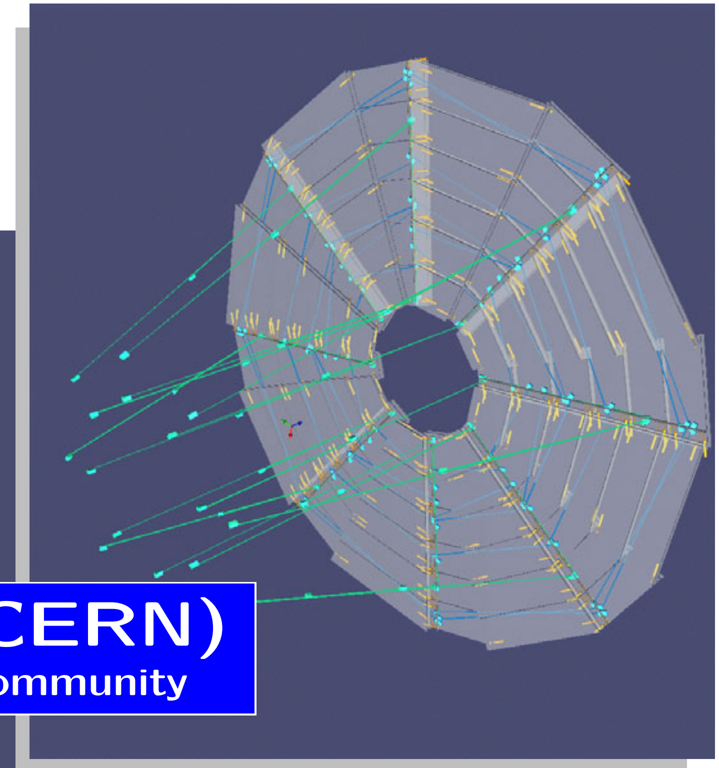
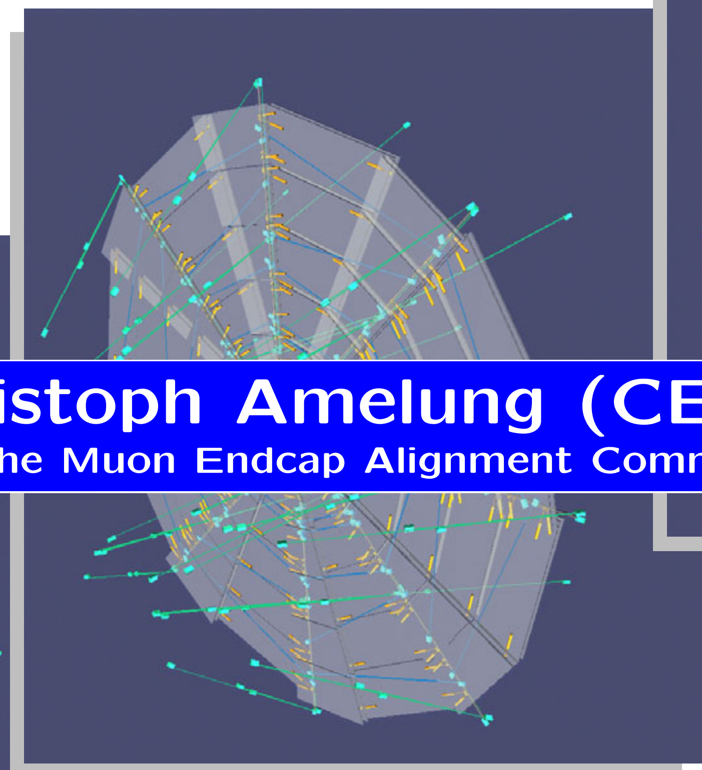
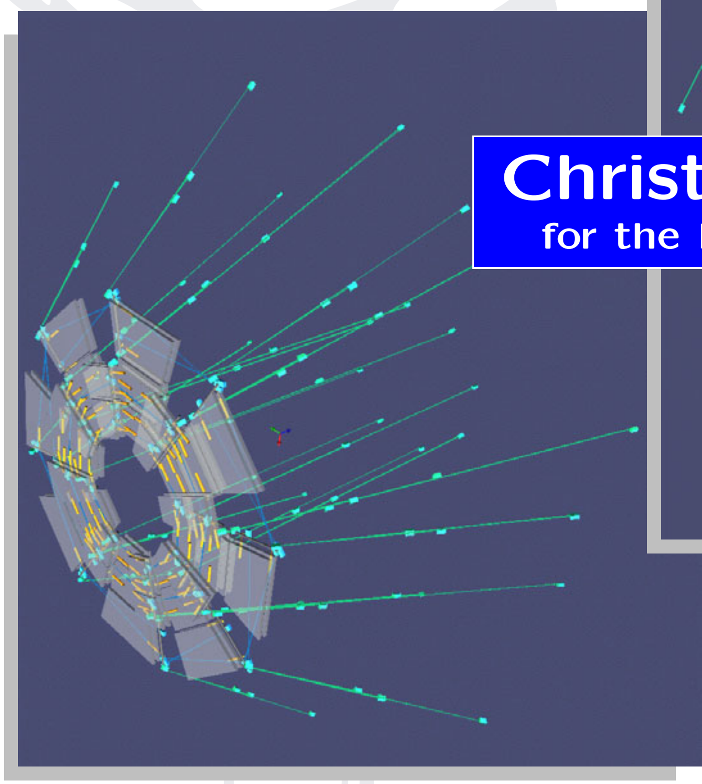
ATLAS Muon Spectrometer

The Optical Alignment System of the Endcaps





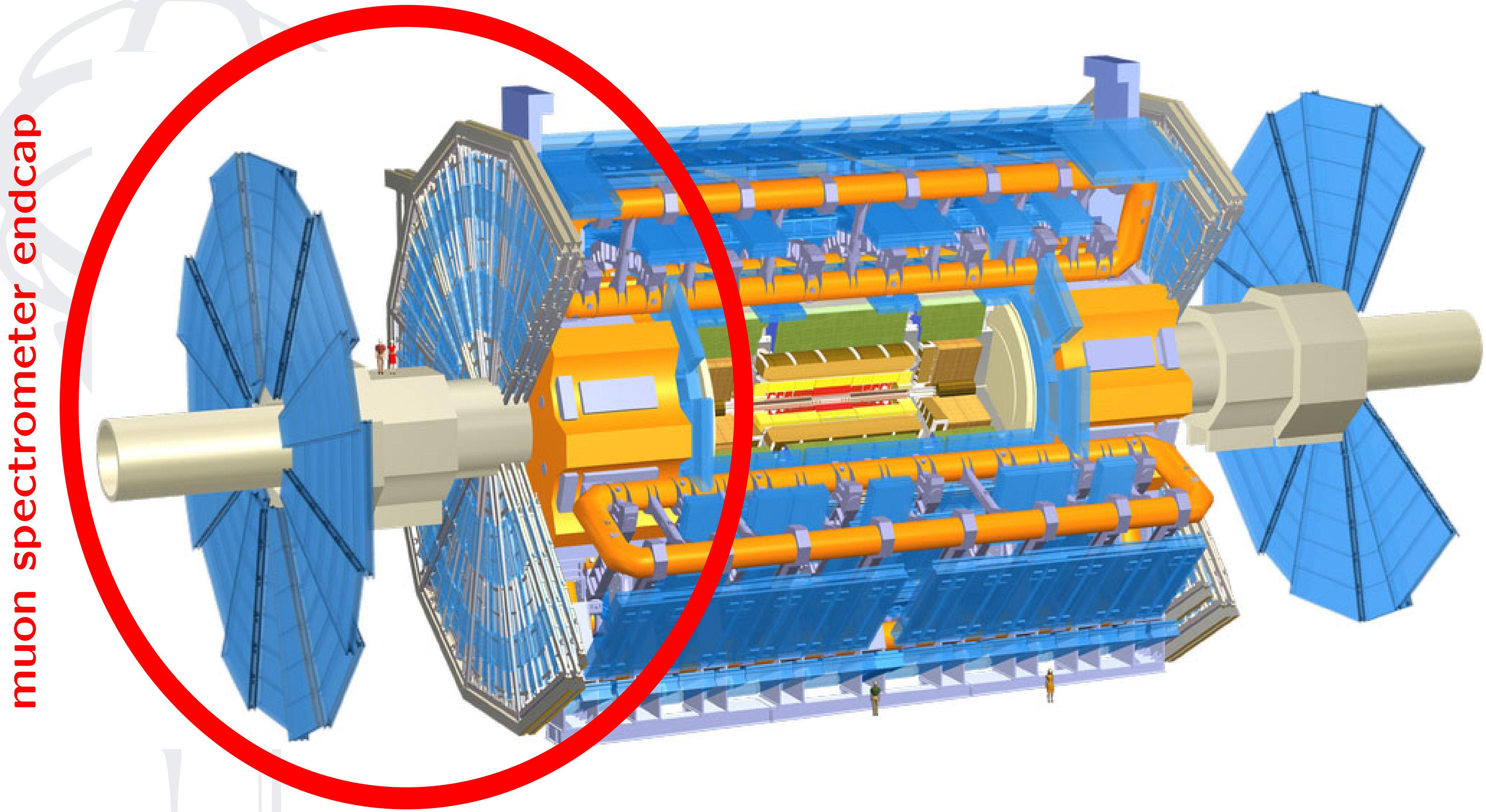
Christoph Amelung (CERN)
for the Muon Endcap Alignment Community



LHC Detector Alignment Workshop
CERN, June 25–26, 2007

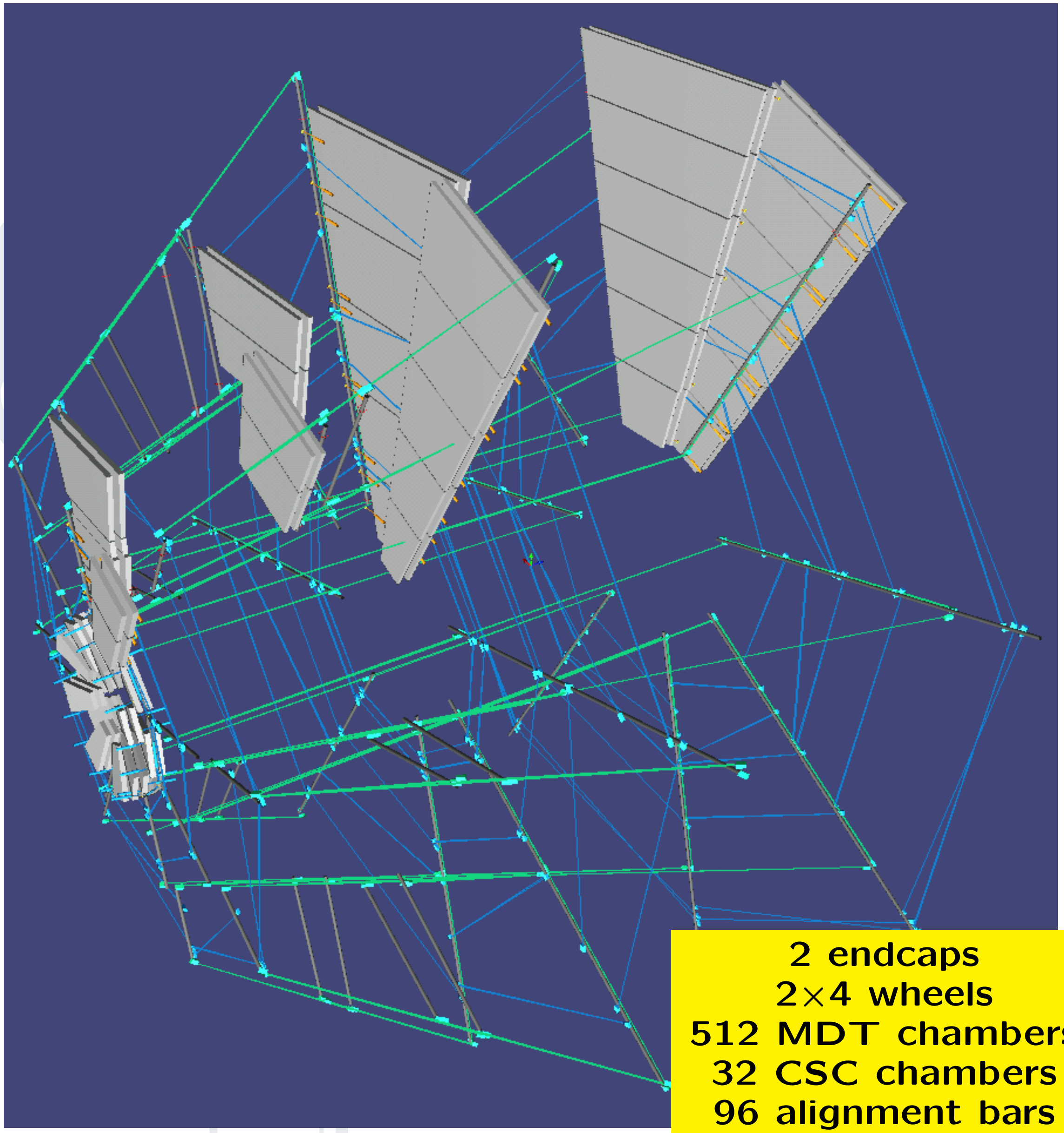
The ATLAS Detector

muon spectrometer | toroid magnets | tile calorimeter | liquid argon calorimeter



solenoid magnet | transition radiation tracker | silicon tracker | pixel detector

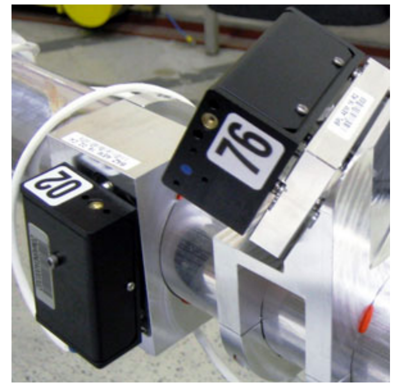
Endcap Optical Alignment System

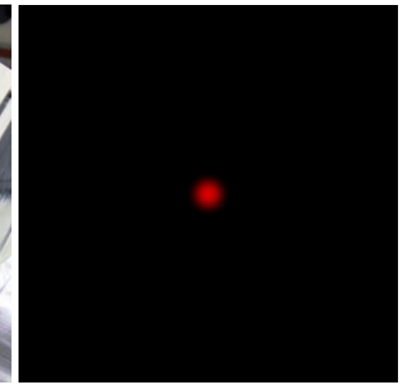


2 endcaps
2×4 wheels
512 MDT chambers
32 CSC chambers
96 alignment bars
≈ 6000 sensors

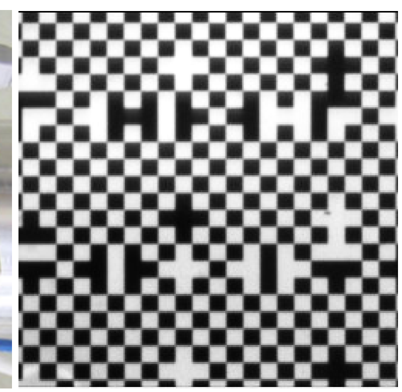
- **Optical sensors:**

  BCAM: camera looks at 1–4 laser diodes, measures bearing angles

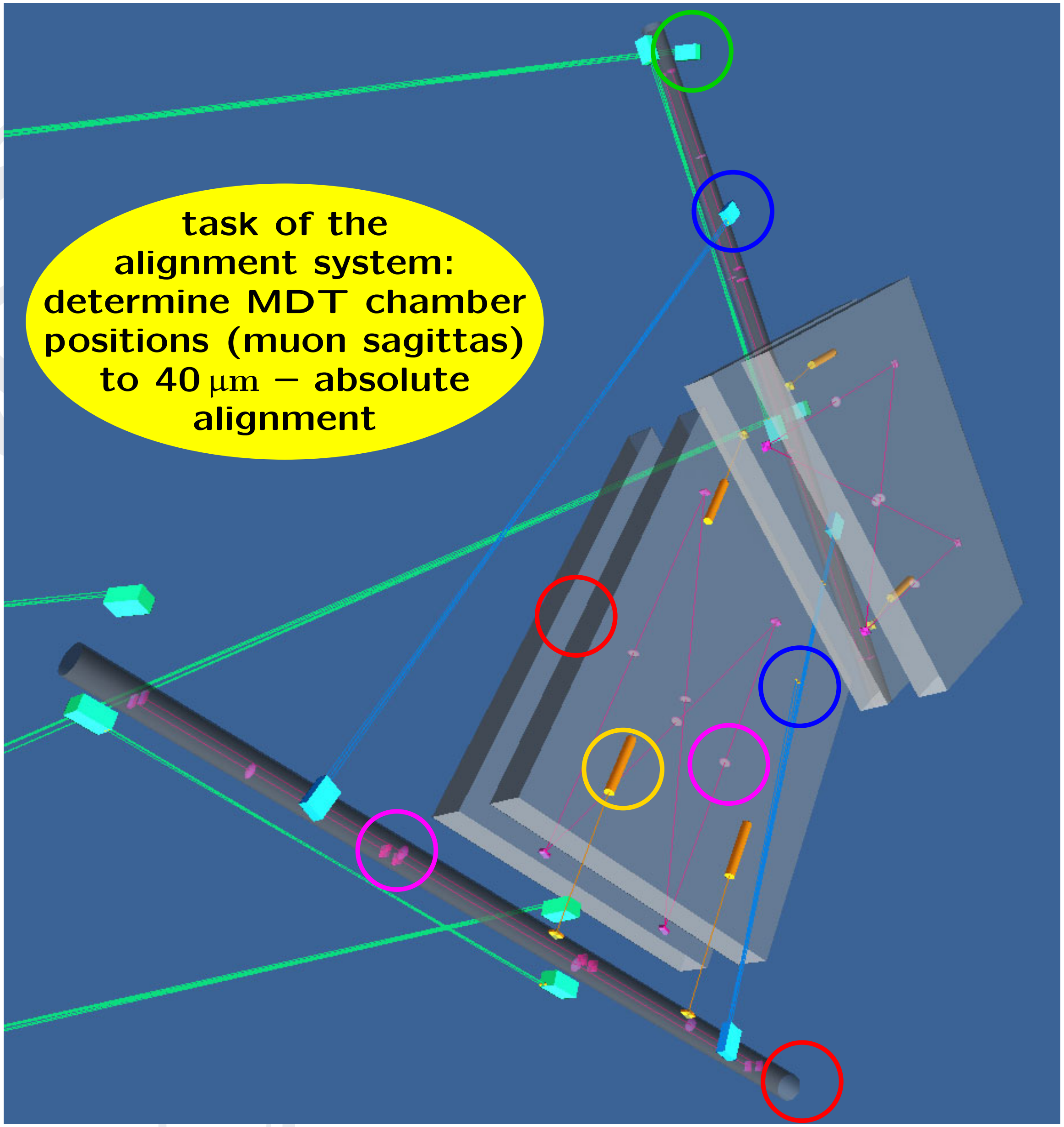




  RASNIK: camera looks at coded chessboard mask, measures displacements



Endcap Optical Alignment System



polar BCAMs

align bars to other wheels

azimuthal BCAMs

align bars within a wheel

chamber sources

align chambers to bars

RASNIK proximity sensors

align chambers to bars

align chamber pairs

in−chamber RASNIKs

measure deformations

in−bar RASNIKs

measure deformations

temperature sensors

measure expansion

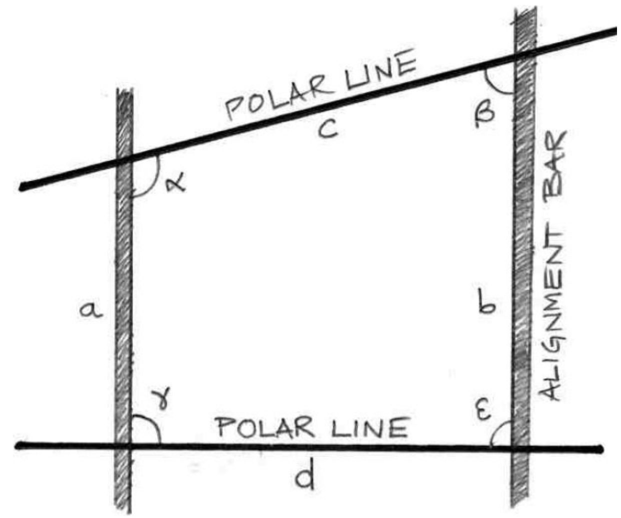
In a Nutshell: Design Idea of the System

- **Quadrangles of bars and BCAMs:**

Quadrangles formed by alignment bars and polar (or azimuthal) BCAM lines

four angles measured by BCAMs, length of two sides given by alignment bars

measurement of absolute positions of alignment bars to ≈ 200 µm



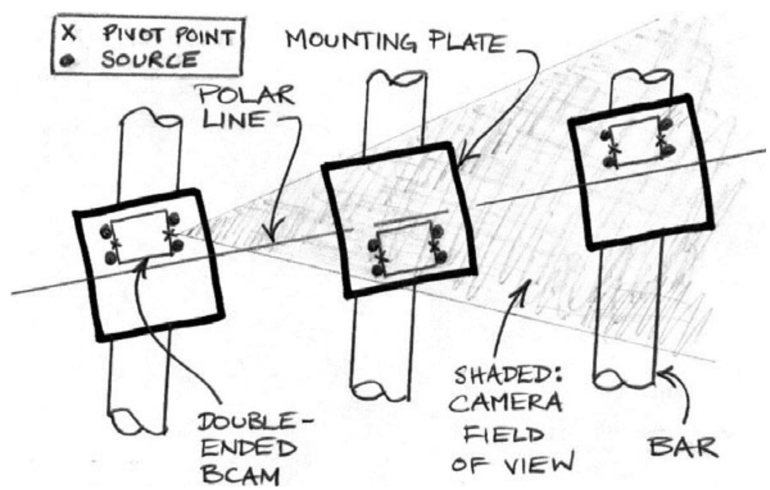
- **Triplets of BCAMs on bars:**

Triplets of BCAMs along polar lines, one BCAM on each bar

each outer BCAM measures the relative positions of the two others – a 3-point straightness monitor like the RASNIK (but less susceptible to mis-positioning)

measurement of relative positions of bars along polar lines to ≈ 30 µm

plus proximity sensors and chamber sources to measure chambers relative to bars to ≈ 30 µm



need both absolute and relative measurements because polar lines non-projective (not pointing to IP)

Alignment Reconstruction Software

- **Alignment problem:**

  many local coordinate systems (one for each object to be aligned), and bar/chamber deformation parameters

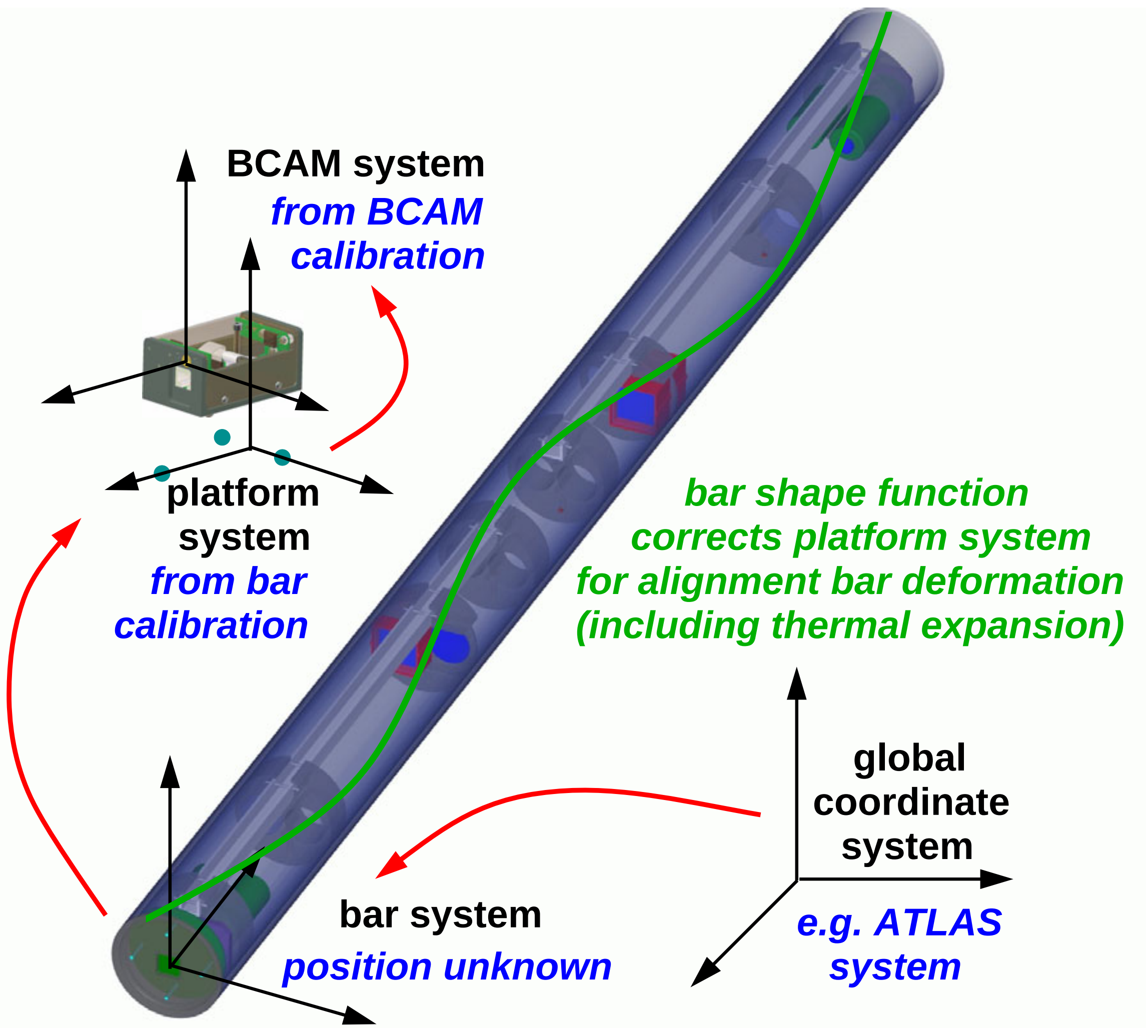
  alignment sensors provide measurements depending on their location

- **ARAMyS software:**

  reconstruct the alignment by varying the unknown positions, rotations, and deformations of alignment bars and chambers

  calculate sensor measurements for an assumed parameter set, compare to actual values from setup, minimize $\chi^2 =$ difference

$$\chi^2 = \sum_{i=1}^{n} \frac{(X_{i,\mathrm{measured}} - X_{i,\mathrm{calculated}})^2}{\sigma^2_{i,\mathrm{intrinsic}} + \sigma^2_{i,\mathrm{mounting}}}$$



Some Computing Aspects

- **CPU performance:**

endcap alignment system has been (cleverly) designed to be

computationally un-intensive

"factorization" – alignment can be reconstructed, without any loss of accuracy or consistency, by splitting the problem into smaller subsets

- chamber and bar deformations: 9 parameters (618×)
- CSC chamber and bar positions: 384 parameters (2×)
- MDT chamber pair positions: 12 parameters (256×)

using MINUIT for χ^2 minimization (Fortran library, recompiled for 8000 parameters)

ARAMyS reconstruction of two full endcaps (10,000 parameters total) on 3.2 GHz Pentium-D: 1.5 min

- **Why use MINUIT:**

MINUIT implements an algorithm that is faster and numerically more stable than a simple matrix-inversion method (not competitive in speed with sparse-matrix algorithms – but our matrices are small, not sparse)

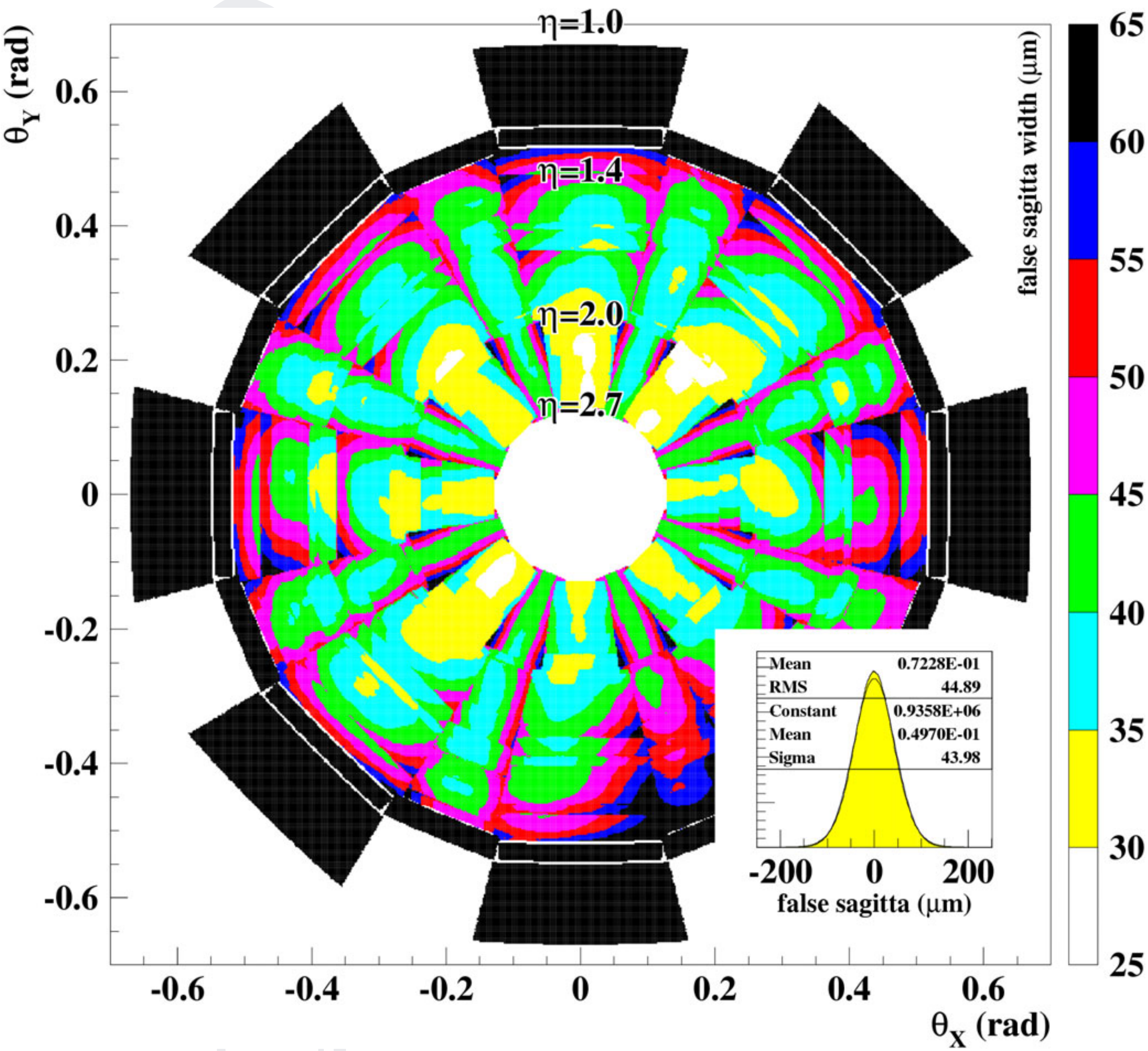
MINUIT knows when it has properly converged (i.e. found minimum of χ^2 function), rather than leaving it to the user to stop iterations (when ?)

MINUIT tells the user when it has failed to converge, and when it cannot converge, due to an ill-posed problem (e.g. some fit parameters not constrained by measurements)

these features were invaluable for development/debugging/understanding

tested up to 4500 simultaneously fitted parameters – no problems

Alignment Simulation Software, too



- **Alignment system MC simulation:**

  for many (100–1000) incarnations of ATLAS, smear simulated sensor measurements according to their resolution, reconstruct chamber positions, compare to truth

  figure of merit: width of false sagitta distribution

  a simulation like this was used to determine design accuracy and resolutions of the alignment sensors (some 10–15 years ago)

typical requirements:
20 μm and 50 μrad for sensor ⊕ platform

Calibration of Sensors and Platforms

- **Alignment sensors:**

  calibrated by measurements with a target at different distances and/or rotations on a calibration stand; some use also CMM measurements

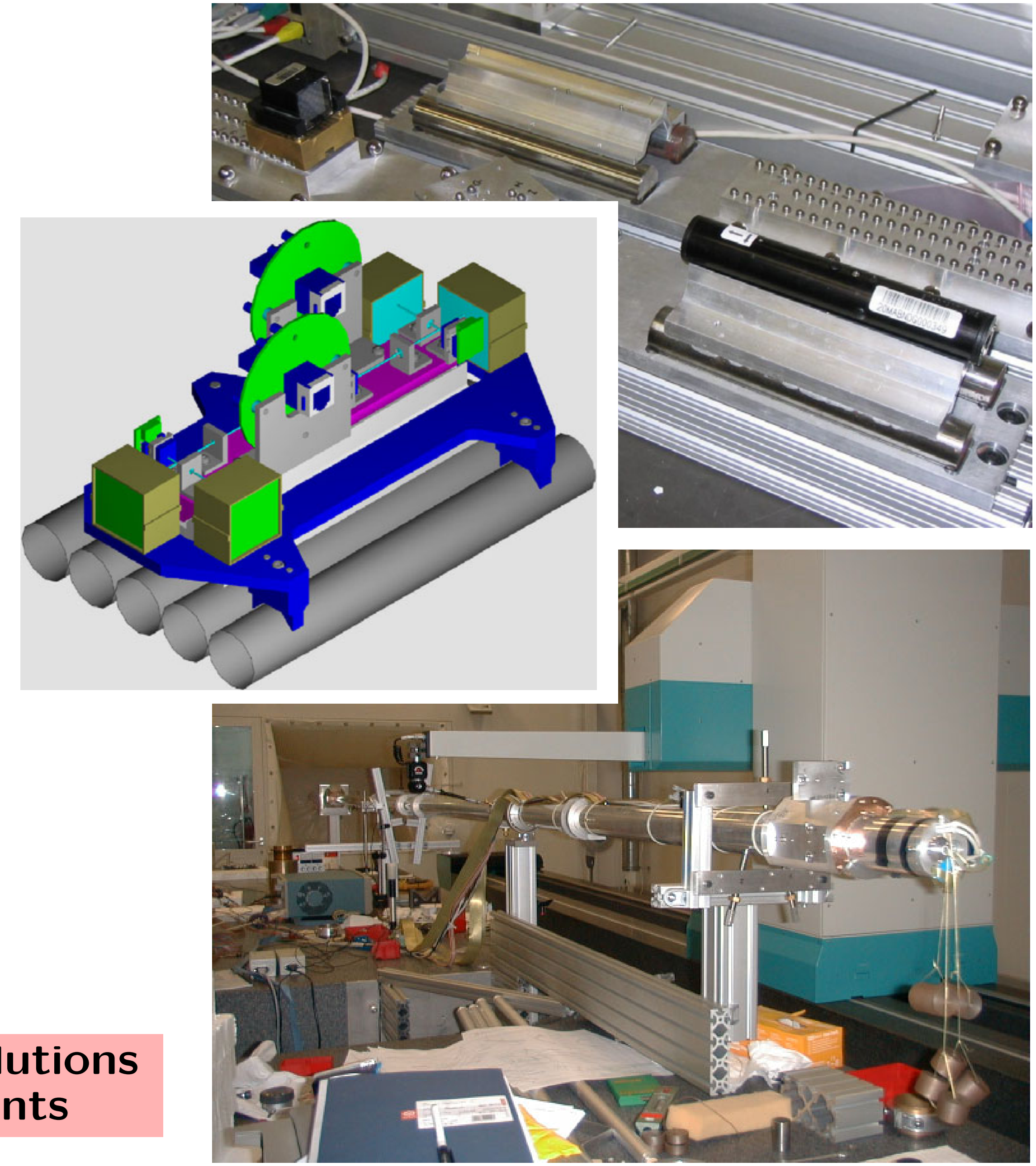
- **Platforms on chambers:**

  calibrated by calibration tools measuring the platforms with respect to the tube surfaces (MDT chambers); and by CMM measurements (CSC)

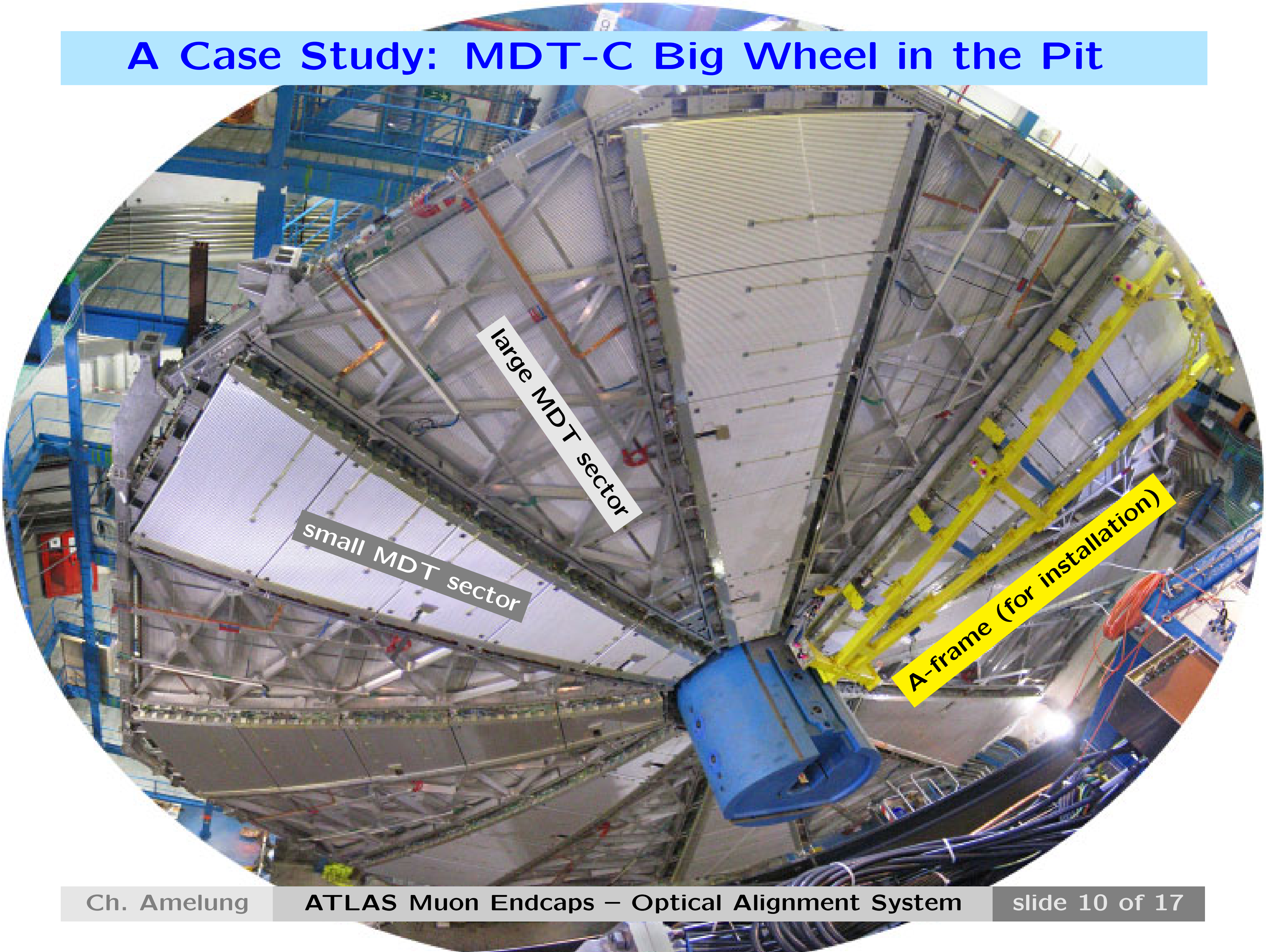
- **Platforms on bars:**

  calibrated by measurements with a CMM, for different deformations of the bar

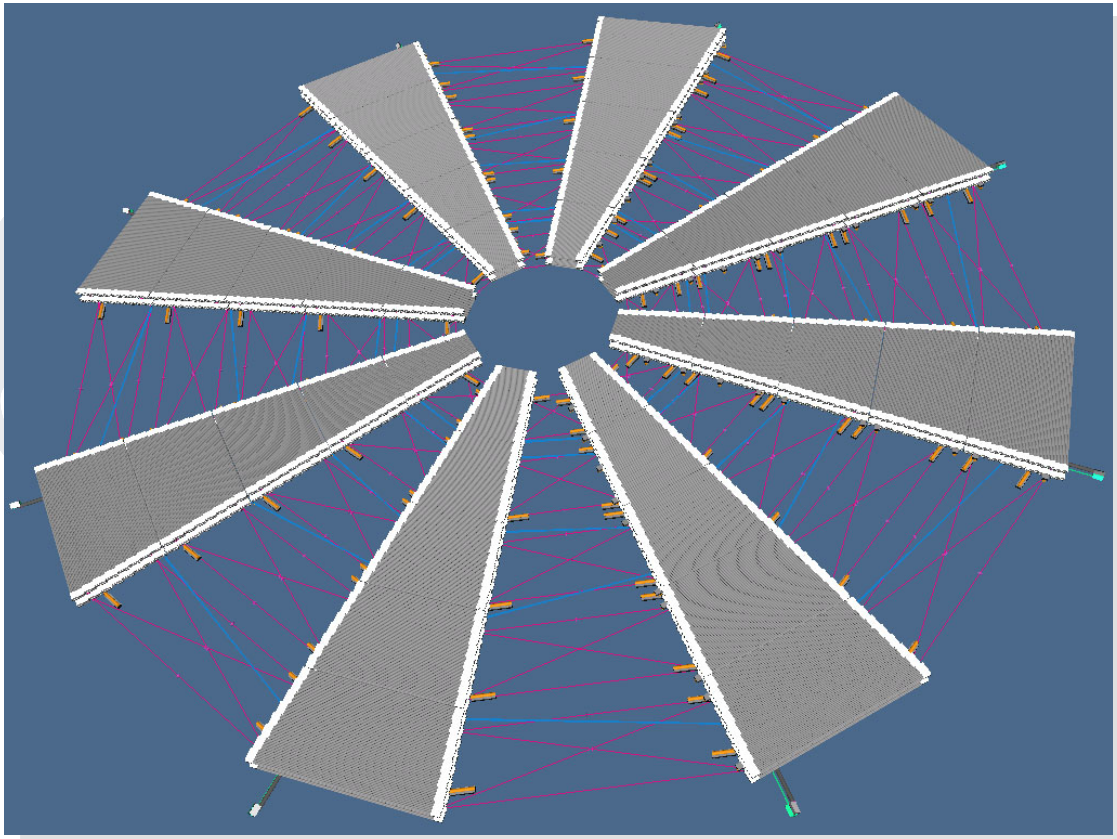
observed accuracies and resolutions
$\approx$ matching the requirements



A Case Study: MDT-C Big Wheel in the Pit



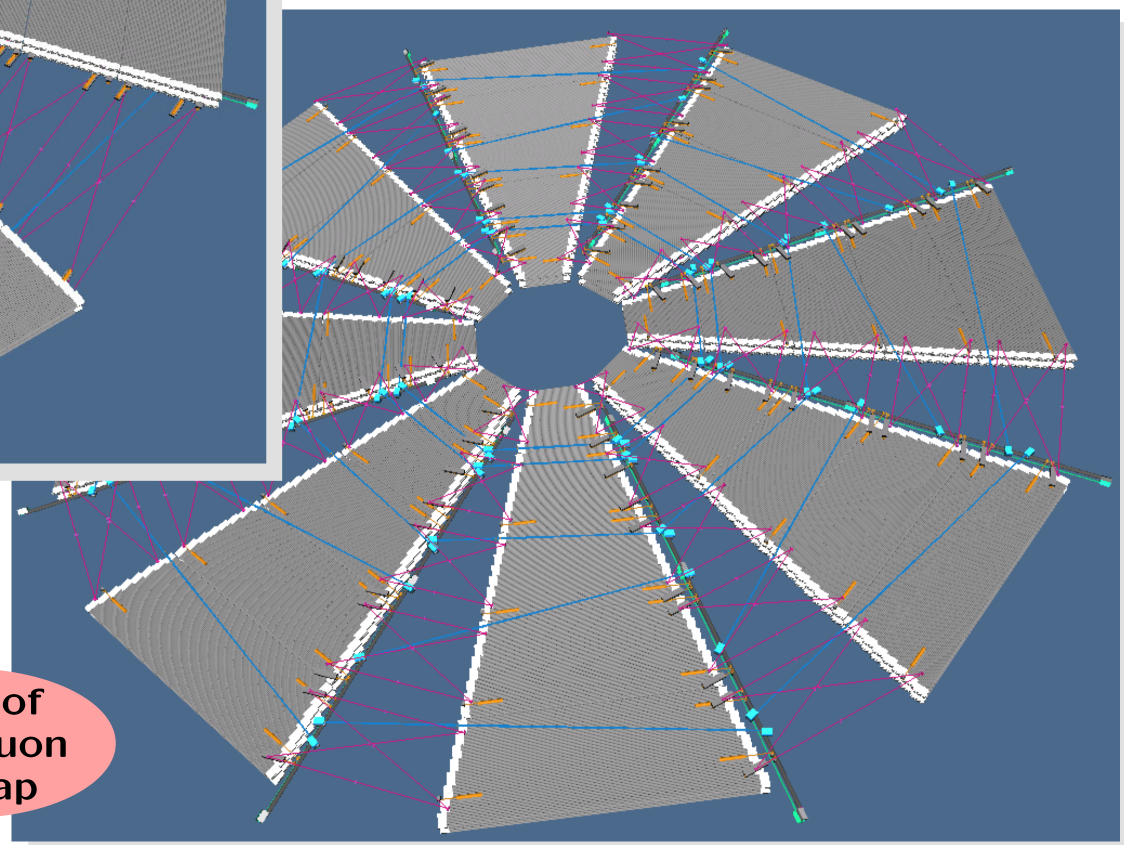
A Case Study: MDT-C Big Wheel in the Pit



alignment data taken in parallel to survey performed by TS/SU

(survey precision $\approx 500\,\mu\mathrm{m}$)

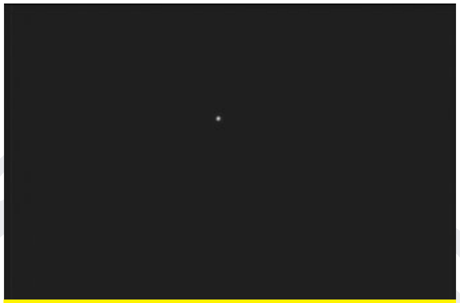
around 99% of all (relevant) sensors working and giving consistent measurements

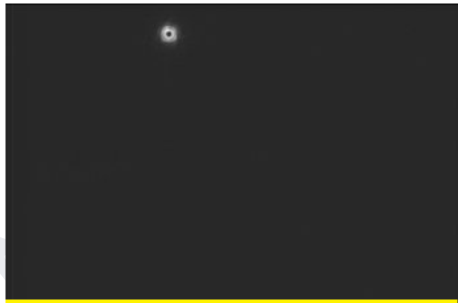


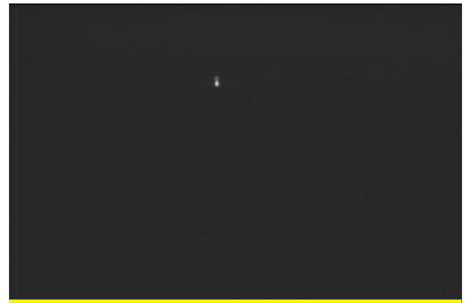
80 MDT chambers
8 alignment bars
128 BCAMs
200 proximity sensors
80 chamber sources
32 in-bar RASNIKs
320 in-chamber RASNIKs

30% of one muon endcap

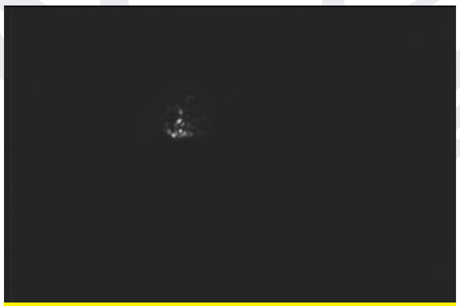
Big Wheel Sensors: Picture Gallery


excellent
BCAM image

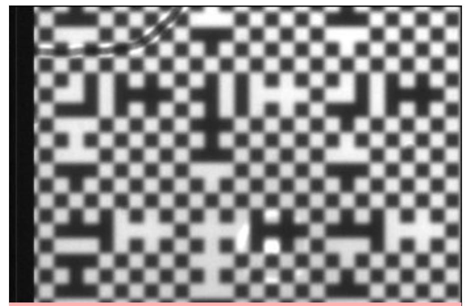

ok – source very
close to camera

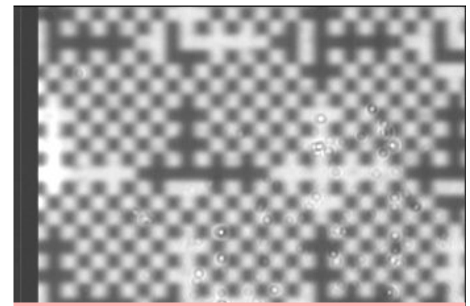

bad – optical line
partially blocked

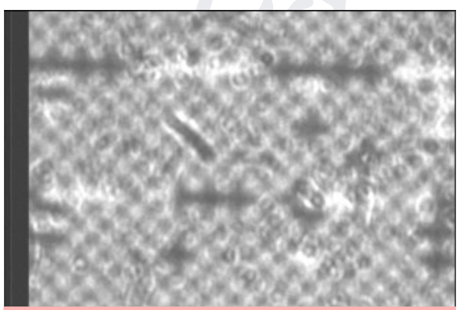

bad – reflections,
source out of range

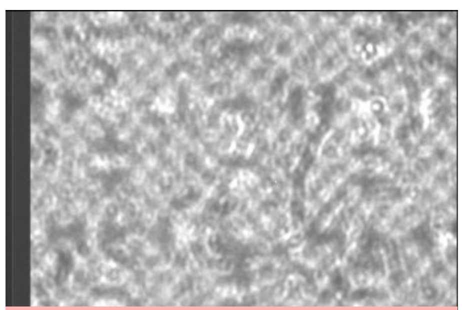

bad – reflections,
optical line blocked

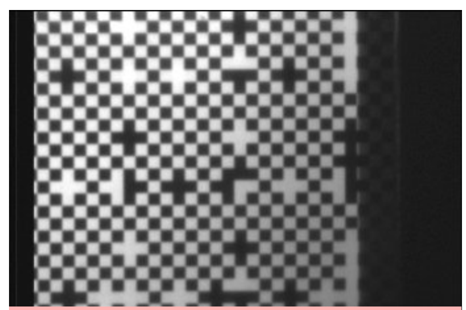

excellent
RASNIK image


ok – hair on mask


ok – dust on CCD


ok – lots of
dust on CCD


bad – too much
dust on CCD


ok – close to edge
of dynamic range


bad – out of range,
too few squares

Big Wheel Alignment Reconstruction Results

- **Reminder:**

$$\chi^2 = \sum_{i=1}^{n} \frac{(X_{i,\text{measured}} - X_{i,\text{calculated}})^2}{\sigma^2_{i,\text{intrinsic}} + \sigma^2_{i,\text{mounting}}}$$

assumed sensor resolutions σ_i are design resolutions; with these we obtain the design performance of the system

rule of thumb: if $\chi^2/N = 1$, alignment is good to 40 μm

and if $\chi^2/N \neq 1$, it scales like $\sqrt{\chi^2/N}$

- **Result for the Big Wheel:**

$\chi^2/N = 1.01$ for $N = 2535$

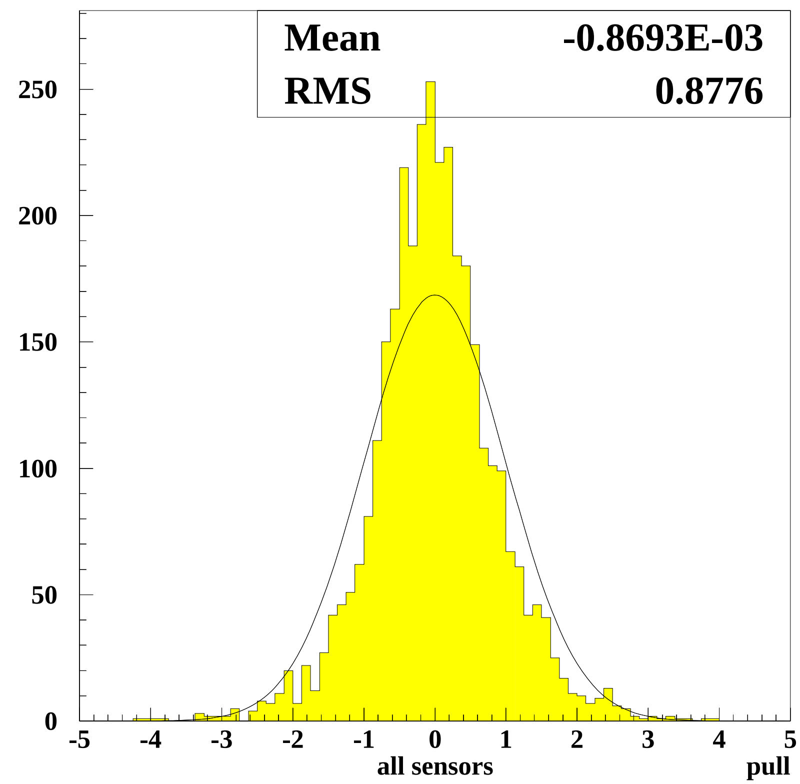
(standard fit: sensors only)

$\chi^2/N = 1.03$ for $N = 3529$

(combined fit: survey and sensors, to check consistency with survey)

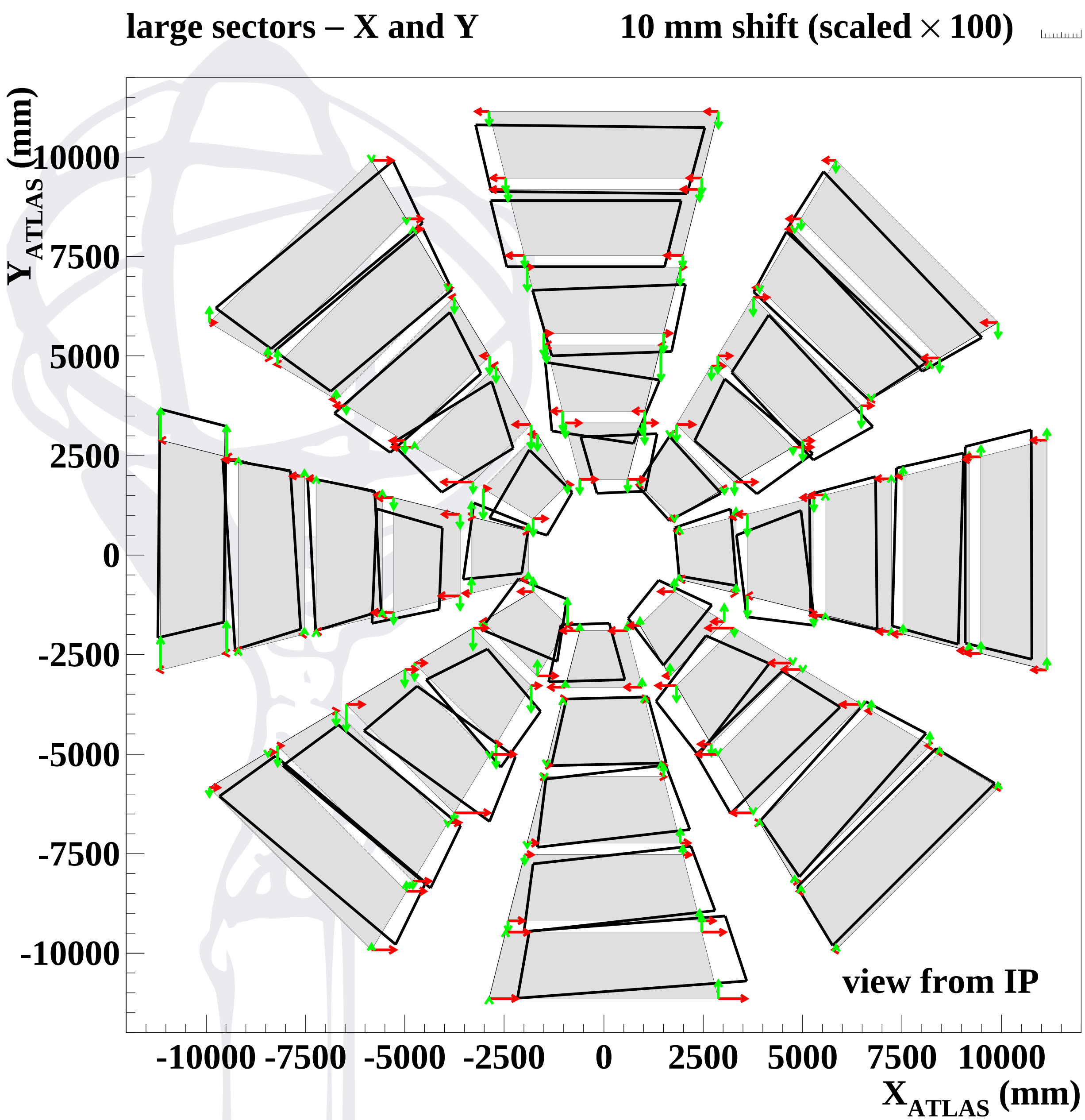
- **Pull distribution:**

pull^2 = sensor contribution to χ^2
(expect rms 0.83 from simulation)



$\rightarrow$ the system really works, all calibrations are accurate, and we are close to 40 μm !

Reconstructed MDT Chamber Positions



- **MDT positions in the Big Wheel plane:**

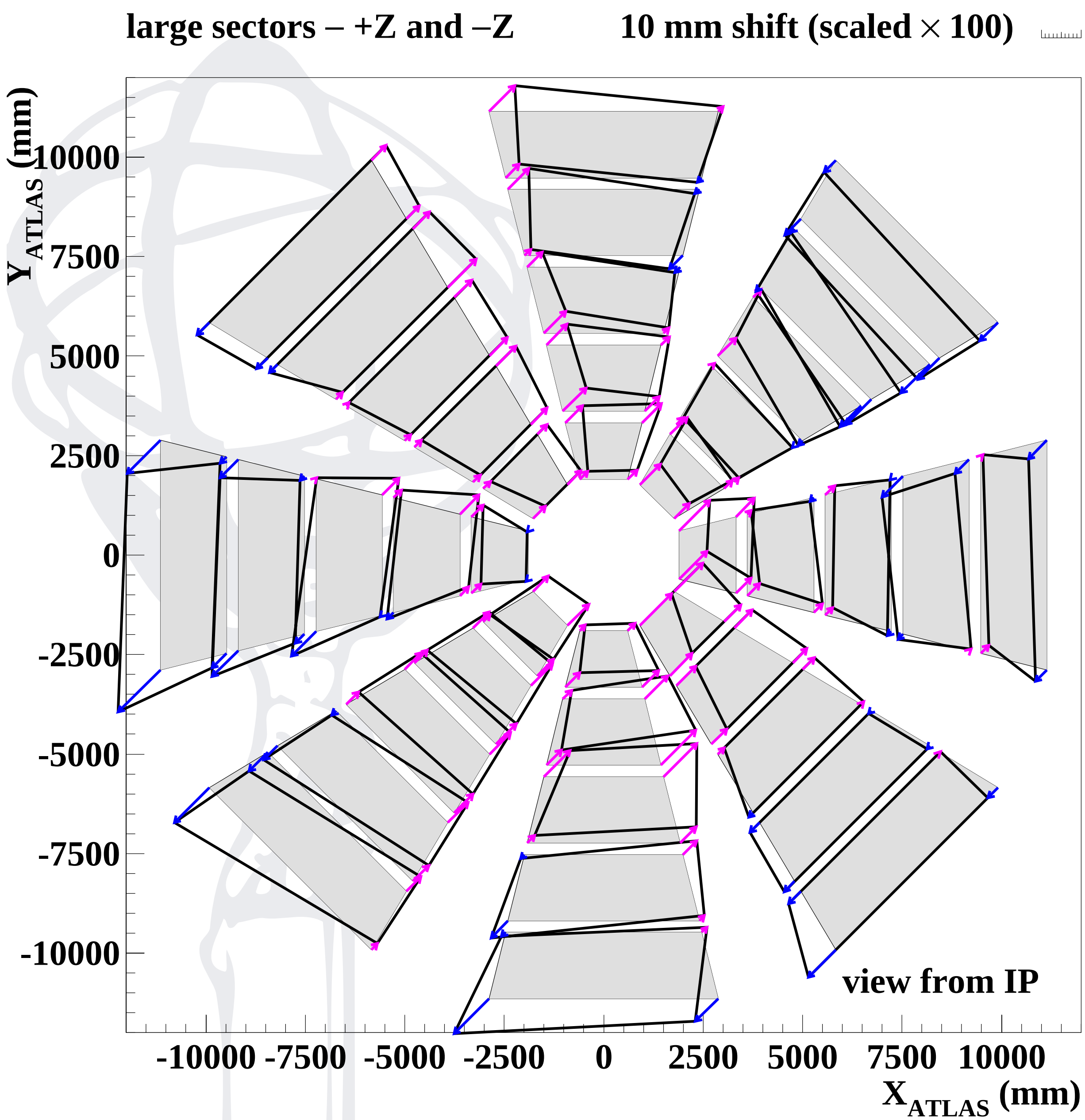
measured by alignment system, confirmed by survey

grey area = nominal position

black lines = actual position (displacement exaggerated)

red/green arrows = shifts of four corner-points in the ATLAS-X/Y directions

Reconstructed MDT Chamber Positions



- **MDT positions out of the Big Wheel plane:**

  measured by alignment system, confirmed by survey

  grey area = nominal position

  black lines = actual position (displacement exaggerated)

  blue/magenta arrows = shifts of four corner-points in the ATLAS-Z direction (towards/away from IP)

Some Remarks on "Initial Geometry"

- **An alignment system working in absolute mode:**

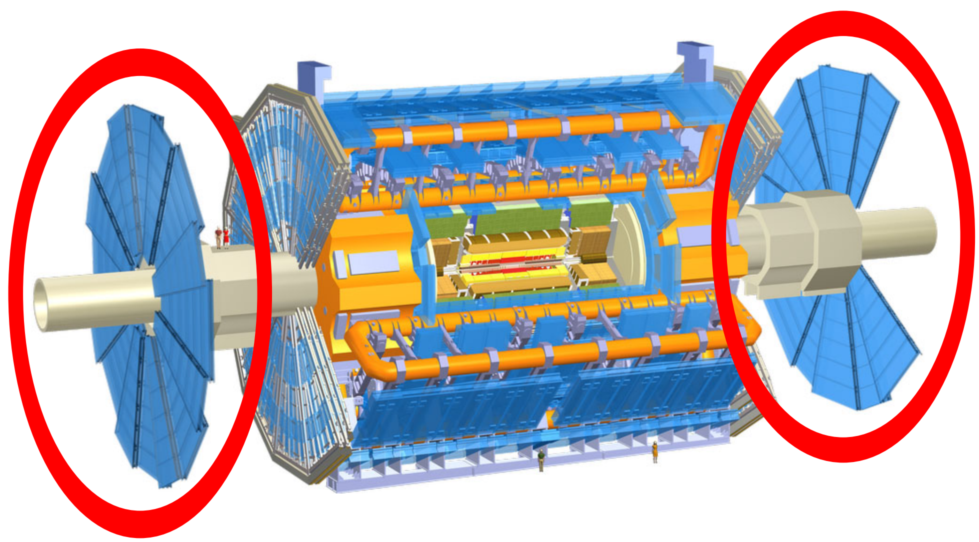
provides (by construction) the "initial geometry", i.e. the positions of all chambers in a common coordinate system

we do not need any tracks to do this (except for cross-checks)

note the endcap coordinate system is not the ATLAS system – no connections between endcap coordinate system and any reference points of the ATLAS system (survey marks in the cavern)

however: outermost wheel of each endcap remains accessible and visible for survey (photogrammetry) after completion of the ATLAS detector

by including survey data from those wheels in the alignment reconstruction (and assuming that their positions are stable in time), can locate the entire endcaps in the ATLAS coordinate system to better than 500 μm at any time during ATLAS running



→ better than any other ATLAS subdetector (?)

Conclusions

- **Summary:**

  after many years of design work and preparations, we have the alignment system of one Big Wheel (15% of the total system) running in the pit

  in a few weeks, second Big Wheel will be in the same state

  we obtained consistent reconstruction results which were confirmed by a survey

  quite unexpected by many, it was (nearly) plug & play

  we are confident to provide 40 $\mu\mathrm{m}$ sagitta accuracy before the first muon from a collision enters the endcaps

  plus absolute location of endcaps in the ATLAS coordinate system to better than 500 $\mu\mathrm{m}$ (with help from surveyors)