First Alignment of the Complete CMS Tracker

CHIPP PhD Winter School 2010

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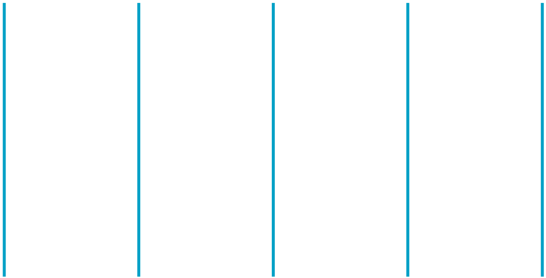
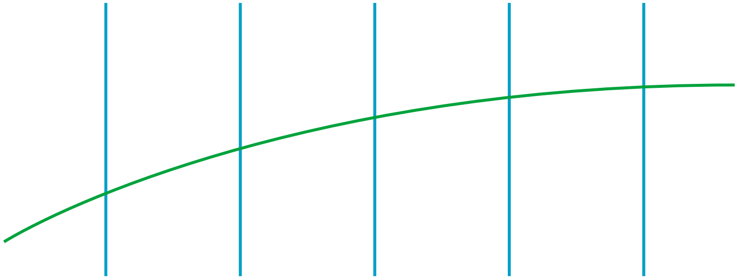
Overview

Alignment of a simple toy tracker



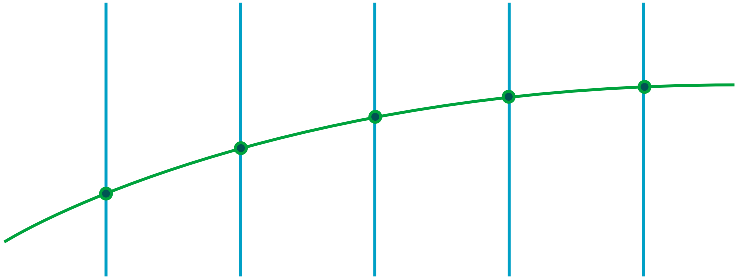
Think of an ideal tracker built of five sensors. . .

Alignment of a simple toy tracker



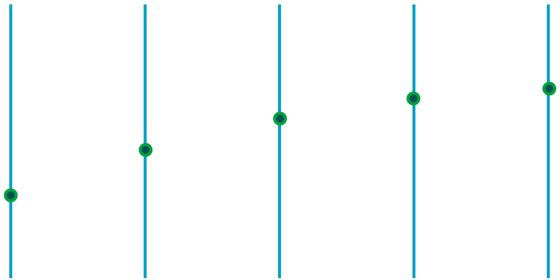
A track runs through our device

Alignment of a simple toy tracker



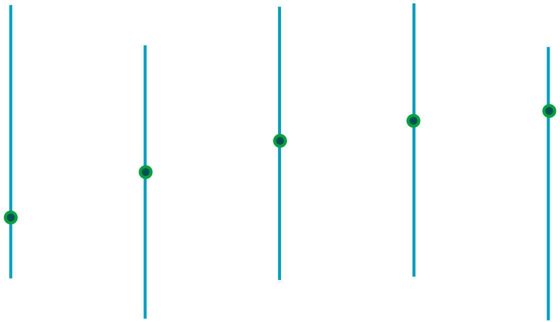
The track generates hits

Alignment of a simple toy tracker



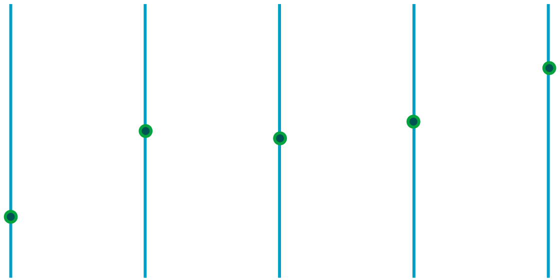
What you really see are the hits

Alignment of a simple toy tracker



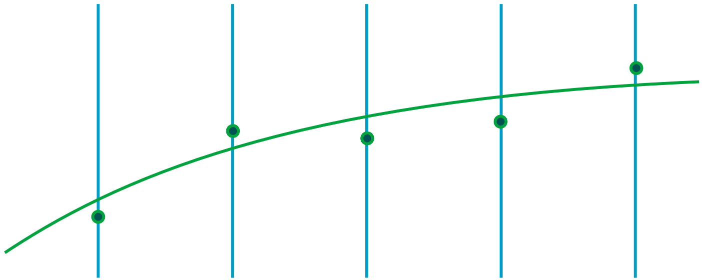
In reality your modules are misaligned

Alignment of a simple toy tracker



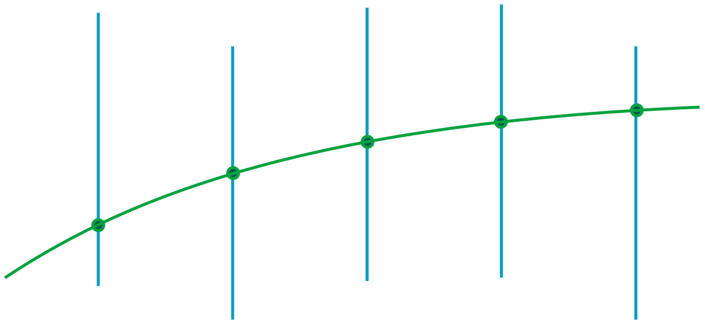
You still assume an ideal tracker

Alignment of a simple toy tracker



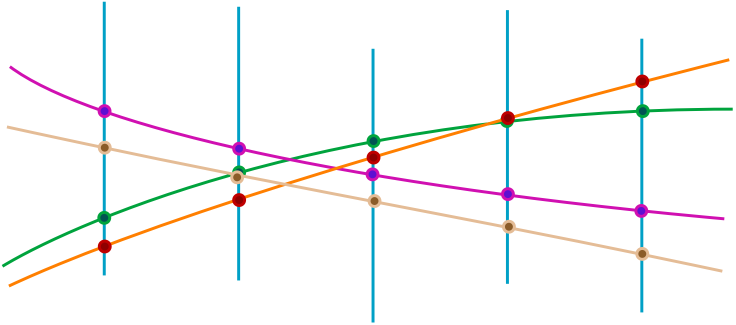
Then your fitted track will look probably like this one

Alignment of a simple toy tracker



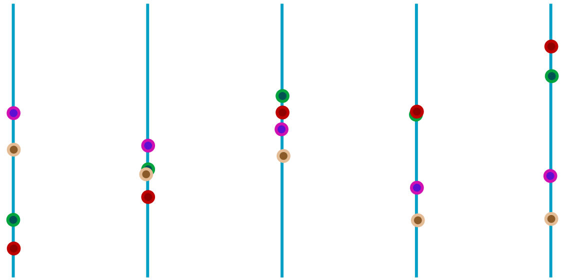
Calculate new positions of the modules and your fit will be better
– limited to track hit precision, of course

Alignment of a simple toy tracker



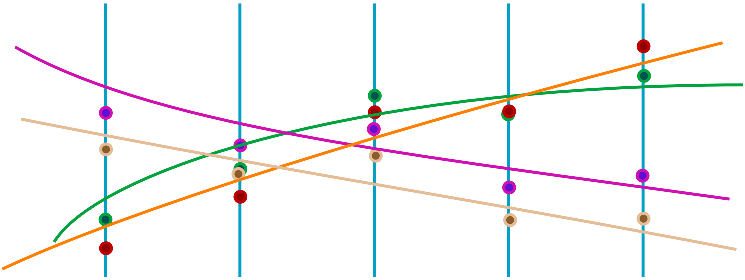
Do this for a lot of tracks collected over time

Alignment of a simple toy tracker



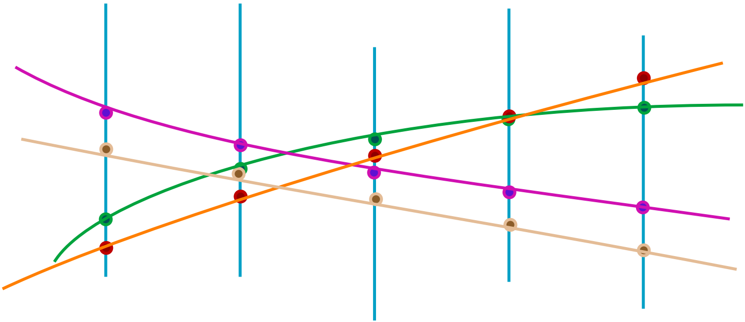
Again, you know nothing about reality, tf. assume ideal geometry

Alignment of a simple toy tracker



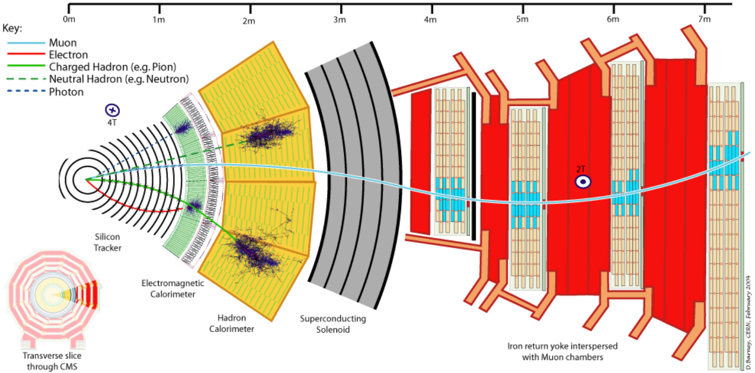
Fit tracks and calculate new positions

Alignment of a simple toy tracker



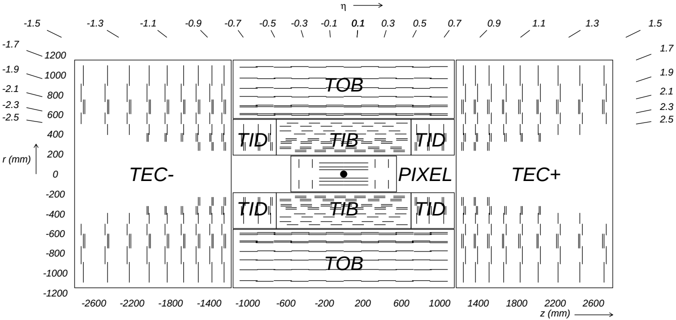
And end up with a better aligned tracker

A slice of CMS



This shows a slice of the CMS experiment. The silicon tracker covers the innermost $\approx 1\,\mathrm{m}$ of the path a particle from the interaction point takes through the experiment.

The CMS inner tracker

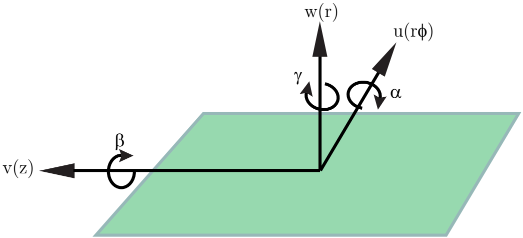


The tracker is split into the following subdetectors:

Pixel:	pixel barrel (PXB) and pixel endcap (PXE)
Silicon strips:	Tracker inner barrel (TIB) and outer barrel (TOB)
	Tracker inner disk (TID) and endcap (TEC)

The pixel consists of 1440 modules, the strip of 15 148 modules

The coordinate system



This shows the local coordinate system definition used in the CMS tracker.

u is defined to be the most sensitive coordinate.

The global coordinates in parantheses are valid in barrel structures only.

The alignment problem

Track based alignment is a case of a *least squares problem*.

- We have to solve for parameters describing the position of the modules:

$$
\begin{aligned}
N_{\text{globpars}} &= N_{\text{modules}} \cdot N_{\text{degrees of freedom}} \\
&= 16\,588 \cdot 6 = 99\,528 \approx 10^5
\end{aligned}
$$

- And we have parameters describing the tracks. Typical alignment for our detector requires $O(10^6)$ tracks with at least 5 parameters to describe one track.

We end up in a least squares problem with $O(10^7)$ parameters, which is challenging to solve in reasonable time, e.g. in 24 hours.

Alignment algorithms used

The expression to be minimized is

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\textit{hits}} \mathbf{r}_{ij}^T(\mathbf{p},\mathbf{q}_j)\,\mathbf{V}_{ij}^{-1}\,\mathbf{r}_{ij}(\mathbf{p},\mathbf{q}_j)$$

where $\mathbf{p}$ are the module parameters and $\mathbf{q}_j$ are the track parameters. Two approaches are used within CMS:

Millepede-II
: This is a **global** approach. Reduces the complexity of the problem by restricting the solution to the module parameters only, therefore the problem is $O(10^5)$.

HIP
: This is a **local** iterative approach reducing the complexity to solving a local problem of $O(10^1)$ at every module. Correlations between modules are recovered while iterating.

Typical run time is a few hours on current CPUs for both algorithms.

Alignment algorithms

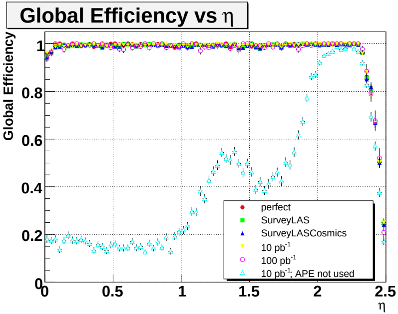
The two algorithms are somewhat complementary:

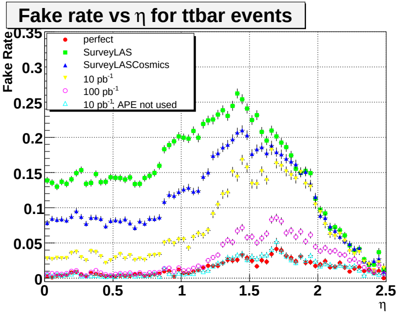
Algorithm	Advantages	Disadvantages
global (Millepede-II)	▶ includes correlations between modules ▶ only a few iterations due to outlier rejection	▶ uses a simplified track model (specific to CMS implementation, this has ben changed meanwhile)
local (HIP)	▶ track model as in CMS track reconstruction (Kálmán filter) ▶ implementation allows use of survey data	▶ ignores correlations between modules ▶ many iterations if start values are far away

Therefore we used a combined approach: first Millepede, then HIP

Motivation for alignment: p_T resolution

Why do we need a good alignment? Some results of MC studies to get a feeling:





Left: Track reconstruction efficiency for single muons with p_T of 100 GeV/c for a selection of misalignment scenarios.
Right: Fake rate for $t\bar{t}$ events.

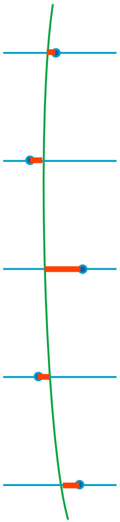
Results

Some information about the results I present in the following slides:

- The cosmics events were recorded in autumn 2008
- The total number of events detected by CMS during this campaign was about 300 million
- 3.2 million of them have hits in the tracker suitable for alignment use
- The rate is about 5 Hz
- The fraction in the pixel detector was $\approx 3\%$ in the barrel and $\approx 1.5\%$ in the endcaps.
- Data used for alignment and validation were not statistically independent due to limited number of events collected.
- **All results shown are preliminary**

Sorry, no 2009 results released yet (but no surprises in there, anyway).

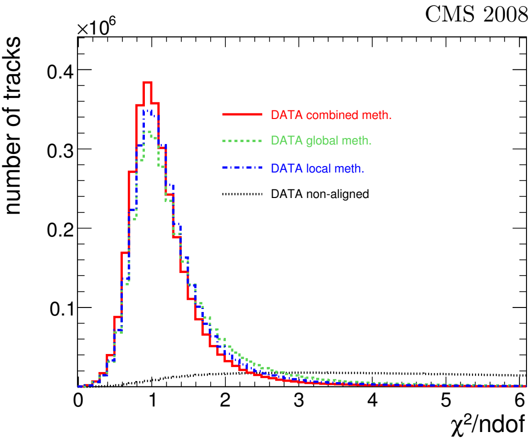
Track χ^2/ndof



For each track χ^2/ndof is calculated and histogrammed. ndof is the *number of degrees of freedom*, which depends on how many hits were read out by the detector for a given track.

This histogram gives a first overview in how good the overall alignment is.

Track χ^2/ndof

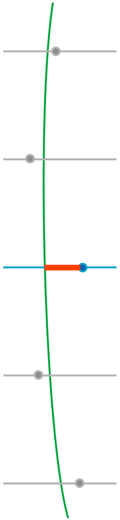


The three alignment approaches show the expected order, where the combined method outperforms the others.

The non-aligned geometry, assuming ideal design geometry, shows the worst result.

This includes proper calibration of the alignment position errors.

Distribution of the median of the residuals (DMR)



Track residual plots are constructed in the following way:

1. loop over tracks
2. for each hit perform a refit of the track *without* this hit
3. calculate the distance between the predicted hit by the track and the measured hit; the so called *unbiased residual*

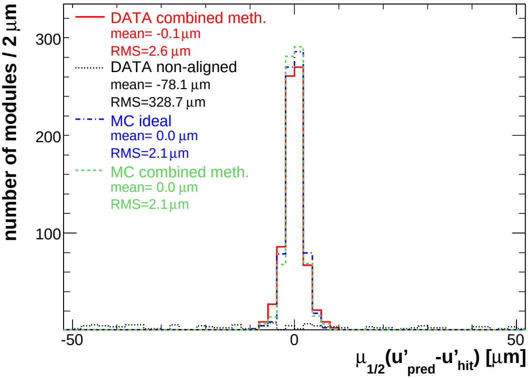
Distribution of the median of the residuals (DMR)

Two effects besides alignment dominate the distribution of these residuals:

1. track extrapolation uncertainties (multiple scattering)
2. hit position uncertainties

Both are random effects. Alignment effects lead to systematic shifts. Therefore for modules with more than 30 hits we calculate the median.

Distribution of the median of the residuals (DMR)



DMR plot of the **pixel barrel** detector as a representative example compared to a Monte-Carlo simulation.

The non-aligned geometry shows very poor results whereas the alignment recovers the performance close to the MC performance.

DMR – Observed values

The table shows the observed RMS values for the individual subdetectors. Note: Pixels detect in two dimensions.

subdetector (coordinate)	non-aligned [μm]	global [μm]	local [μm]	combined [μm]	modules >30 hits
PXB (u')	328.7	7.5	3.0	**2.6**	757/768
PXB (v')	274.1	6.9	13.4	**4.0**	
PXE (u')	389.0	23.5	26.5	**13.1**	391/672
PXE (v')	385.8	20.0	23.9	**13.9**	
TIB (u')	712.2	4.9	7.1	**2.5**	2623/2724
TOB (u')	168.6	5.7	3.5	**2.6**	5129/5208
TID (u')	295.0	7.0	6.9	**3.3**	807/816
TEC (u')	216.9	25.0	10.4	**7.4**	6318/6400

Note: Keep the definition of DMR in mind – we don't know the absolute positions of the modules by that precision. With cosmics we are blind to some deformation modes. Collision tracks will improve this.

DMR – Monte Carlo

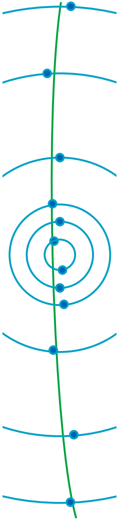
In order to check the performance, the procedure has been compared to a Monte-Carlo simulation for cosmic muons

subdetector (coordinate)	combined [μm]	combined MC [μm]	ideal MC [μm]
PXB (u')	**2.6**	2.1	2.1
PXB (v')	**4.0**	2.5	2.4
PXE (u')	**13.1**	12.0	9.4
PXE (v')	**13.9**	11.6	9.3
TIB (u')	**2.5**	1.2	1.1
TOB (u')	**2.6**	1.4	1.1
TID (u')	**3.3**	2.4	1.6
TEC (u')	**7.4**	4.6	2.5

The achieved alignment is therefore already close to what is possible, according to MC.

The worse results for the PXE match also the expectations by MC. This is due to low percentage of modules hit by cosmics and suboptimal track angles.

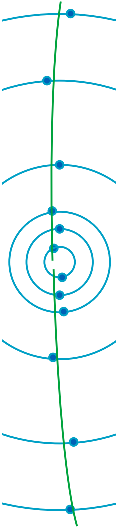
Track parameter resolution



Does the tracker fulfill its purpose? One example to prove this is the following:

1. Take cosmic tracks penetrating the pixel barrel to mimic tracks from collisions

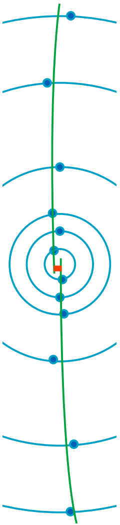
Track parameter resolution



Does the tracker fulfill its purpose? One example to prove this is the following:

1. Take cosmic tracks penetrating the pixel barrel to mimic tracks from collisions
2. Split them at the closest approach to the tracker center

Track parameter resolution

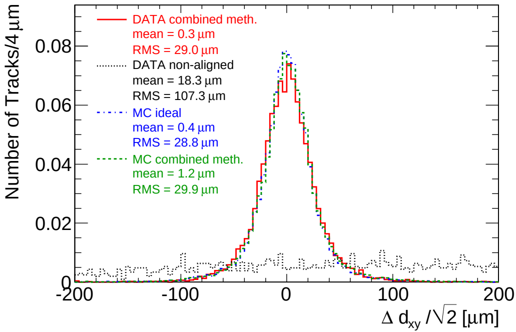


Does the tracker fulfill its purpose? One example to prove this is the following:

1. Take cosmic tracks penetrating the pixel barrel to mimic tracks from collisions
2. Split them at the closest approach to the tracker center
3. Do a refit for both halves
4. Compare the difference in the track parameters (i.e. $1/p_T, dxy, dz, \theta, \phi$) at the point of closest approach of the two tracks

This has been done with real data and in a Monte-Carlo study.

Track parameter resolution ($r\phi$)

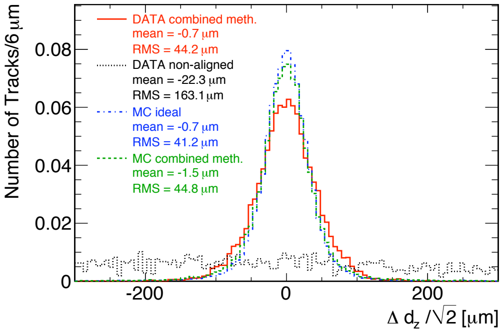


This is the plot for the impact parameter in the $r\phi$ plane.

The aligned tracker (in red) shows a performance close to what is expected in Monte-Carlo for an ideal tracker (in blue), which is about 30 μm.

Note: all track parameters are p_T dependent

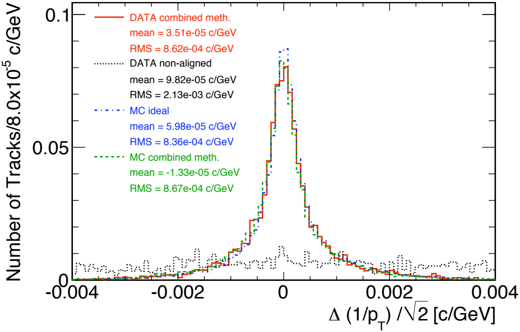
Track parameter resolution (z)



This is the plot for the impact parameter along the z axis.

The aligned tracker (in red) shows a performance close to what is expected in Monte-Carlo for an ideal tracker (in blue), which is about 41 $\mu\mathrm{m}$.

Track parameter resolution (p_T)



The same for the curvature ($1/p_T$).

Again the tracker shows performance close to design.

Conclusions

- Alignment using cosmic tracks has been performed successfully.
- Several validation studies have been carried out, both on low-level and high-level.
- The performance of the tracker is well within the expectations.
- Another run of cosmic data tacking has been performed between August and November 2009 (with interruptions). No surprises found (but results are not yet officially released).
- First experience with collision data gathered. Collected number of events not high enough to perform reasonable alignment. We wait for more data.

References

[1] The CMS Collaboration, *Alignment of the CMS Silicon Tracker During Commissioning with Cosmic Ray Particles*, `http://arxiv.org/abs/0910.2505`, accepted for publication by JINST

[2] V. Karimäki, T. Lampén, F.-P. Schilling, “The HIP Algorithm for Track Based Alignment and its Application to the CMS Pixel Detector”, CMS NOTE-2006/018, 2006.

[3] V. Blobel, “Software Alignment for Tracking Detectors”, Nucl. Instr. Methods Phys. Res. A **566**, 5, 2006.

Acknowledgments

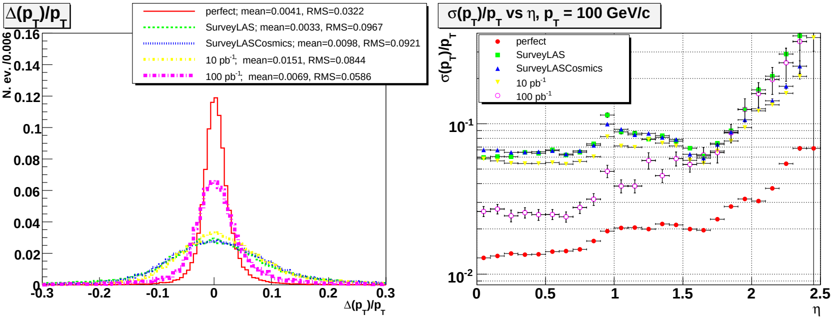
Thank you for your attention!

I would like to thank for the work and all the support to

- my colleagues from the tracker alignment group
- the staff at Cern
- the group members at PSI

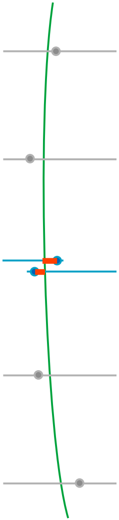
Backup slides

Motivation for alignment: p_T resolution



Left: Muon p_T residual distribution. Right: p_T resolution vs. η. Both for muons with p_T of 100 GeV/c.

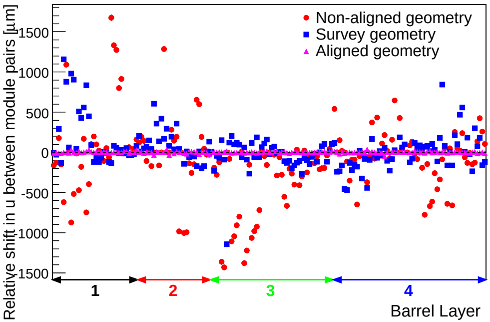
Overlap studies



There are several areas in the tracker where modules overlap. Effects of material and track propagation between two such layers are small.

The method compares the differences in the residuals of two hits in an overlapping module pair.

Overlap studies

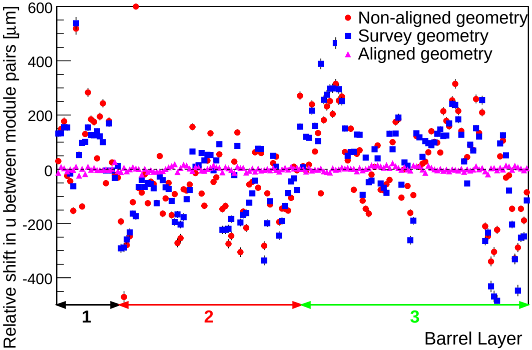


Modules enumerated along abscissa, arrows show associated layer

Relative shift between overlapping module pairs in the sensitive coordinate in the **TIB**.

The survey improves the alignment already, but applying the alignment shows a dramatic improvement.

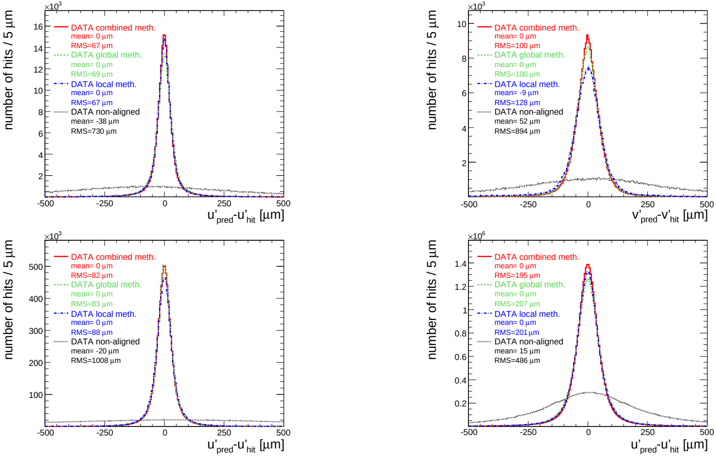
Overlap studies



Relative shift between overlapping module pairs in local *u* coordinate in the pixel barrel. Modules are enumerated along the abscissa.

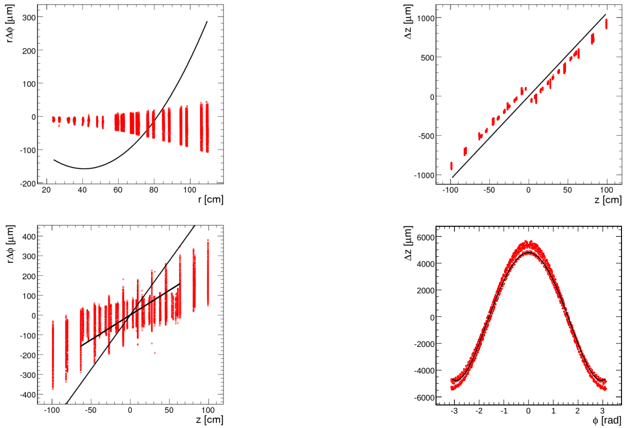
Clearly the alignment shows a dramatic improvement.

Track residual plots



Track residuals. Top: PXB (left: *u*, right: *v*)
Bottom left: TIB, bottom right: TOB.

Systematic misalignment studies



These are some systematic misalignments applied (solid line) and how the global alignment algorithm recovered them using cosmic tracks (red dots).

Top left: Layer rotation, top right: z-expansion

Bottom left: twist, bottom right: skew.

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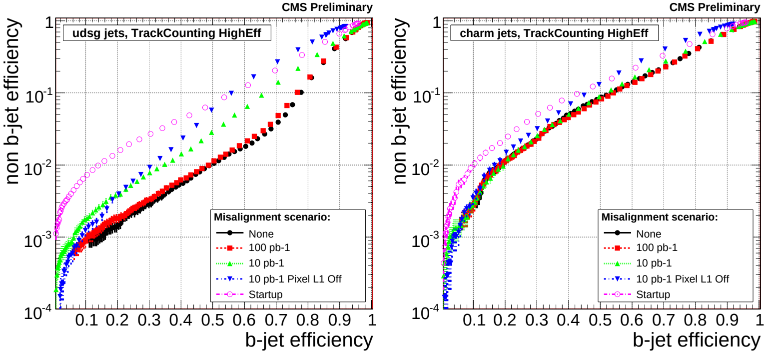
Impact to physics analysis



These plots show the impact on b-jet efficiency vs. non-b-jet efficiency for a selection of misalignment scenarios.