# Track-Based Muon Alignment: 2016 Alignment and Future Plans

TEXAS A&M UNIVERSITY


Luca Perníé

For the Track-Based Muon Alignment group


**CMS Run and DPG Commissioning Workshop**
**24-26 Jan 2016**

25.Jan.2017

# Outline

- Short summary of the Track-Based (TB) muon alignment:
  - → Inputs/outputs of the algorithm
  - → The algorithm: muons, tracks and chamber-level residuals
  - → Developing monitoring tools
- The 2016 experience and plans for 2017:
  - → 2016 re-reco
  - → Extending the coordinates aligned (DOF, degrees of freedom)
  - → Alignment Position Error (APE)
  - → Physic validation
- Outlooks

# TB-alignent inputs/outputs

- TB Muon Alignment inputs:
  - → New Tracker alignment, surface deformation, pixel position, tracker APE
  - → New Global Position Record (GPR)
  - → Initial Muon System Geometry (produced using 2016E data)

- TB Muon Alignment conditions:
  - → Release: CMSSW_8_0_24
  - → Global Tag: 80X_dataRun2_2016LegacyRepro_Candidate_v0
  - → JSON file: Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON_MuonPhys.txt

- TB Muon Alignment output:
  - → Muon geometry (DT and CSC):
    - → In DT all coordinates (DOF) are aligned + non-diagonal APE
    - → In CSC 3 coordinates are aligned + diagonal APE

- Time-scale:
  - → 4 days for alignment (DT and CSC) + 4-5 days for physic validation

# Muon selection

- Refit reconstructed global muons using only tracker information

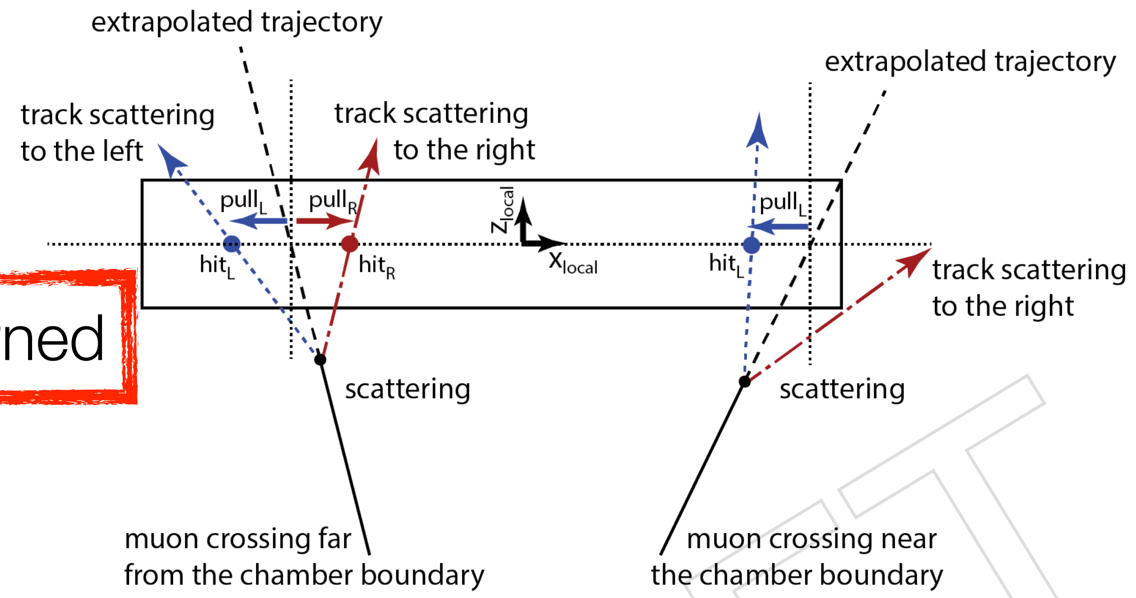
- Selecting only good muons:
  - → 20 GeV < $P_T$ < 200 GeV
  - → Number of hits in Tracker segment: $n_{hit\ in\ TK} > 15$
  - → Impact parameter w.r.t. beam spot position: $D_{xy} < 0.2$
  - → Normalized $\chi^2$ for Tracker segment: $\chi^2/n.d.f. < 10$

- Number of chambers with hits per track: ≥ 2

- Number of hits per aligned chamber:
  - → In DT: SuperLayer 1 and 3: $n_{hits\ SL\ 1} + n_{hits\ SL\ 3} \geq 6$
  - → In DT: SuperLayer 2: $n_{hits\ SL\ 2} \geq 3$

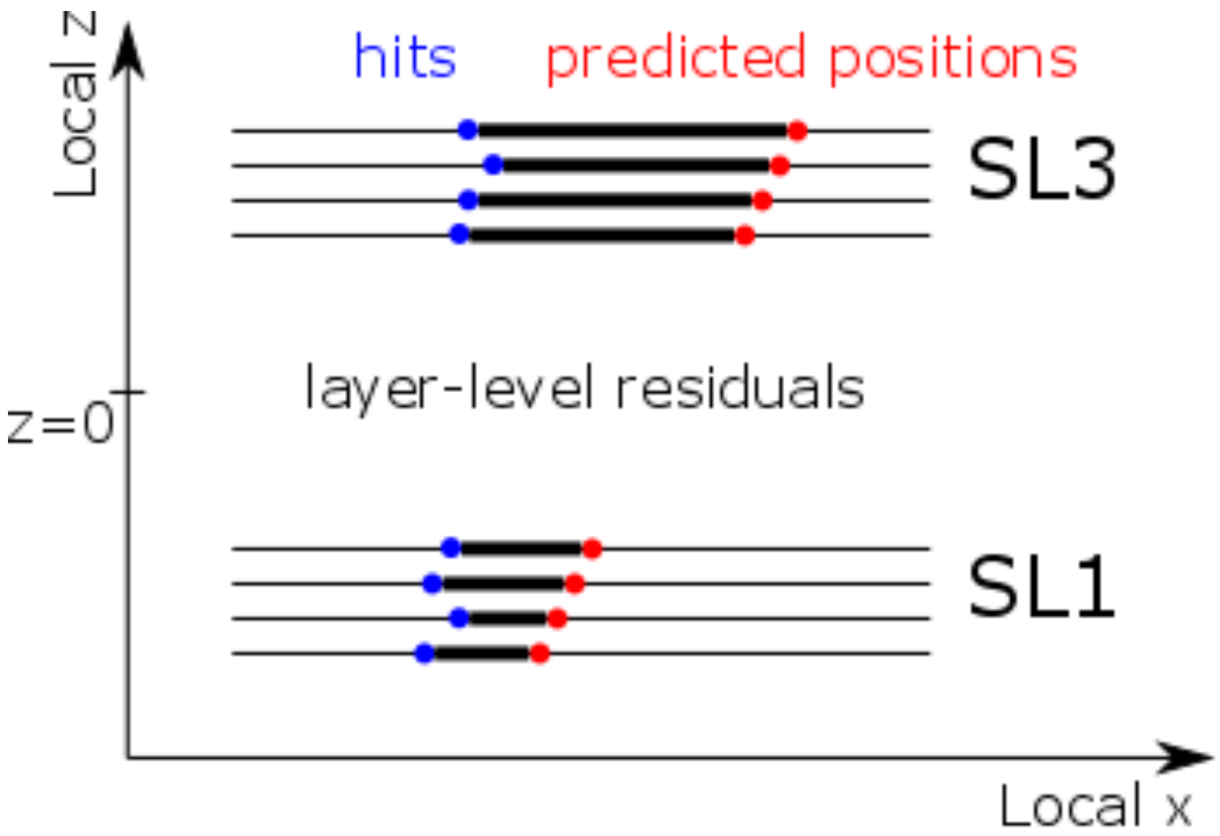
- Fiducial cuts: no muons close to chamber edges

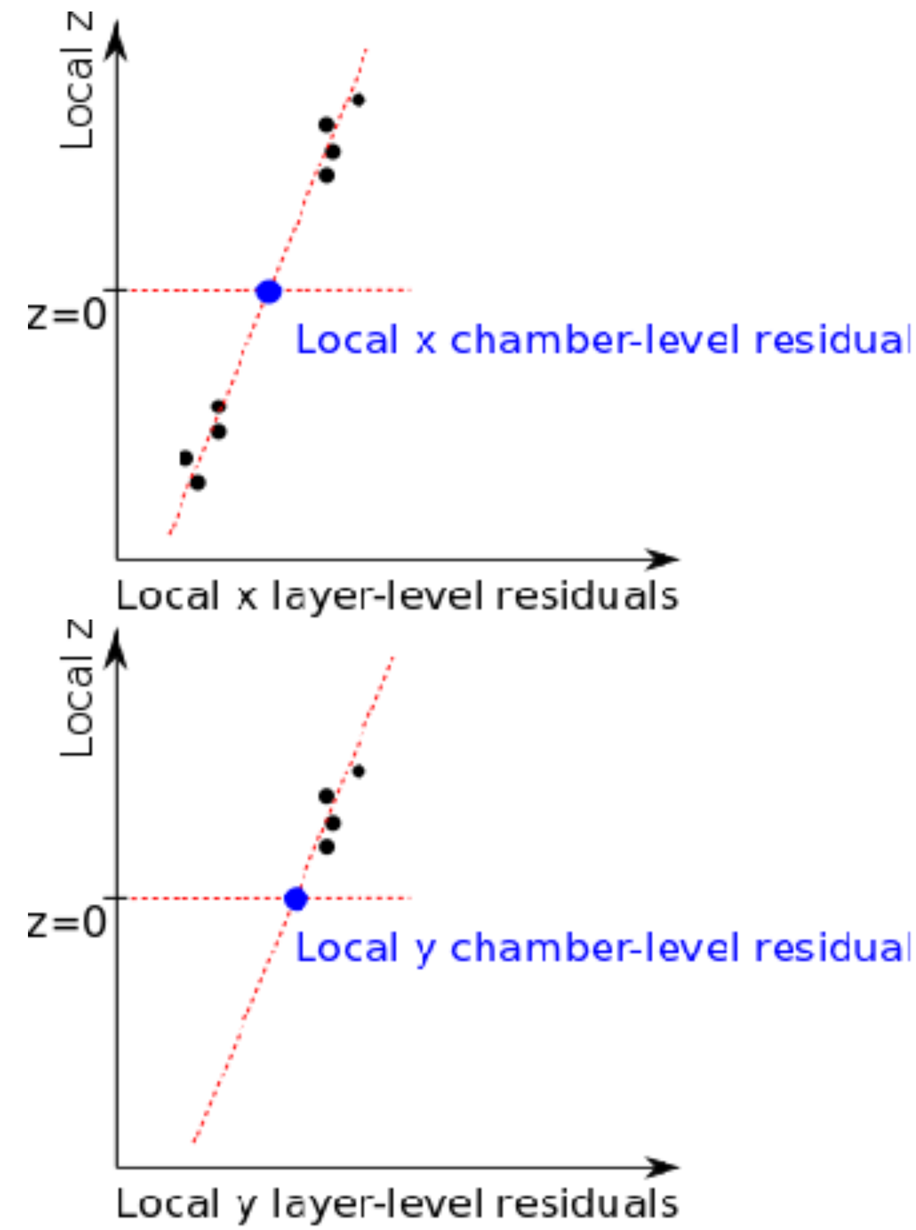
lesson learned



# Chamber level residual

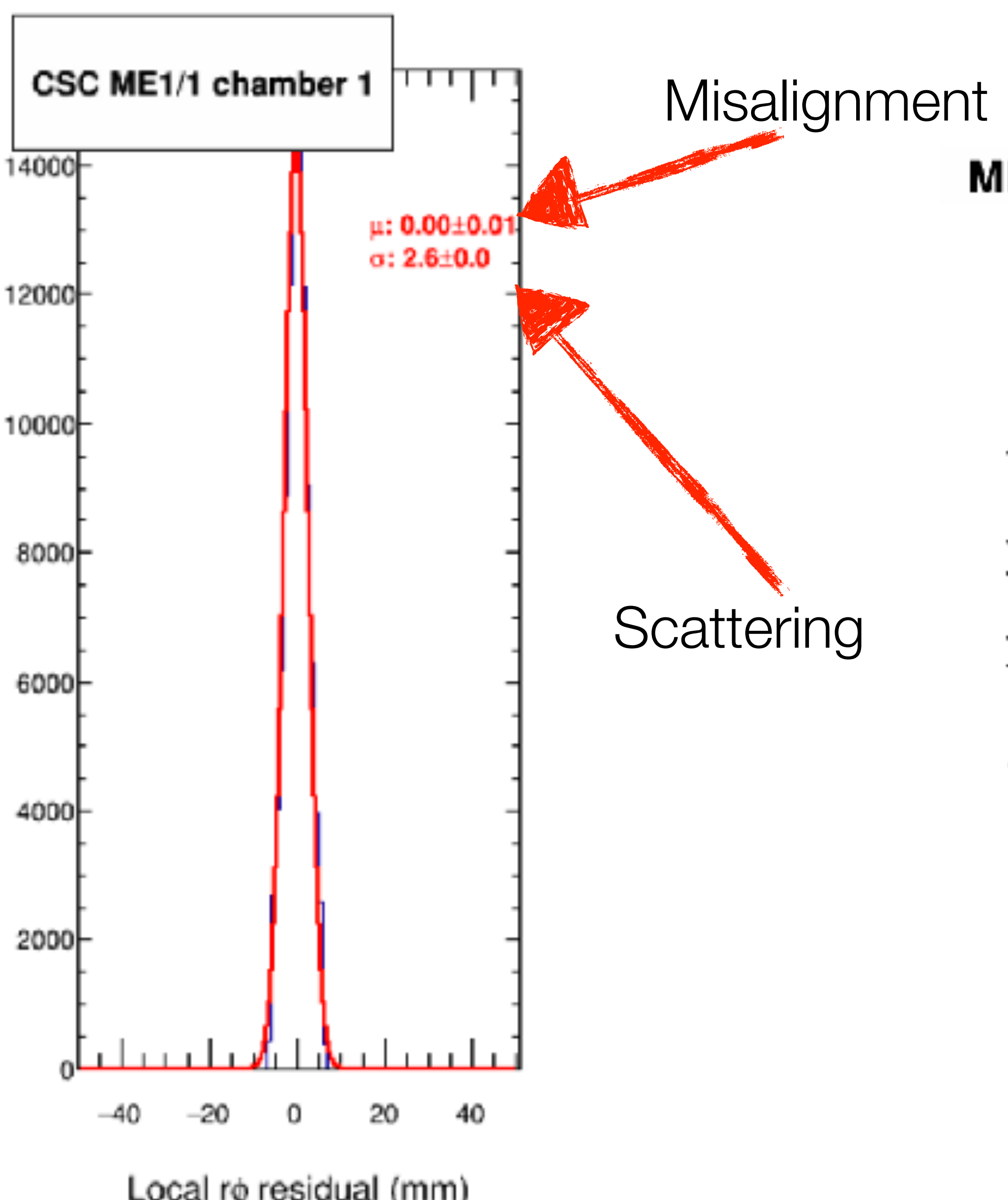
- Track-Based: propagate tracker part of muons into Muon System (below we show DTs)
- Muon residual: difference between measured (with hits) and predicted (i.e. propagated from Tracker) position of the muon in the chamber

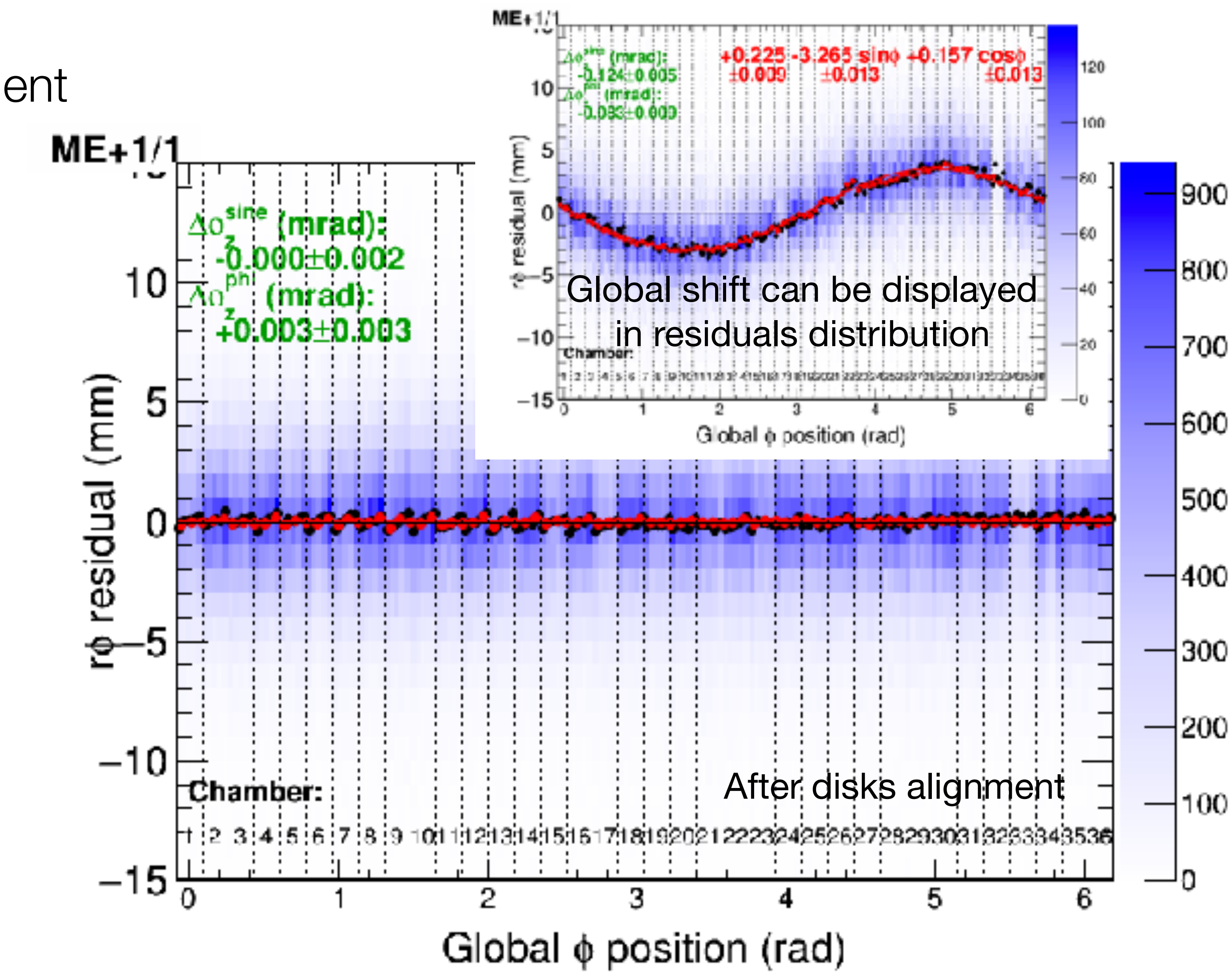


# Residuals as a monitor Tool

- Residual spread is due to scattering. Residual shift is due to misalignment.
- Residuals can be measured as a function of Global coordinates.



# Current alignment procedure

- For DT: use $\Delta x$ and $\Delta y$ residuals, align local x, y, z, $\Phi_X$, $\Phi_Y$ and $\Phi_Z$

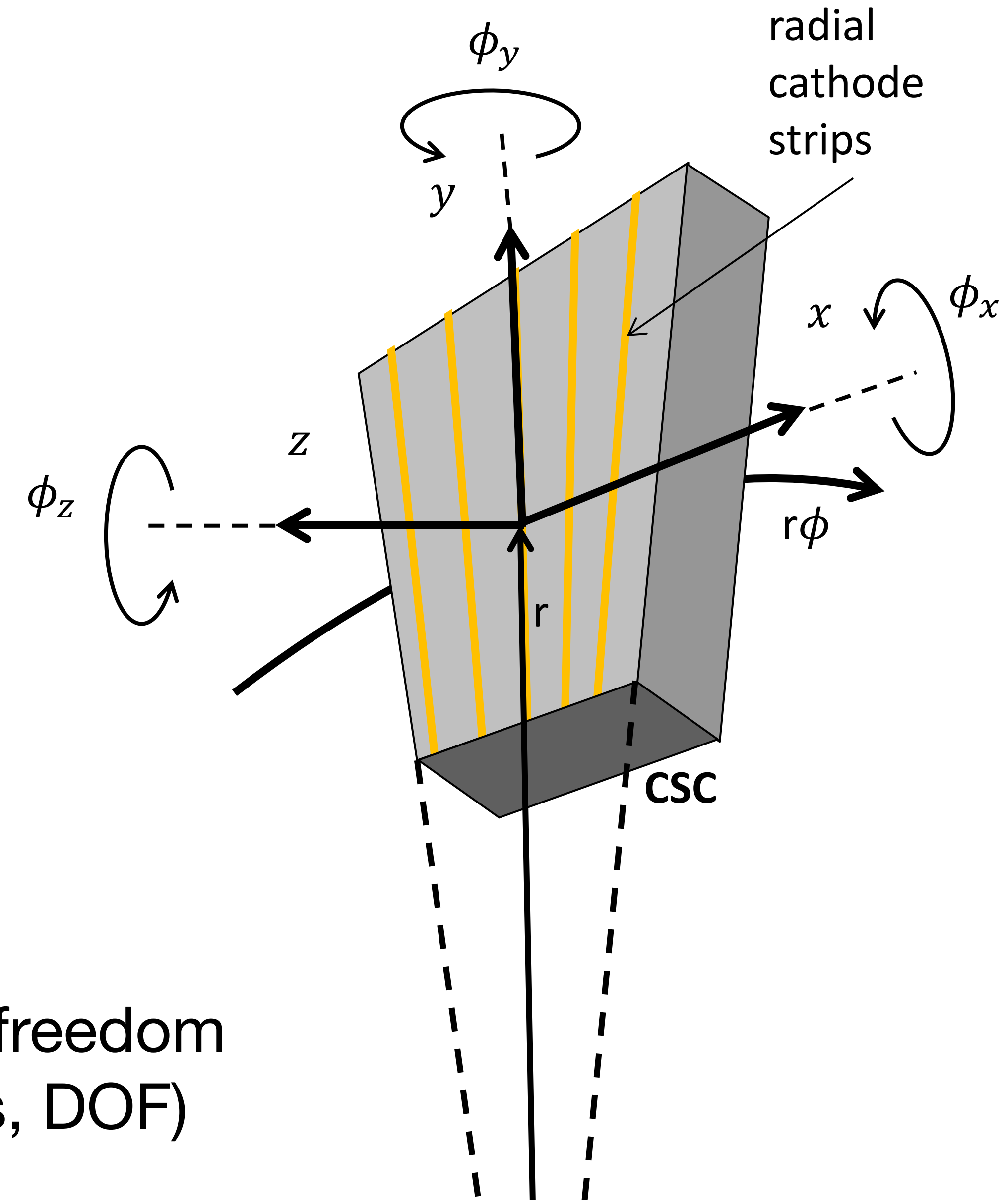
$$\begin{pmatrix} \Delta x \\ \Delta y \\ \Delta \frac{dx}{dz} \\ \Delta \frac{dy}{dz} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & 0 & 0 & -\frac{dx}{dz}\frac{dy}{dz} & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

- For CSC: use $\Delta(r\phi)$ residuals, align local x, y and $\Phi_Z$

$$\begin{pmatrix} \Delta(r\phi) \\ \Delta \frac{d(r\phi)}{dz} \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & -\frac{1}{2R}\frac{dx}{dz} & 0 & \left[\frac{x}{R}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$

Residuals used in the alignment

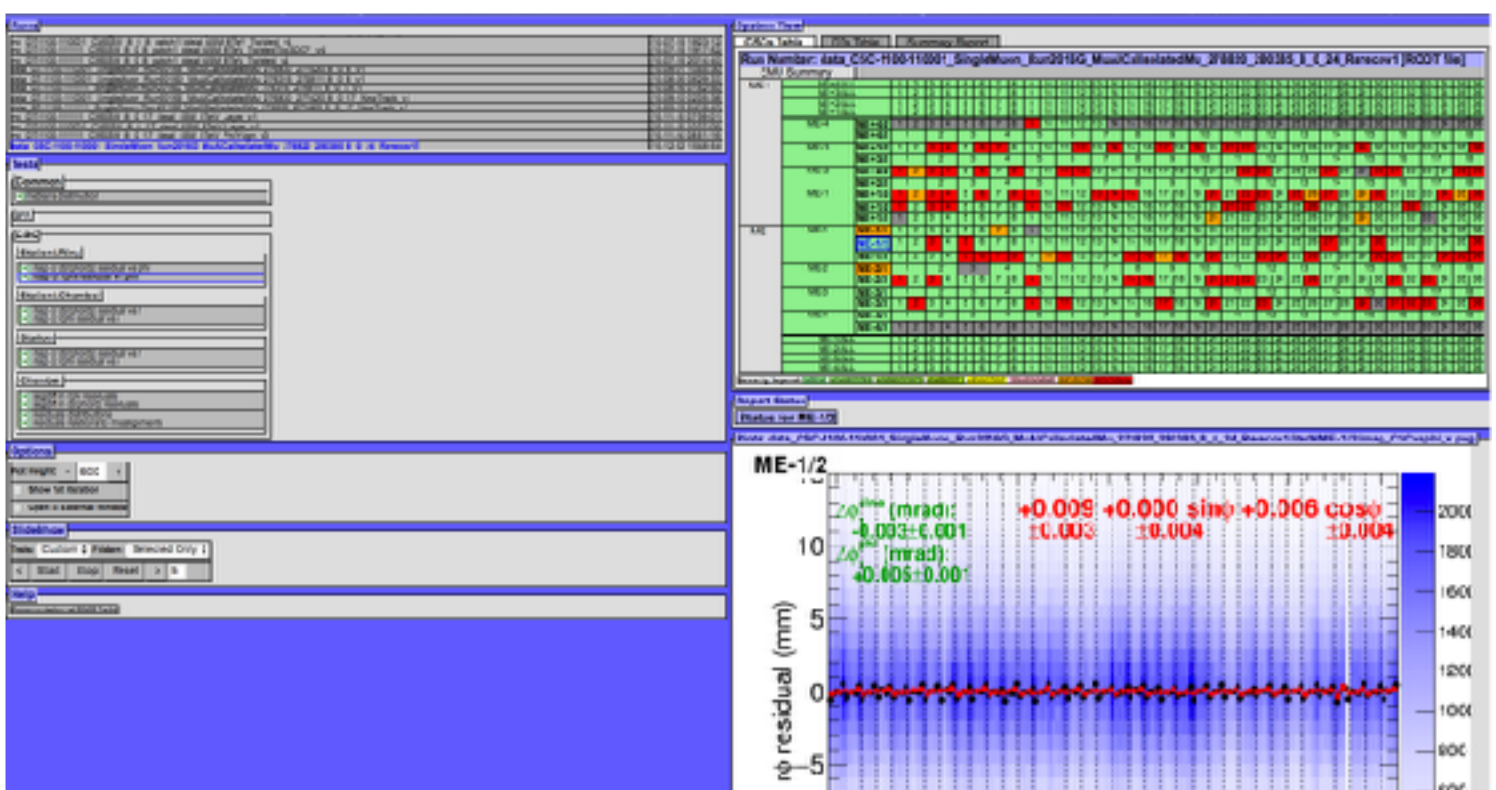
Degrees of freedom (alignables, DOF)



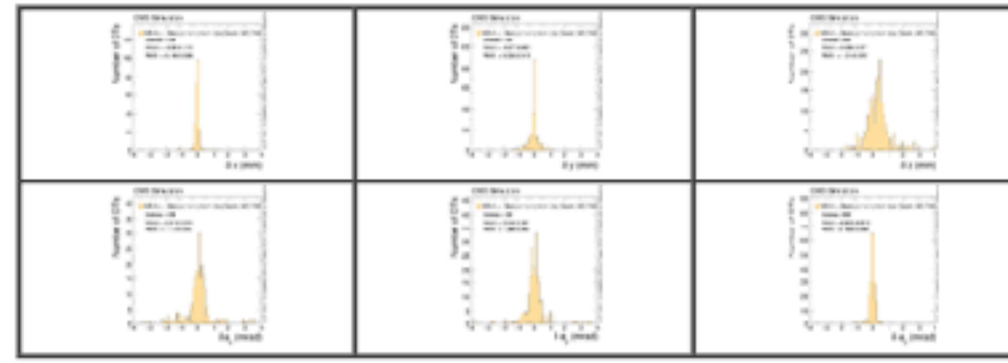

- We can extended the alignment to 6 DOF for DT and 3 DOF for CSC

# Monitoring tools

- We developed special tools for monitoring the alignment quality
- Visualization of the difference between geometries (DT and CSC)
- Residual, occupancy, and correction for each chamber

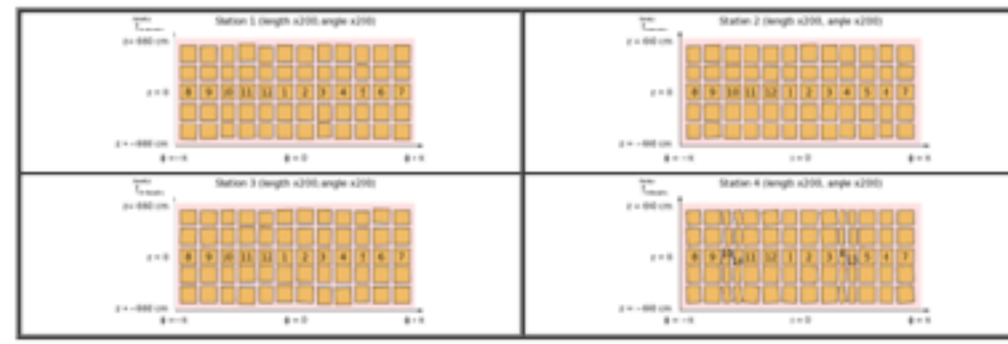



mc_DT-1100-111111_SingleMuon_MCRyan_8TeVspec_RECO_7_4_5_patch3_pt20_v2_FidBSpotFixIdeal_03 - Ideal_DESRUN2_74_V



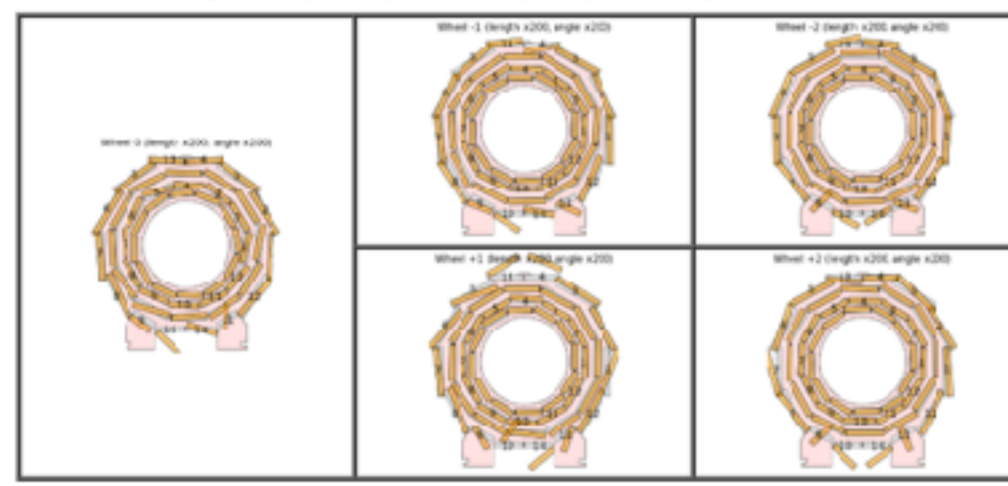
Displacements from Ideal Geom. MC 74X visualization

mc_DT-1100-111111_SingleMuon_MCRyan_8TeVspec_RECO_7_4_5_patch3_pt20_v2_FidBSpotFixIdeal_03 - Ideal_DESRUN2_74_V



Displacements from Ideal Geom. MC 74X visualization

mc_DT-1100-111111_SingleMuon_MCRyan_8TeVspec_RECO_7_4_5_patch3_pt20_v2_FidBSpotFixIdeal_03 - Ideal_DESRUN2_74_V



Displacements from Ideal Geom. MC 74X averaged over homogeneous chambers

mc_DT-1100-111111_SingleMuon_MCRyan_8TeVspec_RECO_7_4_5_patch3_pt20_v2_FidBSpotFixIdeal_03 - Ideal_DESRUN2_74_V

| wheel | stations | $\delta x$ (mm) RMS | $\delta y$ (mm) RMS | $\delta z$ (mm) RMS | $\delta\phi_x$ (mrad) RMS | $\delta\phi_y$ (mrad) RMS | $\delta\phi_z$ (mrad) RMS |
|---|---|---|---|---|---|---|---|
| MB+1 | MB+1/1 | 0.365 | 0.492 | 0.416 | 0.141 | 0.110 | 0.096 |
| | MB+1/2 | 0.348 | 0.374 | 0.385 | 0.157 | 0.114 | 0.103 |
| | MB+1/3 | 0.351 | 0.501 | 0.646 | 0.257 | 0.171 | 0.105 |
| | MB+1/4 | 0.330 | 0.001 | 1.685 | 1.988 | 3.478 | 0.286 |

# DT: 3 vs 6 degrees of freedom

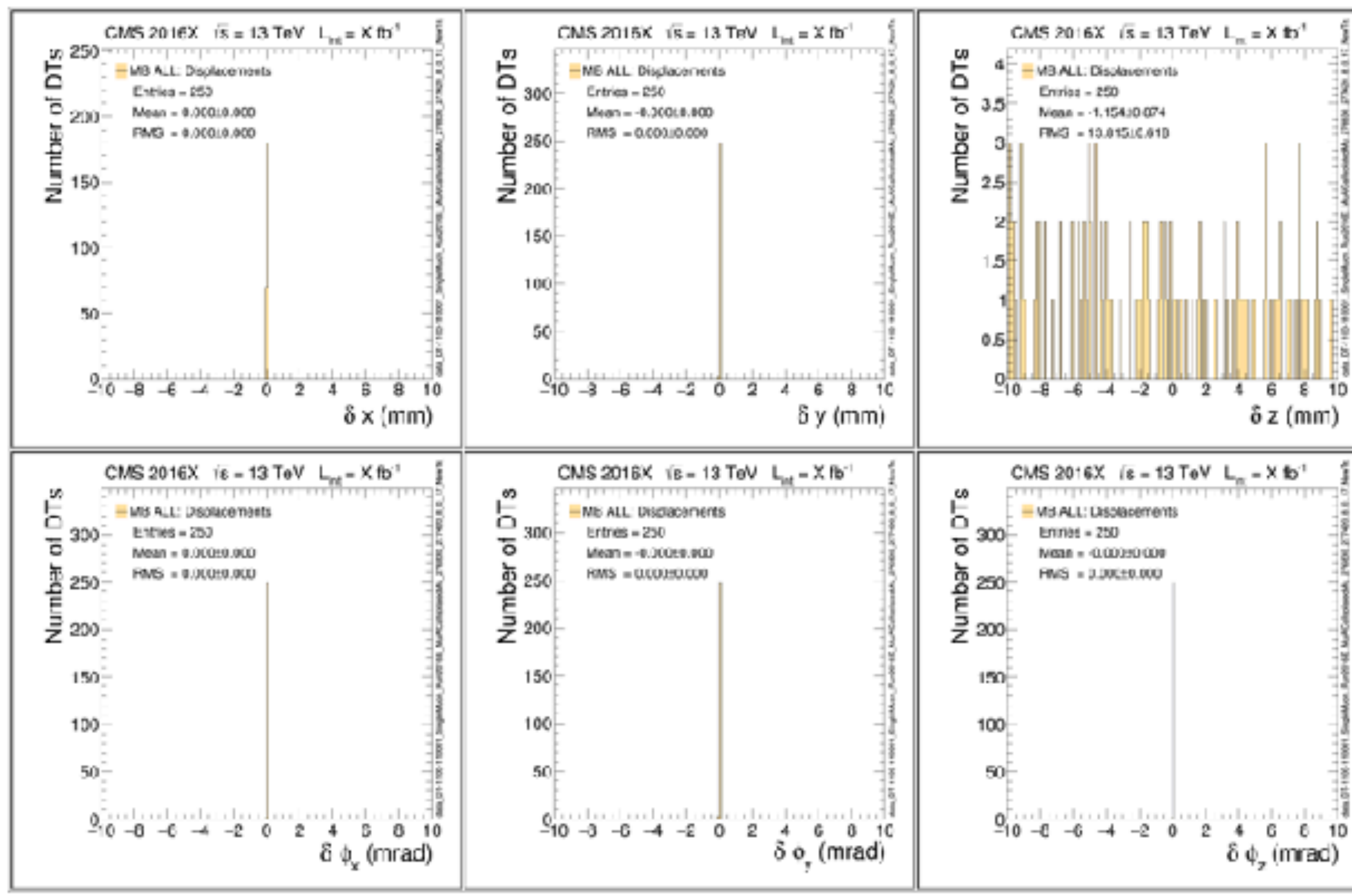
3 DOF: algorithm sensitive to initial misalignment,
not possible to define rigorous APE (Alignment Position Error)

6 DOF: algorithm independent from initial misalignment,
possibility to define correct APE
(including correlation among the coordinates aligned)

- Z coordinate is correlated to X and Y.
  If Z not properly aligned (or biased) → possible effect on X and Y alignment!
- Possibility to define a more rigorous way for evaluating our systematics also thanks to HW alignment:
  → Weak modes and correlations full included in APE

# Example 1:
# Aligning a biased geometry

Input geometry:
2016E geometry, but the z coordinate is smeared of 15 mm



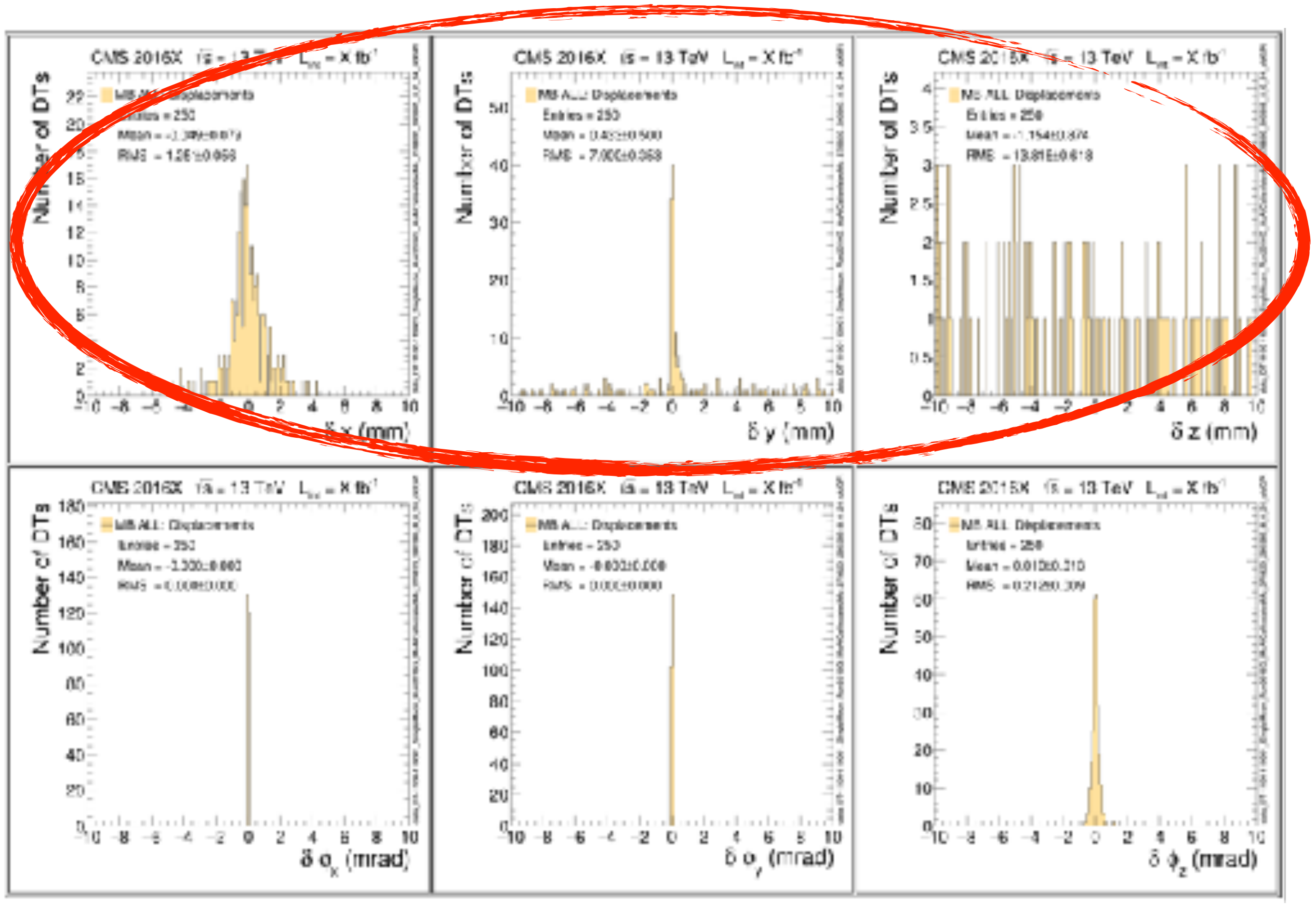

Distributions: difference between the original and the smeared geometry in each coordinate

# Example: initial geometry biased

- Input Geometry: 2016E smeared geometry (15 mm on z coordinate)
- Plots: Difference between final geometry the algorithm produce and the original 2016E geometry
- LEFT: 3 DOF aligned (X, Y and ΦZ)

3 DOF

Starting from 2016E SMEARED geom.



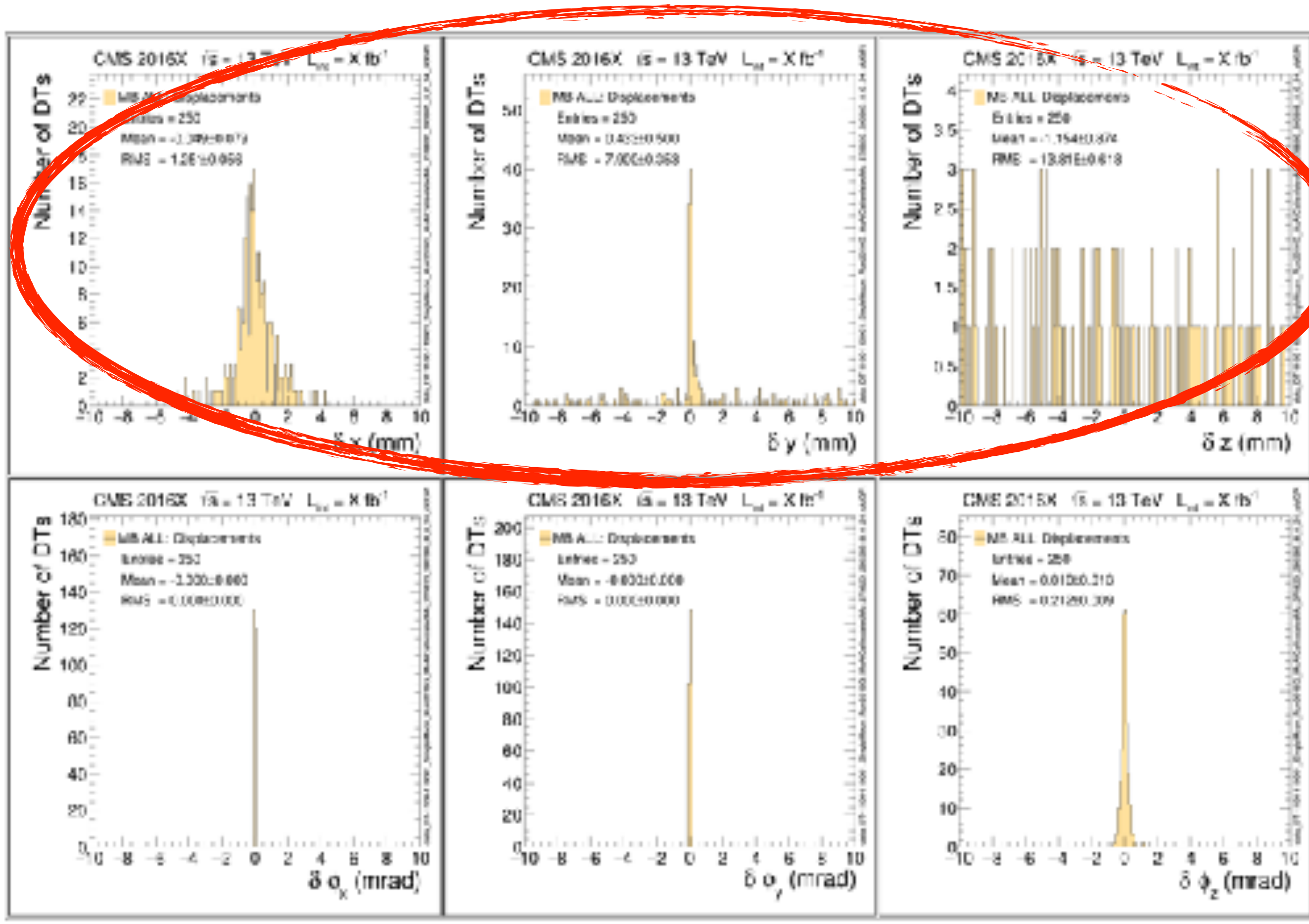

- The Z coordinated is fixed
- The fit cannot converge on Y since it very correlated to Z
- Also X is affected since it is correlated to Y and Z (relevant for $p_T$ measurement)

# Example: initial geometry biased

- Input Geometry: 2016E smeared geometry (15 mm on z coordinate)
- Plots: Difference between final geometry the algorithm produce and the original 2016E geometry
- LEFT: 3 DOF aligned (X, Y and ΦZ) Right: 6 DOF aligned

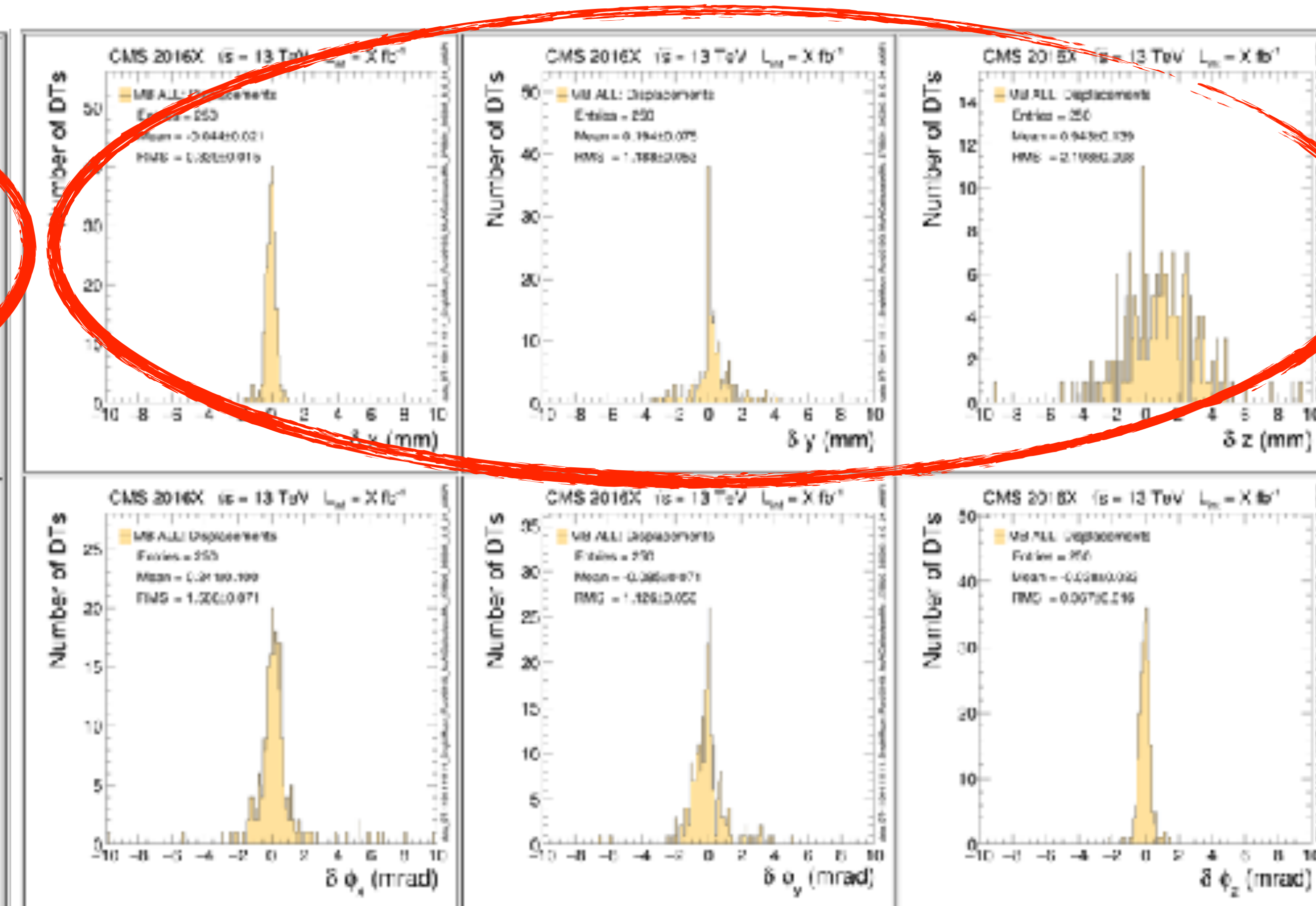
3 DOF

Starting from 2016E SMEARED geom.



6 DOF

Starting from 2016E SMEARED geom.

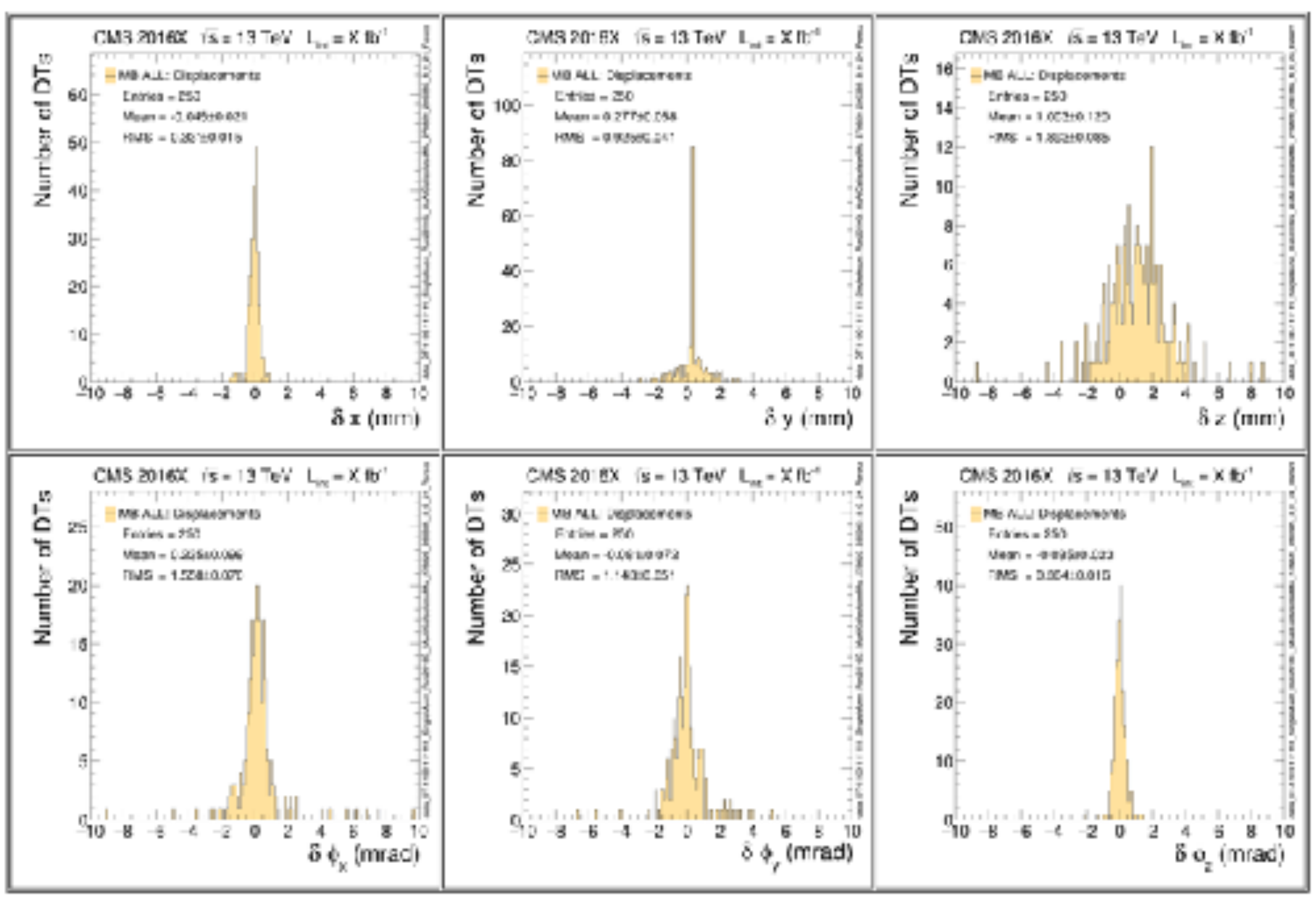


# Example: initial geometry biased

- No matter the initial geometry, you reach the same level of precision
- 6 DOF has a weak mode between the Y and Z position:
  - → Such weak mode can be included in APE (see next slides)
  - → Such weak mode do not affect Physics performance, if treated in APE
- If we start from a perfect geometry 3DOF is better, but if we don't know 6 DOF is safer

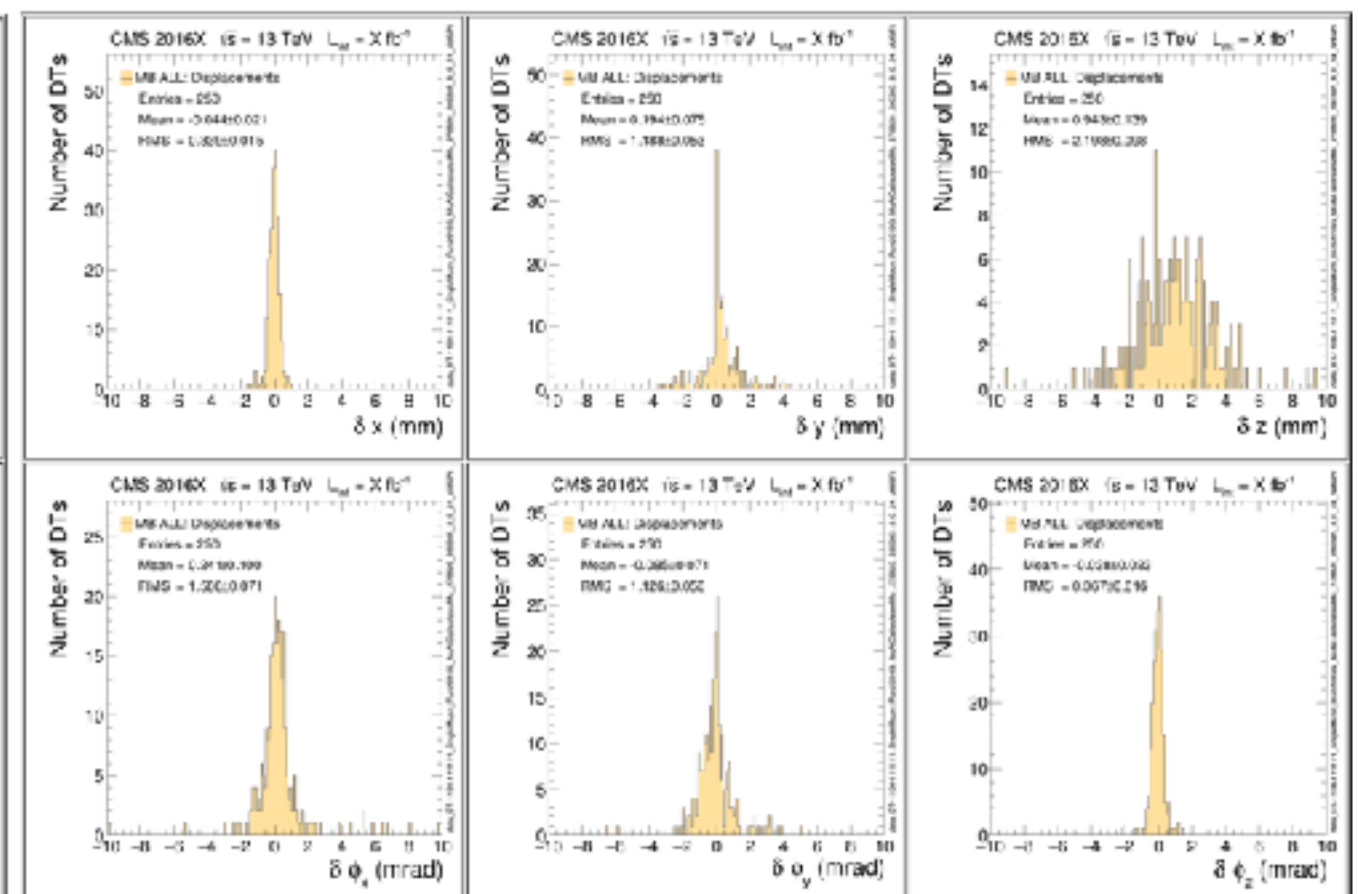
**6 DOF**

Starting from 2016E geom.




**6 DOF**

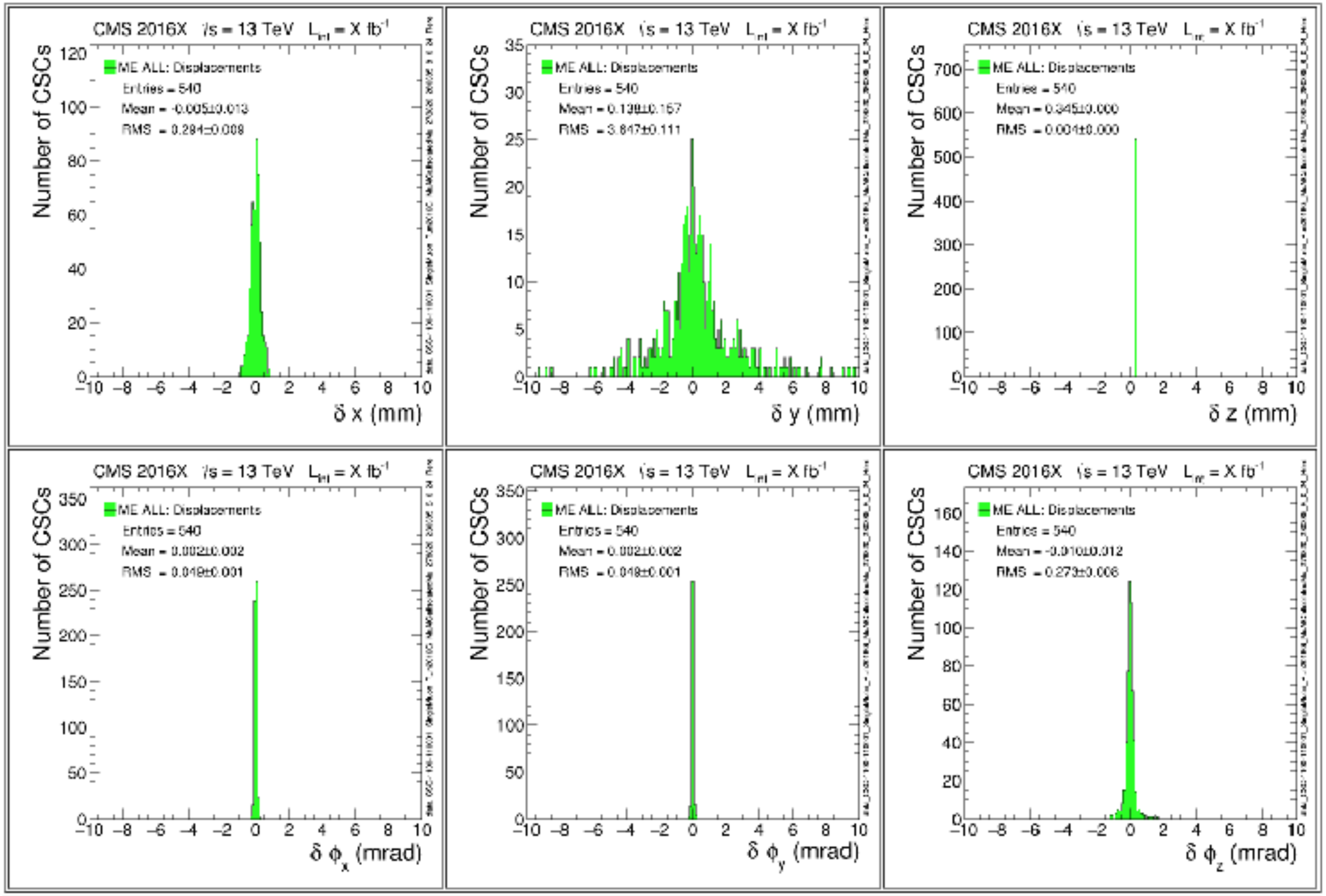
Starting from 2016E SMEARED geom.



# 2016 ReReco Geometry, Physic validation (including Alignment Position Error, APE)

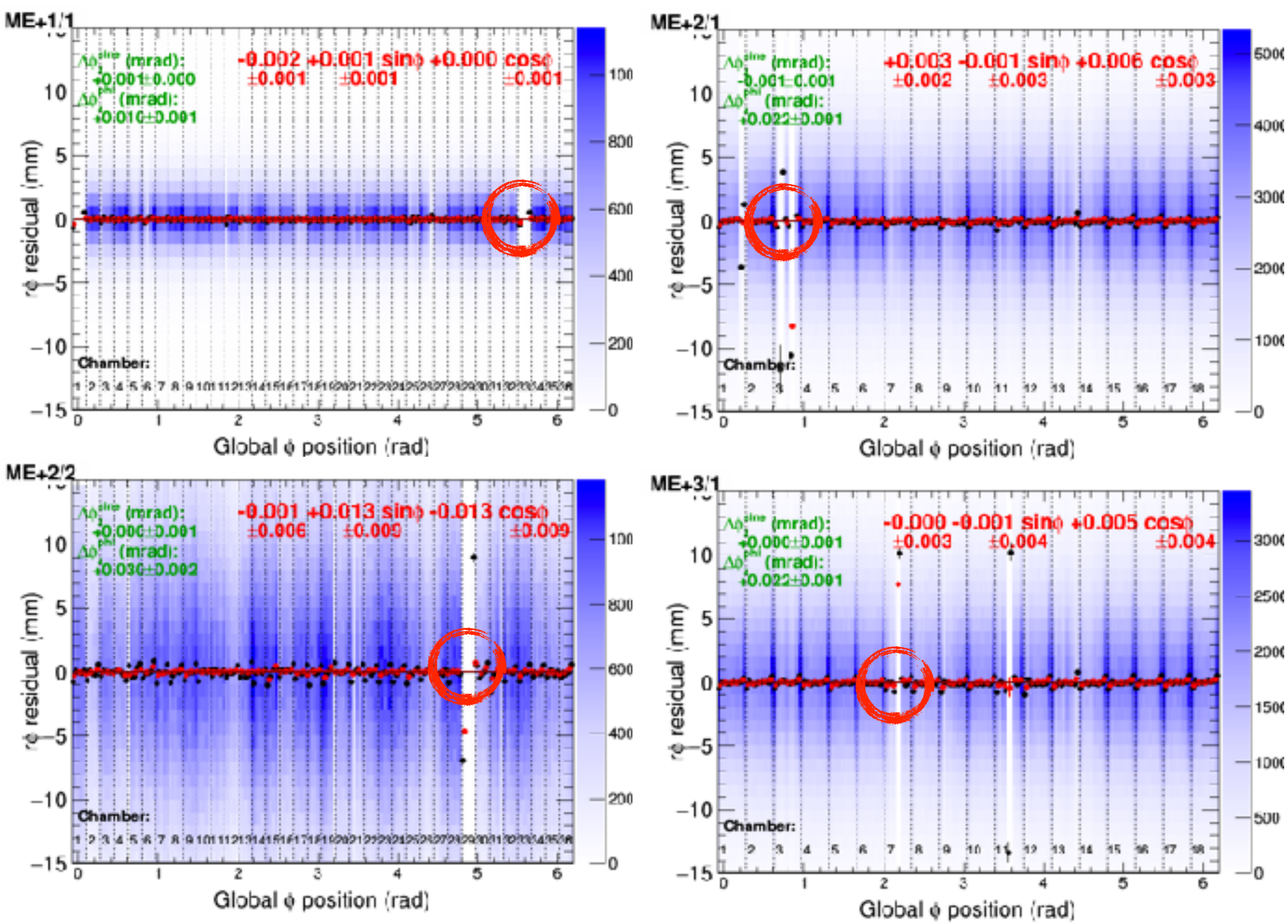
# CSC Alignment

- Final Geometry consistent with the previous one
  - → Distribution: difference between our final geometry and the previous one
  - → Larger spread in Y (expected, not relevant for physics performance)



# CSC Alignment

- Final Geometry consistent with the previous one
  - → Distribution: residual in r Φ vs global Φ for few disks
  - → No need for alignment of the whole disks (CSC has been not opened)




Some disks have no muon in a specific sector (or in few strip of a sector)

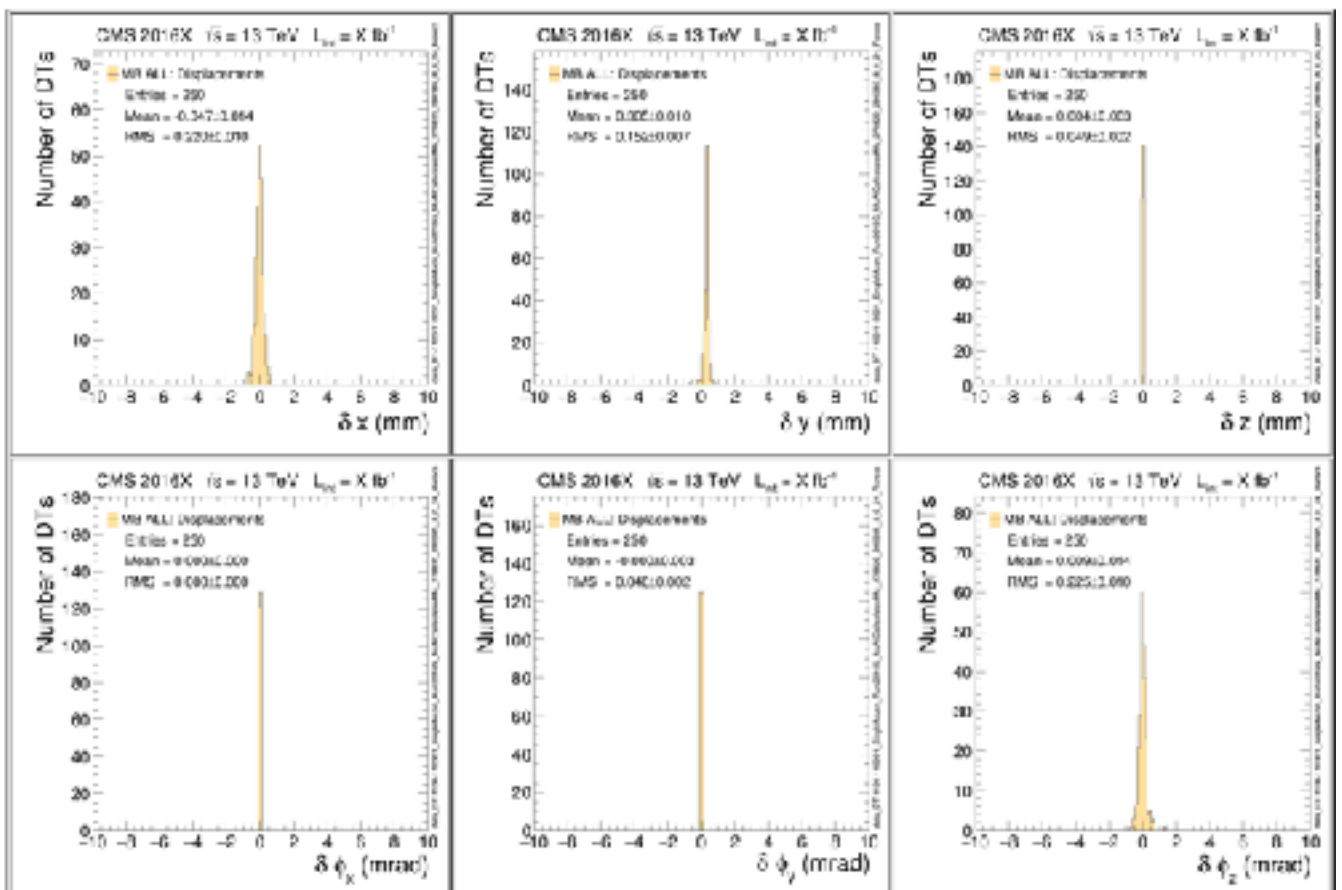
Here just few examples

# DT Alignment

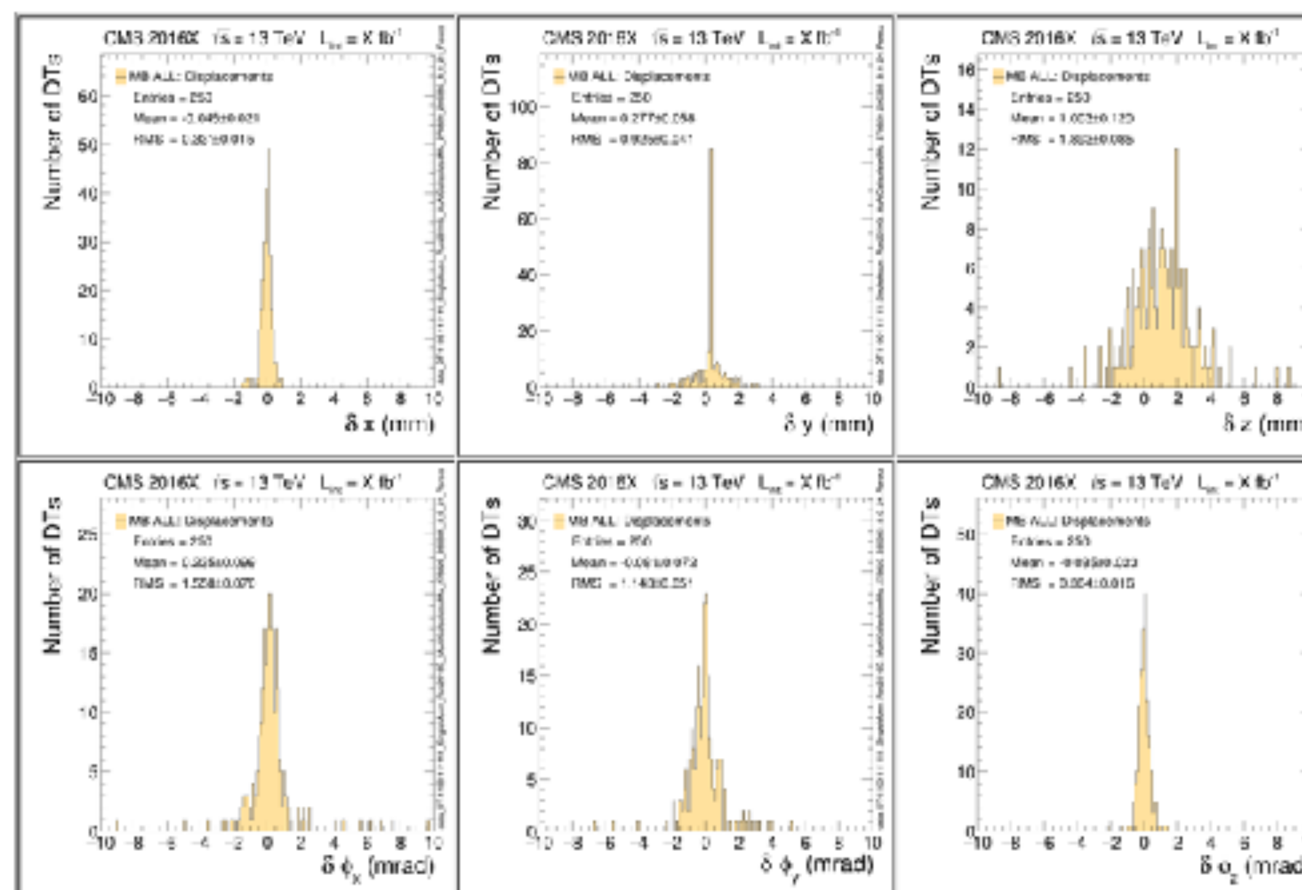
- Final Geometry consistent with the previous one
  → Distribution: difference between our final geometry and the previous one
  → Left: 3 DOF Right: 6 DOF

- Tiny shift in local Y (global Z coordinate)
  → Could be expected since SiStrip geometry has been updated in order to fix the bias seen in the Z mass peak in the very forward rapidity

3DOF

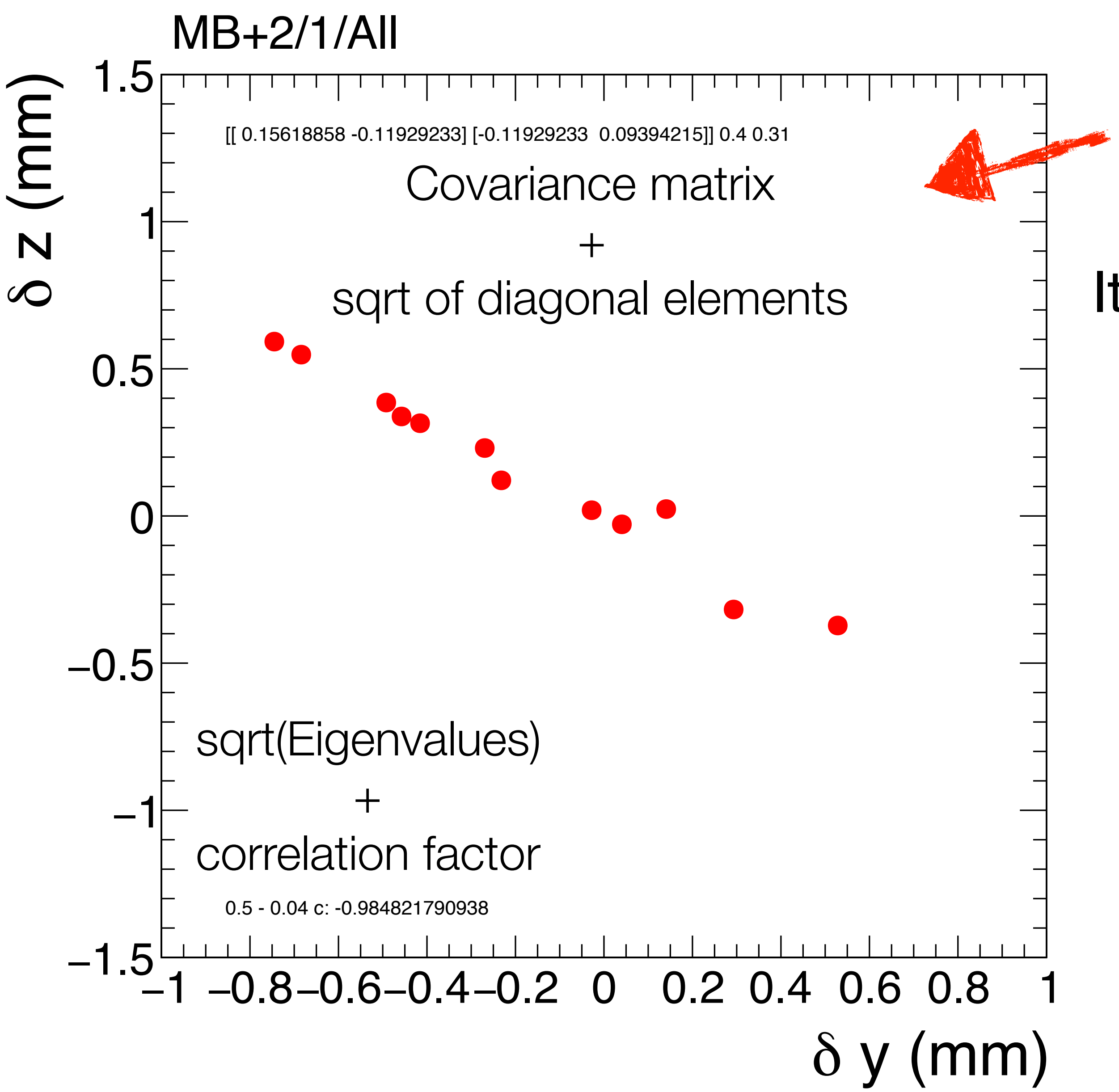


6DOF



# Alignment Position Error

- Alignment Position Error (APE) can be fully determined using 6 DOF
  - → MINUIT provide the full covariance matrix
  - → It includes non diagonal terms that describe weak modes and correlations




Shift in the final geometry in Y vs the shift in Z

It would be not correct treat this as uncorrelated and using diagonal APE

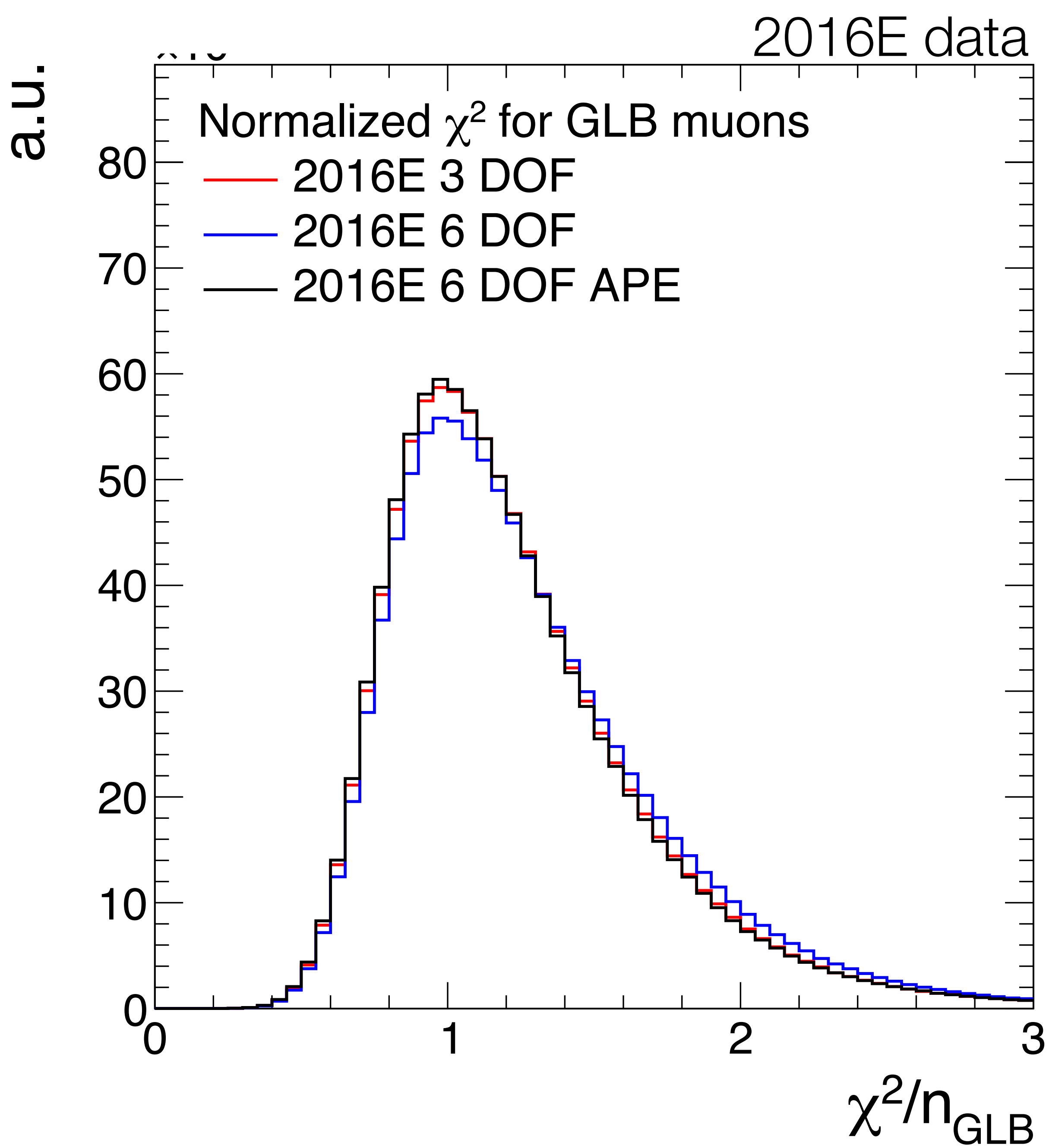
Full APE perfectly describe such correlations (is a 6x6 matrix, here just the Y-Z part)

| | |
|---|---|
| 0.0017476733 | -0.0013962167 |
| -0.0013962167 | 0.0011407589 |

We average APEs of different sectors in the same wheel and station

# Alignment Position Error

❖ Alignment Position Error (APE) can be fully determined using 6 DOF
→ MINUIT provide the full covariance matrix
→ It includes non diagonal terms that describe weak modes and correlations




❖ 3DOF do not allow to use precise APE, thus we use asymptotic diagonal APE

❖ Using 6 DOF method and keep the same APE as 3 DOF worsen the distribution

❖ Using 6 DOF and APE from Covariance Matrix give the best $\chi^2$ distribution

# Physic validation

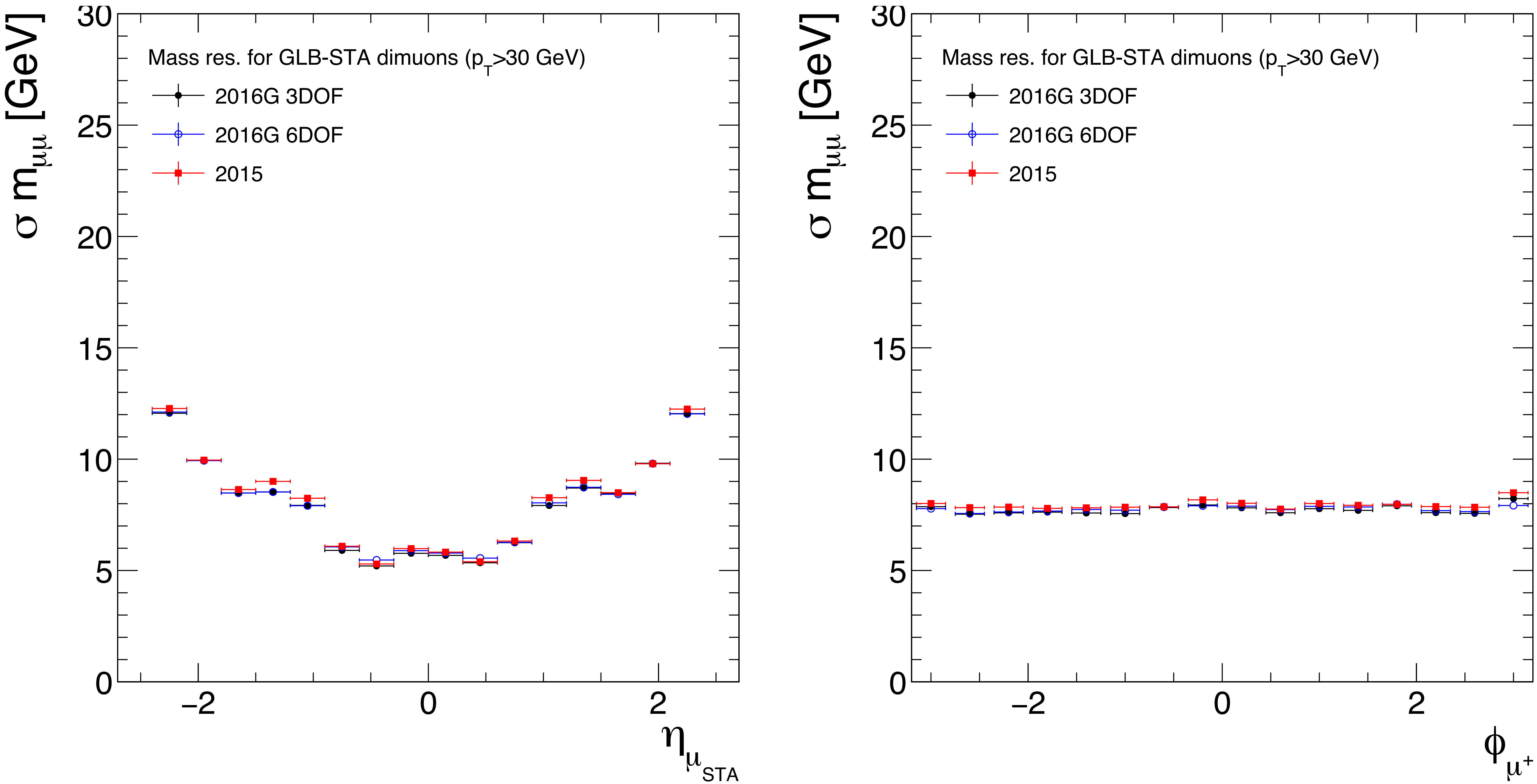
- We reconstruct muons using 2 different geometries:
  - → Geometry obtained using 3 DOF + diagonal APE
  - → Geometry obtained using 6 DOF + APE

- We use 2016G dataset, looking for μ and Z→μμ decays
  - → Plus a basic set of requirements on $p_T(\mu)>30$ GeV, $\chi^2$, num. of hits…
  - → One μ is reconstructed as STA, the other as GLB
  - → The mass resolution is shown as a function of Φ/η of the STA muon

- We do not expect physic performance to be different if initial geometry is accurate
  - → We want to prove that using 6 DOF (more safe vs initial biases) performance similar
  - → If so, moving 6 DOF just make the algorithm more stable and reliable

# Physic validation

- M(Z) resolution as a function of Φ/η of the STA muon:
  → Both 3 and 6 DOF with new alignment give better performance than 2105
  → 3 and 6 DOF give very similar performance

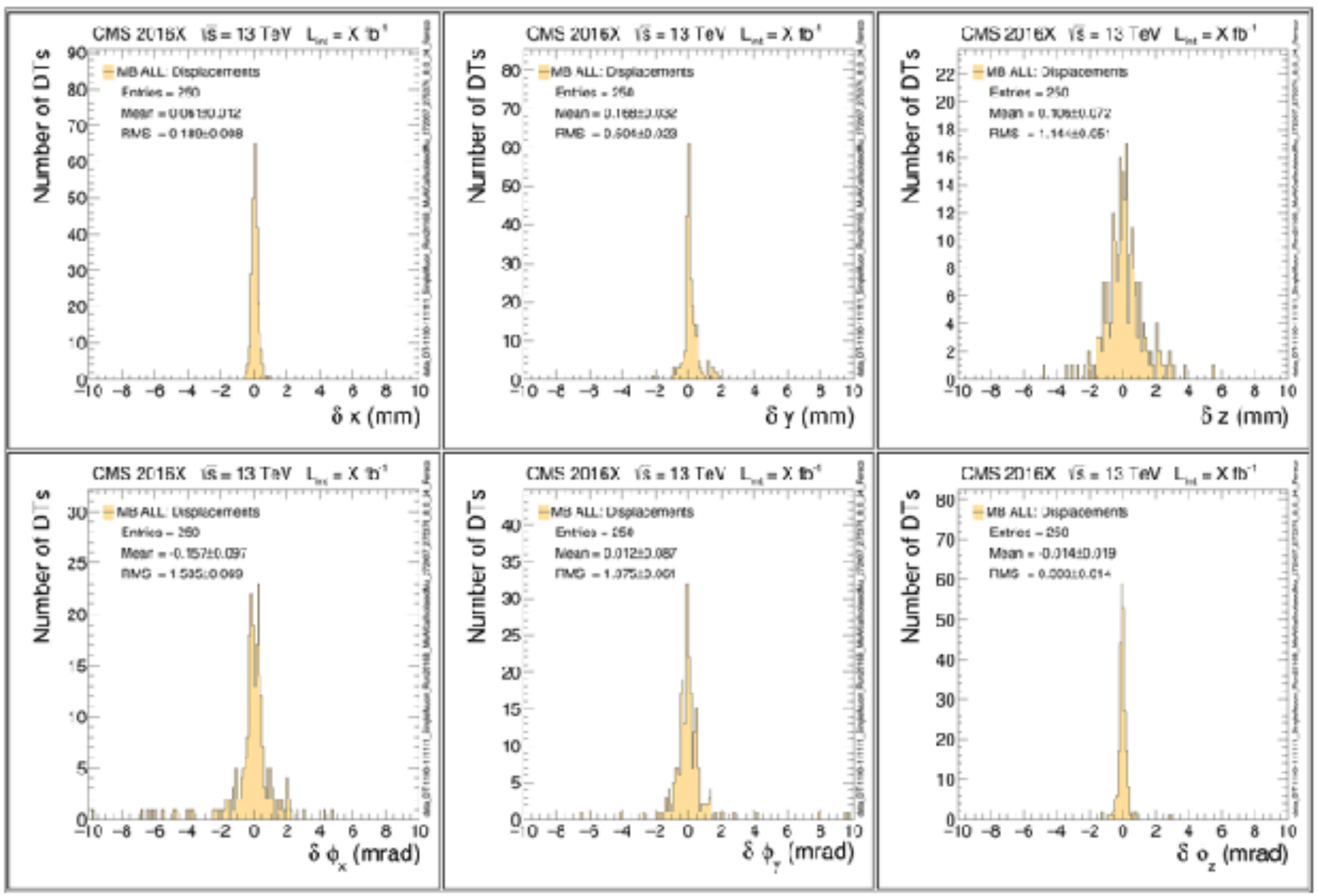


# Additional cross-checks

# Geometry stability over time: DT

- We start from 2016G geometry (latest we provided) with 6 DOF:
  - → We run using the same condition on 2016B
  - → We compare the final geometry and the initial one

data_DT-1100-111111_SingleMuon_Run2016B_MuAlCalIsolatedMu_272007_275376_8_0_24_Rerecov1_03 - 2016G_6DOF

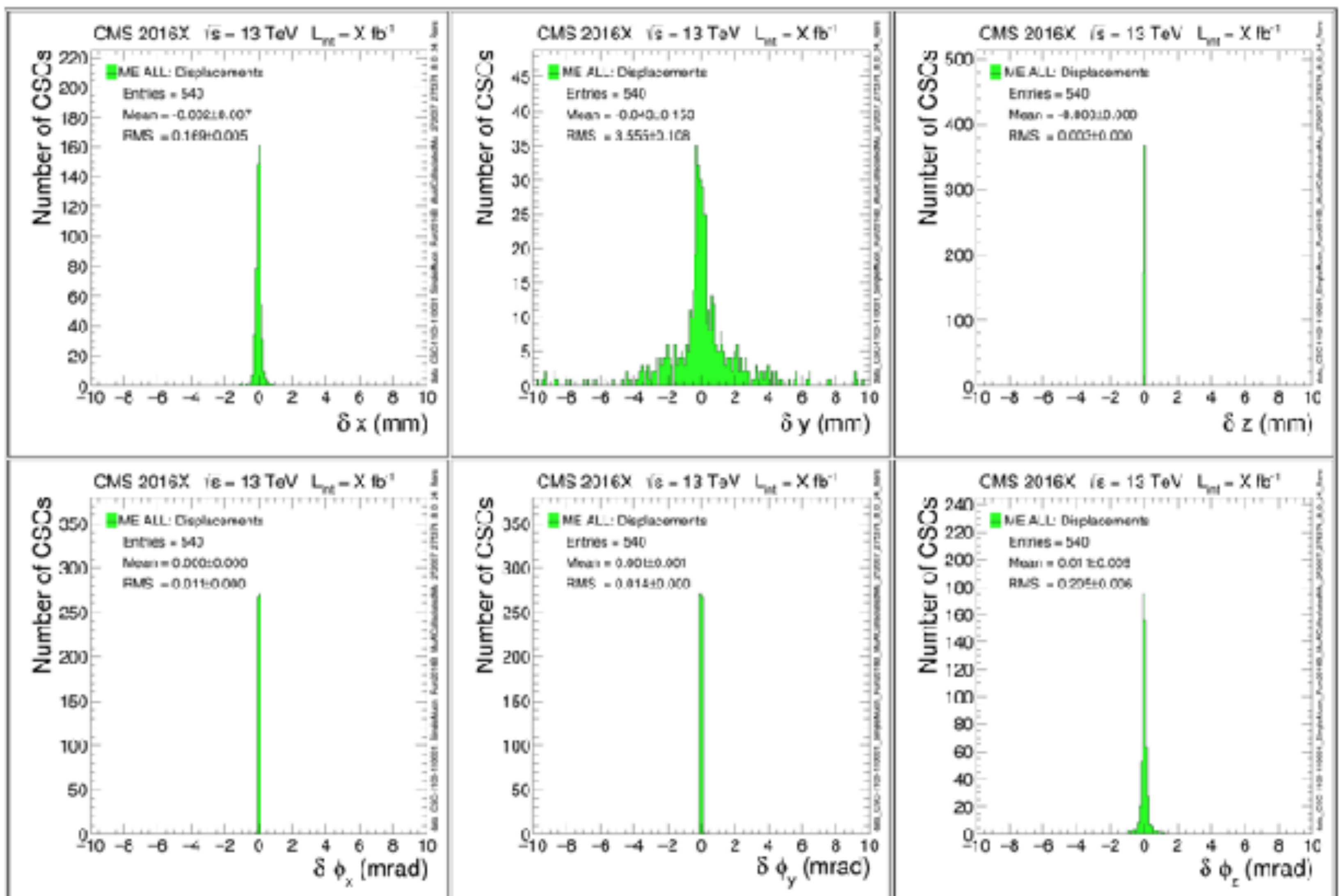



- Everything looks compatible
- X and ΦZ component very similar

# Geometry stability over time: CSC

- We start from 2016G CSC geometry (latest we provided):
  - → We run using the same condition on 2016B
  - → We compare the final geometry and the initial one

data_CSC-1100-110001_SingleMuon_Run2016G_MuAlCalIsolatedMu_272007_275376_8_0_24_Rerecov1_03 - 2016G_6DOF




- Everything looks compatible
- X and ΦZ component very similar

# Performance with biased geometry

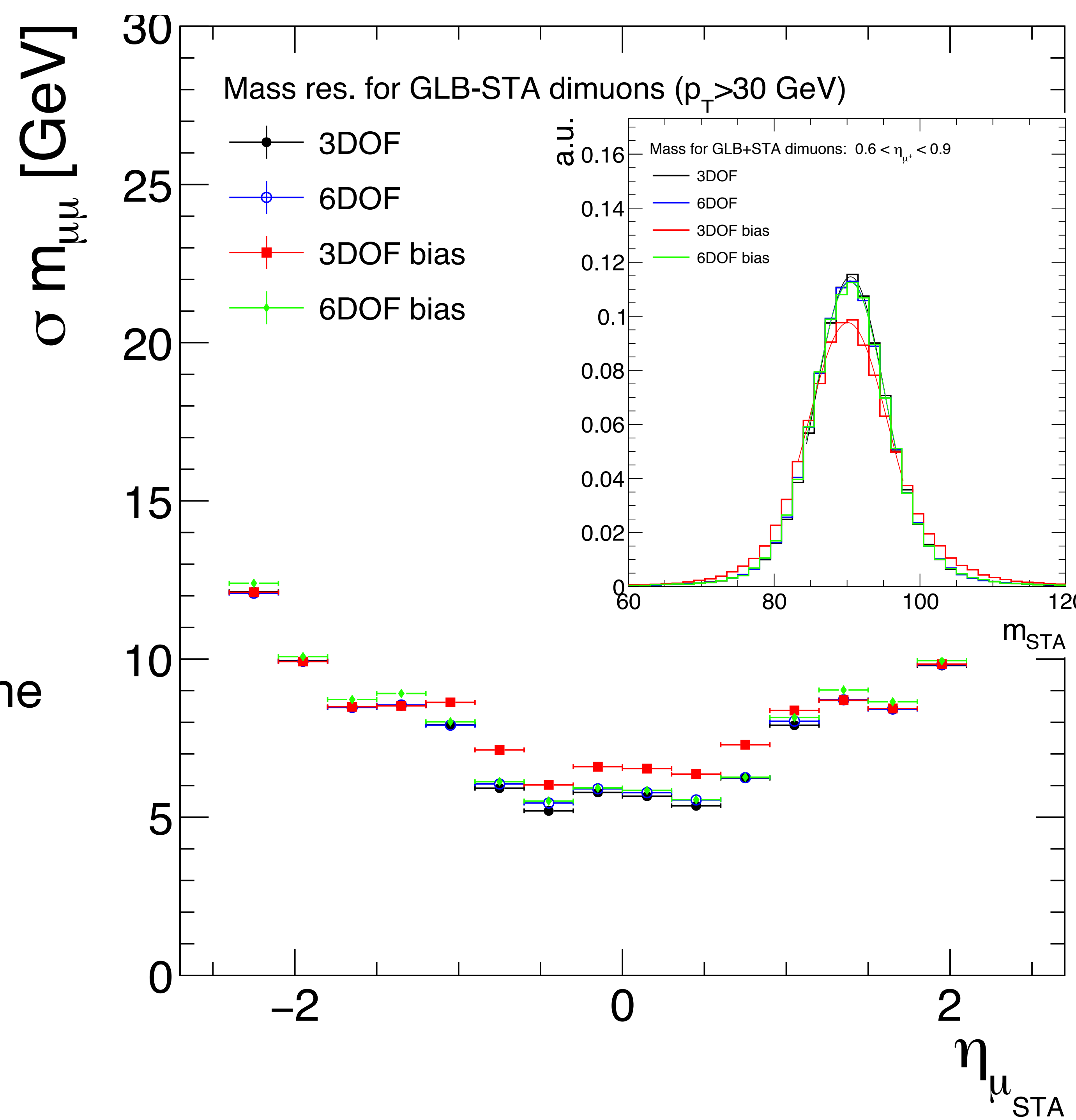
❖ If we start from a biased geometry, 3 DOF will lead to a biased geometry

→ 6 DOF is more resistant to initial biases
Performance are the same

→ 3 DOF get worse if we start from a bias geometry

→ CSC geometry should be ignored for this particular test (just focus on DT)

→ Note: both in the biased geometry I used the old GPR (had not time to redo the studies with the latest)



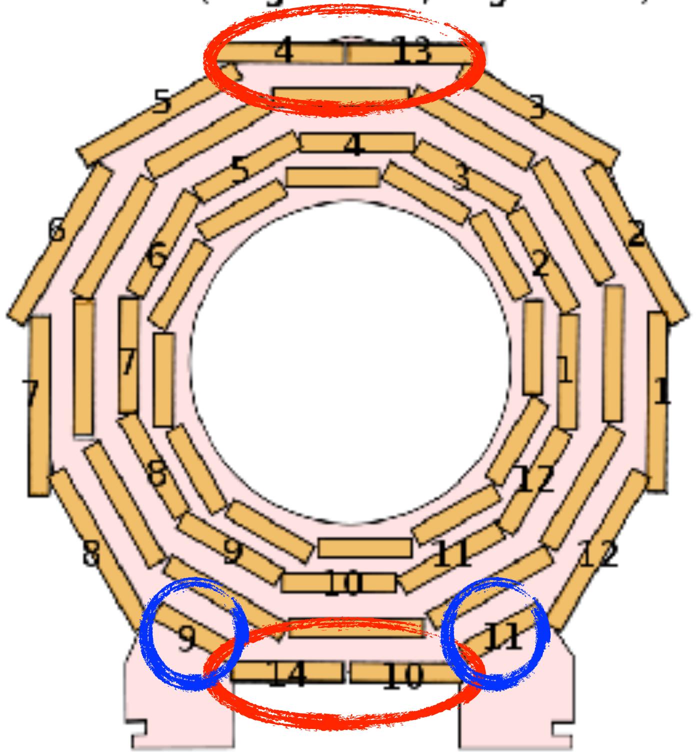
# Conclusions

- Alignment with 6 DOF is ready to be used:
  - → This is what we propose as new default method for 2017

- Still room for improvements (2017, long term):
  - → Few chambers are known for respond with less precision to alignment
  - → Dedicated studies on these chambers could help in improve overall alignment precision
  - → Example: sector 4,10,13,14 station 4 (non pointing)
  - → Example: sector 9,11 station 4 (small size+large scattering)

- We plan to document everything in a Detector Note
  - → A also make a paper from it

Wheel 0 (length x200, angle x200)



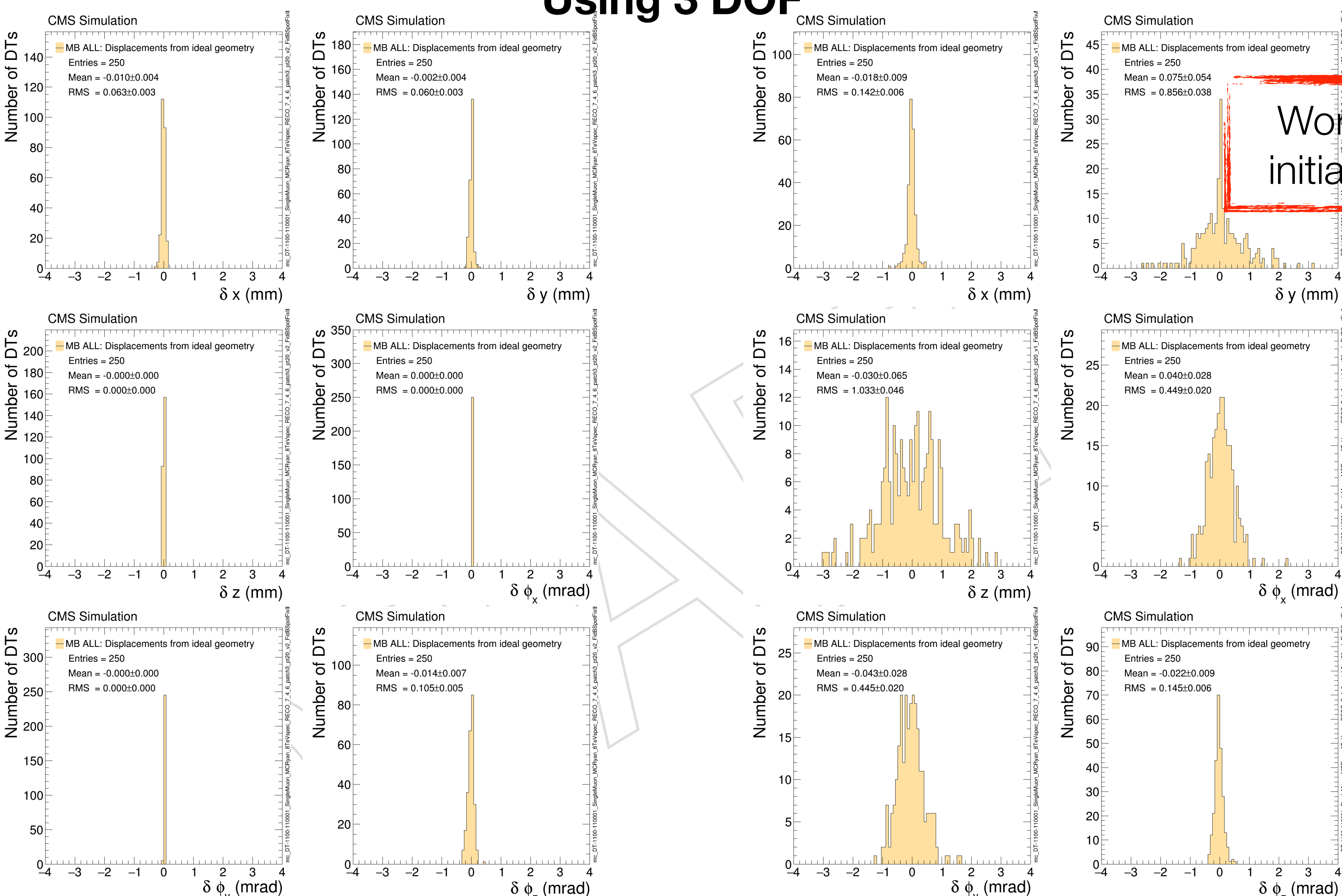
Backup

# 3 vs 6 degrees of freedom

- This plots: difference between ideal geometry and final geometry provided by the algorithm. Ideally should be everything "zero".

## Using 3 DOF

starting with ideal geometry




starting with misal. geometry*

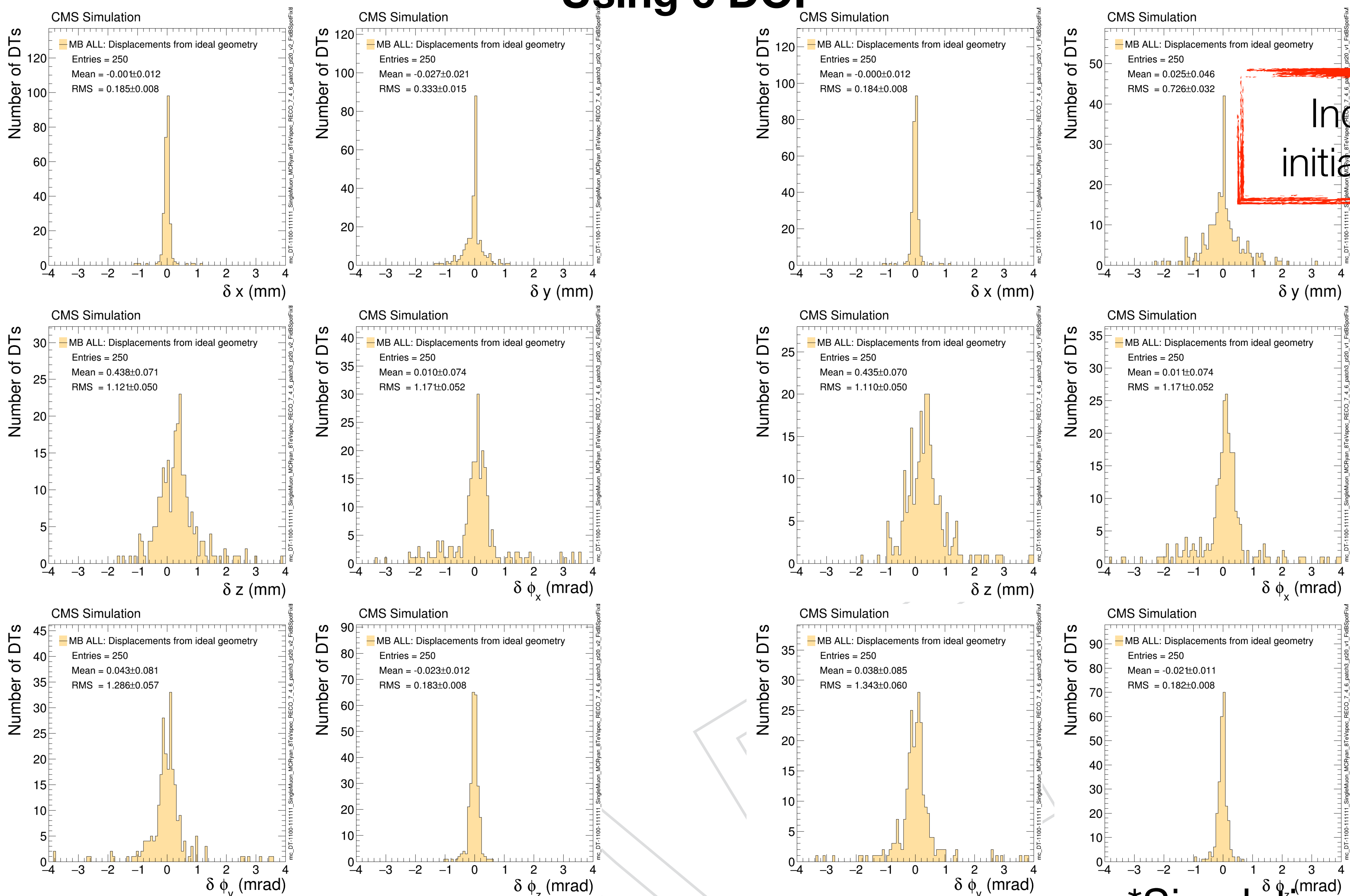
*Simulating HW alignment

# 3 vs 6 degrees of freedom

- This plots: difference between ideal geometry and final geometry provided by the algorithm. Ideally should be everything "zero".

**Using 6 DOF**

starting with ideal geometry




starting with misal. geometry*

*Simulating HW alignment

- We want to start from out latest geometry (derived on 2016G data) and see if correctly describe the whole Run2 period
  → We use it to align 2016B dataset
  → We use it to align 2016D dataset

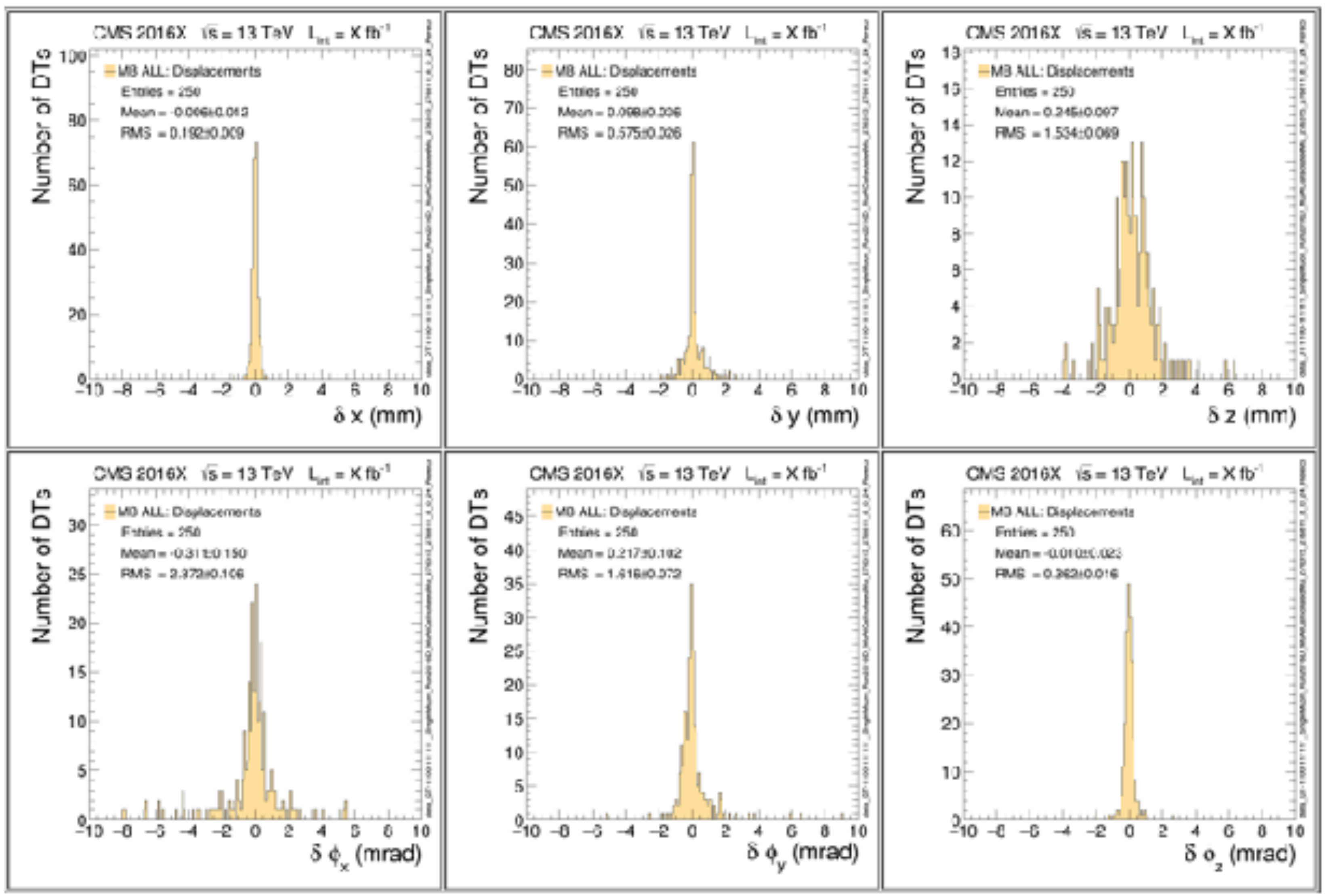
- We expect to find a consistent geometry within the statistic and systematic uncertainties

| RUN | Lumi |
|---|---|
| 2016 B | 5.8 |
| 2016 C | 2.6 |
| 2016 D | 4.3 |
| 2016 E | 4.1 |
| 2016 F | 3.2 |
| 2016 G | 7.5 |

| DATASET | from Run | to Run |
|---|---|---|
| Run2016A | 271036 | 271658 |
| Run2016B | 272007 | 275376 |
| Run2016C | 275657 | 276283 |
| Run2016D | 276315 | 276811 |
| Run2016E | 276831 | 277420 |
| Run2016F | 277772 | 278808 |
| Run2016G | 278820 | 280385 |
| Run2016H | 280919 | 284044 |

- We start from 2016G geometry (latest we provided) with 6 DOF:
  - → We run using the same condition on 2016D
  - → We compare the final geometry and the initial one

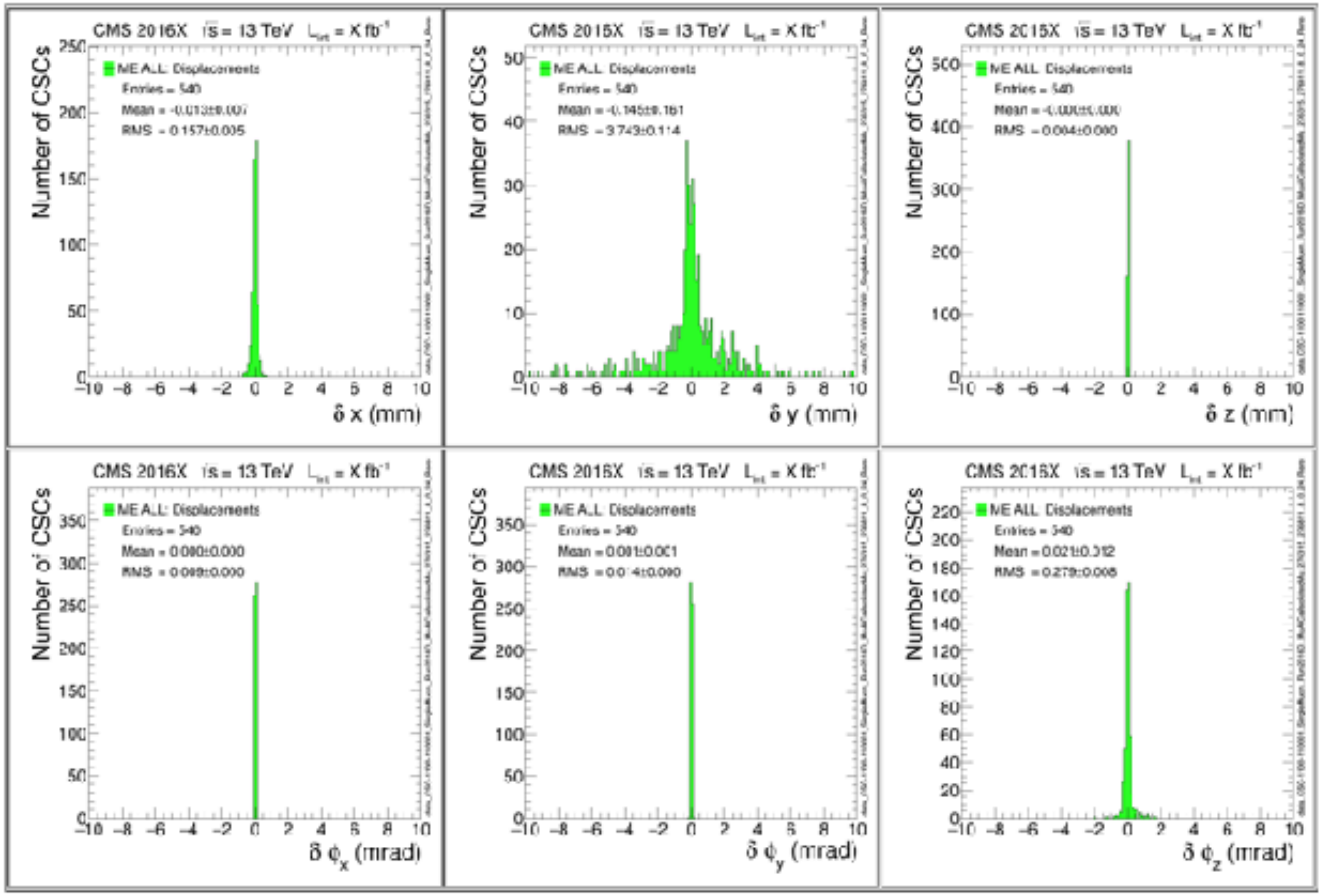
data_DT-1100-111111_SingleMuon_Run2016D_MuAlCalIsolatedMu_276315_276811_8_0_24_Rerecov1_03 - 2016G_6DOF



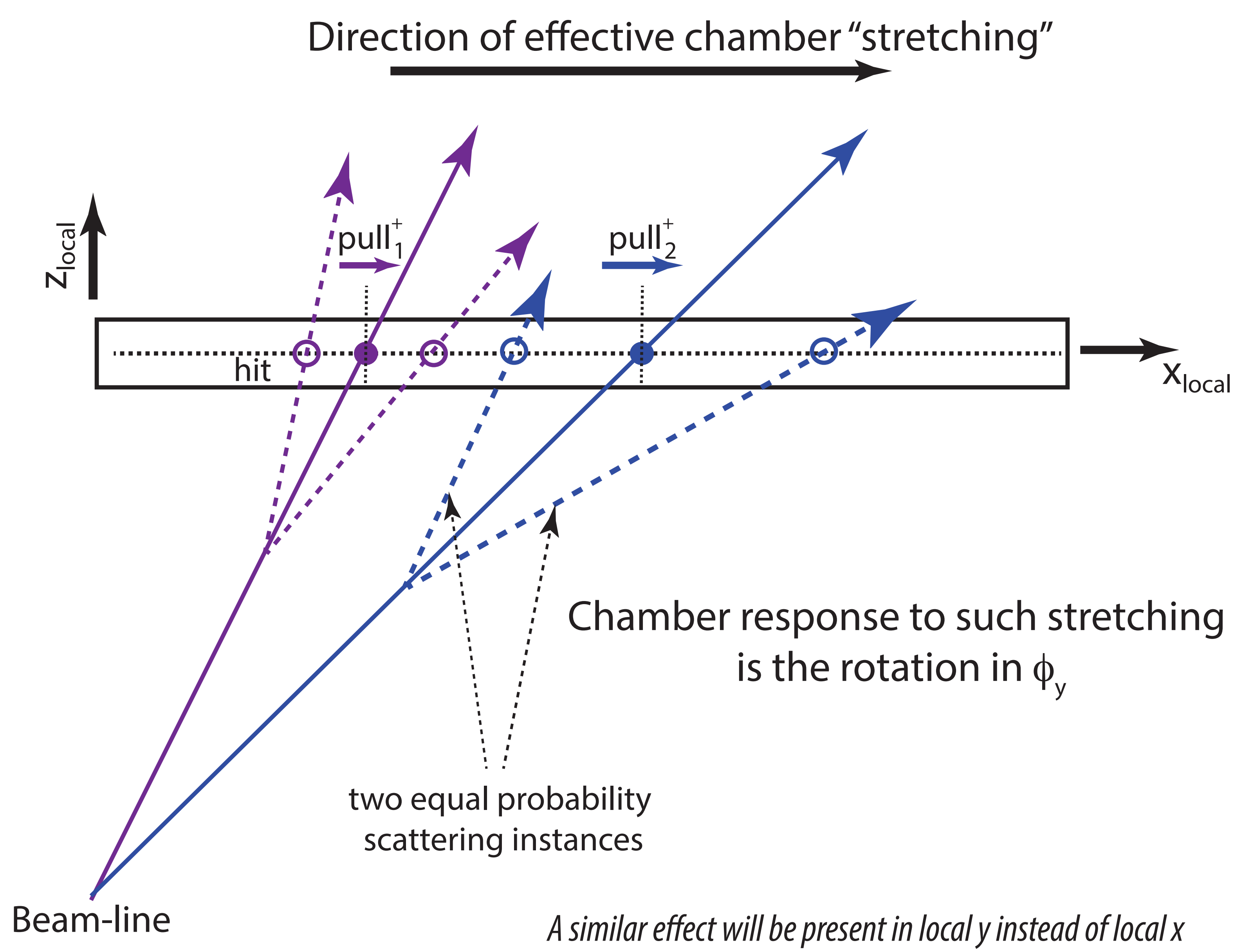

- Everything looks compatible
- X and ΦZ component very similar

- We start from 2016G CSC geometry (latest we provided):
  - → We run using the same condition on 2016D
  - → We compare the final geometry and the initial one

data_CSC-1100-110001_SingleMuon_Run2016D_MuAlCalIsolatedMu_276315_276811_8_0_24_Rereco_v1_03 - 2016G_6DOF




- Everything looks compatible
- X and ΦZ component very similar




*A similar effect will be present in local y instead of local x (higher eta chambers stretching leading to rotation in $\phi_x$)*
*** Far wheels will see the largest effect as both incident ***
***angles dx/dz and dy/dz are large and unbalanced there***

Example 2:
Aligning a conical geometry

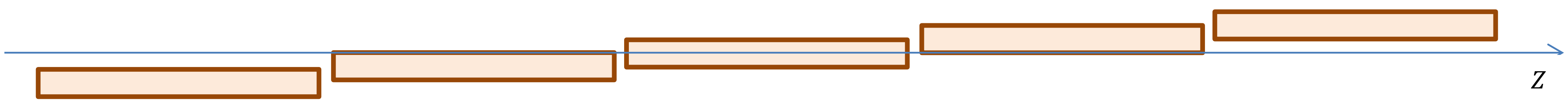
# Initial Conical geometry

- Physic validation shows similar performance if using 3 or 6 DOF (see later)

- We often compare a geometry obtained with 3 and 6 DOF:
  - → Not a fair comparison the original geometry was biased
  - → For example: let’s assume initial geometry has a conical bias

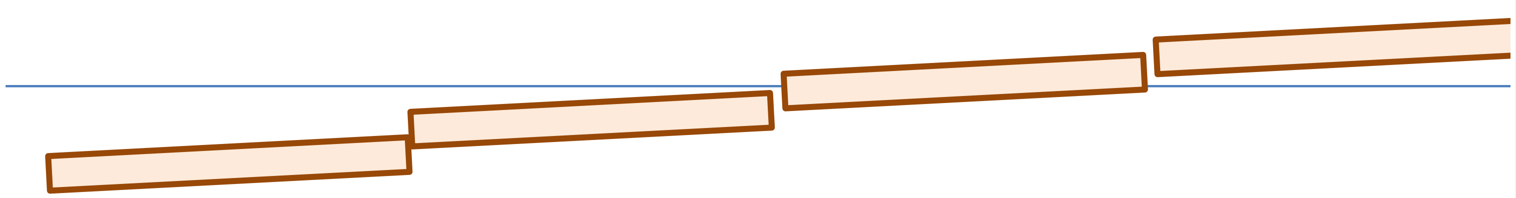
Geometry 1: Steps in local Z

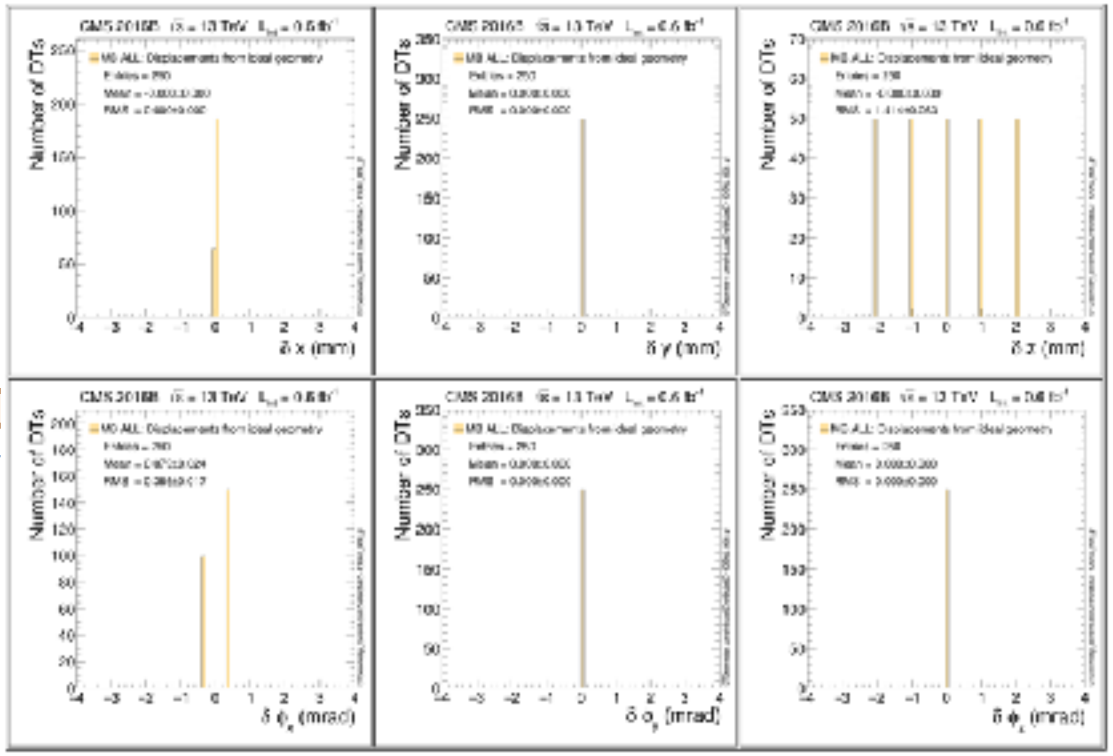
| | w -2 | w -1 | w 0 | w +1 | w +2 |
|---|---|---|---|---|---|
| local Z (mm) | -2 | -1 | 0 | 1 | 2 |




Geometry 2: Steps in local Z, rotations in local $\phi_x = \frac{\frac{1}{2} \cdot stepZ}{\frac{1}{2} \cdot widthZ}$, where $stepZ = 1\ mm$ and $widthZ = 2536\ mm$

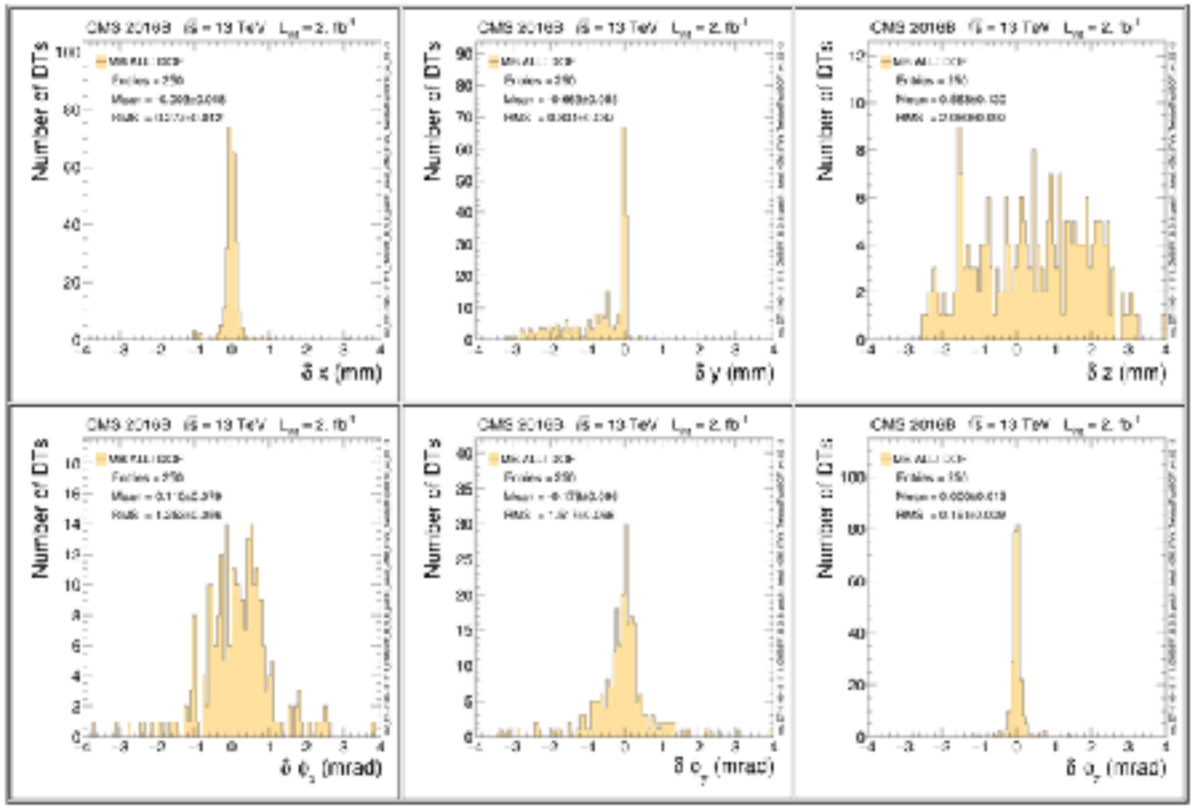
| | w -2 | w -1 | w 0 | w +1 | w +2 |
|---|---|---|---|---|---|
| local Z (mm) | -2 | -1 | 0 | 1 | 2 |
| local $\phi_x$ (mrad) | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |





# Initial Conical geometry

- We have an initial geometry that has a conical bias
- We align the muon system using 3 DOF method
  → we can only compare it with the initial biased geometry in data
- Then we align the muon system using 6 DOF method
  → we can only compare it with the previous geometry obtained with 3 DOF



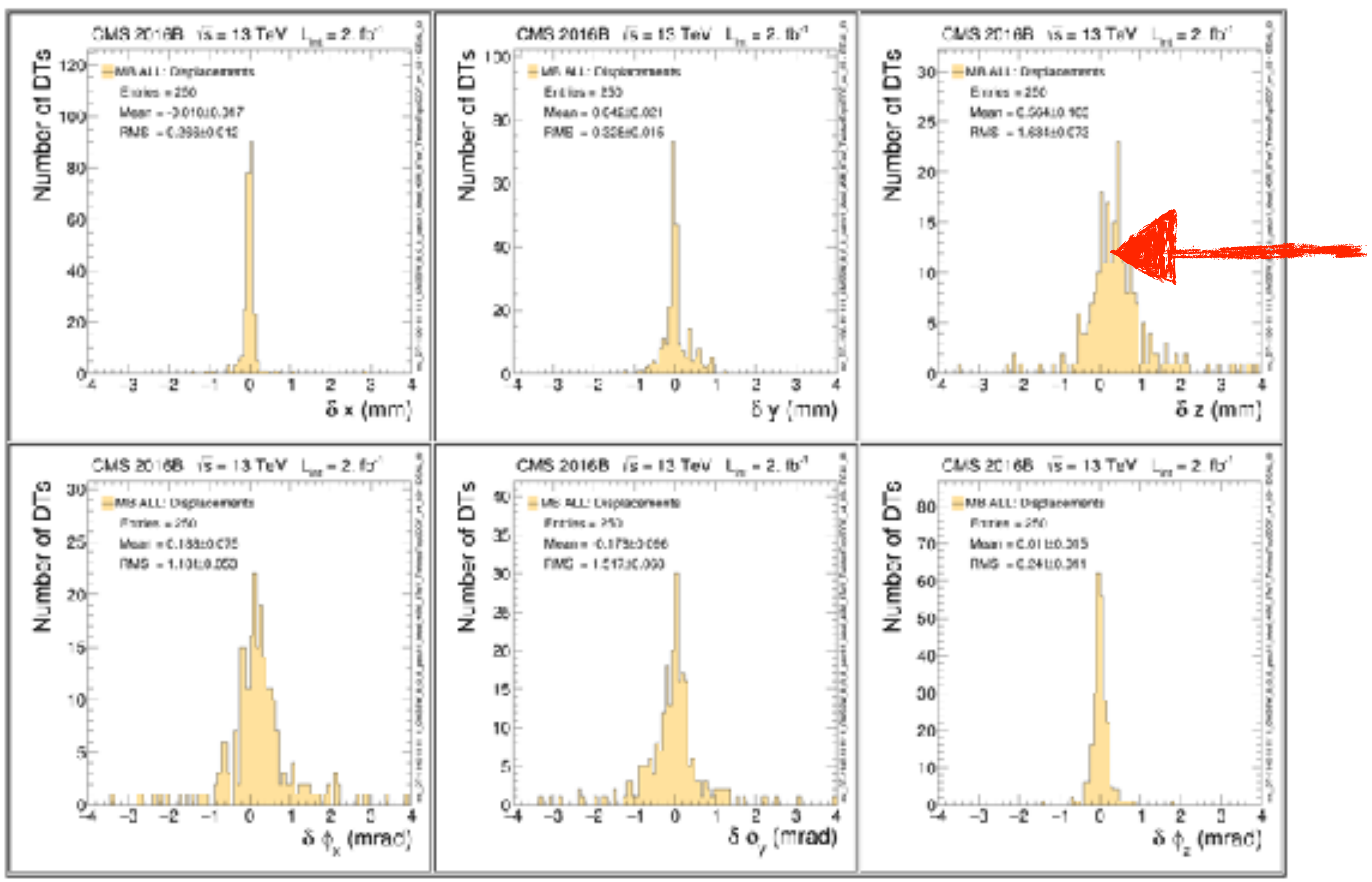
Difference between 6 DOF geometry and 3 DOF geometry

- Large difference would indicate the 6 DOF geometry different from 3 DOF geometry

# Initial Conical geometry

- When comparing to the IDEAL geometry in fact we see that 6 DOF geometry is simply correcting for the BIAS that in 3 DOF was not corrected

- The spread we saw in last slide is really dependent on the kind specific initial bias we have




Difference between 6 DOF geometry and Ideal geometry