The CMS Tracker Alignment

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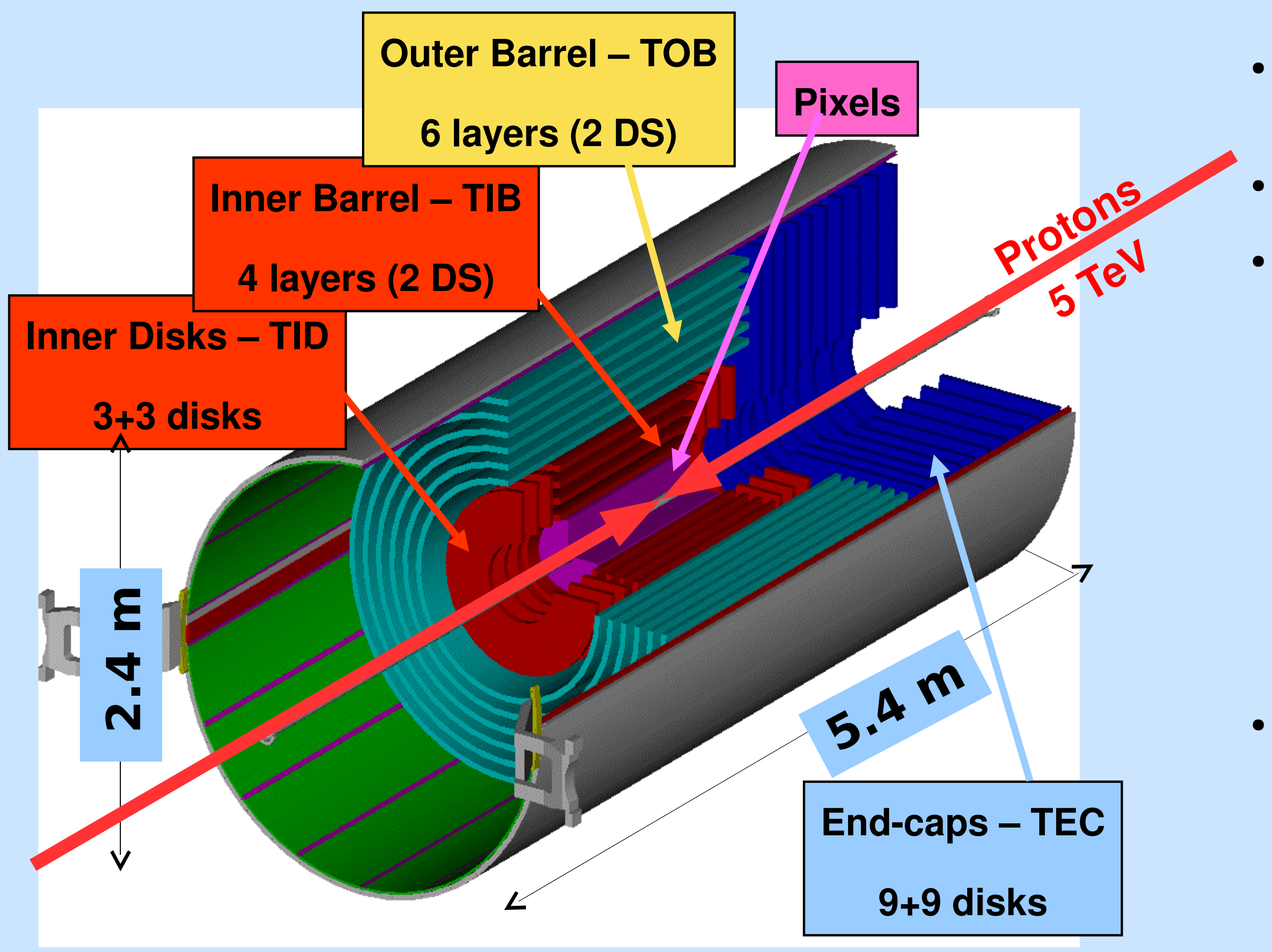


CMS Tracker Layout

- Volume 24 m³ / covered area 200 m²
- Running temperature: -10° C
- **STRIP:**
  - ***15148 modules*** (pitch 80 – 205 µm)
  - single point resolution of 20 – 60 µm
  - 2D measurements from DS modules, mounted back to back (tilt 100mrad)
- **PIXEL:**
  - ***1440 modules*** (pitch 100(r) x150(z) µm²)
  - resolutions: 9 (r) 20 (z) µm

- *Optimization of the particle momenta resolution* is critical for CMS Tracker.
- It depends on two factors:

C₁ depends on the geometry of the detector

$$\frac{\delta p}{p} = C_1 p \oplus C_2$$

C₂ depends on multiple coulomb scattering (MCS)

$$C_1 = \frac{\sigma_{pos}}{\sqrt{N}\cdot B\cdot L^2}$$

B = magnetic field intensity

N = number of track hits

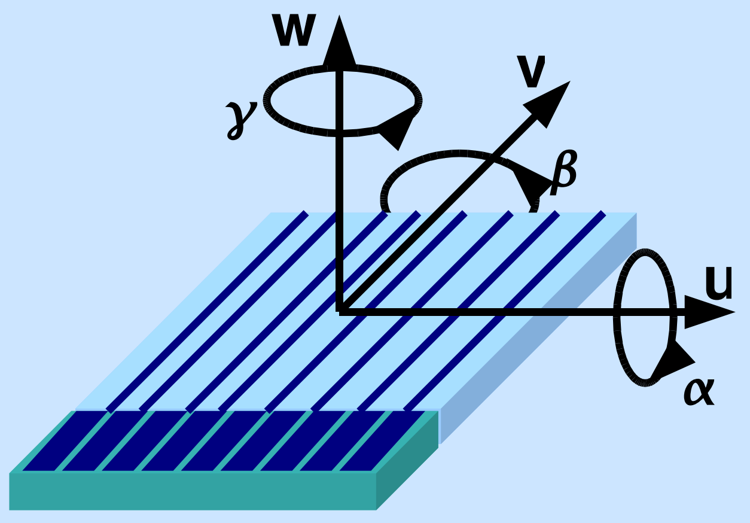
L = track length

$\boldsymbol{\sigma_{pos}}$ = resolution on measured point

~10 µm (Si)

$$\sigma_{pos} = \sqrt{\sigma_{intr}^2 + \boldsymbol{\sigma_{sist}^2}}$$

MISALIGNMENT



- The challenge is to determine at **O(10µm)** corrections for the **6 d.o.f** (3 rotations + 3 translations) of each of the > 19k modules in CMS Silicon Tracker!

$$\mathbf{16.5k}\ \textit{modules} \times \mathbf{6}\ \textit{n.d.of.} \simeq \mathbf{100k}\ \textit{unknowns !}$$

Alignment Formalism

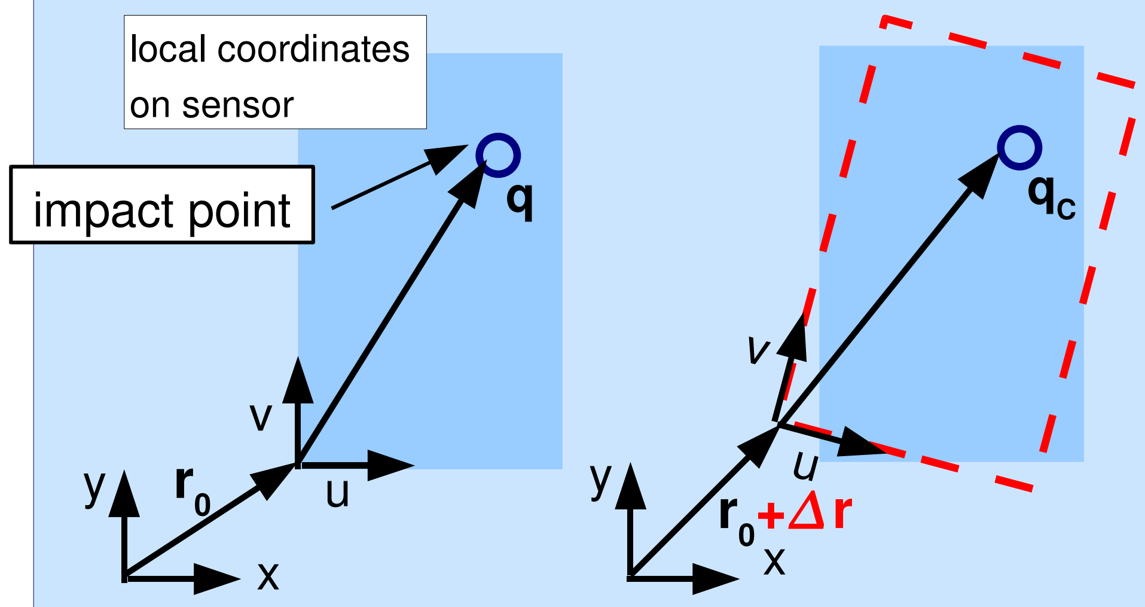
- In the CMS Tracker alignment formalism the hit position in local coordinates of the module is **q = (u,v,w)** and **r =(x,y,z)** w.r.t the global reference frame of CMS.
- The two sets of coordinates are related via a roto-translation:

$$\begin{cases} \mathbf{r} = (x,y,z) \Rightarrow \textbf{global}\ \text{coordinates} \\ \mathbf{q} = (u,v,w) \Rightarrow \textbf{local}\ \text{coordinates} \end{cases} \qquad \mathbf{r} = R^T \mathbf{q} + \mathbf{r_0}$$

- The alignment procedure determines corrections to the original transformation via an additional rototranslation:

$$\mathbf{r} = R^T \Delta R(\mathbf{q} + \Delta \mathbf{q}) + \mathbf{r_0}$$

- The alignment parameters are **Δq = (Δu,Δv,Δw)** which parametrize translations, while the angles **α,β** and **γ** appear in ΔR parametrize the rotation



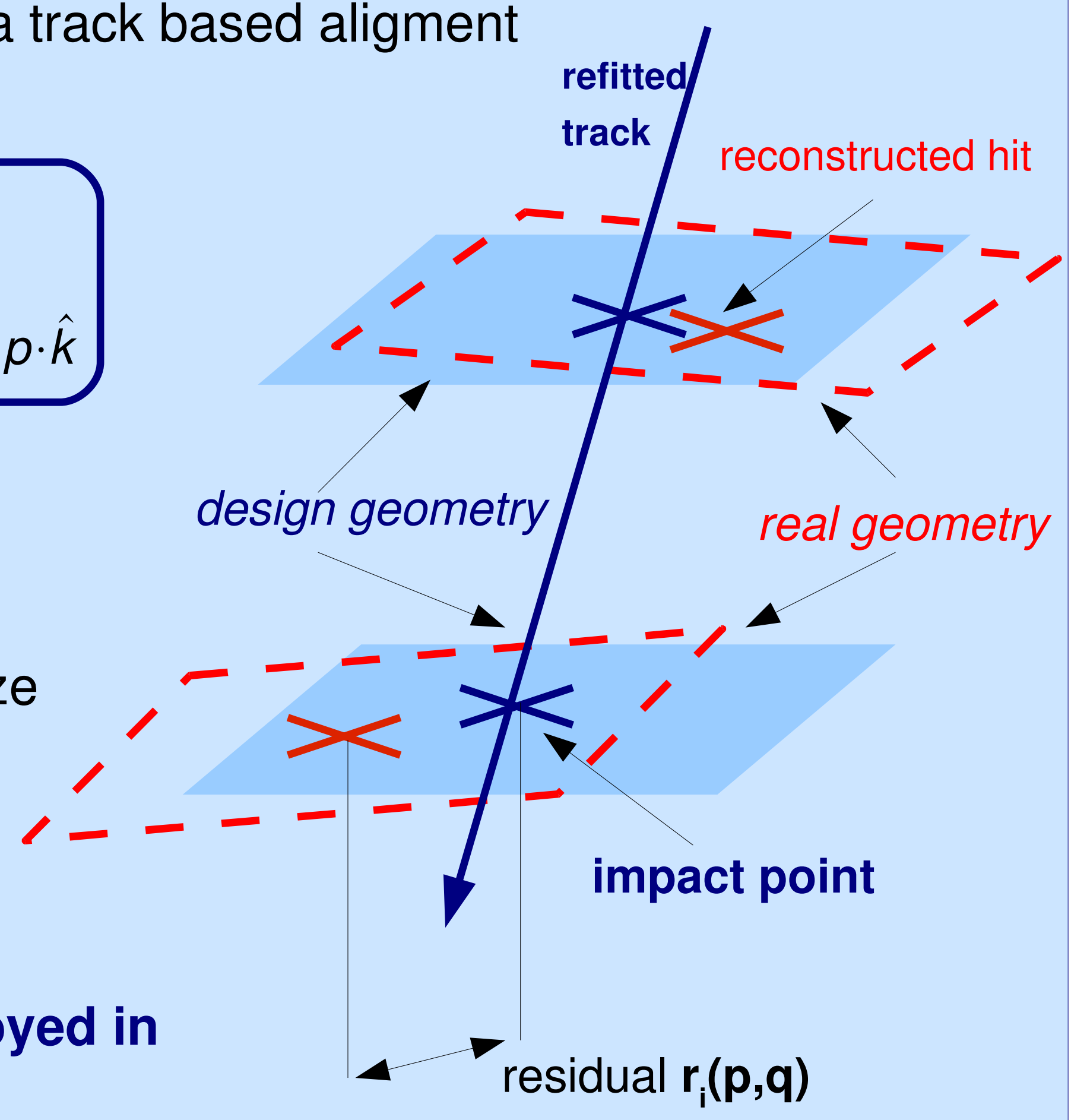
Final goal of alignment:

- Determine for each of the O(16k) detunits the 6 parameters **(Δu,Δv,Δw,α,β,γ)** 3 translations and 3 rotations w.r.t the nominal geometry
- Determine for each of the modules the statistical error associated to the aligned postion **(APE)**

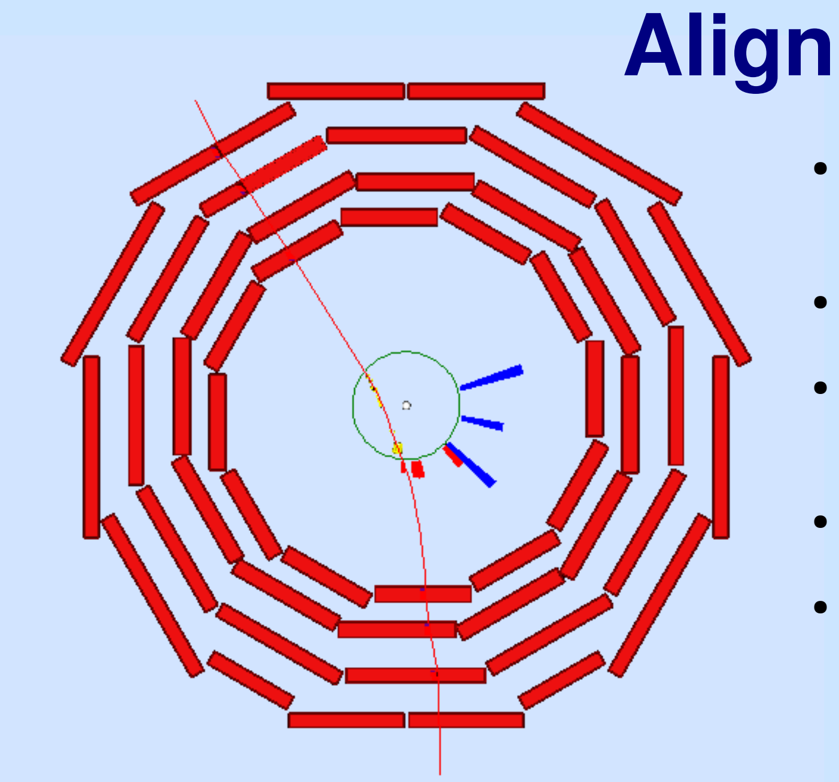
- Several methods are deployed (optical survey/LAS/track based aligment) ultimate precision O(10 µm) reached via track based aligment
- Definition of track χ²:

$$\chi^2 = \sum_{i=1}^{n_{hits}} r_i^T(p,q)\, V_k^{-1}\, r(p,q)$$
$$r_i(p,q) = u^{hit} - u^{fit}(p,q) = u^{hit} - \Delta p \cdot \hat{k}$$

  - V = covariance matrix
  - ***p = alignment parameters***
  - q = track parameters
- Aligment algorithms attempts to minimize this χ² function and therefore track residuals
- A complex system of equations to be solved (O(100k unknowns))
- **Fast and robust algorithms are deployed in CMS framework:**
  - Local Iterative Method: **“Hits an Impact Points”**
  - Global Method: **“Millepede II”**



Alignment at CRAFT*

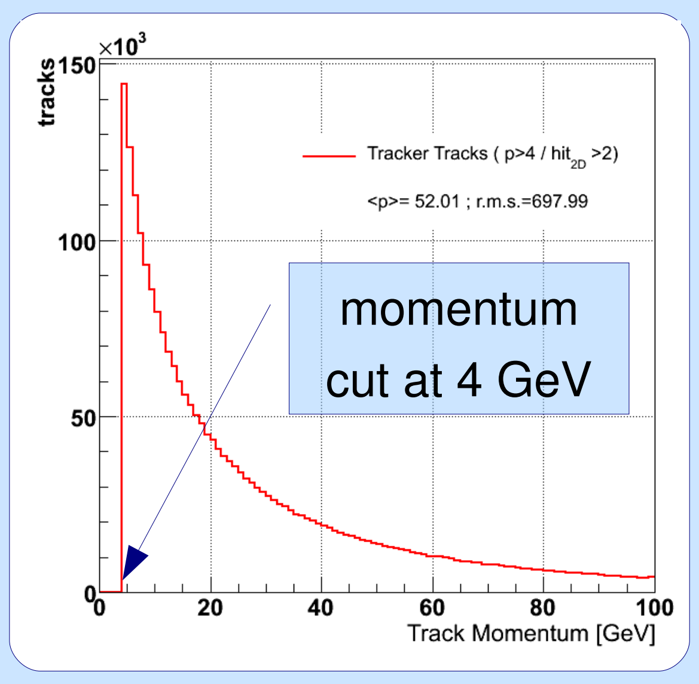


- A ”***global run***”: all CMS subdetectors participating to the data taking
- Data taking 24/7 for 3 weeks (Oct 2008)
- Major milestone demonstrating CMS capability of running over long periods
- **300 Million** cosmic muon triggers collected @ 3.8 T
- Chance of performing alignment and calibration as an input to collision data taking

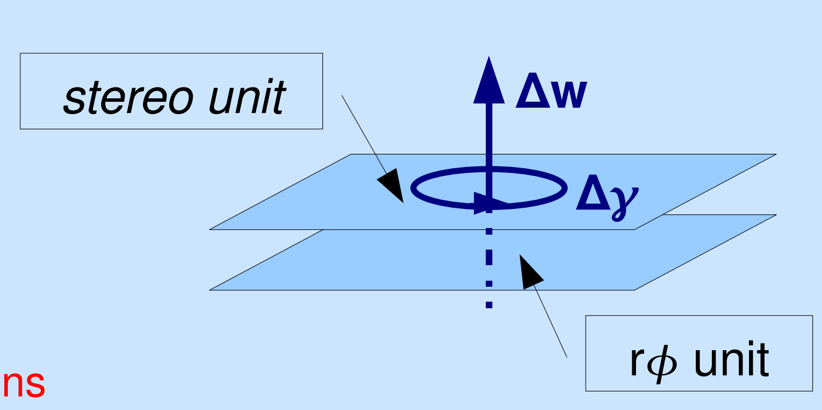
**Cosmic Run At Four Tesla*

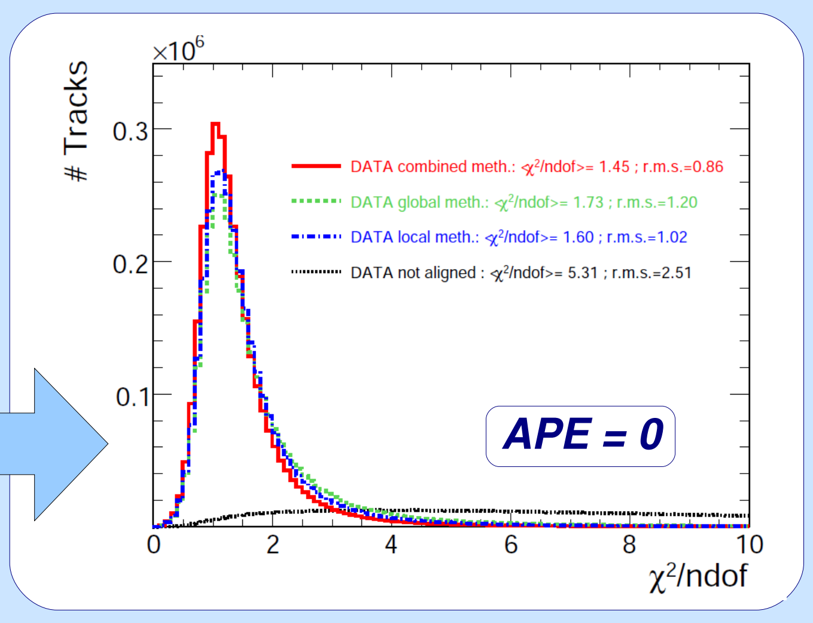
Alignment strategy

- **Require good hit and track quality**
  - **p>4 GeV** (limit the Multiple Scattering)
  - clean hits, oultier rejection, χ² cut, minimum number of hits, 2D hits.
  - After that ~ **4M** tracks useful for alignment (3% +1.5% passing in pixel volume) remain
- **Adopt a multi-step approach for both algorithms:**
  - large *structure* movements (coherent *v* alignment of SS modules)
  - Alignment of the two sides of 2D strip *modules (**units**)* *u,w,γ*
  - **module**-level alignment of strip and pixel modules
- **Algorithms:**
  - **Local:**
    - Pros: Full track model/ simple implementation
    - Cons: many iterations needed to get the full correlations
  - **Global:**
    - Pros: module correlations / less CPU
    - Cons: simple track model / large matrix involved may limit the number of alignable parameters
- **Final Approach**: get the **best** from **both** algorithm, combining the two:
  1) run the global method ⇒ solves global correlations efficiently
  2) run the local method ⇒ solves locally to match track model in all degrees of freedom
  - All the three results are compatible but the **Combined shows the best performance**



a DS module





Validation Methods

DMR:

- *Track residuals* are expected to get narrower when good alignment is reached:
  - ***but*** several effects (multiple scattering, track extrapolation, hit resolution) are folded in the distributions, broadening the residuals
- At ***zero-th order*** alignment should recover the average position of modules along the sensitive coordinate
  - check the **D**istribution of **M**edian of **R**esiduals (DMR)
- **Median:** a robust estimator of the peak position of residuals when dealing with many (~16k) histograms.
- Sensitive to the *remaining shift of the modules* along the measurement coordinate (i.e. modules with incoherent displacements w.r.t. to the others)

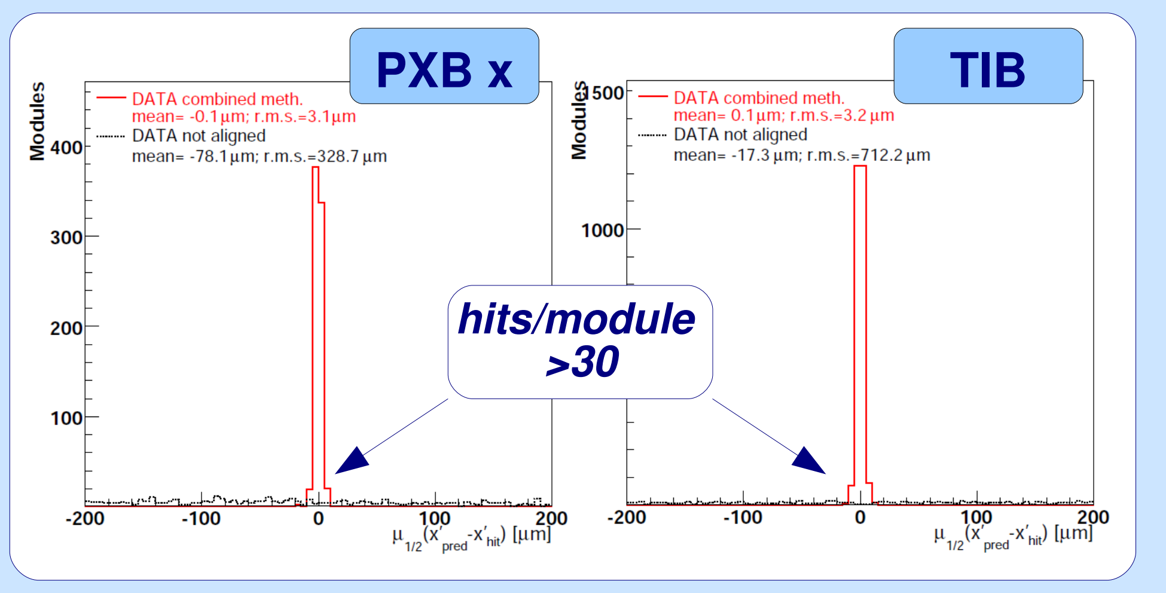


Table of achieved precision:

DMR	not aligned r.m.s. µm	combined meth. r.m.s. µm	modules > 30 hits
PXB (x')	328.7	3.1	757/768
PXB (y')	274.1	4.3	757/768
PXE (x')	389.0	13.8	391/672
PXE (y')	385.8	14.7	391/672
TIB (x')	712.2	3.2	2623/2724
TOB (x')	168.6	3.2	5129/5208
TID (x')	295.0	3.8	807/816
TEC (x')	216.9	7.9	6318/6400

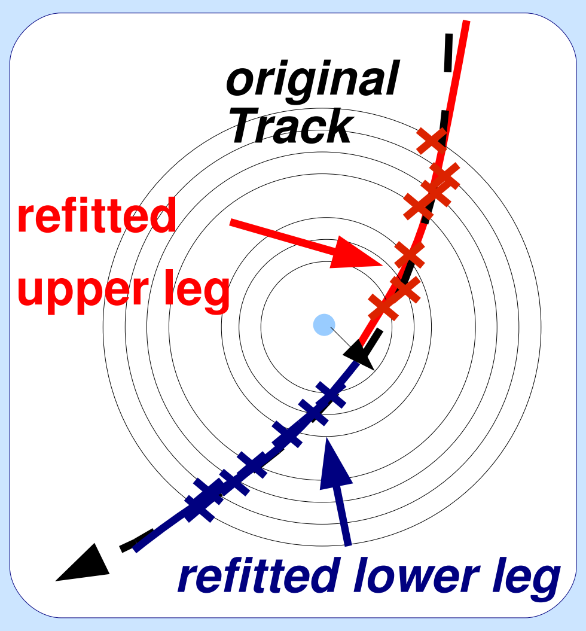
Cosmic Track Splitting:

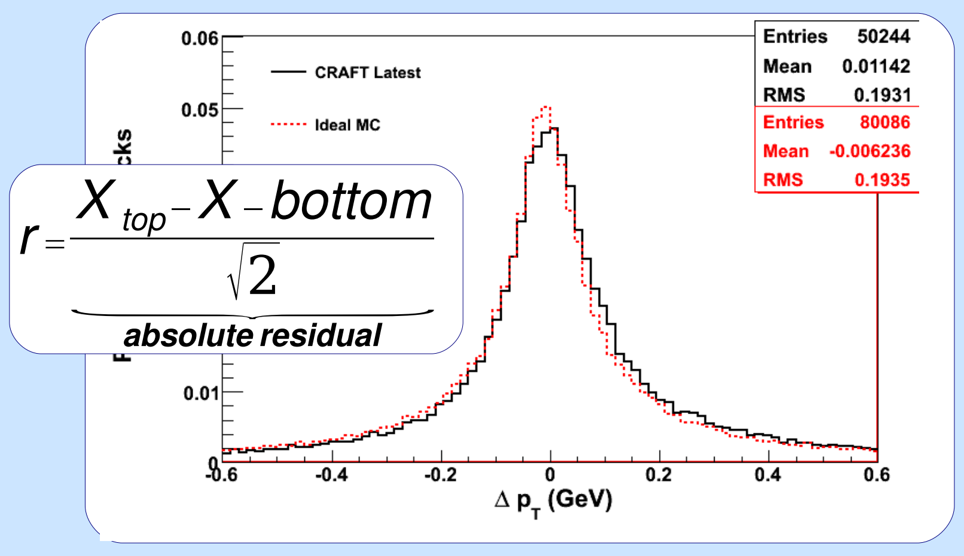
Take a tracker track:

- split it along its ***PCA*** (*P*oint of *C*losest *A*pproach)
- refit separately the two hits collections coming from the two track legs
- compare the track parameters of the the two legs updated at the PCA:

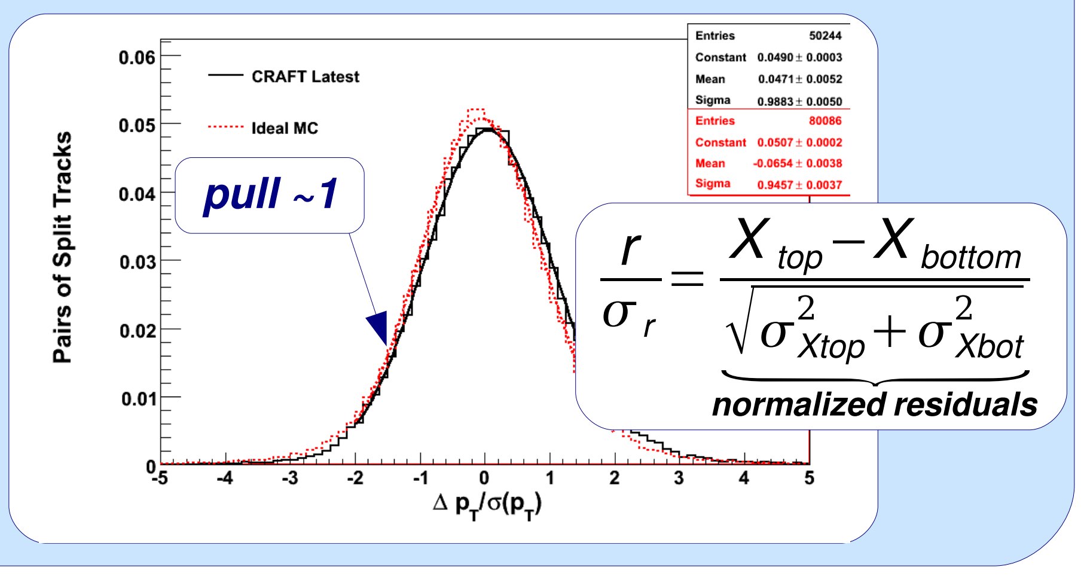
$$X = (d_{xy}, d_z, p_T, \theta_{tk}, \phi_{tk})$$

- if alignment is good the two parameter sets should coincide and *small residuals are expected*





$$r = \underbrace{\frac{X_{top} - X_{bottom}}{\sqrt{2}}}_{\textbf{absolute residual}}$$



$$\frac{r}{\sigma_r} = \underbrace{\frac{X_{top} - X_{bottom}}{\sqrt{\sigma_{Xtop}^2 + \sigma_{Xbot}^2}}}_{\textbf{normalized residuals}}$$

Visit the CMS tracker alignment homepage: http://cmsdoc.cern.ch/cms/performance/tracker/