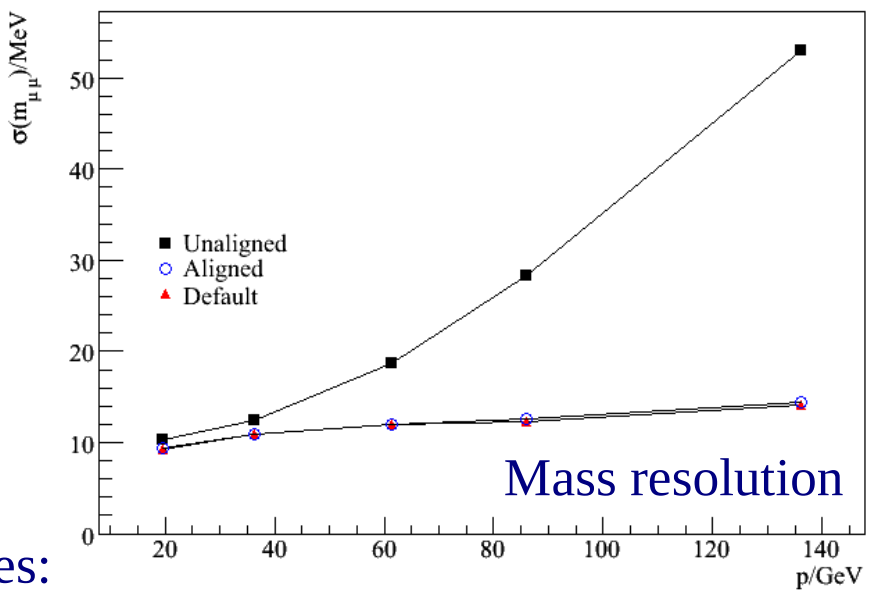


FWHM = 30 μm ==> $\sigma \cong 13 \mu\text{m}$

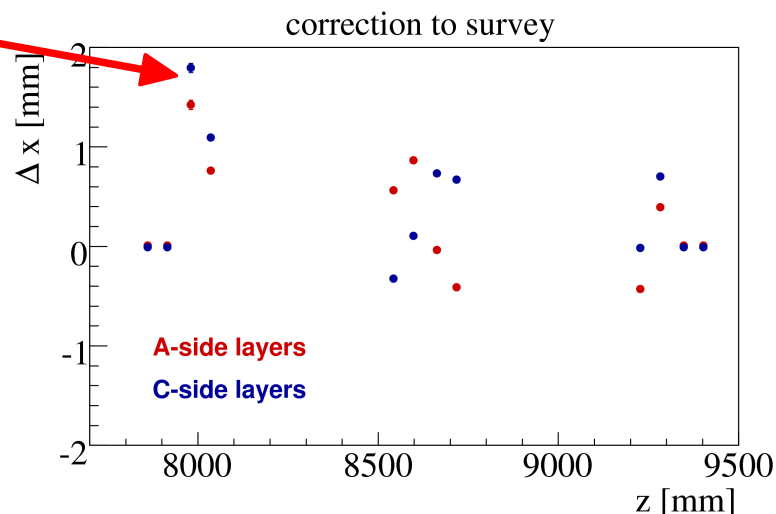
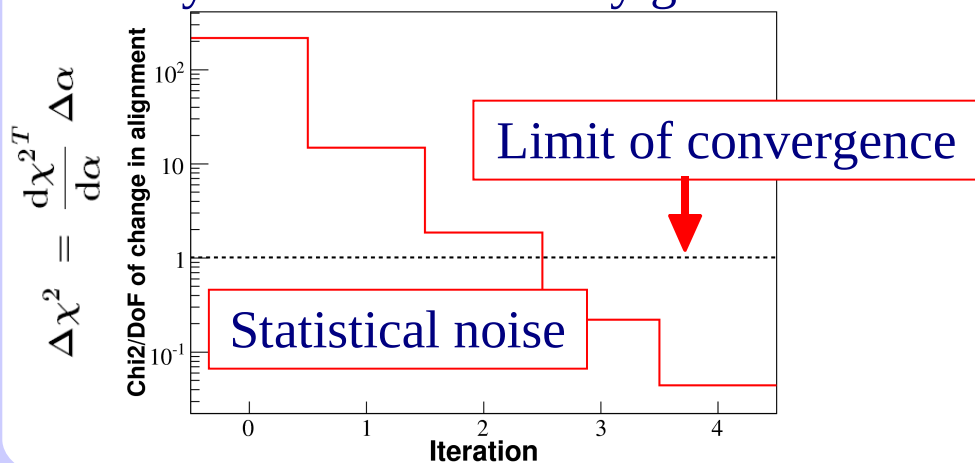
Bias $\cong 10 \mu\text{m}$ (==> bad tracks)

Alignment algorithm has converged, but where are we from the physics point of view?

- Run over 65'500 inclusive J/ψ .
- Loose J/ψ selection
 ==> 31'918 J/ψ candidates.
- Refit of tracks from J/ψ with 3 geometries:
 - Unaligned (before alignment job).
 - Aligned (after alignment job).
 - Default (ideal geometry).
- Look at:
 - Dimuon mass resolution: $M(\text{rec}) - M(\text{true } \mu\mu)$
 - Track χ^2/dof .



- Data-taking runs during the summer:
 - Cosmic rays data: many tracks for OT, but barely any for IT.
 - Beam-dump data: very crowded, good for VeLo but not for tracking stations.
- First alignment of 24 OT half-layers with cosmic rays.
- Align for Tx (16 DoFs, 2 first and 2 last layers fixed).
- Fix average global translations / rotations / shearings.
- Track selection: ==> 8'000 OT tracks left for alignment.
- Convergence in 2 iterations because not all hits found by pattern recognition in first iteration due to large misalignments.
- Survey measurements only good to 2 mm.



- Alignment framework using all the standard LHCb tracking tool.
- No global track model is needed. We use the Kalman-fitted tracks: same tracks as for physics studies, with full complexity (multiple scattering, dE/dx correction, ...).
- We can align any detector element and for any DoF (translations + rotations).
- IT-OT simultaneous alignment has been tested on realistic day-1 misalignment scenarios.
- OT alignment has been performed on real cosmic rays data: procedure works!
- The points to be careful about are:
 - Track selection.
 - Weak mode removal.
 - Alignment in several steps.
- Future plans:
 - More studies of the existing cosmic rays and beam – dump data.
 - Ready for beam – gas and p – p collisions data.

END

BACKUP SLIDES

- We use a global (closed-form) χ^2 minimization:

$$\frac{\partial \sum_i \chi_i^2}{\partial \alpha} = 0 \quad \text{and} \quad \forall_{\text{tracks } i} \frac{\partial \chi_i^2}{\partial X_j} = 0$$

- Compute total derivatives to alignment parameters, by eliminating derivatives to track parameters:

$$\frac{d\chi^2}{d\alpha} = 2 \sum_{\text{tracks}} \frac{\partial r^T}{\partial \alpha} V^{-1} r \quad \frac{d^2\chi^2}{d\alpha^2} = 2 \sum_{\text{tracks}} \frac{\partial r^T}{\partial \alpha} V^{-1} (V - HCH^T) V^{-1} \frac{\partial r}{\partial \alpha}$$

r = residual vector (distance between measurement and track).

V = measurement covariance matrix.

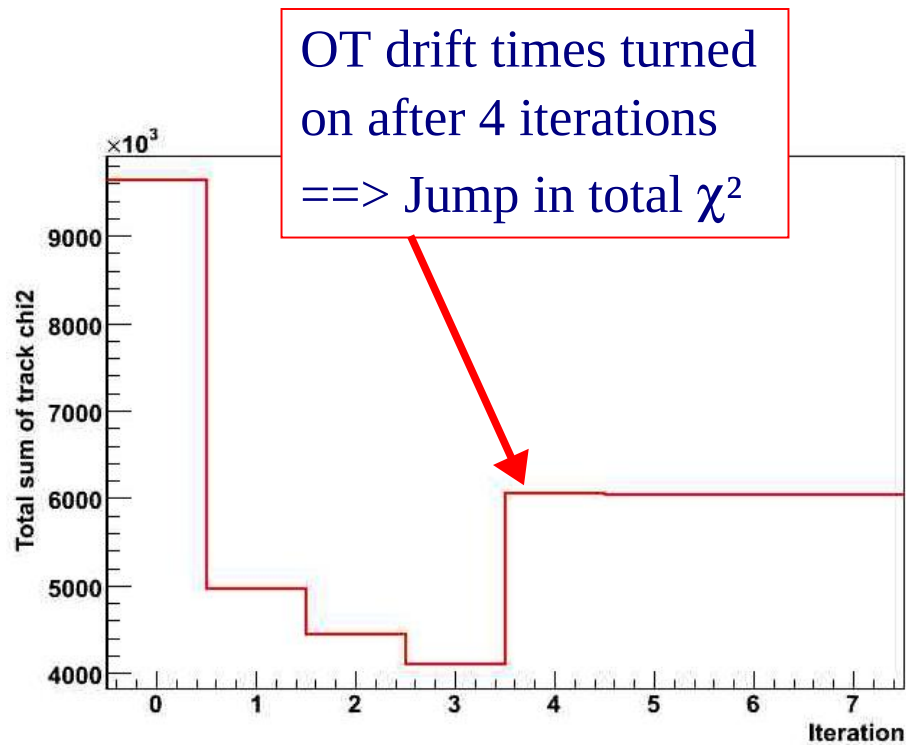
H = Derivatives of residuals to track parameters.

C = Track covariance matrix: incomplete in Kalman filter (no correlations).

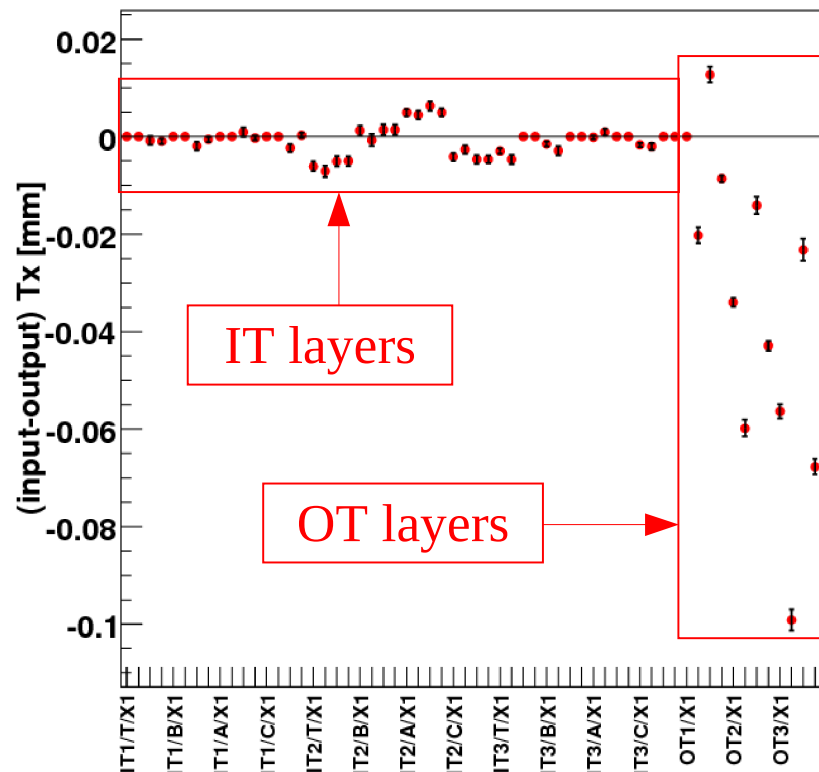
- Mathematically equivalent to Millepede method:
in e.g. V. Blobel, "Software alignment for tracking detectors", NIM A 566 (2006) 5.
 - Notable difference in our method: using Kalman track fit.
 - Calculation of track covariance matrix C is not trivial.
- The maths for this novel calculation are described in arXiv:0810.2241v1.

- Run 8 iterations over 50'000 beam – residual gas, magnet-off events with 450 GeV protons.
- Misalignment scenario: Reasonable day-1 scenario where IT and OT layers have been misaligned at the level of Tx ($\pm 300 \mu\text{m}$), Ry and Rz ($\pm 3 \text{ mrad}$)
- Standalone alignment with T-tracks (IT + OT) for IT and OT simultaneously.
- Important points for the convergence of the alignment algorithm:
 - Track selection: \Rightarrow 4.9 tracks (IT+OT) / event left for alignment.
 - Select event with low occupancy to reduce ghost rate.
 - Use evolving χ^2 cut to remove ghost tracks and interactions.
 - Drift time off in OT in first 4 iterations, turned on after 4 iterations.
 - Convergence more stable without L/R ambiguity resolution.
 - But worse precision (1 mm vs 200 μm).
 - Strategy: get close to minimum, then use power of drift time information.

- Total sum of track χ^2 vs iterations:



- Input – output Tx for all IT/OT layers:

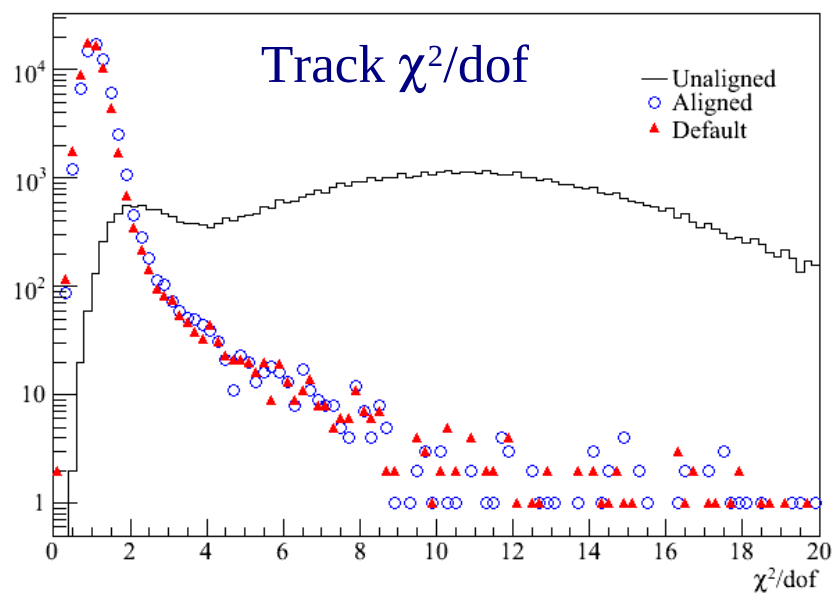
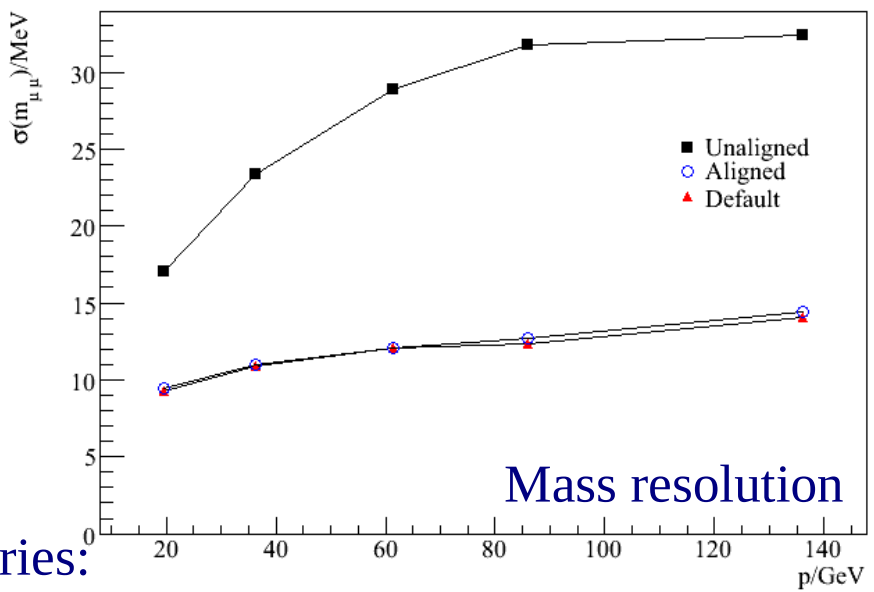


- Looking at χ^2 convergence: alignment converged in 4-5 iterations.

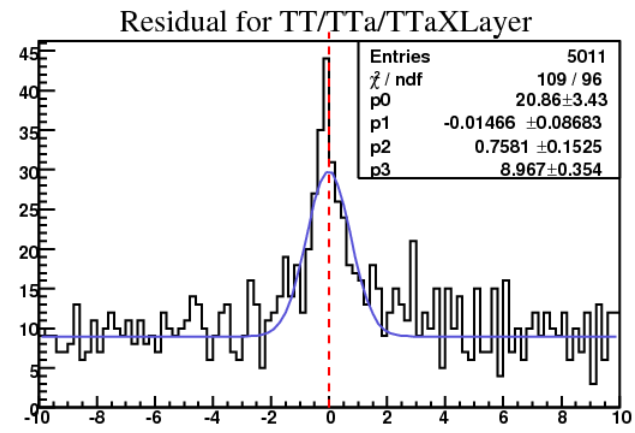
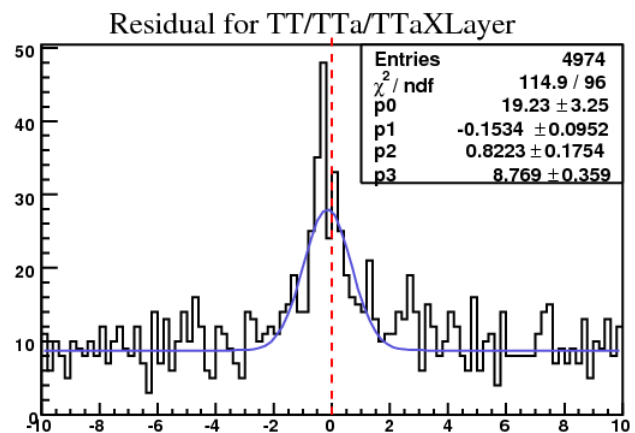
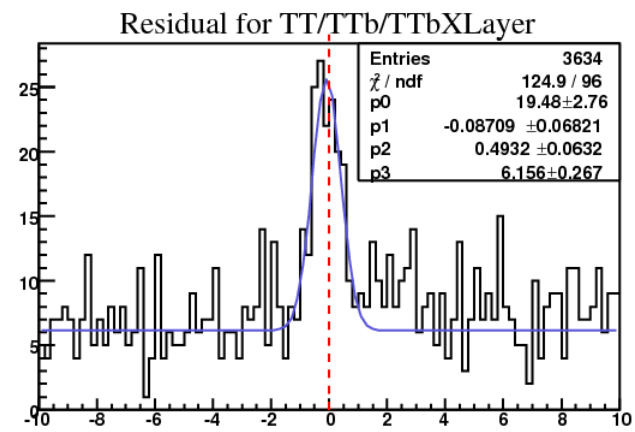
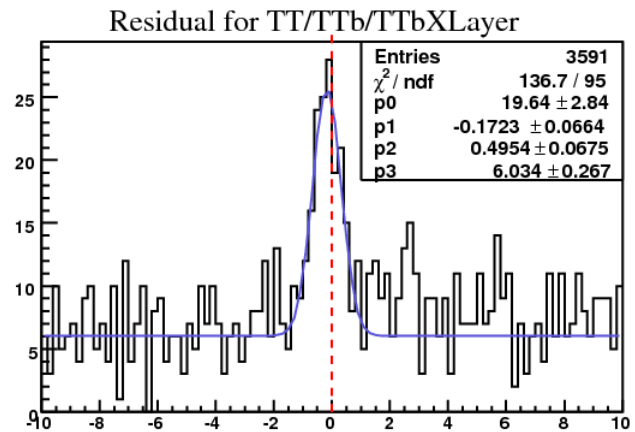
- IT layers aligned in Tx within 10 μm .
- OT layers aligned in Tx within 100 μm (without drift times: to $\pm 180 \mu\text{m}$).

Alignment algorithm has converged, but where are we from the physics point of view?

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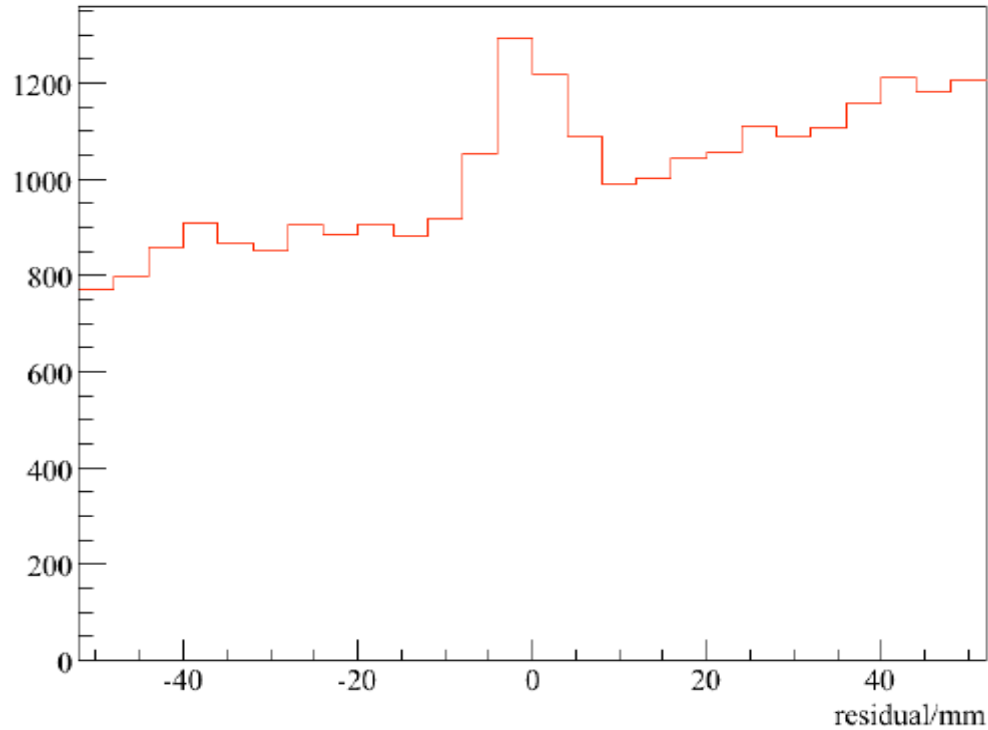


- Distance between TT hits and extrapolated VeLo segments for TT layers:
 - Before alignment
 - After alignment



- Hits within $\sim 300 \mu\text{m}$ of expected, with a resolution of $\sim 500 \mu\text{m}$.
- Peak goes back to the right place after alignment.

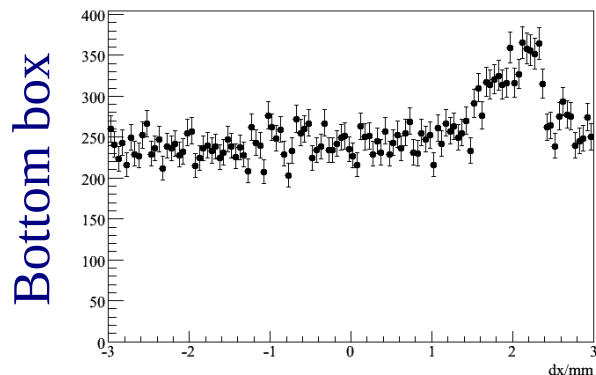
- Distance between IT hits and extrapolated VeLo segments for IT layers.



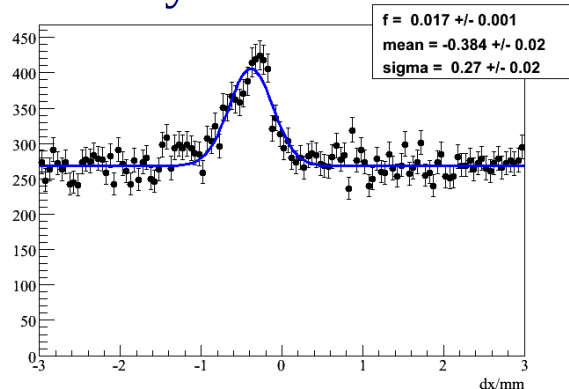
- Looks like a resolution of ~ 3 mm.
- But very long (several meters) extrapolation.

- Take any pair of hits in T1 and T3, draw a line.
- Plot distance between line and all the hits in T2.

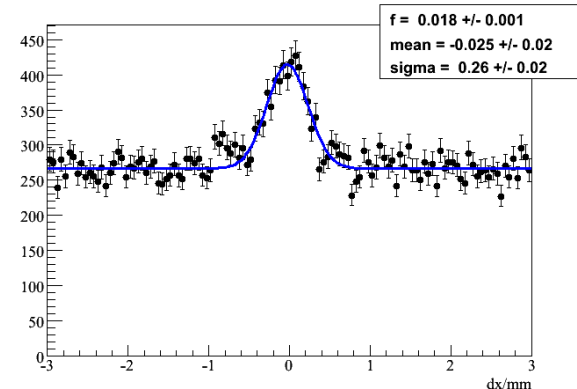
Nominal geometry



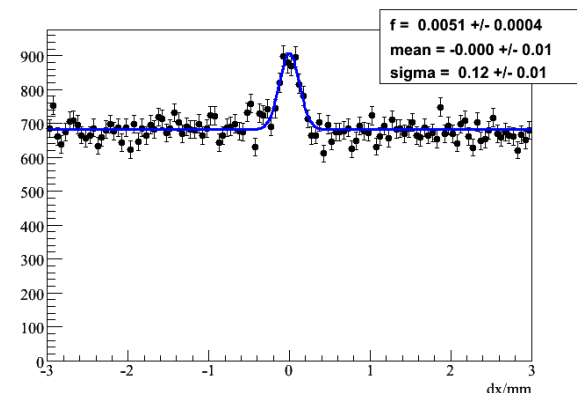
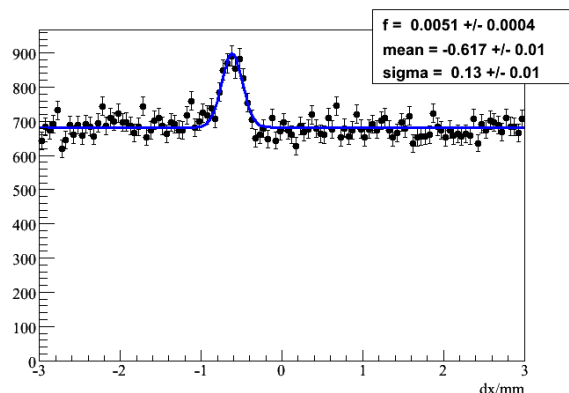
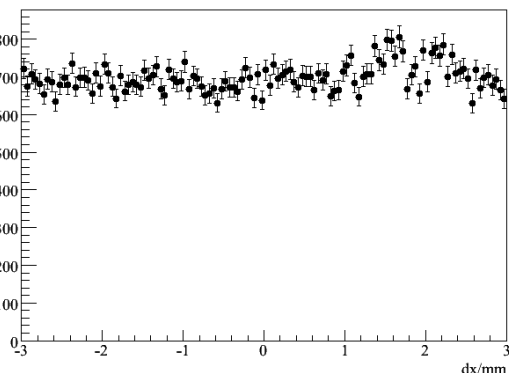
Survey measurements



Additional corrections



C-side box



- Occupancy 10 times larger than nominal running conditions.
 ==> Very hard to find tracks in IT.