Alignment of the inner detector and of the muon spectrometer of the ATLAS experiment

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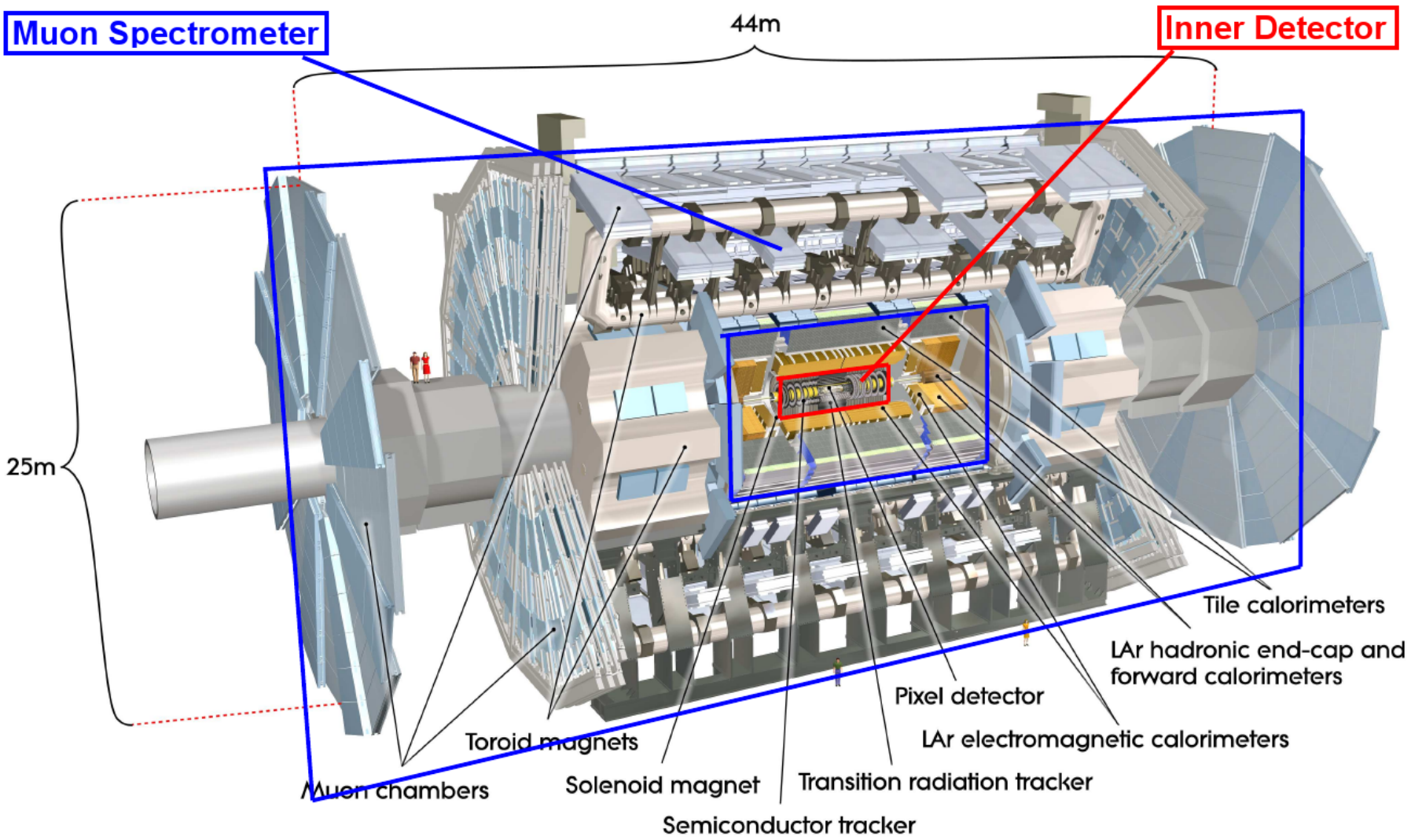
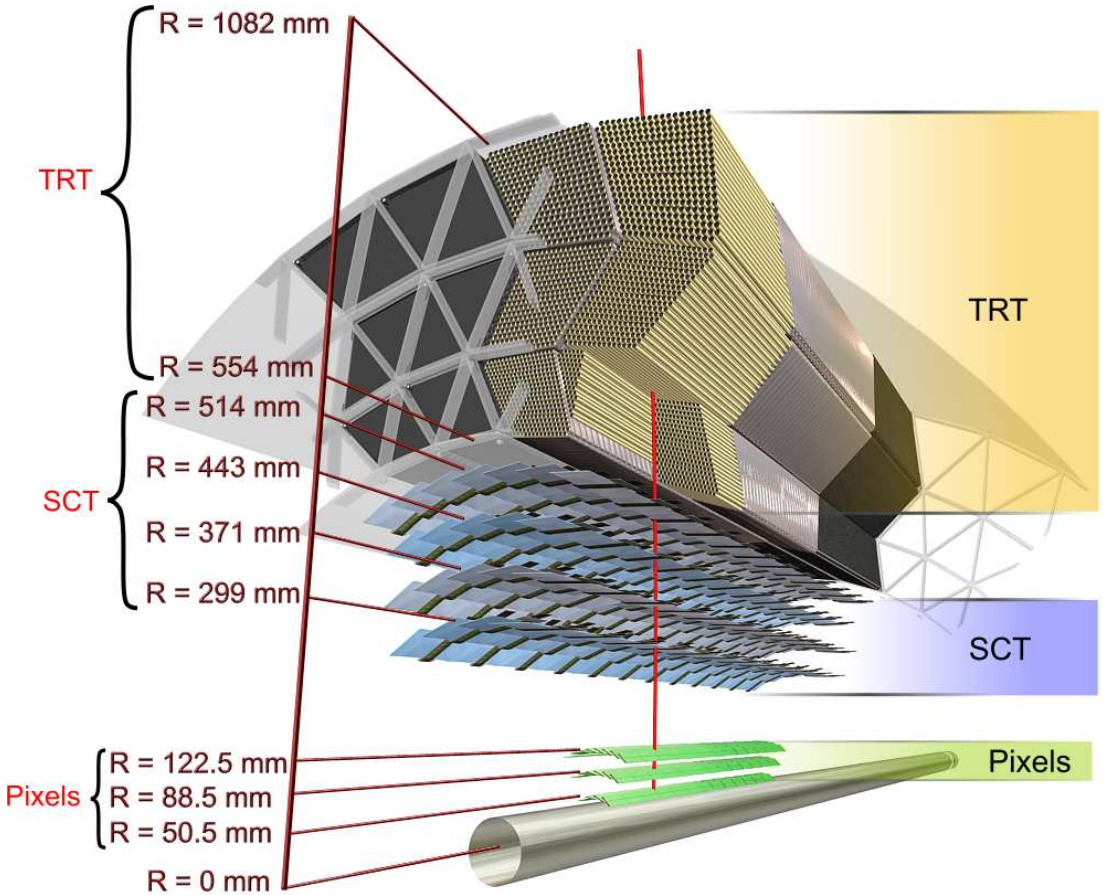
ATLAS Detector



ATLAS Inner Detector

Barrel



Pixels (silicon modules)

- 1774 modules
- intrinsic resolution
  10 μm $(r\phi)$, 115 μm (rz)

SCT (silicon strips)

- 4088 modules
- intrinsic resolution
  17 μm $(r\phi)$, 580 μm (rz)

TRT (straw drift tubes)

- 176 modules
- intrinsic resolution
  130 μm $(r\phi)$ per tube*

* *about 10 hits per one TRT module*

Alignment of the Inner Detector

Alignment Goal

- degradation of resolution on track parameters due to misalignment **< 20%**

Alignment Tolerances

module	Pixel	SCT	TRT
tolerance	7 μm ($r\phi$)	12 μm ($r\phi$)	30 μm ($r\phi$)

Track-based alignment algorithms

Least-square minimization of track hit residuals:

$$\frac{\mathrm{d}\chi^2}{\mathrm{d}\alpha_i} = 0, \qquad \chi^2 = \sum_{tracks} \boldsymbol{r}^T \boldsymbol{V}^{-1} \boldsymbol{r}.$$

$\boldsymbol{r} = \boldsymbol{r}(\boldsymbol{\alpha})$ - vector of track residuals
$\boldsymbol{\alpha}$ - vector of alignment parameters
$\boldsymbol{V}$ - covariance matrix

- Global χ^2
  - correlations between all alignment parameters taken into account
  - 6Nx6N matrix inversion (N $\approx$ 6 000)
- Local χ^2
  - correlations between different modules ignored (restored via many iterations)
  - N of 6x6 matrices inversion
- Robust
  - based on shifting modules according to their observed residual offsets

Tests of three independent approaches have shown consistent results
Results presented in this report were produced with Global χ^2 algorithm

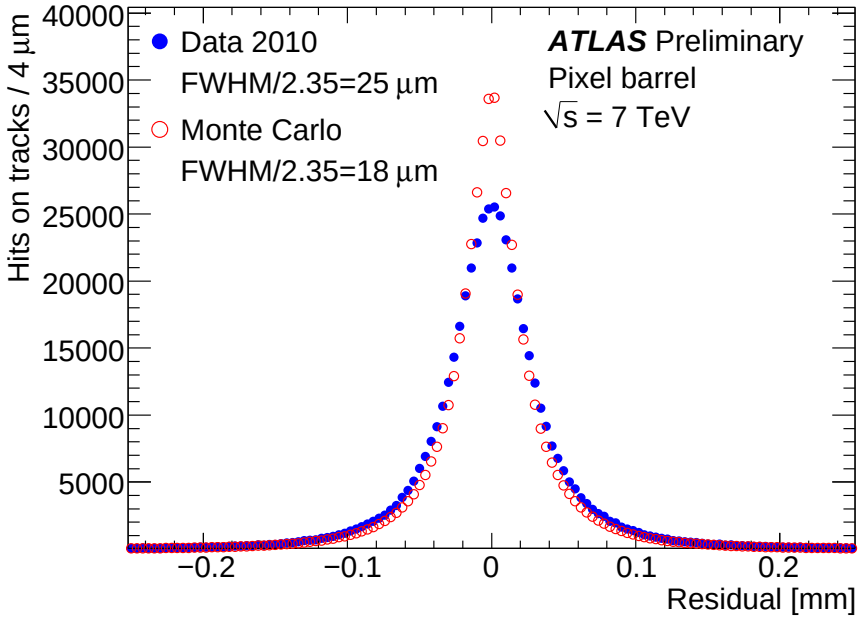
Performance with Collisions at 7 TeV

- first alignment results were produced with Cosmic '08 data (*back-up slides*)

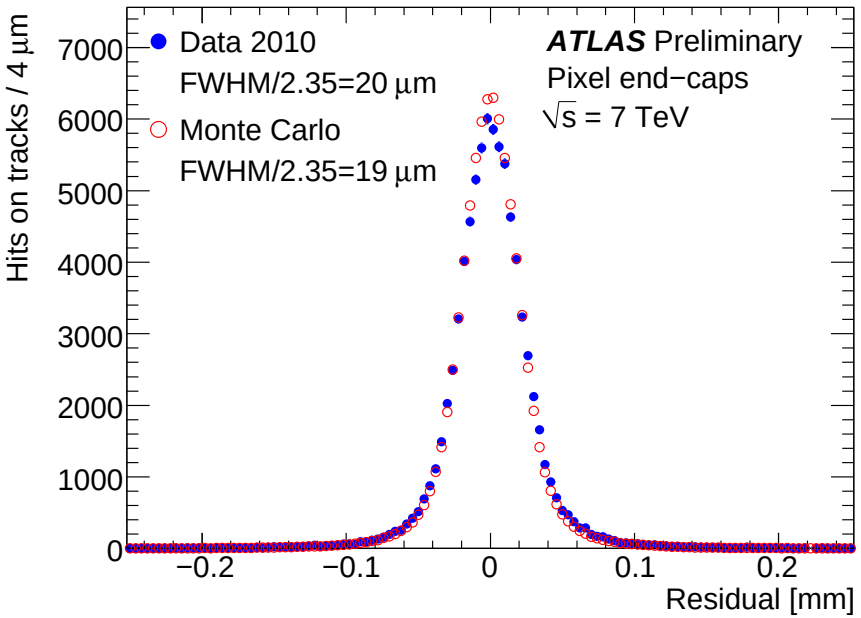
Alignment results at 7 TeV (Data / Ideal MC):

- performance plots produced with 7 TeV collision data
- provided with alignment corrections produced with cosmic'09 and 900 GeV collision data (cosmic data helps to cure week modes of alignment)

Pixel barrel residuals (25 μm / 18 μm)



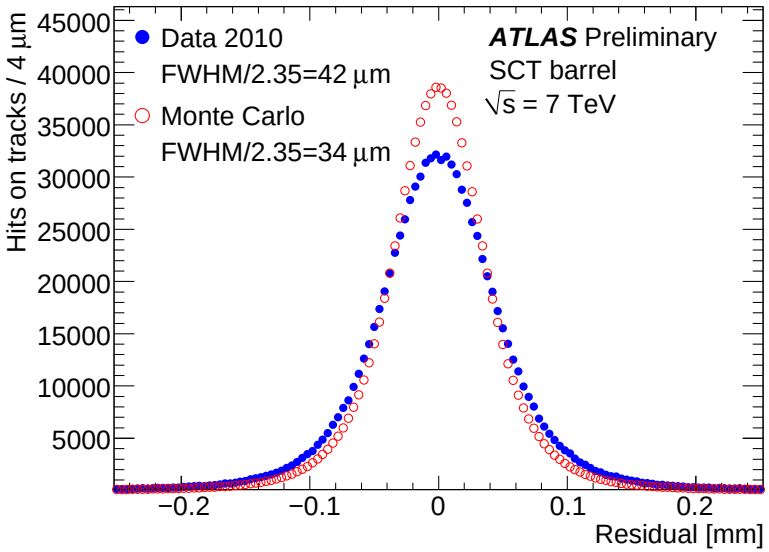
Pixel end-cap residuals (20 μm / 19 μm)



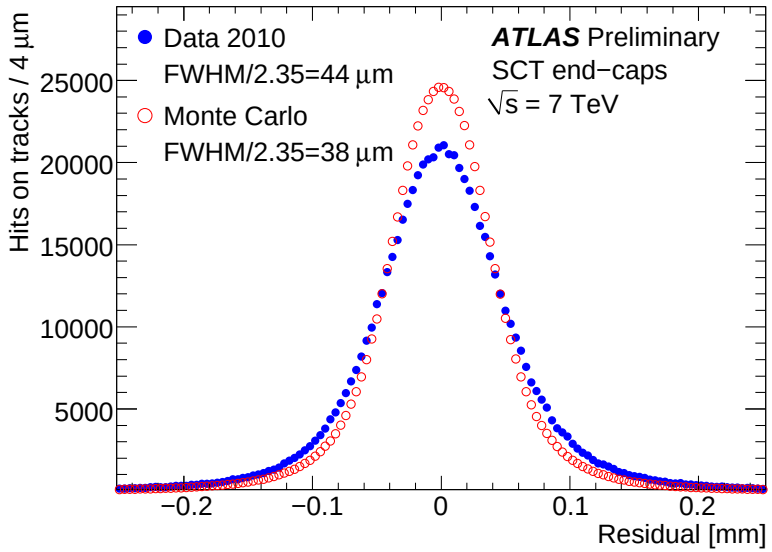
- great improvement of alignment results for the end-cap region (poor illumination with cosmics)

Performance with Collisions at 7 Tev

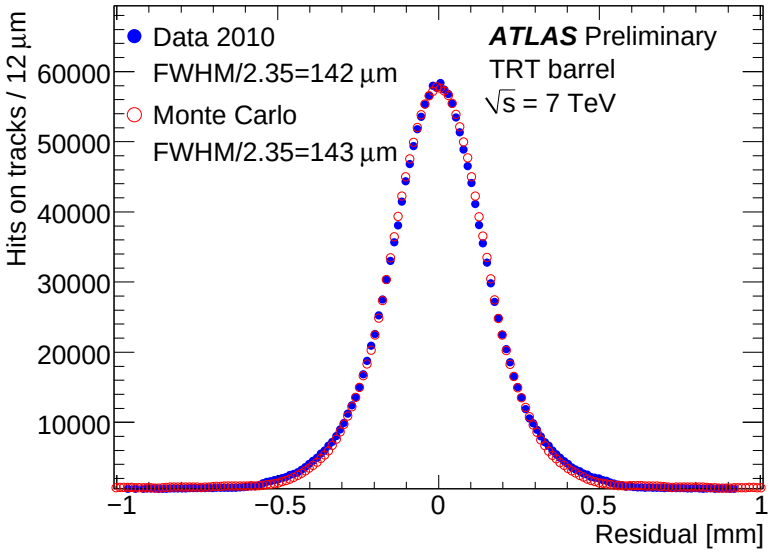
SCT barrel residuals (42 μm / 34 μm)



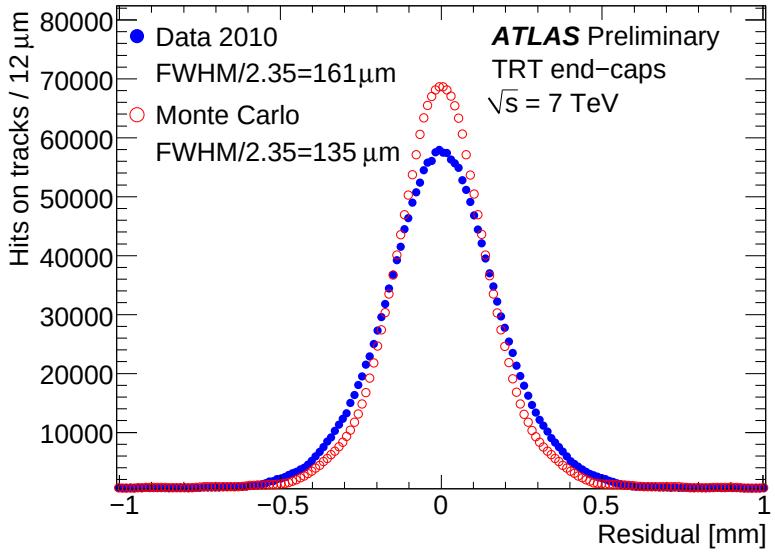
SCT end-cap residuals (44 μm / 38 μm)



TRT barrel residuals (142 μm / 143 μm)



TRT end-cap residuals (161 μm / 135 μm)

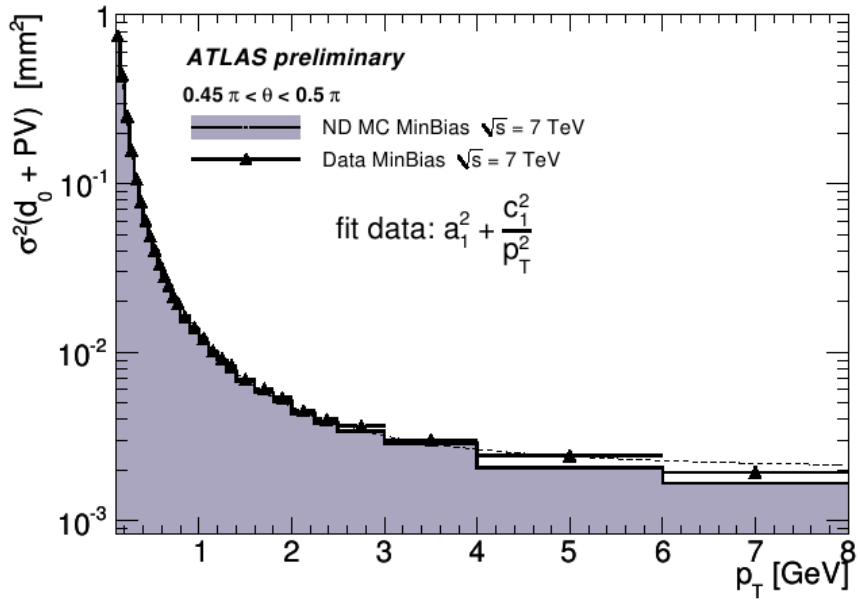


Tracking Performance with 7 TeV Data. Barrel.

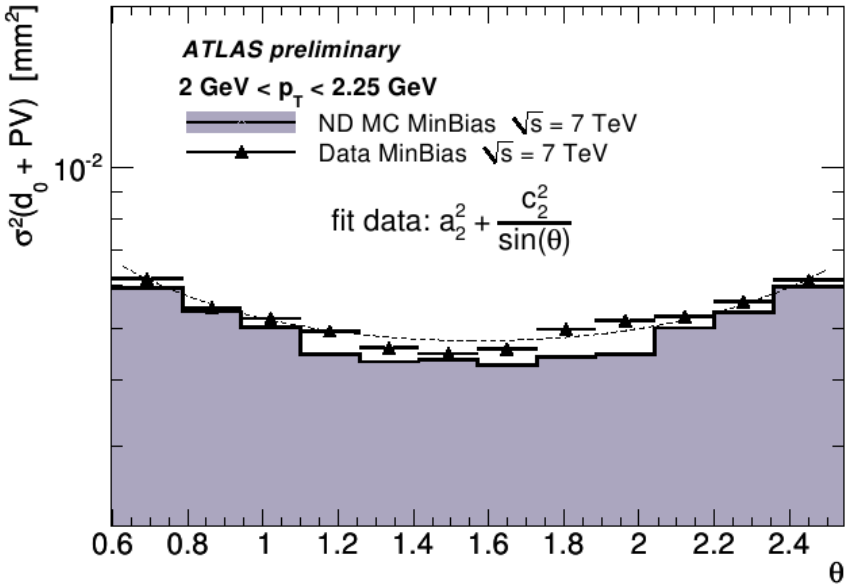
Transverse Impact Parameter Resolution

- plotted squared resolution consist of:
  - $\sigma(d_0)$ – Transverse Impact Parameter Resolution
  - $\sigma(PV)$ – uncertainty on Primary Vertex position
- good agreement between Data and Simulation
- difference between Data and Simulation shows contribution from misalignment and it starts to play role at high p_t region only

Transverse Impact Parameter Resolution vs. p_t

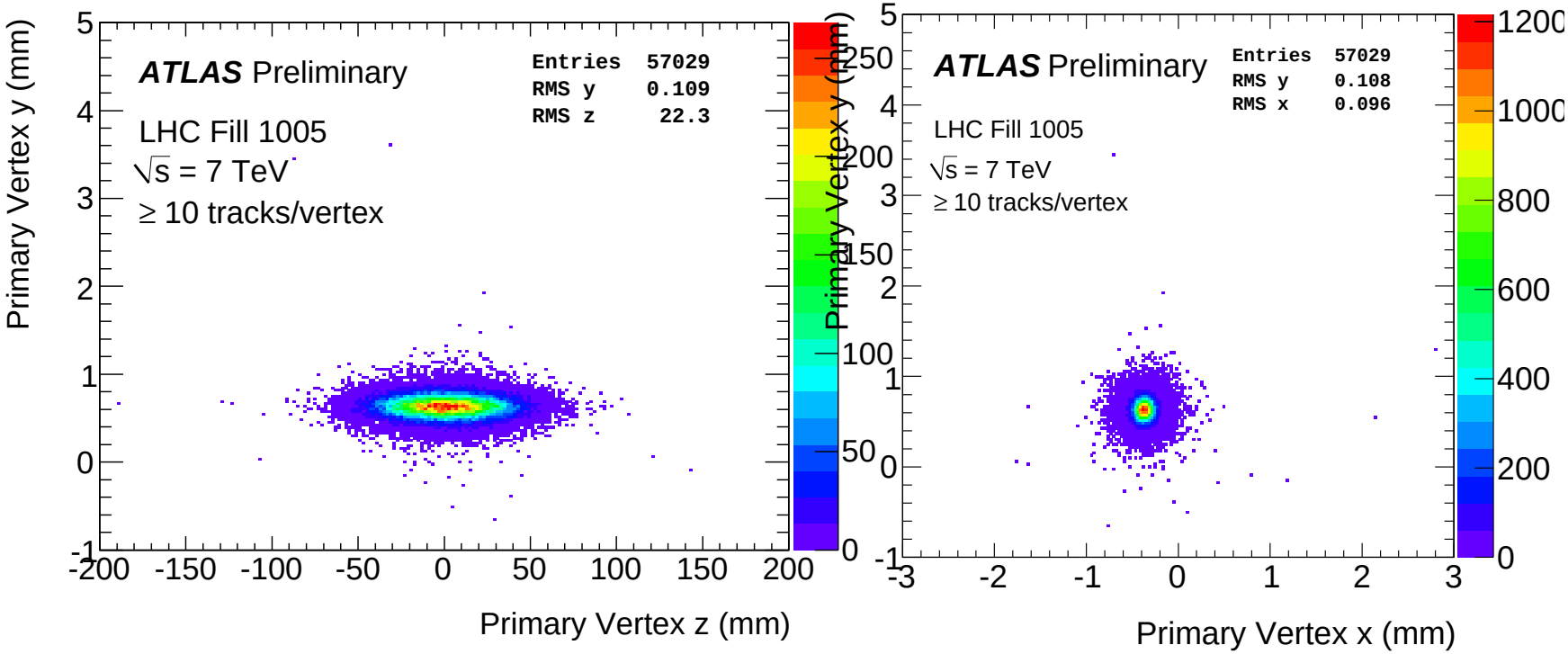


Transverse Impact Parameter Resolution vs. θ



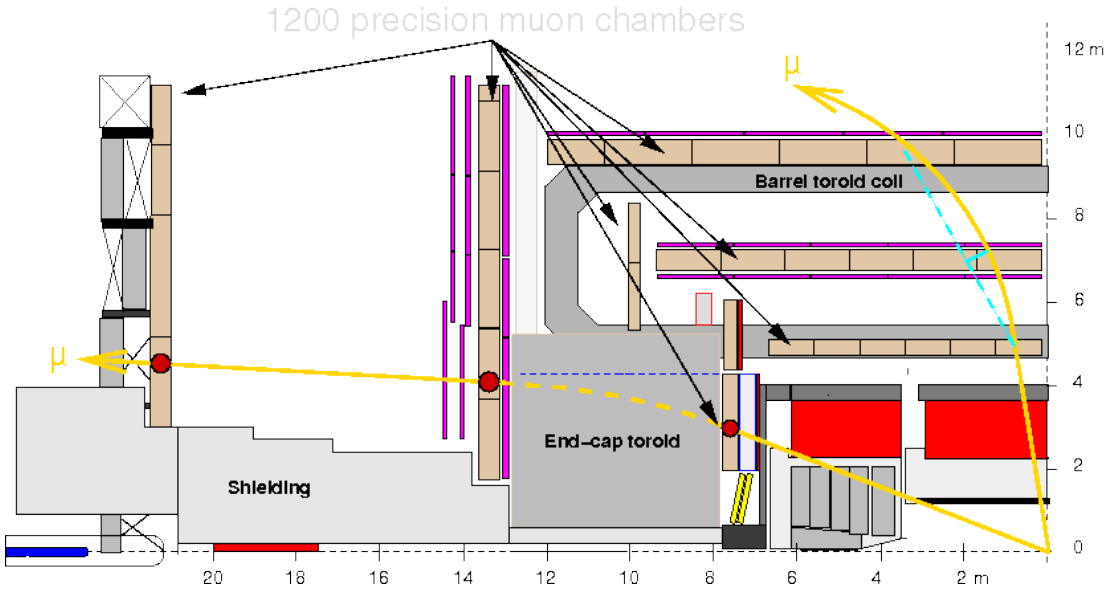
Beam Spot Results at 7 TeV

Primary Vertices



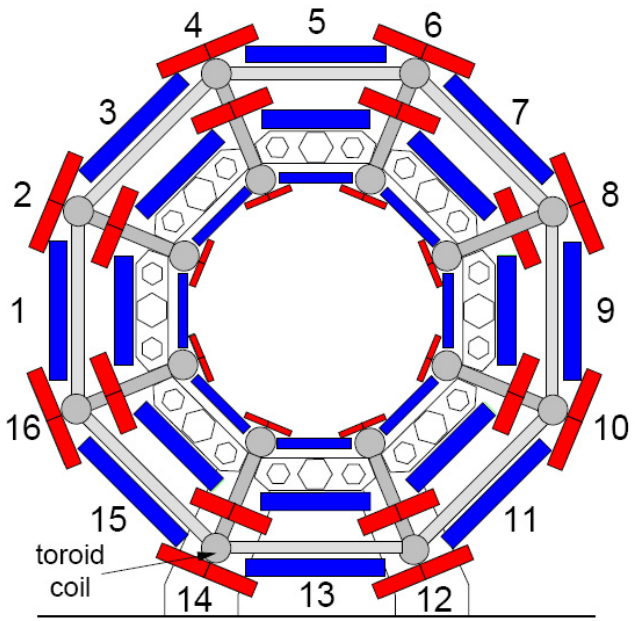
- width of the transverse distribution is dominated by the vertexing resolution $\approx$75 μm
- luminous size is about 45 μm x 70 μm in (x, y)-plane

Muon Spectrometer



Air core toroid magnet to minimize multiple scattering:

- Barrel: 0.15–2.5 T
- End-Caps: 0.2-3.5 T

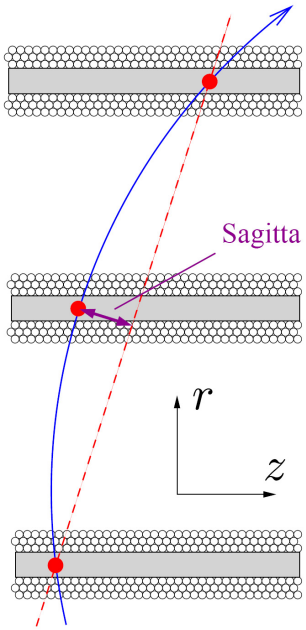


Large (blue color) and Small (red color) sectors of the Barrel part of Muon Spectrometer

Muon Spectrometer Standalone Momentum Resolution

- Resolution goal:
  ∼10% resolution at p_t =1 TeV/c

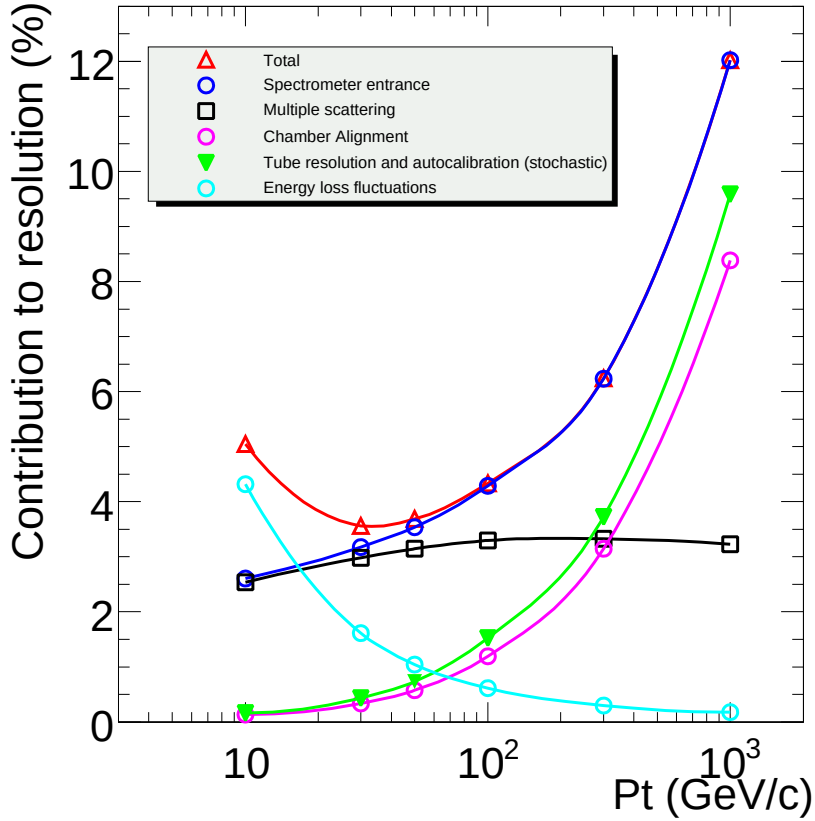
- Track sagitta of 1 TeV/c muon $s \propto 1/p$:
  ∼500 μm
  ⇒ uncertainty on sagitta measurement:
  ∼50 μm



Major contributions to sagitta at 1 TeV/c:

- contribution from MDT tube resolution and calibration:
  ∼40 μm
- contribution from MDT chamber alignment:
  ∼30 μm required

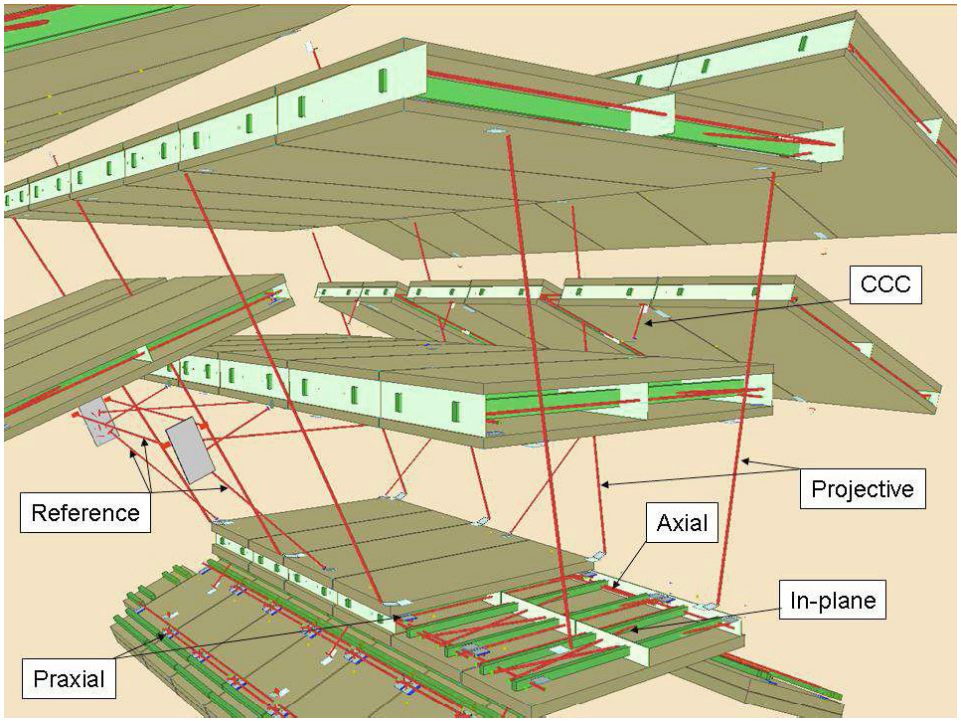
Momentum resolution for muons reconstructed in the Muon Spectrometer (stand-alone)



Muon Alignment System

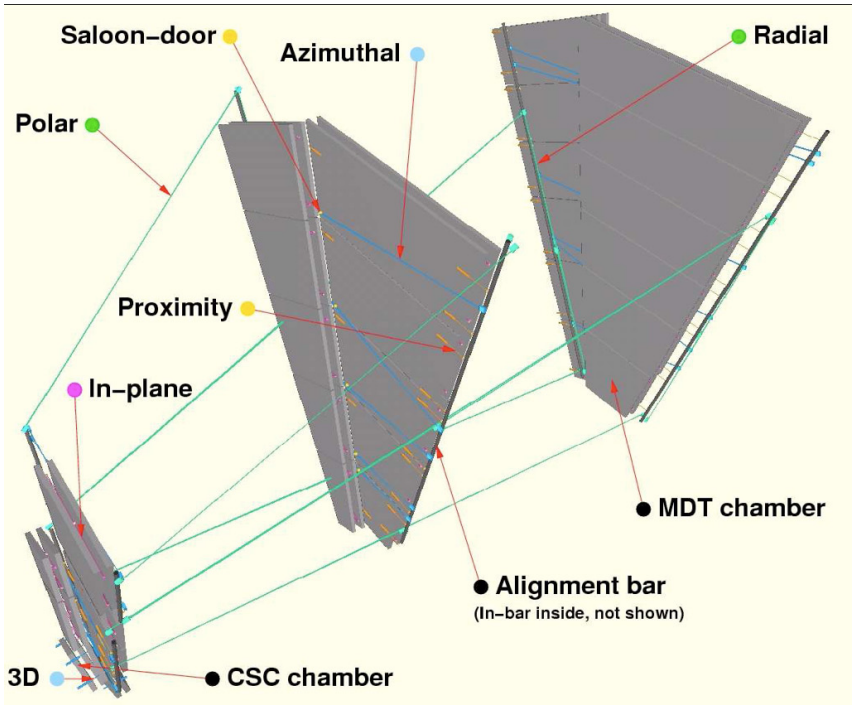
Barrel alignment system:

659 MDT chambers
5817 alignment sensors



End-cap Alignment system:

494 MDT chambers
6536 alignment sensors

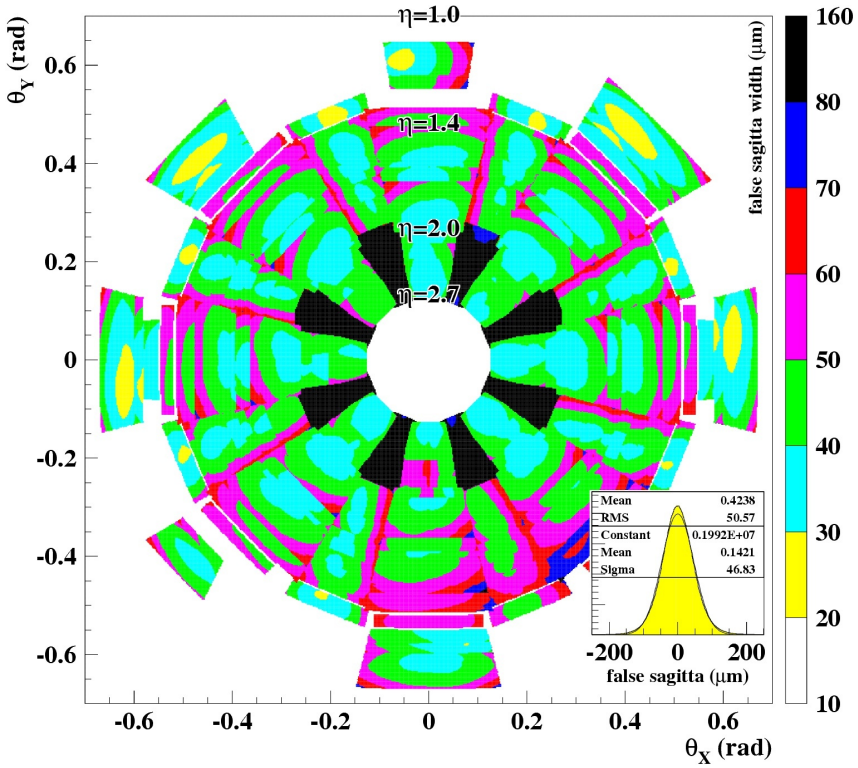


Track-based alignment tasks:

- small-to-large barrel sectors
- Barrel to Endcap
- Muon Spectrometer to Inner Detector

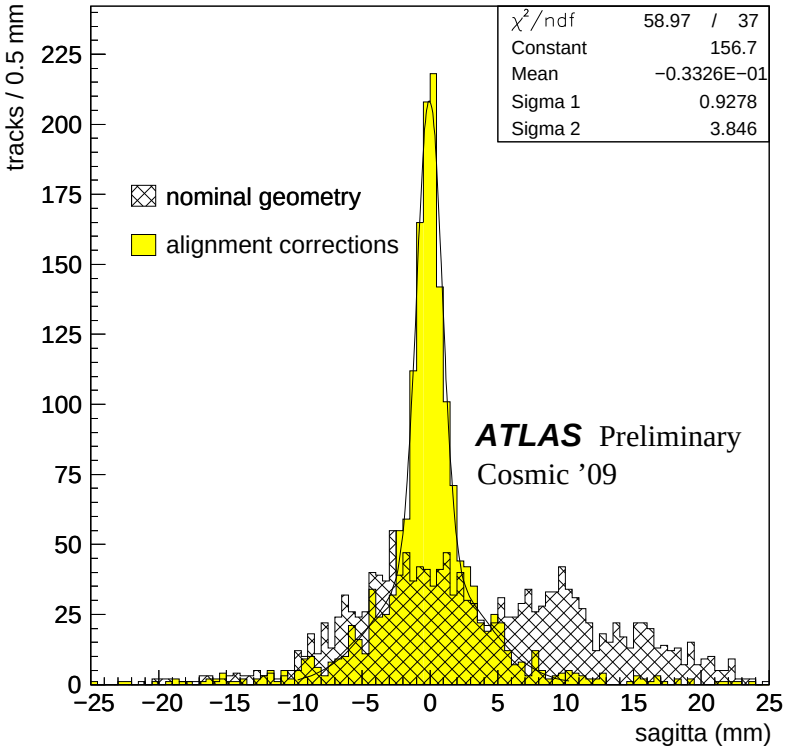
End-Cap Performance

End-Cap performance simulation



- Endcap alignment system designed for 40 μm sagitta accuracy
- simulation using observed optical sensor resolutions predicts 45 μm sagitta accuracy

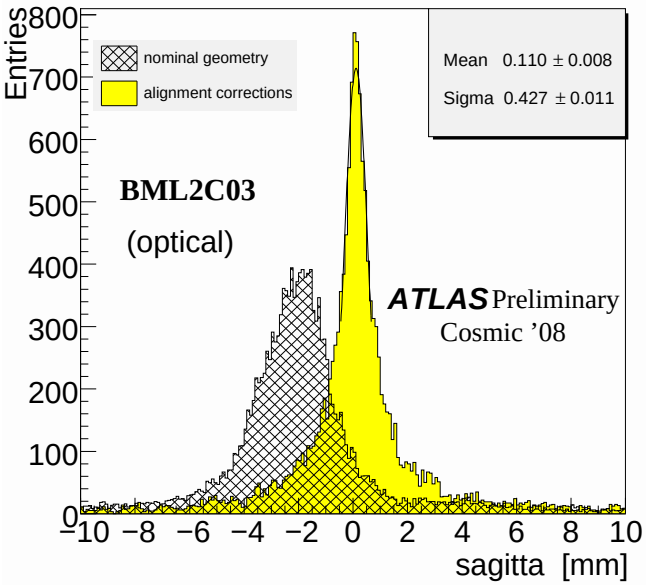
End-cap straight track sagitta

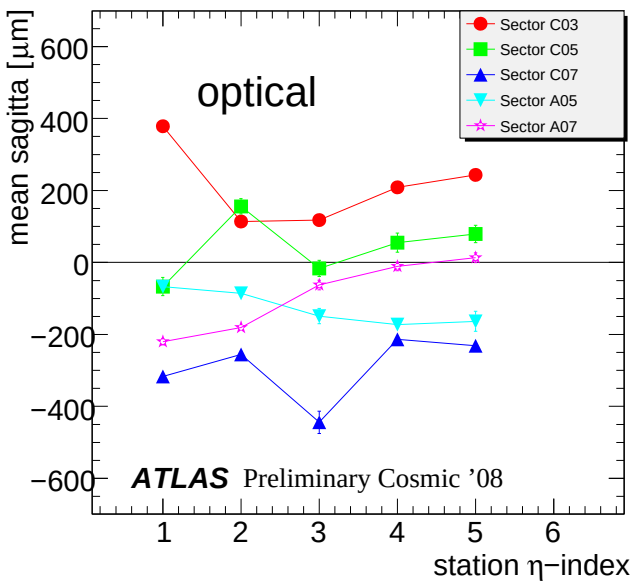


- mean value is compatible with zero
- dominant contribution to the width is from multiple scattering (MC sagitta width is about 1.1 mm for p_t=20 GeV muons)

Barrel Performance. Straight Tracks vs Optical Alignment

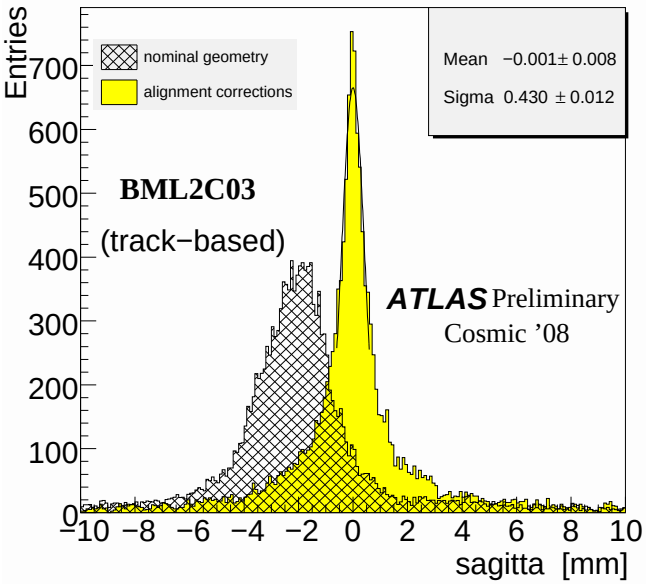
Mean straight track sagitta inside triplets of barrel chambers

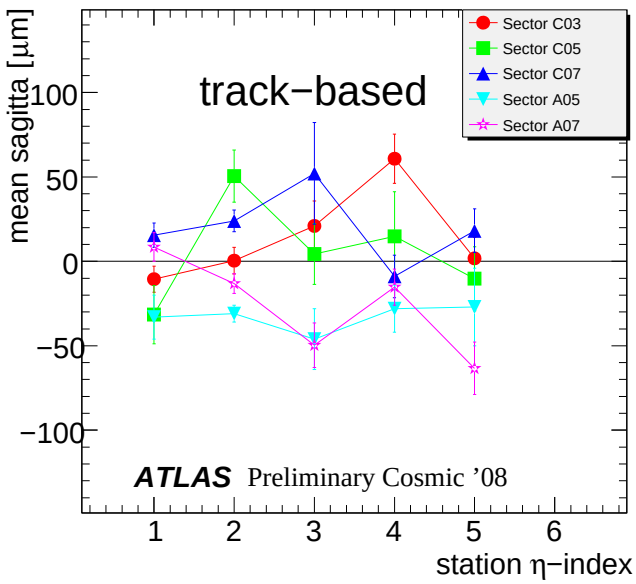




Optical corrections

- performance at the level of 200 μm
- sensor mounting and calibrations are not accurate enough





Track-based corrections

- alignment corrections obtained with straight cosmic tracks
- performance at the level of 30–50 μm (close to the design goal)

Sagitta Resolution. Barrel Sectors.

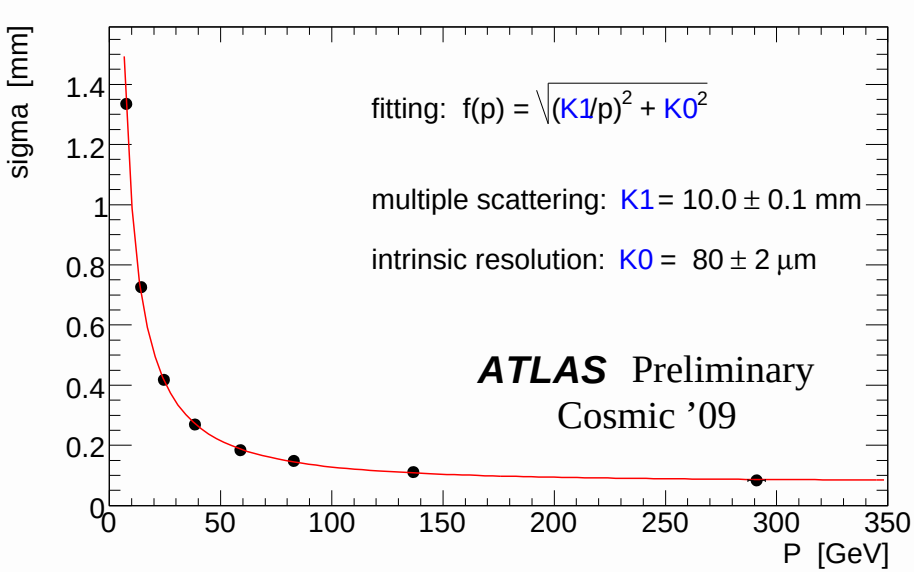
Alignment strategy (used for collisions and cosmic runs):

- initial geometry is determined with straight tracks (*back-up slide*)
- optical system measures relative changes with the time (accuracy of the relative optical alignment is about 10-20 μm inside barrel sector)

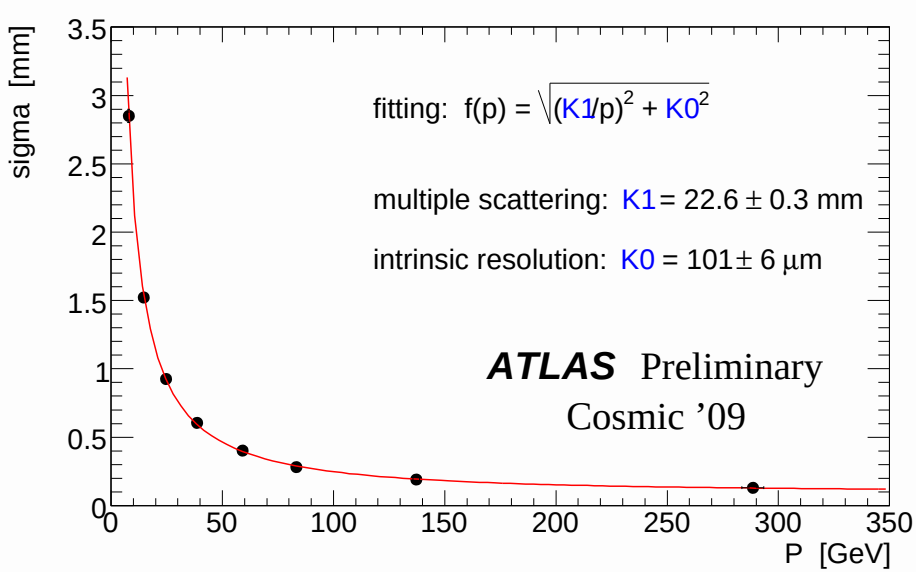
Sagitta resolution (as a function of muon momentum):

- special cosmic runs (Oct 2009) with magnets toroid=OFF / solenoid=ON used

large sectors



small sectors



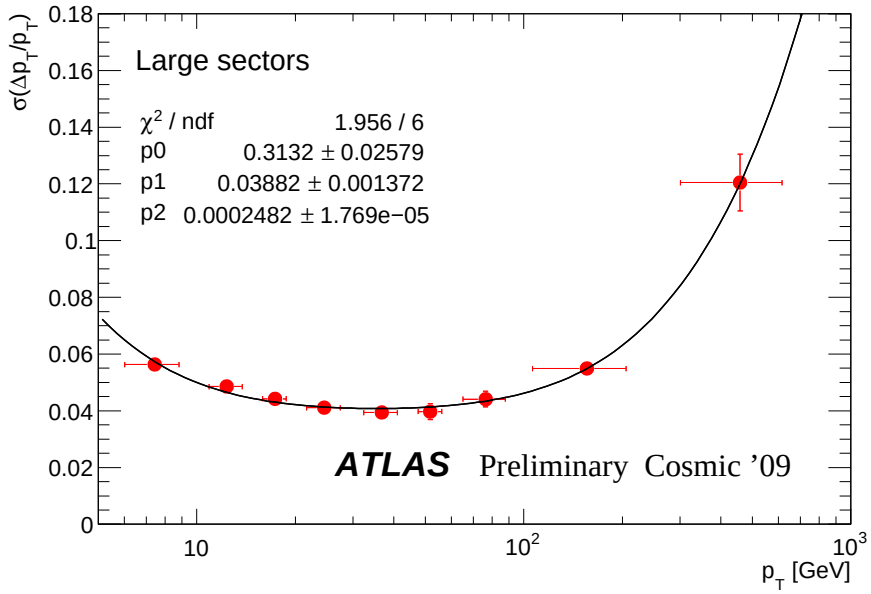
- multiple scattering is about two times larger inside small sectors (presence of toroid coils)
- intrinsic resolution is about 80 μm/100 μm for large/small sectors (60 μm by design)
- contribution from alignment and chamber geometry is about 50-70 μm / 50-100 μm for large/small sectors

Momentum Resolution.

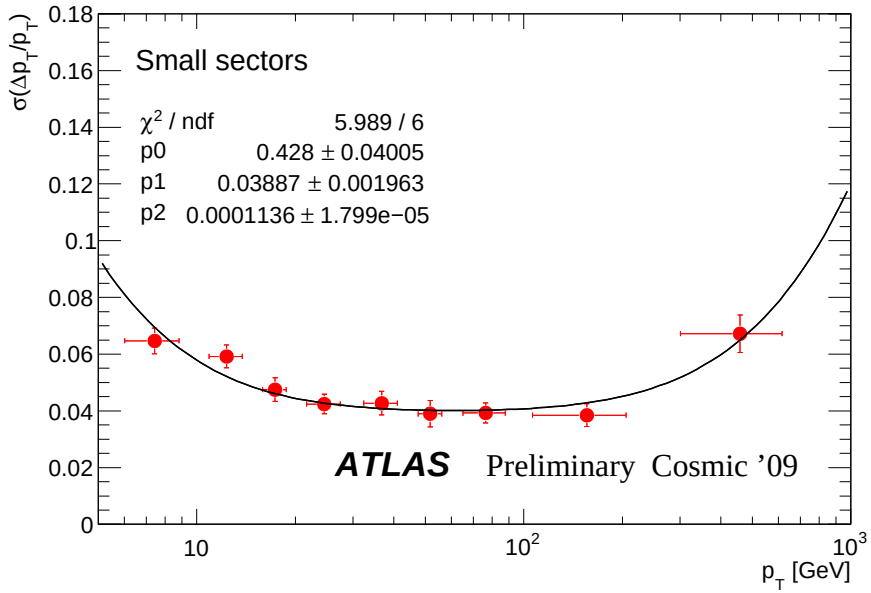
Muon Spectrometer Resolution (stand-alone)

- cosmic tracks splitted into top and bottom parts ($\sigma = \sigma_{tb}/\sqrt{2}$)
- small sectors have better resolution (bending power factor two larger)
- contributions at low p_t:
  - energy loss in the Calorimeter
  - multiple scattering inside the Muon Spectrometer
- contributions at high p_t (intrinsic resolution):
  - drift tube resolution
  - misalignment

Large Sectors



Small Sectors



Summary

Inner Detector

status:

- alignment results have been successfully applied to LHC collision data
- huge progress has been made in the understanding of the tracker with the start of collisions
- current alignment precision already allows good tracking performance for physics

Muon Spectrometer

status:

- end-cap alignment quality is expected to be close to the design goal
- alignment accuracy is of the order of 50-100 μm for different barrel sectors

ongoing tasks:

- implementation of chamber deformations into reconstruction
- track-based algorithms: small-to-large (sectors); barrel-to-endcap; MS-to-ID

plans:

- run of pp collisions with magnetic field switched off is planned to improve the alignment

Back-Up

Inner Detector. Alignment Strategy

Alignment is performed on several different levels of granularity

Alignment sequence:

Silicon detectors

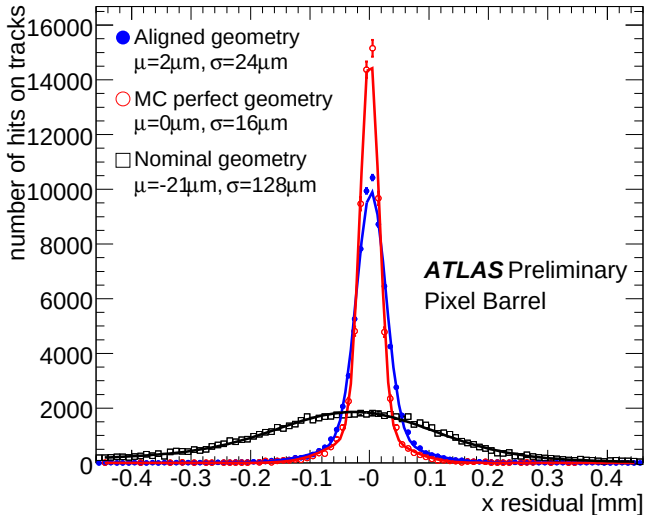
- relative subsystem alignment: Pixel, SCT barrel, 2 x SCT end-cap
- barrel layer/half-shell, end-cap disks
- barrel stave
- barrel module alignment

TRT barrel

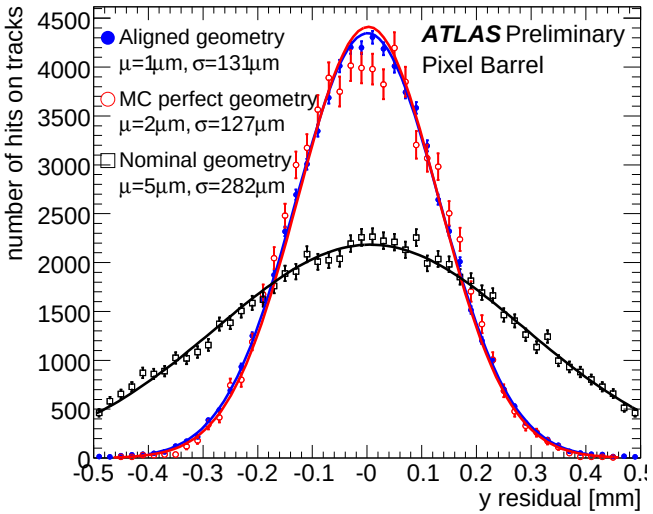
- TRT barrel, 2 x TRT end-cap
- barrel module alignment: 5 DoF per module

Inner Detector. Residual Distributions. Cosmic Data.

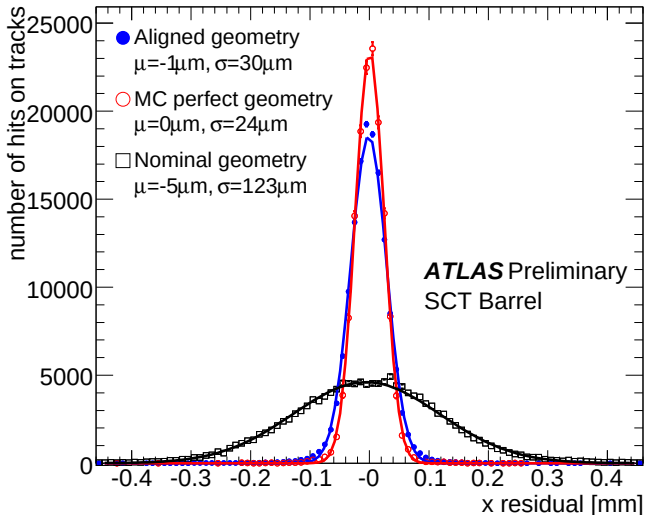
Pixel barrel residuals ($r\phi$)



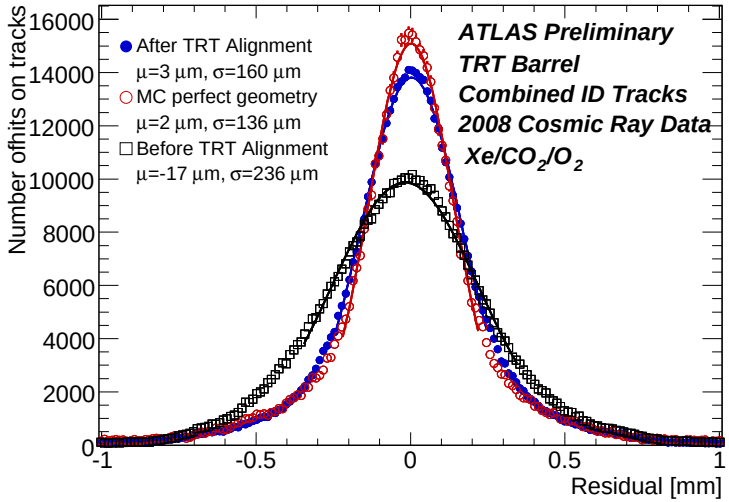
Pixel barrel residuals (rz)



SCT barrel residuals ($r\phi$)



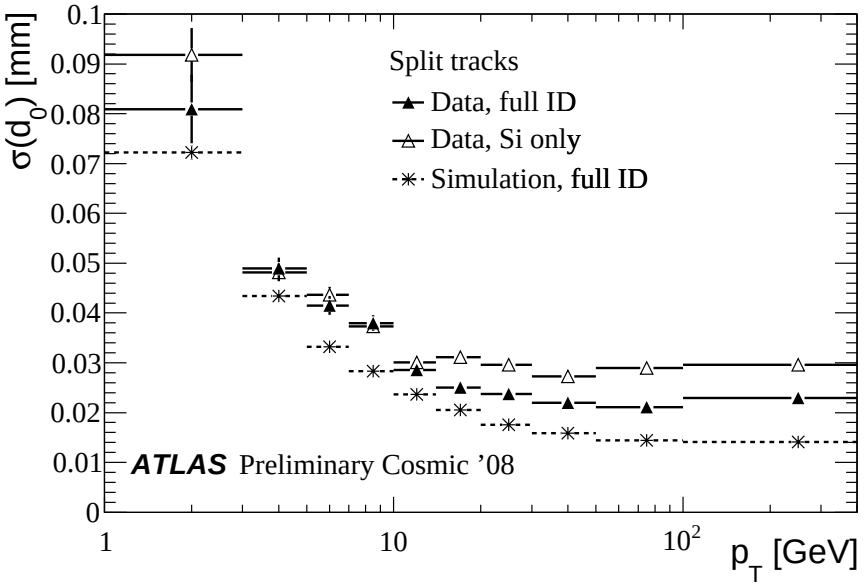
TRT barrel residuals (combined)

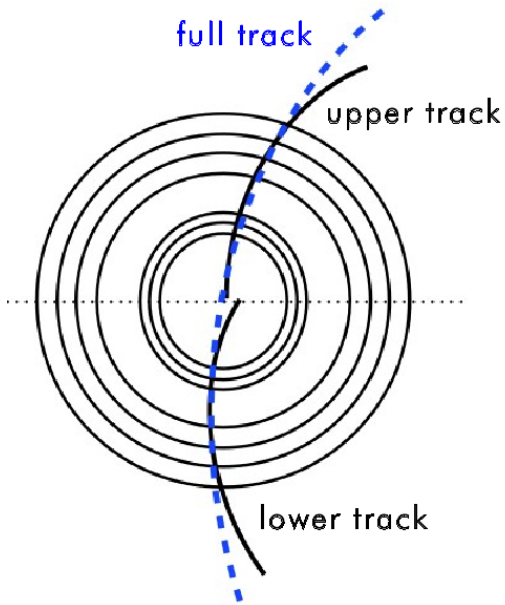


- alignment at the top and bottom is much better than at the sides (cosmic track topology)

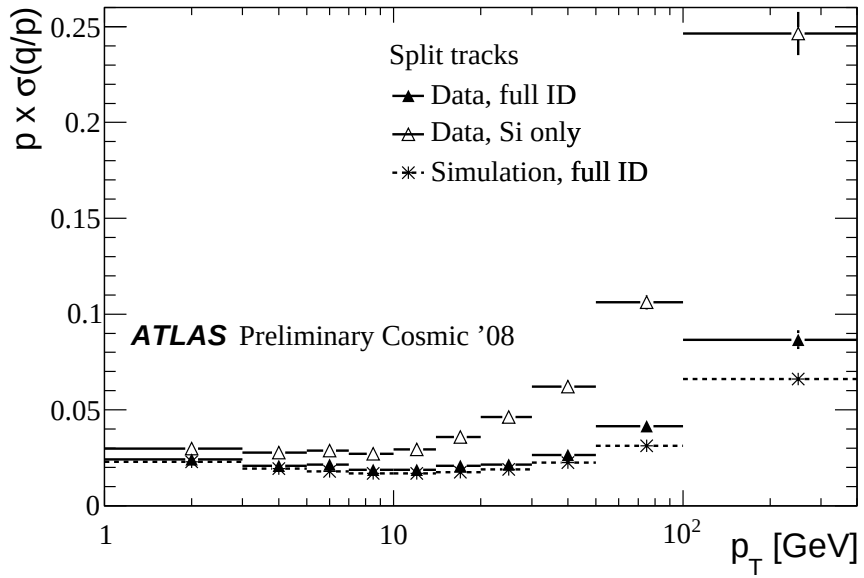
Inner Detector. Track Parameter Resolution. Cosmic.

Impact parameter resolution





Momentum resolution



- split cosmic tracks into top and bottom parts to plot top-bottom distributions ($\sigma = \sigma_{tb}/\sqrt{2}$)
- resolution:
  - low p_t: dominated by multiple scattering
  - high p_t: dominated by intrinsic resolution and misalignment
- TRT information improves momentum resolution at high p_t

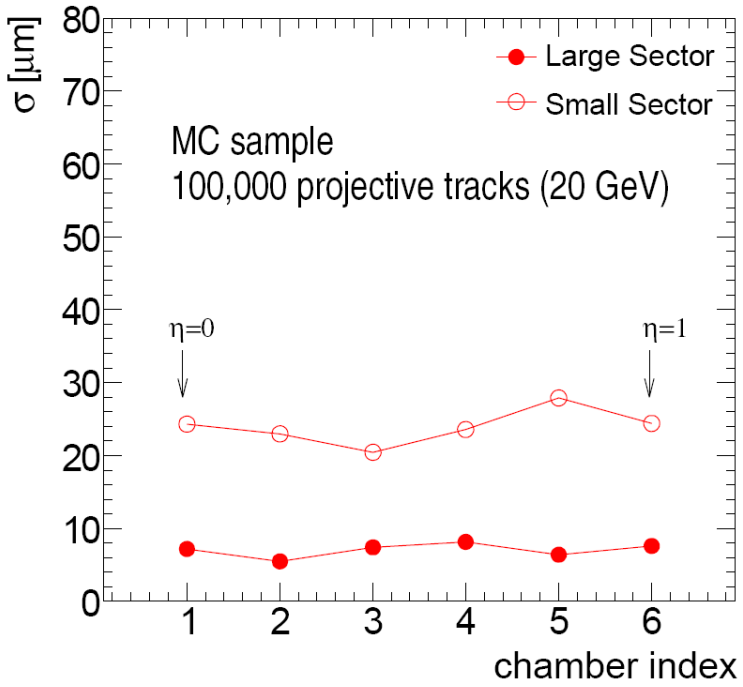
MS. Determination of initial geometry with straight tracks

Algorithm for alignment of muon chambers within barrel sector:

- based upon MILLEPEDE method (V.Blobel)
  http://www.desy.de/~blobel/mptalks.html
- been tested on MC data samples of 20 GeV projective straight muon tracks and on cosmic commissioning data
- 100,000 of 20 GeV tracks per sector needed for 30 μm precision in large and small sectors

* *small sectors have larger uncertainty because of muon multiple scattering in the toroid magnet coils*

Uncertainties on sagitta measurement:



- Run of pp collisions with magnetic field switched off is planned to align the muon spectrometer. For 30 μm: 5 days at $L = 10^{31} cm^{-2} s^{-1}$