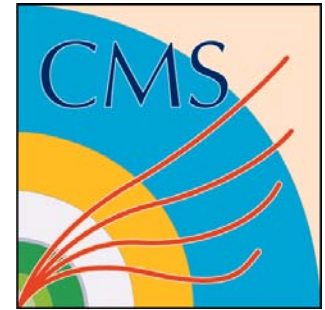




Track based Alignment in CMS



Frank-Peter Schilling (CERN)

LHC Detector Alignment Workshop 05/09/2006

Contents:

- Data samples
- Alignment strategy
- Alignment algorithms
 - HIP
 - Kalman Filter
 - Millepede-II
- Muon alignment with tracks

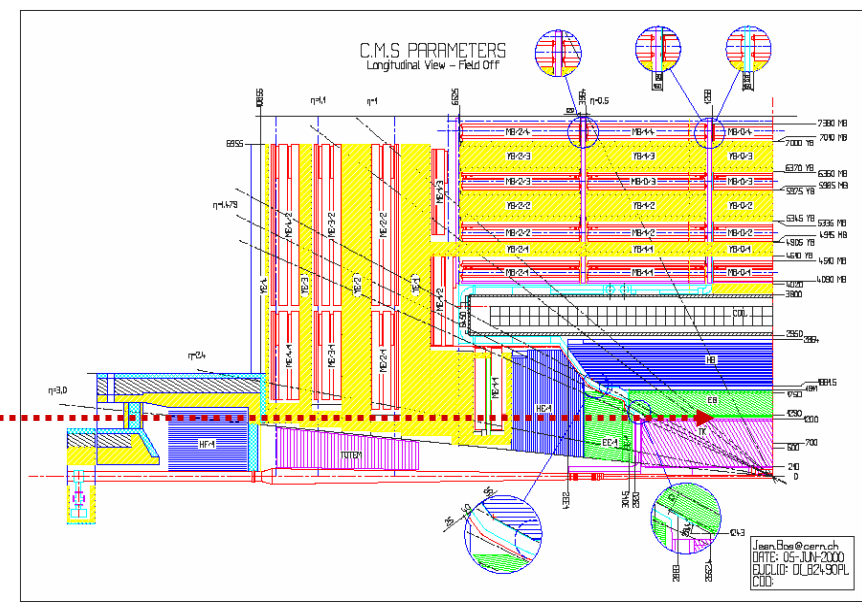
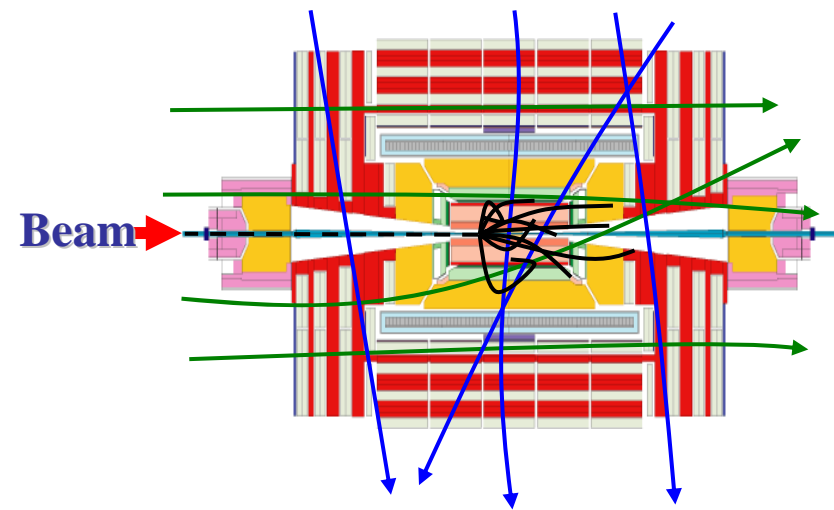


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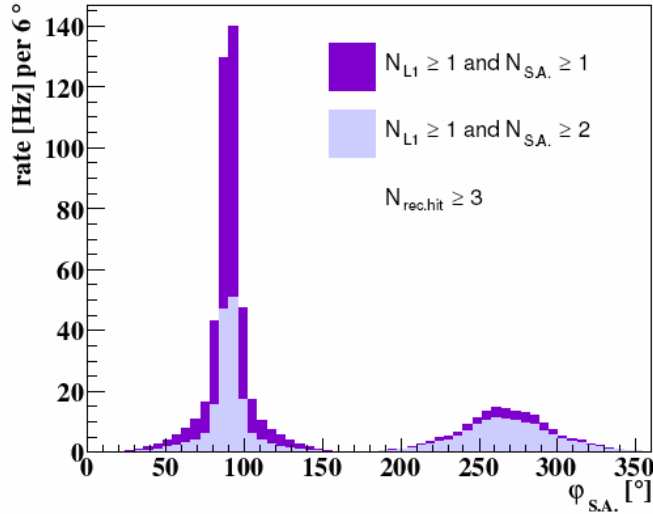


- Large number of alignment parameters (~100,000 in tracker) requires novel techniques
- Three different alignment algorithms implemented in CMS reconstruction software (now transition from “ORCA” to “CMSSW”)
 - ❑ Kalman Filter, Millepede-II, HIP Algorithm
 - ❑ Cross check results using different algorithms with different approaches and systematics
 - ❑ Supported by common software infrastructure
- Alignment using different data sets (dedicated MC generators)
 - ❑ Muons from Z,W; Cosmics; beam halo; muons from J/ψ, B; high pt QCD tracks
- Reduced data format (AlCaReco)
 - ❑ Development of fast Alignment stream (Z,W) produced during prompt reconstruction at Tier-0
- Combine track based alignment with laser alignment and survey data
- Employ mass and vertex constraints; use of overlaps
- Develop observables sensitive to misalignment other than χ^2
 - ❑ Monitoring, fix χ^2 invariant mode
- CMS alignment group ~20 people from ~8 institutes

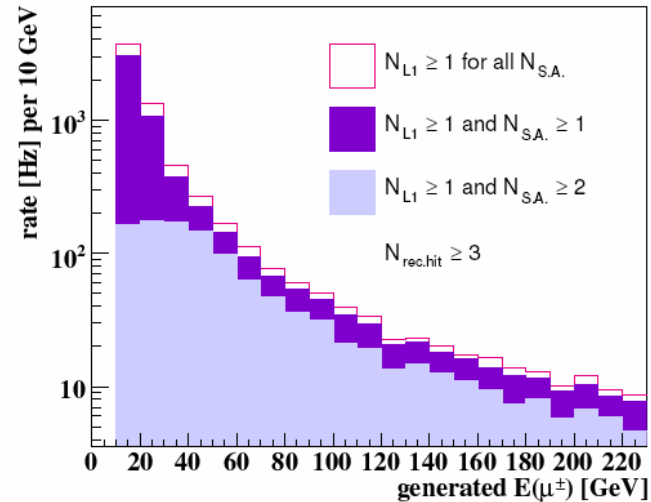
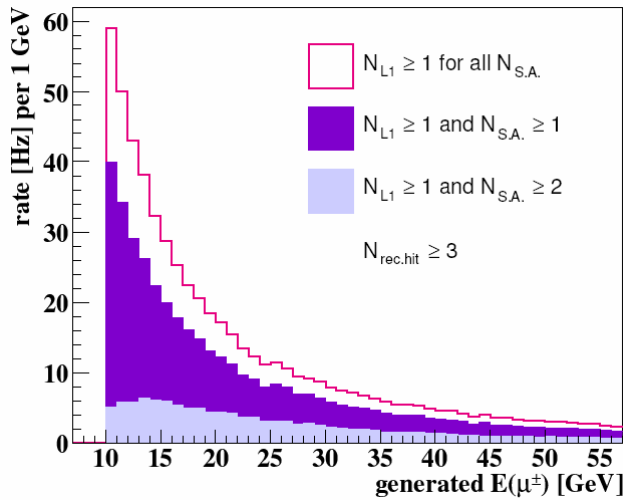
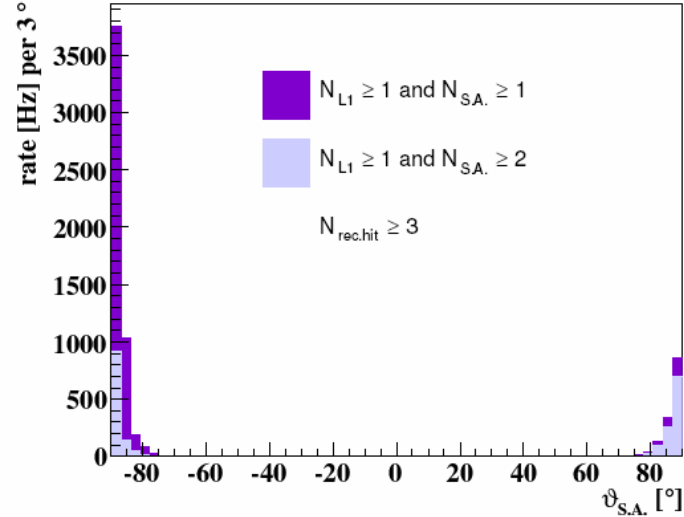
- **High p_T muons from Z,W decays**
 - ❑ Rate: 20k $Z \rightarrow \mu\mu$, 100k $W \rightarrow \mu\nu$ per day at $L=2 \cdot 10^{33}$
 - ❑ Gold plated for tracker alignment (small multiple scattering)
 - ❑ Exploit Z^0 mass constraint
- **Cosmic Muons**
 - ❑ ~400Hz after L1 and s.a. muon reco.
- **Beam Halo Muons**
 - ❑ ~5 kHz per side after L1 and s.a. muon
 - ❑ Problem: Muon endcap trigger outside tracker acceptance in R!
 - ❑ Potentially install scintillators (for startup) or use TOTEM T1
- **Muons from J/ψ and inclusive B decays**
 - ❑ J/ψ mass constraint
- **Min. bias, high pt hadrons from QCD events**
 - ❑ Potentially useful for pixel alignment



- Cosmic muons: 400 Hz**



- Beam halo muons: 5 kHz per side**



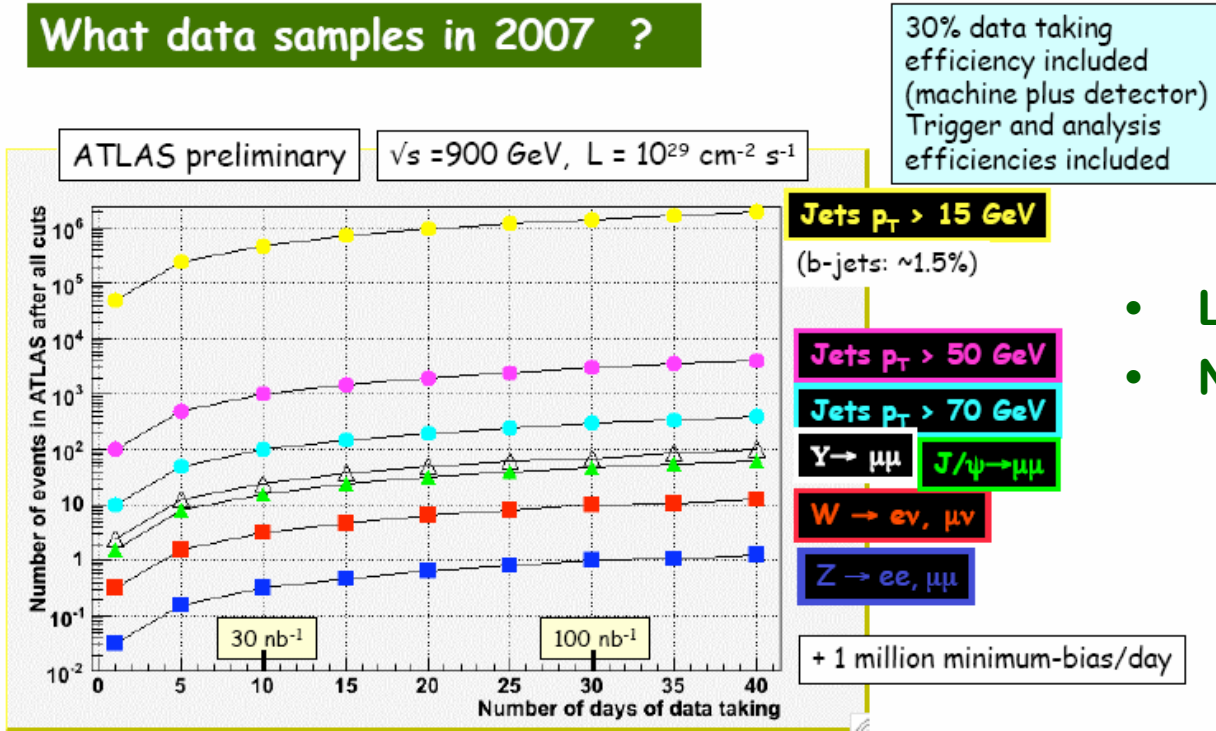
Basic scetch:

- 2007: Before beams:
 - ❑ Cosmics (+laser alignment and survey measurements)
- 2007: single beams
 - ❑ add beam halo muons
- 2007: Pilot run, pixel detector not installed (except few test modules)
 - ❑ Cosmics, beam halo muons
 - ❑ add available high pt muons, tracks
 - ❑ Initial alignment of high level strip tracker structur (layers, rods)?
- 2008:Two-step approach:
 - ❑ Add Larger statistics of muons from Z,W
 - ❑ 1. Standalone alignment of pixel detector
 - ❑ 2. Alignment of strip tracker, using pixel as reference
- **To be layed out in more detail ...**

See next slides
for rate estimates

- Pilot run 2007 @ 900 GeV, $L \sim 10^{29}$

What data samples in 2007 ?



F. Gianotti (ICHEP 2006)

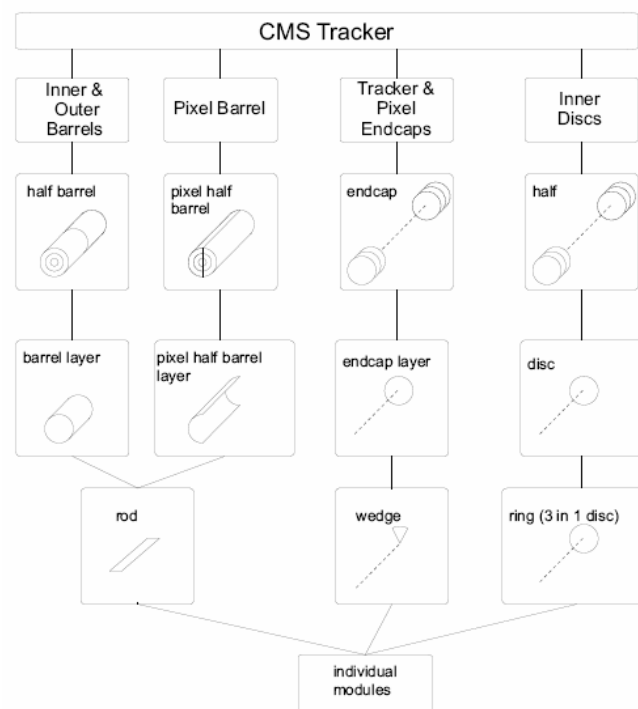
- Loads of min. bias, QCD jets
- Not much of anything else ...

- Physics Run 2008 @ 14 TeV, $L \sim 10^{32...33}$

Luminosity	$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$2 * 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Time	few weeks 6 months	1 day few weeks one year
Int. Luminosity	100 pb^{-1} 1 fb^{-1}	1 fb^{-1} 10 fb^{-1}
$W^\pm \rightarrow \mu^\pm \nu$	700K 7M	100K 7M 70M
$Z^0 \rightarrow \mu^+ \mu^-$	100K 1M	20K 1M 10M

- Large statistics of high pt muons within few weeks!

- (MIs)alignment implemented at reconstruction level:
 - ❑ “Misalignment tools”, move and rotate modules or higher level structures
- Dedicated “Misalignment Scenarios”
 - ❑ Short term scenario
 - o First data taking (few 100 pb^{-1})
 - o Pixel already aligned
 - o Strip tracker misaligned, only survey and laser alignment
 - ❑ Long term scenario
 - o Few fb^{-1} accumulated
 - o Full alignment performed, residual misalignments $\sim 20 \mu\text{m}$
- Fast track refit (without redoing pattern recognition)
- Reduced data format containing only alignment tracks
 - ❑ Small file size, fast processing



- Algorithms implemented in standard CMS reconstruction software using a **common layer of general functionality**
 - ❑ Management of parameters and covariances
 - ❑ Derivatives wrt track and alignment parameters
 - ❑ I/O, Database connection

- Minimization of track impact point (x) - hit (m) residuals in local sensor plane as function of alignment parameters

$$\epsilon = \begin{pmatrix} \epsilon_u \\ \epsilon_v \end{pmatrix} = \begin{pmatrix} u_x - u_m \\ v_x - v_m \end{pmatrix}$$

- χ^2 function to be minimized on each sensor (after many tracks per sensor accumulated)

$$\chi^2 = \sum_i \epsilon_i^T V_i^{-1} \epsilon_i$$

- V: covariance matrix of measurement

- Linearized χ^2 solution:

- δp : vector of alignment parameters
 $\delta p = (\delta u, \delta v, \delta w, \delta \alpha, \delta \beta, \delta \gamma)$

- J_i : derivative of residuals w.r.t. alignment parameters

$$\delta p = \left[\sum_i J_i V_i^{-1} J_i^T \right]^{-1} \left[\sum_i J_i V_i^{-1} \epsilon_i \right]$$

- Local solution on each “alignable object”

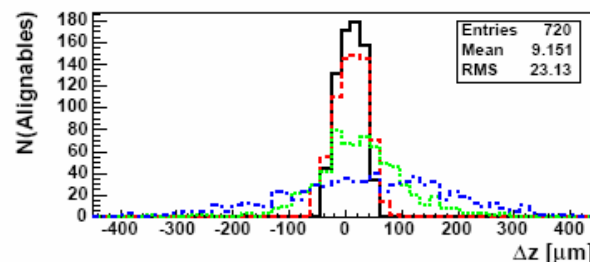
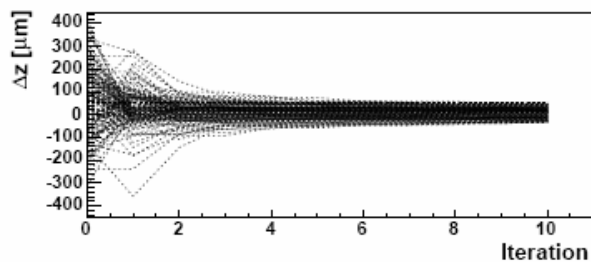
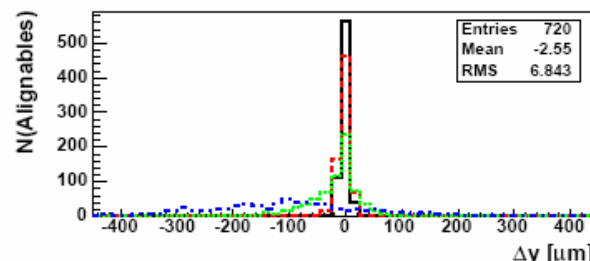
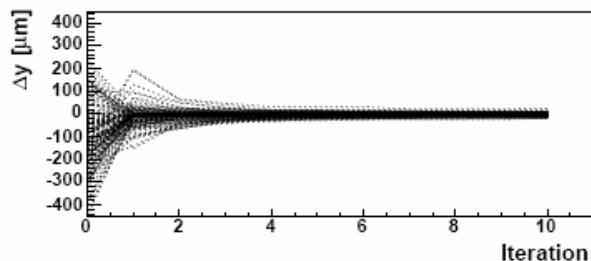
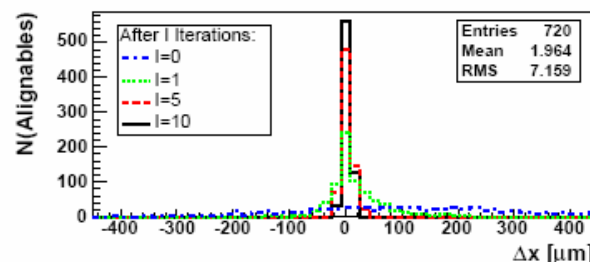
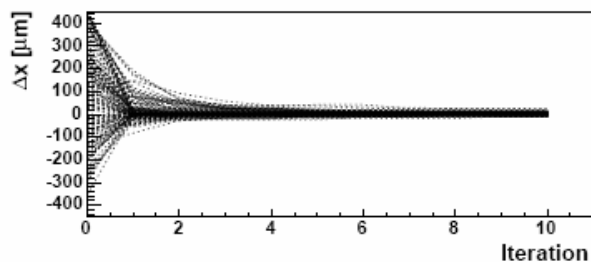
- Only inversion of small (6x6) matrices, computationally light

- o Formalism extended to **alignment of composite detector structures** (ladders, disks, layers etc.)
 - o Minimize χ^2 using all tracks crossing sensors of composite object with respect to alignment parameters of composite object
 - o Implemented using chain rule
- o Correlations between modules not included explicitly
- Implicitly included through iterations
- Large statistics \rightarrow **parallel processing**:
 - ❑ Run on N cpu's processing 1/N of the full sample each
 - ❑ Combine results from all CPUs, compute alignment corrections
 - ❑ Start next iteration on N cpu's

$$\frac{\delta \epsilon_i^S}{\delta p_i^C} = \frac{\delta \epsilon_i^S}{\delta p_i^S} \times \frac{\delta p_i^S}{\delta p_i^C}$$

- **Example: 1M $Z \rightarrow \mu\mu$ events:**
 - ❑ reduced DST format keeps only muon tracks
 - ❑ Refit track, don't re-reconstruct
 - ❑ With 20 CPUs in parallel, **one iteration: ~45'**

- Alignment of 720 CMS Pixel Barrel modules
- “First data taking” misalignment scenario
 - Includes correlated misalignments
- 200K $Z^0 \rightarrow \mu^+ \mu^-$ events, 10 iterations



• Good convergence: RMS $\sim 7\mu\text{m}$ in x, y $\sim 23\mu\text{m}$ in z

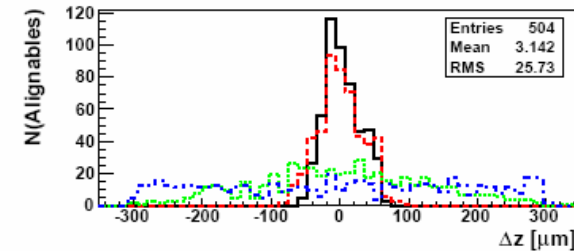
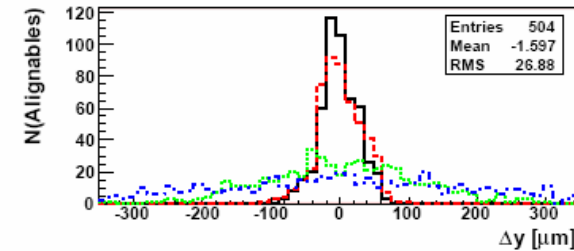
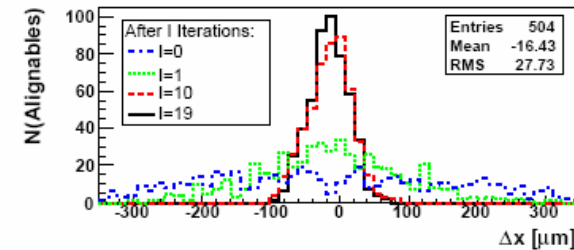
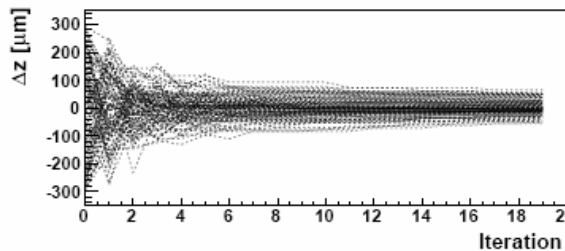
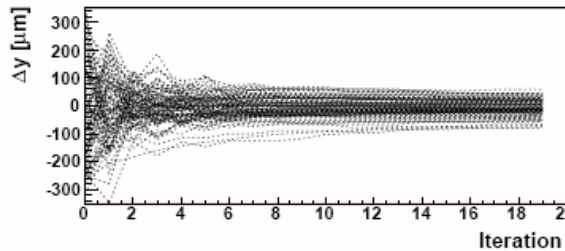
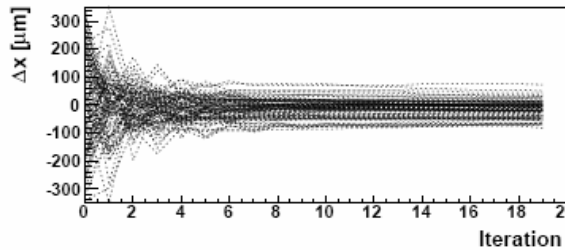
- Caveat: Alignment w.r.t ideal strip tracker

CMS Note 2006/018

- Standalone alignment of pixel modules
- Minimize influence of misaligned strip detector:

- refitting only pixel hits of the tracks
- use momentum constraint from full track (significantly improves convergence)

- Two muons from $Z^0 \rightarrow \mu^+ \mu^-$ are fitted to common vertex
- Flat misalignment $\pm 300 \mu\text{m}$ in x,y,z
- 500k events, 19 iterations
- **Reasonable convergence, RMS $\sim 25 \mu\text{m}$ in all coordinates**



CMS Note 2006/018

- Method for global alignment derived from Kalman Filter
- Ansatz:
 - measurements m depend via track model f not only on track parameters x , but also on alignment parameters d :

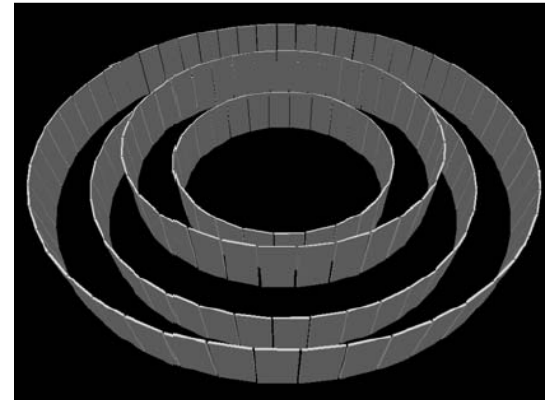
$$m = f(x, d) + \epsilon \quad \text{COV}(\epsilon) = V$$

- Update equation of Kalman Filter:

$$\begin{pmatrix} \hat{d} \\ \hat{x} \end{pmatrix} = \begin{pmatrix} d \\ x \end{pmatrix} + K(m - c - Ad - Bx)$$

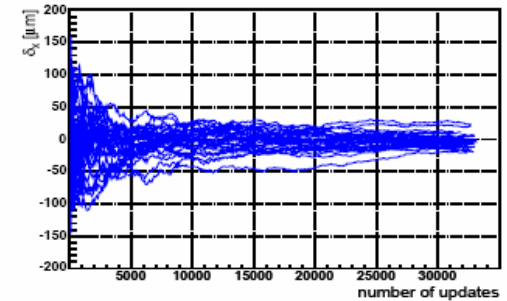
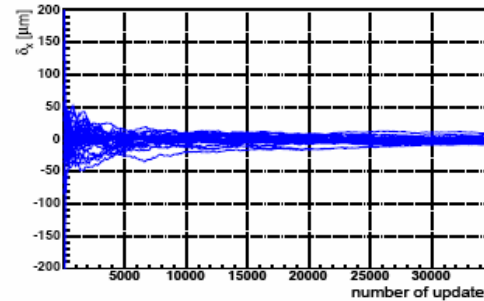
- For details, see talk by R. Fruehwirth!
- Iterative: Alignment Parameters updated after each track
- Global: Update not restricted to modules crossed by track
 - Update can be limited to those modules having significant correlations with the ones in current trajectory
 - Requires some bookkeeping
 - No large matrices to be inverted!
- Possibility to use prior information (e.g. survey data, laser al.)
- Can add mass / vertex constraints

- Wheel-like setup: (part of CMS tracker: 156 TIB modules)
- Pixel detector as reference
- Misalignment:
 - local x, y $\sigma=100\mu\text{m}$
- Update restricted to distance $d_{\text{max}} \leq 6$
- Single muons $p_T=100$ GeV
- Convergence slower in outer layers (distance from reference system, less track statistics)



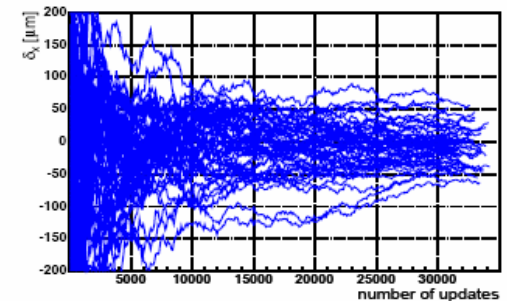
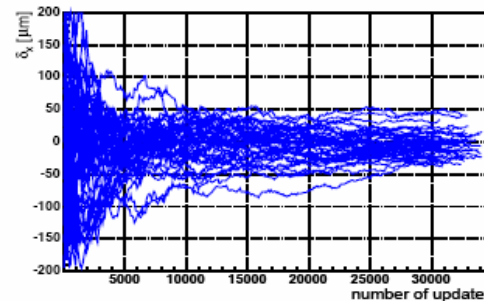
Layer 1

Layer 2



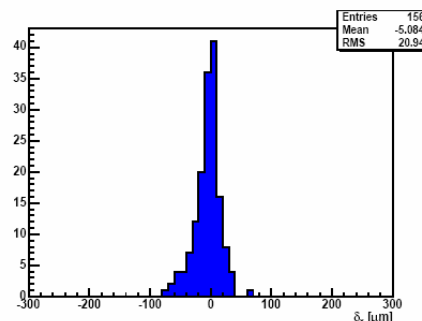
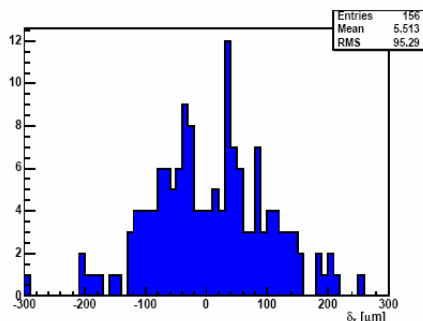
Layer 3

Layer 4



CMS Note 2006/022

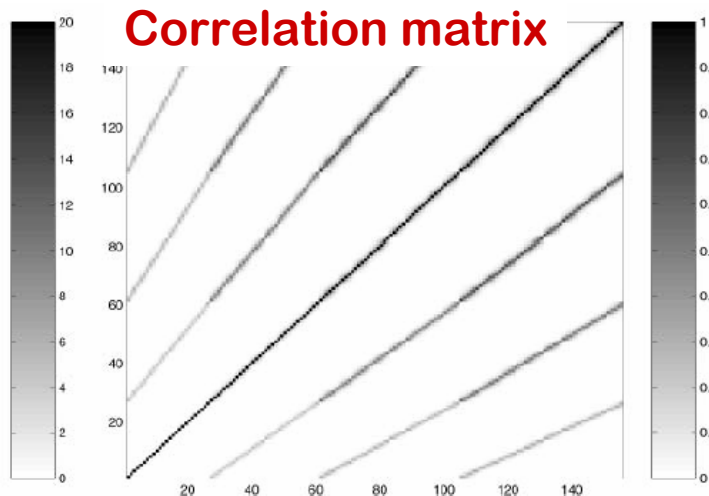
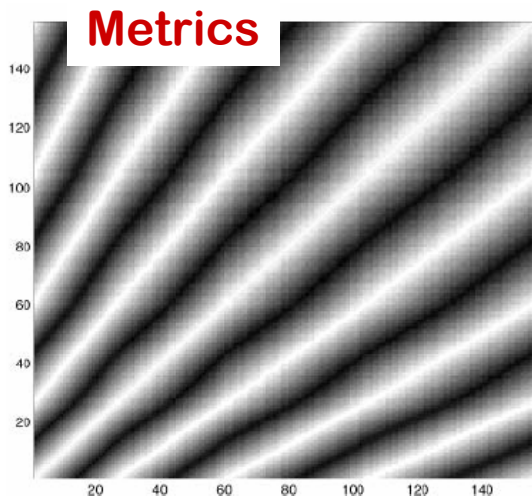
- Overall RMS $\sim 21\mu\text{m}$ after alignment



- Dependence of RMS and CPU time on d_{max}

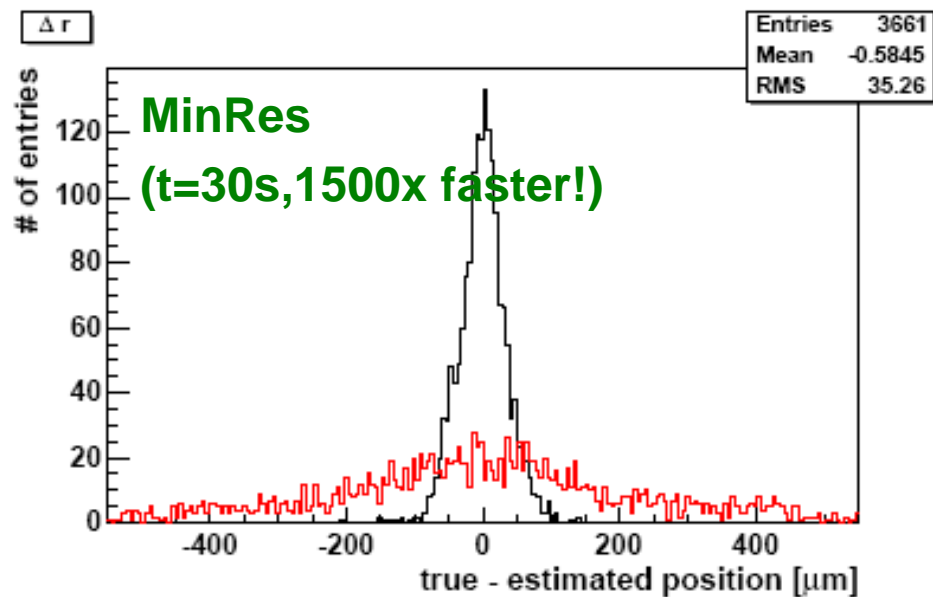
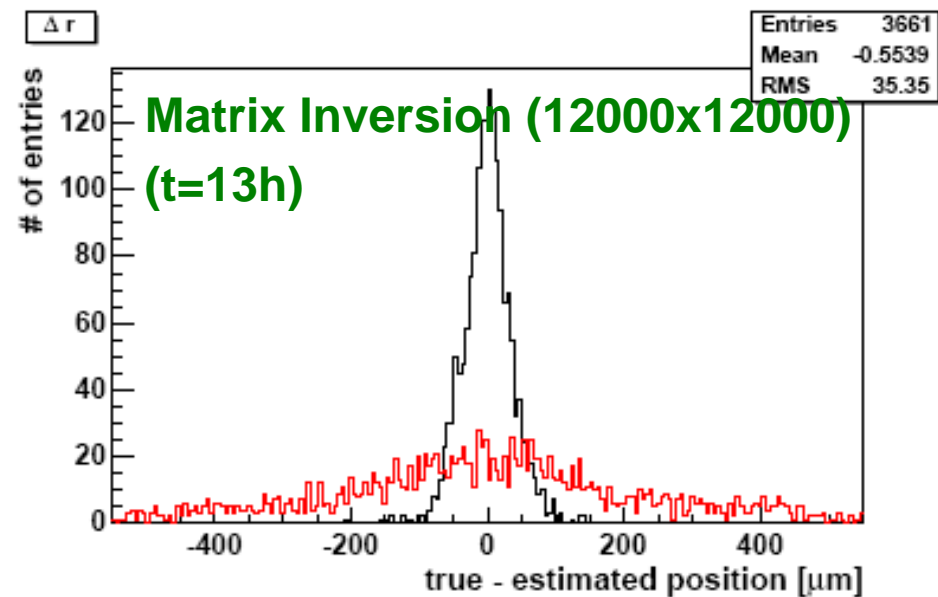
d_{max}	1	2	3	4	5	6
σ [μm]	24.75	21.38	20.97	20.95	20.94	20.94
T [s]	472	604	723	936	1152	1319

- $d_{\text{max}}=6$ does not exclude modules with relevant correlations



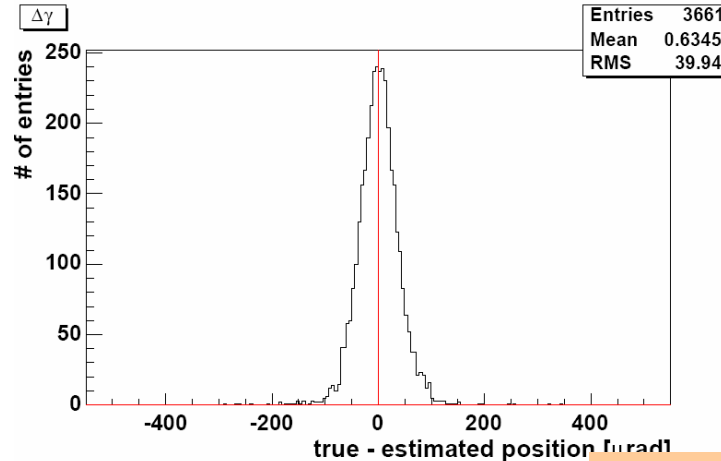
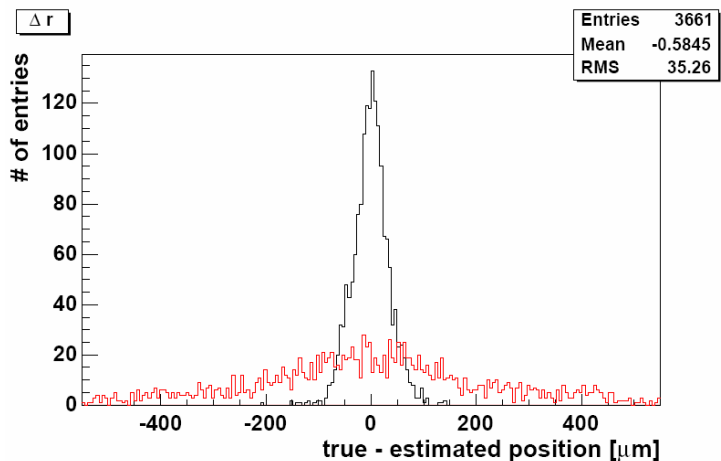
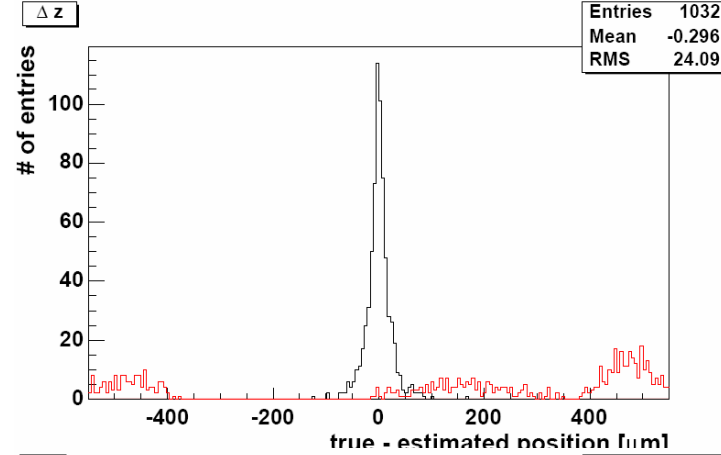
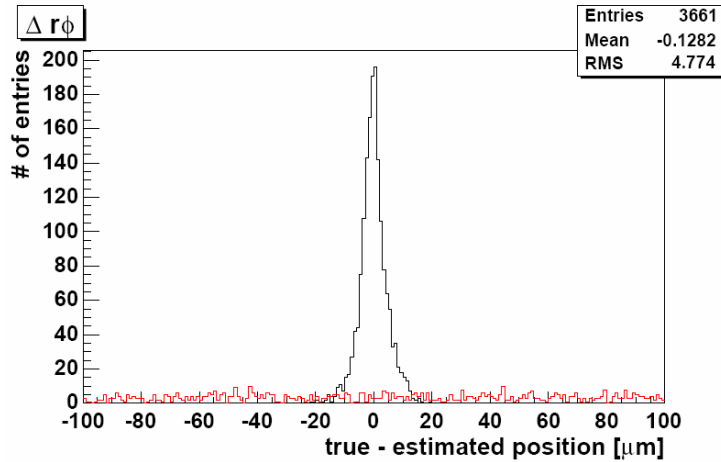
CMS Note 2006/022

- For formalism, see talk of V. Blobel
- Original Millepede method solves matrix eqn. $Ax = B$, by inverting huge matrix A . Can only be done for <12000 alignment parameters
- New Millepede II method instead minimises $|Ax - B|$. Expected to work for ~ 100000 alignment parameters (i.e. for full CMS at sensor level)
- Both successfully aligned $\sim 12\%$ of tracker modules using $2M$ $Z \rightarrow \mu\mu$ events. Results identical, but new method 1500 times faster!



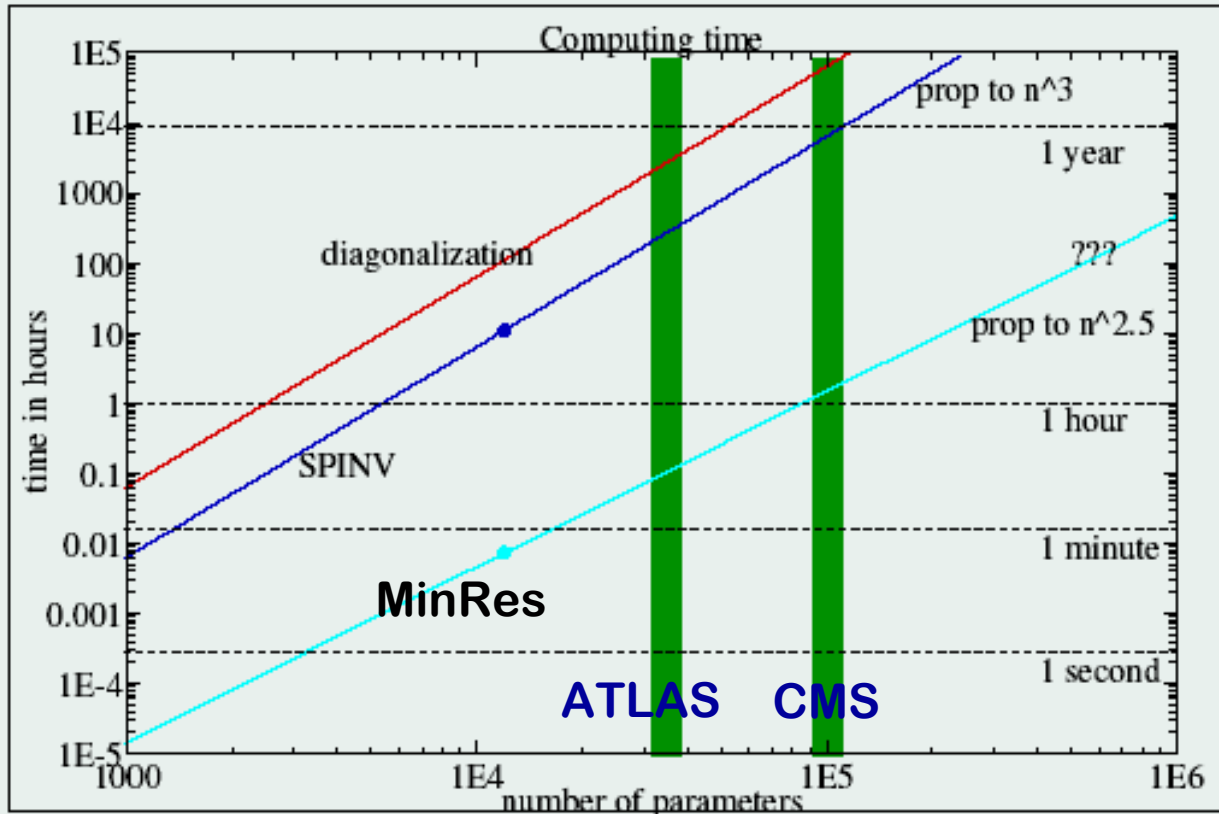
CMS Note 2006/011

- Alignment of the strip tracker at sensor level
- Barrel region, $|\eta| < 0.9$, 12015 alignment parameters
- (Mis)alignment in $r\phi$, r , z , γ at half-barrel / layer / rod / module levels



CMS Note 2006/011

CPU time in hours as a function of number of parameters



CPU Time for CMS (100k parameters):

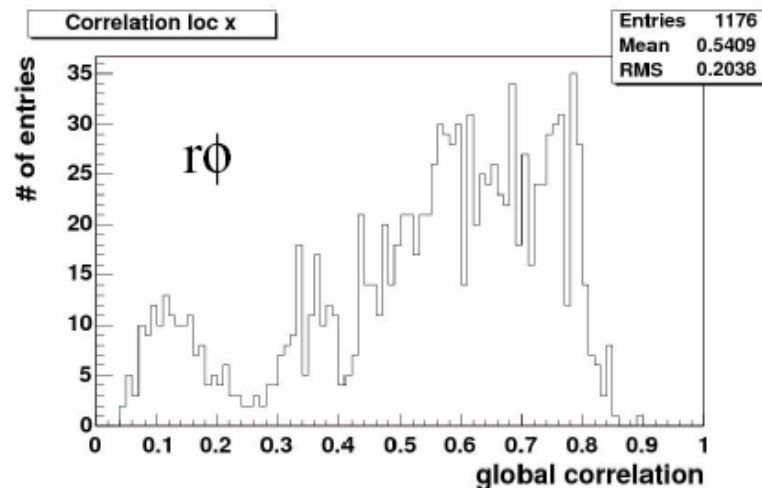
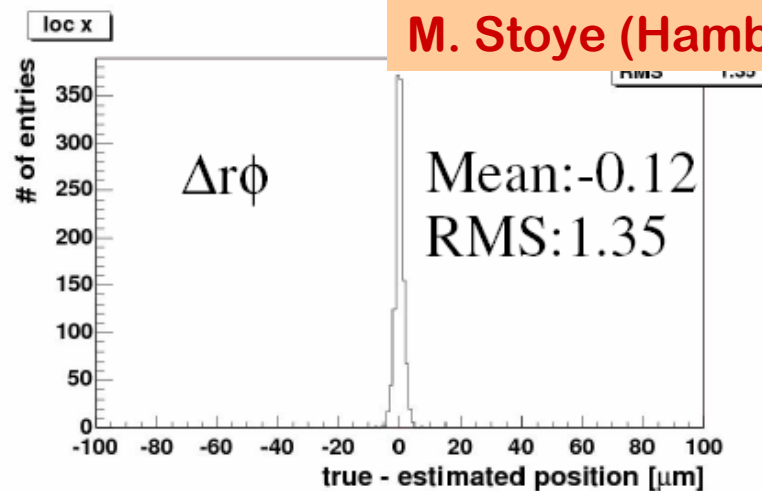
- **Diagonalization**
~10 year at one CPU
- **Inversion:**
~1 year at one CPU
- **Iteration:**
~1 h at one CPU

- **New Millepede-II (iterative method) scalable to full CMS problem**
- **Alternative: massively parallel algorithm (difficult to implement)**
- **Memory needs (dep. on sparseness of matrix) under study...**

Importance of using "complete" datasets

- Collision tracks and cosmics populate different parts of global covariance matrix → **reduce global correlations!**
- Example: Alignment of CMS strip barrel rods and layers
 - ❑ Only one layer fixed
 - ❑ 500k $Z^0 \rightarrow \mu\mu$ with vertex constraint
 - ❑ 100k Cosmics
- Use Z^0 tracks only:
 - ❑ No solution
 - ❑ Matrix singular
- Use Z^0 and Cosmics:
 - ❑ Problem solvable
 - ❑ Reasonable correlations

M. Stoye (Hamburg)



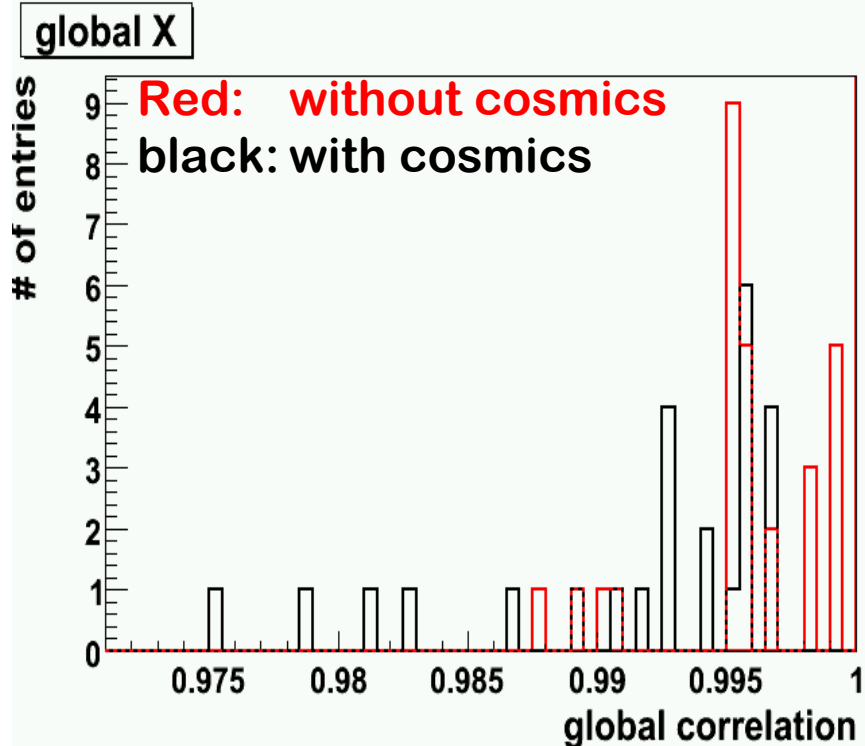
**Simplified simulation and scenario,
Now look at realistic study ...**

M. Stoye (Hamburg)

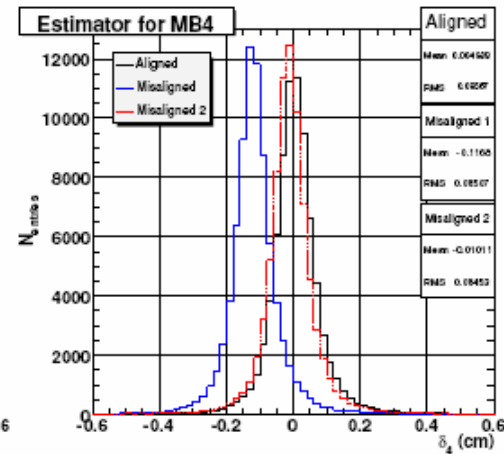
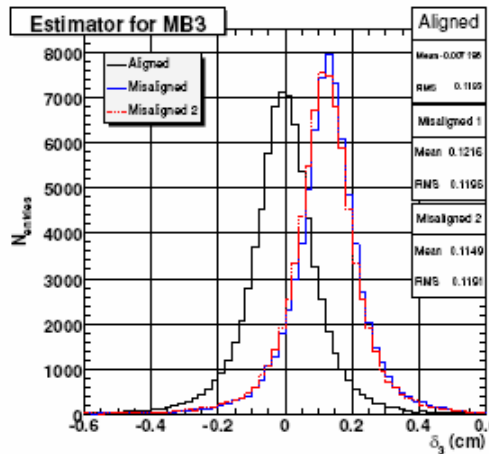
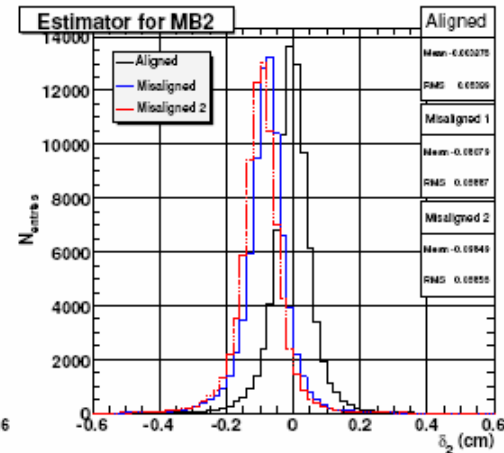
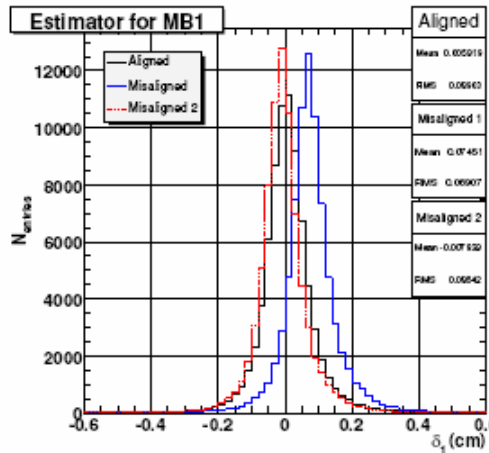
- Realistic alignment scenario of the CMS pixel and strip barrel studied
- Datasets and prior information:
 - ❑ 250k $Z^0 \rightarrow \mu\mu$ with vertex constraint
 - ❑ 500k Cosmics
 - ❑ Survey information
- Global correlations of alignment parameters high (can be >99%)
 - ❑ Independent of alignment algorithm!
- **Cosmics (and beam halo, shifted vertex?!) very important to decrease global correlations!**

Correlations of translations in x

- layers/halfbarrels and
- halfbarrels/CMS



- 790 chambers \Rightarrow "only" ~5000 alignment parameters
- Main differences w.r.t. Tracker Alignment:
 - ❑ Large amount of material for tracks crossing barrel-endcap
 - ❑ Chambers assumed as rigid body: provide vector information useable for alignment
- Two approaches
 - ❑ Alignment using tracks extrapolated from tracker
 - ❑ Standalone muon alignment



- Standalone muon alignment using $W \rightarrow \mu\nu$ events corresponding to 50h of data taking at 10^{34}

- **Alignment of the CMS tracker and muon system is a challenge**
 - ❑ Large number of parameters (~100,000 in tracker)
 - ❑ High intrinsic resolution of devices
- **A lot of ongoing work on track based alignment already now**
 - ❑ **Implementation and further development of algorithms**
 - o Initial results promising
 - o Not yet demonstrated realistic alignment of full tracker at sensor level
 - ❑ **Alignment studies using various MC data sets**
 - ❑ **Dedicated HLT alignment stream**
 - ❑ **Use of overlaps, mass and vertex constraints**
 - ❑ **How to combine with Laser Alignment and Survey?**
 - ❑ **Define monitoring observables other than χ^2 (“global modes”)**
 - ❑ **Condition Database infrastructure**
- **Alignment of test beam and cosmics data**
 - ❑ **Tracker “Cosmic Rack” test structure**
 - ❑ **Magnet Test & Cosmic Challenge (MTCC) data**
- **Aim for having all ingredients in place when data will arrive!**