Alignment of the CMS Silicon Tracker

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on behalf of CMS collaboration

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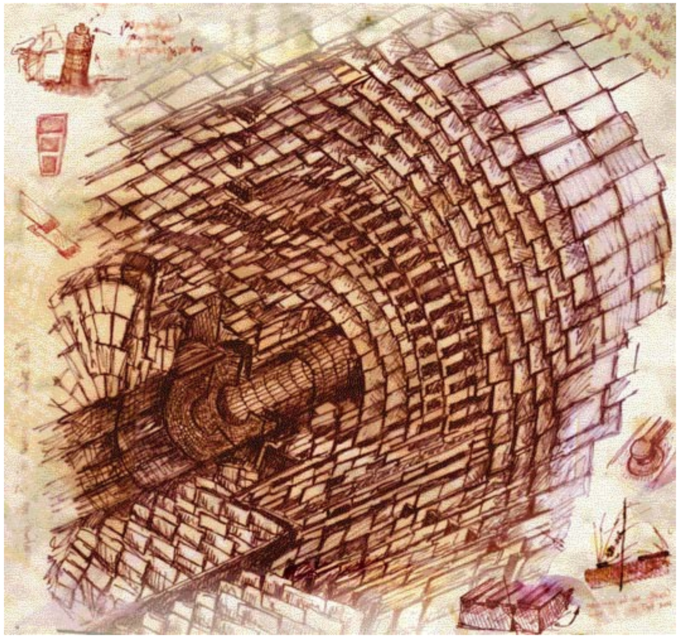
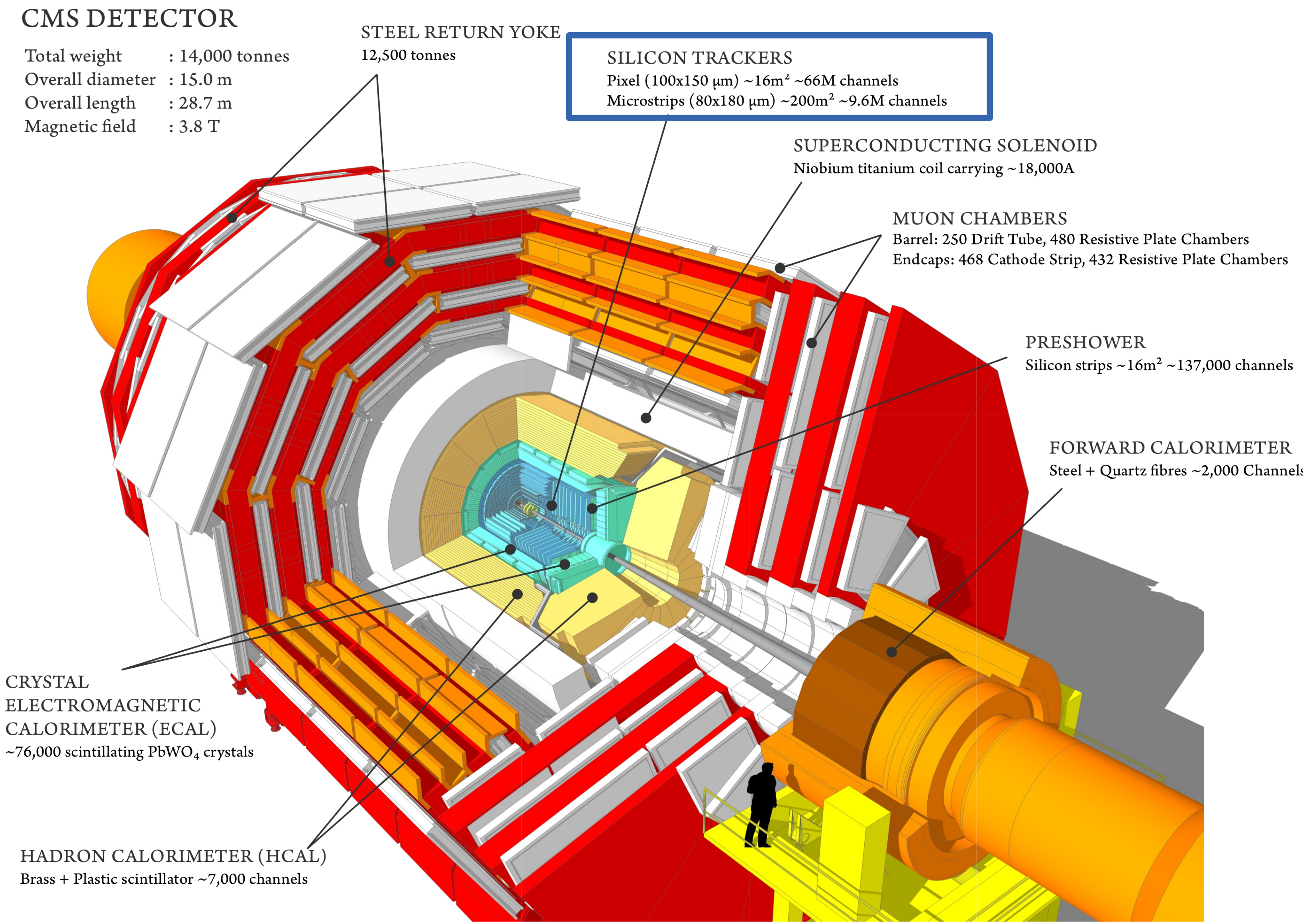
Outline

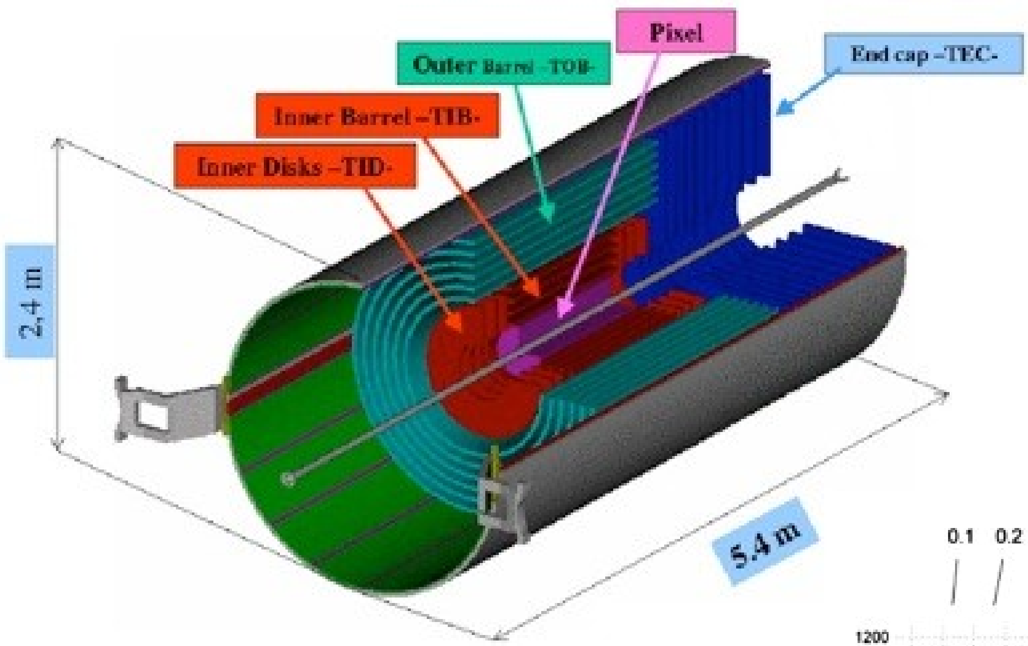
- CMS detector
  - Silicon tracker
- Track based alignment procedure
- Improvements to alignment in 2012



Compact Muon Solenoid



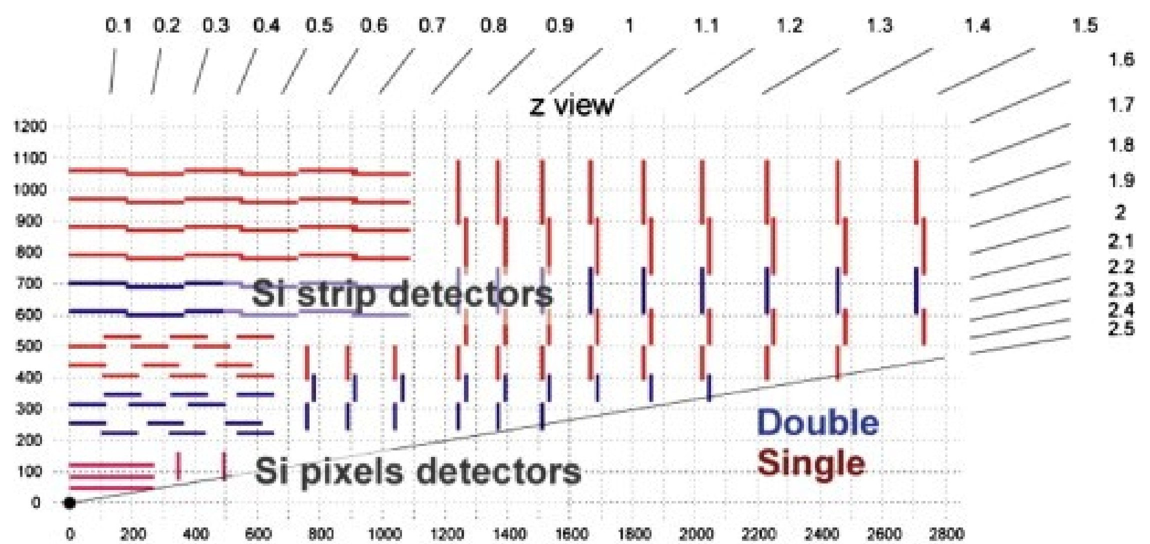
CMS Tracker



Pixel tracker:
- 1440 modules
- Hit resolution ~ 9 μm

Strip tracker:
- 15148 modules
- Hit resolution 20-60 μm

Approximately 200m^2 of active silicon
- Largest silicon tracker ever built



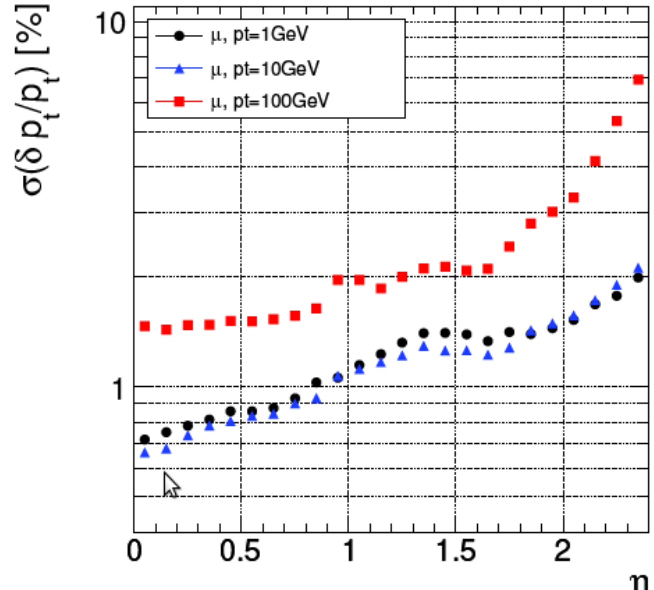
The layout of the CMS inner tracker

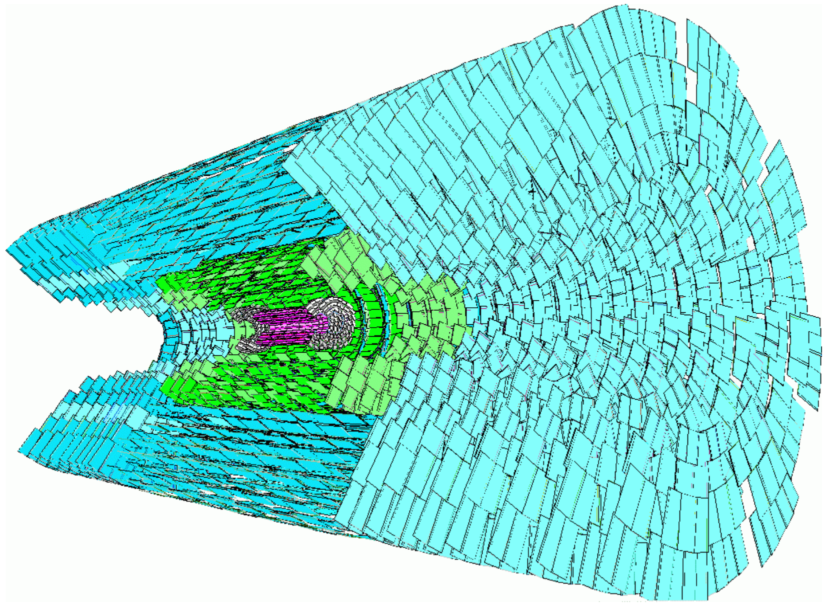
CMS Tracker

- Designed to have a resolution of roughly 1.5% on the transverse momentum (for 100 GeV muons)
- Uncertainty in tracking

$$\sigma^2_{meas} \sim \sigma^2_{hit} + \sigma^2_{alignment}$$

Momentum resolution for simulated muons CMS P-TDR (2006)

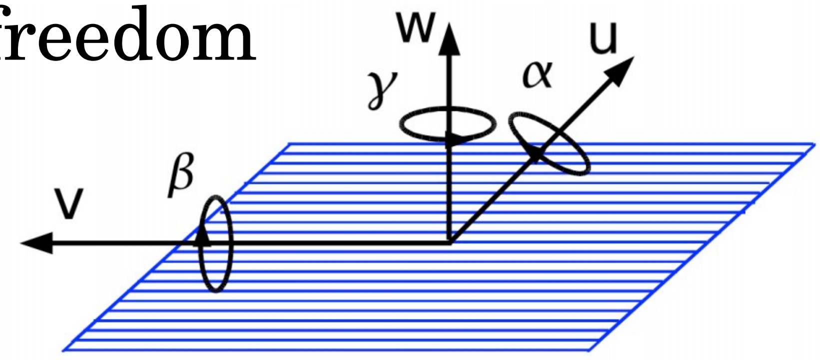




- Possible limiting factor in the measurement uncertainty is the alignment, good alignment is key to getting best performance
- Want to keep $\sigma_{align} < 10$ μm

Alignment

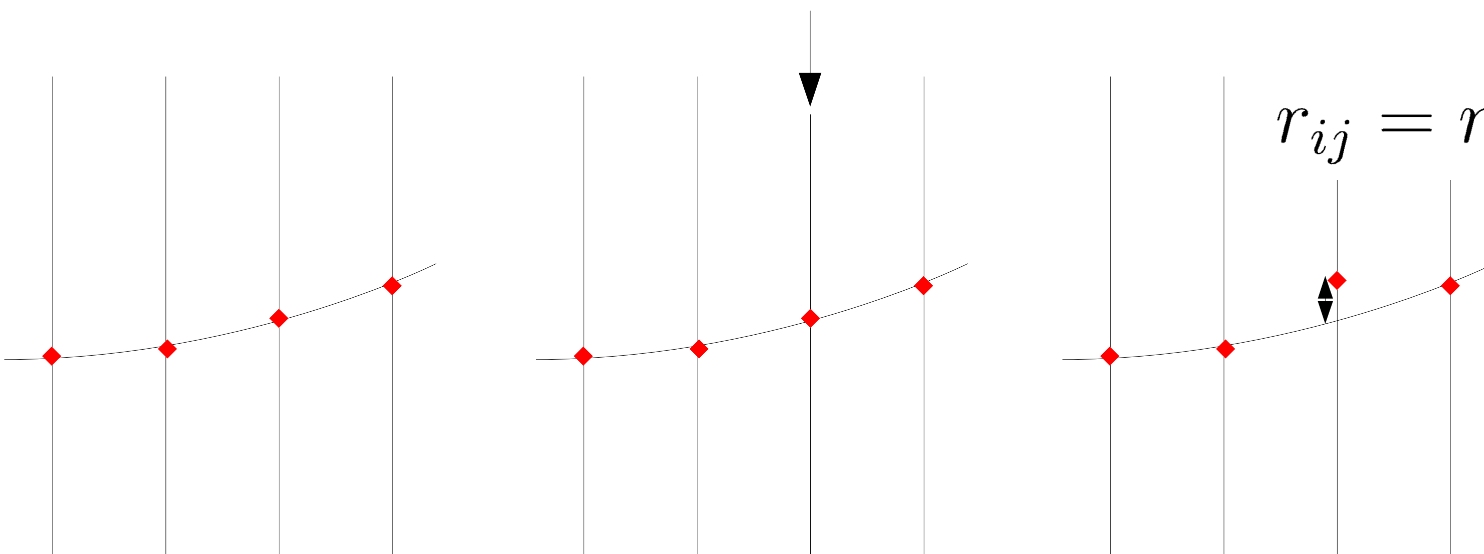
- CMS tracker has a total of 24244 sensors
- Each sensor has 9 degrees of freedom
  - 3 translations
  - 3 rotations
  - 3 curvature



- In total, over 200,000 alignment parameters
- Track-based alignment used
  - Tracks from pp collisions and cosmic rays used for measuring alignment parameters
- Time dependent alignment for larger structures

Alignment

- Misalignment worsens the track residuals (difference between hit and track positions)



Ideal Measurement | **With Misalignment** | **Measured w/ Misalignment**

$$r_{ij} = m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)$$

r_{ij} – residual
m_{ij} – measurement
f_{ij} – track prediction
p – align. parameters
q – track parameters

Track-based alignment

- Basic principle, minimize the sum of the normalized residual

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

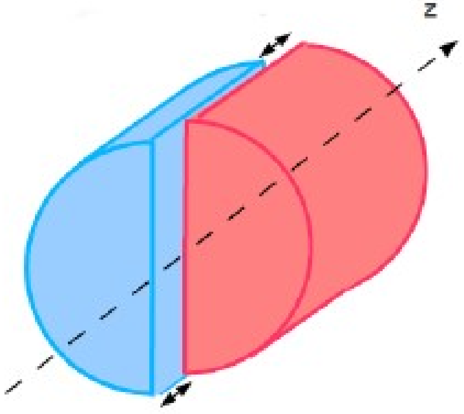
m_{ij} – measurement
σ_{ij} – uncertainty
f_{ij} – track prediction
p – align. parameters
q – track parameters

- f_{ij} linearized around initial values of alignment and track parameters
- Can then be expressed as linear equation system
  $\mathbf{Ca} = \mathbf{b}$; $\mathbf{a}^T = (\Delta\mathbf{p}, \Delta\mathbf{q})$
- Global fit using Millepede II[1]

[1] V. Blobel, "Software alignment for tracking detectors", *Nucl. Instrum. Meth.* **A566** (2006) 5-13, https://www.wiki.terascale.de/index.php/Millepede_II

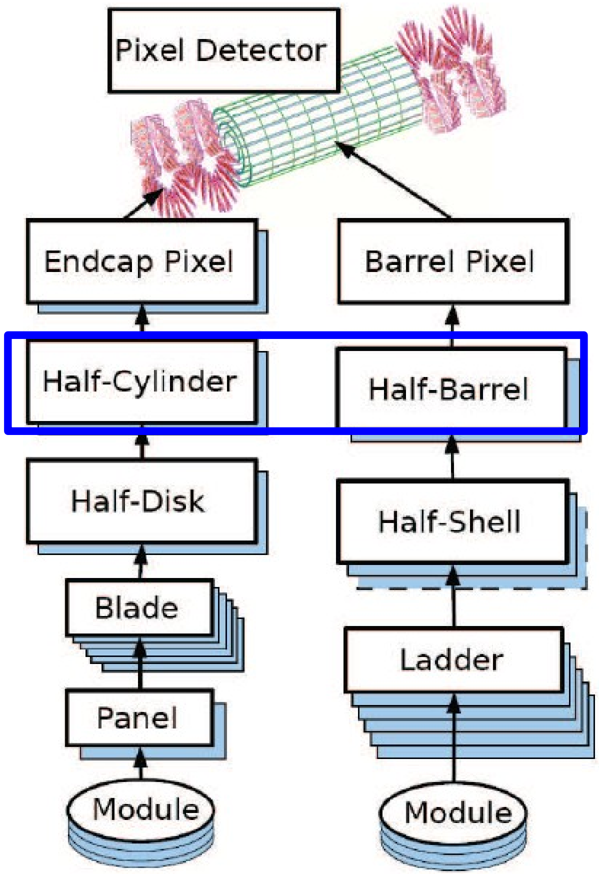
Large Structure Movements

- Pixel detector plays very important role in vertex reconstruction
  - Closest to beam line
  - Best resolution
- Shifts between large structures can degrade physics performance
  - b-tagging is visibly degraded in simulation when a shift of $\Delta z > 20$ μm is introduced



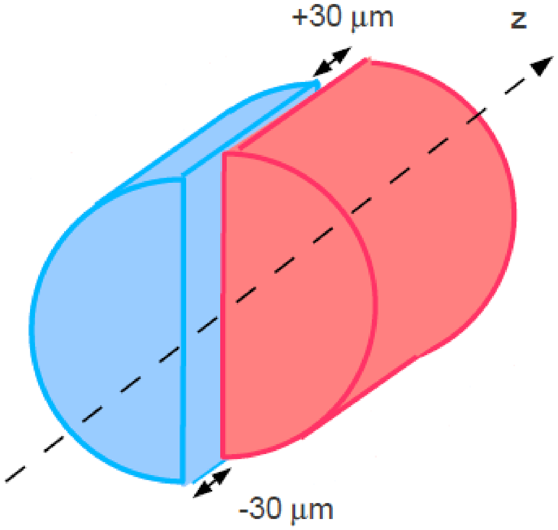
Pixel Alignment in Prompt Calibration Loop

- Over time, movements occur in the large structures
  - Cooling issues, magnet ramp up/down, etc. can result in small but significant movements in the detector
- Monitoring of alignment added in the Prompt Calibration Loop (PCL)
  - Check alignment on a run-by-run basis
  - Measure any movements in short time frame (within 48 h of data collection)
  - Providing feedback in time to correct movements before reconstruction of data



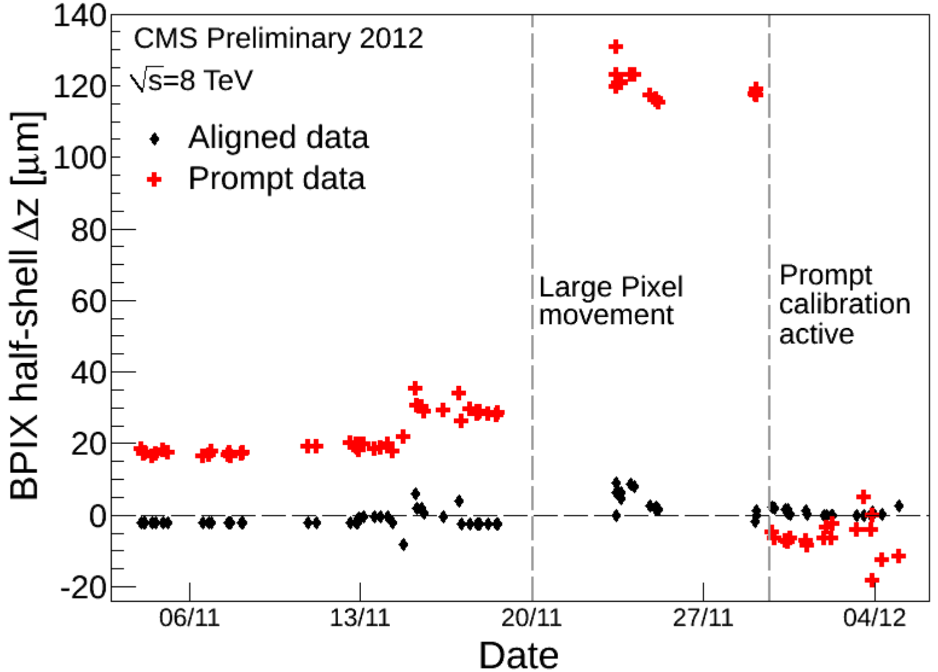
PCL Alignment

- Implemented at end of 2012 pp data taking period
- Align on the large structures of the pixel detector
  - 6 alignment parameters for each structure (3 translation, 3 rotation)
  - 36 total alignment parameters → can be done with far fewer tracks than required for full alignment
- Monitoring for large movements in the pixels
  - Ex: separation between pixel half barrels



November pixel movements

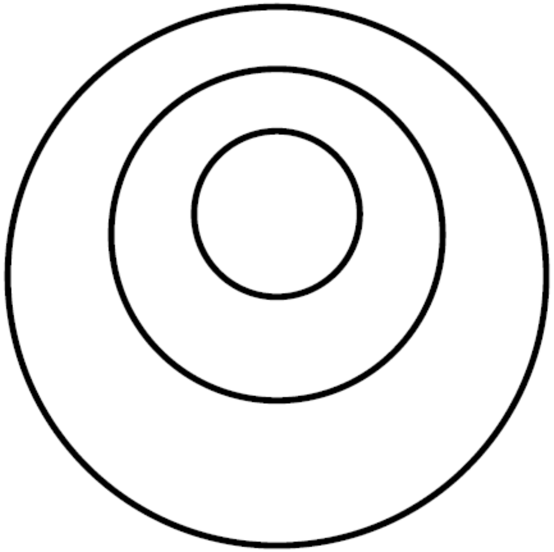
- PCL alignment was monitoring alignment during last months of 2012 data taking (not actively updating alignment)
- Major movement occurred during technical stop week of November 20th
  - Order of 100 microns
- Identified and corrected when PCL became active on Nov. 30th



Day by day relative longitudinal separation of two pixel half barrels

$Z^0 \rightarrow \mu^+\mu^-$ mass

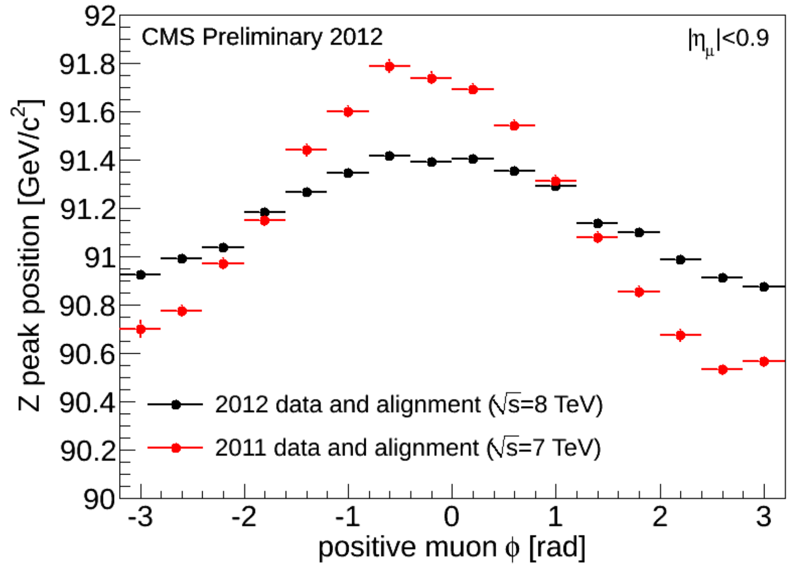
- Certain misalignments (weak modes) have little effect on χ^2, difficult to treat in alignment based on minimization of residuals
  - One example is a "sagita" distortion
  - Can bias track curvature $K \sim \pm 1/p_T$
- Can be seen using the reconstructed $Z^0 \rightarrow \mu^+\mu^-$ mass
  - Invariant mass of dimuons fitted
  - Investigated as a function of muon direction and separating μ^+ and μ^-

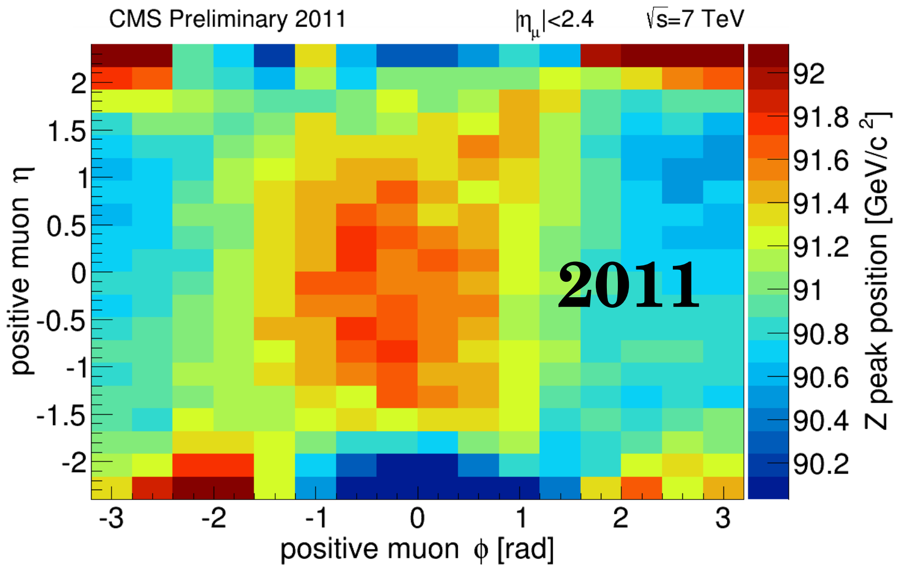


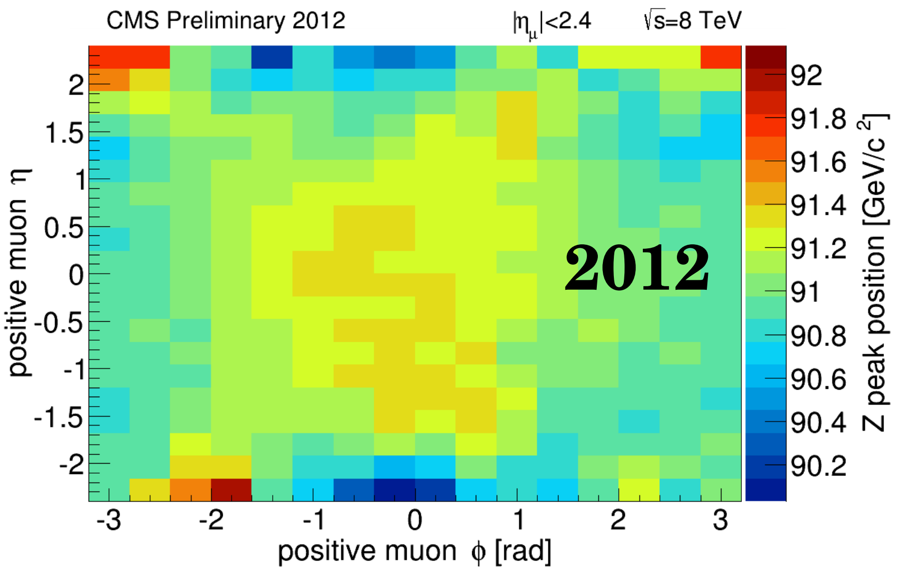
$\Delta y = \varepsilon * r$

$Z^0 \rightarrow \mu^+\mu^-$ mass

- Significantly reduces the directionality dependence of the Z^0 mass
  - In the barrel region, amplitude of dependence reduces from 0.7 GeV to 0.3 GeV

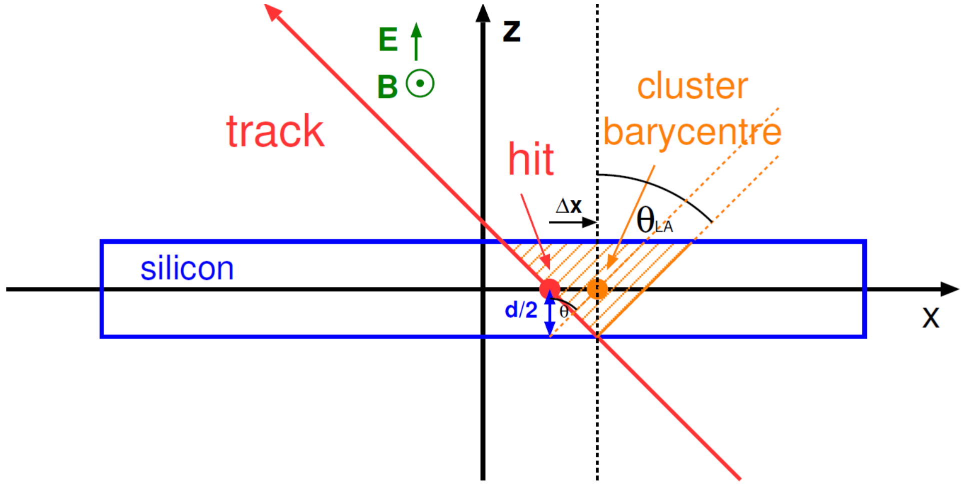






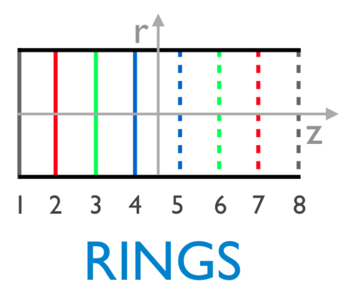
Lorentz Angle calibration

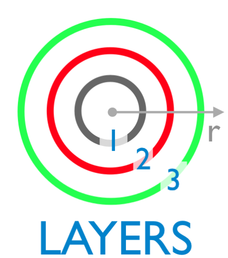
- Measured hit position affected by charge drift inside a magnetic field: $\Delta x = tan\left(\theta_{LA}\right) \cdot d/2$
- $\tan(\Theta_{LA})$ depends on electron mobility, which in turn changes with (among other things) irradiation of silicon, gives it a time dependence
- Most precise corrections found by incorporating Θ_{LA} calibration in Millepede II alignment

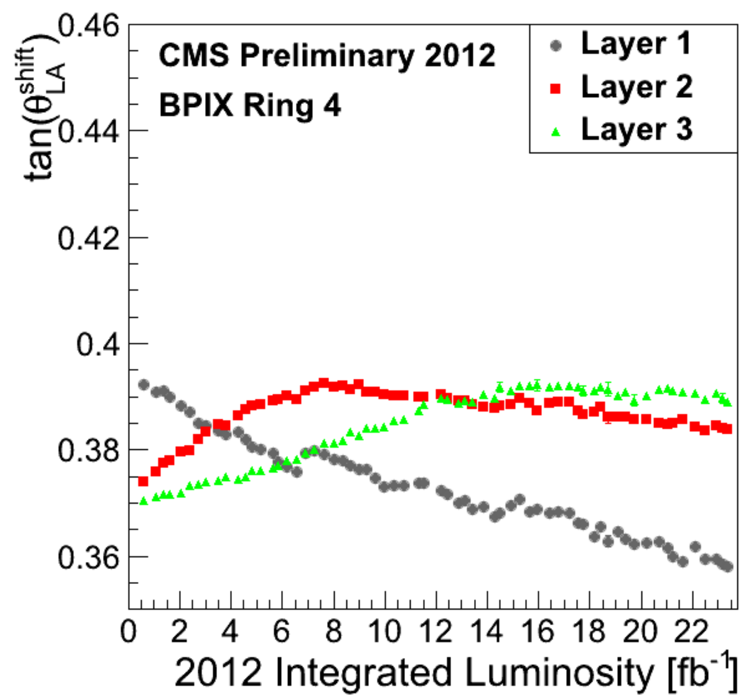


Lorentz Angle calibration

- Add in parameters to account for LA calibration
  - Parameters added for each ring and layer (8 rings, 3 layers) of barrel pixels; 65 time periods
- Aligned using data with and without magnetic field
  - Disentangles module alignment and Lorentz angle calibration
  - 60M tracks

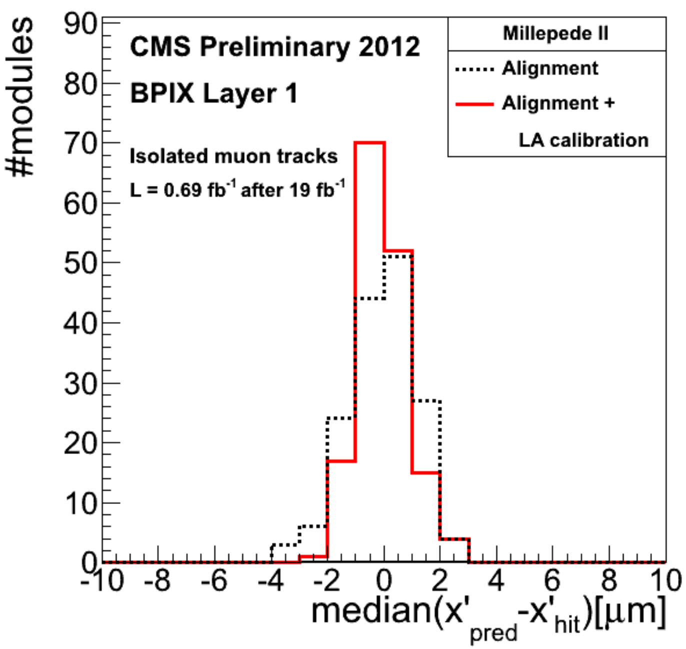


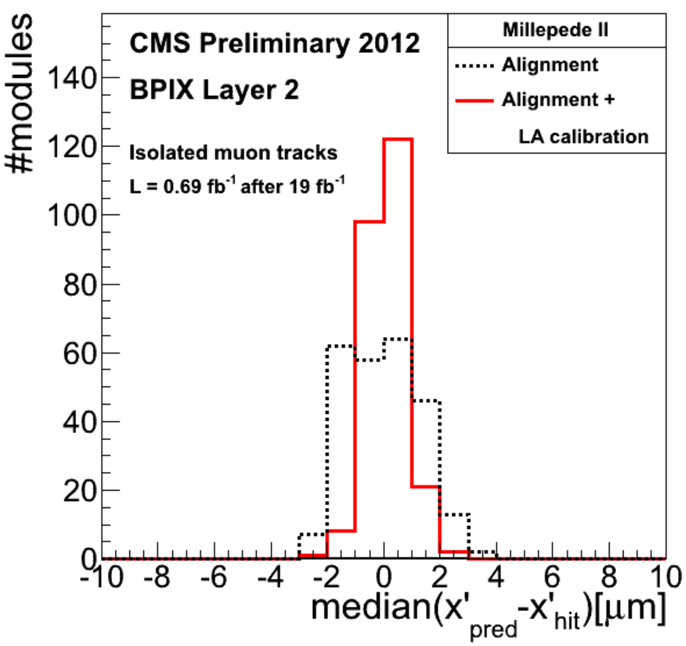


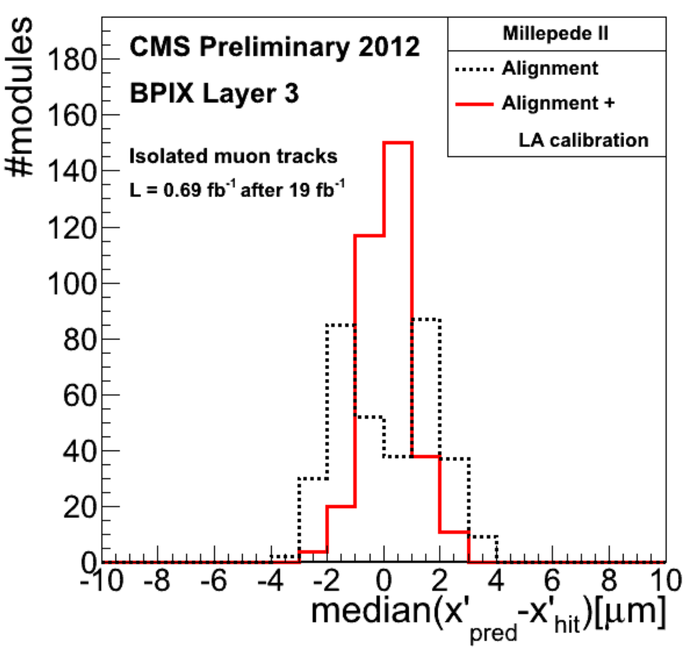


Lorentz Angle calibration

- Clear improvement in track residuals when incorporating LA calibration into alignment
  - Improves the precision of hit reconstruction





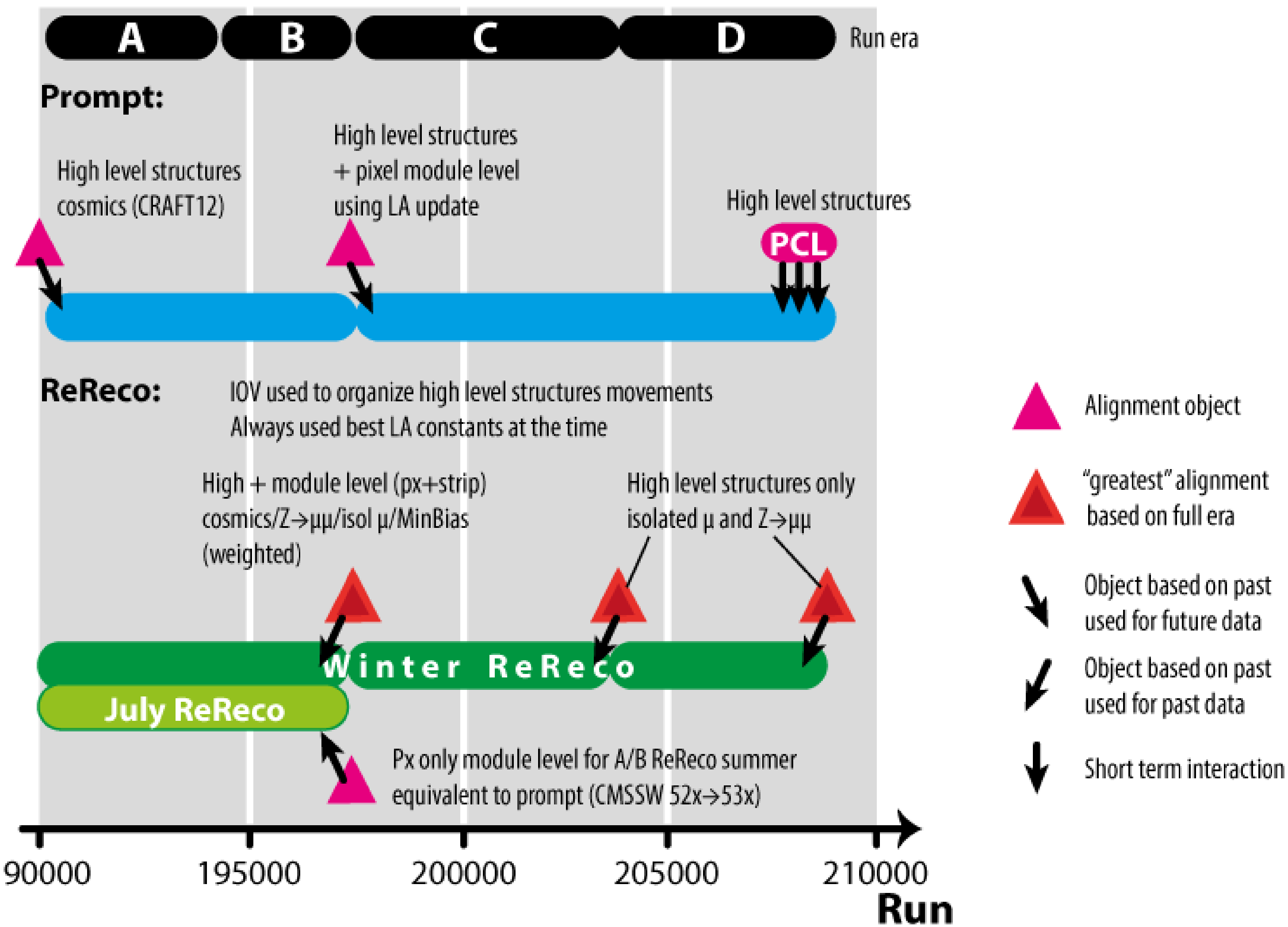


Summary

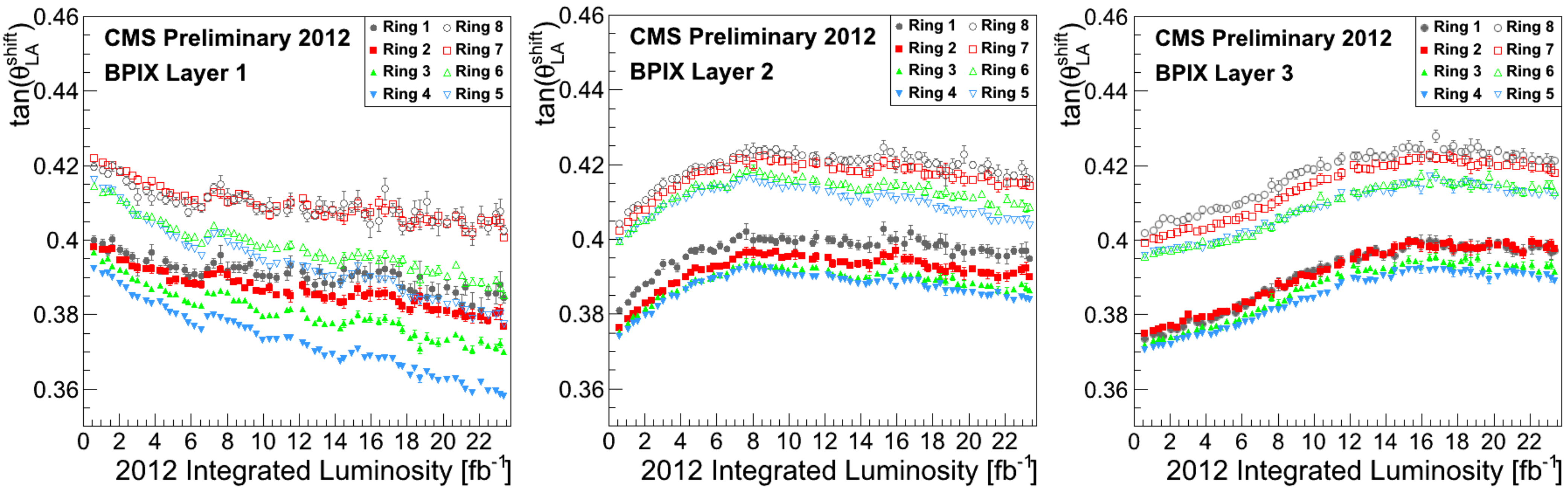
- Improvements made in alignment of CMS tracker during 2012:
  - Inclusion of large structure alignment in PCL
  - Track momentum bias improved using Z mass
  - Alignment extended to incorporate calibration of Lorentz Angle parameters
- Alignment using Millepede II provides the precision required to achieve high resolution tracking
  - Integral for the physics performance of CMS

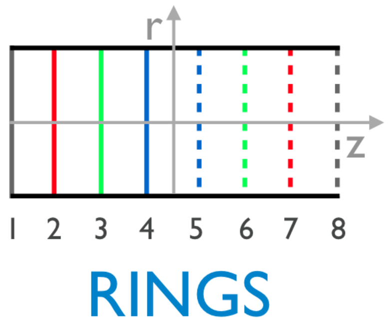
Backup

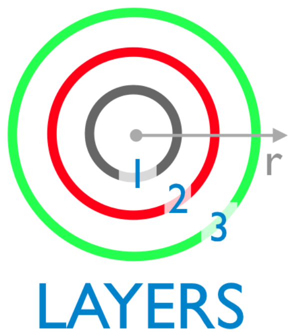
2012 Alignment Overview



Lorentz Angle Calibration

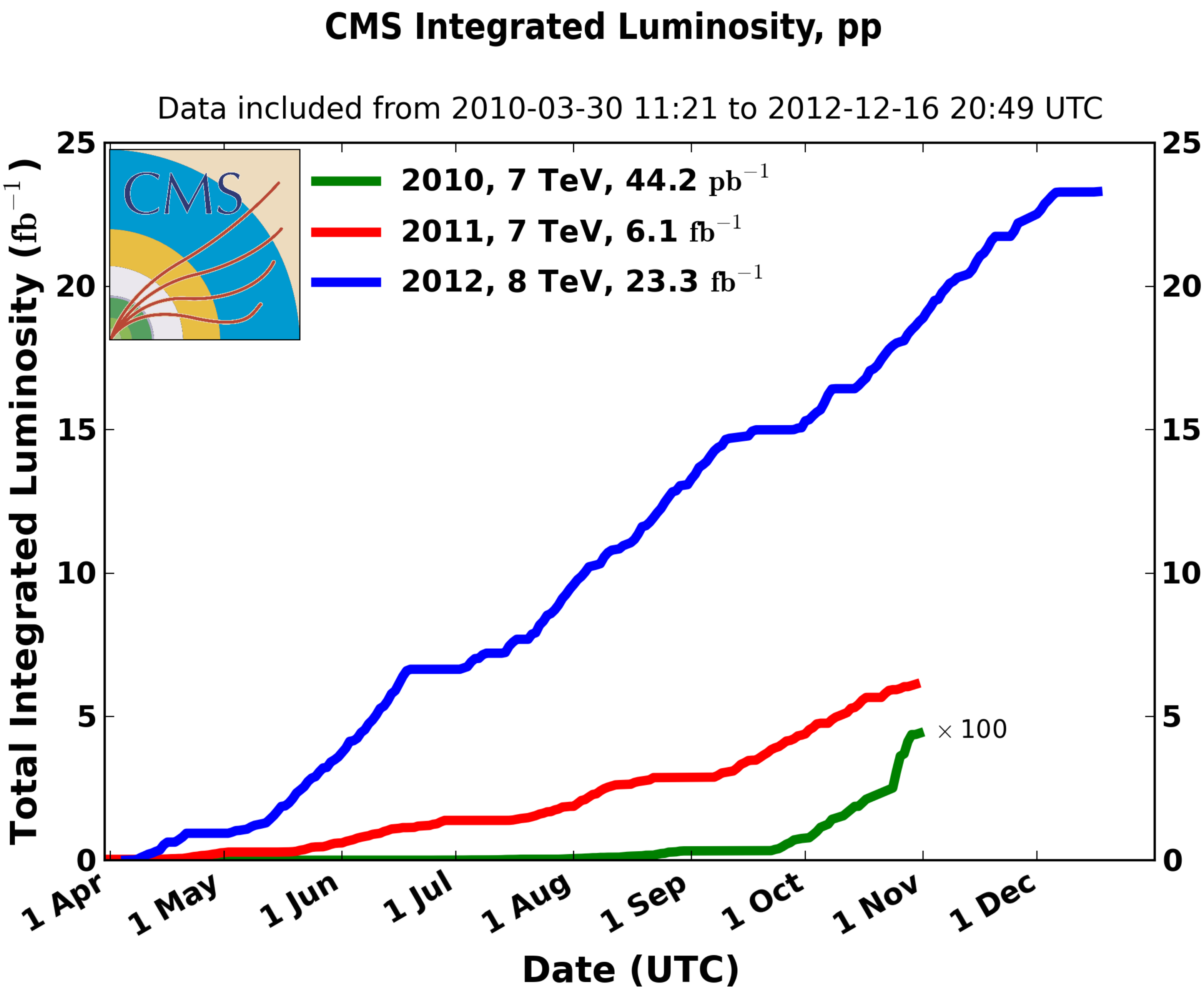






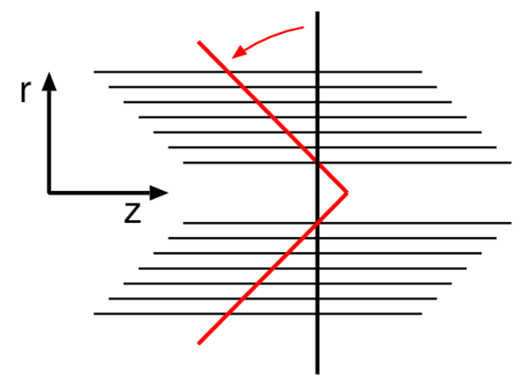
Lorentz Angle Calibration

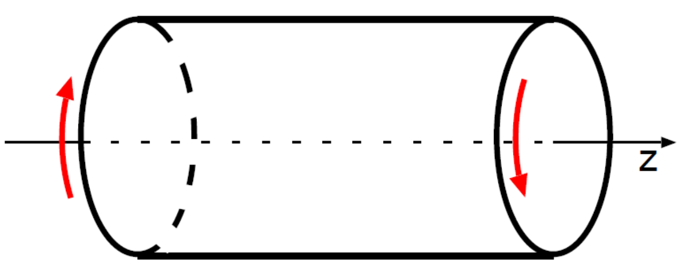
- B-on and B-off data used simultaneously in alignment to disentangle calibration and alignment effects.
- Used 60 million tracks from full 2012 data:
  - tracks of isolated muons,
  - Z->μμ,
  - cosmic ray muons (B-on and B-off),
  - low p_T, B-off pp data from August 2012.
- Lorentz angle in pixel barrel calibrated with granularity of 24 spatial parameters (3 layers x 8 rings) and 65 periods in time.

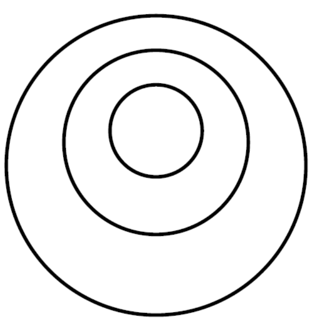

CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
CMS
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
$\times$ 100
Total Integrated Luminosity (fb^{-1})
Date (UTC)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
0
5
10
15
20
25

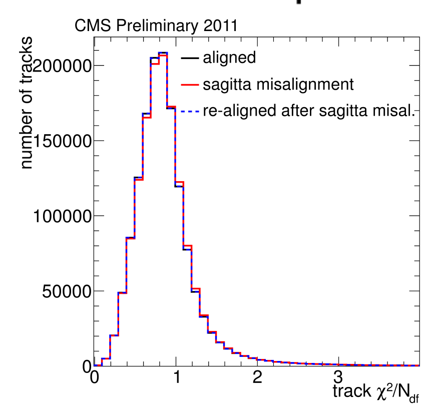
Weak Modes

- Some global movements don't effect the track residuals
  - When a coherent change of alignment Δp can be compensated by changing track parameters Δq
  - Difficult to treat by minimizing χ^2







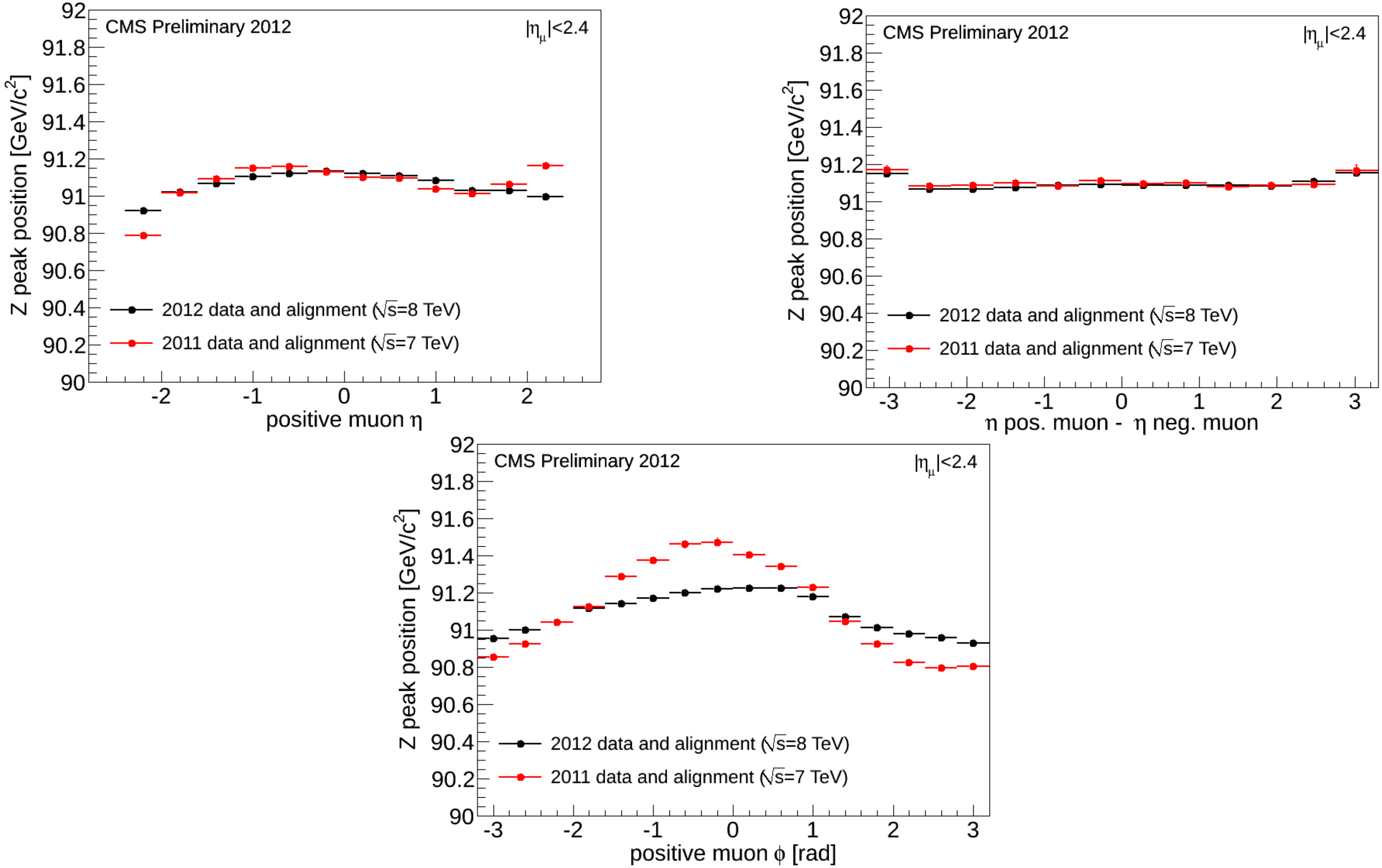


$Z^0 \rightarrow \mu^+\mu^-$ mass

- Distortions of the tracker geometry can lead to a bias in the reconstructed track curvature $K \sim \pm 1/p_T$
- These are investigated using the reconstructed Z->$\mu^+\mu^-$ mass, as a function of the muon direction and separating μ^+ and μ^- (since curvature bias has opposite effect on their p_T).
- Invariant mass distribution is fitted to a Breit-Wigner convoluted with a Crystal ball function (i.e. taking into account the finite track resolution and the radiative tail) for the signal plus an exponential background.
  - Fit range is 75–105 GeV/c^2, Z^0 width fixed to PDG value of 2.495 GeV/c^2.

This does not show the CMS muon reconstruction and calibration performance! It is the tracker input to all object reconstruction. Physics analyses apply momentum calibration on top of this.

$Z^0 \rightarrow \mu^+\mu^-$ mass



Prompt Calibration Loop