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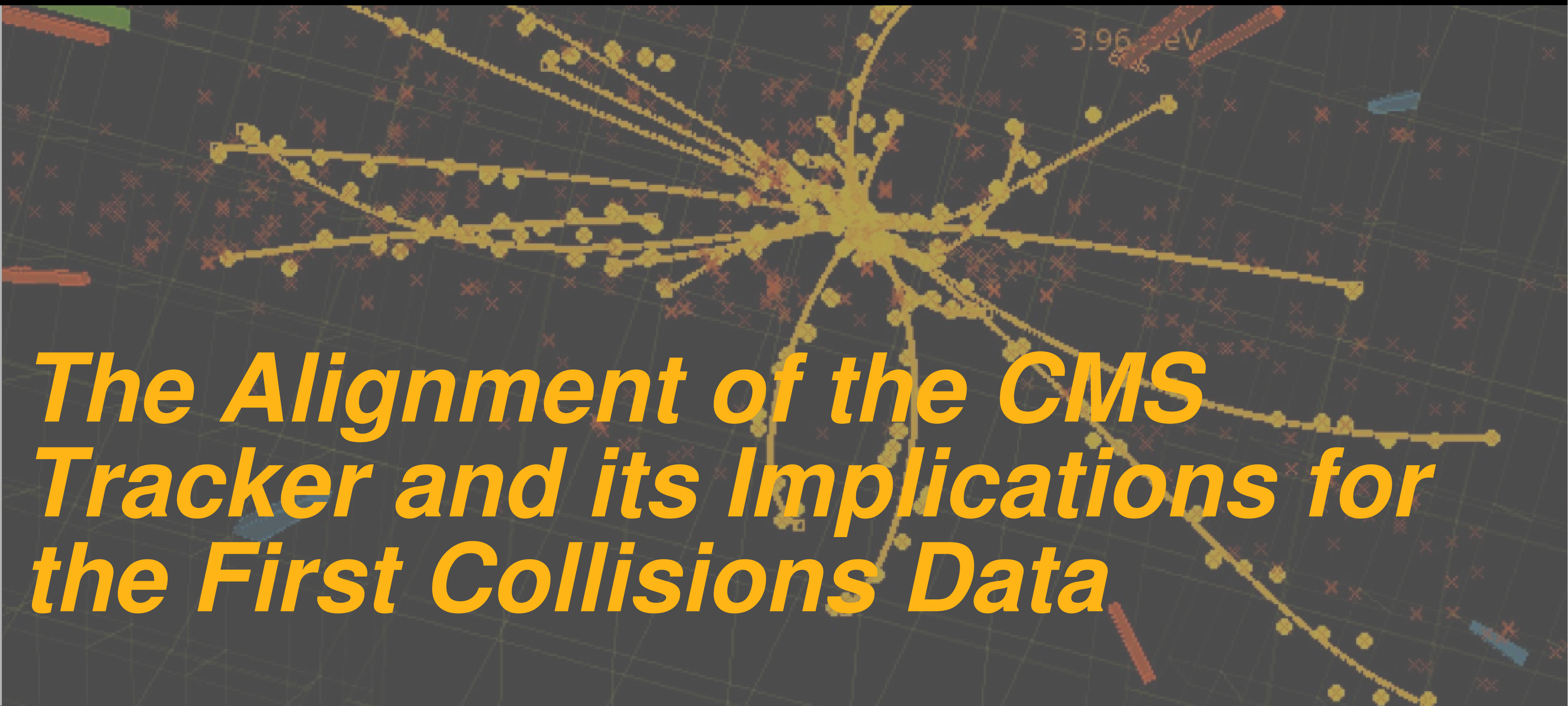


The Alignment of the CMS Tracker and its Implications for the First Collisions Data

M. Musich
Università di Torino/INFN Torino

Supervisor:
Dott. E. Migliore

Outline

Introduction

- The LHC, the CMS Experiment and its Silicon Tracker

Alignment

- Basic Concepts
- Track Based Aligment

My past activity:

Tracker Alignment with real data (cosmic muons / collision tracks)

- *2008-2009* The CMS Global Runs Experience
- *2009-2010* The First LHC Collisions

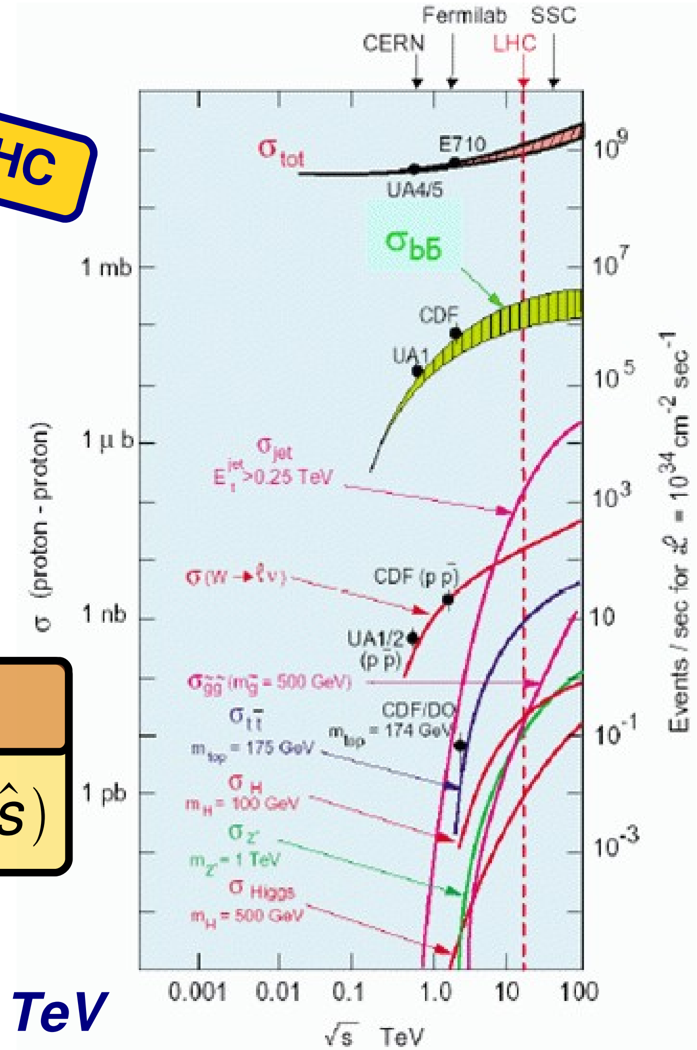
My Future Activity:

Impact of tracker alignment in early physics analyis: $J/\psi \rightarrow \mu\mu$

Introduction

The LHC

- **World's most powerful particle accelerator!**



- will provide pp (and Pb-Pb) collisions at energy scales never explored before...

Master formula at the hadron collider

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

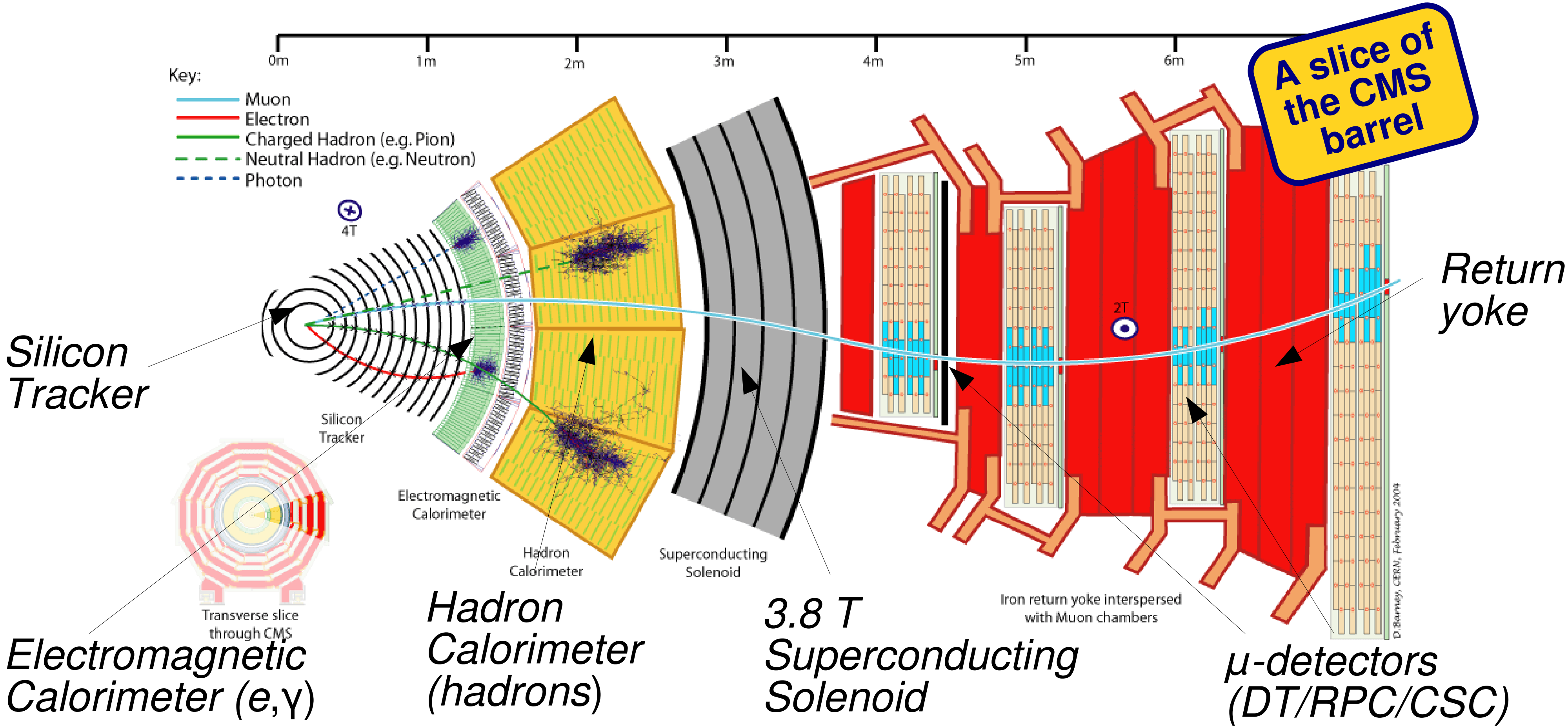
- At the LHC $\sqrt{s} = \mathbf{14\ TeV}$ ($7\ TeV$ in the early phase) and in the partonic scattering: $(\hat{s})^{1/2} = (x_1 x_2 s)^{1/2} \simeq 1-2\ TeV$ **new physics is foreseen!**

- **Higgs search and Electroweak symmetry breaking**: crucial tests for Standard Model

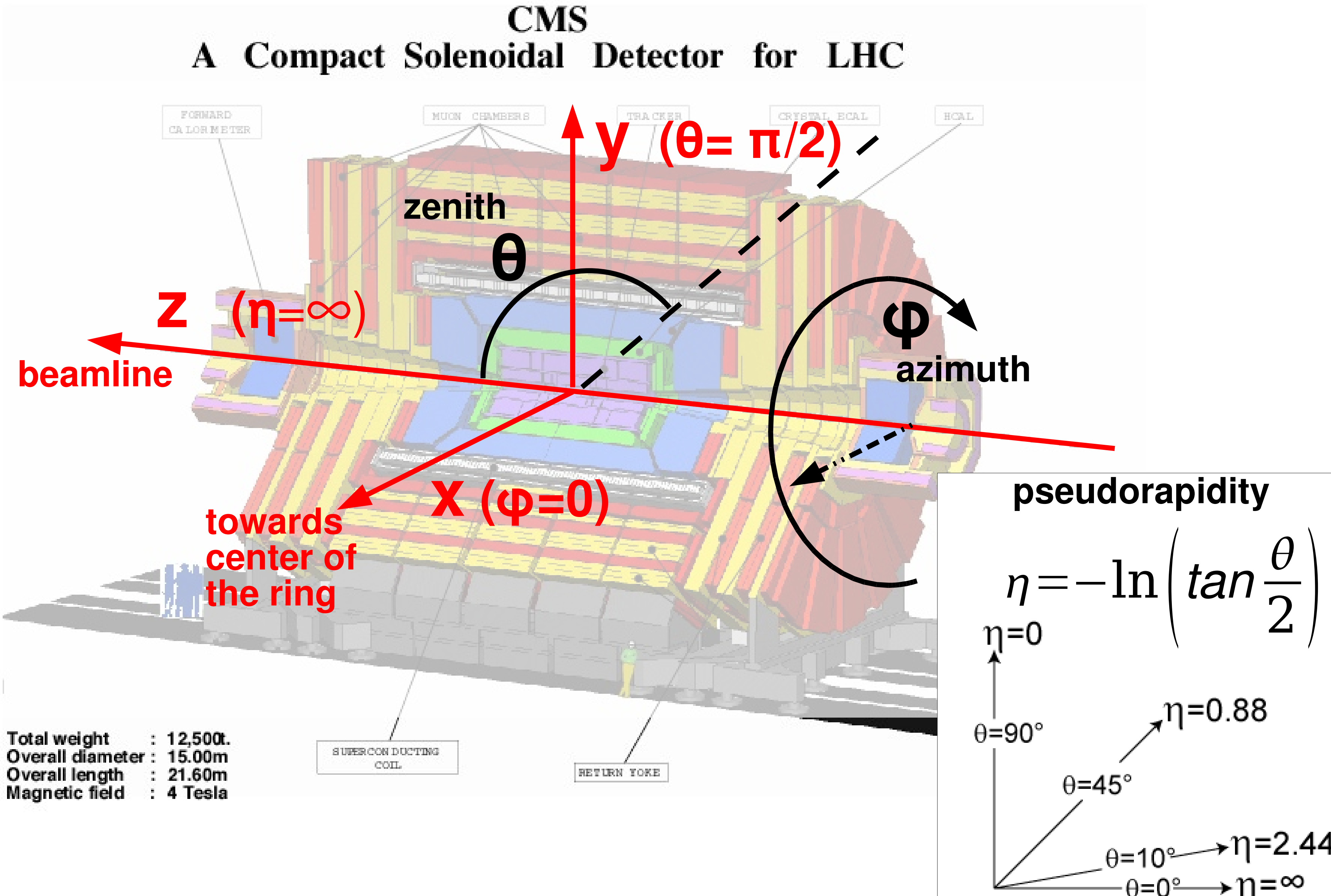
- But many **other interesting processes** have large cross-sections!!

The Compact Muon Solenoid

- The ***CMS Experiment*** is one of the 4 experiments at the p-p accelerator ***LHC***
- Multi-purpose experiment (search for Higgs(es), Supersymmetry, ***new physics at the high energy frontier***
- A system to identify *muons* and measure their momentum with high efficiency up to the TeV scale
- Uses a powerful (*B=3.8T, 2T in return yoke*) solenoidal field to provide enough bending power to track high momentum particles in a relatively compact layout

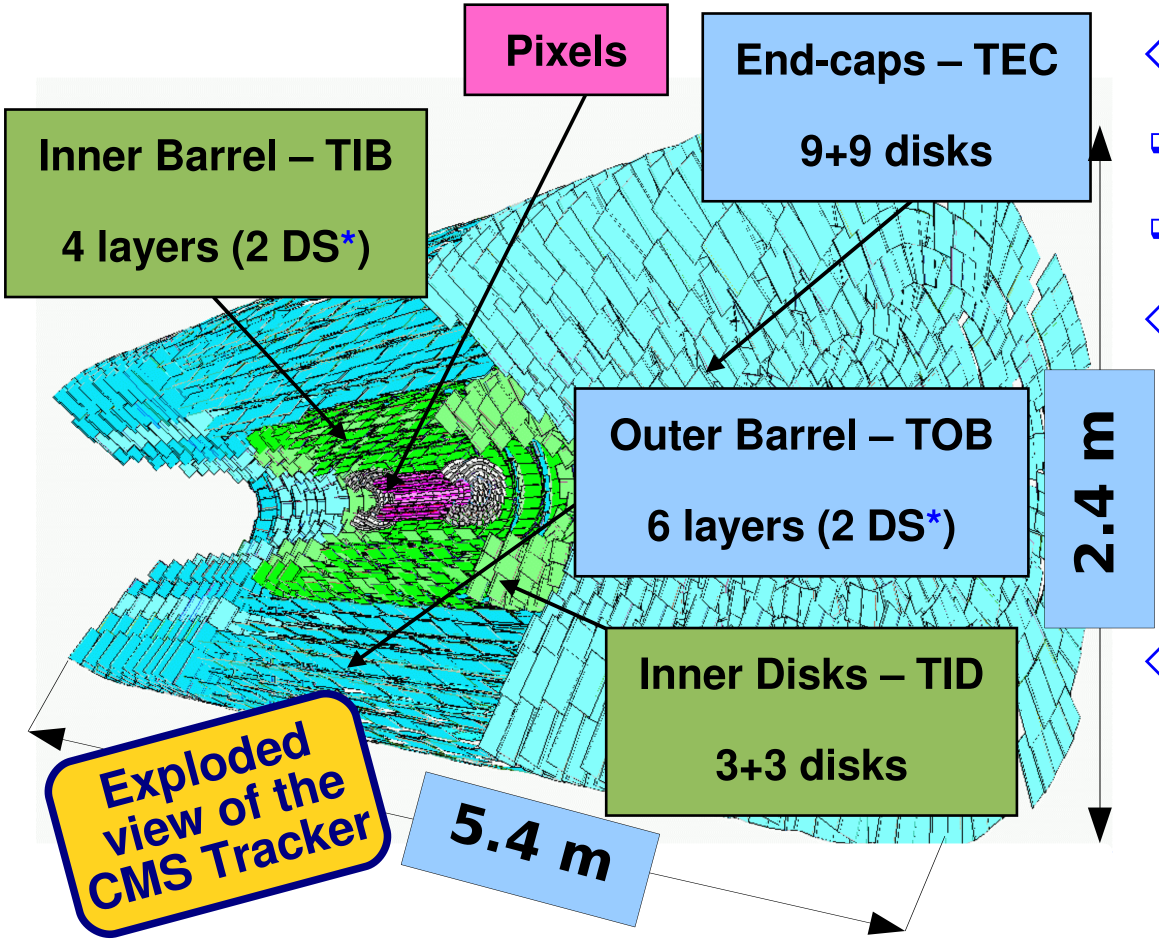


CMS Coordinates



$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

The CMS Silicon Tracker

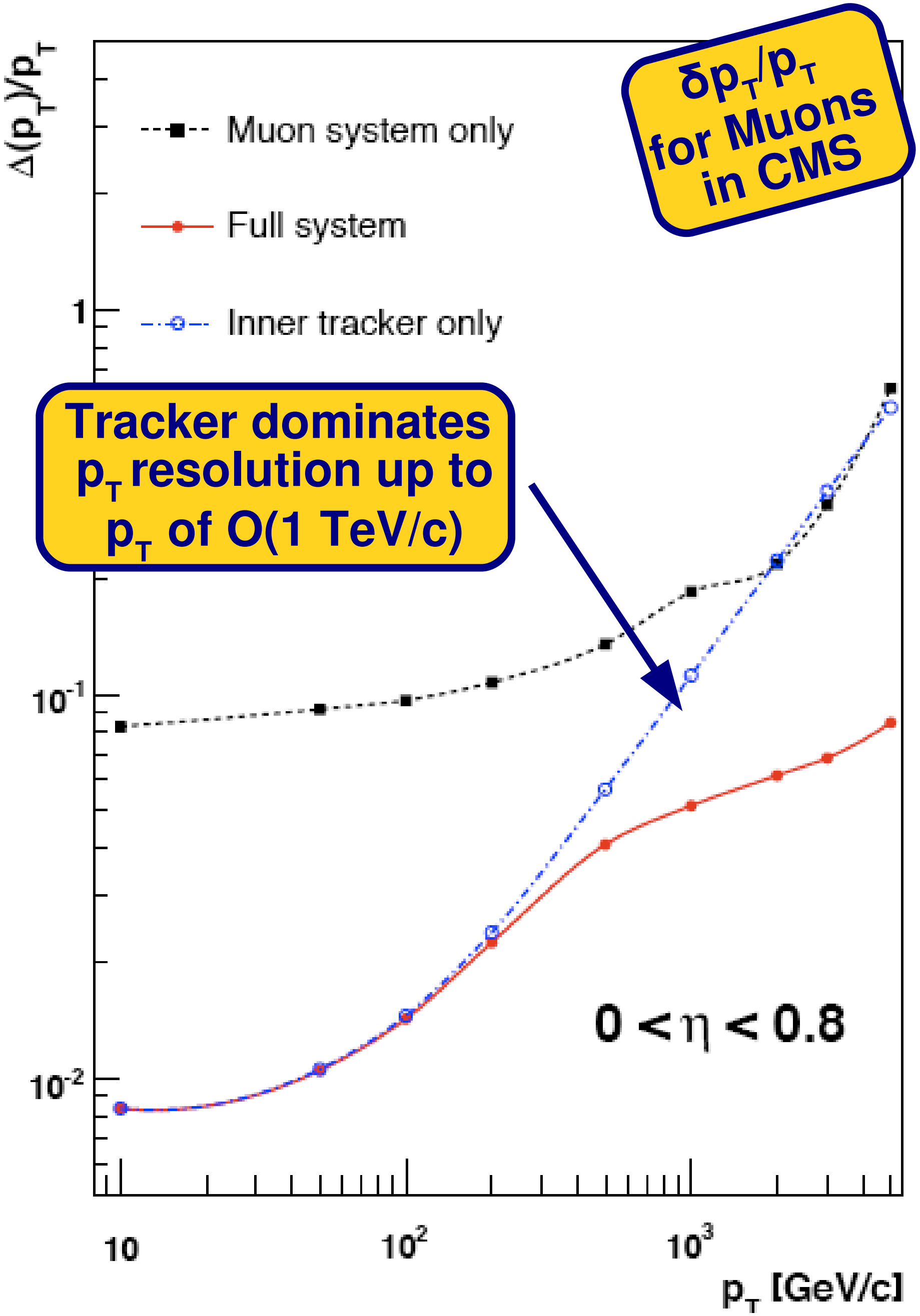


- **World's largest silicon tracker**
  - Volume 24 m^3 / covered area 200 m^2
  - Running temperature: -10 °C
- **STRIP tracker:**
  - ***15148 modules*** (pitch 80 – 205 μm)
  - single point resolution of 20 – 60 μm
  - 2D measurements from *DS modules**
- **PIXEL tracker**:
  - ***1440 modules***
  - pitch: 100(rφ)x150(z) μm^2
  - resolutions: 9 (rφ)- 20 (z) μm

- The ***all-silicon design*** of the tracker is expected to provide precise and efficient measurement of the charged particle trajectories in the LHC collisions:
- *1-2% resolution for 100 GeV* tracks in the central region: **Δpt/pt ~ 1-2% (|η|<1.6)**
- tracking efficiency: ε~99% (μ), ε~90% (hadrons)
- an *efficient tagging of b-jets.*

*Double Sided (2 modules mounted back-to-back tilted by 100 mrad)

Why Tracker Alignment is needed?



- The Tracker is essential to measure the particle's momentum:

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

- For **p < 20 GeV** the $\delta p_T/p_T$ is dominated by the Multiple Coulomb Scattering (MS) C_2 factor in the above expression
- while **for the high momentum muons,** systematic effects of misaligned detectors become relevant.

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

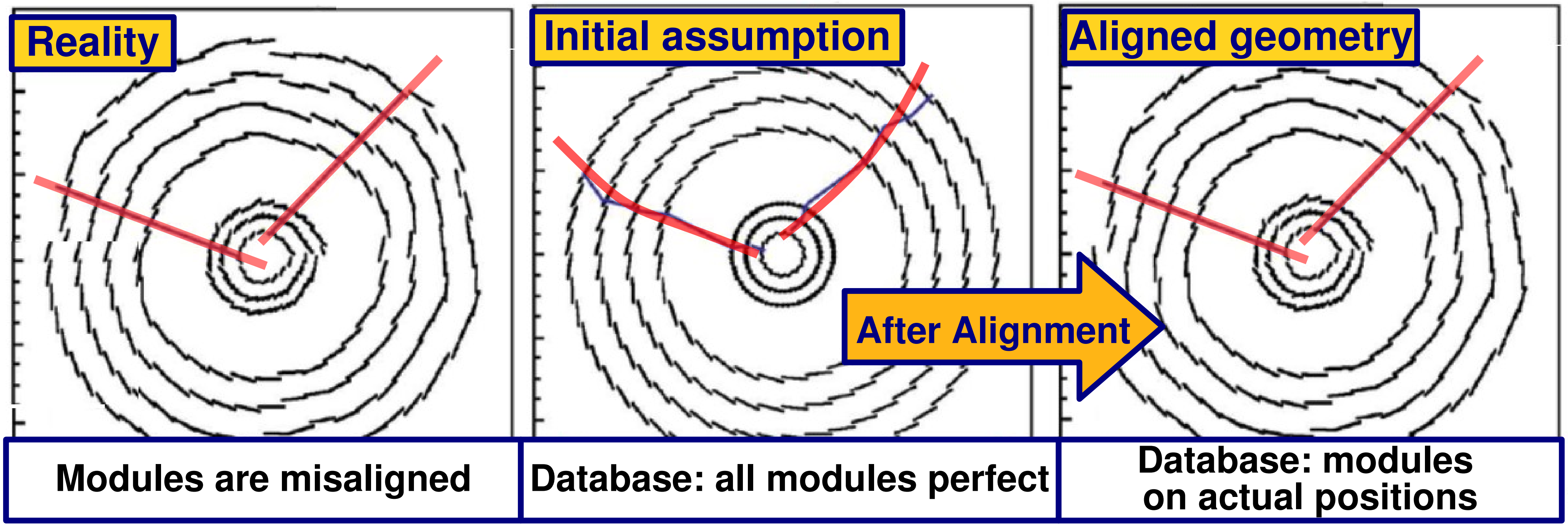
$$\sigma_{pos} = \sigma_{intr} \oplus \boldsymbol{\sigma_{syst}}$$

- **σ_{intr} = O(10μm) in silicon**
- σ_{syst} is due to misalignment of the detector

- **To reach high presision, a knowledge of the detector geometry at O(10μm) is needed**

What is alignment?

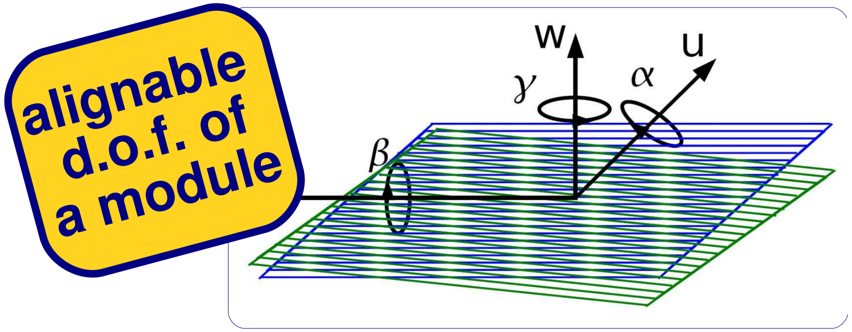
- The mounting precision of modules is finite:



- Track reconstruction initially assumes a perfectly aligned detector
- **Usage of an incorrect assumption** on the tracking geometry in the reconstruction **leads to incorrect estimate** of track parameters $\mathbf{q}= (\varphi,\theta,p_T,d_{xy},d_z)$
- less than 20% deterioration of the track parameters for LHC experiments (few µm, µrad) is **mandatory** for physics analysis
- The alignment procedure is aimed to provide the correct geometry to track reconstuction determining the position of modules *in situ*

Tracker Alignment

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



- Alignment strategy in CMS: use all available data sources:
  - Surveys (optical/mechanical/...)
  - Laser Alignment
  - *Track Based Alignment*

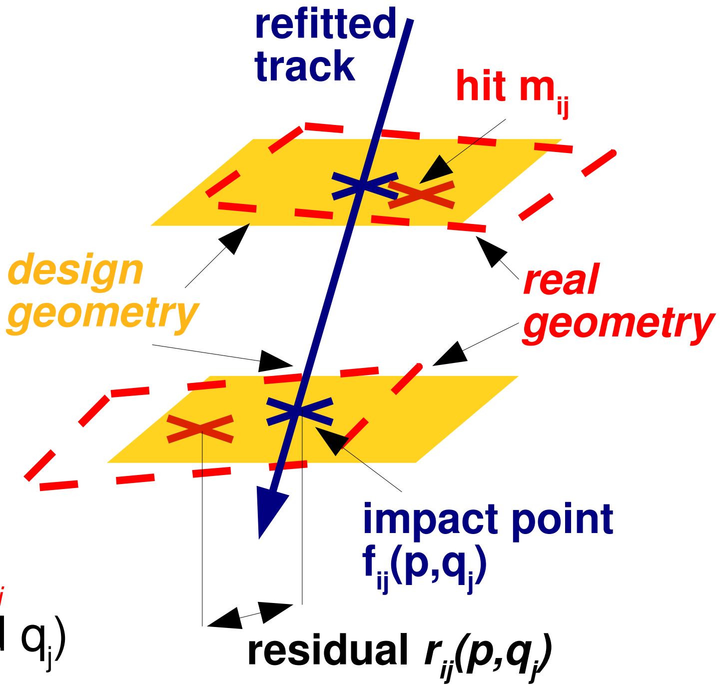
- From older experiments: ultimate precision is achieved using track based alignment, i.e. particles crossing *in situ* the Tracker volume

Track Based Alignment

- Define a Global Track χ^2 function:

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

- 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 χ^2 function and therefore track residuals*

Track Based Alignment in CMS

- 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 x 6N* matrix**
- In CMS there are *O(16k)* modules ⇒ ***16k x 6 = O(100k)*** unknown parameters to be determined!
- This highly challenging task is faced with two main approaches:

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

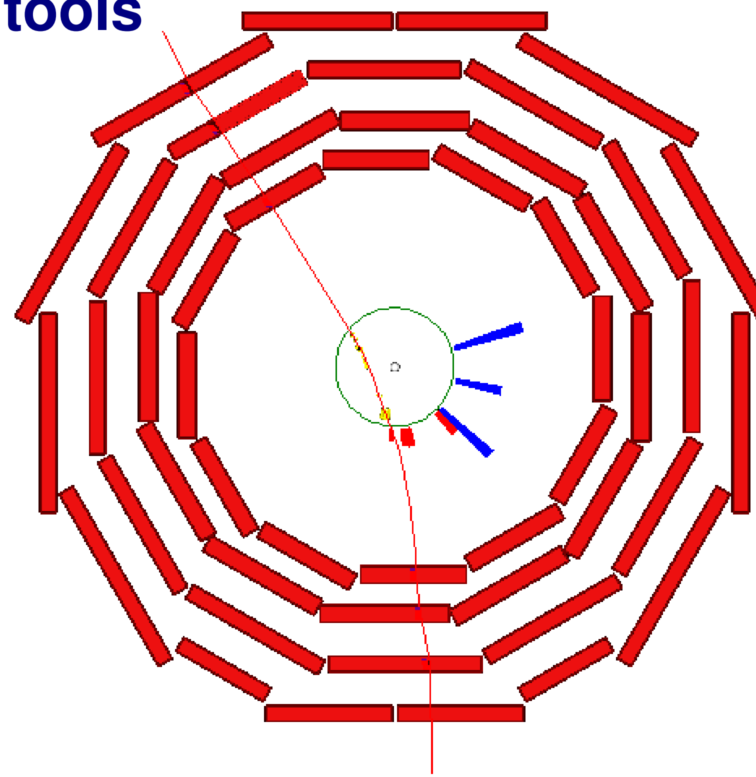
In the ***local method***, ***"Hits and Impact Points HIP"*** N 6×6 matrices are solved. Minimization is attained by **iterating several times** the procedure

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

Activity during 2008-2009

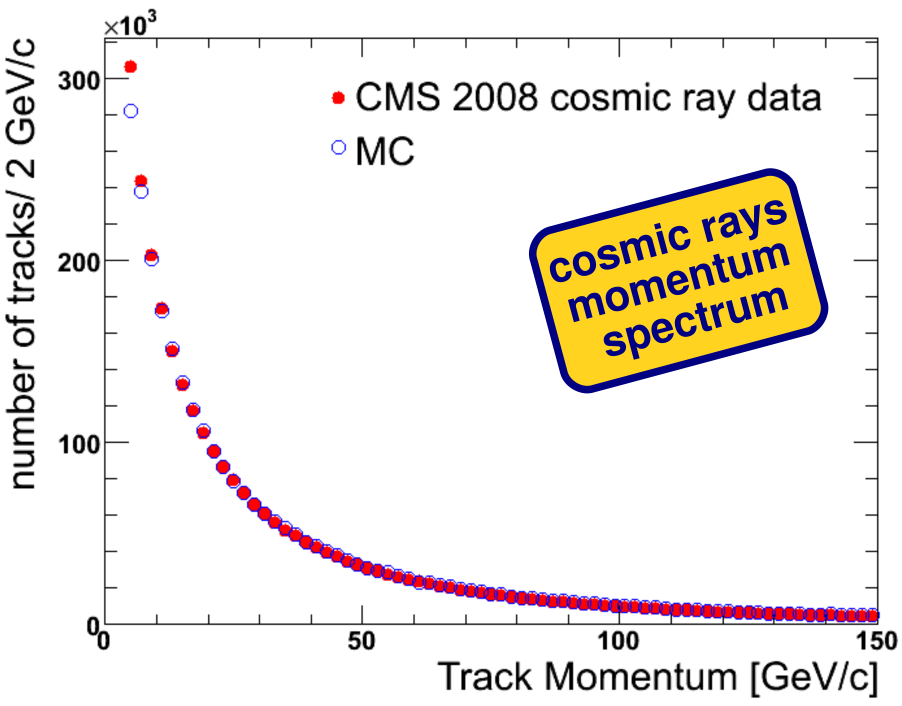
My activity during 2008-2009

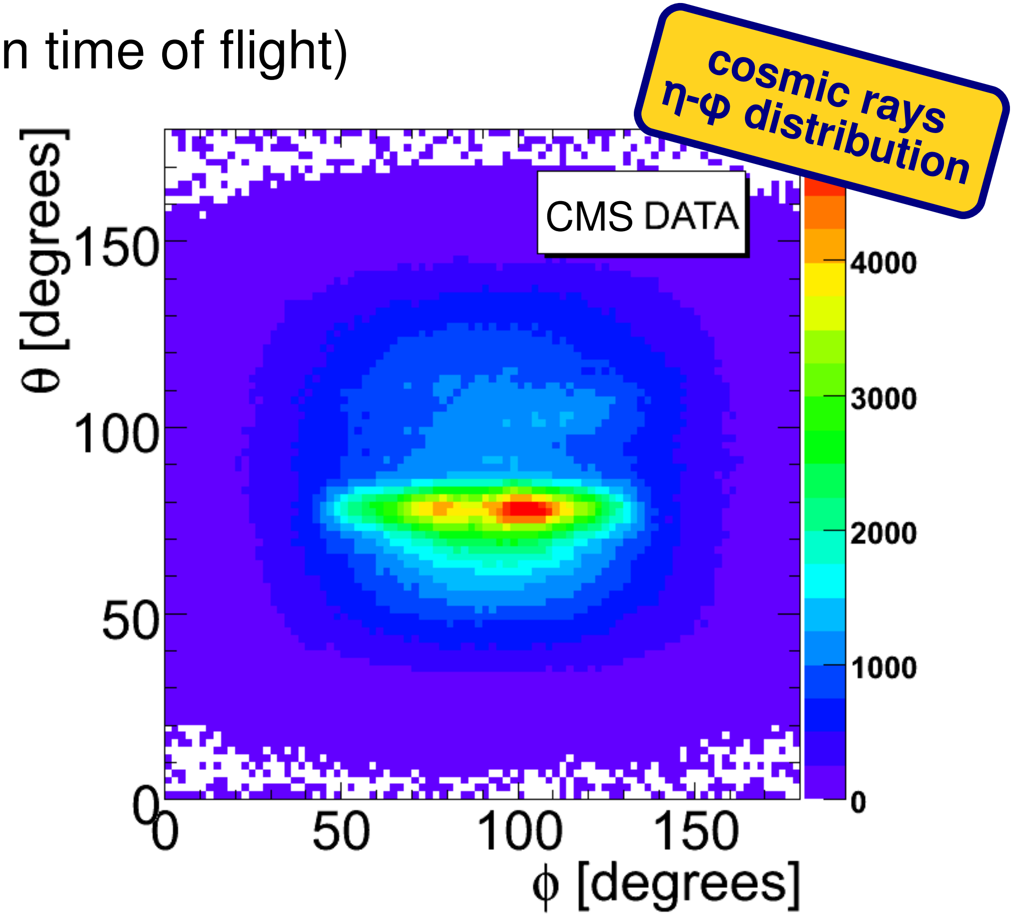
- During the last two years (2008-2009) the CMS collaboration conducted a campaign of long data taking exercises:
- The most important was the **C**osmic **R**un **A**t **F**our **T**esla (*CRAFT*) in which, *with the solenoidal field at its nominal B=3.8 T intensity value,* several million of cosmic ray triggers were collected and analyzed
- In this context my main activity in the Tracker Alignment effort was devoted to:
  - Optimize and run the **alignment validation tools**
  - Estimate the **remaining misalignment**
  - Determine the ***Alignment Position Errors***



Tracker Alignment at the Cosmic Run at Four Tesla (CRAFT)

- First attempt of **full** CMS Tracker alignment with data during the CMS global run
- 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)
- $\Delta t_{top\text{-}bottom}$=*2 x BX=2 x 25 ns=* ***50 ns*** (muon time of flight)

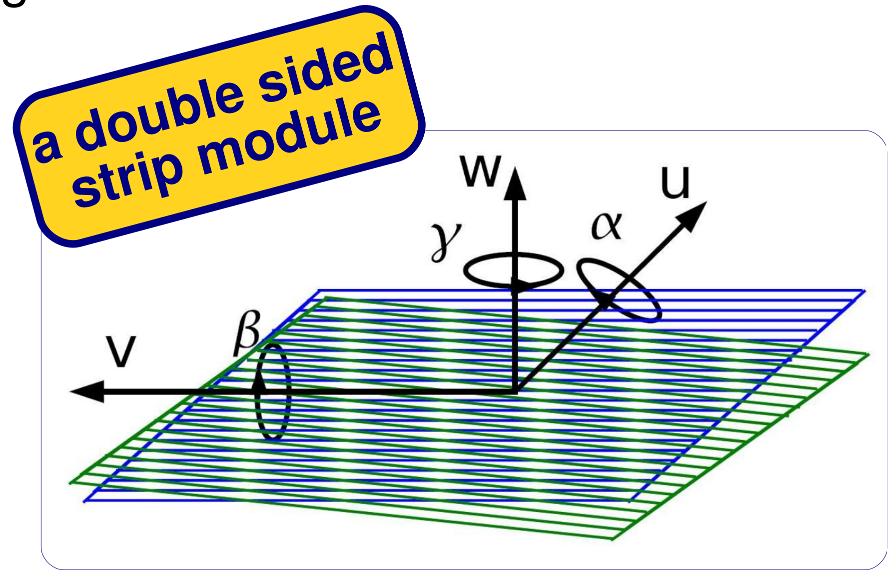




Alignment Strategy

- Apply a set of cuts to select good tracks for alignment

Track Quality cuts	Value
momentum p	*> 4GeV/c*
number of hits	*>7*
number of 2D hits (on Pixel or DS modules)	*>1*
Chi2/ndof of track fit	*<6.0*
Hit Quality cuts	**Value**
S/N (Strip modules)	*>12*
probabiliy pxl hit matching template u (v) dir.	*>0.001*
Track angle relative to the local uv plane	*<20 deg.*
Square pull of hit residual	*<15*



- Run a multi-step approach for both algorithms:
  - *Large structure* movements (coherent ***v*** alignment of Single Sided modules)
  - Alignment of the two sides of the 2D strip *modules (units)* ***u,w,γ***
  - module-level alignment of strip and pixel modules

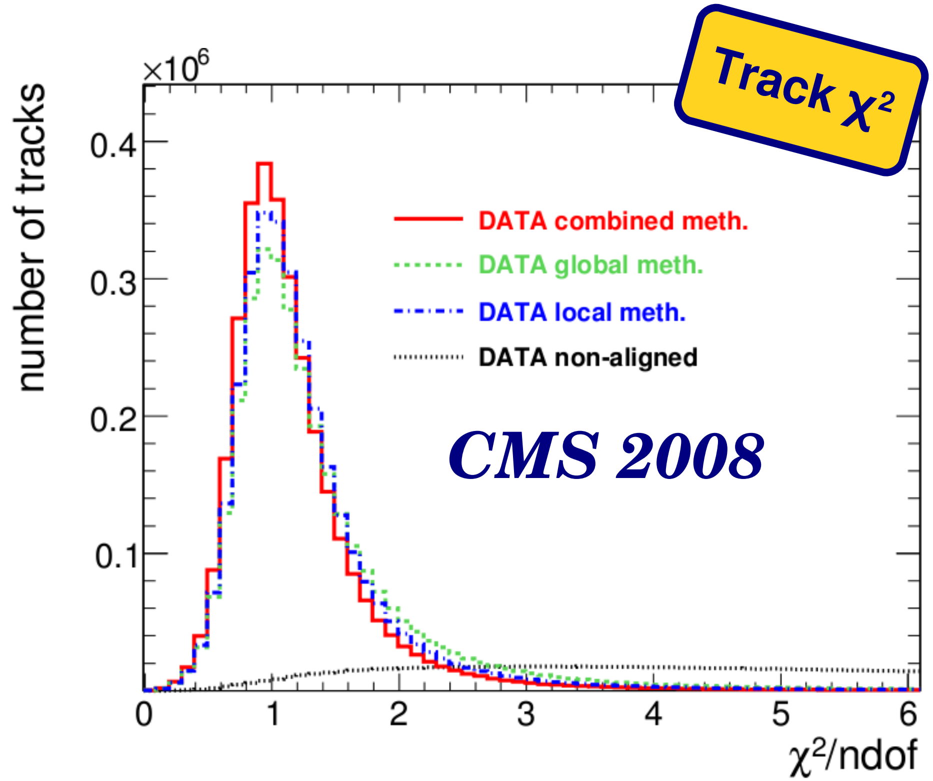
- **Final strategy:**
  - Get the **best** from **both** algorithm, combining the two:
    I. run the ***global method***→ solves global correlations efficiently
    II. run the ***local method*** → solves locally to match track model in all degrees of freedom

Alignment Validation

- Alignment performance is validated **on the data themselves** at three 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*.
  - **checks of the geometry** *of CMS Tracker resulting from track-based alignment*
- Validation is performed **after every alignment cycle**

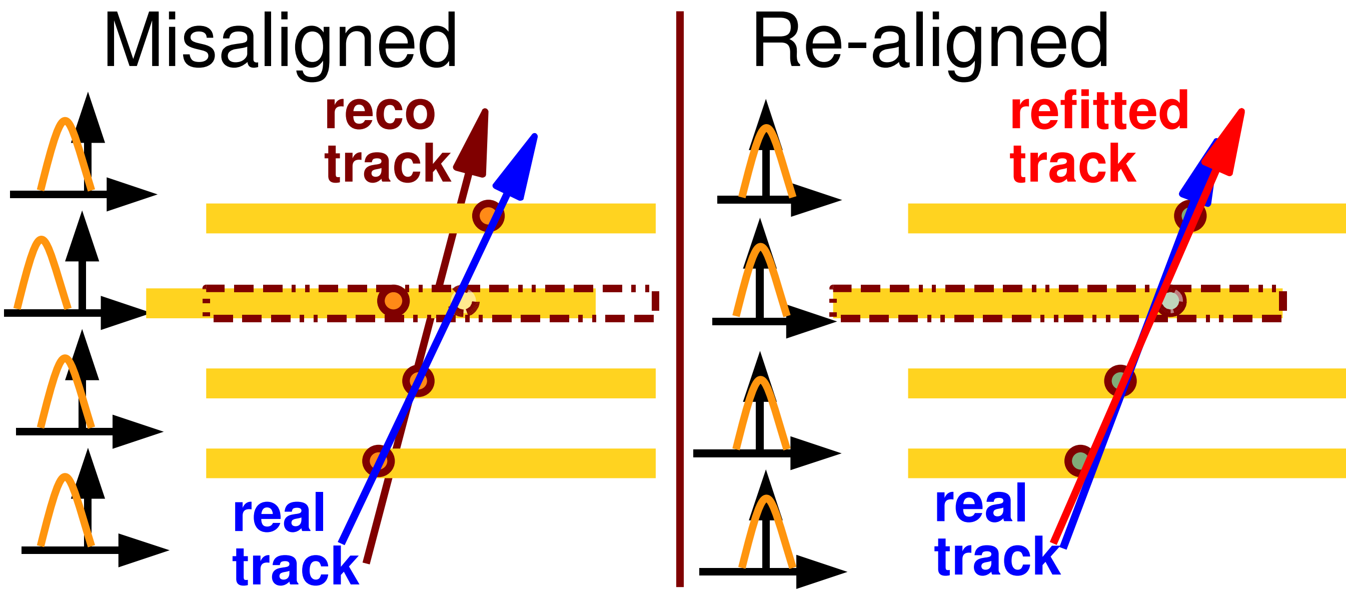
> *During the CRAFT data analysis I have been responsible for the low-level validation and I have provided the results included in the paper**

- Same sample is used for the alignment (i.e. χ^2 minization) and validation
  - statistics is critical evaluating the performance for all subdetectors (*only 1.5% of tracker in PXE with cosmic rays*)

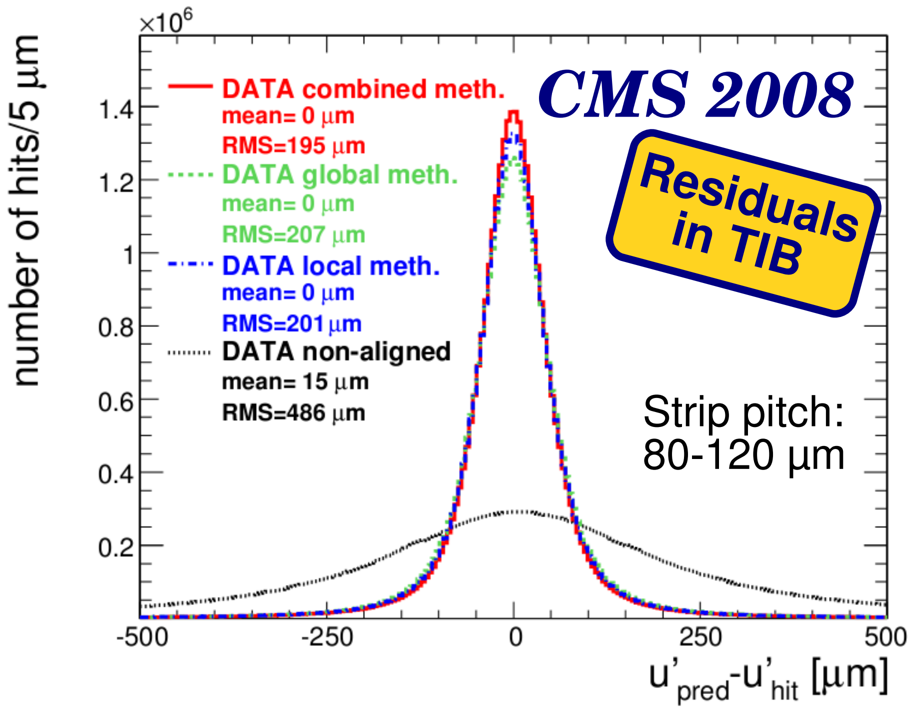


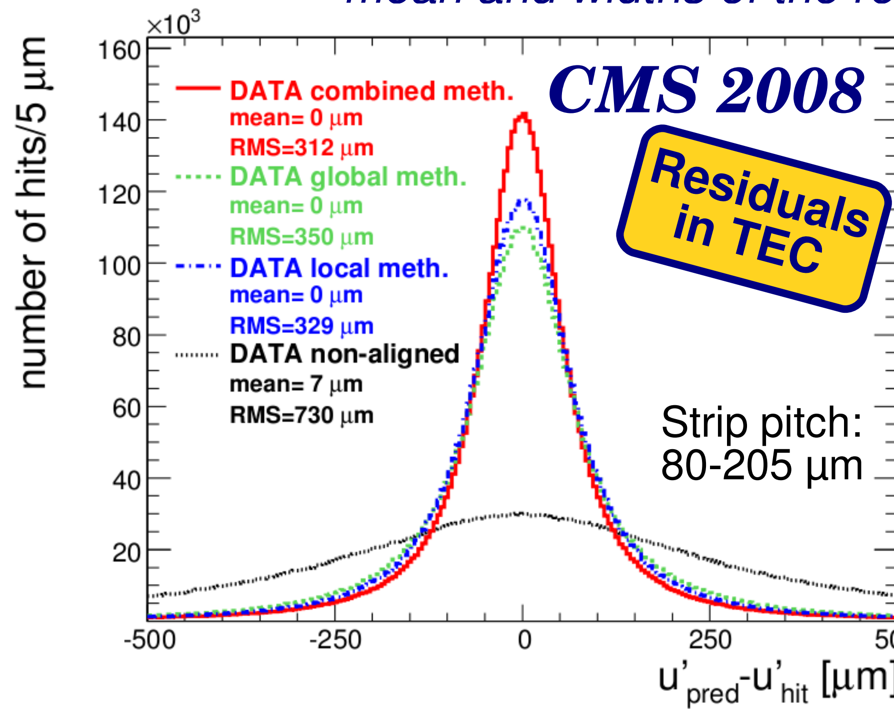
* see bibliography

Track-based Validation (Track Residuals)



- The track residuals *checked to evaluate the residual minimization*
- Computed at the same time as the χ^2 of track fit
- **unbiased** since the hit under evaluation is removed from the track- refit
- Misalignment affects *both mean and widths of the residuals*





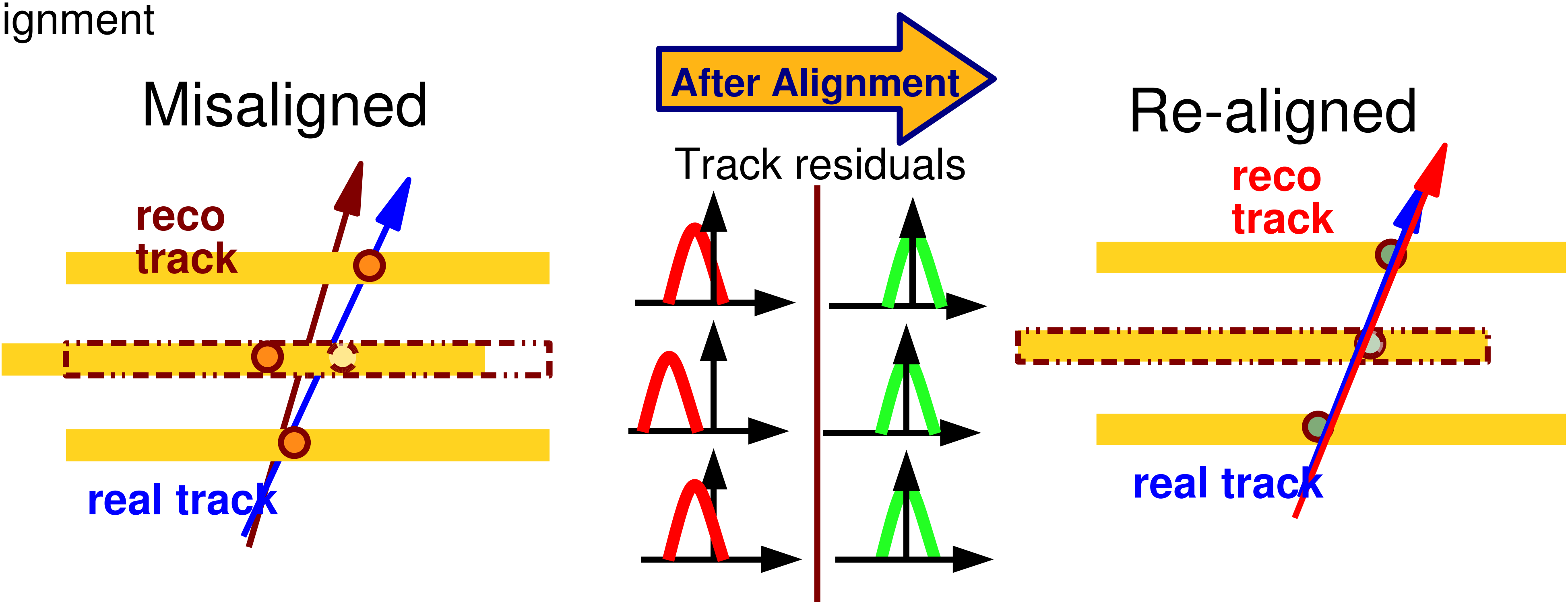
Estimation of residual misalignment

◆ **Residual width dominated by stochastic effects**, like multiple Coulomb scattering or the intrinsic resolution of the hits

$$\sigma_{r_{ij}(p,q)} = \underbrace{\sigma_{intr}}_{Intrinsic} \oplus \underbrace{\boldsymbol{\sigma_{mis}}}_{\boldsymbol{Misalignment}} \oplus \underbrace{\sigma_{MS}}_{Multiple\,Scattering}$$

◆ 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

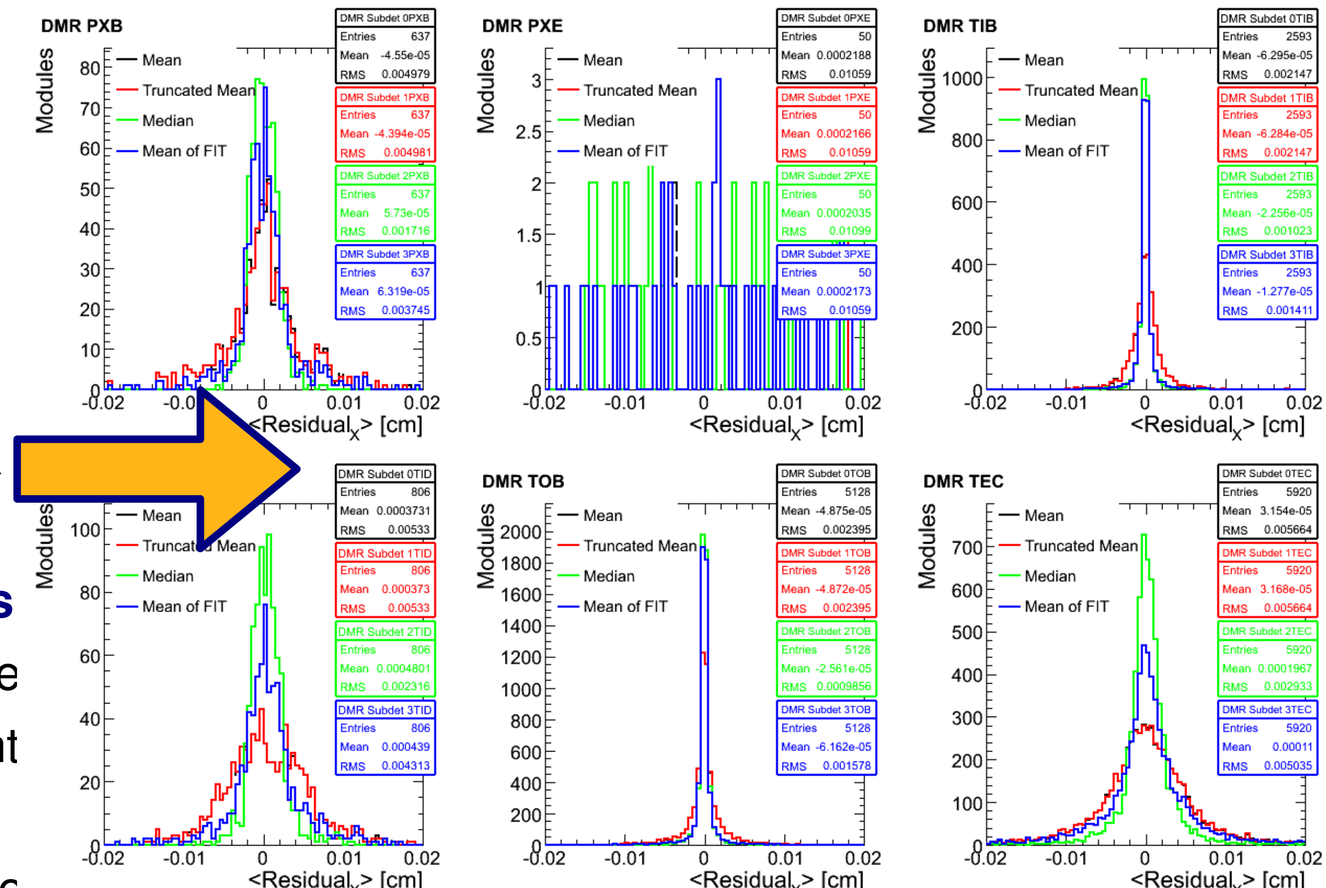


Residual misalignment (the DMR)

◆ **The mean** of residuals is not **a robust** estimator of the position of the "center" of the residuals distribution *because of outliers in real data* ⇒ I have tested several others

The method:

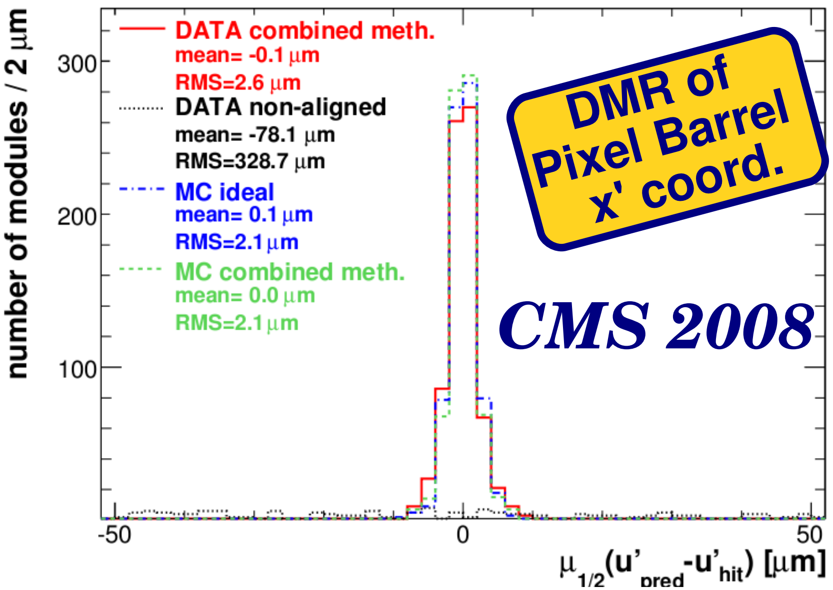
- ◆ Take MC of the detector in ideal conditions and ***apply a random gaussian misalignment of known width***
- ◆ Look at the distributions of "peak estimators"
- ◆ **The Distribution of the Medians of Residuals** has RMS very close to the width of input misalignment
- ◆ Check also statistical precision of the method by splitting data into independent samples and compare the DMRs of the two samples

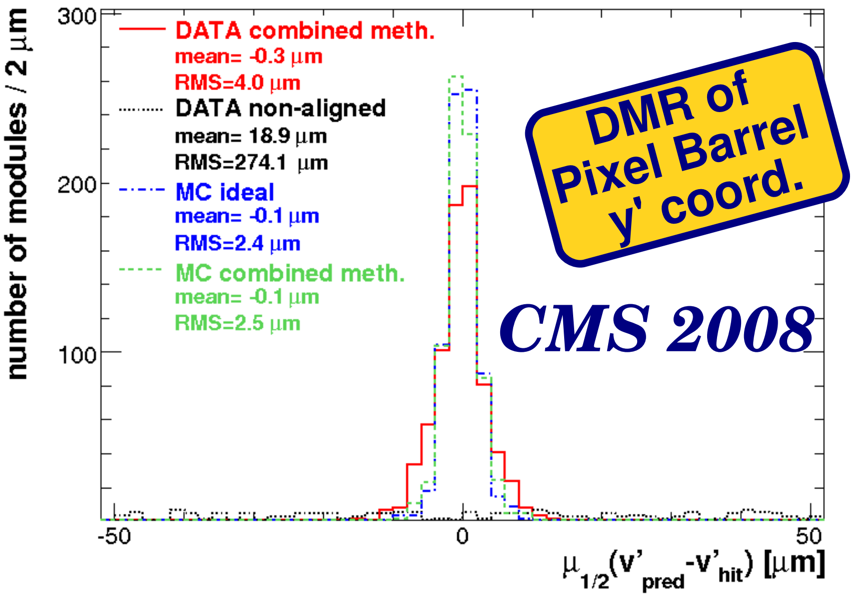


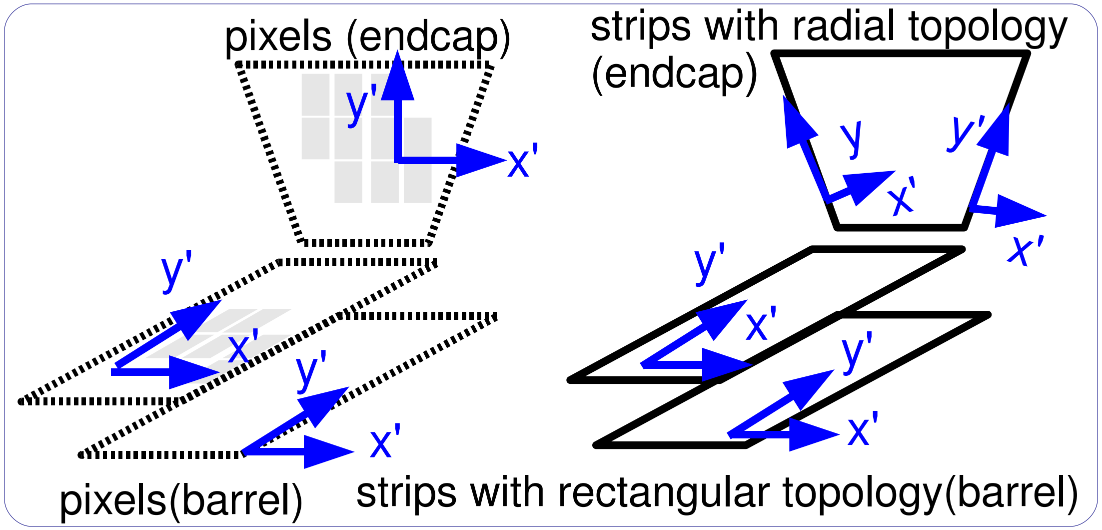
◆ RMS of the Distribution of the Median of Residuals (DMR) measures the remaining random misalignment in the detector
◆ N.B. it is not sensitive to systematic misalignment

DMR distributions for CRAFT alignment

◆ DMR are shown as a function of the local coordinates x' and y' for all subdets







	Non aligned	global	local	combi-ned	combi-ned MC	Ideal MC
PXB (x')	328,7	7,5	3	**2,6**	2,1	**2,1**
PXB (y')	274,1	6,9	13,4	**4**	2,5	**2,4**
PXE (x')	389	23,5	26,5	**13,1**	12	**9,4**
PXE (y')	385,8	20	23,9	**13,9**	11,6	**9,3**
TIB	712,2	4,9	7,1	**2,5**	1,2	**1,1**
TOB	168,6	5,7	3,5	**2,6**	1,4	**1,1**
TID	295	7	6,9	**3,3**	2,4	**1,6**
TEC	216,9	25	10,4	**7,4**	4,6	**2,5**

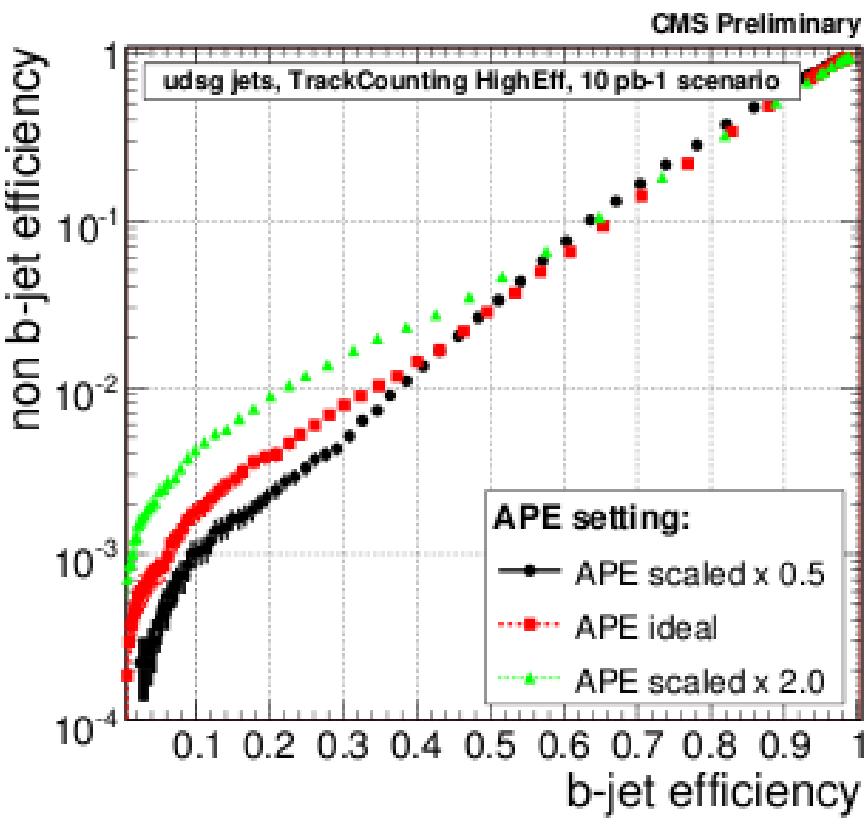
◆ Module positions w.r.t to cosmic ray trajectory measured with a precision of **3-4 µm in the barrel** and of **3-14 µm in the endcap** (along rφ)

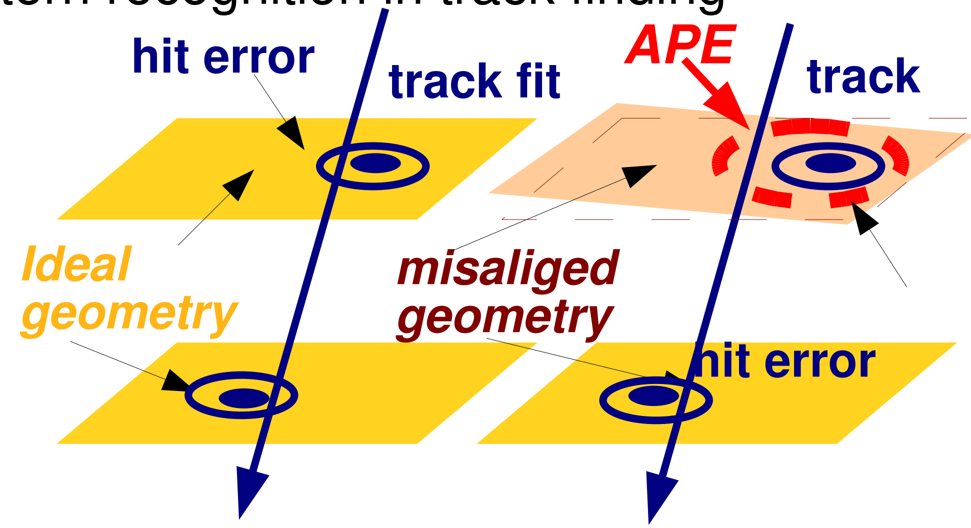
Alignment Position Errors

- *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:

$$\sigma^{HIT}_{TOT} = \sigma^{HIT}_{intr} \oplus \mathbf{APE}(DET)$$

- The APE affects the search window of pattern recognition in track finding





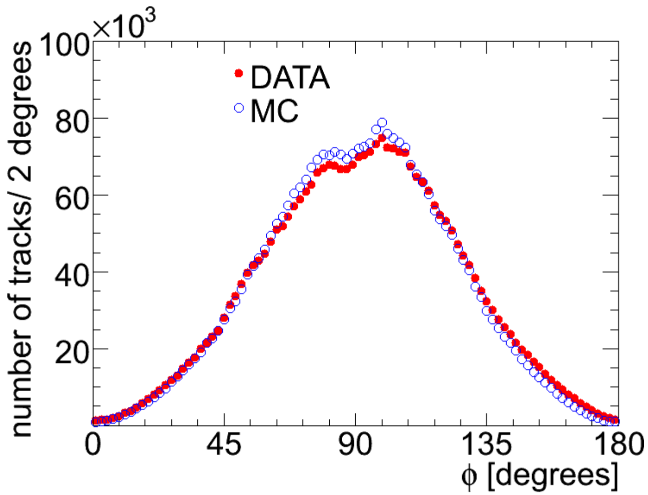
APE have direct impact on:

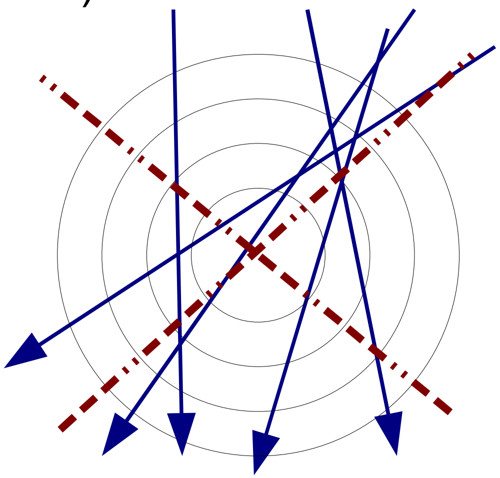
- **performance** of track reconstruction
  efficiency of track reconstruction
- **track quality (χ^2)**
- **fake rate**
- **momentum resolution**
- **vertexing resolution**

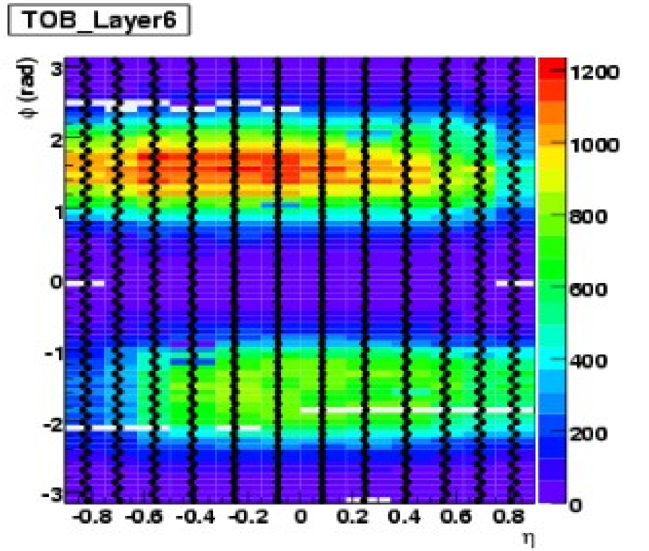
Strategy to determine the *APEs*

- **During CRAFT I have been responsibile for the determination and the validation of tha Alignment Position Errors**

- 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).



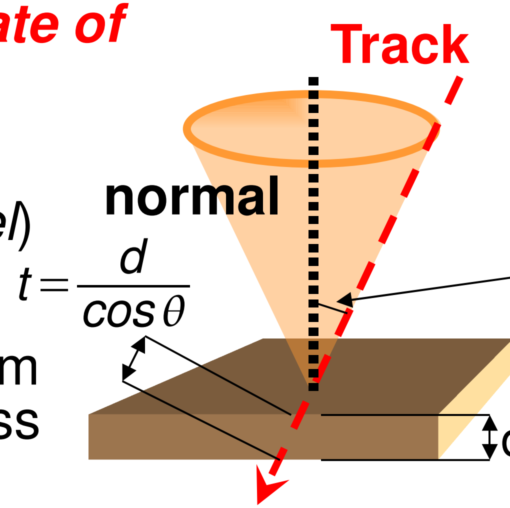


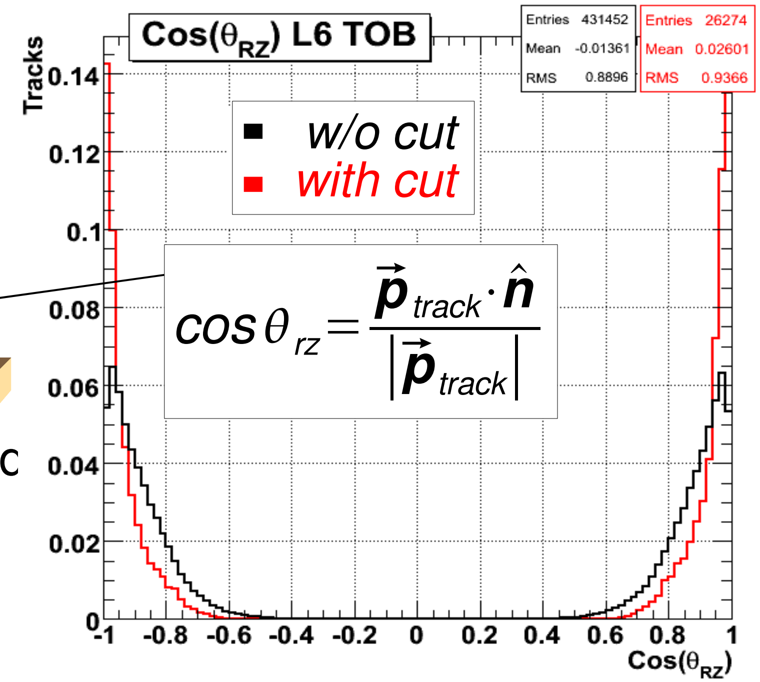


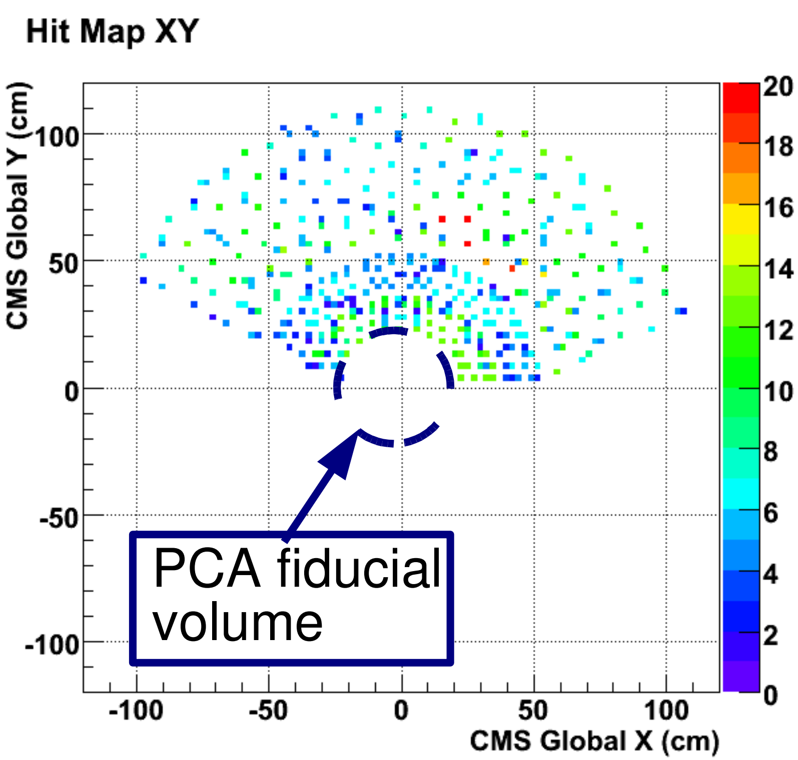
  - So find a region of the detector **well aligned** (top quadrant) and estimate the remaining misalignment (after the alignment procedure) from data
  - The APE value has to **match the value of the remaining random misalignment**
  - Finally estimate the APEs in the rest of the Tracker (outside the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

Selection of control region

- In order to have a sound ***estimate of remaining misaligment***
  - take a well aligned region (*upper quarter of Strip Barrel*)
  - select tracks hit pattern in order to satisfy a test-beam like geometry (all tracks cross the tracker volume with the same angle)







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

$$\sigma_{MS}\simeq\delta x=l\cdot\delta\theta\simeq\frac{l}{p}\cdot\sqrt{\frac{t}{X_0}}$$

Crossed silicon thickness (t)

- one requires that the Point of Closest Approach of the track to the nominal Beamline (PCA) lie inside a cylindrical fiducial volume *roughly equal to the CMS Pixel Volume*

Trends of residuals

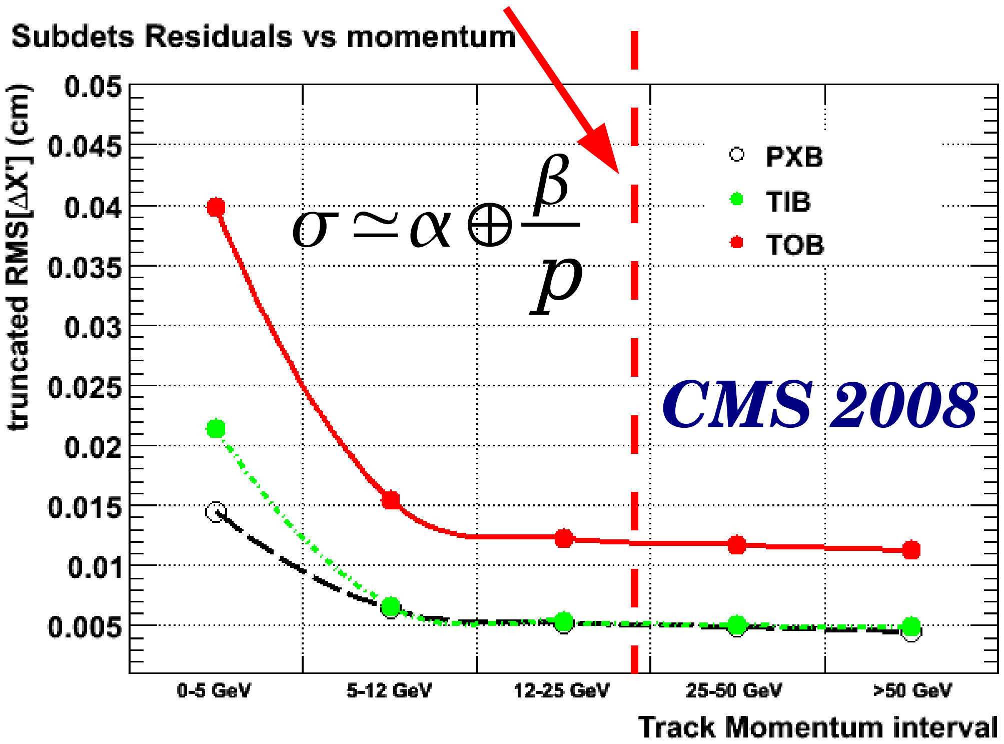
- Once selected the control region to estimate the remaining misalignment one has still to disentangle the MS and intrinsic contributions to the track residuals:

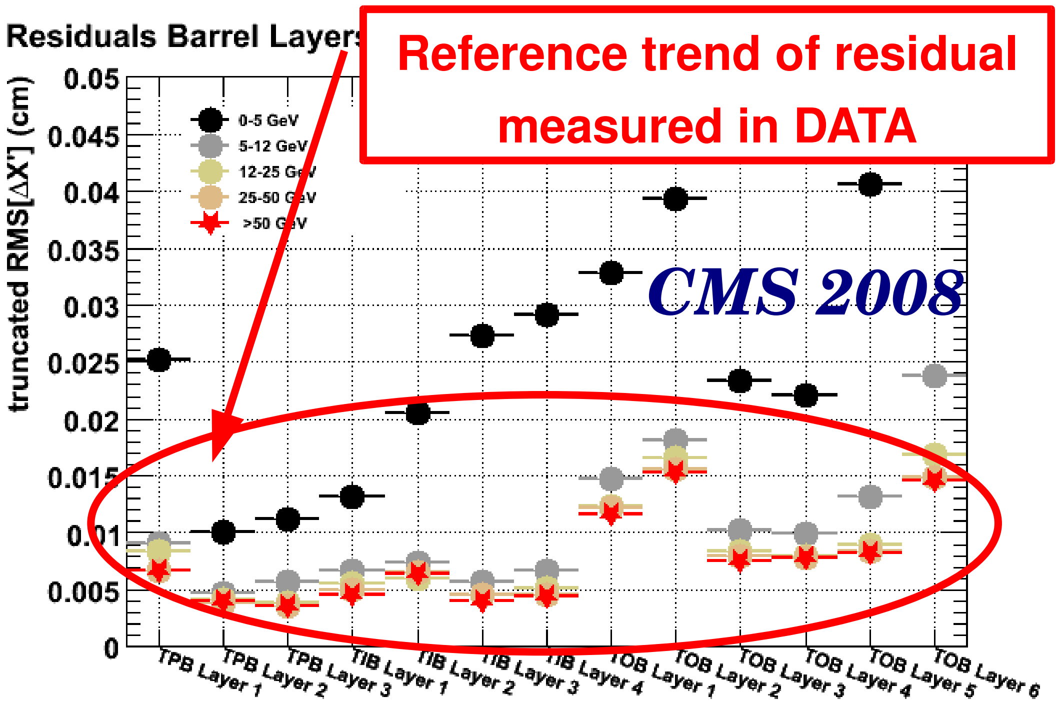
$$\sigma = \sqrt{\sum_i \sigma_i^2} = \sigma_{intr} \oplus \sigma_{mis} \oplus \sigma_{MS}$$

- where the MS contribution goes like *1/p*

$$\sigma_{MS} \simeq \delta x = l \cdot \delta \theta \simeq \frac{l}{p} \cdot \sqrt{\frac{t}{X_0}}$$

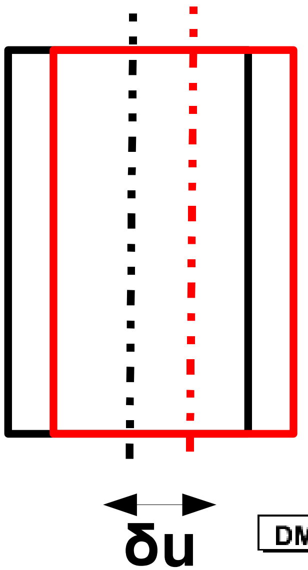
- Track residuals saturate at some threshold, estimated in data to be **~20 GeV** for which the MS is dominated by the detector pitch and the misalignment effects



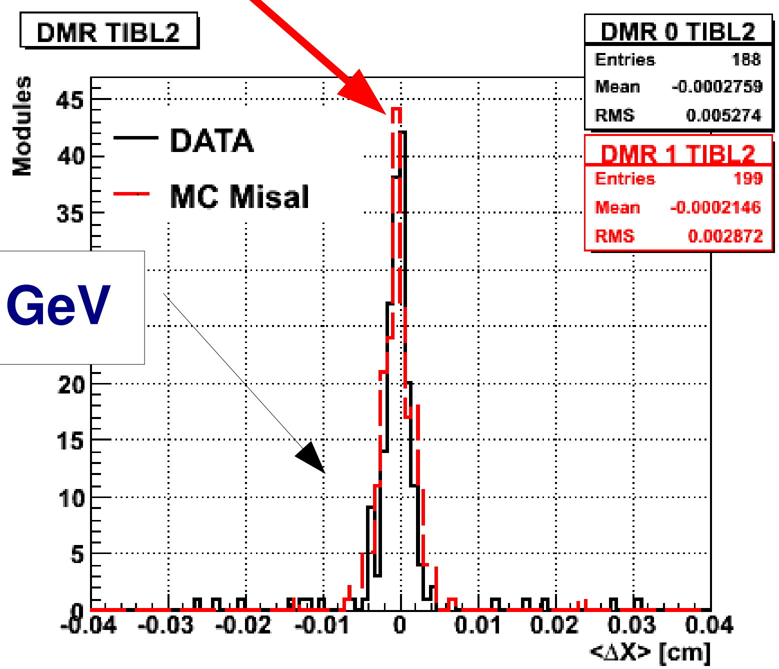


Determination of residual misalignment

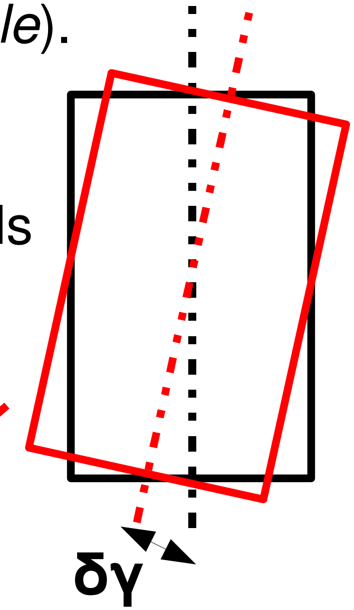
- The APE are estimated introducing a **random** (gaussian smeared) **misalignment** in the CRAFT MC simulation, to match the DMRs and trends of residuals in CRAFT DATA (*in the control region and with the selected track sample*).

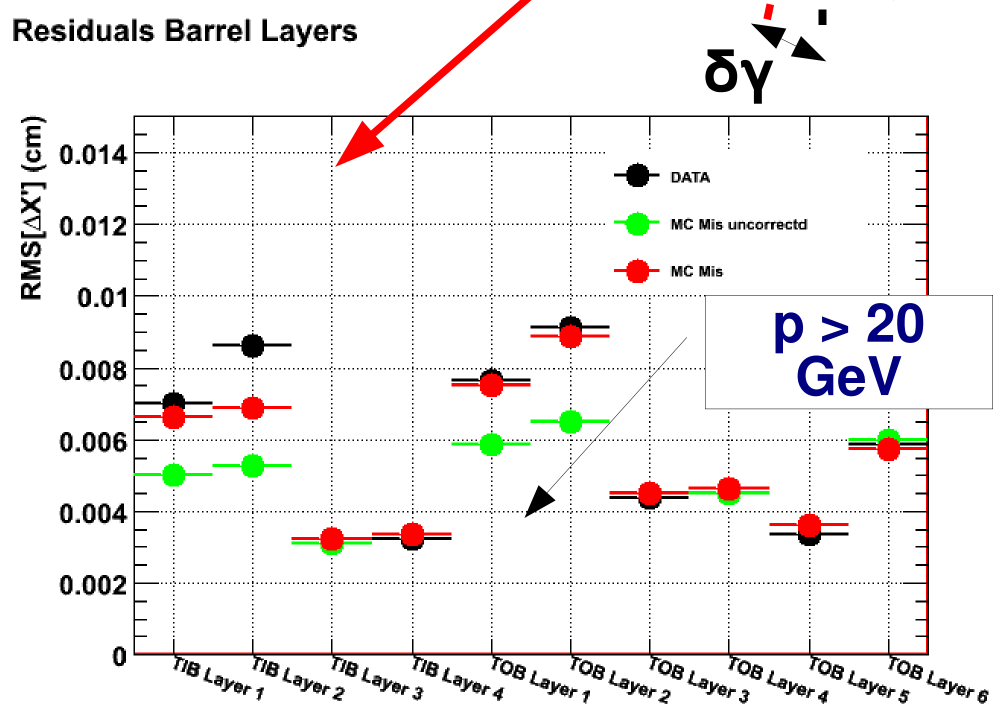


- δu (δv) affecting the DMR
- so tune layer by layer δu comparing **misaligned MC** and **DATA**



- δγ not affecting DMRs but spread in the residuals
- so tune **MC** in order to reproduce the trend of Barrel layer residuals of **DATA**





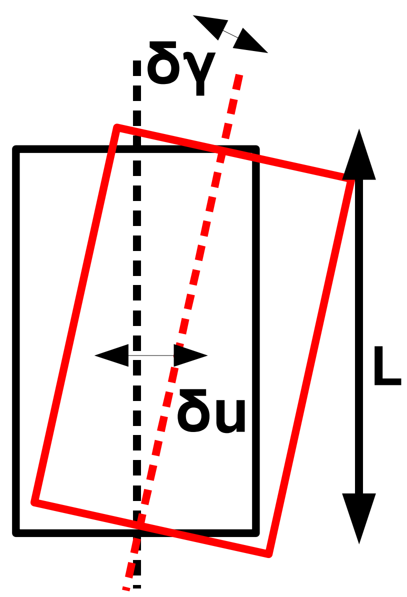
Determination of APE

- 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:

$$R_{APE} = R_0 \cdot \sqrt{\frac{N_0}{N_{hits}}}$$

$$\begin{cases} R_0 = RMS[\mu_{1/2}] \\ R_0 = k\left(\delta u \oplus \frac{L}{4}\delta\gamma\right) \end{cases}$$

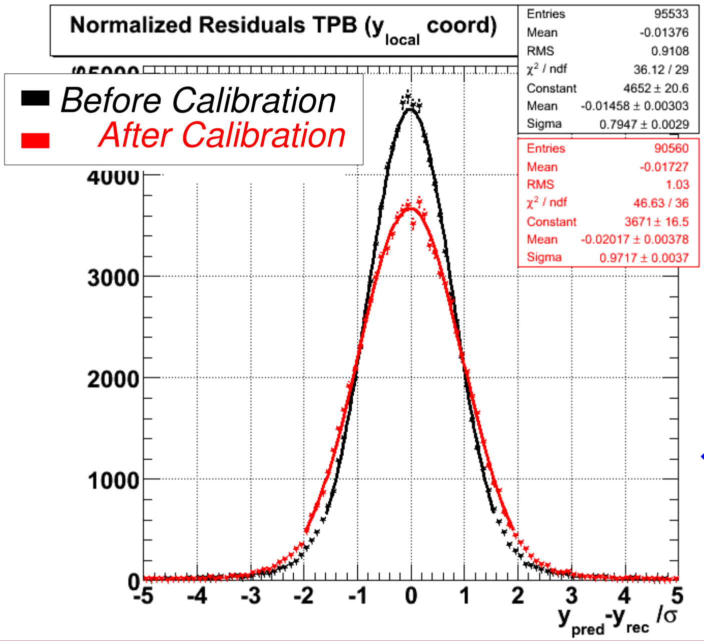
- **(1) In TID/TEC (Endcaps) In PXB/PXE (Pixel)**
- **(2) In TIB/TOB (Barrel)**



- (1) **In the endcaps** and in the pixel detectors use the width of the DMR distribution measured in DATA
- (2) **In the barrel detectors** use the misalignment parameters δu,(δv for DS), δγ 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
- **k and N_0 are parameters tuned on data**

APE Tuning and validation with cosmic data

- The k-factor is tuned in order to have the pull of residuals **(r/σ) ~1**



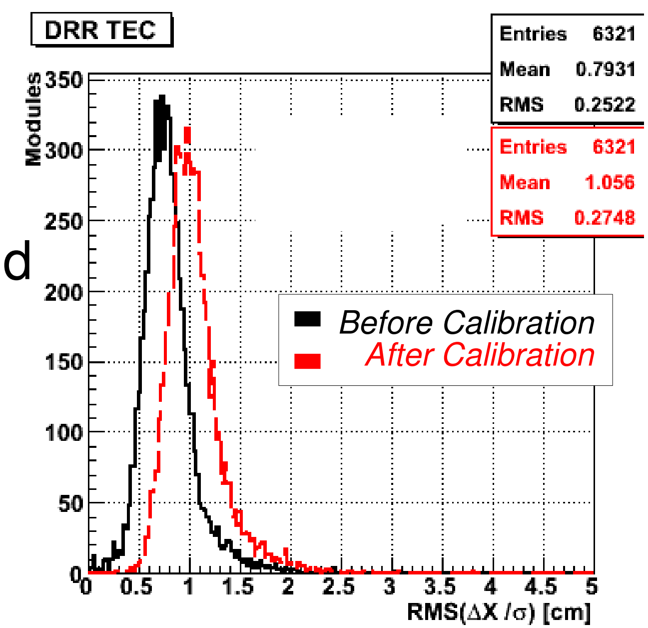
- Define the normalised residuals:

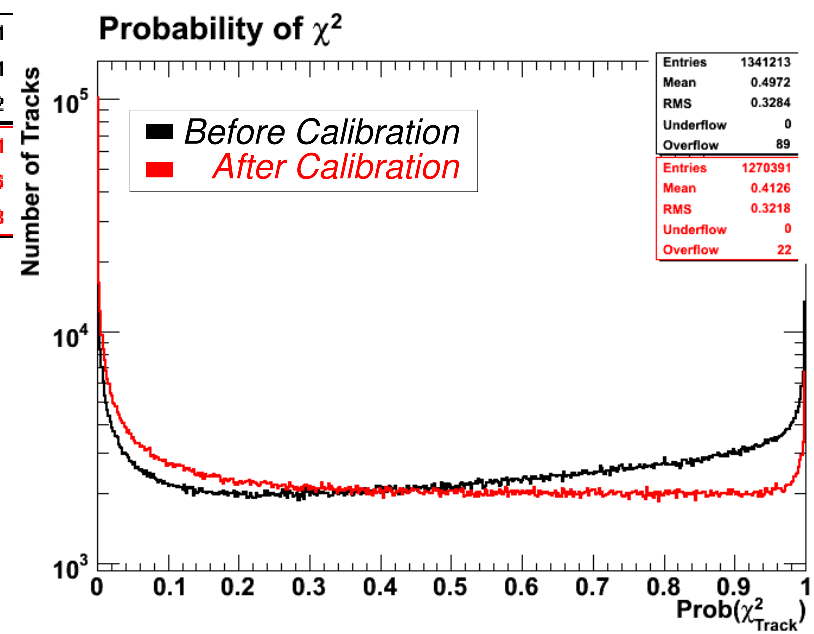
$$\frac{r_i}{\sigma_i}=\frac{u_i^{hit}-u_i^{fit}}{\sigma_i}=\frac{m_{ij}-f_{ij}(\mathbf{p},\mathbf{q})}{\sigma_i}$$

$$\sigma_i=\sigma_i(APE(\mathbf{k}))$$

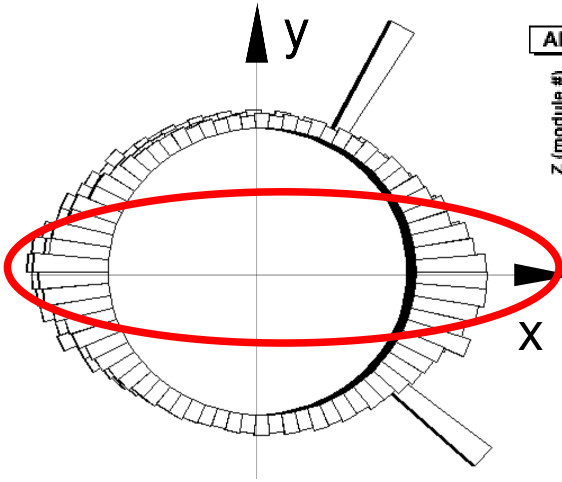
- **The k factor is tuned** with an iterative procedure until the contribution to the hit error determines the pull of residual to be **~1**

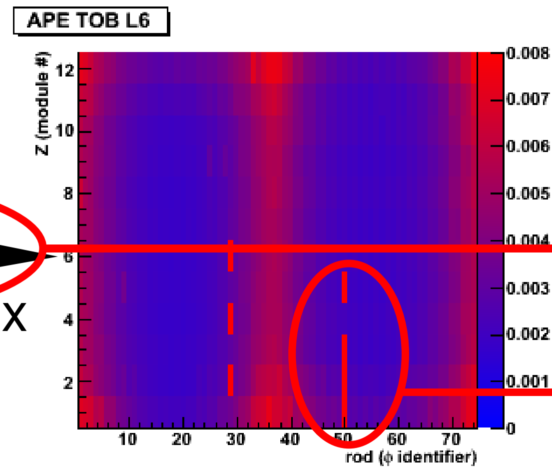
- After the tuning of the APE, the peak of the χ^2 is shifted to 1. The prob(χ^2) flattens, and the distribution of the RMS (DRR)of normalized residuals goes to 1





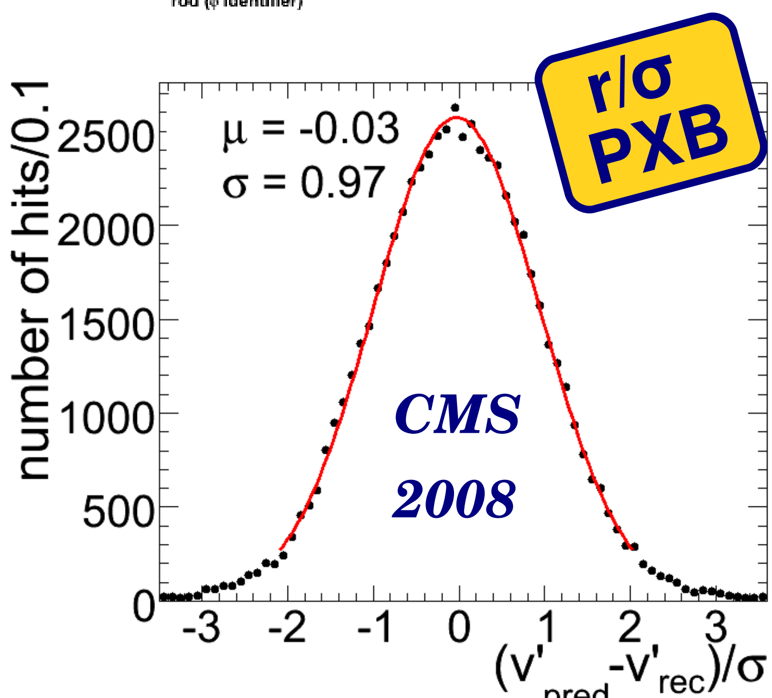
APE Validation

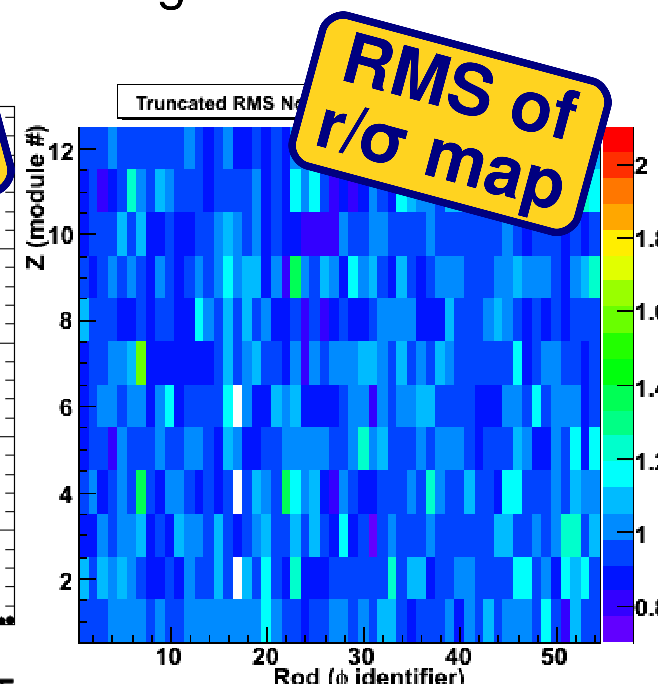




- After tuning of the APE, the topological distribution of the errors is controlled.
- Alignment position errors are larger int the horizontal plane (y=0)
- Spiked due to not aligned modules ⇒ impose by hand large errors

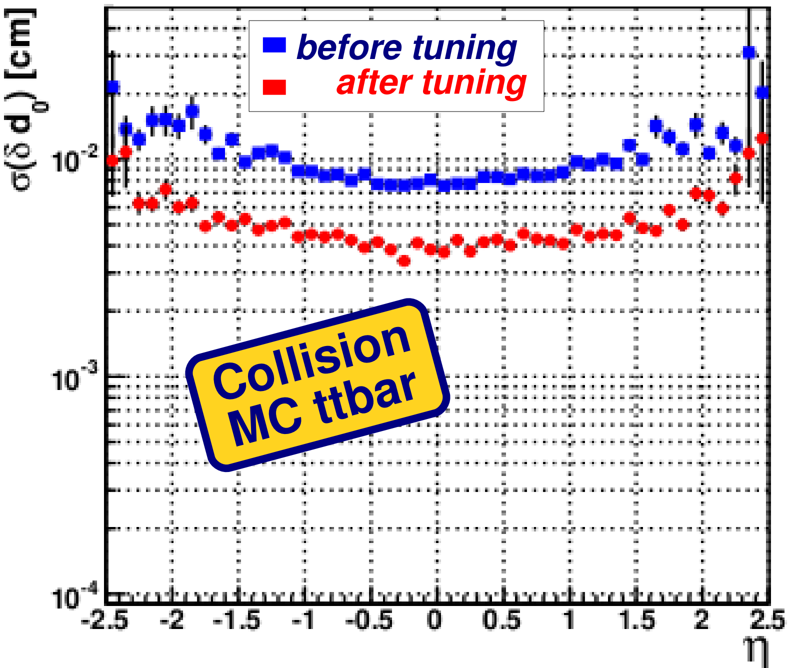
- Finally the pull of residuals is evaluated and is found to be consistent with 1.
- Summary plots of RMS of r/σ on a module-by-module basis are checked
- *<u>The entire procedure needs to be repeated aftery every alignment cycle (i.e. after every intervention on the detector)</u>*





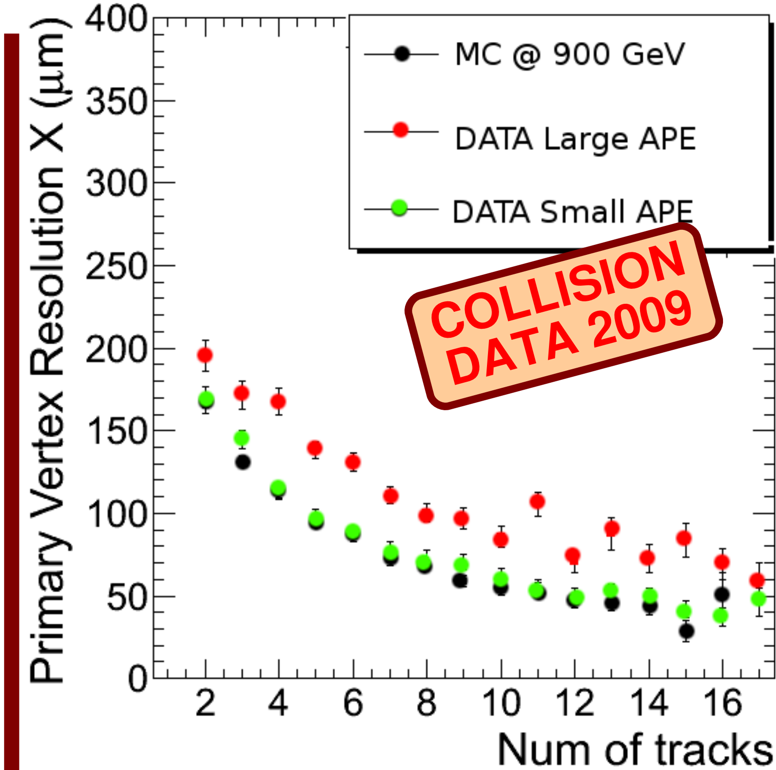
- **The Alignment Position Errors so determined were used for the reconstruction of the first LHC *pp* collision data taken by the CMS detector in November 2009**

APE Performance



◆ **Resolution on the transverse impact parameter** as a function of pseudorapidity for a sample of collision tracks at high multiplicity ($pp \rightarrow t\ \bar{t} + X$) .

◆The resolution improves using the correct APE for track reconstruction

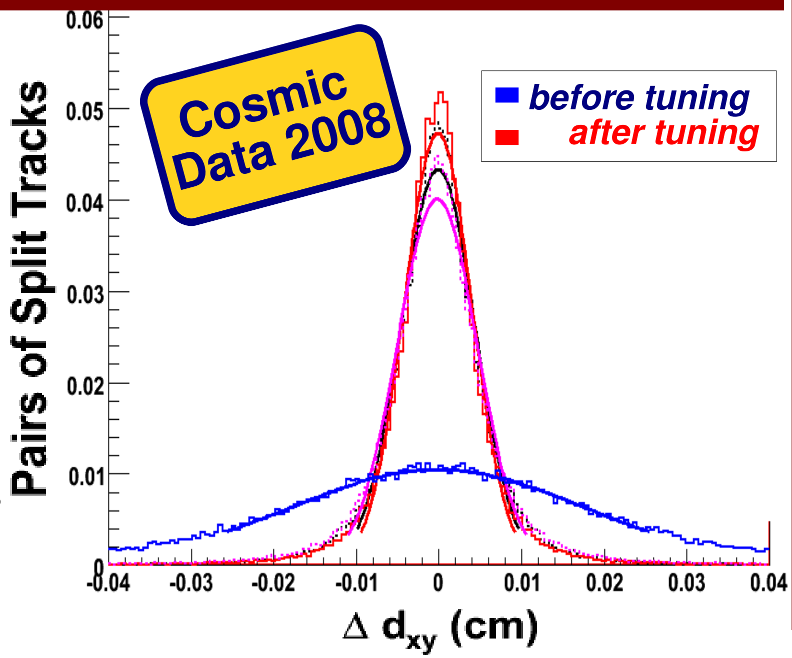


◆**Track transverse impact parameter d_0**

◆ is obtained by comparing segments of cosmic ray tracks split into two halves at the PCA to the nominal beamline.

◆ Each leg is *refitted separately*

◆ The five track parameters of each leg, updated at the perigee, are compared.



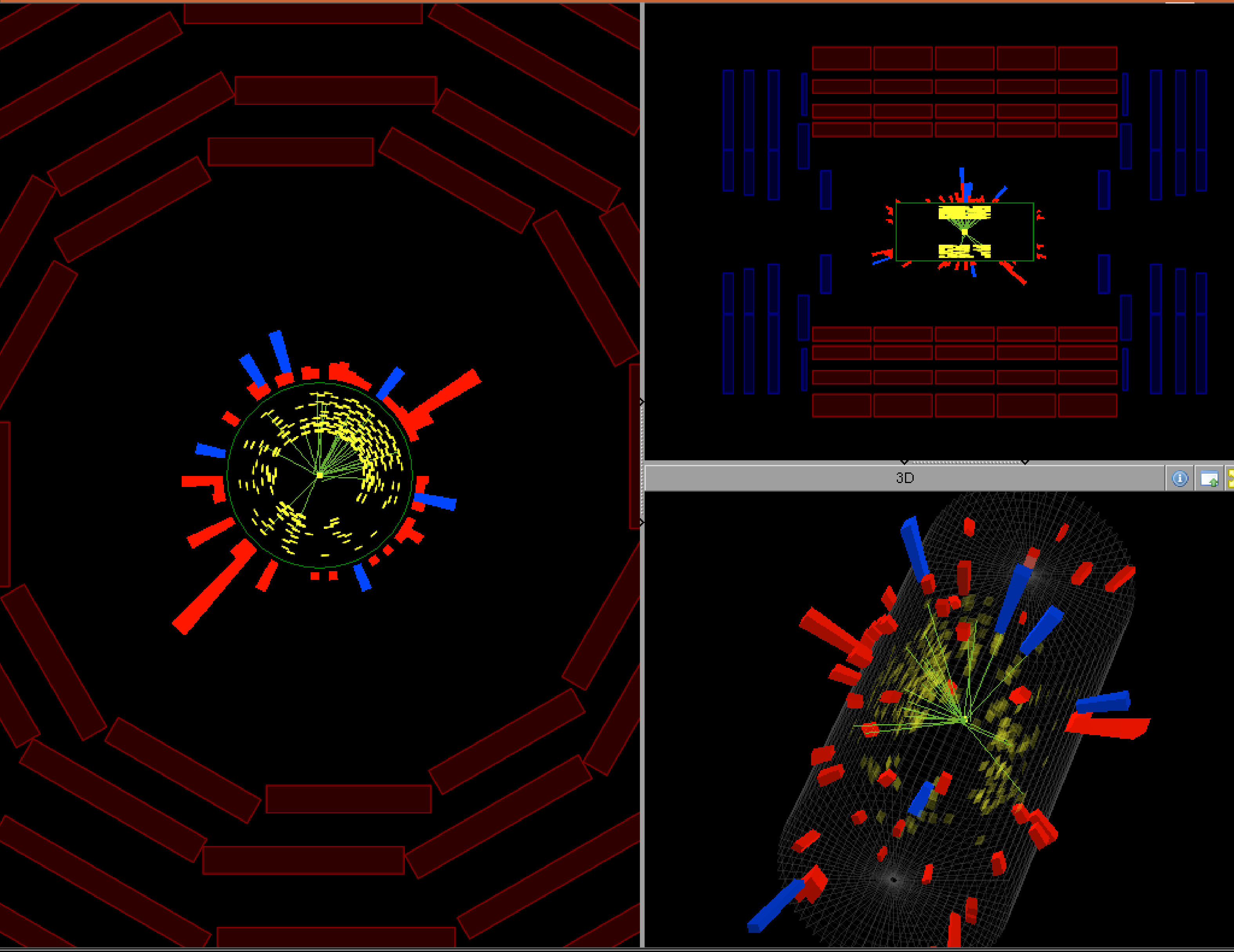
◆ **Resolution on the x coordinate of Primary vertex.**

◆The resolution is obtained on real data:

- ◆ by randomly separating the tracks of an event in 2 independent samples
- ◆ refitting separately two primary vertices
- ◆ comparing the coordinates

Present and future activity

23.11.09 First Tracks with LHC Beams

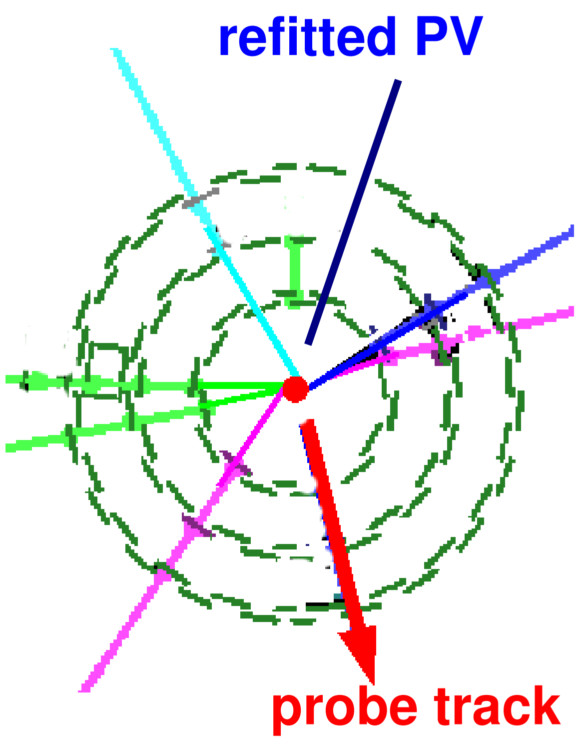


- On 23rd of November 2009 the LHC starts delivering collisions and the CMS detector to collect collision tracks

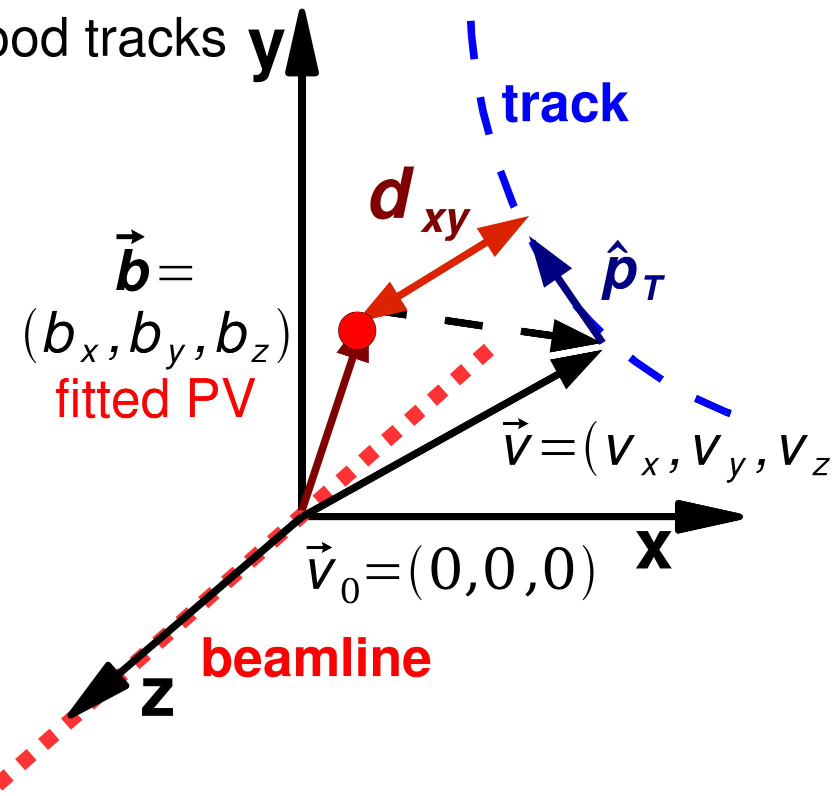
- First real occasion to test the tracker alignment with beam data..

- ... and to apply our knowledge of the tracker to physics studies

Primary Vertex Validation



- **Idea:** use primary vertices residuals to test alignment of the pixel detector
  - 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 (r-φ) and longitudinal (x=0) planes
  - Iterate over all good tracks



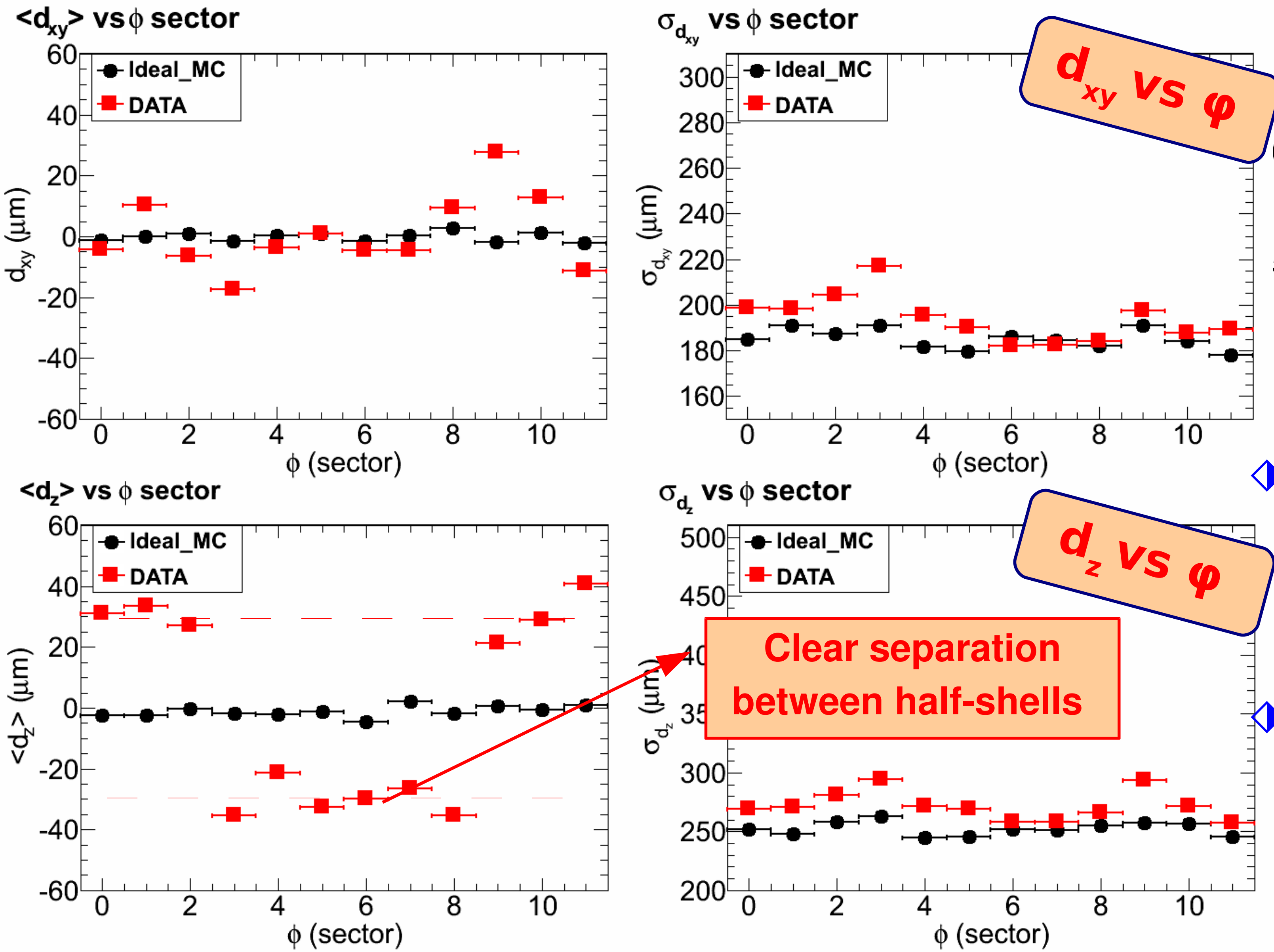
- The d_{xy} residual in the defined as the distance in the transverse plane between the refitted vertex and the perigee of the track:

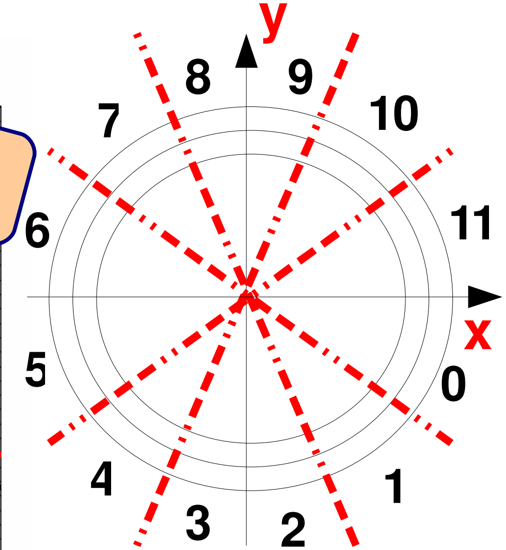
$$d_{xy} = [(\vec{b} - \vec{v}) \times \hat{p}_T] \cdot \hat{z}$$

$$d_{xy} = \frac{-(v_x - b_x) p_y + (v_y - b_y) p_x}{\sqrt{p_x^2 + p_y^2}}$$

Results on Data (900 GeV Minimum Bias)

- **Run the validation on collision data:** should be able to spot systematic misalignments remained uncorrected after alignment with cosmic data

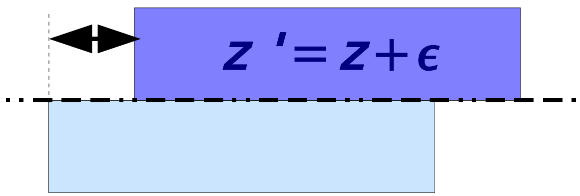


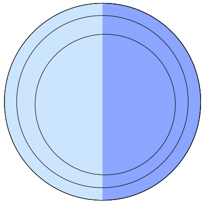


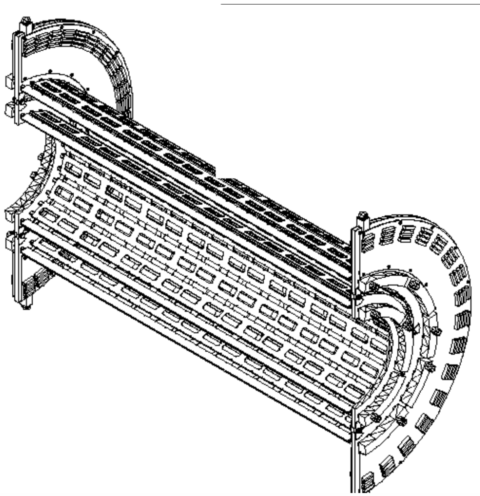
- Some trend is visible in the rφ plane, but a clear separation in the z residual is visible.
- Hint of a displacement of the two half-shells of Tracker Pixel Barrel

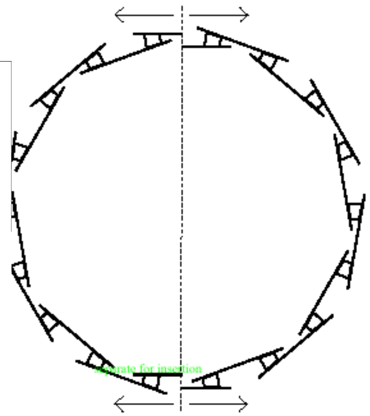
Comparison with MC

- Try to quantify the z offset between halfshells by using a misaligned MC (apply an offset in the z direction)
- Use two scenarios (*strips are kept fixed*):
  - **z offset ε=50 μm** (displace x>0)
  - **z offset ε=60 μm** (displace x>0)

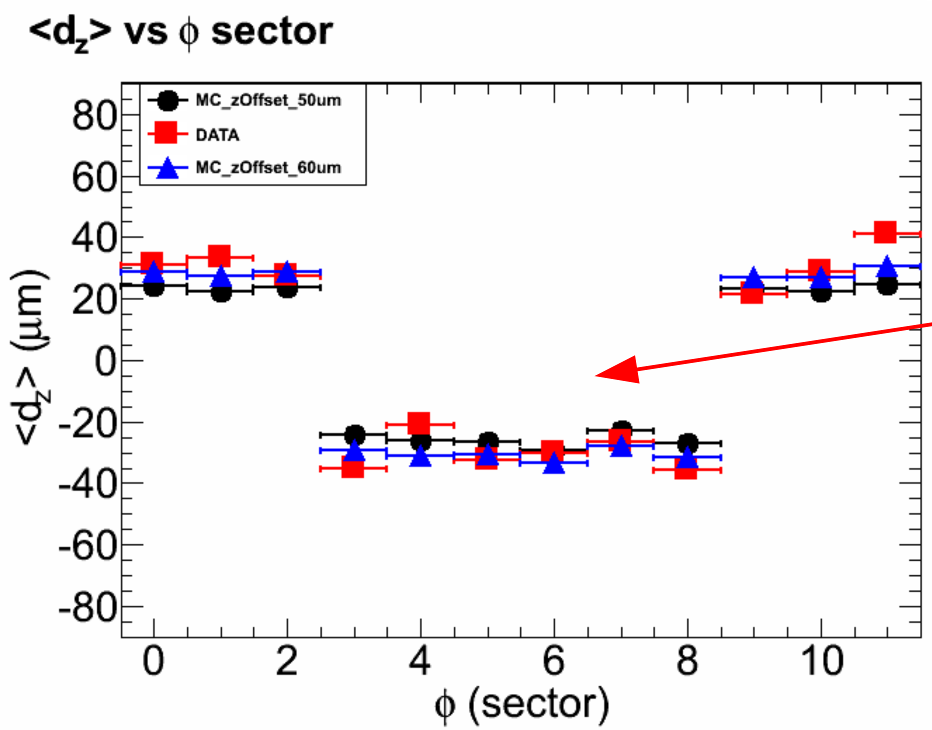


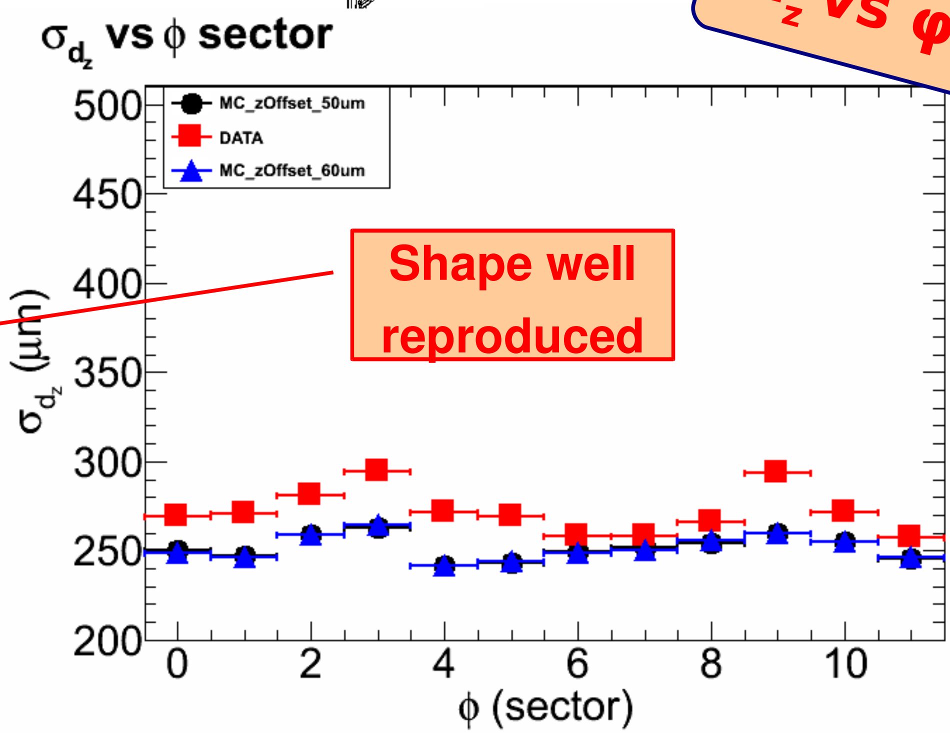






d_z vs φ



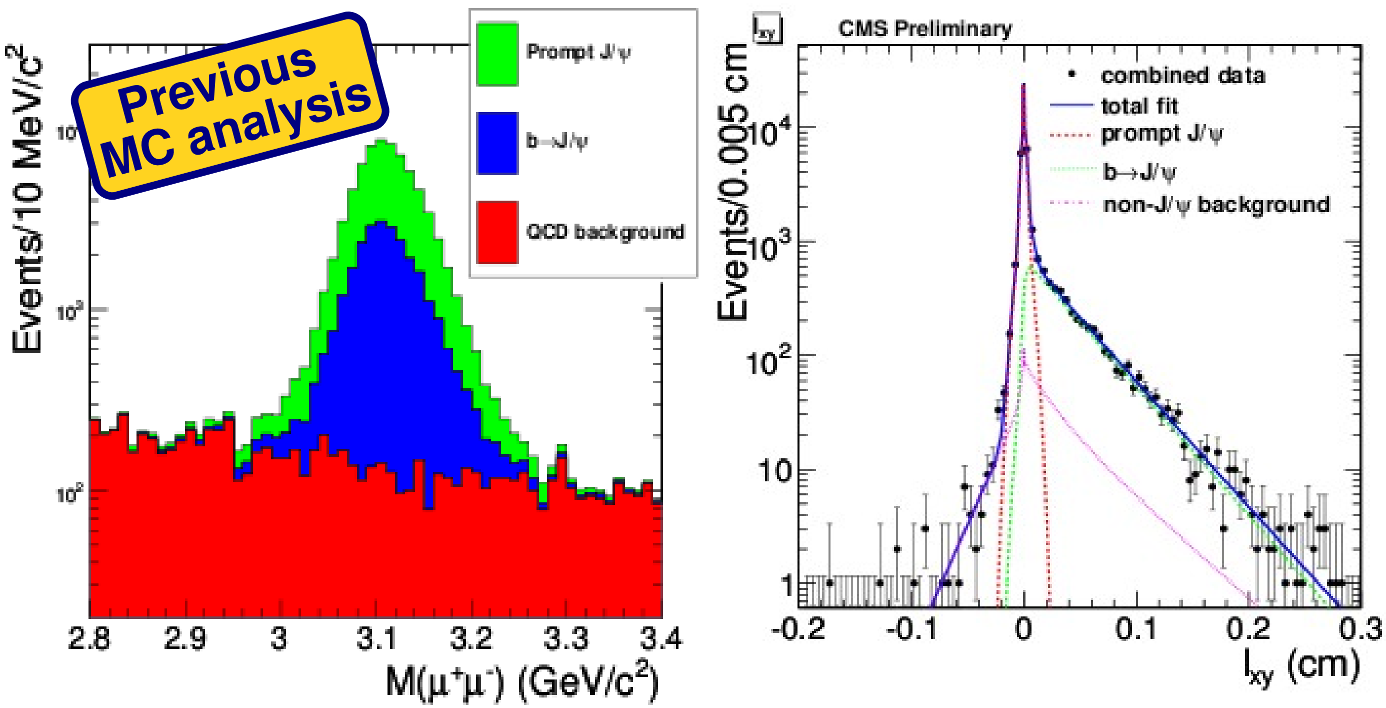


Shape well reproduced

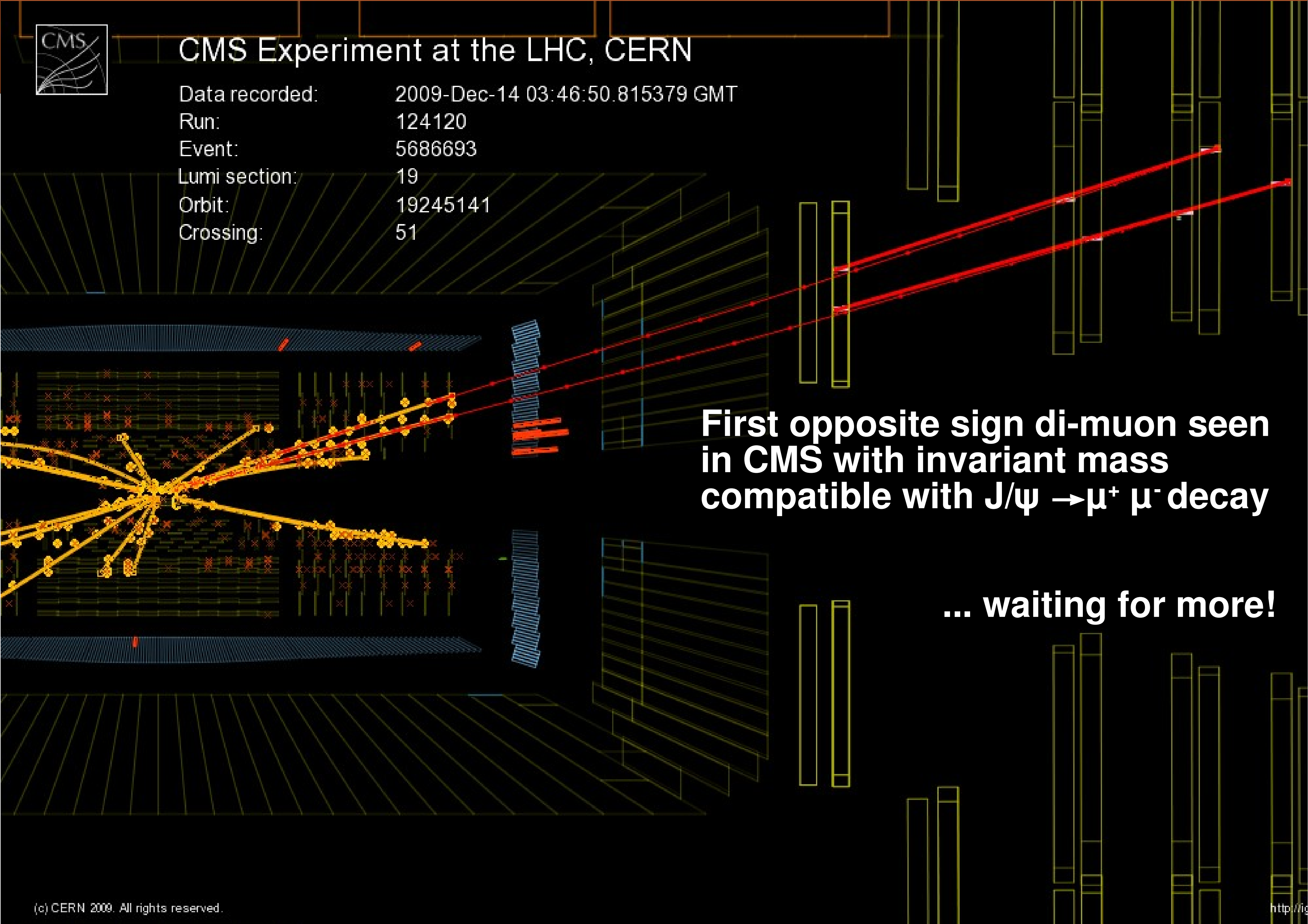
The future: pp → J/ψ + X → μ⁺μ⁻ cross-section

- J/ψ production mechanism in hadronic collisions is not yet completely understood ⇒ interesting process to study
- It has a relatively large cross-section ⇒ one of the first analysis in CMS involving muons in the final state
- Muon resonances important to calibrate the detector in early phases
- The production cross-section of J/Ψ's in the muon channel can be estimated as:

$$\sigma(pp \to J/\psi + X) \times B.R.(J/\psi \to \mu^+ \mu^-) = \frac{N^{fit}_{J/\psi}}{\int L\,dt \cdot A \cdot \lambda^{corr}_{trigger} \cdot \lambda^{corr}_{reco}}$$



- The $N^{fit}_{J/\psi}$ parameter comes from a simultaneous fit to the dimuon mass shape and the apparent measured lifetime.
- This is done in order to disentangle the prompt di-muon from the ones coming from open bottom decay chains (b→J/ψ)
- the apparent lifetime is proportional to l_{xy} ⇒ **highly sensitive to tracker alignment**

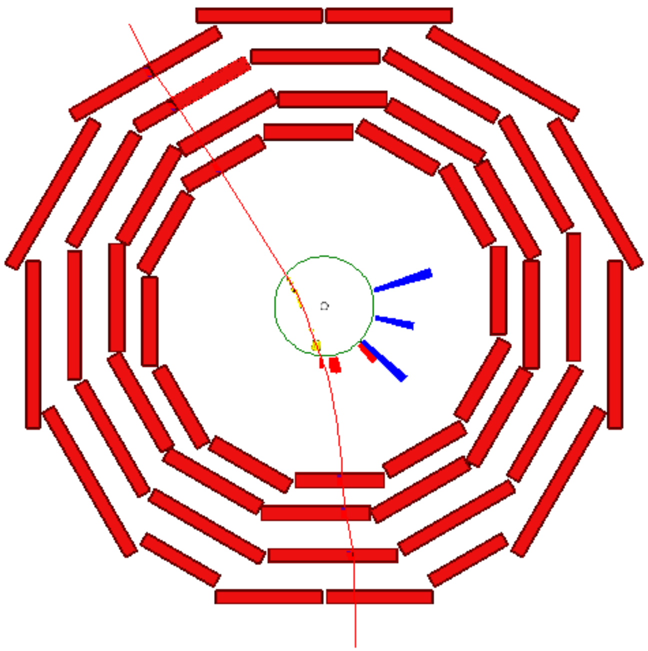


First opposite sign di-muon seen in CMS with invariant mass compatible with J/ψ →$\mu^+ \mu^-$ decay

... waiting for more!

Conclusions

- Challenging demands of CMS for the momentum measurement led to **design a complex inner tracking** system.
- Unknown position of the **15k modules is the main source of systematic error** for physics.
- Tracker alignment has been carried out using cosmic tracks $\Rightarrow$ highly non-trivial task that needs **frequent and complex validations**
- Alignment errors have high impact in tracking and vertexing performance $\Rightarrow$ a ***data-driven method has been used to estimate them on cosmic data***
- Started to look to **impact of alignment in collision data**



TO DO:

- Finalize and commission alignment validation on collision data
- Start to look into the di-muon physics analysis

Thanks for the attention!

Bibliography

Publications:

1) Title: ***The CMS experiment at the CERN LHC***
Author: R. Adolphi et al.
date: 2008
journal: JINST 3:S08004 (2008)

2) Title: ***Search strategy for the Higgs boson in the ZZ(*) channel with the CMS experiment***
Author: S. Baffioni [...] M. Musich, et al.
Date: 2008
Journal: CMS Analysis Note 2008/050

3) Title: ***Projected exclusion limits on the SM Higgs boson cross sections obtained by combining the H to WW* and ZZ* decay channels***
Author: S. Baffioni [...] M. Musich, et al.
Date: 2009
Journal: CMS Analysis Note 2009/020

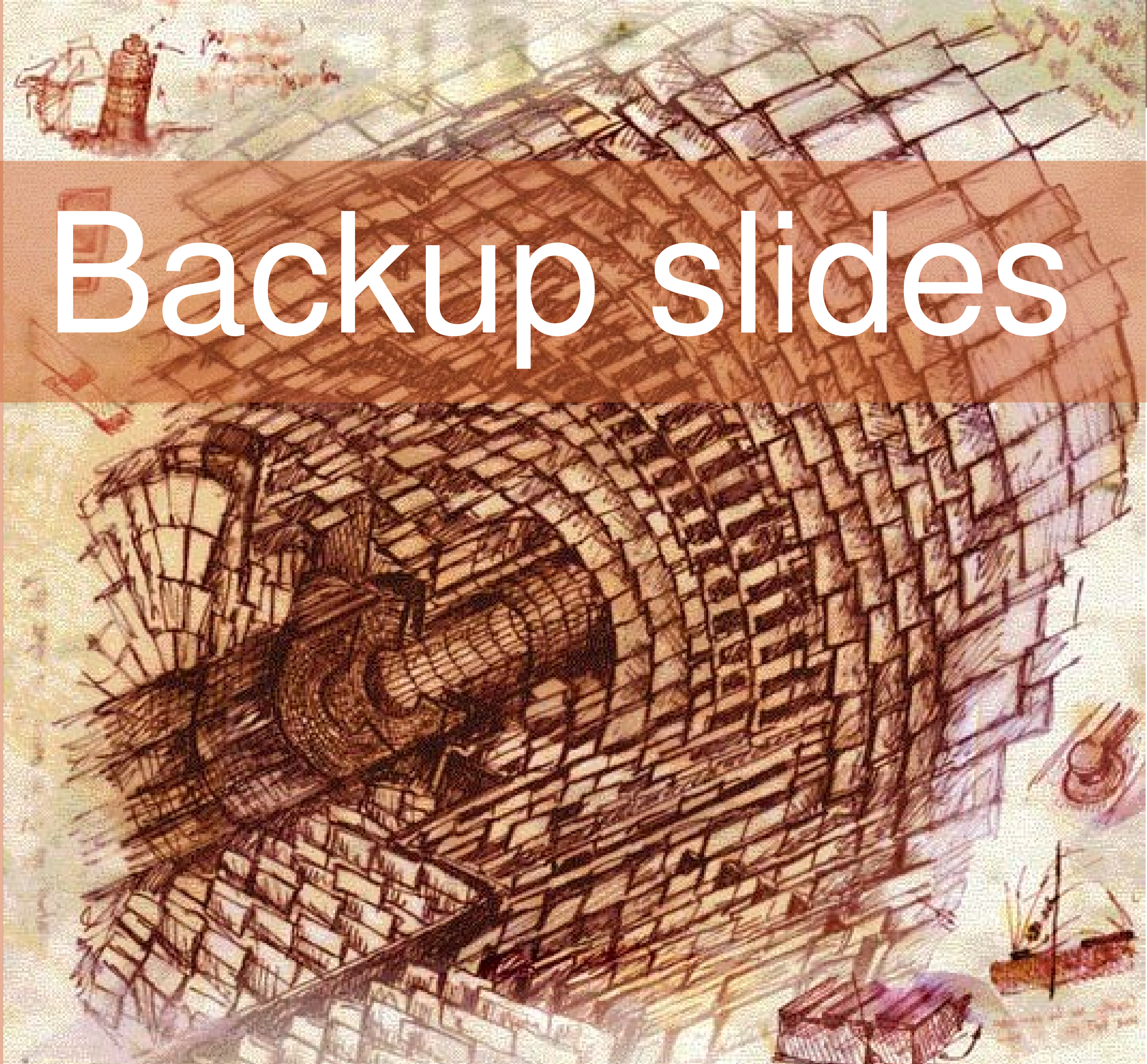
4) Title: ***Alignment of the CMS Silicon Tracker during Commissioning with Cosmic Rays***
Author: The CMS Collaboration
Date: 2009
Journal: arXiv:0910.2505 (Accepted by JINST)

5) Title: ***First Alignment of the CMS Tracker and Implications for the First Collision Data***
Author: M. Musich
Date: 2009
Journal: CMS Conference Report 2009-317
(to be published in "Proceedings of the XXIX Physics in Collision International Symposium")

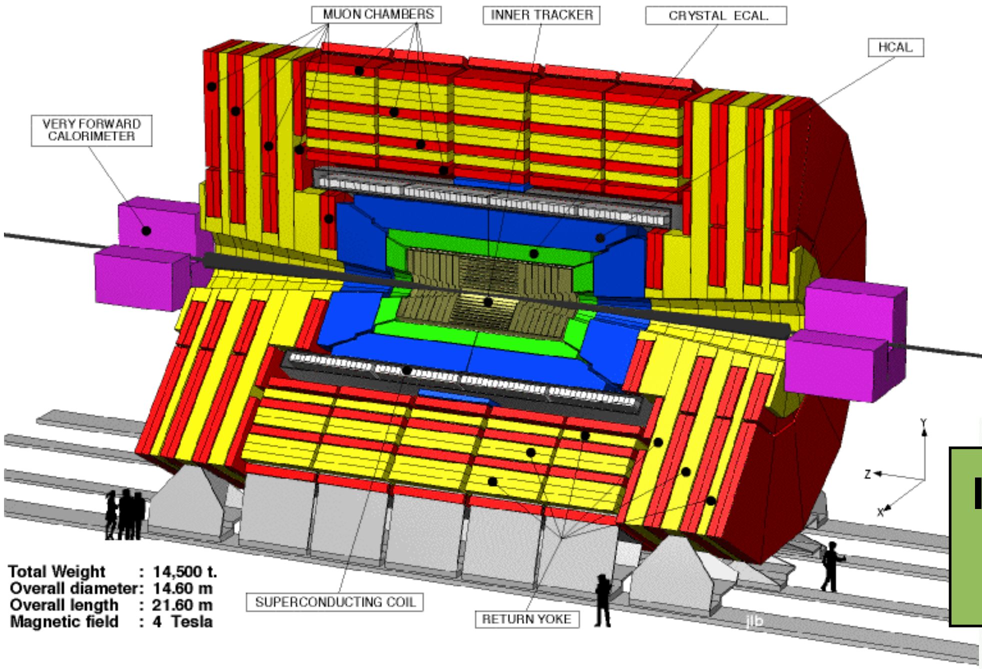
Talks / Posters

- **Presentations at Conferences / International Schools**
  - Talk: ***Allineamento del Tracker di CMS con raggi cosmici***
    XCIV Congresso Nazionale Societa Italiana di Fisica, Genova (ITALY)
    22nd - 26th September 2008
  - Poster: ***The CMS Silicon Strip Tracker***
    XVIII International Conference on Particle And Nuclei (PANIC08)
    Eilat (ISRAEL) - 9 - 14th November 2008
  - Poster: **The CMS Tracker Alignment**
    The 2009 European School of High Energy Physics (EPSHEP09)
    Bautzen (GERMANY),14th - 27th June 2009
  - Talk/Poster: **First Alignment of the CMS Tracker and its Implications for Collision Data**
    XXIX International Symposium on Physics in Collision (PIC09)
    Kobe (JAPAN) - August 30th - September 2, 2009

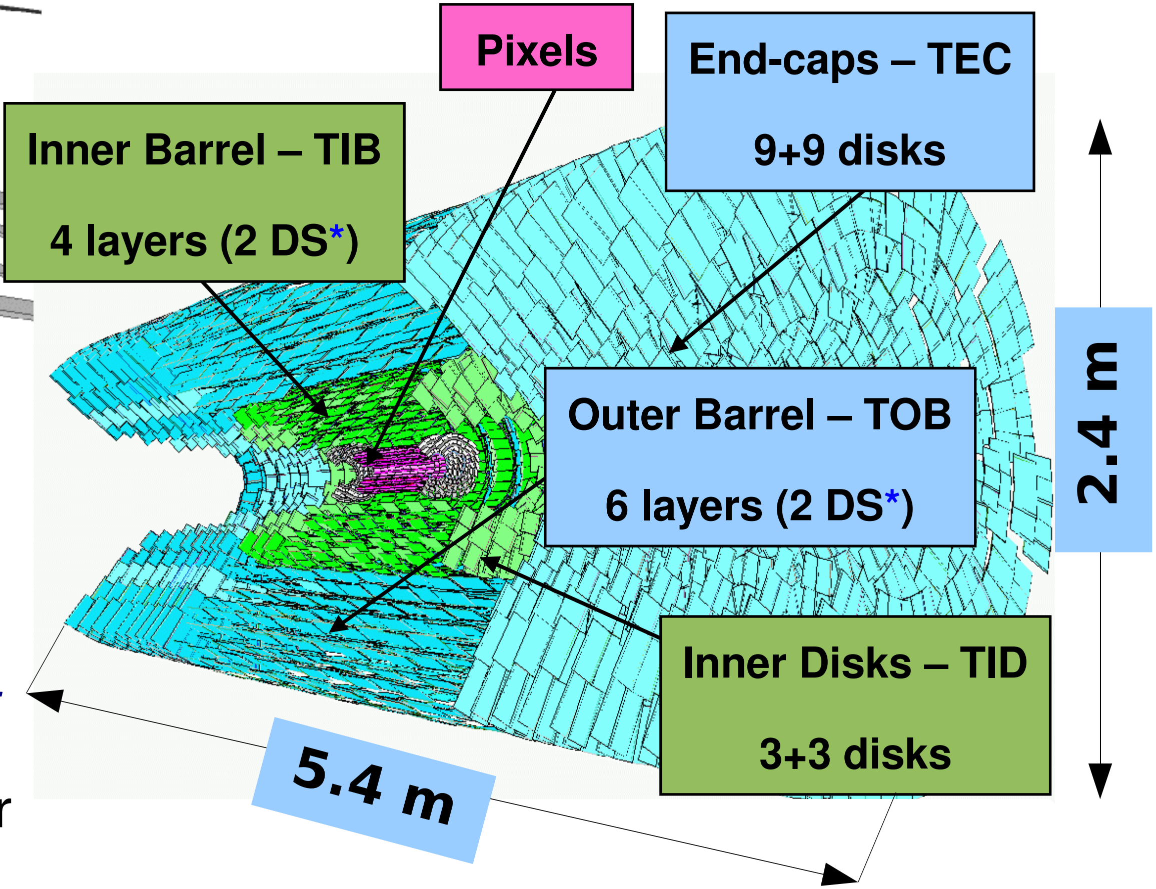
Backup slides



CMS Experiment and its Tracker



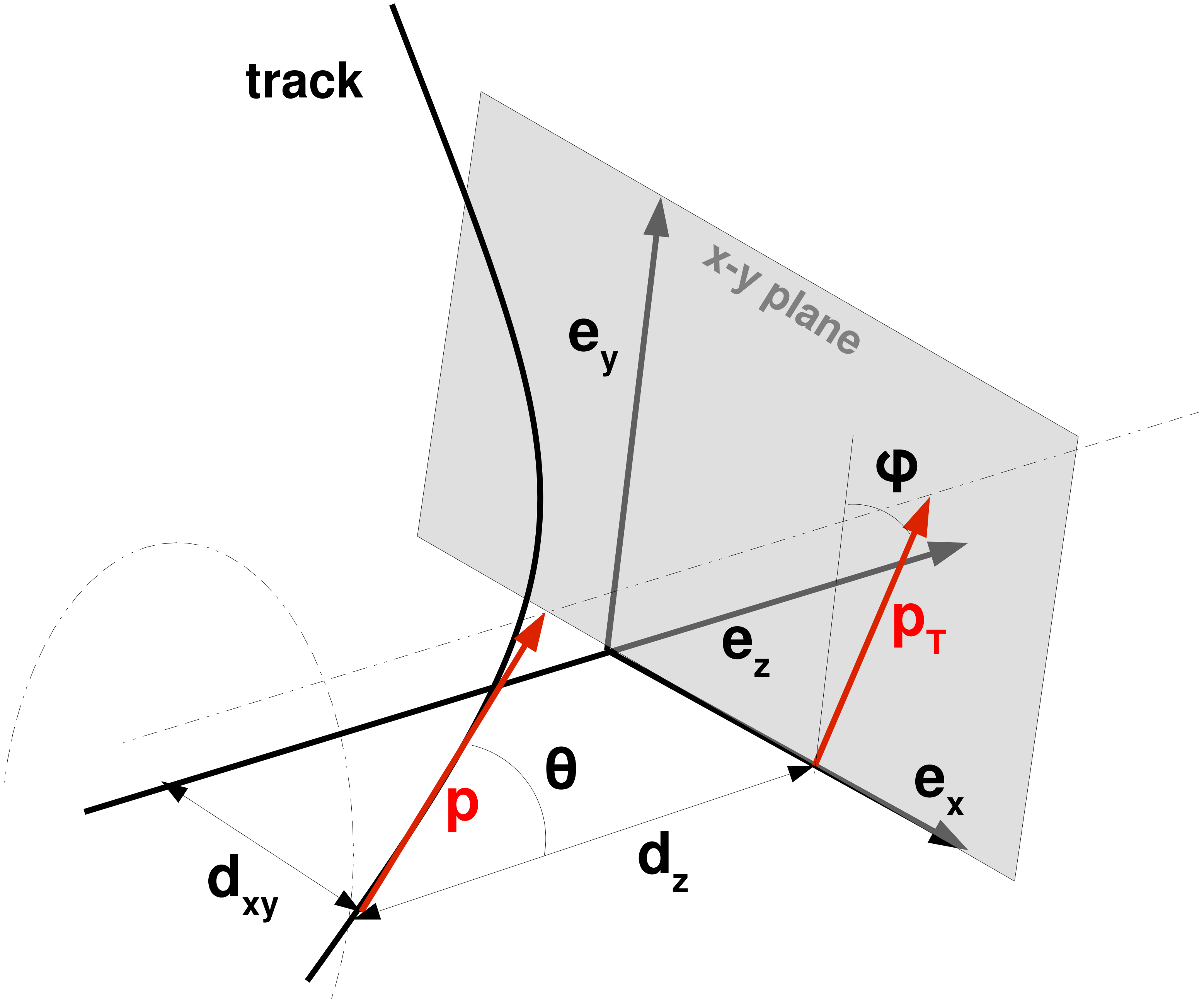
- The ***CMS Experiment*** is one of the 2 *multi-purpose experiments* at the p-p accelerator ***LHC*** at CERN
- It will provide insight in Higgs(es) physics / Super-symmetry / ***new physics at the high energy frontier***



- The ***all-silicon design*** of the tracking system of the CMS experiment is expected to provide *1-2% resolution for 100 GeV* tracks and an *efficient tagging of b-jets.*
- The *alignment of the Silicon Tracker* is crucial to reach the design resolution of the CMS experiment for most physiscs channels

*Double Sided (2 modules mounted back-to-back tilted by 100 mrad)

Track Parametrization in CMS



Why Tracker Alignment is needed?

- The trajectory of a particle of charge ***z*** and transverse momentum $\boldsymbol{p_T}$ in a magnetic field of intensity ***B*** is an helix, these physical quantities are correlated:

$$p_T[GeV] = 0.3 \cdot z \cdot B[T] \cdot R[m] = \frac{0.3\, z \cdot B}{k} \qquad k = 1/R$$

- The measured distribution is rather ***R*** (or ***k*** which is normally distrubuted). The uncertainty on track curvature ***k*** depends on two contributions:

$$\delta k = \sqrt{\delta k_{res}^2 + \delta k_{ms}^2}$$

- Parametrizing in terms of transverse momentum:

C_1 depends on the geometry of the detector

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

C_2 depends on multiple coulomb scattering

B = magnetic field intensity
N = number of track hits
L = track length
$\boldsymbol{\sigma_x}$ = resolution on position

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

~10 µm (Si)

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

MISALIGNMENT

Alignment formalism

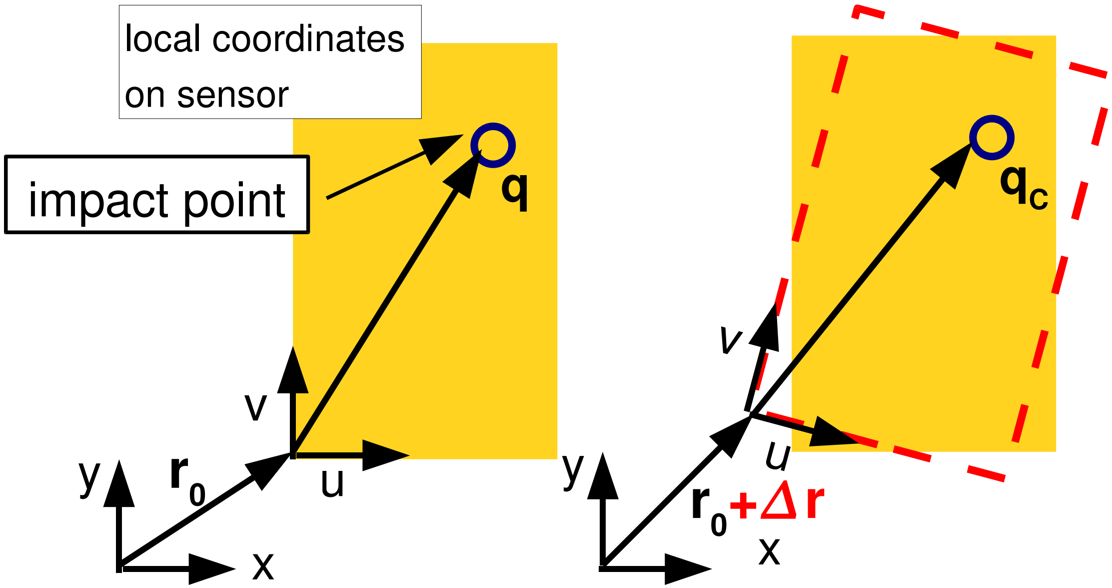
- The hit position in local coordinates of the module is **p**= *(u,v,w)* and ***r*** = *(x,y,z)* w.r.t the global reference frame of CMS.
- The two sets of coordinates are related via a roto-translation:

$$\boldsymbol{r} = R^T \boldsymbol{p} + \boldsymbol{r_0}$$

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

$$\boldsymbol{r} = R^T \Delta R (\boldsymbol{p} + \boldsymbol{\Delta p}) + \boldsymbol{r_0}$$

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

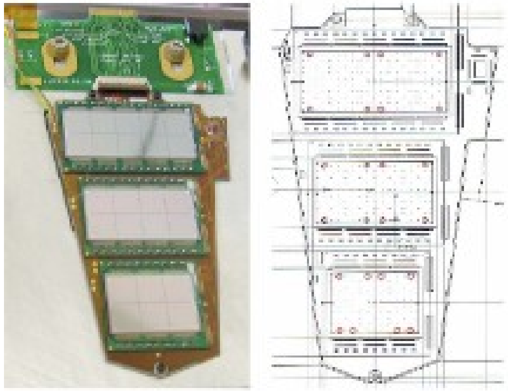


Final goal of alignment:

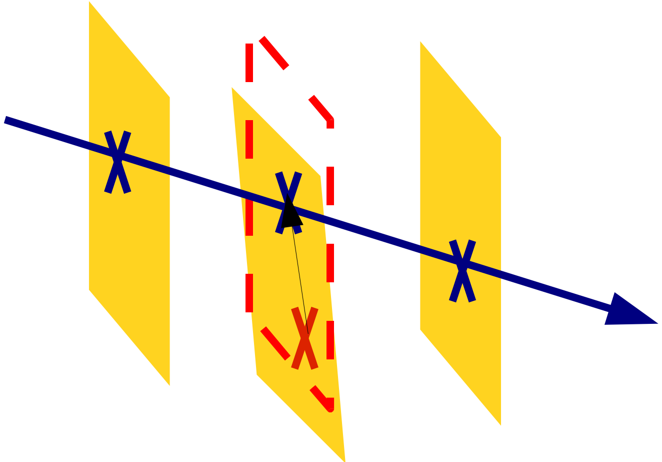
- Determine for each of the O(20k) detunits the 6 parameters **(Δu,Δv,Δw,α,β,γ)** 3 translations and 3 rotations w.r.t the nominal geometry
- Determine for each of the modules the statistical error associated to the aligned postion **(APE)**

Inputs to alignment

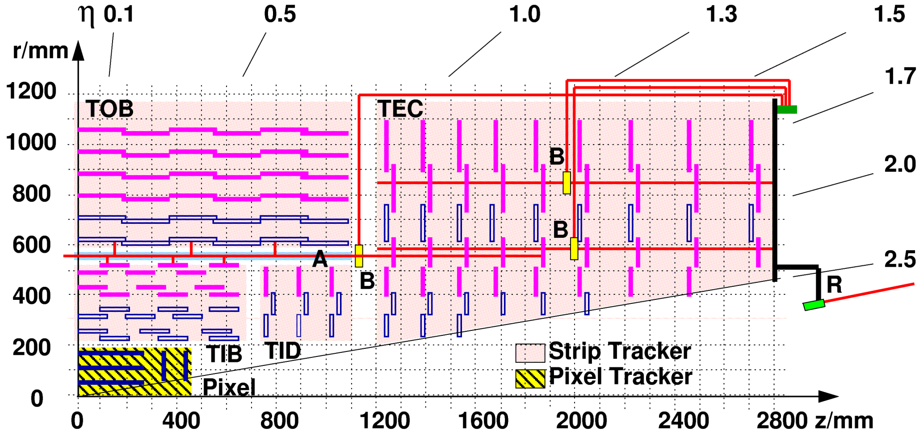
- **Survey measurements:**
  - during assembly of the Tracker using Coordinate Measure Machine (CMM): precision of the sensor on carbon fiber **10 μm**
  - Photogrammetry: precision of **100 μm**



- **Track-based alignment:**
  - different kind of tracks (cosmic ray μ, μ from and W decay, etc..)
  - final expected precision on the module position of less than **10 μm** along their sensitive coordinate

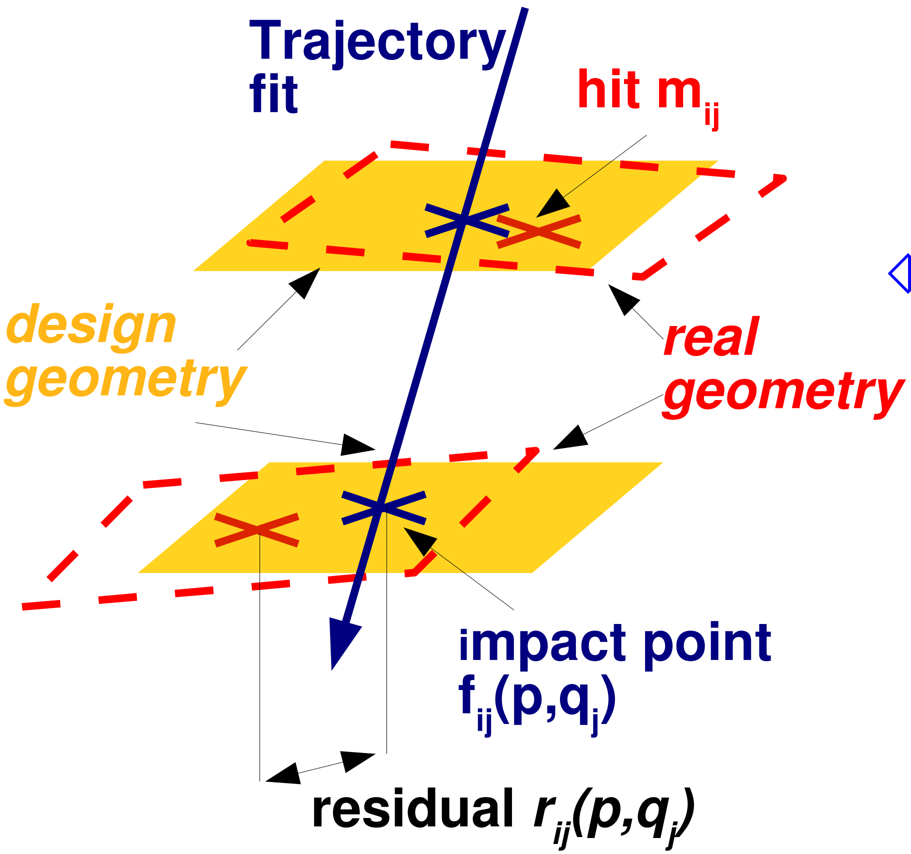


- **Laser Alignment System (LAS):**
  - continuous position measurement of large scale structures using laser beams
  - TEC discs position with spatial precision of **100 μm** and **100 mrad**
  - relative alignment of TIB/TOB vs TEC



How track-based alignment is achieved?

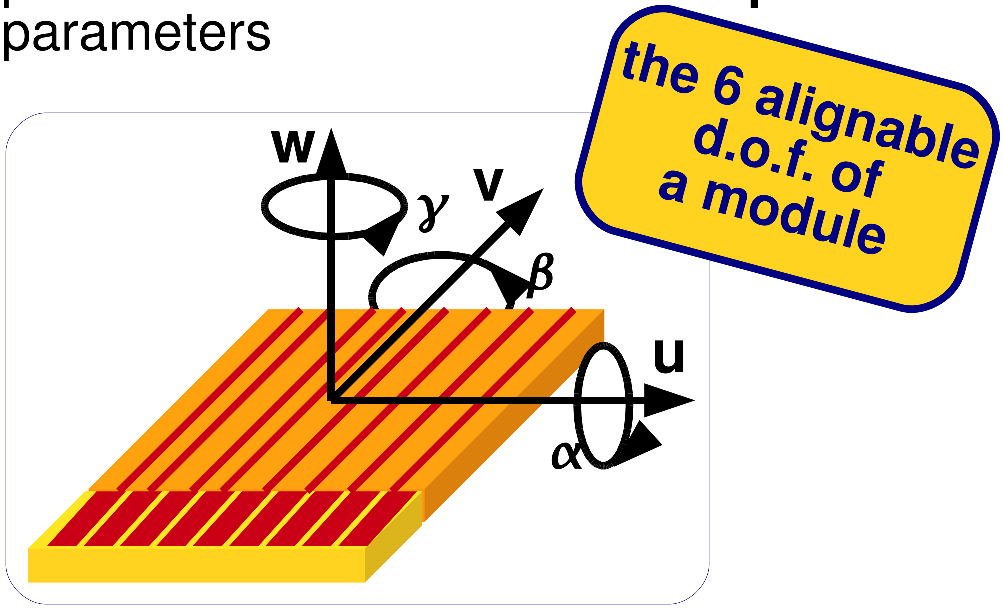
- When a particle crosses the tracker volume, releases an amount of energy on the silicon layers ⇒ a charge deposit is detected
- Clusterize the neighboring strips or pixels sharing the deposited charge
- Reconstruct a **hit** by taking the barycenter of charge of the cluster



- Misalignment affects the track-to-hit residuals defined as:

$$\underbrace{r_{ij}(p,q_j)}_{\text{track residual}} = \underbrace{m_{ij}}_{\text{measured hit}} - \underbrace{f_{ij}(p,q_j)}_{\text{trajectory extrapolation}}$$

- Where **p** are the geometric alignable parameters of the module and **q** the track parameters



How track-based alignment is achieved?

- Define a Global Track χ^2 (objective) function:

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

  - V_{ij} = covariance matrix from fit
  - $r_{ij}(p,q_j)$ = track-to hit residual with *p = alignment parameters (module position/orientation)*

- to achieve alignment and hence minimize the residuals, minimize the global χ^2 function w.r.t the alignment parameters

$$\frac{d\chi^2}{d\boldsymbol{p}_m} = 0$$

- The optimization problem is solved assuming that the objective function can be linearized in terms of the alignment corrections $\boldsymbol{\delta p_m} = p_m - p_{m0}$

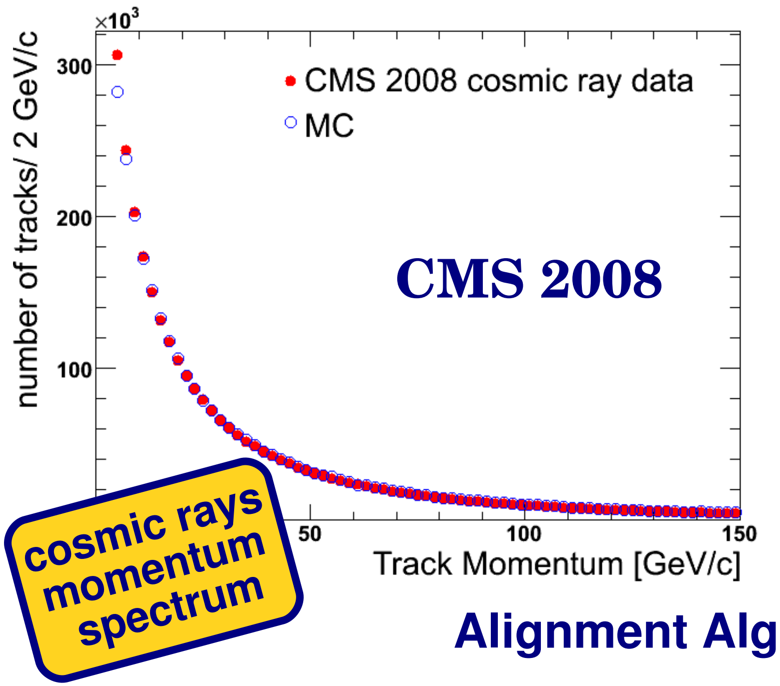
$$\underbrace{\chi^2(\boldsymbol{p}_m) = \chi^2(\boldsymbol{p}_{m0}) - \frac{d\chi^2}{d\boldsymbol{p}_m}\boldsymbol{\delta p}_m}_{\text{linearization of } \chi^2 \text{ around starting alignment parameter } p_{m0}} \Rightarrow \underbrace{\boldsymbol{\delta p}_m = \left(\left.\frac{d^2\chi^2}{d\boldsymbol{p}_m^2}\right|_{p_{m0}}\right)^{-1}\frac{d\chi^2(p_{m0})}{d\boldsymbol{p}_m}}_{\chi^2 \text{ equation}}$$

linearization of χ^2 around starting alignment parameter p_{m0}

χ^2 equation

Large 6N x 6N matrix to be inverted

Track Based Alignment with cosmic rays



- First complete alignment of the CMS Traker performed at the Cosmic Run at Four Tesla (CRAFT)
- A "*global run*": all CMS subdetectors participating to the data taking
- 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

Alignment Algorithms used during cosmic data taking:

- minimizing the χ^2 with millions of tracks requires sophisticated algorithms, two complementary methods were used:

"Hits and Impact Points HIP" *(local method)*:

- Estimates alignment parameters per module, **iterates** due to correlations.
- Stabilizes minimization **by including survey**.

☺ Uses same track model as reconstruction.

☹ Needs many iterations to include correlation

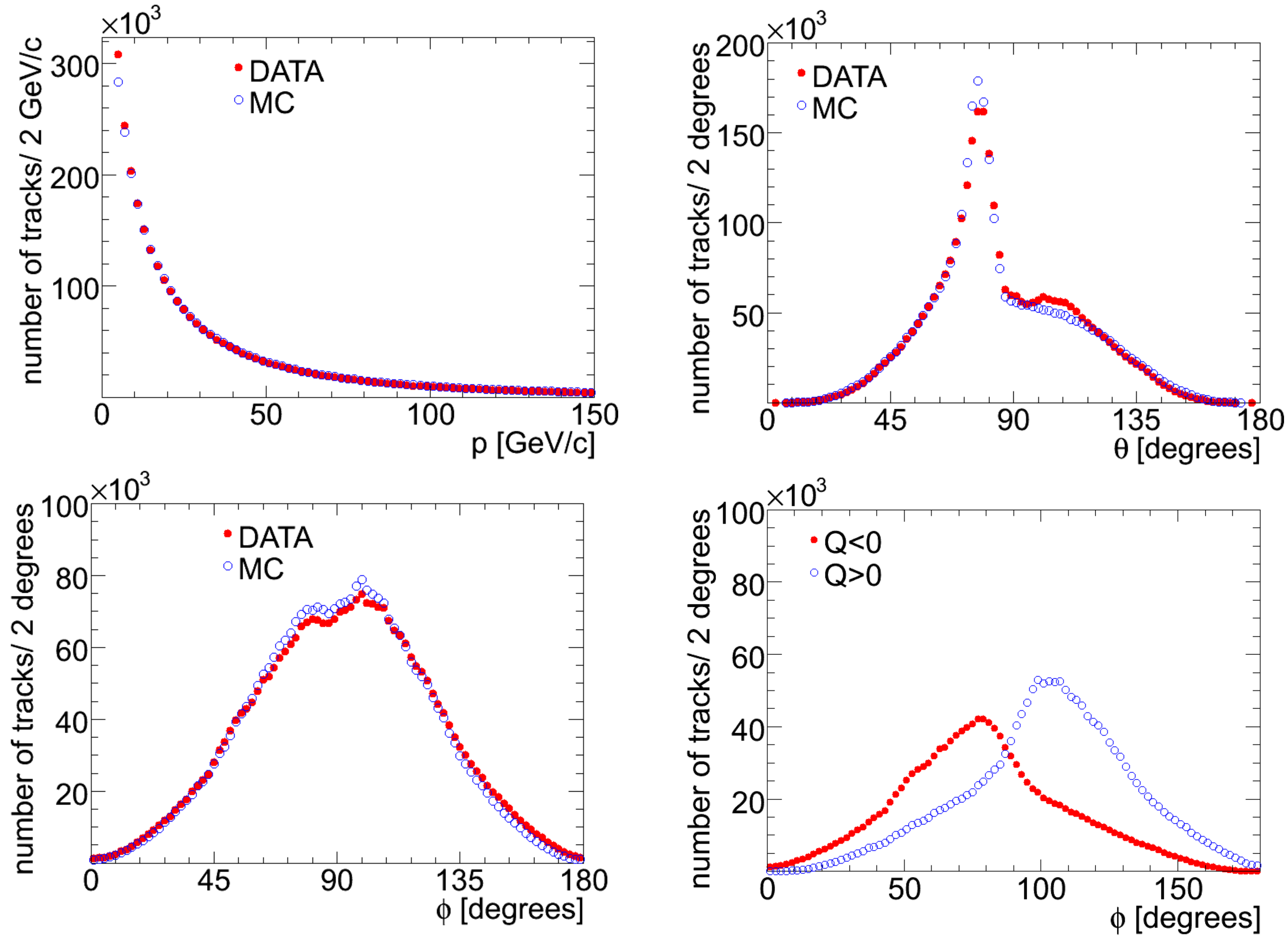
"MillePede II" *(global method):*

- **Fits** track and alignment parameters simultaneously **in one step**.

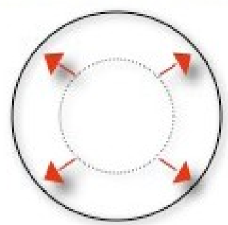
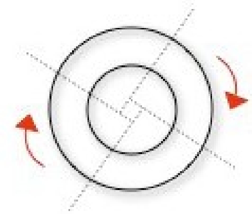
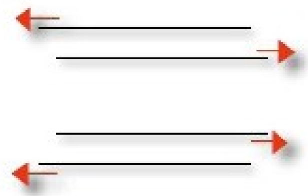
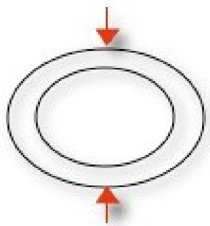
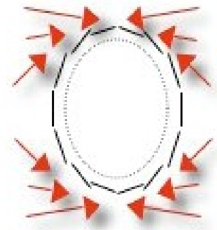
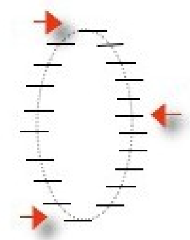
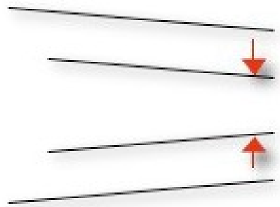
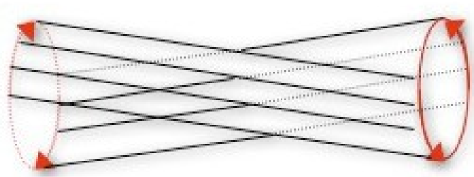
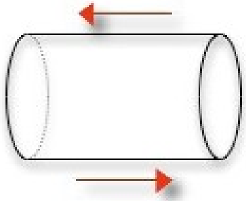
☺ All correlations considered, no need for iterations.

☹ Uses 5-parameter helix as track model.

CRAFT Muon Spectra

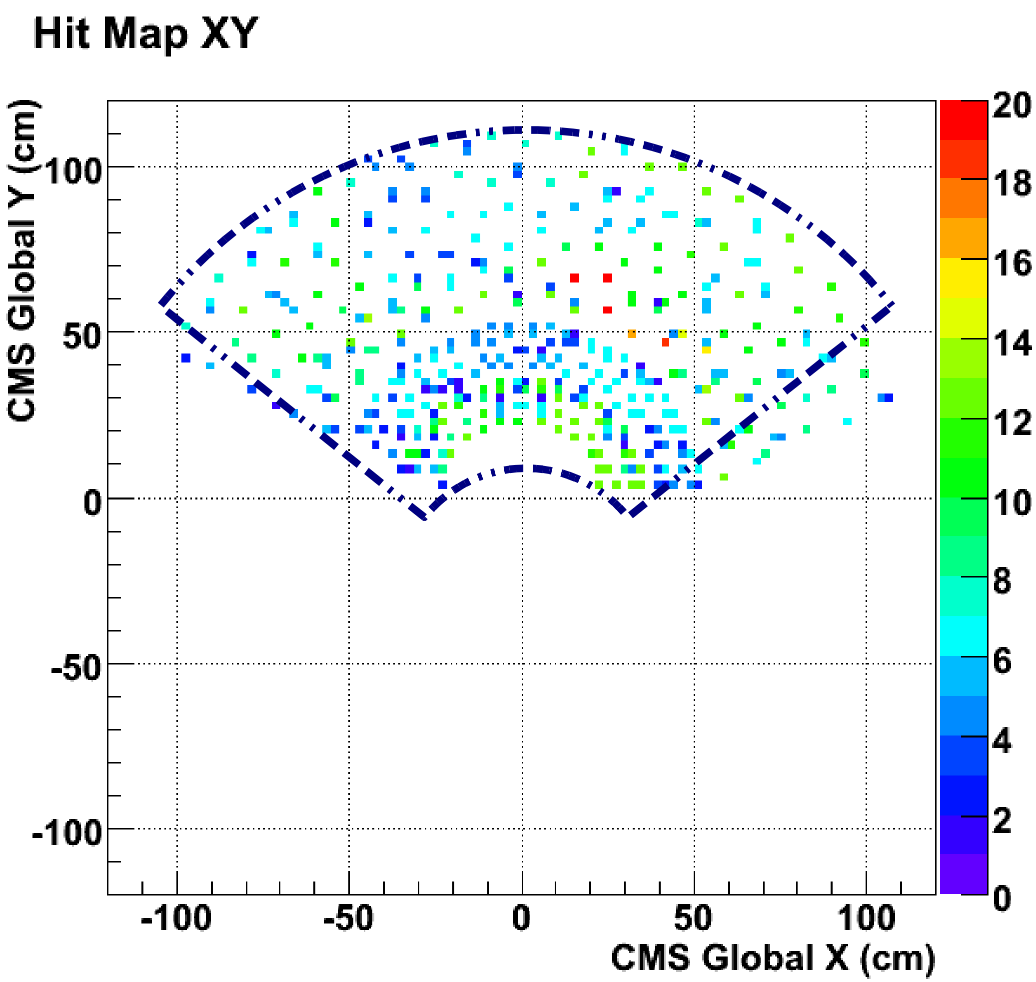


Systematic misalignment

	ΔR	$\Delta\phi$	ΔZ
R	**Radial Expansion** (distance scale) 	**Curl** (Charge asymmetry) 	**Telescope** (CM boost) 
ϕ	**Elliptical** (vertex mass) 	**Clamshell** (vertex displacement) 	**Skew** (Z momentum) 
Z	**Bowing** (total momentum) 	**Twist** (vertexing) 	**Z expansion** (distance scale) 

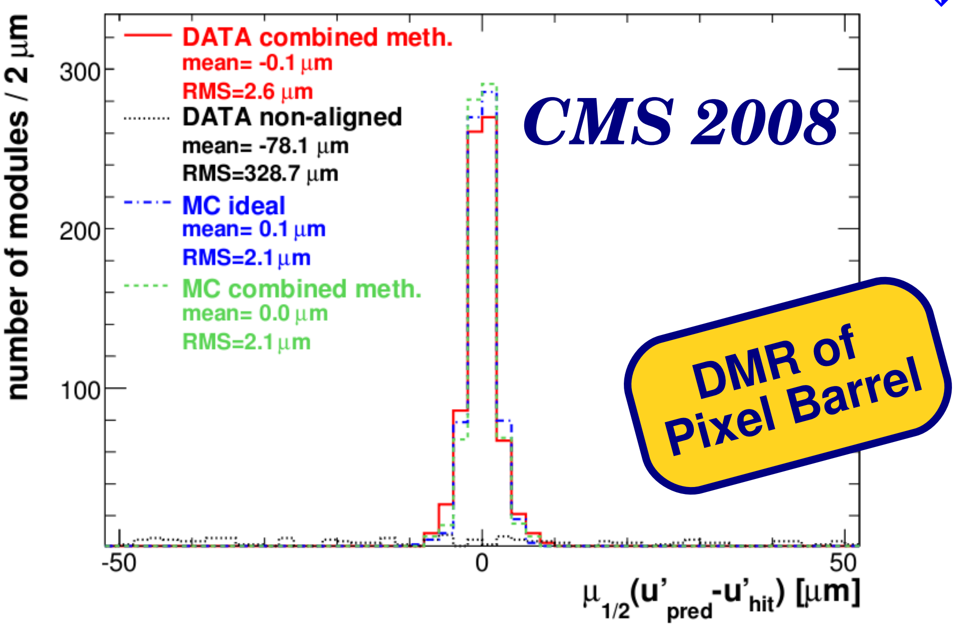
Strategy

- Tuning of remaining misalignment (`Tracker_Geometry_v3_offline` as reference for DATA)
  - selecting tracks / hits where MS and extrapolation are small (**p> 20GeV**)



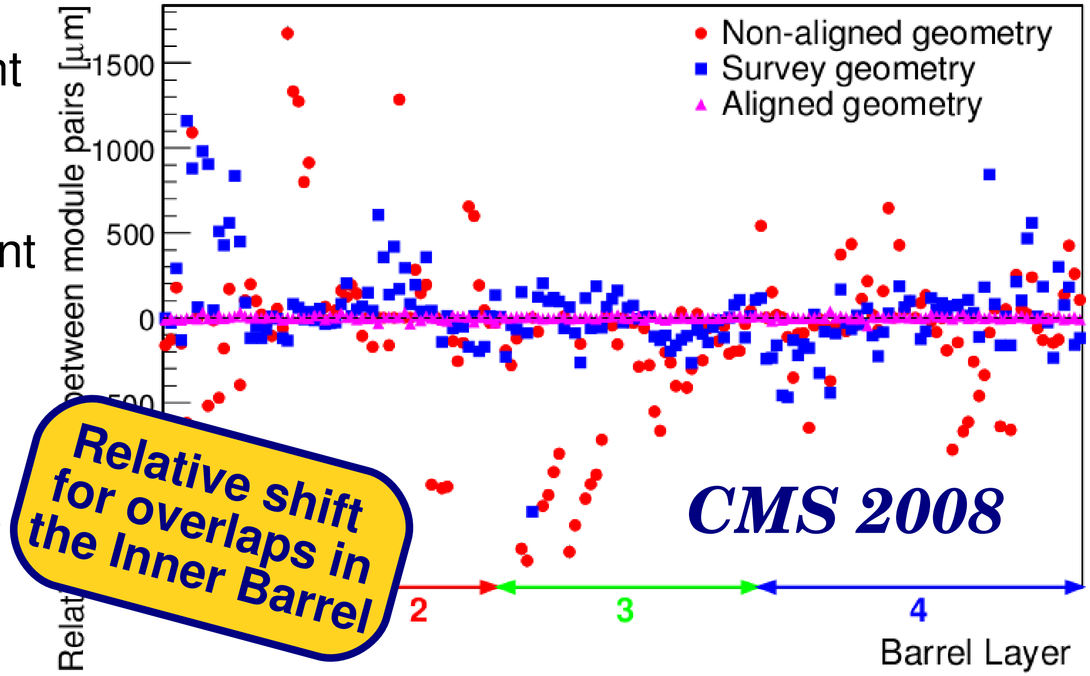
- Track/Hits quality cuts applied
  - **Standard Validation cuts**
    - $N_{hits} > 10$
    - $N_{hits\ -2D} > 2$
    - $S/N_{cluster} > 18$
  - **Fiducial (pixel-like) volume cuts**
    - $(x^2_{DCA} + y^2_{DCA})^{1/2} < 11$ cm
    - $|z_{DCA}| < 60$ cm
  - **Hit pattern selection**
    - **14 split hits (10 SS + 4 DS)**
    - **Test-Beam like topology:**
      - **TOB L6**
        - **TOB L5**
          - **...**

Validation Methods



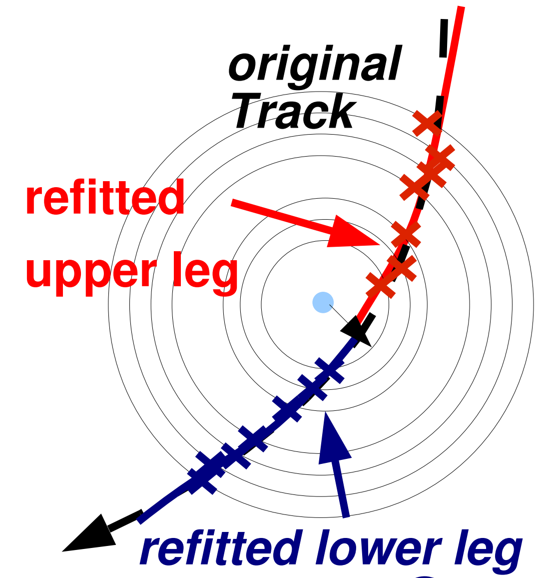
- **Measure for remaining misalignment:**
  - Module-wise informations: **D**istribution of **M**edian of **R**esiduals (**DMR**)
  - Spread gives the lower limit for misalignment (given sufficient statistics)
  - Sensitive to the ***incoherent displacements*** of the modules w.r.t each other in the *sensitive coordinate*
  - Used to estimate misalignment corrections to intrinsic hit errors

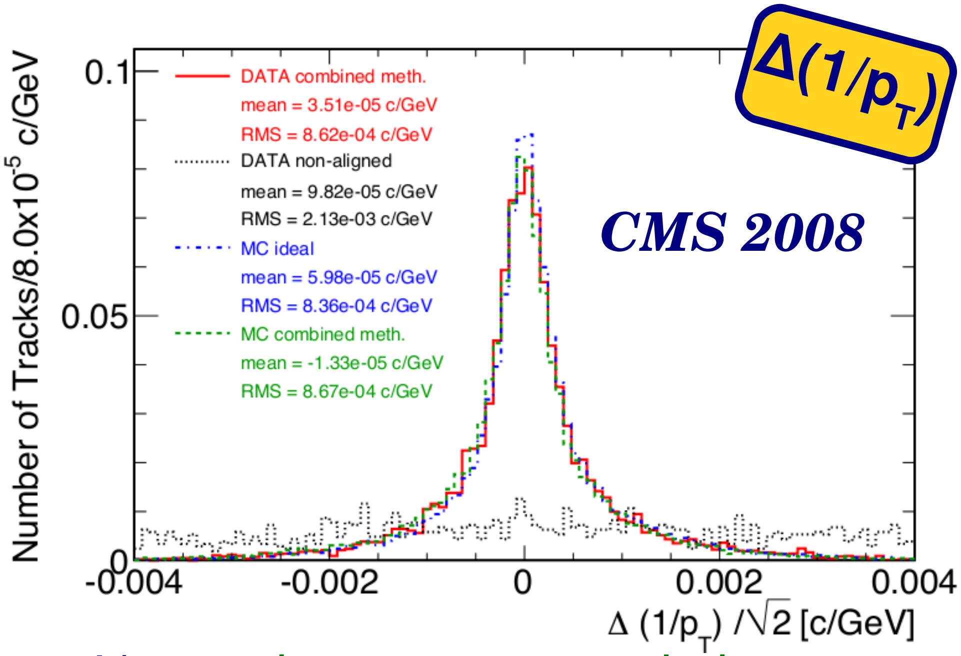
- **Overlapping modules** of *same layer* might have hits from same track.
- *Difference of their residuals* (overlap residuals): sensitive to relative misalignment within one layer. **Offsets indicate shifts**.
- Modules of TIB show significative improvement (RMS decreases)
- Same order of magnitude achieved in TPB and TOB

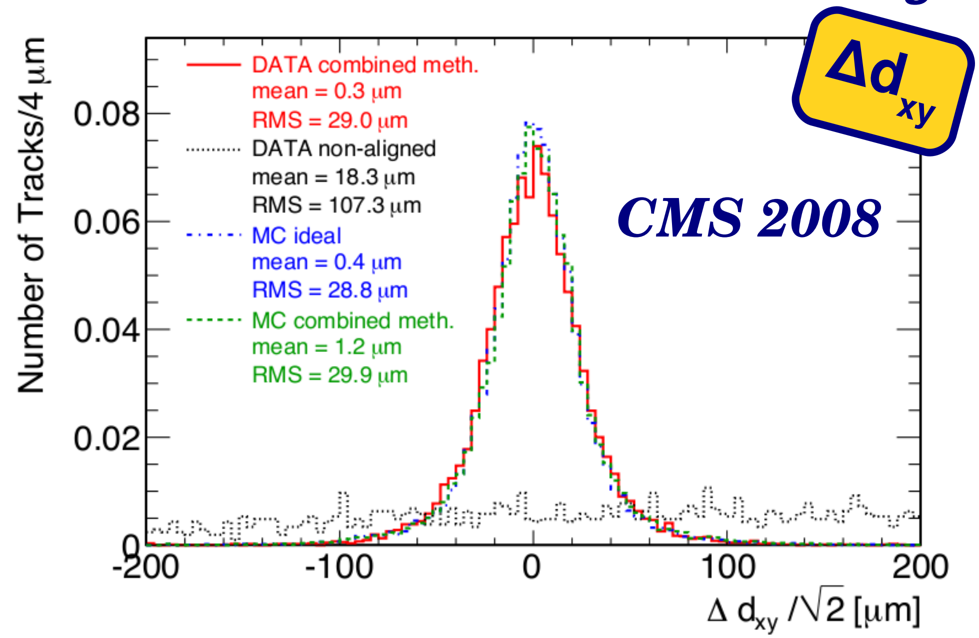


Implications for tracking

- Track parameter resolutions depend on alignment
- Idea: split the cosmic tracks along impact parameter and compare the five track parameters $X=(p_T, d_{xy}, d_z, \varphi_{tk}, \theta_{tk})$ of top and bottom halves independently reconstructed
- Define residuals as: $$r=\frac{X_{top}-X_{bottom}}{\sqrt{2}}$$
- Alignment has a dramatic impact on the resolutions



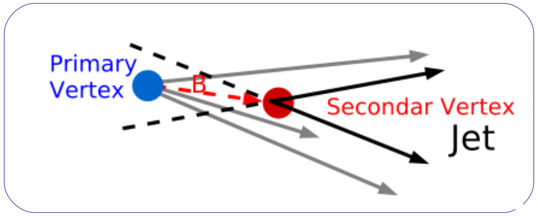




- ***1/p$_T$*** track curvature resolution as good as in simulation
- ***d$_{xy}$*** transverse impact parameter resolution already good (σ ≃ 30 μm)

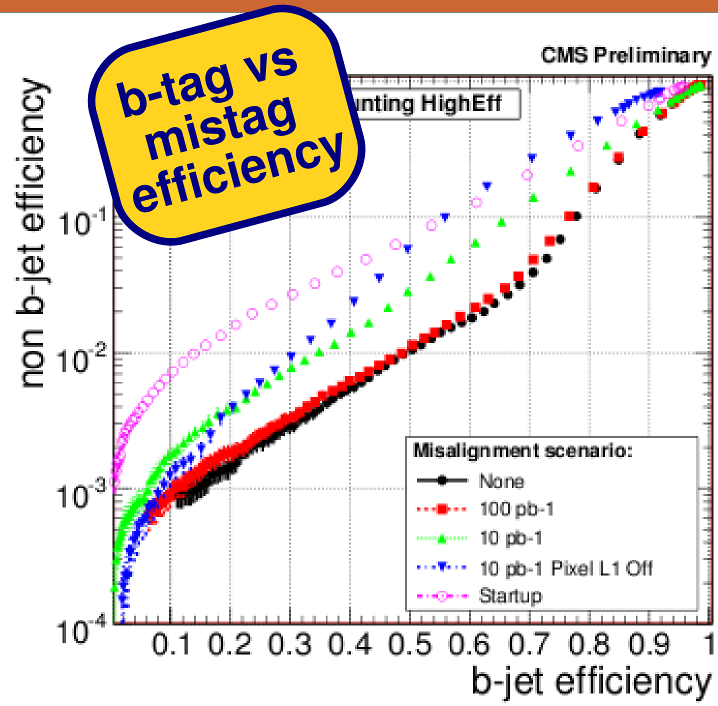
Implications for early physics

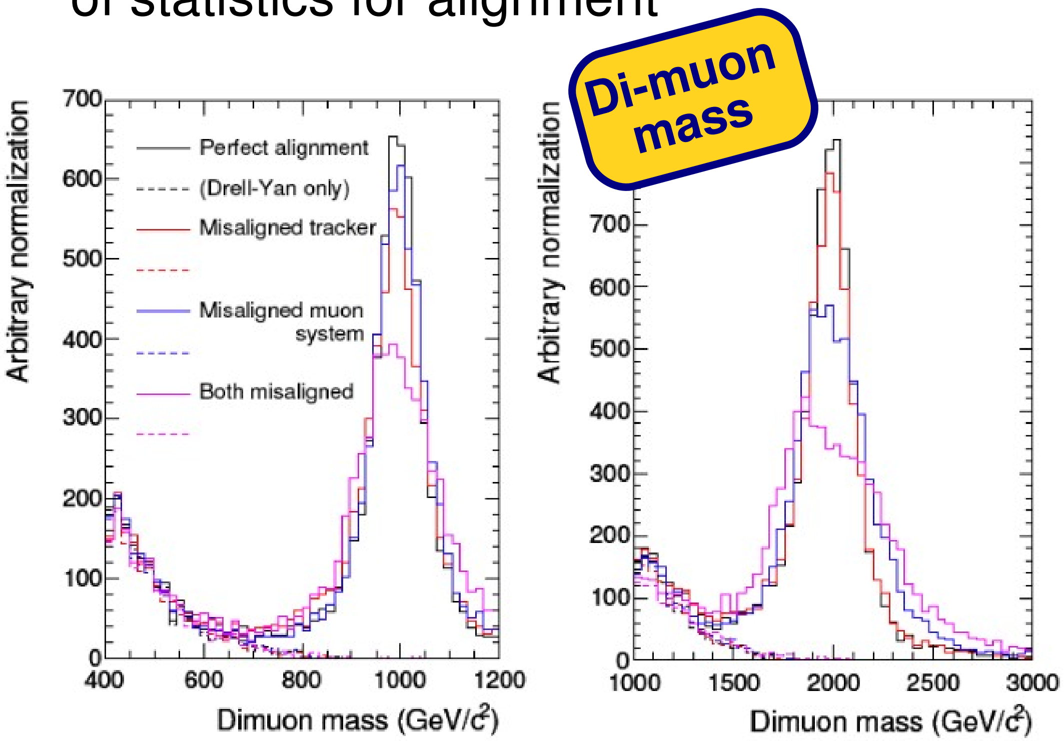
- B-tagging relies completely on tracking performance:



Needs clear separation between *primary* and *secondary vertices*

- all b-tag algorithm are sensitive to alignment
- Several misalignment scenarios considered
- b-tag efficiency improves with accumulation of statistics for alignment

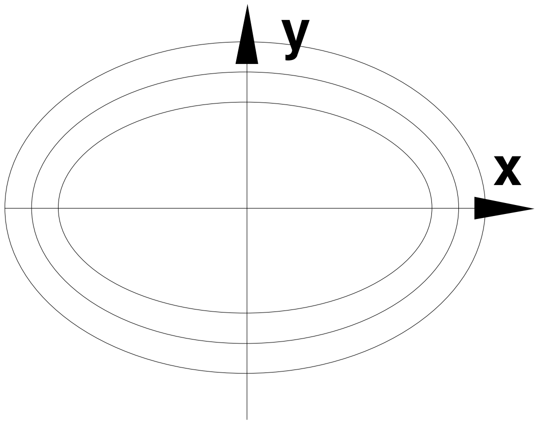




- Further MC studies check prospects of finding “new” physics, e. g. in dimuon resonances.
- Detectability and resonance width depend on both tracking systems.
- Alignment affects heavily high p_T muon resolution

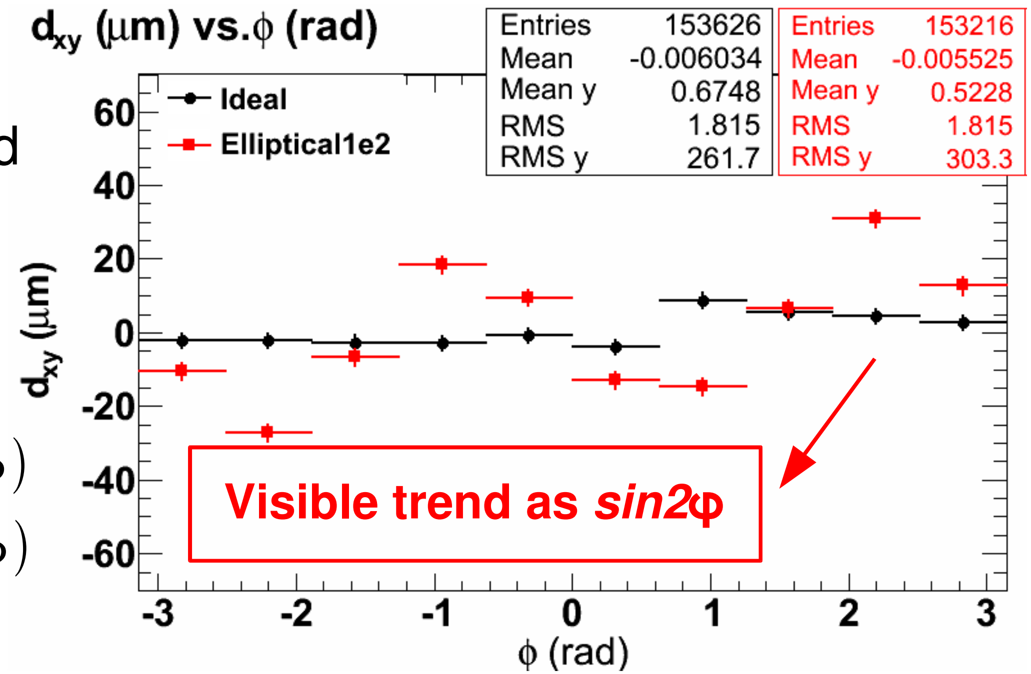
Results on misaligned MC

- **Apply a sistematic misalignment in pixels:** an elliptical deformation and look to residuals obtained running on simulated collision tracks

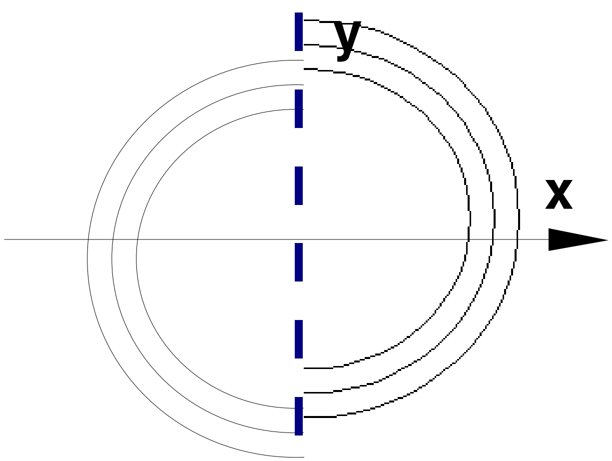


Elliptical ε=0.01

$$\begin{cases} x' = x(1+\epsilon\cos 2\phi) \\ y' = y(1+\epsilon\cos 2\phi) \end{cases}$$



- **Apply a sistematic misalignment in pixels:** an offset in y direction and look to residuals



Y Offset ε= 50 μm

$$x > 0$$

$$\begin{cases} x' = x \\ y' = y + \epsilon \end{cases}$$