Alignment of the CMS Silicon Tracker

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on behalf of the CMS collaboration

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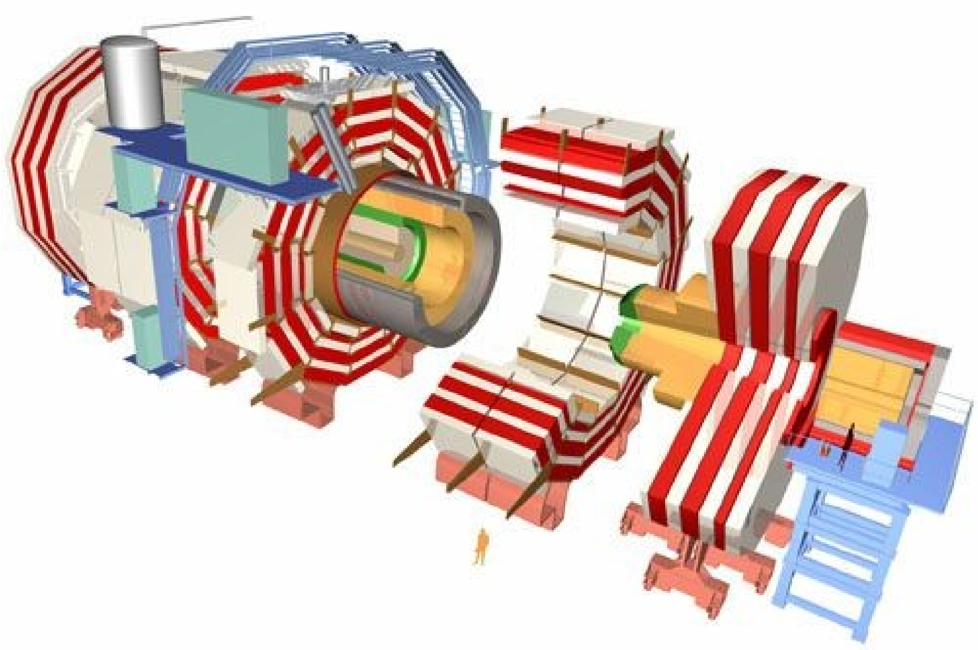
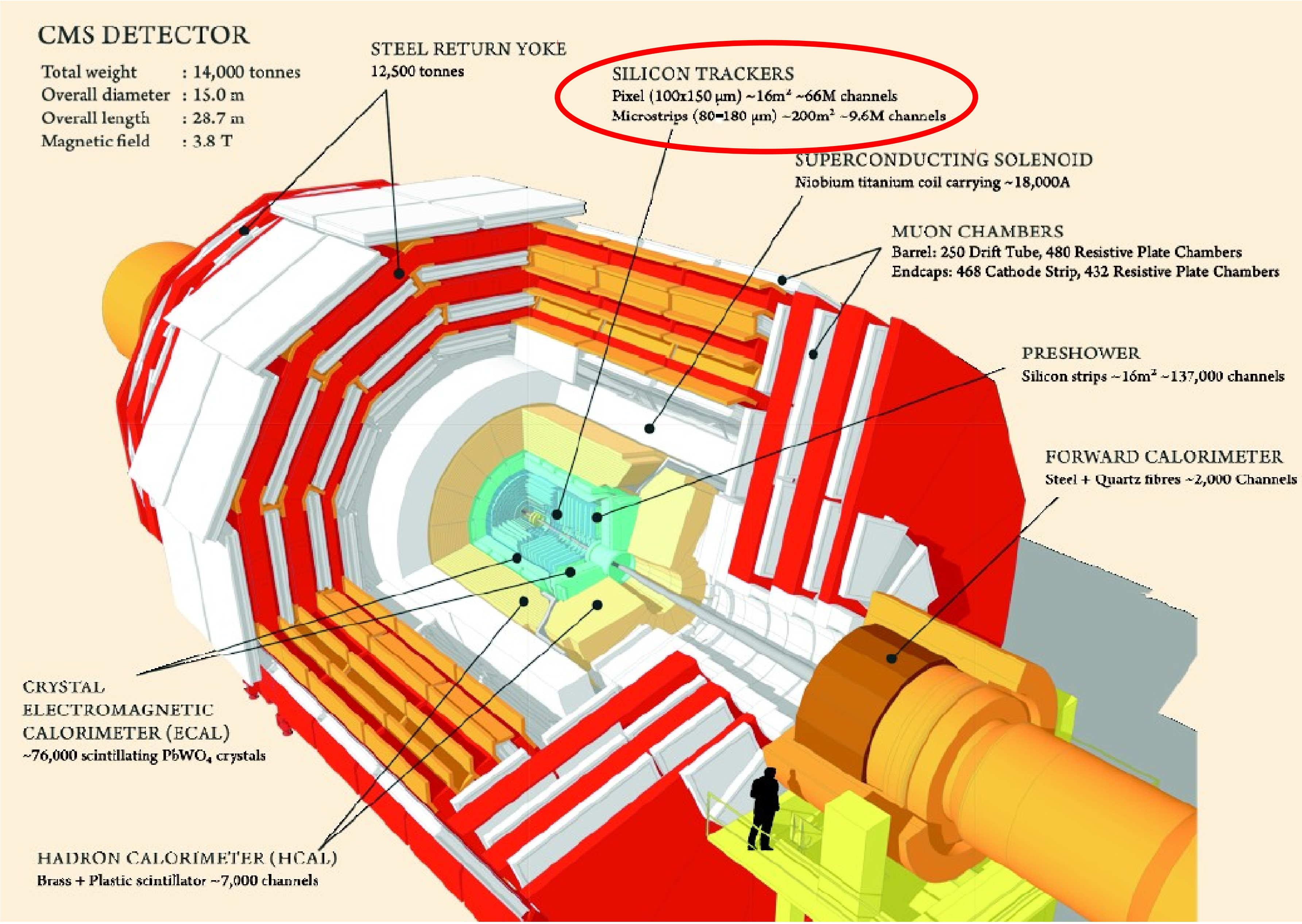
Outline

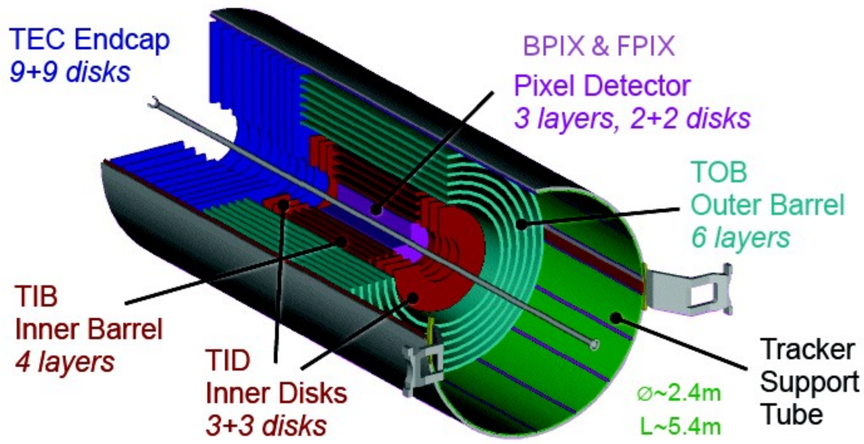
- Overview of CMS Tracker
- Track-based alignment
- Improvements in CMS Tracker alignment in 2012
- Summary

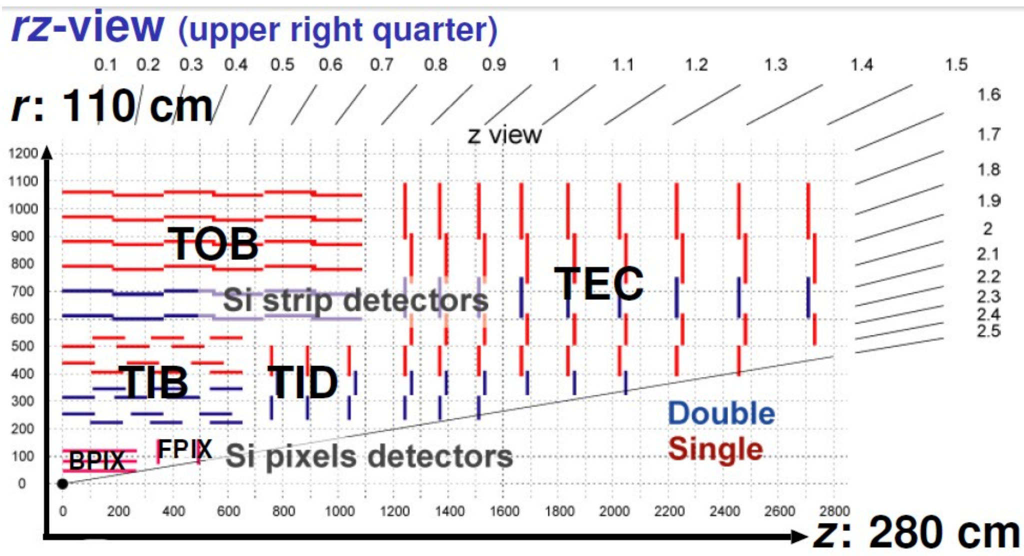


CMS Detector



CMS Tracker



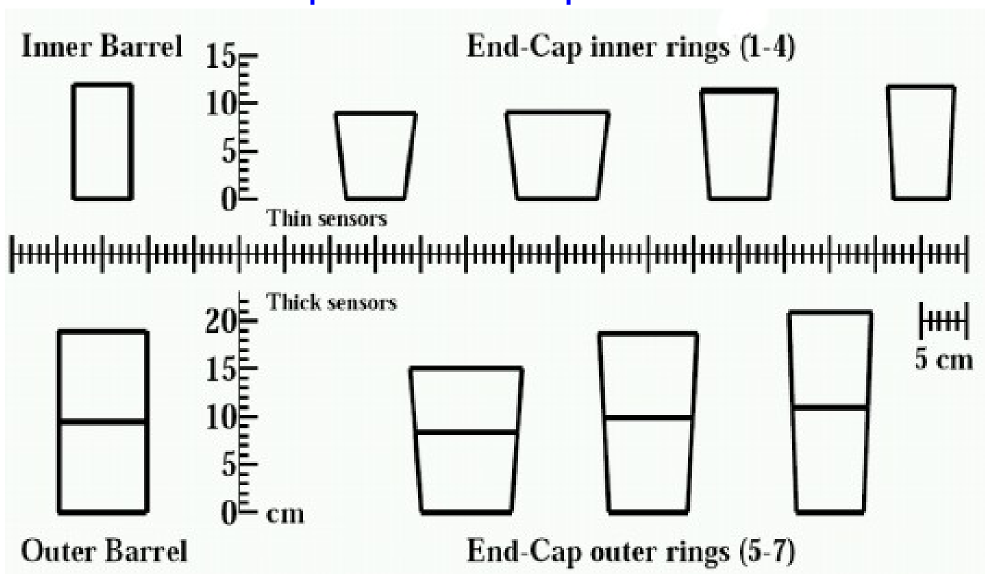


1440 pixel modules
15148 strip modules (24244 sensors)

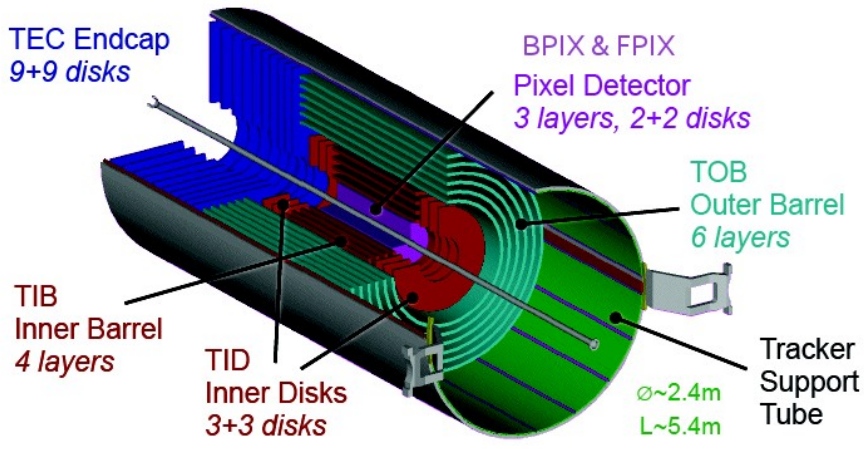
each has 3 translational and 3 rotational degrees of freedom + 3 curvature parameters

→ alignment challenge of 200.000 parameters

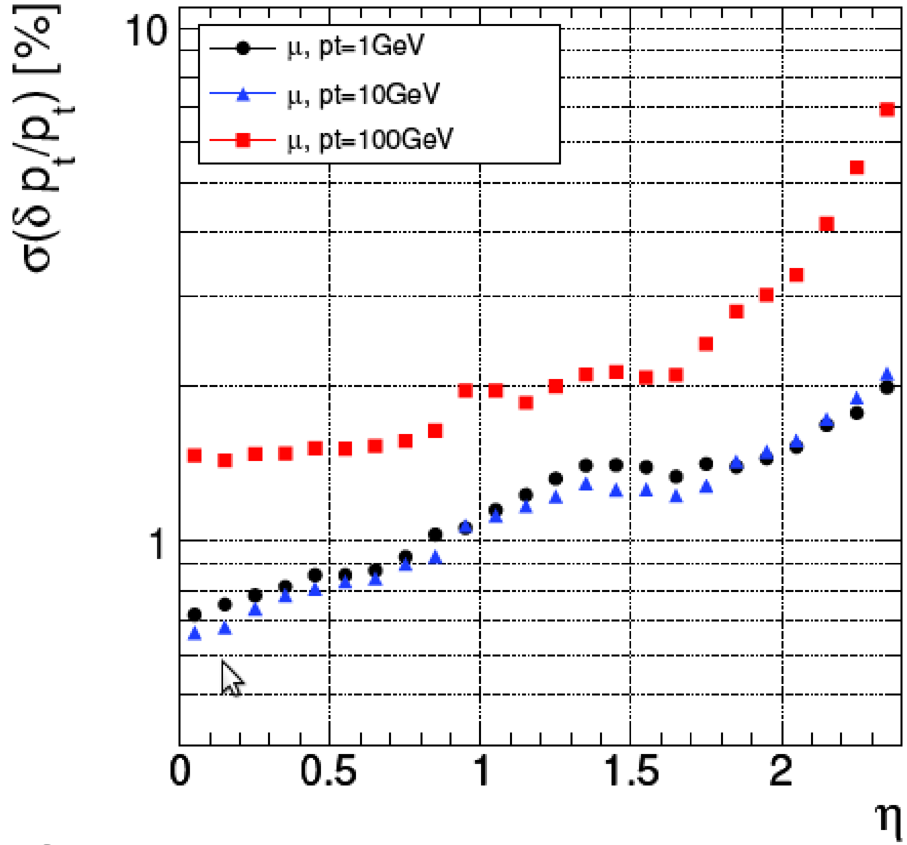
Various strip module shapes



Why alignment?



Tracker momentum resolution for single muons,
Simulation, CMS P-TDR (2006)



- intrinsic resolutions
  - σ_{hit}=9μm for pixel,
  - 20-60μm for strip
- $\sigma_{meas} \sim \mathrm{sqrt}(\sigma^2_{hit} + \sigma^2_{alignment})$
- Momentum resolution is $\delta p_T / p_T = C_1 * p_T \oplus C_2$,
  where C_1 depends on geometry: $C_1 \sim \sigma_{meas} / (B*L^2*\mathrm{sqrt}(n))$
- Need to keep $\sigma_{alignment}$<10μm
  → track-based alignment essential

Track-based alignment

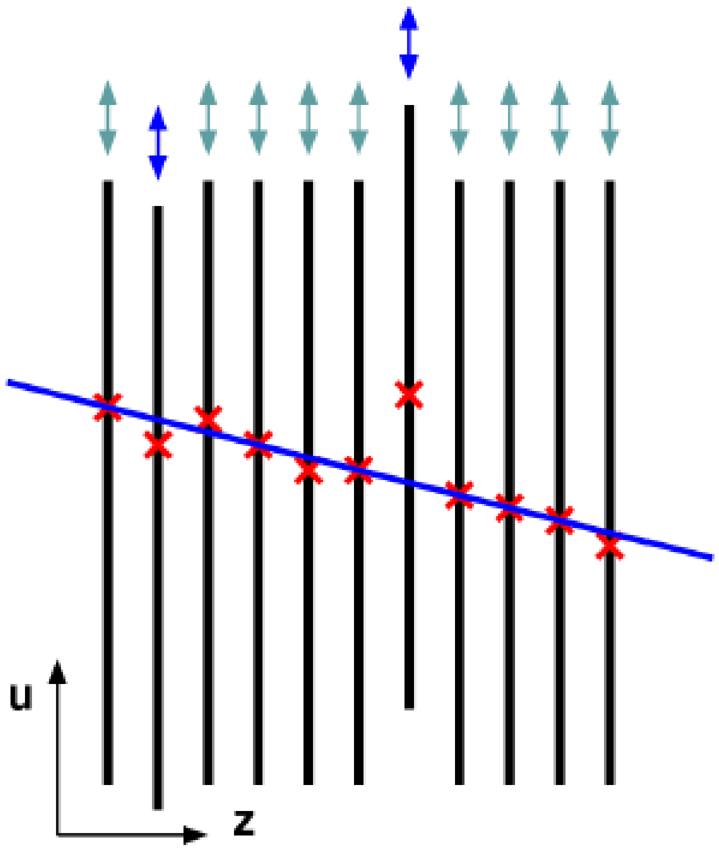
- Basic principle in all track-based alignment methods: minimization of

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{tracks} \sum_i^{measurements} \left(\frac{m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

m_{ij} measurement
f_{ij} track model prediction
p alignment parameters
q track parameters
σ uncertainty

with respect to alignment parameters **p** (together with **q**)

- Modules cannot be treated independently, as alignment parameters correlate via tracks; approach used in CMS in 2012 is the *global fit* approach (Millepede II):
  - f_{ij} linearisation leads to a linear equation **Cp**=**b**,
  - all alignment parameters solved simultaneously
  - method can treat time-dependent effects and is now extended to position sensitive calibration parameters



Alignment in CMS

- **Full-scale alignment**: individual sensors (sensor-level):
  - 9 degrees of freedom (DoF) for pixel modules,
  - 8 DoF's for strip sensors
  - time-dependence of large pixel structures
- **Alignment of larger rigid structures** (frames of modules, layers, subdetectors); faster and less tracks required!
- **Alignments applied in 2012:**
  - Prompt reconstruction: twice
  - Re-reconstruction: three times

<u>Computing aspects in Millepede II (Full-scale alignment 2011):</u>

Matrix equation to solve: **Cp**=**b**
where **C** is n*n matrix, n~200.000 (in practice 30% of elements non-zero, depends on input data)

Using Fortran program optimized for speed and space:
- iterative MINRES method
- OpenMP used for parallelized computing
- sparsity taken into account

CPU use 45h, Wall clock 10h with 8 threads on Intel Xeon L5520, 2.27 GHz,
memory consumption 30 GB

Alignment – sensor deformations

In reality, sensors are not planar
Non-perpendicular tracks are biased, depending on tan Ψ!

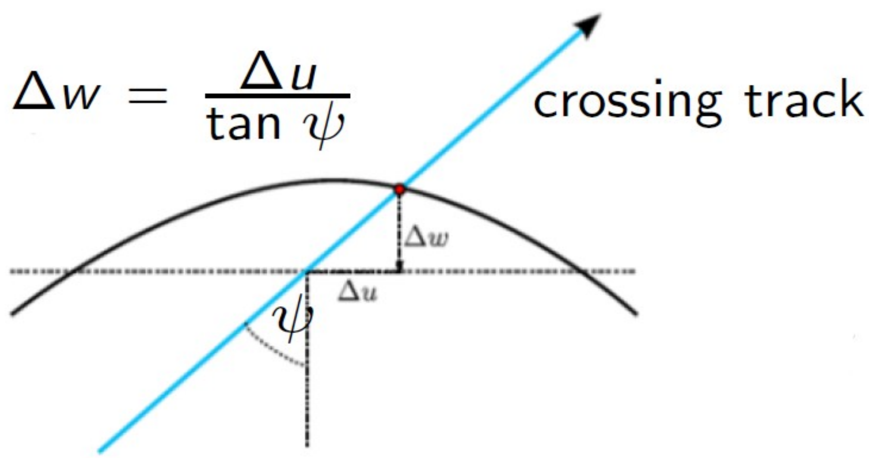
Investigation of surface shape using:

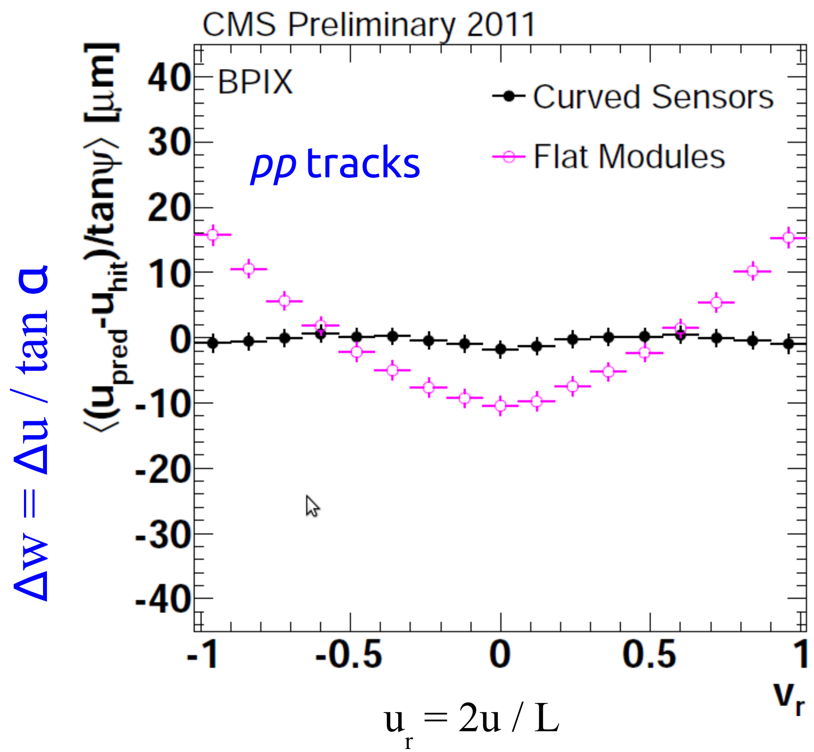
$\Delta u = \Delta w * \tan \Psi$

Important for BPIX layer 1, large track angles, systematic residuals ~100μm at edge of the 66mm wide module

Alignment determines bow parameters, taken into account in hit reconstruction.

Also angles and offsets between two daisy-chained modules in outer Tracker are corrected in alignment

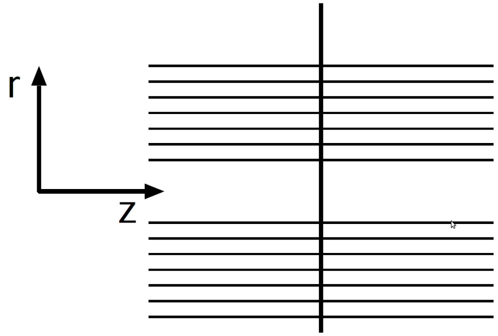


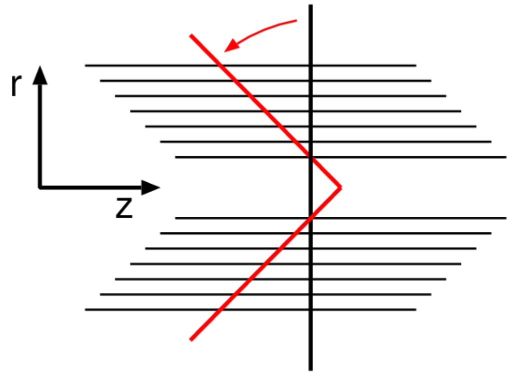


Weak modes and mass constraints

- Minimization of residuals insensitive to some global distortions
- These **weak modes** can however bias track parameters

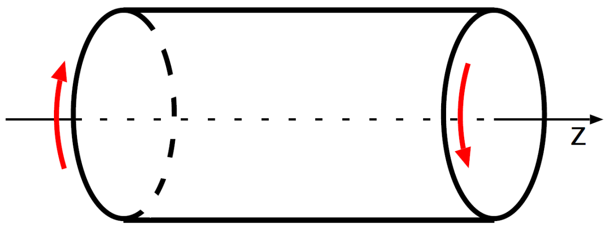
Example 1:
"telescoping": dz ~ r
creates bias in η





Solution: cosmic muon tracks

Example 2:
"twist": dΦ ~ z
curvature bias of charged particles



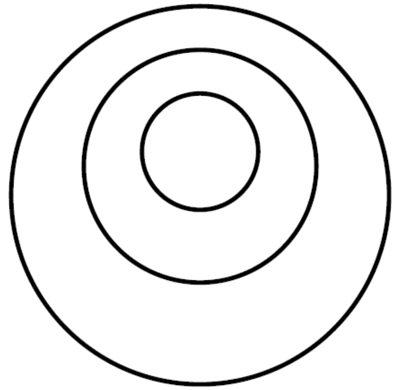
$$\Delta\phi = \tau * z$$

weak mode even with cosmic muon tracks

Solution: 0T cosmic muon tracks or mass constraint ($Z \rightarrow \mu\mu$)

2 muons from Z decay not fitted independently (2x5 parameters), but
as a fit of 9 parameters and Z mass as virtual measurement (RMS as uncertainty)

Example 3:
"sagitta": dy ~ r
curvature bias



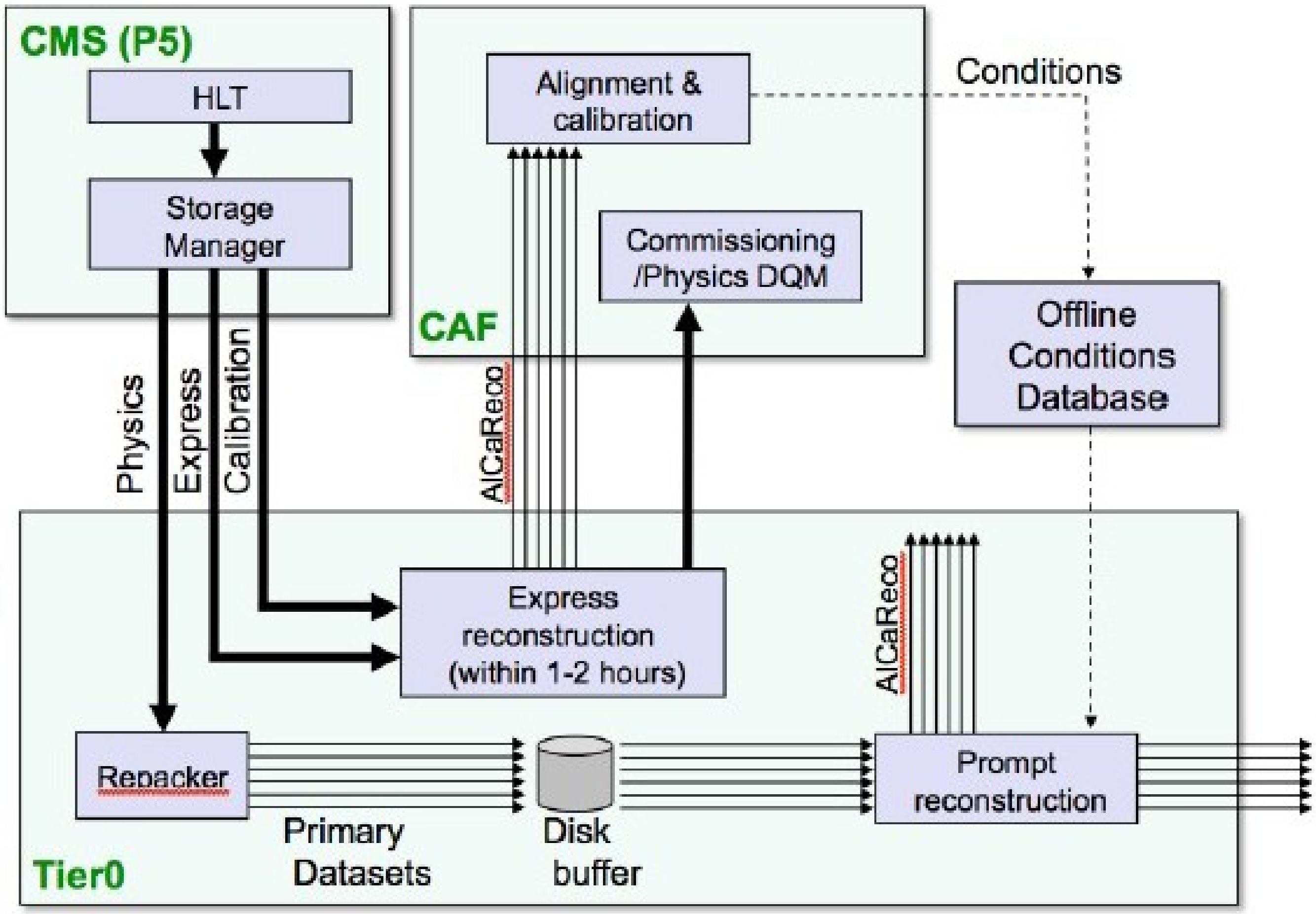
$$\Delta y = \varepsilon * r$$

suspected in 2011, observed variation of Z mass as function of Φ of positively charged muon

phi-dependent curvature bias

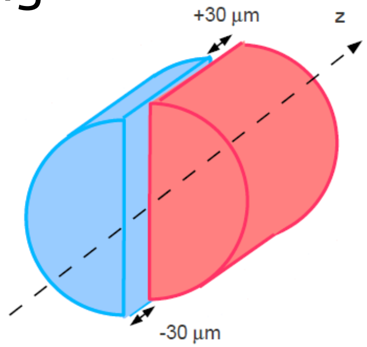
Prompt Calibration Loop

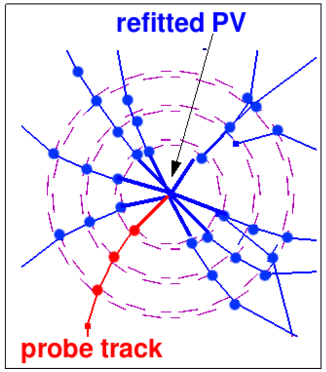
- *Prompt Calibration Loop (PCL)*
  - calculates 6 alignment parameters for large structures of pixel
  - provides feedback within 48h with latest data to reconstruct the same run



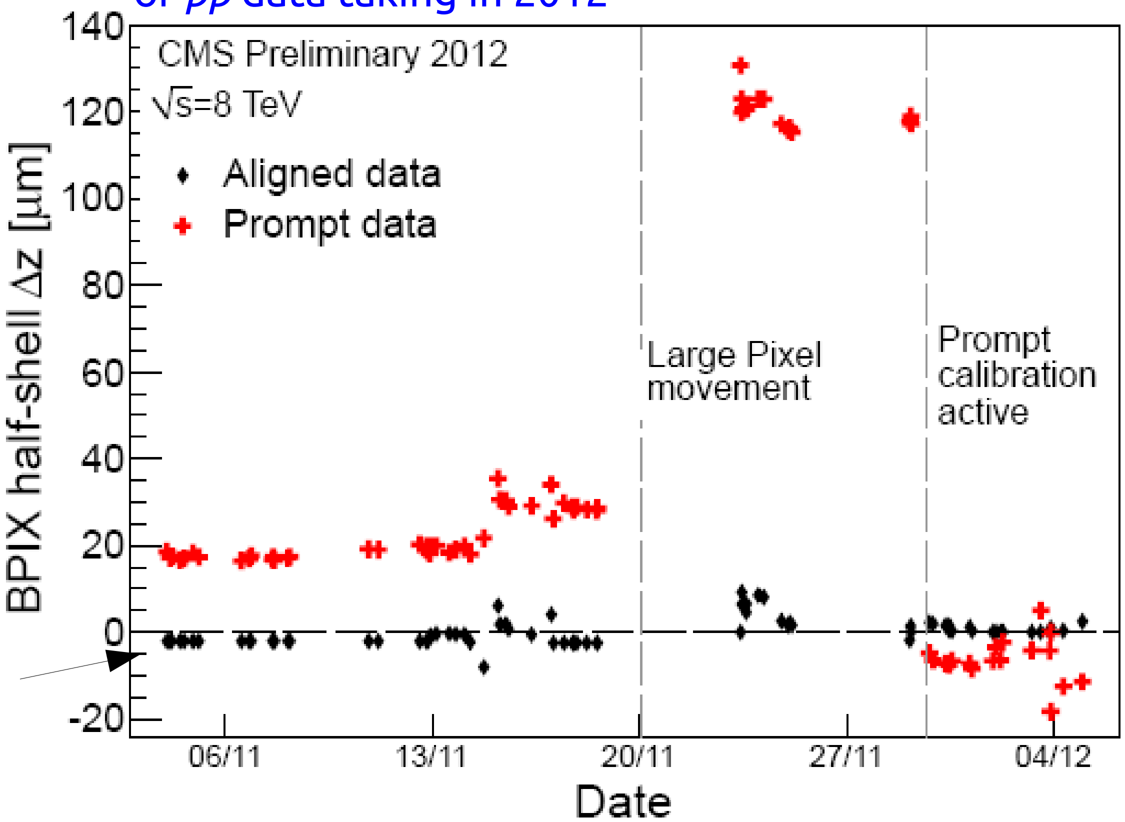
PCL and Pixel movement in November

- During last month of *pp*-running in 2012 PCL was running for monitoring (not active)
- Major sudden movement of pixel half-shells along *z* detected in Nov 22nd (cooling failure)
- PCL activated on Nov 30th to recover this movement





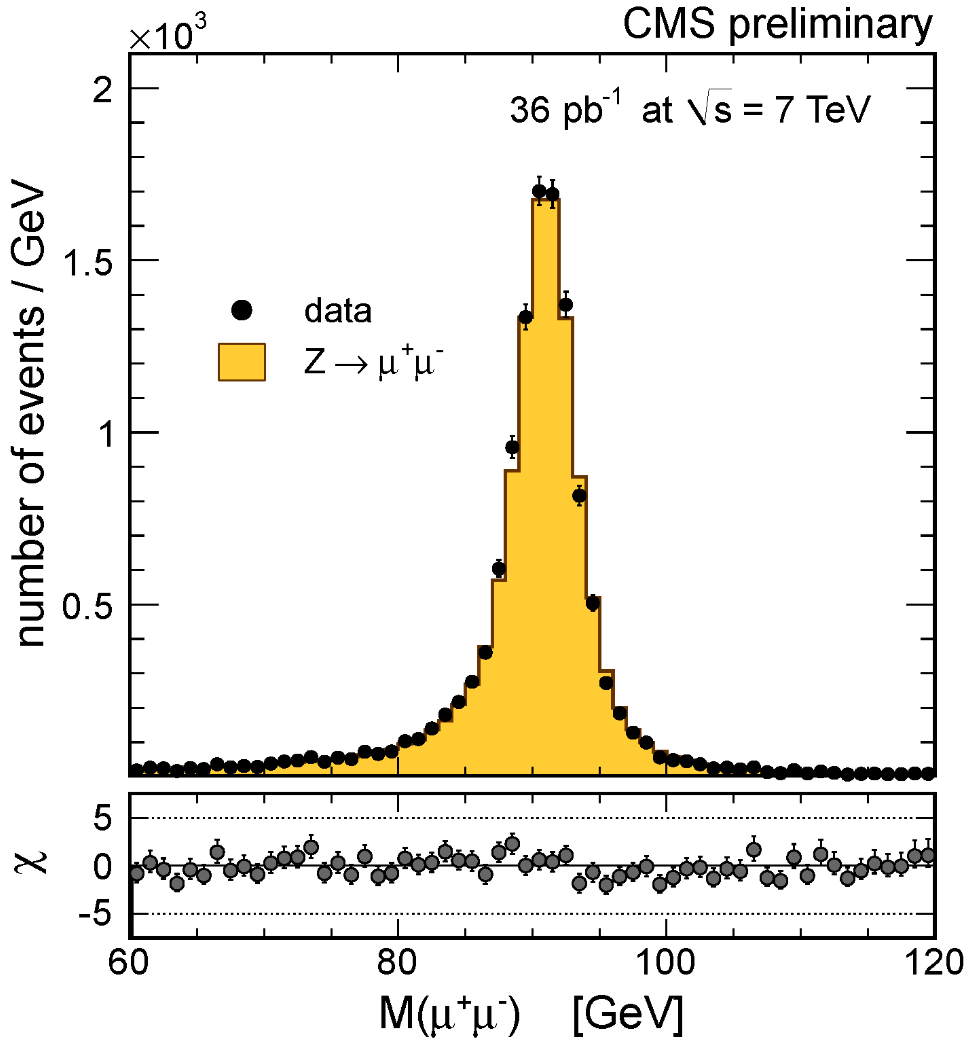
Relative z-shift of BPIX half-shells in last month of *pp* data taking in 2012



Same events re-reconstructed after the **2012 alignment campaing** taking into account the major displacements

Muon Curvature Bias

- Several systematic distortions can bias track curvature $K \sim \pm 1/p_t$
- $Z_0 \to \mu^+\mu^-$ events reveal this bias: invariant mass fitted[1] as function of muon direction, separating μ^+ and μ^-

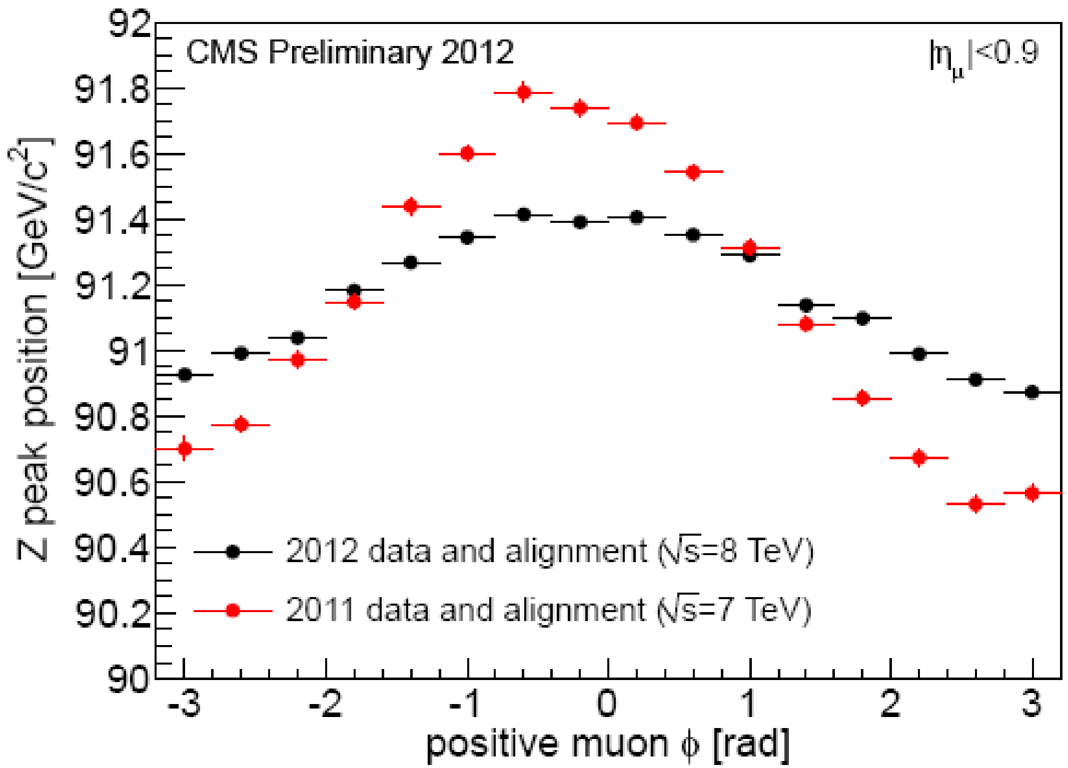


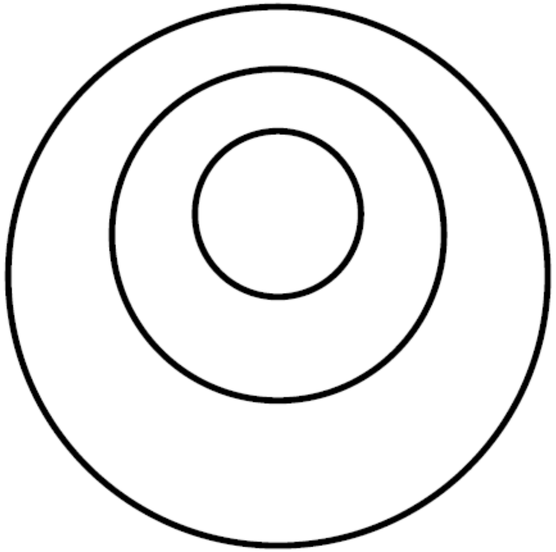
1) invariant mass distribution fitted with wide fit range 75-105GeV/c^2, Z_0 width set to PDG value of 2.495 GeV/c^2; Fit function: a Breit-Wigner function convoluted with Crystal ball function (models finite track resolution and radiative tail) + exponential background

Reconstructed Z_0 Mass peak

Reconstructed $Z_0 \to \mu^+\mu^-$ mass peak as function of Φ

Azimuthal angle Φ of μ^+, **barrel** muons





$\Delta y = \varepsilon * r$

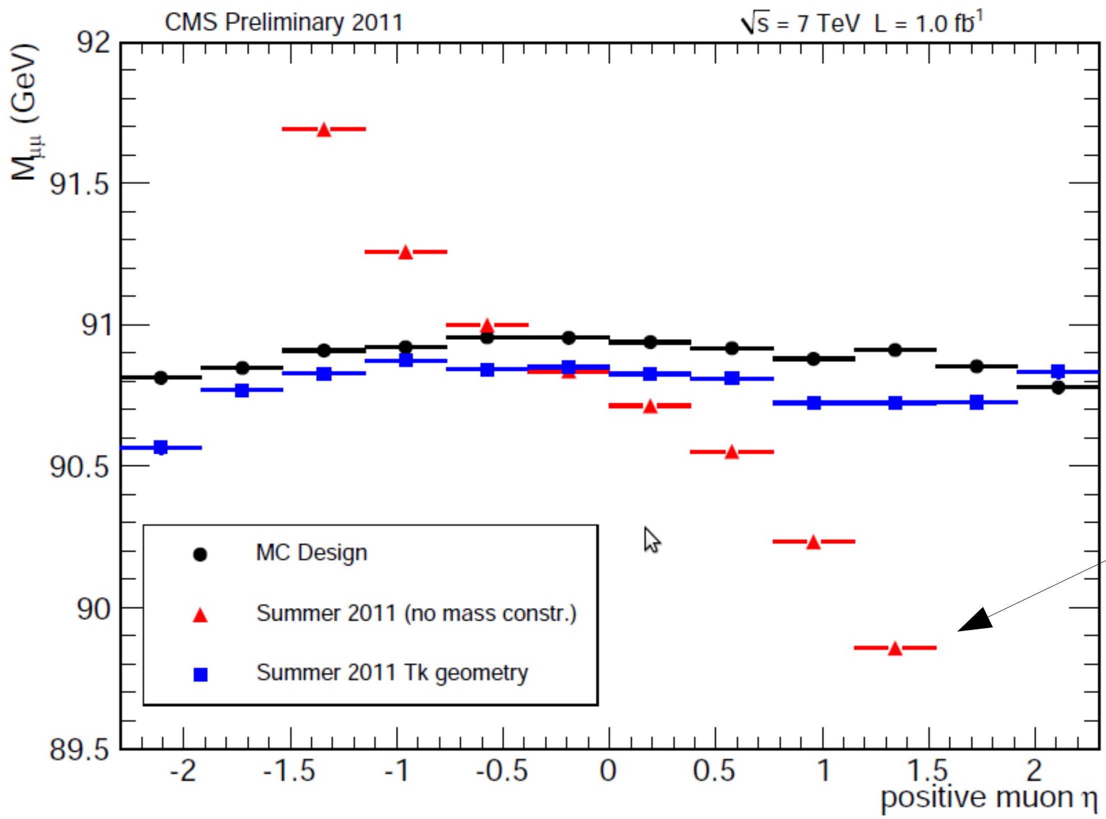
"Sagitta" distortion causes this kind of effect

Amplitude of sinusoidal shape clearly decreased with **weighted** input data, from 0.7 GeV/c^2 to 0.3 GeV/c^2 in barrel

N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

Necessity of Z_0 Events

Reconstructed $Z_0 \rightarrow \mu^+\mu^-$ mass peak as function of pseudorapidity
2011 data



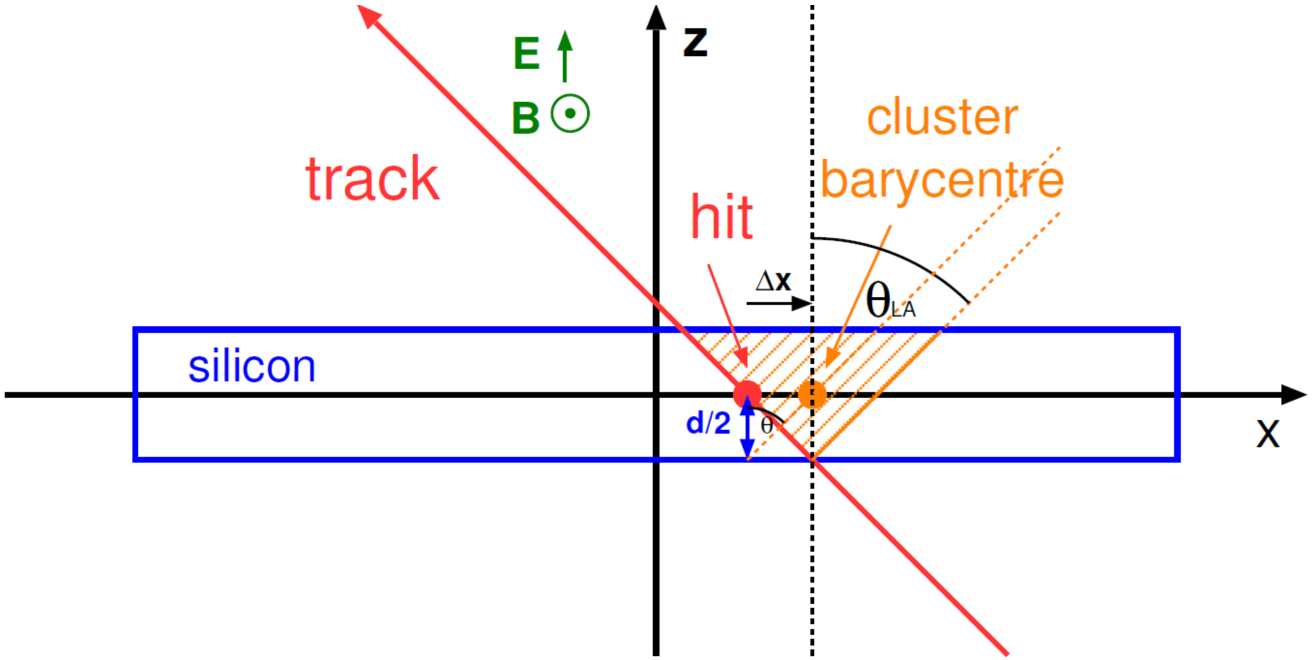
No mass constraint

Pseudorapidity of μ^+

N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

Lorentz Angle calibration and alignment

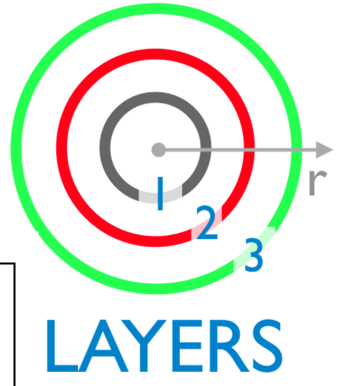
- Charge drift in magnetic field affects the measured hit position as $\Delta x=\tan(\theta_{LA})*d/2$
- Most precise way to correct this is integration of θ_{LA} calibration to Millepede II alignment procedure
- Data with magnetic field ON and OFF used simultaneously: 60 M tracks (isolated muons, $Z_0 \rightarrow \mu^+\mu^-$, cosmic ray muons and field OFF collision data)



Granularity:
3 layers
8 rings
65 periods of time
→ 1560 additional parameters

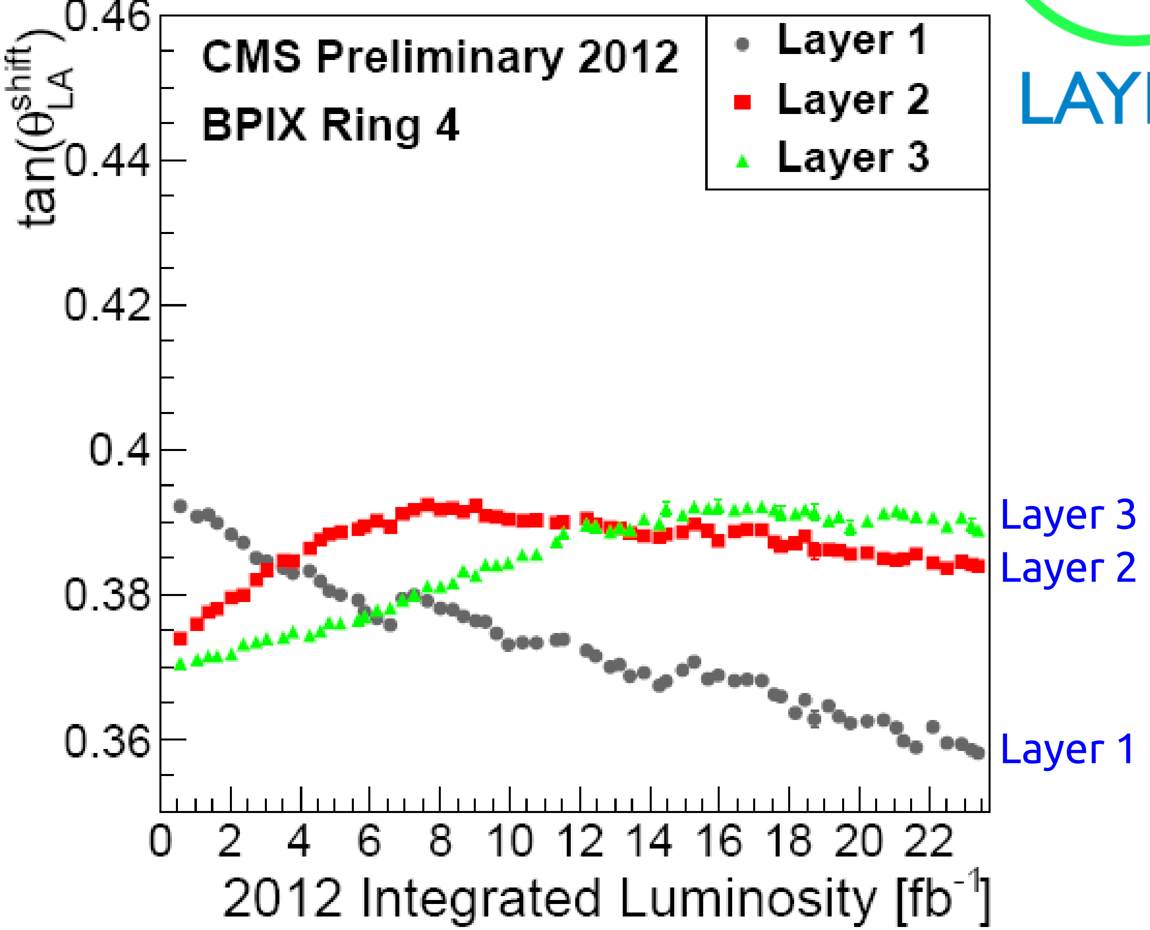
Recent extension – not yet used in full 2012 alignment

Comparison of centermost modules from different layers



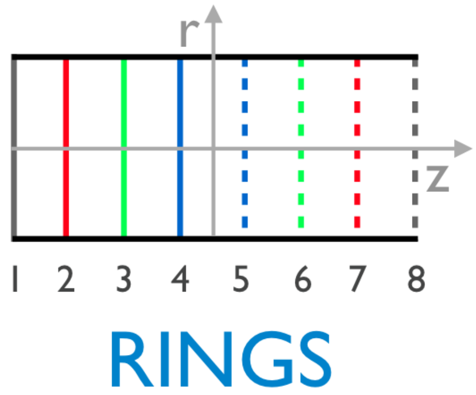
Similar behaviour for three layers:
more intense radiation in layers 2 and 1 causes earlier decrease.

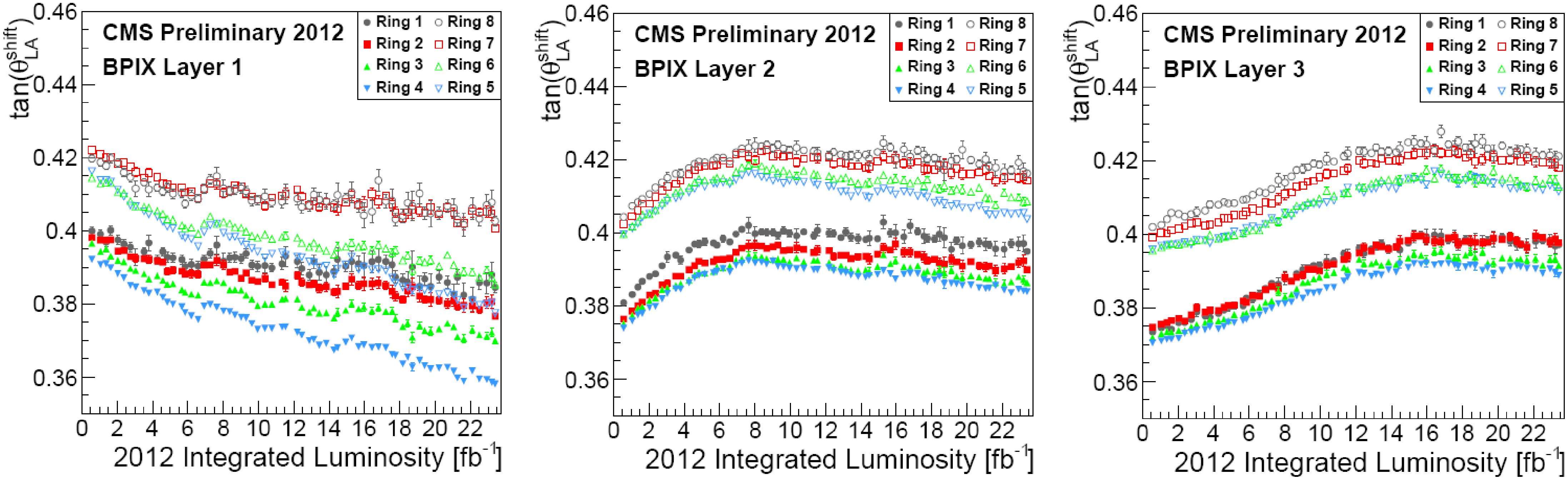
A few μm effect, but will be relevant in 2015 with increased LHC luminosity



For each layer: LA for modules of one ring as function of integrated luminosity

Offset between R1-4 and R5-8 related to different bias voltages.





Slow decrease pronounced for innermost rings

Increase followed by a decrease; more rapid for layer 2 smaller difference between rings

Summary

- Alignment with Millepede II of 200.000 alignment parameters used routinely for 2 years
- Quick response to data taking with **run-by-run alignment** of large structures
- **Improvements** in 2012:
  - Sensor bows widely used
  - Prompt Calibration Loop operational (end of 2012)
  - Curvature bias modes in better control with $Z_0 \to \mu^+\mu^-$ events
  - Alignment framework extended to treat calibration parameters
  - Lorentz Angle calibration integrated to alignment

Challenges ahead

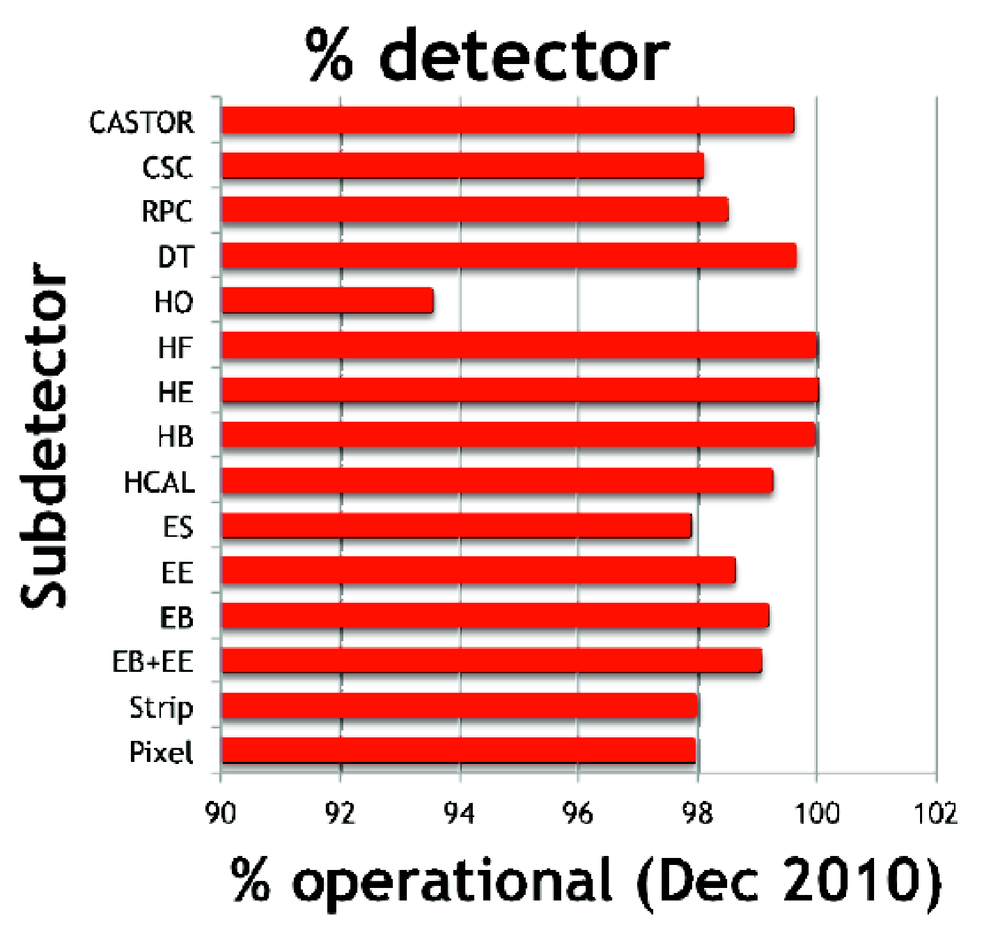
From R. Steerenberg, CERN-LHC, LHC Beam Operation Workshop Evian Dec-2012

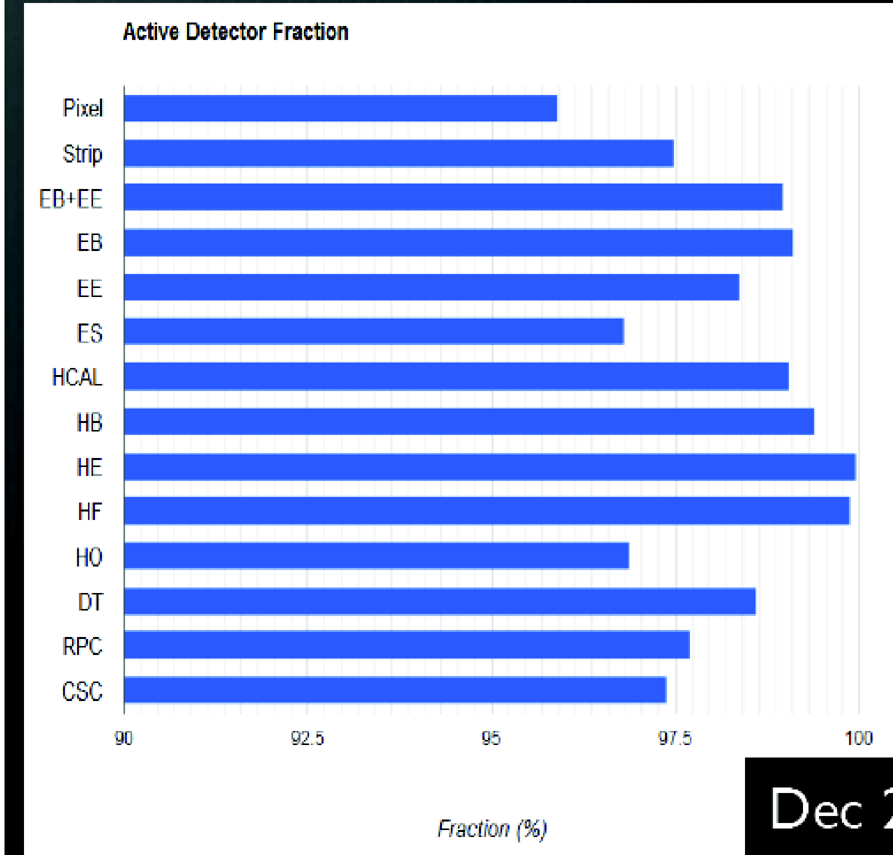
Acknowledgements

- CMS Tracker Alignment group
- Helmholtz Alliance “Physics at the Terascale”
  https://www.wiki.terascale.de/index.php/Millepede_II
- Magnus Ehrnrooth Foundation
- Waldemar von Frenckell Foundation

Thank you for your attention!

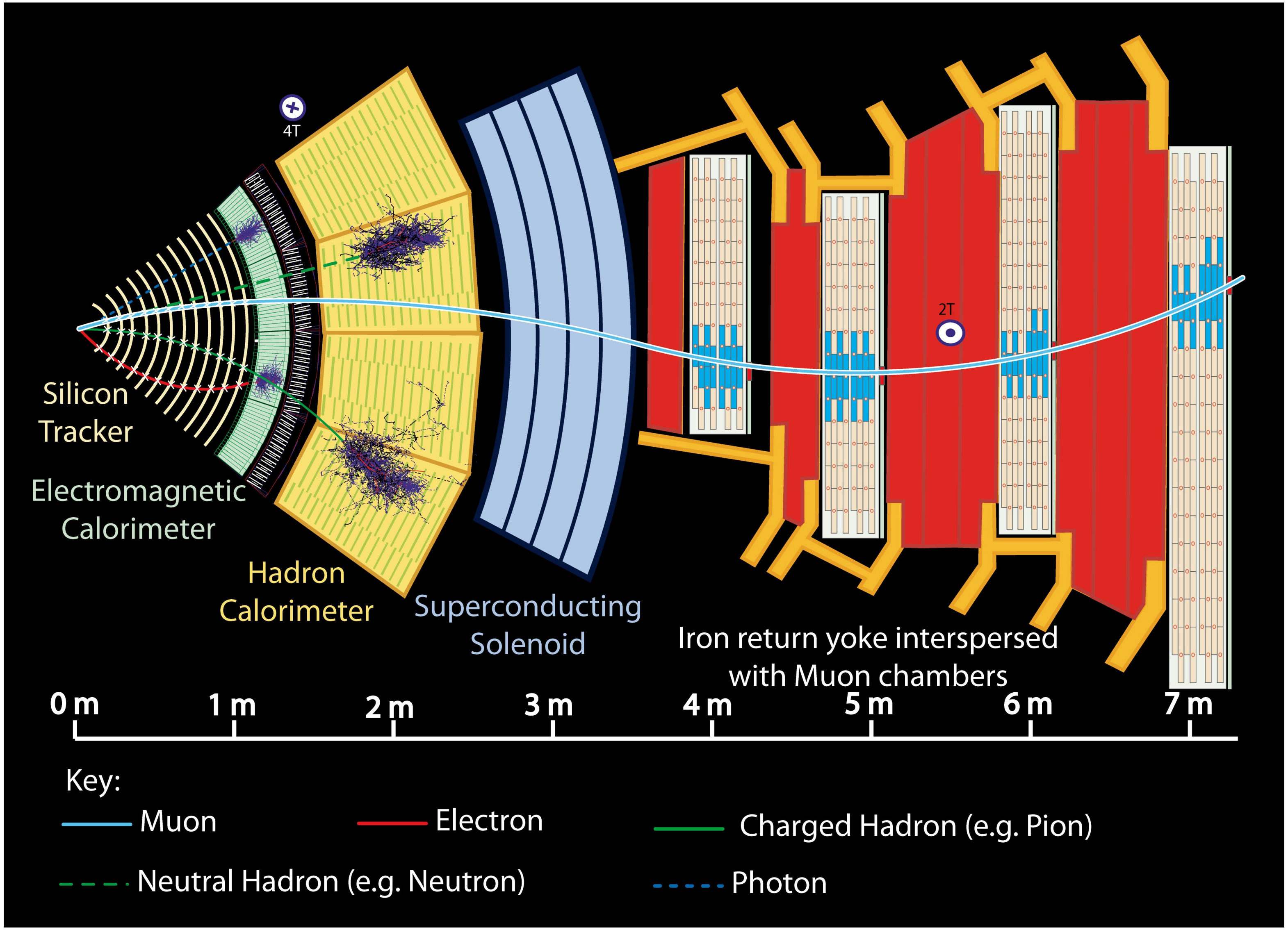
Backup





Dec 2012

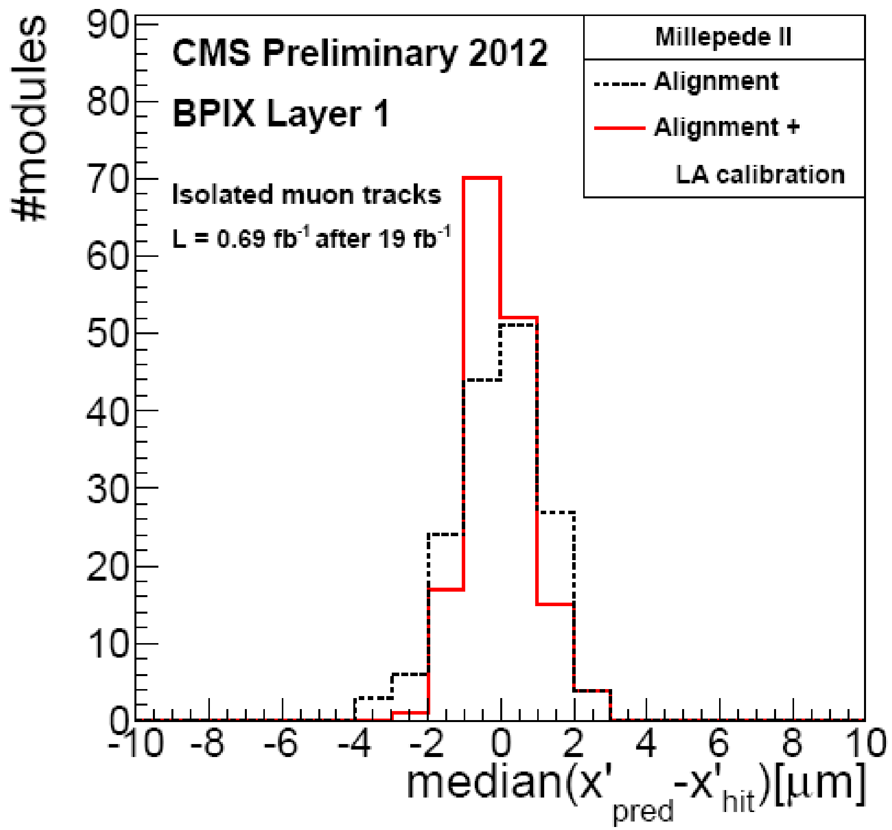
CMS Detector - transverse view

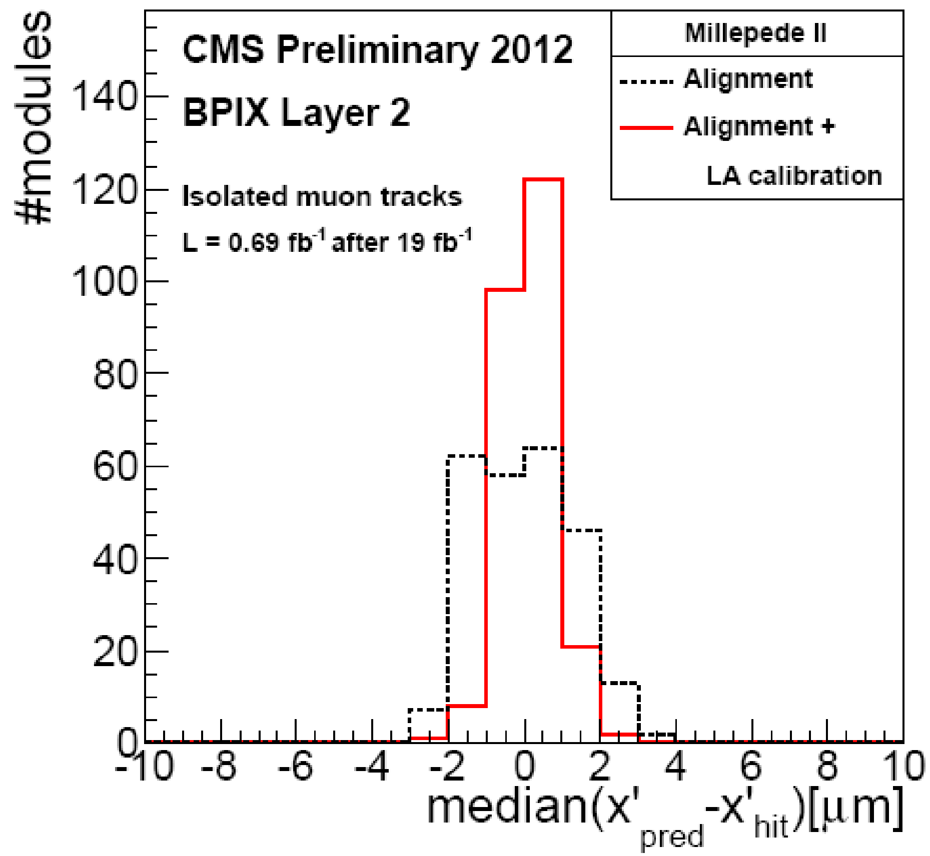


Lorentz Angle validation, BPIX layers 1&2

Obtained LA calibration validated by comparing the combined Millepede approach (alignment + LA) to alignment with standalone calibration.

Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module. Independent set of tracks from isolated muons used in validation.





Small, but visible improvement using integrated alignment and calibration.

Lorentz Angle validation

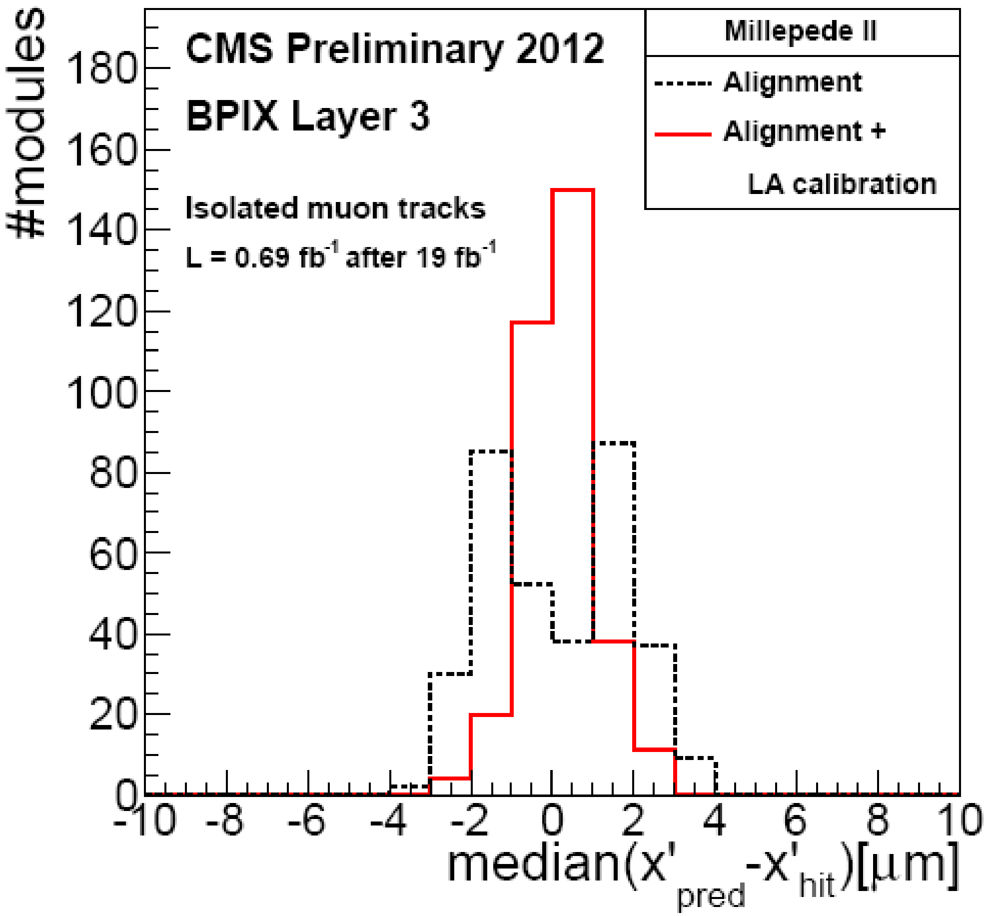
LA calibration validated by comparing to alignment with standalone calibration.

Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module. Independent set of tracks from isolated muons used in validation (from end of 2012).

Clear improvement using integrated alignment and calibration.

Double peak illustrates inconsistency between LA and alignment, corrected in the combined approach.

A few μm effect, but this approach will be more relevant in 2015 with increased LHC luminosity.

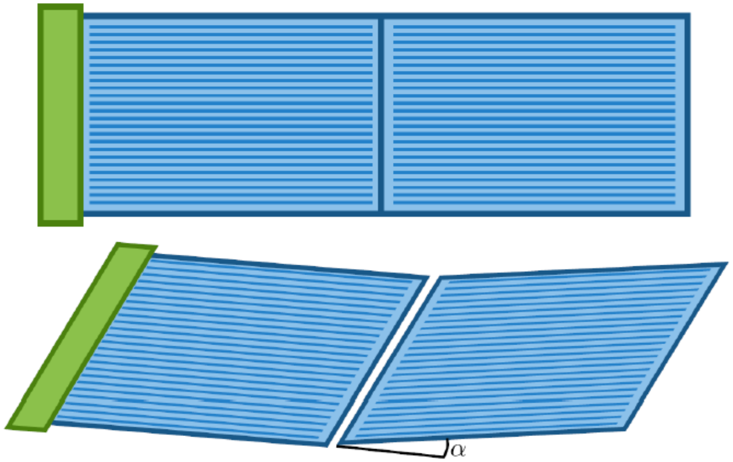


Alignment – sensor deformations

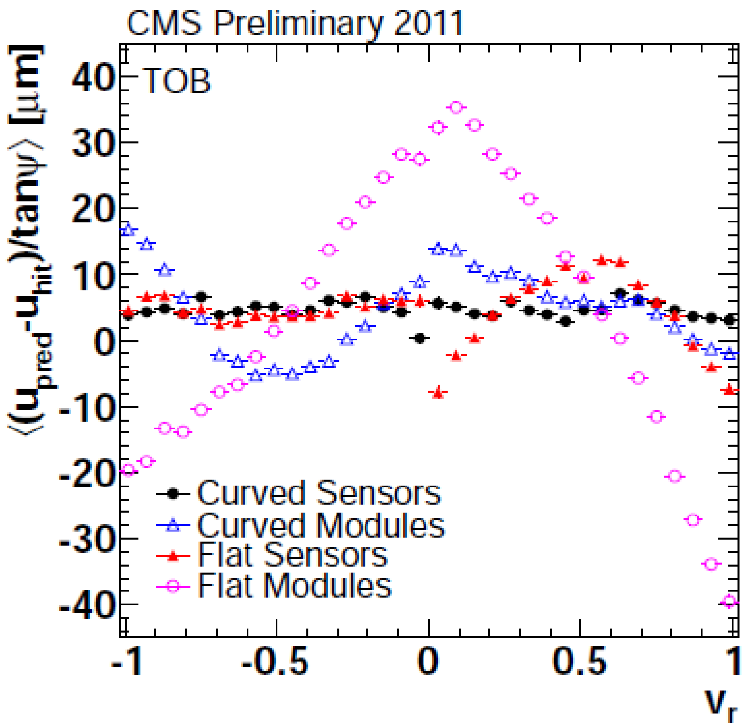
Also, long strip modules in outer Tracker (TOB, outer TEC), consist of two daisy-chained sensors

Typical “kink” angle ~1.6 mrad, resulting to larger effect than sensor bow

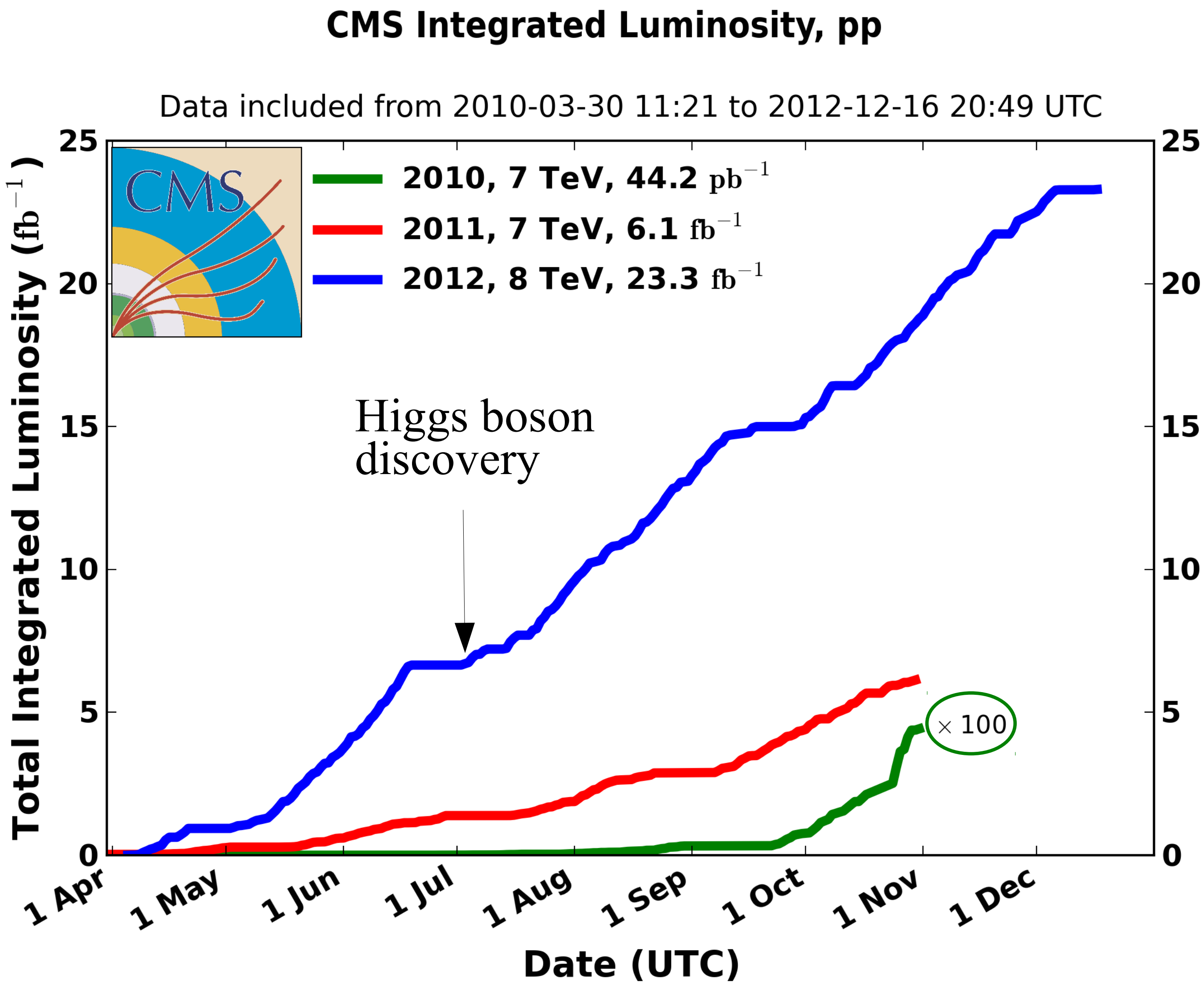
3 additional parameters from bows and kink



Taking in to account both kinks (TOB, TEC) and bows (TIB, TOB, TEC, BPIX) makes the dw distribution flat

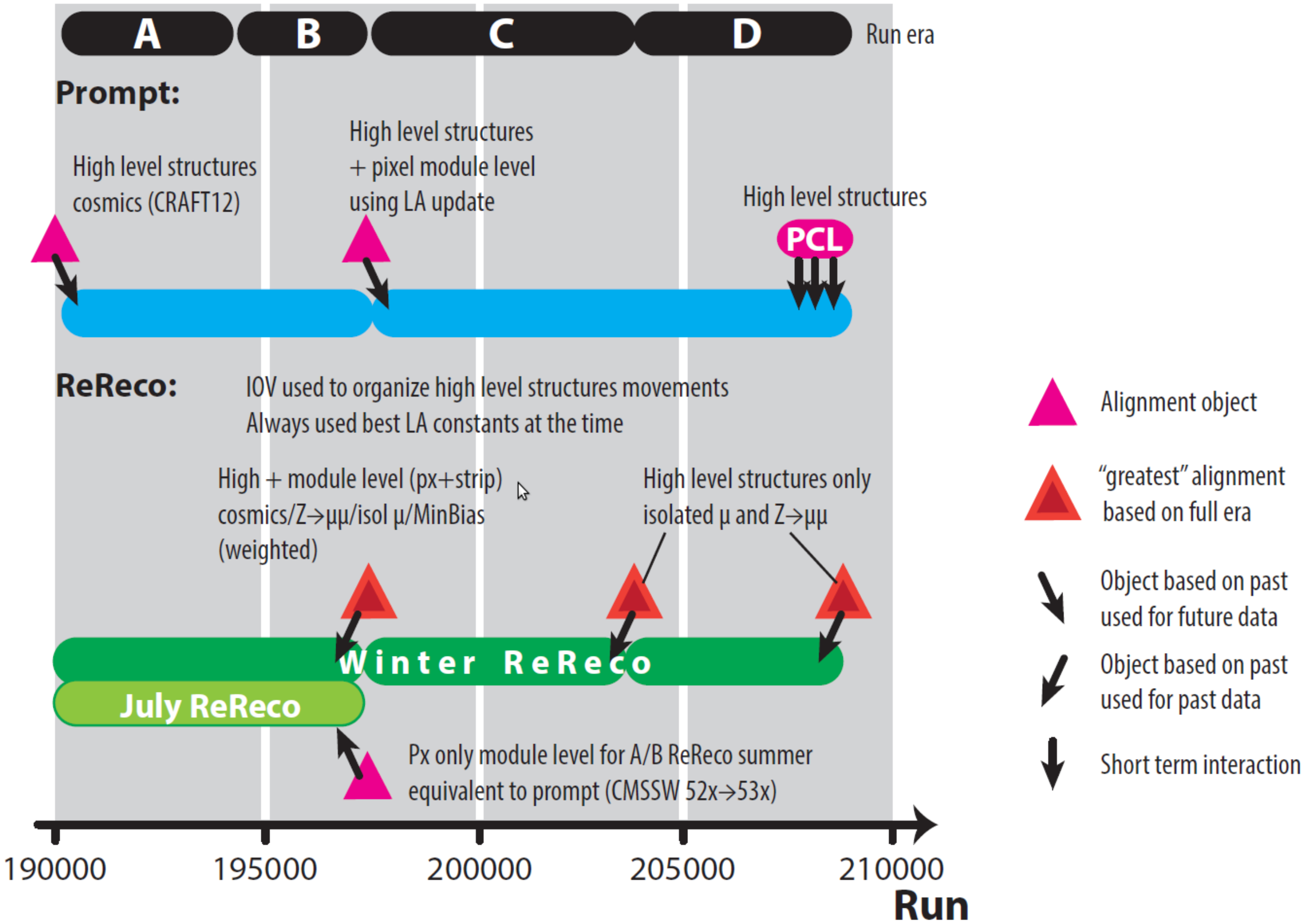


Data recorded in 2012



Out of the 23.3 fb^{-1} of data delivered, CMS recorded 21.79 fb^{-1}

Timeline of Alignment in 2012

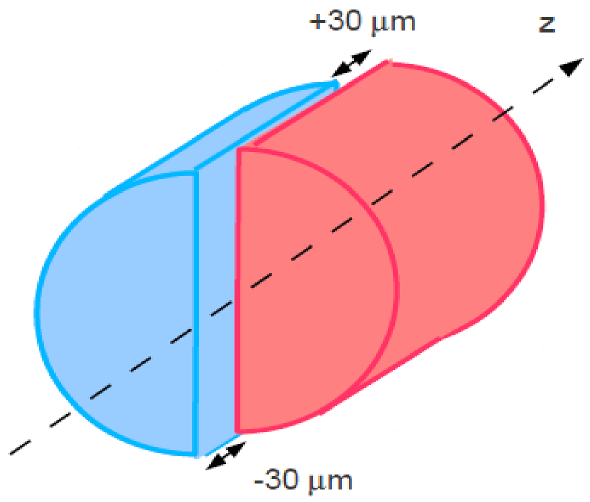


Full scale alignment based on 2012A+B and CRAFT data

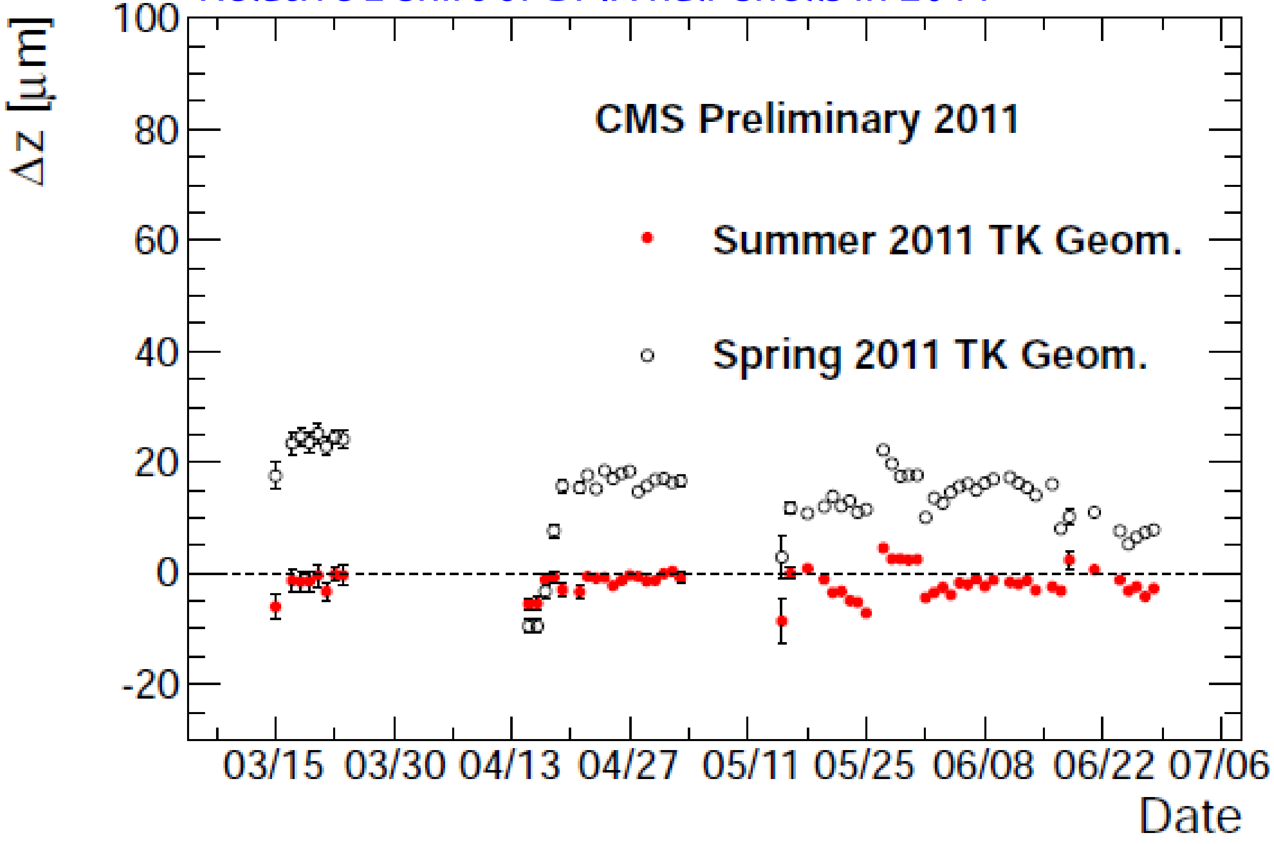
2012C+D data used to align high-level structures

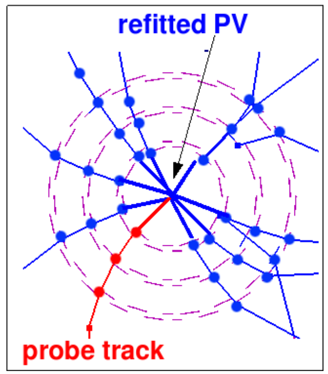
Displacements of pixel half barrels

- Time-dependent relative shift of 2 pixel half barrels noticed in 2011
- Monitored along z with **unbiased primary vertex track-residuals**
- 9 intervals found in 2011



Relative z-shift of BPIX half-shells in 2011

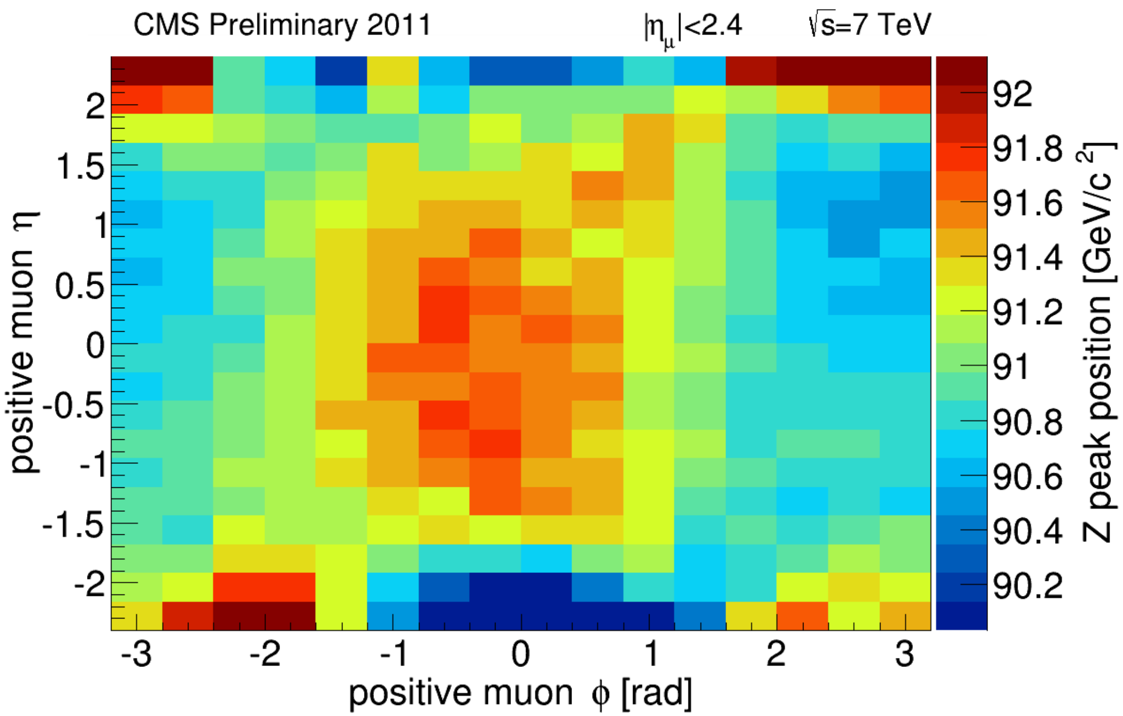


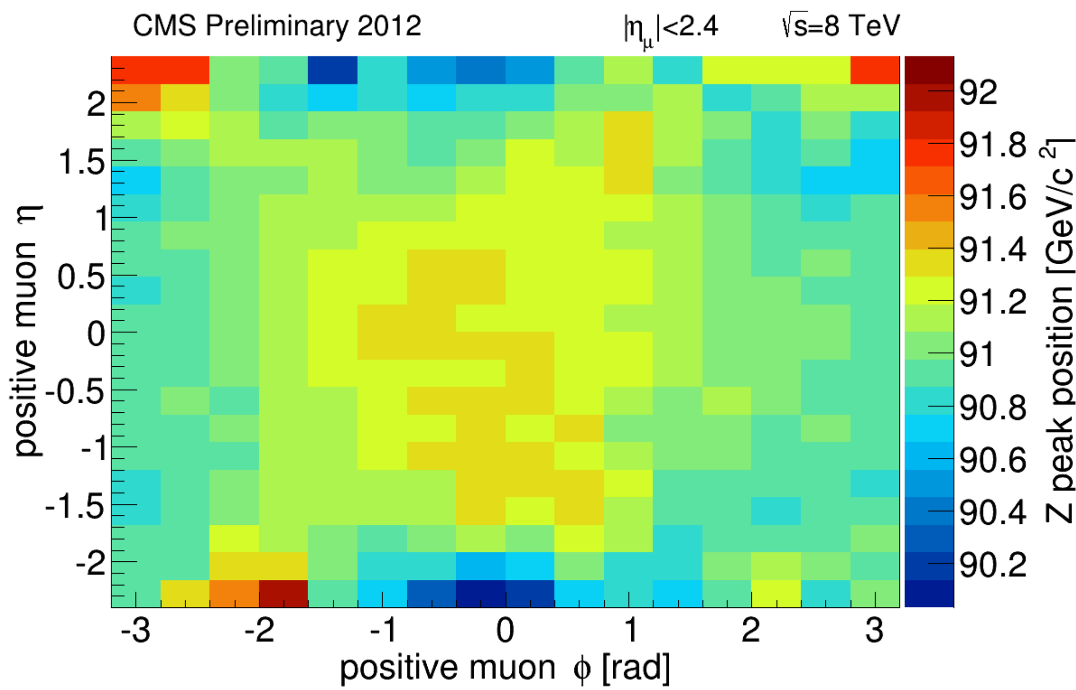


Reconstructed Z_0 Mass peak

Reconstructed $Z_0 \to \mu^+\mu^-$ mass peak as function of both pseudorapidity η and azimuthal angle φ of positive muon (previous plot with η dimension)

Z-axis same in both pictures, centered at peak value of all 2011 events (91.08 GeV/c^2)





Overall pattern significantly reduced for 2012!

N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses