The CMS GEM Commisioning and Alignment Status

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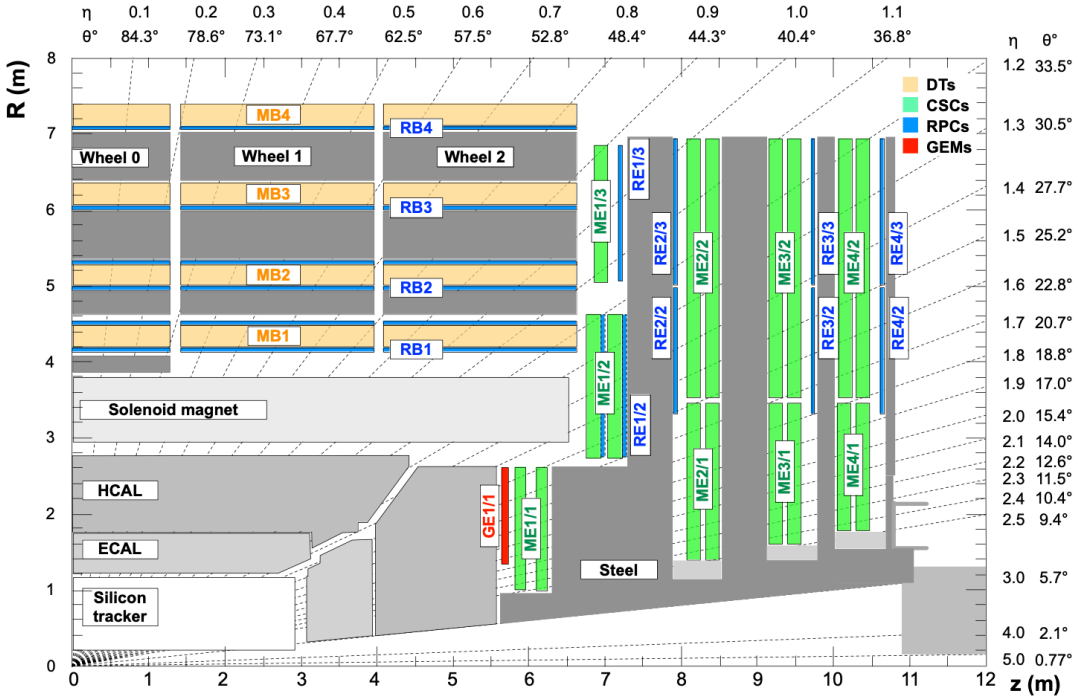
What is CMS/GEM

- **The CMS muon system plays an important role in the discovery of new physics like the Higgs boson and new particles.**
- The high luminosity LHC (HL-LHC) upgrade will improve the discovery power by increasing luminosity but will require high-performance muon trigger and muon track reconstruction, especially in the forward endcap region.
- **The CMS collaboration has been developing a Gas Electron Multiplier (GEM) detector for the endcap regions of the CMS muon system.**
- The new sub-detector system requires a new procedure of commissioning and alignment to be developed.



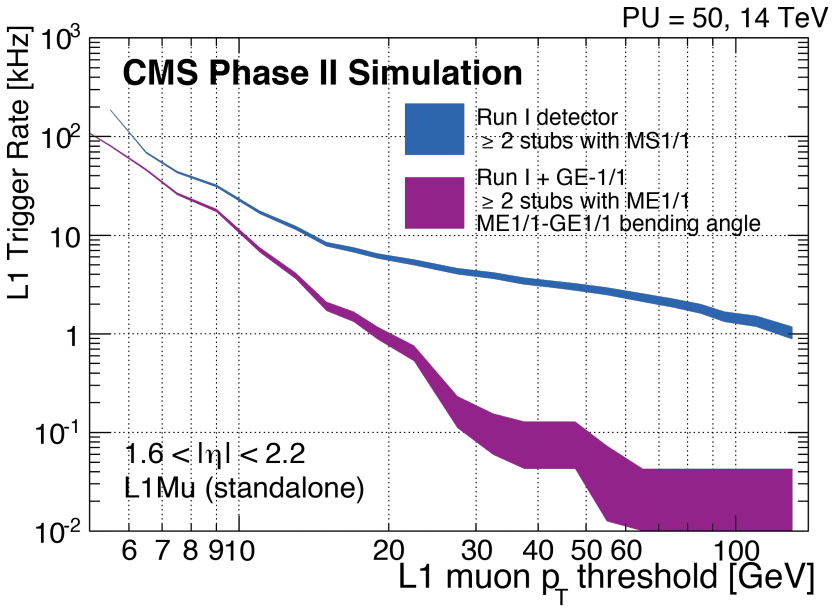
CMS-TDR-013 Fig. 1.1

GE1/1: GEM End-cap station1 ring1

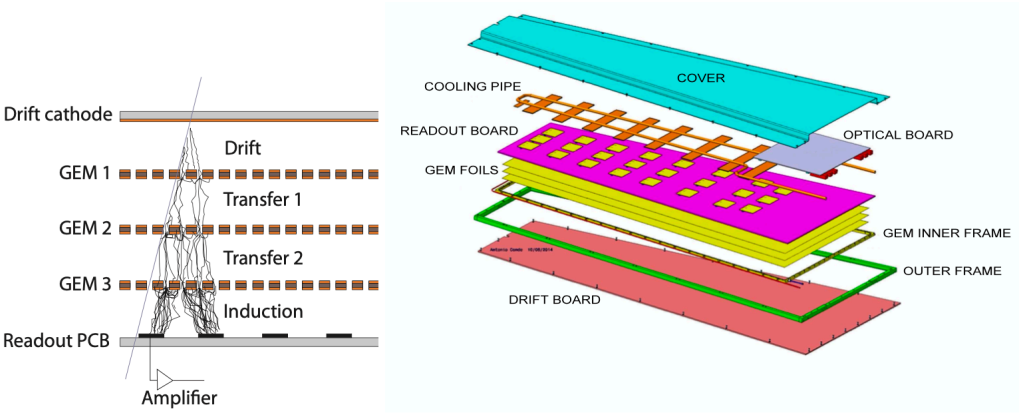
Drift Tube chambers (DTs)
Cathode Strip Chambers (CSCs)
Resistive Plate Chambers (RPCs)

Why Add GEM

- Motivations in the high luminosity LHC collider (HL-LHC)
  - GEM-CSC combined operation measures the bending angle at trigger level, thus strongly reducing the rate of mis-measurements
  - Improve tracking performance in high background rate environment
  - Will reduce trigger rate by a factor of 10
  - See previous talk by Brendan Regnery for more on the detector:
    Installation and commissioning status of the new GEM muon detectors in the CMS experiment
    https://indico.cern.ch/event/1034469/contributions/4431721/

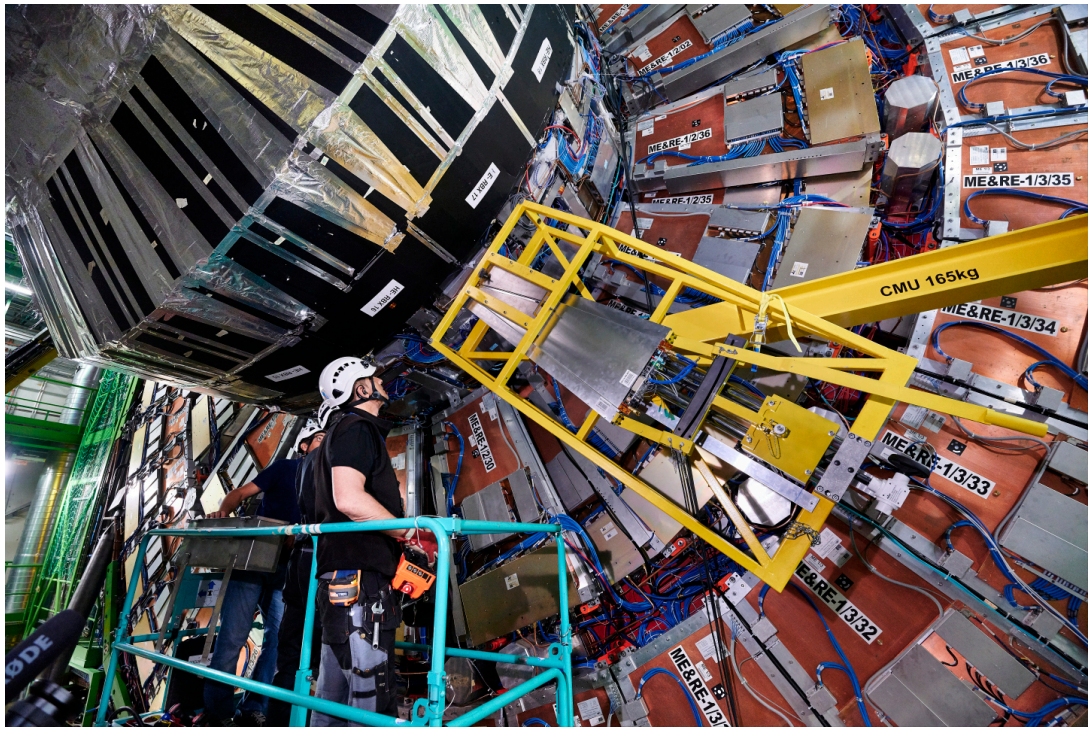


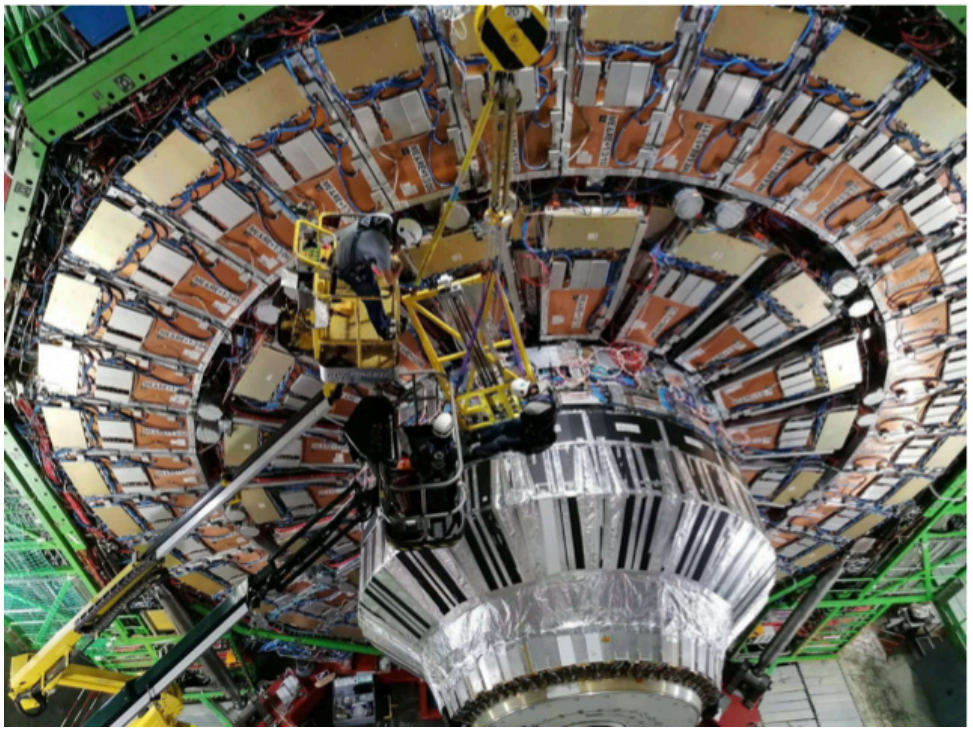
CMS-TDR-013 Fig. 1.2



CMS-TDR-013 Fig. 1.3

GE1/1 Installation



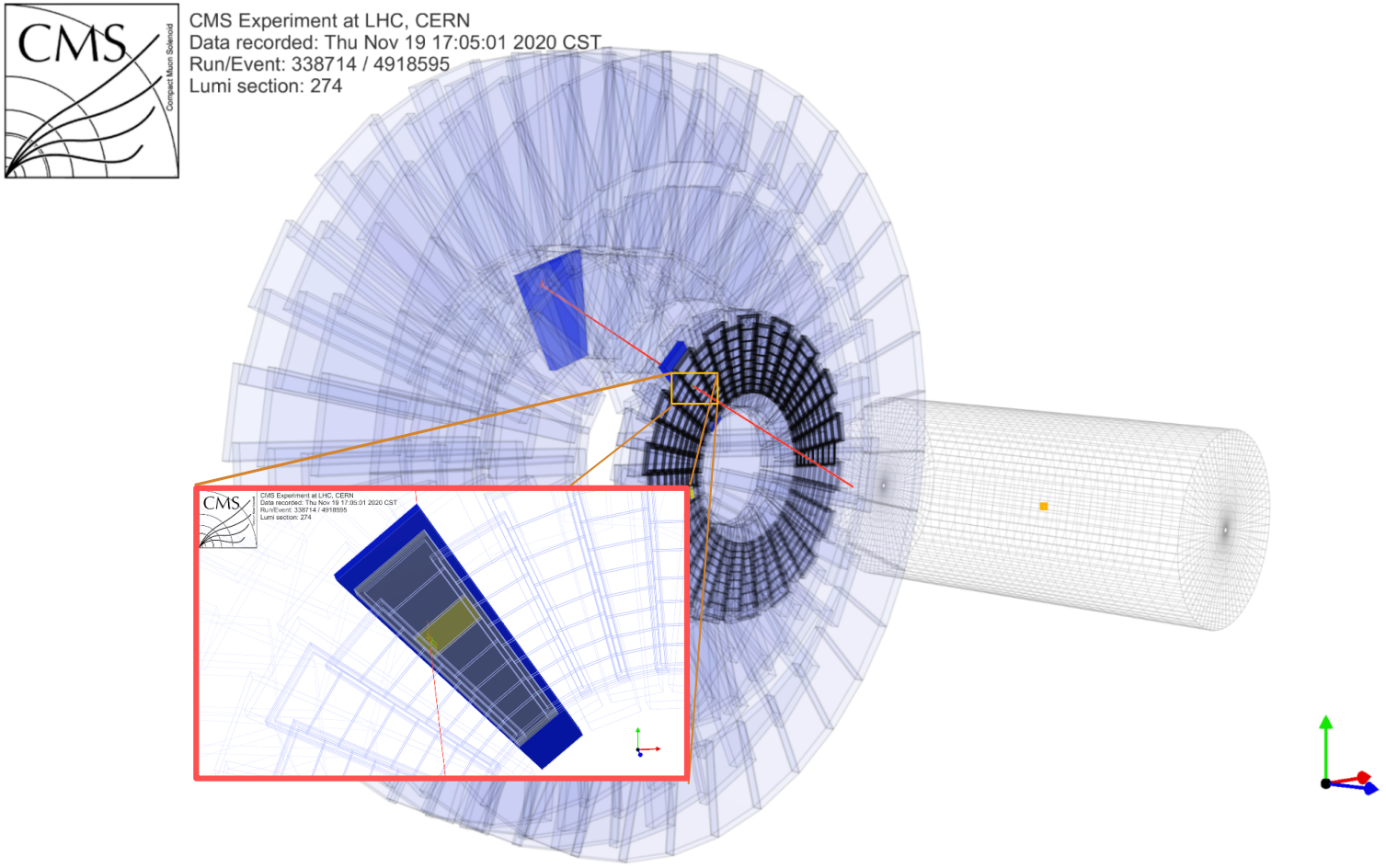


- GE-1/1 (negative endcap): Completed in Oct. 2019
- GE+1/1 (positive endcap): Completed in Oct. 2020, delayed 6 months due to pandemic

Global Run

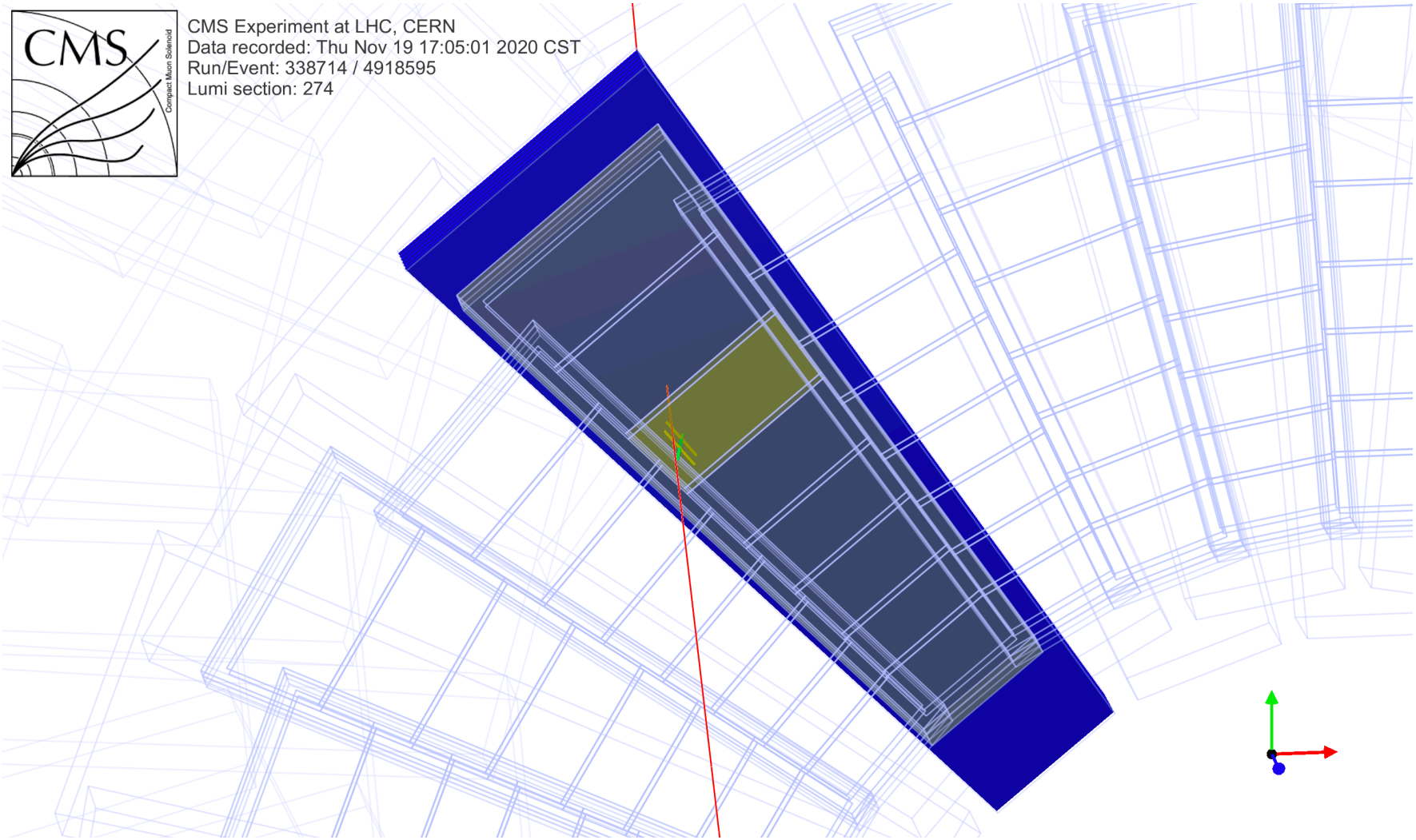
- CMS GE1/1 demonstration during Run2 (slice test)
  - All new DAQ system has been integrated
  - Challenges have been successfully overcome and have lead to significant improvements in system design
  - Improved GEB and VFAT design reduced electronic noise and channel loss
- CMS GEM has participated in global commissioning (cosmic run)
  - The DAQ system shows correct data format integrity through data quality monitoring
  - Latency and HV scans performed
- On/offline Data Quality Monitoring has been integrated
- Data certification procedure is ready

Event Display



Cosmic ray muon candidate recorded during the CMS data taking exercises in November 2020. A muon track (red line) through ME chambers (in blue) at Stations 3 → 1 points back at **GE-1/1** super-chamber 14 (Sector 3).

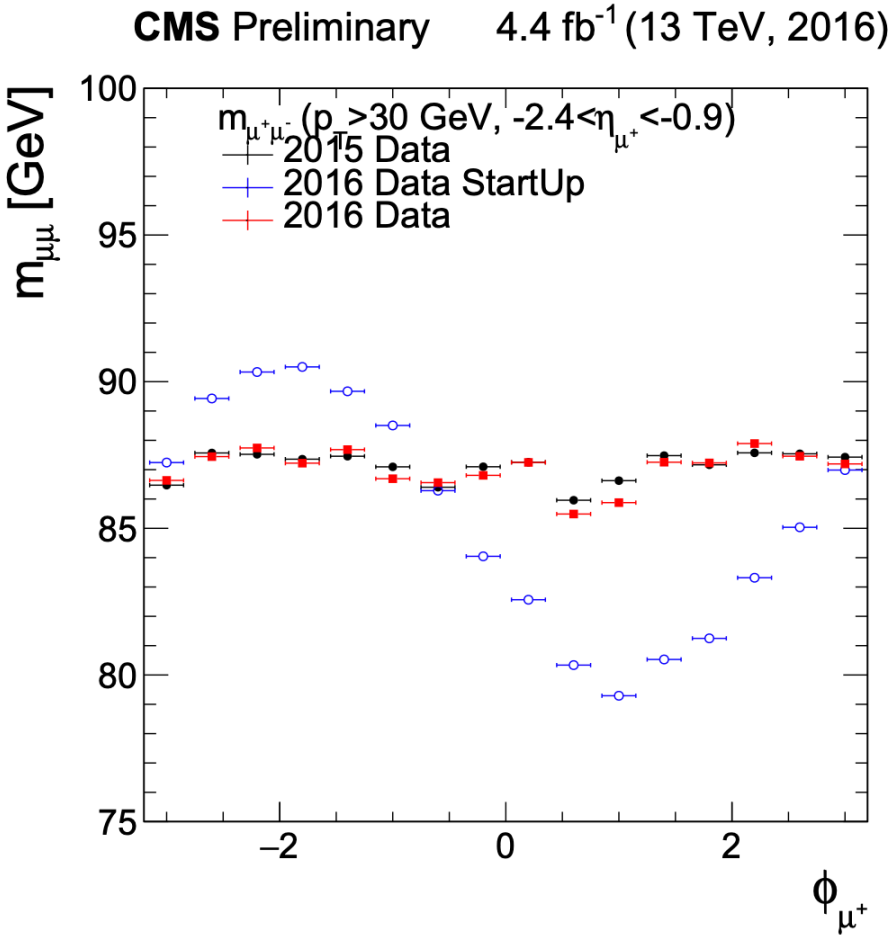
Event Display



Cosmic ray muon candidate recorded during the CMS data taking exercises in November 2020. A muon track (red line) through ME chambers (in blue) points back at **GE-1/1** super-chamber 14 (Sector 3) (highlighted in yellow). GEM hits on layers 1 and 2 are shown with yellow lines. The green line is a reconstructed GEM muon segment.

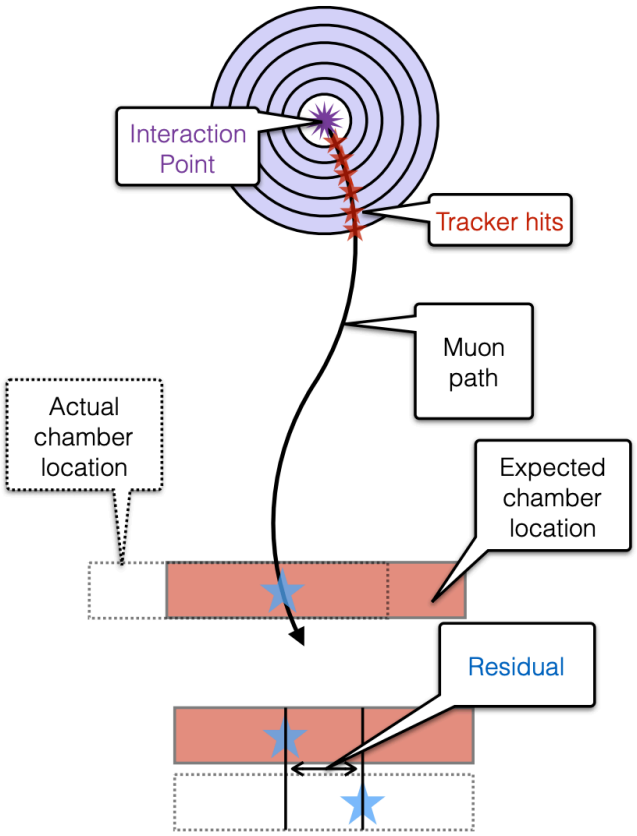
Alignment

- Misalignment causes incorrect particle reconstruction
- **Why alignment is important for GEM**
  - End-cap is opened frequently - creating small misalignments
  - GEM-CSC trigger uses bending angle between GEM and CSC for triggering, requiring accurate relative alignment



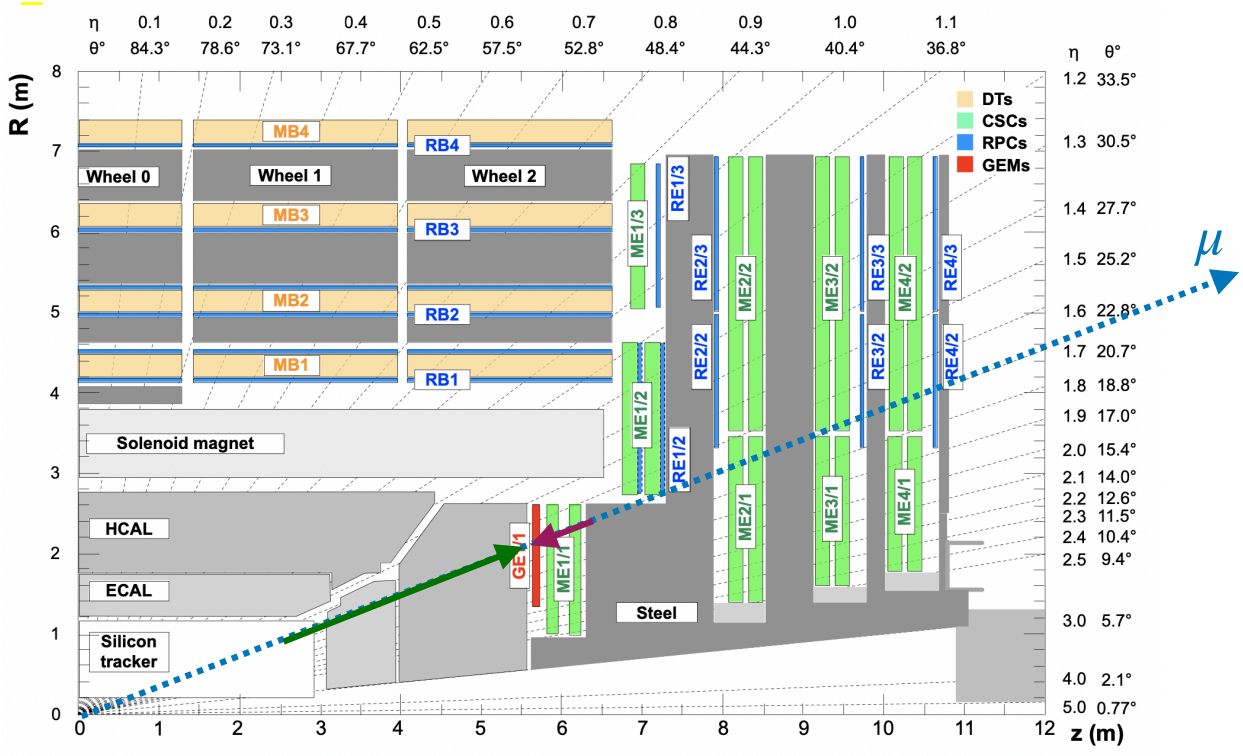
Comparison of di-muon (Z candidate) mass between misaligned geometry (blue dot) and aligned geometry (red dot) shows significant reconstruction improvement

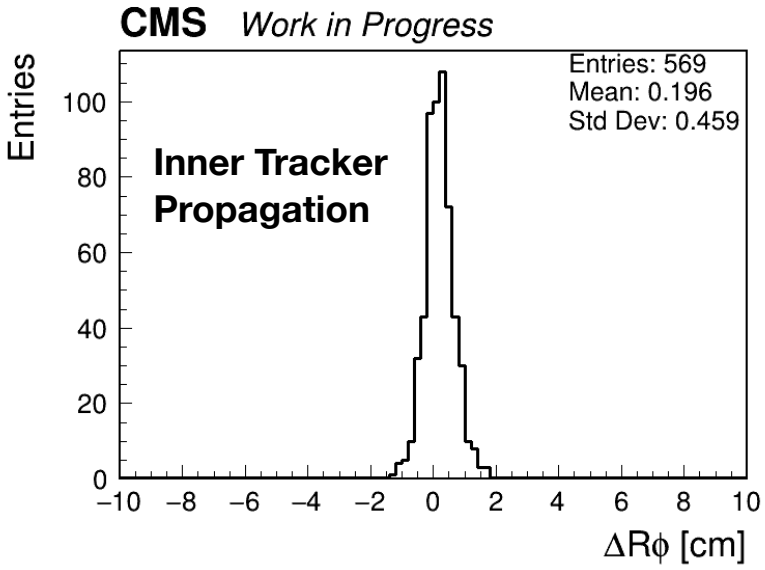
Track-based Muon Alignment

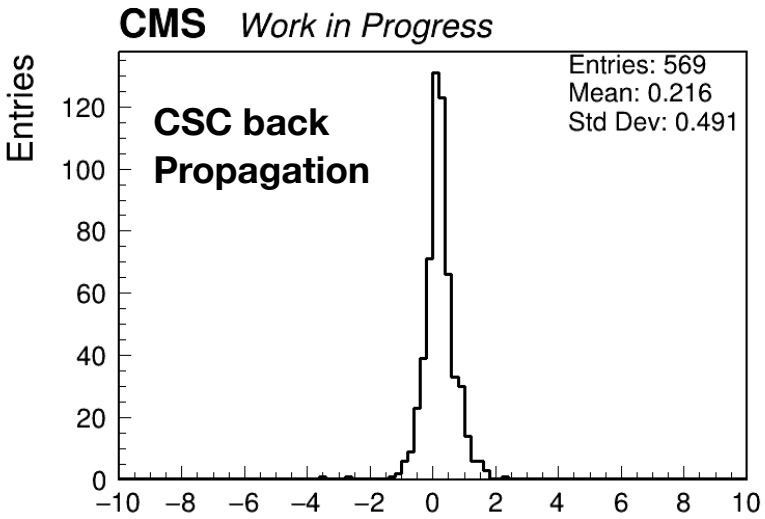


- **Track-based muon alignment (TBMA)**
  - Propagate the tracker part of muons into muon system
  - Muon residual: difference between reconstructed position and predicted position on the muon chamber
- **The TBMA technique is proven to be efficient, robust, and stable in Run1 and Run2**
- The algorithm is developed and integrated into CMSSW framework
- Sources of possible systematic uncertainties have been investigated and various improvements to reduce their effect are being developed
- **Muon system alignment is very important for muon reconstruction and TBMA has good accuracy of 100 μm order**
- **GEM-CSC trigger requires good GEM alignment accuracy**
  - **The relative GEM-CSC position is more important for the GEM alignment due to its use in the trigger**
  - **GEM alignment needs a new method**

GEM-CSC Back-propagation



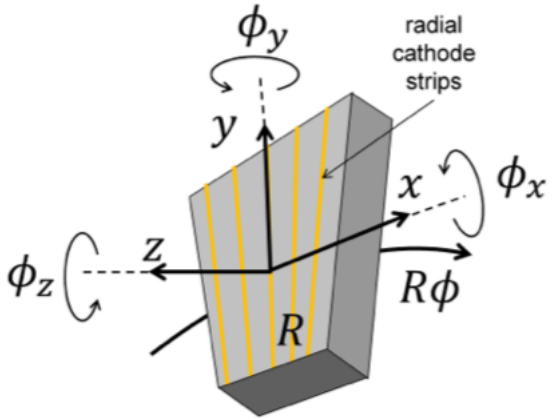


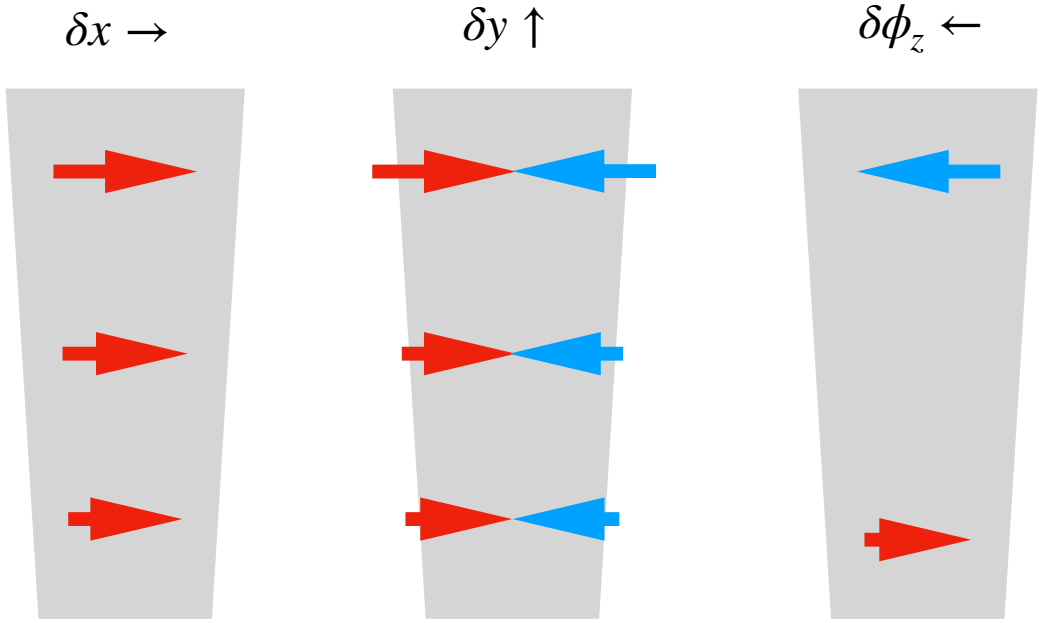


- **Inner tracker propagation: pass through large mass, reference position is inner tracker**
- **CSC-back propagation: less scattering, reference position is ME1/1**

2018 Slice Test Data:
Region -1, Chamber 28, Layer 2
$P_T > 30$ **GeV, contains ME11 segment**

GEM Alignment Variables





$\Delta R\phi = \cos\theta * \Delta x + \sin\theta * \Delta y$

θ: strip angle of recHit

Δx: $X_{prediction} - X_{recHit}$

Δy: $Y_{prediction} - Y_{recHit}$

Measured Position

Residual

$$\begin{pmatrix} \Delta(R\phi) \\ \Delta y_o \\ \Delta\frac{d(R\phi)}{dz} \\ \Delta\frac{dy}{dz}_o \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & -\frac{1}{2R}\frac{dx}{dz} & 0 & \left[\frac{x}{R}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta\phi_x \\ \delta\phi_y \\ \delta\phi_z \end{pmatrix}$$

Misalignment

$$\Delta(R\phi) = \underline{\delta x} + \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right]\underline{\delta y} - \frac{dx}{dz}\delta z - y\frac{dx}{dz}\delta\phi_x + x\frac{dx}{dz}\delta\phi_y - \underline{y\delta\phi_z}$$

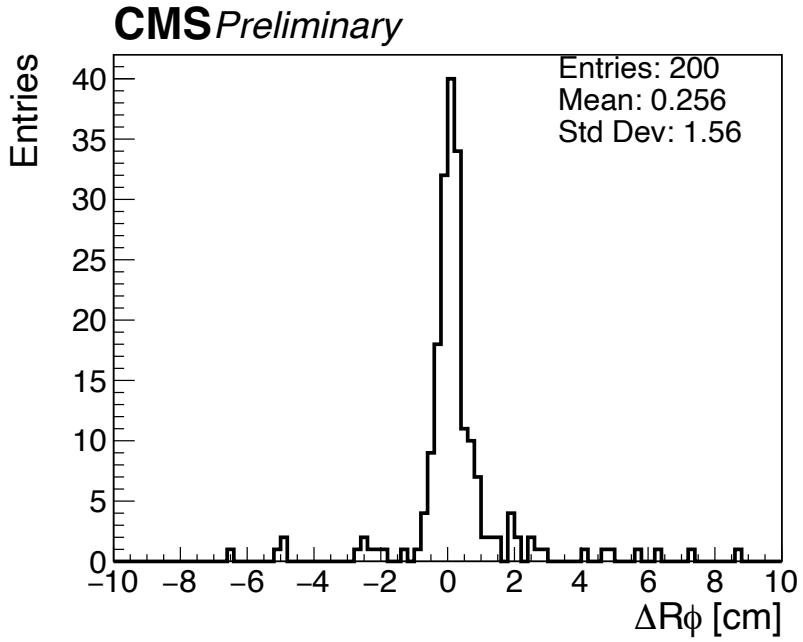
GEM Alignment Status

- Accuracy studies have been done - 300 μm expected
  - Test with a CMSSW simulation
  - The GEM alignment accuracy is comparable to the GEM spatial resolution
- Minimizer
  - MINUIT package
  - 1 DOF (δx, dominant alignment parameter) is working
  - Based on the alignment of the CSCs
- Test with dataset
  - Several global runs
  - 2018 slice test datasets

GEM Alignment Residual

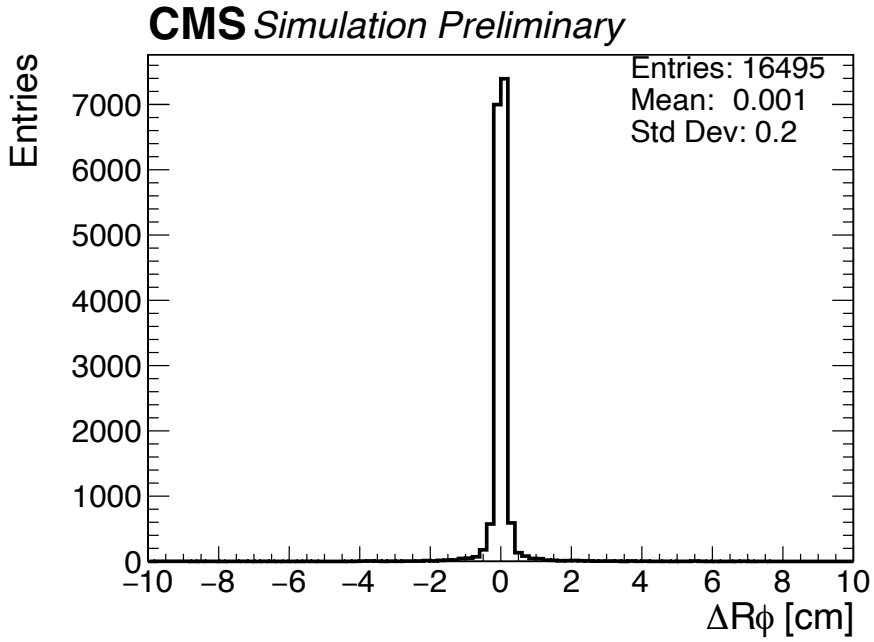
- GEM hits were detected during the CMS data taking exercises in November 2020. Each muon has GEM hits on the same η sector at the position predicted by back-propagation of an ME muon track. The matching requirement is $\left|\Delta R\phi\right| \equiv \left|R\phi_{GEM} - R\phi_{pred}\right| < 10$ cm (bottom left). This is compared to Monte Carlo simulation (bottom right). ⇒ Cosmic ray muons will be used for an initial GEM-ME alignment.

ME segments back-propagated



Before alignment

Cosmic Muon Simulation



Ideal geometry

Summary

- CMS GEM was developed to improve muon endcap trigger and tracking for HL-LHC
- First upgrade GE1/1 installation is completed
- Commissioning activities
  - Noise investigation
  - Thresholds and HV working point optimization
  - GEM-CSC EMTF trigger test
- CMS GEM has participated in global commissioning
- GEM Alignment is important for the GEM-CSC trigger
  - Accuracy studies have been done - 300 μm expected
  - Tested with several MCs and datasets

References

[1] CMS Collaboration, “The CMS Experiment at the CERN LHC,” *JINST,* vol. 3, p. S08004, 2008.

[2] CMS Collaboration, “Alignment of the CMS muon system with cosmic-ray and beam-halo muons,” *JINST,* vol. 5, p. T03020, 2010.

[3] CMS Collaboration, “Alignment of the CMS tracker with LHC and cosmic ray data,” *JINST,* vol. 9, p. P06009, 2014.

[4] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV,” *JINST,* vol. 13, p. P06015, 2018.

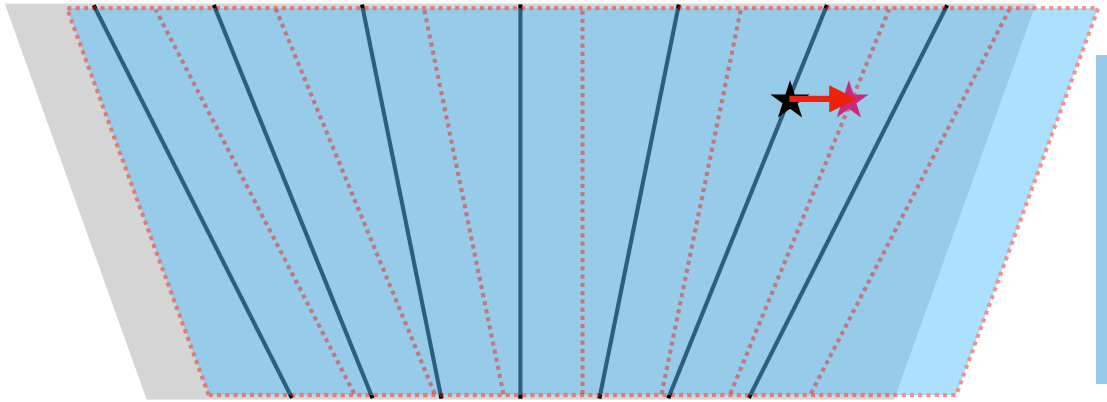
[5] CMS Collaboration, "CMS Technical Design Report for the Muon Endcap GEM Upgrade", 2015

Backup

Projection Matrix δx

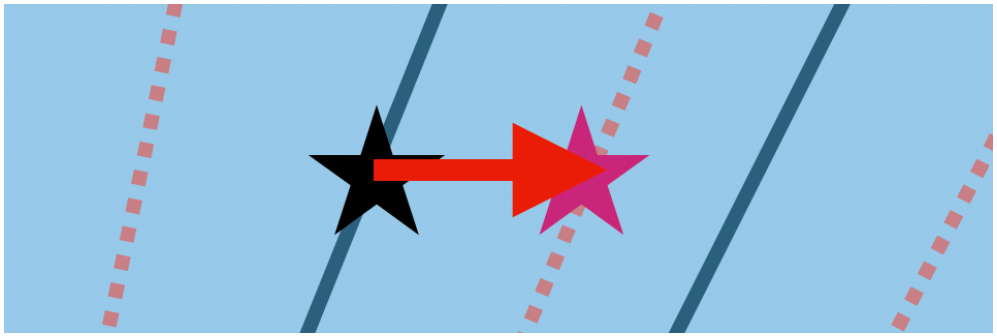
$$\begin{pmatrix} \boxed{\Delta(R\phi)} \\ \Delta y_o \\ \Delta\frac{d(R\phi)}{dz} \\ \Delta\frac{dy}{dz}_o \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & -\frac{1}{2R}\frac{dx}{dz} & 0 & \left[\frac{x}{R}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta\phi_x \\ \delta\phi_y \\ \delta\phi_z \end{pmatrix}$$

Chamber shift $+\delta x$



★ **GEM recHit**

★ **Propagation position**



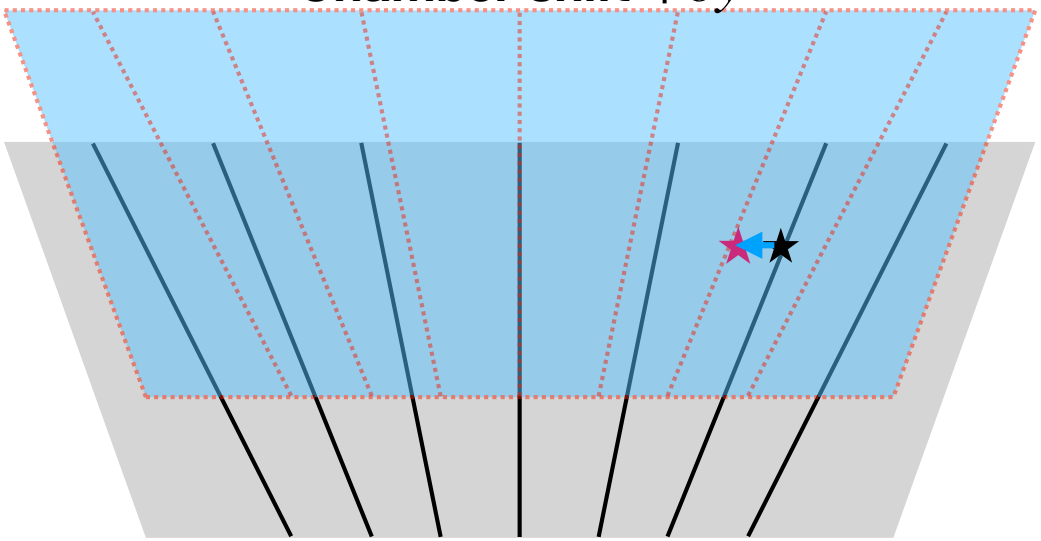
$$\Delta R\phi = \boxed{\delta x}$$

δx contributes to $\Delta R\phi$ residual with coefficient 1, the dominant parameter.

Projection Matrix δy

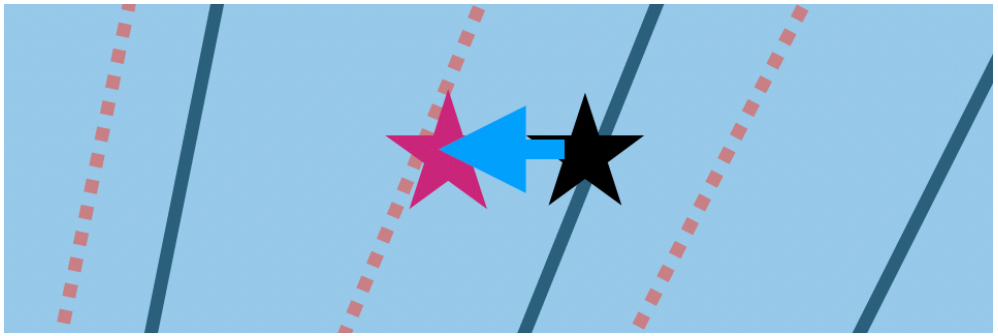
$$\begin{pmatrix} \Delta(R\phi) \\ \Delta y_o \\ \Delta\frac{d(R\phi)}{dz} \\ \Delta\frac{dy}{dz}_o \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & -\frac{1}{2R}\frac{dx}{dz} & 0 & \left[\frac{x}{R}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta\phi_x \\ \delta\phi_y \\ \delta\phi_z \end{pmatrix}$$

Chamber shift $+\delta y$



★ **GEM recHit**

★ **Propagation position**



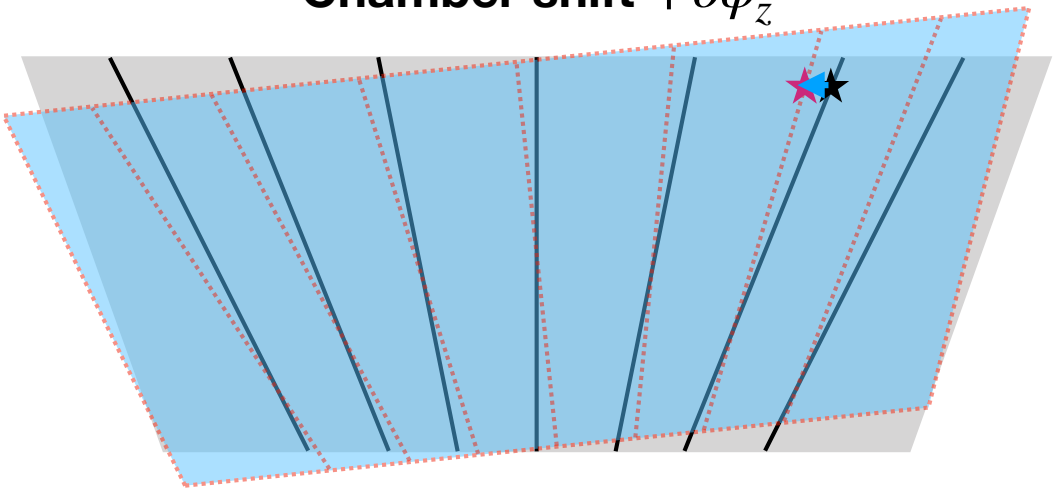
$$\Delta R\phi = \delta x - x/R \cdot \delta y$$

δy contributes to $\Delta R\phi$ residual with coefficient -x/R (local x and global R of propagation position, x/R ~ 0.014).

Projection Matrix $\delta\phi_z$

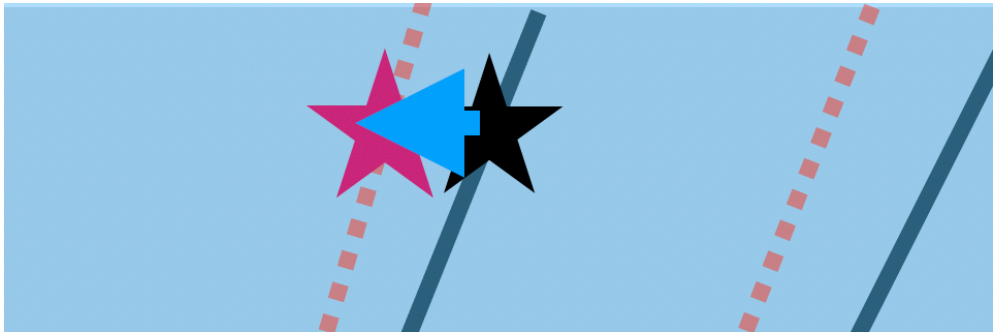
$$\begin{pmatrix} \Delta(R\phi) \\ \Delta y_o \\ \Delta\frac{d(R\phi)}{dz} \\ \Delta\frac{dy}{dz}_o \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{R}+3\left(\frac{x}{R}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & -\frac{1}{2R}\frac{dx}{dz} & 0 & \left[\frac{x}{R}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ \delta\phi_x \\ \delta\phi_y \\ \delta\phi_z \end{pmatrix}$$

Chamber shift $+\delta\phi_z$



★ **GEM recHit**

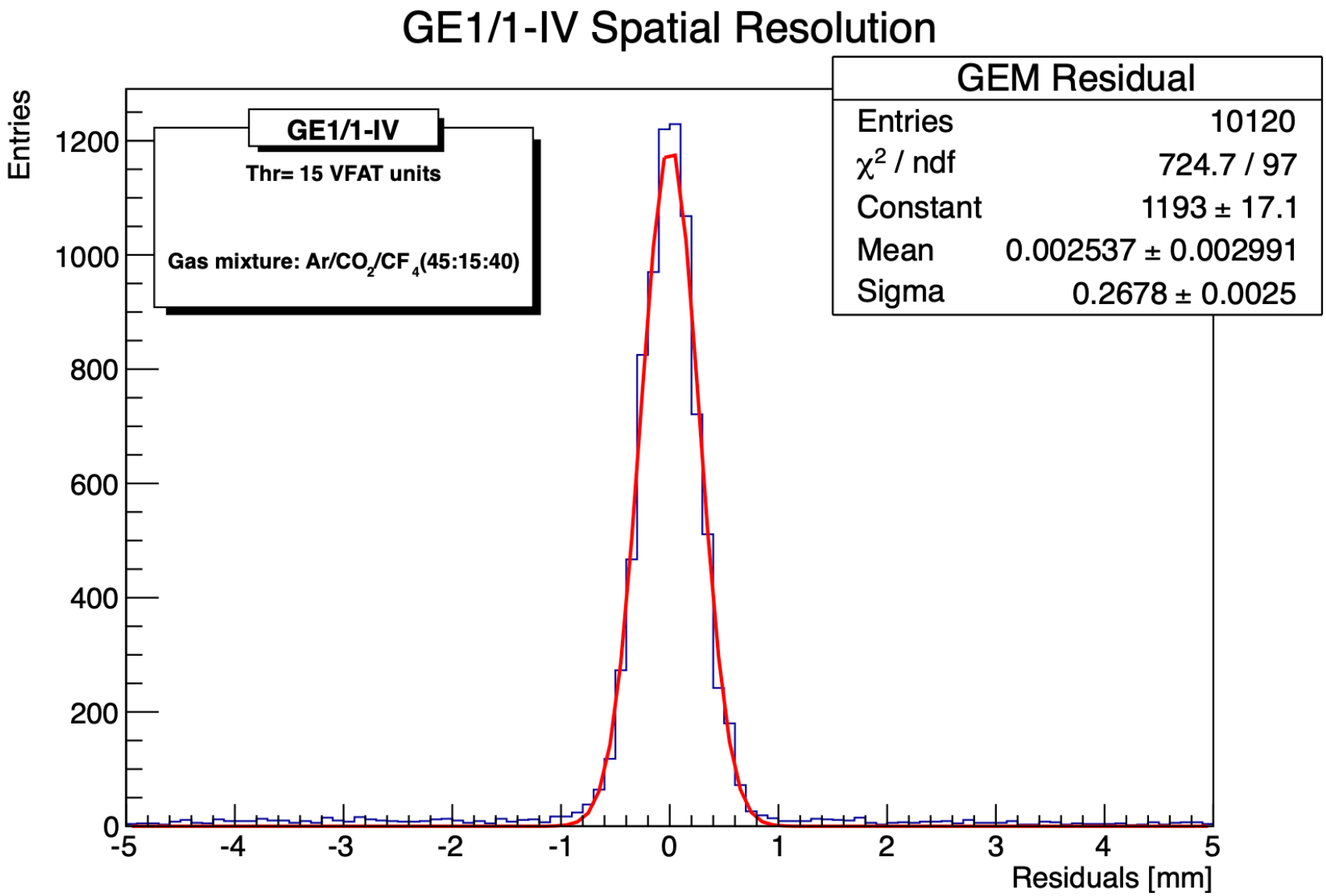
★ **Propagation position**



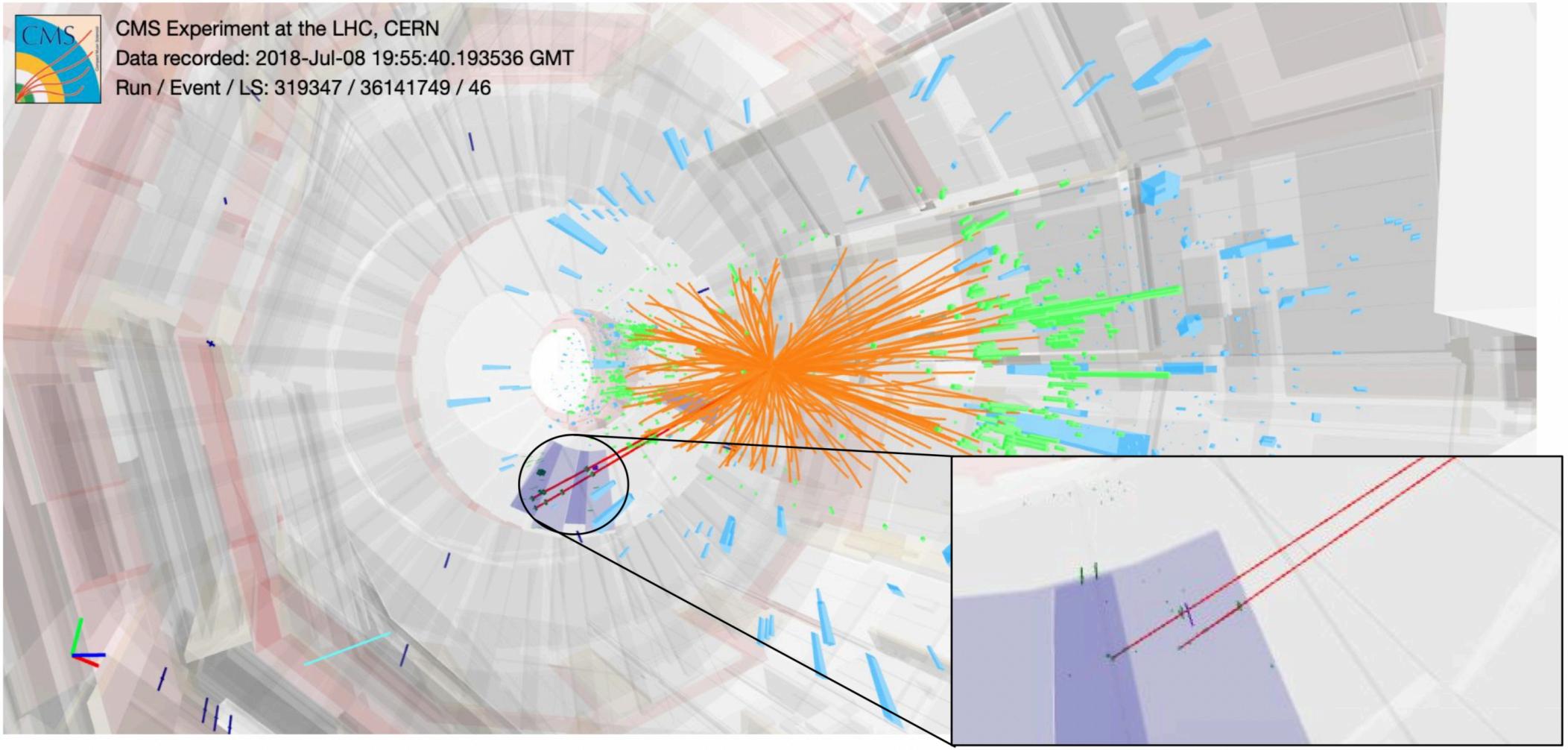
$$\Delta R\phi = \delta x - x/R \cdot \delta y - y \cdot \delta\phi_z$$

$\delta\phi_z$ contributes to $\Delta R\phi$ residual with coefficient -y (local y position of the propagation).

CMS-TDR-013 Fig.2.11



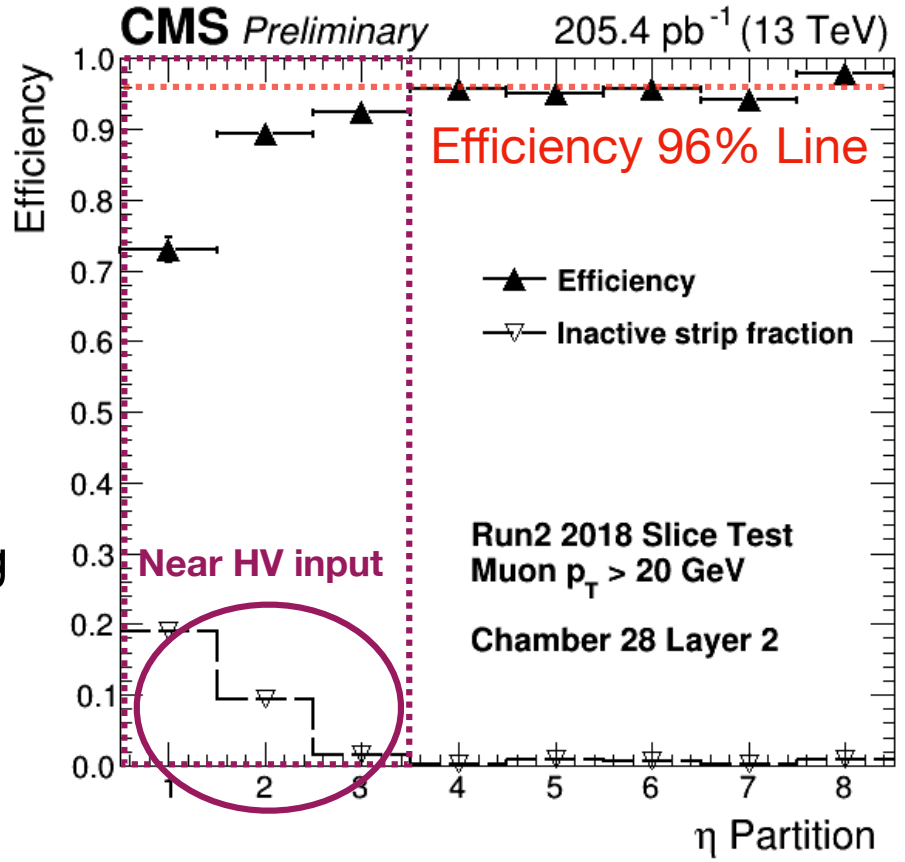
Slice Test Event Display



LHC Proton-proton collision event with muons from a reconstructed J/ψ candidate passing through one of the GE1/1 slice test super chambers

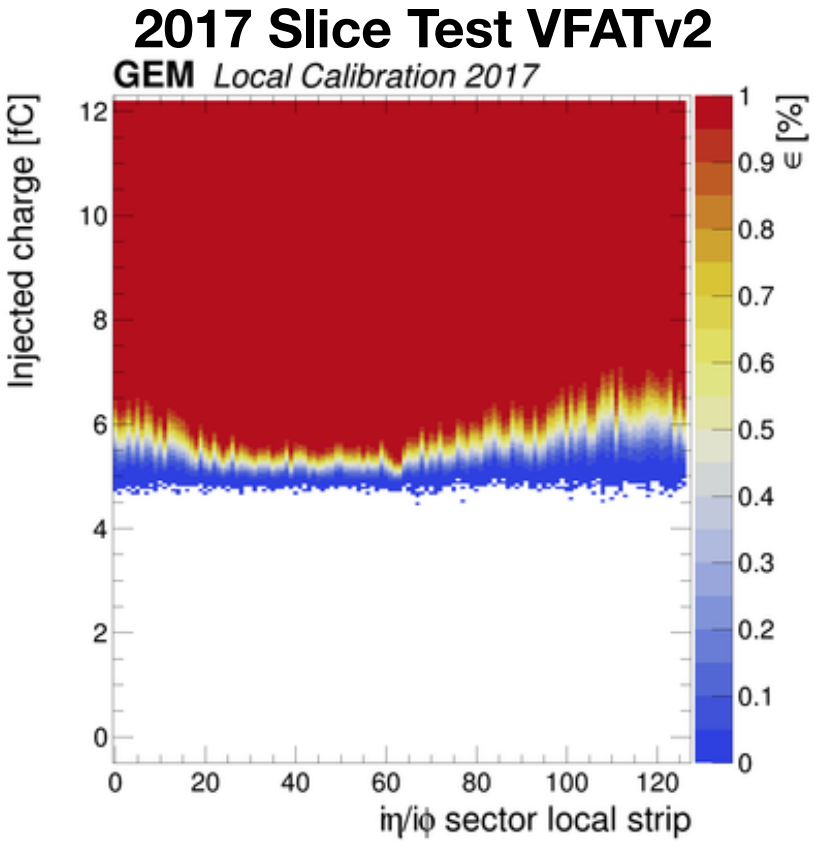
Slice Test

- During Run2, GEM performed operating demonstration
- 5 super chambers installed
  - Two detectors grouped into a super chamber
- GE1/1 Slice Test was an excellent learning opportunity
- Unforeseen technical and operational challenges occurred during the data taking
  - High electronic noise at GEB due to ground loop
  - Channel loss in VFAT
- **Re-designed GEB after Slice Test**
  - Added shield layer
  - Removed ground loop
- **Added VFAT input protection to prevent channel loss**



Slice Test efficiency measurement results by eta partition. Efficiency is strongly correlated with inactive strip fraction.

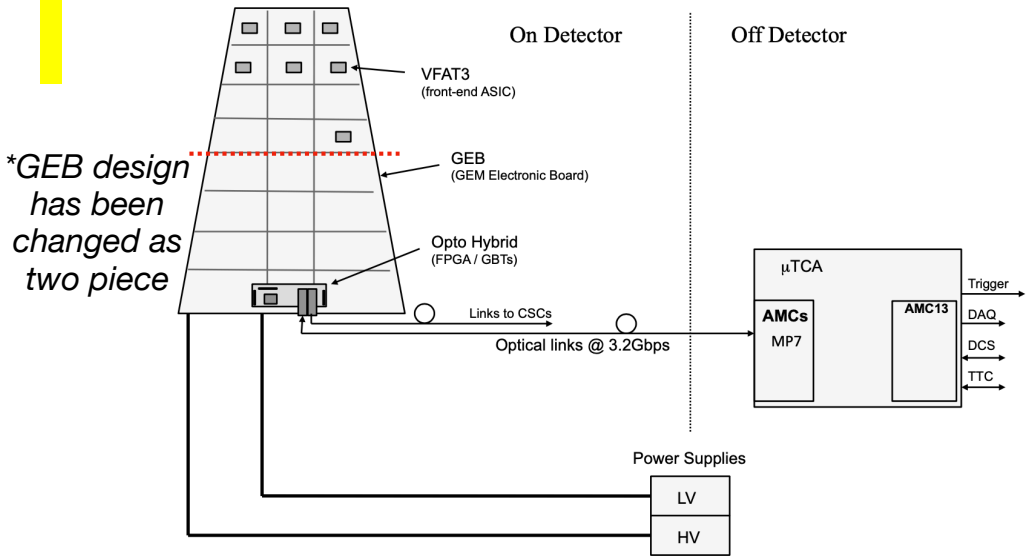
Calibration



S-curves calibration is performed by sweeping injected charge and counting number of hits at constant comparator threshold

- **Since digitized data comes from VFATs, RAW data has no charge or pedestal information**
- GEM DAQ system can perform daily calibration scan
- Calibration results mask channels that are noisy or dead
- **GEM hit reconstruction considers masked channel information to avoid splitting hits**

CMS GEM Readout System



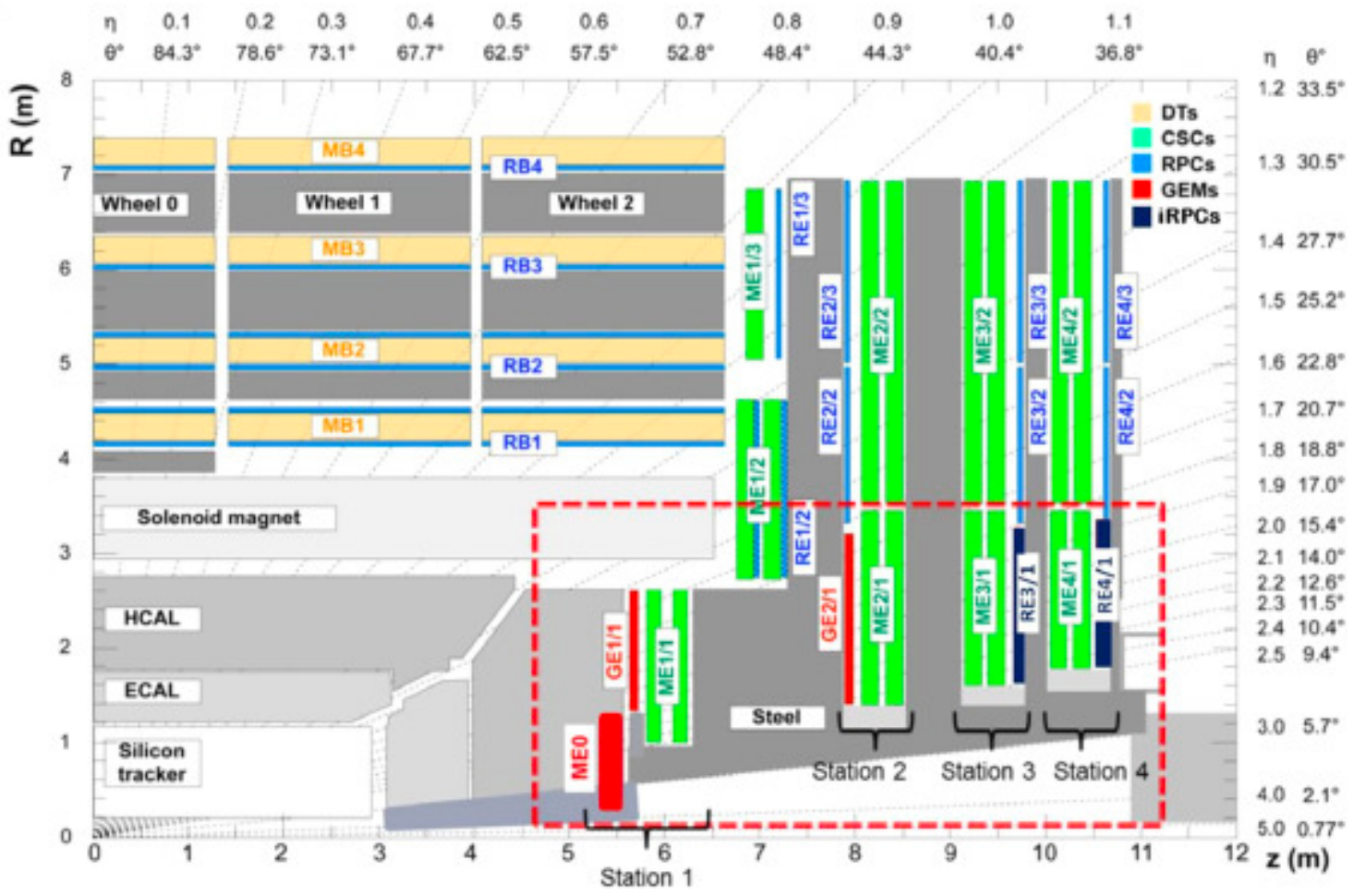
*GEB design has been changed as two piece

CMS-TDR-013 Fig. 3.1

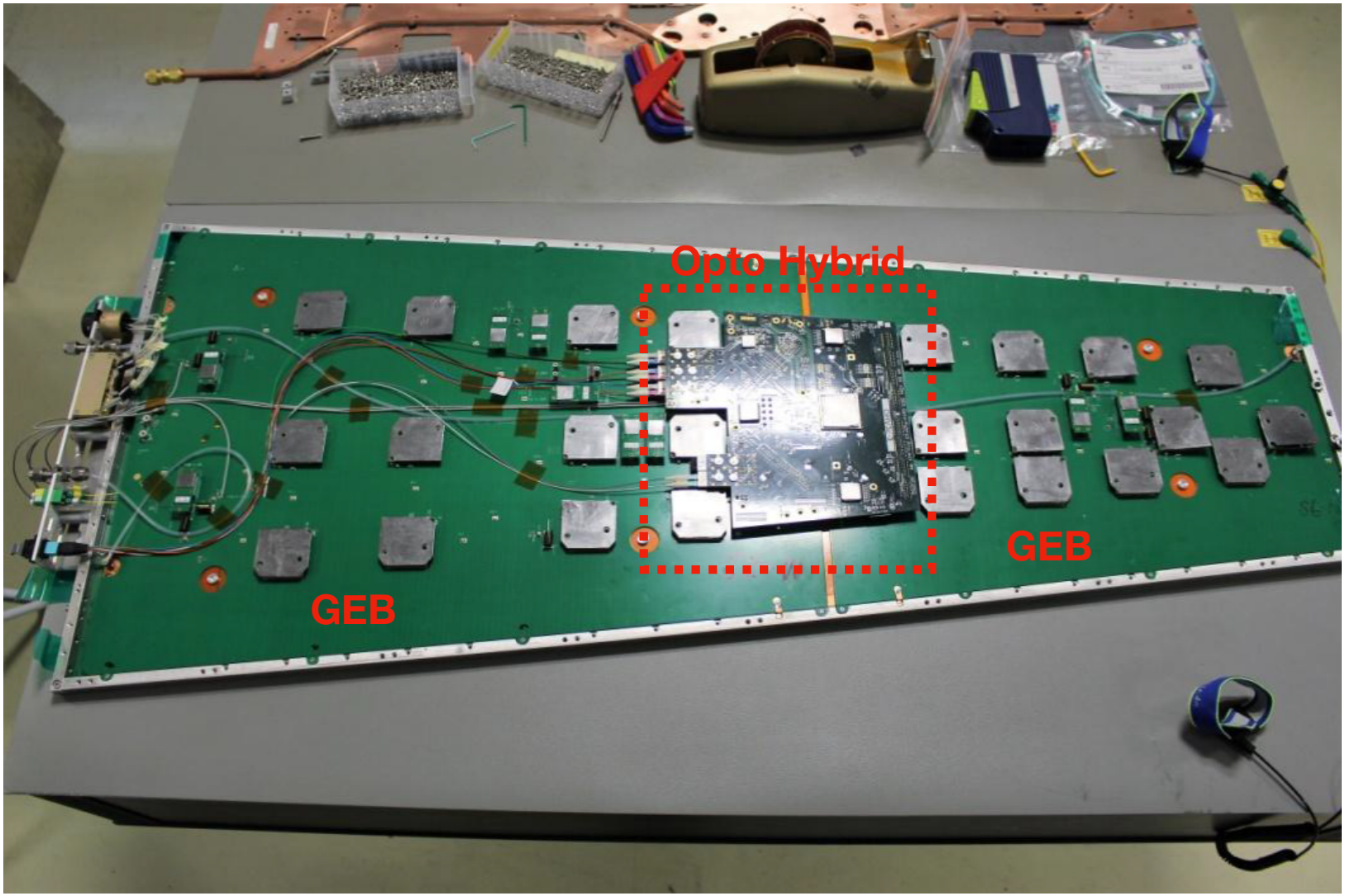
- CMS GEM readout system is fully new electronics chain
- Front-end ASIC (VFAT) reads GEM detector strip charge and sends digitized data
- One VFAT has 128 channels
- One detector has 24 VFATs (8 eta partitions and 3 local phi)

- 128 channel chip
- Provide tracking and trigger information
- Trigger information: Minimum fixed latency with granularity of 2 channels
- Tracking information: Full granularity after Level-1 trigger accept (L1A).
- L1A capability: L1A latency beyond 12.5 μs
- Time resolution of less than 7.5 ns (with detector).
- Radiation resistant up to100 MRads (radiation hardness of up to1MRad is sufficient for the GE1/1 application through Phase-II)

ME0, GE1/1, and GE2/1

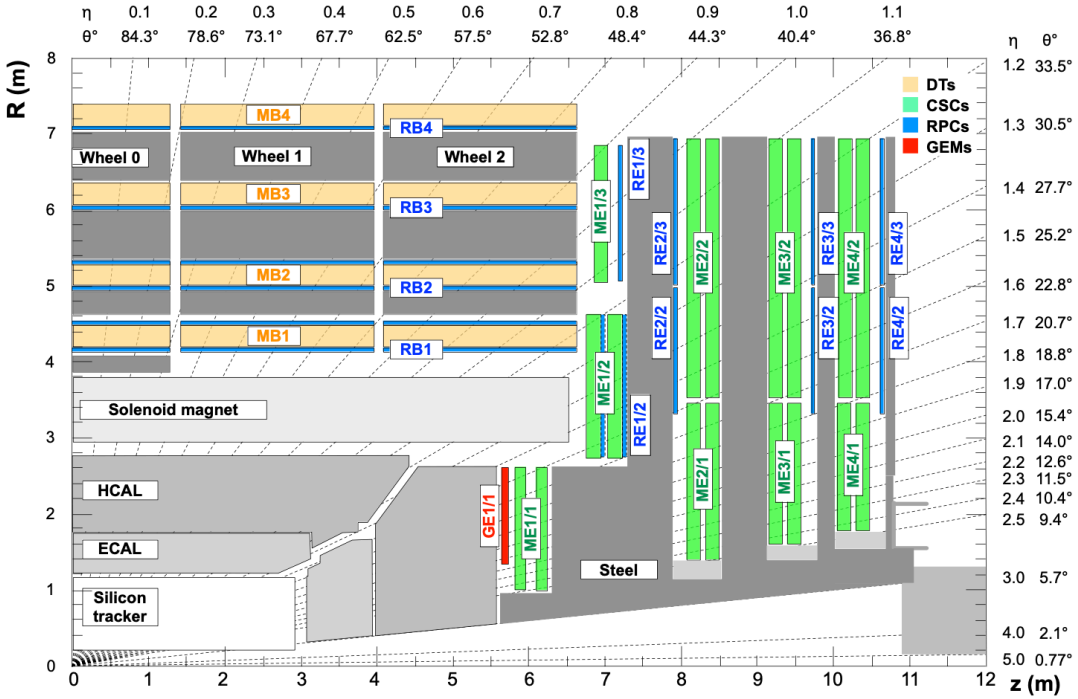


GEM GEB



What is CMS/GEM

- **The CMS muon system plays an important role in the discovery of new physics like the Higgs boson and new particles.**
- The next phase of the LHC is planned to improve the discovery power by increasing luminosity. The high luminosity LHC (HL-LHC) will be a harsh environment of pp collisions and will require high-performance muon trigger and muon track reconstruction, especially in the forward endcap region.
- **In order to maintain the performance of the CMS muon system, the CMS collaboration has been developing a Gas Electron Multiplier (GEM) detector for the endcap regions of the CMS muon system.**
- The new sub-detector system requires a new procedure of commissioning and alignment to be developed.



CMS-TDR-013 Fig. 1.1

GE1/1: GEM End-cap station1 ring1

Drift Tube chambers (DTs)
Cathode Strip Chambers (CSCs)
Resistive Plate Chambers (RPCs)

Commissioning

- Noise investigation
  - Reduce the noise to < 1 fC per chamber
  - Studies performed on chamber with high noise
  - Modifications made to connectors on LV cables
- Thresholds and HV working point optimization
  - Thresholds and HV working point to be determined iteratively
  - Efficiency measurements with reconstructed cosmic muons (CSC to GEM propagation)
- CMS endcap muon track finder (EMTF)
  - GEM-CSC trigger test