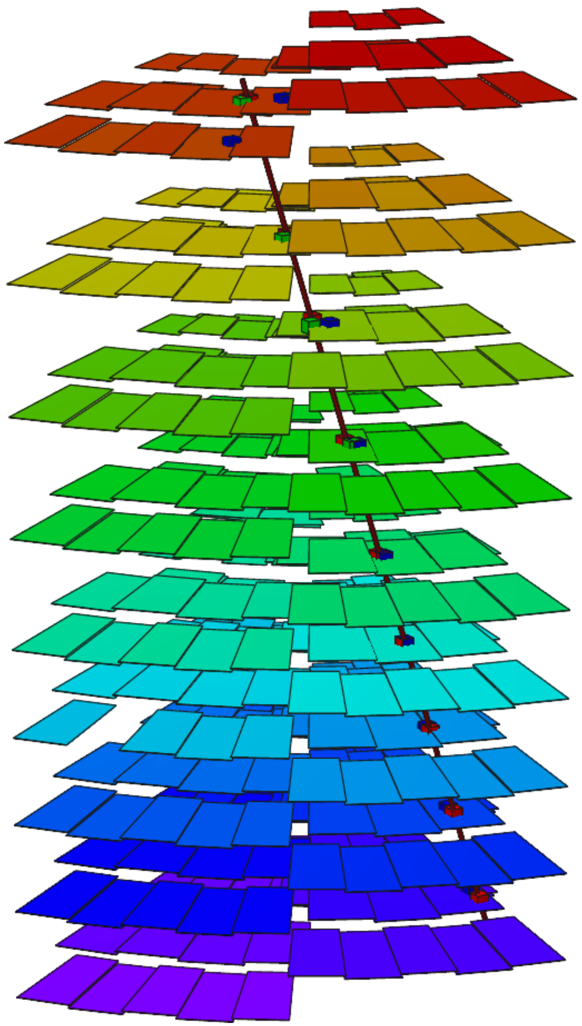
Alignment strategy for the CMS tracker



Martin Weber
RWTH Aachen
on behalf of the
CMS collaboration

Victoria, B.C., Canada
5 September 2007

Contents & Introduction: Overall alignment concept

- Misalignment
  - Estimate misalignment
  - Use misalignment scenarios for physics analysis simulation
- Detector assembly and survey
  - Measure modules, substructures, subdetectors, Tracker, everything possible
  - Provide first position estimate and errors
- Hardware based alignment system
  - Laser Alignment System
- Track based alignment
  - Data flow, algorithms, results on simulation
- Provide early alignment
  - Preliminary, not optimal but something that can be used for first analysis.
  - Improve with statistics and understanding of "features".

Precision

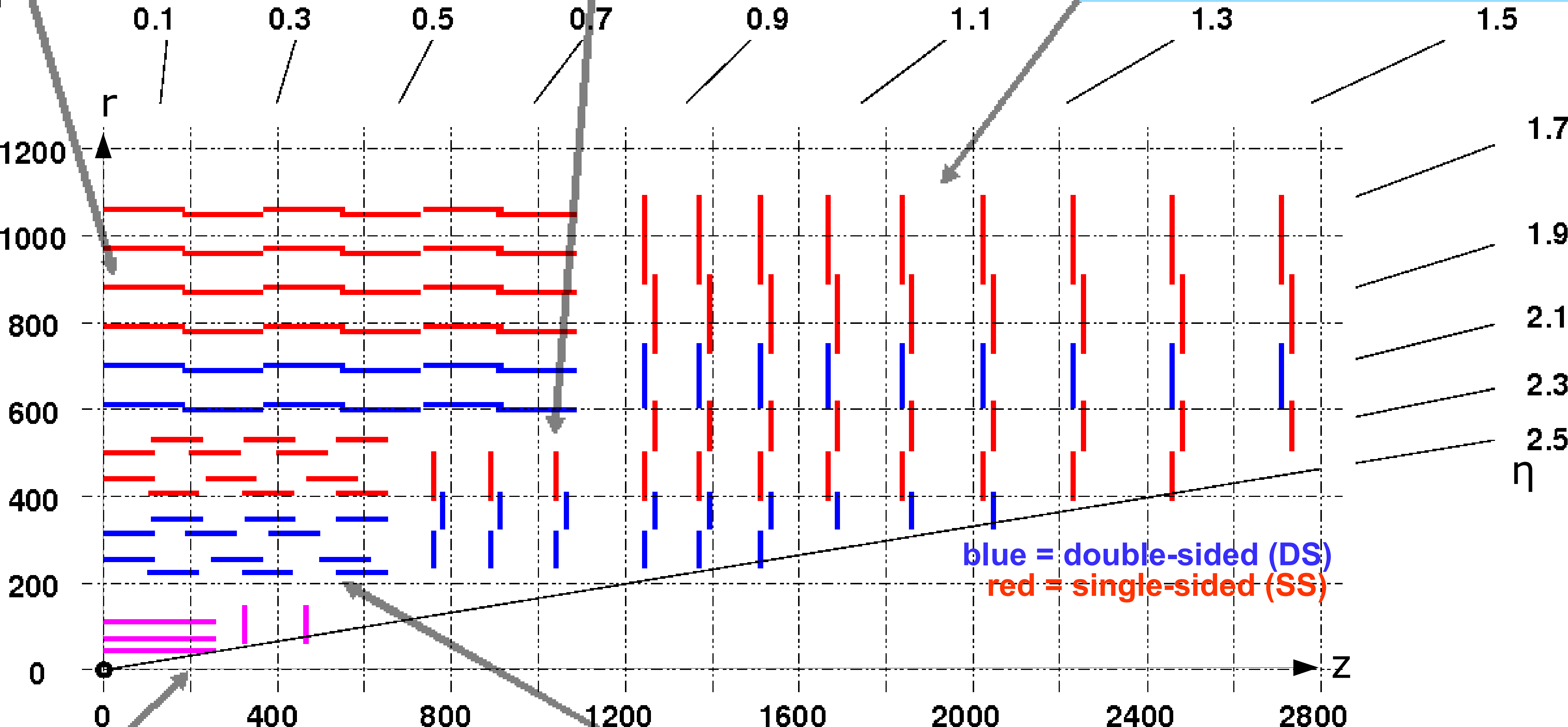
Time

CMS Silicon Tracker

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)



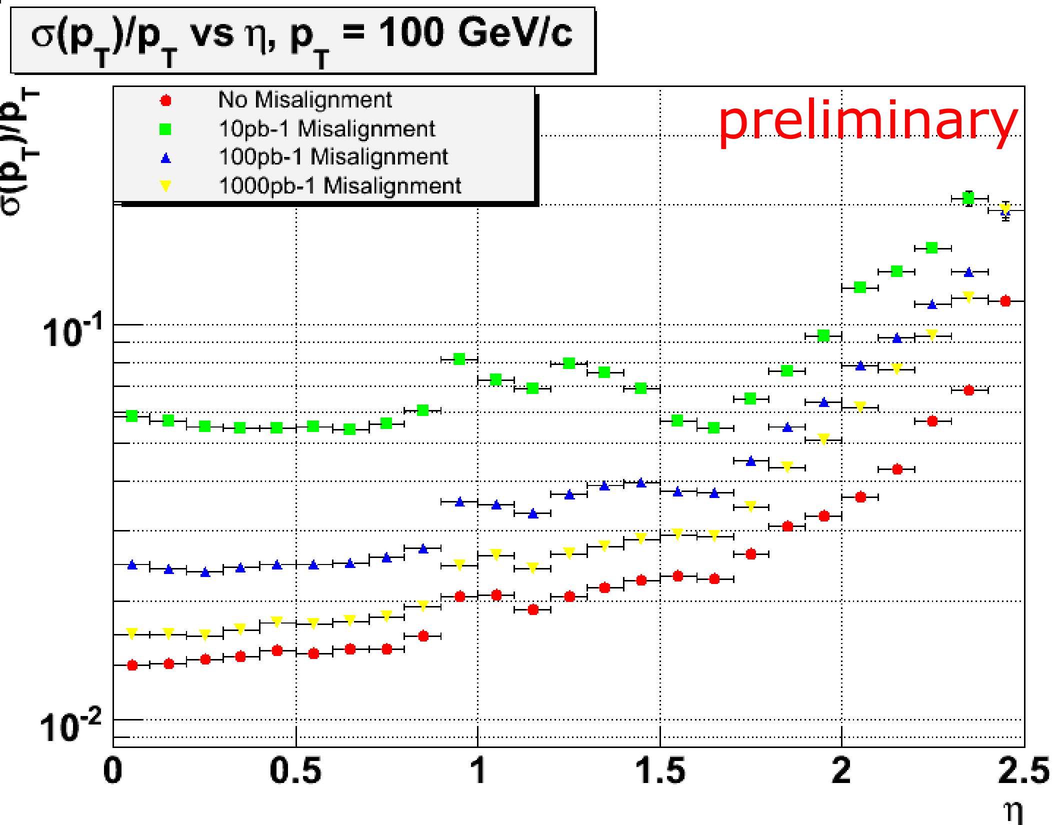
Pixel barrel and endcap
40+26 million pixels
1200+700 modules

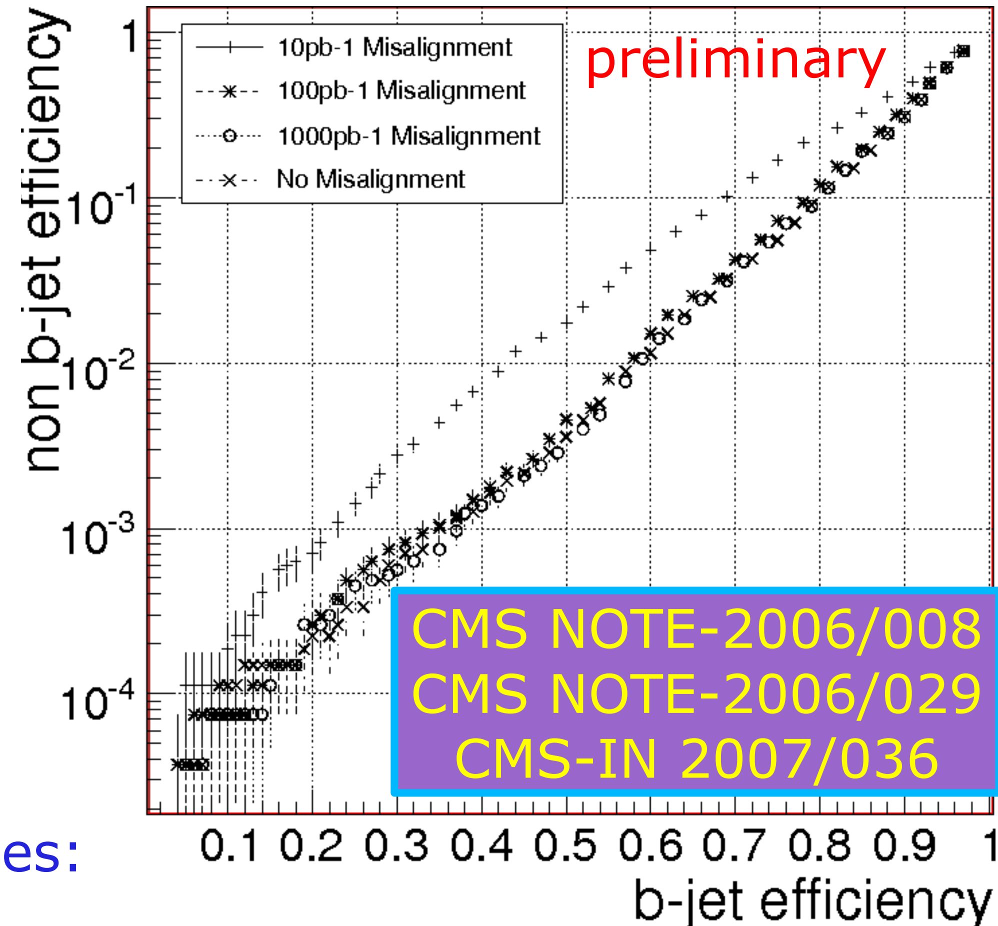
Inner Barrel (TIB)
4 layers 320 µm Si

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

Misalignment

- Due to assembly precision, B-field, +20°C→ -10°C, CFC dry-out, access





CMS NOTE-2006/008
CMS NOTE-2006/029
CMS-IN 2007/036

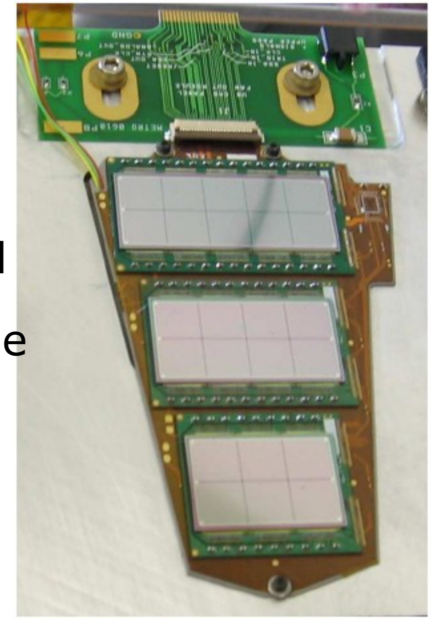
- Updated scenarios for physics studies:
  - 10 pb^{-1}: Hardware alignment, cosmic pre-alignment
  - 100 pb^{-1}: First large data sets available
  - 1 fb^{-1}: Increased statistics, refined detector understanding

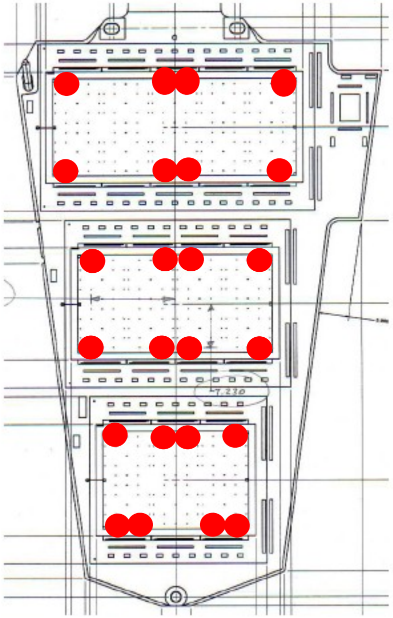
Implemented in reconstruction

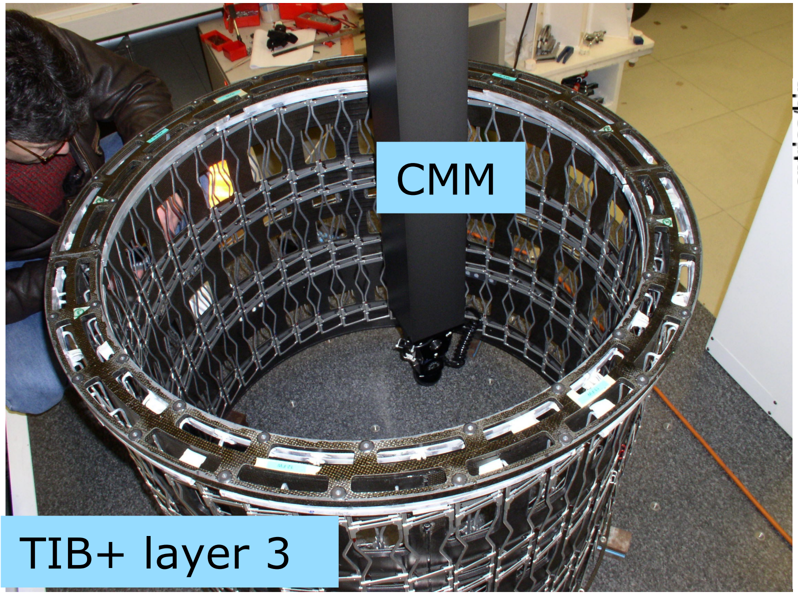
Assembly knowledge

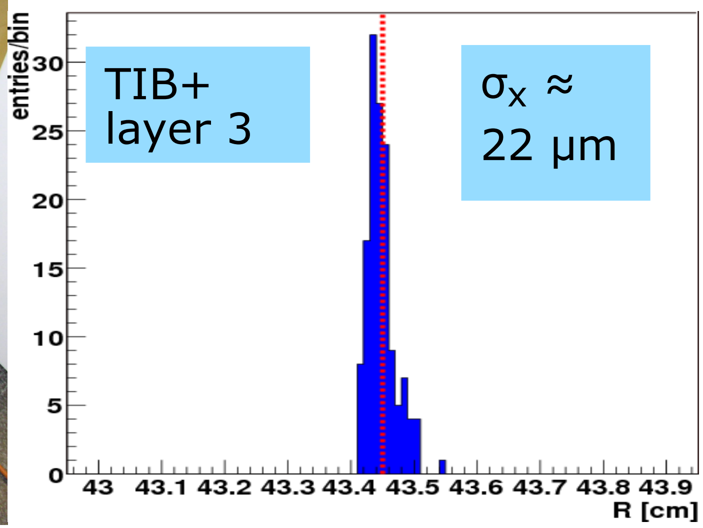
Survey measurements

- Survey: CMM, Photogrammetry
- Pixel forward panels & half-disk survey
  - Panel assembly precision typ. 50 µm, 1 mrad
  - Survey precision typ. 5 µm z, few µm in plane
- TIB/TID survey
  - 1900-2400 sample points for each layer/disk
  - Information on module level & higher levels





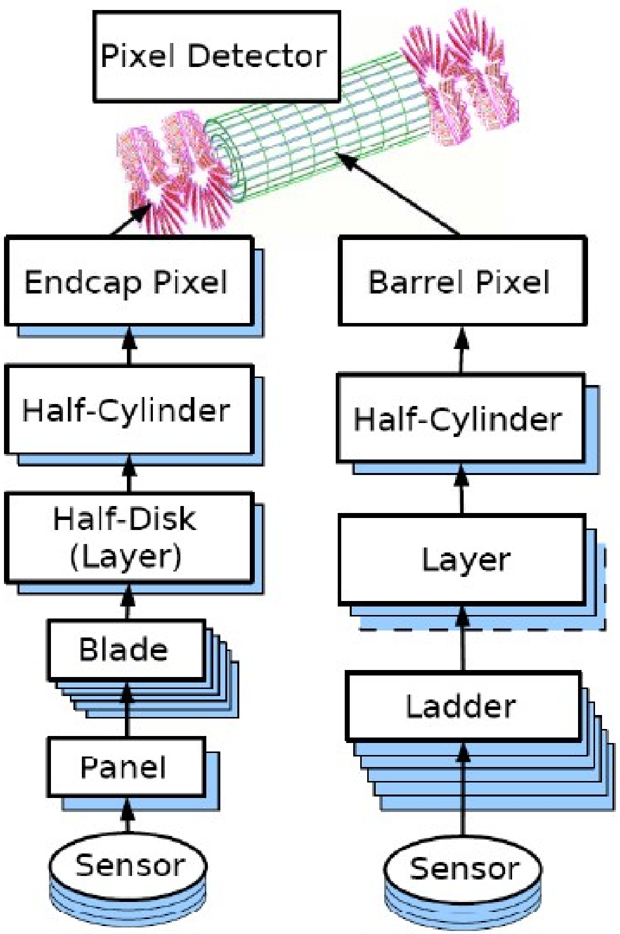




- TEC, TOB
  - No survey at module levels available
  - Higher level data available
- Pixel barrel
  - Partial survey planned

Survey in software, DB model

- Values: TrackerSurveyRecord
  - Filled once for each module
  - 3 positions, 3 euler angles (global frame)
  - Detector ID (32 bit unsigned integer)
- Error: TrackerSurveyErrorRcd
  - 6x6 covariance matrix (21 numbers stored)
    - With respect to ideal frame of higher level structure
  - Structure type (8 bit unsigned int)
  - Detector ID (1st daughter of composites)
- Compute survey residuals
- Combination with track based alignment



$$\chi^2 = \sum_{i,\text{track}} \epsilon^T_{i,\text{track}} \mathbf{V}^{-1}_{i,\text{track}} \epsilon_{i,\text{track}} + \sum_{i,\text{survey}} \epsilon^T_{i,\text{survey}} \mathbf{V}^{-1}_{i,\text{survey}} \epsilon_{i,\text{survey}}$$

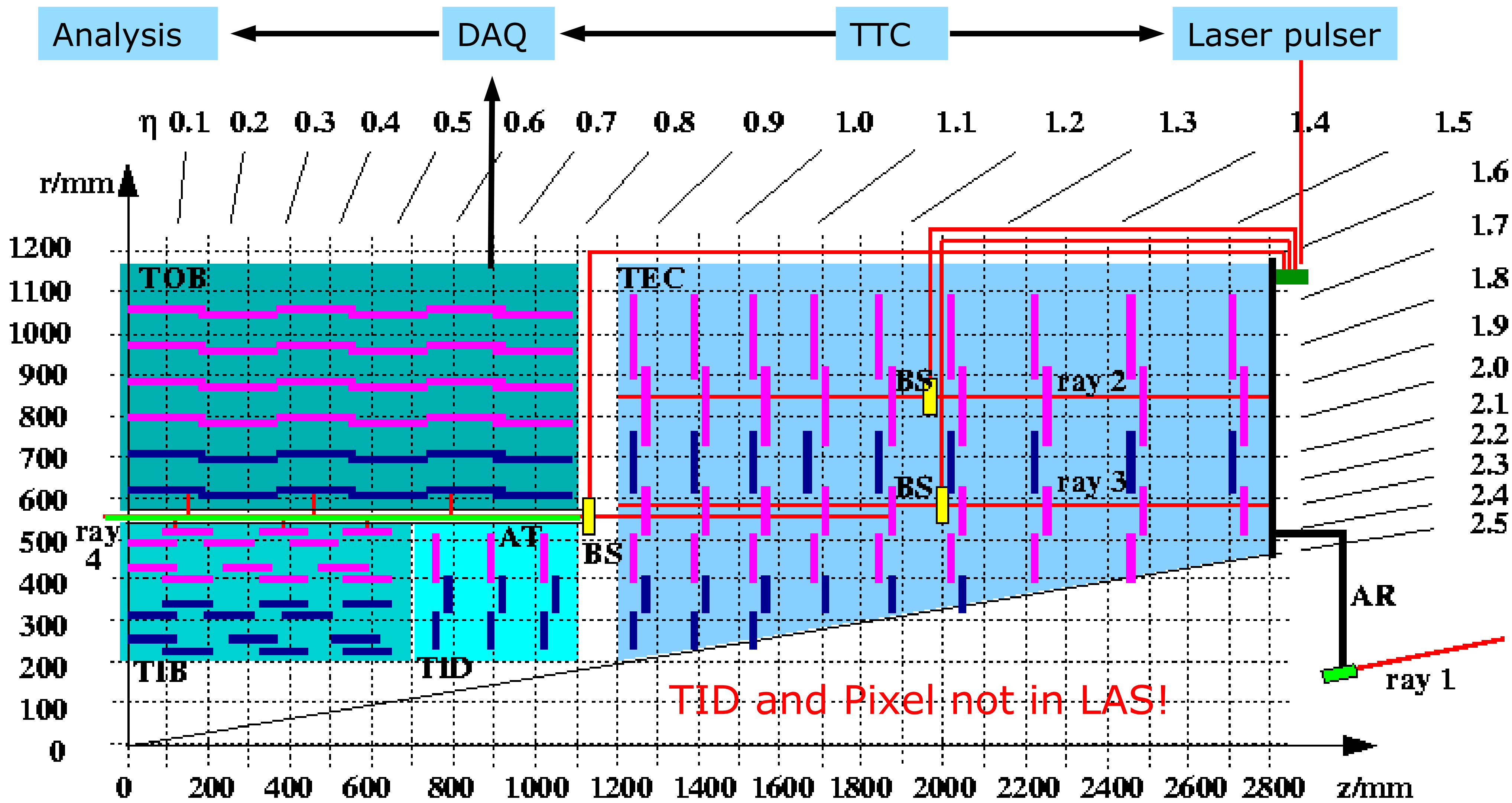
i: hierarchy

$$\chi^2_{\text{survey}} = \sum_{i:} \left[\left[\sum_{j=1}^{3} \frac{(R_{i,j} - r_j)^2}{\sigma^2_{Ri,j}} \right] + \left[\sum_{j=1}^{3} \frac{(\Omega_{i,j} - \omega_j)^2}{\sigma^2_{\Omega i,j}} \right] \right]$$

i: hierarchy, j: x,y,z

Laser alignment

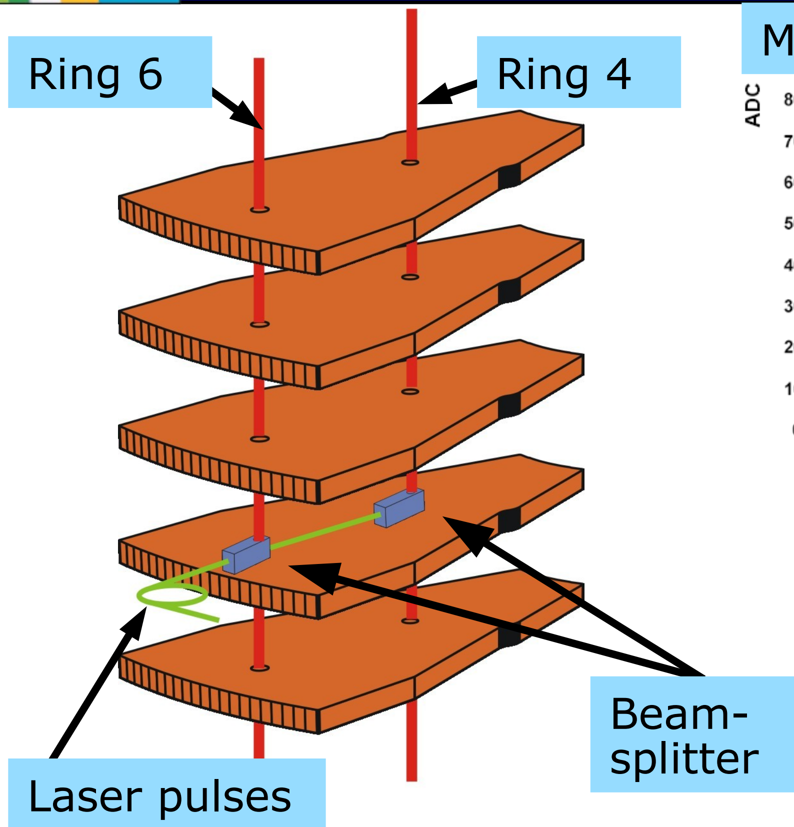
Laser Alignment System Overview



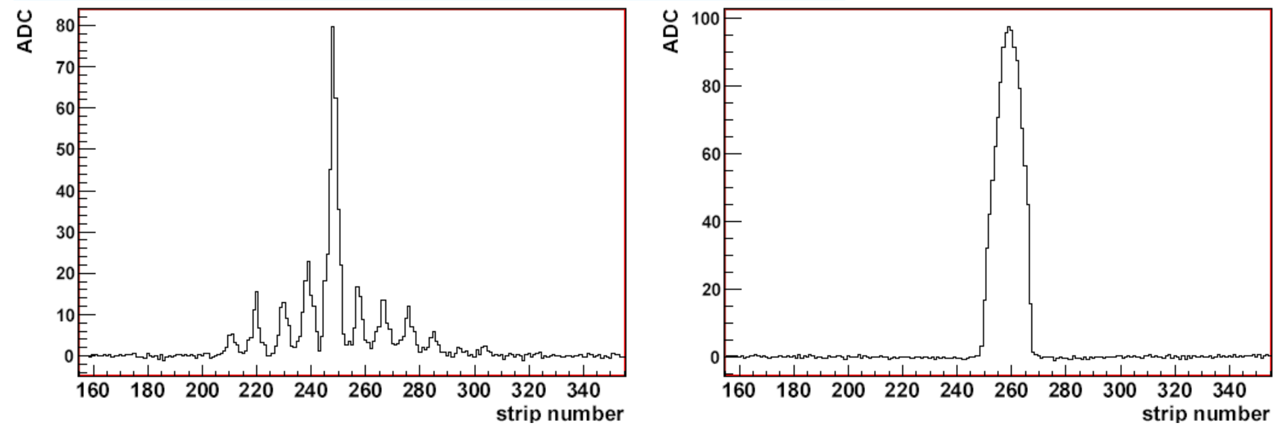
BS: Beam Splitter AT: Alignment tube **AR: Alignment ring**

- Relative measurement TIB vs TOB vs TEC and disks within TEC

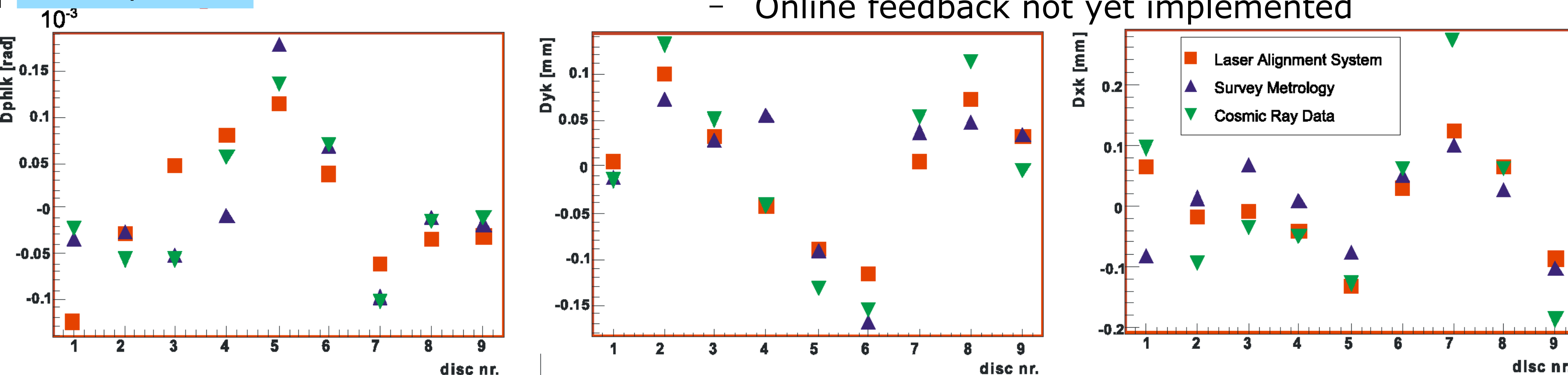
Laser alignment system in TEC integration



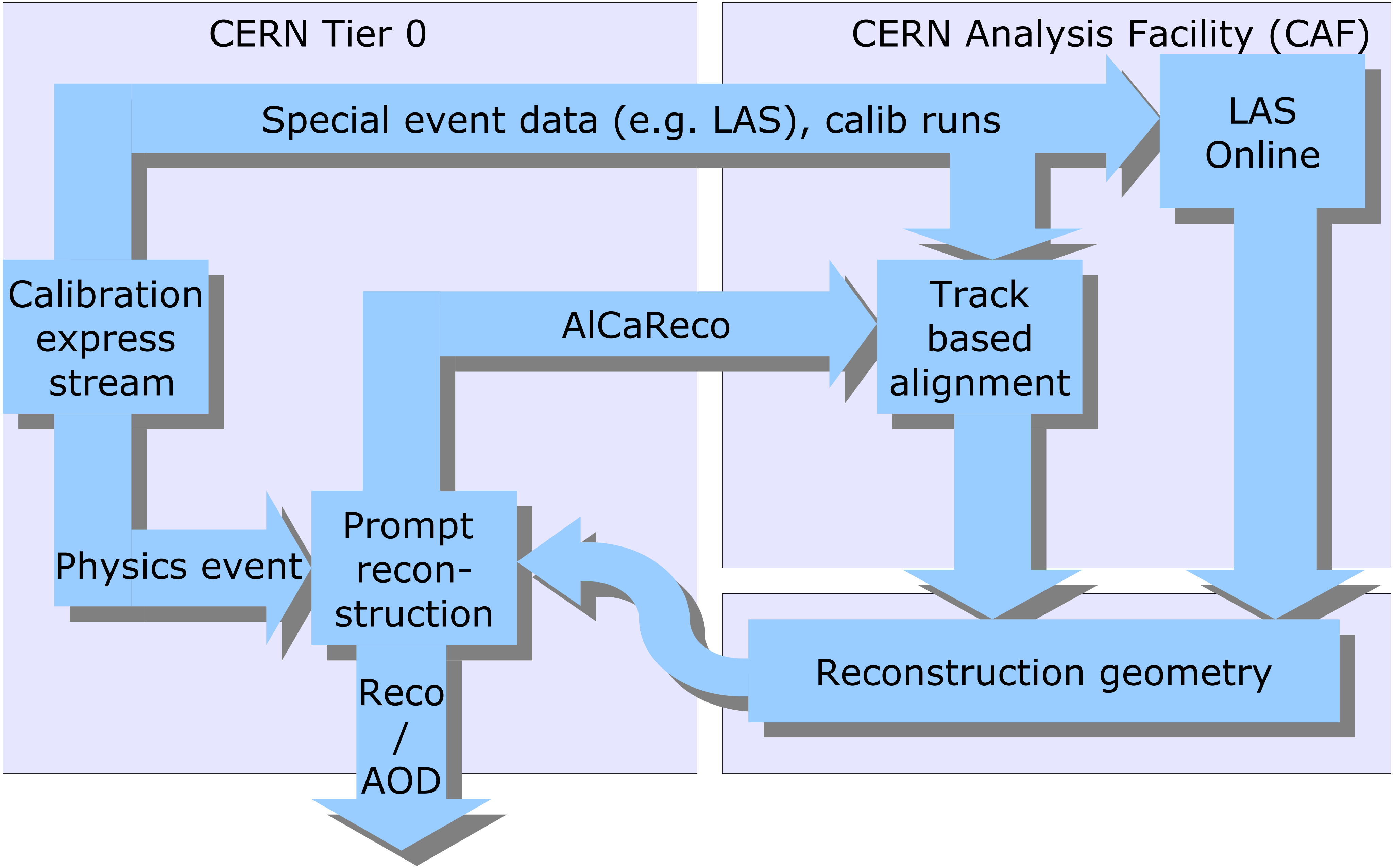
Measured profiles on disk 2 and 6



- LAS, cosmics & metrology in agreement
- Position resolution < 70 µm
- Monitoring of relative positions ≈ 10 µm
  - Online feedback not yet implemented



Track based alignment


CERN Tier 0
CERN Analysis Facility (CAF)
Special event data (e.g. LAS), calib runs
LAS Online
Calibration express stream
AlCaReco
Track based alignment
Prompt recon-struction
Physics event
Reco / AOD
Reconstruction geometry

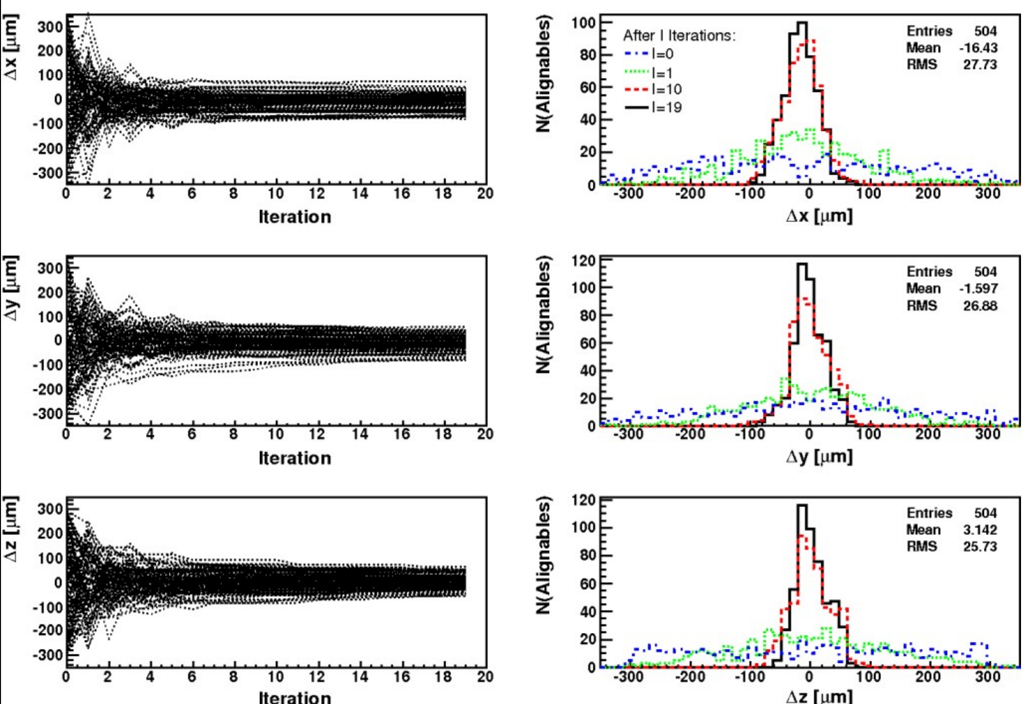
HIP and Kalman Filter
Case studies on MC

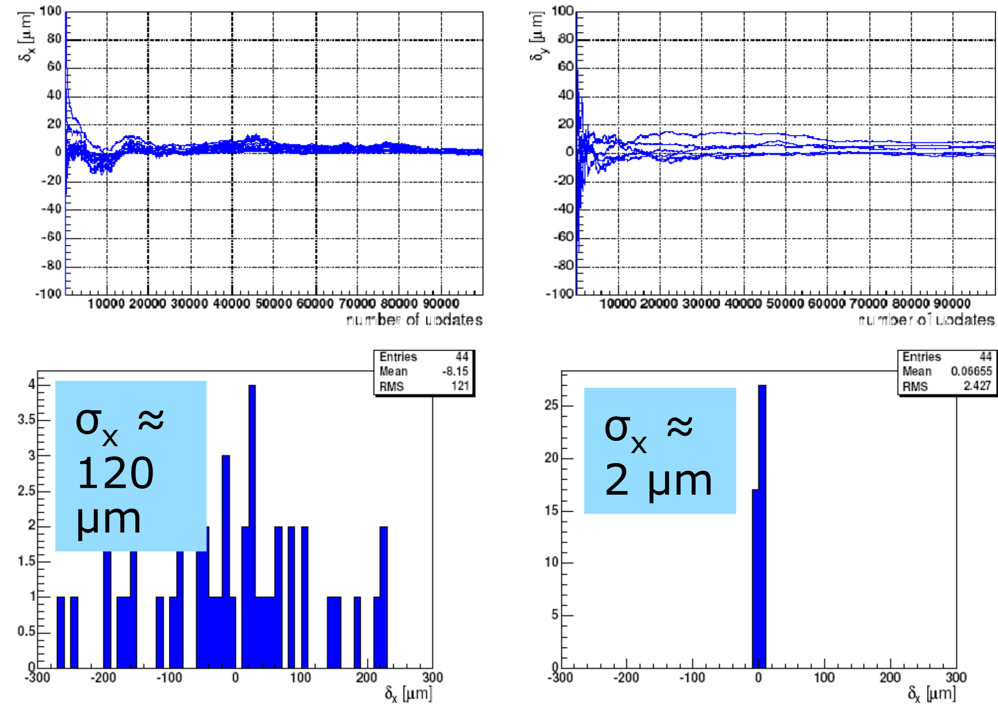
- "Local" HIP algorithm
  - invert 6x6 matrices, iterate
- Pixel barrel standalone alignment with 504/750 modules
- 500k $Z\rightarrow\mu\mu$, vertex constraint
- Resolution ≈ 25 μm

CMS NOTE 2006/018

- Kalman Filter Alignment
  - Tunable between "local" and "global"
- Alignment of 44 TIB modules, pixel detector fixed
- 100k single μ, p_T>100 GeV
- Poster by E. Widl

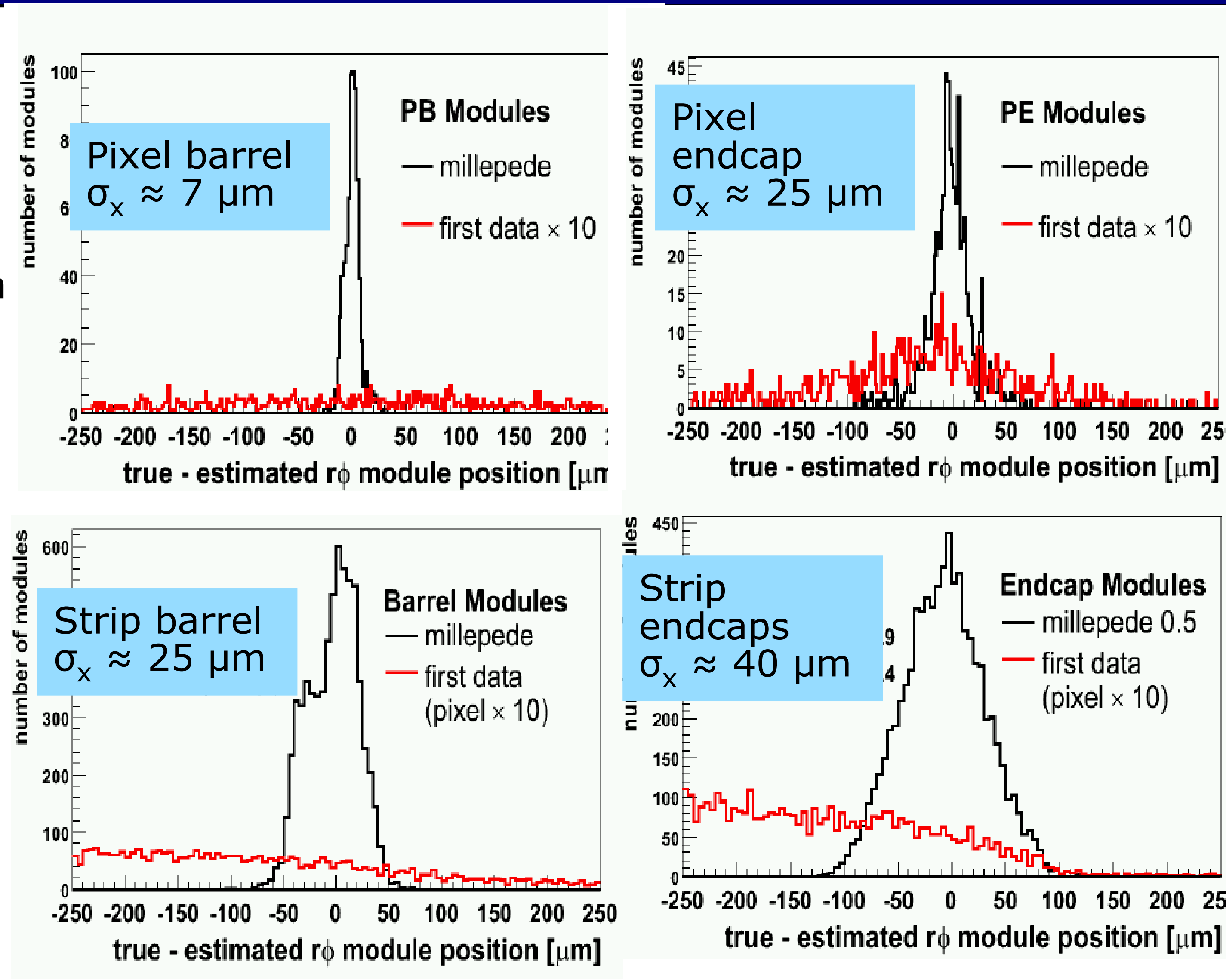
CMS NOTE 2006/022





Full Tracker Alignment in MC

- Optimal "global" algorithm
  - V. Blobel
  - All correlations taken into account
- Startup conditions
- 100 pb^{-1} data
  - 0.5 million $Z \rightarrow \mu\mu$
  - Cosmics
  - Structure survey
- Turnaround time
  - few h preparation
  - < 2 h solving time
  - ~ 1 day
- Talk by M. Stoye



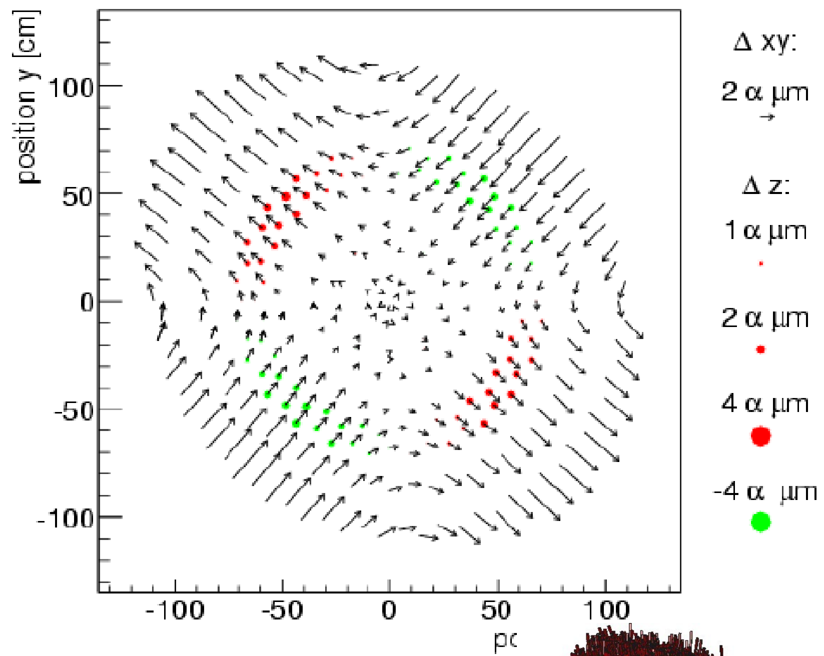
hep-ex/0208021
CMS NOTE 2006/022
CERN Thesis 2007-049

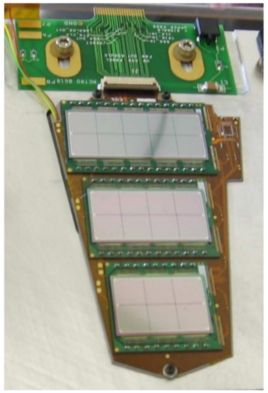
Summary

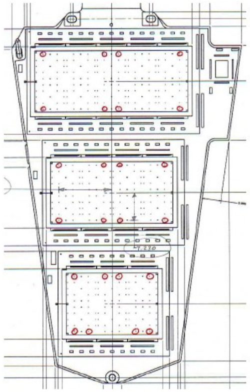
Summary: CMS tracker alignment strategy

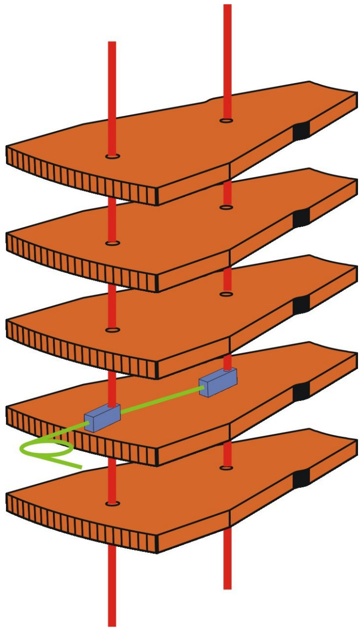
- Employ different data sets for optimal constraints of weak modes
  - Cosmic muons (no beam, B=0T, B=4T)
  - beam halo muons (single beam)
  - minimum bias, J/psi and Upsilon (early data taking)
  - $Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$ (with increasing statistics)
- Combine survey, LAS, tracks
  - Choose optimal combination (varies with time)
  - Studies starting / ongoing

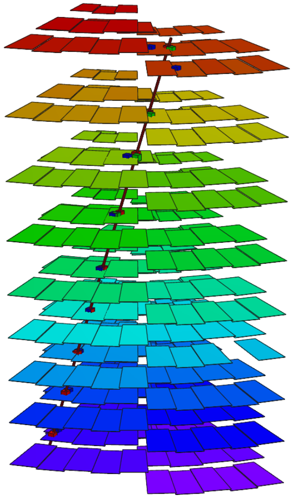
Illustration of χ^2 invariant deformations

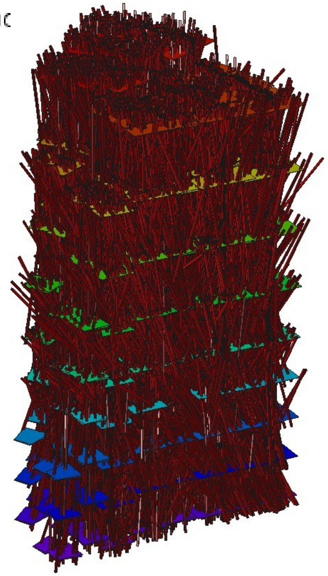










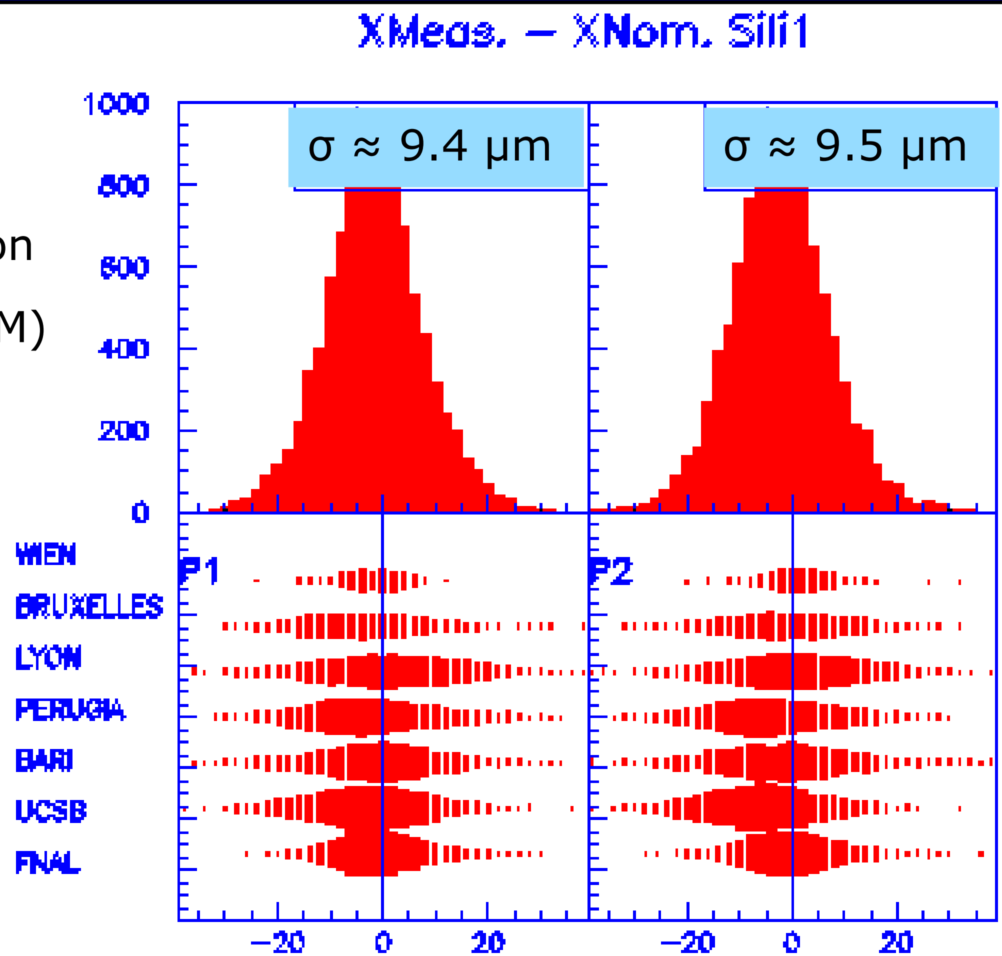


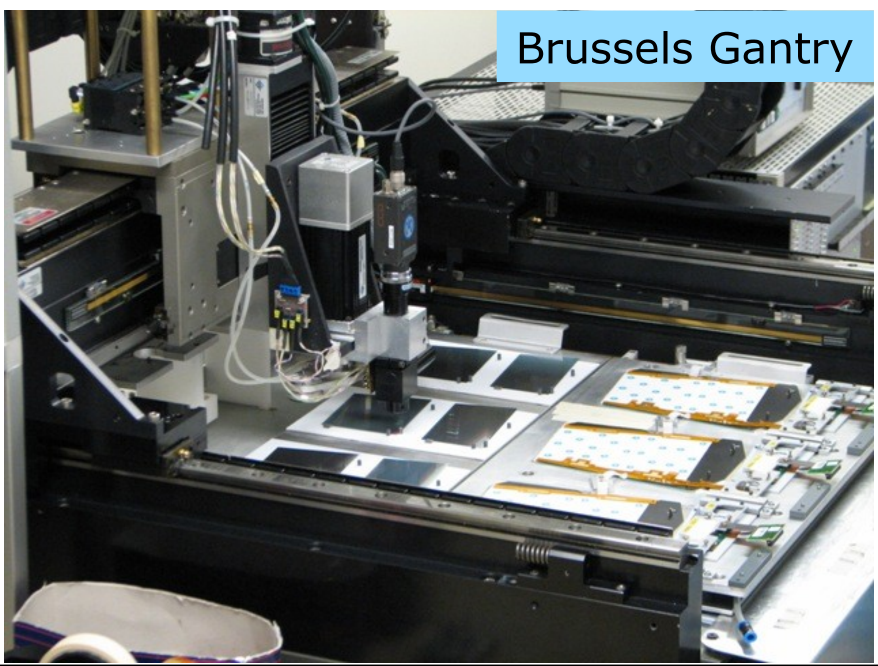
Backup

Assembly knowledge

Assembly knowledge

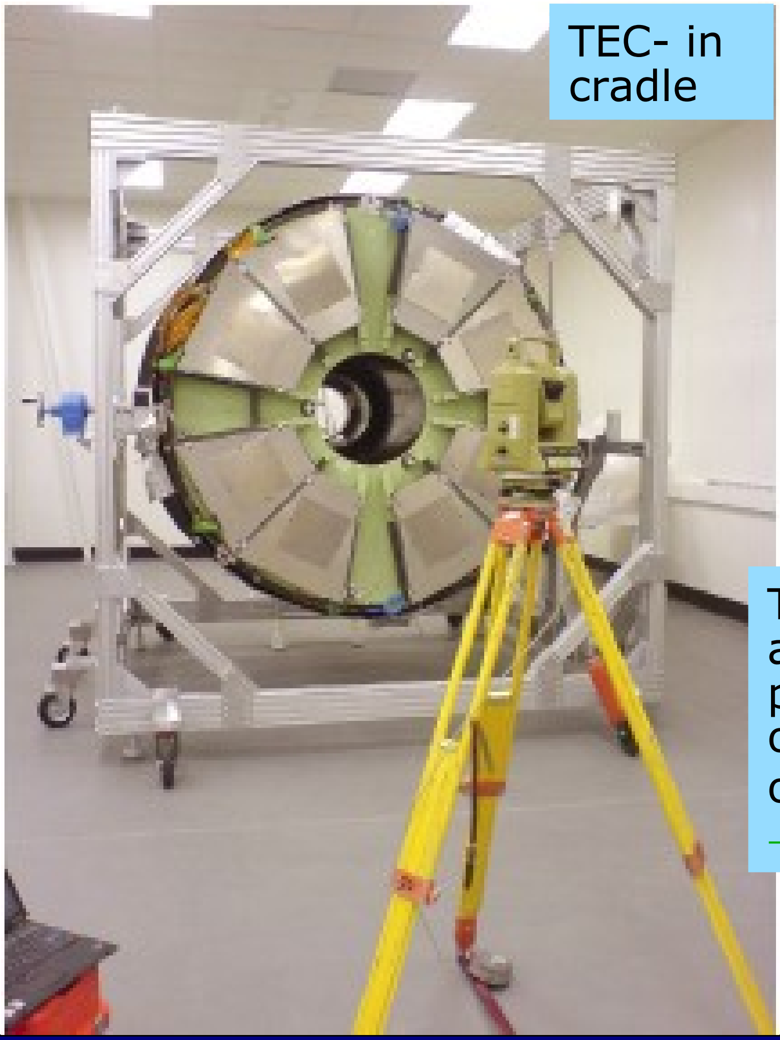
- Wide variety of measurements
  → Some examples shown
  - Gantry robot used for module production
  - Coordinate measurement machine (CMM)
  - Photogrammetry
- Example from module production
  - Sensors are mounted with a robot on modules with a precision ≤ 10 µm

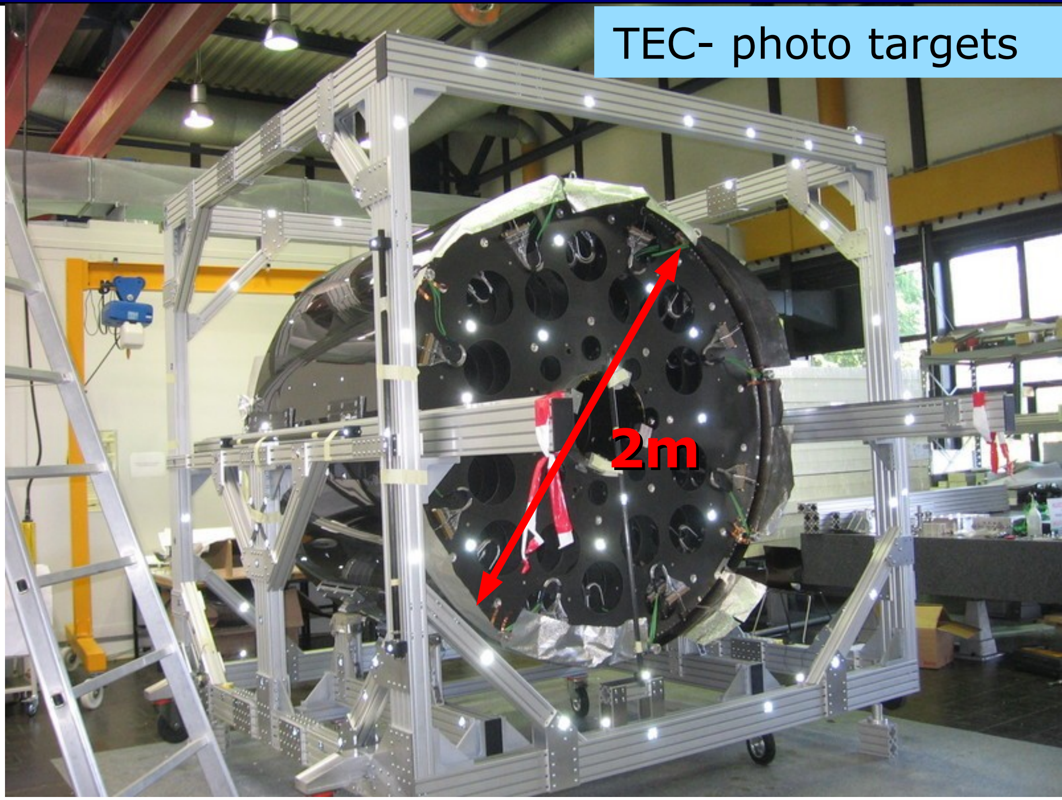




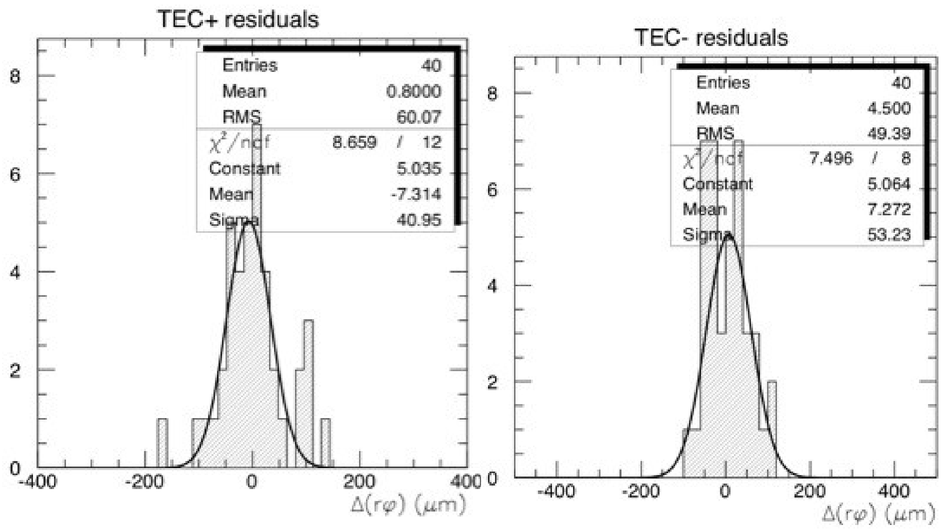
TEC photogrammetry

- Both Tracker Endcaps are surveyed with photogrammetry
  - measurement precision ≤ 50 μm



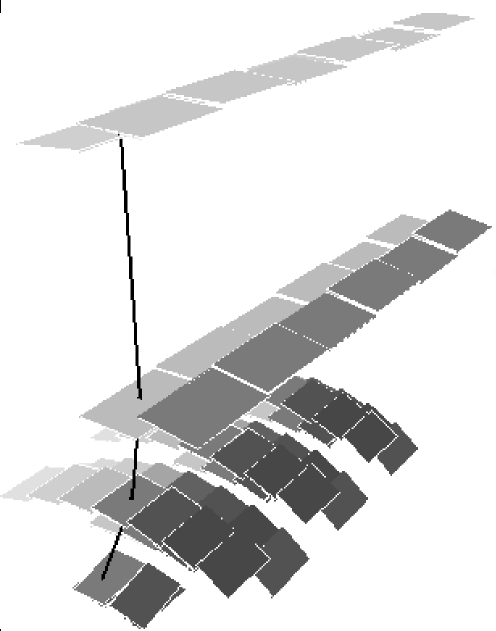


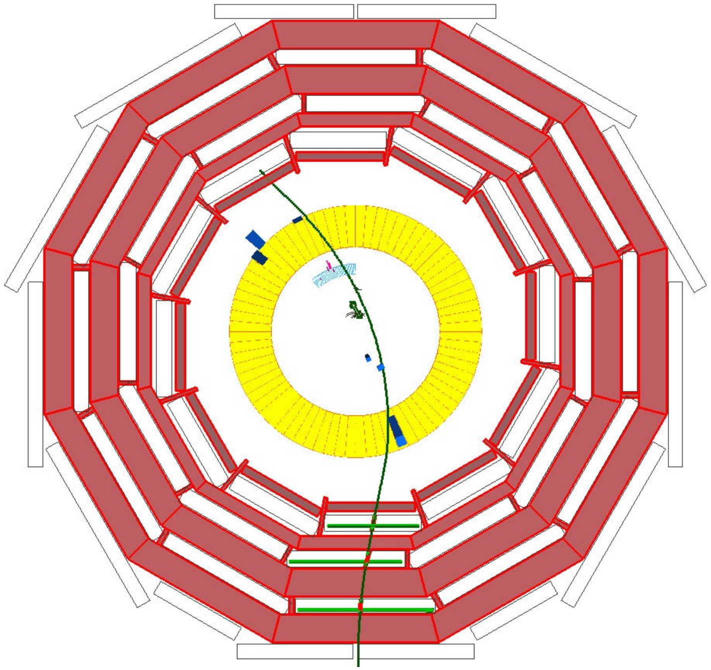
TEC structure assembly precision:
$\sigma_{xy} \approx 50\ \mu m$
$\sigma_z \approx 150\ \mu m$
→ very precise!

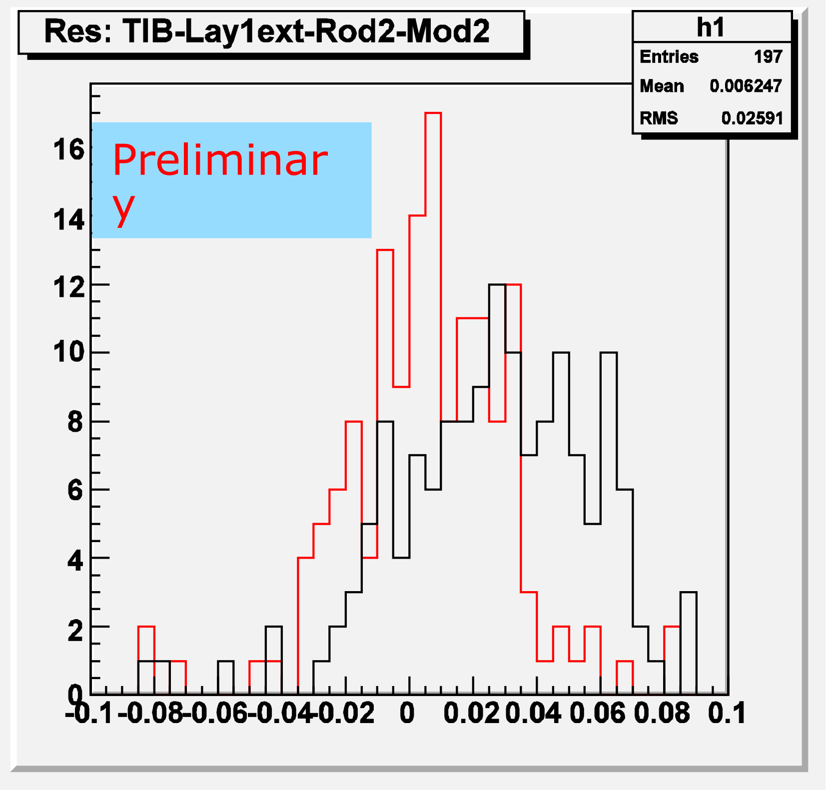


CMS Magnet Test and Cosmic Challenge: Survey helps!

- MTCC tracker setup
  - 3 TOB rods
  - Modules on TIB layer 3 and 4
  - 2 TEC petals (not shown)
- Survey results implemented by hand
  - Better residual distribution (centered, smaller width)



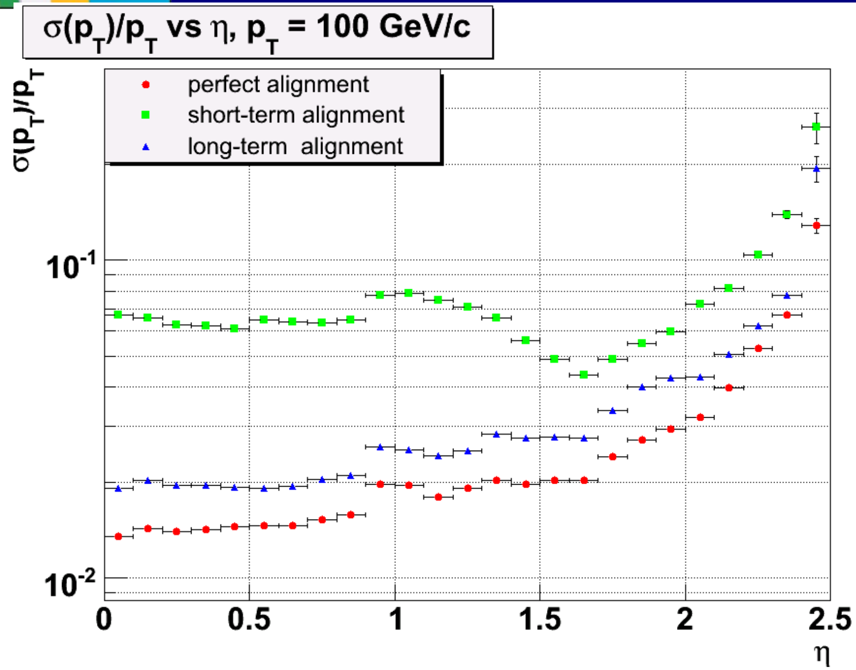


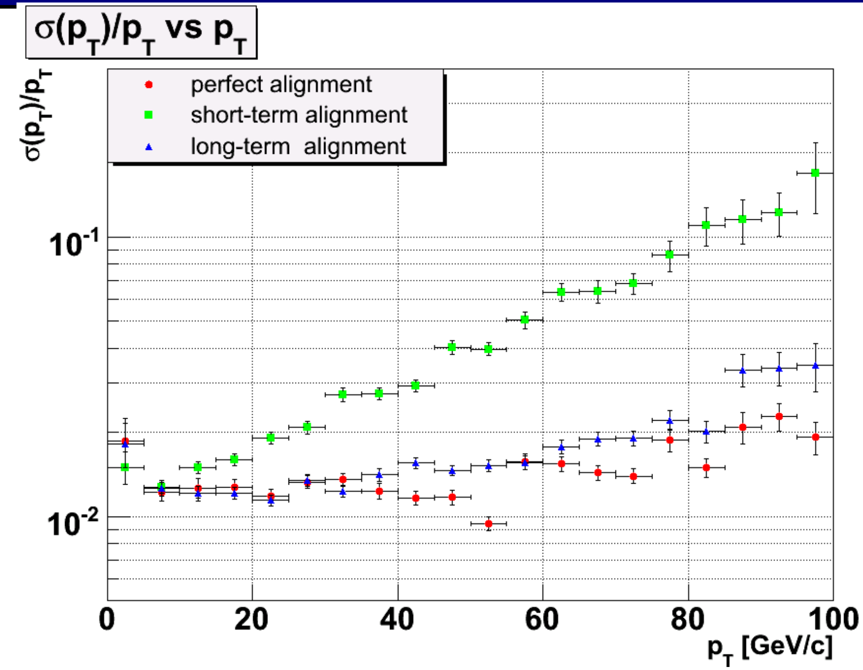


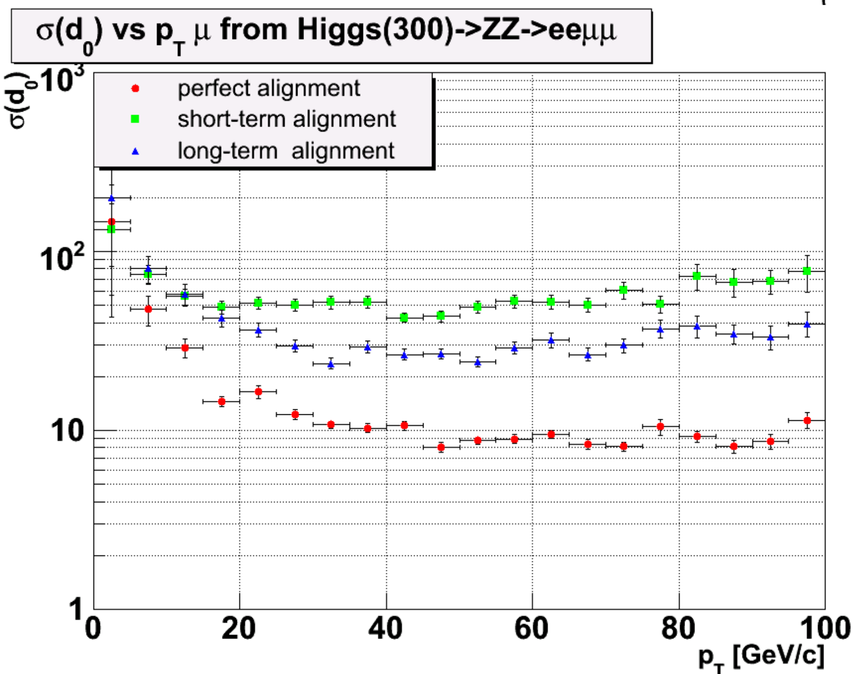
- Work in progress
  - Black: Before survey
  - Red: Survey constraints used

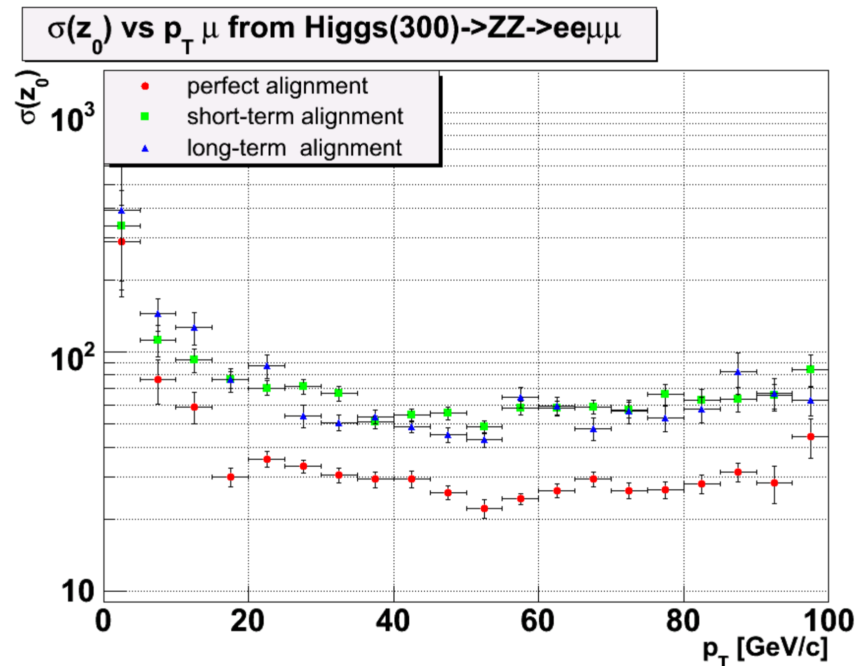
Misalignment

Misalignment – Impact on Physics









- Estimated accuracy of sensor positioning (used for misalignment scenarios)

TOB	Δ [μm]
Sensor vs. Module	$\pm$ 10
Module vs. Rod	$\pm$ 100
Rod vs. Cylinder	$\pm$ **100** - 500
Cylinder vs. Cylinder	$\pm$ 100 - **500**
TIB	
Sensor vs. Module	$\pm$ 10
Module vs. Rod	$\pm$ 200
Rod vs. Cylinder	$\pm$ 200
Cylinder vs. Cylinder	$\pm$ 100 - **500**
TEC	
Sensor vs. Module	$\pm$ 10
Module vs. Petal	$\pm$ **50** - 100
Petal vs. Disc	$\pm$ **100** - 200
Disc vs. Disc	$\pm$ 100 - **500**

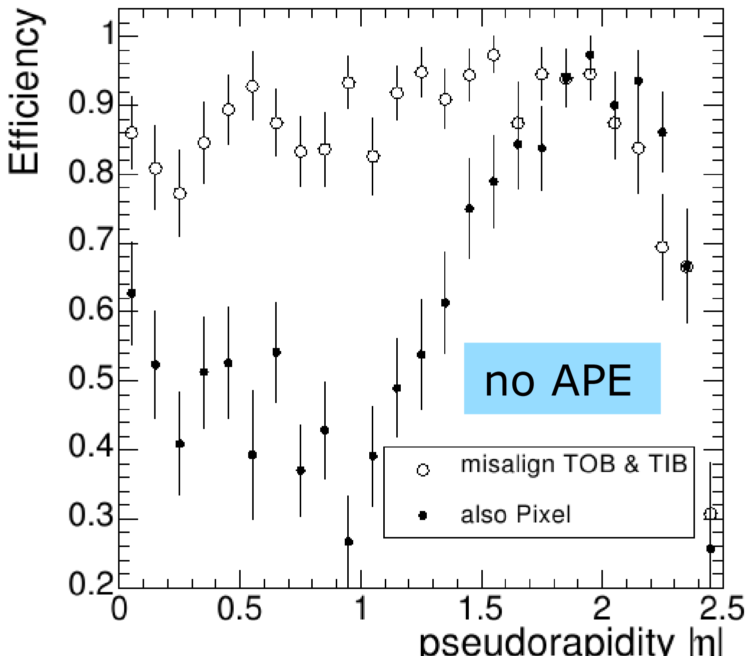
TPB	Δ [μm]
sensor within barrel module	$\pm$ 30 in 2D
module within ladder	$\pm$ 100 in 3D
ladder within one half-layer	$\pm$ 50 in 3D
half-layer within half-barrel	$\pm$ 100 in 3D
half-barrel within TPB	$\pm$ 300 in 3D
TPB within SiTK	$\pm$ 250 in x and y $\pm$ 500 in z
TPE	
sensor within disk blade	$\pm$ 25 in 2D
disk blade within half-disk	$\pm$ 50 in 3D
sensor within half-disk (after optical survey)	$\pm$ 25 in 3D
half-disk within disks-half-service-cylinder	$\pm$ 50 in 3D
disks-half-service-cylinder within TPE	$\pm$ 300 in 3D
TPE within SiTK	$\pm$ 500 in 3D
TID	
Sensor within TID module	$\pm$ 5 in 2D
module within ring	$\pm$ 100 in 2D, 250 in 3D
ring within disk	$\pm$ 300
disk within the TID	$\pm$ 400
TID within TIB	$\pm$ 500

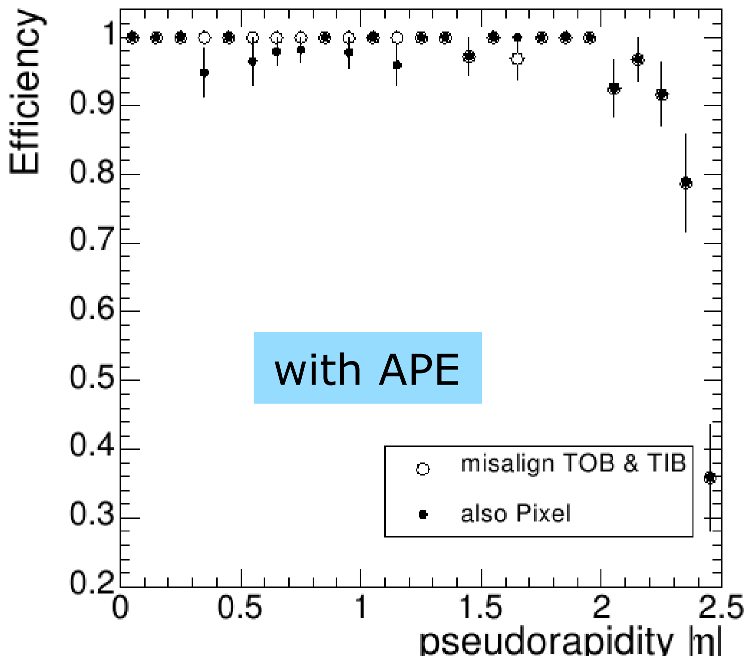
- Misalignment scenario input (from CMS Physics TDR, volume 2)

Table 6.18: Mounting precisions (in μm) used in the misalignment simulation.

	Pixel		Silicon Strip			
	Barrel	Endcap	Inner Barrel	Outer Barrel	Inner Disk	Endcap
First Data Taking Scenario						
Modules	13	2.5	200	100	100	50
Ladders/Rods/Rings/Petals	5	5	200	100	300	100
Long Term Scenario						
Modules	13	2.5	20	10	10	5
Ladders/Rods/Rings/Petals	5	5	20	10	30	10

- Use survey data for initial track reconstruction
  - Precision roughly ~ 100-500 µm. Measurements existing but database format to be negotiated
- Measurements that are performed for each object
  - will directly be used as a correction of the object position → alignment!
  - Example: Rod precision pin positions, Sensor position on modules
- Measurements that are performed on a sample basis (as cross-check)
  - Will be used as "Alignment Position Error" to increase track reconstruction efficiency

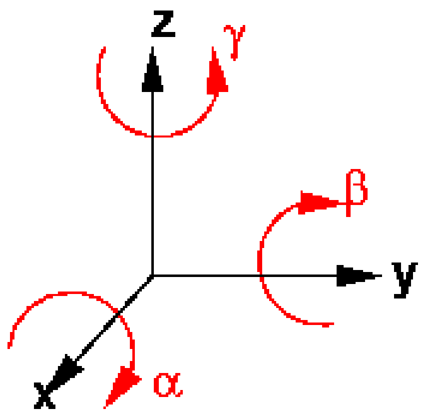




Track based alignment

Alignment is...

- 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 precision, CMM + photogrammetry
  - Hardware alignment (Muon: MA, strip: LAS) PRE-COLL
    - Laser, LED, CCD, proximity & tilt sensors
  - Track based alignment (Muon, pixel, strip) COLLISION
    - $Z \to \mu\mu$ as single muons, $Z \to \mu\mu$ with mass constraint, Cosmics, beam halo, ...
- 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 χ^2-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 $\frac{\partial \chi^2}{\partial \vec{p}} = 0$
  - 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

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

- A Kalman filter is a **global** <u>iterative</u> LLS-Estimator
  - Iterative: Process track after track. Update parameters and covariance for each track. Measurements here: all hit positions in one track n~O(20)
  - Global: Update **all** parameters in each step
  - In the beginning alignment uncertainties are large, therefore $W=\left(V'+A\,E\,A^T\right)^{-1}$ (V' is the hit error matrix, and E is the covariance matrix of the parameters)
- Computing $\frac{\partial \chi^2}{\partial \vec{p}}=0$ one gets the solution
  - For the parameters: $\tilde{\vec{p}}=\vec{p}_0+\left(A^T W A\right)^{-1} A^T W \left(\vec{m}-\vec{f}\,(\vec{p}_0)\right)$
  - For their covariance: $\tilde{E}=E-E\,A\,W\,A^T\,E$
  - The new, updated parameters are used for the next iteration (next track)
- Only recently proposed (J. Phys. G: Nucl. Part. Phys. 29 (2003) 561)
  - R. Frühwirth, T. Todorov and M. Winkler
  - Advantages: No large matrix inversion needed, Parameters can be easily refined (just add tracks to get a new alignment, no rerunning of previous data necessary)
  - Disadvantages: Needs some bookkeeping to avoid using full covariance matrix, Never tried before, thus refined understanding of algorithm needed

Matrix inversion?

- Back to the χ^2:

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

- Solution of $\frac{\partial\chi^2}{\partial\vec{p}}=0$ as another matrix equation:

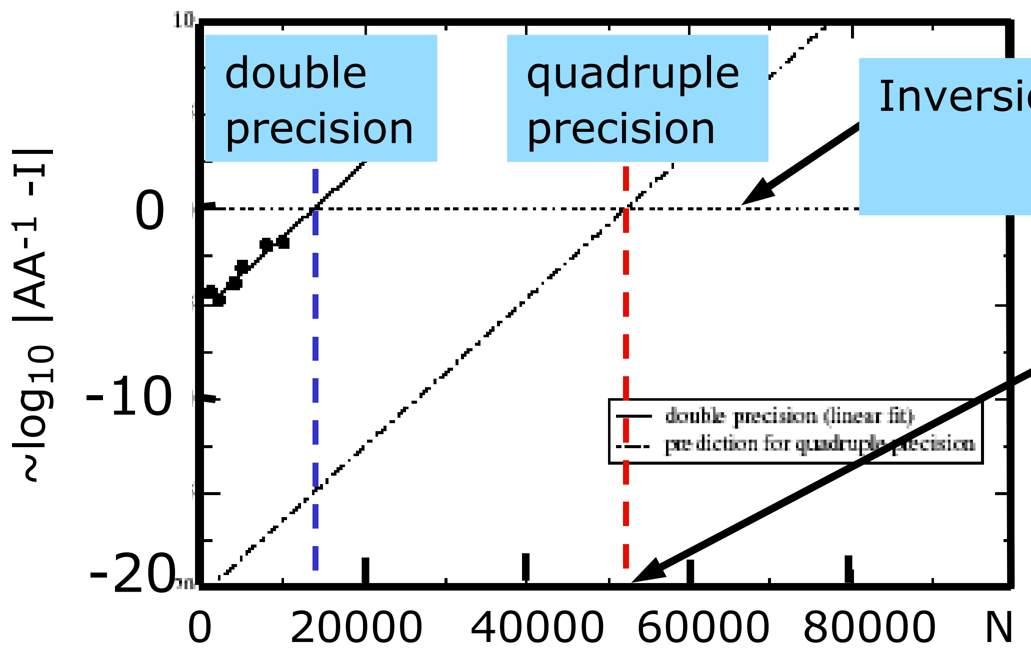
  $$\left(A^T W A\right)(\vec{p}-\vec{p}_0)=A^T W\left(\vec{m}-\vec{f}(\vec{p}_0)\right)$$

- Assume W diagonal (uncorrelated measurements) with entries $w_i=1/\sigma_i^2$
  - Define $C=\sum_{i=1}^n w_i A_i A_i^T,\ \Delta\vec{p}=(\vec{p}-\vec{p}_0),\ \vec{b}=A^T W(\vec{m}-\vec{f}(\vec{p}_0))$ and we obtain

    $C\Delta\vec{p}=\vec{b}$, which can be solved by matrix inversion: $\Delta\vec{p}=C^{-1}\vec{b}$
  - Since the matrix C is of size n x n with n~100.000 (CMS), even clever algorithms as Millepede (V.Blobel, C.Kleinwort, Proceedings of the Conference on: Advanced Statistical Techniques in Particle Physics, University of Durham, UK March 18th-22nd, 2002) do fail.
- Difference between Kalman Filter and Matrix inversion:
  - For iterative treatment (KF) the matrix inversion of $C=A^T W A$ where C is a n x n matrix (n ≈ 100.000) can be drastically compacted to size m x m where m ≈ 20 is the number of measured parameters in each track!
  - Possible since in $A=\left.\frac{\partial\vec{f}}{\partial\vec{p}}\right|_{\vec{p}=\vec{p}_0}$ most measurements are zero (A extremely sparse!)

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)

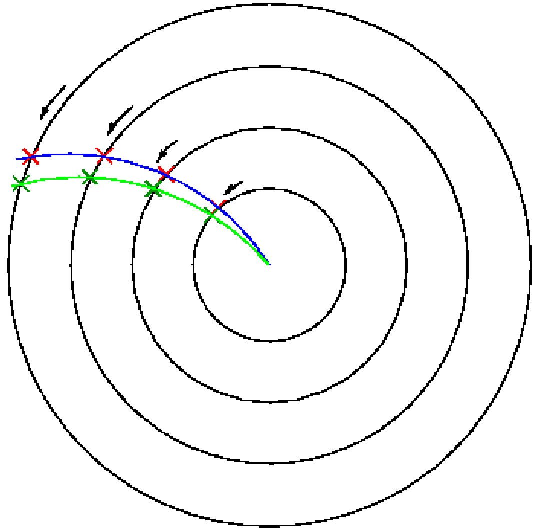
→ We need more clever algorithms!

V. Blobel, Mon 10:45

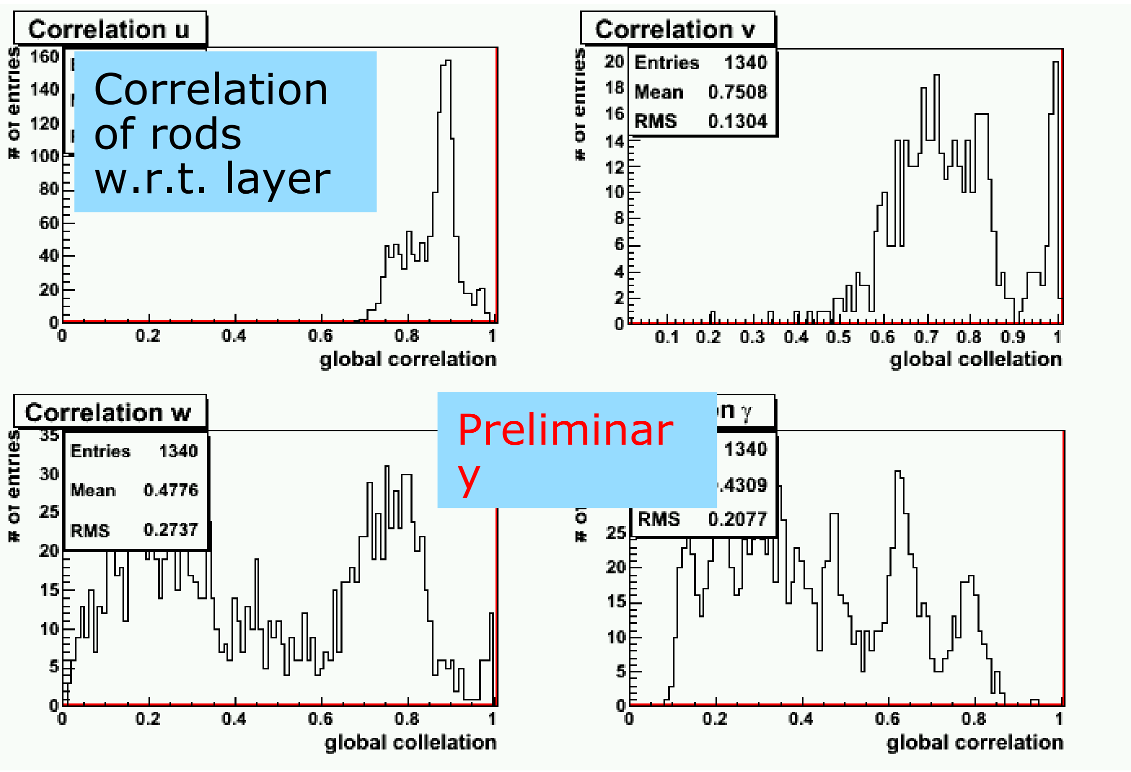
R. Frühwirth, Mon 11:45

Strip tracker: The challenge of constraints

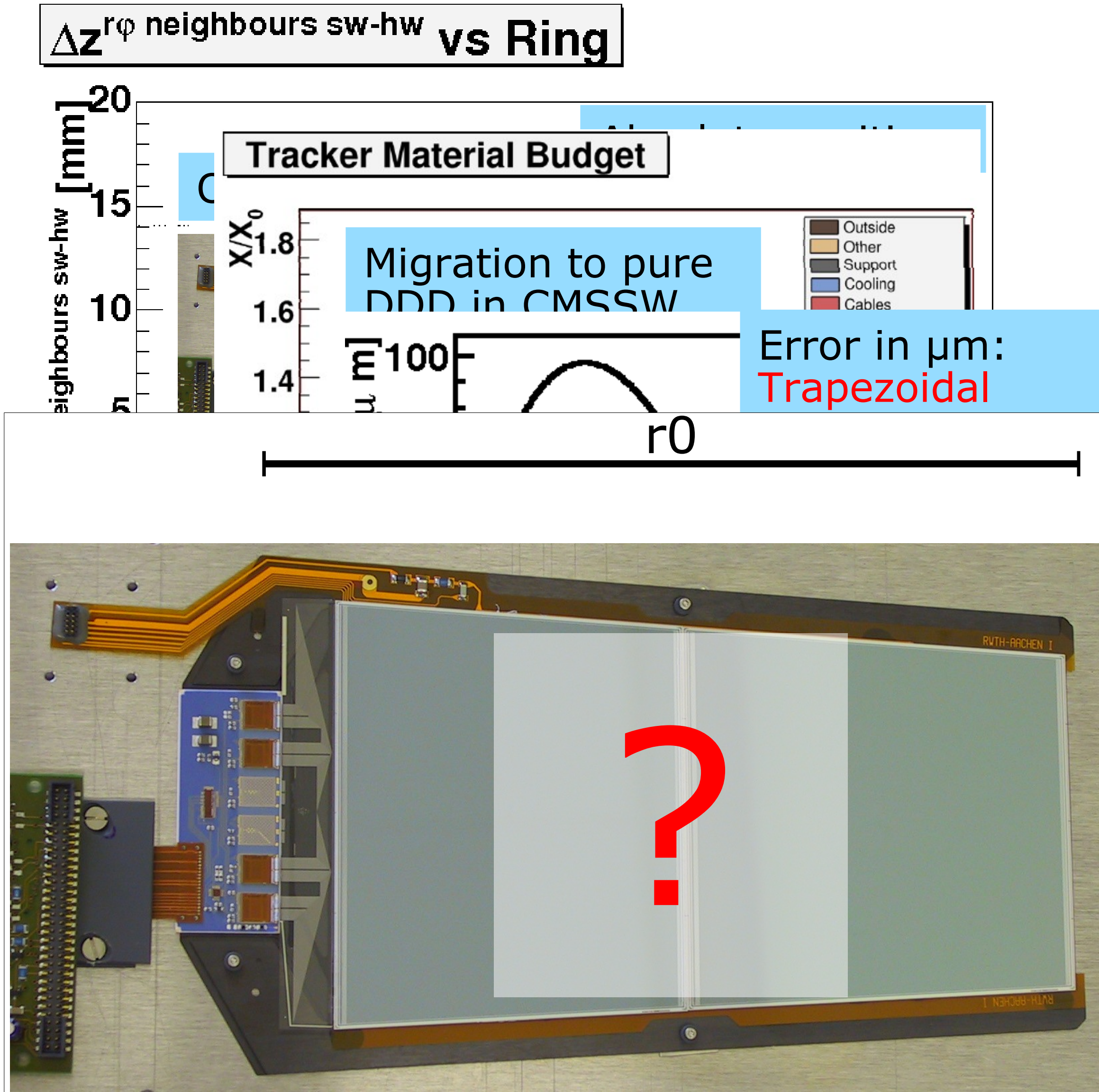
- Certain transformations leave χ^2 unchanged ("weak modes")
  - Simplest: Layer rotation $\alpha \sim R$
    - Distorts p_T spectrum and inv. Mass → impact on physics!
  - A lot more higher modes...
  - High global correlation observed by using single tracks without any constraint
- Use constraints (under study)
  - Laser Alignment System
  - $Z \rightarrow \mu\mu$ 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: $Z \rightarrow \mu\mu$ 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)



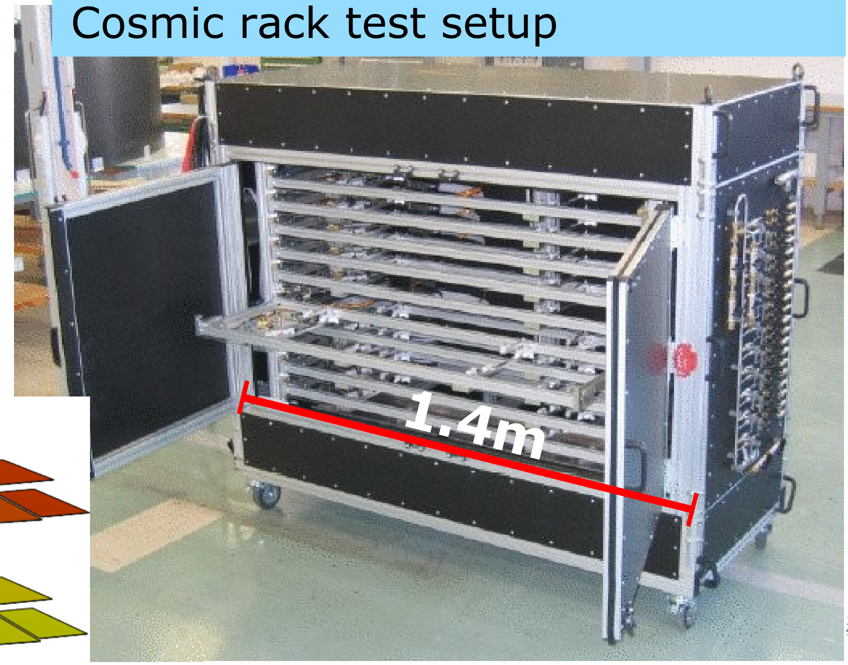
Ring 3	438146	447430	140.82	140.79
Ring 4	551201	561680	126.27	126.17

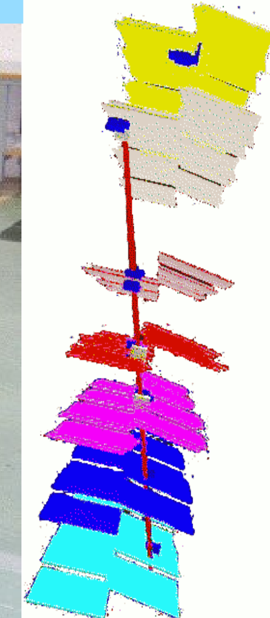
Test and integration setups

Experience from test setups and integration

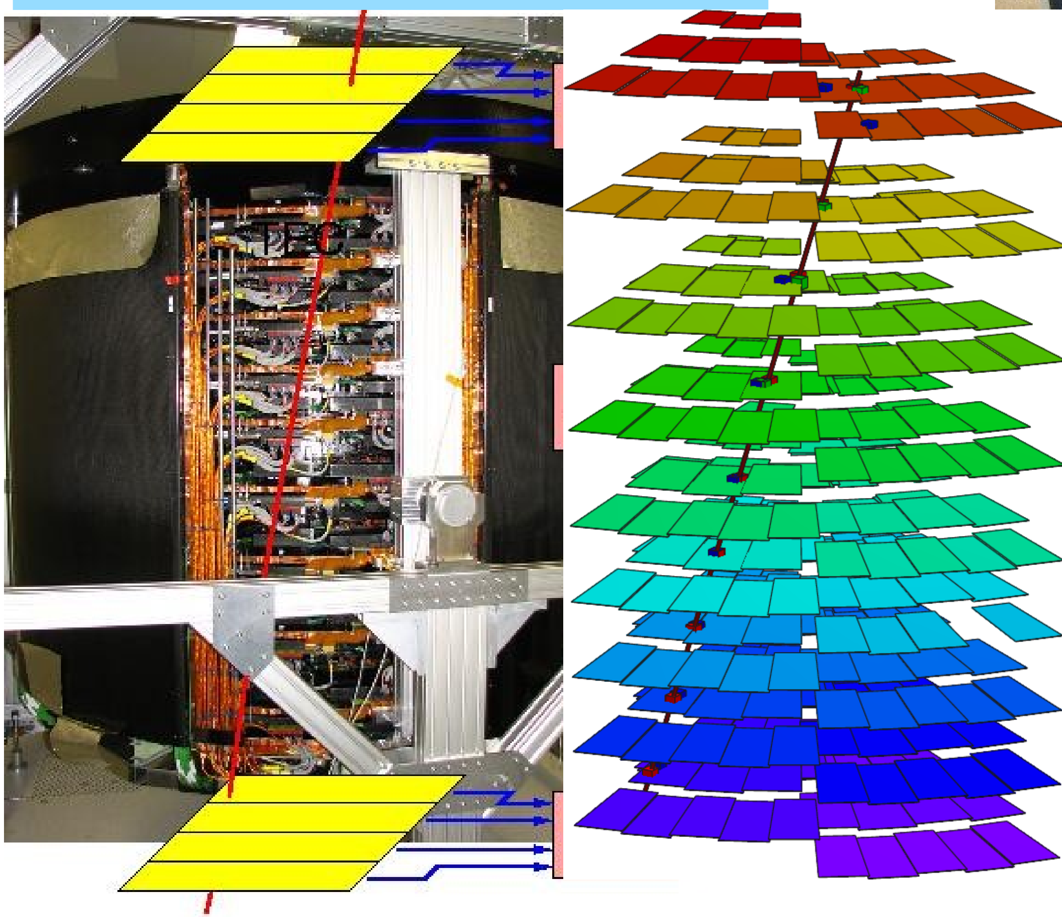
- Many data available
- Corrections to software module layout, orientation (local axis), ...
- Alignment efforts ongoing

Cosmic rack test setup

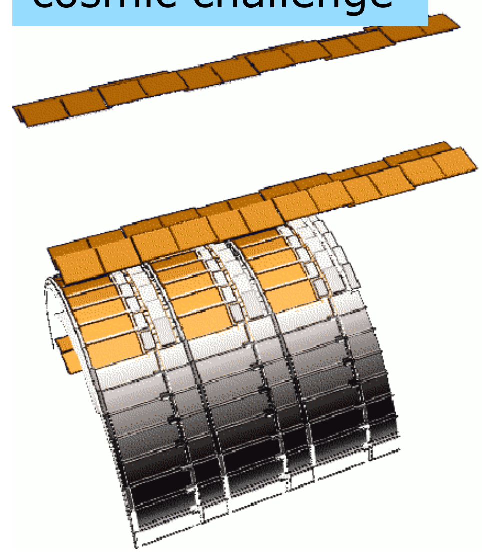


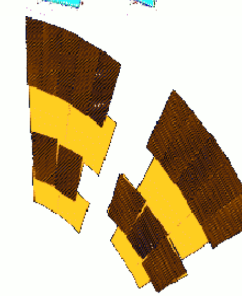


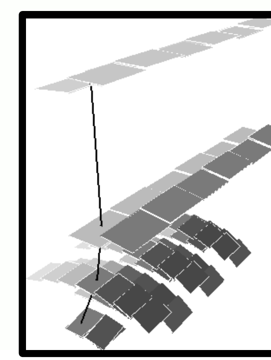
TEC integration, 400 modules



Magnet test and cosmic challenge



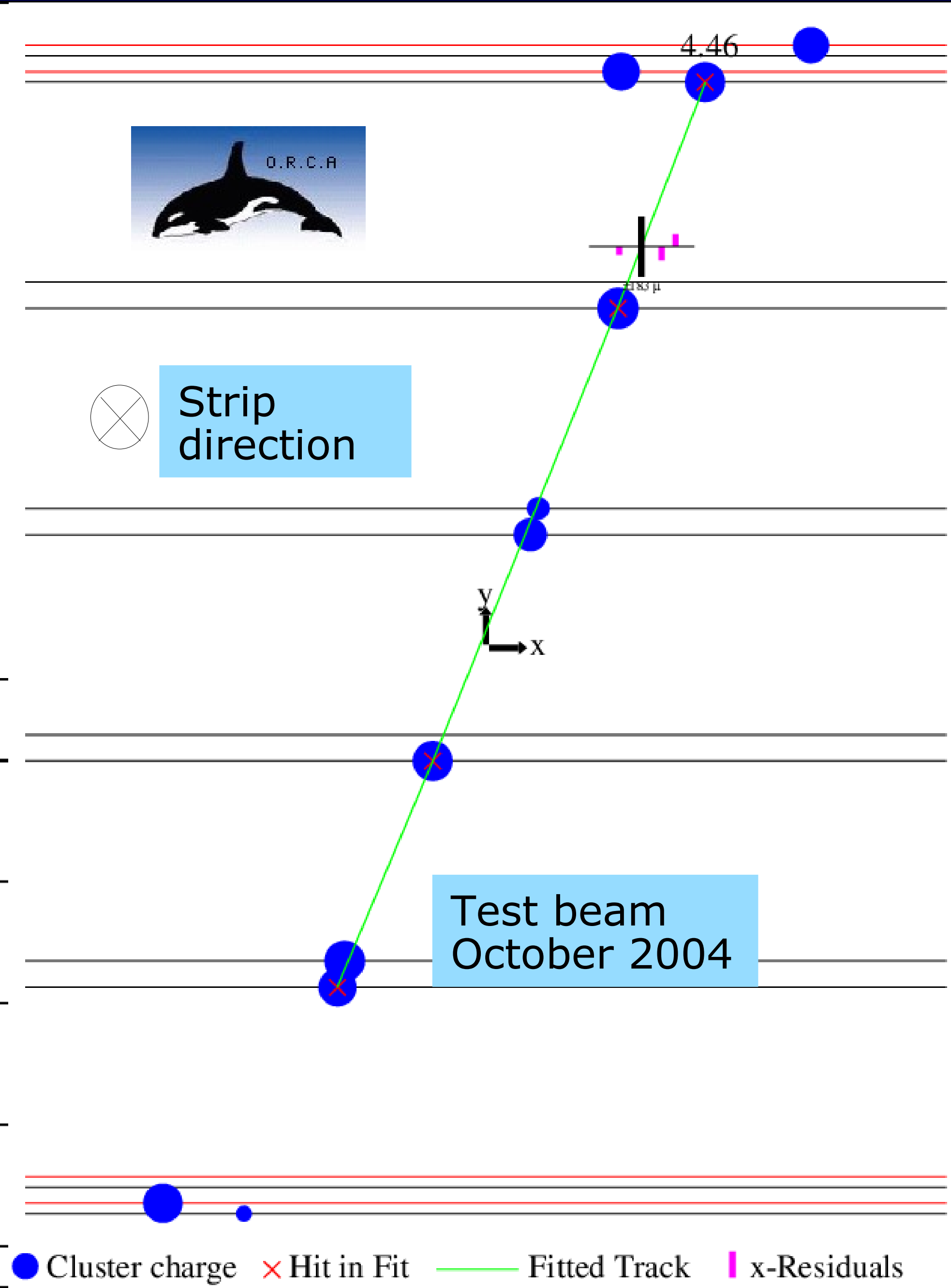




Cosmic Rack alignment: Test Beam data

- Reconstruction of tracks
- Determination of residuals
  - “manual alignment”: shift detector positions until residuals minimized
- Usually starting point of alignment
  - track fit does not take alignment into account → bias
- Use unbiased fitter → CMS PTDR

	manual	HIP-1D	Millepede	HIP-2D	
	x [μm]	x [μm]	x [μm]	x [μm]	γ [mrad]
Rod 2					
Detector 3	-105	-105±2	-101±4	-114±6	-0.12±0.08
Detector 4	363	380±7	379±17	356±13	-0.37±0.18
Rod 3					
Detector 3	-454	-466±2	-457±4	-466±6	-0.00±0.08
Detector 4	-99	-61±7	-96±15	-77±13	-0.26±0.19
Rod 4					
Detector 3	-935	-946±2	-938±6	-954±4	-0.11±0.06
Detector 4	-579	-541±6	-544±16	-532±9	0.22±0.14
Rod 5					
Detector 3	-457	-470±2	-467±4	-479±4	-0.13±0.05
Detector 4	-141	-80±7	-91±17	-67±9	0.27±0.15
mean track χ^2	1.75	1.72	1.73	1.69	



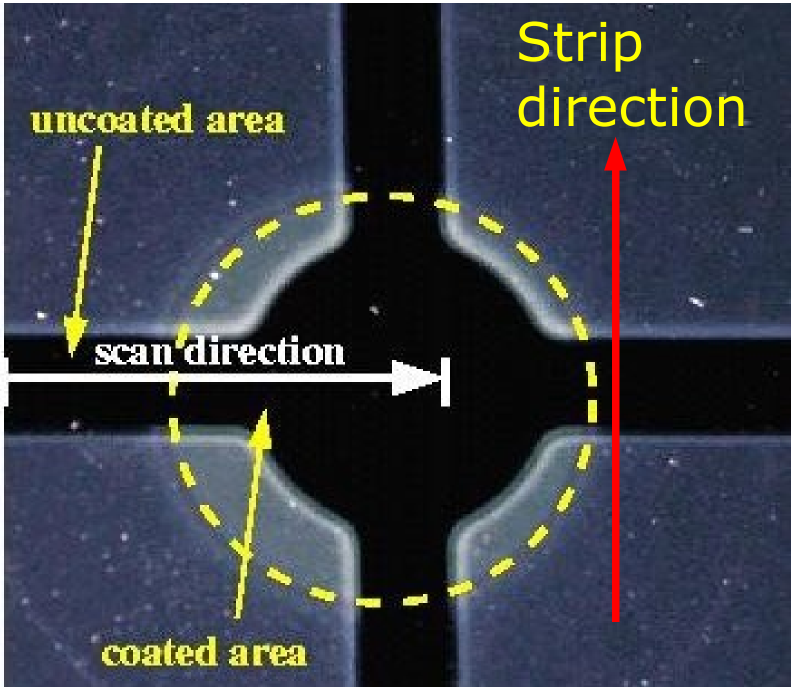
Laser alignment

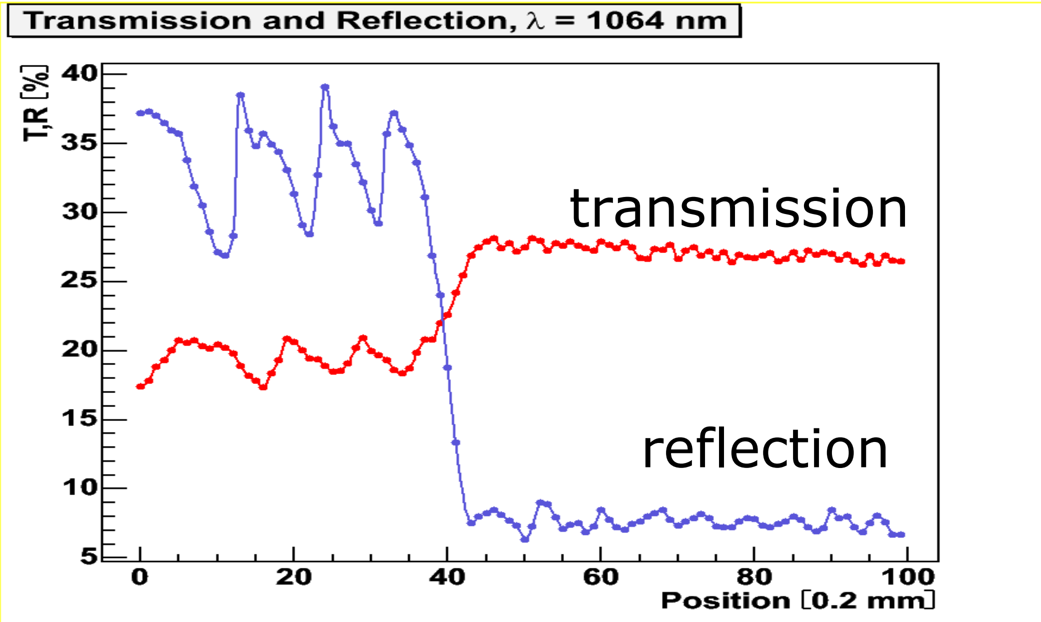
LAS goals and concepts

- External alignment (for joint Tracker+Muon system track fit)
  - ≤ 150 μm measurement of Muon System position w.r.t. Tracker
  - ≤ 30 μrad measurement of Muon System orientation w.r.t. Tracker
- Internal alignment:
  - ≤ 100 μm measurement of sub-detector relative positions for track pattern recognition (between TIB and TEC, between TOB and TEC)
  - ≤ 50 μm for 50% of TEC petals → 70 μm for 50% of TEC modules
  - ≤ 10 μm monitoring of relative sub-detector position stability for track parameter reconstruction

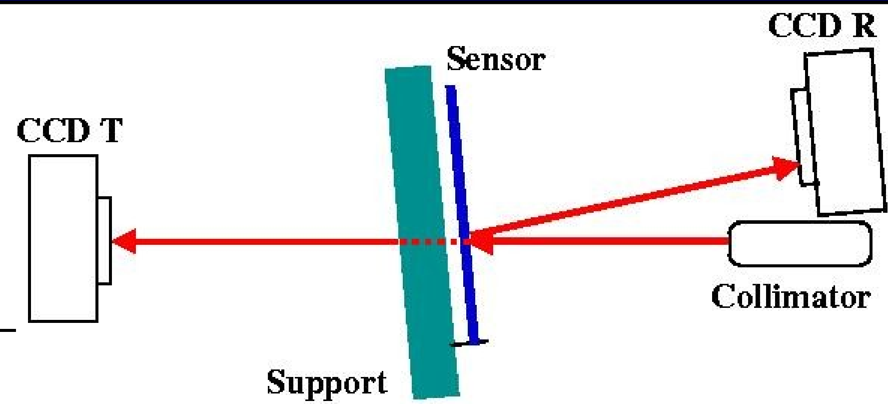
TEC Alignment sensors and modules

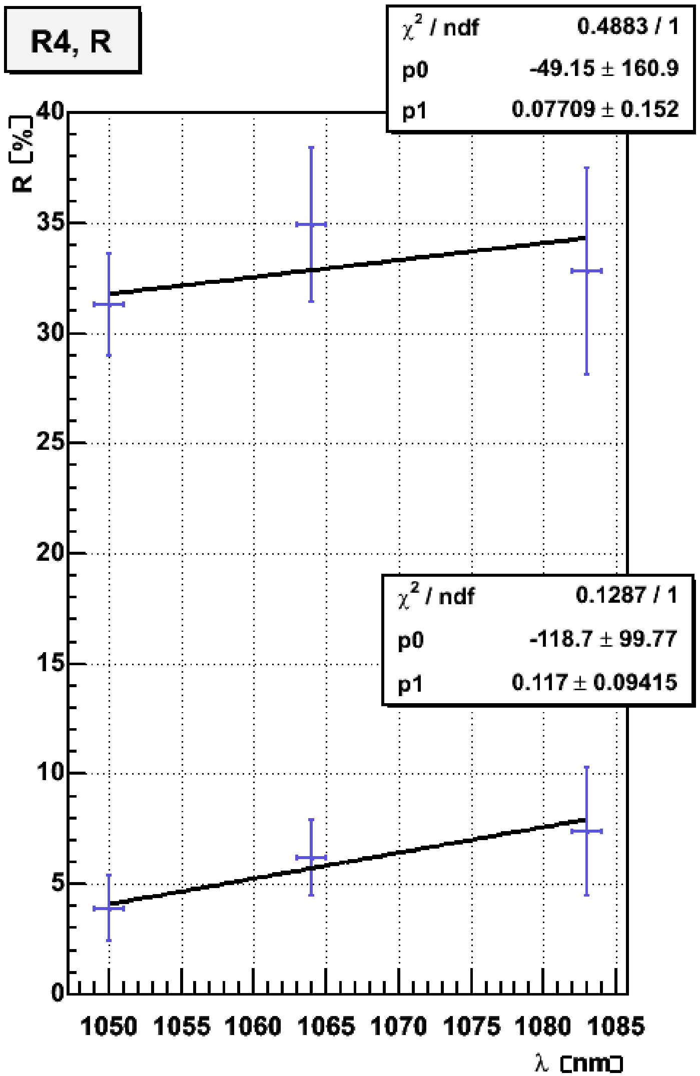
- Main concepts
  - Use Tracker silicon sensors and Tracker DAQ
  - No external reference structures necessary
  - No precise positioning of LAS beams required (redundancy)
- Module design
  - 420 Ring 4 + 140 Ring 6 B sensors produced by HPK
  - 10 mm hole in aluminum backside coating
  - All sensors with anti-reflectve coating
    - Transmission 14-20% (R4) and 13-18% (R6) (at λ=1075 nm)
    - Reflectivity <= 6%
    - Reduced interference effects

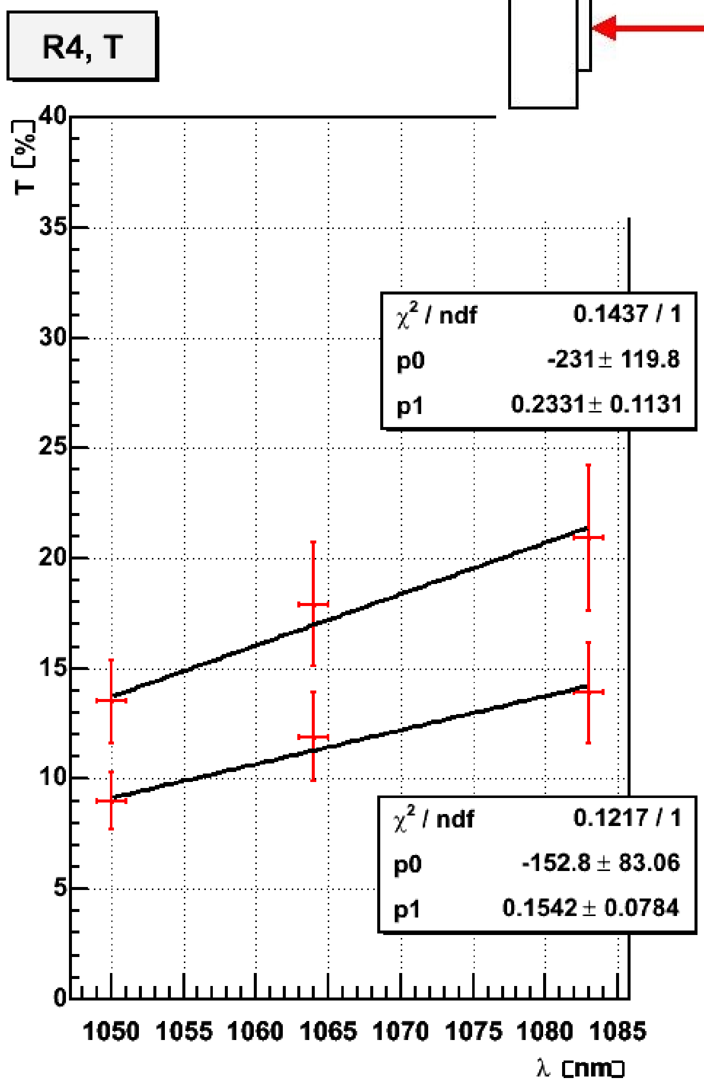




- T, R, and A are functions of the wavelength λ!

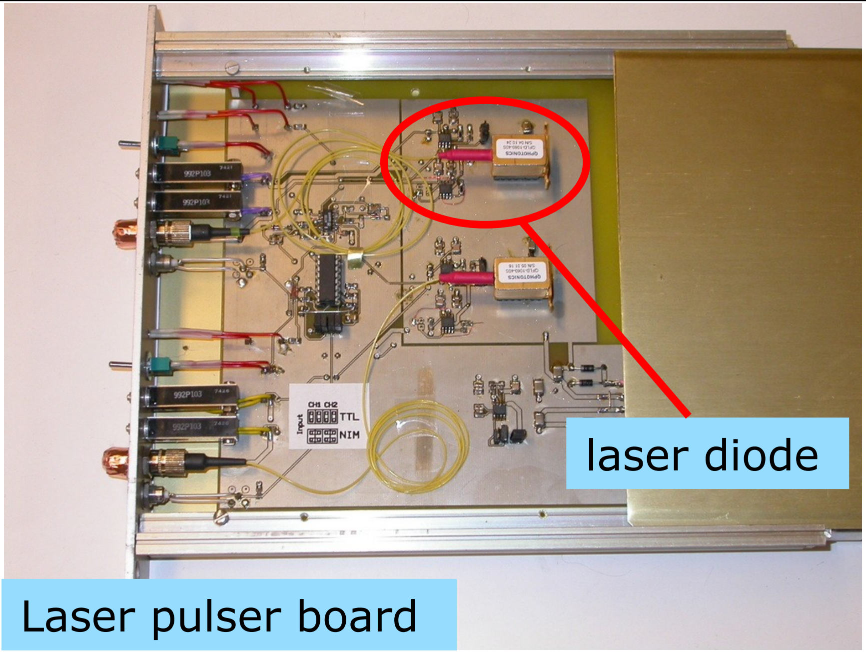


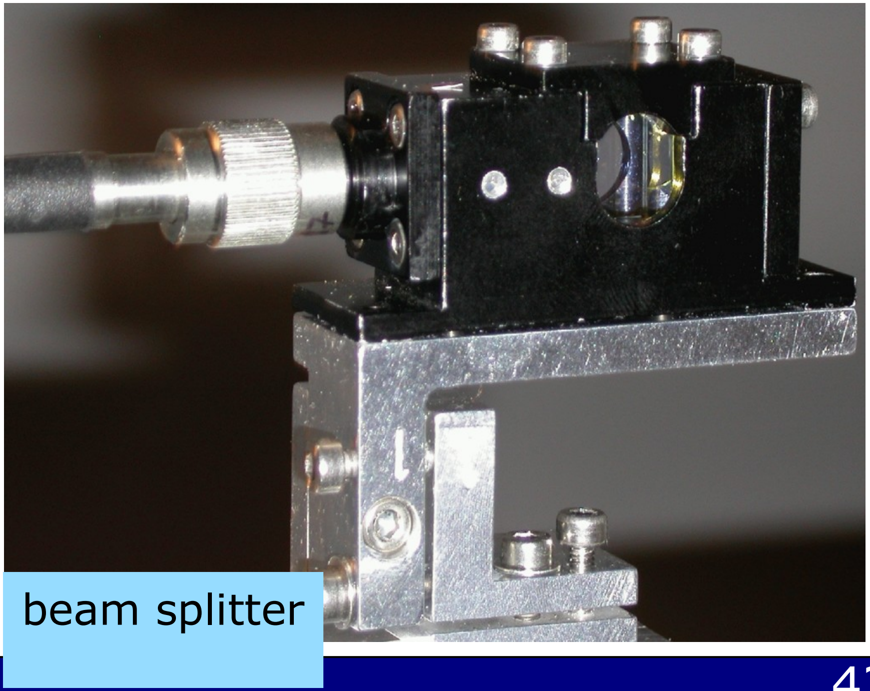




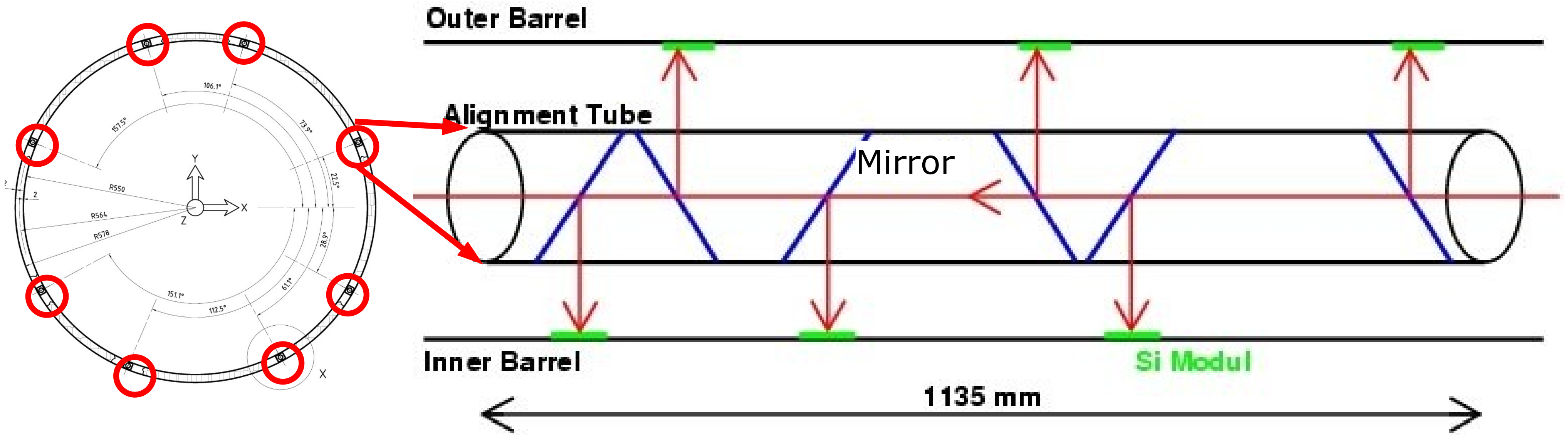
Fibers and beam splitters

- Laser diode:
  - Qphotonics
  - λ = 1075±4 nm (near infrared)
  - spectral width Δλ = 2nm,
- Fibers
  - from Corning, cabling by Ericsson
  - non-magnetic radiation-hard FC connectors
- Cables
  - All 15 km fibers/cables in Aachen
  - 50 cables terminated
- Beam Splitters
  - 40 beam splitters (BS) type TEC produced in Islamabad
  - now in Aachen,
  - 32 with cables connected





Alignment tubes / mirrors



- 16 alignment tubes in total (8 for z>0 and 8 for z<0)
  - 6 mirrors in each tube: 3 for TIB, 3 for TOB
- Prototype tube from Pakistan measured
  - Mirror reflectivity 5%, accuracy of deflected beam 3 mrad
- Alignment tubes production progress
  - Manufactured in Aachen workshop (Aluminum)
  - All tubes are ready, two tubes have been sent to Pakistan for mirror assembly
  - First assembled production tube is about to be sent to Aachen for measurements
  - Remaining tubes scheduled for February