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Beam Particle Tracking for the MUSE Experiment at PSI

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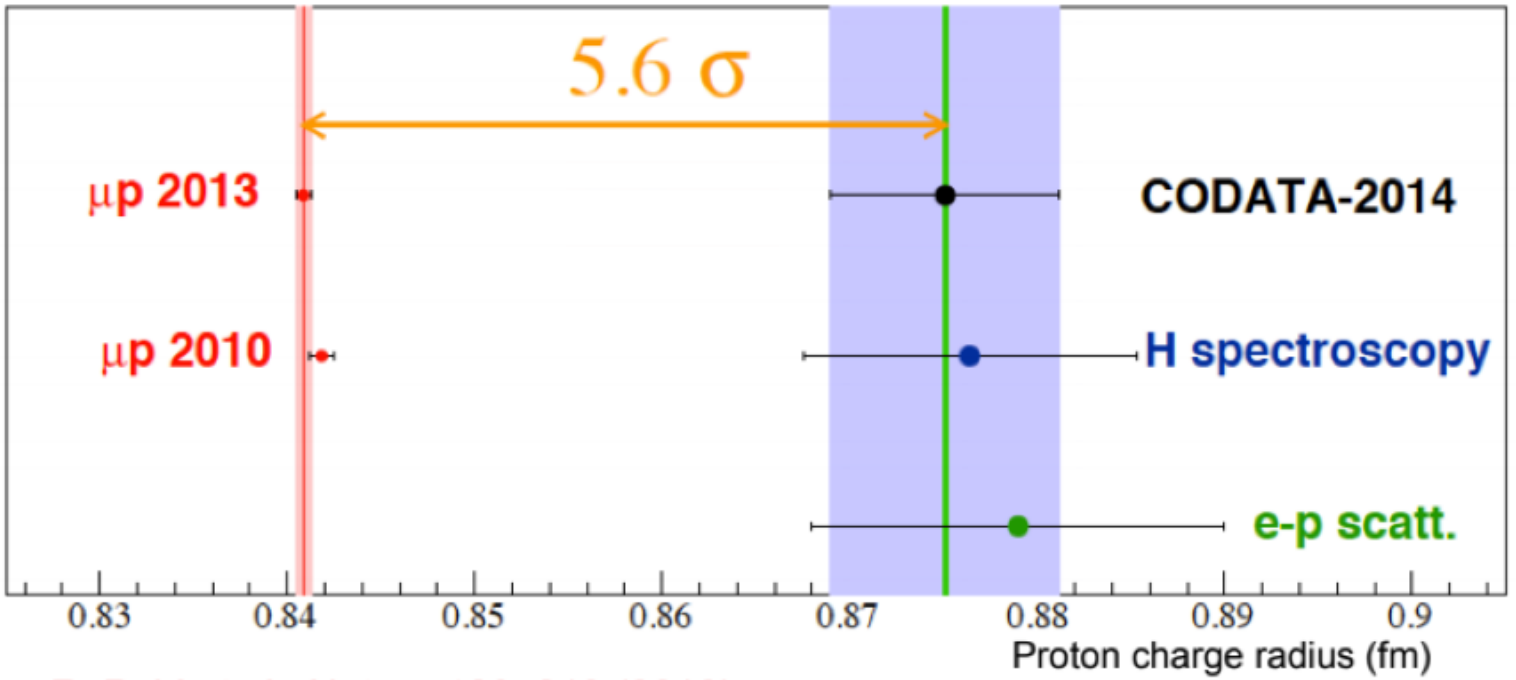
- Proton Radius Puzzle
- **MU**on **S**cattering **E**xperiment (MUSE)
- Experimental Set-up at Paul Scherrer Institute (PSI)
- GEM Detectors
- GEM Analysis
- Conclusion

Proton Radius Puzzle

The proton rms charge radius measured with

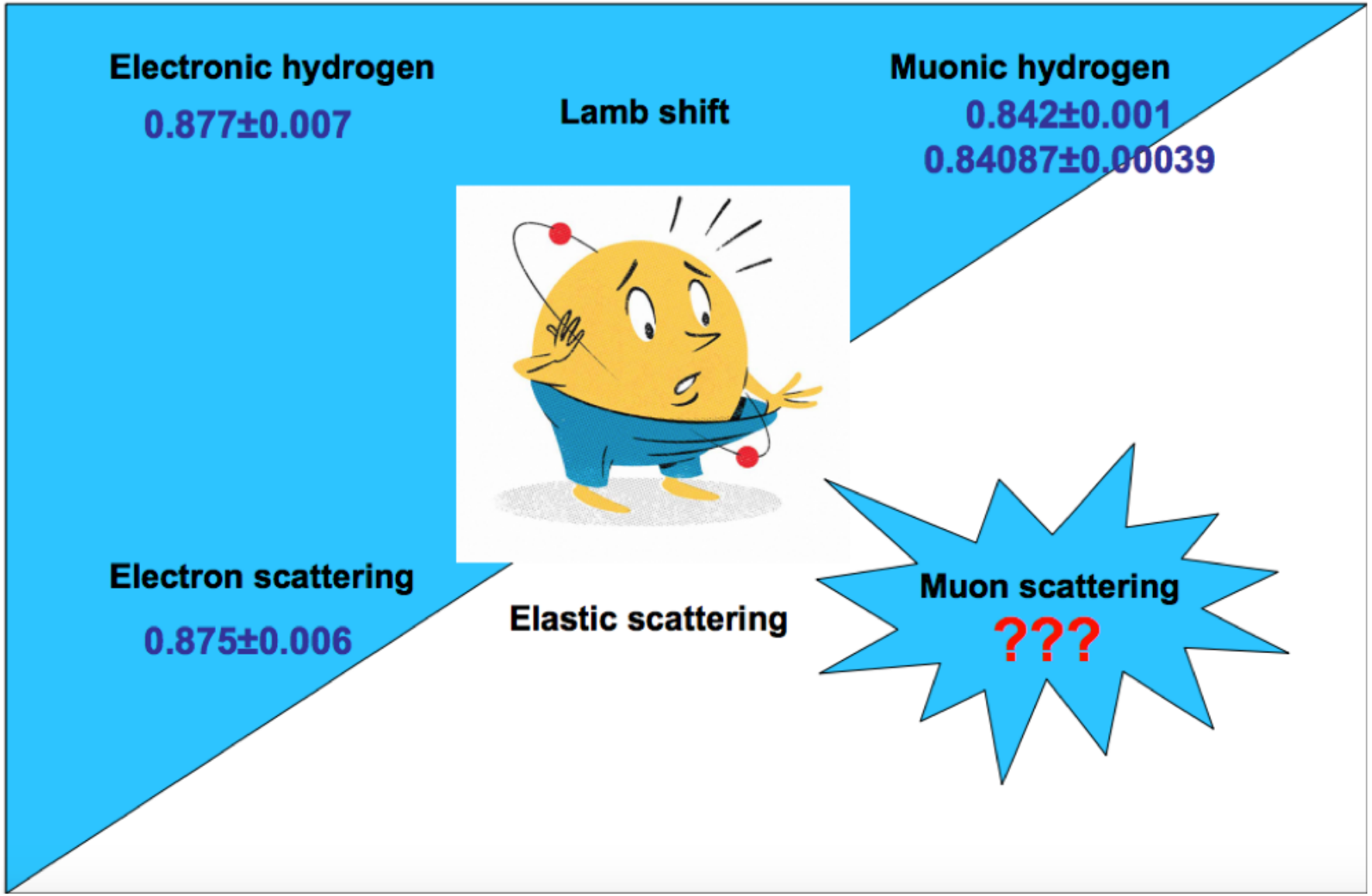
electrons: 0.8751 ± 0.0061 fm (CODATA2014)

muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

Motivation for μp Scattering



MUSE


Paul Scherrer Institute
Villigen, Switzerland

- Measurement of elastic electron and muon scattering on the proton.
- Measuring with both beam polarities.
- Determine cross section, form factors, precise radius, test lepton universality, and measure two-photon exchange.

Beam Specification:

- 590 MeV, 50 MHz, 2 mA (1.2 MW) proton beam;
- Momentum range: 100 - 500 MeV/c
- Secondary beam up to 3 MHz of $\approx$ 2 – 15 % μ's, 10 – 98 % e's, 0 – 80% π's

Experimental Set-up at PSI

To identify the scattered particles

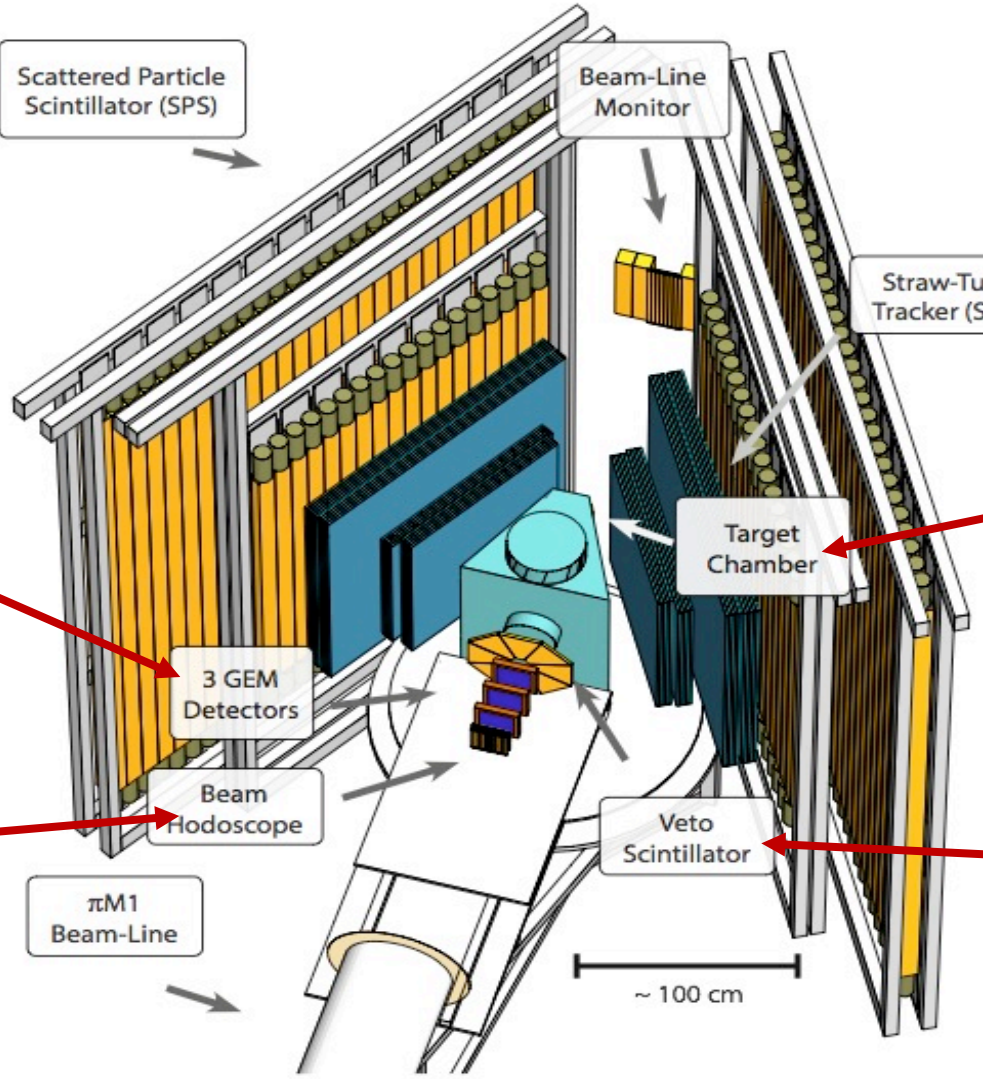
Measure the trajectories of scattered particles

To measure the trajectory into target

Liquid hydrogen

Measures RF time and provides TOF

Vetoes any event if beam particle hits the Veto Scintillator

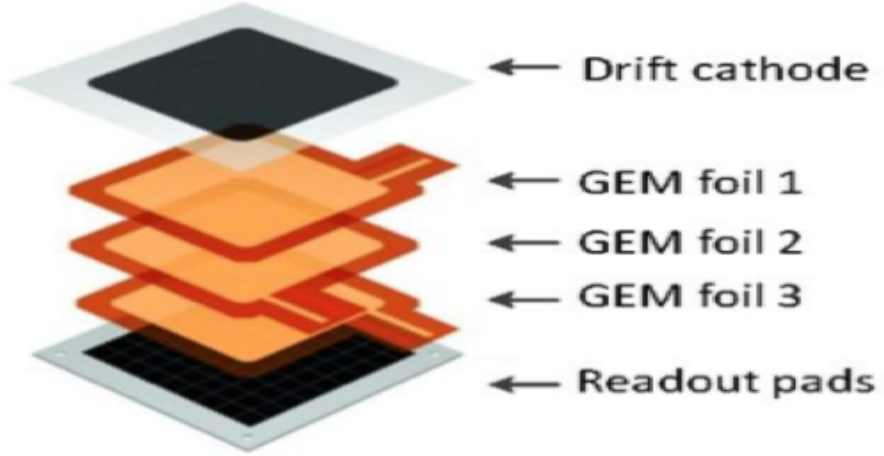


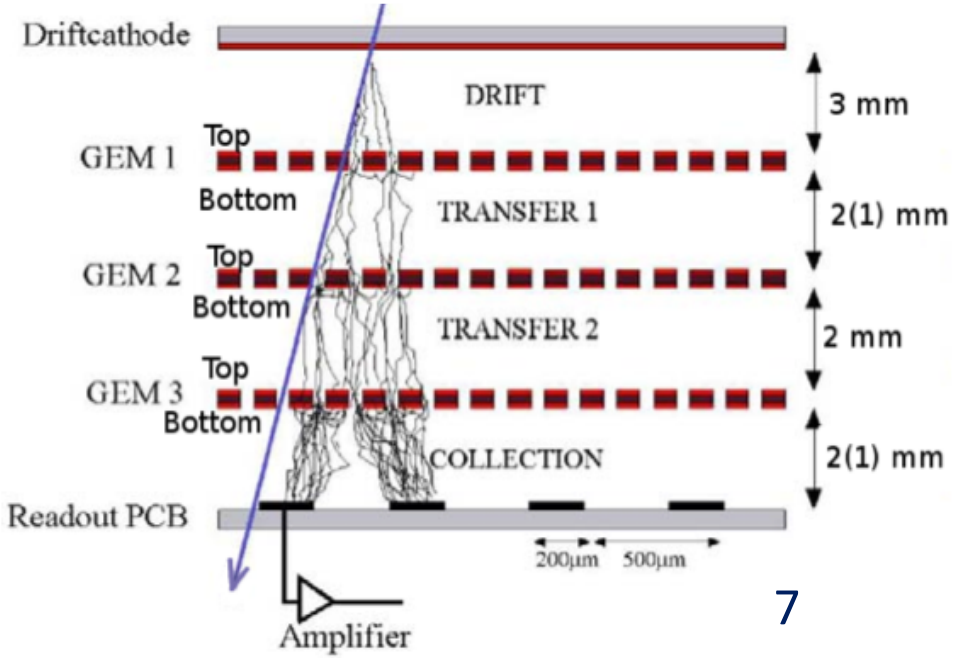
- **Using 115, 153, and 210 MeV/c**
- **$\theta \approx 20° - 100°$, $Q^2 \approx 0.002 – 0.08$ GeV²**

Gas Electron Multiplier (GEM)

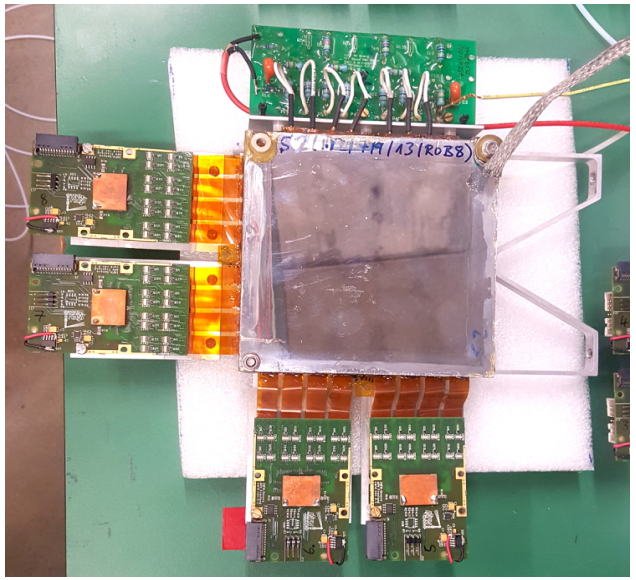
- Made up: kapton foil and copper clad
- Coulomb interaction ionize the gas and create electron-ion pairs.
- With suitable potentials, electrons released in the upper gas layer drift into the first GEM.
- Avalanche amplification occurs in the holes.
- 2-D readout plane consist of copper strips.

Schematic of triple-GEM detector

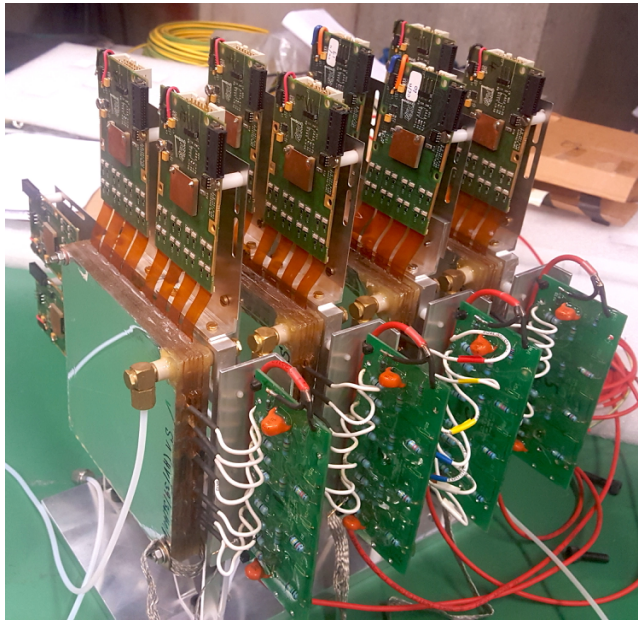


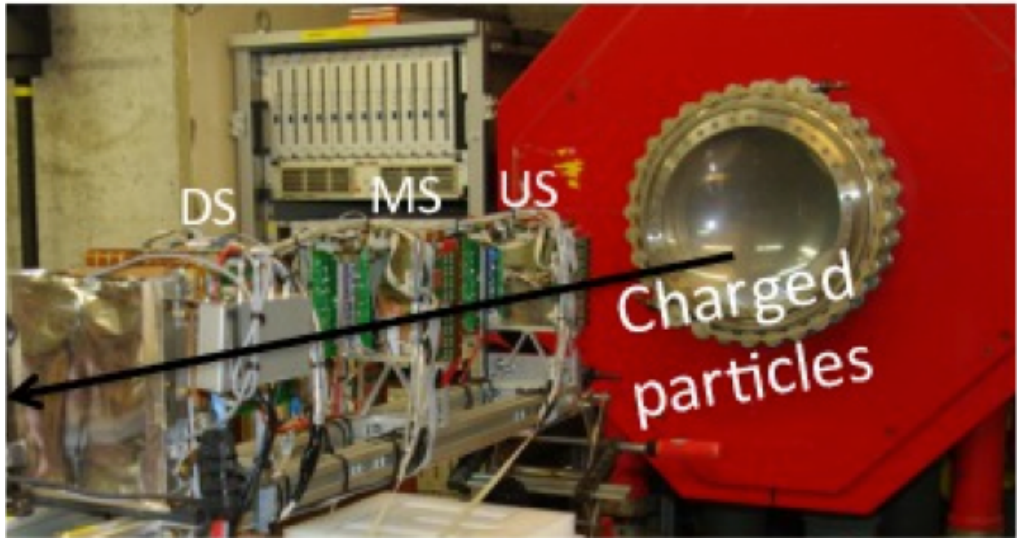


GEMs for MUSE



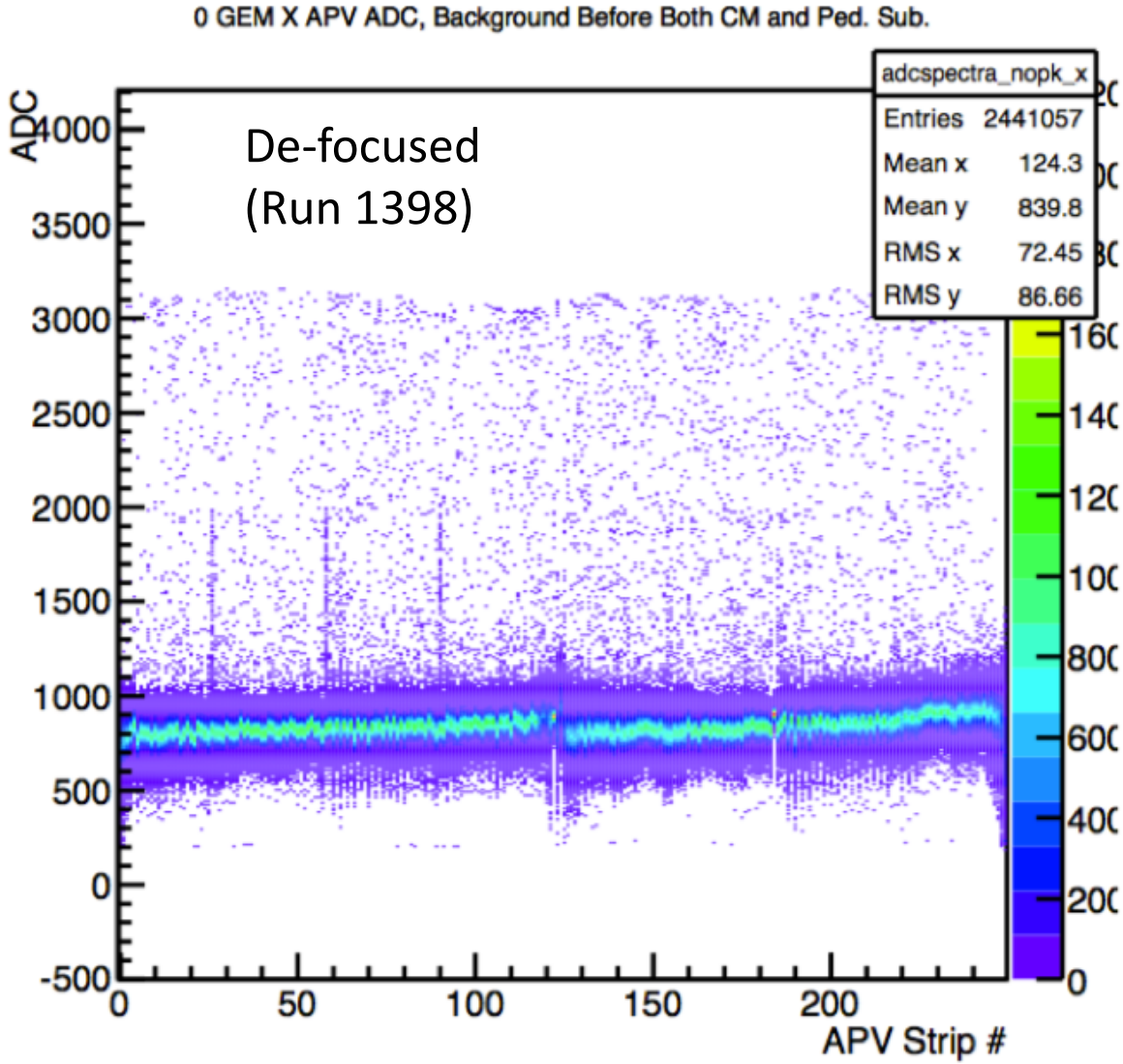
- These GEMs were built at Hampton University for OLYMPUS experiment.
- Three 10 x 10 cm² triple layer GEM detectors.
- Supplied $ArCO_2$ gas mixture (70:30 ratio)
- Each GEM with four APV-25 frontend chips to read analog signals from the readout strips.
- Total of 1500 readout channels per telescope (500 per element).

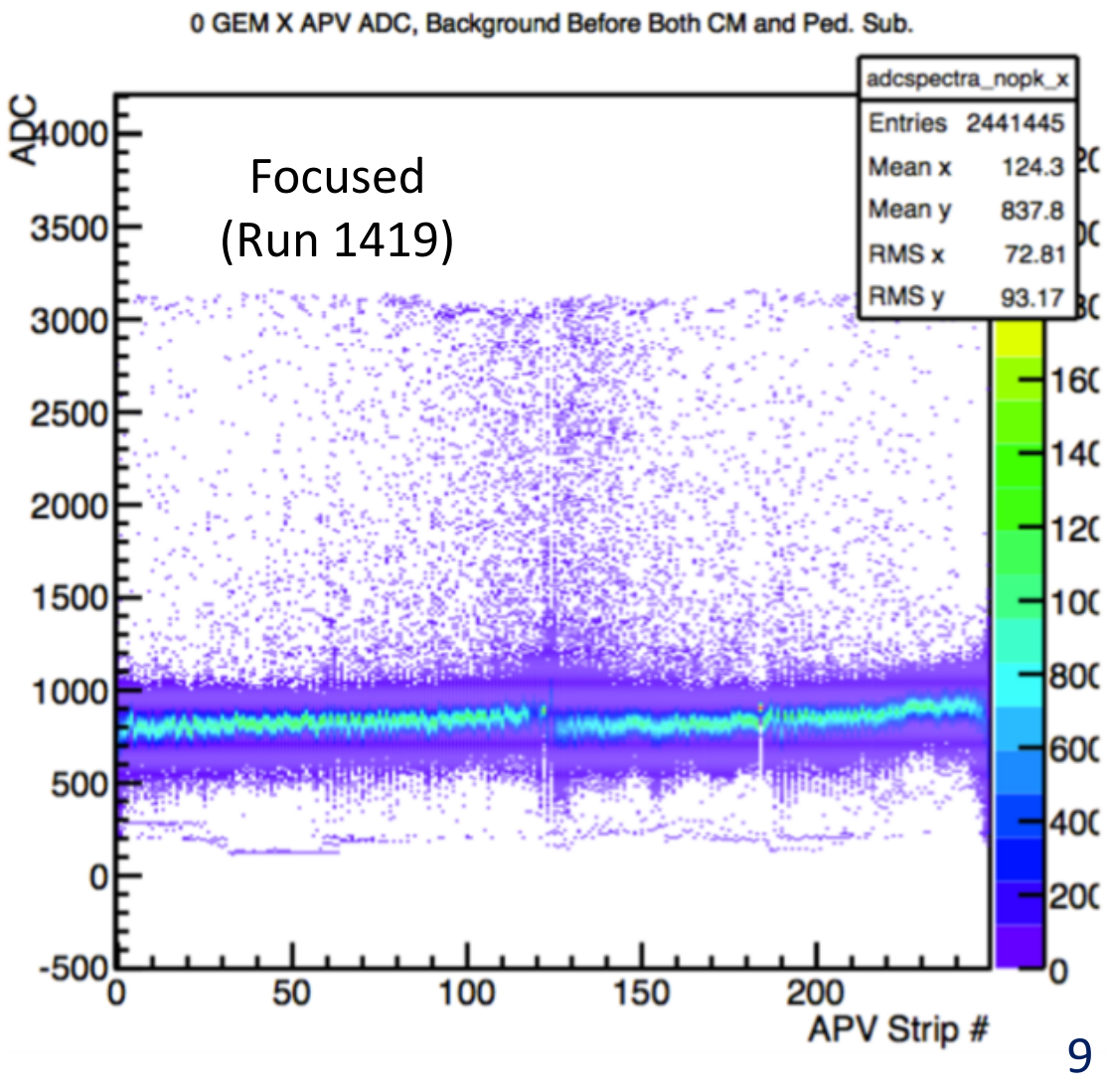




GEM Data Analysis: Raw ADC vs. Strip Number (US)

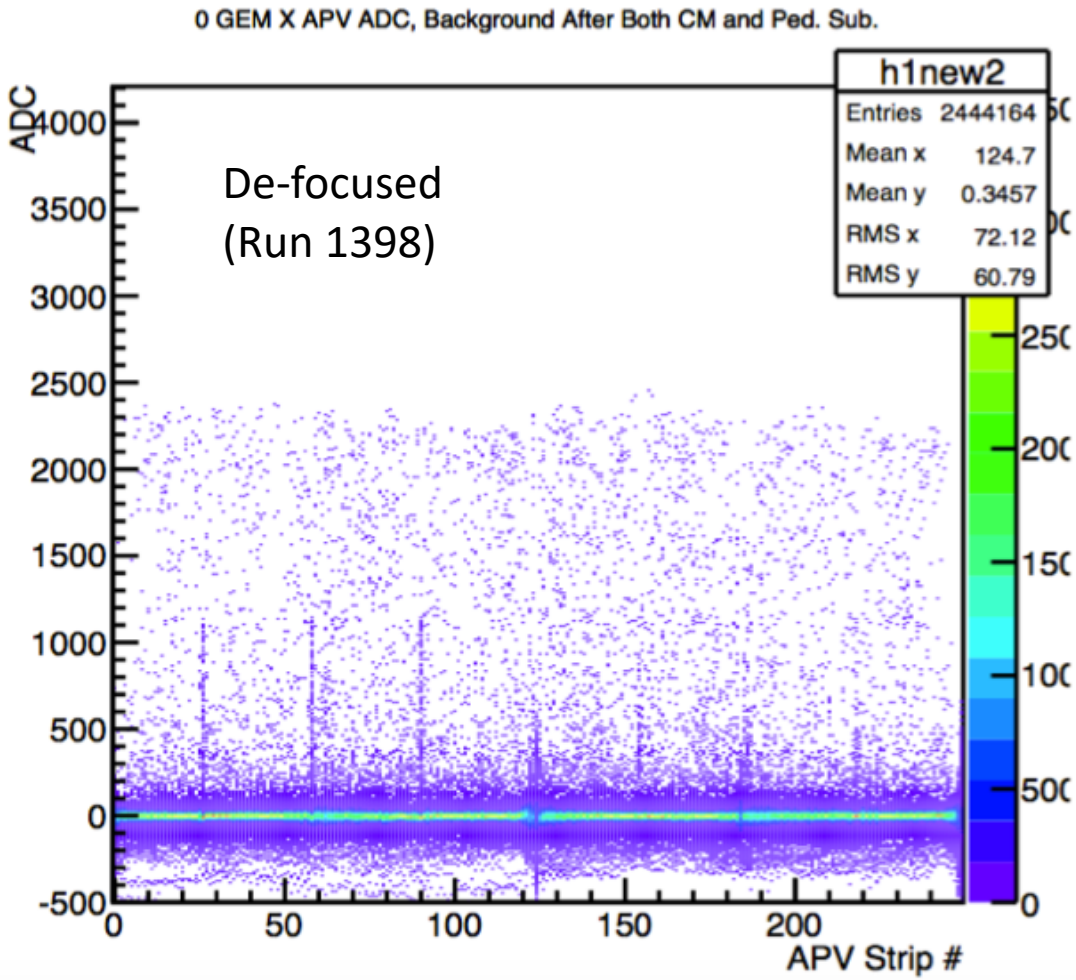
- The analog signals are digitized by Analog Digital Converter (ADC).
- ADC records the integration of the analog signals over time for the total charge registered by a strip.

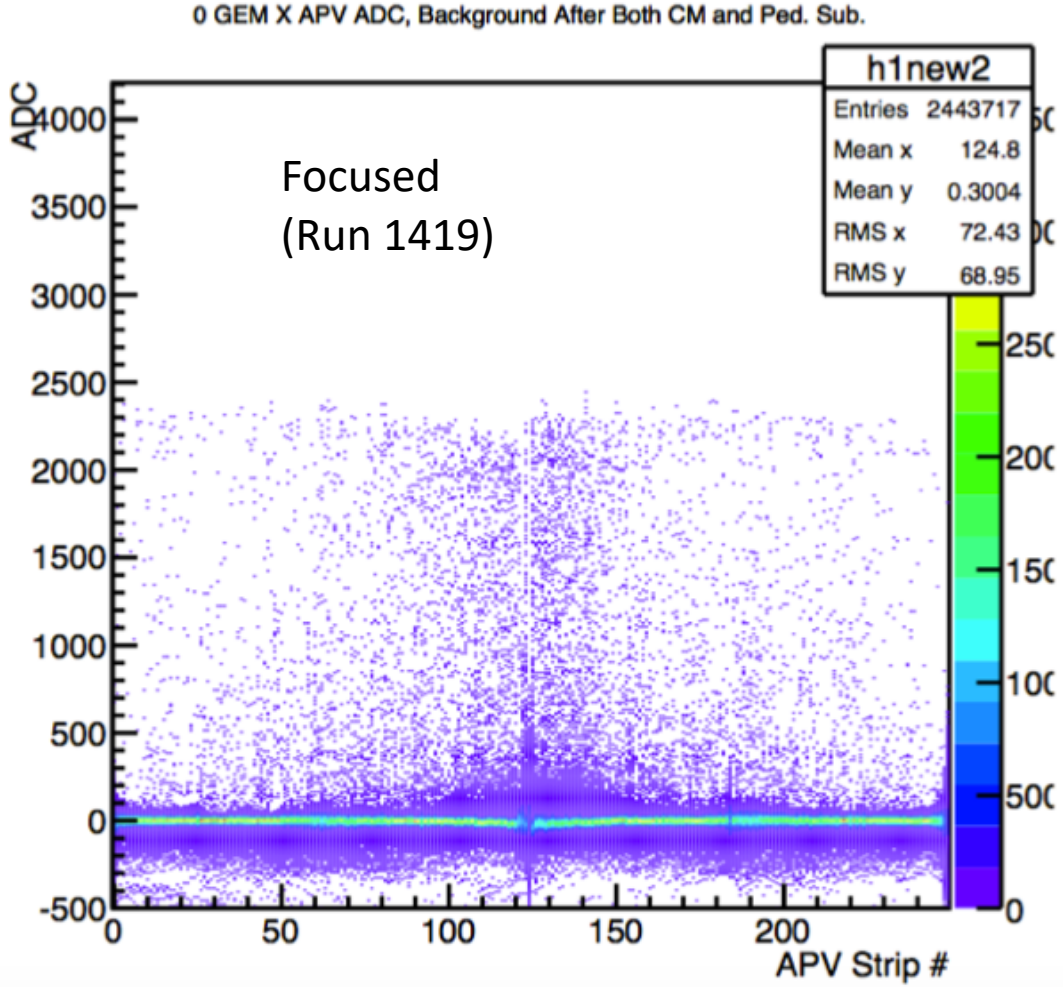




GEM Data Analysis: ADC vs. Strip Number (US)

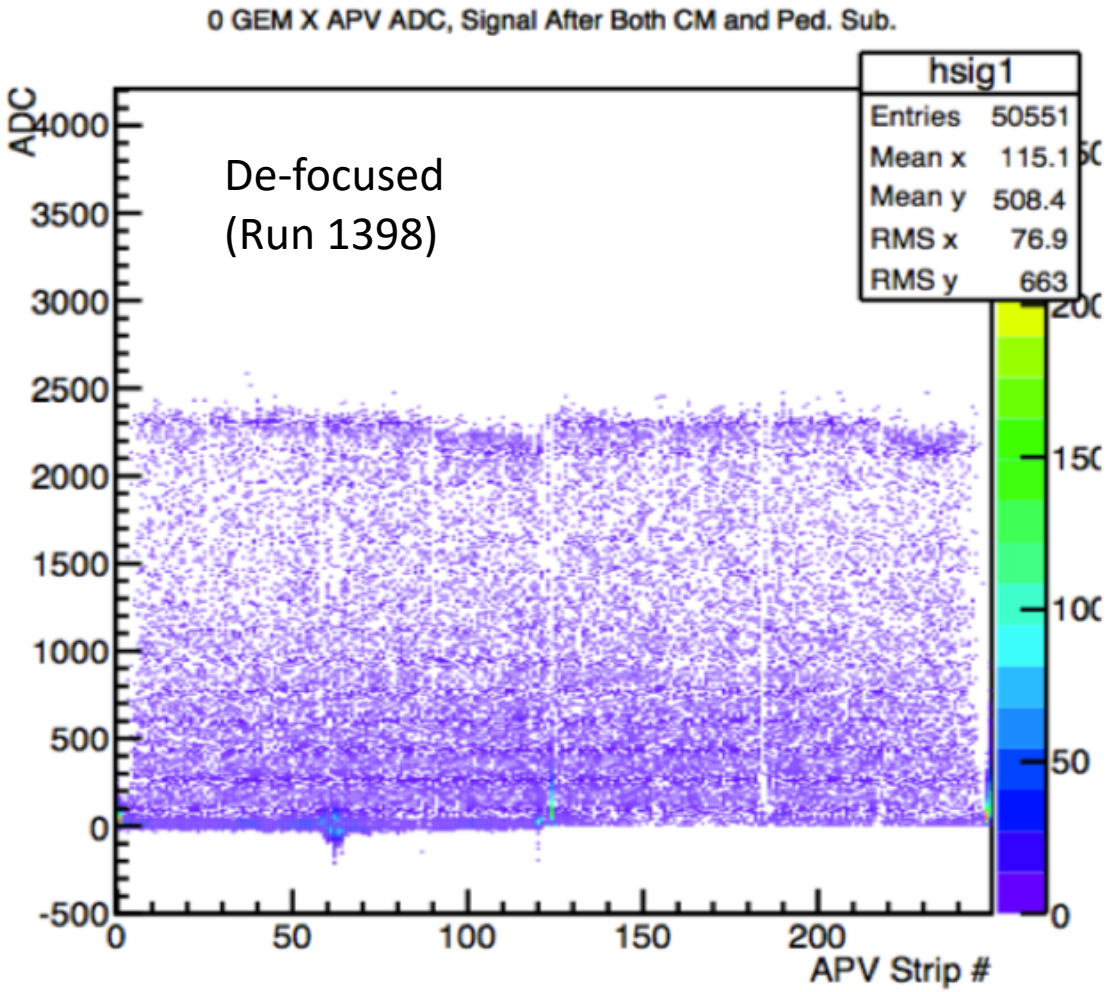
- The background noise present in the raw ADC would affect the original signal.
- To reduce the background noise, common-mode and pedestal subtraction was applied on raw data.

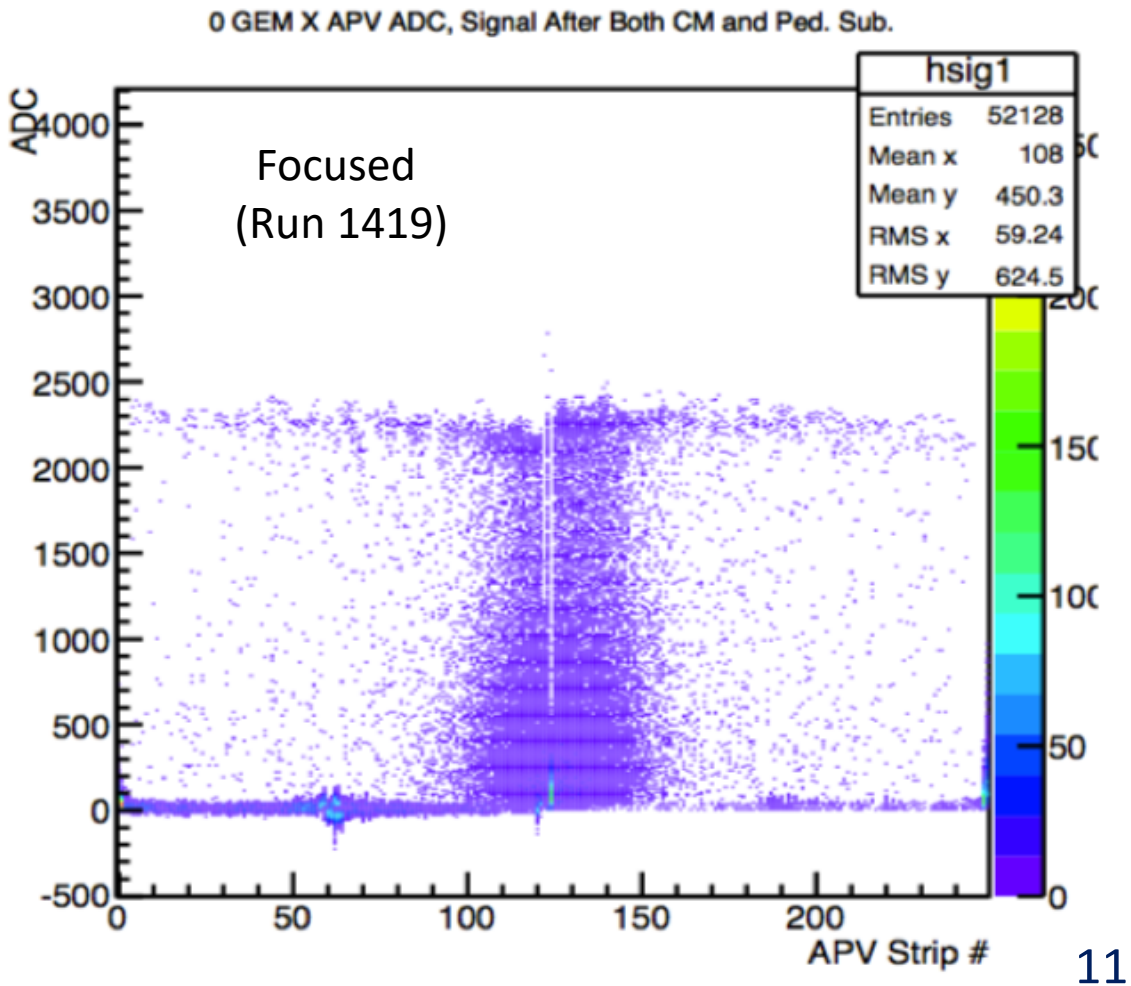




GEM Data Analysis

- Only channels with hits participating in clusters.
- Hits: channels above the threshold
- Clusters: 2 or more arrays of adjacent hits. Cluster candidates are chosen by pairing the X and Y local maxima and charge sharing.

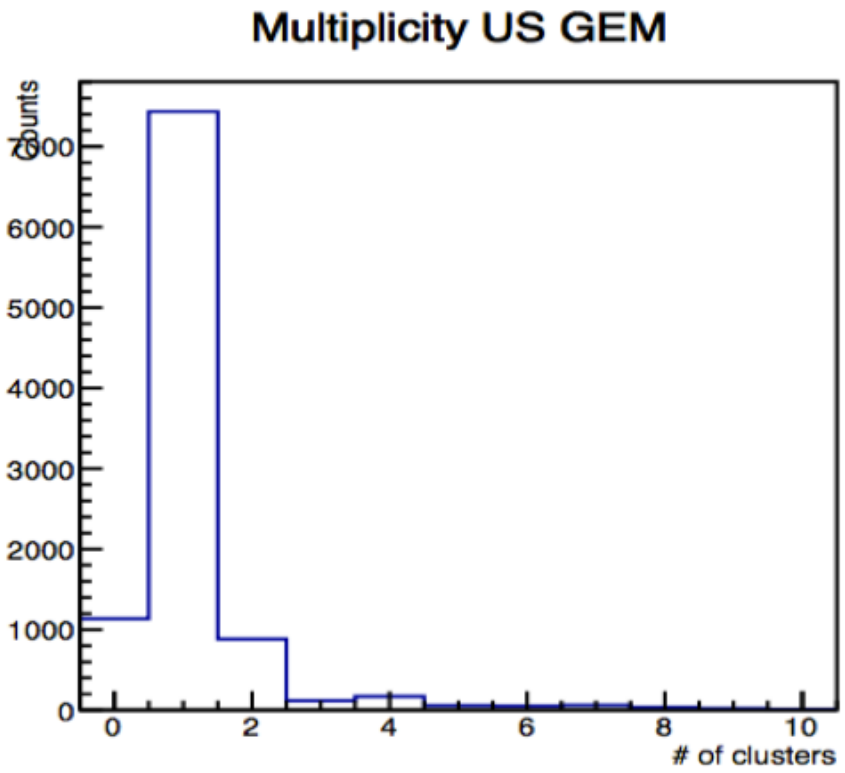




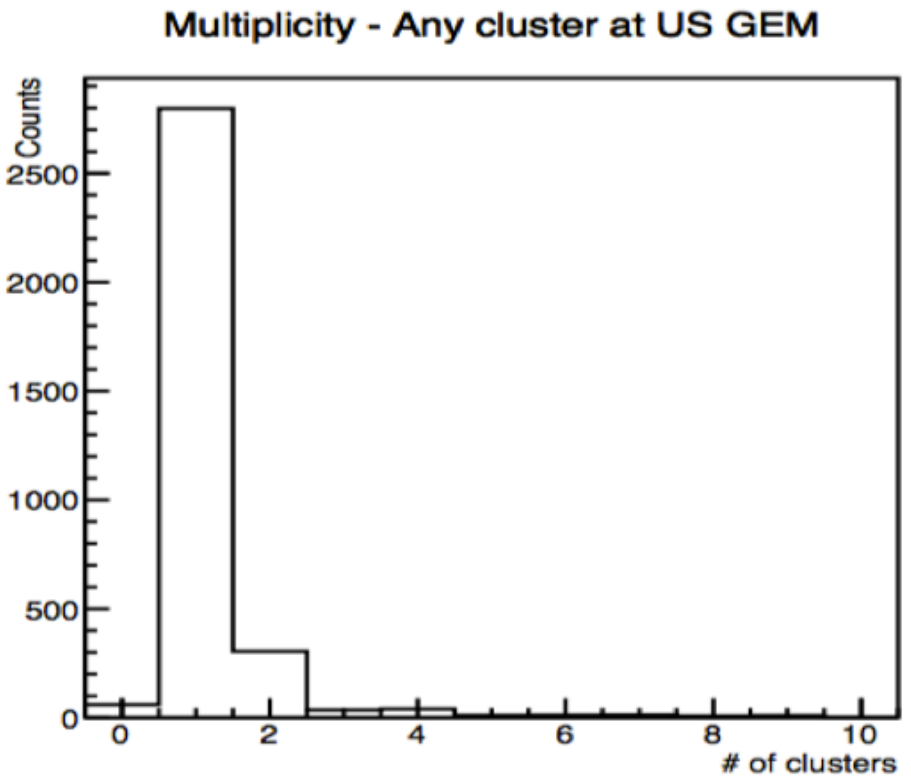
GEM Data Analysis: Cluster Multiplicities per event

- Cluster multiplicities: Independently checked the number of clusters recorded for each event on each GEM.

De-focused (Run 1398)



Unbiased

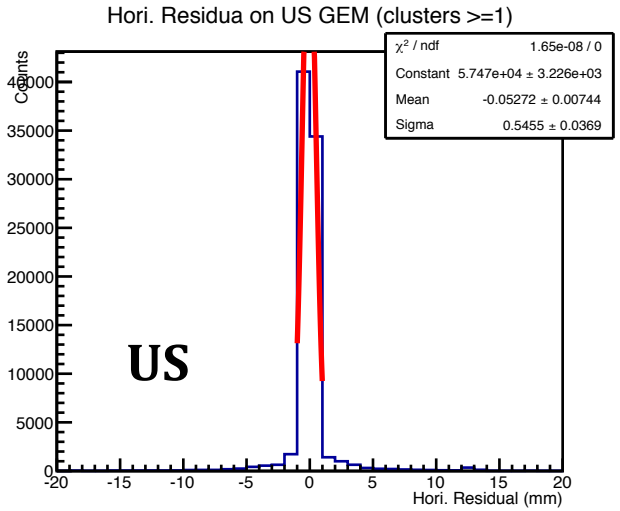


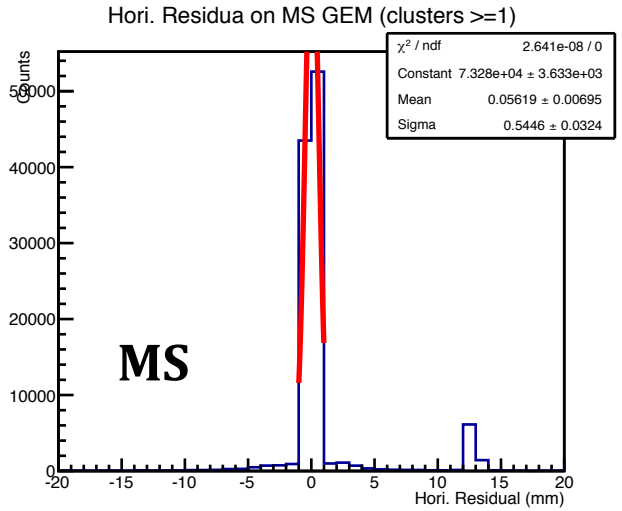
1 cluster in MS & DS

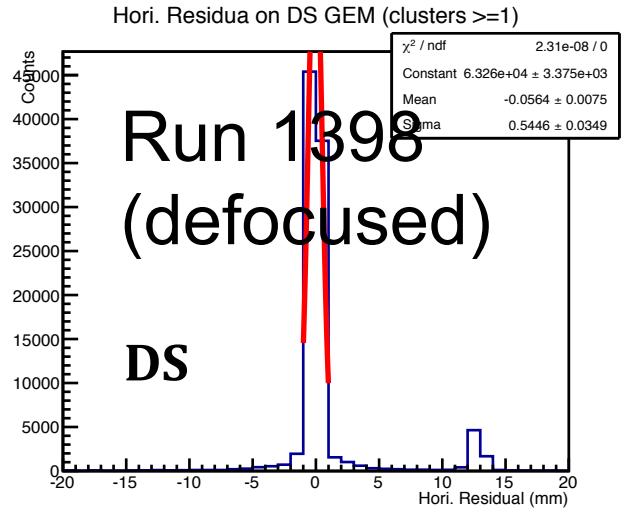
- Requirement: 1-cluster in 2 GEMs for candidate track

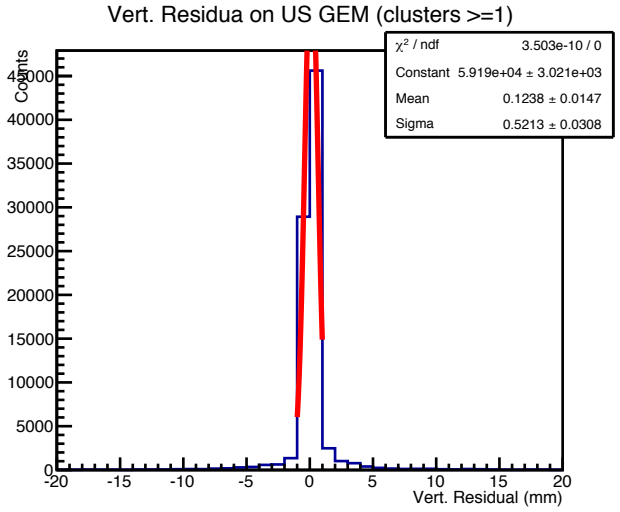
GEM Data Analysis: Track Residuals

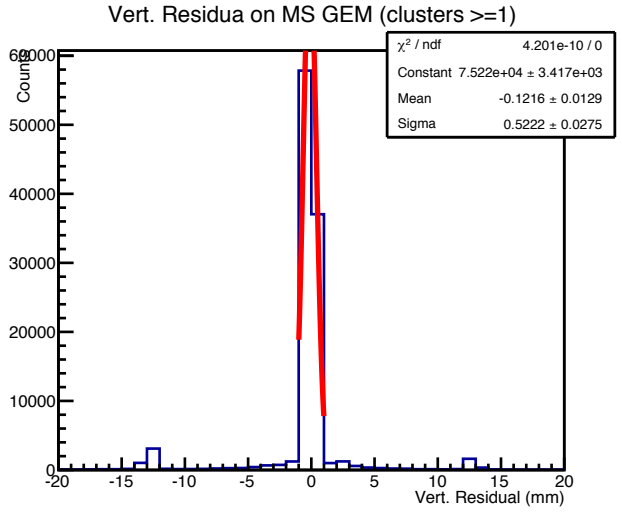
- Determine straight line tracks from the cluster candidates on 2 GEMs and project on 3rd GEM.
- Compare track and hit at the third GEM for track residuals.

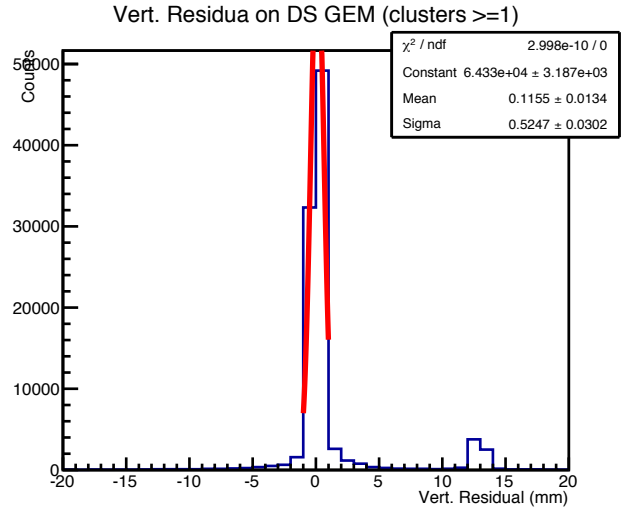








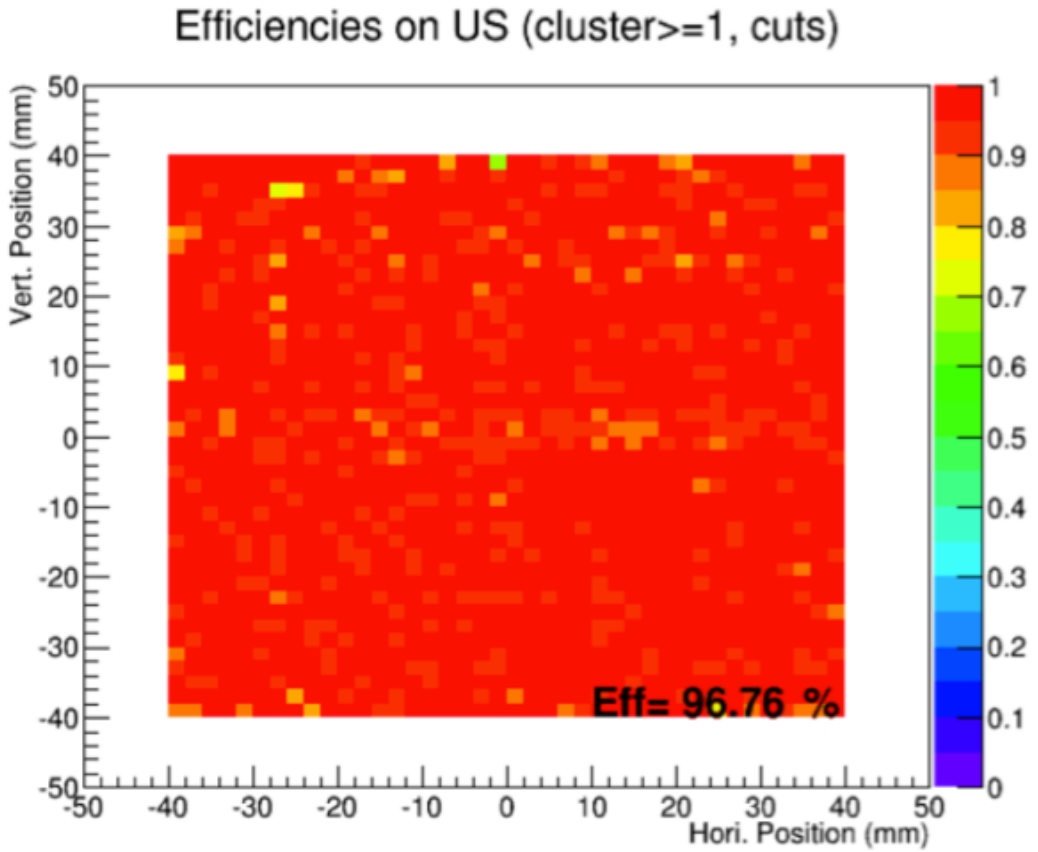




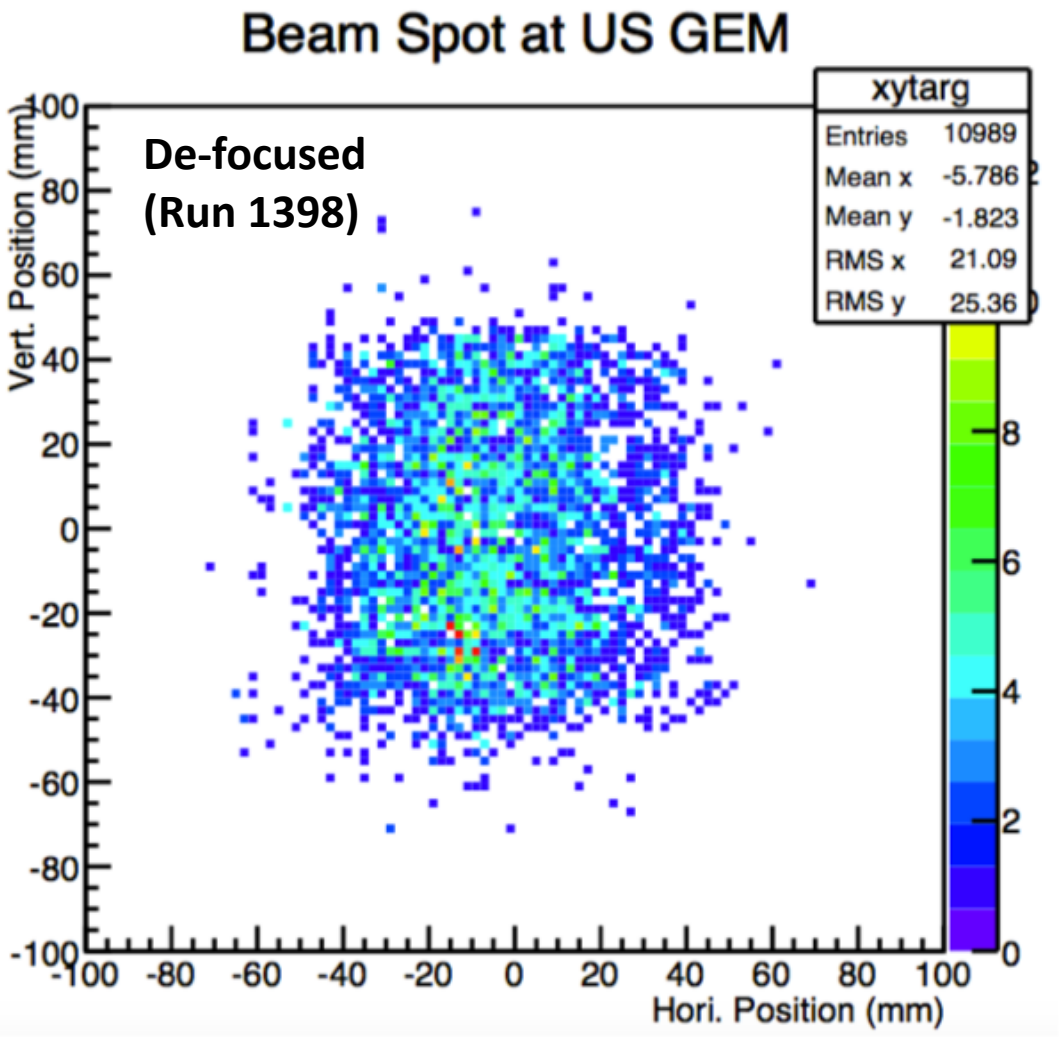
Track residuals: Variance ~ 0.5 mm on each GEM. Similar with and without focused beam

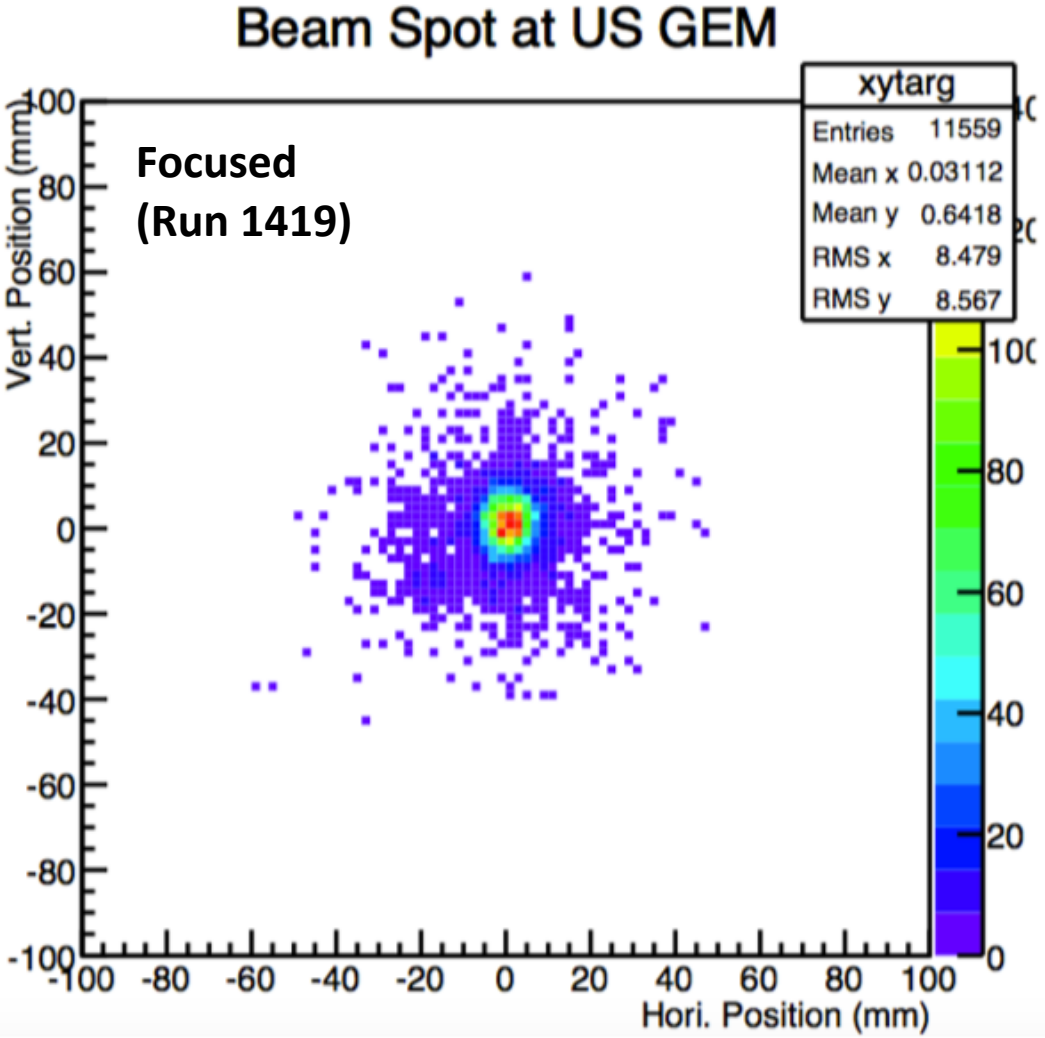
GEM Efficiencies

- The maximum charge cluster is selected on two of the three GEMs to form the track which is projected on the third GEM.
  - $Efficiency = \frac{Projected\ track\ positions\ with\ at\ least\ one\ cluster}{Projected\ track\ positions}$

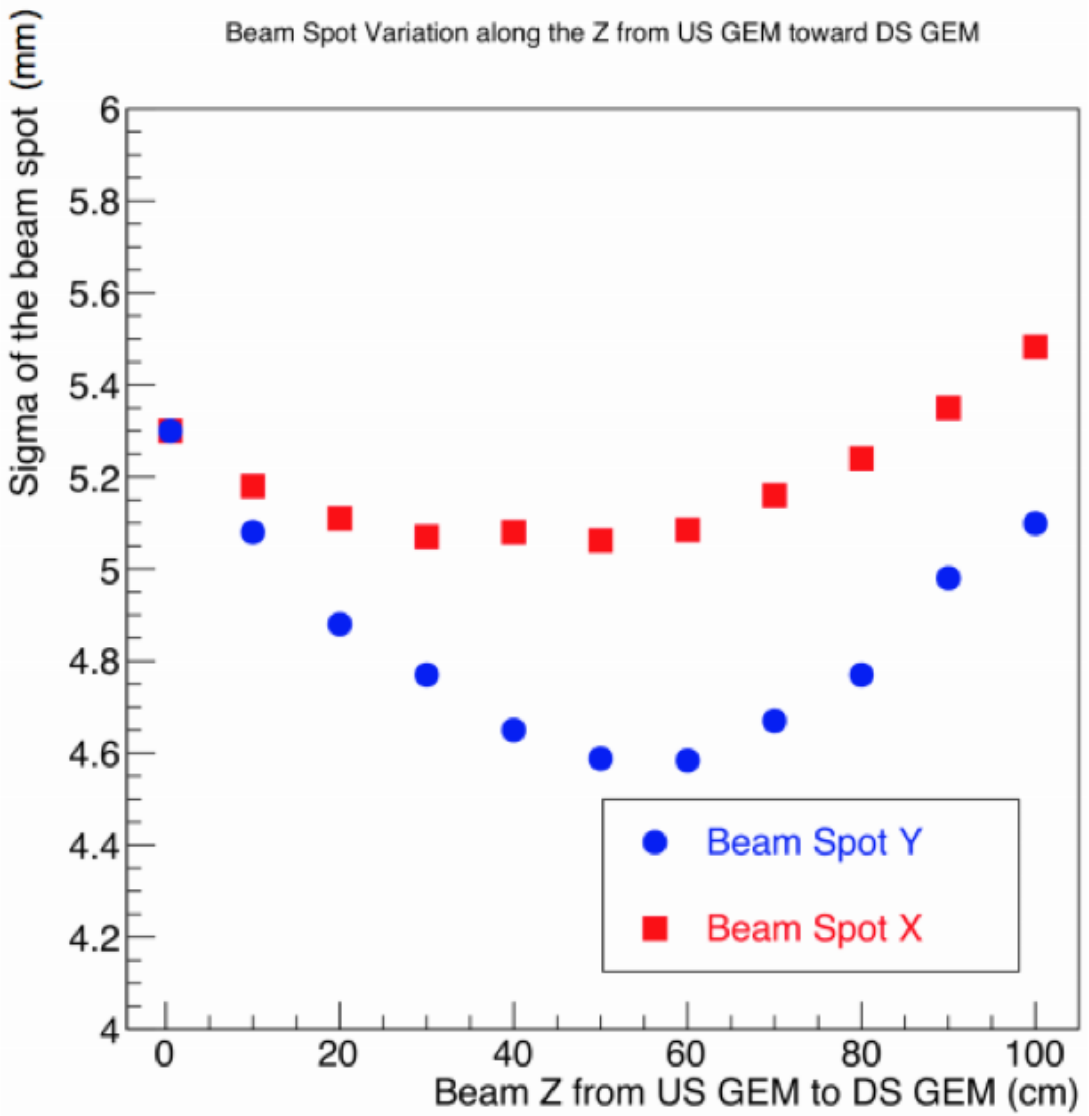


GEM Data Analysis: Beam Focus

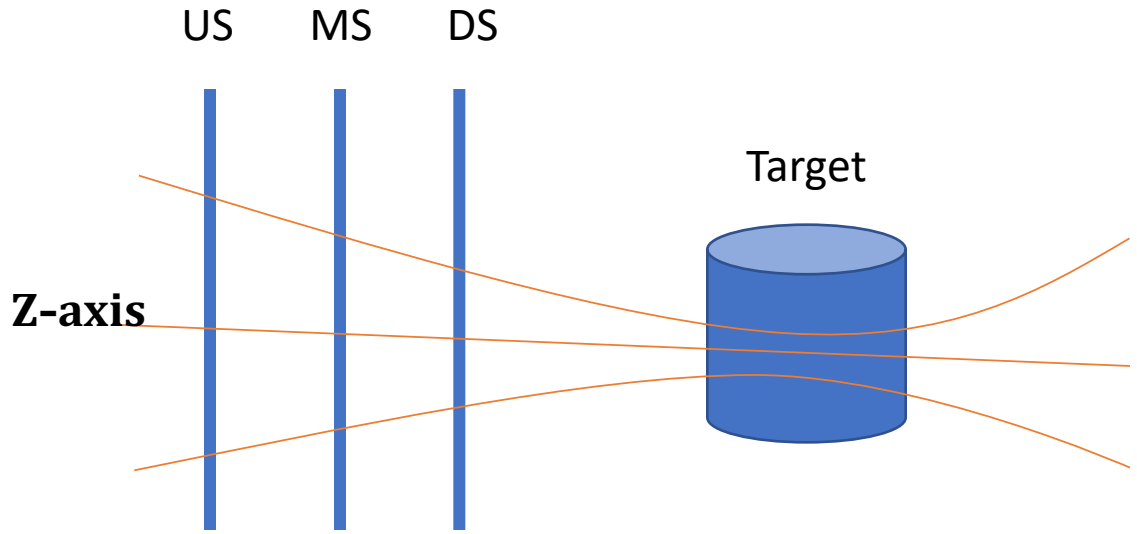




Beam Tomography



US: z = 0 cm
MS: z = 8.5 cm
DS: z = 17 cm



Conclusion

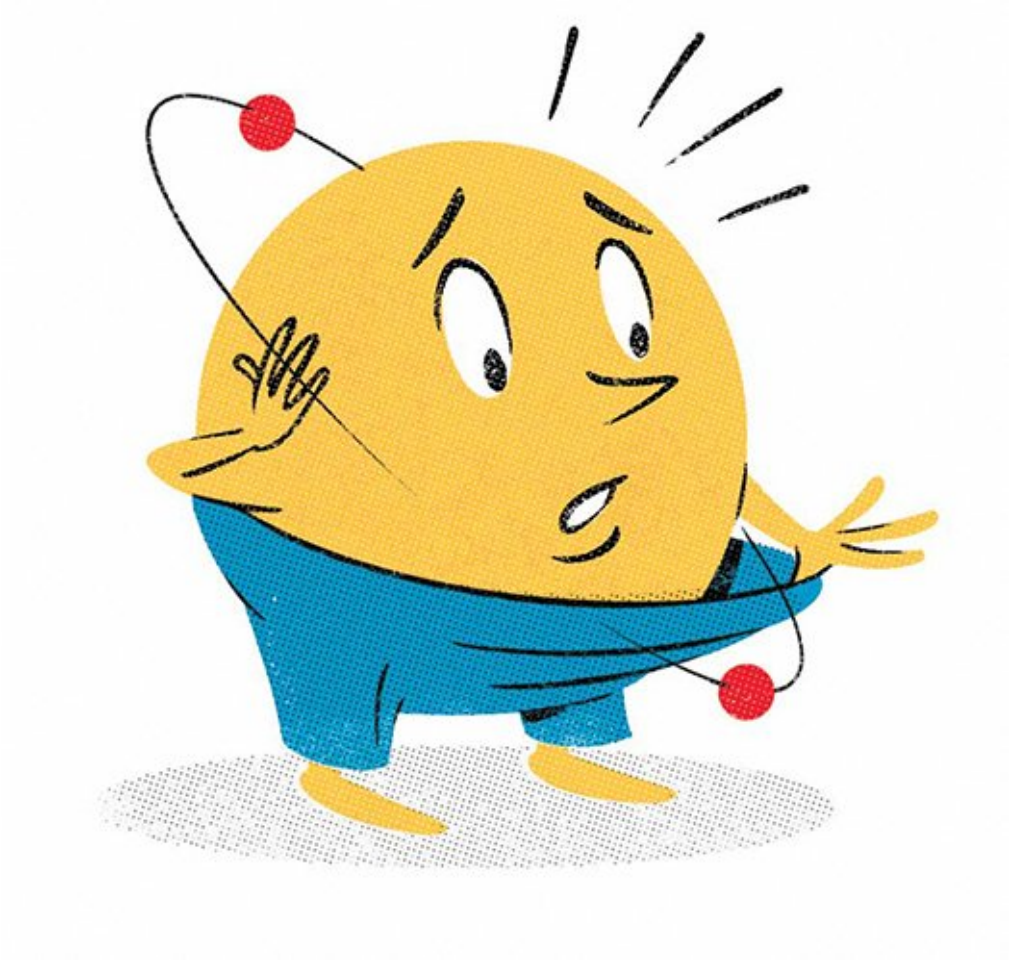
- The construction of MUSE will end this year (2018) and the experiment will take place between 2019-2020

- GEM telescope has been demonstrated to work.

- Work in progress: to optimize the alignment,
  full characterization of the resolution and efficiency,
  to increase the DAQ speed,
  improve tracking algorithms at high intensity.

MUSE Collaborators from 24 Institutions in 5 Countries

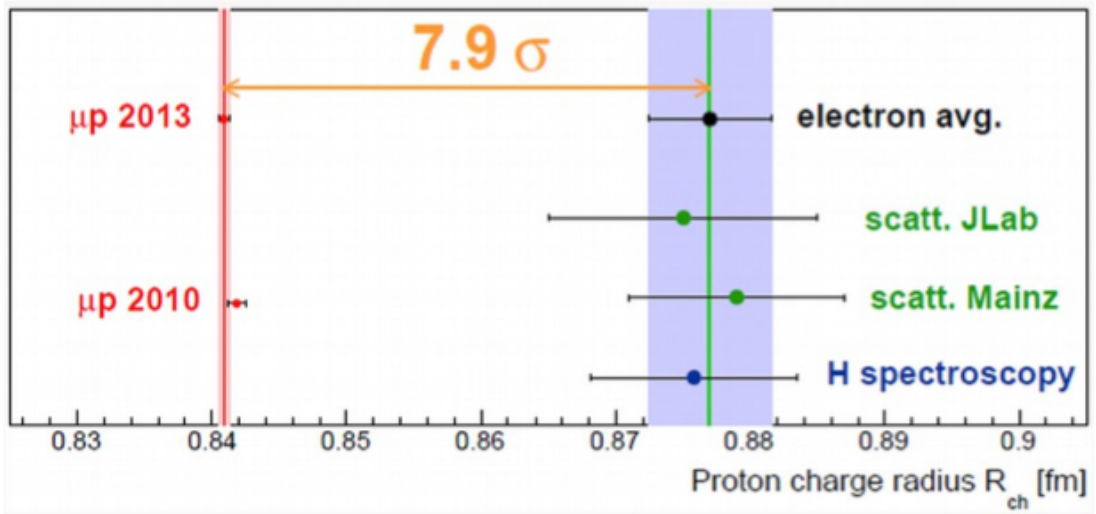
[a]George Washington University, [b]Montgomery College, [c]Argonne National Lab, [d]Temple University, [e]College of William & Mary, [f] Duquesne University, [g]Massachusetts Institute of Technology, [h]Christopher Newport University, [i] Hampton University, [j] Rutgers University, [k]Hebrew University of Jerusalem, [l]Tel Aviv University, [m]Paul Scherrer Institut, [n]Johannes Gutenberg-Universität, [o]Old Dominion University, [p]University of Virginia, [q]University of South Carolina, [r]Jefferson Lab, [s]University of Basel, [t]University of Michigan, [u]Los Alamos National Laboratory, [v]Technical University of Darmstadt, [w]St. Mary's University, [x]Weizmann Institute



Questions?

BACKUP

- Electric radius in agreement with Pohl 0.84087 ± 0.00039 fm
  - 7.9σ from 2010 CODATA
    - Analysis gives:



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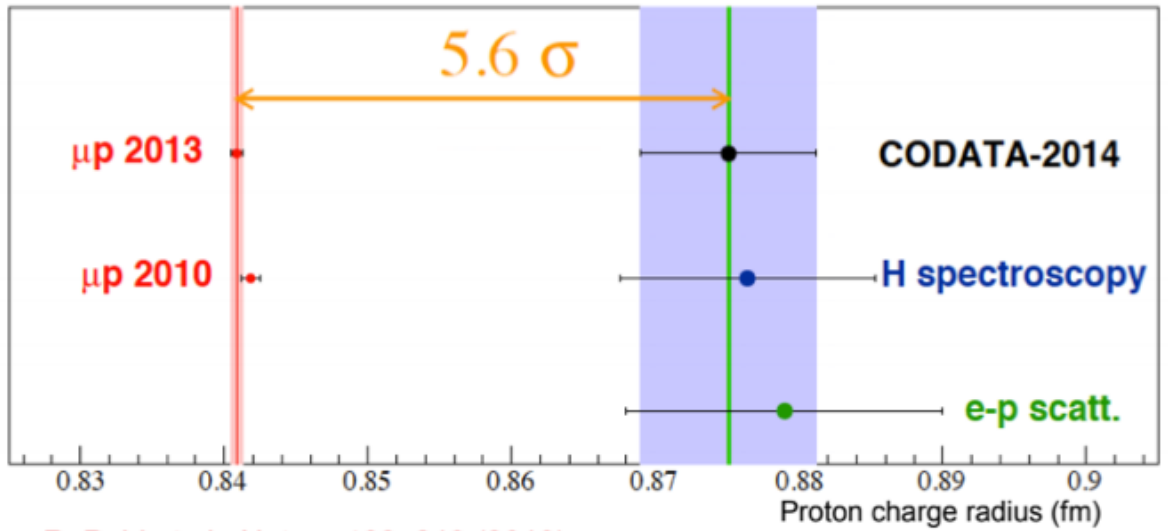
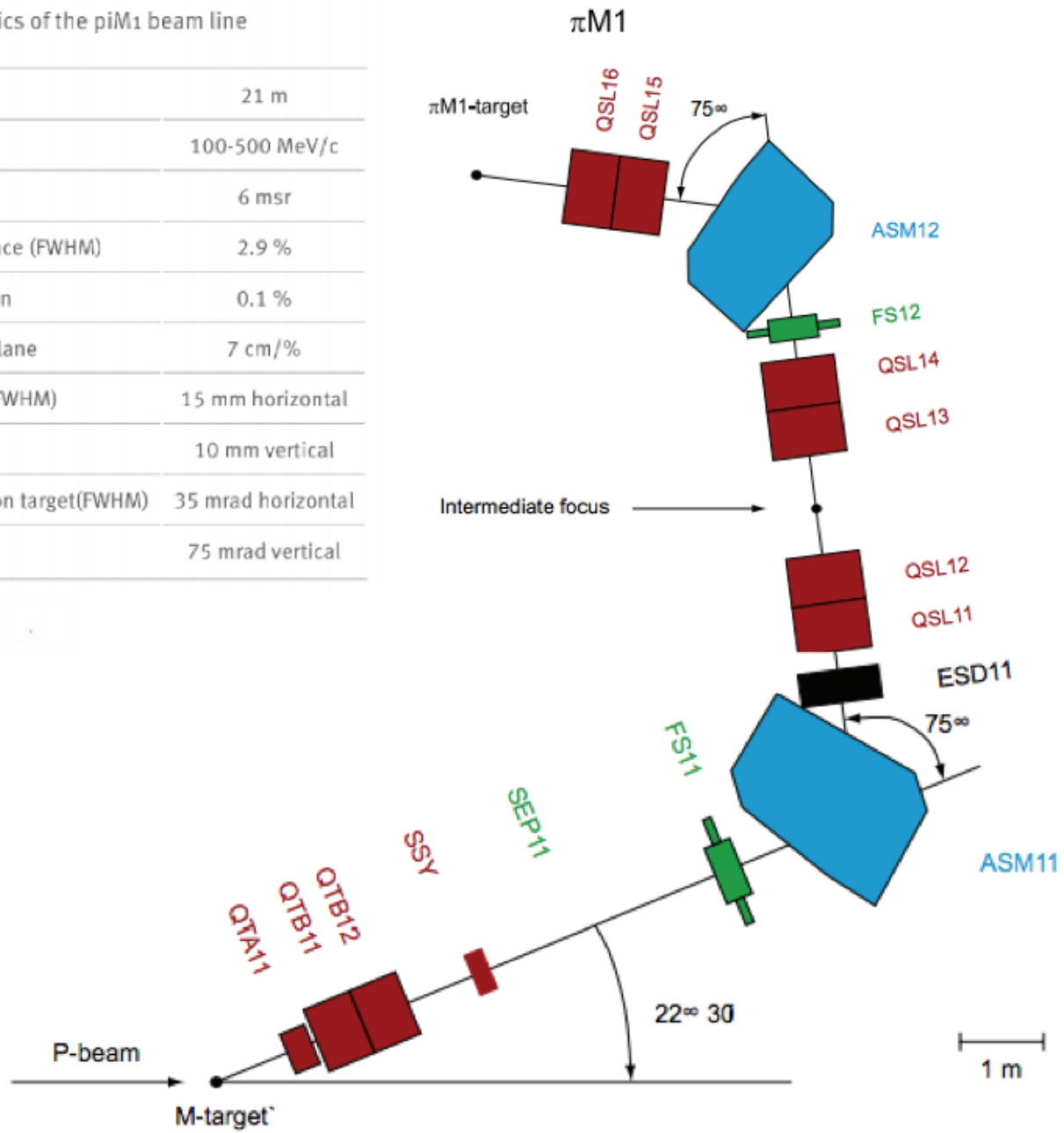


R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

Old Data

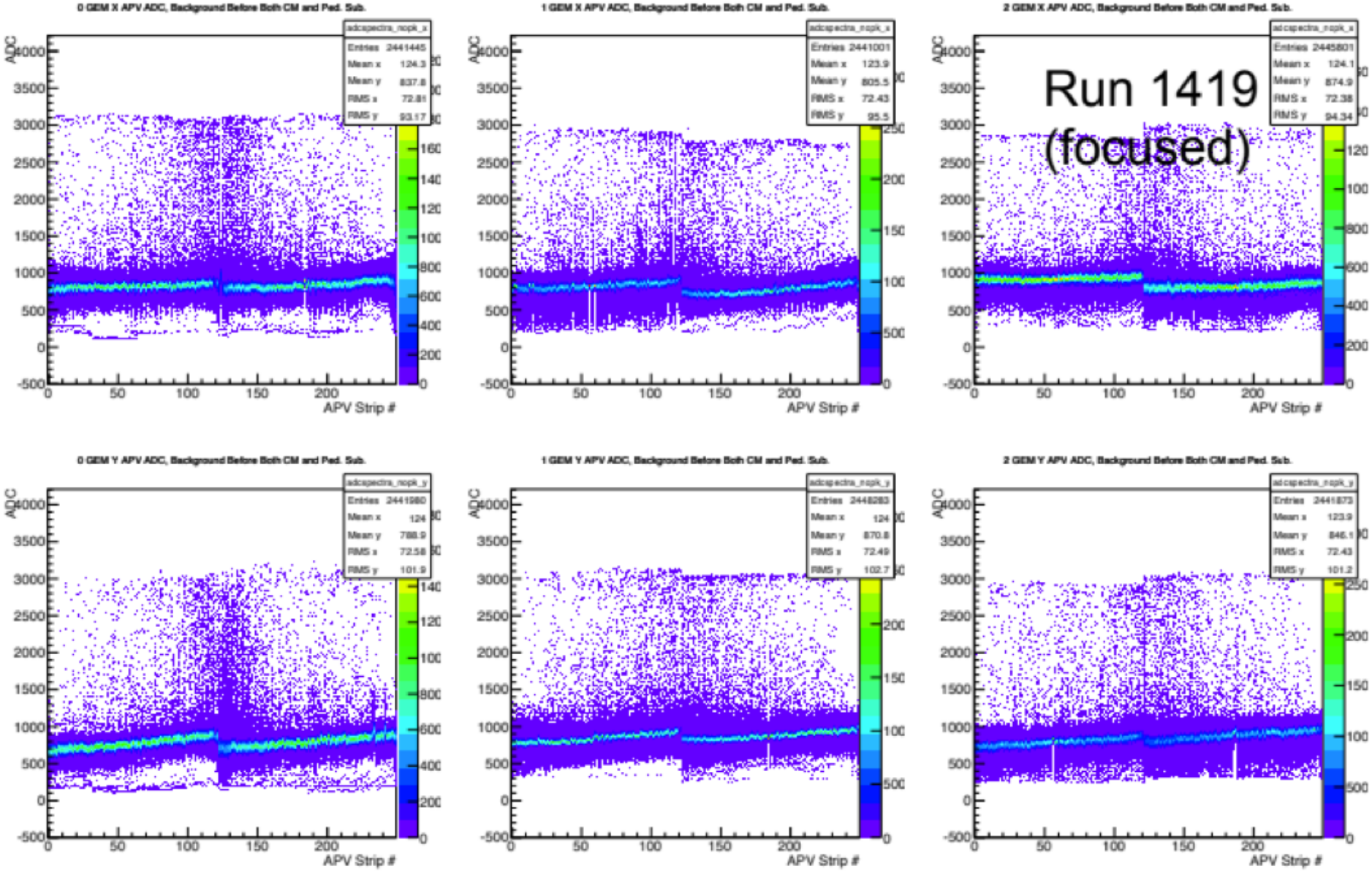
Table 1 : Characteristics of the piM1 beam line

Total path length	21 m
Momentum range	100-500 MeV/c
Solide angle	6 msr
Momentum acceptance (FWHM)	2.9 %
Momentum resolution	0.1 %
Dispersion at focal plane	7 cm/%
Spot size on target (FWHM)	15 mm horizontal
	10 mm vertical
Angular Divergence on target(FWHM)	35 mrad horizontal
	75 mrad vertical

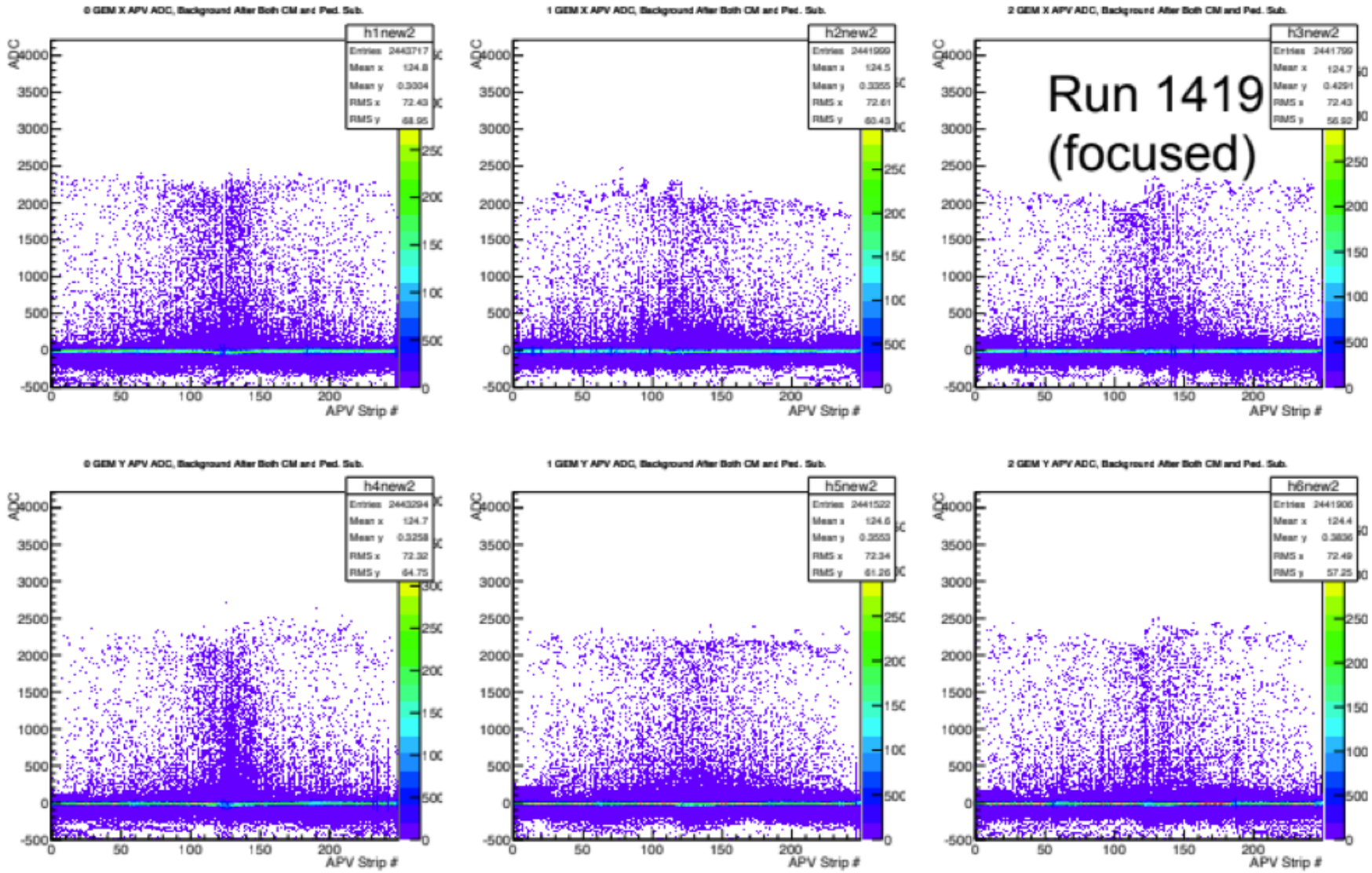


PiM1 beamline at PSI

Raw ADC vs Strip Number



ADC vs Strip Number



GEM Data Analysis: Cluster Multiplicities