Track based Alignment in CMS

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LHC Detector Alignment Workshop 05/09/2006

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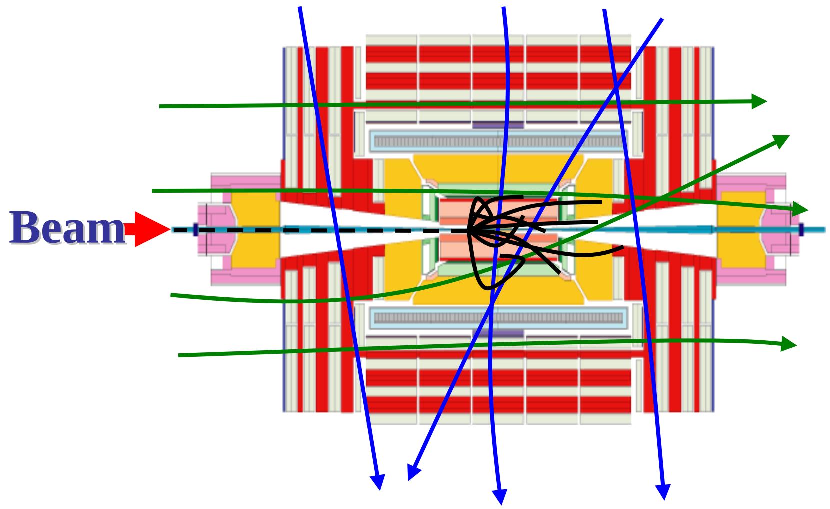
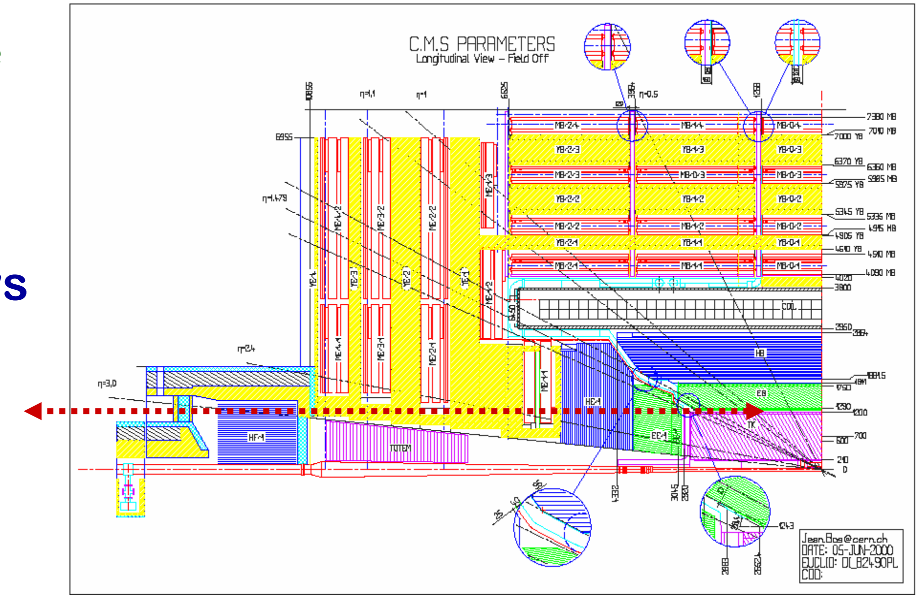
Track based Alignment in CMS

- 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

Data Samples

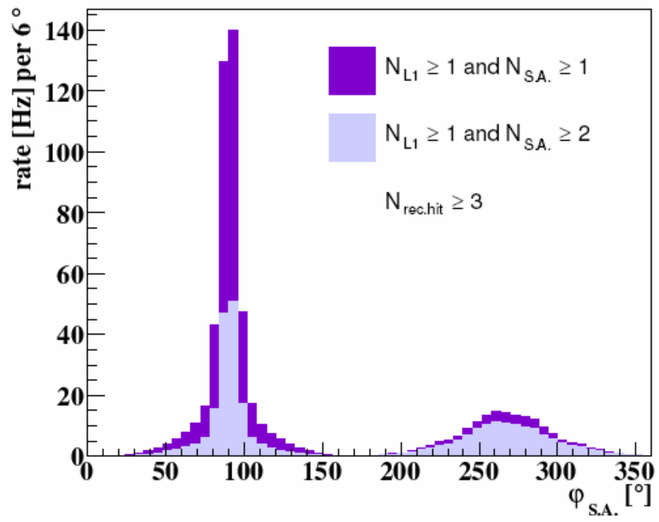
- High p_T muons from Z,W decays
  - Rate: 20k $Z\rightarrow\mu\mu$, 100k $W\rightarrow\mu\nu$ per day at L=2*10^{33}
  - Gold plated for tracker alignment (small multiple scattering)
  - Exploit Z^0 mass constraint
- Cosmic Muons
  - ~400Hz after L1 and s.a. muon reco.
- Beam Halo Muons
  - ~5 kHz per 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

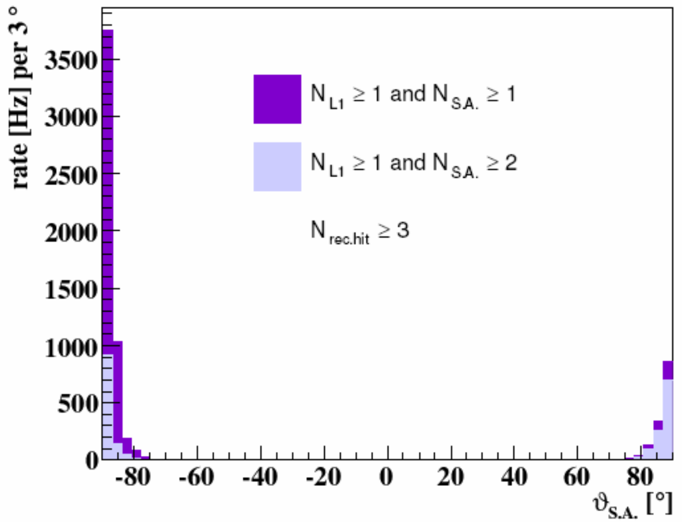


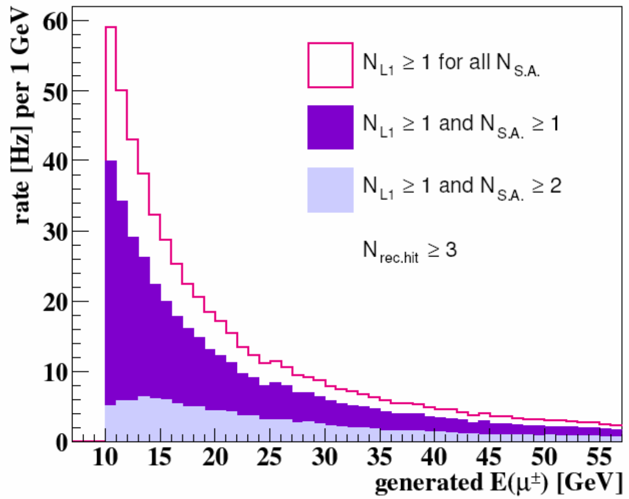


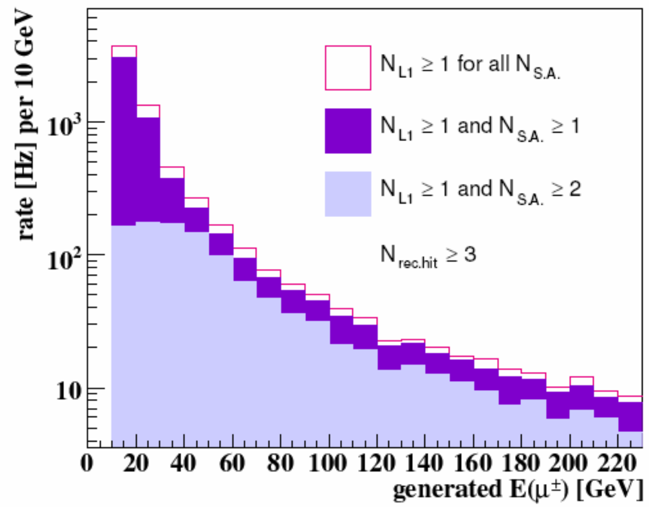
Simulation of Cosmics and Beam halo muons in CMS

- **Cosmic muons: 400 Hz**
- **Beam halo muons: 5 kHz per side**









CMS Note 2006/012

- **Rates after L1 and standalone muon reconstruction**

Alignment Strategy

Basic scetch:

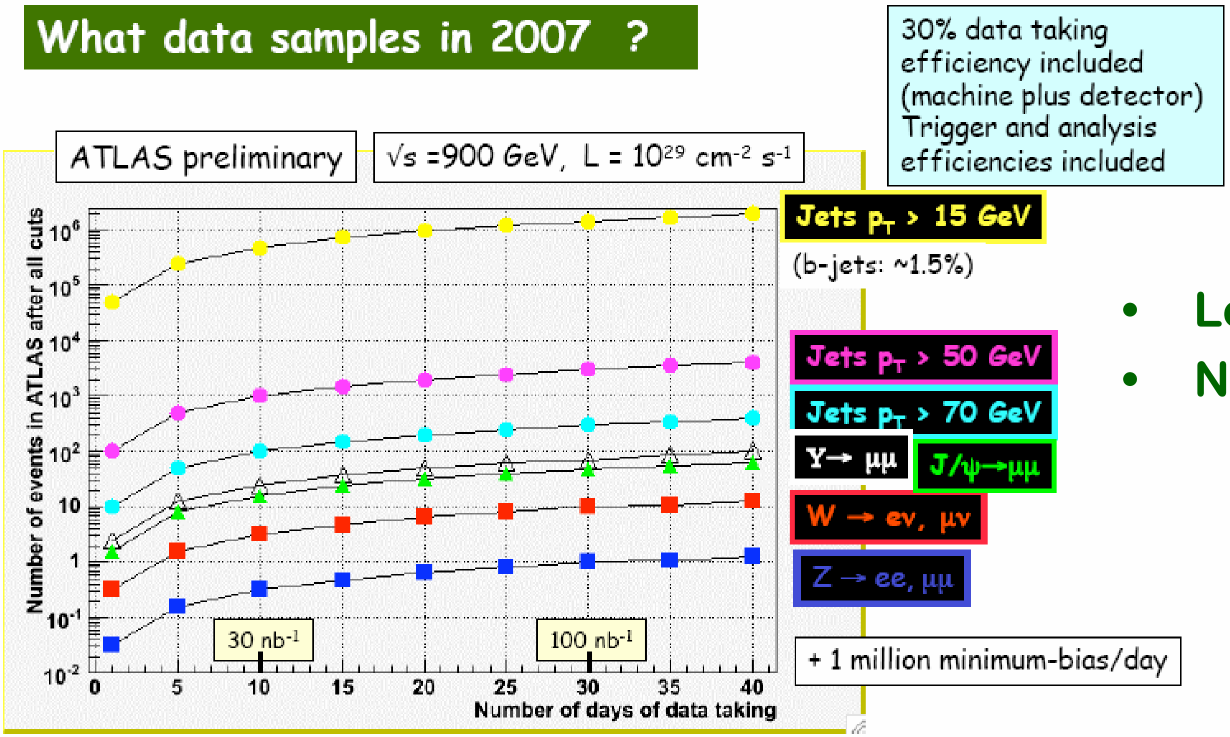
- **2007: Before beams:**
  - Cosmics (+laser alignment and survey measurements)
- **2007: single beams**
  - add beam halo muons
- **2007: Pilot run, pixel detector not installed (except few test modules)**
  - Cosmics, beam halo muons
  - add available high pt muons, tracks
  - Initial alignment of high level strip tracker structurs (layers, rods)?

See next slides for rate estimates

- **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 …**

Expected event rates

- **Pilot run 2007 @ 900 GeV, L~10^{29}**



F. Gianotti (ICHEP 2006)

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

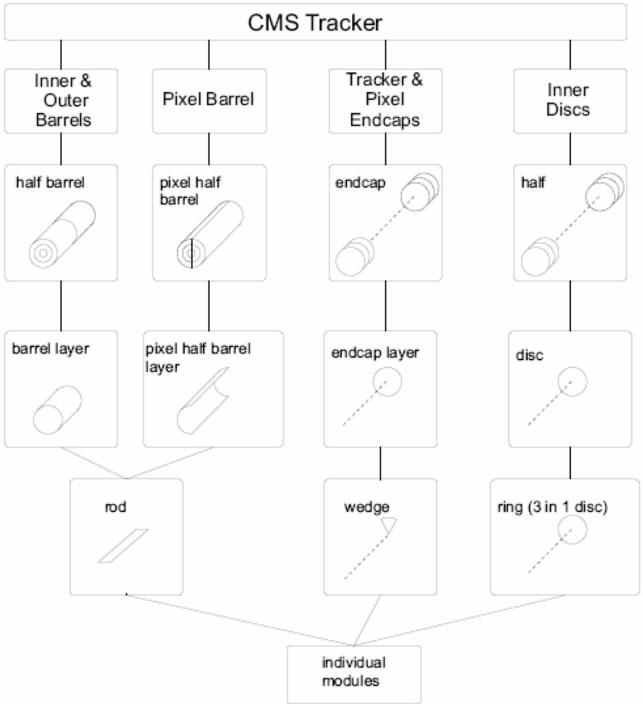
- **Physics Run 2008 @ 14 TeV, L~$10^{32...33}$**

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

- Large statistics of high pt muons within few weeks!

General Software Framework

- (MIs)alignment implemented at reconstruction level:
  - "Misalignment tools", move and rotate modules or higher level structures
- Dedicated "Misalignment Scenarios"
  - Short term scenario
    - First data taking (few 100 pb^{-1})
    - Pixel already aligned
    - Strip tracker misaligned, only survey and laser alignment
  - Long term scenario
    - Few fb^{-1} accumulated
    - Full alignment performed, residual misalignments ~20μm
- 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

HIP Algorithm: Formalism

- 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)
  - V: covariance matrix of measurement

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

- 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

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HIP Algorithm: Formalism (cont.)

- Formalism extended to alignment of composite detector structures (ladders, disks, layers etc.)
  - Minimize χ^2 using all tracks crossing sensors of composite object with respect to alignment parameters of composite object
  - Implemented using chain rule

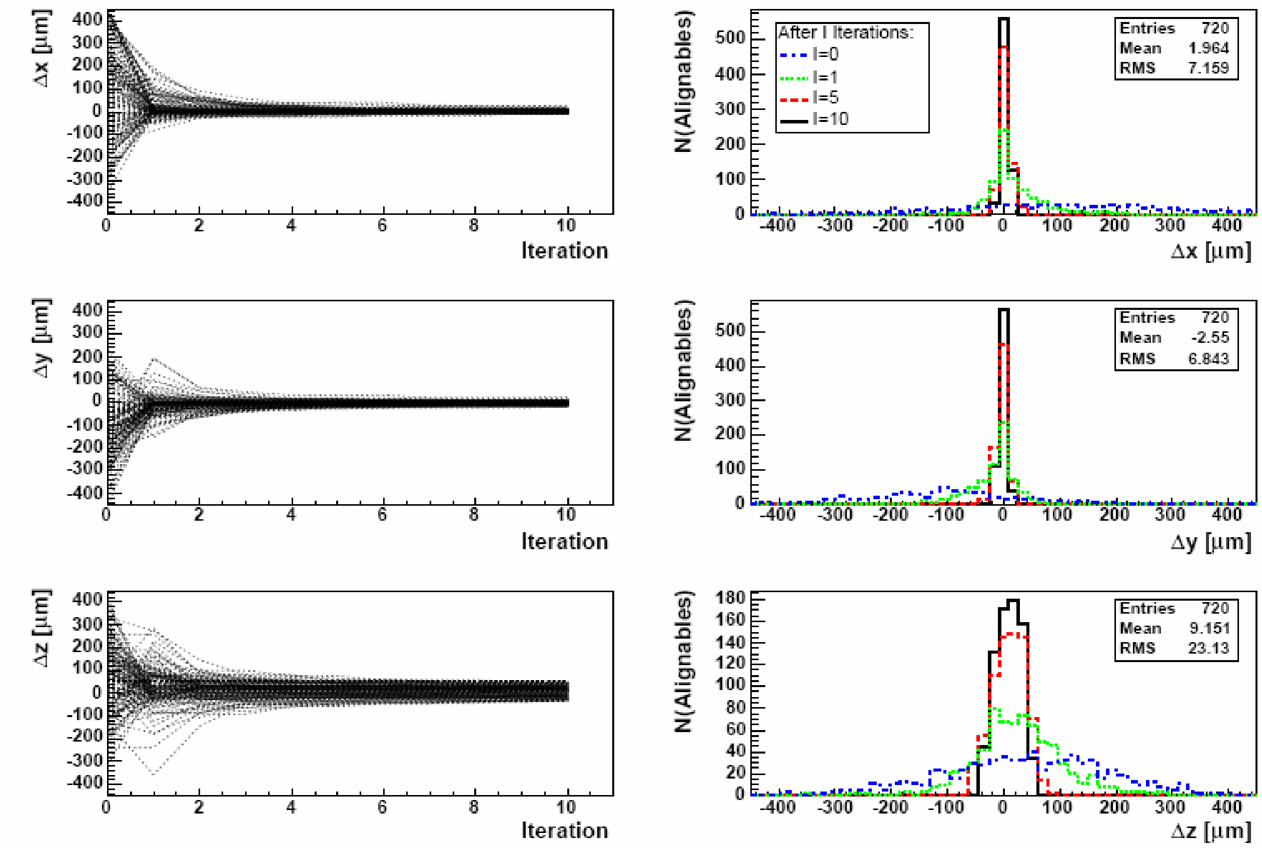
$$\frac{\delta\epsilon_i^S}{\delta p_i^C} = \frac{\delta\epsilon_i^S}{\delta p_i^S} \times \frac{\delta p_i^S}{\delta p_i^C}$$

- Correlations between modules not included explicitely
- Implicitely 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
  - Stard next iteration on N cpu's

- 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'

HIP Algorithm studies

- **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 ~7μm in x,y ~23μm in z**

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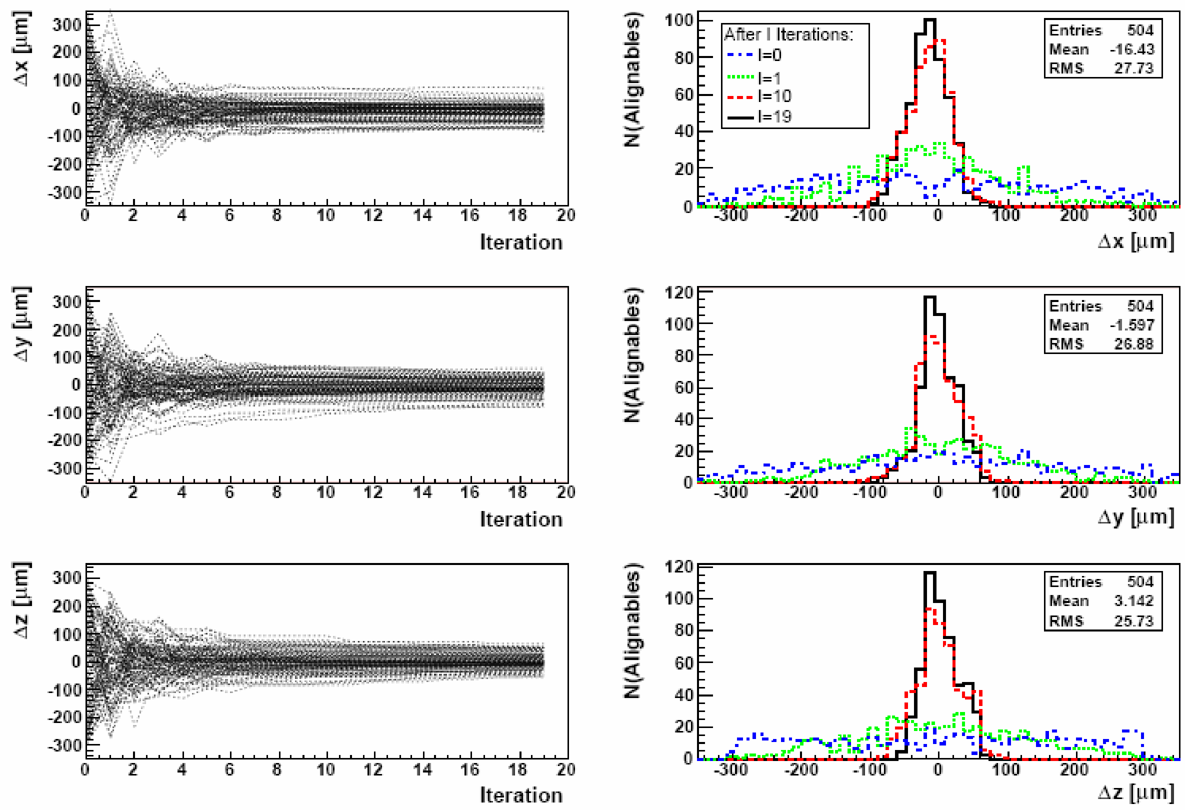
- **Caveat: Alignment w.r.t ideal strip tracker**

HIP Algorithm studies

- 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 $Z^0 \to \mu^+\mu^-$ are fitted to common vertex
- Flat misalignment $\pm 300\mu m$ in x,y,z
- 500k events, 19 iterations
- Resonable convergence, RMS ~25μ m in all coordinates



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Kalman Filter Alignment

- 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:

$$m = f(x, d) + \epsilon \qquad \mathrm{cov}(\epsilon) = V$$

  - 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

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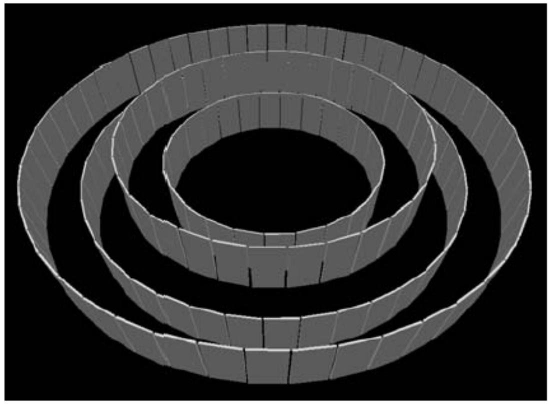
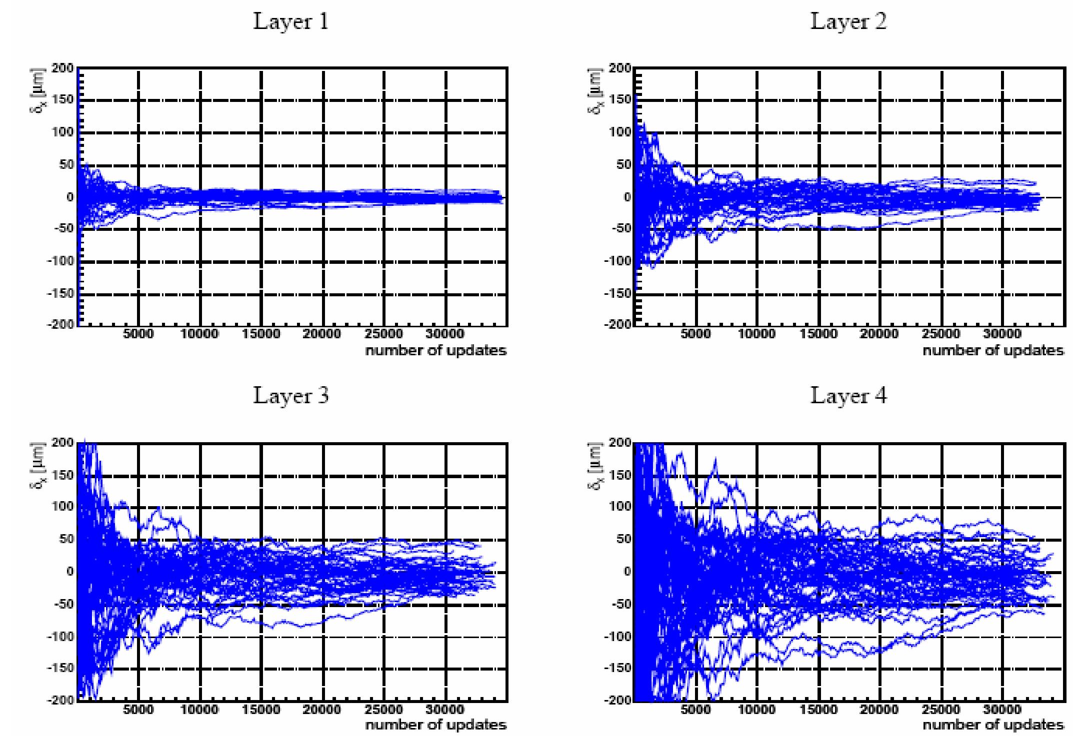
Kalman Filter Alignment (cont.)



- Wheel-like setup: (part of CMS tracker: **156 TIB modules**)
- Pixel detector as reference
- Misalignment:
  - local x,y σ=100μm
- Update restricted to distance **$d_{max} \leq 6$**
- Single muons **p_T=100 GeV**

- Convergence slower in outer layers (distance from reference system, less track statistics)



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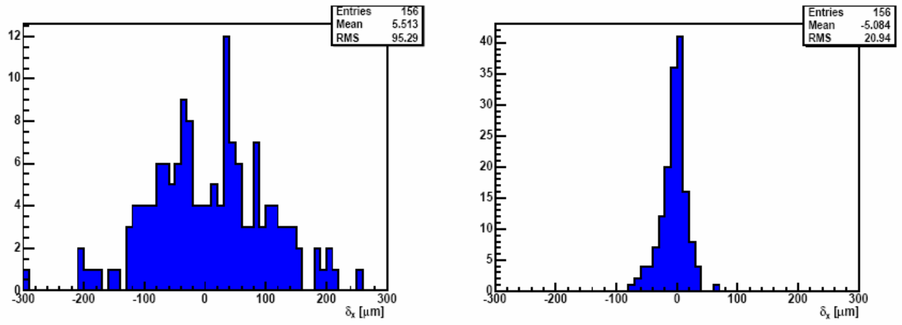
Kalman Filter Alignment (cont.)

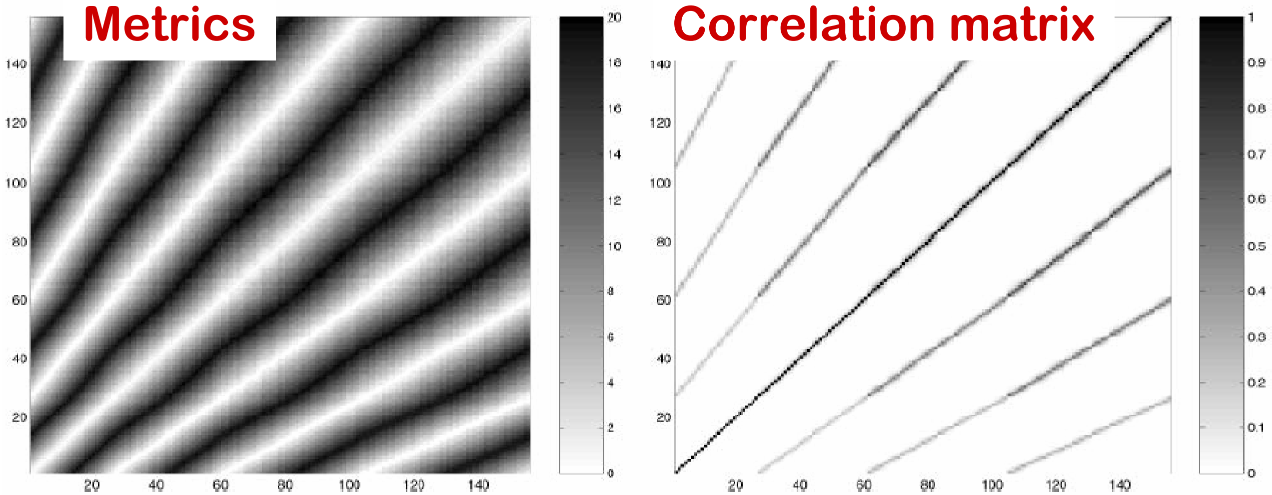
- **Overall RMS ~21μm after alignment**



- **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_{max}=6 does not exclude modules with relevant correlations**



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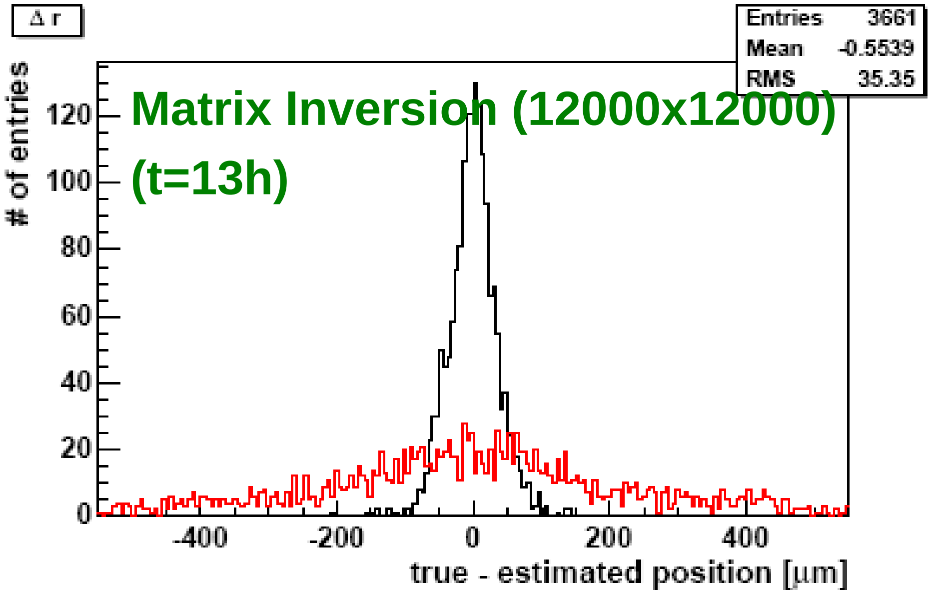
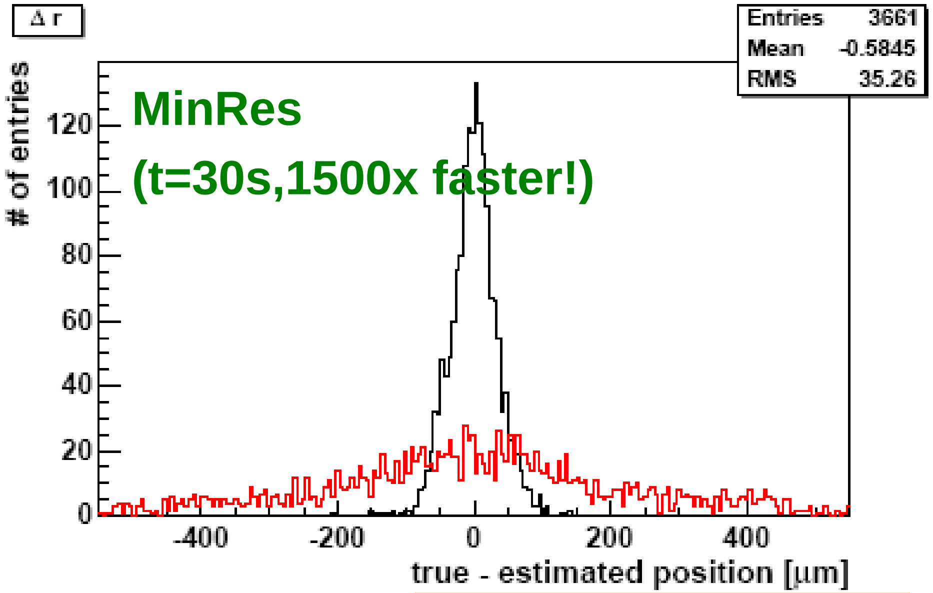
Millepede II Algorithm

- 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 **|A x – B|**. Expected to work for ~100000 alignment parameters (i.e. for full CMS at sensor level)
- Both successfully aligned ~12% of tracker modules using 2M **Z**$\rightarrow\mu\mu$ events. Results identical, but new method 1500 times faster!





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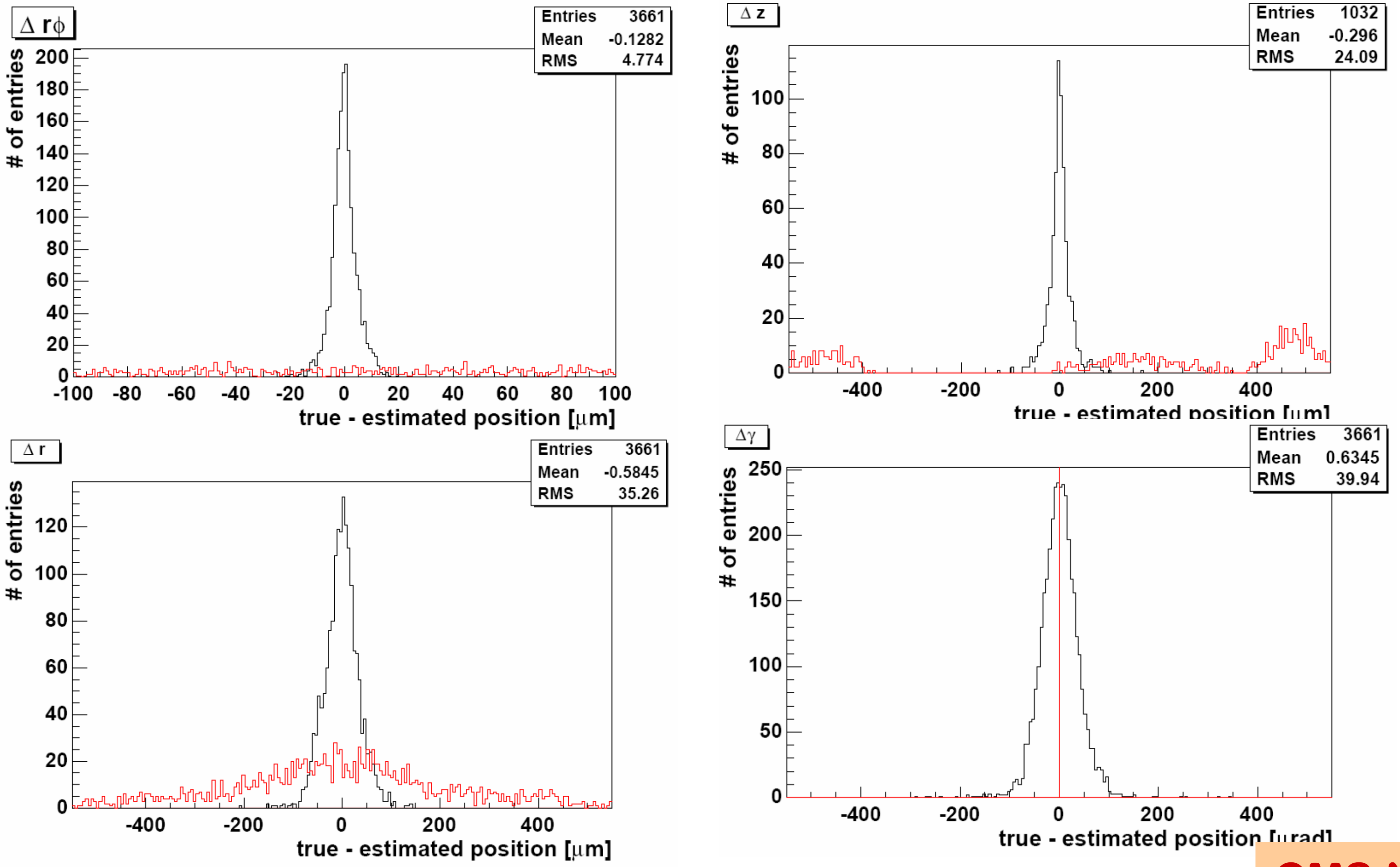
Millepede-II in CMS

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



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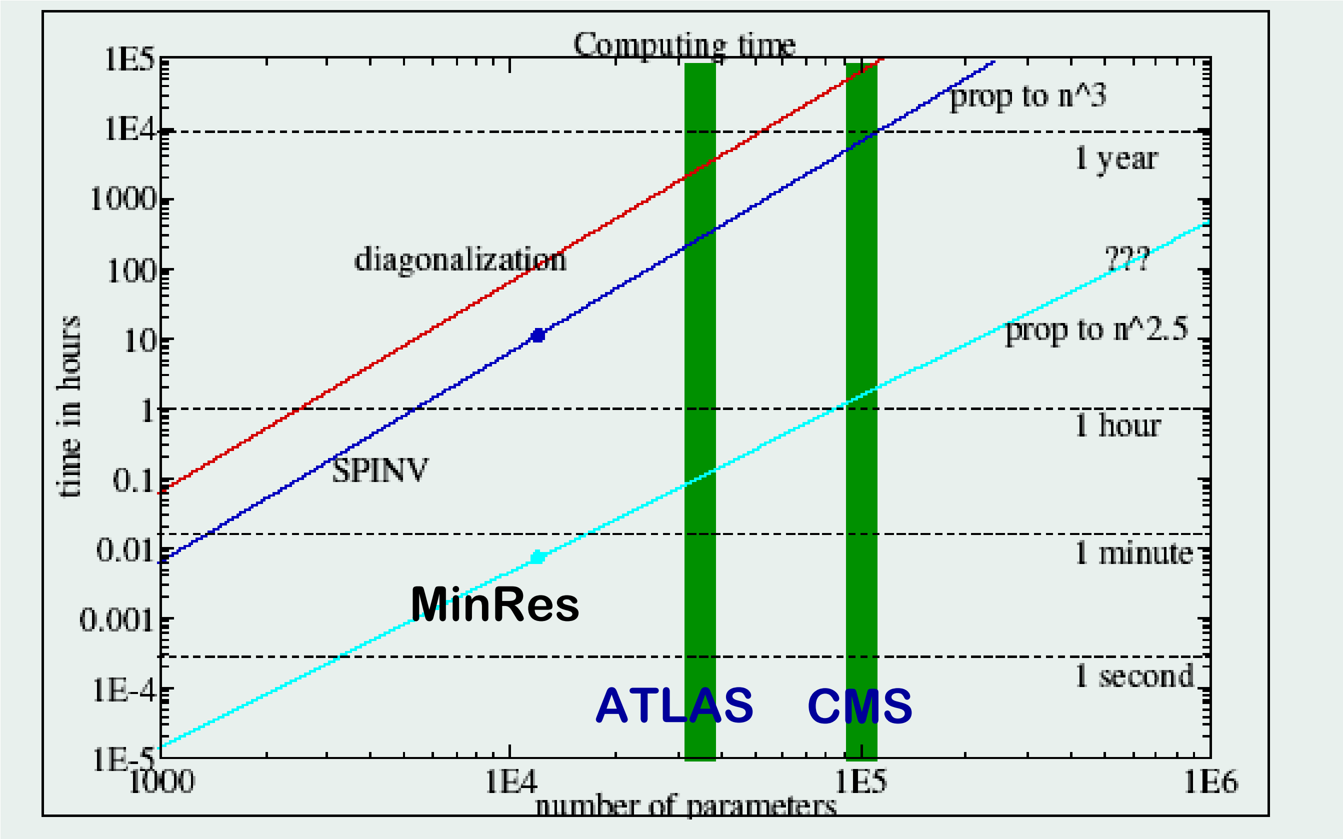
CPU Requirements (Millepede-II)

CPU time in hours as a function of number of parameters



CPU Time for CMS (100k parameters):

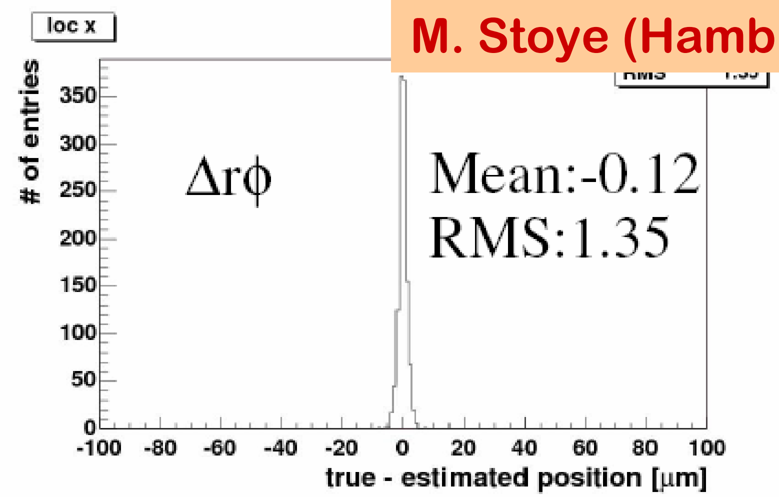
- **Diagonalization**
  ~10 year at one CPU
- **Inversion:**
  ~1 year at one CPU
- **Iteration:**
  ~1 h at one CPU

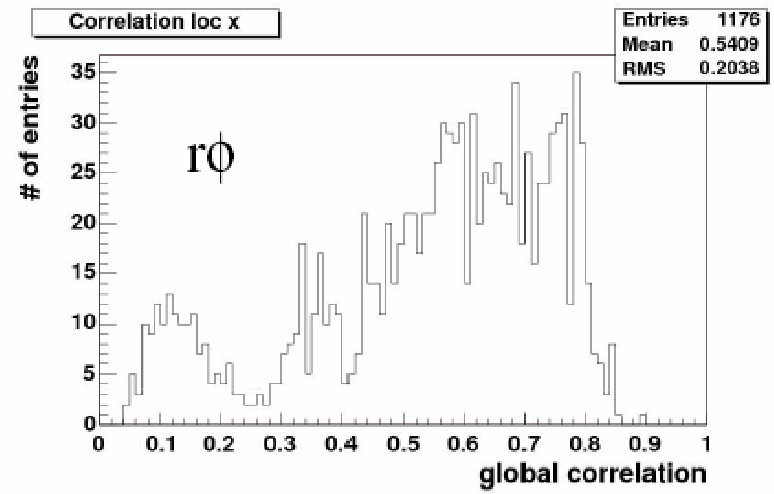
- **New Millepede-II (iterative method) scaleable to full CMS problem**
- **Alternative: massively parallel algorithm (difficult to implement)**
- **Memory needs (dep. on sparseness of matrix) under study…**

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**
  - ❑ **Resonable correlations**

M. Stoye (Hamburg)





Simplified simulation and scenario, Now look at realistic study …

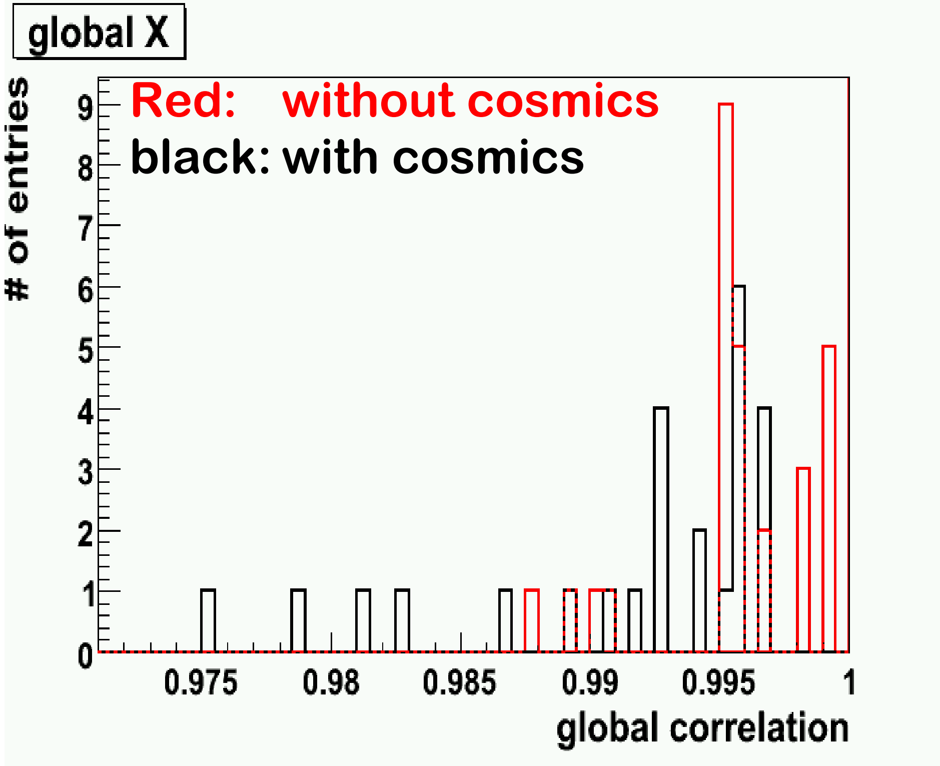
Global correlations: Realistic scenario

M. Stoye (Hamburg)

- **Realistic alignment scenario of the CMS pixel and strip barrel studied**
- **Dasets 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!**

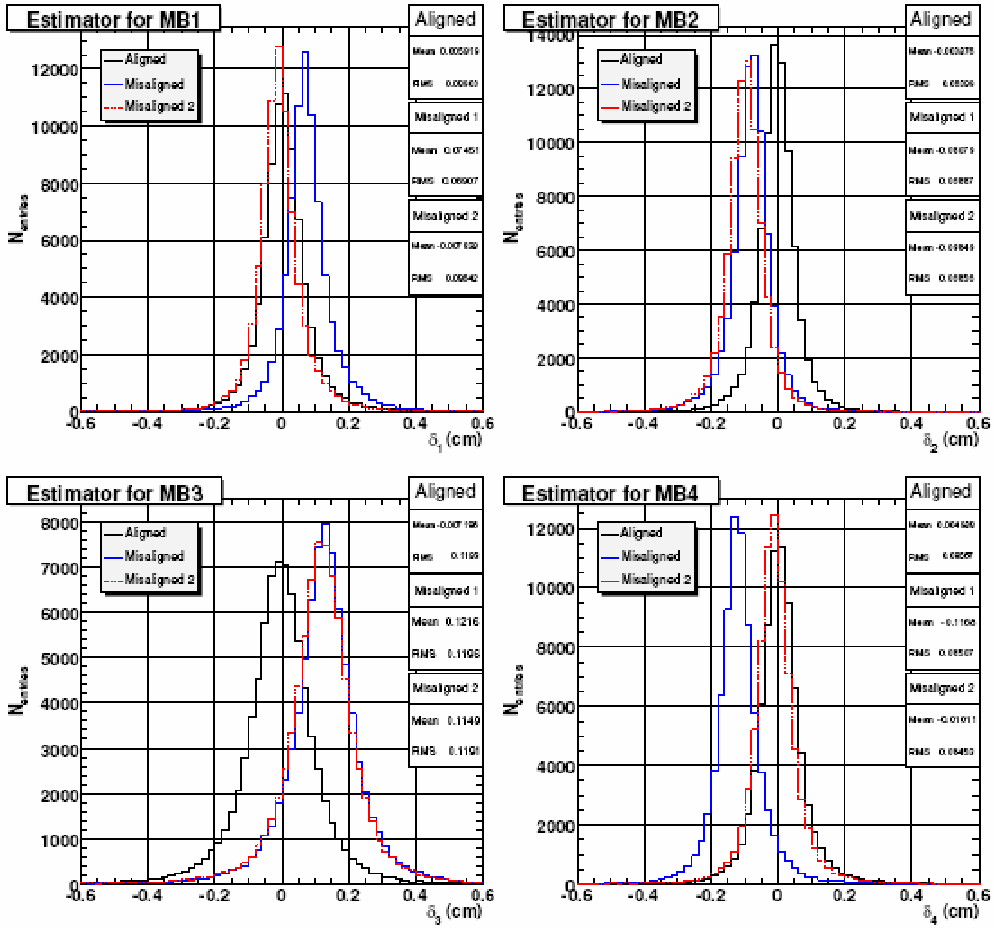
Correlations of translations in x

- layers/halfbarrels and
- halfbarrels/CMS



Muon system Alignment with tracks

- **790 chambers ⇒ "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 $W \to \mu\nu$ events corresponding to 50h of data taking at 10^{34}**

CMS Note 2006/016

Conclusions

- **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**
    - **Initial results promising**
    - **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!**