Status of PRad Experiment

Chao Gu

Duke University

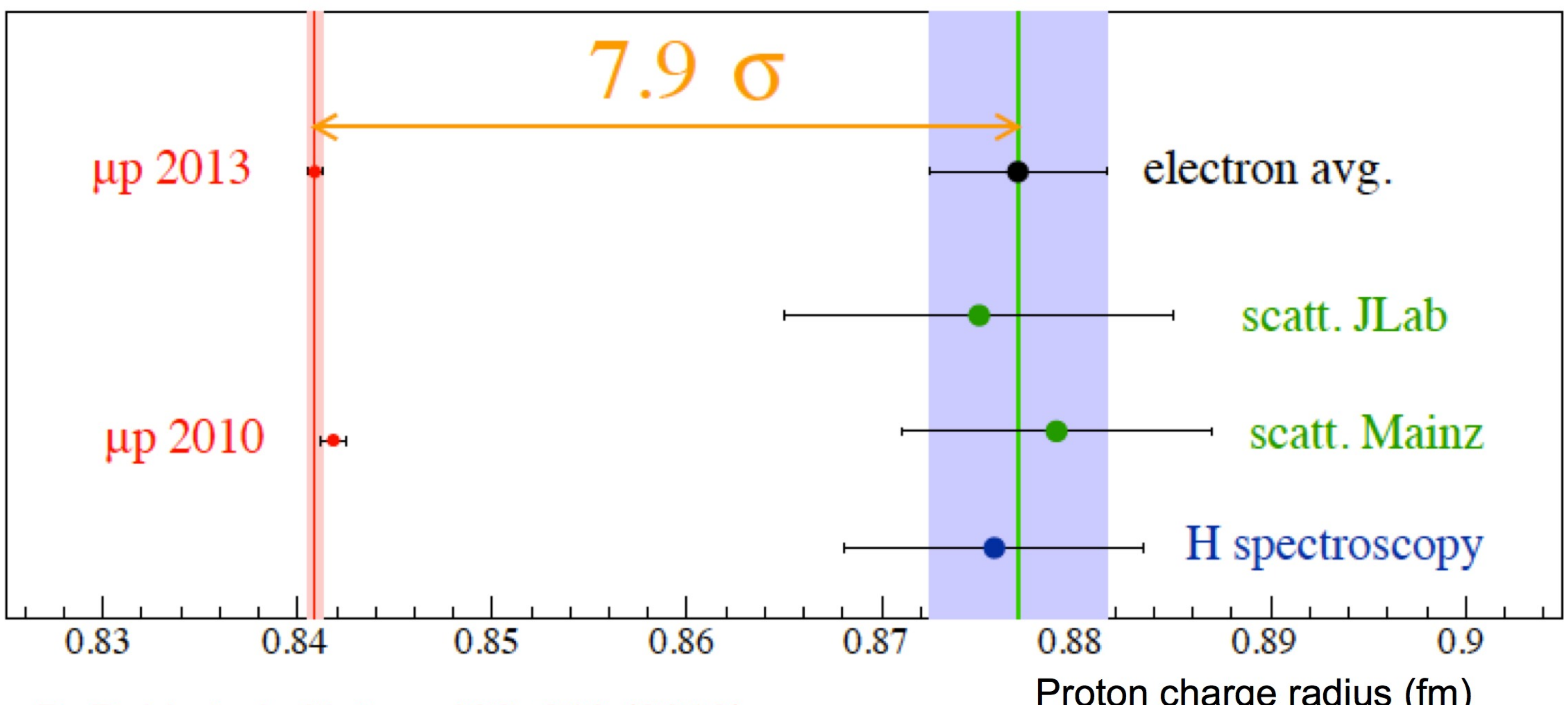
For PRad Collaboration

Outline

- The Proton Charge Radius
- Experiment Setup
- Analysis Status and Preliminary Results

The Proton Charge Radius Puzzle

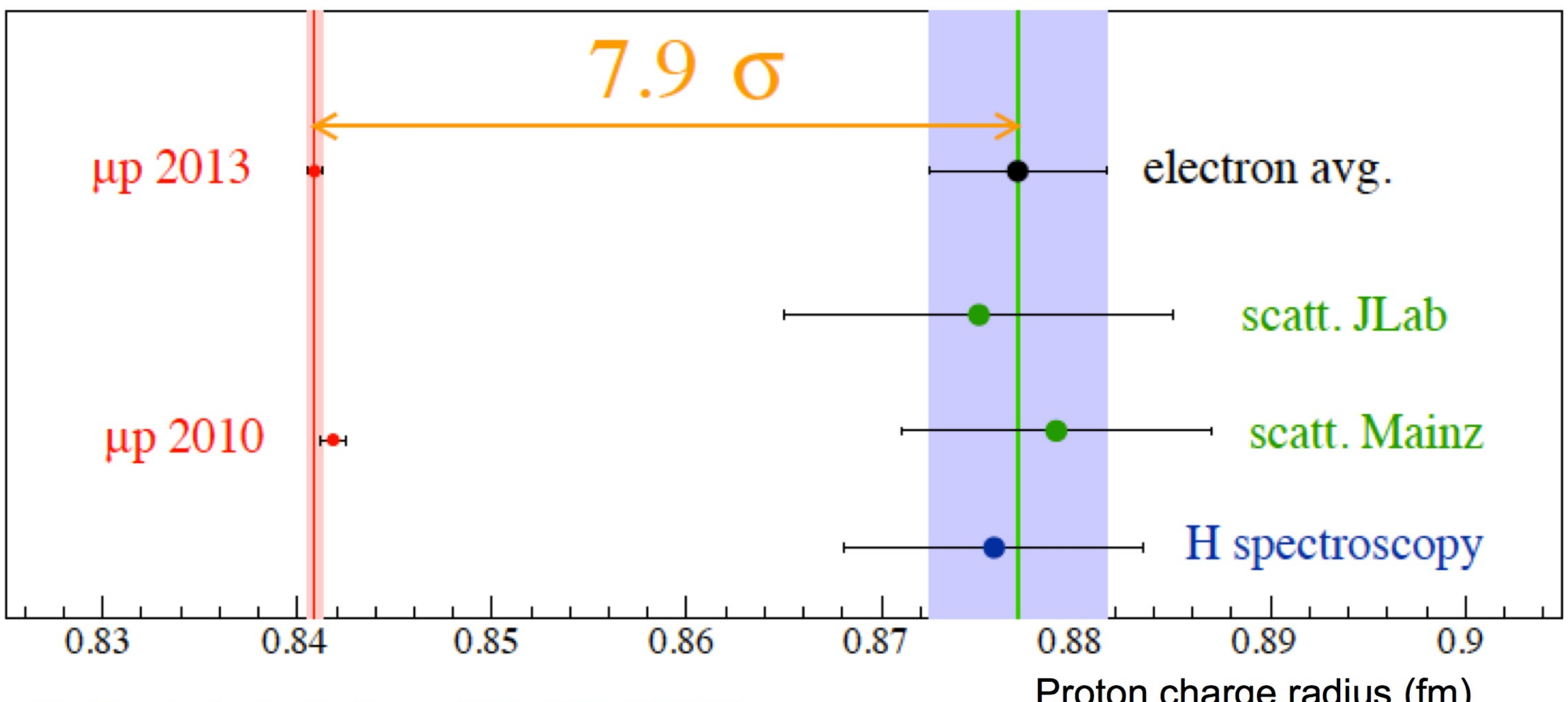
- Proton radius is one of the most fundamental quantities in physics:
  - Critically important for atomic physics in precision spectroscopy of atom
  - Precision test of nuclear/particle models
  - Connects atomic and subatomic physics



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

The Proton Charge Radius Puzzle

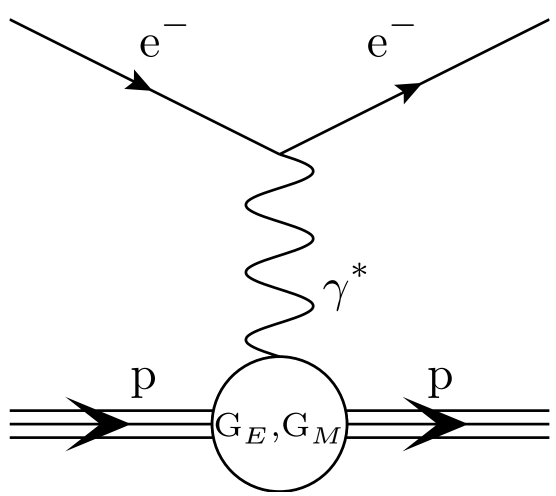
- 4 different methods to measure the proton charge radius:
  - Hydrogen spectroscopy (ordinary hydrogen, muonic hydrogen)
  - Lepton-proton elastic scattering (ep, μp)
- The proton charge radius puzzle:
  - ~8σ discrepancy between the new muonic-hydrogen spectroscopy measurements and all previous results



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

ep Scattering

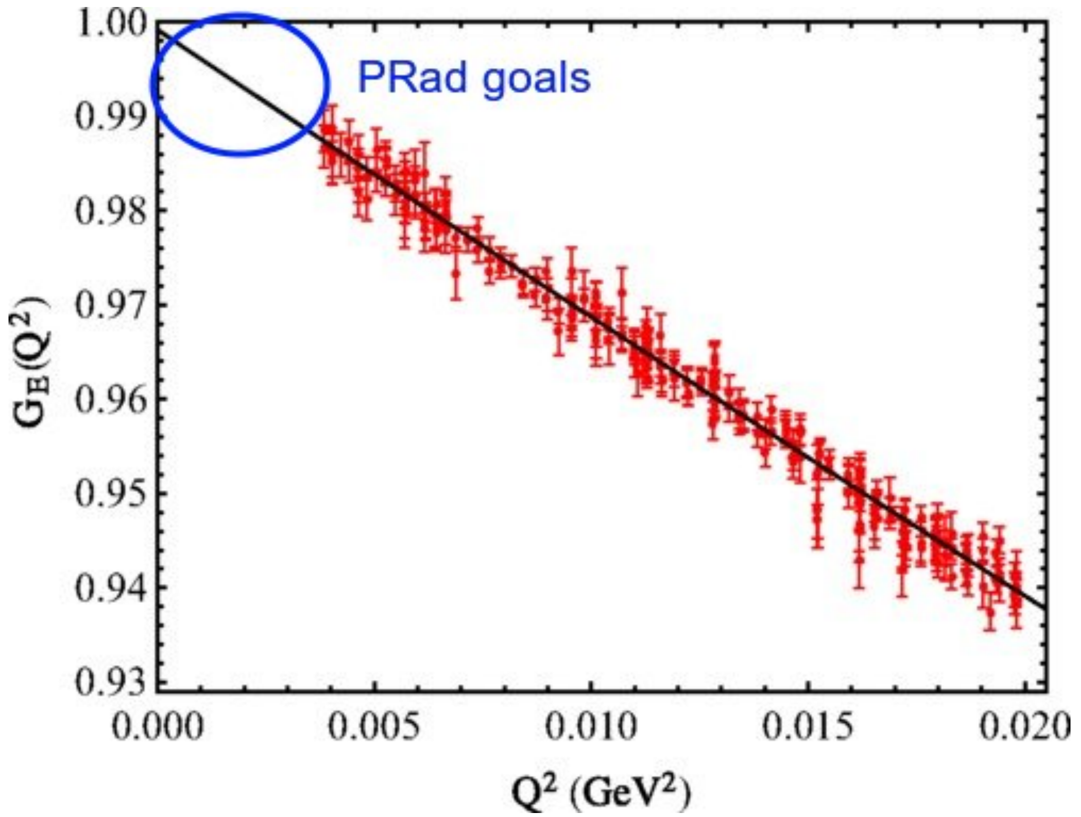
- Extraction of $\langle r^2 \rangle = -6 \frac{\mathrm{d}G_E^p(Q^2)}{\mathrm{d}Q^2}\Big|_{Q^2=0}$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

- Previous measurements have large systematic uncertainties and a limited coverage at small Q^2

- Requirements for PRad Experiment:
  - Extend to very low Q^2 (2×10^{-4}~6×10^{-2} GeV^2)
  - Cover relatively large Q^2 range with a single experiment configuration
  - Controlled systematics at sub-percent precision



Mainz Low Q^2 data set

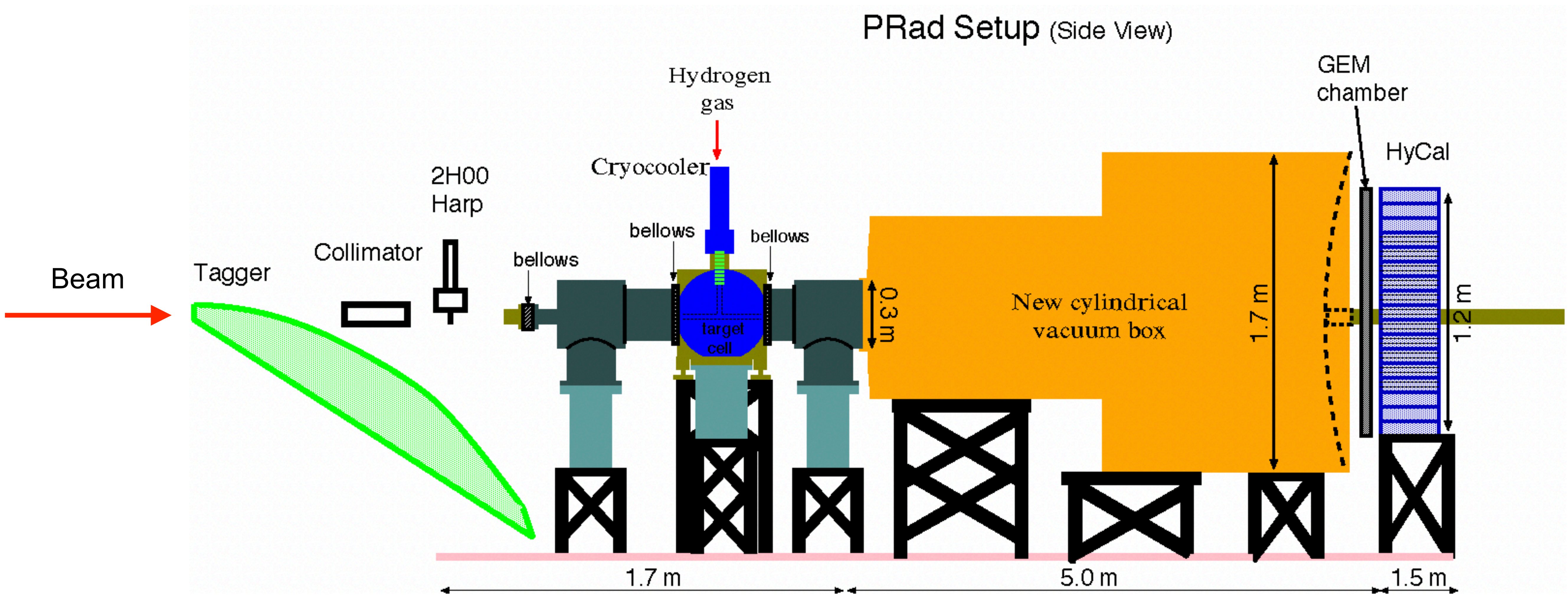
Phys. Rev. C 93(2016)065207

PRad Timeline

2011 - 2012	Initial proposal
2012	Approved by JLab PAC39
2012	Funding proposal for windowless H2 gas flow target
2012 - 2015	Development, construction of the target
2013	Funding proposals for the GEM detectors
2013 - 2015	Development, construction of the GEM detectors
2015, 2016	Experiment readiness reviews
Jan - Apr 2016	Beam line installation
May 2016	Beam commissioning
May 24 - 31 2016	Detectors calibration
Jun 4 - 22 2016	Data taking

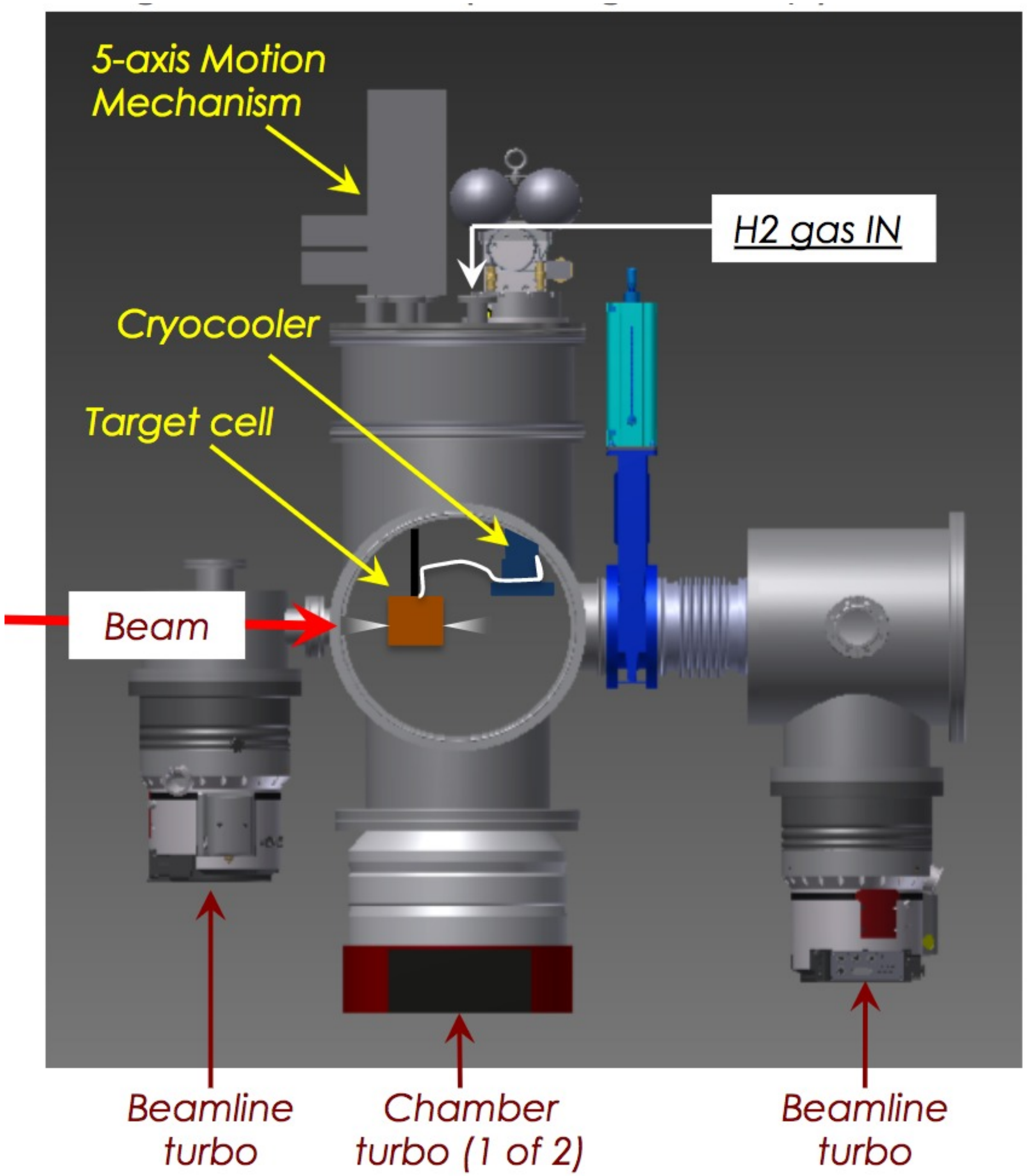
PRad Setup

- Electron beam at 1.1 GeV and 2.2 GeV
- Windowless H_2 gas flow target
- Vacuum box
- GEM detectors
- PrimEx HyCal



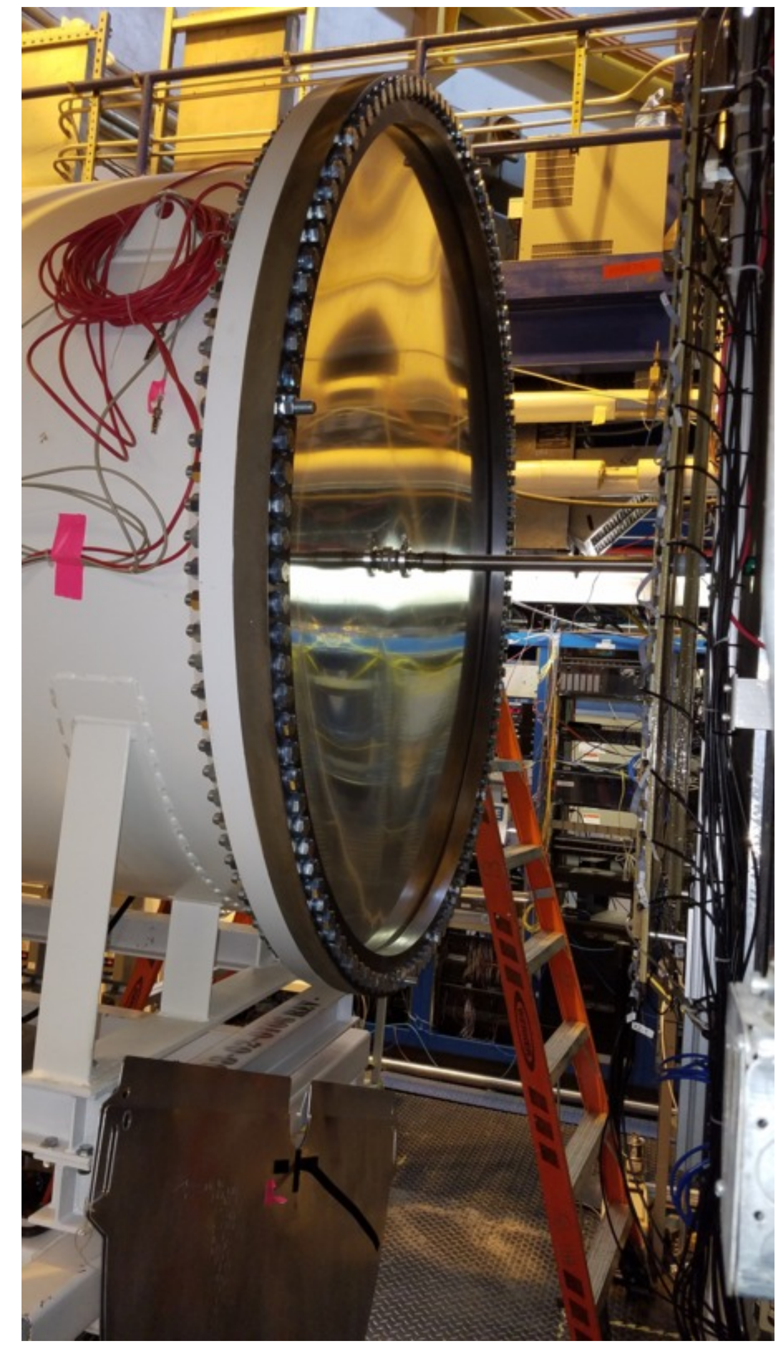
Windowless H_2 Gas Flow Target

- A windowless gas target of cryogenically cooled hydrogen:
    - 4 cm long copper target cell
    - 7.5 μm kapton windows with 2 mm beam orifices
    - H2 gas cooled at 19.5 K
    - Target density: ~2×10^{18} H atoms/cm^2
    - Five-axis motion system to position the target cell with 10 μm accuracy
- Pressures:
    - Cell pressure: 471 mTorr
    - Chamber pressure: 2.34 mTorr
    - Vacuum chamber pressure: 0.3 mTorr
- Additional solid target foils: 1 μm ^{12}C



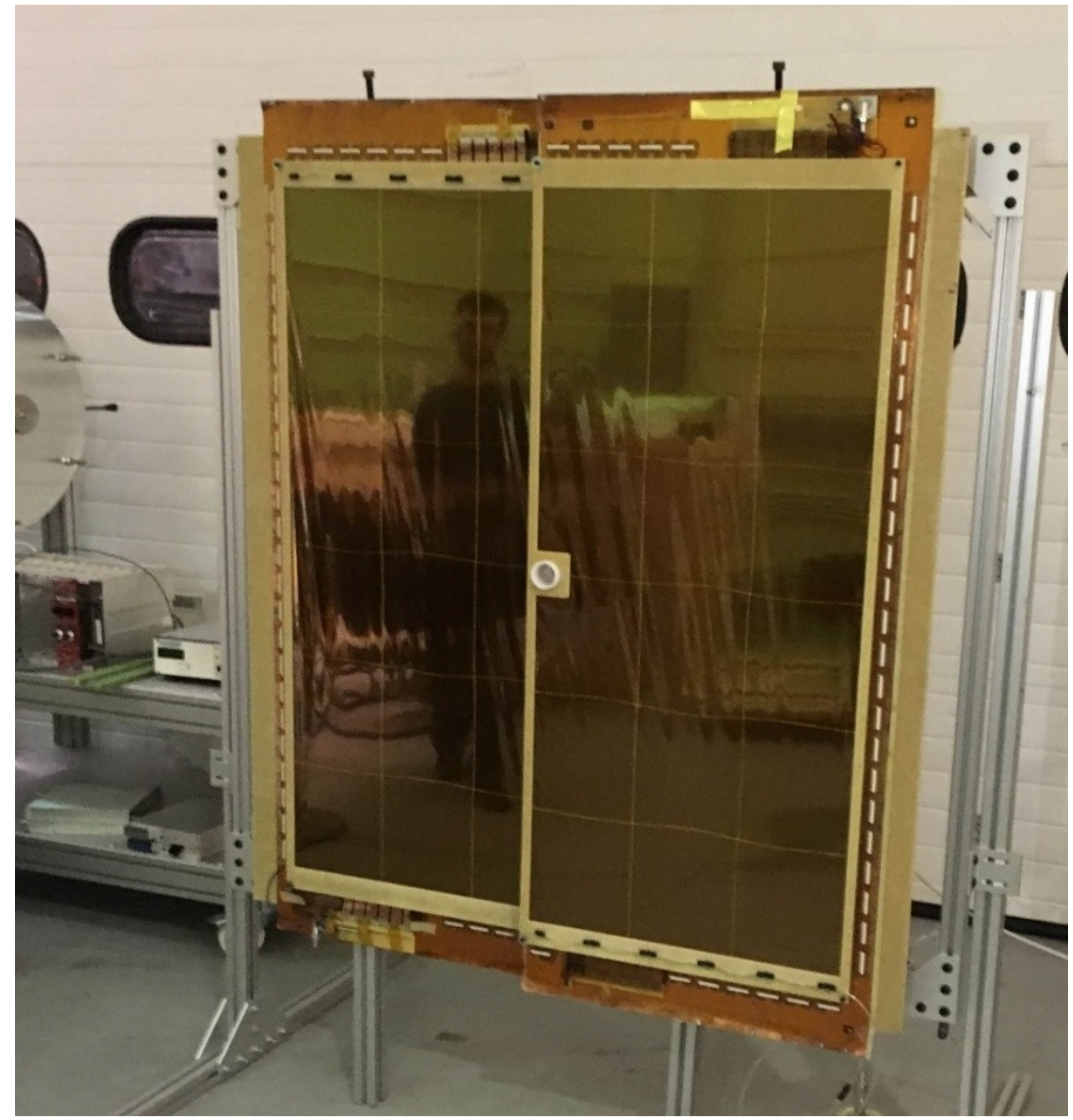
Vacuum Chamber

- 1.7 m diameter, 1.6 mm aluminum vacuum window



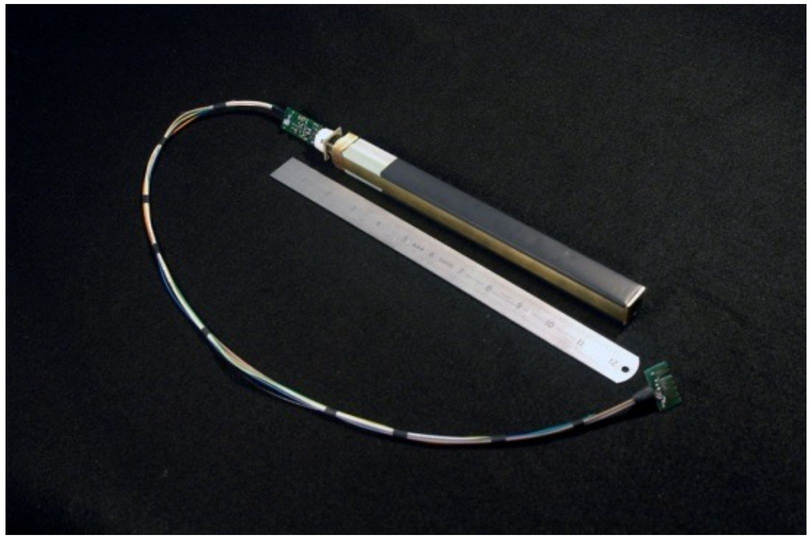
GEM Detectors

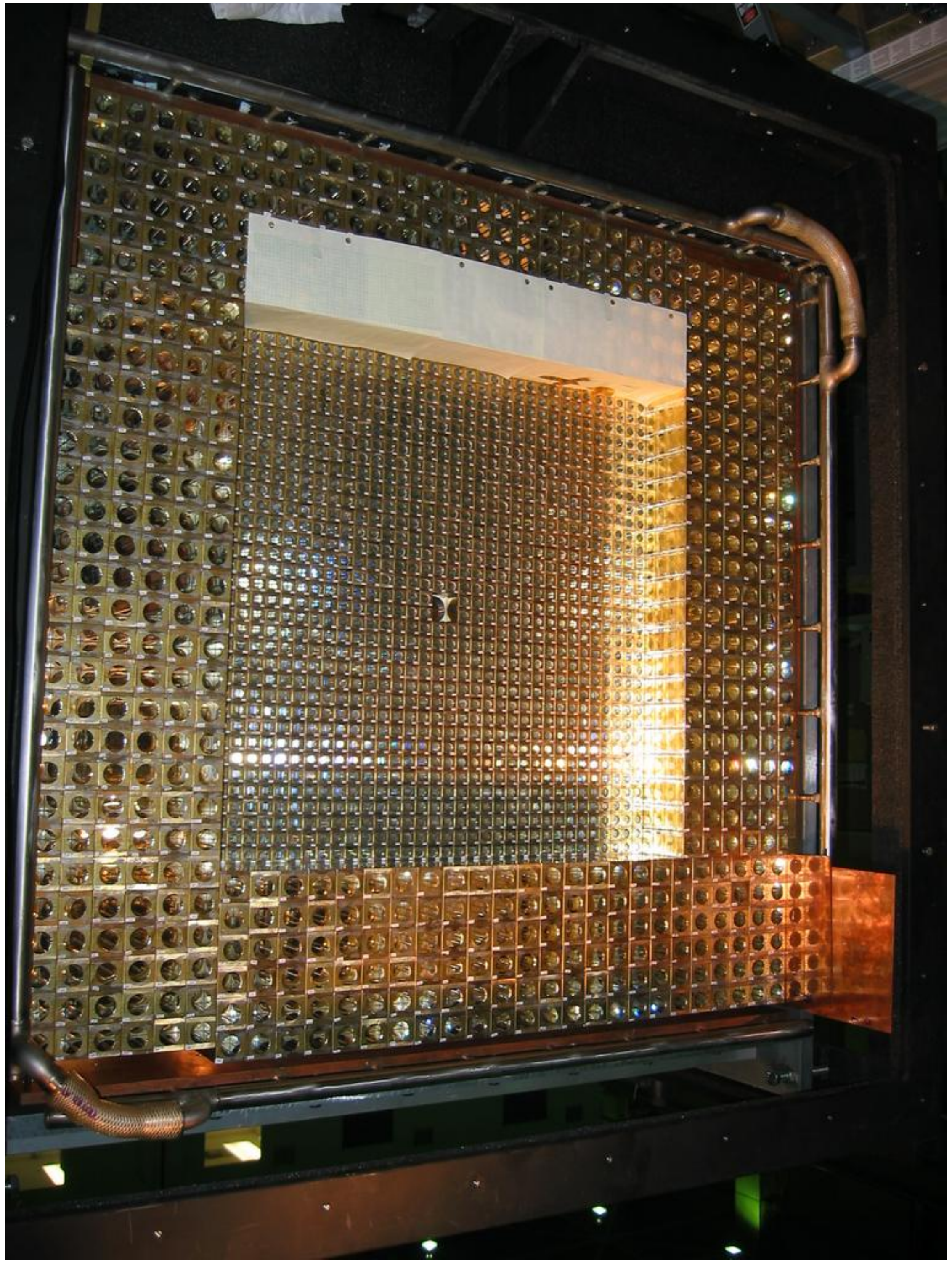
- Two large area GEM detectors (55 cm x 123 cm)
  - Central overlapped between two planes with a hole for the beam passage
- Purpose:
  - A factor of >20 improvements in coordinate resolutions
  - Similar improvements in Q^2 resolution (important)
  - Unbiased coordinate reconstruction
  - Increase Q^2 coverage by including HyCal Pb-glass part
- Designed and built at University of Virginia (UVa)



Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118 x 118 cm^2)
  - 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors
  - 576 Pb-glass shower detectors (3.82 x 3.82 x 45 cm^3)
  - 2 x 2 $PbWO_4$ modules removed in the middle for beam passage
- 5.8 m from the target
- Successfully used for PrimEx experiments



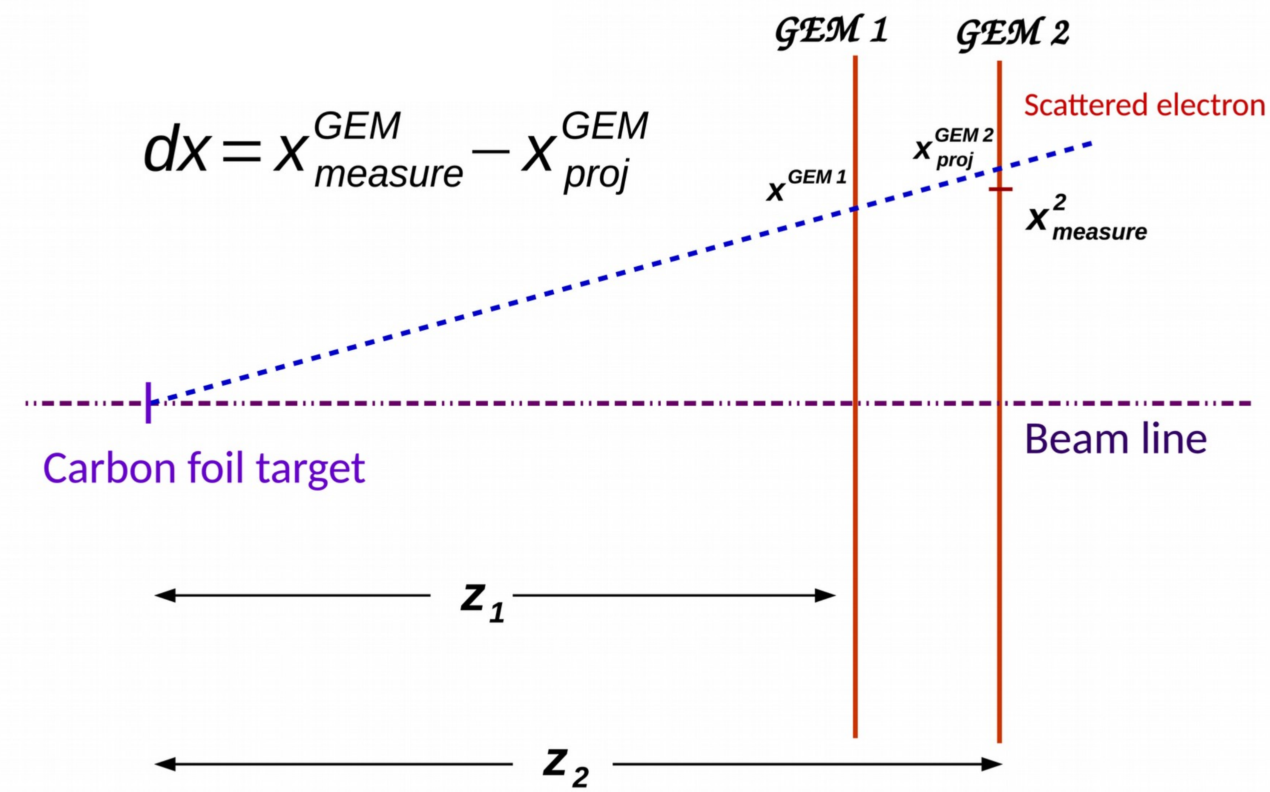


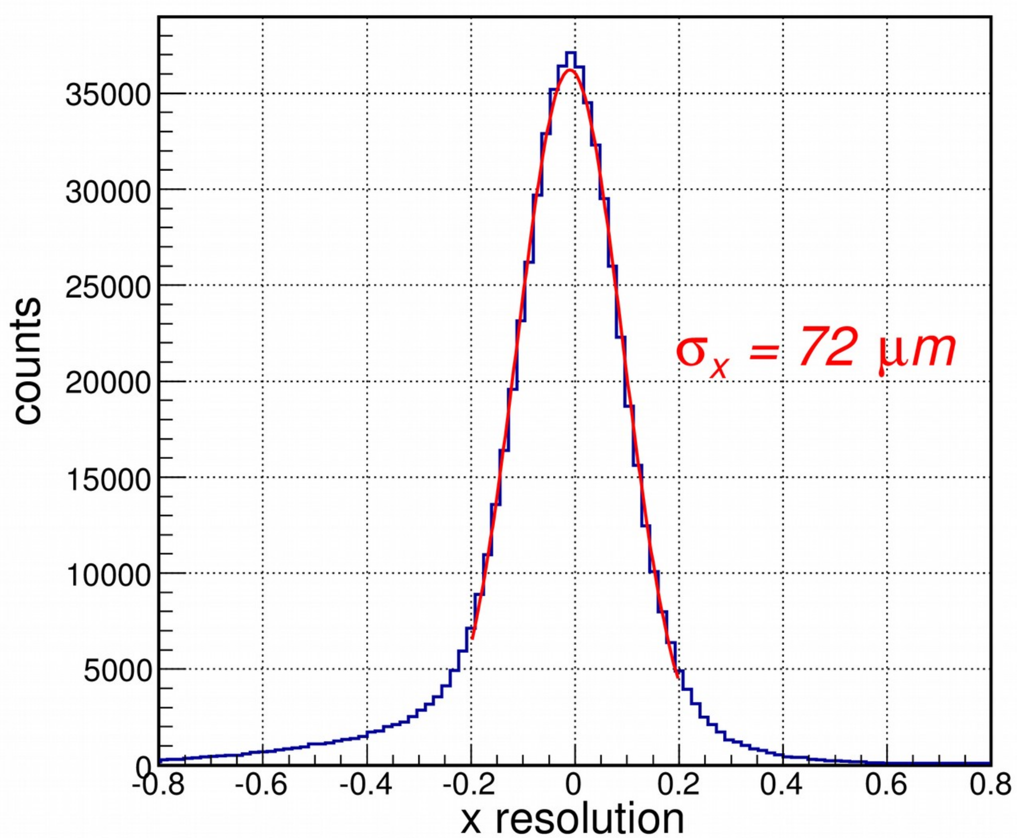
Experiment Data Collected

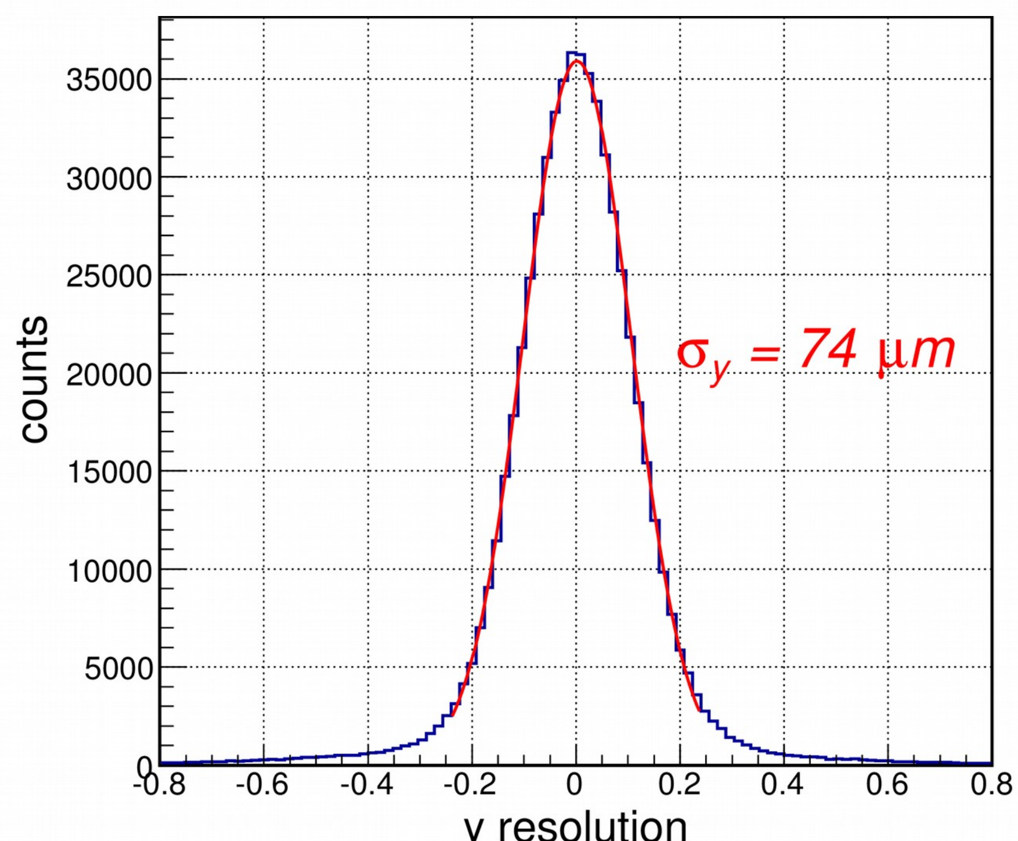
- With 1.1 GeV beam:
  - Collected 4.2 mC
  - 604 M events with H_2 target
  - 53 M events with "empty" target
  - 25 M events with ^{12}C target for calibration
- With 2.2 GeV beam:
  - Collected 14.3 mC
  - 756 M events with H_2 target
  - 38 M events with "empty" target
  - 10.5 M events with ^{12}C target for calibration

GEM Resolution

- Extraction of GEM spatial resolution using GEM central overlapping region
- Good spatial resolution achieved: ~70 um, close to the expected value



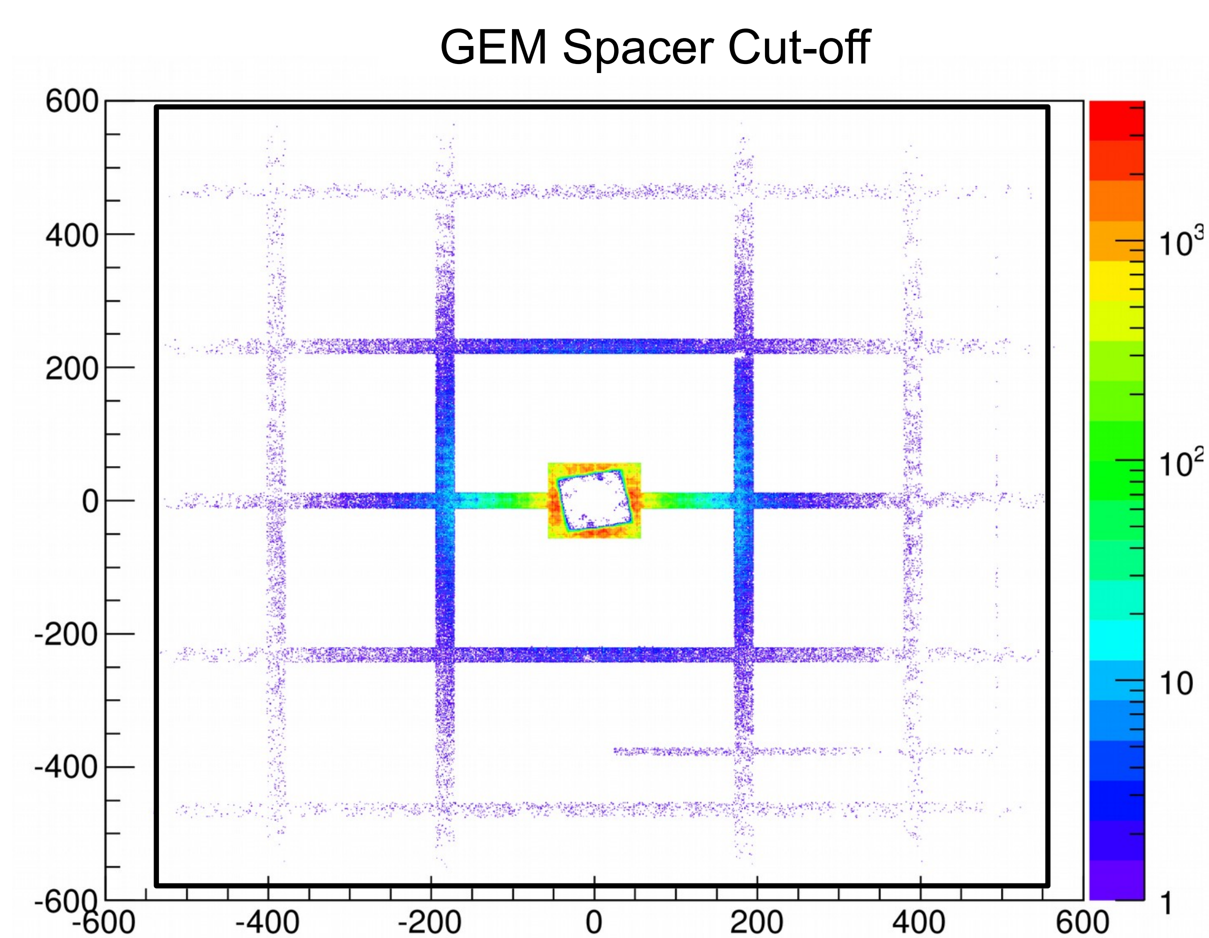


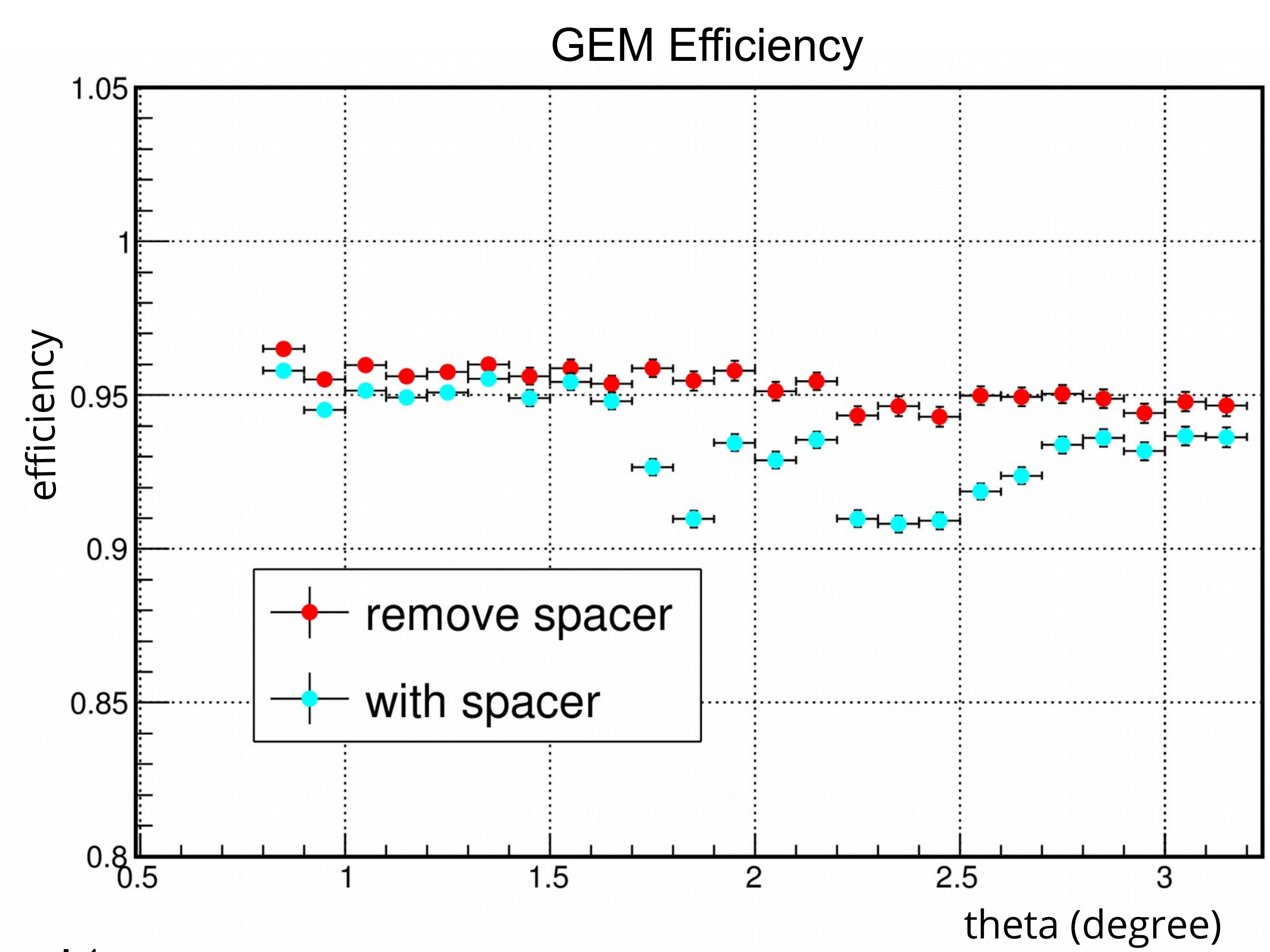


Plots courtesy of X. Bai

GEM Detection Efficiency

- GEM detection efficiency calibrated using physics runs
  - GEM spacer introduces deficient area
  - Evenly distributed efficiency after spacer cut-off
- Stable GEM efficiency over time
  - Average efficiency fluctuation: ~0.5% level

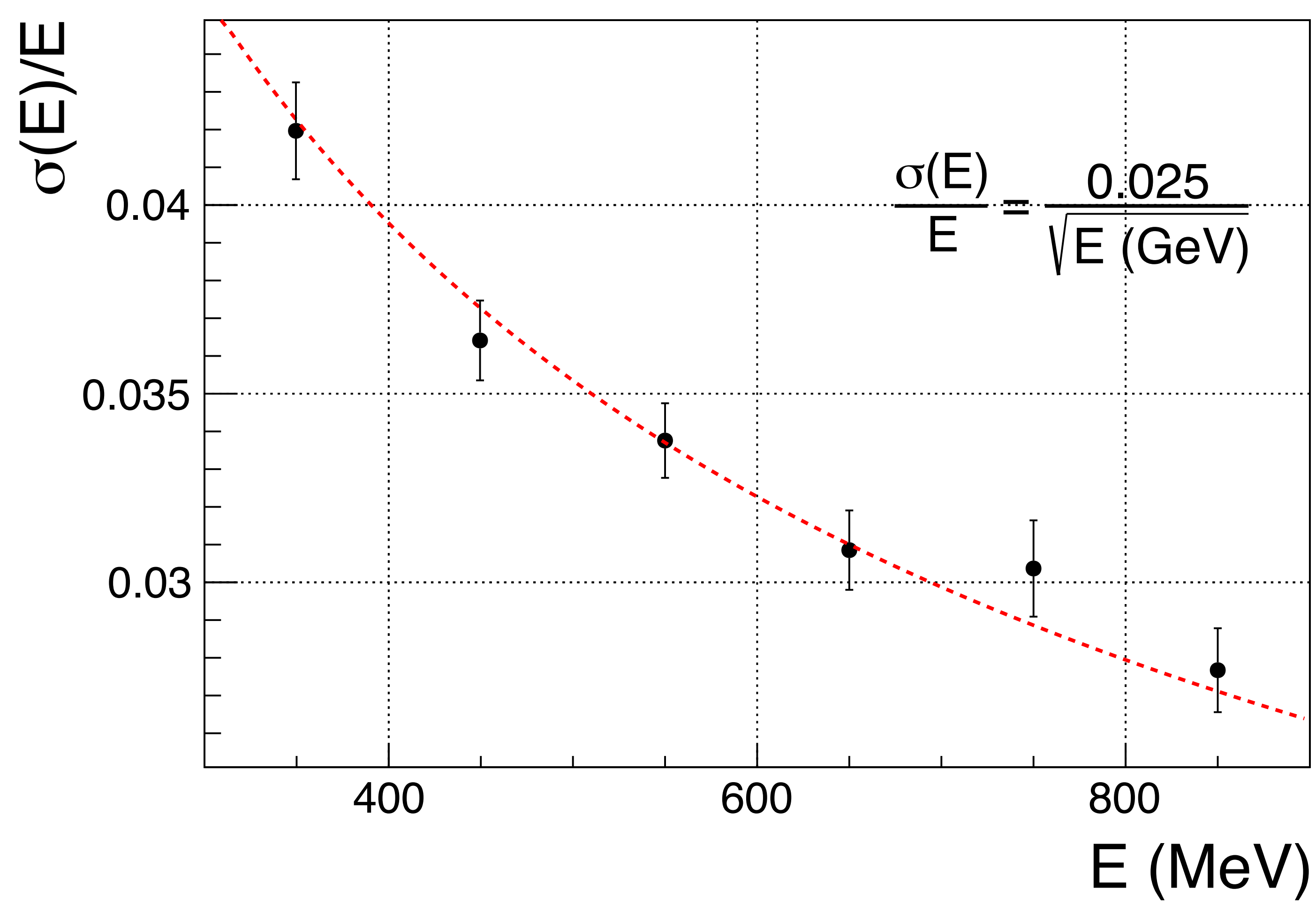




Plots courtesy of X. Bai

HyCal Calibration

- Gains controlled by Light Monitoring System (LMS)
- Two different calibrations:
  - Before data taking: Scan with 250-1050 MeV tagged photon beam moved in front of each module to study of resolution, efficiency and non-linearity
  - During data taking: With Moller and ep elastic events
- Achieved expected energy resolution:
  - 2.5% at 1 GeV for $PbWO_4$ part
  - 6.1% at 1 GeV for Pb-glass part
- Plot shows the energy resolution for PbWO4 part with statistical uncertainties and systematic coming from non-uniformity



Plots courtesy of M. Levillain

Extraction of ep Cross Section

- To reduce the systematics uncertainty, the ep elastic cross section is normalized to the Moller cross section:

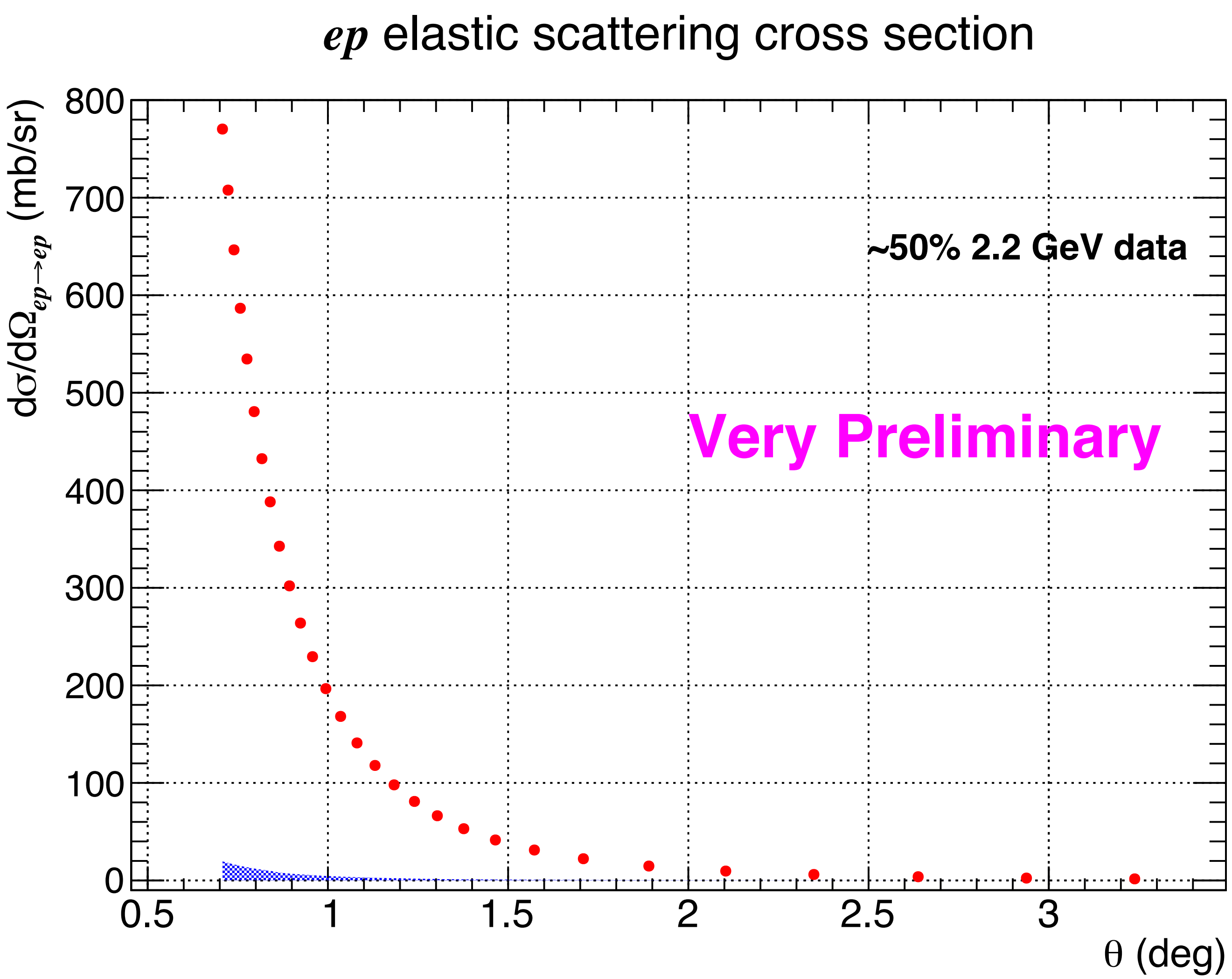
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{ep} = \left[\frac{N_{\mathrm{exp}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\mathrm{exp}}(ee \to ee)} \cdot \frac{\varepsilon^{ee}_{\mathrm{geom}}}{\varepsilon^{ep}_{\mathrm{geom}}} \cdot \frac{\varepsilon^{ee}_{\mathrm{det}}}{\varepsilon^{ep}_{\mathrm{det}}}\right] \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{ee}$$

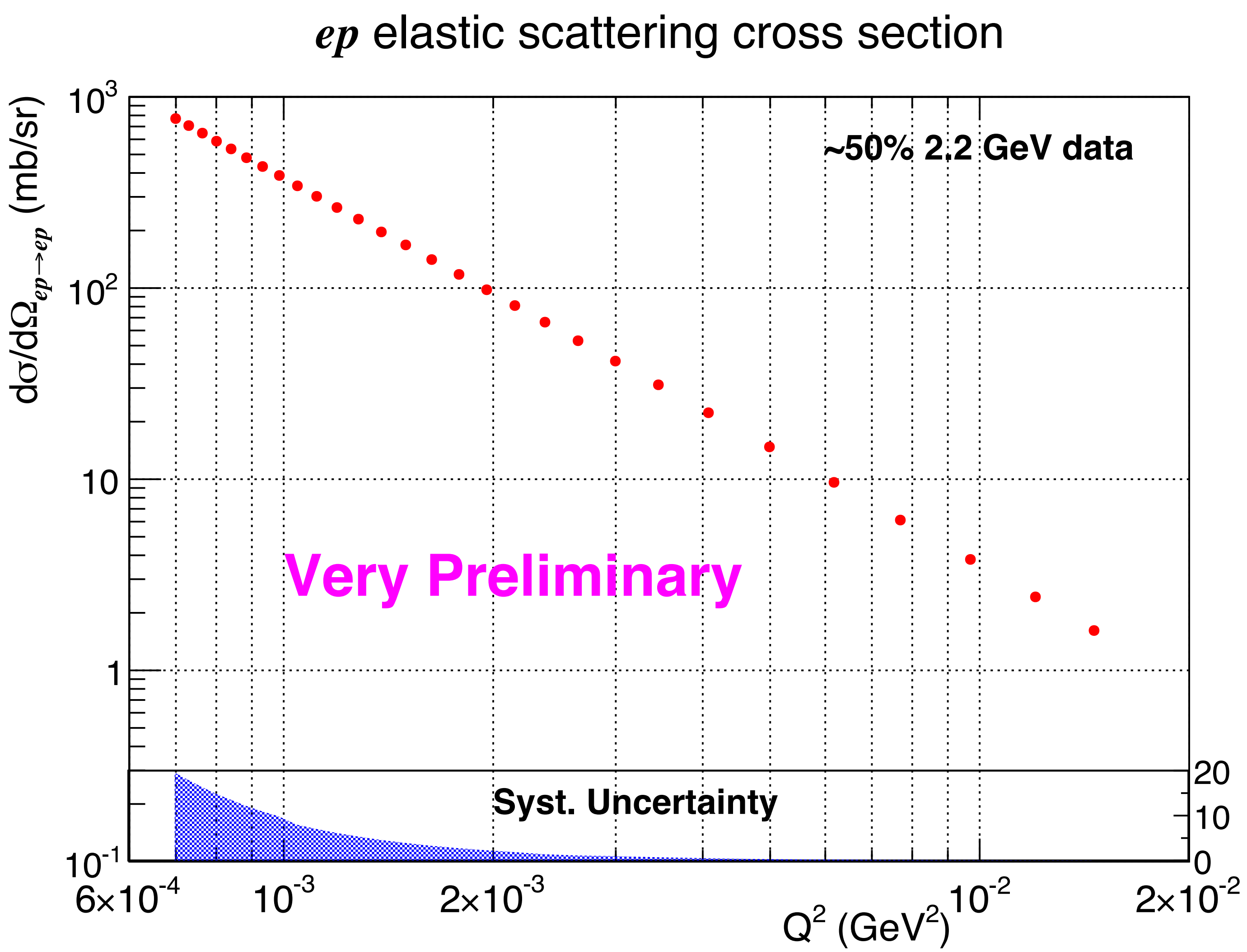
- Event generators for unpolarized elastic ep and Moller scatterings have been developed based on complete calculations of radiative corrections beyond the ultra relativistic approximation
    - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
    - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
- A Geant4 simulation package is used to study the radiative effects:

$$\sigma_{ep}^{\mathrm{born}} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\mathrm{exp}} \cdot \left(\frac{\sigma_{ee}}{\sigma_{ep}}\right)^{\mathrm{sim}} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\mathrm{born}} \cdot \sigma_{ee}^{\mathrm{born}}$$

Elastic ep Cross Section (Preliminary)

- The plots show the extracted differential cross section vs scattered angle, for 2.2 GeV incident beam energy in 0.7 - 3.5 deg range (Very Preliminary)
- Statistical errors at this stage are ~0.2% per point
- Systematic errors at this stage are estimated to be at 2% level (shown as the shadow area).





Plots courtesy of W. Xiong

Elastic ep Cross Section (Preliminary)

- We are currently still working to reduce and determine the systematical errors
  - Cosmic events, GEM efficiency, Background subtraction, RC …
- Analyses plan:
  - Finish the extraction of cross sections for the 2.2 GeV run, to include all data
  - Finalize the systematic errors on 2.2 GeV cross sections (by September, 2017)
  - Fit to extract the proton radius from the 2.2 GeV data set (preliminary, October, 2017, DNP meeting)
  - Parallel work on extraction of cross sections for 1.1 GeV run (preliminary, December, 2017)
  - Finalize cross sections for both energy runs (July, 2018)
  - Final extraction of the proton charge radius (December, 2018)

Conclusion

- The PRad experiment was uniquely designed to address the "Proton Radius Puzzle"
- Experiment had been successfully performed in May - June, 2016
- About half of the 2.2 GeV beam energy data have been analyzed so far:
  - Very preliminary differential cross sections for the elastic ep scattering have been extracted for the forward angle range from 0.70 to 3.00 deg
- Fit to extract the proton radius from the 2.2 GeV data set is expected to be done by October this year

PRad is supported in part by NSF MRI award #PHY-1229153
and US DOE grant DE-FG02-03ER41231.

Thanks

Backups

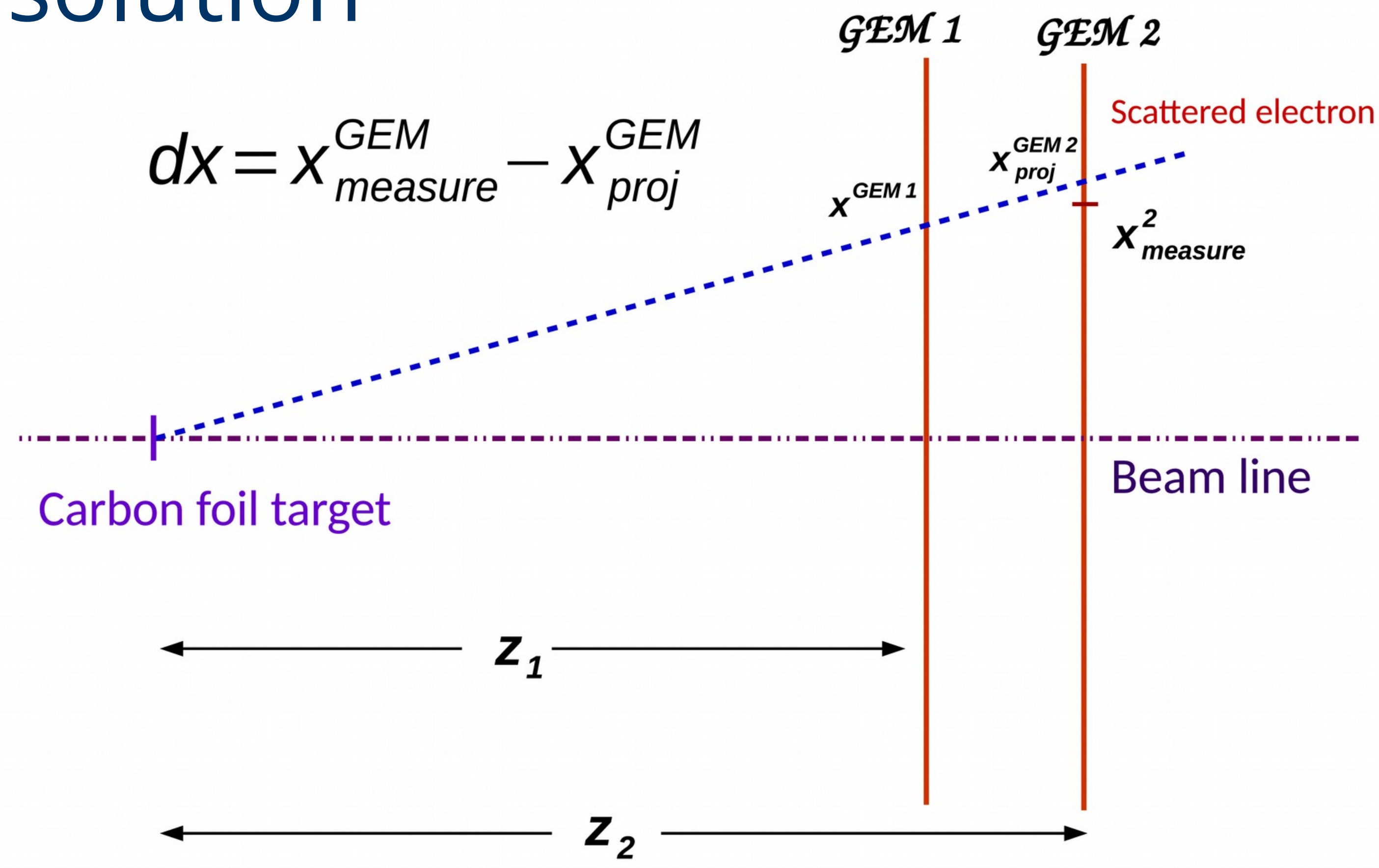
Resolution

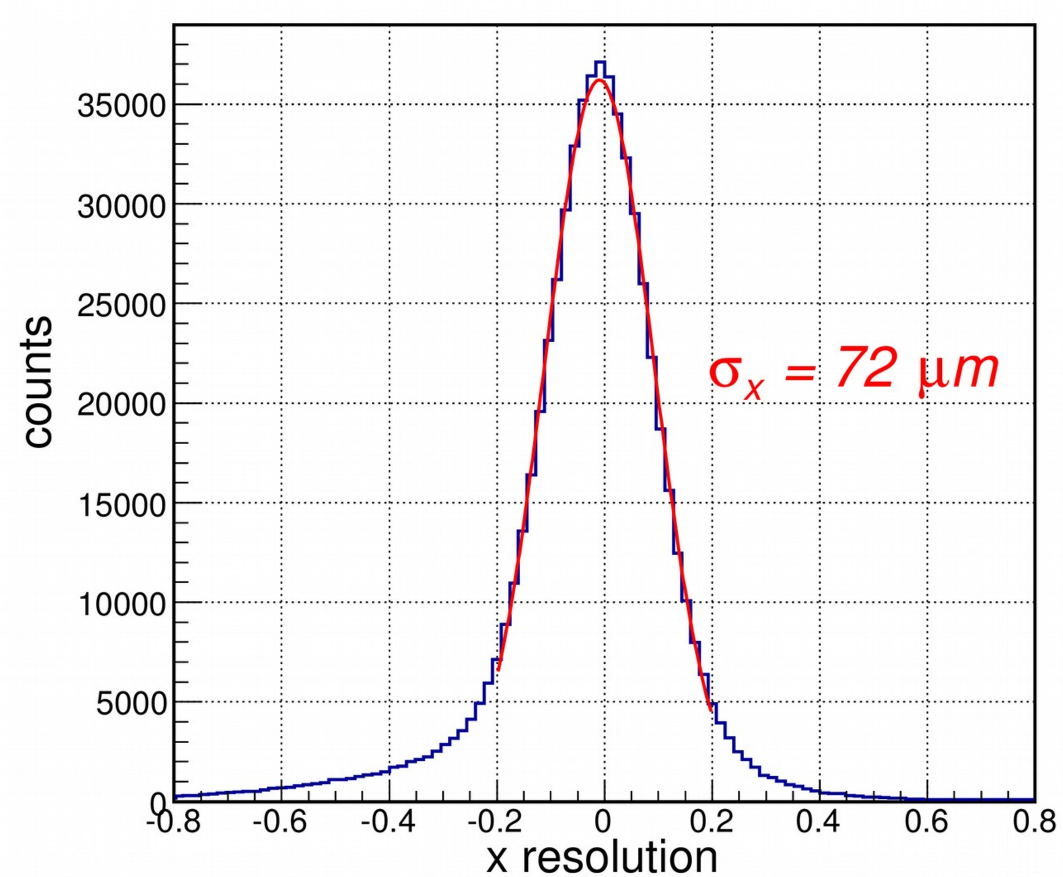
Position resolution:

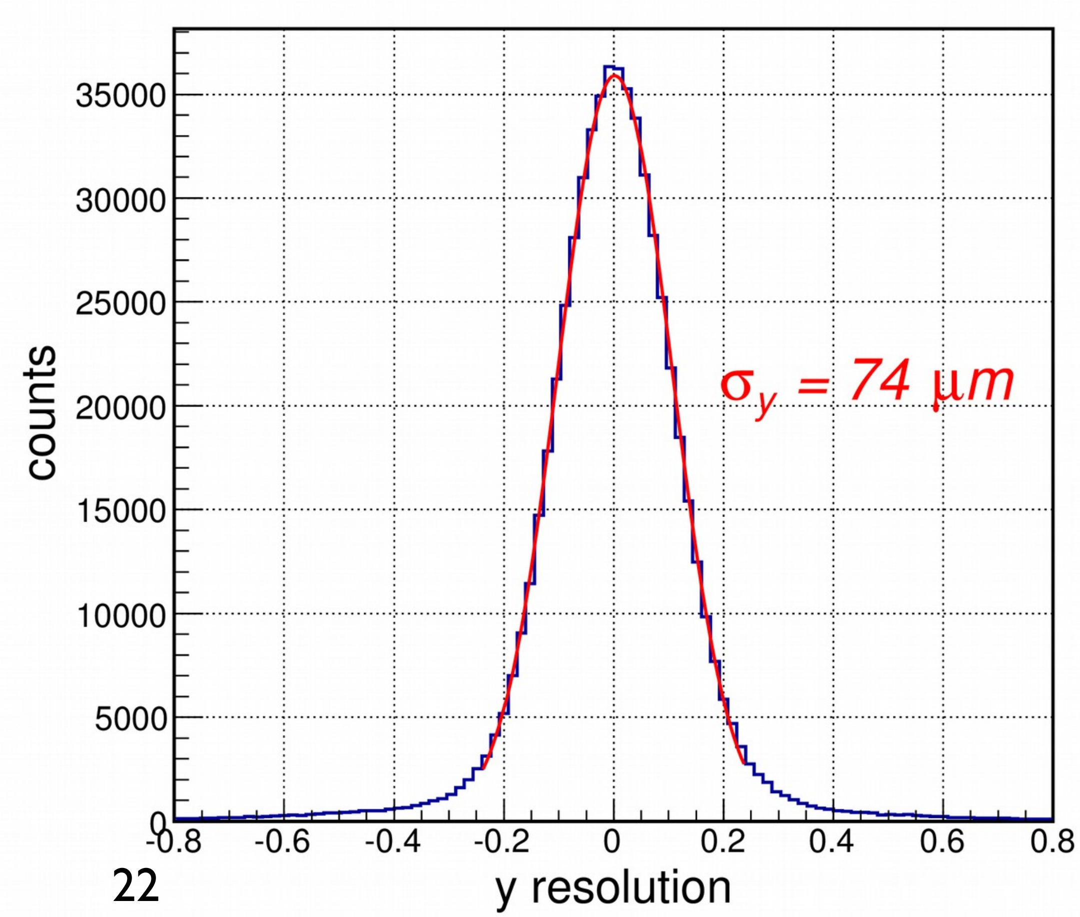
- Carbon foil target run, designed for calibration
- Well controlled detector offsets.
- Project GEM1 coordinates to GEM2.
- Find statistical width.
- Assume two chambers have the same resolution:

$$\sqrt{\sigma^2_{gem\,1}+\sigma^2_{gem\,2}}=\sigma_{stat}$$

$$\sigma_{gem}=\sigma_{stat}/\sqrt{2}$$



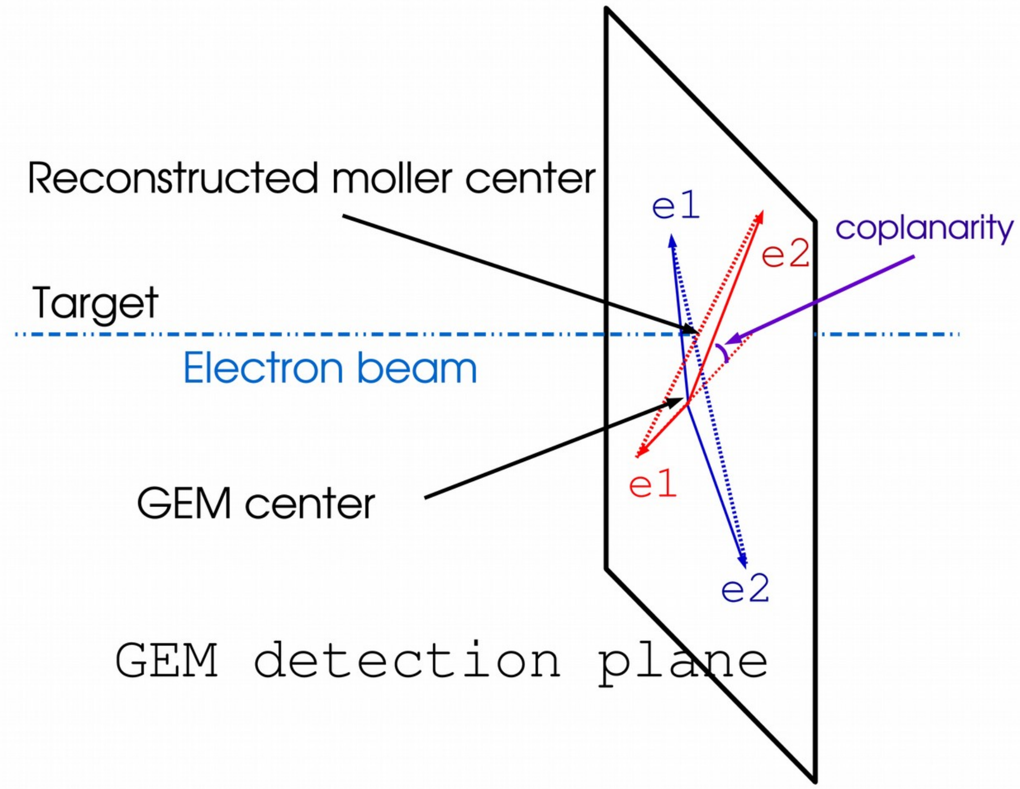


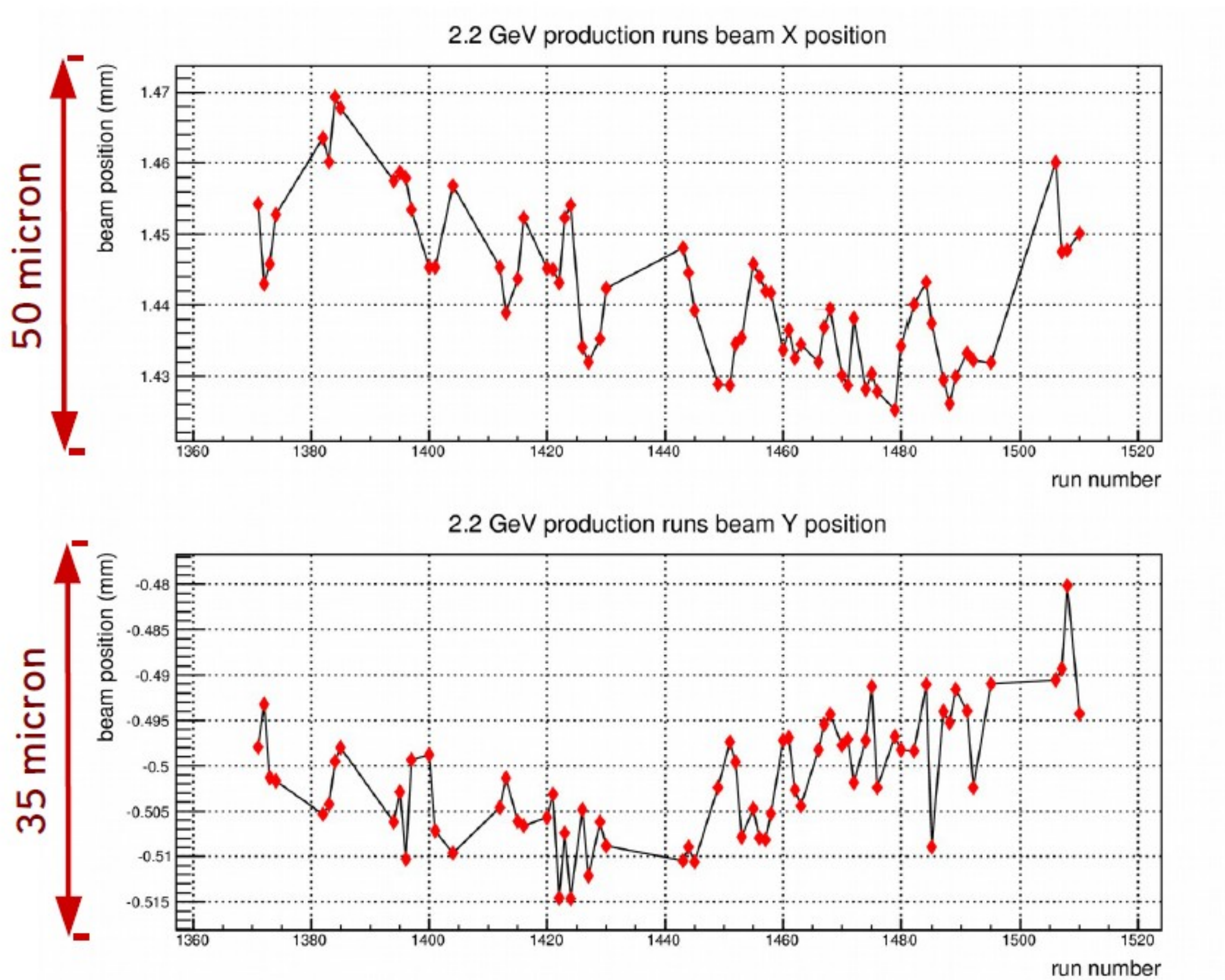


1

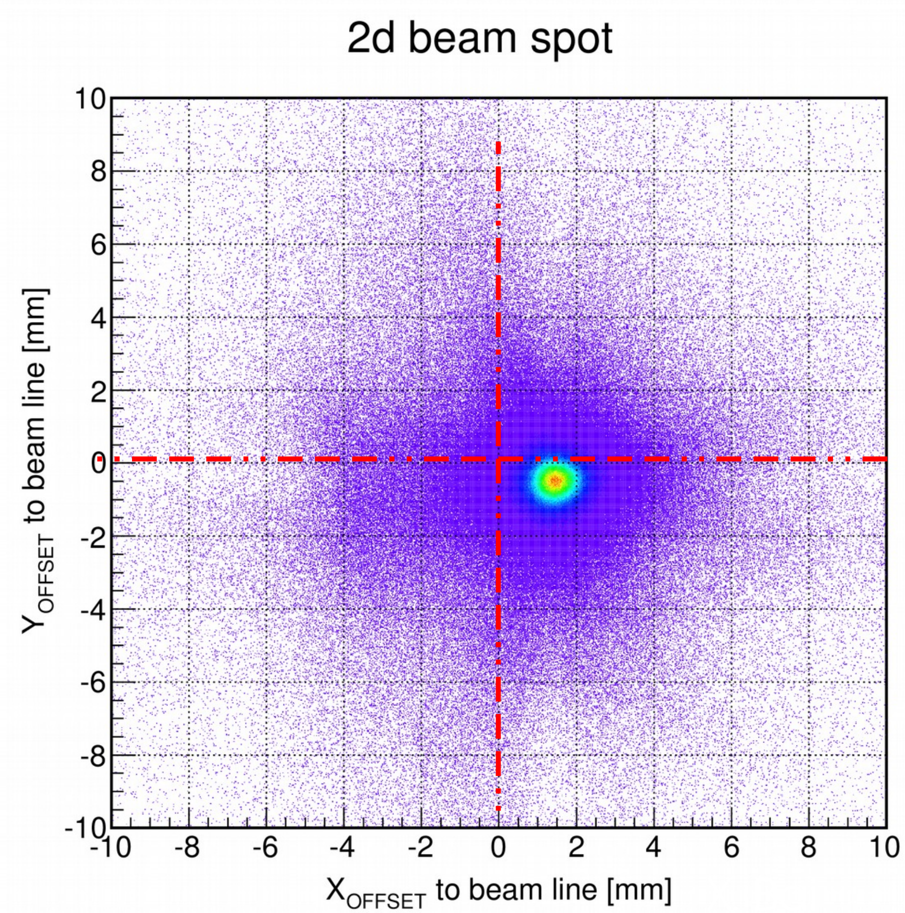
Beam positions monitored by GEM detectors

- Beam position important to the experiment.
- Using moller events to find beam position.
- Allows us to continuously monitor beam position upto *0.05mm* level.



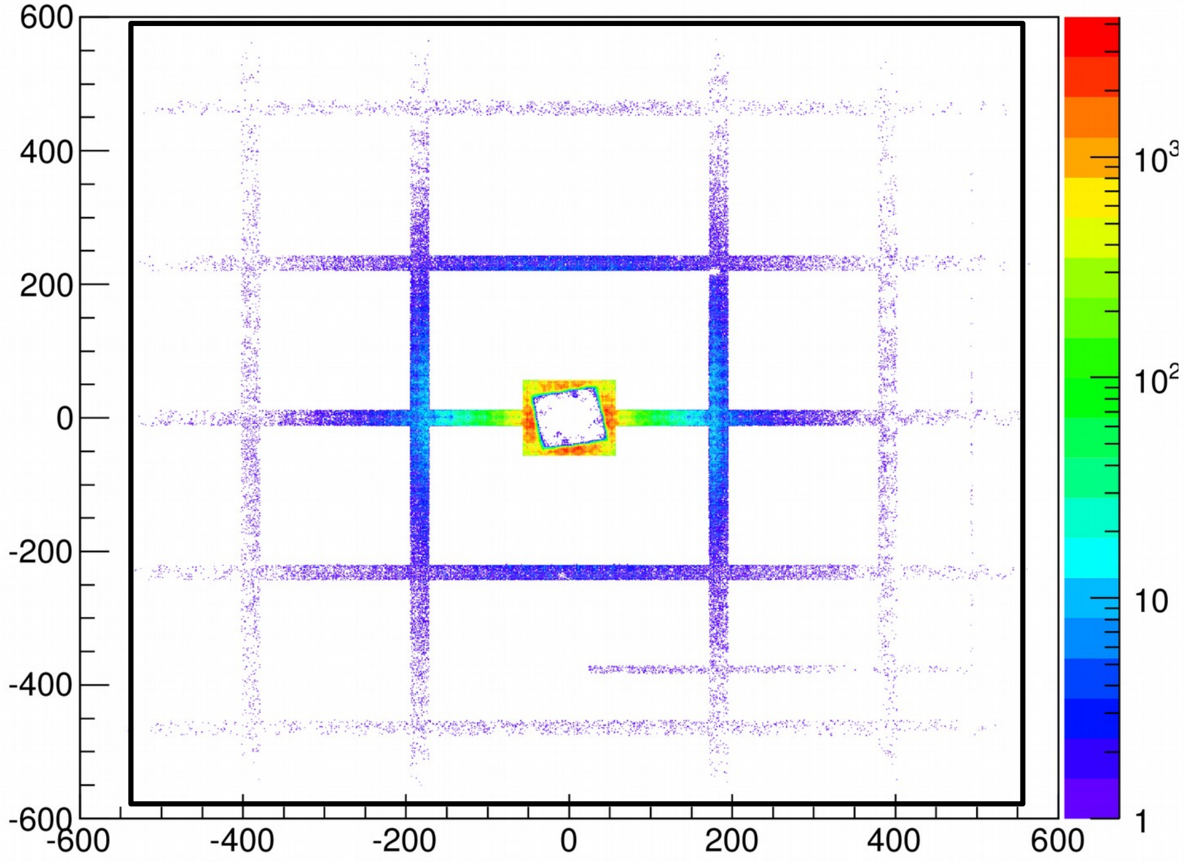


Beam position monitored by GEM detectors in different runs

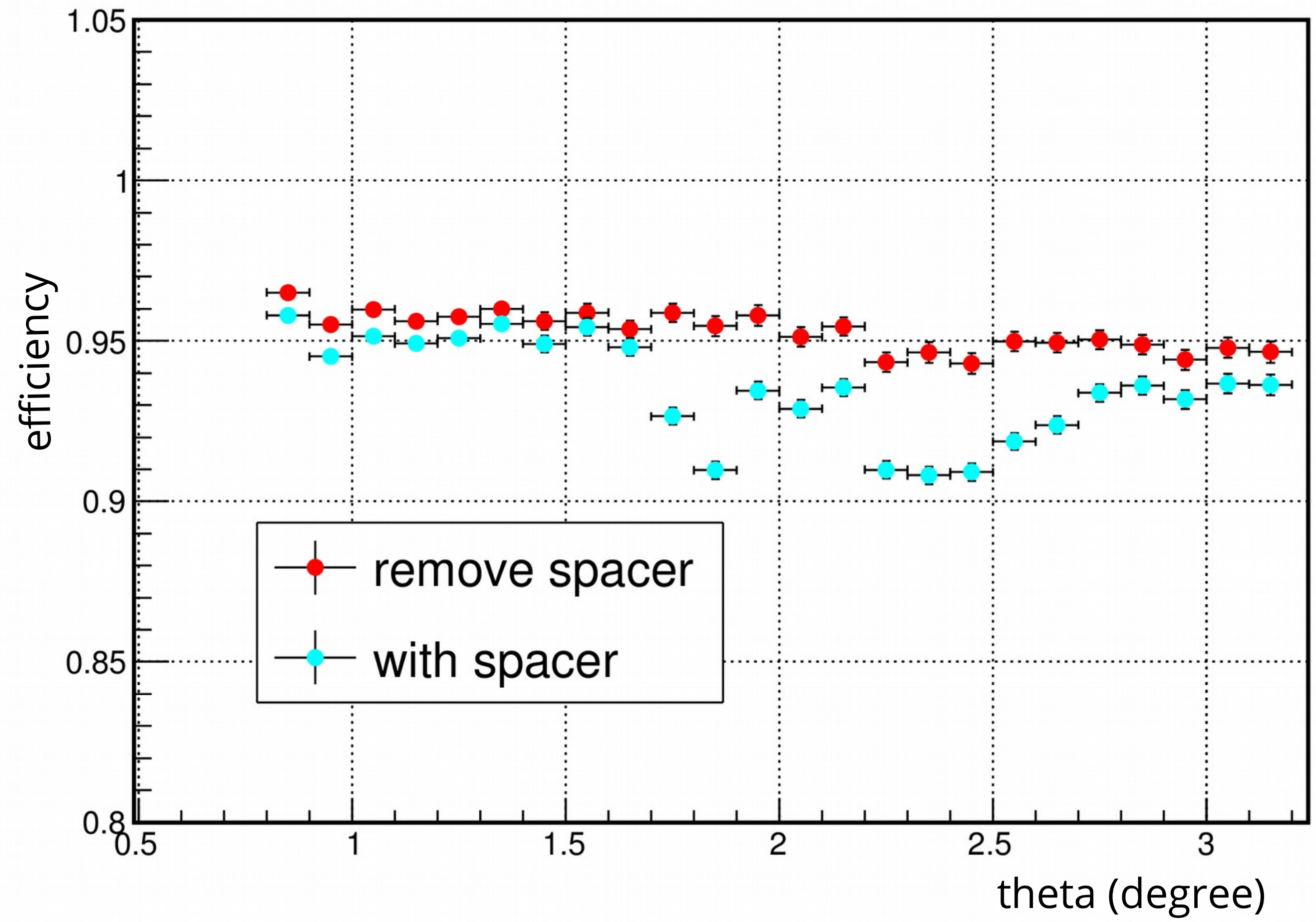


Efficiency From Production Data

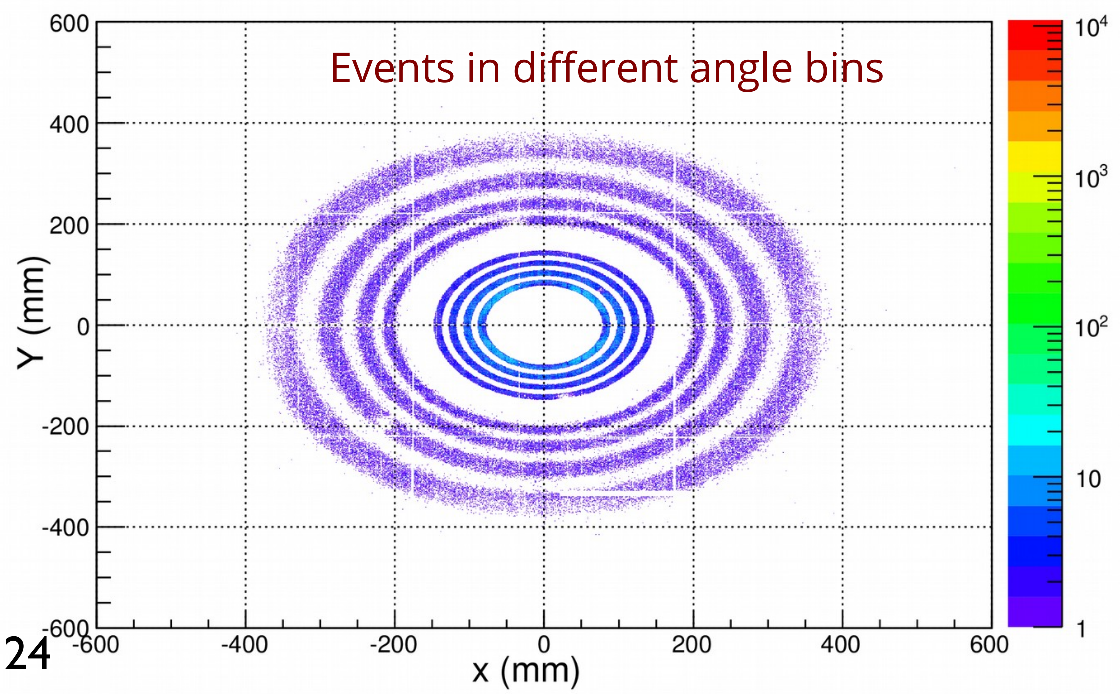
Spacer area cut off



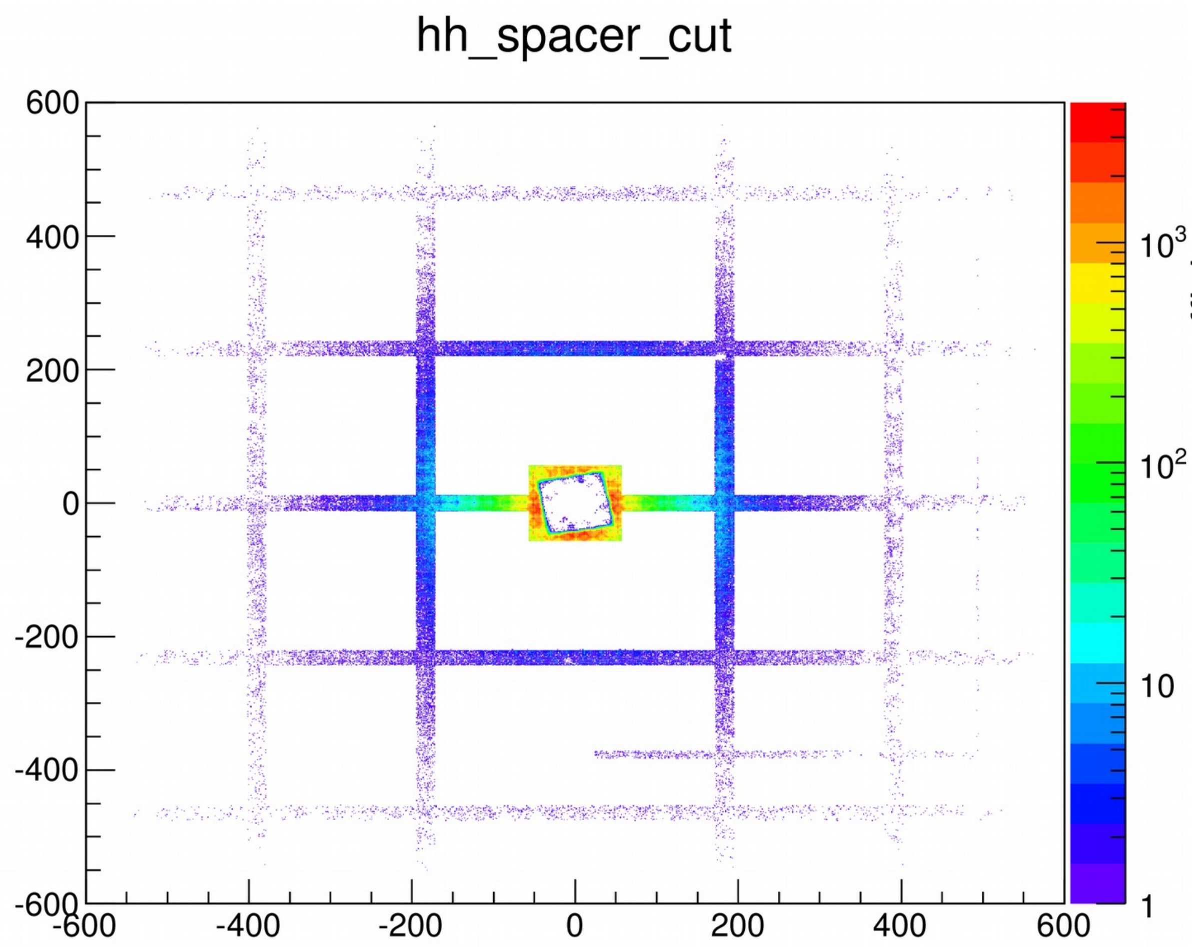
GEM efficiency

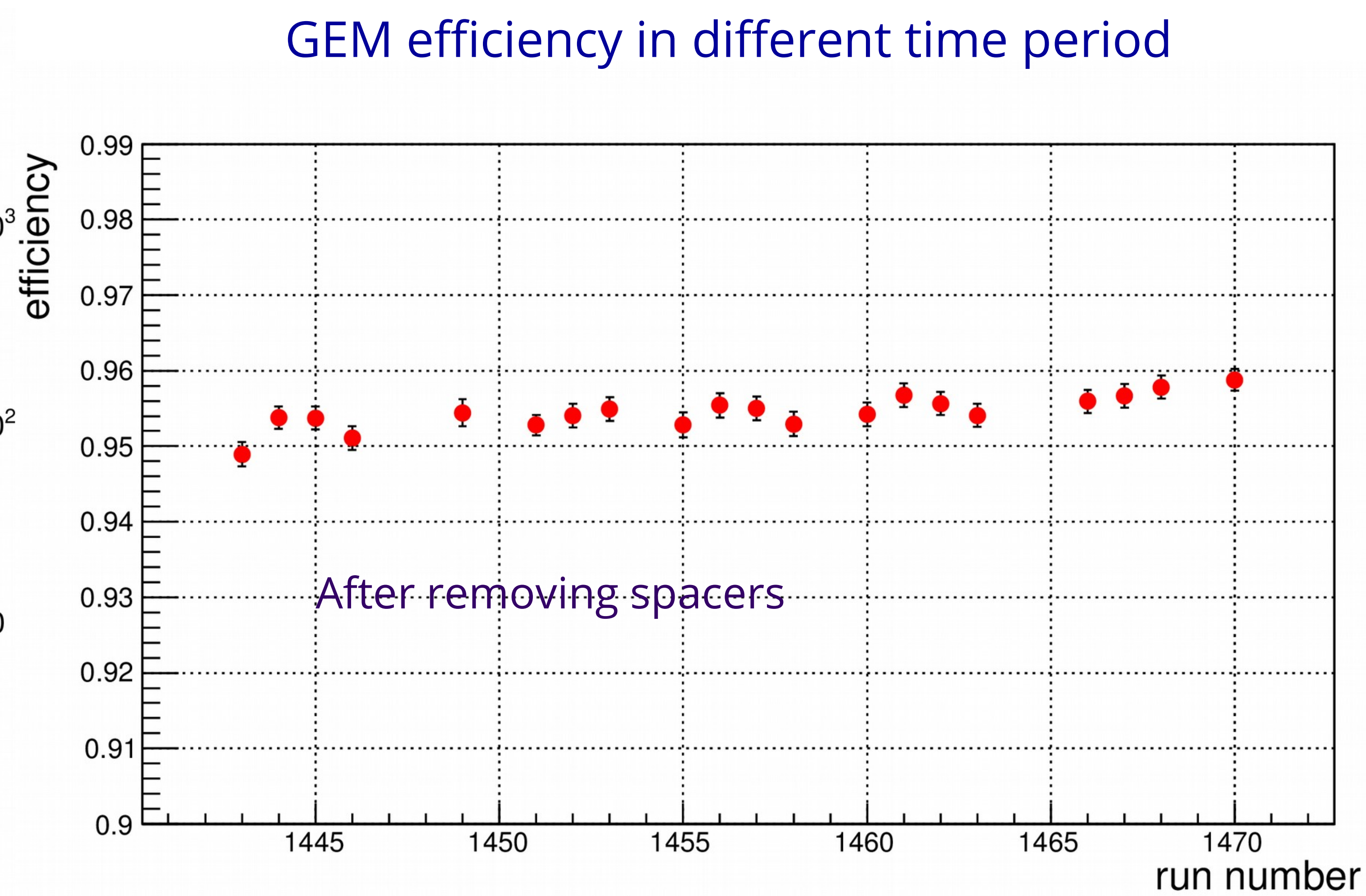


- GEM spacer introduces deficient area
- 5% data loss from spacer area cut off
- Evenly distributed efficiency after spacer correction



Efficiency from production data





- GEM spacer introduces deficient area
- 5% data loss from spacer area cut off
- Evenly distributed efficiency after spacer correction

- Relatively clean e-p and e-e events from experiment
- Continuously monitor GEM efficiency for each run
- High, stable GEM efficiency over time
- Average efficiency fluctuation ~ 0.5% level
- Due to gas pressure, humidity, temperature, change, etc

Extracting the ep / ee ratio

- At least four different ways to form the ratio, luminosity is always canceled by the ratio:
  - ep / single arm Moller (ee1): for ep in each theta (Q^2) bin, normalize it to the Moller yield selected using single arm Moller technique
    - Best at cancellation of energy independent detector acceptance and efficiency
    - Worst in ee signal to background ratio
  - ep / double arm Moller (ee2): for ep in each theta (Q^2)bin, normalize it to the Moller yield selected using double arm Moller technique
    - Partial cancellation for energy independent detector acceptance and efficiency
    - Best at ee signal to background ratio
  - ep / integrated double arm Moller (inte Moller)
    - No cancellation for energy independent detector acceptance and efficiency
    - The only way to include ep bins in region that is not "effectively" covered by Moller
- GEM detectors are always required for the above three types of ratio
  - ep / (HyCal double arm + GEM single arm Moller) (s_ee1): using HyCal to select double arm events first. When using GEM, apply the ep / single arm Moller method
    - Excellent ee signal to background ratio
    - Complete cancellation for the energy independent acceptance and efficiency from GEM

19

PRad Data Analysis Status (May, 2017)

- About half of the 2.2 GeV beam energy data have been analyzed so far:
  - ✓ preliminary (very) differential cross sections for the elastic ep → ep scattering have been extracted for the forward angle range from 0.7^0 to 2.0^0, (shown in Fig. 1, Fig.2 and Fig.3 with different format);
  - ✓ statistical errors are on the level of 0.2% at this analysis stage (not seen on plots);
  - ✓ systematic errors are conservatively estimated to be on the level of 4% at this analysis stage and differ for angular range (shown with a dashed area).

- Current analyses plan:
  - ➢ finish the extraction of diff. cross sections for the 2.2 GeV run, to include the larger angles, $\theta_e = 2.0^0$ to 6.0^0 (by June, 2017, Users meeting);
  - ➢ finalize the systematic errors on 2.2 GeV diff. cross sections (by September, 2017) ;
  - ➢ fit to extract the proton radius from the 2.2 GeV data set (preliminary, October, 2017, DNP meeting);
  - ➢ parallel work on extraction of diff. cross sections for 1.1 GeV run (preliminary, December, 2017);

  - ➢ finalize diff. cross sections for both energy runs (July, 2018).
  - ➢ final extraction of the proton charge radius (December, 2018)