Track based Alignment in CMS

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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 $\chi^2$
  - Monitoring, fix $\chi^2$ 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 $L=2\times10^{33}$
  - Gold plated for tracker alignment (small multiple scattering)
  - Exploit $Z^0$ mass constraint

- Cosmic Muons
  - $\sim 400$Hz after L1 and s.a. muon reco.

- Beam Halo Muons
  - $\sim 5$ 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 $J/\psi$ and inclusive B decays
  - $J/\psi$ 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

Rates after L1 and standalone muon reconstruction

CMS Note 2006/012
Alignment Strategy

Basic sketch:

- **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 structures (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 laid out in more detail …

See next slides for rate estimates
Expected event rates

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

  - What data samples in 2007 ?
  - ATLAS preliminary
    - $\sqrt{s} = 900$ GeV, $L = 10^{29}$ cm$^{-2}$ s$^{-1}$

  - 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...33}**

  - Large statistics of high pt muons within few weeks!

  | Luminosity | $10^{32}$ cm$^{-2}$s$^{-1}$ | $2 \times 10^{33}$ cm$^{-2}$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 |
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

\[
\begin{pmatrix}
\epsilon_u \\
\epsilon_v
\end{pmatrix} =
\begin{pmatrix}
u_x - u_m \\
v_x - v_m
\end{pmatrix}
\]

- \(\chi^2\) function to be minimized on each sensor (after many tracks per sensor accumulated)
  - \(V\): covariance matrix of measurement

- Linearized \(\chi^2\) solution:
  - \(\delta p\): 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

CMS Note 2006/018
HIP Algorithm: Formalism (cont.)

- Formalism extended to alignment of composite detector structures (ladders, disks, layers etc.)
  - Minimize $\chi^2$ 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 explicitly
  - 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
  - Start next iteration on N cpu’s

\[
\frac{\delta \varepsilon_i^S}{\delta p_i^C} = \frac{\delta \varepsilon_i^S}{\delta p_i^S} \times \frac{\delta p_i^S}{\delta p_i^C}
\]

- 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: $\sim 45'$
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 $\sim 7\mu$m in x,y, $\sim 23\mu$m 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
- Reasonable convergence, RMS $\sim 25 \mu m$ in all coordinates
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 $d$:
    $$ m = f(x, d) + \epsilon \quad \text{COV}(\epsilon) = V $$
  - 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
Kalman Filter Alignment (cont.)

- Wheel-like setup: (part of CMS tracker: 156 TIB modules)
- Pixel detector as reference
- Misalignment:
  - local $x, y \sigma = 100 \mu m$
- 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)

CMS Note 2006/022
Kalman Filter Alignment (cont.)

- Overall RMS $\sim 21\mu m$ after alignment

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

| $d_{\text{max}}$ | 1   | 2   | 3   | 4   | 5   | 6   |
|------------------|-----|-----|-----|-----|-----|-----|
| $\sigma [\mu m]$ | 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
Millepede II Algorithm

- For formalism, see talk of V. Blobel
- Original Millepede method solves matrix eqn. $A x = B$, 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 $\sim 100000$ 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!

Matrix Inversion ($12000 \times 12000$)
(t=$13h$)

MinRes
(t=$30s$, $1500x$ faster!)

CMS Note 2006/011
Millepede-II in CMS

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

CPU time in hours as a function of number of parameters

- 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...

CPU Time for CMS (100k parameters):
- Diagonalization: ~10 year at one CPU
- Inversion: ~1 year at one CPU
- Iteration: ~1 h at one CPU
Importance of using “complete” datasets

1. Collision tracks and cosmics populate different parts of global covariance matrix → reduce global correlations!

2. Example: Alignment of CMS strip barrel rods and layers
   - Only one layer fixed
   - 500k $Z^0 \rightarrow \mu\mu$ with vertex constraint
   - 100k Cosmics

3. Use $Z^0$ tracks only:
   - No solution
   - Matrix singular

4. Use $Z^0$ and Cosmics:
   - Problem solvable
   - Resonable correlations

Simplified simulation and scenario, Now look at realistic study …
Global correlations: Realistic scenario

- 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!

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M. Stoye (Hamburg)
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 $\chi^2$ (“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!