The Alignment of the CMS Tracker and its Impact on the early Quarkonium Physics

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Outline

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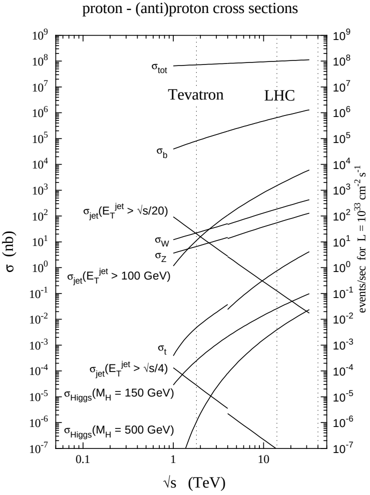
The LHC

- World's most powerful particle accelerator!
- Delivers pp (and Pb-Pb) collisions at energy scales never explored before...
- Master formula at the hadron collider:

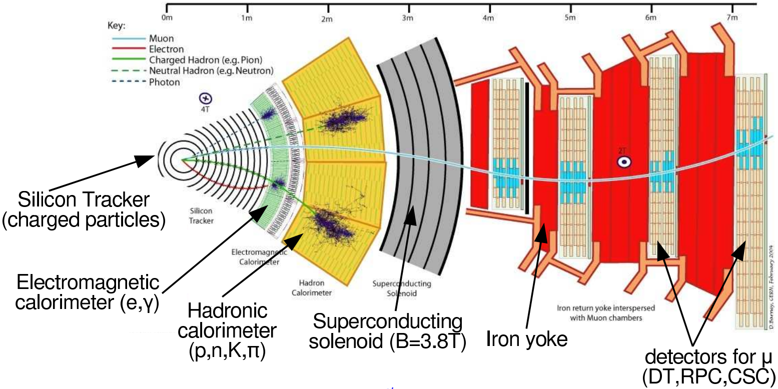
$$\sigma(pp \to X, s) = \int dx_1 dx_2 f_1(x_1) f_2(x_2) \hat{\sigma}(q_1 q_2 \to X, \hat{s})$$

- At the LHC $\sqrt{s} = 7$ TeV (14 design) and in the partonic scattering $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = 1 \div 2$ TeV. New physics is foreseen!
- Higgs search and Electroweak symmetry breaking: crucial tests for Standard Model
- But many other interesting processes have large cross-sections!!
- Already $\approx 40\ pb^{-1}$ delivered to the CMS experiment

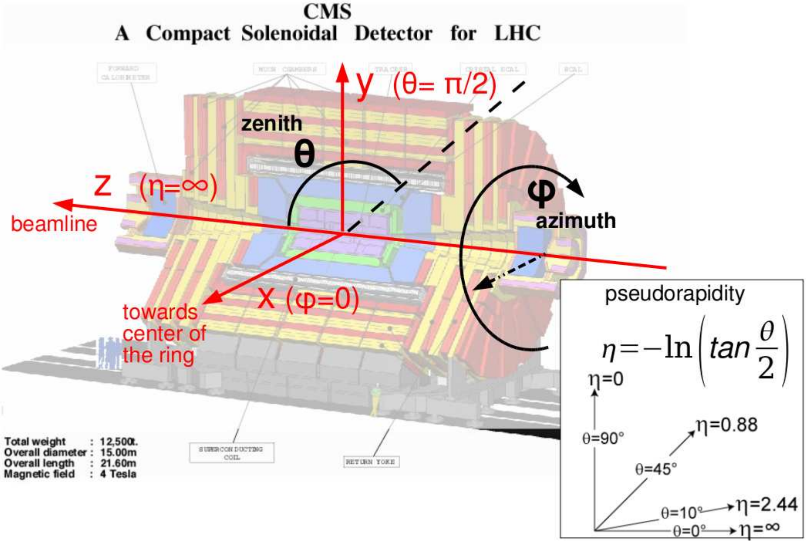


The Compact Muon Solenoid

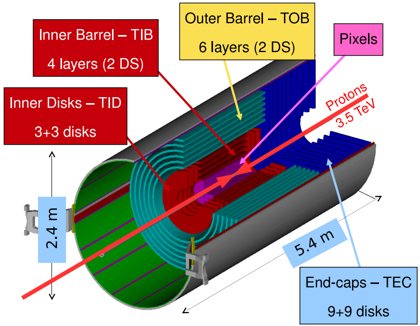
- One of the four *L*arge *H*adron *C*ollider experiments (with *ALICE*, *ATLAS* and *LHCb*)
- Multi-purpose experiment (search for Higgs, Supersymmetry,...)
- A system to identify muons and to measure their momentum up to the TeV scale
- A CMS muon is defined as a charged particle capable to produce a signal (hit) in the μ-chambers (trigger)
- Minimal p_T to reach the μ-chambers is about 3 GeV/c (using solenoidal B=3.8T)

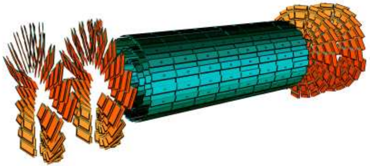


CMS Coordinates



The CMS Silicon Tracker





- **The World's largest Silicon detector**
- Volume: 24 m^3 / Covered *Si* Area: 200 m^2 / running T = -10 °C
- **Strip Tracker**
  - 15148 modules
  - Single point resolution 20-60 μm
  - 1D + 2D meas. (DS modules)
  - DS: 4 layers in Barrel + 5+5 rings in Endcaps
- **Pixel Tracker**
  - 1440 pixel dets
  - 2D meas.
  - Area: $100(r\phi) \times 150(z)\ \mu m^2$
  - $\sigma_{xy} = 9\ \mu m$; $\sigma_z = 20\ \mu m$

Why alignment is needed?

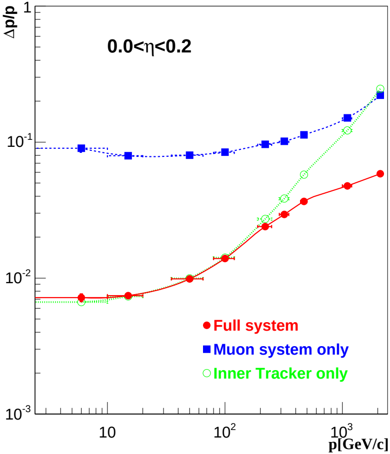


Figure: *$\delta p/p$ in the CMS central region from CMS Physics TDR*

- The tracker is essential to measure the momentum of the particles:

$$\frac{\delta p_T}{p_T} = C_1 p_T + C_2$$

- $C_1 \propto \sigma_{pos}$ single point resolution:

$$C_1 \propto \frac{\sigma_{pos}}{\sqrt{N_{hits}} \cdot B \cdot L^2}$$

- C_2 depending on Multiple Coulomb Scattering (material)
- For $p < 20$ GeV, $\delta p_T/p_T$ dominated by C_2
- For high p_T particles, systematic effects of misalignment become relevant (C_1)
- This contribution is minimized by alignment procedures

Tracker Alignment: the basic idea

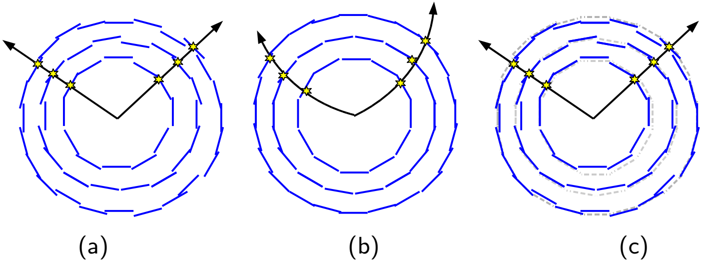


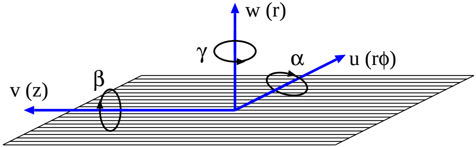
Figure: *Effect of misalignment on straight tracks.*

- In the reality the detector is misaligned: a particle of high momentum (e.g. p=1 TeV) is a "straight line" assuming real geometry (Fig. a)
- Using the design geometry the track reconstruction could assign a curvature and consequently give a wrong momentum estimate (Fig. b)
- After *alignment* the track is re-fitted with the new geometry (near to the real one) and a correct measurement of the momentum is performed (Fig. c)
- Same for the other parameters of a track

Outline

Tracker Alignment

- Goal: nail down to a few μm the positions of all 16 588 ($\times$ 6 dof) silicon modules of CMS Tracker.



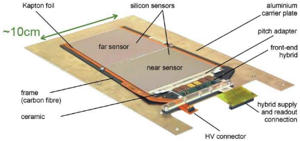
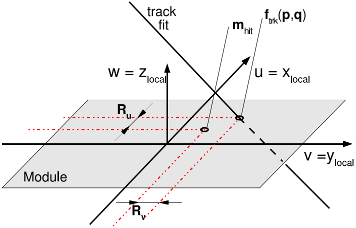


Figure: *Alignable degrees of freedom of a strip module*

- Alignment strategy in CMS: use all available data sources:
  - **Surveys** during assembly of the Tracker. CMM (small scale structures): precision 10 μm. Photogrammetry (large scale structures): precision 100 μm
  - **Laser Alignment**: TEC disks position with 100 μm and 100 μrad precision. Relative alignment of TIB, TOB vs. TEC
  - **Track Based Alignment**
- From older experiments: ultimate precision is achieved using track based alignment, i.e. particles crossing *in situ* the Tracker volume.

Track based alignment



- The *track-to-hit residual* is defined as:

$$\mathbf{R}_\xi(\mathbf{p},\mathbf{q}) = \mathbf{m}_{\xi,hit} - \mathbf{f}_{\xi,\mathbf{tk}}(\mathbf{p},\mathbf{q})$$

- difference between measured position $\mathbf{m}_{ij}$ and position extrapolated from fit $\mathbf{f}_{ij}(\mathbf{p},\mathbf{q}_j)$ depending on $\mathbf{p}$ = alignment parameters (module position / orientation) and $\mathbf{q}_j$ track parameters.

Define a Global Objective function to be minimized $\Omega(\mathbf{p},\mathbf{q})$:

$$\Omega(\mathbf{p},\mathbf{q}) = \sum_j^{tracks}\sum_i^{hits} = \mathbf{R}_{ij}^T(\mathbf{p},\mathbf{q}_j)\mathbf{V}_{ij}^{-1}\mathbf{R}_{ij}(\mathbf{p},\mathbf{q}_j)$$

in which:

- V_{ij} = covariance matrix from track fit;
- $\mathbf{R}_{ij}(\mathbf{p},\mathbf{q}_j)$ = track-to-hit residual.

Alignment algorithms attempt to minimize this objective function and therefore track residuals.

Alignment Algorithms

The χ^2 minimization problem can be solved in context of the linear least squares, involving inversion of large matrices:

- In case of N modules with six degrees of freedom (three rotation and three translations) solving the χ^2 equation implies solving a system of equations by inversion of a huge $6N \times 6N$ matrix
- In CMS there are $\mathcal{O}(16\text{k})$ modules $\Rightarrow 16k \times 6 = \mathcal{O}(100k)$ unknown parameters to be determined!
- This highly challenging task is faced with two main approaches:

Millepede II

In the *global* method the $6N \times 6N$ matrix is inverted. Minimization is achieved by fitting track and alignment parameters simultaneously in one step.

HIP

In the *local* method $N 6 \times 6$ matrices are solved. Minimization is attained by iterating several times the procedure

- Alignment algorithms return **$\mathcal{O}(100\text{k})$** numbers which must be validated!
- need to monitor simultaneously the geometry, tracking performance, physics implications, ...
- to every of these parameters **need to assign an error**!

Alignment Validation

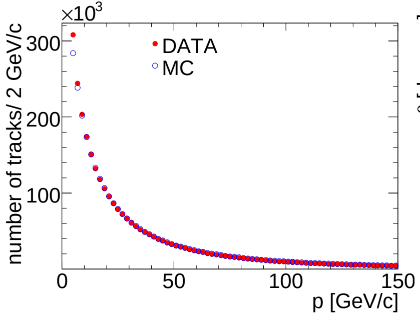
- Track-based alignment represents only half of alignment, after that validation of the $\mathcal{O}$(**100k**) constants is needed!
- Alignment performance is validated on the data themselves at four different levels:
  - **low level validation**: checking the effective improvement of the post-alignment residuals (track χ^2 and track-to-hit residuals);
  - **high level validation**: comparing segments of split cosmic ray tracks, and with the analysis of the residuals in overlapping regions of the detector, check impact of alignment on physics observables;
  - **checks of the geometry** of CMS Tracker resulting from track-based alignment;
- Validation is performed after every alignment cycle
- The CMS Silicon Tracker is expected to provide extremely precise measurement of charged particle tracks $\Rightarrow$ need to develop precise tools to assess alignment precision

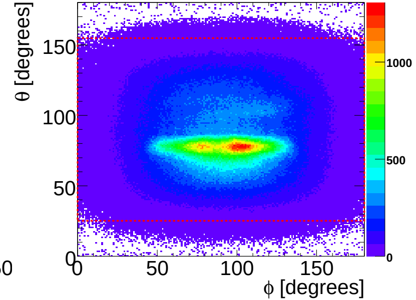
Outline

Comsics Rays data-taking

During 2008-2009 the CMS collaboration conducted a campaign of long data taking exercises: Most important ⇒ **Cosmic Run At Four Tesla** (*CRAFT*):

- Tracker operating with all other CMS subdetectors
- 270 M of cosmics collected with magnetic field switched on (only 2% in Strip Tracker, 1 ‰ in Pixel Tracker)
- 300 Hz cosmic muon Level 1 trigger rate (6 Hz in the Tracker), $\Delta t = t_{top} - t_{bottom} = 2 \times BX = 2 \times 25$ ns $= 50$ ns (muon T.o.F.)
- First attempt of full CMS Tracker alignment with data during the CMS global run





Low level validation

- Clear improvement after alignment compared with the non-aligned geometry
- Best results in terms of χ^2 and residuals given by combined method obtained by running first the *global* method to solve correlation and then the *local* to match the track model in all d.o.f
- Track refitted with properly tuned Alignment Position Errors (APE)

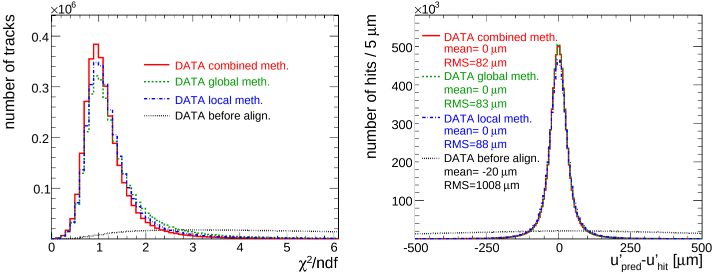


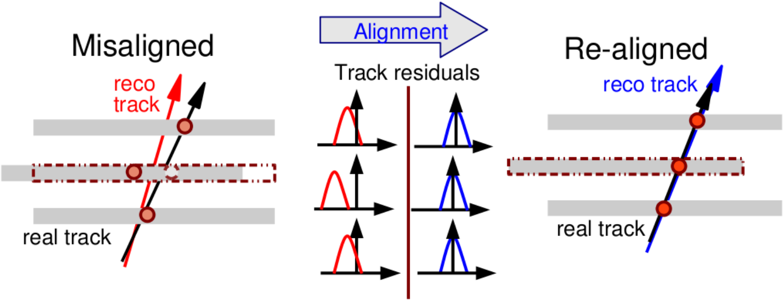
Figure: *Left: χ^2 of tracks, right: track-to-hit residuals in TIB*

Estimation of residual misalignment

- Residual widths dominated by stochastic effects, like multiple Coulomb scattering or the intrinsic resolution of the hits:

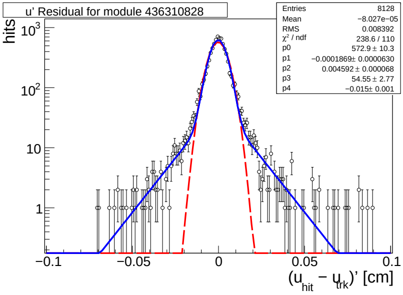
$$\sigma_R = \underbrace{\sigma_{hit}}_{\text{intrinsic}} \oplus \underbrace{\sigma_{MS}}_{\text{Multiple Scattering}} \oplus \underbrace{\sigma_{mis}}_{\text{misalignment}}$$

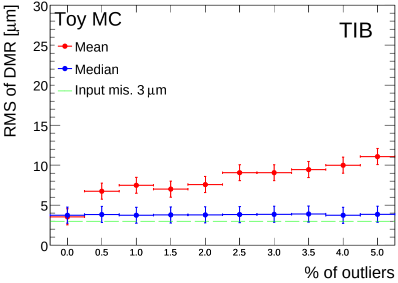
- Goal: disentangle random effects from systematic ones produced by remaining misalignment
- at *zero*th order the alignment recovers the true position of modules along the measurement coordinate ⇒ check that the residuals are "centered" after the alignment



Effect of outliers on residuals

- Outliers are present in the distribution of residuals
- The mean value of the distribution is not a robust estimator of the mean value because of non-gaussian tails
- Check effect of outliers via MC pseudo-experiment:
    - Generate random distributions of residuals, taking number of entries taken by data;
    - Introduce outliers, modeling non gaussian tails with exponential function;
    - check widths of the distributions of median and mean values.

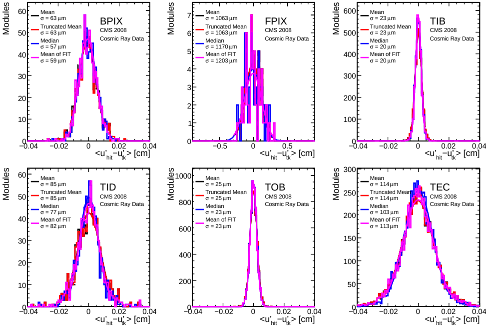




Residuals Misalignment: the DMR (MC studies)

- Mean of residuals is not a robust estimator of the position of the "center" of the residuals distribution because of outliers in real data;
- Tested several others: median, truncated mean[a], mean of a gaussian fit;
- Take MC of the detector in ideal conditions and apply a random gaussian misalignment of known width;
- Look at the distributions of "peak estimators";
- The Distribution of the Medians of Residuals has RMS very close to the width of input misalignment;

[a] Excluding 5% of hits fartest form the core.



Subdet	Misal. (μm)	Mean (μm)	T. Mean (μm)	Median (μm)	Fit Mean (μm)
BPIX	50	62	62	56	58
FPIX	1000	\	\	\	\
TIB	20	23	23	20	20
TOB	20	24	24	22	22
TID	100	84	84	86	81
TEC	100	114	114	100	111

DMR at CRAFT

- RMS of the Distribution of the Median of the Residuals (DMR) measure the remaining misalignment in the detector.

	DATA before	DATA global	DATA local	DATA combined	MC combined	MC ideal	modules
BPIX (u')	328.7	7.5	3.0	2.6	2.1	2.1	757/768
BPIX (v')	274.1	6.9	13.4	4.0	2.5	2.4	
FPIX (u')	389.0	23.5	26.5	13.1	12.0	9.4	393/672
FPIX (v')	385.8	20.0	23.9	13.9	11.6	9.3	
TIB (u')	712.2	4.9	7.1	2.5	1.2	1.1	2636/2724
TOB (u')	168.6	5.7	3.5	2.6	1.4	1.1	5129/5208
TID (u')	295.0	7.0	6.9	3.3	2.4	1.6	807/816
TEC (u')	216.9	25.0	10.4	7.4	4.6	2.5	6318/6400

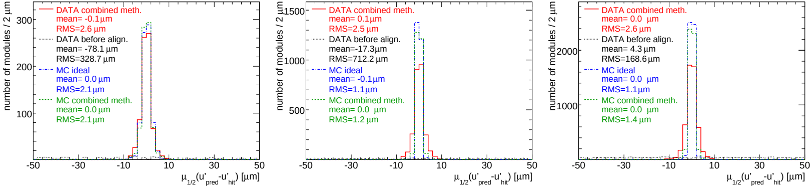


Figure: *DMR fot BPIX (left) and TIB (center) and TOB (right).*

- Module positions w.r.t to cosmic ray trajectory measured with a precision of 3-4 μm in the barrel and of 3-14 μm in the endcap (along rϕ).

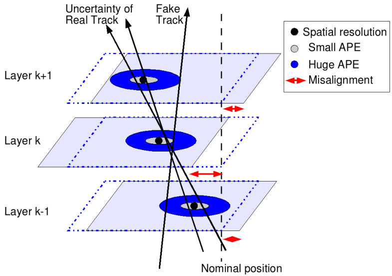
Alignment Position Errors

- The *alignment position error* (APE) characterizes the measurement uncertainty of each detector due to misalignment effects.
- The APE is combined with the spatial (intrinsic) resolution of the detector giving the total error of hit positioning on the silicon modules:

$$\sigma^2_{\xi,eff} = \sigma^2_{\xi,hit} + \sigma^2_{\xi,align}$$

The APE affects the search window of pattern recognition in track finding and have direct impact on:

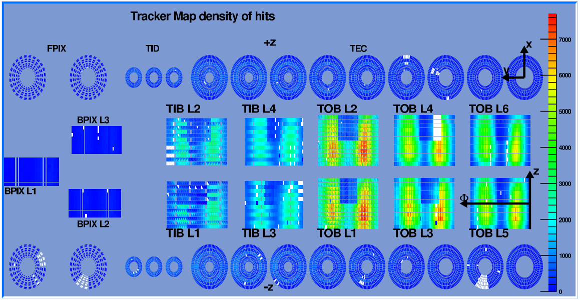
- performance of track reconstruction
- efficiency of track reconstruction
- track quality (χ^2)
- fake rate
- momentum resolution
- vertexing resolution



Strategy for determination of APE

Strategy for the determination of the APE:

- They need to be module-dependent since alignment with cosmic rays is better in some regions than others (due to higher illumination in the top and bottom quandrants of the tracker).



1. So find a region of the detector well aligned (top quadrant)
2. estimate the remaining misalignment (after the alignment procedure) from MC-data matching: the APE value has to match the value of the remaining random misalignment
3. Finally estimate the APEs in the rest of the Tracker (outside the fiducial volume) by taking into account the different illumination of cosmic rays

Determination of residual misalignment

The APE are estimated introducing a random (gaussian smeared) misalignment in the CRAFT MC simulation, to match the DMRs and trends of residuals in CRAFT DATA (in the control region and with the selected track sample).

- translation in δu affect the DMR
- so tune layer by layer δu comparing DMR fo misaligned MC and DATA

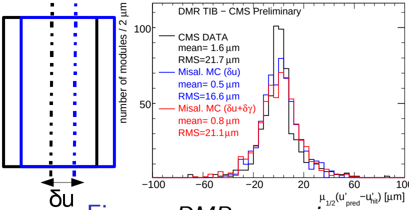


Figure: *DMR comparison*

- $\delta\gamma$ not affecting DMRs but spread in the residuals
- so tune MC to reproduce trend of barrel layer residuals of DATA

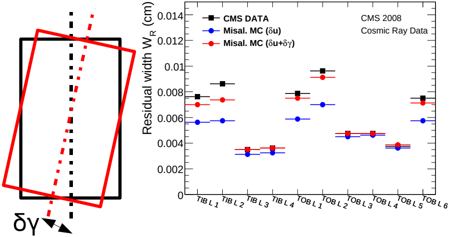
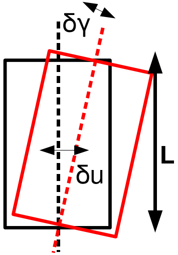


Figure: *Trend of residuals comparison*

Determination of APE

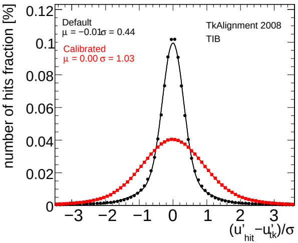
- The APE has to be specified in 3 directions (u,v,w)
- Choose to neglect correlations between directions: use spheres
- The radius of the sphere is defined as:

$$R_{APE} = R_0 \cdot \sqrt{\frac{N_0}{N_{hits}}} \begin{cases} RMS(\mu_{1/2}(R_i)) & \text{in Pixel and Encaps} \\ \kappa\left(\delta u \oplus \frac{L}{4}\delta\gamma\right) & \text{in TIB/TOB} \end{cases}$$



- In the endcaps and in the pixel detectors use the width of the DMR distribution measured in DATA
- In the barrel detectors use the misalignment parameters δu, $\delta\gamma$ obtained as described before to match the DATA distribution (in the sensitive coordinate) with the misaligned simulation
- R_0 asymptotic value reached for the well aligned modules with $N_{hits} > N_0$. The APE radius is scaled according to the statistics available
- κ and N_0 are parameters tuned on data

APE Calibration

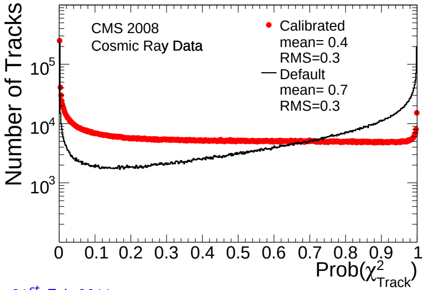


- Define the normalised residuals:

$$\widehat{R} = \frac{R}{\sigma_R} = \frac{u_{hit} - u_{tk}}{\sigma_R} \qquad \sigma_R = \sigma_R(APE(k))$$

- The κ factor is tuned with an iterative procedure until the contribution to the hit error determines the pull of residual to be $\simeq 1$

- After the tuning of the APE, the peak of the track χ^2 is shifted to 1
- The $Prob(\chi^2)$ becomes more uniform
- The distributions of the RMS of normalized residuals (DRR) peak to 1

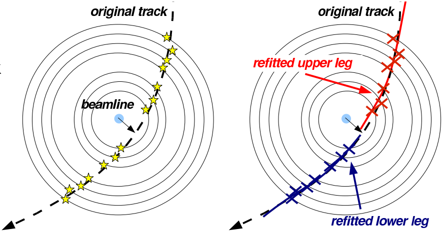


APE Validation

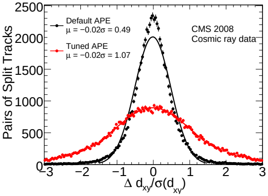
The Alignment Position Errors are validated in terms of tracking performace using the cosmic track splitting method:

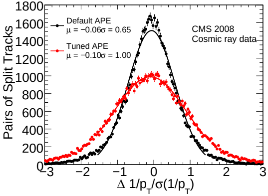
- split a long cosmic track passing through the Pixel volume, along it P.C.A.[a]
- reconstruct separately the two legs
- check the normalized residuals of the track parameters $q = (d_{xy}, d_z, q/p_T, \theta, \phi)$:

$$\frac{q(PCA)_{TOP} - q(PCA)_{BOT}}{\sqrt{\sigma^2_{q_{TOP}} + \sigma^2_{q_{BOT}}}}$$



[a] Point of Closest Approach



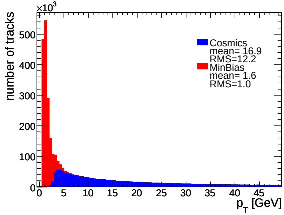


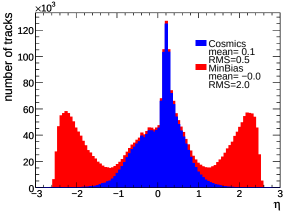
- After APE calibration all the pulls are found of $\mathcal{O}(1)$, showing correct assignment of the errors.

Outline

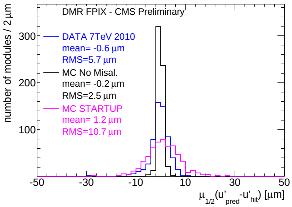
Alignment with collision tracks

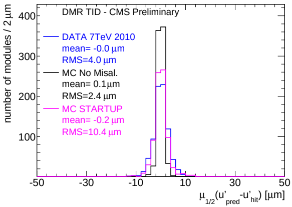
- First alignment performed with $\mathcal{O}(1\ \text{nb}^{-1})$. Only Minimum bias available $\Rightarrow$ low constraining power
- The first alignment with collision tracks performed mixing cosmics and Minimum Bias





- The use of Minimum Bias tracks passing mainly at high η allowed to improve alignment in forward detectors

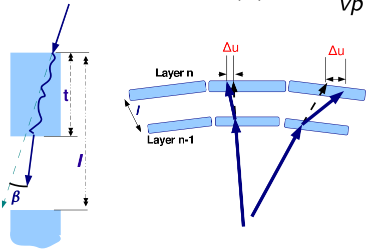




Track-to-hit residuals vs momentum

- A charged particle crossing silicon experiences Multiple Coulomb scattering
- The uncertainty on the deflection angle β is:

$$\sigma(\beta) = \frac{13.6 MeV}{vp} z \sqrt{\frac{t}{X_0}} [1 + 0.038 \ln(t/X_0)]$$



- If the lever arm betwenn adjacent layers is L the track extrapolation uncertainty is:

$$\sigma_{tk} \approx L \cdot \sigma(\beta) \propto \frac{L}{p}\sqrt{\frac{t}{X_0}}$$

- thus residuals widths decrease as a function of track momentum:

$$\sigma_R = \underbrace{\sigma_{tk}(p)}_{\propto 1/p} \oplus \underbrace{\sigma_{hit} \oplus \sigma_{mis}}_{\sim const} \rightarrow \sigma_R(p) = \frac{A(t/X_0)}{p} \oplus B$$

Track-to-hit residuals vs momentum

- Extract for each layer and each momentum bin the width of residuals
- Fit trend of residuals with function:

$$\sigma_R(p) = \sqrt{\frac{A^2}{p^2} + B^2}$$

- extract B parameter and deconvolve the intrinsic hit resolution σ_{hit} (obtained with an independent method):

$$B = \sigma_{hit} \oplus \sigma_{mis} \rightarrow \sigma_{mis} = \sqrt{B^2 - \sigma_{hit}^2}$$

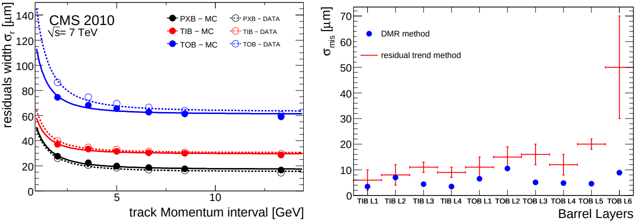


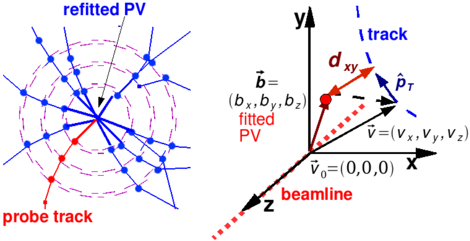
Figure: *Left: trend of width of residuals as a function of p. Right: comparison of the alignment precision obtained with the DMR method and the residual trend method.*

- Results obtained are in crude agreement with the ones obtained with the DMR method.

Primary Vertex Validation

With collision tracks it is possible to monitor the performance of alignment in the Pixel detector: use unbiased residuals of tracks w.r.t reconstructed primary vertices to test alignment.

- Select a sample of *"good" collision tracks*
- Extract from those a *probe track*
- Fit the primary vertex with the remaining ones
- Evaluate the unbiased track residual in the transverse and longitudinal planes
- Iterate over all good tracks



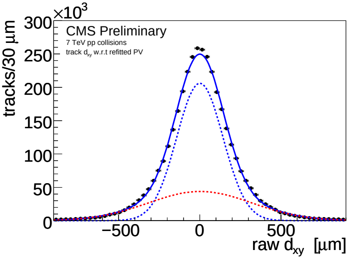
Transverse and longitudinal impact parameters are defined as:

$$d_{xy}(PV) = [(\mathbf{b}-\mathbf{v})\times\hat{\mathbf{p}}_T]\cdot\hat{z}$$

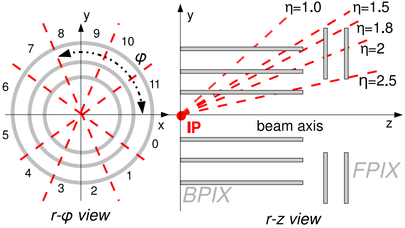
$$d_z(PV) = \left[\left(\frac{(\mathbf{b}-\mathbf{v})\cdot\hat{\mathbf{p}}_T}{p_T}\mathbf{p}\right)-(\mathbf{b}-\mathbf{v})\right]\cdot\hat{z}$$

Primary Vertex validation

- The width of the distributions of track impact parameter have two contributions:
  - uncertainty due to track extrapolation
  - uncertainty on PV position
- so fit the IP distributions with double gaussian *pdf*.

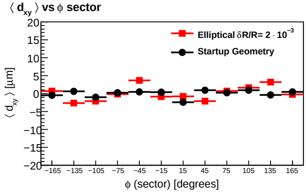


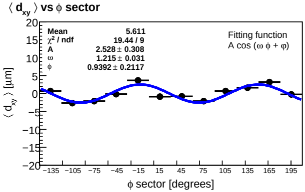
- The mean value and the RMS of the distributions of unbiased track IP are extracted in bins of ϕ and η of the probe track
- deviations from expected behaviours are attributed to misalignment effects



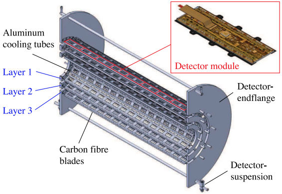
Studies with simulation

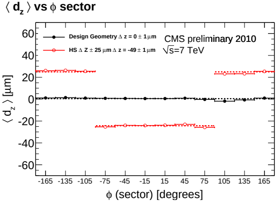
- Pixel systematic elliptical distorsion for testing algorithm capability to spot it
- For each module: $\delta r/r = 1 - c_1 cos2\phi$ where $c_1 = 2 \cdot 10^{-3} \Rightarrow \delta r \approx 100\mu m$





- To test sensitivity in the z direction introduce for each module a displacement $z' = z + \delta z$ (for $|\phi| > \pi/2$) with $\delta z = 25\ \mu m$

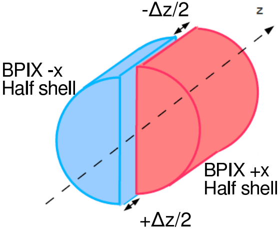




- Method tested to be sensitive to movements in $r\phi$ and in the rz plane down to $\mathcal{O}(10\mu m)$.

Performance in 2010 data

- *Lifetime* measurements sensitive to movements of the inner layers of BPIX and FPIX, so monitor constantly pixel geometry
- during 2010 most striking deformation observed is the *sporadic* movement of the BPIX half-shells in the *z* direction
- **dayly** the PV validation is performed and the relative separation is measured
- when realigning for reprocessing of data, divide dataset in different periods accounting for different positions of BPIX half-shells



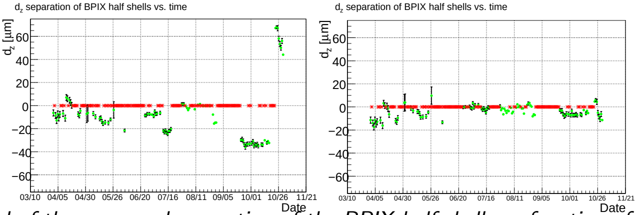


Figure: *Trend of the measured separation of the BPIX half-shells as function of the day before (left) and after (right) alignment.*

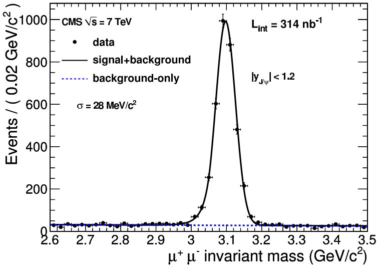
Outline

J/ψ production in CMS

J/ψ mesons, at hadron colliders are produced according to three different mechanisms:

- prompt J/ψ produced directly in the proton-proton collision;
- prompt J/ψ produced indirectly (via decay of heavier charmonium states such as χ_c);
- non-prompt J/ψ from the decay of a b hadron.

The CMS experiment measured for the first time, at $\sqrt{s}$=7 TeV, the total and differential in p_T production cross-section for prompt and non-prompt J/ψ, using 27000 di-muon candidates collected in the first 314 nb^{-1} of 2010 data.



The narrow width of the resonance allows to use the J/ψ as a benchmark for detector performance, and to test alignment impact on physics observables.

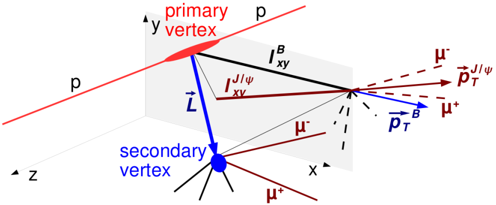
Separation of B-fraction

It is possible to measure the fraction of J/ψ produced in b-hadron decays

The quantity $\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi}/p_T$ is computed for each J/ψ candidate:

$$L_{xy} = \frac{\mathbf{u}^T \sigma^{-1} \mathbf{x}}{\mathbf{u}^T \sigma^{-1} \mathbf{u}}$$

where **x** vector joining di-muon vertex and PV, in the transverse plane, $\mathbf{u} = \mathbf{p}_T/|\mathbf{p}_T|$, and σ = combined error



An unbinned likelihood fit is performed using:

$$\ln L = \sum_{i=1}^{N} \ln F(\ell_{J/\psi}, m_{\mu\mu})$$

where N is the total number of events and $m_{\mu\mu}$ is the invariant mass of the muon pair. The expression for $F(\ell_{J/\psi}, m_{\mu\mu})$ is

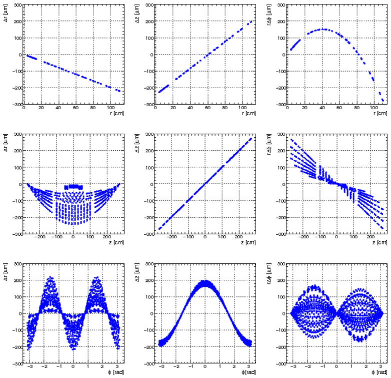
$$F(\ell_{J/\psi}, m_{\mu\mu}) = f_{Sig} \cdot F_{Sig}(\ell_{J/\psi}) \cdot M_{Sig}(m_{\mu\mu}) + (1 - f_{Sig}) \cdot F_{Bkg}(\ell_{J/\psi}) \cdot M_{Bkg}(m_{\mu\mu})$$

In the $\ell_{J/\psi}$ projection appears the b fraction parameter f_b

$$F_{Sig}(\ell_{J/\psi}) = f_B \cdot F_B(\ell_{J/\psi}) + (1 - f_B) \cdot F_p(\ell_{J/\psi})$$

Tracker weak modes

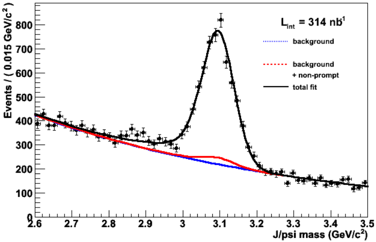
- Statistical precision reached after track-based alignment is not the final step of alignment
- Non-trivial transformation, leaving the χ^2 of the tracks unchanged (weak modes) can affect Tracker, surviving after track based alignment
- *Physics can be affected* by those distortions in subtle ways, if not corrected

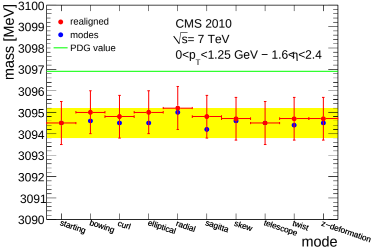


- To assess the impact of possible remaining χ^2-invariant modes of the geometry on physics observables:
- 9 $(\Delta r, \Delta z, \Delta\phi) \times (r, z, \phi)$ distortions are introduced on top of the aligned geometry
- the Tracker is realigned usign the same strategy used for alignment with collision data
- the 9 resulting geometries are used to re-reconstruct the tracks

Effects on the J/ψ mass

- Re-reconstruct the tracks with all the 9 considered modes;
- for each bin of $y - p_T$ of the J/ψ perform the two-dimensional fit;
- extract for each $y - p_T$ bin and each mode the measured value of the J/ψ mass.
- in each bin the largest excursion Δm ($\mathcal{O}$(0.5 MeV)) w.r.t to the nominal geometry is taken as systematic error

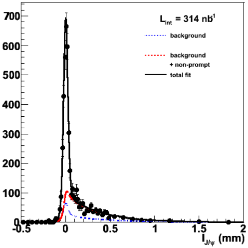


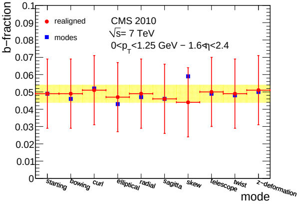


- A bias in the measurement of the mass is found w.r.t the PDG value,
- effect is present also in the *MC simulation, without misalignment* $\Rightarrow$ uncertainties due to imperfect knowledge of the magnetic field, detector material, biases in track fitting algorithm.
- systematic uncertainty on the mass shape for residual systematic misalignment $<<$ than one introduced by the momentum scale correction procedure to recover the bias

Effects on the b-fraction

- Extract for each $y - p_T$ bin and each mode the measured value of the b-fraction from the two-dimensional fit
- in each bin the largest Δf_b w.r.t to the nominal geometry taken as systematic error





y	p_T (GeV)	Δf_b	$\Delta f_b/f_b$ (%)	mode
0-1.2	4.5 - 6.5	0.0045	2.5	skew
0-1.2	6.5 - 10.0	0.0016	0.6	sagitta
0-1.2	10.0 - 30.0	0.0021	0.5	sagitta
1.2-1.6	2.0 - 4.5	0.0066	4.7	z-deformation
1.2-1.6	4.5 - 6.5	0.0019	1.0	twist
1.2-1.6	6.5 - 10.0	0.0019	0.9	z-deformation
1.2-1.6	10.0 - 30.0	0.0057	1.6	sagitta
1.6-2.4	0.0 - 1.25	0.0051	10.5	skew
1.6-2.4	1.25 -2.0	0.0050	5.7	elliptical
1.6-2.4	2.0 - 2.75	0.0044	3.7	sagitta
1.6-2.4	2.75 - 3.5	0.0018	1.4	curl
1.6-2.4	3.5 - 4.5	0.0016	1.0	telescope
1.6-2.4	4.5 - 6.5	0.0066	3.7	z-deformation
1.6-2.4	6.5 - 10.0	0.0016	0.7	bowing
1.6-2.4	10.0 - 30.0	0.0056	1.6	radial

- The relative uncertainty on f_b due to alignment ranges from 0.6 to 10.5 %
- In most bins the largest contribution comes from *distortions involving the z-scale*

Measurment of the b fraction

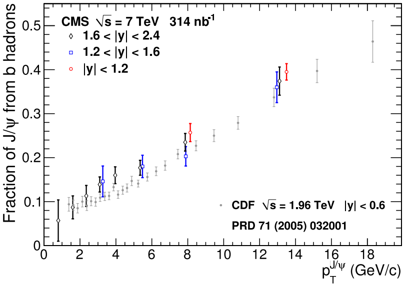


Table: *Summary of relative systematic uncertainties in the b-fraction yield $\Delta f_b/f_b$ (in %). The range shows the min-max $\Delta f_b/f_b$ excursion found when changing the p_T bin for each of the three rapidity regions. In general, uncertainties are p_T-dependent and decrease with increasing p_T.*

	$\lvert y\rvert < 1.2$	$1.2 < \lvert y\rvert < 1.6$	$1.6 < \lvert y\rvert < 2.4$
Tracker misalignment	0.5 — 2.5	0.9 — 4.7	0.7 — 10.5
b-lifetime model	0.0 — 0.1	0.5 — 4.8	0.5 — 11.2
Vertex estimation	0.3	1.0 — 12.3	0.9 — 65.8
Background fit	0.1 — 4.7	0.5 — 9.5	0.2 — 14.8
Resolution model	0.8 — 2.8	1.3 — 13.0	0.4 — 30.2
Efficiency	0.1 — 1.1	0.3 — 1.3	0.2 — 2.4

Outline

Summary

- Challenging demands of CMS for the momentum measurement led to design a *complex inner tracking system*.
- Unknown position of the 15k modules is one of the main sources of systematic error for physics
- Methods to assess the alignment precision have been developed and tested with cosmic ray data
- Alignment during commissioning with cosmic rays (CRAFT) significantly improved alignment statistical precision to 3-15 μm
- An algorithm to calibrate Alignment Position Errors have been developed using cosmic ray data
- Collision track topology allowed to estimate remaining misalignment in the barrel region by a fit procedure to the track-to-hit residuals as a function of track momentum
- A flexible data-driven tool, based on the unbiased adaptive refit of primary vertices was developed and tested on the 2010 data sample allowing *to monitor alignment performance in the Pixel Tracker*
- The impact of possible remaining systematic misalignment on physics observables have been tested on a sample of $J/\psi \to \mu\mu$ decays corresponding to 300 nb^{-1}

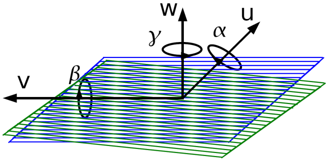
Thanks for the attention!

Backup

CRAFT: alignment strategy

- Dedicated alignment stream (AlCaReco) 4.5 M of events
- 3.2 M of tracks selected for alignment (only 3.5% have at least 1 hit in Pixel volume)
- Large statistics available allow for a separate alignment of stereo and r-ϕ components of the DS modules (module unit)
- DS modules:
  - 2-D measurement in the combined plane
  - 100 mrad stereo angle between two components: $\Delta v \simeq 10 \times \Delta u$
- Alignment in v of a DS module found to be not consistent with assembly accuracy
- Separate alignment of r-ϕ and stereo component improve dramatically residuals

Track Quality cut	Value
momentum p	> 4 GeV
number of hits	≥ 8
number of 2-d hits	≥ 2
(on Pixel or DS modules)	
χ^2/ndf of the track fit	< 6.0
Hit Quality cut	**Value**
S/N (Strip modules)	> 12
pixel hit prob. matching	> 0.001 (0.01)
template shape in u (v) dir.	
track angle w.r.t. uv plane	$< 20^\circ$
square pull of the hit residual	< 15

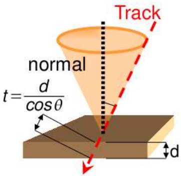


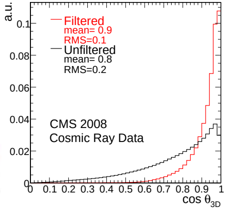
Determination of a control region

In order to have a sound estimate of remaining misaligment:

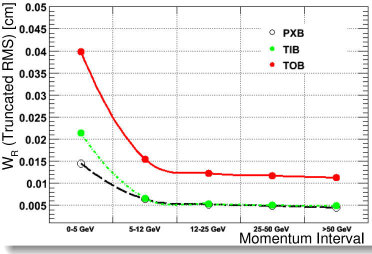
- take a well aligned region (upper quarter of Strip Barrel)
- to select tracks crossing the tracker volume with the same angle

$$\cos\theta_{3D} = \left(\frac{\mathbf{p}\cdot\widehat{\mathbf{w}}}{|\mathbf{p}|}\right)$$





select tracks hit pattern in order to satisfy a test-beam like geometry

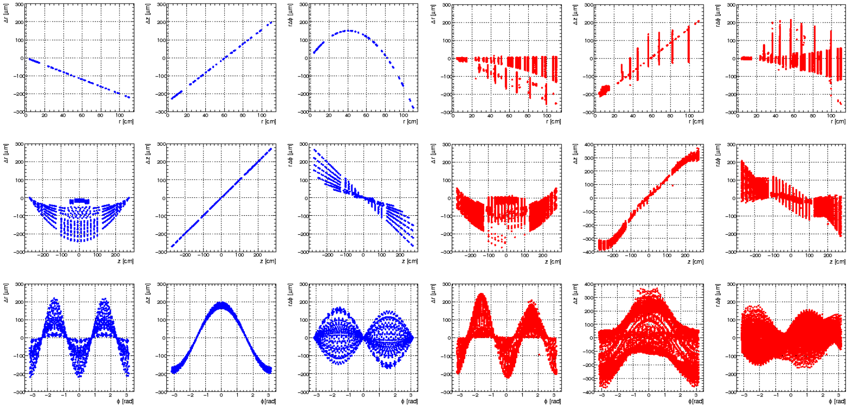


- Then in order to minimize the MS contribution to the track hit:

$$\sigma_{MS}(p) \propto L\cdot\sigma_\theta \propto \frac{L}{p}\sqrt{\frac{t}{X_0}}$$

- Select tracks with $p > 20$ GeV where residuals start to saturate

Tracker weak modes



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