Alignment of the CMS Tracking Detector

3rd Beam Telescopes and Test Beams Workshop, DESY, Hamburg

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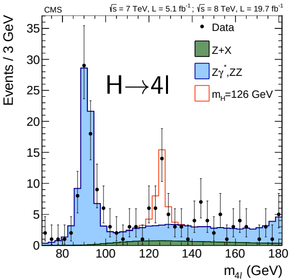
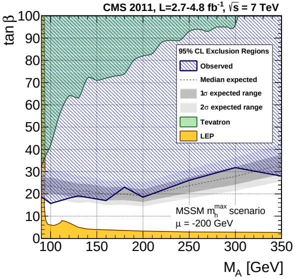
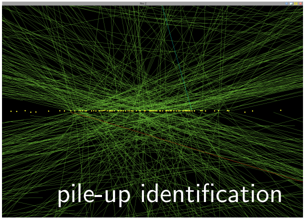
January 19, 2015

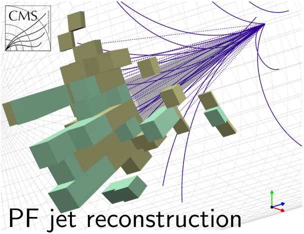
Precise Tracking is Key to CMS Physics Performance



MSSM $\Phi \to b\bar{b}$







Physics performance depends crucially on precise tracker alignment

What Alignment Precision is Needed?

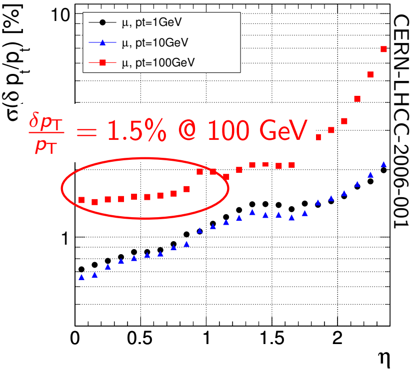
- Track p_T resolution

$$\frac{\delta p_T}{p_T} = \underbrace{C_1 \cdot p_T}_{\text{position res.}} \oplus \underbrace{C_2}_{\text{multiple scat.}}$$

with $C_1 \propto \frac{\sigma_{meas}}{B \cdot L^2 \cdot \sqrt{N}}$

- Effective position resolution
  - $\sigma_{meas} \propto \sigma_{hit} \oplus \sigma_{align}$
- Intrinsic hit-position resolution
  - $\sigma_{hit} \approx 9\ \mu m$ (pixel)
  - $\sigma_{hit} \approx 20 - 60\ \mu m$ (strip)

design tracker p_T-resolution of single-μ



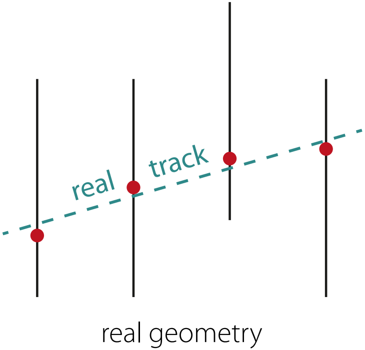
Need to keep $\sigma_{align} \ll \sigma_{hit}$

Outline

1. Track-Based Alignment
2. Alignment Challenge at CMS
   - CMS Tracking Detector
   - Global-Fit Approach with MILLEPEDE-II
3. Alignment Accuracy
4. Advanced Corrections
   - Sensor Shape Parameters
   - Lorentz-Angle Calibration
5. Sensitivity to Systematic Distortions
6. Summary & Outlook

Track-Based Alignment

Difference between real and assumed geometry affects track measurement



- **Idea:** residuals r between measured and predicted hit positions to detect mis-alignments of modules

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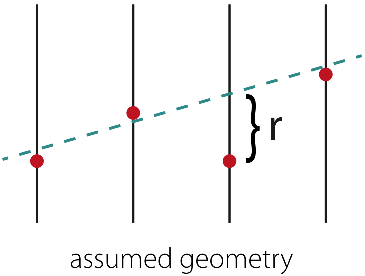

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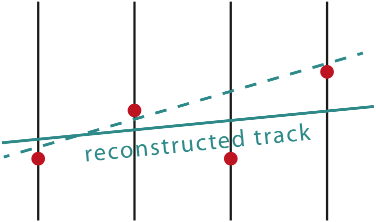

assumed geometry

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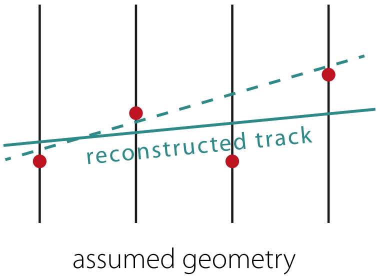


- **Idea:** residuals r between measured and predicted hit positions to detect mis-alignments of modules
- Cannot simply move module by $-r$
  - Change of position (alignment) parameter
  - Change of track parameters
  - Change of other residuals

$\rightarrow$ Tracks correlate alignment parameters

$\rightarrow$ Use many tracks

Simultaneous fit of alignment + track parameters for many tracks

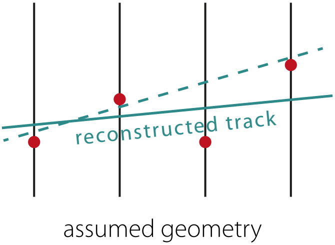
Global-Fit Approach to Tracker Alignment

- Minimise χ^2 computed from track-hit residuals of many tracks

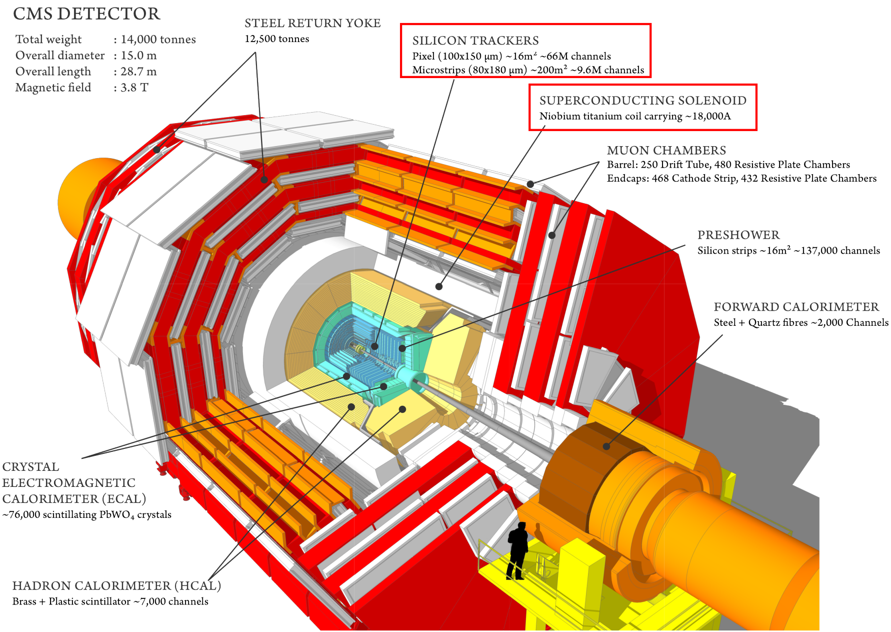
$$\chi^2(\mathbf{p}, \mathbf{q}) = \sum_i^{\text{tracks}} \sum_j^{\text{hits}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p}, \mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

with

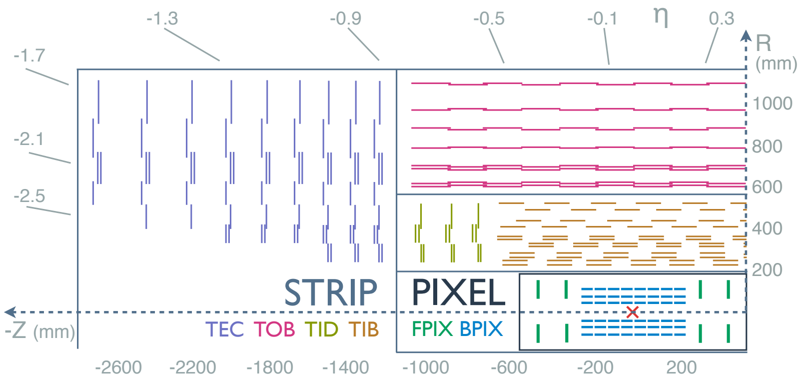
- measured hit positions m_{ij} and
- predicted positions $f_{ij}(\mathbf{p}, \mathbf{q}_j)$



- *Simultaneous* fit of all alignment parameters $\mathbf{p}$ and track parameters $\mathbf{q}_j$ takes into account all correlations


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 PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

CMS Tracking Detector

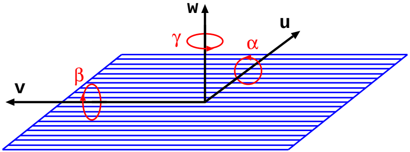


- 1 440 silicon pixel modules
  - 3D hit-position measurements
- 15 148 silicon strip modules (24 244 sensors)
  - Generally 2D measurements (rϕ direction)
  - In some layers: additional modules rotated by 100 μrad

The Alignment Challenge

- At CMS
  - Up to 6 parameters per sensor

$\leftrightarrow$	$x \;\; y \;\; z$	*shift* along axis
$\circlearrowleft$	$\alpha \;\; \beta \;\; \gamma$	*tilt* around axis



The Alignment Challenge

- At CMS
  - Up to 9 parameters per sensor

$\leftrightarrow$	$x\ \ y\ \ z$	*shift* along axis
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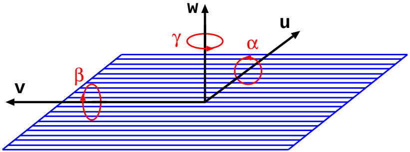
$\smile$	$w_0\, w_1\, w_2$	surface *distortion*



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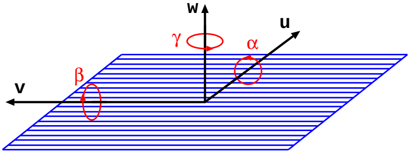
$\smile$	$w_0 w_1 w_2$	surface *distortion*

  - Additional parameters for Lorentz angle corrections



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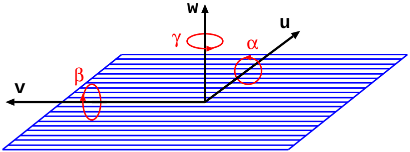
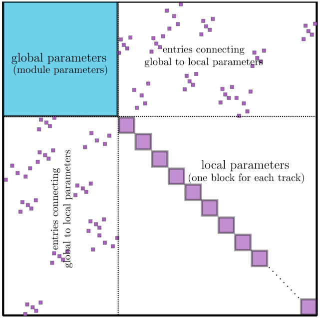


- $N_{\text{alignment pars}} = N_{\text{sensors}} \cdot N_{\text{dof}} \approx 2 \cdot 10^5$
- Typical fit requires $\mathcal{O}(10^6)$ tracks with ≥ 5 parameters

Alignment of CMS tracker: least squares fit with $\mathcal{O}(10^7)$ parameters

Global-Fit with MILLEPEDE-II[1]

- Local linearisation of track model and minimisation requiring $\mathrm{d}\chi^2(a)/\mathrm{d}a = 0$
  - System of linear equations $\mathbf{Ca} = \mathbf{b}$ with $\mathbf{a}^T = (\boldsymbol{\Delta}\mathbf{p}, \boldsymbol{\Delta}\mathbf{q})$
- Track parameters $\mathbf{q}$ in part of data only
  - Block structure in $\mathbf{C}$
- Only interested in alignment parameters $\mathbf{p}$
  - Problem can be reduced to $\mathbf{C}'\boldsymbol{\Delta}\mathbf{p} = \mathbf{b}'$
  - Solution provides alignment parameters
  - All correlations still taken into account



- $\mathbf{C}'$, $\mathbf{b}'$ by solving $N_{\text{track pars}} \times N_{\text{track pars}}$ matrix per track
- Dramatic cost reduction

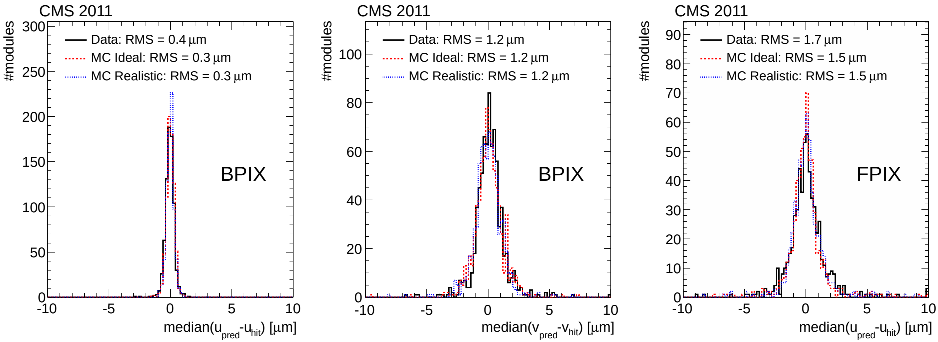
$$N^2_{\text{align pars}} + N_{\text{tracks}} \cdot N^2_{\text{track pars}} \ll (N_{\text{align pars}} + N_{\text{tracks}} \cdot N_{\text{track pars}})^2$$

  - Full-scale alignment performed within $\lesssim 24$ h

[1] V. Blobel, *Software alignment for tracking detectors*, Nucl. Instrum. Meth. A566 (2006) 5-13, doi:10.1016/j.nima.2006.05.157

Alignment Accuracy

Studied with distribution of medians of residuals (DMR) per module



— Observed RMS in data: 0.4-2 μm (pixel detector)

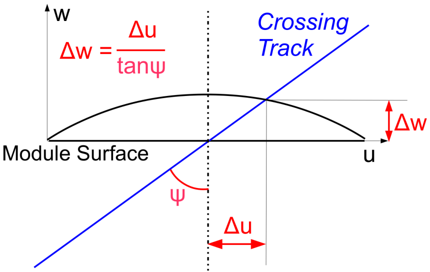
- - Well described by expectations from simulation

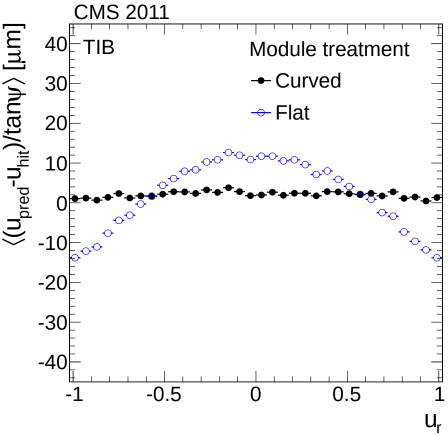
· · · Close to ideal conditions, i. e. at limit of DMR precision

Far better than performance specifications

Alignment of Sensor Deformations

- Real sensors possibly not planar
- Bias in coordinate measurement of non-perpendicular tracks

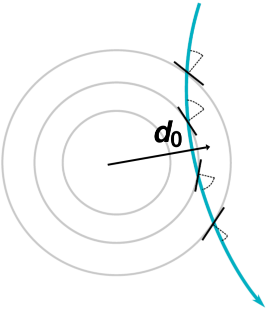


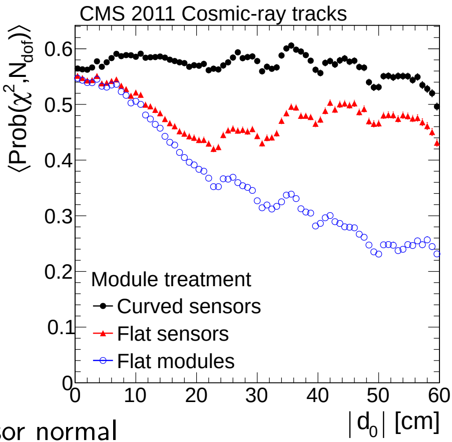


- Fit 3 additional parameters describing sensor curvature

Correction of Deformations Improves Cosmic-μ Tracking

- Cosmic-μ tracks mainly from above





- Increasing d_0

$\rightarrow$ increasing average angle from sensor normal

$\rightarrow$ increasing sensitivity to deviation from flat sensor

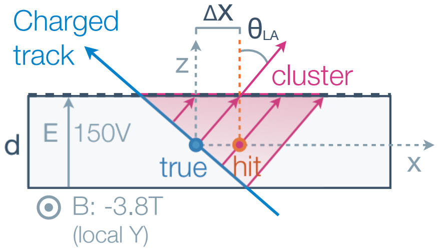
Improved $\langle \text{Prob}(\chi^2, \text{ndof}) \rangle$ at large d_0 for curved-sensor model

Lorentz-Angle Calibration

- Charge drift in B field affects measured hit position

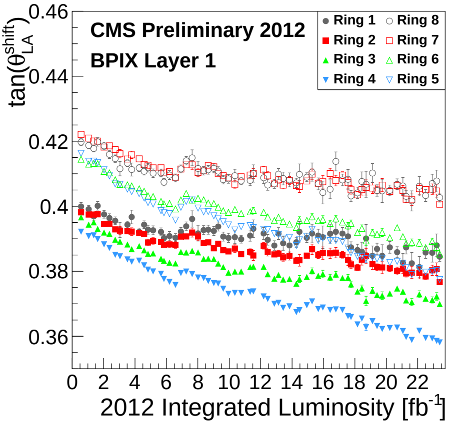
$$\Delta x = \frac{d}{2}\tan(\theta_{\mathrm{LA}})$$

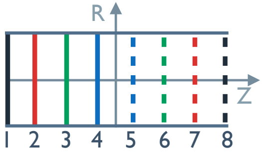
- Knowledge of Lorentz angle θ_{LA} essential for position resolution



- Determination of θ_{LA} incorporated in alignment fit
  - Sensitivity by simultaneous fit to field-off and field-on data
- θ_{LA} depends among others on irradiation dose
  - Expect significant time dependence in particular in pixel tracker

Lorentz-Angle Calibration



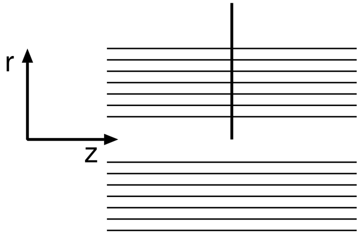


- Time dependence of θ_{LA} correction for each ring of barrel pixel detector
  - Offset between R1-4 and R5-8 due to different bias voltages
- Decrease with integrated luminosity (=irradiation)
  - Strongest for innermost rings
- θ_{LA} calibration equivalent to module shift of $\approx 4\ \mu$m

Few μm effect, but relevant for upcoming LHC run

Weak Modes

- Likelihood insensitive ($\Delta\chi^2 \approx 0$) to certain global distortions
- However, potential bias of track parameters



- *Example:* tracks are straight lines in rz

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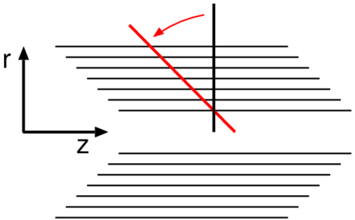

- *Example:* tracks are straight lines in rz
- "telescope" distortion $\Delta z \propto r$
  - Track is still straight line
  - $\rightarrow$ bias in η

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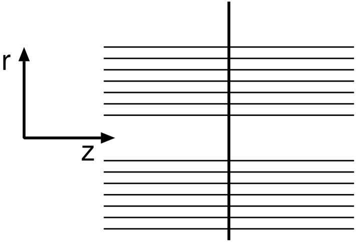

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- *Solution:* adding cosmic-μ tracks

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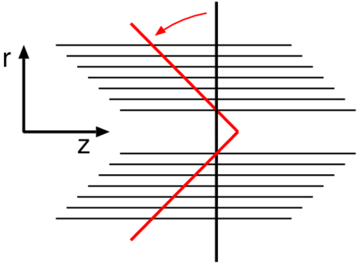
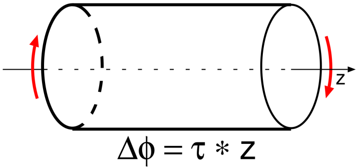
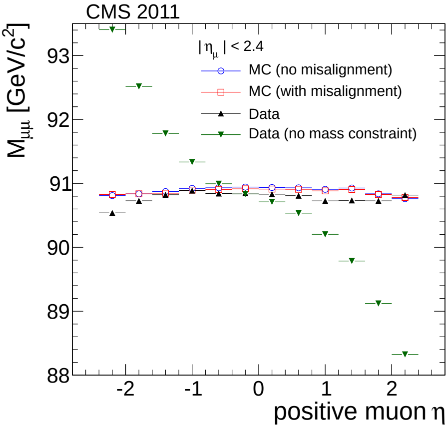


- *Example:* tracks are straight lines in rz
- "telescope" distortion $\Delta z \propto r$
  - Track is still straight line
  - $\rightarrow$ bias in η
- *Solution:* adding cosmic-μ tracks
  - Telescope mis-alignment leads to kink
  - $\rightarrow$ not allowed in track model

Weak Modes

- "twist" distortion $\Delta\phi \propto z$
  - Weak mode even when including cosmic-μ tracks
  - η-dependent curvature ($= p_T$!) bias

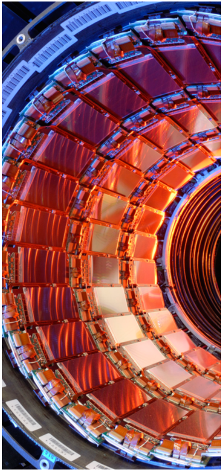




- Reconstructed Z mass in $Z \rightarrow \mu\mu$ decays depends on $\eta(\mu)$
- *Solution:* Z-mass information in alignment fit (or field-off cosmic μ)

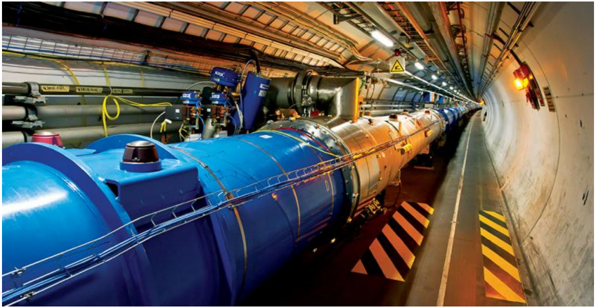
Weak modes controlled by combining different event topologies

Summary



- Precise alignment of the CMS tracker achieved by track-hit residual minimisation
- Requires simultaneous determination of $\approx 200\,000$ parameters
- Possible with global-fit approach of MILLEPEDE-II
  - Takes into account all correlations
  - Sensitivity to subtle effects such as surface deformation and Lorentz angle
  - Combination of tracks from different event topologies crucial
- Local precision of $< 10\ \mu$m achieved in most regions
- Has become routine operation in CMS

A new LHC-run at $\sqrt{s} = 13$ TeV Lies Ahead...



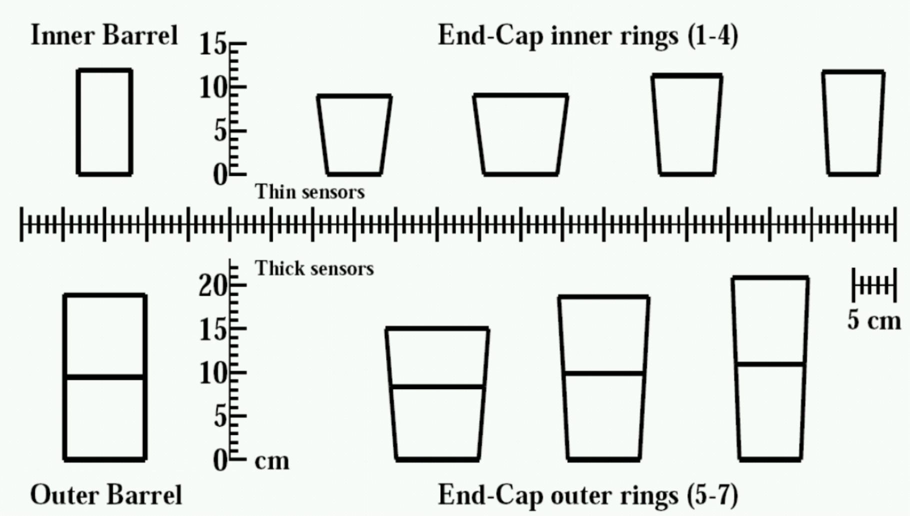
- Precise tracker alignment essential to perform high-precision measurements and exploit full LHC physics-potential
- Powerful and well-understood alignment procedure in place

Additional Material

More Information

- CMS Collaboration, "Alignment of the CMS tracker with LHC and cosmic ray data", *JINST* **9** (2014) P06009, doi:10.1088/1748-0221/9/06/P06009
- V. Blobel, "Software alignment for tracking detectors", *Nucl. Instrum. Meth.* **A566** (2006) 5-13, doi:10.1016/j.nima.2006.05.157
- V. Blobel, C. Kleinwort, and F. Meier, "Fast Alignment of a Complex Tracking Detector using Advanced Track Models", *Comp. Phys. Com.* **182** (2010) 1760, doi:10.1016/j.cpc.2011.03.017
- C. Kleinwort, "General Broken Lines as Advanced Track Fitting Mehtod", *Nucl. Instrum. Meth.* **A673** (2012) 107, doi:10.1016/j.nima.2012.01.024, `https://www.wiki.terascale.de/index.php/GeneralBrokenLines`

Strip Modules



Example: Number of Events in Full-Scale Alignment

data type	N(events)
0 T collisions	320000
0 T cosmics	857970
CRAFT cosmics	1073931
interfill cosmics	1946573
interfill cosmics (peak mode)	1770243
isolated μ	14788959
minimum bias	1952099
Z $\rightarrow \mu\mu$	2419834