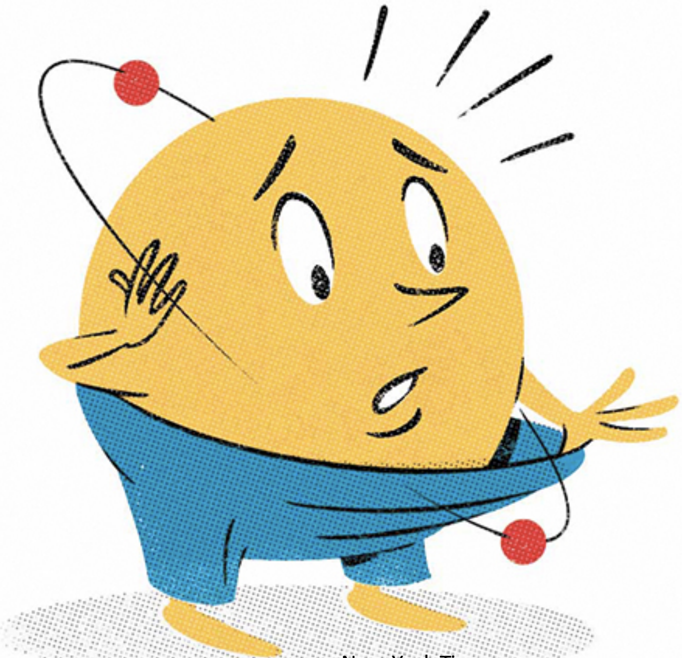
Status of the PRad Experiment

Weizhi Xiong
Duke University
for the PRad Collaboration

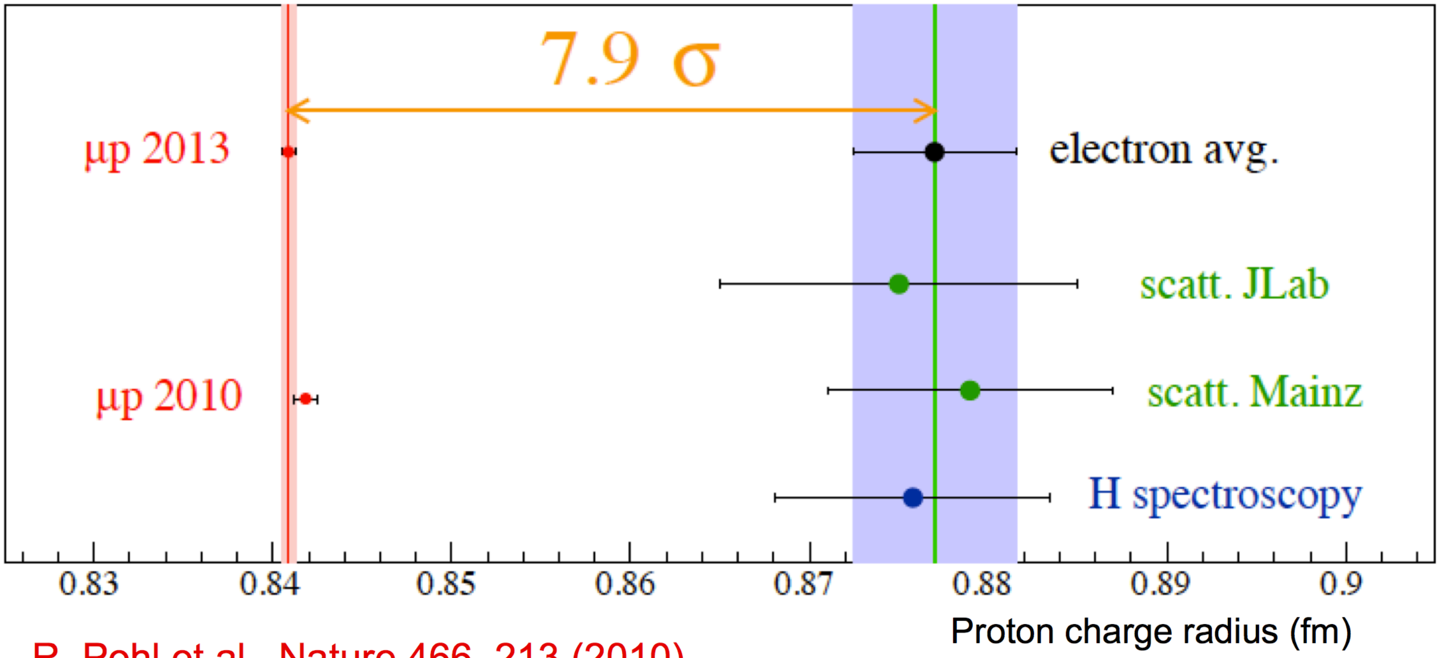
JLab User Group Meeting

Outline

- Proton charge radius puzzle and PRad experiment
- PRad experimental apparatus
- Analysis and preliminary cross section
- Summary



Proton Charge Radius Puzzle



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

- μp Lamb shift measurements by CREMA (2010, 2013)
  - Unprecedented precision, <0.1%

Proton Charge Radius from ep Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):

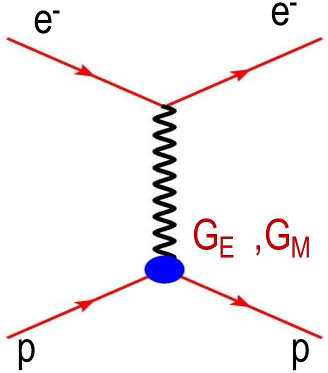
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

- Structure-less proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2 \left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- G_E and G_M can be extracted using Rosenbluth separation
- For PRad, cross section dominated by G_E



Taylor expansion of G_E at low Q^2

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

Derivative at low Q^2 limit

$$\langle r^2\rangle = -6 \left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

PRad Experiment Overview

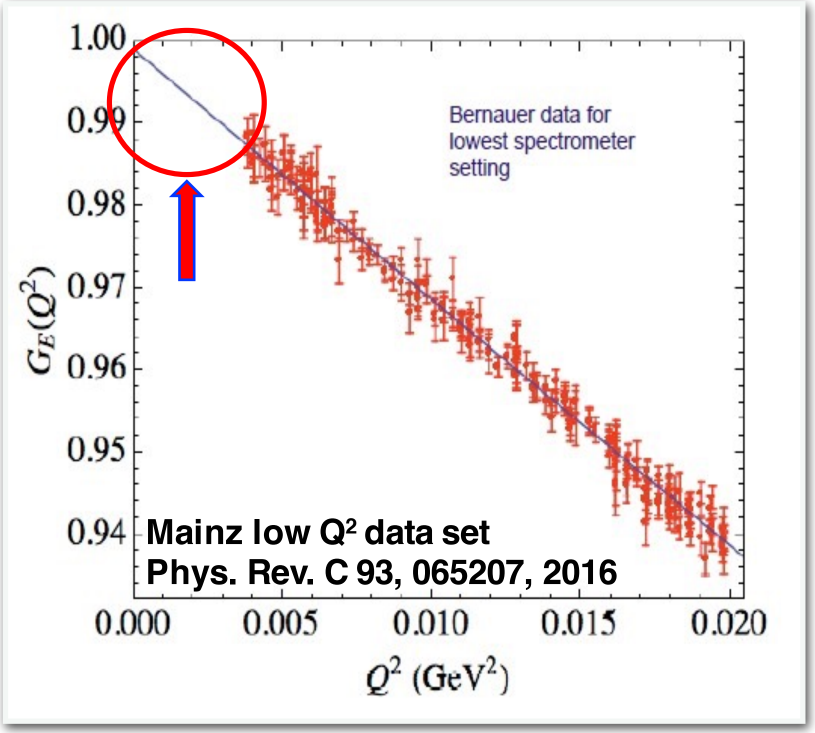
- PRad goal: Measuring proton charge radius using ep elastic scattering

- Unprecedented low Q^2 (~2x10^{-4} GeV^2)
  - Fill in very low Q^2 region
- Covers two orders of magnitude in low Q^2 with the same detector setting
  - ~2x10^{-4} - 6x10^{-2} GeV^2
- Normalize to the simultaneously measured Møller scattering process
  - best known control of systematics
- Aims to extract cross section and radius to sub-percentage precision

PRad Experiment Overview

- PRad goal: Measuring proton charge radius using ep elastic scattering

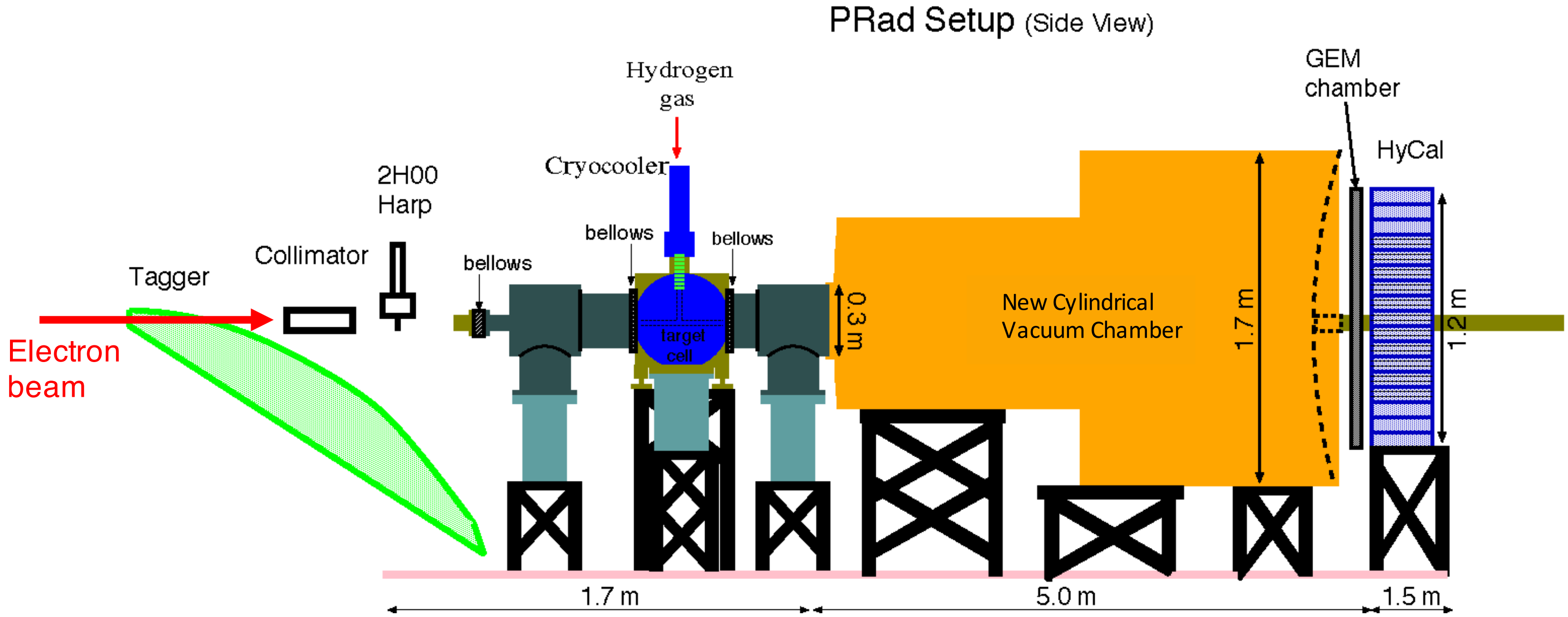
- Unprecedented low Q^2 (~2x10^{-4} GeV^2)
  - Fill in very low Q^2 region
- Covers two orders of magnitude in low Q^2 with the same detector setting
  - ~2x10^{-4} - 6x10^{-2} GeV^2
- Normalize to the simultaneously measured Møller scattering process
  - best known control of systematics
- Aims to extract cross section and radius to sub-percentage precision



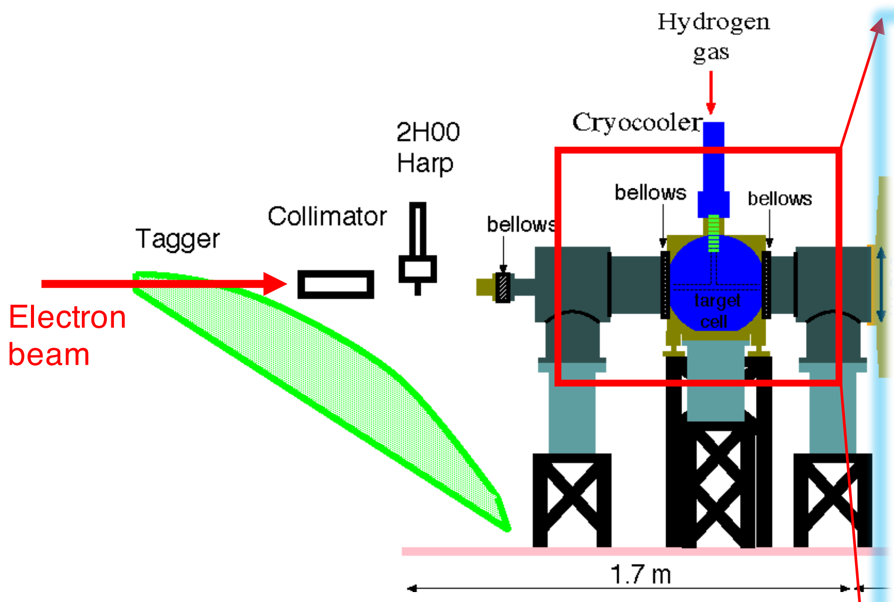
PRad Timeline

- 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

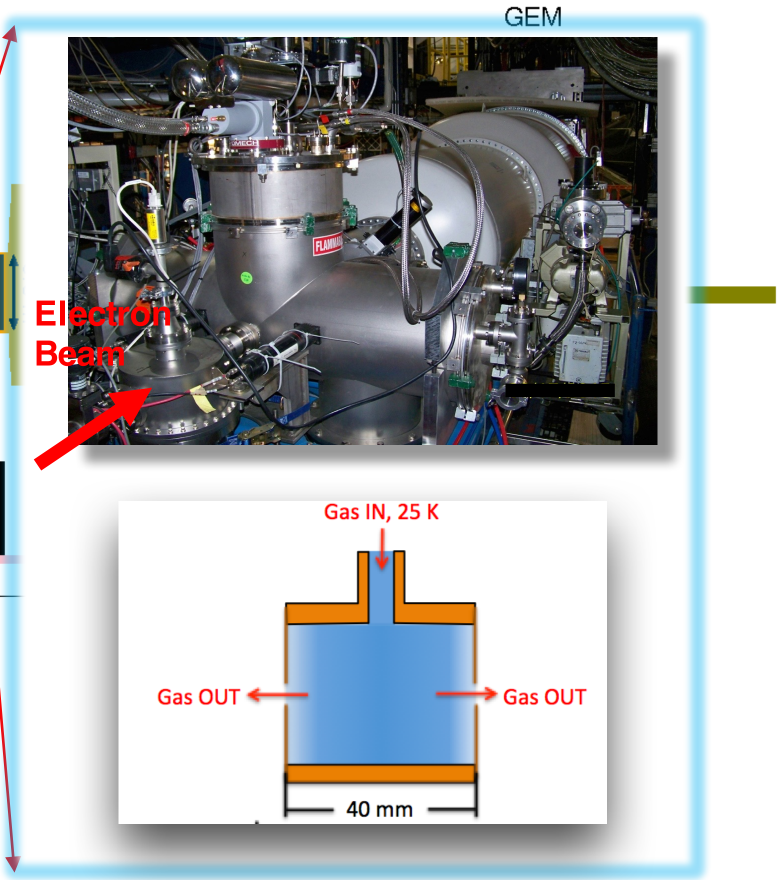
PRad Experimental Apparatus



PRad Experimental Apparatus

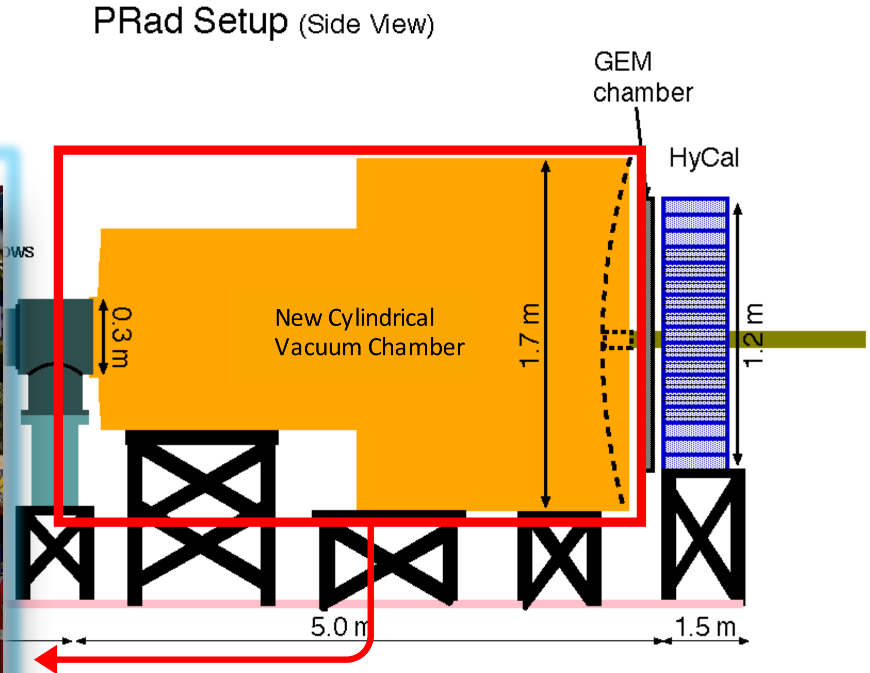


PRad Setup (Side View)



- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2

PRad Experimental Apparatus



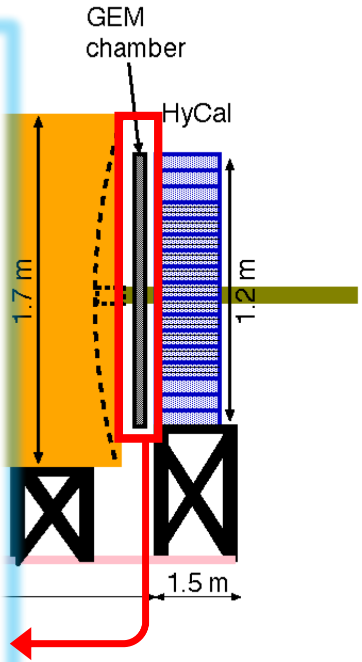
- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum chamber pressure: 0.3 mTorr

PRad Experimental Apparatus

PRad Setup (Side View)

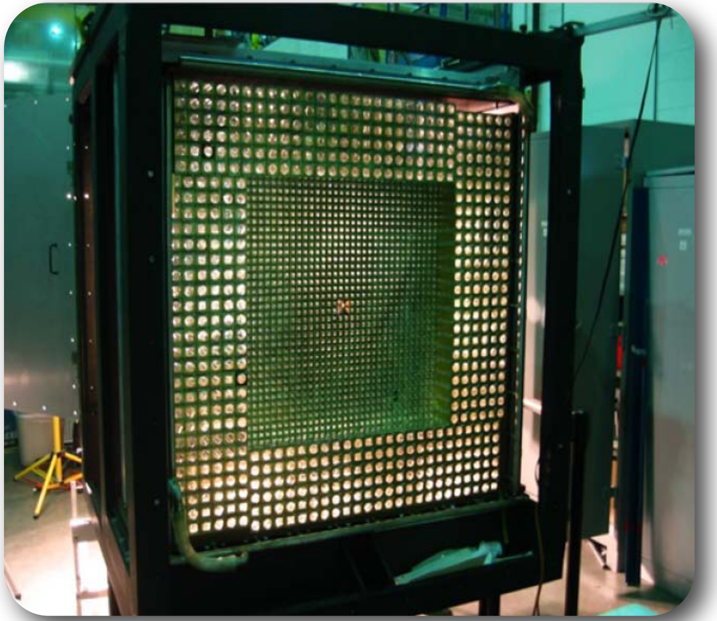
Hydrogen

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Large improvement for Q^2 determination



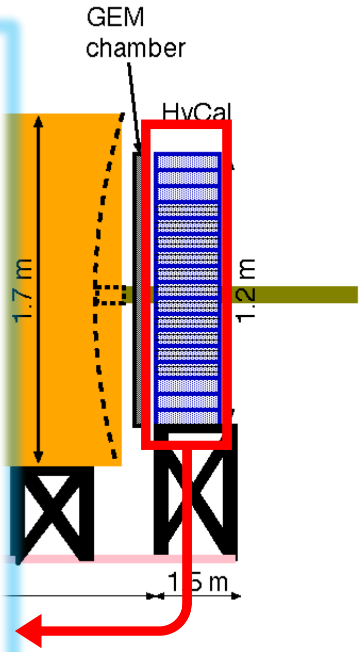
PRad Experimental Apparatus

Hydrogen



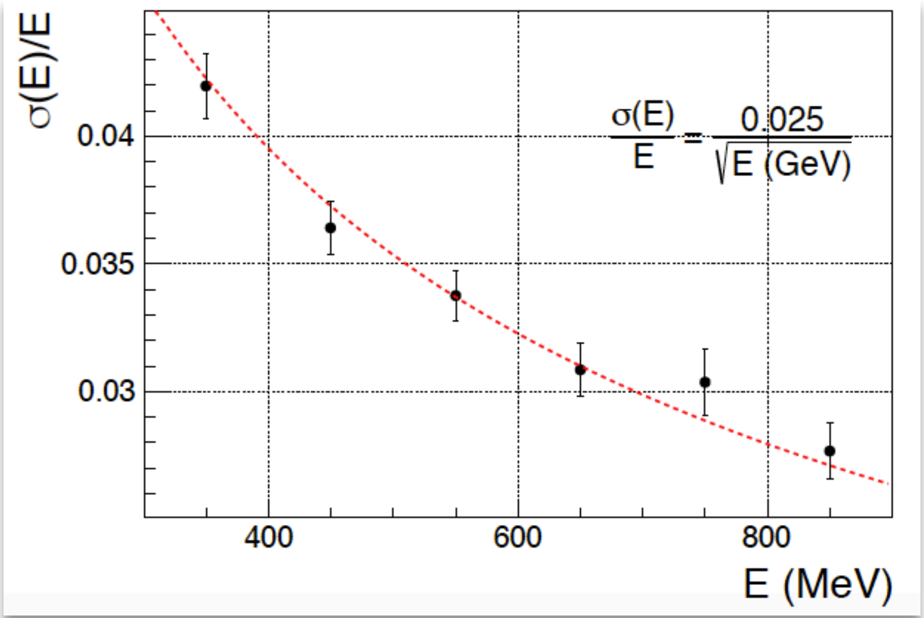
- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO_4 modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~ 0.6° to 7.5°
- Full azimuthal angle coverage
- High resolution and efficiency

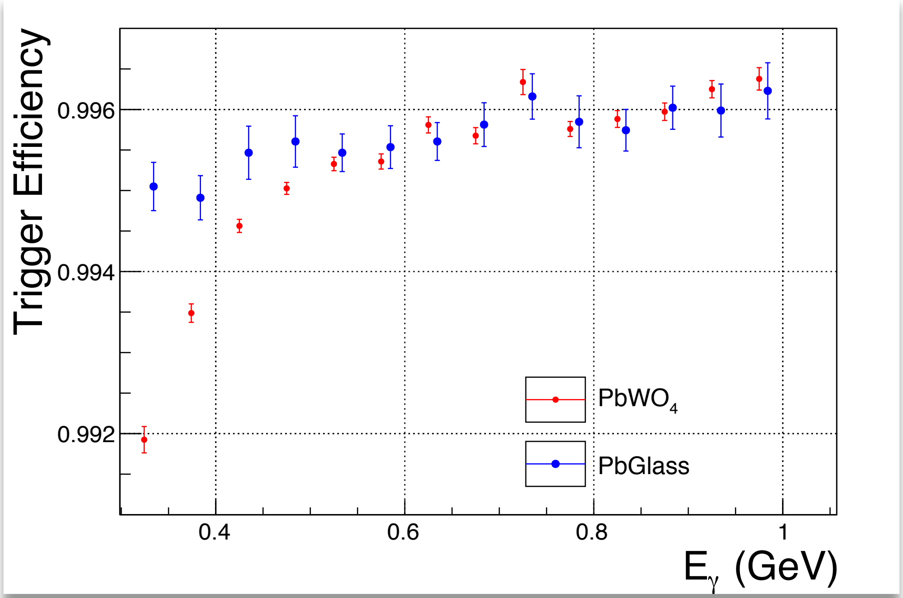
PRad Setup (Side View)



HyCal Resolution and Efficiency

- HyCal energy resolution and trigger efficiency extracted using high energy photon beam from Hall B at Jlab
  - $> 99.5\%$ trigger efficiency obtained for $E_\gamma > 500$ MeV, for various parts of HyCal
  - Energy resolution ~2.5% for PWO_4 part, lead glass part about 2.5 time worse

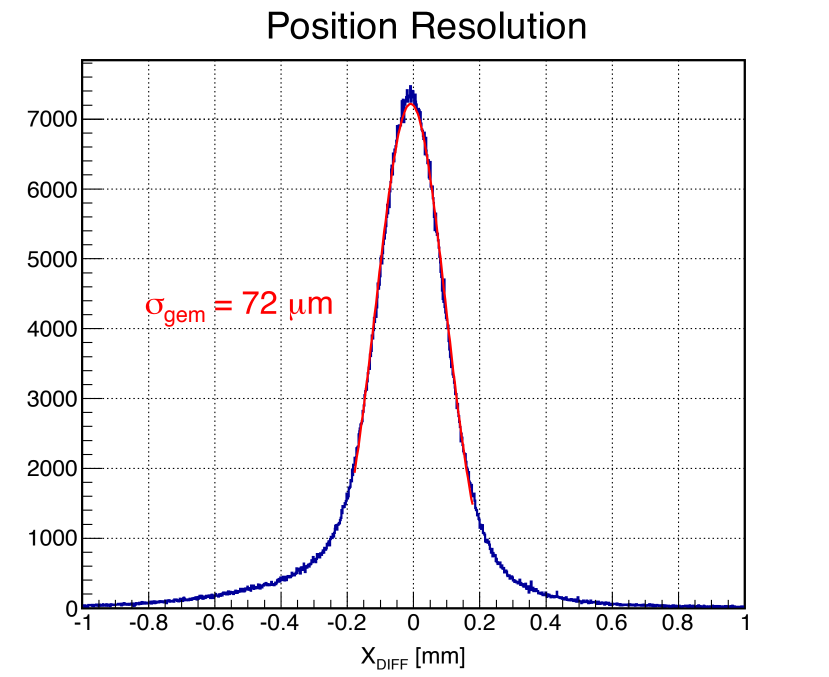


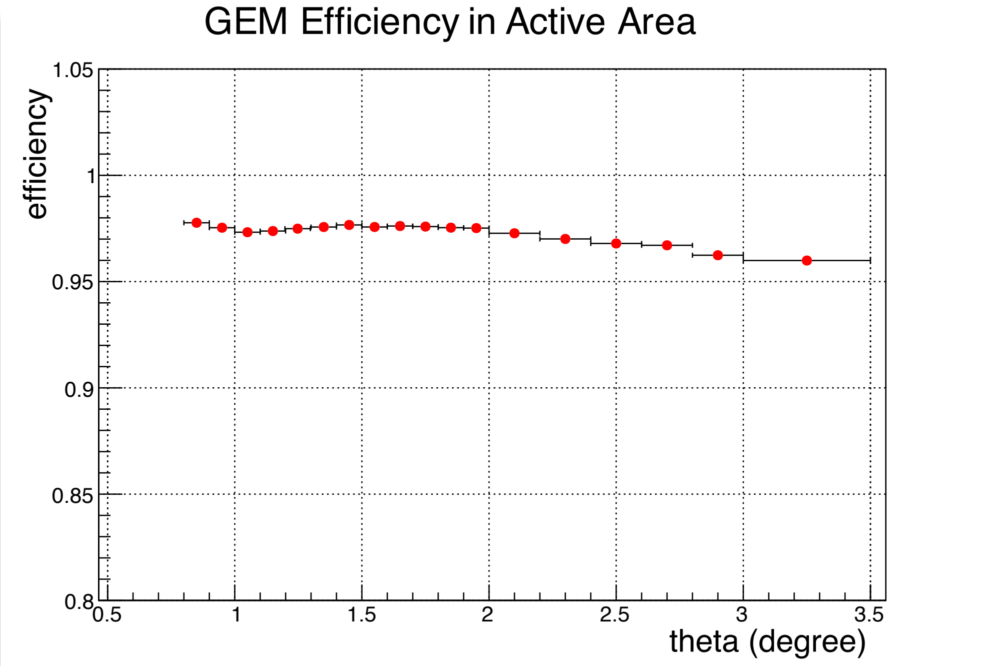


Plots courtesy of M. Levillain

Performance of GEM Detectors

- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (*ep* and *ee*)
- Using overlap region of GEMs to measure position resolution (72 μm)

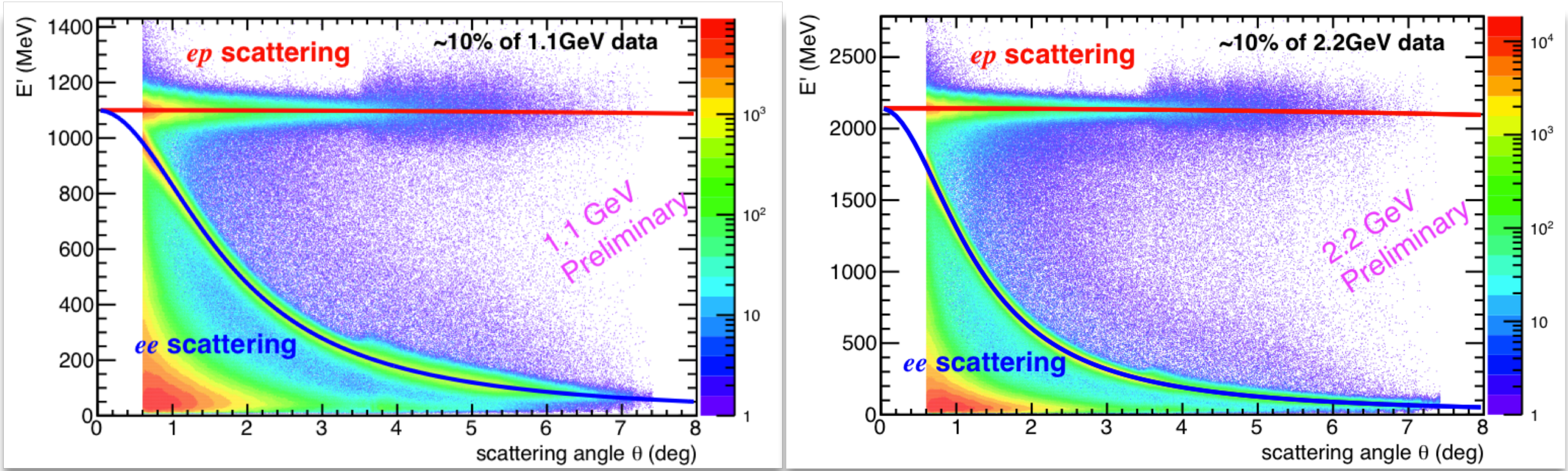




Plots courtesy of X. Bai

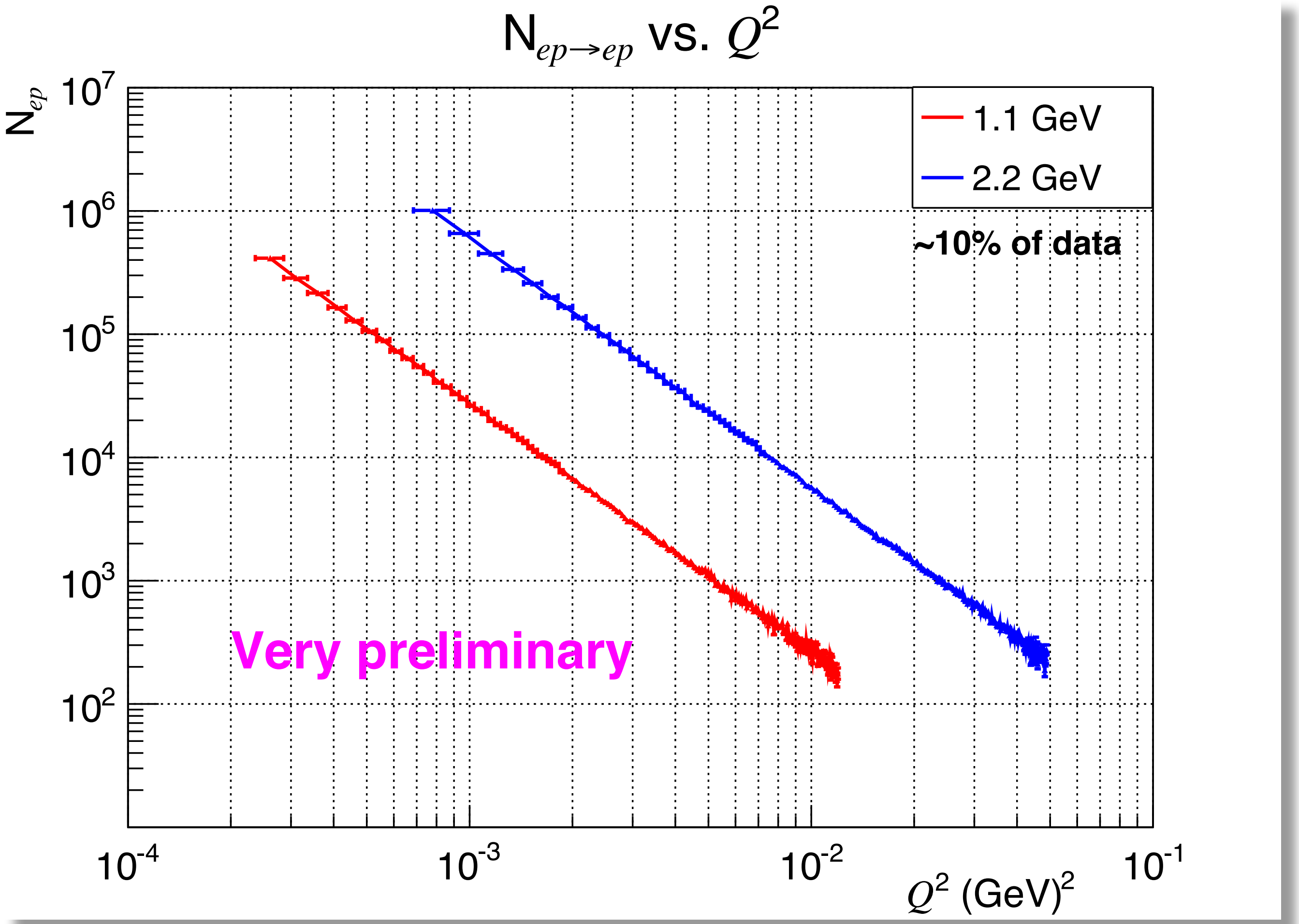
Cluster Energy E' vs. Scattering Angle θ

(after cluster matching between GEMs and HyCal, and background subtraction)



- Clear separation of *ep* and *ee* elastic scattering peak at both energy settings

ep Experimental Yield



Extraction of *ep* Elastic Cross Section

- To reduce the systematic uncertainty, the ep cross section is normalized to the Møller cross section:

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

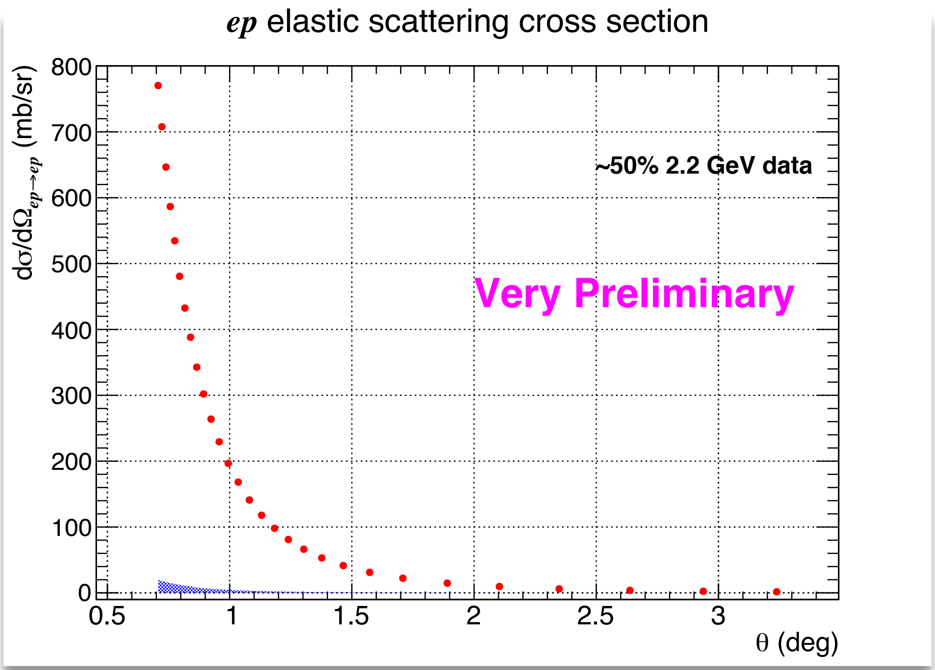
- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections beyond ultra relativistic approximation
    - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
    - I. Akushevich et al., Eur. Phys. J. A 51(2015)1

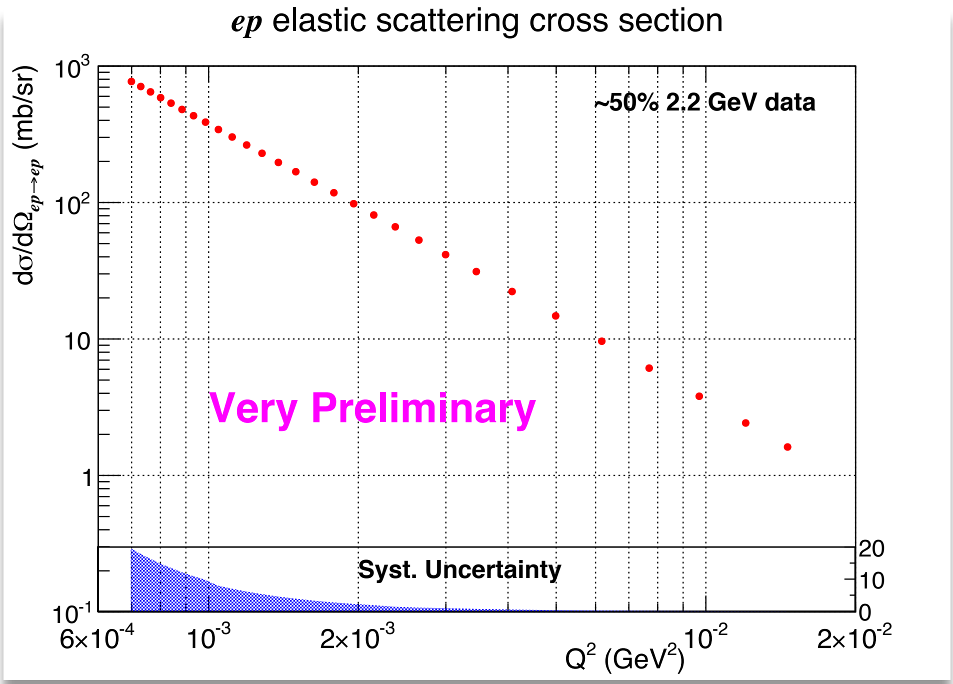
- A Geant4 simulation package is used to study the radiative effects:

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

Preliminary Elastic *ep* Cross Section

- Plots show the extracted differential cross section v.s. scattering angle and Q^2, with 2.2 GeV data in 0.7 ~ 3.5 deg range (very preliminary)
- Statistical error at this stage: ~0.2% per point
- Systematic errors are conservatively assigned at ~2% at current stage (shown as shadow area)





Analysis Plan

- We are currently still working on reducing and determining the syst. errors:
  - Cosmic contamination, GEM efficiency, background subtraction, RC…
- Finish cross section extraction for 2.2 GeV, include all runs and full angular range (0.7 ~ 6.0 deg)
- Finalize syst. error on 2.2 GeV cross section (by Sep 2017)
- Fit to extract proton charge radius from 2.2 GeV data (preliminary, Oct 2017, DNP meeting)
- Parallel work to extract cross section from 1.1 GeV runs (preliminary, Dec 2017)
- Finalize cross sections for both energy runs (Jul 2018)
- Final extraction of proton charge radius (Dec 2018)

Summary

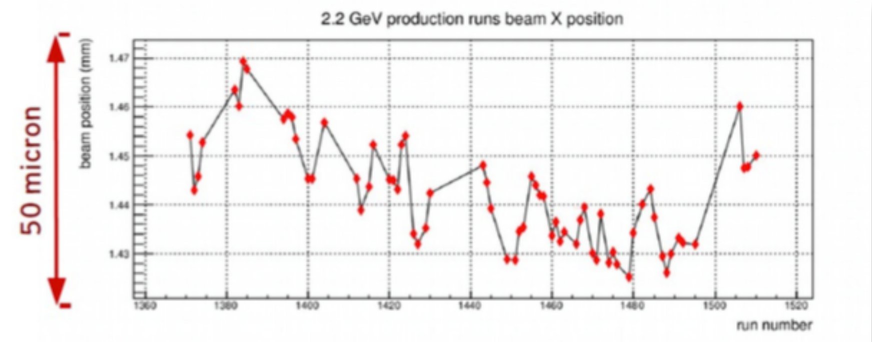
- The *Proton Radius Puzzle* is still unsolved after seven years
- PRad experiment is uniquely designed to address the puzzle
  - Performed in May – June, 2016
  - Lowest Q^2 data set (~2×10^{-4} GeV^2) has been collected for the first time in ep elastic scattering experiment
  - Data with two orders of magnitude in low Q^2 range (~2×10^{-4} – 6×10^{-2} GeV^2)
- Very preliminary cross section extracted from 2.2 GeV data, covering Q^2 from 7×10^{-4} to 1.5×10^{-2} GeV^2
- Expect to obtain proton charge radius from 2.2 GeV data by Oct 2017

This work was supported in part by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-03ER41231

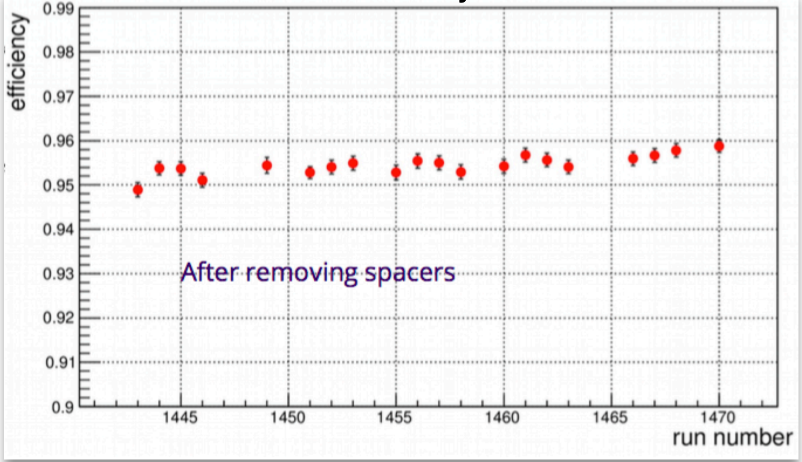
Backup

Stability

Beam spot position v.s. run



GEM efficiency v.s. run



Integrated ep/ee v.s. run