Alignment of the CMS Silicon Tracker using Millepede II

DPG, Wuppertal

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Outline:

- Alignment procedure at the CMS experiment
- The problem of weak modes
- Solutions

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CMS tracker

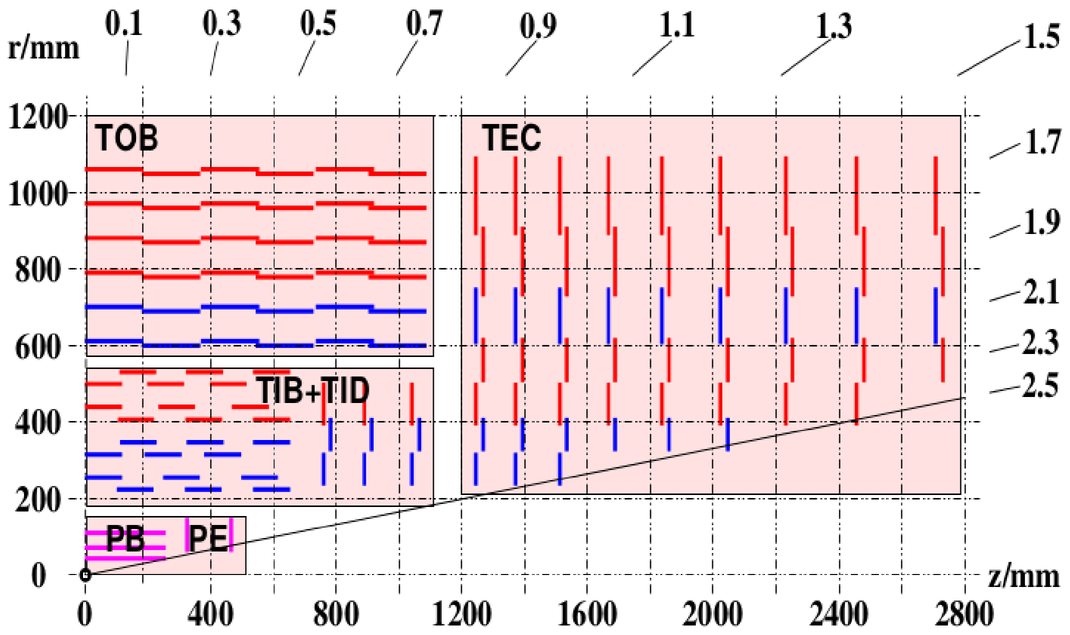
Silicon tracker :

1440 pixel:

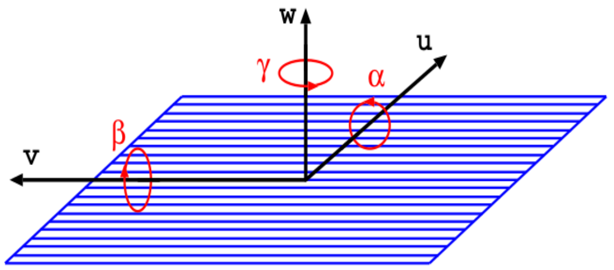
FPIX BPIX

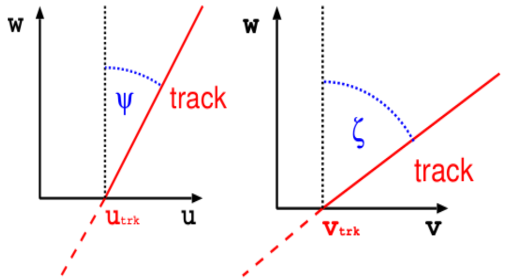
~15118 strip modules (24244 sensors)

TEC TIB TOB TID



Displacement of the modules :

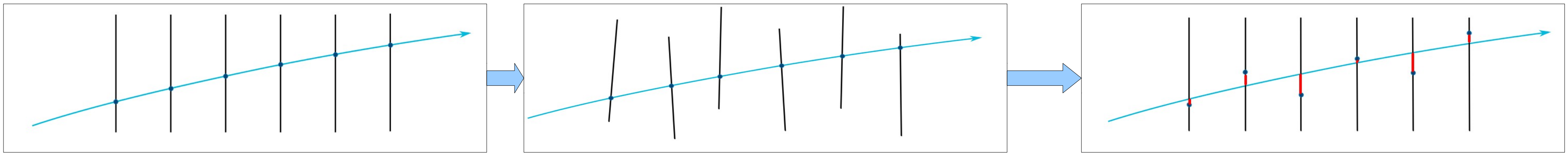




We have set of parameters for each module :

up to 3 *parameters* of position
3 *parameters* of orientation
3 *parameters* of deformation

Global fit approach



Doing the alignment :

- Calculate normalized residuals, z_{ij} :
$$z_{ij} = \frac{u_{ij;m} - u_{ij;p}(\boldsymbol{\tau}_j, \boldsymbol{p})}{\sigma_{ij}},$$

j – track numbers , i – track's hits numbers , $u_{ij;m}$ – measured value of the hit position, $u_{ij;p}$ – predicted value, depend on the vector of track parameters $\boldsymbol{\tau}_j$ and the alignment parameters $\boldsymbol{p}$ that describe the position, orientation and deformation

- Alignment algorithm minimizes the χ^2 function: $\chi^2(\boldsymbol{\tau}, \boldsymbol{p}) = \sum_j \left(\sum_i z_{ij}^2(\boldsymbol{\tau}_j, \boldsymbol{p}) \right),$
  - Linearize the minimization problem
  - Minimization of the function $\chi^2(\boldsymbol{\tau}, \boldsymbol{p})$, leads to a system of linear equations
  - Solution of the linear equations is a complex mathematical problem
    - 200000 equations
    - Number of $\boldsymbol{\tau}$ parameters – in the order of millions!

MillePede II introduction

Organization of MillePede II program which is using for alignment :

- Considers all correlations between track and alignment parameters
- The minimization of the function χ^2 leads to a system of linear equations
- In the global case we have (from normal equations of least squares) :

$$\boldsymbol{Ca} = \boldsymbol{b},$$

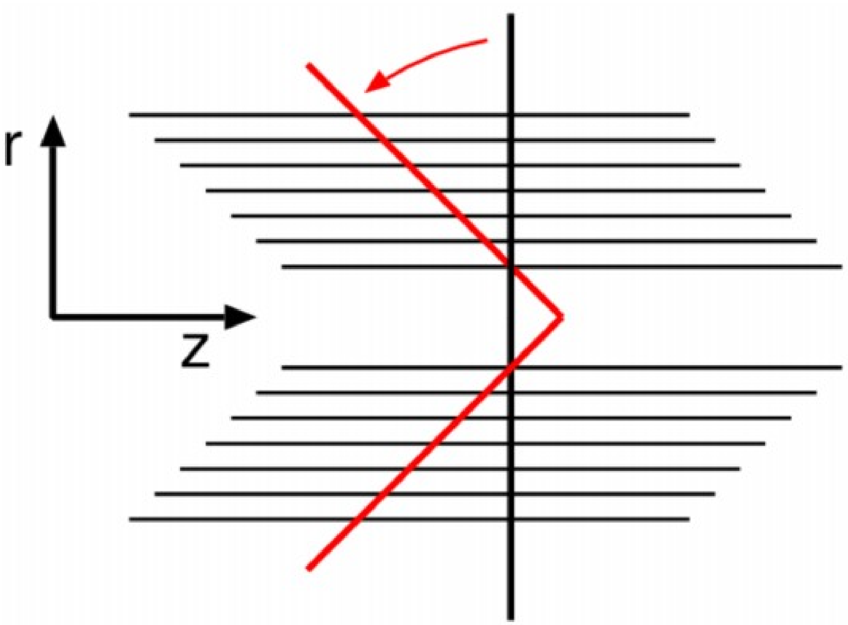
where **C** - symmetric n-by-n matrix (measured),
a - vector of alignment alignment (global) and track (local) parameters
b - products of residuals and global derivatives (measured)

- Individual tracks are independent of each other → block structure of the equation matrix
- Structure can be exploited to reduce the matrix size
- Will get $\boldsymbol{C'a' = b'} \rightarrow \boldsymbol{a' = C'^{-1}b'}$
- Have smaller equation system, where a' contains only the alignment parameters
- The achieved statistical accuracy on the module alignment is found to be significantly better than 10 μm

Program also include constraints between module parameters

Weak modes introduction

- Procedure is doing the fit with all tracks parameters and with all modules parameters simultaneously
- There are situations when coherent changes of alignment parameters can be compensated by changes of the track parameters → WEAK MODES
- Weak modes bias the track measurements:
  - curvature → p_t bias
- In this analysis we studied the so-called SAGITTA ans TWIST weak modes

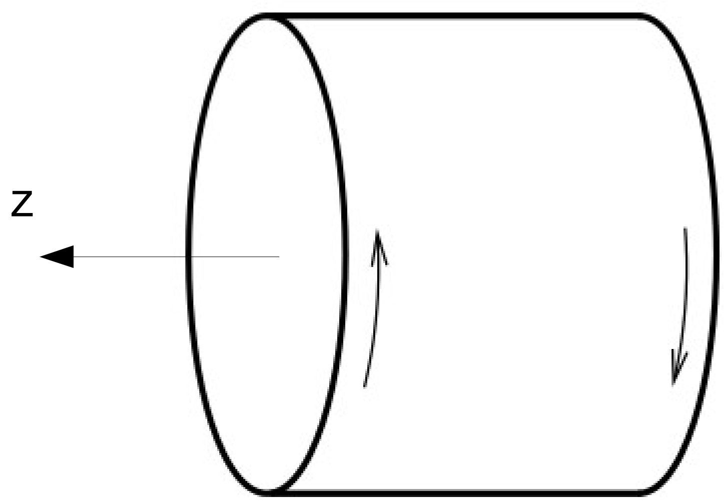


Examples of χ^2-invariant deformation

Twist weak mode

TWIST is a deformation of the tracker, in which the modules are moved coherently in φ by an amount directly proportional to their longitudinal position :

$$\Delta\varphi = const \cdot z$$



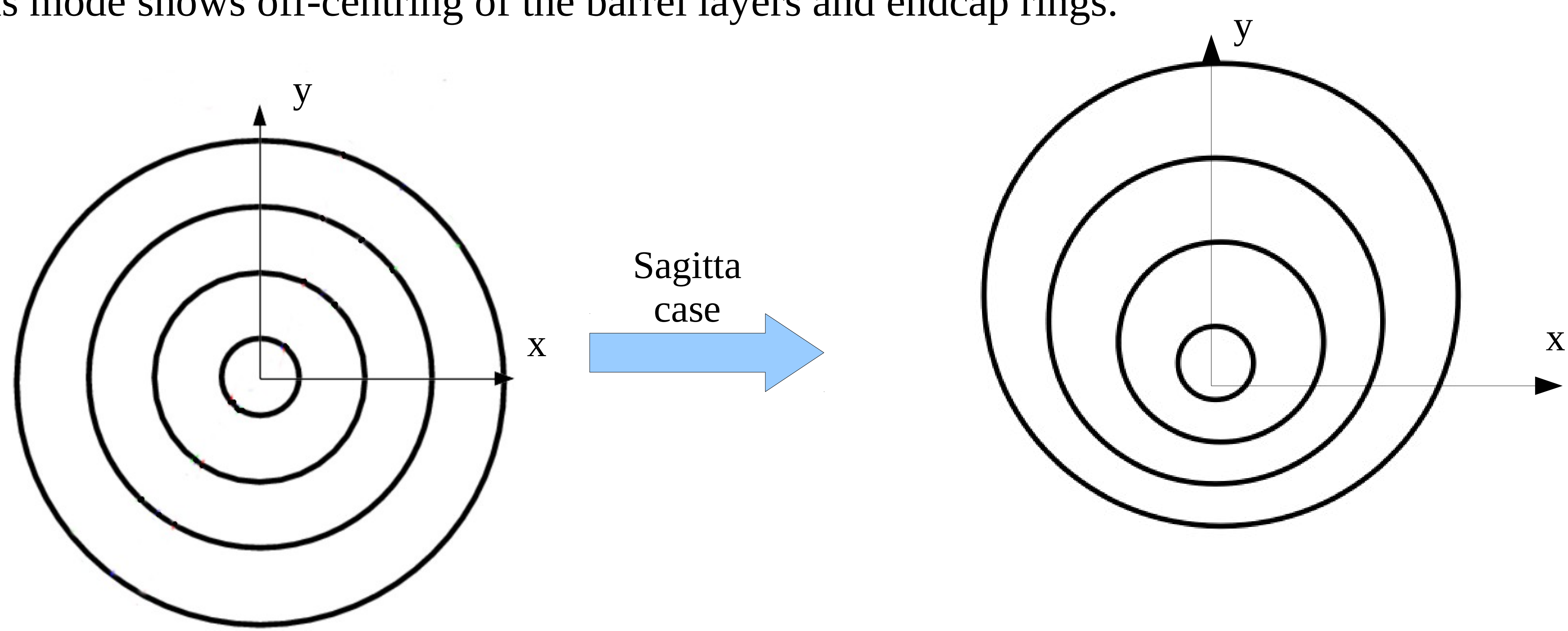
- Modules are moved in φ by an amount proportional to z position
- Further from the center – large displacements
- Compensated by changes of the track parameters

Sagitta weak mode

SAGITTA is a deformation of the tracker, in which the modules are moved coherently in Y by an amount directly proportional to their radius r (in a cylindrical coordinate system) :

$$\Delta y = const \cdot r$$

This mode shows off-centring of the barrel layers and endcap rings.



In this case, again deformation of the detector could leave χ^2 without significant changes

Weak modes control

To control weak modes it is crucial to include additional data samples:

- Cosmic ray tracks that break the cylindrical symmetry (help in Twist & Sagitta cases)
- Straight tracks without curvature, recorded when the magnetic field is off (help in Twist & Sagitta cases)
- Knowledge about the production vertex of tracks
- Knowledge about the invariant mass of a resonance (Z boson) (help in Sagitta & Twist cases)

Procedure to controle weak modes:

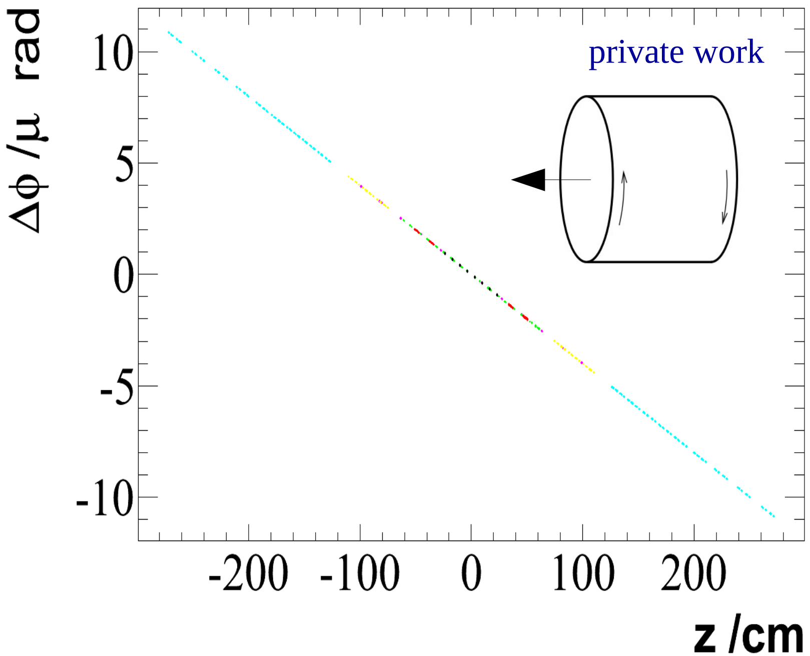
- Took recent well converged alignment with 2012 data and use misalignment scenario (Sagitta/Twist)
- Using all data samples (cosmic, collision data , 0T, 4T)
- Apply alignment procedure
- Compare obtained geometry with legacy alignment object

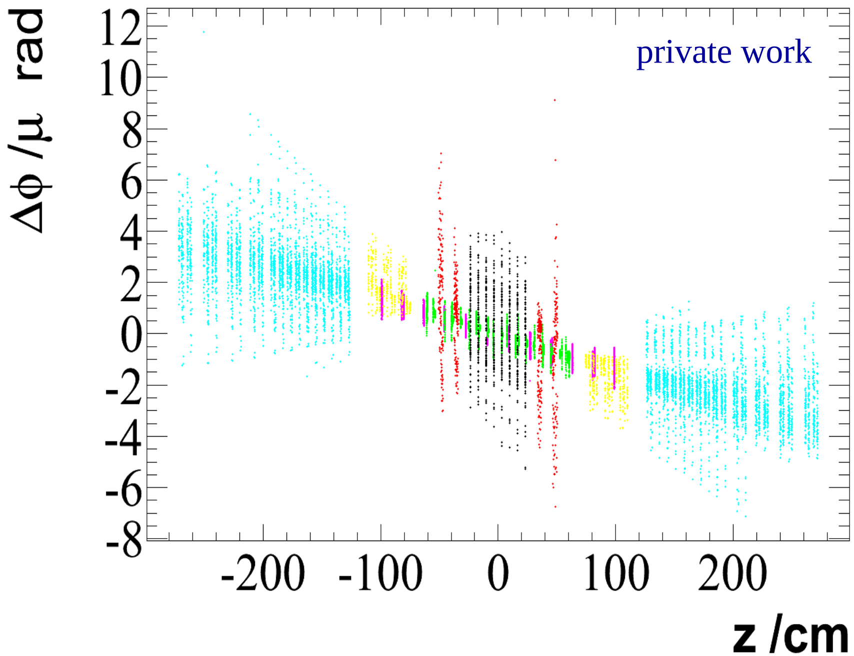
Misalignment recovery with twist mode

Twist ($\Delta\varphi = c \cdot z$)

Twist misalignment → **Re-alignment**
- no 0T cosmic data
- no $Z_{\mu\mu}$

PXB PXF TIB TID TOB TEC





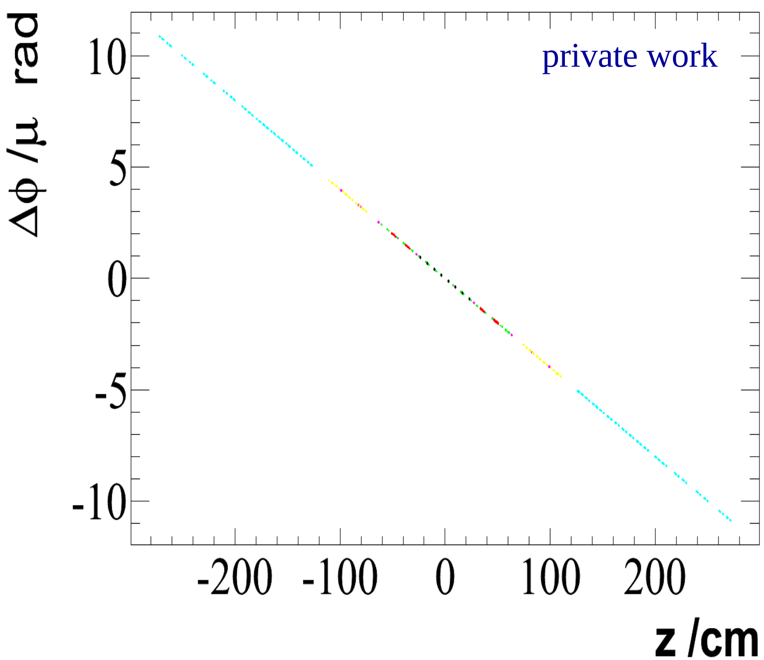
- Alignment procedure makes some improvements
- Need to use different data types

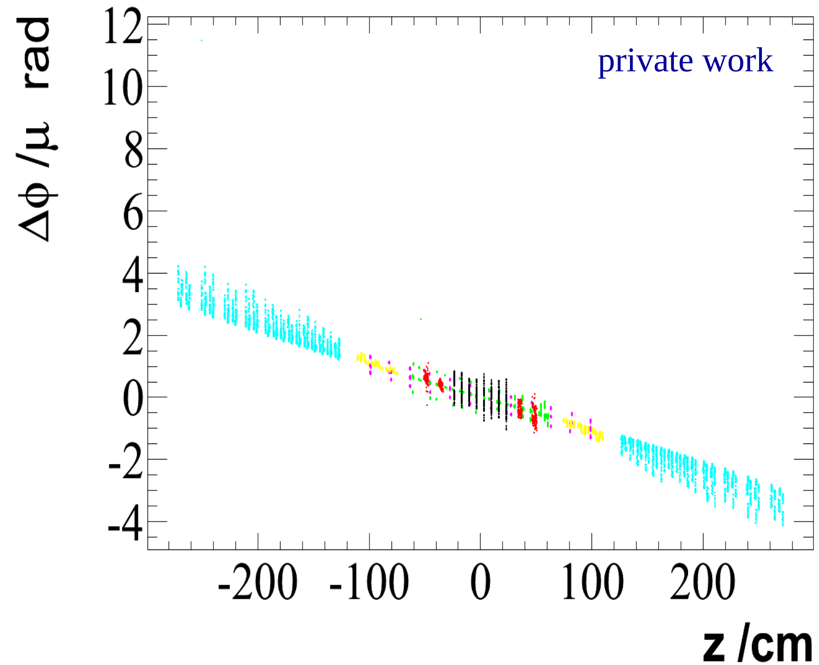
Misalignment recovery with twist mode

Twist ($\Delta\varphi = c \cdot z$)

Twist misalignment → Re-alignment full data

PXB PXF TIB TID TOB TEC



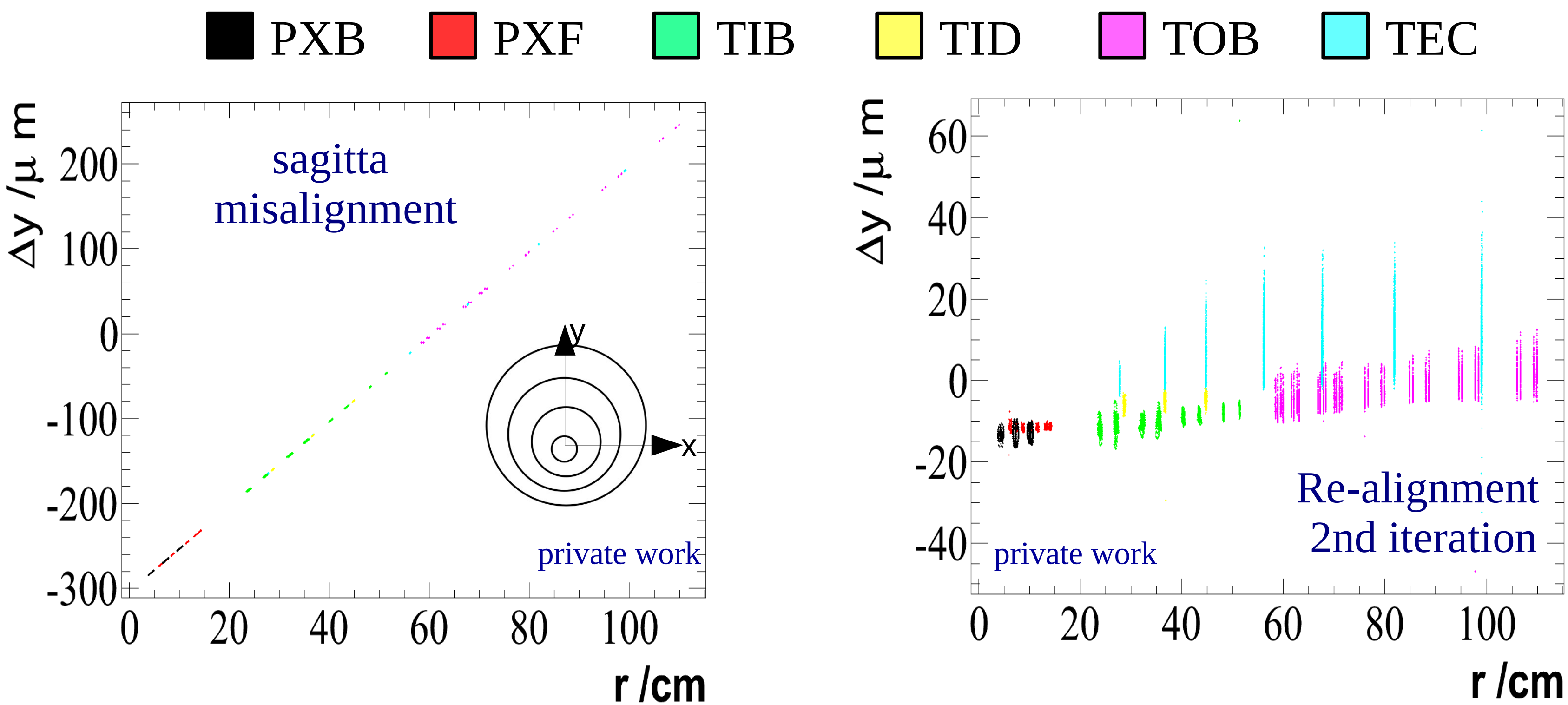


- Alignment procedure is sensitive to the twist weak mode with different data types
- Good recovery of twist mis-alignment with $Z_{\mu\mu}$, 0T cosmic data

Misalignment recovery with sagitta mode

Use all data, include 0T cosmic & $Z_{\mu\mu}$!

sagitta ($\Delta y = c \cdot r$)

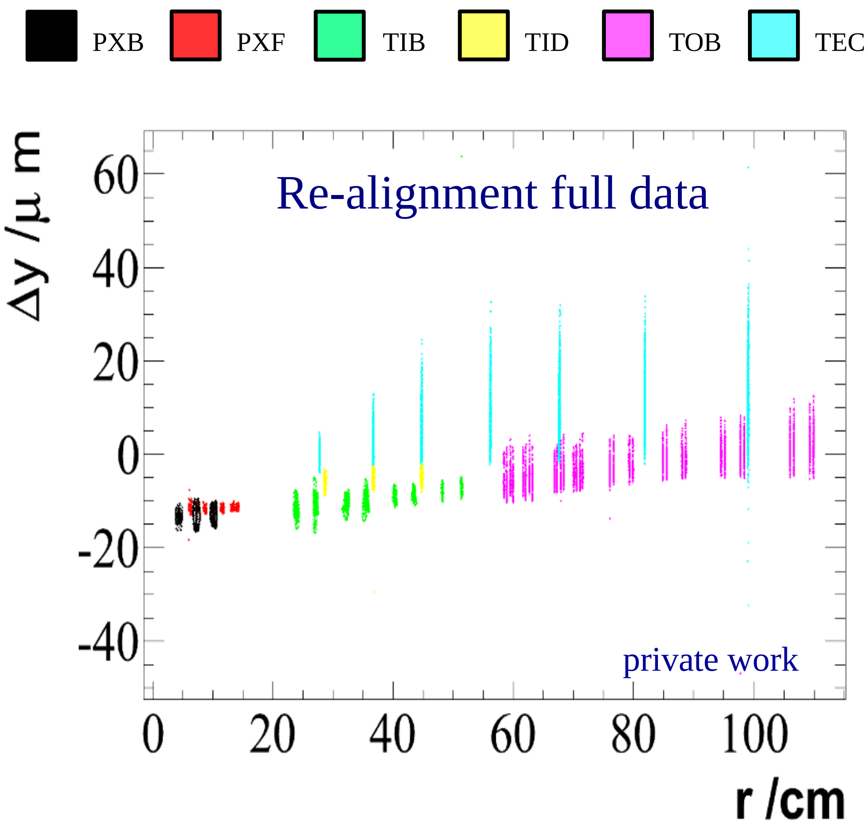


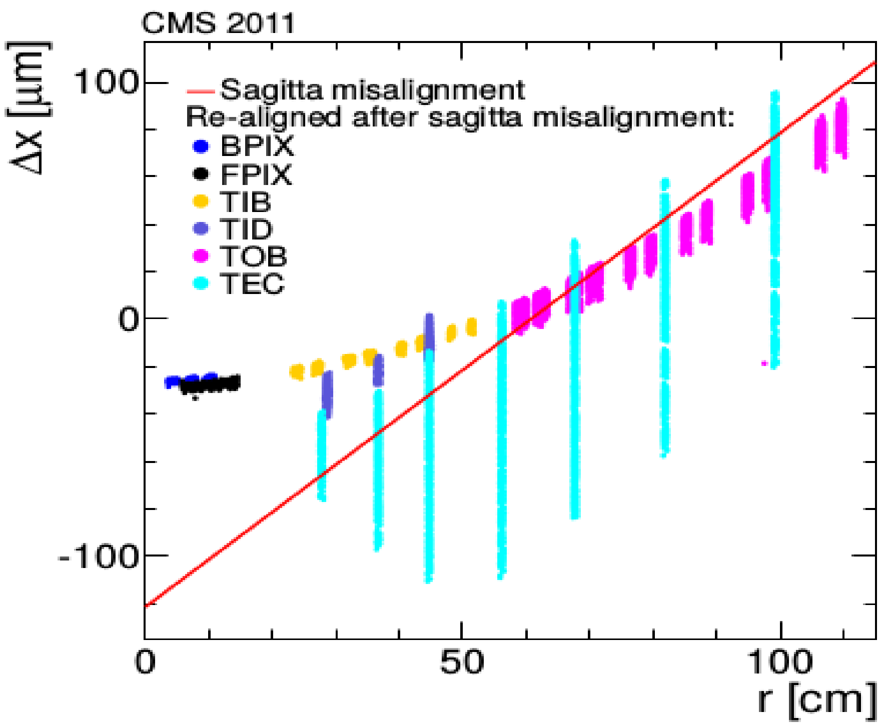
- In the case when mis-alignment is not linear – have to use few iterations
- Alignment procedure is sensitive to the sagitta weak mode
- Good recovery of sagitta mis-alignment

Comparison with previous alignment studies

sagitta (Δy = c ⋅ r)

Based on 2012 Alignment | **Based on 2011 Alignment**





Significant improvements with respect to the realignment of 2011 Alignment

Summary & Plans

Summary

- Track-based alignment procedure of the CMS tracking detector has been explained
- Certain systematic distortions of the tracker geometry are very challenging for track-based alignment ("weak modes")

- Weak modes can be controlled by combining different data types in the alignment fit
  - good recovery has been demonstrated for the twist and sagitta weak-modes
  - further weak modes will be studied

- Significant improvements with respect to similar study with 2011 alignment

Plans

- Study additional weak modes
- Apply legacy alignment methodology to Run II data

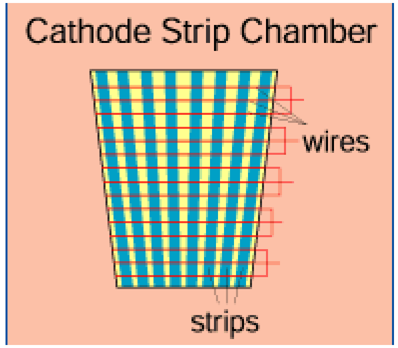
Back Up

Data type N(events)

0 T collisions :	320000
0 T cosmics :	857970
CRAFT cosmics:	1 073 931
interfill cosmics:	1 946 573
interfill cosmics (peak mode) :	1 770 243
isolated μ :	14 788 959
minimum bias:	1 952 099
$Z \rightarrow \mu\mu$:	2 419 834

Back Up

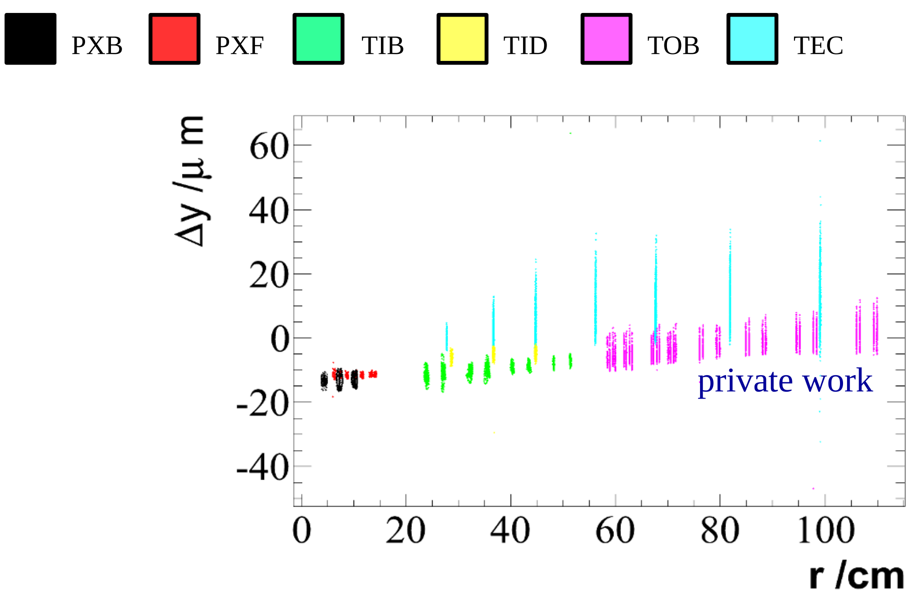
sagitta ($\Delta y = c \cdot r$)

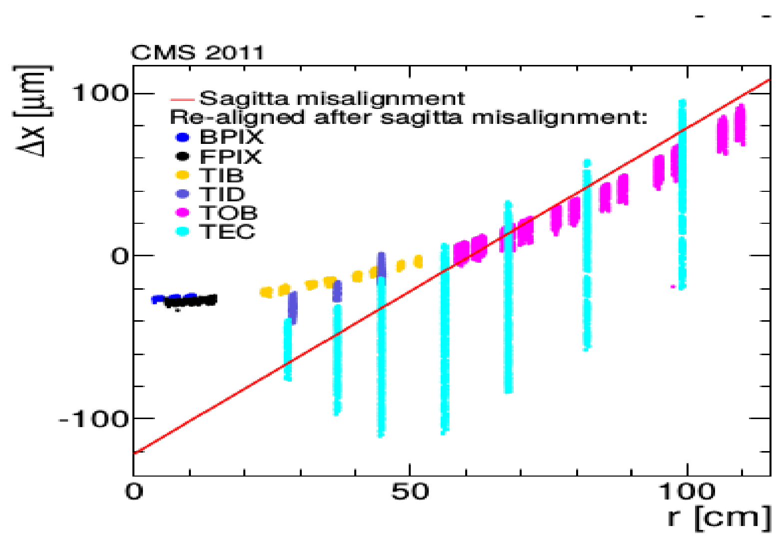


TEC consist of overlapping strip modules. Hence it has low sensitivity in Y directions.

Based on 2012 Alignment

Based on 2011 Alignment



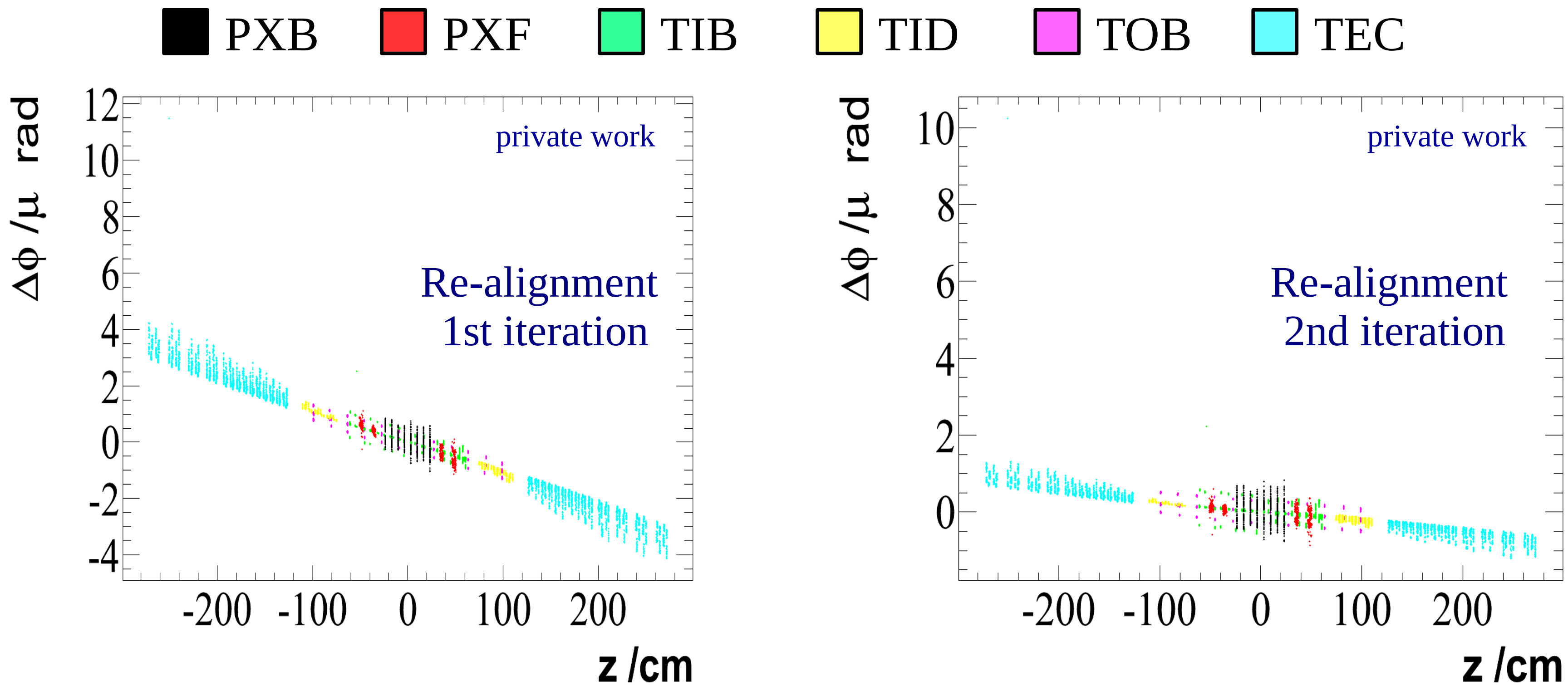


Significant improvements with respect to the realignment of 2011 Alignment

Back Up. Misalignment recovery with twist mode

Twist ($\Delta\varphi = c \cdot z$)

Re-alignment full data → Re-alignment full data



- Alignment procedure is sensitive to the twist weak mode with different data types
- Good recovery of twist mis-alignment with $Z_{\mu\mu}$, 0T cosmic data