Towards the start-up of CMS detector: CMS tracker alignment

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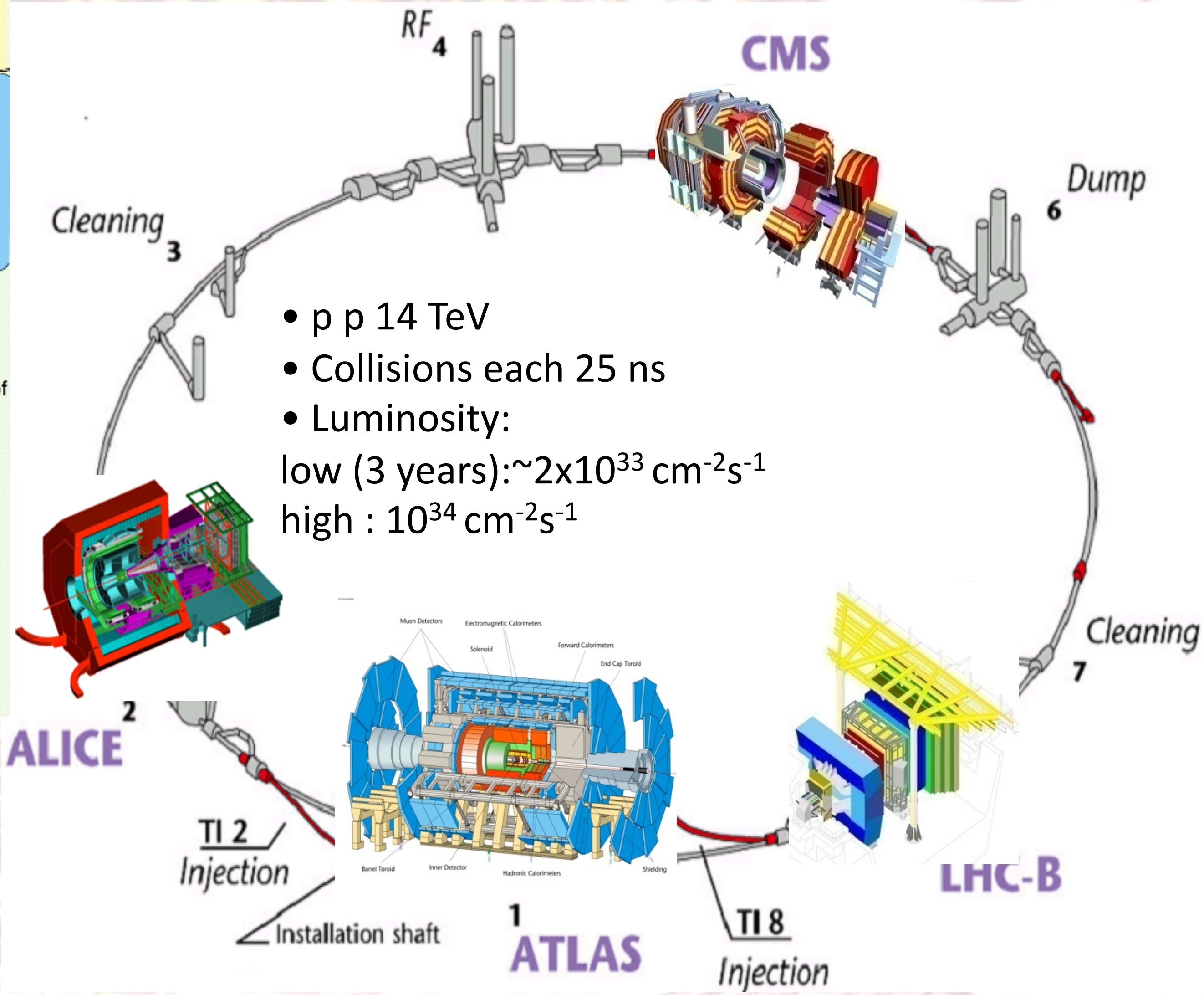
Outline

- LHC and CMS detector
- Alignment and Physics
- Alignment Strategy
- Validation of an Alignment
- Readiness
- Conclusion

LHC The Large Hadron Collider Project

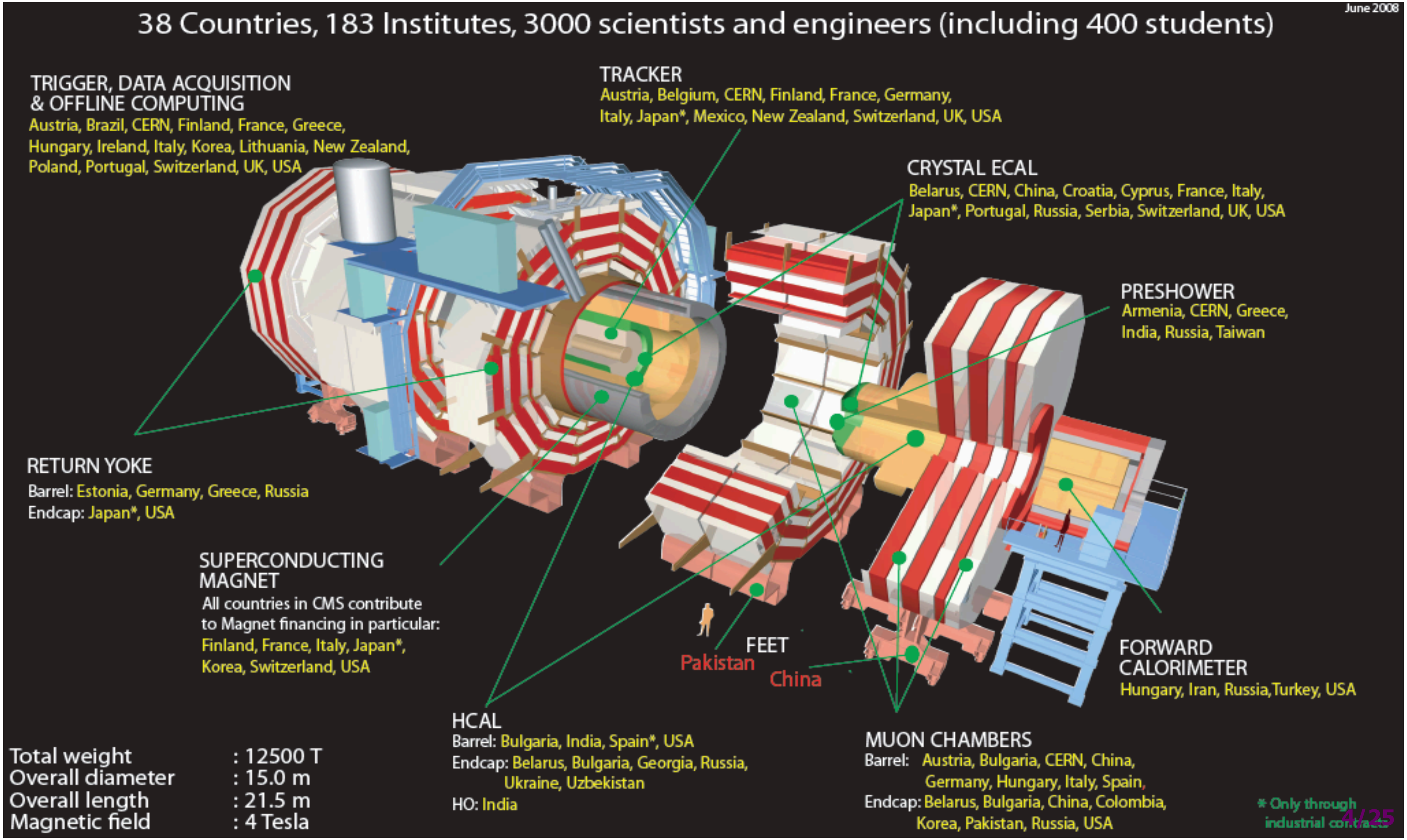


- p p 14 TeV
- Collisions each 25 ns
- Luminosity:

low (3 years):~2×10^{33} $cm^{-2}s^{-1}$

high : 10^{34} $cm^{-2}s^{-1}$

CMS Detector



CMS Tracker

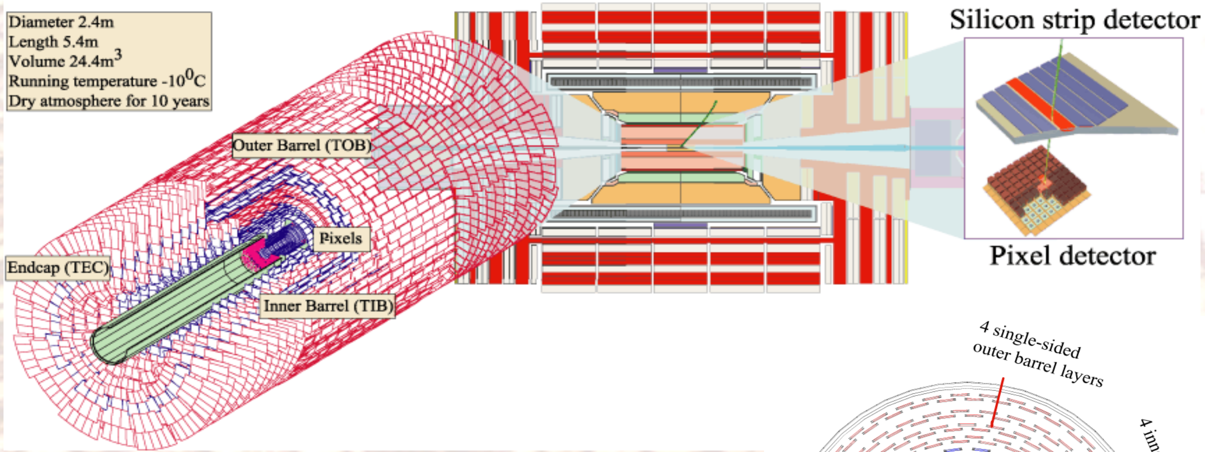
Specifications:

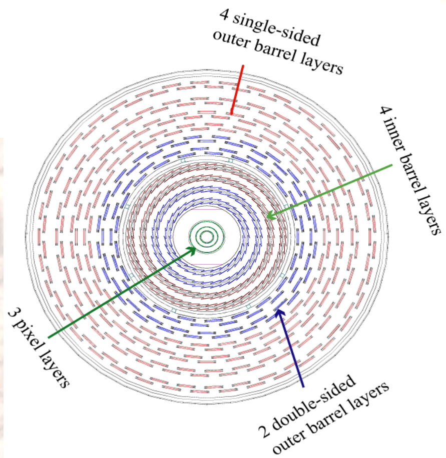
- **High resolution on isolated high momentum tracks**
- **Transverse impact parameter resolution better than 35µm for pT>10 GeV**
- **50% b-tagging efficiency with a mistag rate of the order to percent**

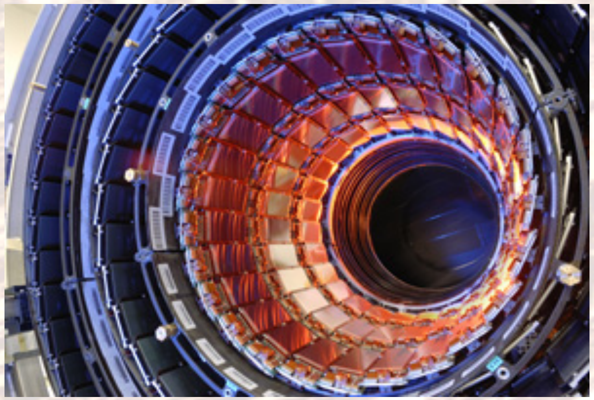
Sub-system:

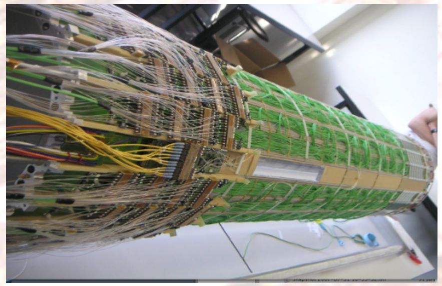
- **Vertex detector (Silicon pixel)**
- **2 Layers subdetectors (SiStrip)**
- **Disks for EndCap (SiStrip)**

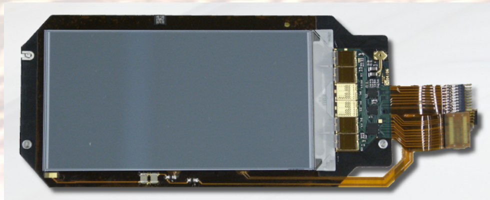
➔ **207m^2 of silicon sensors**
➔ **10.6 million silicon strips**
➔ **65.9 million pixels ~ 1.1m^2**



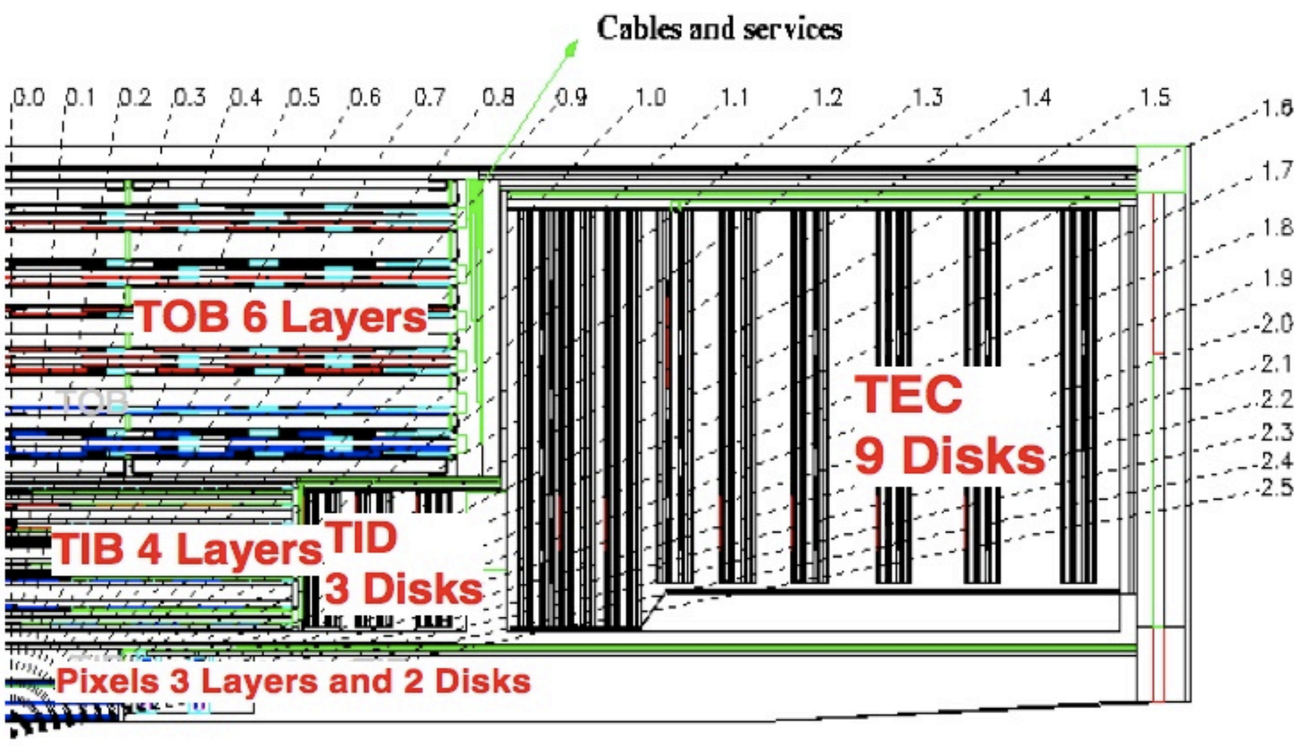








CMS Tracker Status



Tracker channel status at the end of August

- **Strip Tracker**
  - **TOB(1) : 98%**
  - **TIB/TID(2) : 96.6%**
  - **TEC+ : 99.2%**
  - **TEC-(3) : 97.8 %**
- **Pixels**
  - **Barrel pixels : 99.1%**
  - **Forward pixels(4) : 94.0%**

(1) 0.6% recovered since August
(2) 1% at least recoverable
(3) 1.7% recovered since Augusts
(4) 5% recovered during shutdown (power cables repair), 0.5% still recoverable

Pixels: 1440 Modules

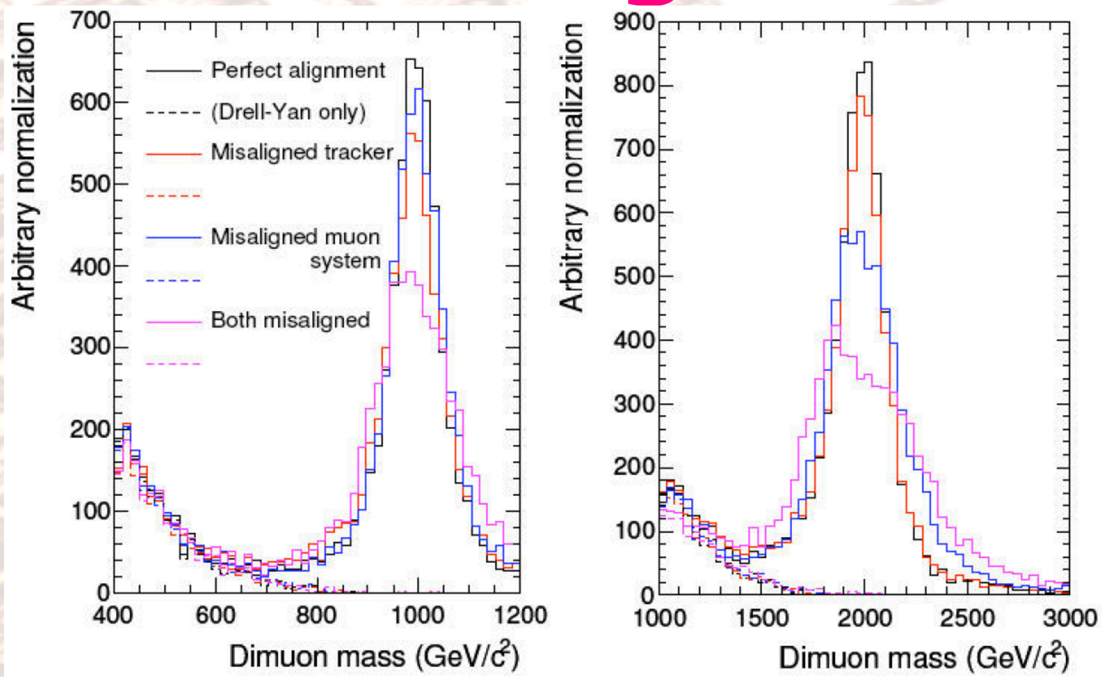
100 μm x 150μm
rφ and z resolution: ~15 μm

Strips: 15148 Modules

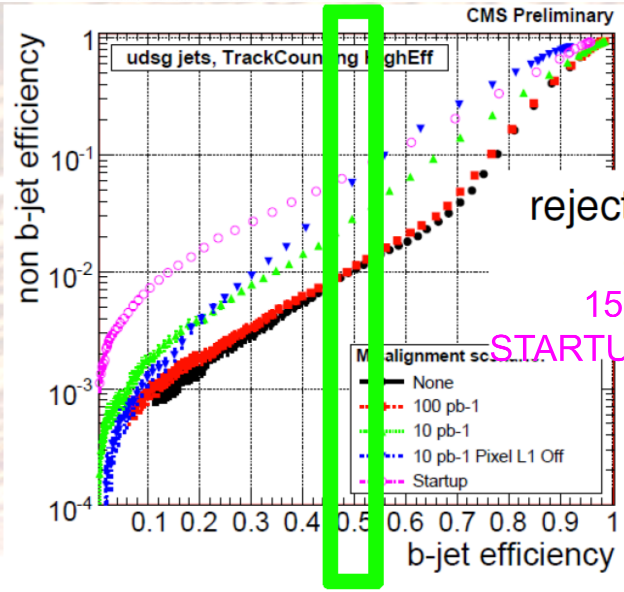
Pitch: 80 μm to 180μm
Hit Resolution: 20 μm to 50μm

Why do we have to align?

Alignment impact on dimuon invariant mass resolution:
➔ critical for high pT muons

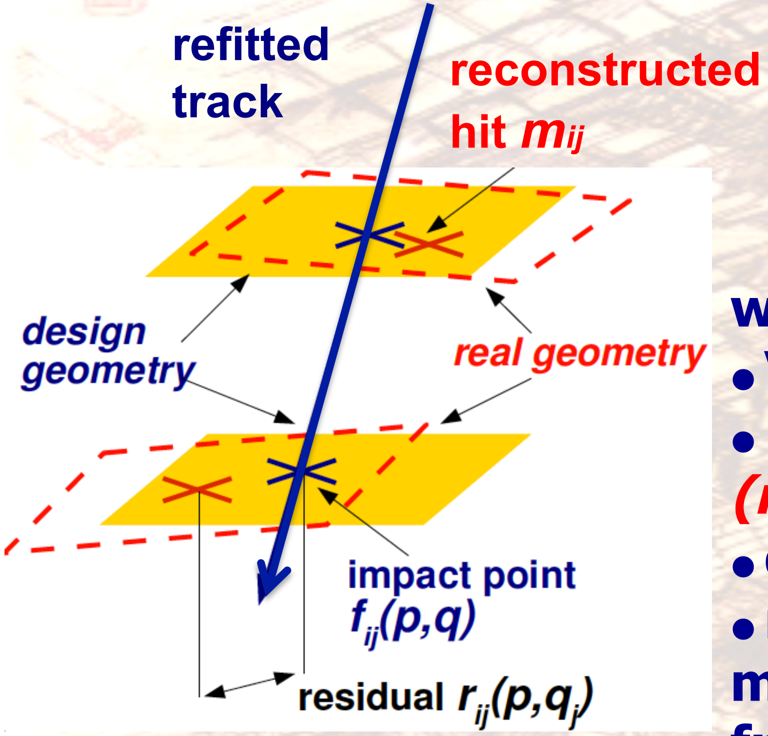


B-tagging relies completely on tracking performance:
all b-tag algorithms are sensitive to alignment
-both positions and errors are important
- Flight distance significance and hence b-tag efficiency
➔ improves with accumulation of statistics for alignment



rejection of udsg jets
@ ε_b=50%:
15 → 100 → 100
STARTUP → 100/pb → ideal

Alignment



Define a Global Track χ2 function:

$$\chi^2 = \sum_{i=1}^{N_{tracks}} \sum_{i=1}^{n_{hits}} r_{ij}^T(p,q_j)\, V_{ij}^{-1}\, r_{ij}(p,q_j)$$

$$r_{ij}(p,q_j) = m_{ij} - f_{ij}(p,q_j)$$

where:

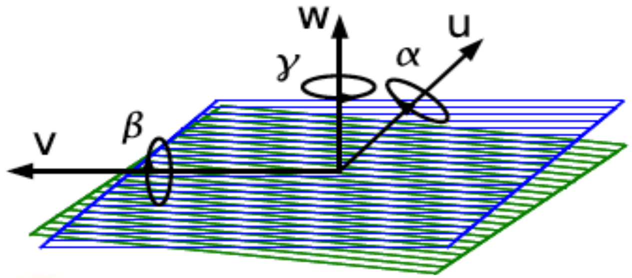
- **V_{ij} = covariance matrix from fit**
- ***p = alignment parameters (module position/orientation)***
- **q_j = track parameters**
- **$r_{ij}(p,q_j)$ = residual: difference between measured position *m_{ij}* and position extrapolated from fit *$f_{ij}(p,q_j)$* (depending on p and q_j)**
- **Aligment algorithms attempt to minimize this χ2 function and therefore the track residuals**

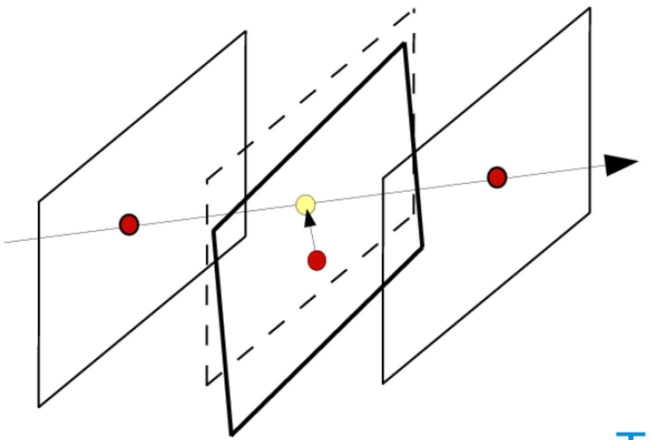
CMS Alignment Strategy

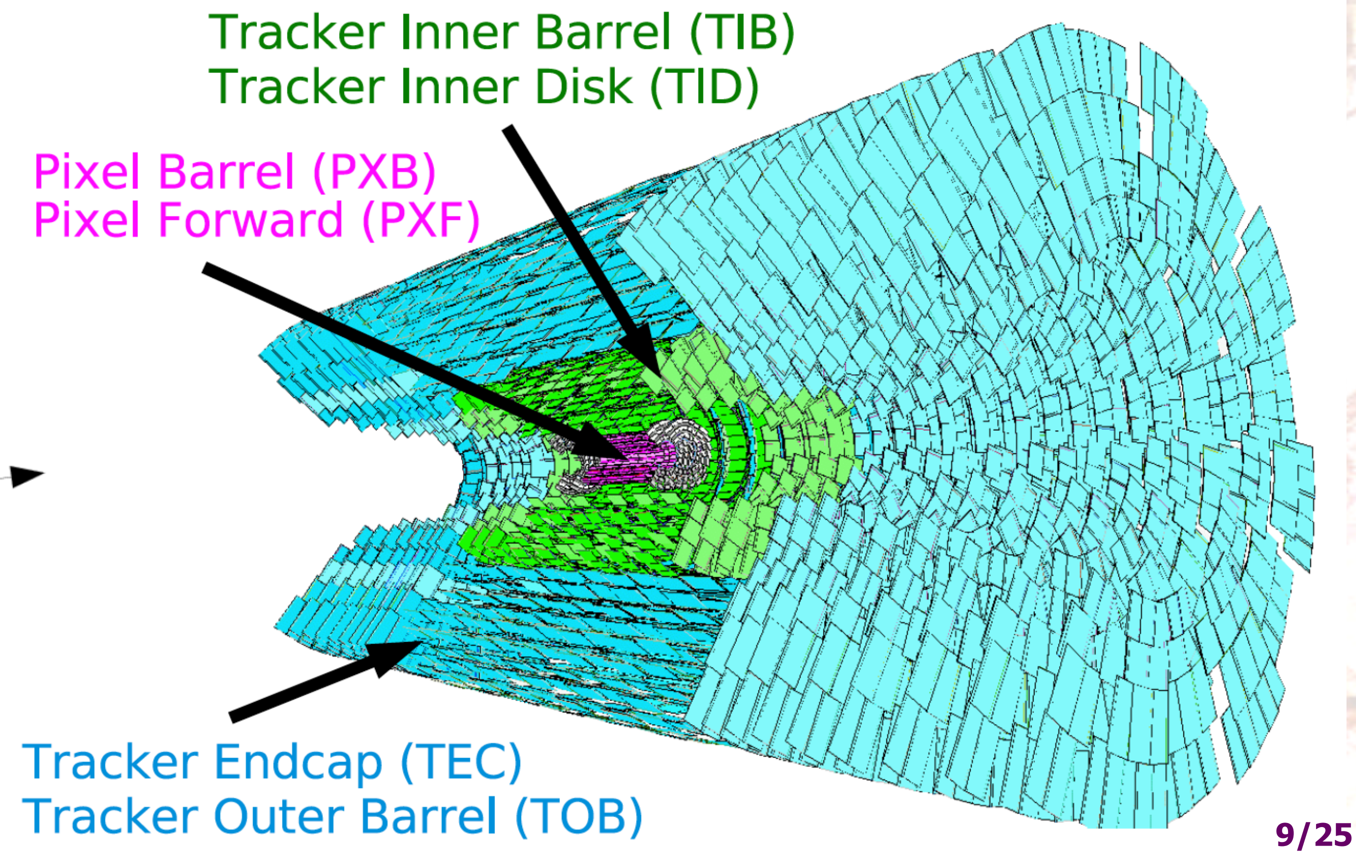
Tracker alignment is one of the crucial factors in reaching the design resolution of the CMS detector

The challenge is to determine at O(10µm) the corrections for the 6 d.o.f (3 rotations + 3 translations) for each of the > 16k modules of CMS tracker

- **Complex system of equations: 16.5k modules x 6 d.o.f. ≃ 100k unknowns**
- **Fast and robust algorithms are deployed in the CMS framework.**

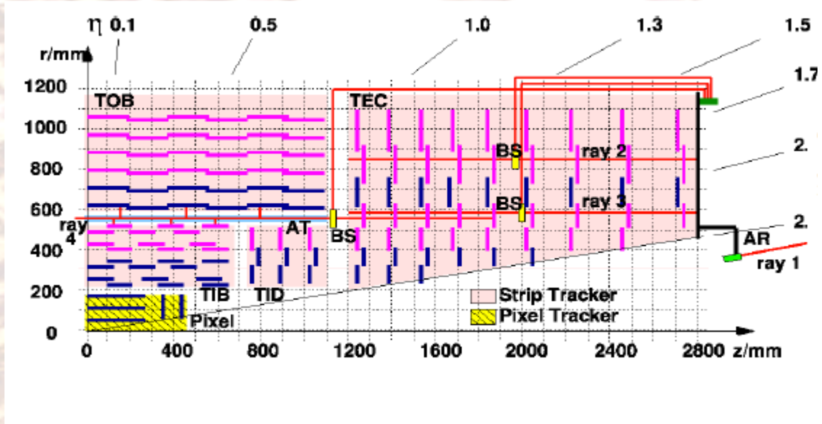






Different Source of Alignment

Input to CMS Tracker alignment algorithms:
– Laser Alignment System
– optical survey
– tracks from cosmic muon runs → ultimate precision



Laser Alignment System (LAS):
Connect large structures (8 sectors in φ): TIB - TOB - TEC
- **Cosmic runs for commissioning: standalone ~100µm, relative ~20µm**
- **Tracker geometry: note 2D (100 mrad strip angle) and 1D modules**

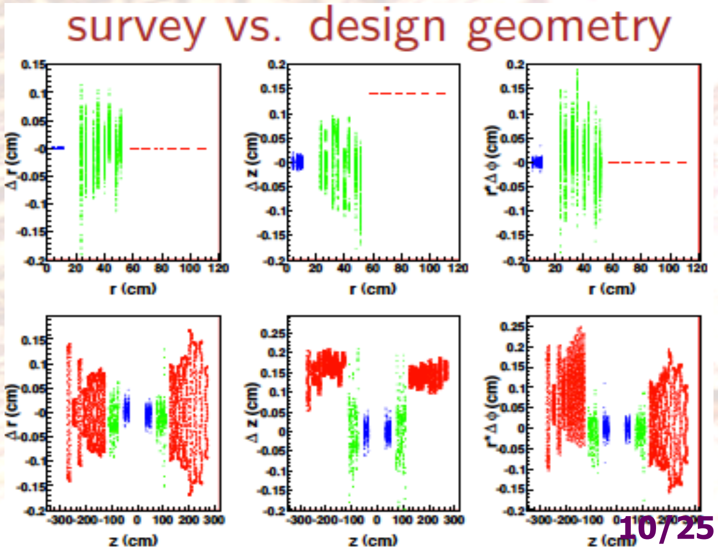
Use previous measurement to control and constraint the cosmic one

Barrels:

- PXB - modules (2D only)
- TIB - modules and up
- TOB - barrel

Endcaps:

- PXF - modules and up
- TID - modules and up
- TEC - disks and endcap



Track Based Alignment

Alignment Algorithms

Local Iterative Method: "Hit and Impact Points"

CMSNote 2006/018

$$\chi^2_{loc} = \sum_i^{hits} r_i^T(p_m)\, V_i^{-1}\, r_i(p_m) + \sum_i^{surveys} r_{*j}^T(p_m)\, V_{*j}^{-1}\, r_{*j}(p_m)$$

Tracks + Surveys to fix all the alignable degrees of freedom

$$\Delta p_m = \left[\sum_i J_i^T V^{-1_i} J_i\right]^{-1} \left[\sum_i J_i^T V^{-1_i} r_i\right]; \quad J_i = \partial r_i / \partial p_m$$

Pros: use same tracking algorithm than CMS, simple implementation, all d.o.f.

Cons: ignore correlations in one iteration iterations, large CPU with many

Global Method: "Millepede II"

NIM A 566, 5 2006

Linearize track model $f_{ij}(p,q_j)$ as a function of the corrections to alignment parameters a

$$\chi^2(p,q) = \sum_j^{tracks} \sum_i^{hits} \frac{\left(y_{ij} - f_{ij}(p_0, q_{j0}) + \frac{\partial f_{ij}}{\partial p} a + \frac{\partial f_{ij}}{\partial q_j} \delta q_j\right)^2}{\sigma_{ij}^2}$$

Minimization leads to the matrix equation which has to C a=b be solved to extract a

Pros: include module correlations, less CPU with one or few iterations

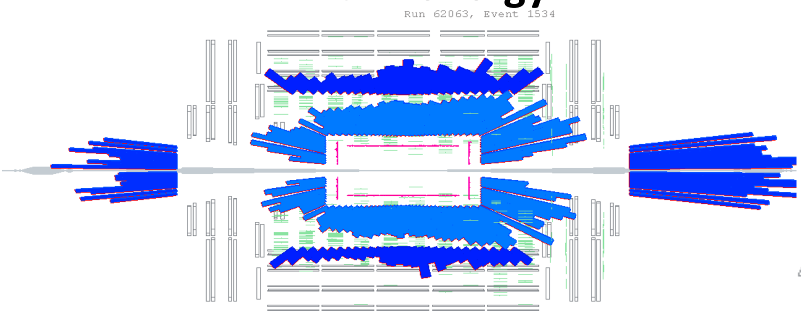
Cons: simple helix trajectory model, large matrix may limit total N of alignables

CRAFT: Cosmic Run At Four Tesla

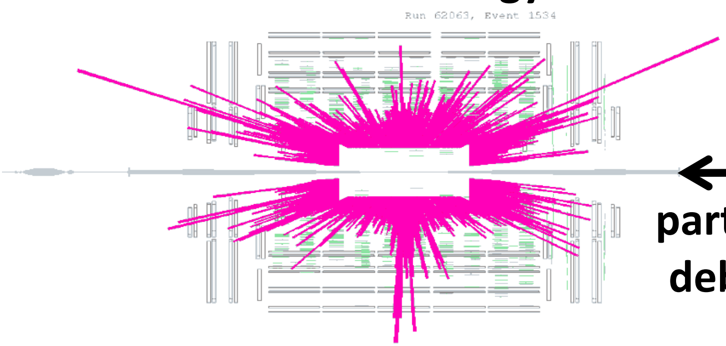
Numerous global runs with CMS detector have been performed.
2 main period of 3 weeks of continuous data taking
→ CMS has recorded 300 Millions cosmics events with magnetic field ON each time.

Beam from LHC
(tracker OFF)

HCAL energy

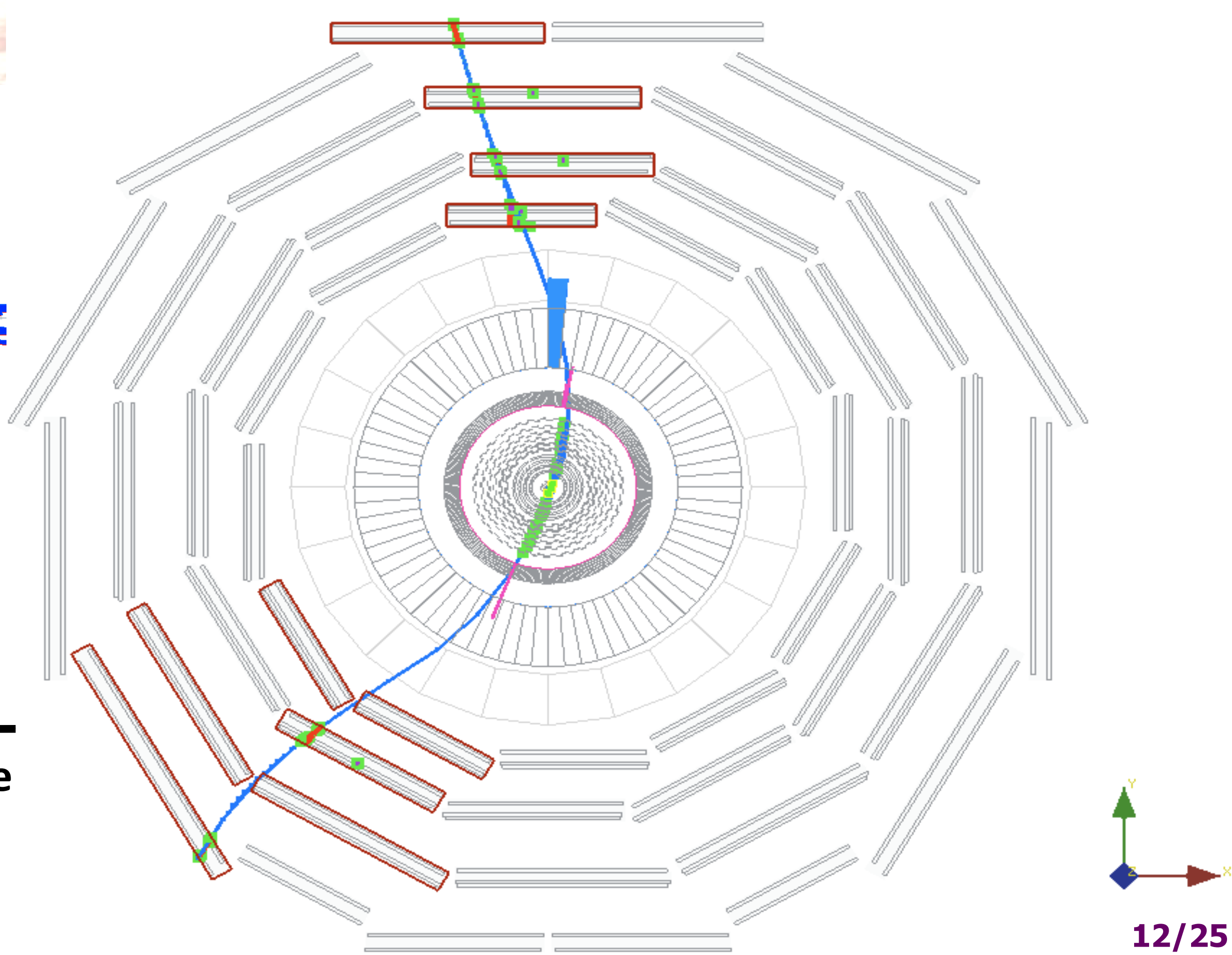


ECAL energy



← particle debris

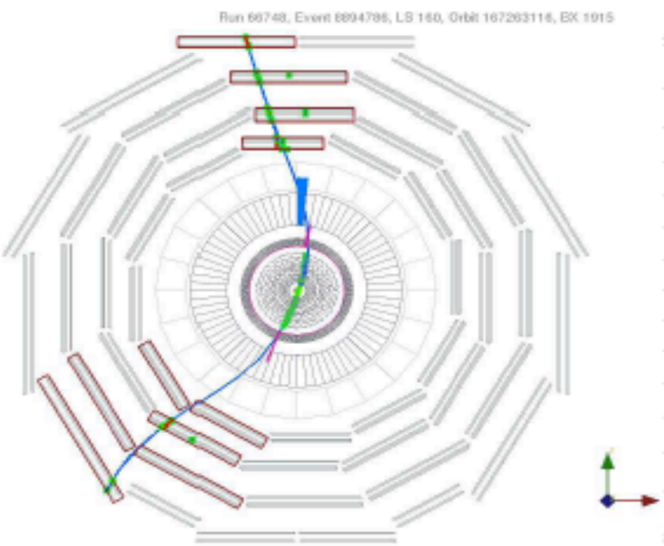
Cosmic Run

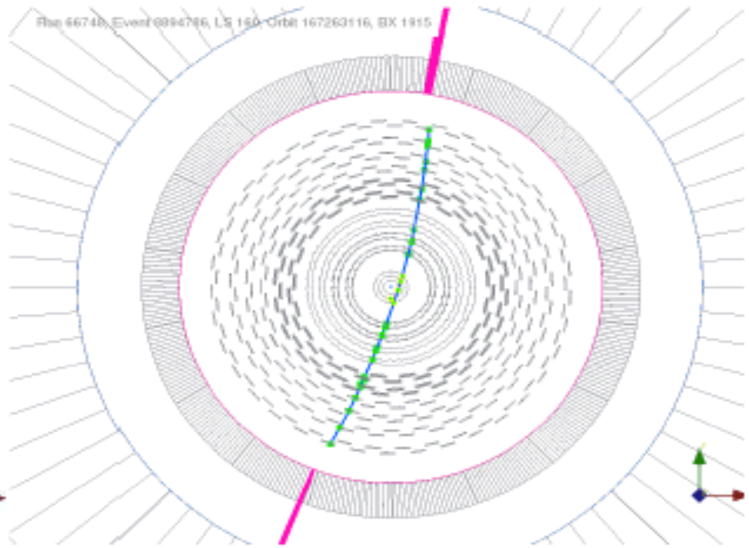


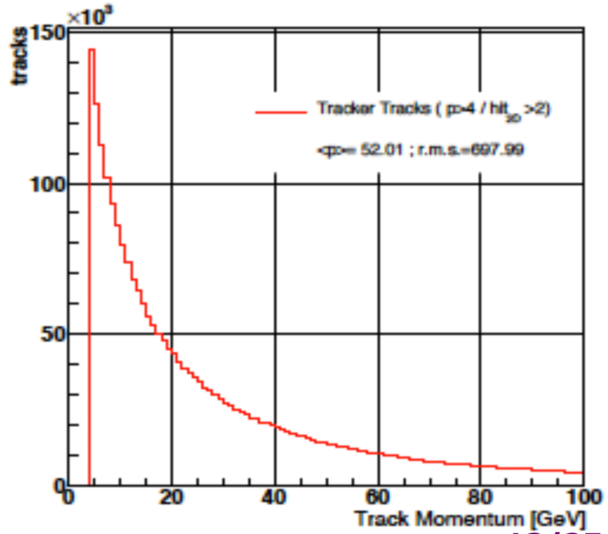
Longitudinal views

First data for alignment

Best data for alignment of CMS Tracker: fall 2008 (“CRAFT08”)
[CRAFT09 studies are on going]
~ 4M cosmic tracks for Tracker alignment (with B-field = 3.8T)
account for multiple scattering, p > 4 GeV/c
• Require good quality tracks and hits:
clean hits, outlier hit rejection, χ^2 cut, min hits, 2D hits
accept all good tracks (statistics limited): only 3%+1.5% in Pixels

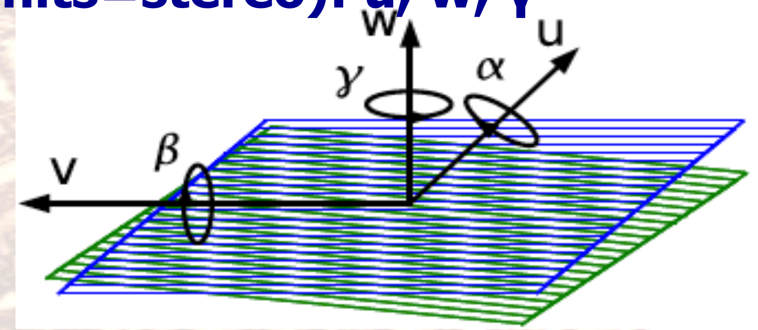






Multiple steps alignment

Multi-step approach by both algorithms to address CMS geometry:
– large structure movement: coherent v alignment of 1D modules
– alignment of two sides of 2D strip modules (units=stereo): u, w, γ



• Global method:
→ 3 steps from "design"
(1) large structures (6 dof) & units (3 dof)
(2) module alignment: add α,β for TIB;
6 dof for PXB
(3) repeat (1); note above: keep <46,300 parameters, use pre-sigma

• Local method:
→ 5 steps from survey; ~50 iterations each
(1) large structures (u, v, w, γ)
(2),(3) Strip: modules (6 dof) with survey; units (3 dof)
(4),(5) Pixels: ladders (6 dof); modules (6 dof)

Merging Algorithms

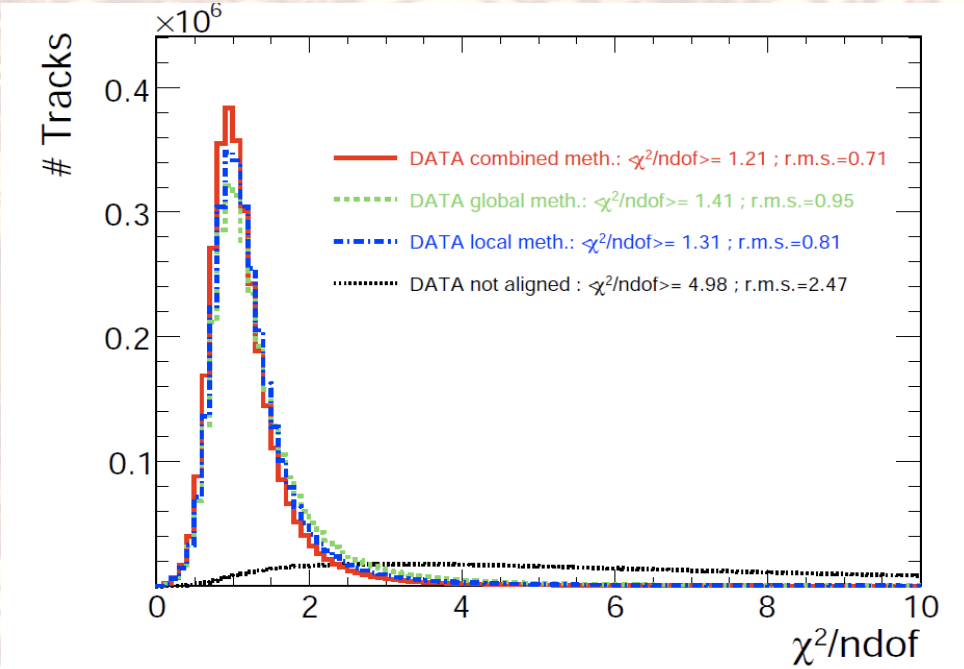
- **Combined method**

(1) run global method

→ solve global correlations efficiently

(2) run local method

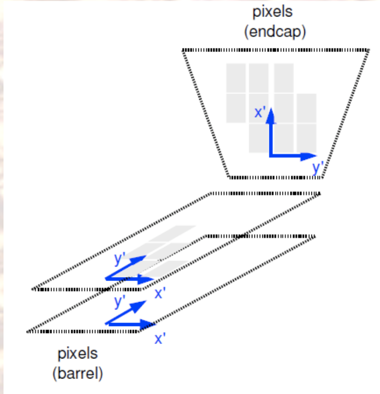
→ solve locally to match track model in all dof

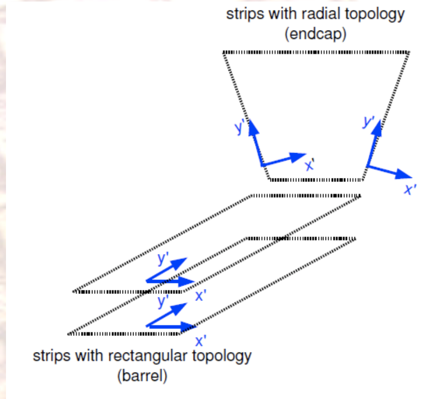


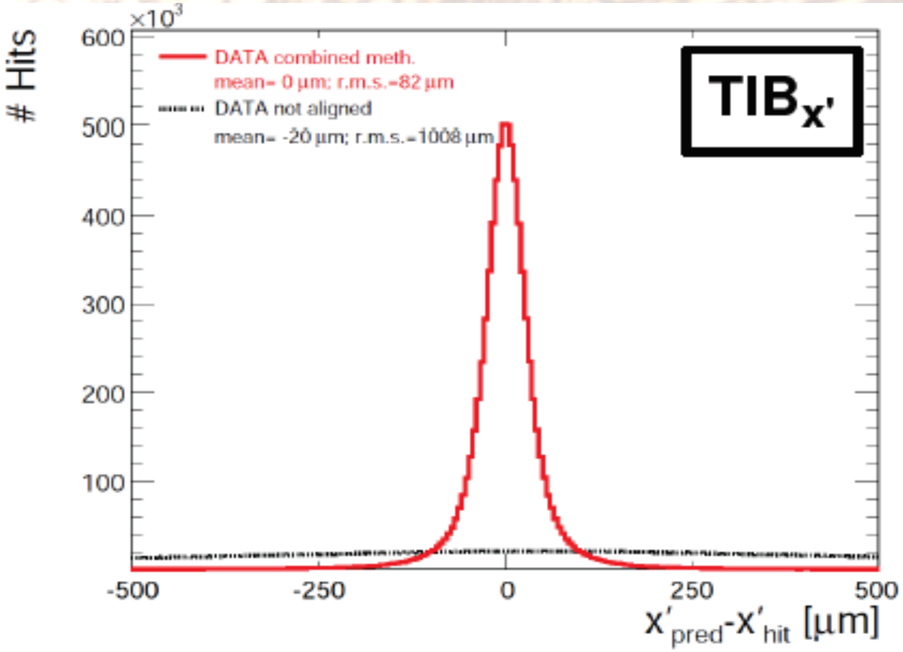
All three results are compatible, but combined is the best also compare to "not aligned"

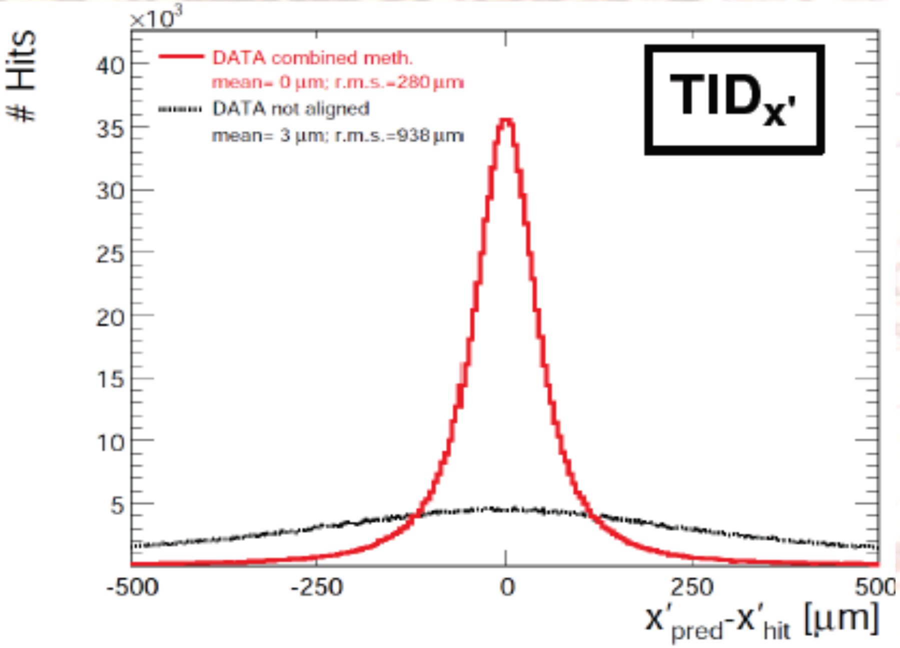
Low Level Validation: unbiased residuals

Computed at the same time as χ2 /ndof unbiased as the hit on the module under investigation is removed from the re-fit of the track shown as function of the local coordinates x' and y'

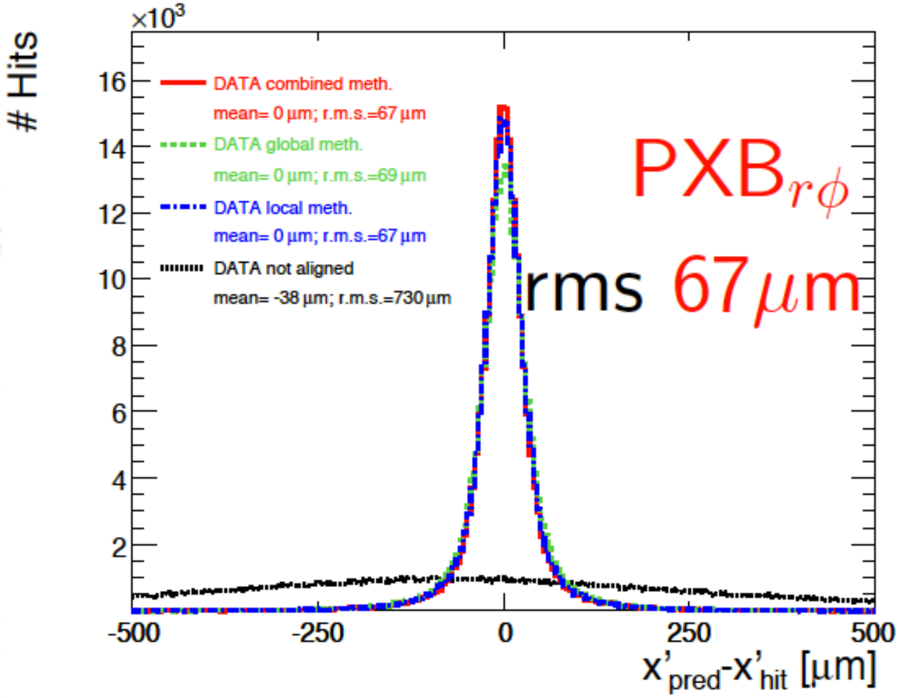


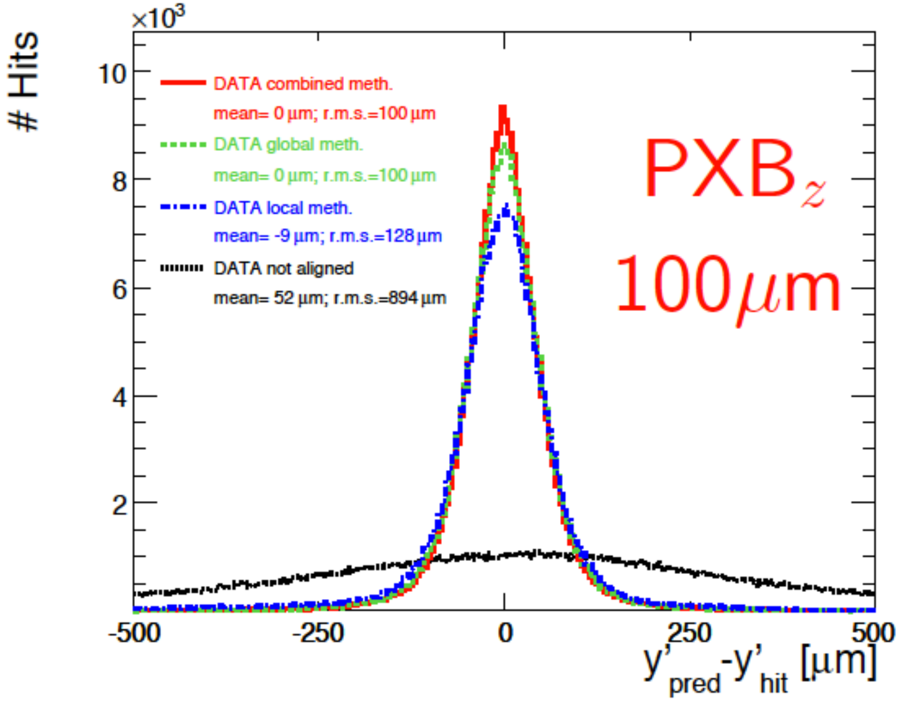






Pixel Residuals





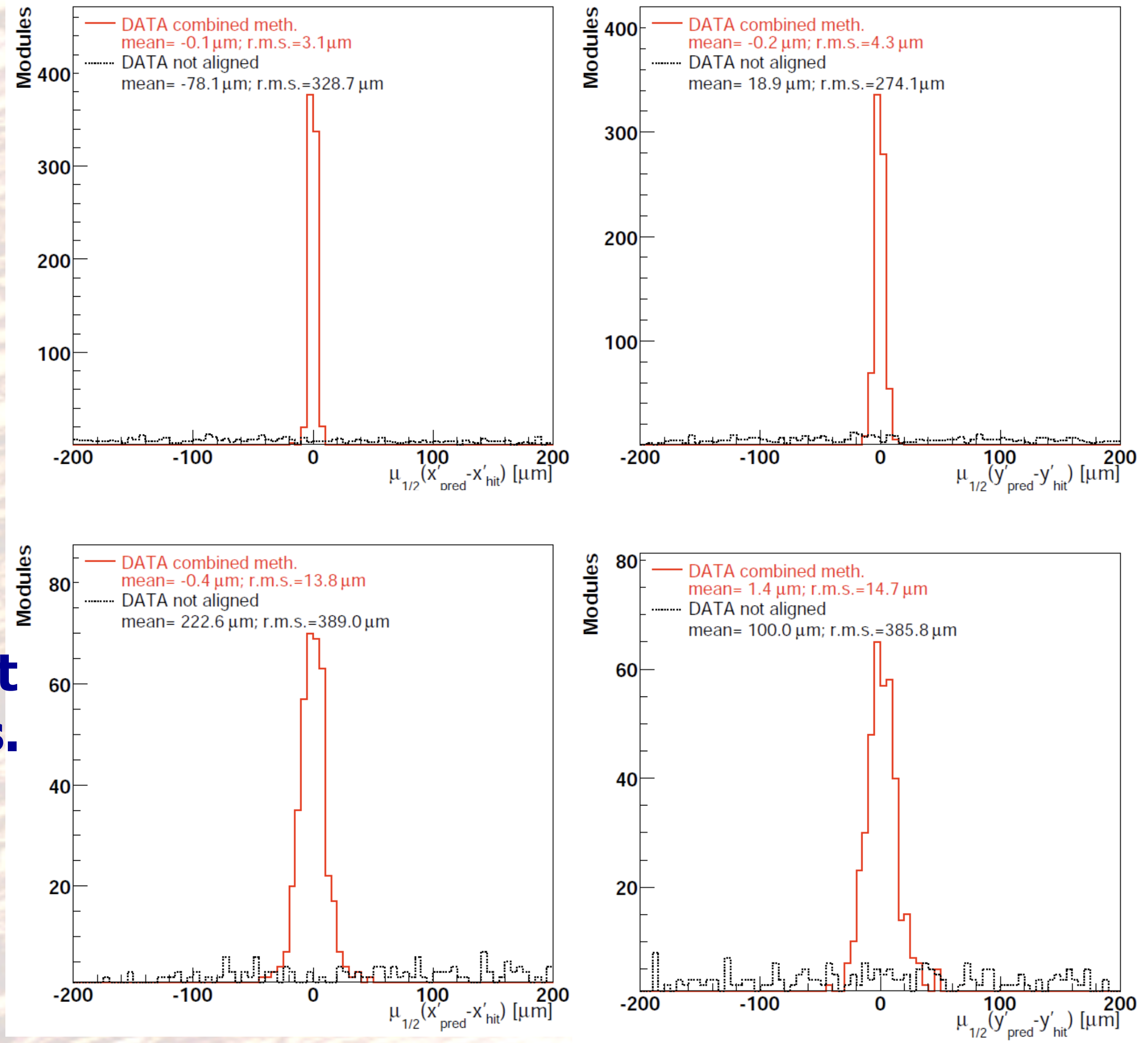
Residuals → multiple scattering + hit errors + alignment errors
(random) (random) (systematic)

rφ pixel hit errors ~ 19µm here

Median of Residuals

Measure for remaining misalignment:
- **Module-wise information, distribution of median of the residuals DMR regarded.**
- **Medians of several modules plotted.**
- **Spread gives lower limit for misalignment (for sufficient statistics).**
- **Used to estimate misalignment corrections to intrinsic hit errors.**

Alignment performance : Pt > 4 GeV/c, 1 entry per module with Nhits>30

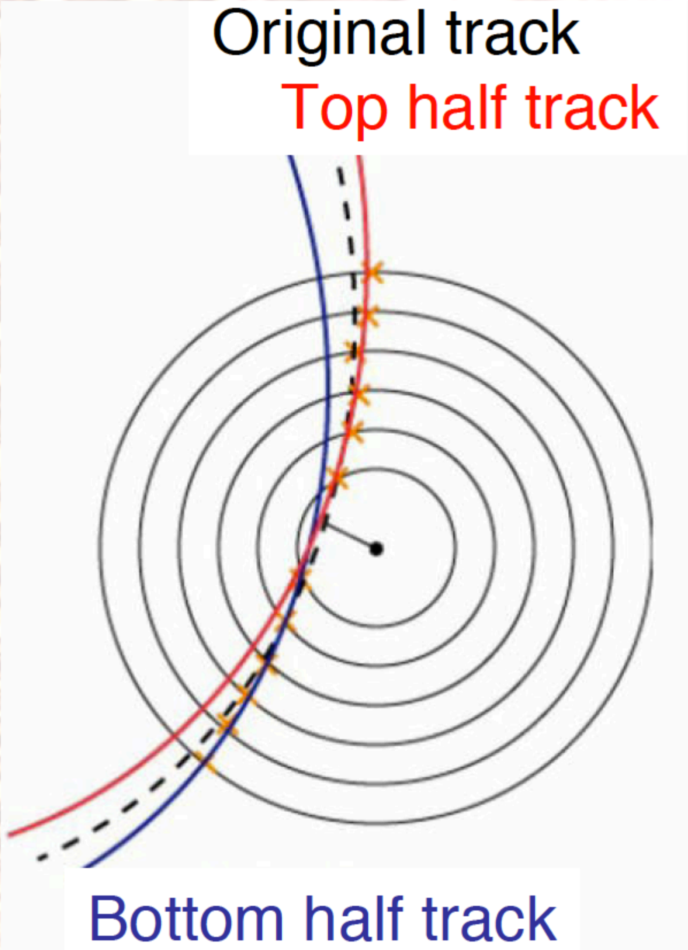


Cosmic data causes asymmetric module illumination different regions reach different alignment quality.

Performance close to Simulation

High Level Validation: Cosmic Track Splitting

Consider the point of closest approach (PCA) to the nominal beamline
Re-fit separately top and bottom legs and compare the 5 track parameters at the PCA
Track selection: pT>4 GeV/c, χ2/dof<100
Nhit≥10, N2Dhit≥2, NPXLhit≥2
PCA in the volume of the pixel
Each split track: Nhit≥6
~50k evts selected



In the following:
absolute residuals:

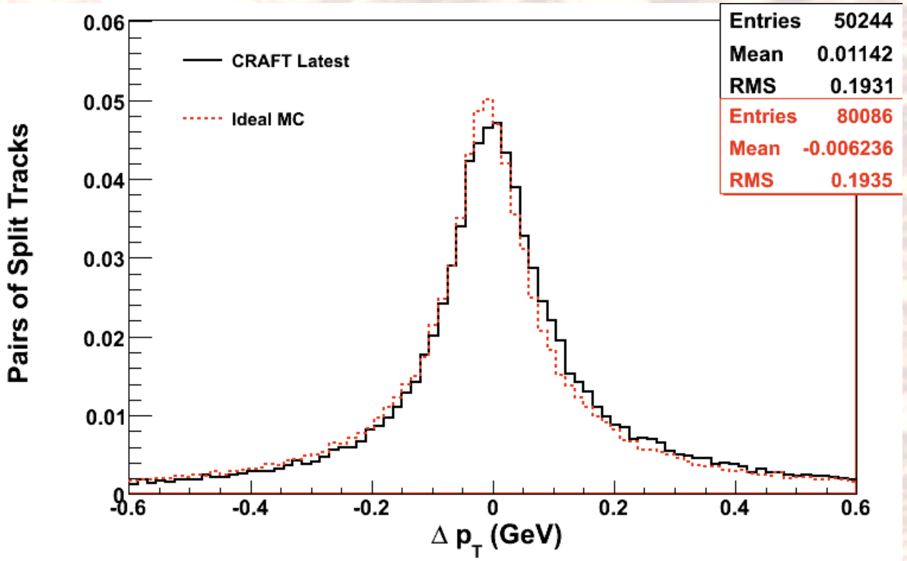
$$\frac{x_{top} - x_{bottom}}{\sqrt{2}}$$

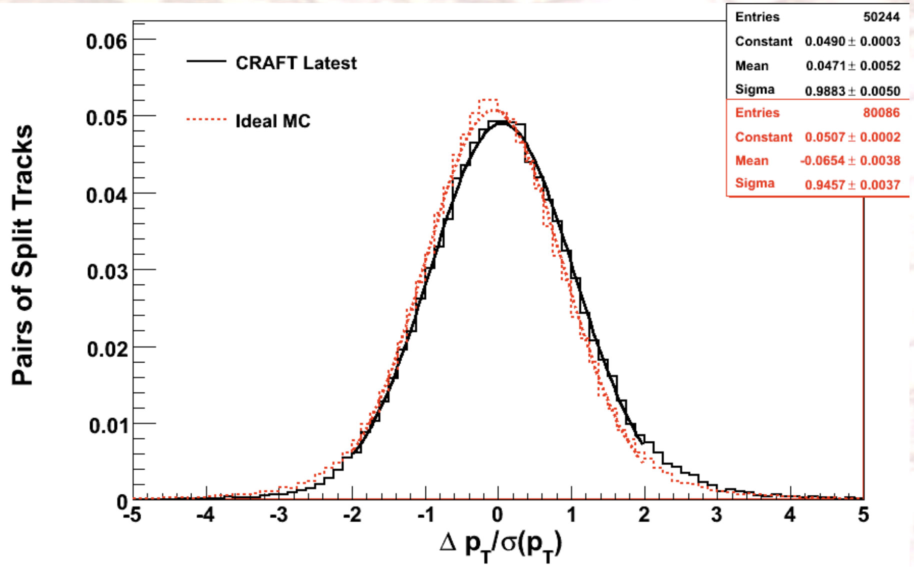
normalized residuals:

$$\frac{x_{top} - x_{bottom}}{\sqrt{\sigma^2_{x_{top}} + \sigma^2_{x_{bottom}}}}$$

x = dxy, dz, φ, θ, 1/pT

Cosmic track splitting absolute residuals

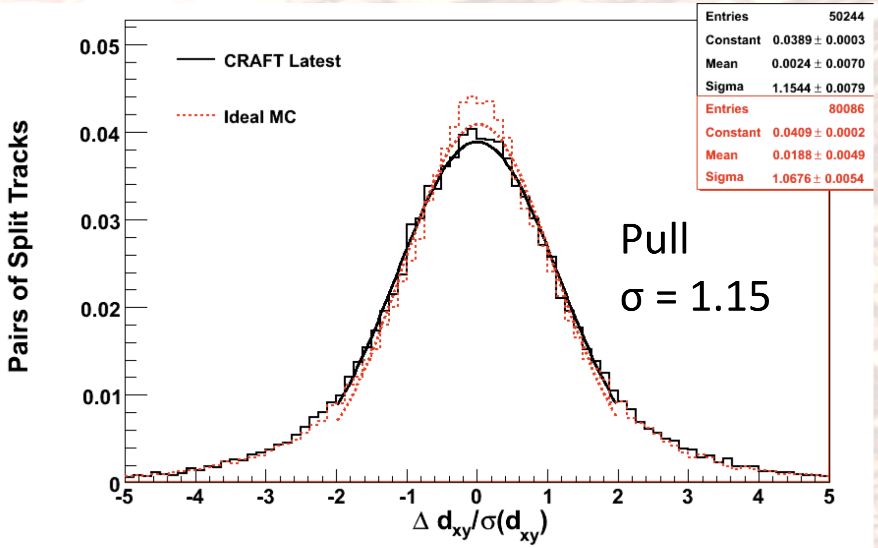


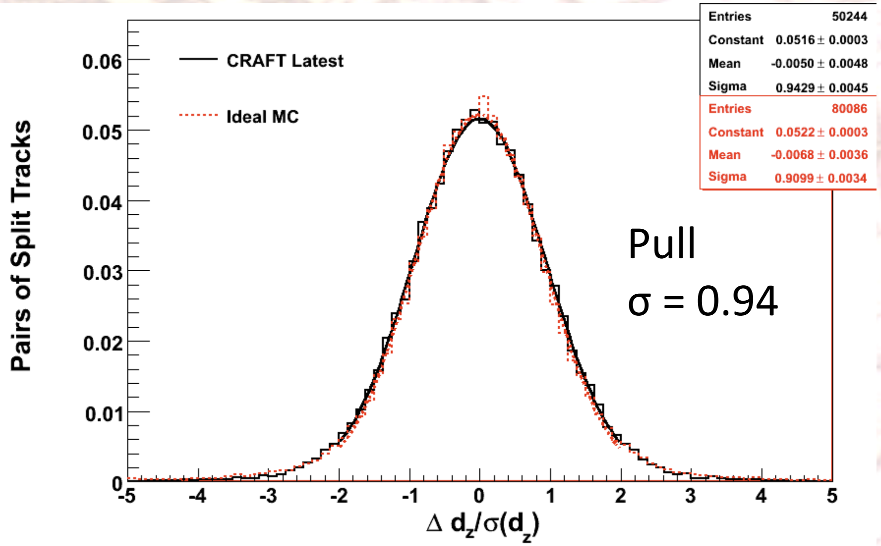


absolute residuals	DATA combined meth. r.m.s.	MC ideal r.m.s.
Δp_T (MeV/c)	193	193
Δd_{xy} (μm)	44	37
Δd_z (μm)	59	47
$\Delta\phi$ (μrad)	425	406
$\Delta\theta$ (μrad)	639	511

pT mainly sensitive to the alignment in the strips: close to the ideal performance for cosmics-like track topology.
dxy and dz mainly sensitive to the alignment in the pixels

Cosmic track splitting normalized residuals





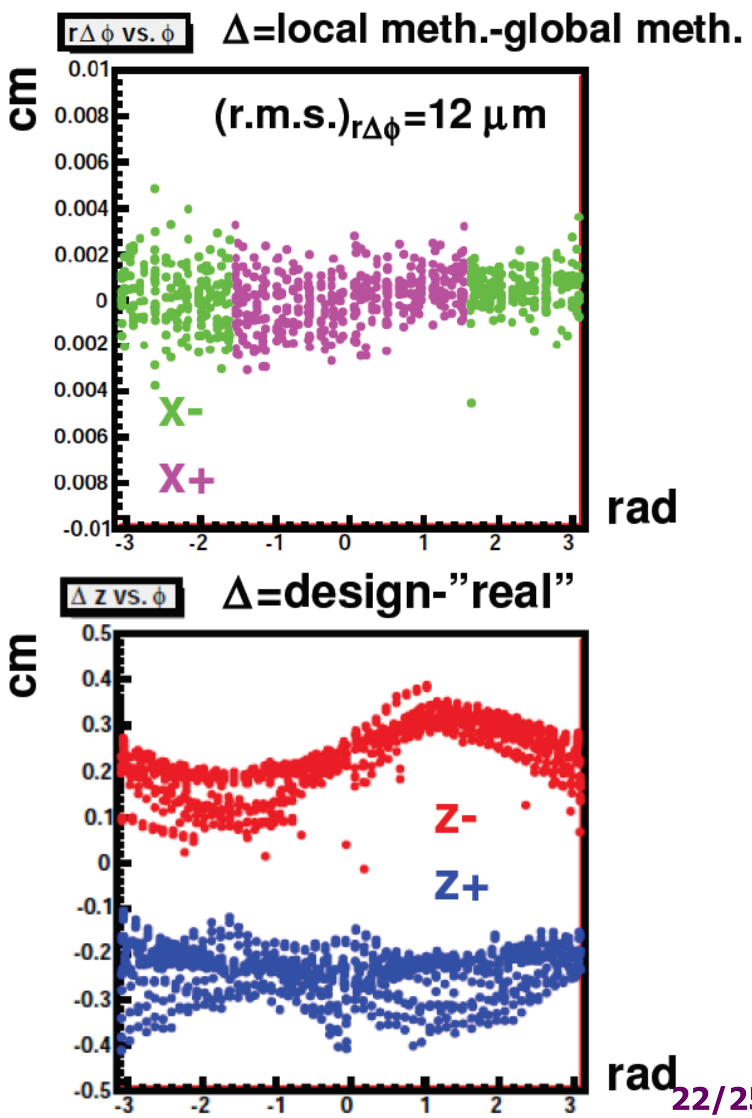
normalized residuals	DATA combined meth. σ	MC ideal σ
$\Delta p_T/\sigma(p_T)$	0.99	0.95
$\Delta d_{xy}/\sigma(d_{xy})$	1.15	1.07
$\Delta d_z/\sigma(d_z)$	0.94	0.91
$\Delta\phi/\sigma(\phi)$	1.14	1.05
$\Delta\theta/\sigma(\theta)$	0.97	0.96

Checks of the geometry

Deformations leaving the track χ2 unchanged not caught by low level validation (χ2,DMR)

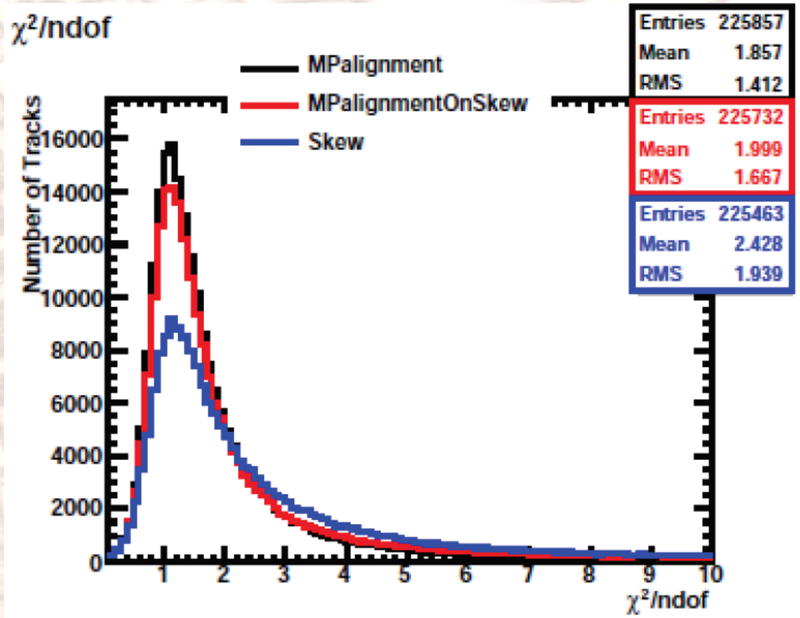
Compare geometries from two methods:
case study: local meth. vs global meth. geometries in PXB (2D measurements, small lever arm)
Effects can be much larger (x10) when dealing with structures of size O(1m)!

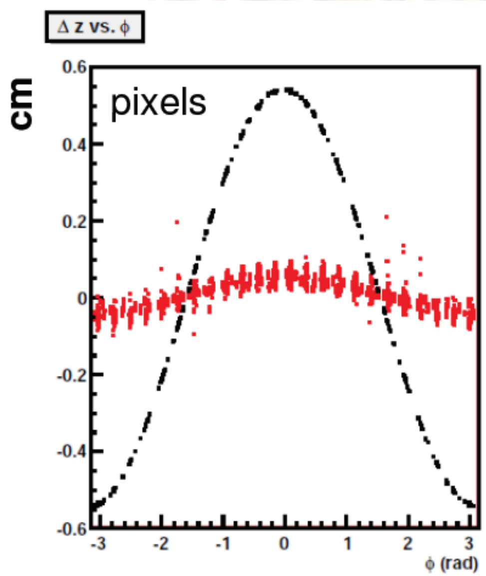
Compare the "real" (from combined meth.) to the design geometry
TIB: 5 mm shift of the two HalfBarrels along z-axis (two halves shifted apart) confirmed by optical survey
remaining scatter: indication of "skew"?

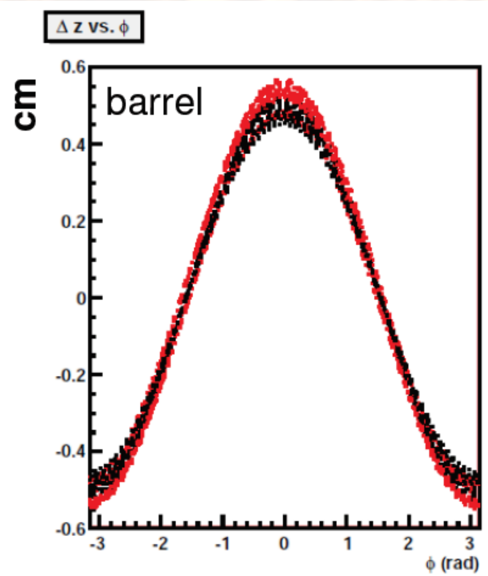


Sensitivity to weak modes from cosmic: skew

"skew" Δz vs φ
Systematic misalignment added to the geometry from the global method
Re-align (global method) using DATA starting from the systematically misaligned geometry



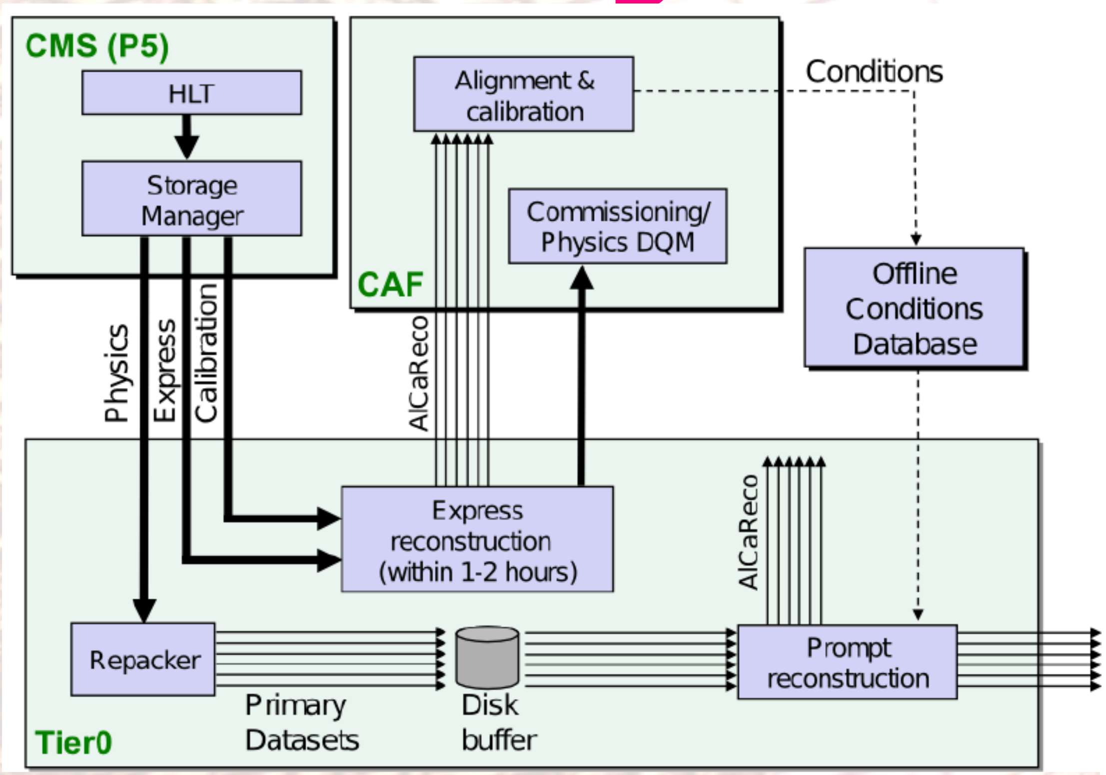




In the plots: shifts w.r.t starting alignment geometry (flat horizontal line at zero if the mode is recovered)
Skew is not recovered in the barrel!

Towards data taking

Currently, as running on cosmics, all events are recorded.
Aim: alignment as prompt as possible to perform physics searches
→Need to ensure large statistics of events in a short period of time



Events selected on the physics HLT menu
Express Stream will include events selected for alignment and calibration

Event reconstruction:
Express reconstruction:
production of AlCaReco (keep a few object to improve iterative algorithms)
Prompt reconstruction:
buffer all the data to disk, execute subset of alignment and calibration tasks in O(24 h) using (semi-) automated tools
Use alignment/calibration results for prompt reconstruction

Complete workflow (with buffer disk for data) has been exercised successfully over CRAFT09

Conclusion

Start up of experiment → Commissioning phase
Alignment and calibration of the different subdetector should be determined precisely to reach the design performance of CMS detector.

Tracker alignment is a complex task due to the number of modules.

Tracker alignment strategy is well defined and used all previous available information and complementarities of two algorithms.

Results obtained using CRAFT08 data show alignment precision close to ideal geometry (better than expected)

Full workflow has been exercised:

CMS is ready to get data and will finalize the tracker alignment