Track based Alignment of the CMS Silicon Tracker

Frank-Peter Schilling (CERN)

Univ. Karlsruhe, 15/09/2006

- Personal Introduction
- Impact of misalignment
- Data samples
- Alignment strategy
- Alignment algorithms
  - HIP
  - Kalman Filter
  - Millepede-II

Personal Introduction

1998-2001: Ph.D. thesis, Univ. Heidelberg (H1 @ HERA,DESY)

- Analysis: Measurement of jet cross sections in "diffractive" deep-inelastic scattering
  - ❑ Published in H1 Coll., Eur. Phys. J. C20 (2001) 29
- Hardware: H1 Backward Drift Chamber detector
  - ❑ Maintenance, data quality, 24/7 "on-call" service
- Data taking as shift leader

2001-2004: Post-Doc at DESY (H1 Experiment)

- Analysis: Measurement and QCD analysis of the inclusive diffractive structure function $F_2^{D(3)}(x_{IP},x,Q^2)$
  - ❑ Published in H1 Coll., acc. by Eur. Phys. J. C, hep-ex/0606004
- Convenor of the Diffractive Physics Working Group of H1 (2001-2003)
- H1 Trigger Coordinator (2003-2004)
  - ❑ Optimization of trigger budgets in coordination with physics groups
  - ❑ Integration of new trigger systems
  - ❑ Trigger setup for HERA-II phase (high lumi, initially high backgrounds)
    - o Reject beam induced backgrounds at L1
    - o Increase trigger thresholds
- Data taking as Run Coordinator (2 week coordination of data taking)

Personal Introduction (cont.)

Since 10/2004: CERN research fellow (CMS Experiment)

- **Track based alignment of the CMS silicon tracker**
  - Implementation of a common software framework for track based alignment algorithms in ORCA
    - CMS IN 2005/051
  - Implementation of the HIP alignment algorithm and alignment studies of the CMS pixel detector
    - CMS Note 2006/018
  - Co-editor of Physics TDR, Vol. 1, section 6.6: Alignment
    - CMS/LHCC 2006/001
  - Coordination of the migration of the CMS alignment software to CMSSW
  - Coordination of the “Alignment Exercise” in the coming CSA06
  - Development of alignment strategies for the CMS startup
  - Since 06/2006 co-convenor of the PRS b/tau alignment group (with O. Buchmueller)
- **Reconstruction of K0s in the CMS tracker (Energy flow group)**
  - Development of a dedicated seeding in outer layers of strip tracker
  - Development of a dedicated V0 track finder

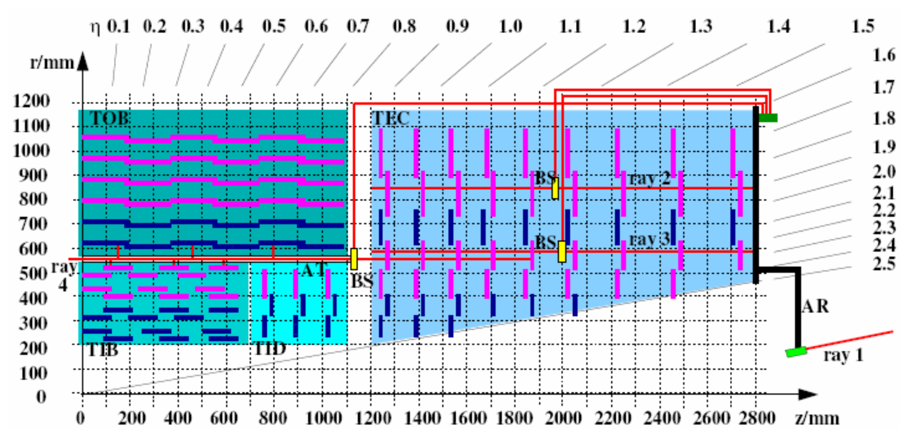
The CMS Tracker Alignment Challenge

O(16k) modules of Pixel and Strip tracker to be aligned to equal or better precision than intrinsic resolution of 10…50μ

- **Determination of O(100k) alignment parameters**
- **Cruical for performance of CMS tracker (e.g. b-tagging, W-mass)**
  - ❑ **Example: σ(Mw)~15 MeV → alignment 10μm in rϕ**

Basic ingredients

- **Measurements from Construction**
  - •Initial positions of modules and structures known to O(few 100μ)
- **Laser Alignment System**
  - •Can monitor only larger structures (TEC discs, TIB,TOB)
  - •Pixel and TID not included!
- **Track based alignment**
  - •Only way to carry out full alignment at sensor level
  - •Requires large samples of tracks with different topologies **(CPU, memory intensive, may require dedicated hardware)**



Impact of misalignment

- Misalignment implemented at reconstruction level by moving/rotating modules/layers etc
- Can be studied even at DST/RECO level using track refitter

Two misalignment scenarios developed for PTDR studies:

- "first data" scenario
  - ❑ Situation at LHC start-up (first few 100 pb-1)
  - ❑ Construction information, LAS, pixel aligned with tracks
- "long term" scenario
  - ❑ After first few fb-1 have been taken
  - ❑ Tracker aligned at the sensor level to ~20 μm

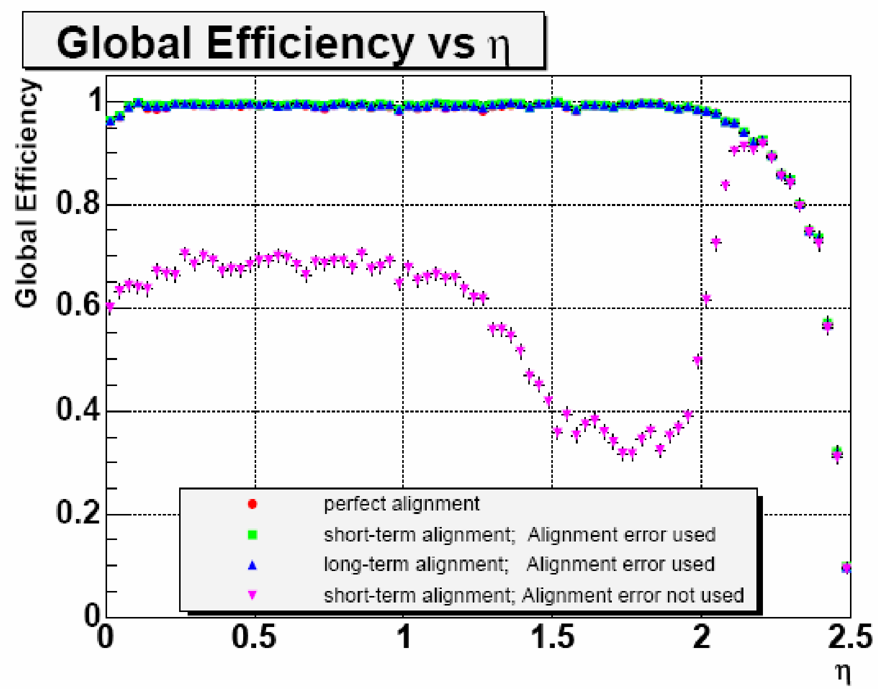
	Pixel		Silicon Strip			
	Barrel	Endcap	Inner Barrel	Outer Barrel	Inner Disk	Endcap
First Data Taking Scenario						
Modules	13	2.5	200	100	100	50
Ladders/Rods/Rings/Petals	5	5	200	100	300	100
Long Term Scenario						
Modules	13	2.5	20	10	10	5
Ladders/Rods/Rings/Petals	5	5	20	10	30	10

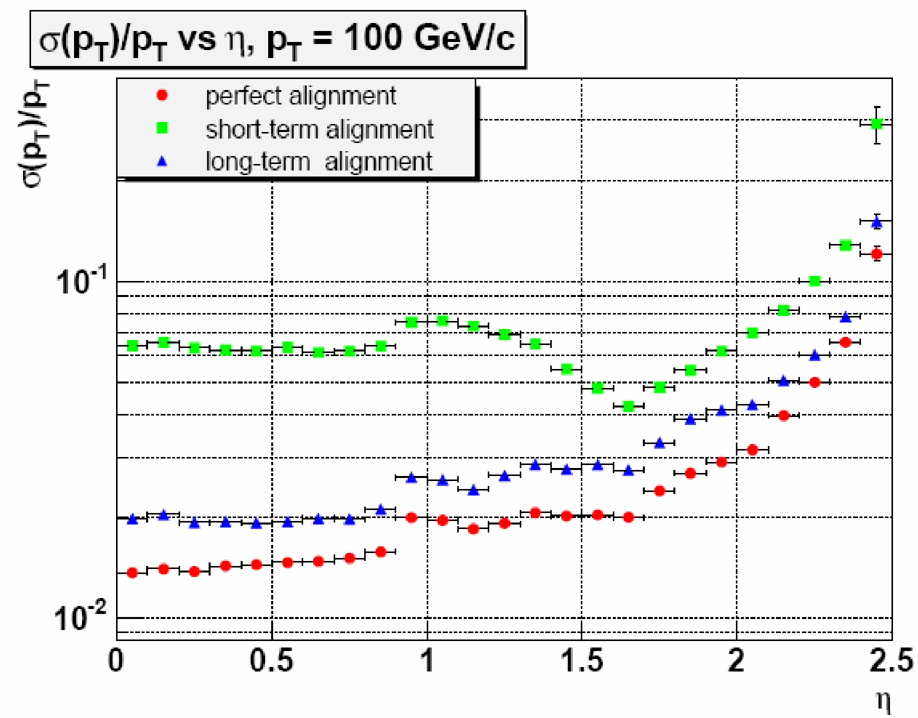
CMS-Note-2006/008

CMS-Note-2006/029

Impact of Misalignment

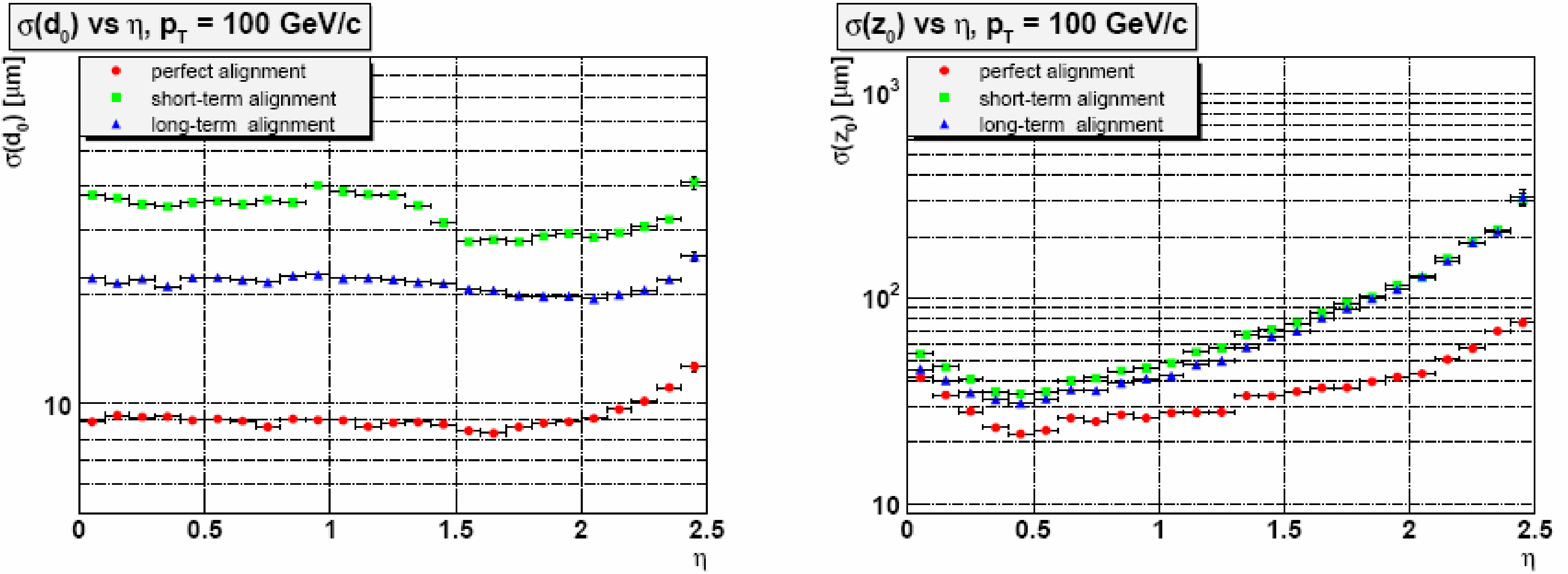
- Single muons with Pt=100 GeV (typical scale for LHC physics, resolutions not dominated by multiple scattering)





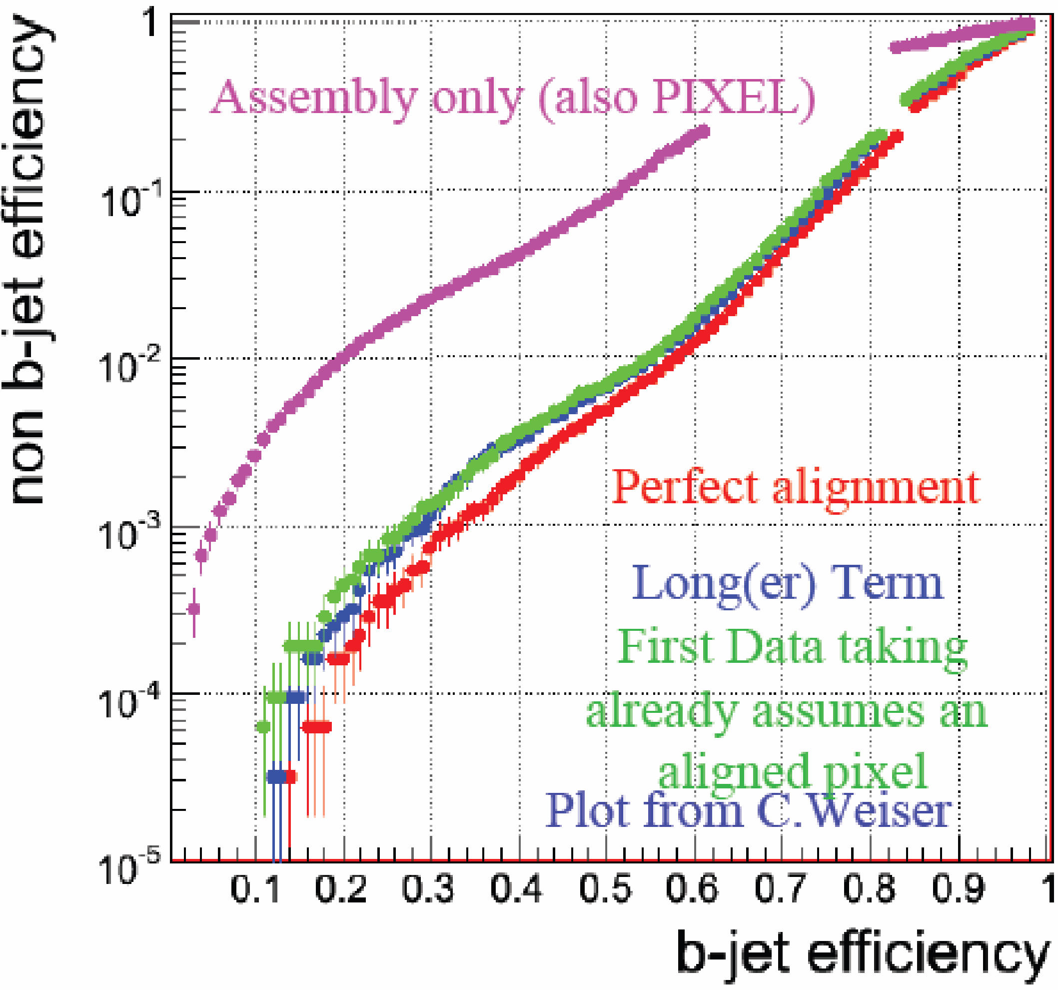
- Inefficiency in barrel, if alignment unc. not added to meas. error
- Worse in TID region (larger initial uncertainty from mounting)
- Pt resolution worse by factor ~5 for short-term scenario

- **Transverse and longit. Impact parameter resolution**



- **d0 resolution ~9, 35, 20 μm (ideal, short term, long term)**
- **Note: Pixel detector assumed aligned even in short term scenario**

Impact of Misalignment



- **No b-tagging performance with currently assumed assembly precision for pixel**

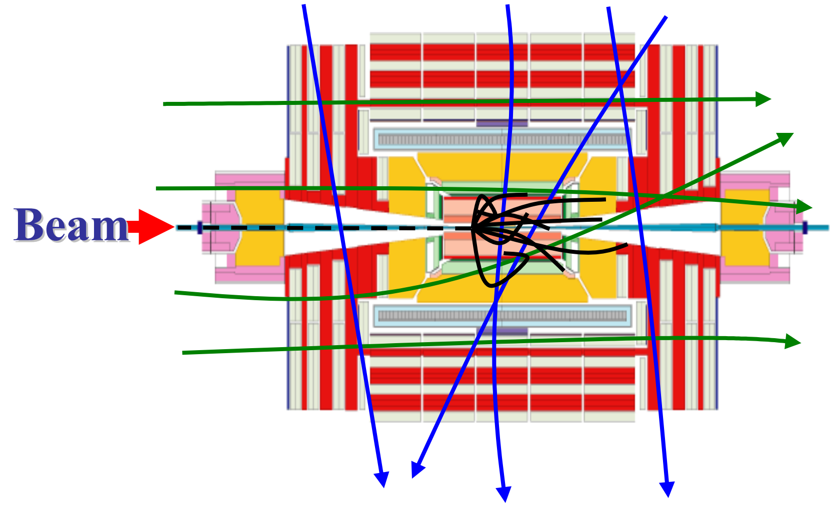
- **Fast Pixel alignment mandatory (also to provide reference for strip alignment)!**

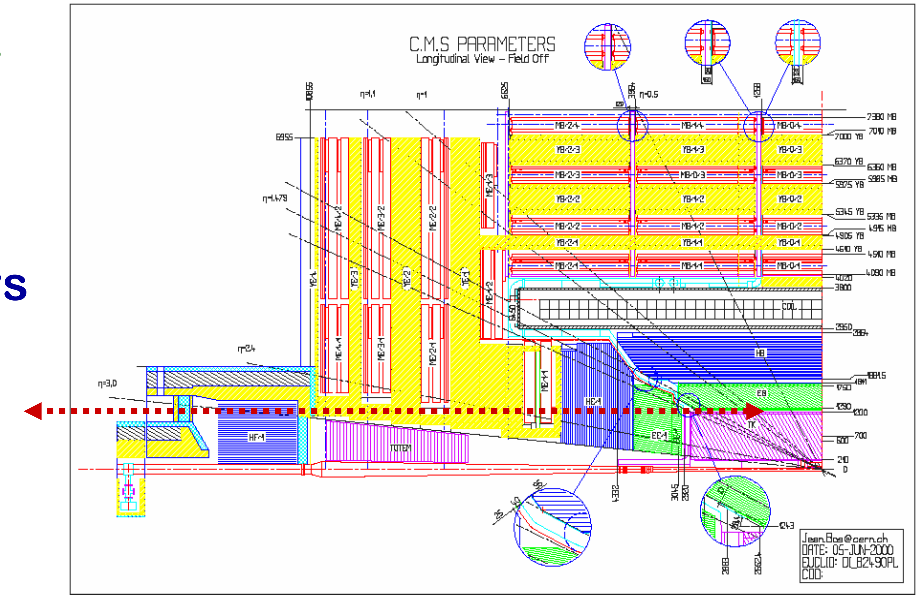
Track based Alignment in CMS

- 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 (Germany: Aachen, Hamburg)

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





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 laid out in more detail …**

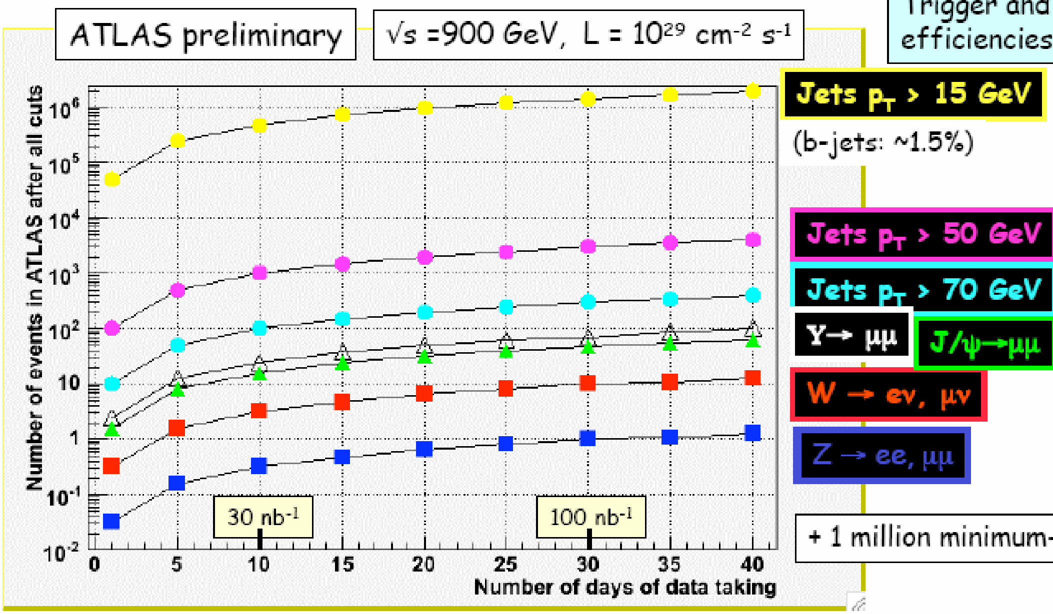
Expected event rates

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

What data samples in 2007 ?

30% data taking efficiency included (machine plus detector)
Trigger and analysis efficiencies included

F. Gianotti (ICHEP 2006)



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

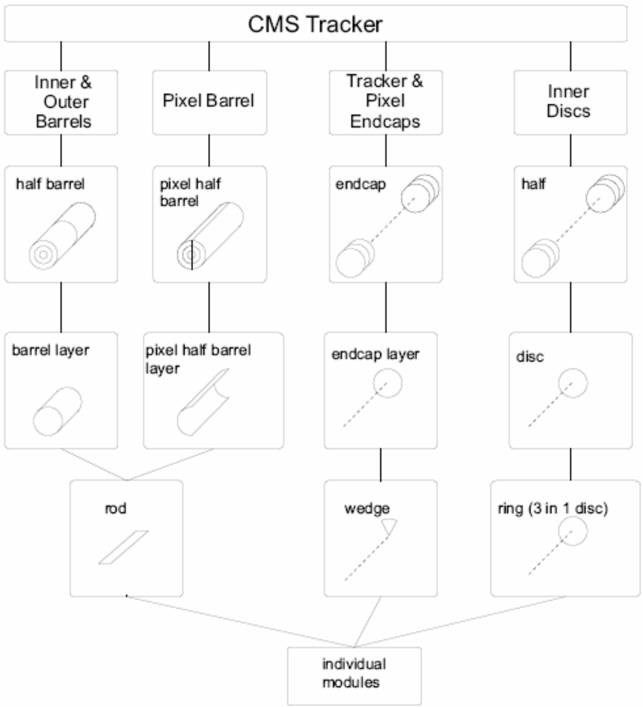
- **Physics Run 2008 @ 14 TeV, L~$10^{32 \ldots 33}$**

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)**

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

  - **V: covariance matrix of measurement**
- **Linearized χ^2 solution:**
  - **δp: vector of alignment parameters δp=(δu, δv, δw, $\delta\alpha$, $\delta\beta$, $\delta\gamma$)**
  - **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**

CMS Note 2006/018

HIP Algorithm: Formalism (cont.)

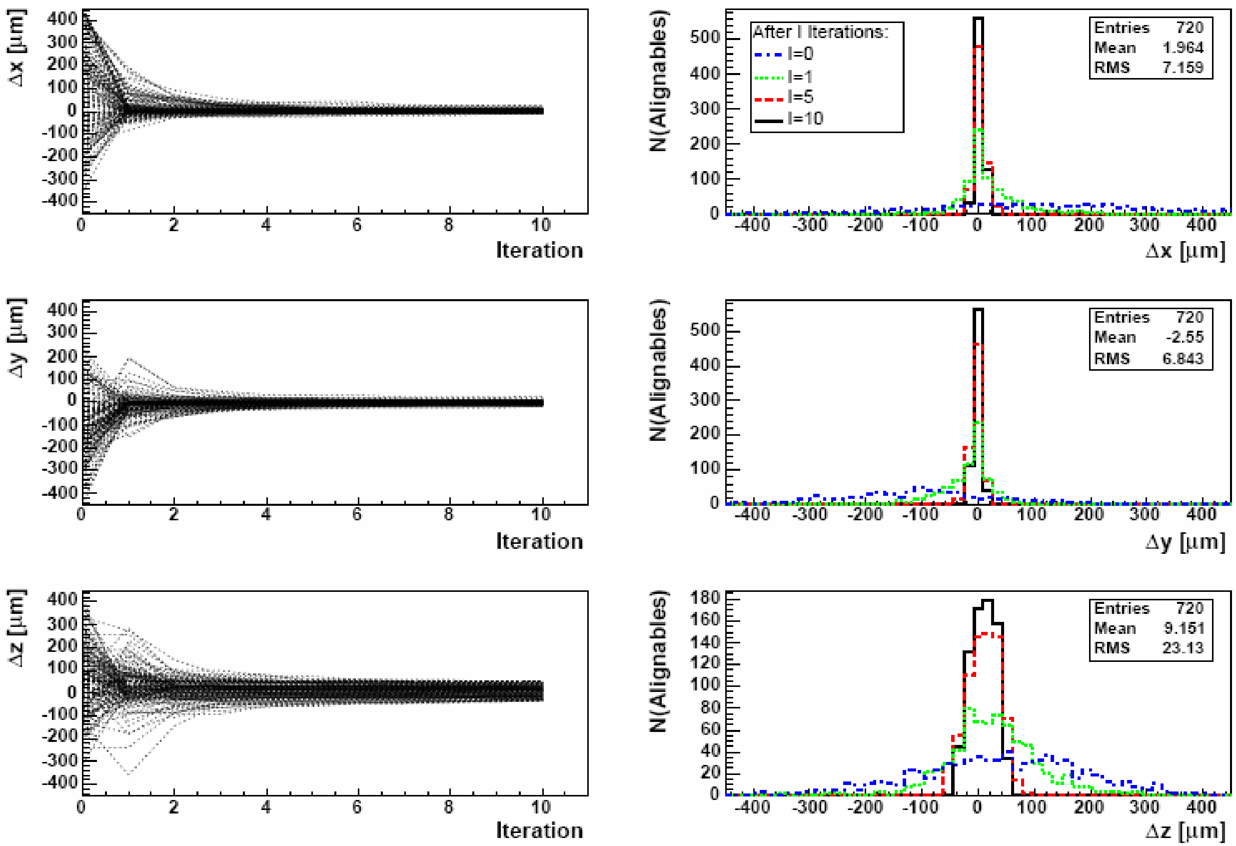
- Formalism extended to **alignment of composite detector structures** (ladders, disks, layers etc.)
  - Minimize χ^2 using all tracks crossing sensors of composite object with respect to alignment parameters of composite object
  - Implemented using chain rule
- Correlations between modules not included 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

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

- 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'**

HIP Algorithm studies

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



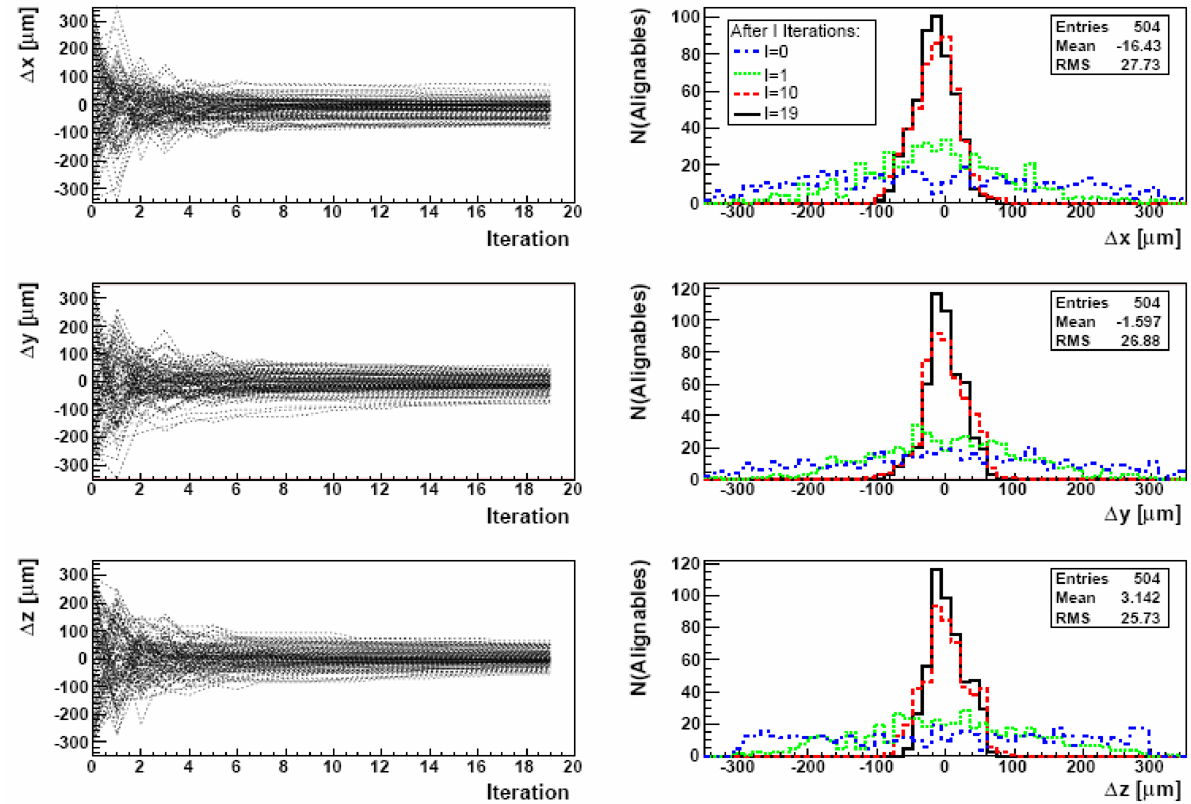
- **Good convergence: RMS ~7μm in x,y ~23μm in z**

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

CMS Note 2006/018

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 $Z^0 \rightarrow \mu^+\mu^-$ 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**



CMS Note 2006/018

Kalman Filter Alignment

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

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

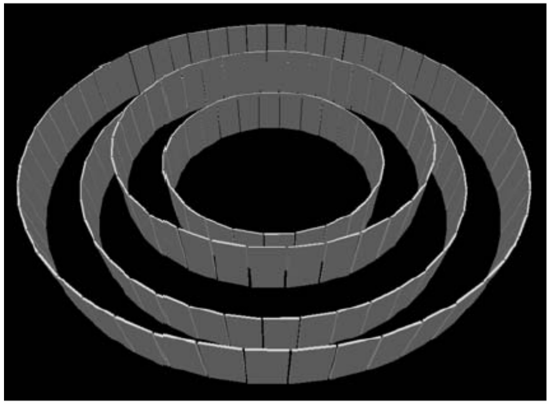
  - Update equation of Kalman Filter:

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

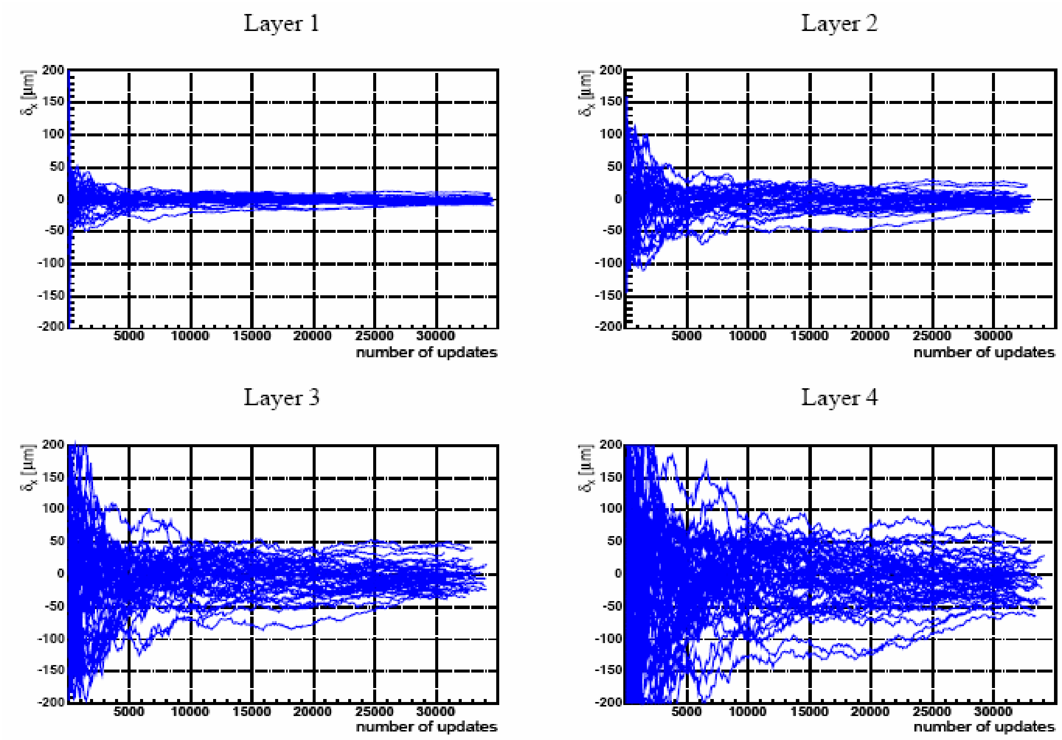
- Iterative: Alignment Parameters updated after each track
- Global: Update not restricted to modules crossed by track
  - Update can be limited to those modules having significant correlations with the ones in current trajectory
  - Requires some bookkeeping
  - No large matrices to be inverted!
- Possibility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

CMS Note 2006/022

- Wheel-like setup: (part of CMS tracker: 156 TIB modules)
- Pixel detector as reference
- Misalignment:
  - local x,y σ=100μm



- Single muons p_T=100 GeV

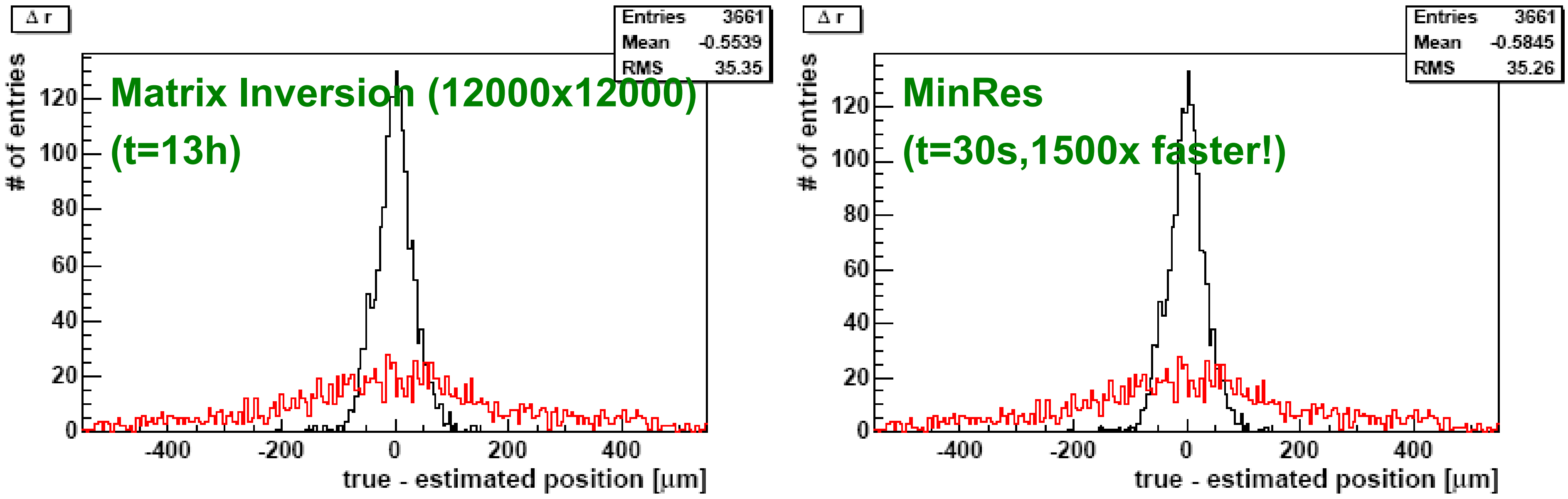


- Convergence slower in outer layers (distance from reference system, less track statistics)

CMS Note 2006/022

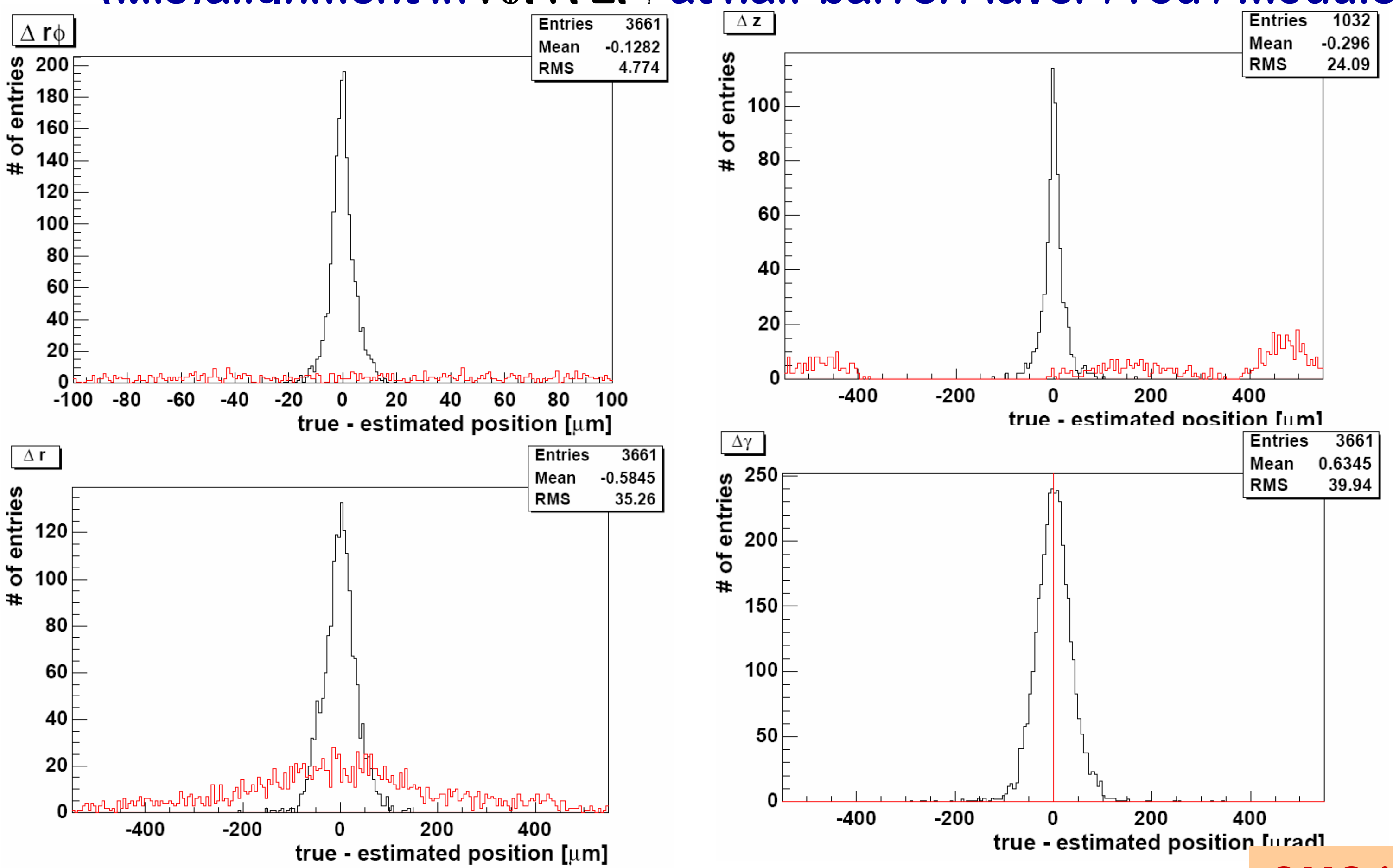
Millepede Algorithm (V. Blobel)

- Global chi2 minimization, fitting (local)track and (global) alignment parameters at once
  - Correlations between modules included
  - No iterations needed
- 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)



Millepede-II in CMS

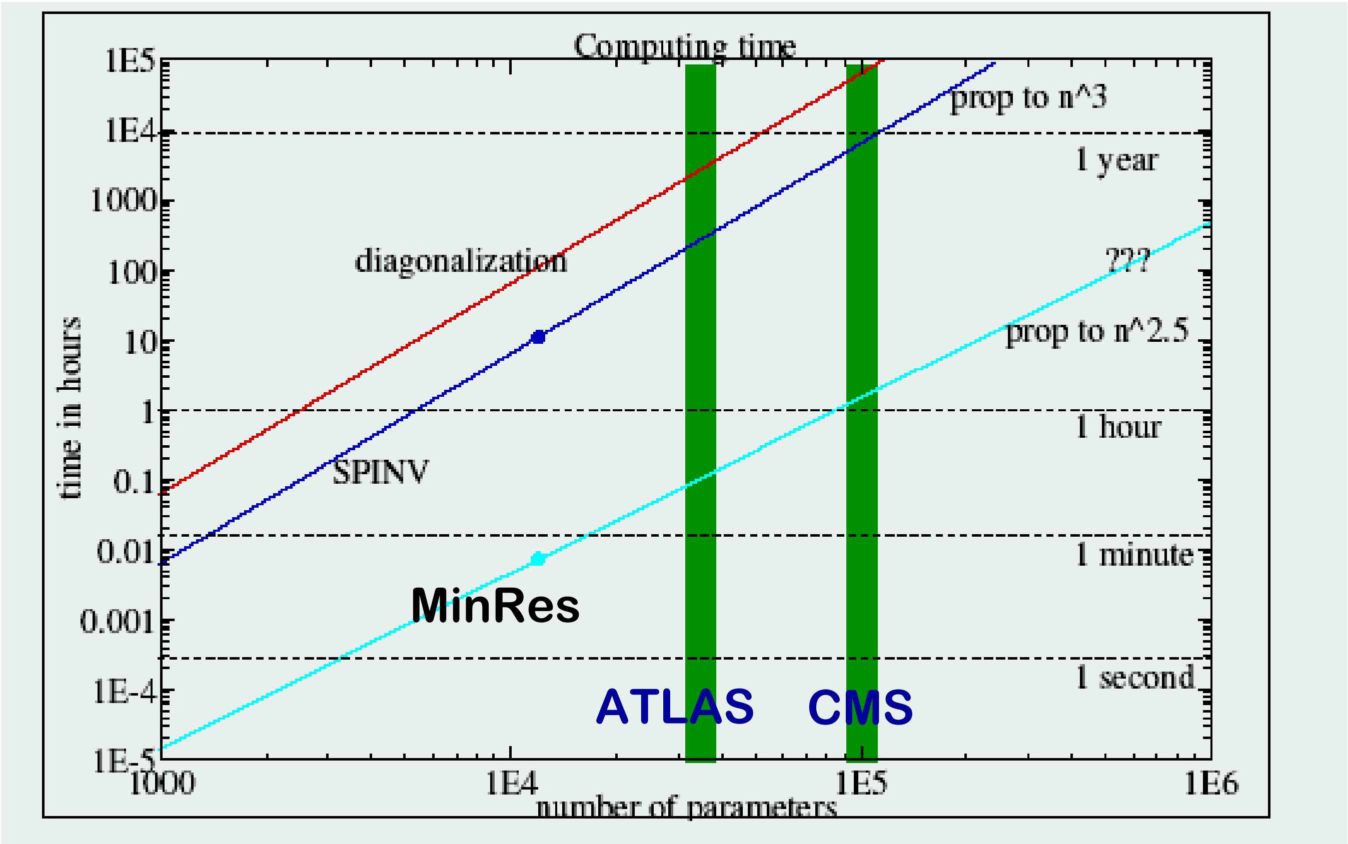
- **Alignment of the strip tracker at sensor level**
- **Barrel region, |η|<0.9, 12015 alignment parameters**
- **(Mis)alignment in rϕ, r, z, γ at half-barrel / layer / rod / module levels**



CMS Note 2006/011

CPU Requirements (Millepede-II)

CPU time in hours as a function of number of parameters



CPU Time for CMS (100k parameters):

- **Diagonalization**
  ~10 year on one CPU
- **Inversion:**
  ~1 year on 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…**

D-CMS Contributions to Alignment

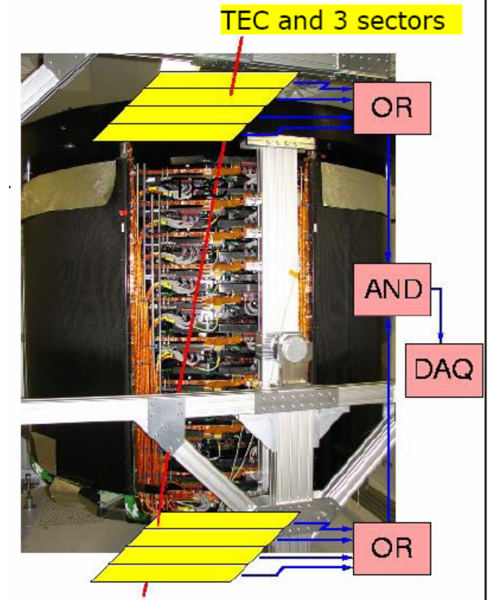
- **Aachen (L. Feld, F. Raupach, M. Weber):**
  - 2nd Implementation of the Kalman filter algorithm
  - Alignment studies of TEC+ with cosmics

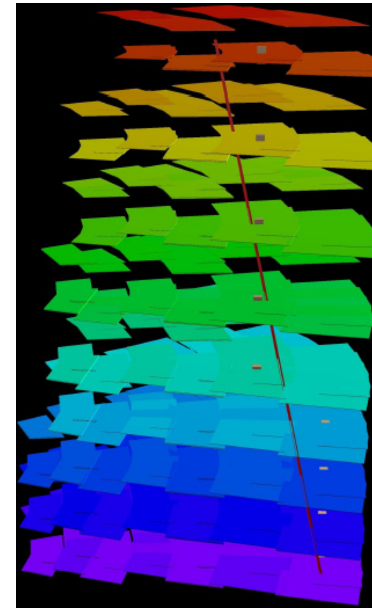
- **Hamburg (G. Flucke, P. Schleper, G. Steinbrueck, M. Stoye)**
  - Close collaboration with V. Blobel (MillePede developer)
  - Implementation of MillePede I and II for CMS
  - Alignment studies for PTDR-I
  - Alignment with simulated cosmics
  - Study of monitoring observables other than chi2 (e.g. sensitive to global distortions)

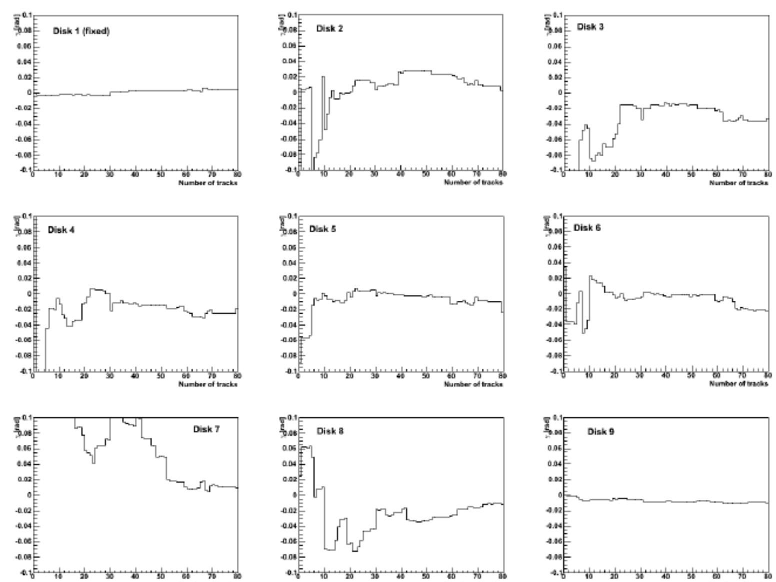
- **Aachen+CERN**
  - Prepare proposal for Alignment @ TIF
    - Validate alignment software with real data and real geometry
    - Balance against many constraints (schedule, lead thickness below ST etc)

TEC+ alignment with cosmics (Aachen)

- **Updating/debugging geometry**
- **Kalman Filter alignment algorithm implemented**
- **First results obtained with small statistics, ongoing …**
- **Plans:**
  - **Compare alignment with LAS**
  - **Implement Millepede and compare with Kalman filter**
- **First low statistics results aligning disks 2-8 (1,9 fixed)**







Importance of using "complete" datasets (Hamburg)

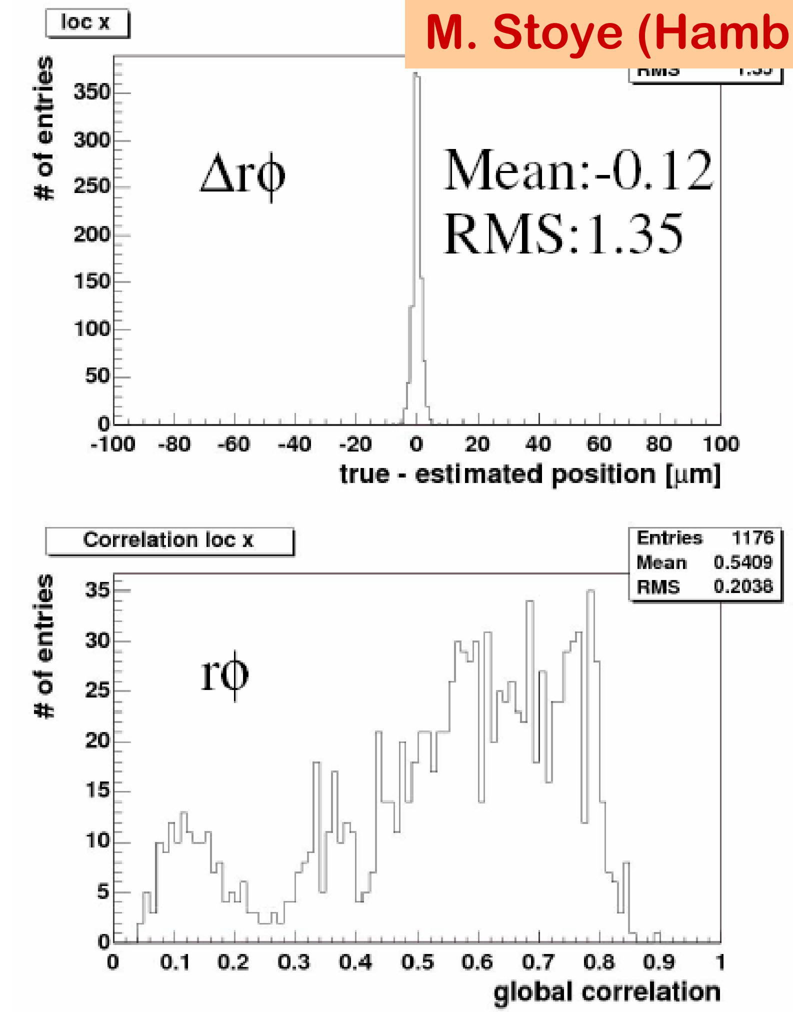
- **Collision tracks and cosmics populate different parts of global covariance matrix → reduce global correlations!**

- **Example: Alignment of CMS strip barrel rods and layers**
  - ❑ **Only one layer fixed**
  - ❑ **500k $Z^0 \to \mu\mu$ 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)



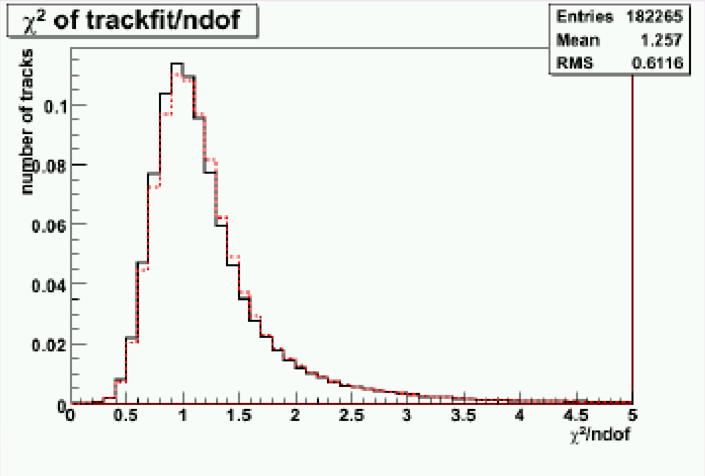
Simplified simulation and scenario, Now look at realistic study …

χ^2 invariant deformations (Hamburg)

Example: Curvature

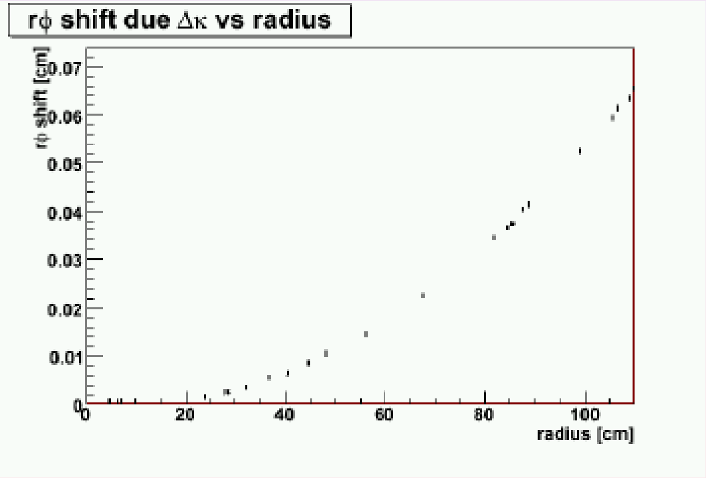
The average curvature is changed via misalignment

The difference in the $\frac{\chi^2}{ndof}$ id very small, the shift due to misalignment up to 700 μm

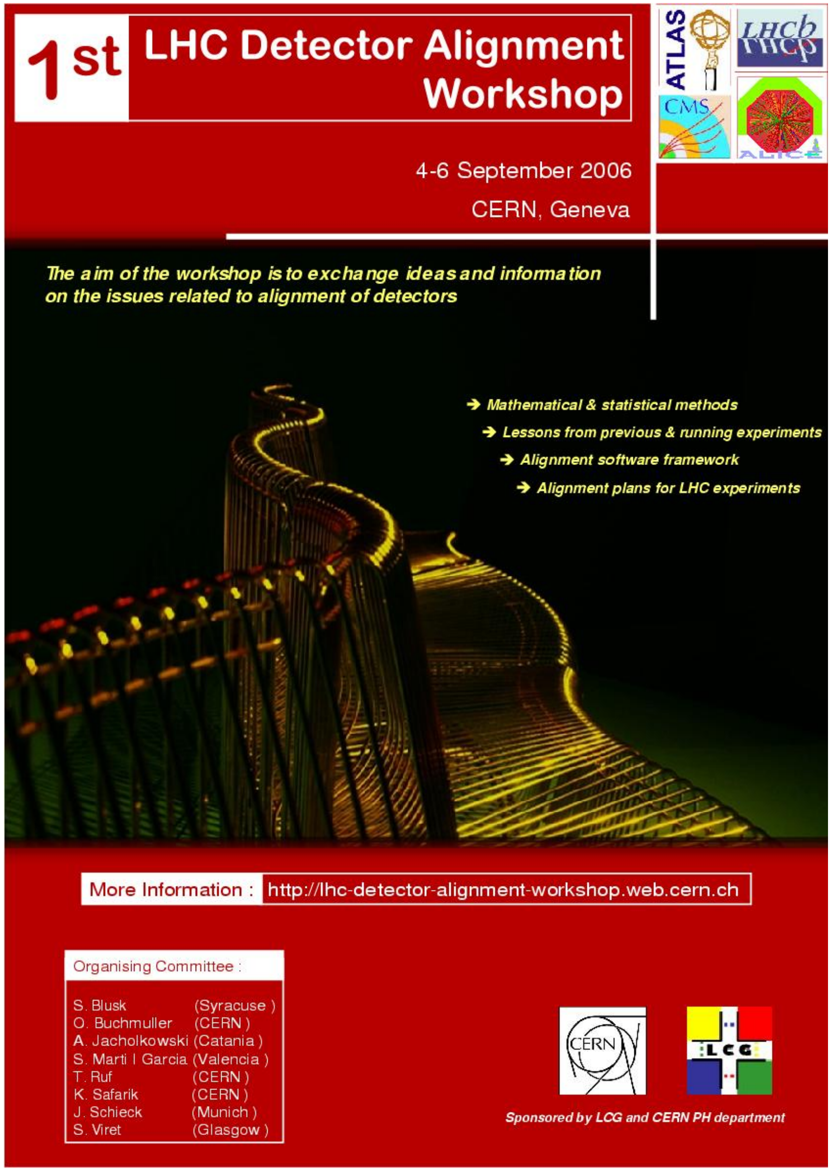


black: ideal

red: misaligned



misalignment in $r\phi$ vs radius of sensor position



- **CMS initiative**

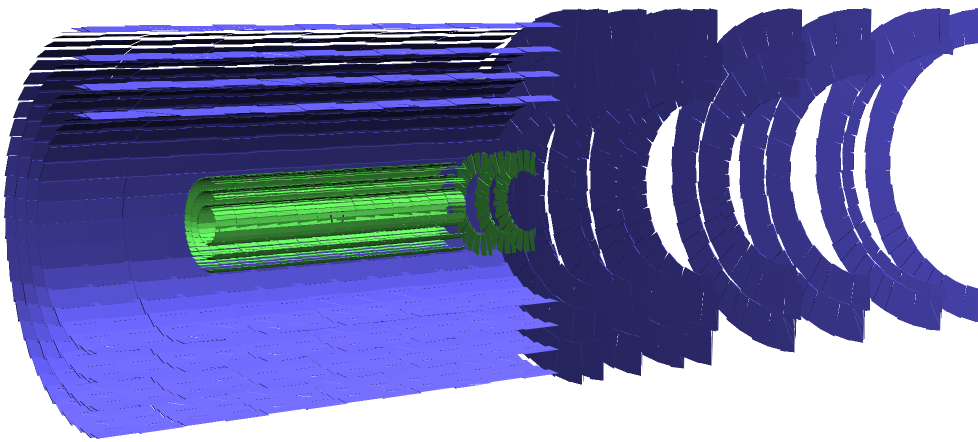
- **Alignment strategies of 4 LHC experiments**
- **Experience from other experiments**
- **External algorithm experts (V. Blobel, R. Fruehwirth)**

- **Workshop page** http://physics.syr.edu/~lhcb/public/alignment/LHCAlignmentWorkshop/

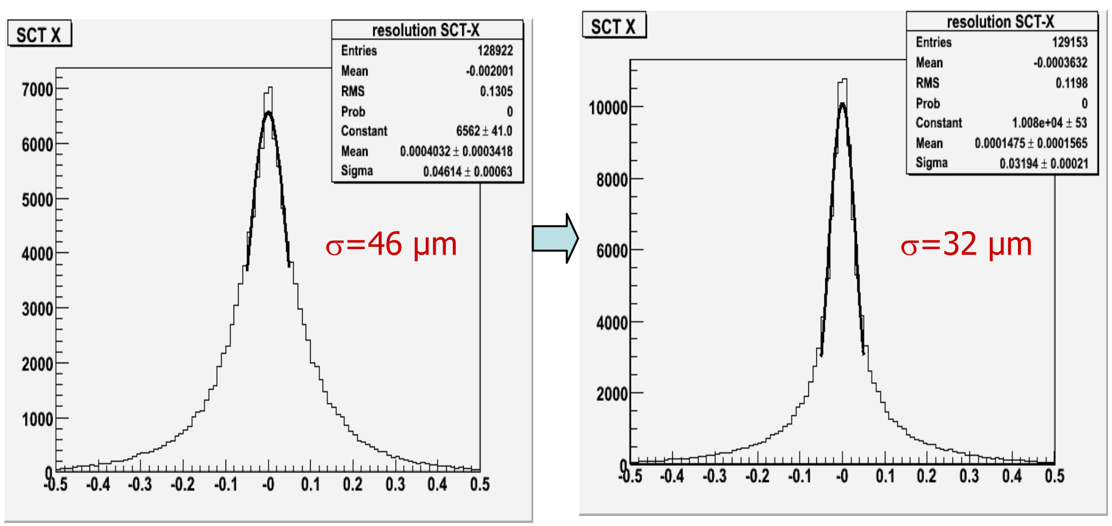
- **Featured in this week's CMS times** http://cmsinfo.cern.ch/outreach/CMStimes/2006/09_11/index.html

How far is ATLAS?

- **Atlas Inner Detector: Pixel+SCT+TRT**
  - ❑ **“only”~36000 parameters**
- **Three algorithms considered**
  - ❑ **“Robust alignment”**
    - o **Minimization of residuals, overlaps**
  - ❑ **Local chi2 approach**
    - o **Equivalent to CMS HIP algorithm**
  - ❑ **Global chi2 approach**
    - o **Equivalent to MillePede-I**
    - o **~32 nodes in parallel**
- **Misalignment only possible at simulation level (cpu intensive)**
- **More experience with real data**
  - ❑ **2004 Combined test beam**
  - ❑ **Cosmics at surface build.**



- **Global chi2 with 250k SR1 tracks**



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**

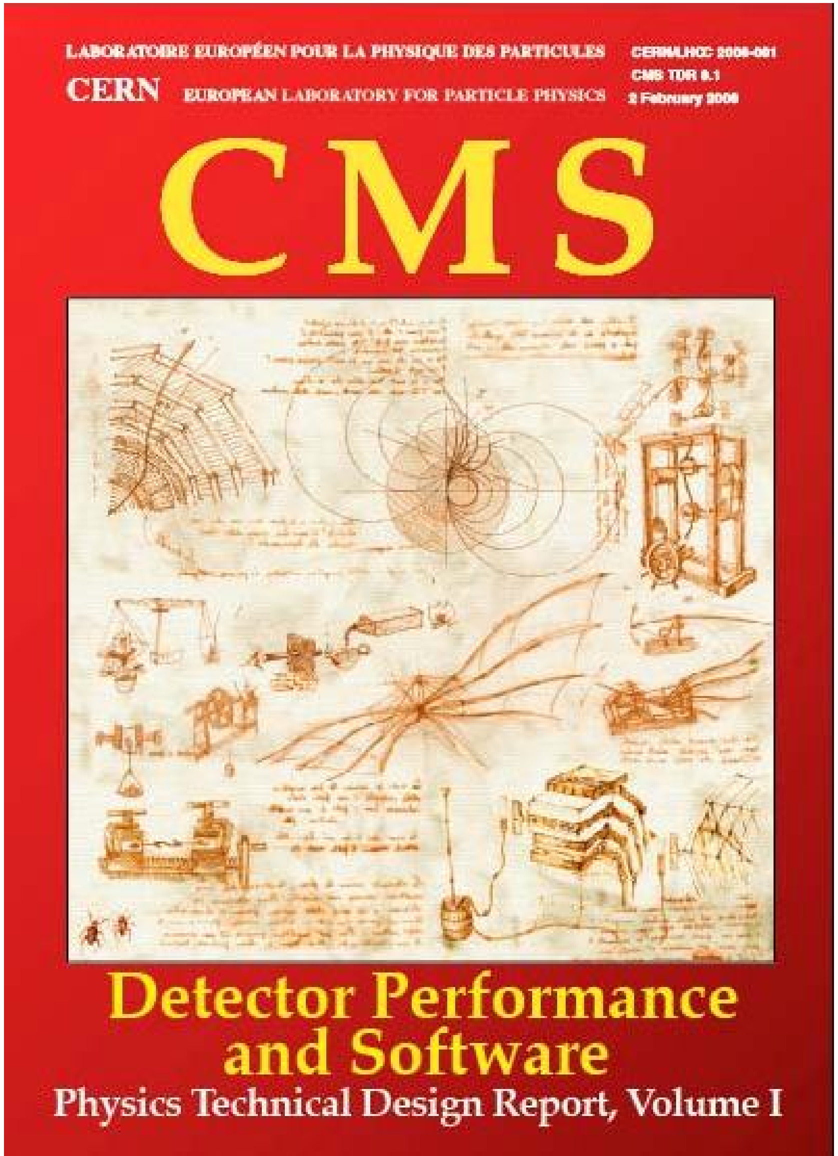
- **A lot of ongoing work on track based alignment already now**
  - **Implementation and further development of algorithms**
    - **Initial results promising**
    - **Not yet demonstrated realistic alignment of full tracker at sensor level**
  - **Alignment studies using various MC data sets**
  - **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!**

BACKUP

CMS Physics TDR Vol. 1



- **Section 6.6 "Alignment"**
  - **14 pages summary of work done so far (Feb 2006)**
- **8 accompanying CMS Notes**
- **Contents**
  - **Alignment strategy and data samples**
  - **Simulation and impact of misalignment**
  - **Track based alignment algorithm studies**
  - **Alignment of test beam data**
- **Impact of misalignment also studied in several physics analyses documented in Vol.2**

PTDR: Supporting CMS Notes

- A lot of effort of work and documentation by many groups
- Algorithms and applications
  - CMS 2006/022 -- A Kalman Filter for Track Based Alignment
  - CMS 2006/018 -- The HIP Algorithm for Track Based Alignment and its Application to the CMS Pixel Detector
  - CMS 2006/006 -- Alignment of the Cosmic Rack with the HIP Algorithm
  - CMS 2006/011 -- Software Alignment of the CMS Tracker using MILLEPEDE II
  - CMS 2006/016 -- Muon System alignment with tracks

- Misalignment simulation and Physics Impact
  - CMS 2006/008 -- Simulation of Misalignment Scenarios for CMS Tracking Devices
  - CMS 2006/029 -- Impact of CMS Silicon Tracker Misalignment on Track and Vertex Reconstruction
  - CMS 2006/017 -- Influence of Misalignment Scenarios on Muon reconstruction

Alignment Algorithms

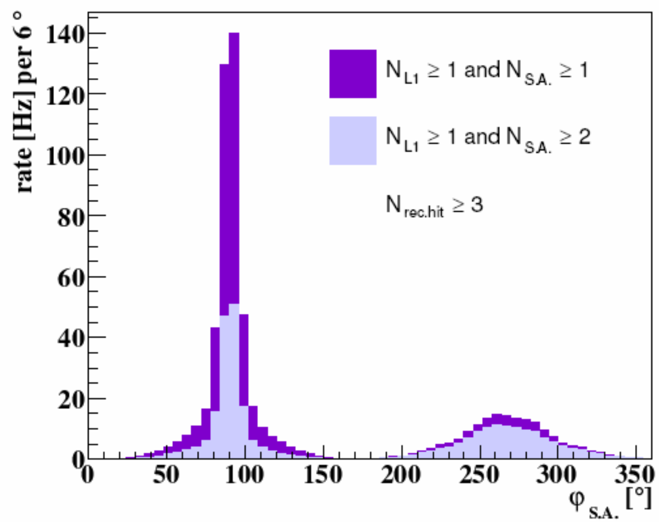
Three algorithms being studied in CMS (using common software):

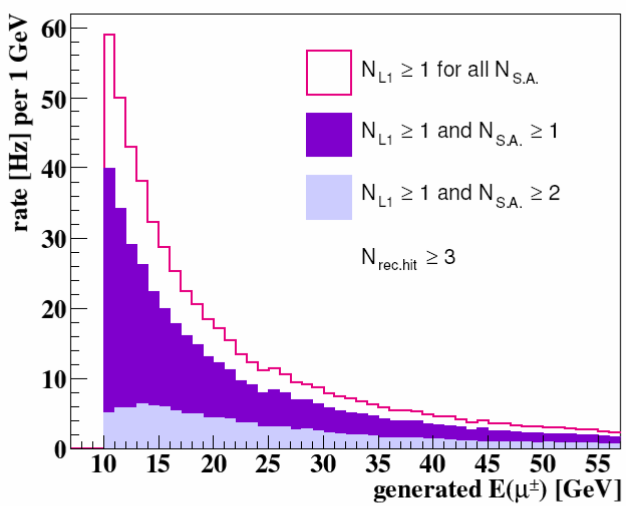
- **Kalman filter (Vienna, Aachen) CMS-Note-2006/022**
  - Parameters and correlations updated after each track
  - No large matrix inversions, but book-keeping of relevant correlations
- **Millepede (Hamburg) CMS-Note-2006/011**
  - Used successfully in other experiments (e.g. CDF, H1)
  - New version Millepede-II, expected to be scaleable to CMS problem (see next slides)
- **HIP Algorithm (Helsinki, CERN) CMS-Note-2006/018**
  - Robust approach, no large matrices (ignores module correlations)
  - Pixel alignment

- **Successfully used to align**
  - parts of CMS tracker in simulation
  - the TOB Cosmic Rack with real data
  - Working on demonstrating scaleability to full CMS tracker

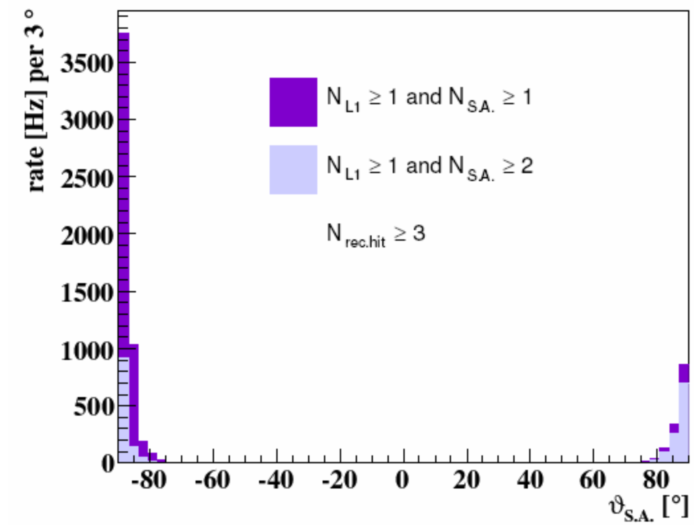
Simulation of Cosmics and Beam halo muons in CMS

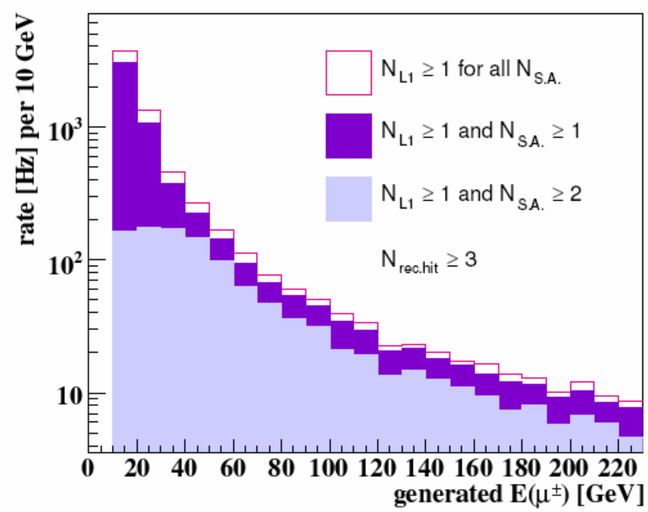
- **Cosmic muons: 400 Hz**





- **Beam halo muons: 5 kHz per side**



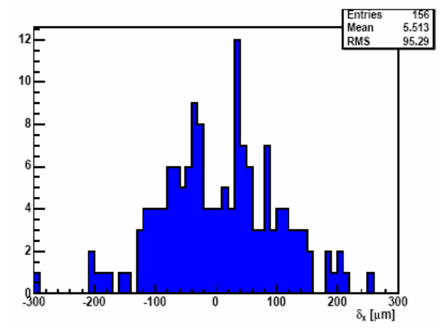


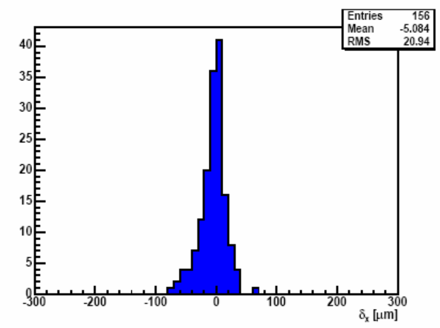
CMS Note 2006/012

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

Kalman Filter Alignment (cont.)

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

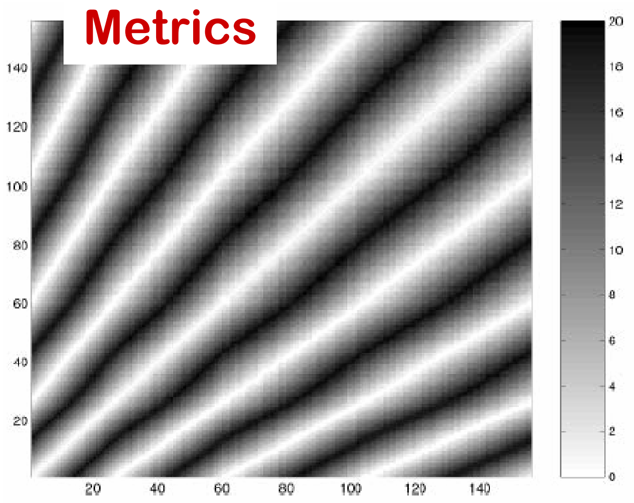


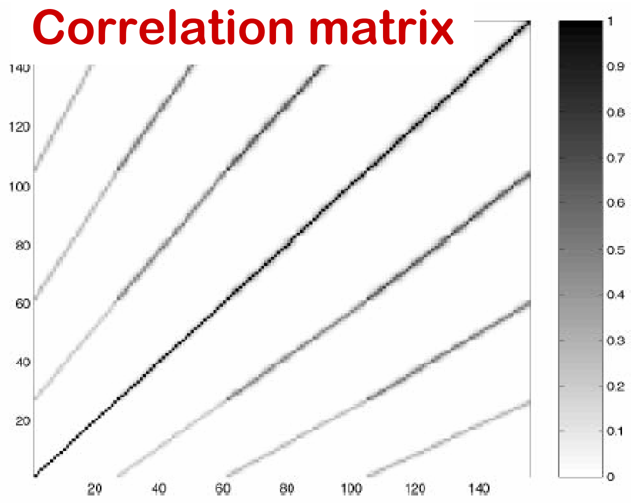


- **Dependence of RMS and CPU time on d_{max}**

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**





CMS Note 2006/022

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