Track-based alignment and calibration with Millepede-II and General Broken Lines

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Overview

- Millepede
  - Introduction
  - Examples
    - Calibration of H1 Central Jet Chambers
    - Alignment of CMS Silicon Tracker
- General Broken Lines
- GENFIT
- Summary

MP - Introduction

- Millepede is a software package for linear least squares fits with a large number of parameters
- Developed and implemented in FORTAN77 by Volker Blobel (Univ. Hamburg), started 1996
- Used by several experiments for track based alignment and calibration
- Now maintained by Statistics Tools group of Analysis Center in Helmholtz Terascale Alliance

V. Blobel: Track based alignment,
Nuclear Instruments and Methods A, 566 (2006), pp. 5-13)

MP basics

$$\chi^2(\Delta\mathbf{p},\Delta\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \frac{1}{\sigma_{ij}^2} \left(\mathbf{m}_{ij} - \mathbf{f}_{ij}\left(\mathbf{p}_0, \mathbf{q}_{j0}\right) - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{p}} \Delta\mathbf{p} - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{q}_j} \Delta\mathbf{q}_j \right)^2$$

- Track based alignment and calibration
  - Minimizing χ^2 sum
    - for large number of global (align., calib.) parameters $\Delta\mathbf{p}$
    - from large number of local fits (tracks $\Delta\mathbf{q}_j$)
    - with model $\mathbf{f}$ linearized at initial parameters $(\mathbf{p}_0,\mathbf{q}_0)$
  - Linear equation system with bordered band matrix
    - Border populated due to global derivatives $\partial\mathbf{f}/\partial\mathbf{p}$
    - Block diagonal by (independent) local derivatives $\partial\mathbf{f}/\partial\mathbf{q}_j$
  - Local fits ($\partial\chi^2/\partial\Delta\mathbf{q}_j=0$) done with $\mathbf{p}=\mathbf{p}_0$
    - Size of lin. eqn. system reduced to number of global par.
    - Correlations of global trough local parameters maintained

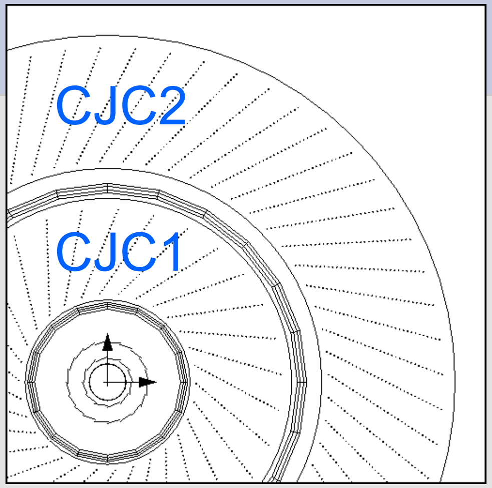
Millepede basics (II)

- Power of method (condition of matrix) improves with **variety** of inputs:
  - Data sets with different phase space
    - Tracks from collisions, cosmic rays, ..
  - Detectors with different sensitivity, systematics, ..
    - Common alignment and calibration
    - E.g. for muons use complete track from first (pixel) to last (muon detector) hit
  - Operational conditions
    - E.g. scan of E, B field

MP-II implementation

- Split into two parts
  - "Mille"
    - Integrated into software of experiment (Fortran, C/C++)
    - Producing binary files containing the required information from the tracks (measurements, errors, derivatives)
  - "Pede"
    - Standalone Fortran90 program to solve the (large) linear equation system produced from the binary files
    - Implemented in 64bit to access more than 8GB of memory
    - Parallelized with OpenMP™

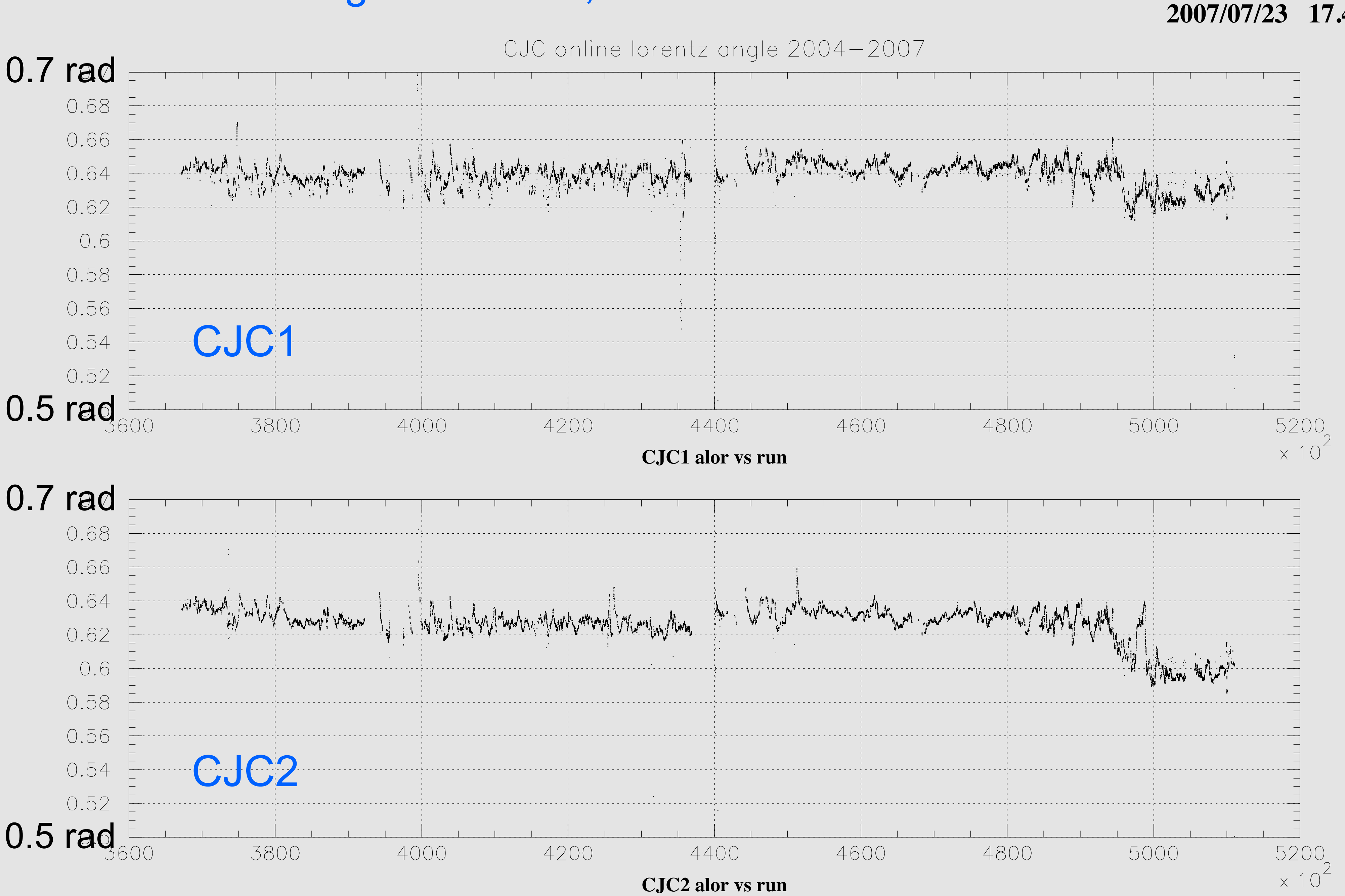
Calibration example (I)



- Calibration of H1 Central Jet Chambers
  - Relation drift time to drift distance
    - Depends in first order on drift velocity, Lorentz angle
    - Higher order corrections (track angle, inhomogeneities)
  - Online calibration:
    - Time dependence of mean drift velocity, Lorentz angle
  - Offline calibration:
    - Spatial variations: v_d, α_{lor} vs R, φ, B(Z,R)
    - Dependence on E-field, air pressure (➔ compensation)
    - Isochrone, close wire corrections

Calibration example (II)

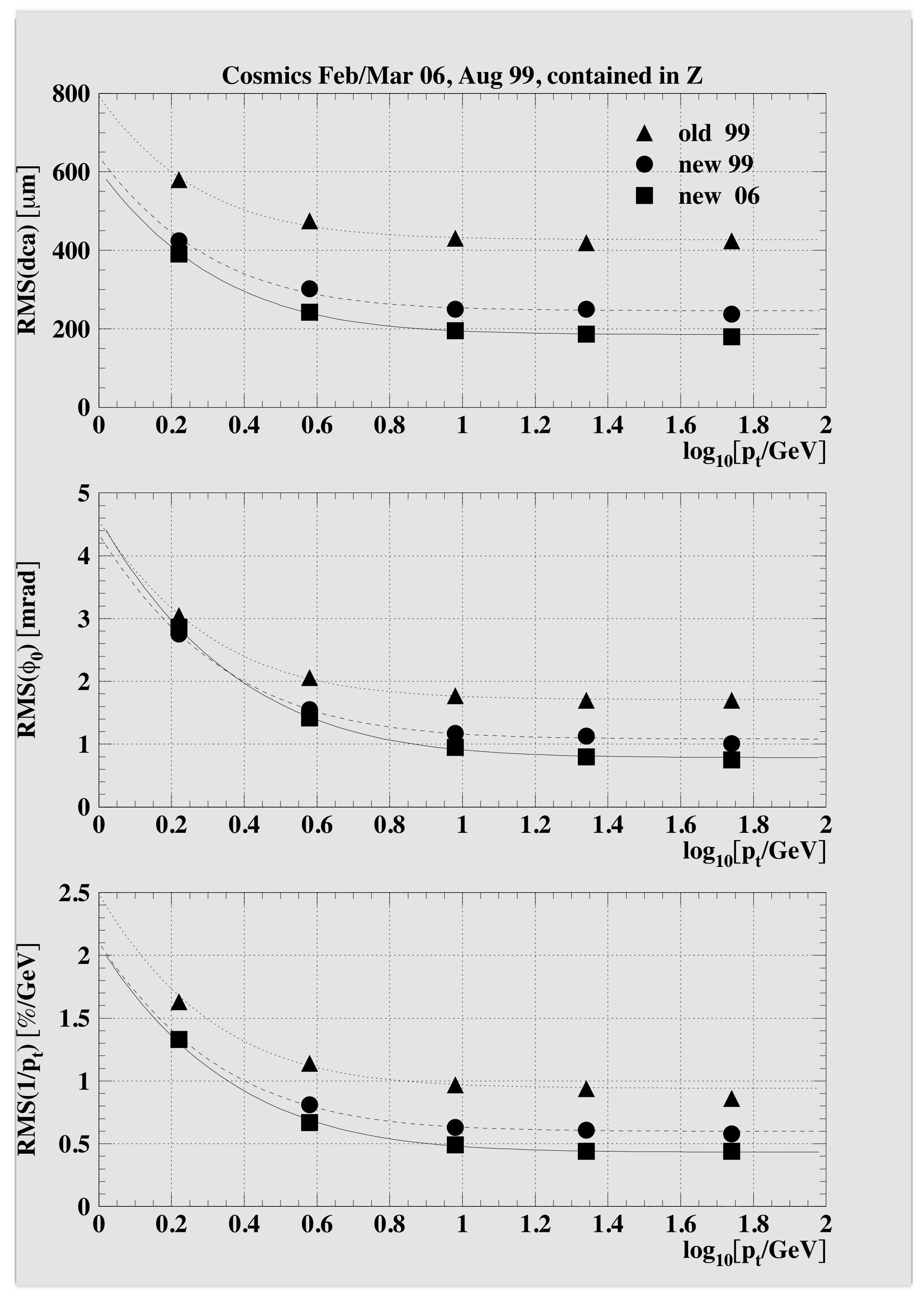
Online Lorentz angle for CJC1, CJC2 vs run number for 2004-2007



Varies with air pressure (, space charge, gas composition)

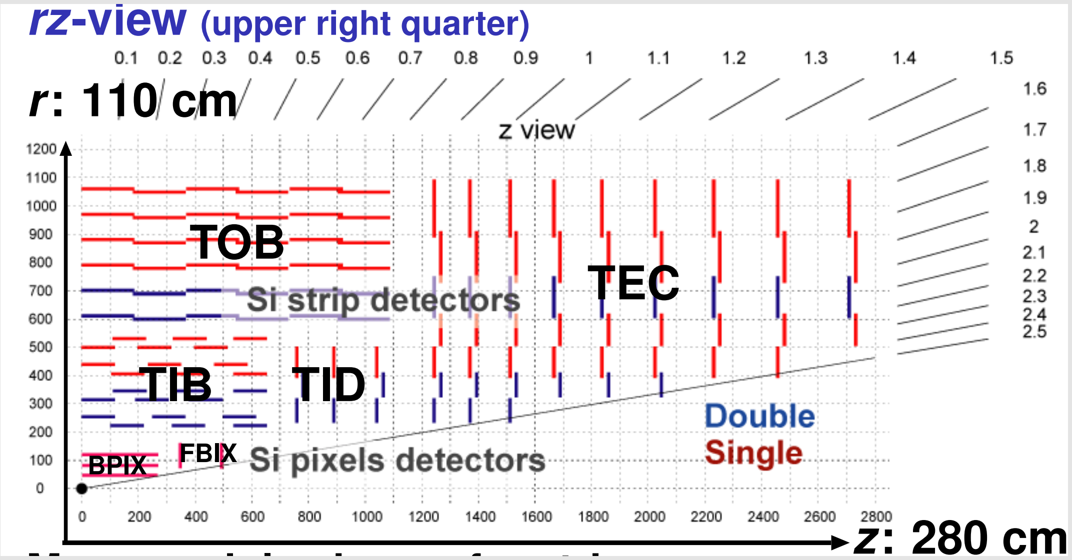
Calibration example (III)

- HERA-I ▲ to ●
  - Variations of E(φ,R)
- HERA-II ● to ■
  - Variations of B(Z,R)
- Resolution
  - of track parameters (for high momenta) improved by factor 2



Alignment example (I)

- Alignment of CMS Silicon Tracker
  - 25k strip (pixel) sensors with 5 (6) rigid body alignment parameters



  - Additional surface deformations
    - Described by sum of Legendre polynomials
    - For 2nd order (curved sensors) 3 more parameters
  - In total 200k alignment parameters

Alignment example (II)

CMS 2011 Tracker Alignment: ~1 fb^{-1}

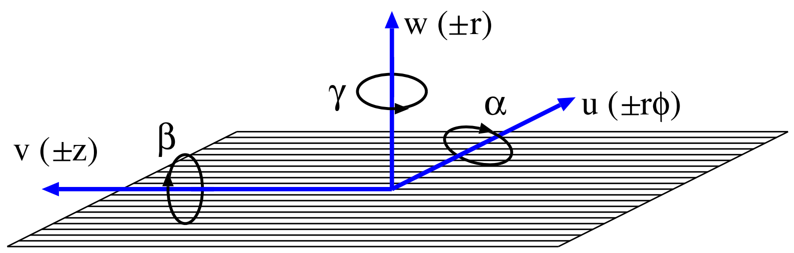
Input Data

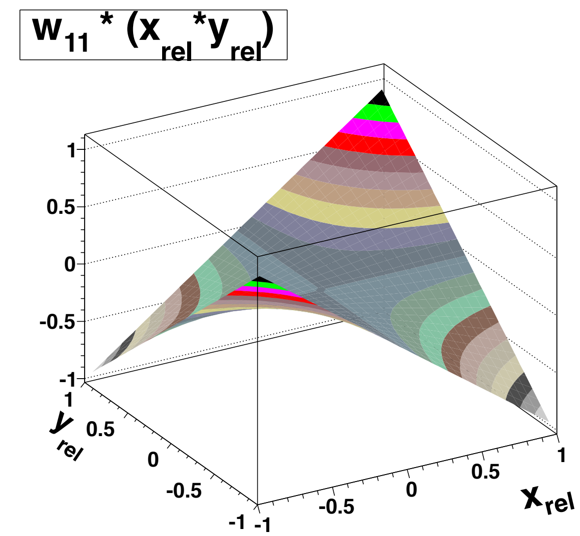
- Loosely selected isolated muons: 15 million.
- Muon pairs from $Z \rightarrow \mu^+\mu^-$ decays: 375 thousand pairs.
- Low momentum tracks: 3 million.
- Cosmic tracks (e.g. recorded in between LHC fills): 3.6 million.

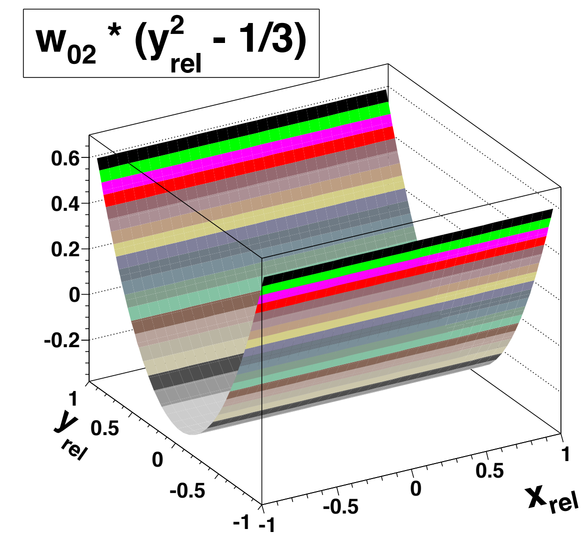
From talk by Gero Flucke, ACAT2011

Alignment example (II)

CMS 2011 Tracker Alignment







Alignment Algorithm and Parameters

- Millepede II algorithm with ~200 000 free alignment parameters.
- 8 (9) parameters per strip (pixel) sensor:
  - 5/6 rigid body like parameters (one insensitive for strips),
  - 3 bow parameters.
- Time dependent rigid body parameters for larger pixel structures:
  - 9 time periods in common fit,

  ⇒ moving structures, modules constant within.
- $Z \rightarrow \mu^+\mu^-$ combined object, adding Z mass “measurement” (⇒). (fix momentum scale !)

Alignment example (III)

CMS 2011 Tracker Alignment

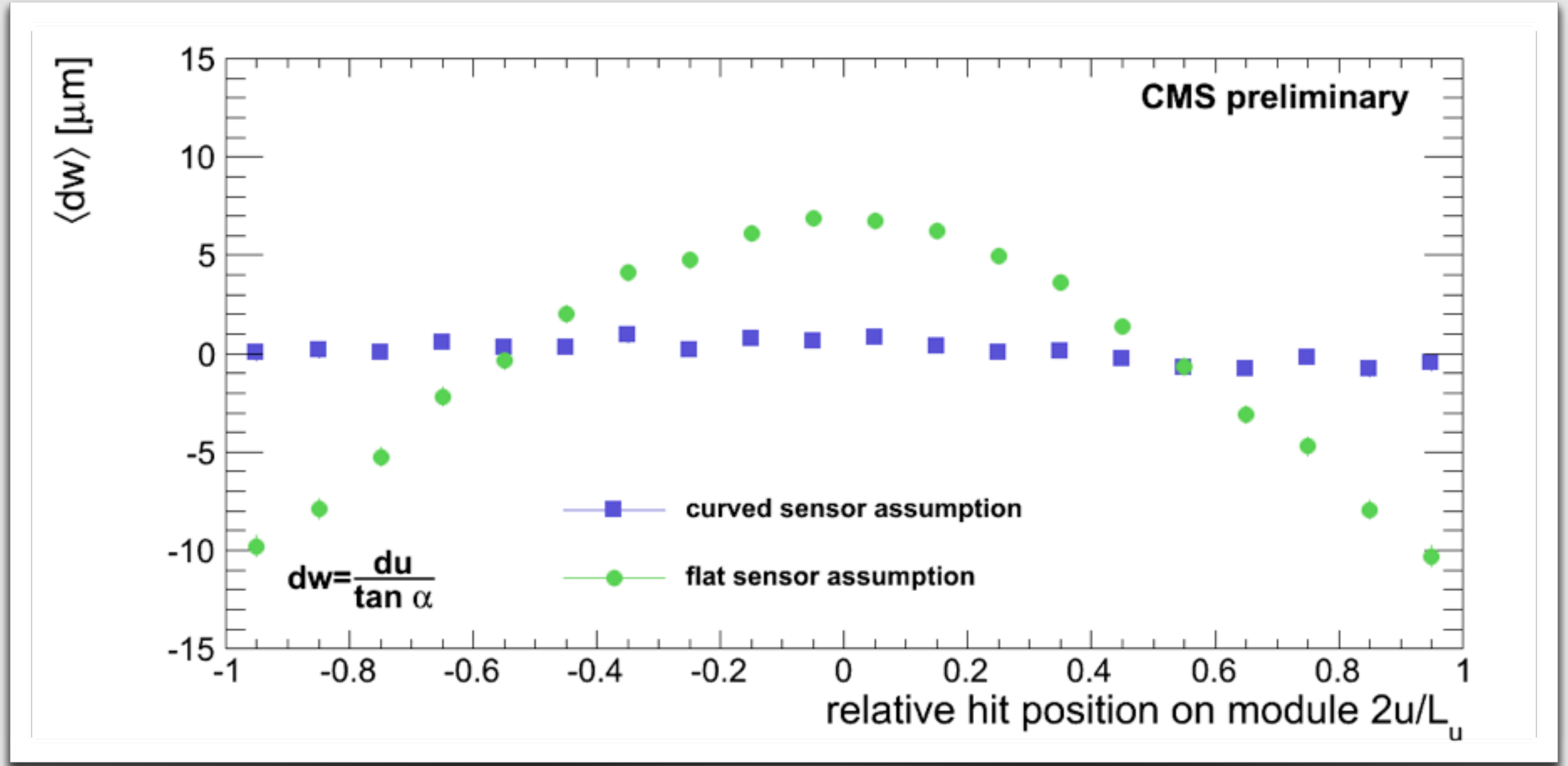
Millepede II at Work

- 246 zipped binary files ($\sum$ 46.5 GB), read 13 times.
- 22.6 million local fit objects,
  - bordered band matrix structure: max(border) = 9, max(width) = 4.
- MINRES iterating 3 times (tightening outlier rejection) to solve $\boldsymbol{C}' \, \boldsymbol{a}^{global} = \boldsymbol{b}'$.
- 200 614 fit parameters (including 138 Lagrange multipliers). (from hierarchy constraints)
- Matrix with 31% non-zero off-diagonal entries, compression ratio 40%, $\Rightarrow$ fits well into 32 GB memory.
- Total CPU 44.5 h, Wall 9:50 h using 8 threads on Intel® Xeon® L5520, 2.27 GHz.

$\Rightarrow$ **Very efficient usage of resources with fast turnaround for analysis!**

CMS example (IV)

Remaining surface deformation $\Delta w \cong \Delta u / \tan(\alpha)$ vs (normalized) u (TIB)



Typical sagitta values: 20-40 μm

General Broken Lines

- Track model for Millepede
  - For detector with substantial material multiple scattering has to be described properly
  - Fit must be implemented as single linear equation system delivering the complete covariance matrix ➜ Kalman filter can't be used
  - Use trajectories based on **broken lines**

V. Blobel: Fast track-fit algorithm based on broken lines, Nuclear Instruments and Methods A, 566 (2006), pp. 14-17

GBL - Basics

- General Broken Lines constructed from
  - Sequence of thin scatterers
  - Offsets (**u**) as fit parameters at scattering planes
  - Jacobians ($\partial \mathbf{u} / \partial \mathbf{p}_{loc}$) for propagation between measurement and scattering planes
  - Interpolation of offset pairs for measurements
  - Kinks from offset triplets to describe multiple scat.
- Track fit time linear in number of measurements
  - Linear equation system with (bordered) band matrix
    - Fast solution by root-free Cholesky decomposition

GBL vs Kalman filter

- Comparison with Kalman filter
  - Mathematically equivalent
    - Same measurements, scattering, propagation as input
  - Computationally different
    - Add all measurements and scatterers in one step, not one at a time
    - One large bordered band matrix, not many 5x5 matrices
    - Track fit (≅filtering + smoothing) up to factor 2 faster than Kalman filtering (first toy detector studies)

GBL - Implementations

- GeneralBrokenLines@svnsrv.desy.de
  - Provided by Statistics Tools group of Analysis Center in Helmholtz Terascale Alliance
  - FORTRAN version available
  - C++ version under construction
  - Interface to Millepede-II (“Mille step”) included

GENFIT

- GENFIT is generic track fitting framework providing infrastructure needed by GBL
  - (virtual) measurement planes with hits
  - propagation between planes
- GENFIT is used by Belle-II
- Idea: Implement GBL in GENFIT
  - work has started (S. Yaschenko)
  - needs mature C++ version of GBL

C. Höppner et al.: A novel generic framework for track fitting in complex detector systems, Nuclear Instruments and Methods A, 620 (2010), pp. 518-525

Summary

- Based on H1 and CMS experience
  - Use MP⊗GBL for tracker calibration and alignment
- Important is a variety of track samples
  - Interactions, cosmics, different E, B fields, ..
  - To avoid weak modes (χ^2 invariant distortions)
- Technical implementation
  - GENFIT as interface, or
  - Custom coded GBL and Mille step (as CMS)