Alignment Challenge @ CMS

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1st LHC Detector Alignment workshop
CERN
4th September 2006

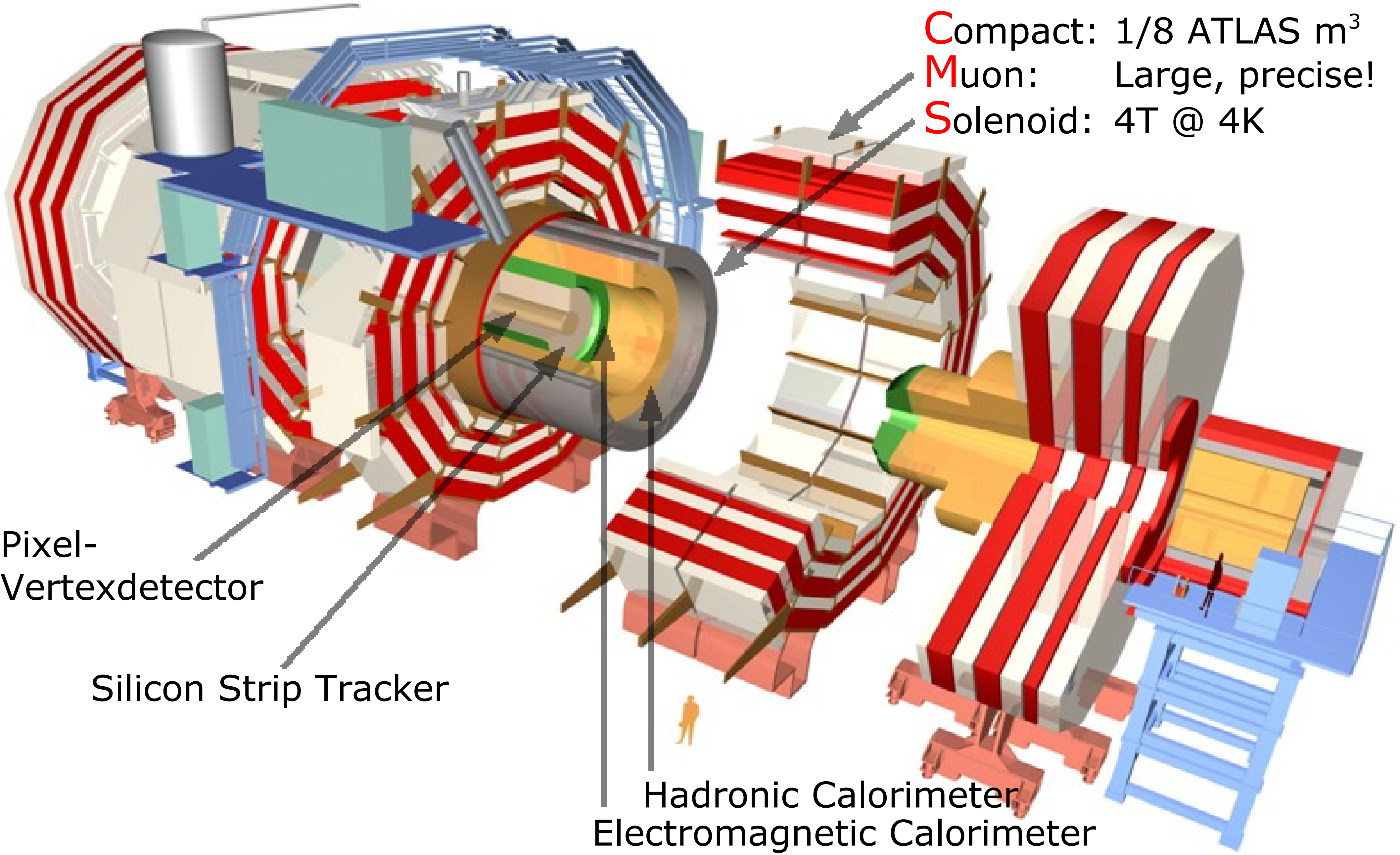
Part I
CMS

Part II
Alignment

Part III
The Challenge

Part I:

CMS



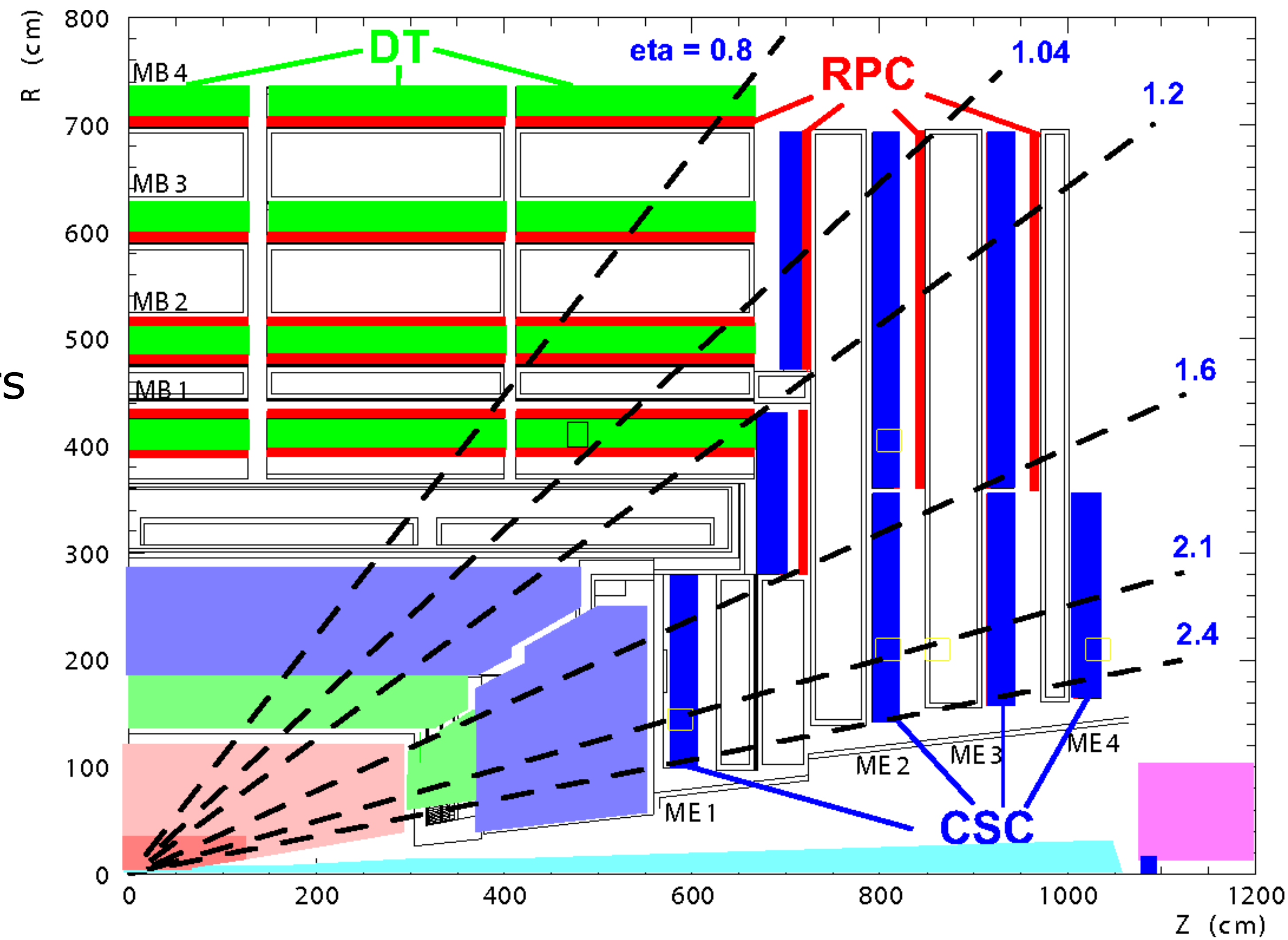
Compact: 1/8 ATLAS m^3
Muon: Large, precise!
Solenoid: 4T @ 4K
Pixel-
Vertexdetector
Silicon Strip Tracker
Hadronic Calorimeter
Electromagnetic Calorimeter

Barrel station:
Drift tube
$\sigma_{single} \approx 200\ \mu m$
$\sigma_{position} \approx 100\ \mu m$
$\sigma_{angle} \approx 1$ mrad

Endcap:
Cathode Strip Chambers
$\sigma_{single} \approx 200\ \mu m$
$\sigma_{angle} \approx 10$ mrad

RPC:
$\Delta\eta \times \Delta\varphi \approx 0.1 \times 5/16°$

250 Drift chambers
468 CSCs
360+252 RPCs

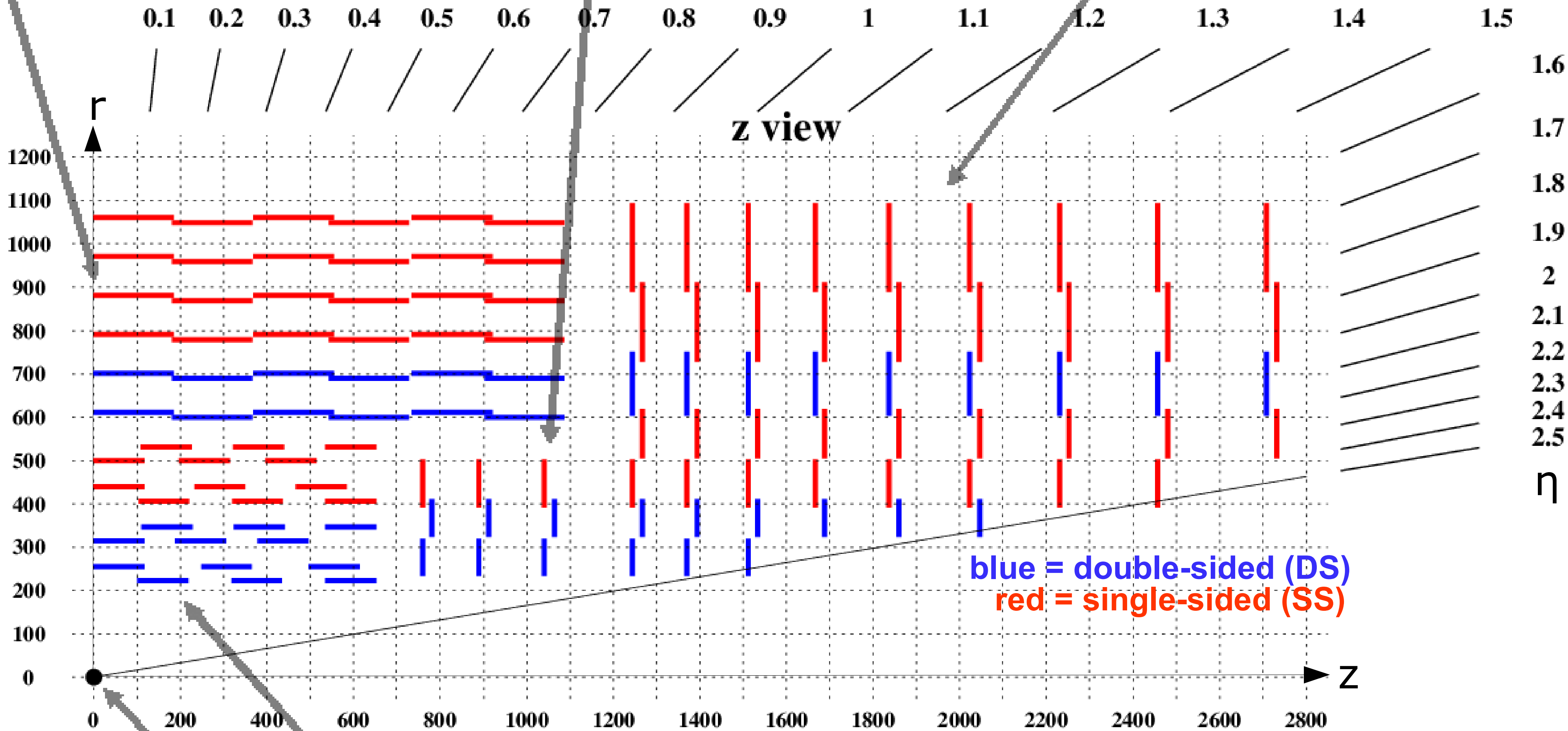


Myon system shrinks by 0.5 cm (barrel) and 1 cm (endcap) with field on!

Outer Barrel (TOB)
6 layers 500 μm Si

Inner Disc (TID)
3 discs, 3 rings 320 μm Si

Endcap (TEC)
9 discs, 4-7 rings
(1..4 320 μm, 5-7 500 μm)

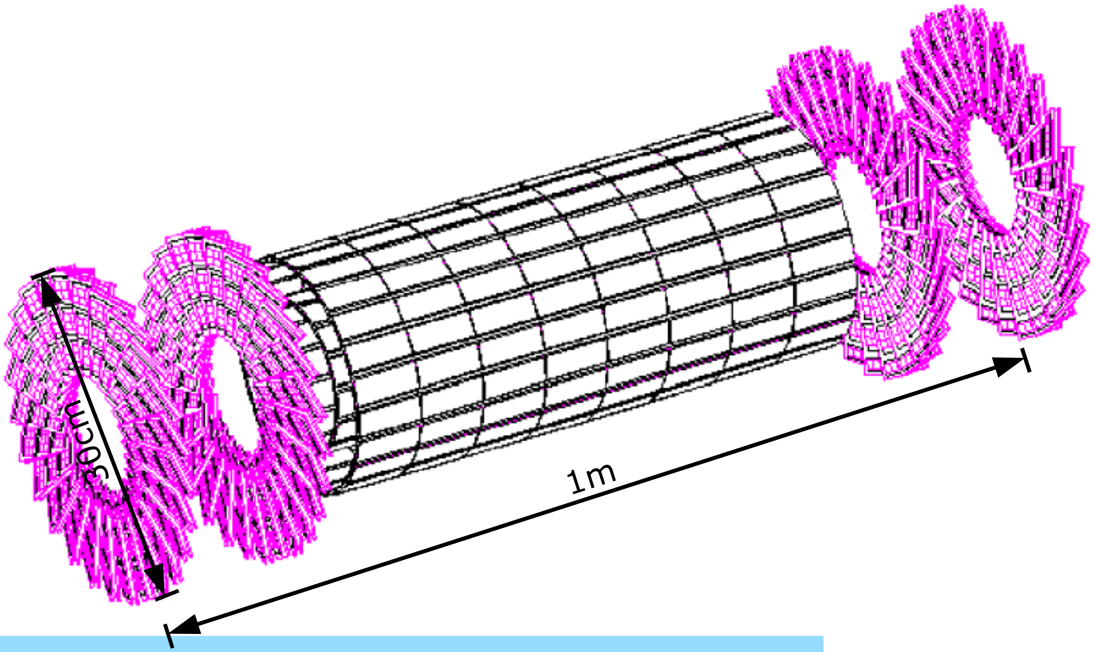


Interaction point

Inner Barrel (TIB)
4 layers 320 μm Si

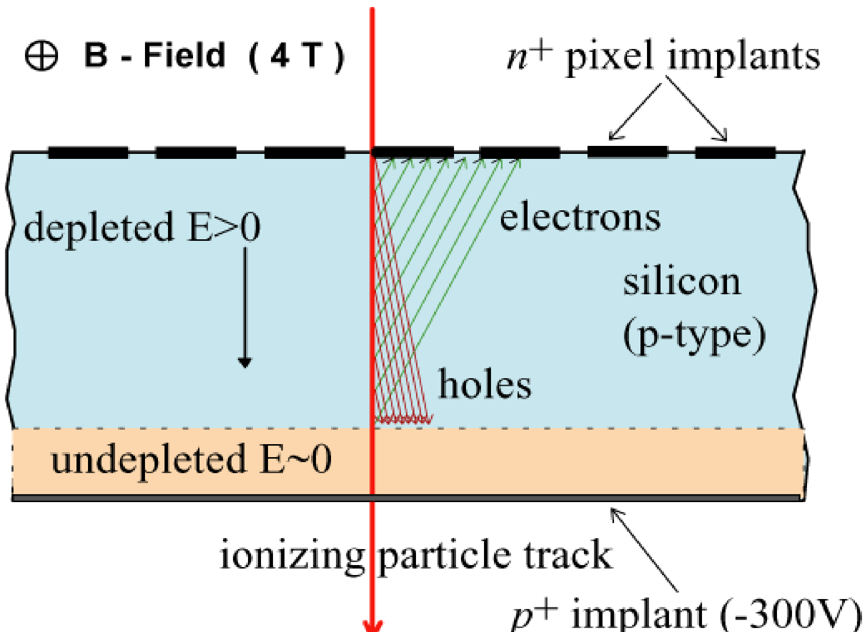
Strip pitch 80-205 μm
σ ≈ 23-60 μm
15148 modules

CMS Pixel Detector



General layout
- active area ~ $1m^2$
- dimensions: 100 cm x 30 cm
- $66*10^6$ channels
- pixel size: 100 µm (rφ) x 150 µm (z)

Hit resolution
- electron drift
- lorentz angle (23°) -> charge sharing
- resolution: 10 µm (rφ) x 15 µm (z)



Barrel layers
- 2007 pilot run: few modules only
- From 2008: r=4.4cm 7.3cm 10.2cm
- 1200 modules
- η< 2.4 (collision centered)
- η< 2.2 (collision 1σ displaced)

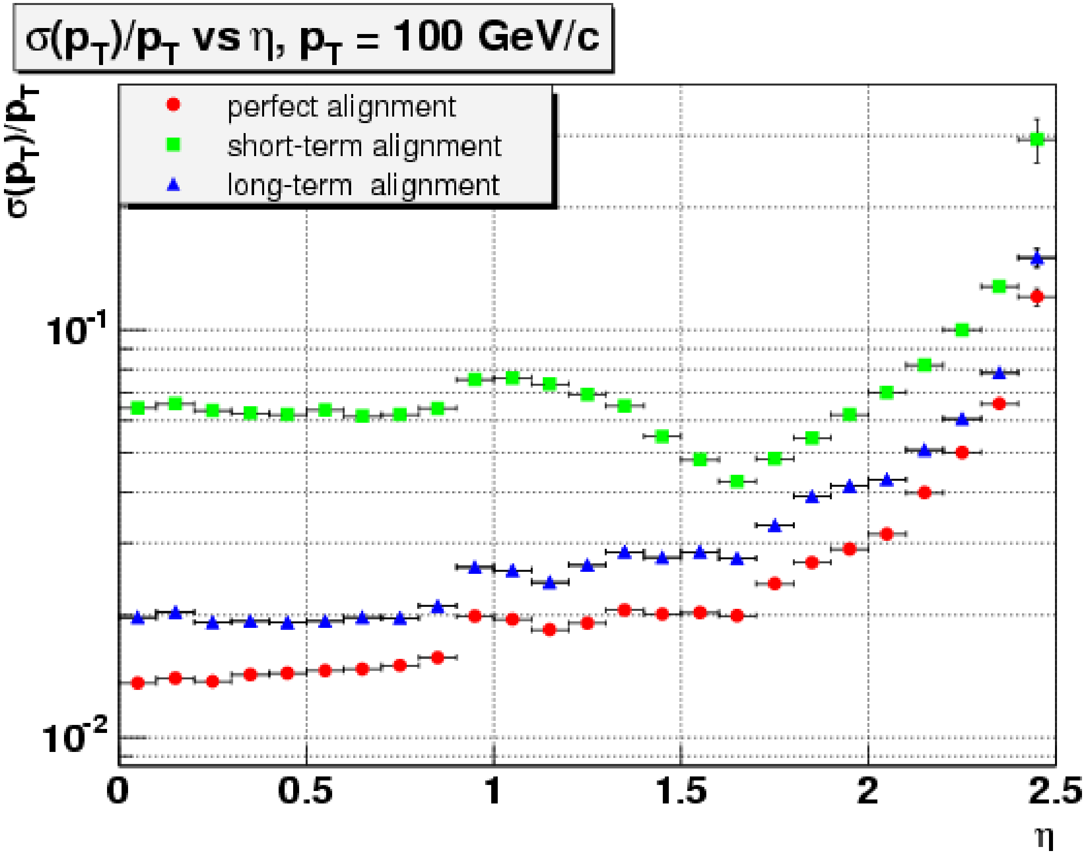
Endcap disks
- r=6cm...15cm
- 700 modules
- rotate endcap petals by 20° for lorentz angle

Part II:

Alignment

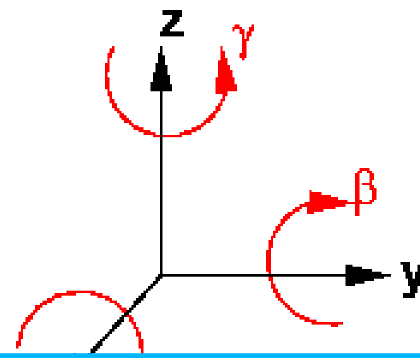
- Misalignment is due to
  - Precision of assembly
  - Stress from magnetic field or thermal stress
  - Changes due to humidity and gas evaporation (from carbon fiber support)
- Misalignment will be time dependent!

G. Steinbrück, Tue 10:00



- Ideal geometry
  - No misalignment
- Short-term (<1 fb^{-1})
  - First data taking
  - Hardware alignment used
- Long term (1-5 fb^{-1})
  - First alignment with high-statistics tracks, for first physics analysis
- Final alignment
  - Do not deteriorate detector res.

- Estimation of
  - Sensitive detector position, orientation (6 parameters)
  - \+ ... module bending ... magnetic field ... material budget ...



- Different approaches considered (time / method)
  - Assembly knowledge (Muon, pixel, strip) NOW
    - Knowledge of ideal geometry, assembly precisio
  - Hardware alignment (Muon: MA, strip: LAS) PRE-CO
    - Laser, LED, CCD, proximity & tilt sensors
  - Track based alignment (Muon, pixel, strip) COLLISIO
    - Z→ μμ as single muons, Z→ μμ with mass constraint, Cosmics, beam halo, ...

C. Lasseur, Wed 9:30

B. Wittmer, Tue 11:15

I. Vila, Tue 14:00

P. Arce, Tue 14:25

F.-P. Schilling, Tue 14:50

- Different databases, measured objects, precision, correlations...
  - Combining measurements will help in the beginning

- Linear least-squares (LLS): Application of Gauss-Markov Theorem
  - Gives best linear unbiased estimators (**BLUE**) of parameters (best = minimal MSE)
  - Measurement function $\vec{f}(\vec{p})$ (where $\vec{f}$ are the hit coordinates, 1D, 2D, ..., 6D)
  - Depending on unknown parameters $\vec{p}$ (track parameters, alignment parameters)
  - Linearize function $\vec{f}(\vec{p})=\vec{f}(\vec{p}_0)+A(\vec{p}-\vec{p}_0)+O((\vec{p}-\vec{p}_0)^2),\ A=\left.\frac{\partial \vec{f}}{\partial \vec{p}}\right|_{\vec{p}=\vec{p}_0}$
  - Write a χ2-function, minimize difference between prediction $\vec{f}$ and measurement $\vec{m}$:

$$\chi^2=(\vec{f}(\vec{p}_0)+A(\vec{p}-\vec{p}_0)-\vec{m})W(\vec{f}(\vec{p})+A(\vec{p}-\vec{p}_0)-\vec{m}),\quad V=cov(\vec{f}-\vec{m}),\quad W=V^{-1}$$

  - Minimize by computing $$A^T W A$$
  - In a clever algorithm, track parameters are not fitted → $A^T W A$ has size NxN (N = Number of alignment parameters)
  - Brute force solution: Inversion or Diagonalization

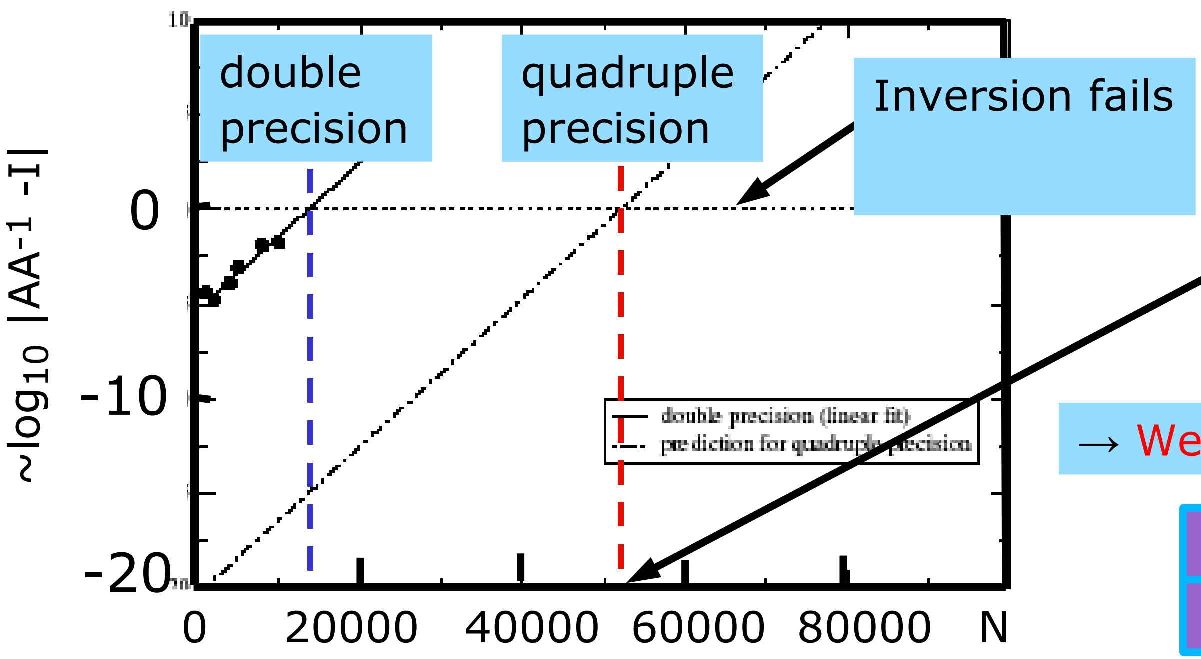
$$\tilde{\vec{p}}=\vec{p}_0+\left(A^T W A\right)^{-1} A^T W\left(\vec{m}-\vec{f}(\vec{p}_0)\right)$$

Part III:

The challenge

Strip tracker: Algorithmic challenge

- Estimate ~6 parameters per strip tracker module
  - CMS strip tracker is built of 15148 modules → alignment parameter covariance matrix E or matrix to be inverted $A^T W A$ are sized (15148*6)^2 = 90888^2
  - Store E or $A^T W A$ in memory (~32 GB for double precision → sparse storage)
- Experience from ATLAS (COM-INDET-2004-011)
  - Matrix inversion and Diagonalization algorithms break down at ~50000 parameters due to CPU time limitation and floating point precision:

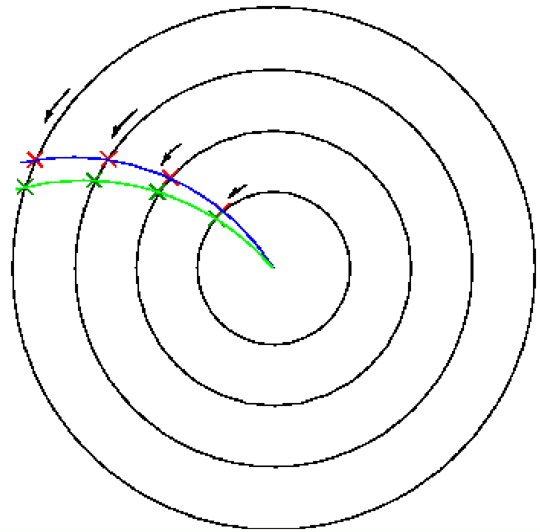


Not more than ~50000 parameters possible even with quadruple precision!
(ATLAS: 34992)

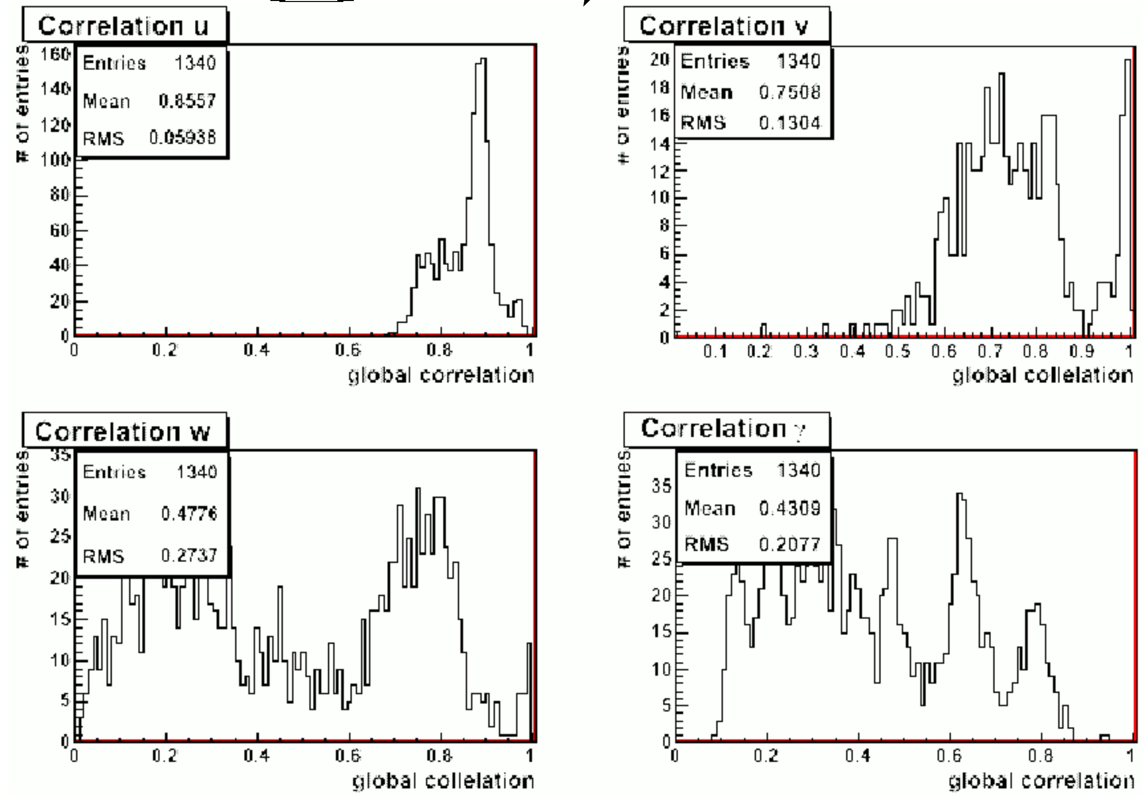
→ We need more clever algorithms!

V. Blobel, Mon 10:45
R. Frühwirth, Mon 11:45

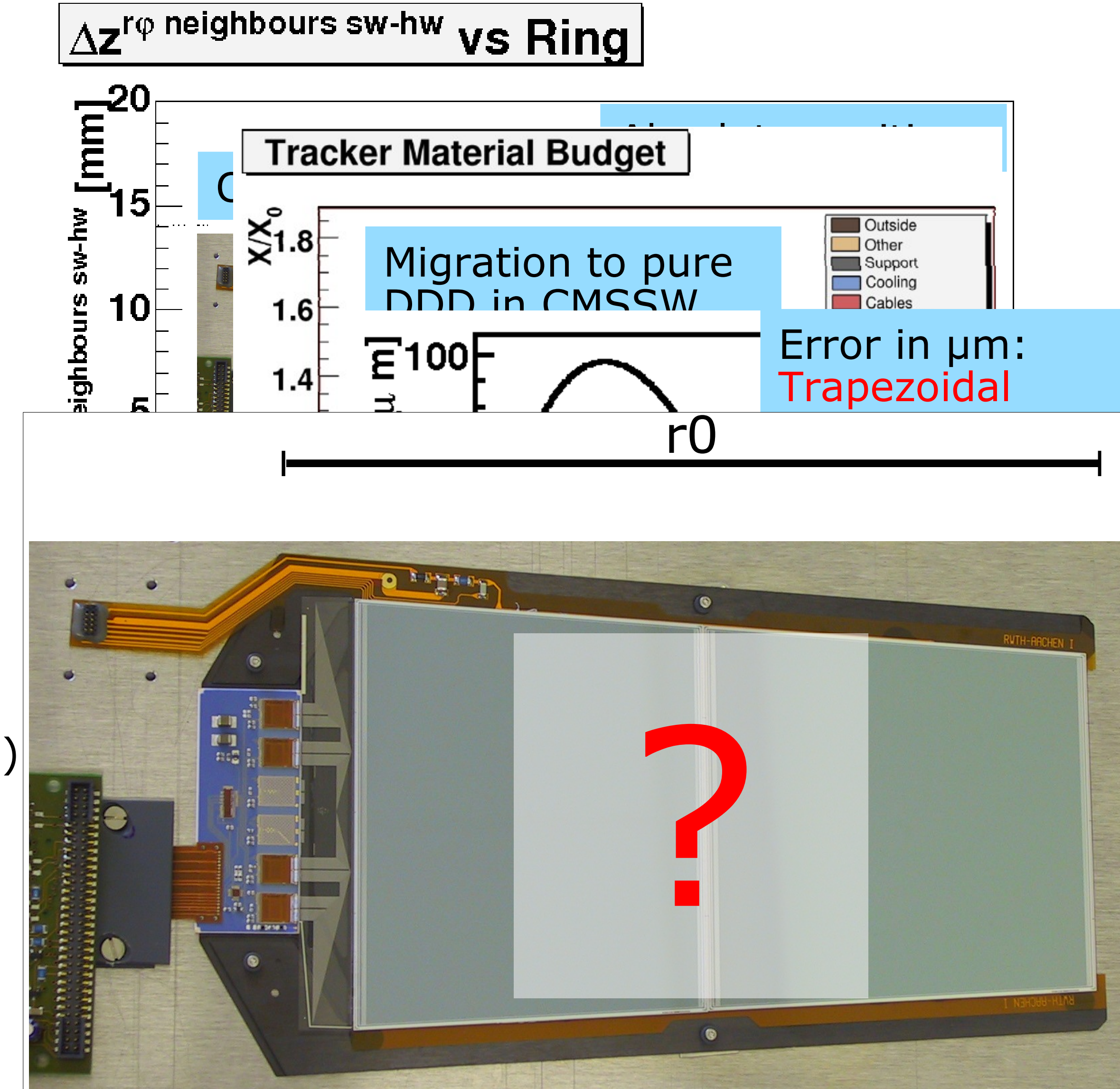
- Certain transformations leave χ^2 unchanged
  - Simplest: Layer rotation by angle α
    - Distorts p_T spectrum and inv. mass
  - A lot more higher modes...
  - High global correlation observed by using single tracks without any constraint
- Use constraints (under study)
  - Laser Alignment System
  - Z→μμ with Z mass (helps)
  - Cosmics (helps a lot in the barrel)
  - Beam halo (useful for endcaps)
  - Implement global & survey constraints in χ^2
- Best use of all available data!



Alignment of barrels, layers, rods:
Example using Z→μμ with mass constraint, cosmics, survey information



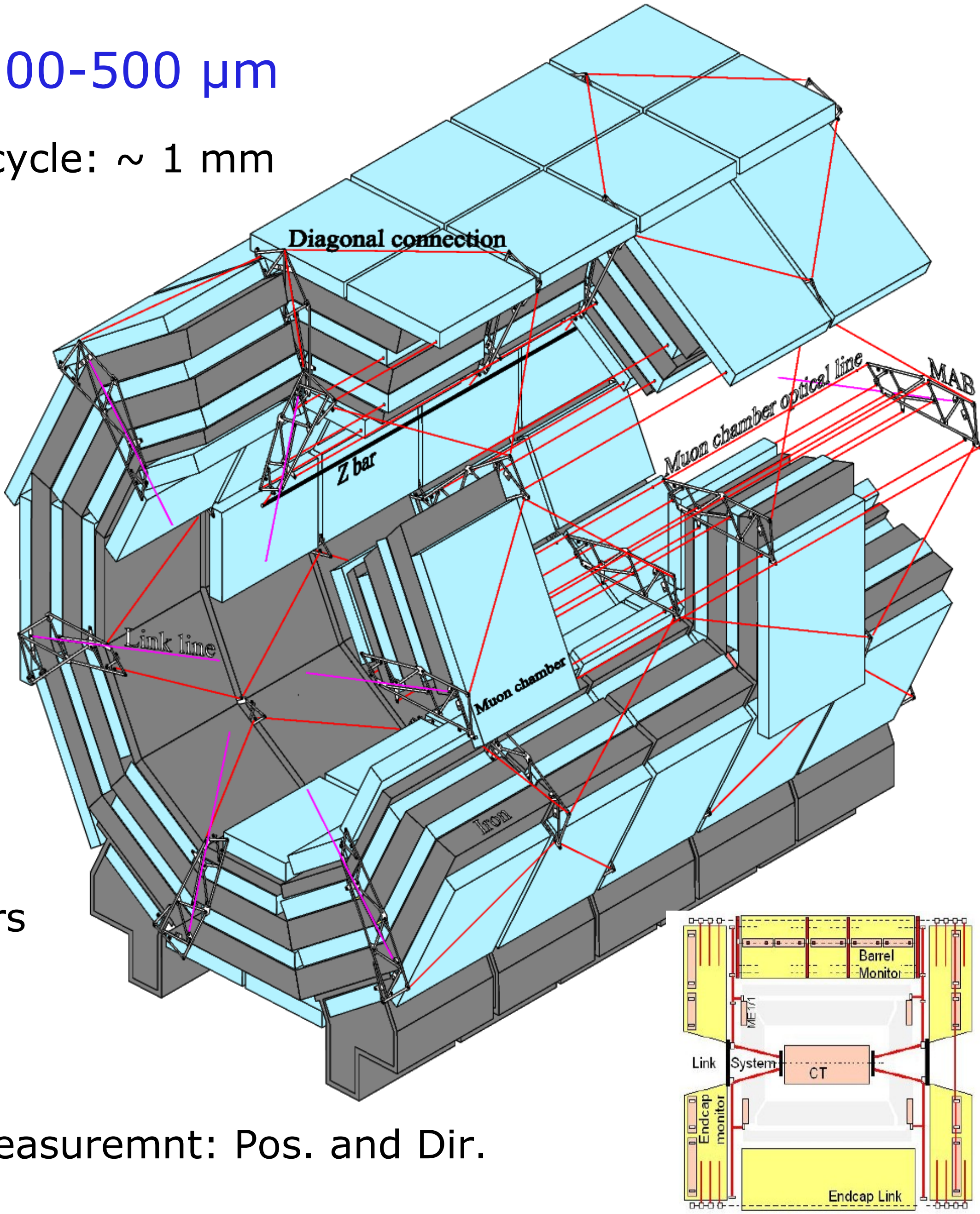
- If it gets to high precision everything matters:
  - Verified ideal detector geometry description (position/orientation)
  - Verified material budget (more detailed description in new CMSSW geometry)
  - TEC Sensor topology (wrongly assumed trapezoidal instead of radial topology)
  - Module strip layout (wrong values in current CMSSW)
  - Two sensor module layout (sensor mask did not take into account 100 µm gap between sensors)
  - The Great Unknown (something we have neglected or not thougt about)



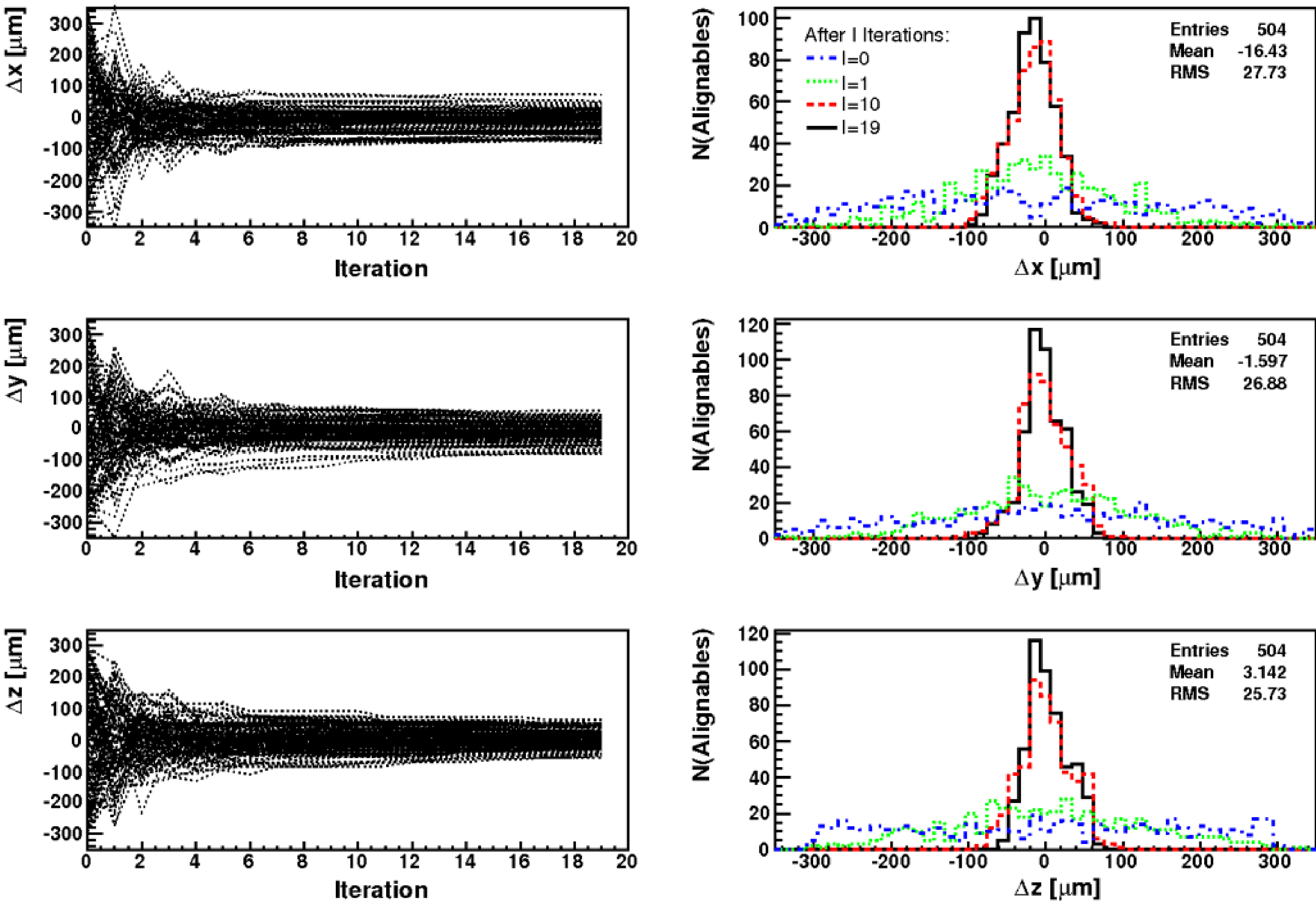
Ring 3	438146	447430	140.82	140.79
Ring 4	551201	561680	126.27	126.17

Muon system: The challenge

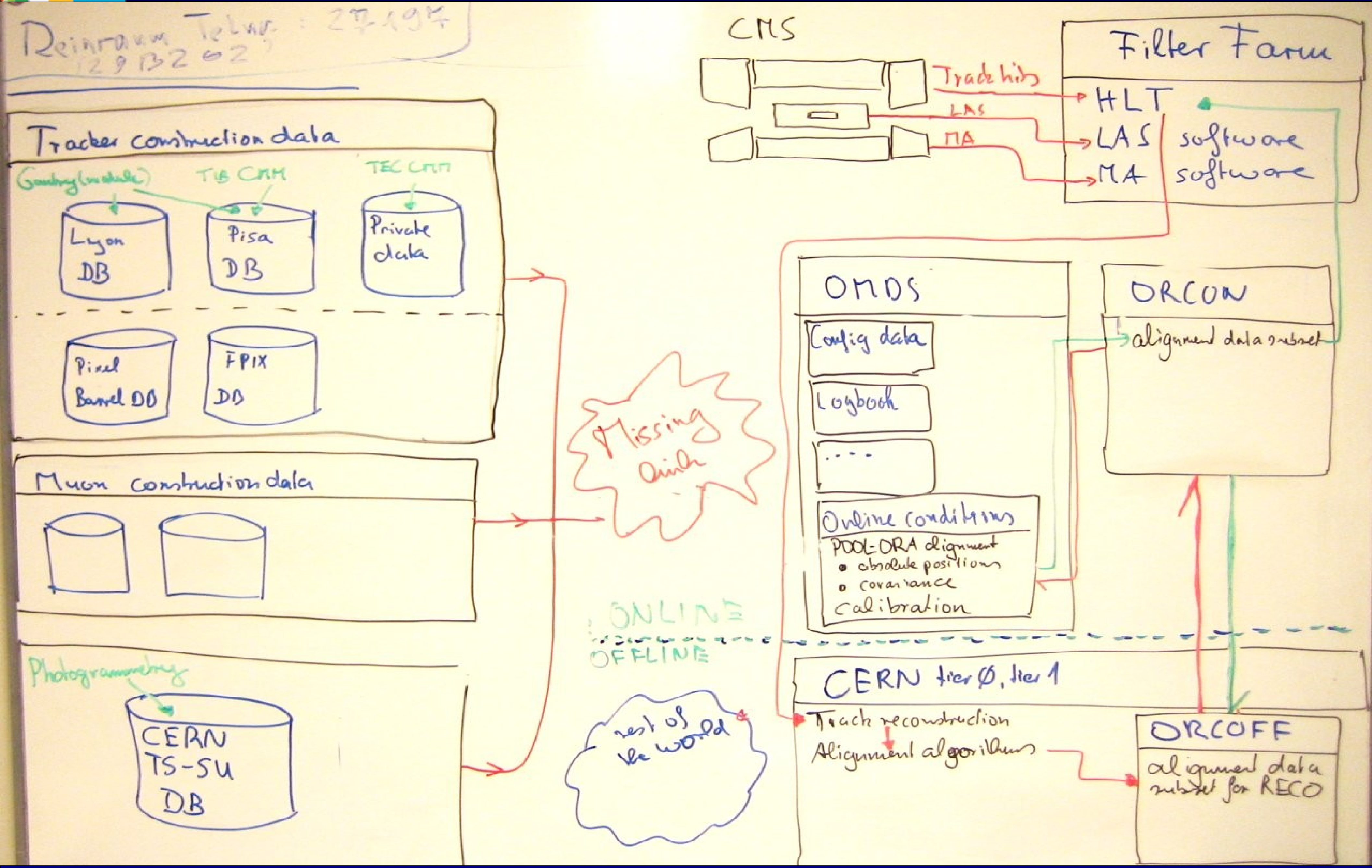
- Muon chamber alignment within 100-500 μm
  - Expected effects after magnet power cycle: ~ 1 mm
- MA system
  - Full standalone measurement
  - Monitoring of all 250 DT chambers
  - Monitoring of 23% of all CSC's
  - Real size validation of ½ plane successful!
    - ≈200 μm rφ and ≈400 μm in z
  - Challenge: Extrapolation to full CMS
- Track based alignment
  - "Small" O(5000) number of parameters
  - Non-uniform magnetic field
  - Large amount of material
  - Chamber as rigid body provides 6D measuremnt: Pos. and Dir.



- Pixel barrel standalone alignment with 504 / 750 modules (Z→μμ)
- HIP algorithm
- Resolution ≈ 25 μm
- CMS note 2006/018
- Challenge: Align all modules, include FPix



The challenge of putting it all together: Alignment data flow



Conclusion

- Many challenges in front of CMS
- Some are more challenging than others, but all need to be met
- Alignment only possible after many other detector effects are understood
  - Non-uniform magnetic field, material budget, time dependent effects, algorithmic challenge (number of parameters), position & orientation of sensors, module topology, combining different alignment data sources, ...

Alignment is “The Art of Calibration”

Thank you for your attention