CMS Alignment

"Detector alignment with a strong focus on tracker alignment"

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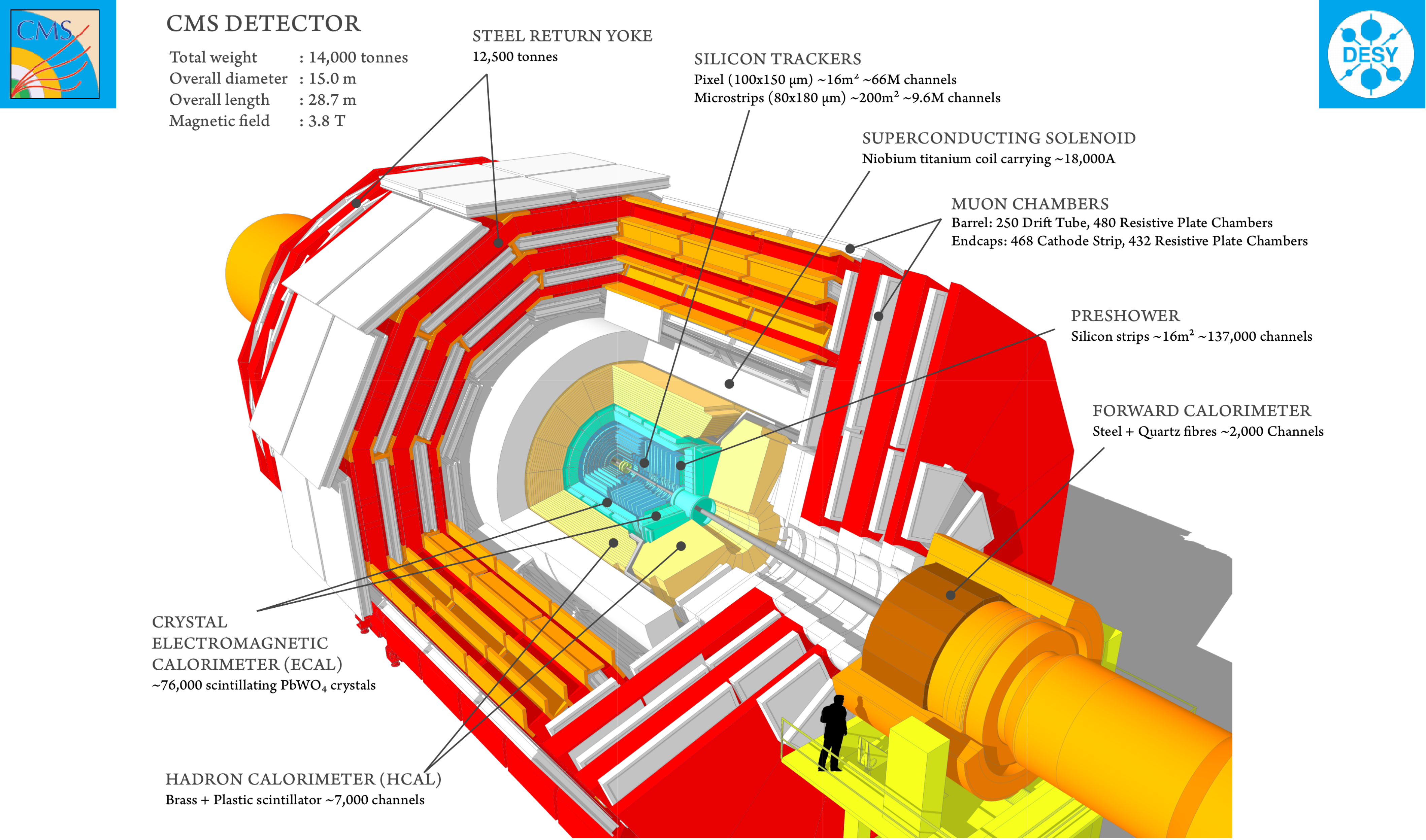
on behalf of the CMS Collaboration

Deutsches Elektronen-Synchrotron (DESY)

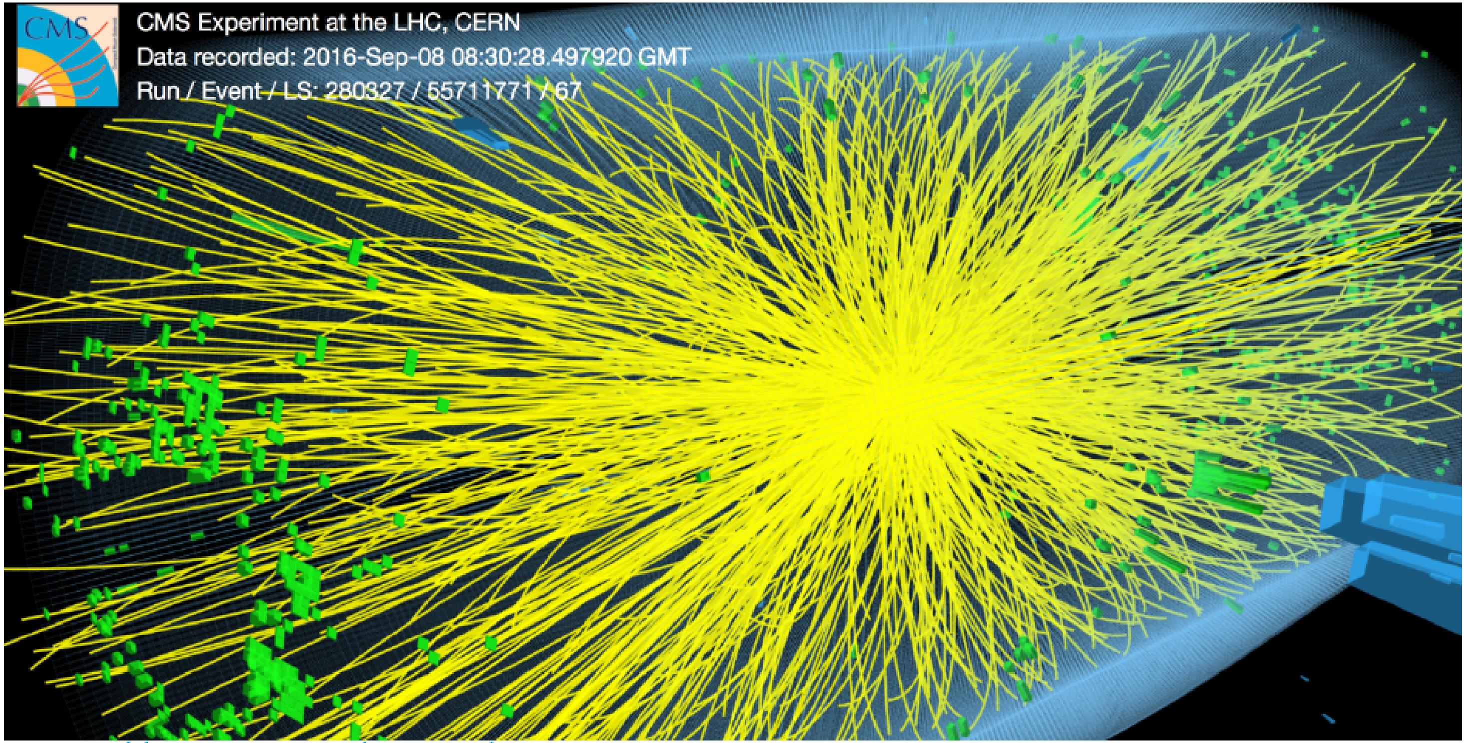
CLIC Workshop

9th March 2017


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Why is track infomation important?

- Central to event reconstruction
- Gives very precise measurements of charged-particle properties, e.g. p_T , η, φ – Charge
- Challenges: High occupancy of the tracking device due to multiple interactions (pile-up), multiple scattering



https://cds.cern.ch/record/2241144

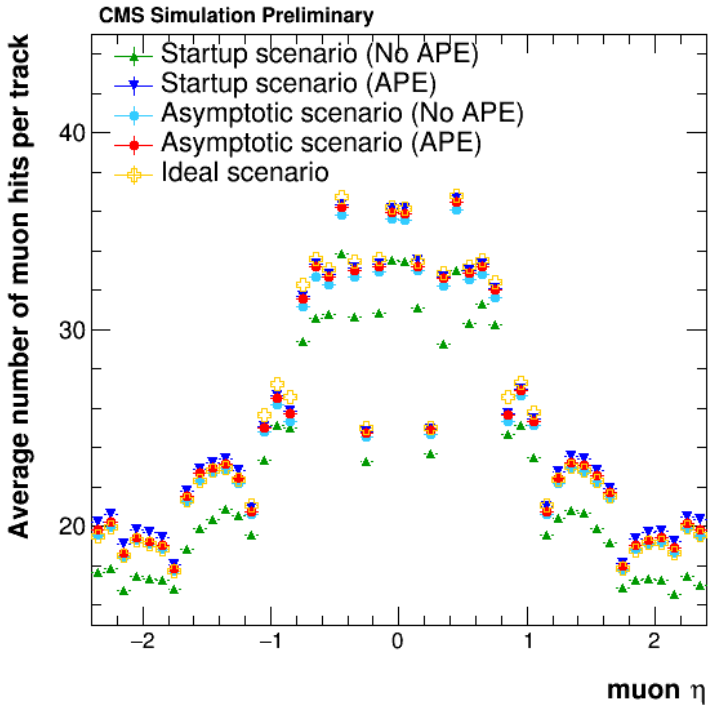
Why do we need alignment?

- Module mounting precision is >100 μm
  - Worse than intrinsic resolution of the sensors → O(10 μm)
  - Positions, orientations & curvatures of the sensors must be corrected to push the alignment precision well below the intrinsic resolution

    ⇒ This is the task of tracker alignment
- Alignment can be done using track survey information or laser systems
  - Ultimate performance needs the information from many tracks

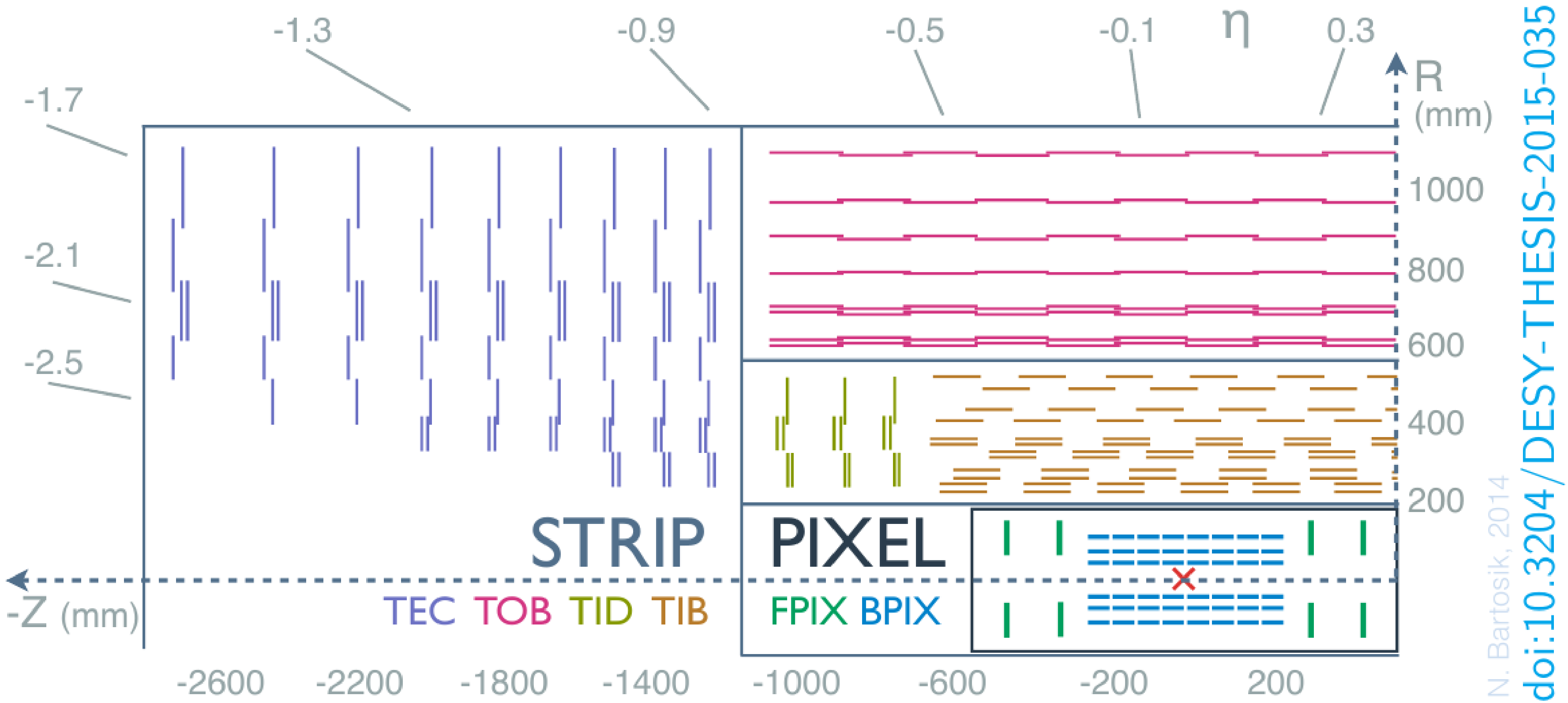
Muon System Alignment

- Muon Alignment Position Errors (APE) describe uncertainties on the position of muon chambers after alignment
- Hardware uncertainties dominate startup alignment then track-based uncertainties give final alignment
  - e.g. Muon system alignment uncertainty ~2mm after 2015 end-of-year shutdown. After the full track-based alignment (asymptotic alignment) uncertainties were reduced by ~order of magnitude.



- Startup scenario without APE: fewer muon hits are reconstructed on average per track.
- Using APE brings this into agreement with the ideal scenario.
- In the asymptotic scenario the effect of APE is less, but a small improvement is seen, towards the ideal case.

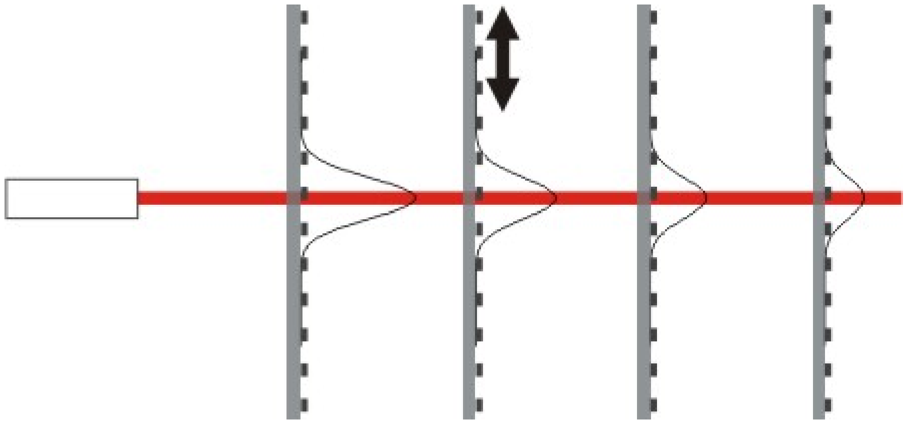
https://cds.cern.ch/record/2229697

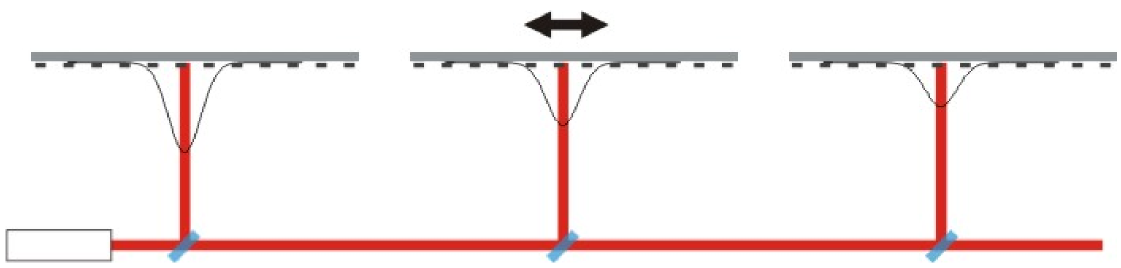


- The CMS tracker has a hierarchical structure
  - e.g. Barrels > half-barrels > layers > modules

Laser Alignment System (LAS)

- Detects and monitors movements and deformations of the tracker support structure at < 100 micron. IR laser beams.
  - Method 1.Infrared light passes through several layers of silicon sensors. Some of the light is absorbed in each layer, generating a signal in the strips.





https://arxiv.org/pdf/1701.02022.pdf

  - Method 2.One laser beam is split into several sub-beams each of which hits one module.
- Ultimately the LAS is not relied on since track-based alignment gives superior results

Track-based alignment

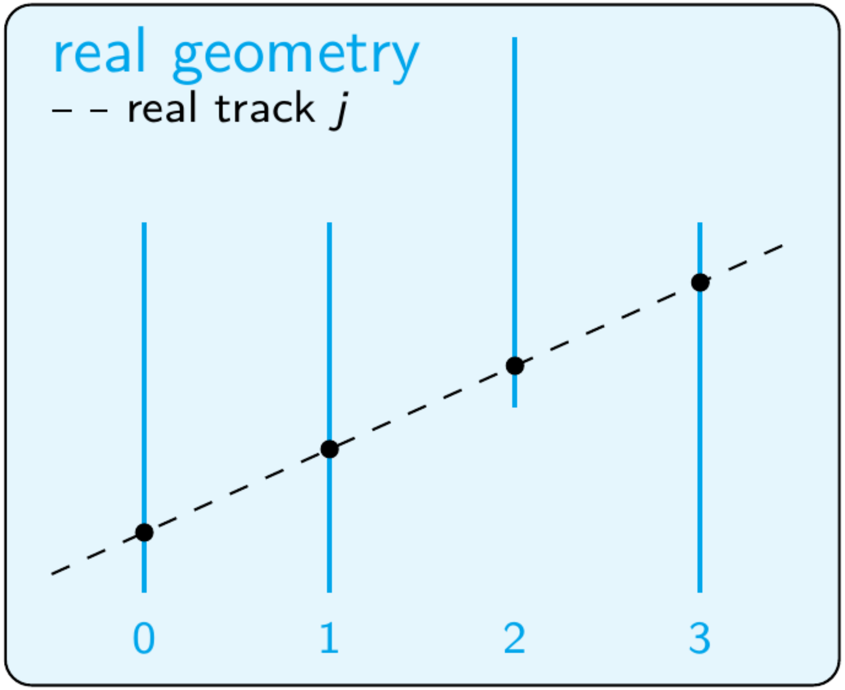
- Global alignment corrects shifts, rotations and sensor surface deformations
- Time dependence taken into account as movements of the high-level structures. Assume that module positions are constant wrt. their high-level structure
- CMS tracking uses a Combinatorial Track Finder (CTF), Modification of Combinatorial Kálmán Filter
- Alignment constants have been derived for each data-taking period using the data collected during that period.
- Alignments studied using a global (Millepede-II) [1], [2] and local (HipPy) fit approach [2]

[1] CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data " 2014 JINST 9 P06009 doi:10.1088/1748-0221/9/06/P06009

[2] CMS Collaboration "Alignment of the CMS silicon tracker during commissioning with cosmic rays" 2010 JINST 5 T03009 doi:10.1088/1748-0221/5/03/T03009

Track-based alignment

- Real detector geometry is not precisely known



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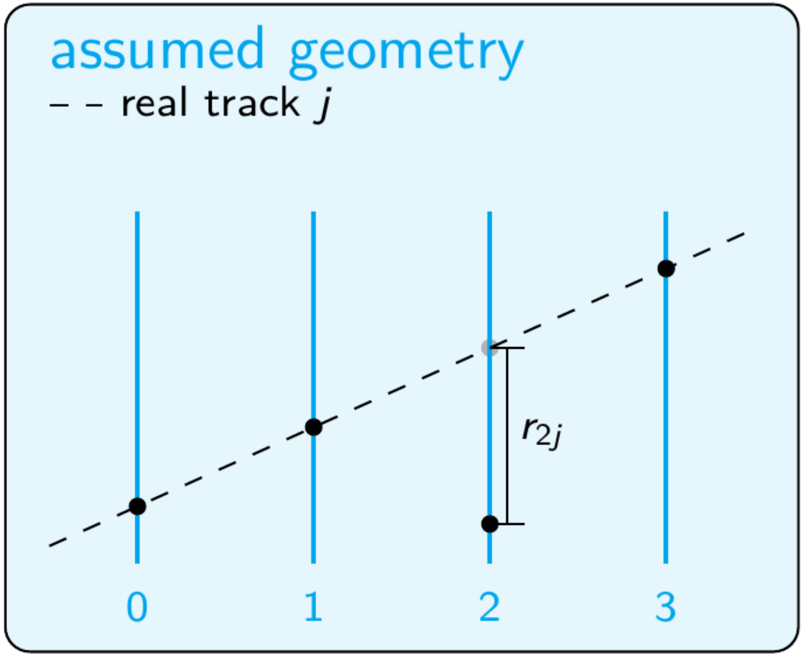
Track-based alignment

- Real detector geometry is not precisely known
  - ⇒ Assume geometry based on independent measurements
  - Difference between real and assumed geometry affects track measurement
- Idea: track-hit residuals r_{ij} between predicted and measured hit positions as a measure of misalignment



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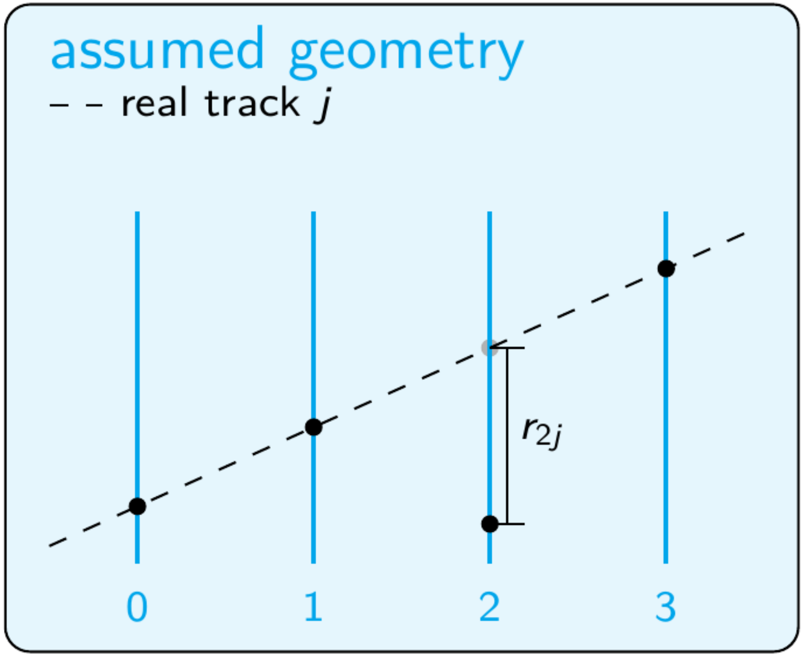
  → Change of alignment parameters $\boldsymbol{p}$



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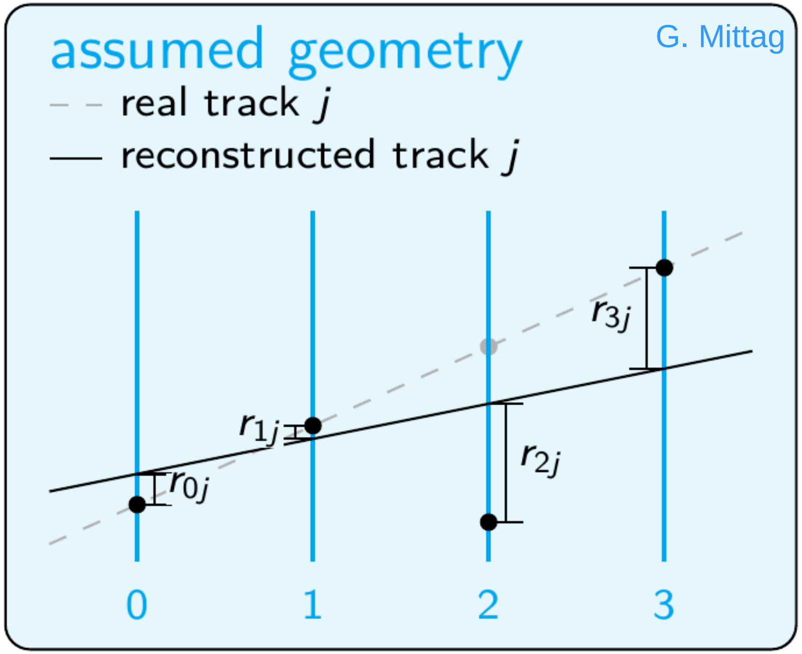

- Tracks correlate alignment and track parameters, i.e. moving one alignment parameter results in:
  - Change of track parameters $\boldsymbol{q}_j$
  - Change of other residuals $\boldsymbol{r}_{ij}$
  - ⇒ $\boldsymbol{r}_{ij} = \boldsymbol{r}_{ij}(\boldsymbol{p}, \boldsymbol{q}_j)$ for a given track j

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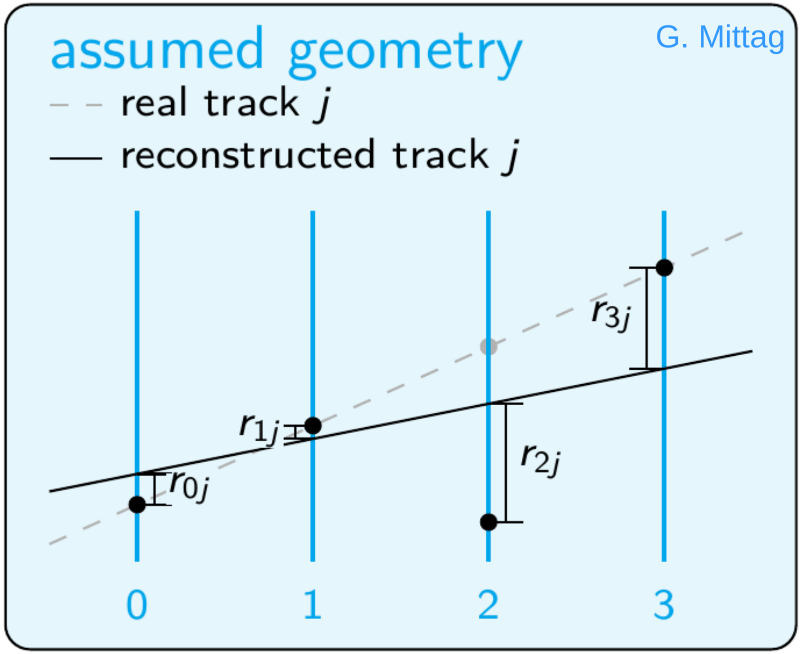

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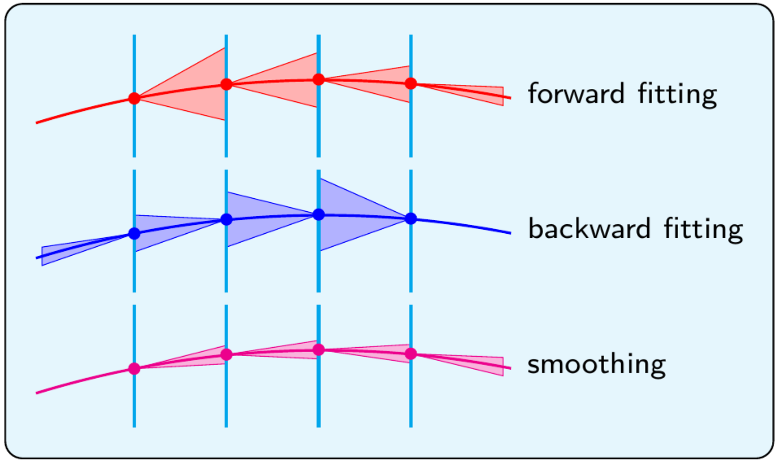
- **Approach**: Minimize $\chi^2 = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \frac{r_{ij}^2}{\sigma_{ij}^2}$ (here: uncorrelated uncertainties σ_{ij}) for many tracks to determine all alignment parameters

Kálmán filter

- Step through the measurements with alternating updates and predictions
  - Material effects are treated locally
  - Requires only inversion of small matrices
  - Full precision is reached at the end of the track fit
    - Smoother provides full precision at all points
    - Can be realized as combination of forward and backward fit
  - No correlations between track parameters at different layers



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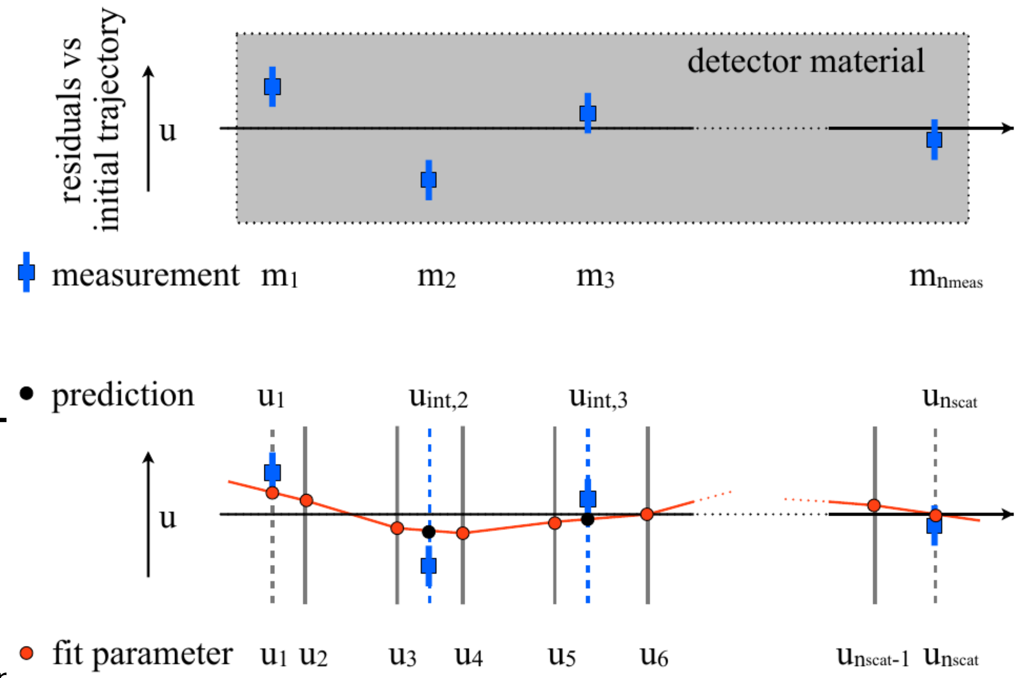
- Requires a first guess for the first iteration
- Can provide intermediate results
- Several Kálmán filters run in parallel and the best candidate is chosen

General Broken Lines (GBL)

- General Broken Lines (GBL)[1] trajectory is a global track refit to add the description of multiple scattering to an initial trajectory
  - Based on propagation in magnetic field & average energy loss
  - Constructed from a sequence of thin scatterers
  - Describes multiple scattering in material between adjacent measurement layers
- Initial trajectory should be in linear regime – already a reasonable estimate of the track
- Can provide correlations between track parameters at different locations
  - ⇒ Well suited as track model for calibration and global alignmer e.g. Millepede II
  - It is also possible to obtain these correlation for Kálmán filter tracks[2]
- For full track fit GBL results are equivalent to Kálmán results



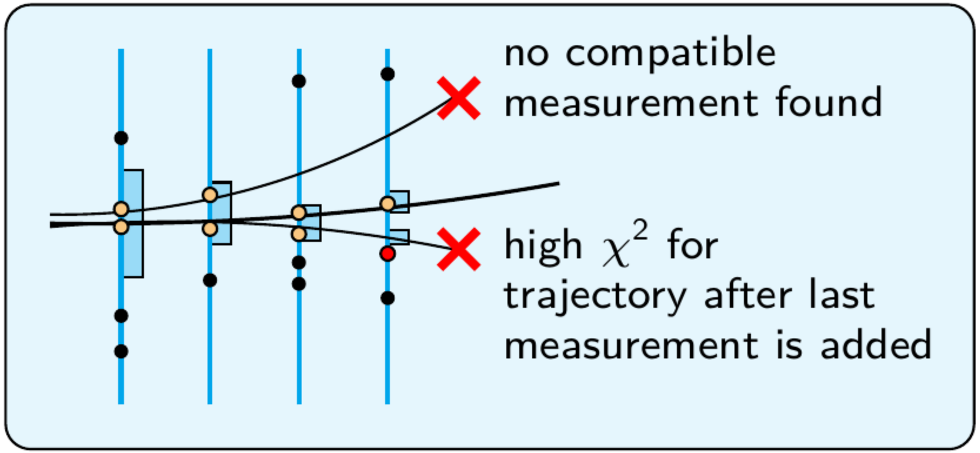
doi:10.1016/j.cpc.2011.03.017

[1] V. Blobel, C. Kleinwort, F. Meier, *Comput.Phys.Commun.* **182**, 1760 (2010)
C. Kleinwort, *Nucl.Instrum.Meth.* **A673**, 107 (2012)

[2] W.D. Hulsbergen, *Nucl.Instrum.Meth.* **A600**, 471 (2009)

Local Methods

- Starting point of local track finding is a seed, i.e. a short track segment
  - Need method to generate seeds
  - Need track model to interpolate between measurements
  - Need criterion to separate good from bad track candidates



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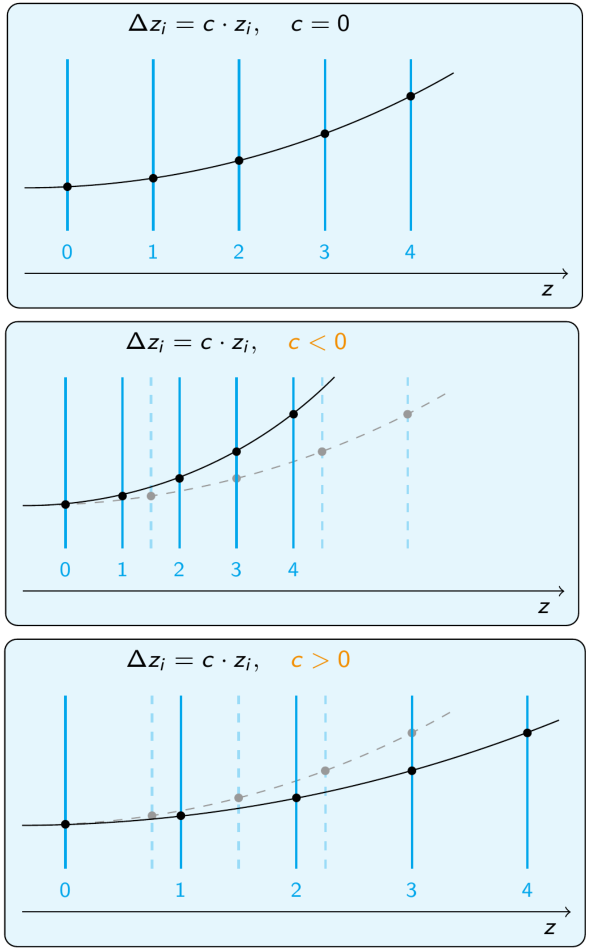
- Local approaches are typically some kind of track following
  - Starts from seed, possibly including constraint to point to interaction region
  - Track is extrapolated to next detector layer
    - Measurement closest to the extrapolated track is included
    - Iterate this procedure to the last layer or until too many layers without measurements are found

Weak modes

- Alignment procedures use track-hit residuals to estimate alignment parameters
  - Systematic global distortions can transform one set of valid tracks into another set of valid tracks
  - ⇒ Leave the overall χ^2 invariant
  - ⇒ Undefined or weakly defined global degrees of freedom → weak modes
- Weak modes depends on track model and symmetries of the track topology
- Weak modes can be compensated by the track parameters
- Example: Rescaling of the z coordinate axis can be compensated by track curvature
  - Shrinkage → lower p_T
  - Expansion → higher p_T
- Happens typically in forward part of detector
  - Use cosmic muons to break cylindrical symmetry of collision/test-beam tracks



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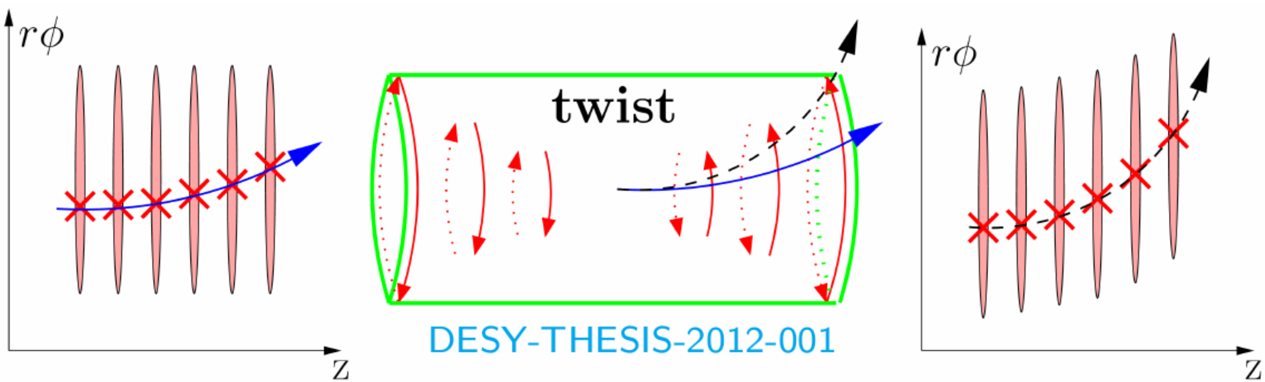
Weak Mode: Twist

- Reconstructed Z-boson mass studied wrt. muon kinematics
  - Certain systematic long-range distortions are visible here
- Effect of Z → μμ mass and vertex constraint is clearly visible
  - See black vs. green curve



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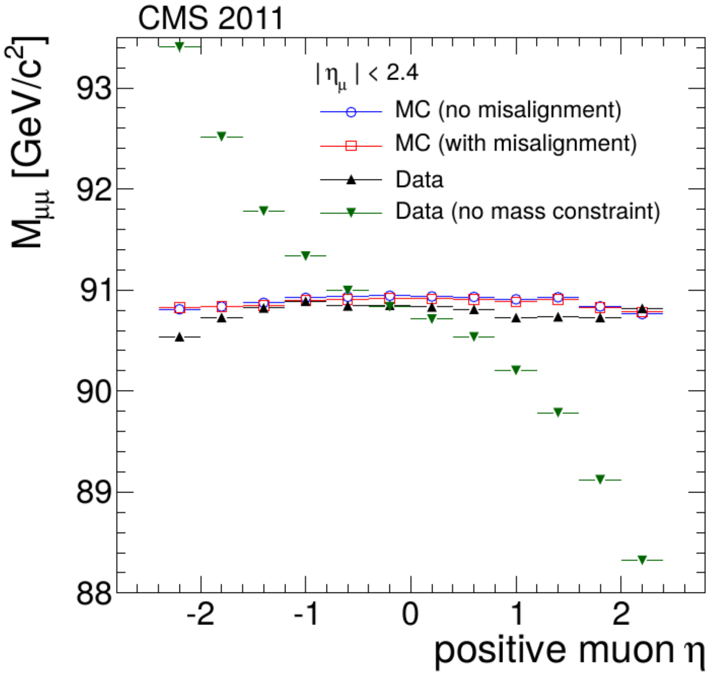
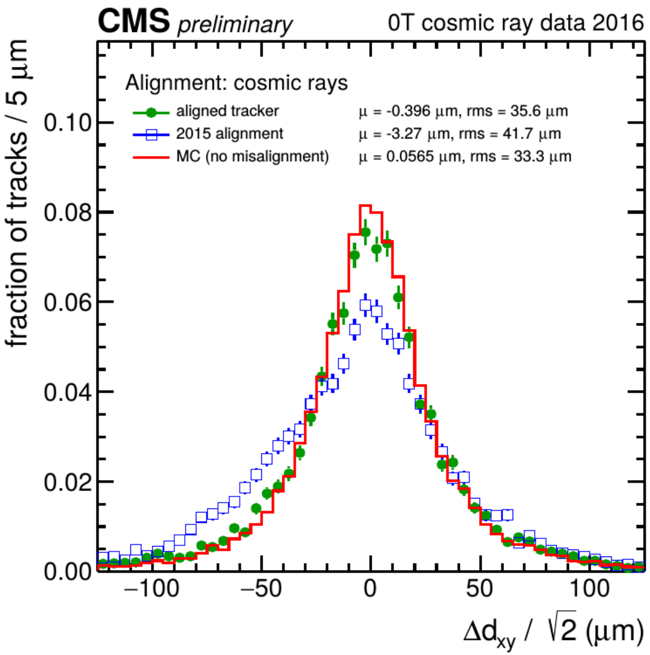
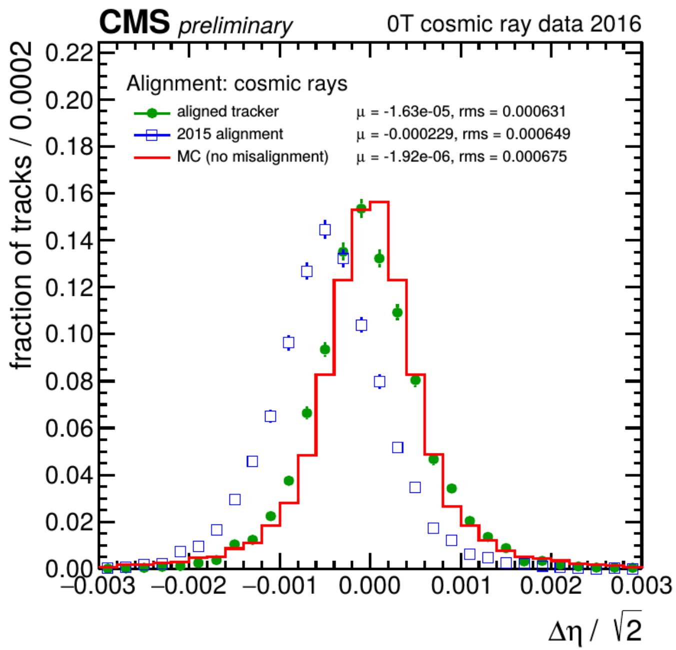


doi:10.1088/1748-0221/9/06/P06009

Cosmic track split validation



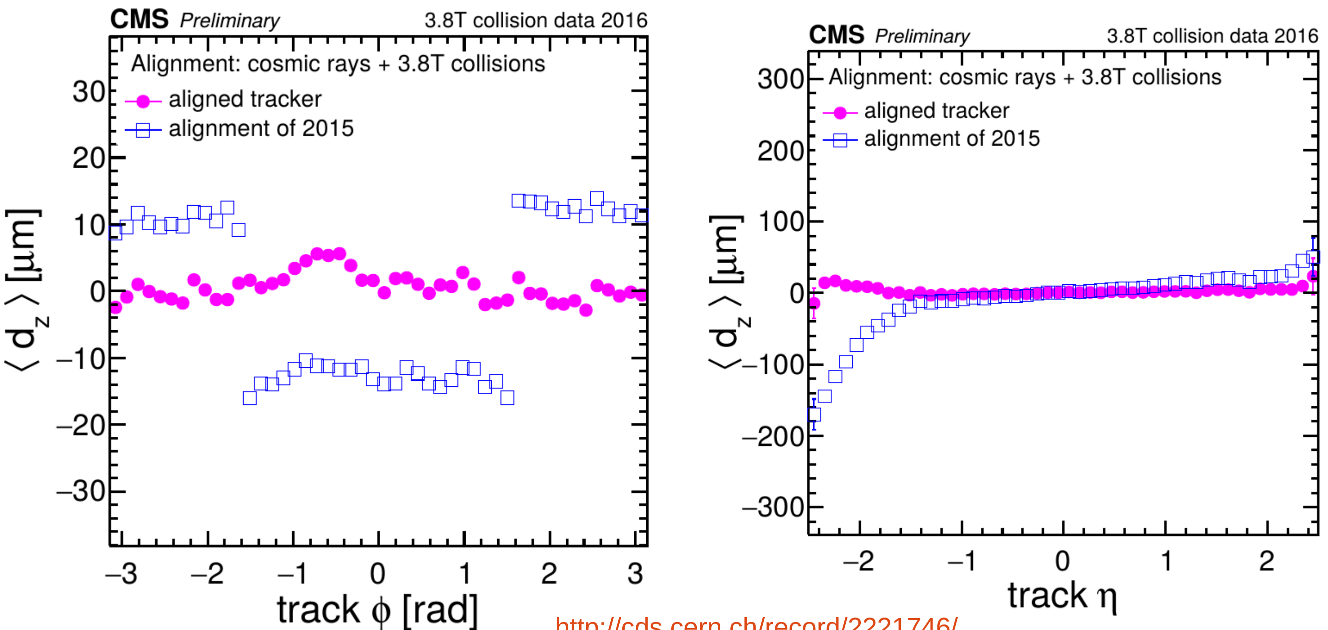


http://cds.cern.ch/record/2221746/

- Split cosmic tracks in horizontal plane at point of closest approach to interaction region
- Differences in track quantities between the two parts indicate misalignment

- Updated alignment with 0 T cosmic data prior to 2016 data-taking start-up
- Results show reduced bias of updated alignment wrt. 2015 geometry
- Performance of updated geometry very close to ideal Monte Carlo

Primary vertex validation



http://cds.cern.ch/record/2221746/

- Study unbiased residuals between tracks and primary vertices
  - In longitudinal andtransverse plane
  - In bins of η and φ

- Cosmic-ray and collision data @ 3.8 T are used for alignment
- Sample of 1 M events collected through minimum bias triggers @ 3.8 T used for validation
- Systematic z-offset of the pixel half-shells is corrected by the updated alignment

Prompt calibration loop (PCL)

- CMS now continuously monitors high-level-structure movements in the pixel tracker, e.g. due to magnetic field changes
- Geometry is automatically updated, if alignment corrections exceed certain thresholds

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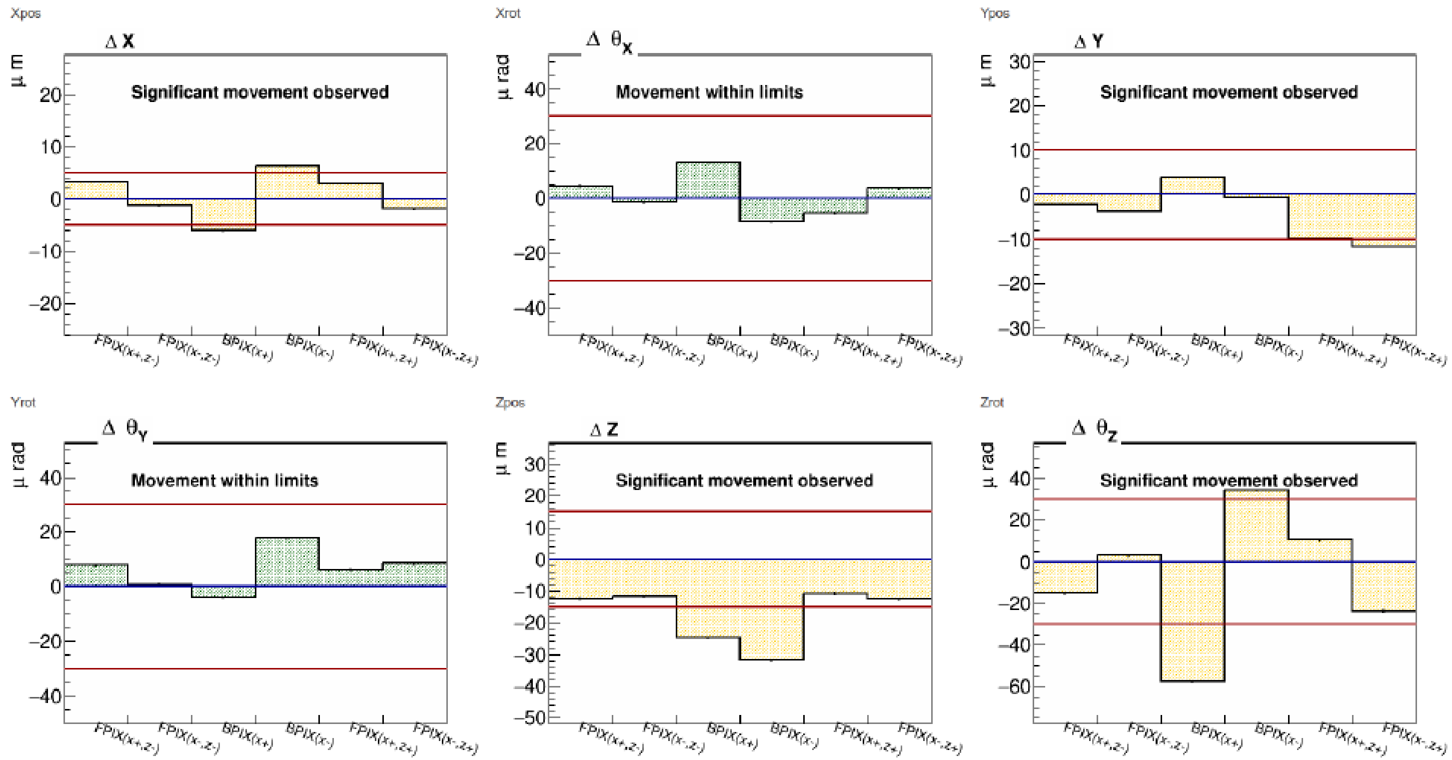
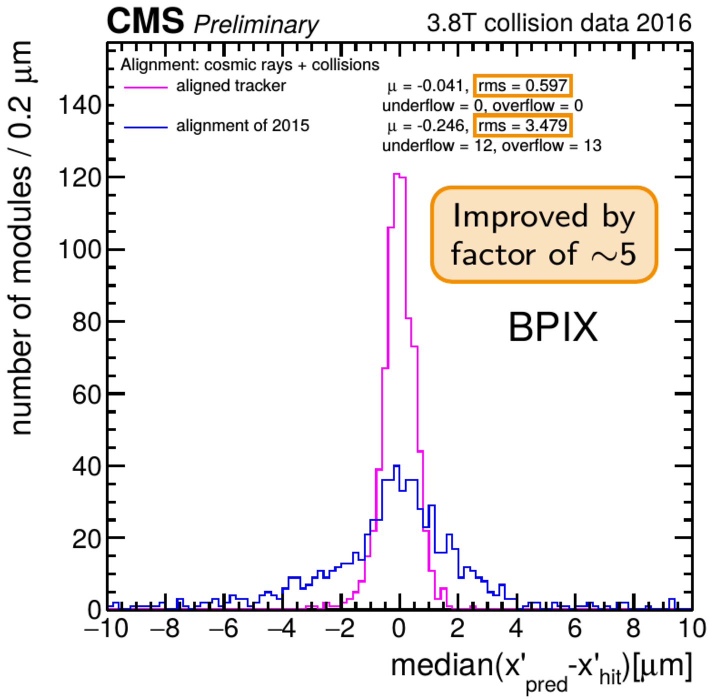
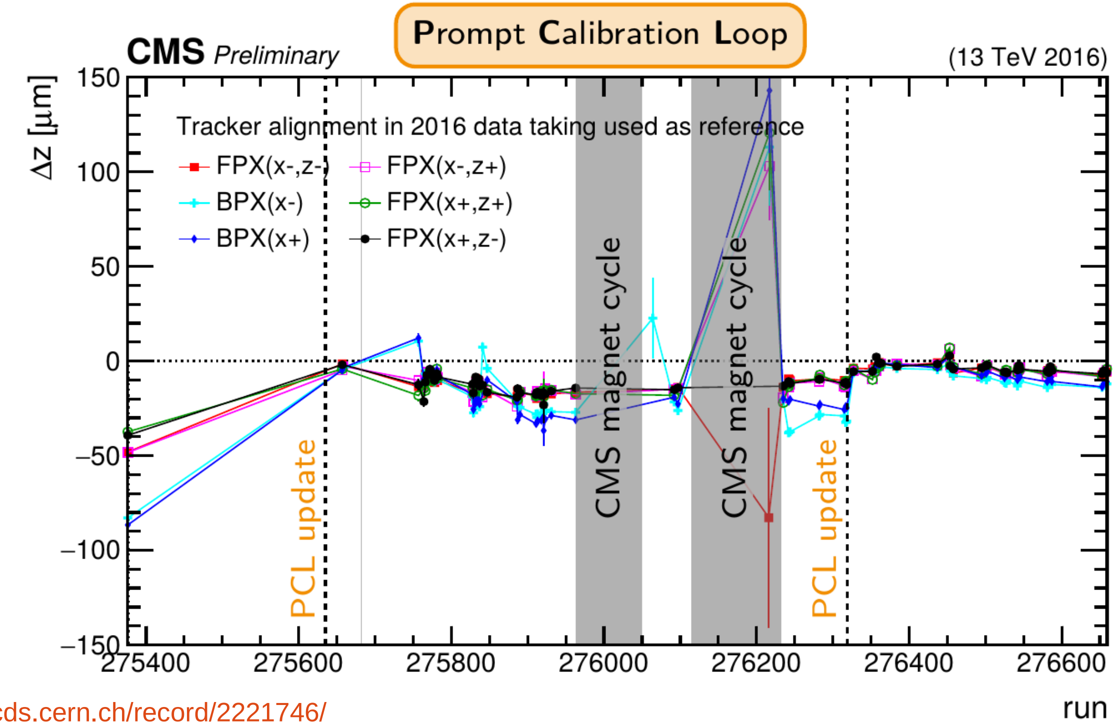


Highlights: CMS Tracker Alignment 2016





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- Tracker-alignment updates in 2016 significantly improved the performance at start-up and during data taking
- Geometry changes due to temperature and magnetic-field changes are nicely compensated
- An automatic online calibration workflow (PCL) successfully put in place, improves prompt reconstruction

Resources

- Millepede II, global alignment software – experiment independent
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideMillepedeIIAlgorithm
- HipPy, local alignment software
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideHIPAlgorithm
- General Broken Lines (GBL), software – models multiple scattering effect
  - http://www.desy.de/~kleinwrt/GBL/doc/cpp/html/
- CMS Tracker alignment contacts:
  - Conveners: Matthias Schröder, Meng Xiao -- cms-tracker-alignment-conveners@cern.ch
  - Gregor Mittag, Claus Kleinwort, Tapio Lampen
- CMS Muon alignment contacts:
  - cms-pog-conveners-MUO@cern.ch
- References

  - Performance of muon reconstruction including Alignment Position Errors for 2016 Collision Data, https://cds.cern.ch/record/2229697
  - CMS Tracker Alignment Performance Results Summer 2016, CMS-DP-2016-063, http://cds.cern.ch/record/2221746/
  - Alignment of the CMS tracker with LHC and cosmic ray data, 2014 JINST 9 P06009, doi:10.1088/1748-0221/9/06/P06009
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