Alignment & Calibration Experience Under LHC Data-Taking Conditions in the CMS Experiment

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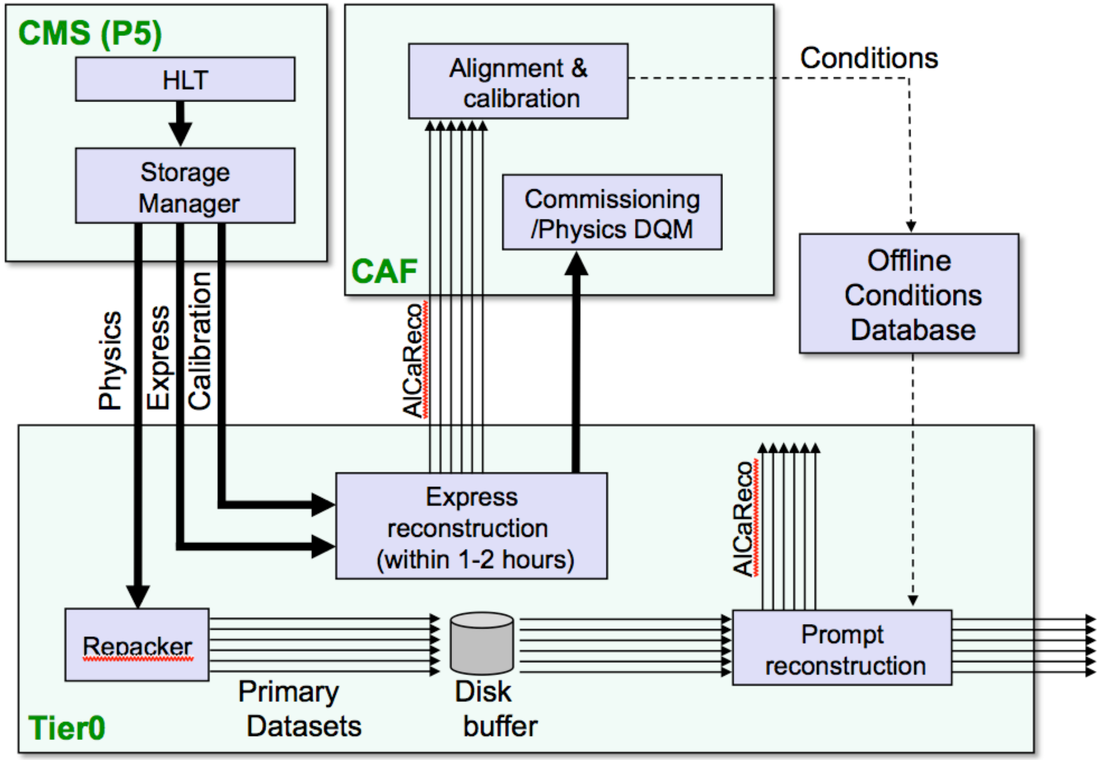
CMS Alignment & Calibration Challenge

- Full resolution & physics performance of CMS detector can only be achieved with optimal alignment & calibration of its components. This requires:
  - powerful framework & infrastructure
  - fast turnaround → fast publication of results
  - state-of-art workflows, elaborate conditions management
- CMS alignment & calibration framework has been put to the real-life test in the first half year of the LHC high energy run
  - increasing luminosity → evolution of strategies
  - increasing number of workflows & dependencies
  - frequent reprocessing campaigns

→ Experience & results will be presented

Alignment & Calibration in the CMS Offline Workflow

- Express and calibration streams are generated besides the main physics stream already at the detector site
- Express reconstruction of ~10% of the data at low latency
  - prompt reconstruction of bulk dataset takes longer
- Compact dedicated skims ("AlCaReco") derived automatically both during the express and the prompt processing
  - transferred to the CERN Analysis Facility (CAF)
- Alignment/calibration workflows operate at CAF and feed derived constants into the conditions database



Selected Alignment/Calibration Workflows & Dependency Levels

- Online determination of beam spot (not for conditions DB) ☆
- All detectors: channel status calibrations
- ECAL energy scale and inter-calibration ☆
- HCAL energy scale and inter-calibration
- Muon system optical alignment
- DT time pedestal and drift-time calibration
- Tracker gain calibration (pixel & strip)
- Tracker Lorentz angle calibration (pixel & strip)
    - Tracker alignment ☆
        - Tracker-muon system cross alignment
        - Muon system track-based alignment
        - ECAL & preshower alignment
        - Offline determination of beam spot ☆

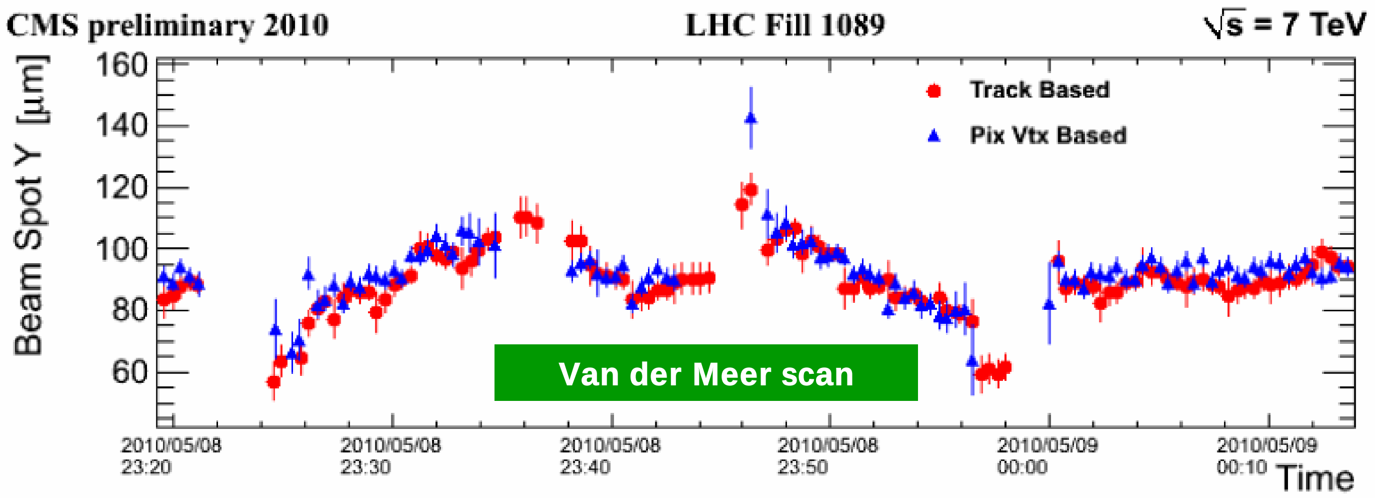
☆ = examples shown in this presentation

→ Large number of workflows & database objects to manage

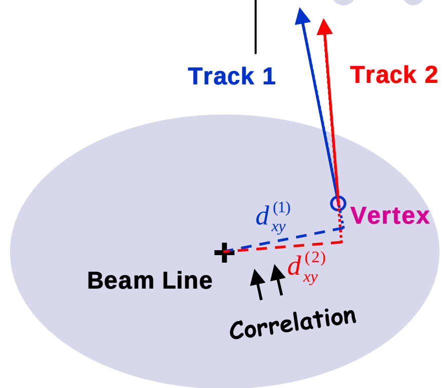
→ For consistent conditions, must address all dependencies adequately

Online Determination of Luminous Region ("Beam Line") Parameters

- Attempt determination with two methods in the online DQM environment at the end of every luminosity section (23s)
- Tracks / vertices (pixel-only tracking) are accumulated for up to 5 luminosity sections (≥ 150 tracks or 35 vertices required)
  - ➔ fed back to LHC to monitor beam parameters
  - ➔ for optimal accuracy, beam line for final analysis is determined offline

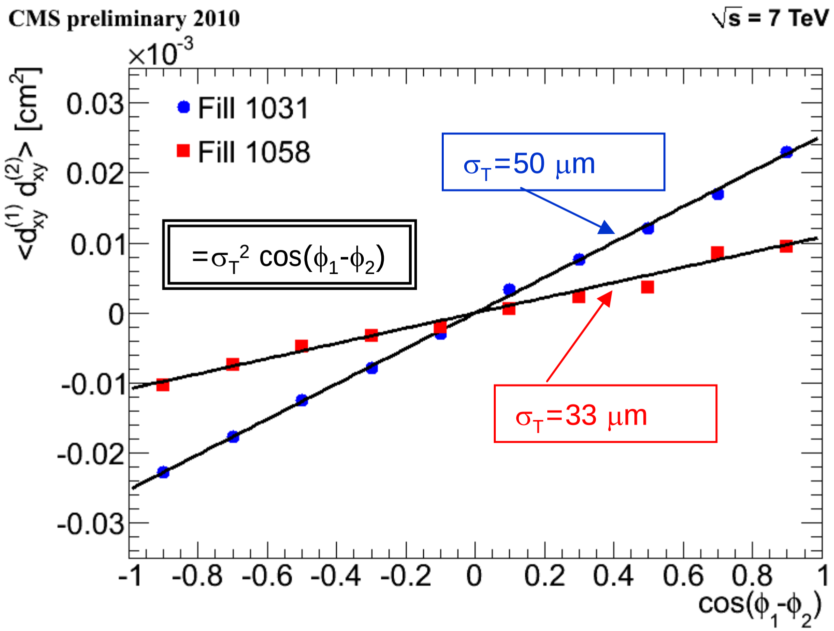


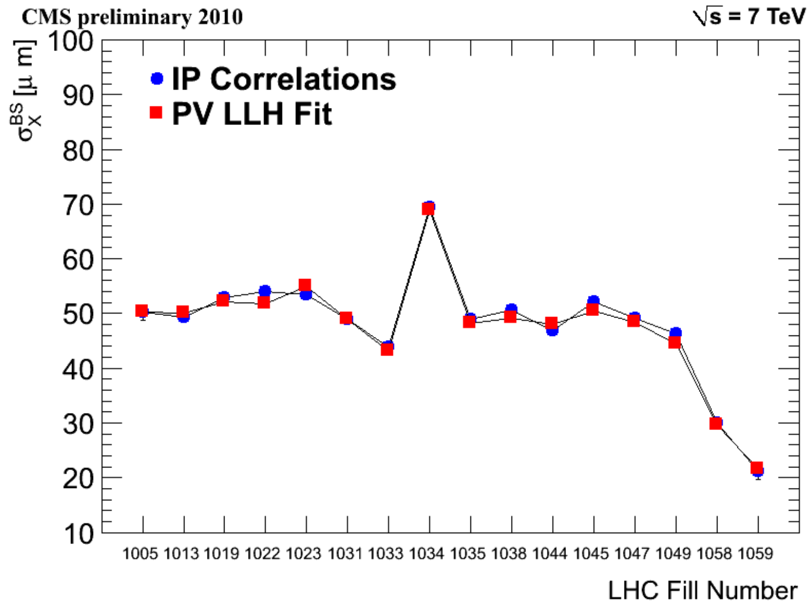
Determination of Beam Line Width



- Besides analysis of primary vertex distributions, CMS uses impact parameter correlations for determining beam line width
  - no unfolding of resolutions required → complementary systematics

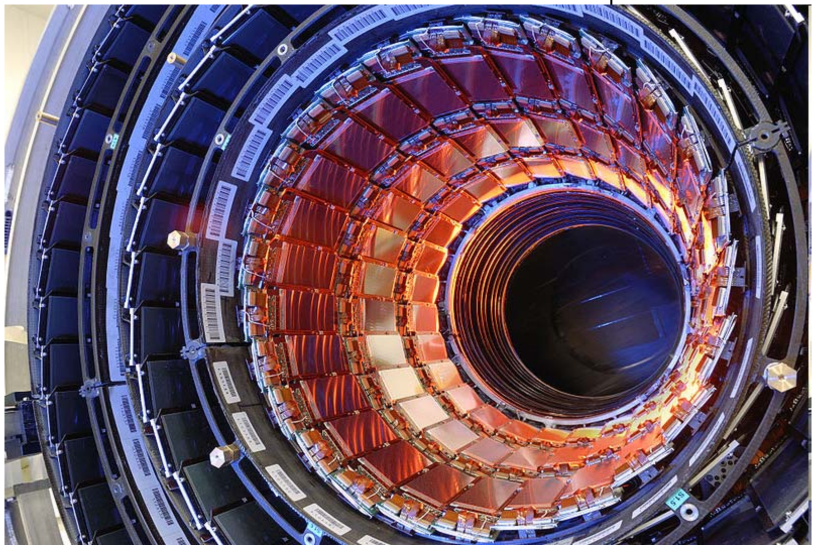
→ Very good agreement between methods
  - → highlights good understanding of tracking resolutions





Tracker Alignment

- Largest silicon tracker ever built (~200 m^2, 16588 modules)
  - alignment huge challenge both methodically & computationally
- CMS performs track-based alignment mainly with two methods:
  - local method (HIP):
    - fit alignment parameters for each alignable individually from set of residuals in a dataset
    - refit the tracks with alignment parameters applied
    - repeat this many times until parameters converge
  - global method (Millepede-II):
    - perform simultaneous fit of all alignment and all track parameters
- both methods combined for best results



See also:

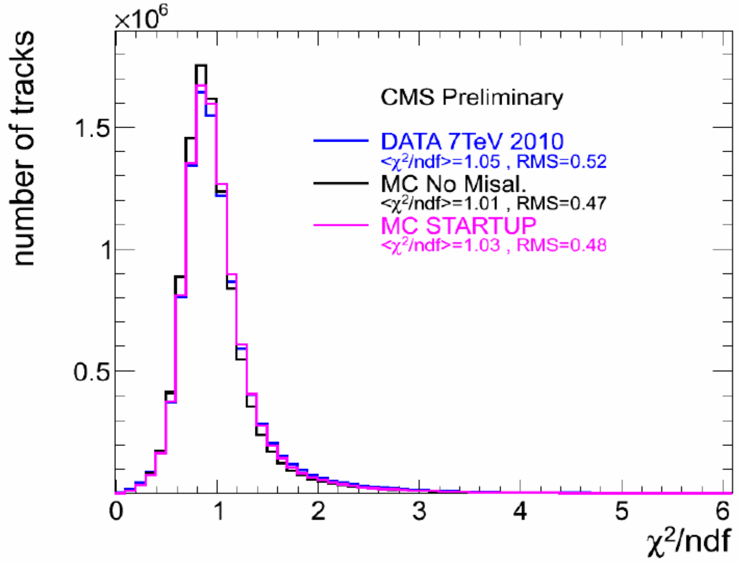
Tapio Lampen: The alignment of the CMS Silicon Tracker (Poster)

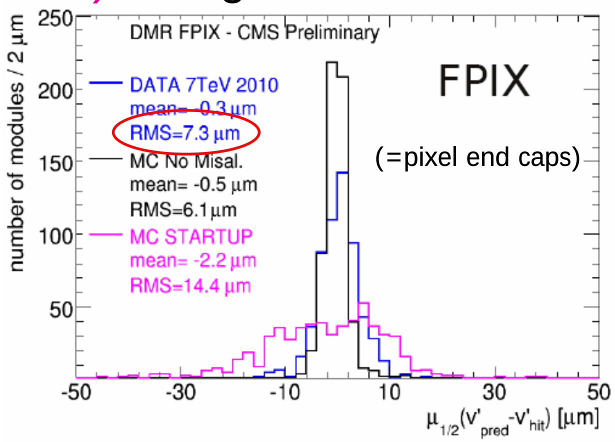
Tracker Alignment: Results

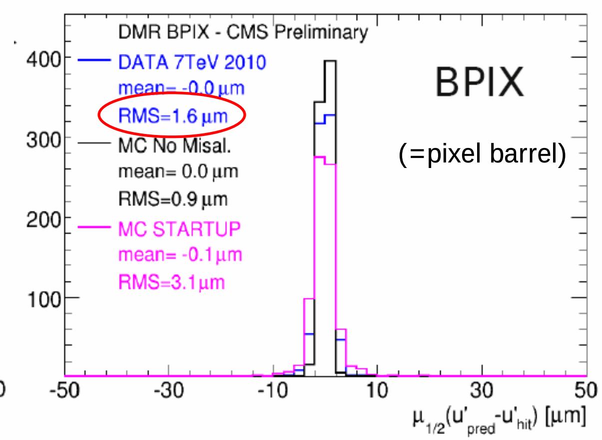
- Based on combination of cosmic ray data taken in early 2010 with the first nb^{-1} of 7 TeV collisions data
  - further improvement of goodness of fit beyond cosmic ray-level ("STARTUP") alignment
  - close to result expected with perfect alignment
- Narrow distributions of medians of residual distributions (DMR) → high alignment accuracy

→ Addition of tracks from collisions has largest impact in pixel endcaps (FPIX)

→ Extend to full 2010 dataset (underway)

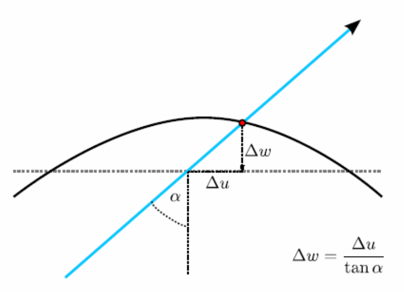


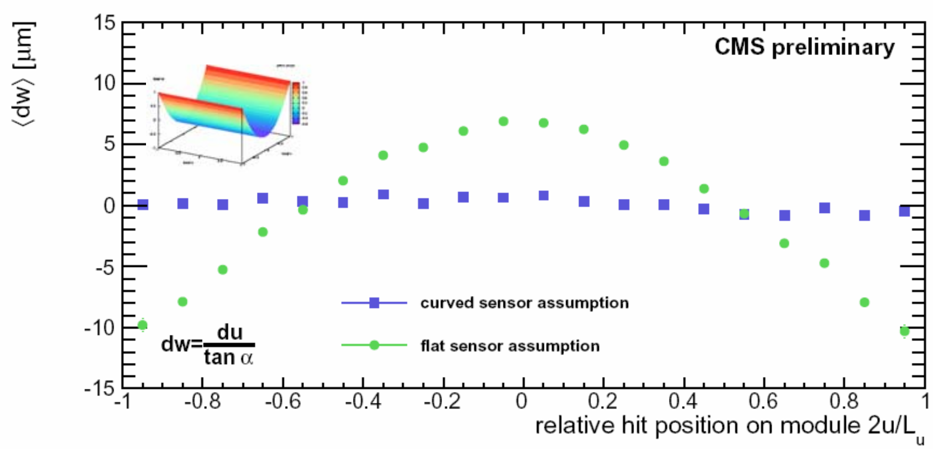




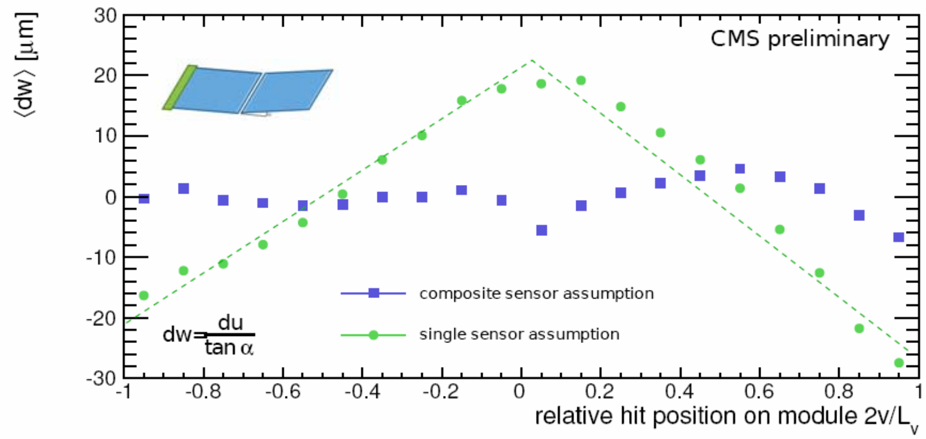
Further Improvements: Curvatures & Kinks

- Sensor curvature → additional hit bias depending on slope and position of track



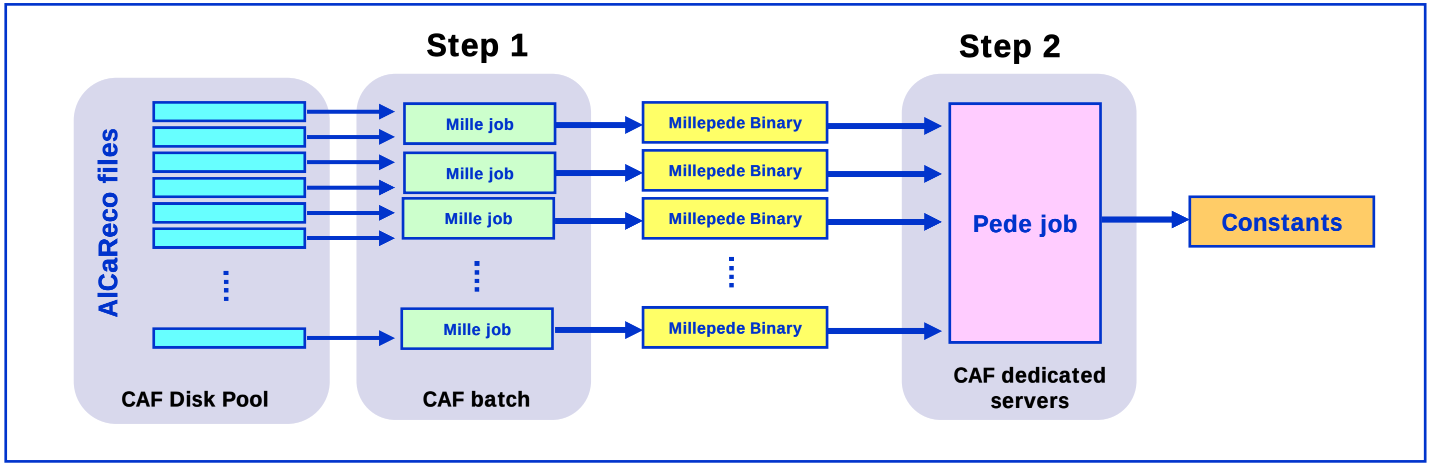


- Composite modules can have kink angle between two sensors
- Solution: determine curvatures & kinks as additional alignment parameters module-by-module
  - based on extended version of Millepede-II
  - increases number of alignment parameters → ~200000
  - computationally demanding



Alignment Computing-Workflow (Millepede-II)

- Step 1:
  - event-by-event processing (→ residuals, derivatives etc) performed in parallel, typically 100-200 jobs on CMS-CAF → each job results in a compact binary file
- Step 2:
  - one global fit determines all track and alignment parameters simultaneously
  - very CPU and memory intensive → two dedicated CAF servers with 48 GB of memory
  - most CPU-intensive parts parallelized using OpenMP™
    - multi-threaded operation, optimal value currently at ~7 CPU cores
    - with ~200000 parameters & ~1M tracks, wall time reduced from 9 hours → 1.5 hours



Electromagnetic Calorimeter Calibration

- Calibration strategy:
  - pre-calibration (e^- test-beam, cosmics)
  - LHC beam dump data
  - fast inter-calibration within rings of same η assuming ϕ symmetry in minimum bias events
  - inter-calibration using π^0 and η decays (initially also used to set the energy scale)

→ Dedicated calibration triggers & streams.

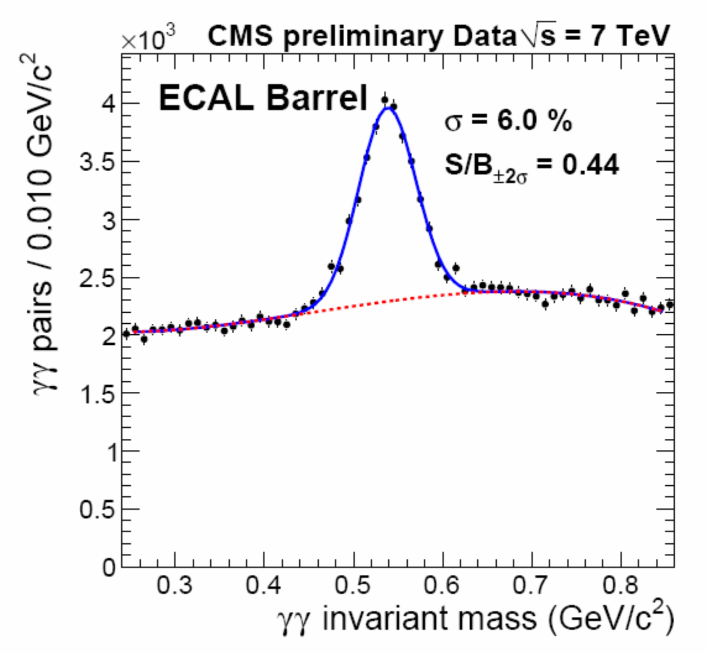
See: Stefano Argiro': Triggers and streams for calibration in CMS

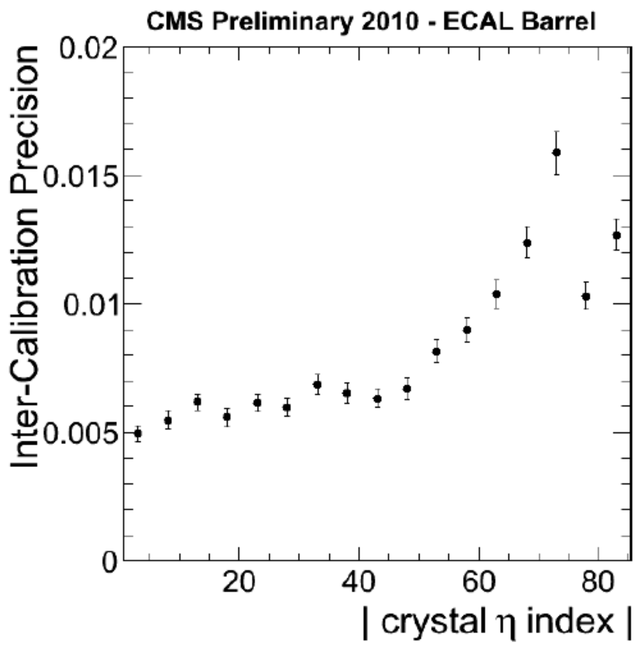
  - isolated electrons from W→eν and Z→ee decays, using momentum measured in tracker as reference
    - ➔ main channel-by-channel calibration tool at multi-fb^{-1} luminosity

Future

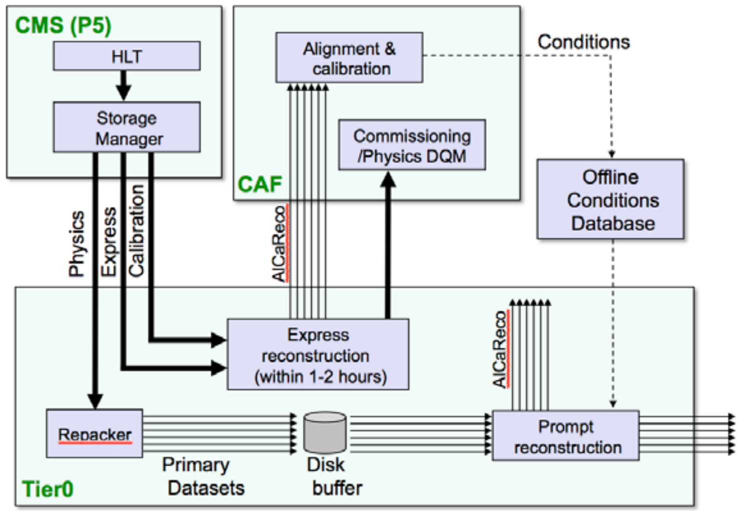
ECAL Calibration Performance

- Combination of ϕ symmetry, π^0/η and beam dump data: inter-calibration accuracy in barrel shows smooth trend with η from 0.5% to ~1.5%
- Energy scale accuracy ~1% (EB), ~3% (EE)





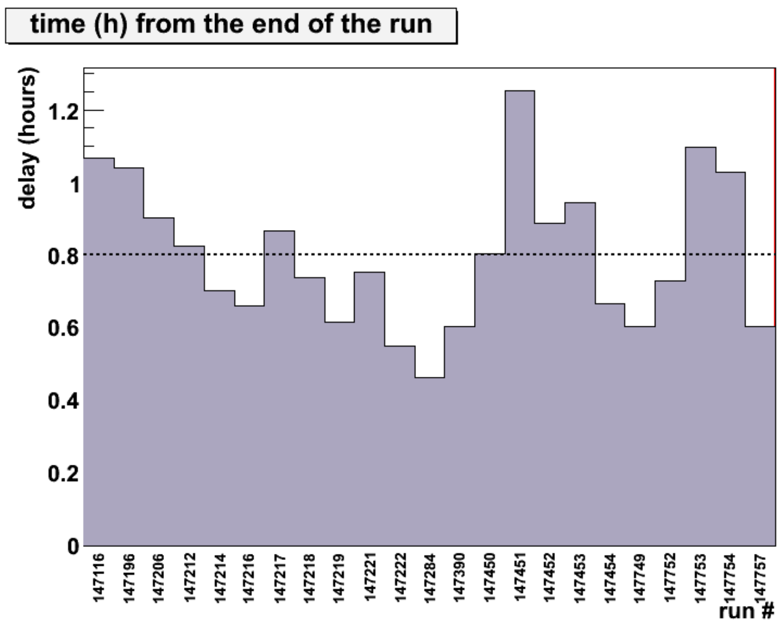
Prompt Calibration Loop



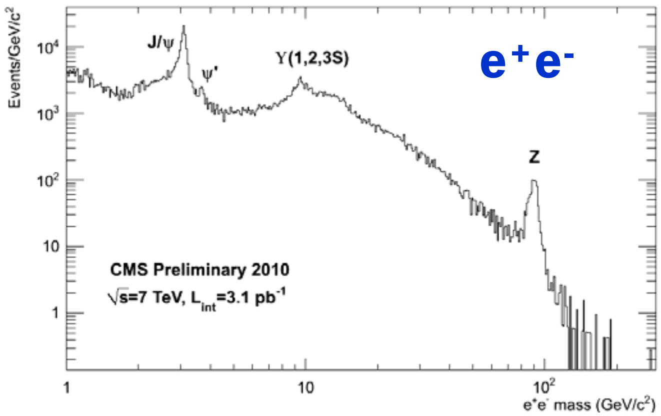
- Aim: make already "prompt" reconstruction of data fully "analysis-ready"
  - with fast-changing constants determined from run X applied in reconstruction of run X (beam spot, channel status)
- Requires intentional delay between data-taking and prompt reconstruction
  - ➔ bulk of raw data buffered on disk
  - ➔ selected calibration workflows performed on express stream processing output
  - ➔ constants uploaded before prompt reconstruction
- During first months of LHC operation CMS did not operate prompt calibration since the (still small) data sample could be reprocessed quickly & frequently
- Intensive tests have been performed with the beam line calibration workflow
  - step 1: beam line fit once per luminosity section
  - step 2: "collapsing" ranges of stable constants into larger intervals of validity
    - increase precision, reduce database storage size
  - step 3: validation & upload to database

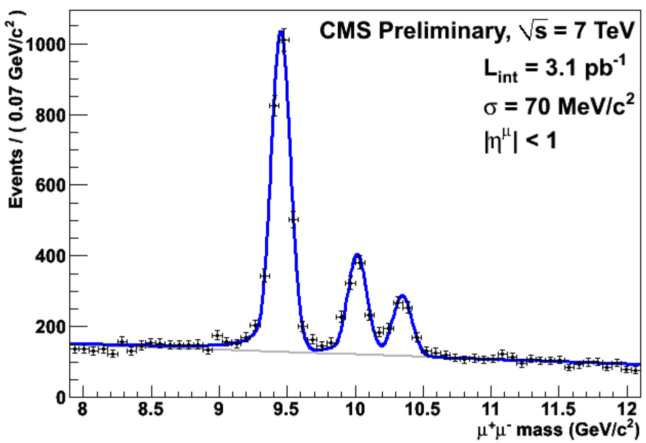
Prompt Calibration Tests

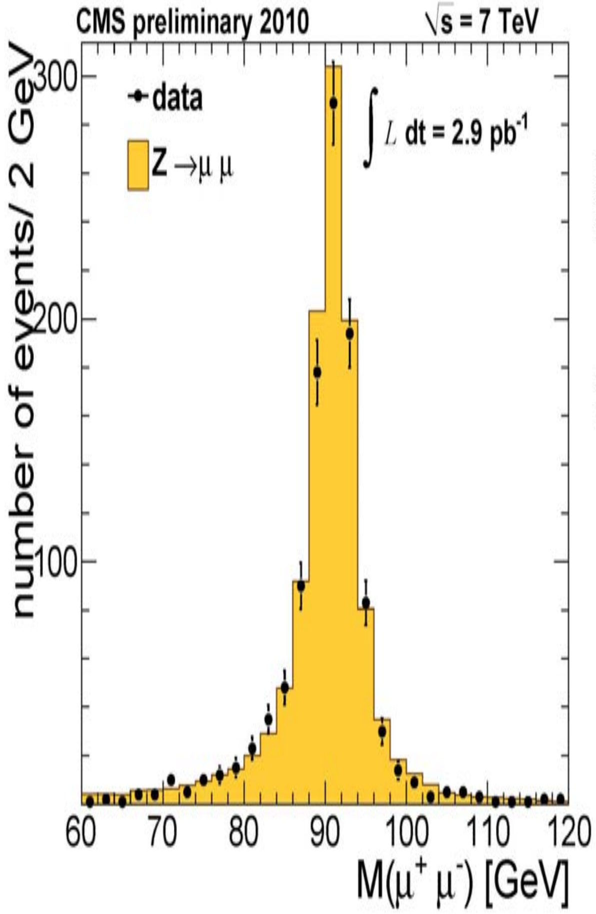
- Steps 1+2 continuously under test along with the ongoing express stream processing
  - ➔ smooth operation
  - ➔ constants payloads with multiple intervals of validity are available typically within 1-2 hours after end of data-taking for a run
- Once prompt beam spot calibration becomes part of standard operation, plan to deploy further prompt calibration workflows
  - channel status of various sub-detectors

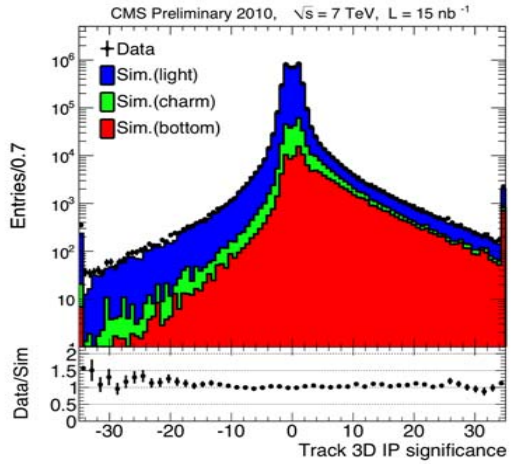


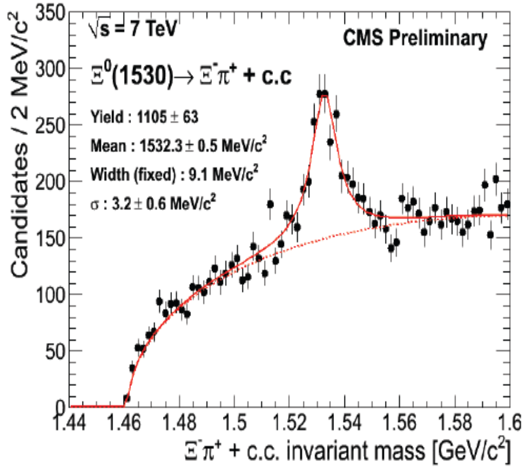
Alignment/Calibration Success: Judge by Physics Performance











Summary

- CMS alignment & calibration have mastered turn-on in the first LHC high energy data-taking period
  - multitude of workflows operated on dedicated alignment & calibration skims
  - constants in preparation of major conferences have been delivered in time
  - high quality of physics results
  - overall concept proven to be sound and efficient
- Outlook
  - complete commissioning of prompt calibration
  - add additional workflows becoming feasible with mounting luminosity → improved statistical & systematic accuracy

Related CMS Presentations

- Oral presentations:
  - Antonio Pierro: Fast access to the CMS detector condition data employing HTML5 technologies
  - Stefano Argiro': Triggers and streams for calibration in CMS
  - Hassen Riahi: Large scale and low latency Analysis Facilities for the CMS experiment: development and operational aspects
  - Dirk Hufnagel: The architecture and operation of the CMS Tier-0
  - Salvatore di Guida: Time-critical database condition data handling in the CMS experiment during the first data taking period
- Poster presentations
  - Tapio Lampen: The alignment of the CMS Silicon Tracker
  - Tapio Lampen: CMS Silicon Strip Tracker calibration work-flow and tools

Backup

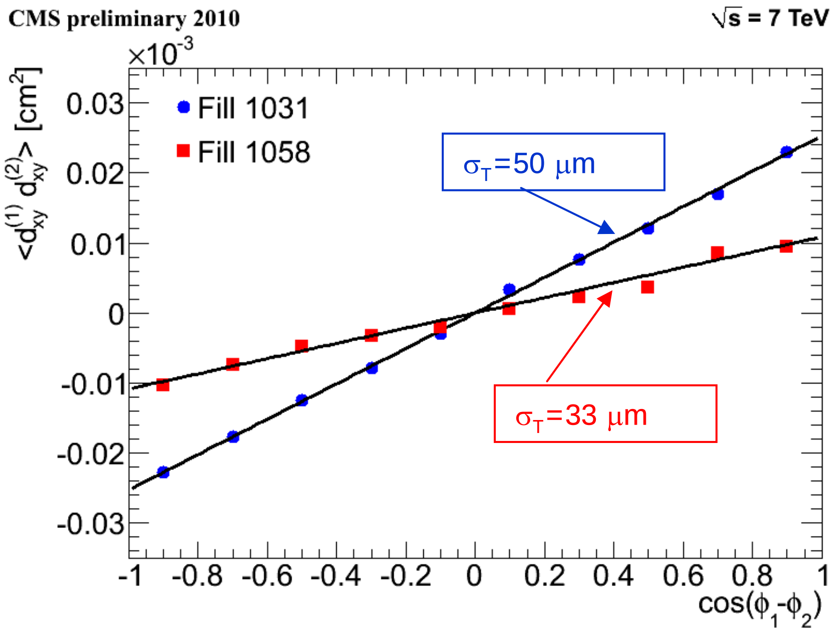
Measuring Beam Line Width with Impact Parameter Correlations

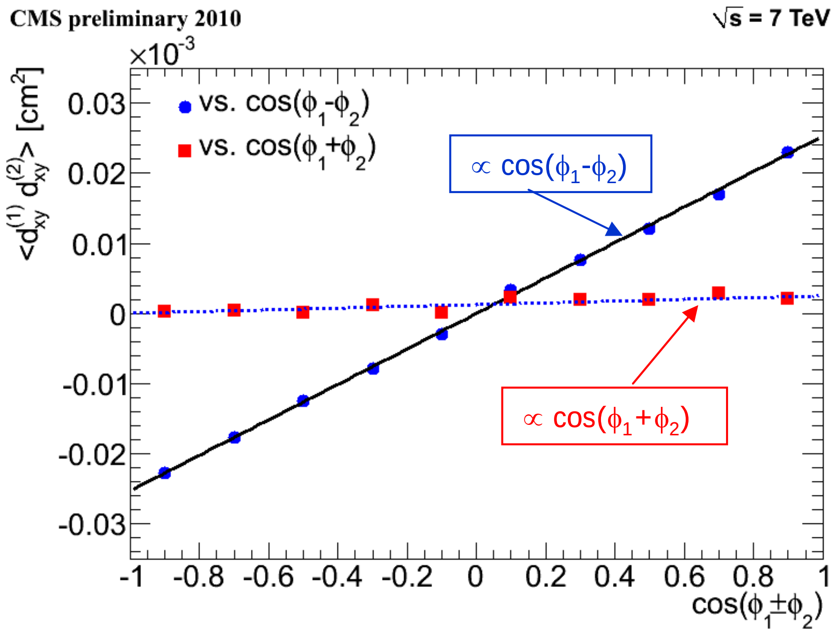
- Traditional methods probe beam line width using primary vertices or impact parameters as probes
  - must correct for probe resolution → systematics
- Impact parameter correlations allow measuring the beam spot width without unfolding any resolutions
  - ➔ select pairs of tracks from the same interaction
  - ➔ by measuring the correlation, we can deduce the beam spot size
    - ➔ reflected in slopes of impact parameter covariance vs $\cos(\phi_1 \pm \phi_2)$

$$\left\langle d_{xy}^{(1)} d_{xy}^{(2)} \right\rangle = \frac{\sigma_x^2 + \sigma_y^2}{2} \cos(\phi_1 - \phi_2) + \frac{\sigma_y^2 - \sigma_x^2}{2} \cos(\phi_1 + \phi_2)$$

7 TeV Real Data

- Slope vs $\cos(\phi_1 - \phi_2)$ shows different beam line widths for different fills
- Positive slope vs $\cos(\phi_1 + \phi_2)$ indicates $\sigma_y > \sigma_x$





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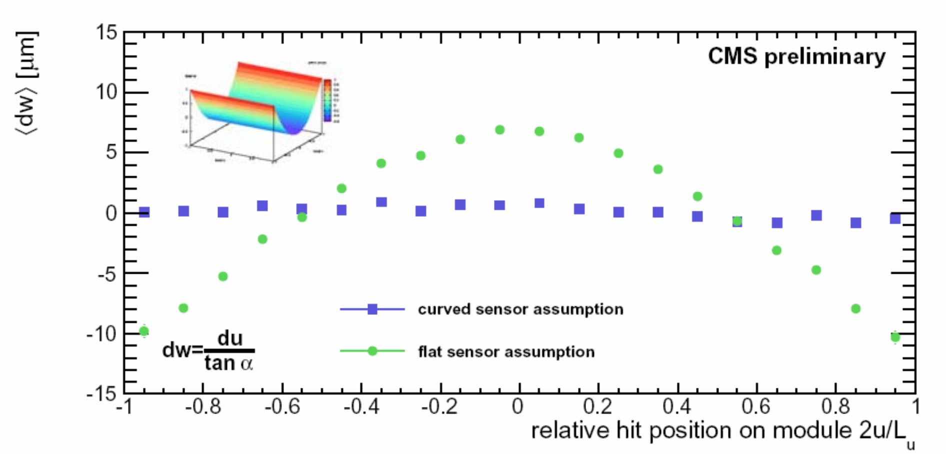
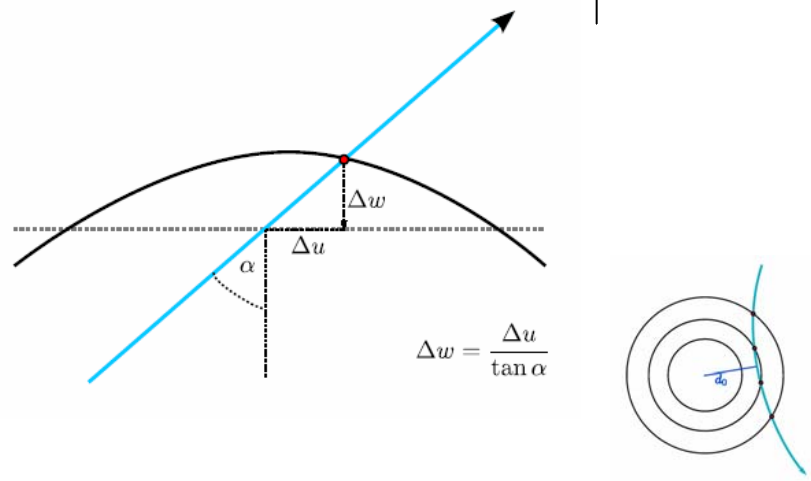
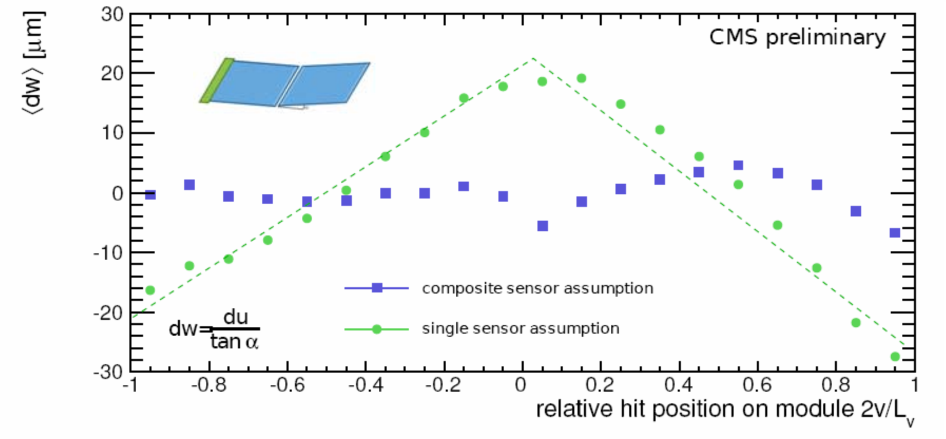
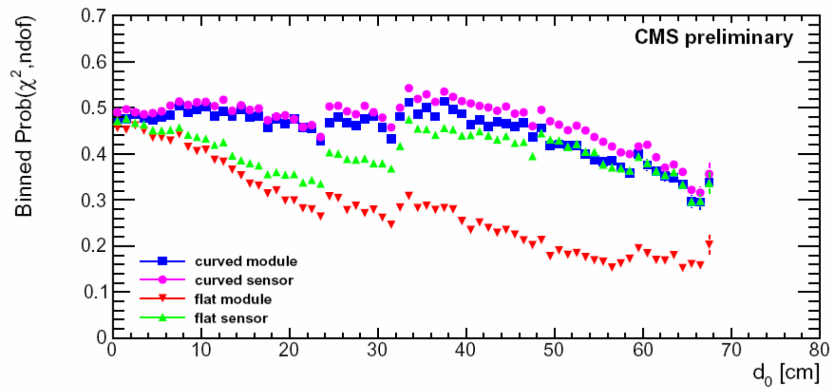




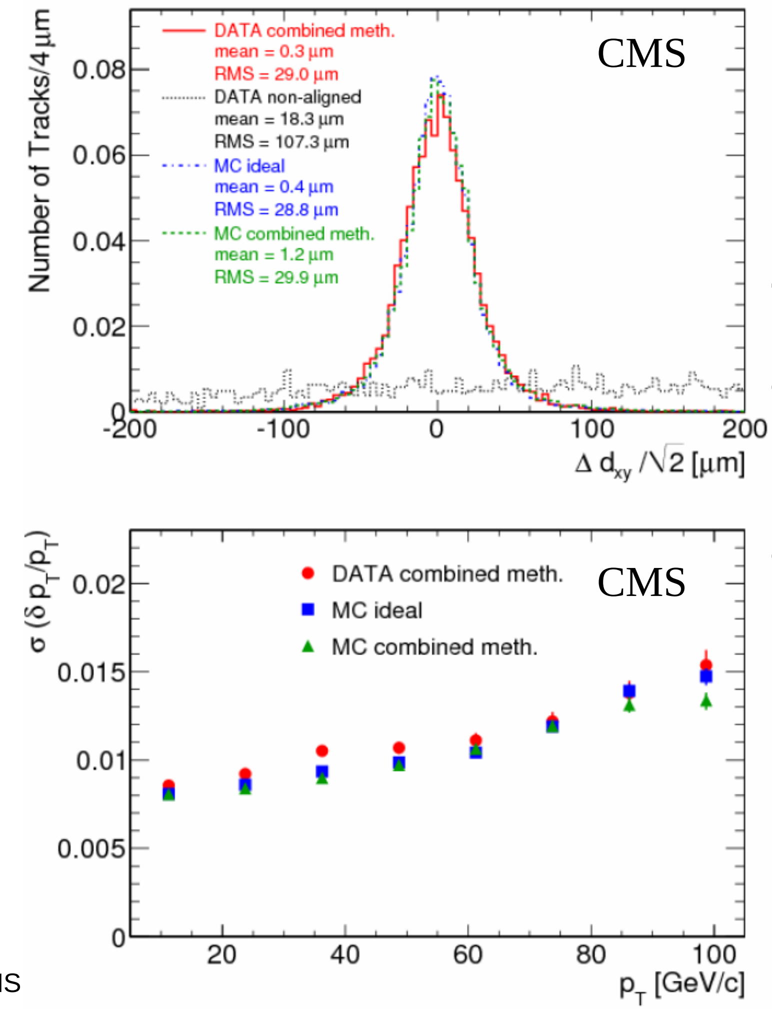




Alignment with Cosmics

- Initial alignment was determined with cosmic rays taken in early 2010 before startup of LHC collisions
  - ➔ combination of local and global algorithms gives best result
- Validation by "splitting" the trajectory into two parts, independently reconstructing the two tracks and comparing the parameters

➔ Already very good accuracy demonstrated in most of the detector
  - ➔ especially in pixel detector, accuracy still limited by statistics



comparing two "legs" of cosmics