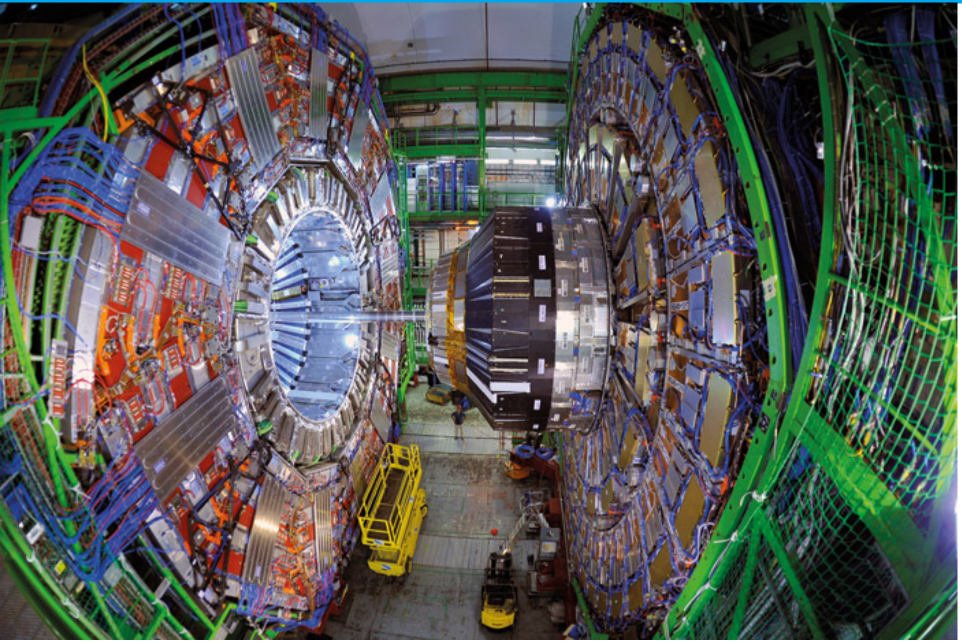
Alignment Requirements for Upgrade Trackers



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7th Detector Workshop of the Helmholtz Alliance "Physics at the Terascale"

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HGF-Alliance Project "Enabling Technologies for Silicon Tracking detectors at HL-LHC" (PETTL)

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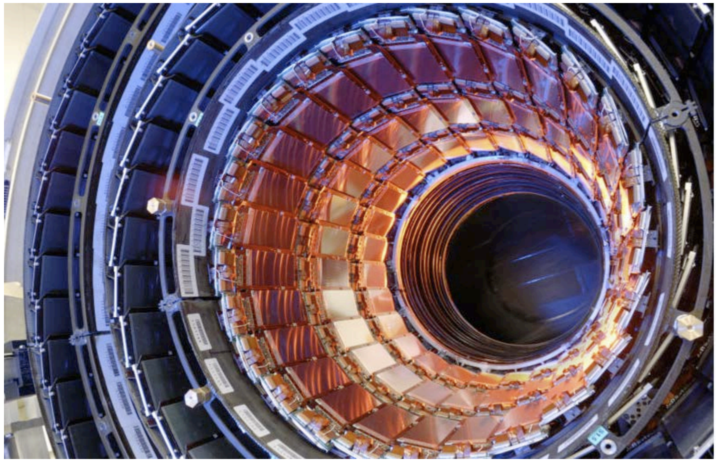
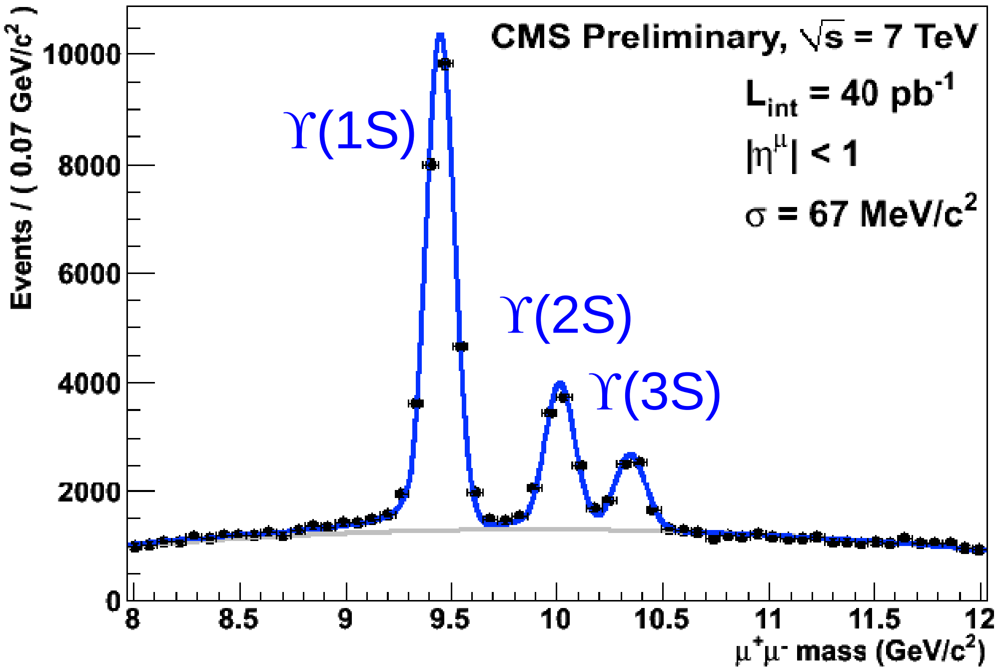
Introduction

- With high resolution & high segmentation of tracking detectors, alignment has become a key issue
- Performance of silicon trackers depends critically on alignment performance
- In this presentation, try to identify alignment aspects important for design of HL-LHC tracking detectors
- Based on the CMS experience in Run-I



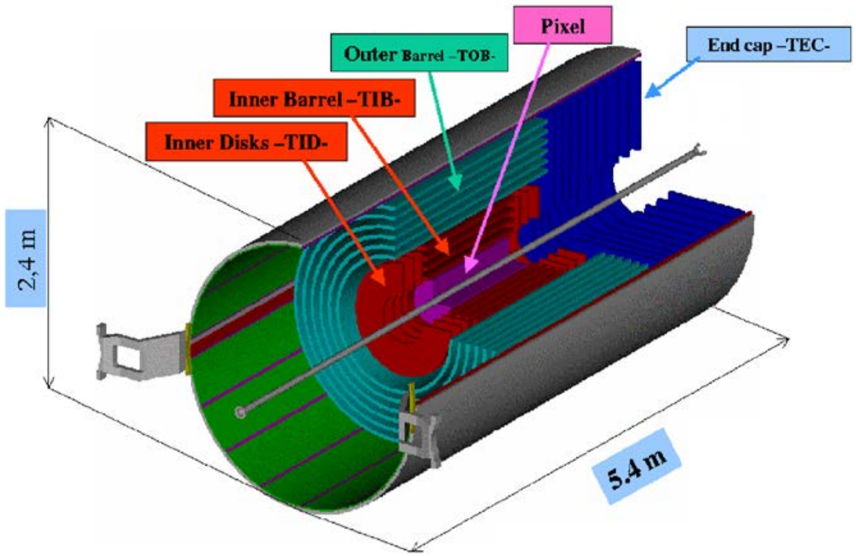
The Big Picture

- In the beginning, we were entering new territory in terms of tracker complexity. Even in 2008, it was not entirely clear if the problem could be managed
- In the end, with many new solutions, the alignment technology turned out to be more powerful than ever thought. Expectations were exceeded.
  - the LHC incident in fall 2008, regretful as it was, helped us in the alignment case. It gave us a long cosmics run and enough time to digest the data.
  - ➔ very good alignment from cosmics already at first 7 TeV physics run in spring 2010



Alignment Lessons Learned from LHC Run 1

The CMS Tracker



Pixel Tracker:

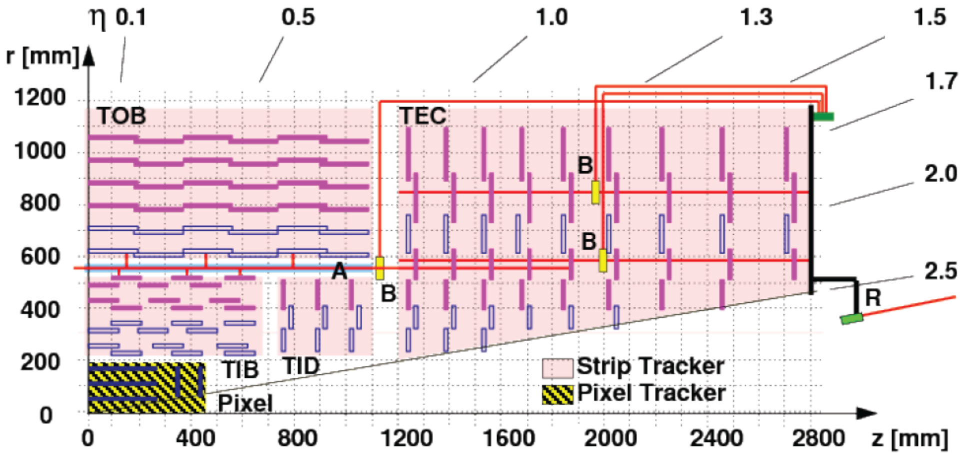
- 1440 modules
- hit resolution ~9 μm

Strip tracker:

- 15148 modules
- hit resolution 20-60 μm

Largest and most complex silicon detector ever built

- about 200 m^2 of silicon



Why is Alignment Important?

- Intrinsic coordinate resolution:
  - σ_{hit} ~9 μm (pixel)
  - σ_{hit} ~20-60 μm (strip)
- The effective coordinate resolution emerges from combination of intrinsic resolution and alignment

$$\sigma_{meas} \sim \sqrt{\sigma_{hit}^2 + \sigma_{alignment}^2}$$

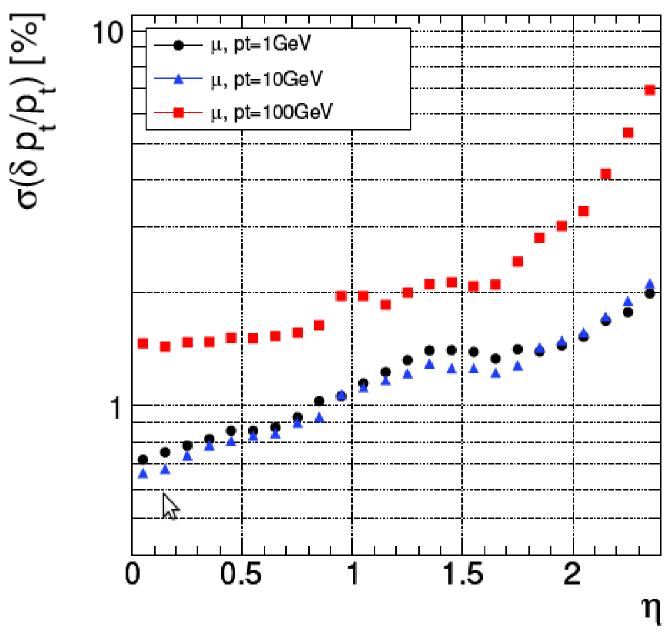
- In a simplified model, the relative momentum resolution is the combined effect of coordinate resolution and multiple scattering

$$\frac{\delta p_T}{p_T} = C_1 \cdot p_T \oplus C_2$$

where $C_1 \propto \sigma_{meas}$

➔ Need to keep $\sigma_{alignment} << \sigma_{hit}$

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



How Alignment Works (in CMS)

- Basic principle: minimize global χ^2 computed from track-hit residuals
- If we change the alignment parameters → track parameters change as well → huge coupled system
- To treat all correlations properly, perform global fit of all track parameters and all alignment parameters simultaneously

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

m_{ij}: measurement
σ_{ij}: uncertainty
f_{ij}: track prediction
p: alignment param.
$\mathbf{q}_j$: track parameters

- Gigantic fitting problem → requires very powerful tool
  - MILLEPEDE-II program [1]
  - General Broken Lines Track Refit (GBL) [2]
- Combine datasets of different event topologies
  - Isolated muons & minimum bias (15M + 3M)[2011]
  - cosmic muons (3.6 M)
  - Z→$\mu\mu$ decays (375 k)

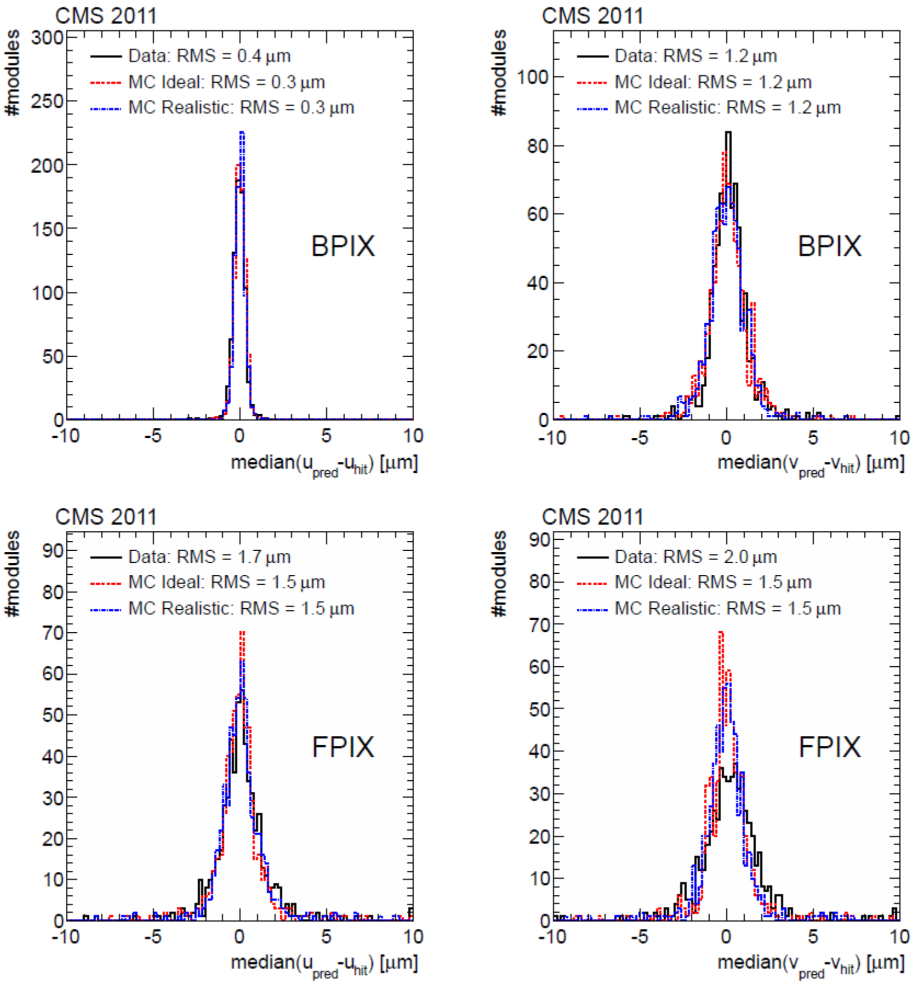
[1] V. Blobel, "Software alignment for tracking detectors", *Nucl. Instrum. Meth.* **A566** (2006) 513, https://www.wiki.terascale.de/index.php/Millepede_II
[2] https://www.wiki.terascale.de/index.php/GeneralBrokenLines

Alignment Accuracy (Pixel)

- Alignment performance was studied in great detail in context of the 2011 data-taking period

- Statistical accuracy of pixel tracker:
  - studied with distribution of medians of residuals (DMR)
  - observed in data: 0.4 – 2 µm
  - close to ideal MC: 0.3 – 1.5 µm
  - well described by realistic MC

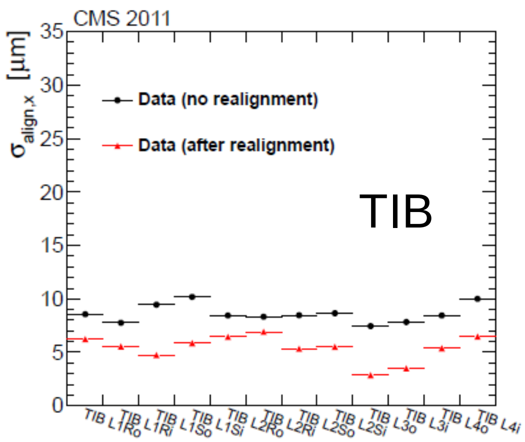
➔ Far better than specifications

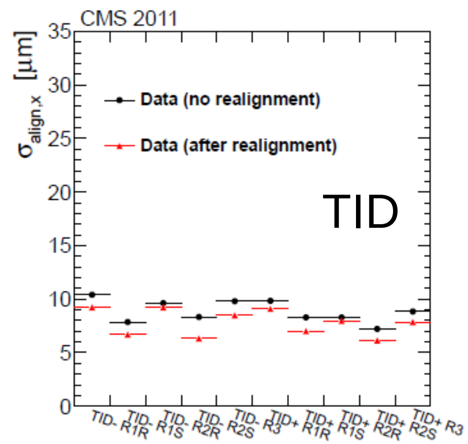


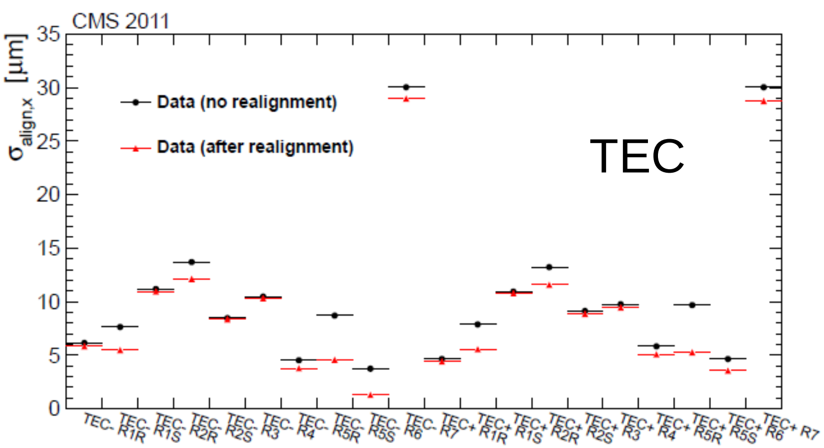
Alignment Accuracy (Strip)

- Granularity: sensor group
- Determined using distributions of normalized residuals
  - widened by misalignment
  - compensated by adding alignment error in quadrature to resolution
  - iterative process

➔ Results:
  - TIB: 3 – 8 µm
  - TID: 6 – 10 µm
  - TEC: 3 – 13 µm







How Many Modules Can We Handle?

- The current CMS tracker: 1440 Si pixel and 15148 Si strip modules
  - 5-6 alignment parameters for position & orientation per module / sensor
  - plus 3 shape parameters per module / sensor (2^{nd} order)
  - ➔ around 200 000 parameters for full alignment
  - with advanced optimization using multi-processor architectures, ~10h wall-clock time
    - sparse matrix storage → <32 GB of memory

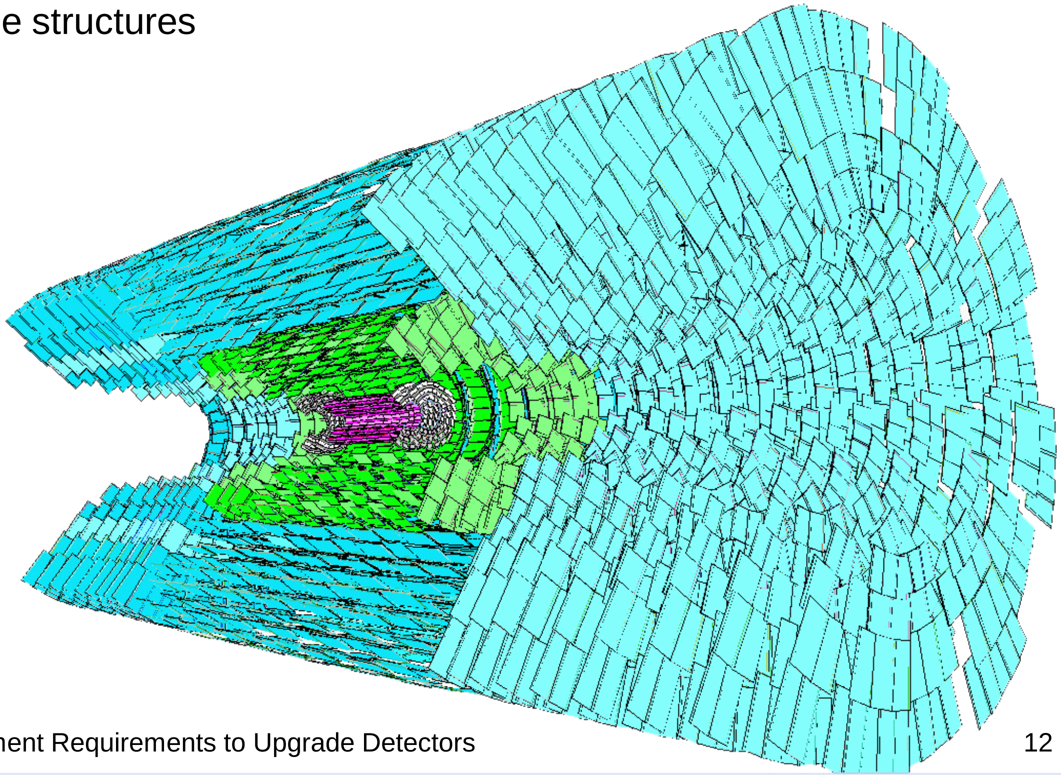
- The Millepede-II based methodology is not yet stretched to the limit
  - however, memory footprint needs to be watched
  - planned inclusion of $\Upsilon \to \mu\mu$ signatures will populate further the off-diagonal regions
  - ordered 96 GB machines for CERN CAF

➔ It is reasonable to expect that a moderate increase of the number of modules (up to ~30%) can be accommodated (but this has not been tested)
  - CPU and memory demands grow quadratically with number of alignment parameters !
  - expect increase of computing performance by time of HL-LHC

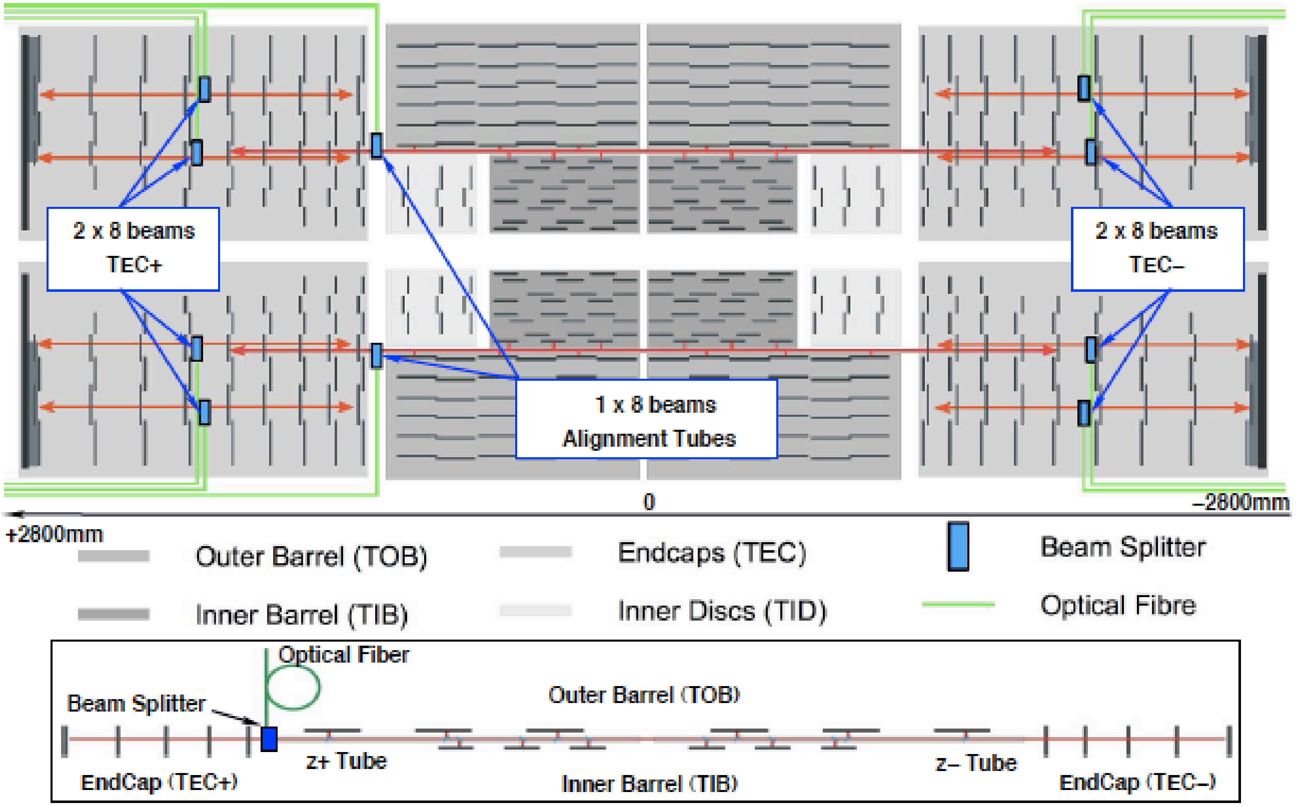
Monitoring and Stability

Mechanical Stability & Monitoring

- We rely strongly on mechanical stability of the tracker. In case of quick & complex movements, we would not be able to perform full re-alignment every couple of hours
- A quick look at the time-dependent alignment of the current CMS tracker
  - laser alignment
  - track-based monitoring of large structures



Laser Alignment System

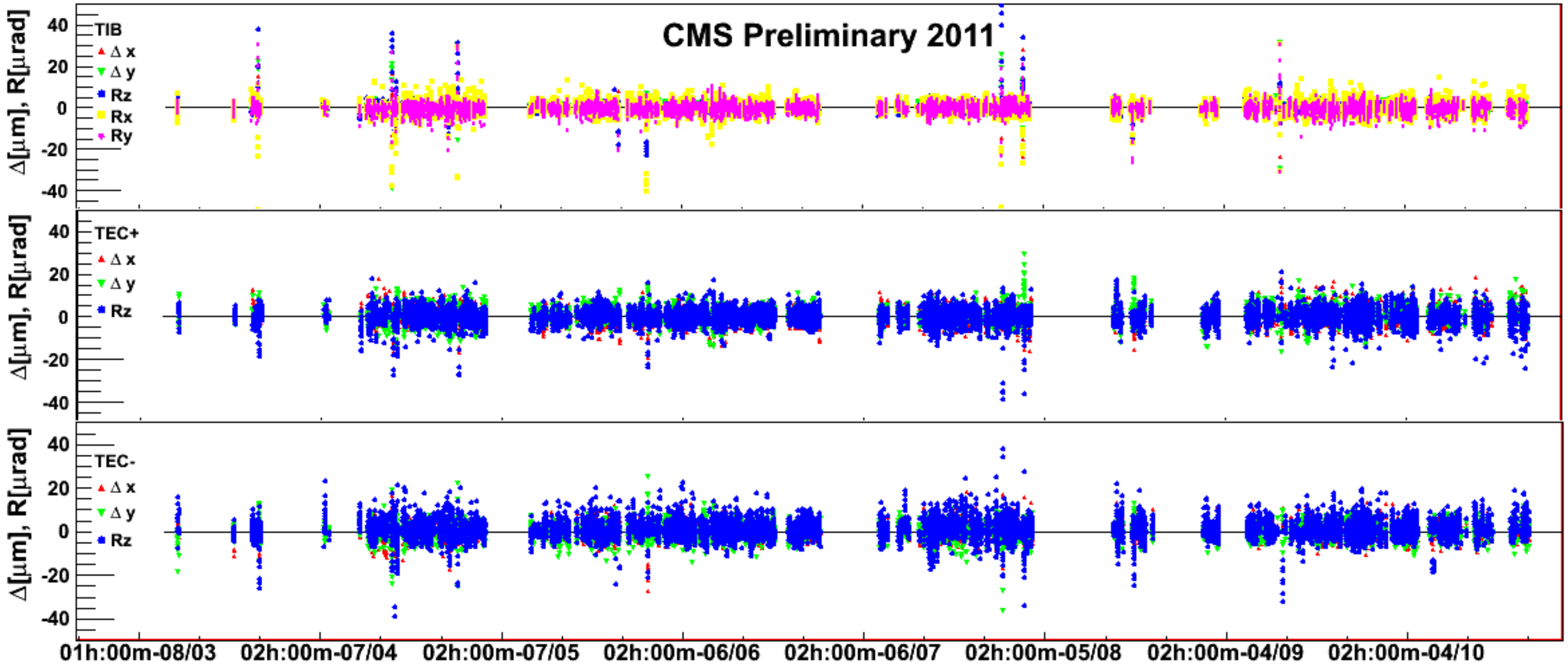


Slide adapted from Adrian Perieanu

- Si strip modules: 434 modules (3%) are illuminated by the laser beams
- Data taking during pp collisions and cosmic muon runs using same data acquisition system as for physics data
- Calibration triggers fire the lasers at 100 Hz in orbit gap – 2000 triggers every 5 min

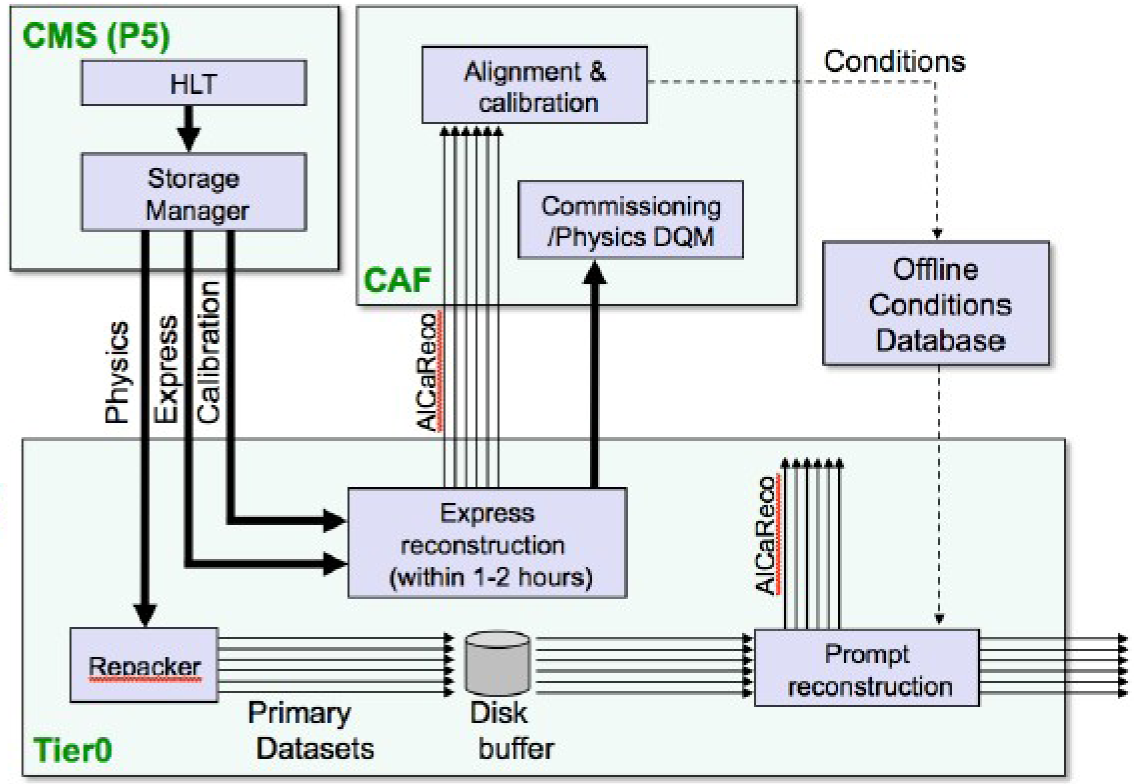
Laser Alignment System (cont'd)

- Very fast (!) determination of high-level alignment parameters
- Results show very good stability within a run (shown: changes wrt. last 5 minutes)
- Strip tracker very stable → no frequent re-alignment needed
- LAS does not cover pixel tracker → dedicated track-based monitoring

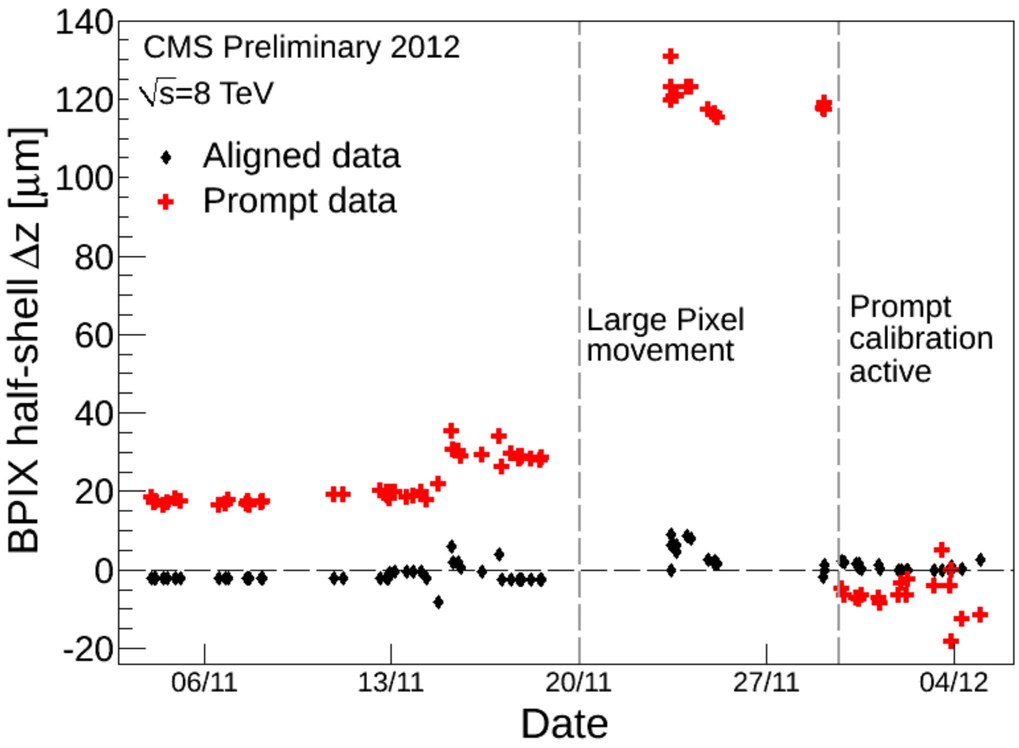


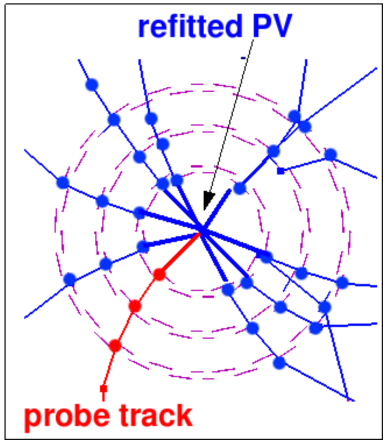
Prompt Calibration Loop

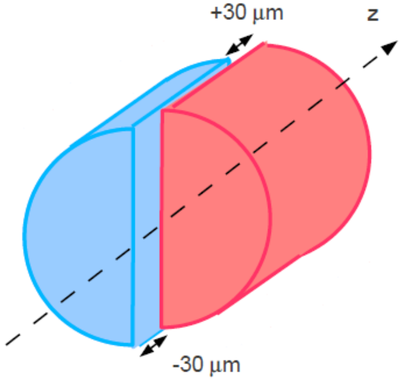
- Computes six alignment parameters per large structure of pixel tracker
- ➔ Feedback within 48 hours of data-taking, in time for prompt reconstruction



Monitoring & Prompt Alignment





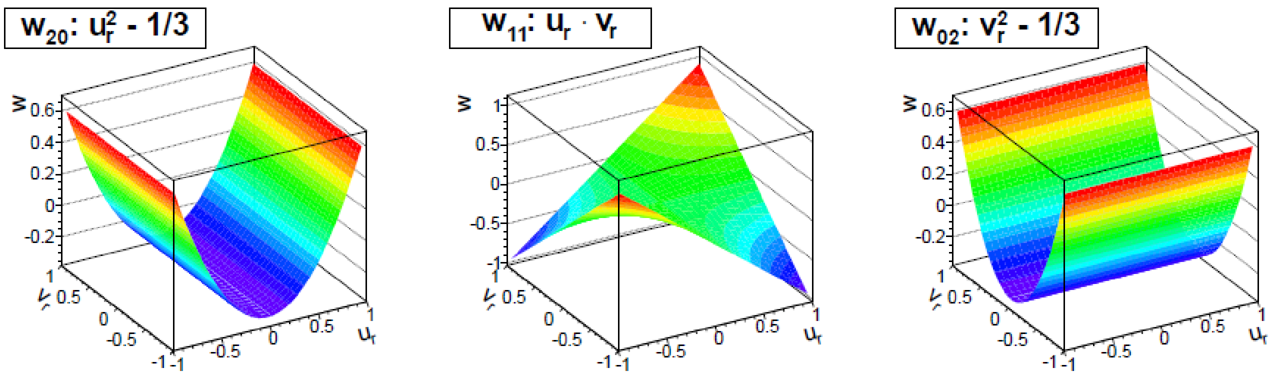


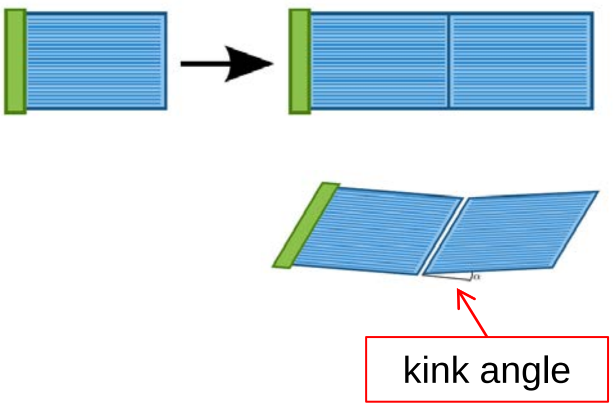
- In CMS, the main movement is between the barrel half-shells of the pixel tracker
  - ➔ can exceed 100 microns (!)
  - ➔ sophisticated prompt alignment procedure → correct in advance of the prompt reconstruction
  - ➔ preempt such movements & mitigate them with an optical system in future trackers?

Systematics of Alignment

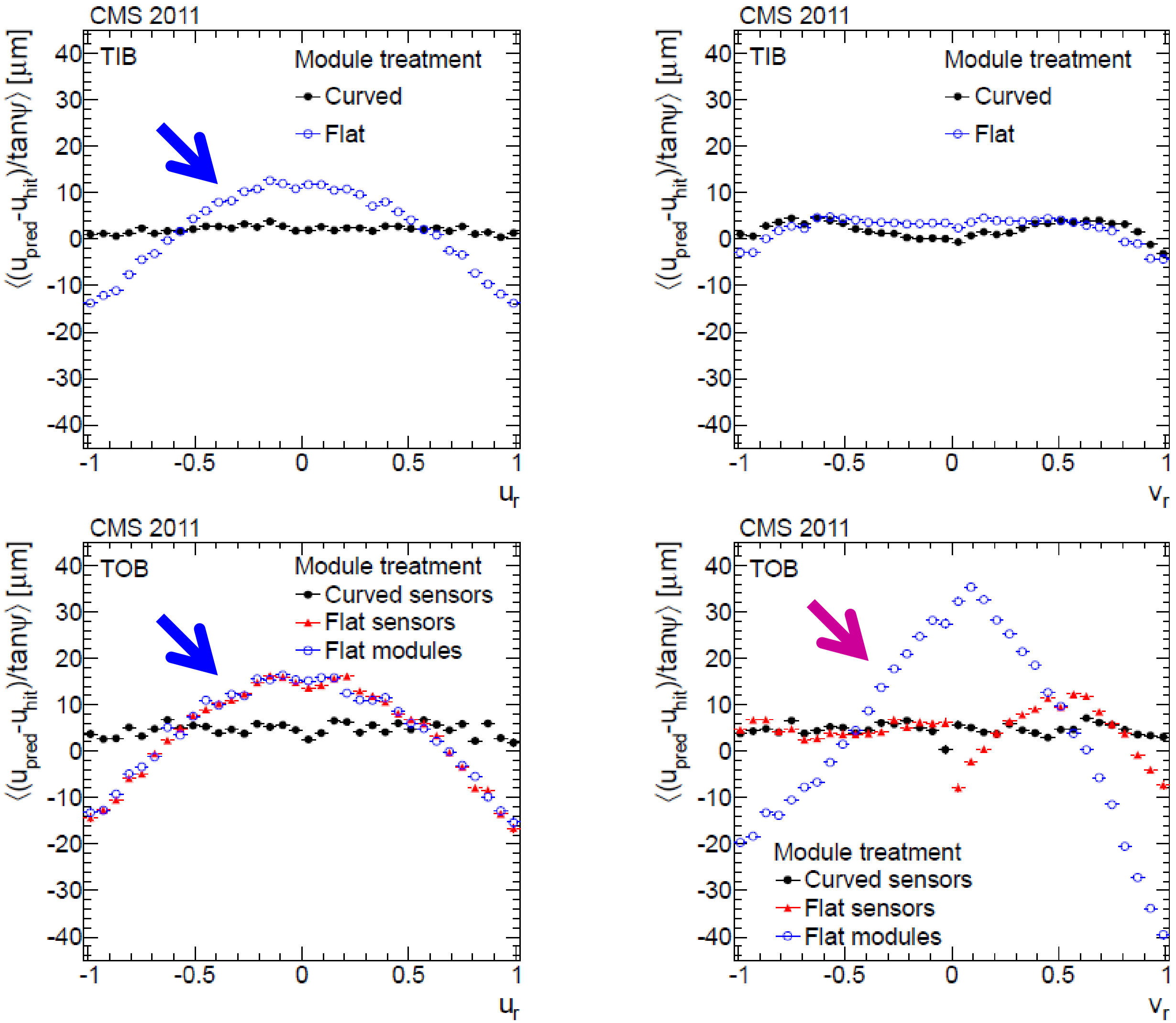
Sensor Shape Parameters

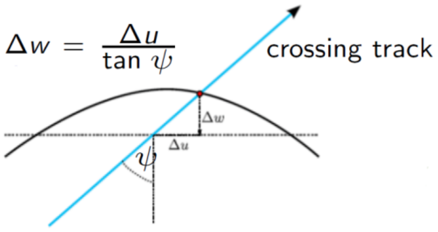
- In real life, sensors are not planar
  - ➔ without correction, coordinate measurement of non-perpendicular tracks is biased
- ➔ Introduce three additional curvature parameters per sensor
- ➔ In addition, "kink angles" and offsets are introduced between daisy-chained sensors in TOB modules
- ➔ Increases the number of alignment parameters 80 000 → 200 000





Sensor Shape Parameters





- Curvature in TIB and TOB modules (in direction transverse to strips)
- Kink between sensors in TOB modules (in direction parallel to strips)

Curvature Parameters vs Module Group

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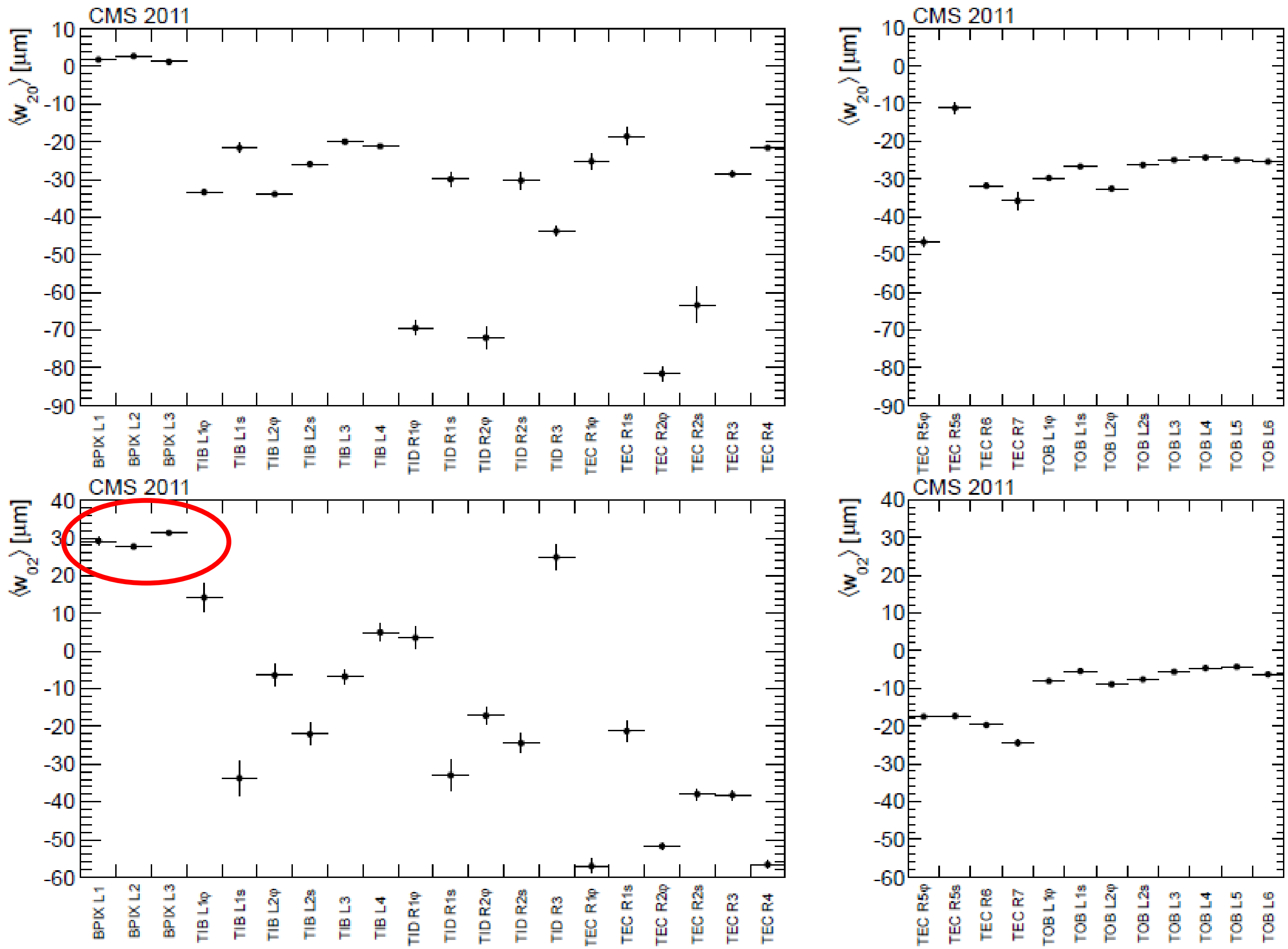


Sensor Shape Parameters (cont'd)

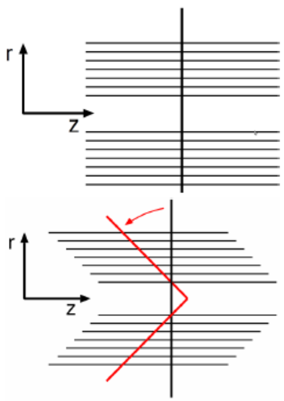
- CMS alignment found and corrected curvature sagittae of up to 200 μm (in the tail of the distribution)
  - specification was < 100 μm → perhaps larger in situ due to stresses

- Alignment takes care of such curvatures very efficiently
  - ➔ specifications could be even relaxed

Weak Modes

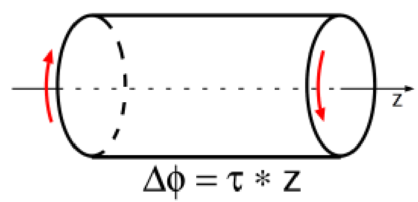
- Many small modules → vulnerability to weak modes
  - ➔ global distortions that can bias track parameters

- Example 1: "telescope" $\Delta z \propto r$
  - creates bias in η



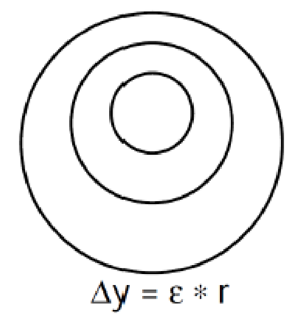
- Solution: cosmic muon tracks

- Example 2: "twist" $\Delta\phi \propto z$
  - creates η-dependent curvature bias



  - not fully cured by cosmics
- Solutions:
  - field-off cosmics
  - $Z \rightarrow \mu\mu$ decays

- Example 3: "sagitta" $\Delta r \propto y$
  - creates ϕ-dependent curvature bias

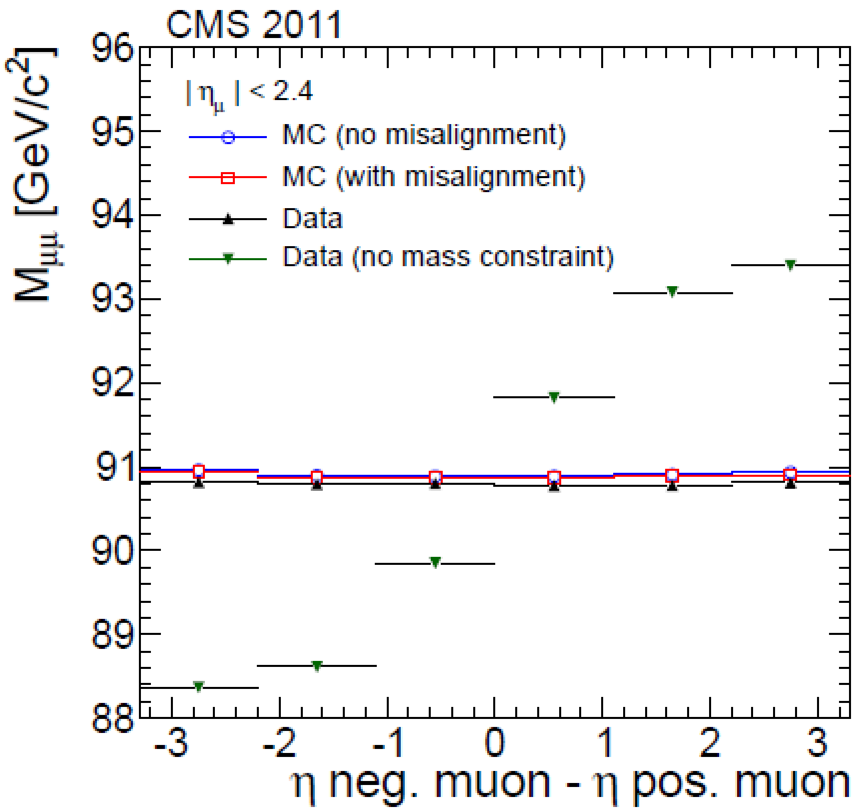


- Solutions:
  - field-off cosmics
  - $Z \rightarrow \mu\mu$ decays

Weak Modes

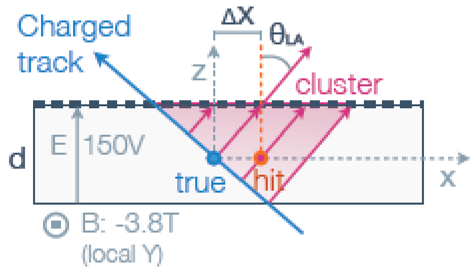
- Weak modes are effectively controlled by combining various different event topologies
  - tracks from interaction point (pp collisions)
  - cosmic ray tracks
  - $Z \rightarrow \mu\mu$ decays
  - plus B=0 tracks, $\Upsilon \rightarrow \mu\mu$ if available
- → It is essential to foresee acquisition of such data samples regularly in sufficient quantity
  - especially cosmic muons
- → Module size is important
  - smaller modules → higher vulnerability to weak modes
- → Overlaps between adjacent sensors help
  - resilience against weak modes
  - very useful for monitoring

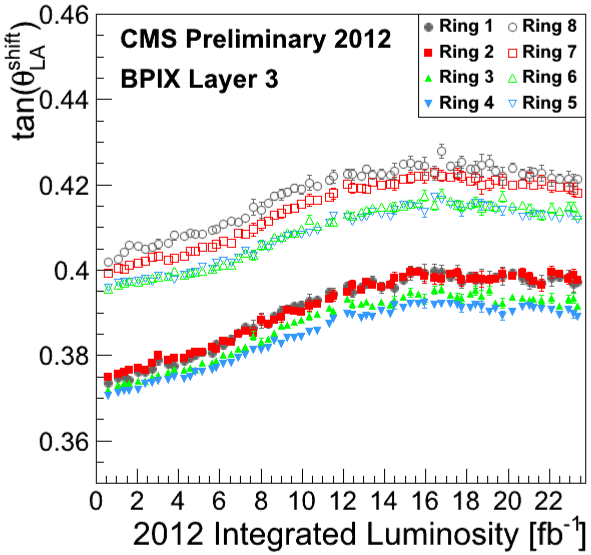
Monitoring of weak modes: bias of reconstructed Z mass

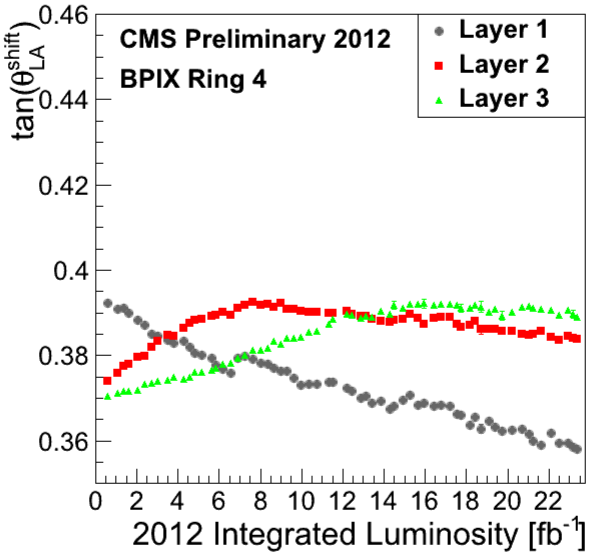


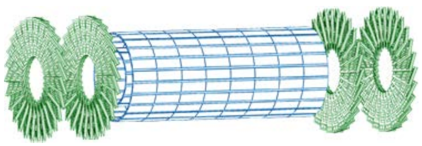
Integrated Determination of Lorentz Angle

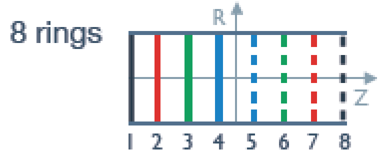
- Precise determination of Lorentz angle is essential for track resolution
- High radiation dose in pixel tracker → expect significant location- and time-dependence of LA
  - ➔ determine at high granularity in space and time
  - ➔ 1560 additional "alignment" parameters (BPIX) for 65 time intervals
  - ➔ inclusion of field-off tracks





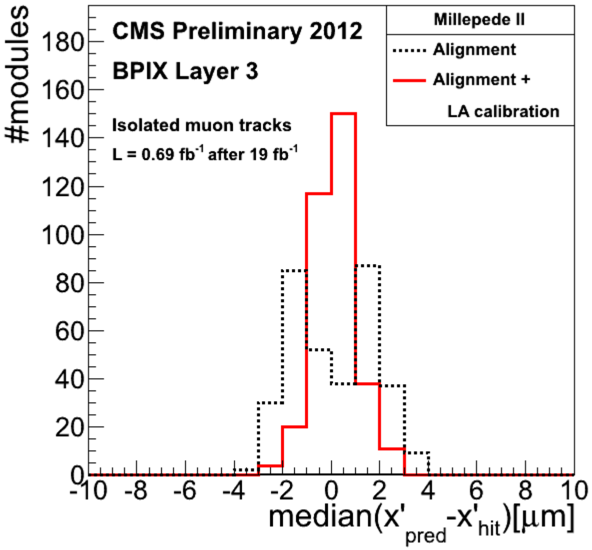






Lorentz Angle (cont'd)

- Integration of Lorentz angle calibration into alignment procedure works well
- Clear time-dependence of Lorentz angle observed
  - consistent development in all rings
  - different shape evolution among layers
  - expect much stronger effects with increased luminosity (after LS1)
- Variation of Lorentz angle equivalent to a module shift of 4 μm
  - improvement clearly visible in DMR validation plots (narrower peak)



Implications for Future Trackers (Summary)

Implications for Upgrade Detectors

- Number, size and arrangement of modules
  - ➔ alignment can handle the current number of modules well → expect that a moderate increase (~30%) is still tolerable
  - ➔ the smaller the modules, the bigger the relevance of weak modes
  - ➔ shape parameters (e.g. curvatures) can be determined simultaneously
  - overlaps between adjacent modules are very helpful
- Stability
  - ➔ it is important that the geometry is mostly very stable with time
  - alignment can handle time dependence of a limited number of parameters. A full re-alignment every couple of minutes is hardly feasible.
- Material
  - state-of-the-art alignment technology treats multiple scattering rigorously
    - in case of CMS: general broken lines fit (GBL)
- Weak mode treatment is essential
  - cosmic data-taking is vital → need appropriate triggers, in particular for shallow angles
  - ➔ schedule stand-alone data-taking for both field-on and field-off cosmics
  - ➔ large rates of di-muon resonances (Z bosons, Υ quarkonia etc)

Implications for Upgrade Detectors (cont'd)

- Survey data
  - especially in the initial phase, precise metrology data are important, even if they are only measured within planar substructures (rods, staves, petals etc)
    - can be used as initial (low-level-hierarchy) alignment constants, to be superseded later with track-based constants
  - ➔ it is highly commendable to **think at an early stage** about the interface between measurement database and the use of such survey data in the alignment process
- Hardware-based alignment (laser)
  - in CMS, a laser system using directly the tracker sensors is operated successfully
    - mainly used to monitor the (very good) stability of the strip tracker
    - in case of marked time dependence, would have been essential to spot movements & define intervals of validity for alignment constants
    - in retrospect, an additional system monitoring the pixel tracker half barrels would have been attractive → feasible for upgrade ?
    - all reconstruction-relevant alignment constants were derived from tracks
  - could be important for future track triggers
    - latency of prompt alignment probably too high

Summary

- Alignment is a **key driver for physics performance**

- Originally one of the major challenges, alignment has been **highly successful** during Run-I of the LHC
  - far exceeded expectations
  - a major prerequisite for high tracker performance, leading to **excellent physics results**

- Given the experience, we can be **reasonably confident** that alignment can be managed with well-designed upgrade detectors

- It is important to take alignment aspects into account in the design of the new trackers. Various lessons have been detailed during this presentation

Final Remarks

- Thanks for material and helpful discussions:

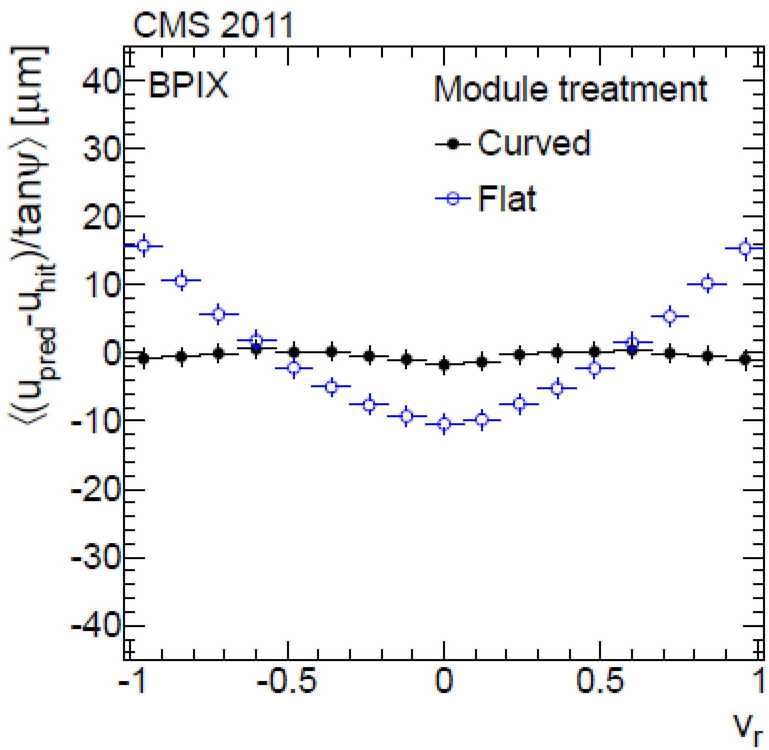
  Claus Kleinwort, Marco Musich, Danny Noonan, Matthias Schröder

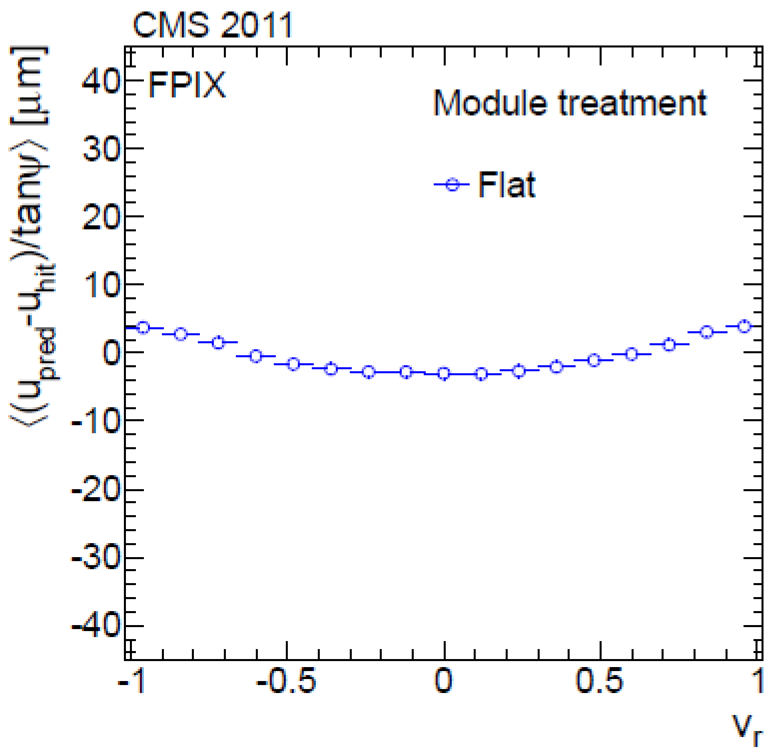
- Comprehensive CMS Tracker Alignment paper:

  just being submitted to arXiv and JINST !

Backup

Sensor Shape Parameters (Pixels)





CMS Detector