Preliminary Results from the JLab PRad Experiment

A. Gasparian
NC A&T State University, NC USA

for the PRad collaboration

Outline

- the Proton Radius Puzzle, current status
- our approach for a new ep-experiment
- the PRad experiment
- data analysis status
- some preliminary results (not for the radius)
- summary and outlook

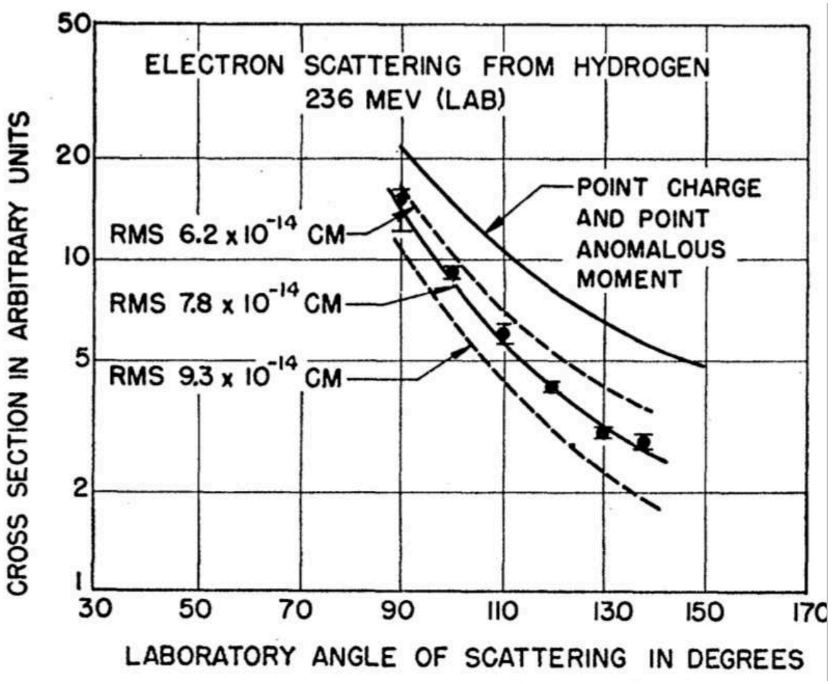
Methods to Measure the Proton Radius

Different methods to measure the Proton Radius.

- Hydrogen spectroscopy (lepton-proton bound state, Atomic Physics):
  - regular hydrogen;
  - muonic hydrogen.

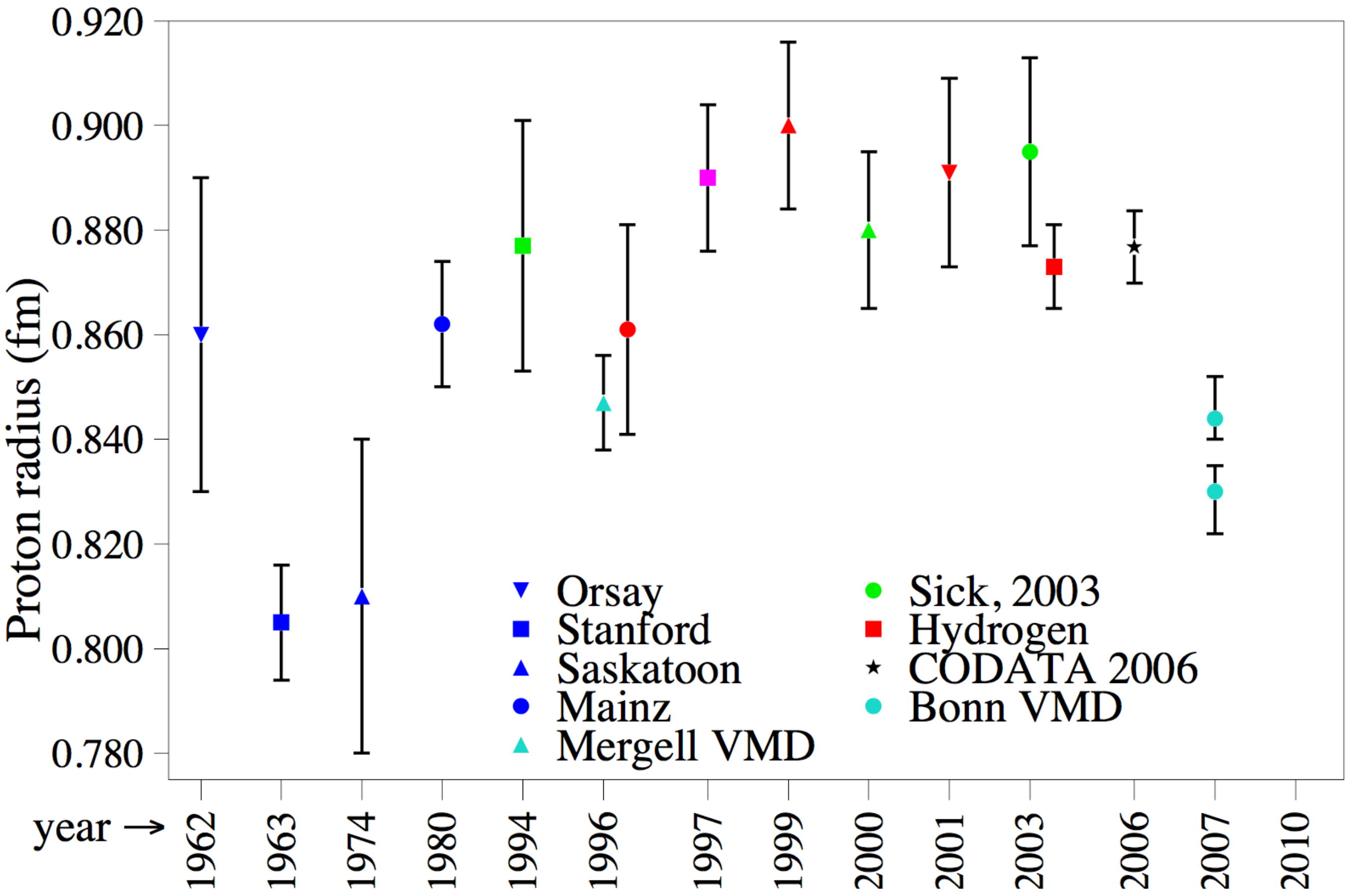
- Lepton-proton elastic scattering (Nuclear Physics):
  - ep- scattering;
  - μp- scattering.

- Over 60 years of experimentation!
  - started from 7.8 10^{-14} cm (0.78 fm) (R. Hofstadter);
  - ended to 0.895 fm by 2010.



Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

Proton Radius vs. Time (before 2010)



● ● ● electron scattering

slope of G_E at $Q^2 = 0$

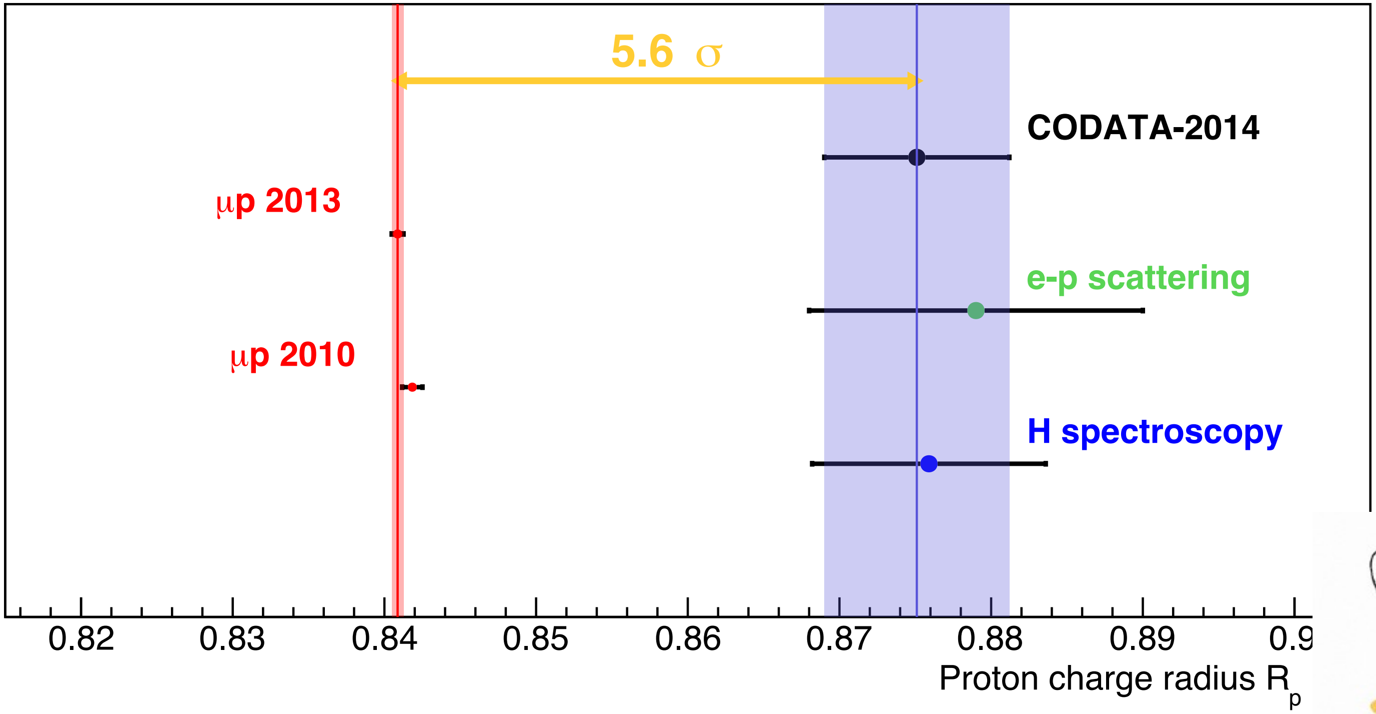
● ● hydrogen spectr.

Lamb shift (S-states)

R. Pohl

e-p scattering:	0.895(18) fm (σ_r = 2%)
Hydrogen spectroscopy:	0.8760(78) fm (σ_r = 0.9%)

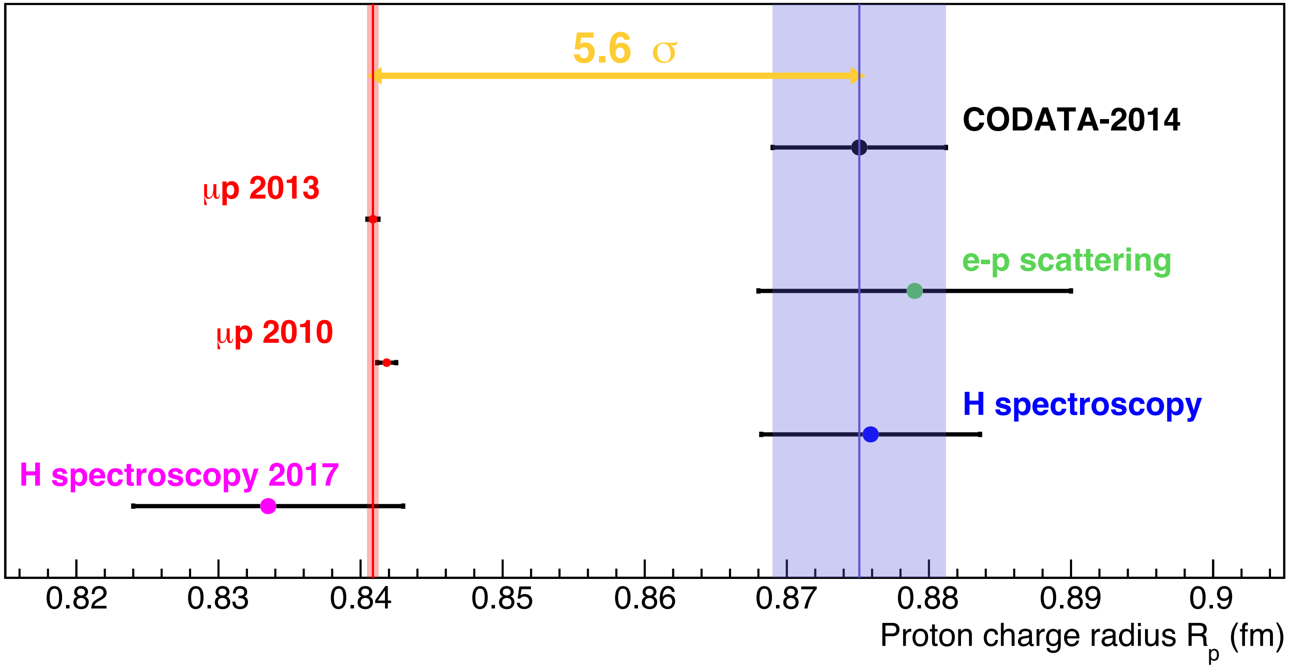
Proton Radius Puzzle (before October, 2017)



NY Times, July 12, 2010

Regular hydrogen and electron scattering:	0.8751 ± 0.0061 fm (CODATA 2014)
Muonic hydrogen:	0.8409 ± 0.0004 fm (CREMA 2010, 2013)

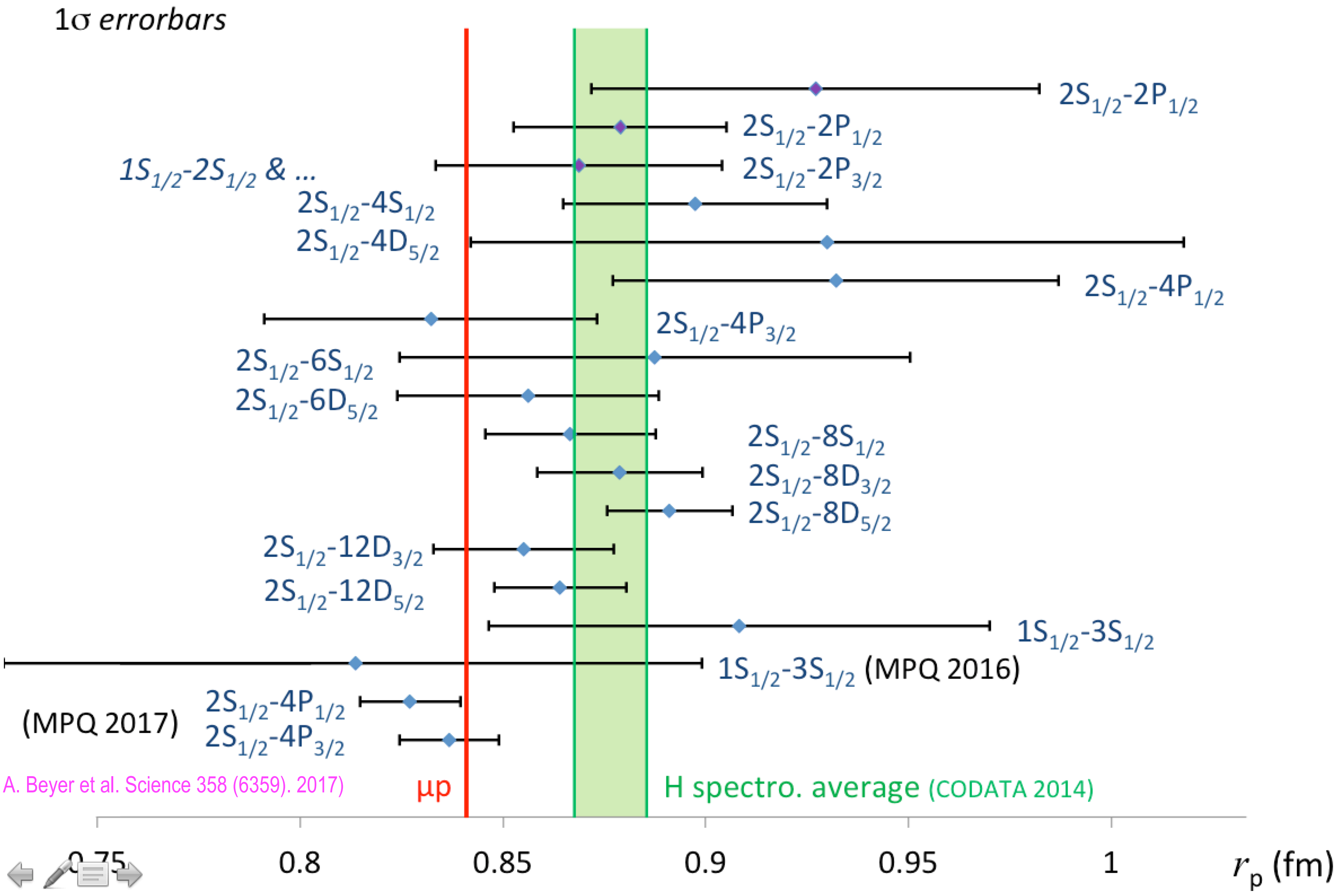
Proton Radius Puzzle (recent status)



Regular hydrogen and electron scattering:	0.8751 ± 0.0061 fm (CODATA 2014)
Muonic hydrogen spectroscopy:	0.8409 ± 0.0004 fm (CREMA 2010, 2013)
New regular hydrogen spectroscopy:	0.8335± 0.0095 fm (Science 358 (6359). 2017)

- Confirmation needed from other regular hydrogen spectroscopy experiments.
- Discrepancy between ep-scattering and muonic hydrogen experiments is still there.

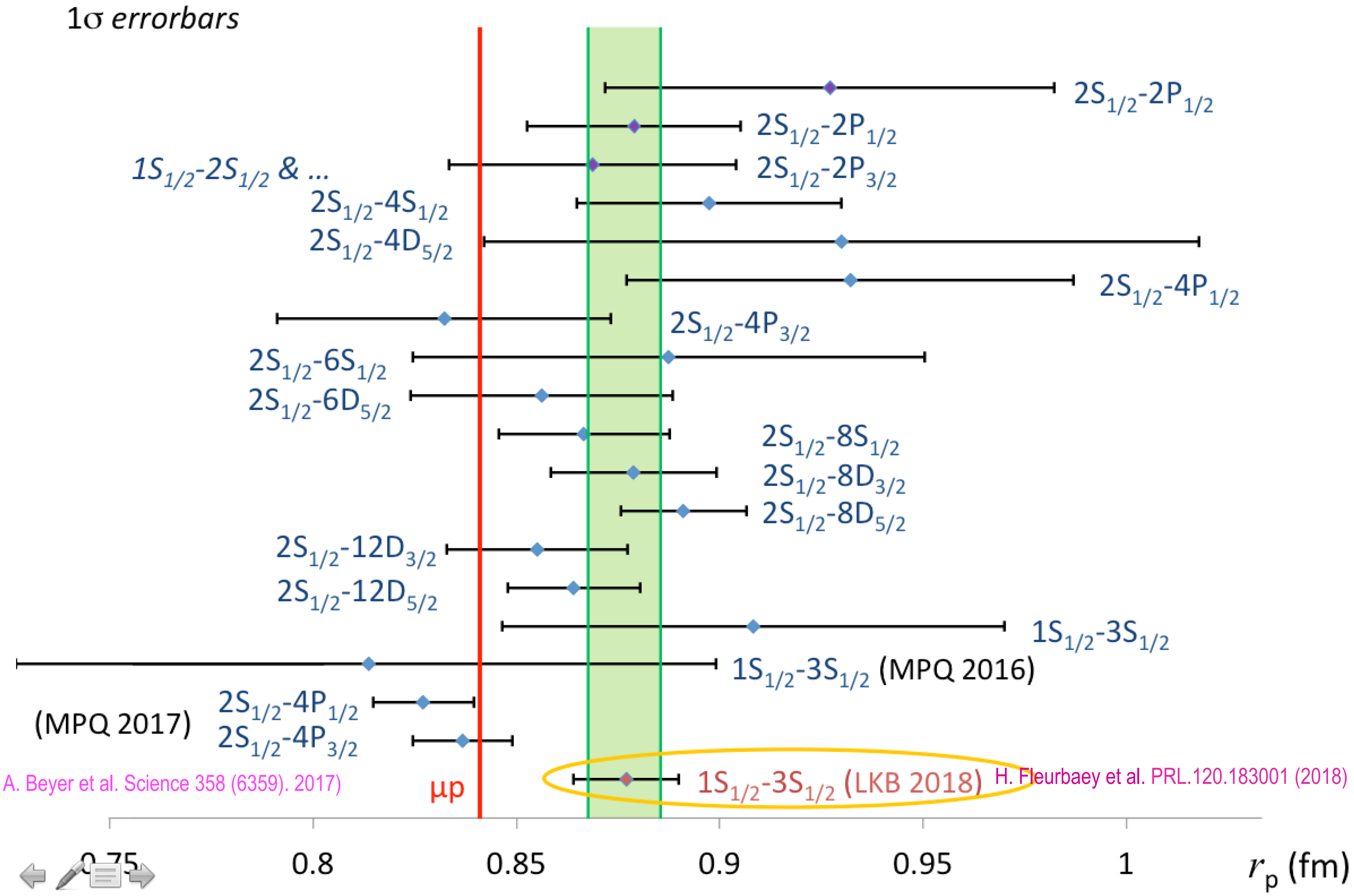
Proton Radius Puzzle (recent status)



A. Beyer et al. Science 358 (6359). 2017)

from H. Fleurbaey, CIPANP2018

Proton Radius Puzzle (recent status)

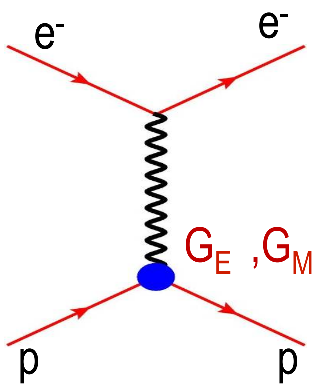


A. Beyer et al. Science 358 (6359). 2017)

H. Fleurbaey et al. PRL.120.183001 (2018)

from H. Fleurbaey, CIPANP2018

Proton Radius from ep→ep Scattering Experiments



- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

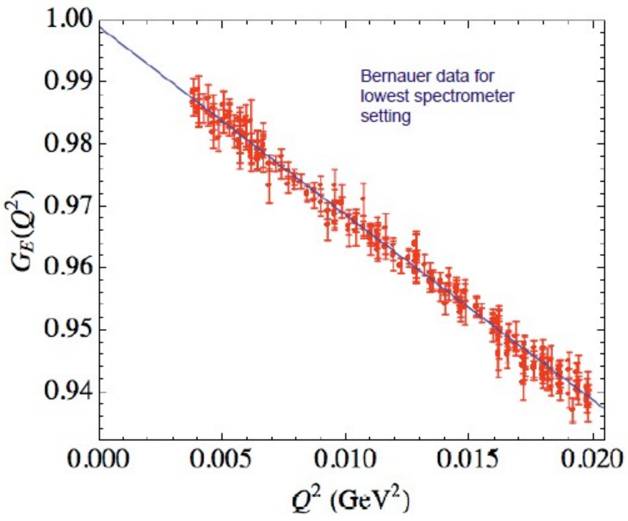
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2) \right)$$

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

- Structureless 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 were extracted using Rosenbluth separation (or at extremely low Q^2 the G_M can be ignored, like in the PRad experiment)



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

- The Taylor expansion at low Q^2:

derivative in $Q^2 \longrightarrow 0$ limit:

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2 \rangle + \frac{Q^4}{120}\langle r^4 \rangle + \ldots \quad \Longrightarrow \quad \langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

A New ep→ep Experiment?

- Practically all ep-scattering experiments are done with the magnetic spectrometers!

- Limitation on minimum Q^2: 10^{-3} GeV/C^2
  - ✓ limitation on min. scattering angle: $\theta_e \approx 5^0$
  - ✓ Typical beam energies: ~ 0.1 ÷1 GeV

- Absolute cross section measurement is needed ($d\sigma/d\Omega$):
  - ✓ statistics is not a problem (<0.2%)
  - ✓ control of systematic errors???
    - ➢ electron beam flux;
    - ➢ target thickness and windows;
    - ➢ geometrical acceptances;
    - ➢ detection efficiencies, …
    - ➢ Typical uncertainty: ~ 2 ÷ 3%

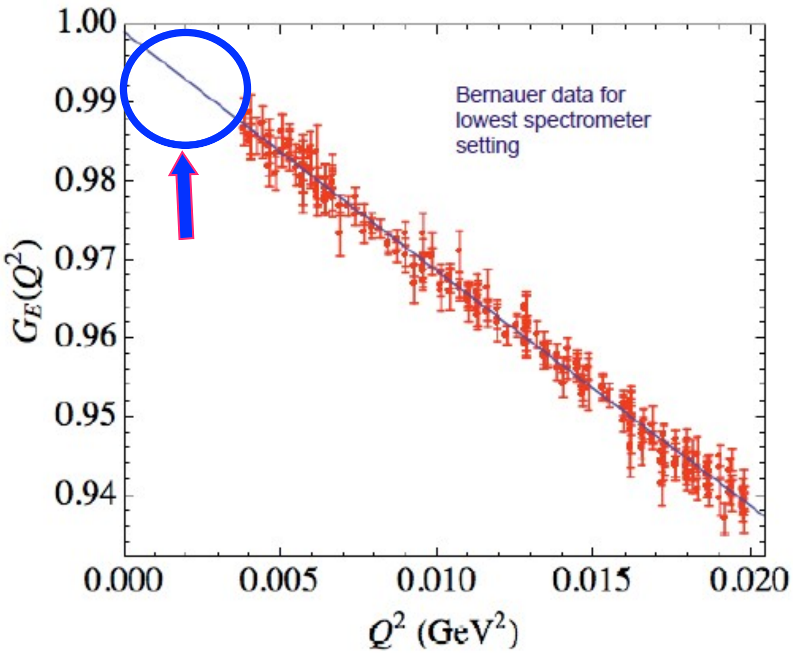
Three spectrometer facility of the A1 collaboration:

Mainz magnetic spectrometers

- A possible solution (the PRad approach):
  - ✓ Non-magnetic-spectrometer method
  - ✓ Calibrate with other well-known QED processes
  - ✓ No target windows

The PRad Experimental Approach

- Experimental goals:
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - reach to sub-percent precision in cross section
  - large Q^2 range in one experimental setting
- Suggested solutions (PRad):
  - ✓ use high resolution high acceptance calorimeter:
    - reach smaller scattering angles: ($\theta = 0.7^0 - 7.0^0$)
      ($Q^2 = 2 \times 10^{-4} \div 6 \times 10^{-2}$) GeV/c^2
      large Q^2 range in one experimental setting!
      essentially, model independent r_p extraction
  - ✓ Simultaneous detection of *ee* → *ee* Moller scattering
    - (best known control of systematics)
  - ✓ Use high density windowless H_2 gas flow target:
    - beam background funder control
    - minimize experimental background



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision in r_p extraction
- Approved by JLab PAC39 (June, 2012) with high "A" scientific rating

PRad Experiment Timeline

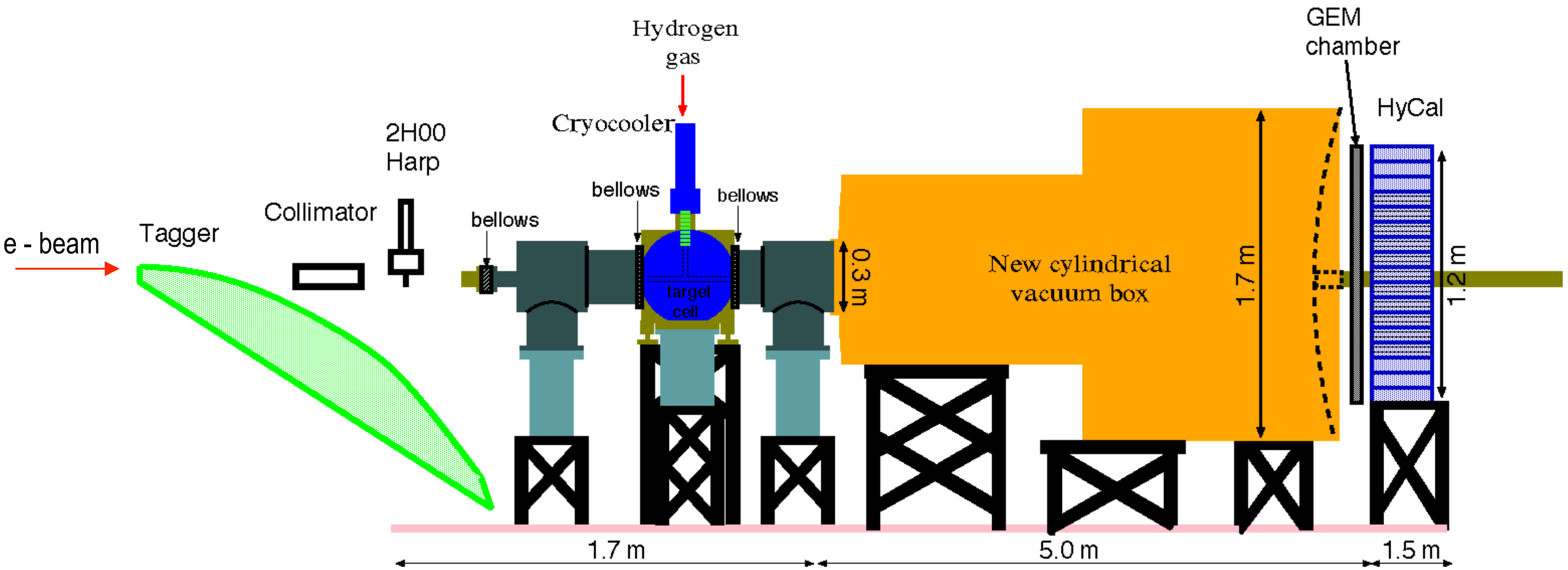
2011-12	Initial proposal, approved by PAC39
2012	Funding proposal for windowless H2 gas flow target (NSF MRI #PHY-1229153)
2012 – 15	Development and construction of the target
2013	Funding proposals for the GEM detectors (DOE awards)
2013-15	Development, construction of the GEM detectors, 2015
2015-16	Experiment Readiness Reviews
January /April 2016	Beam line installation
May 2016	Beam Commissioning, detector calibration
May, June 2016	Experimental data taking

PRad Experimental Setup in Hall B at JLab (schematics)

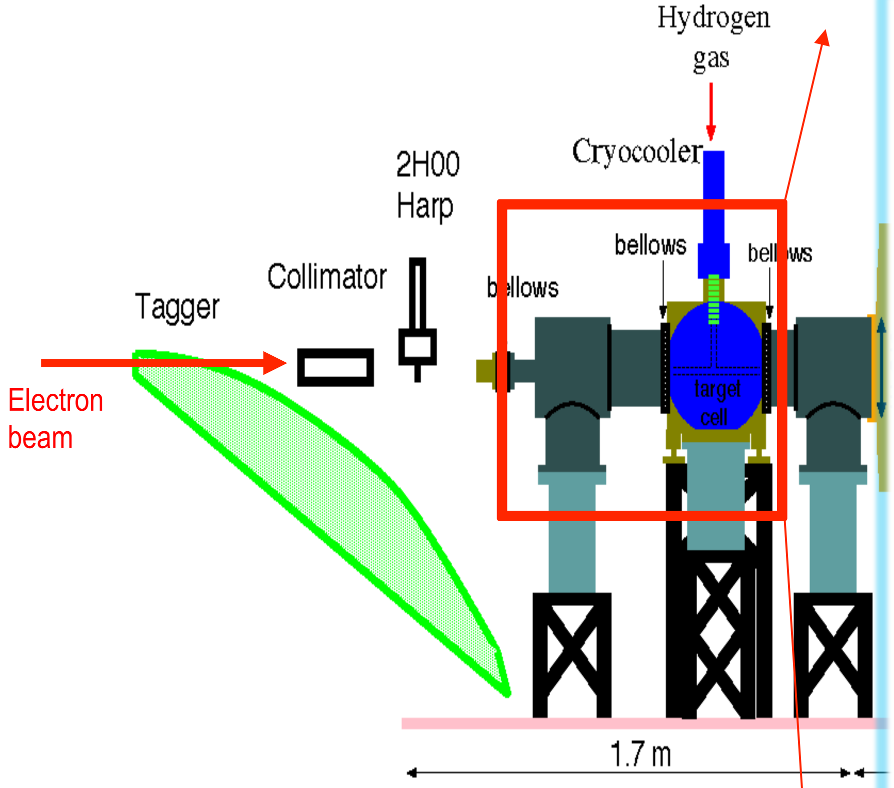
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo “cleanup”)
  - Harp 2H00
  - pipe connecting Vacuum Window through HyCal

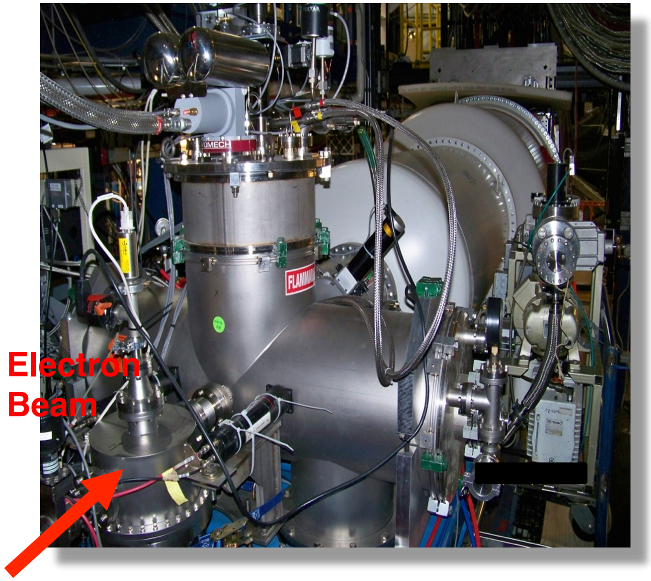
PRad Setup (Side View)

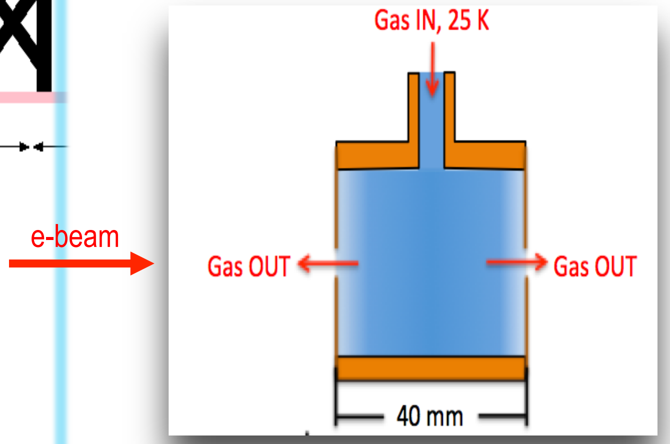


PRad Experimental Apparatus



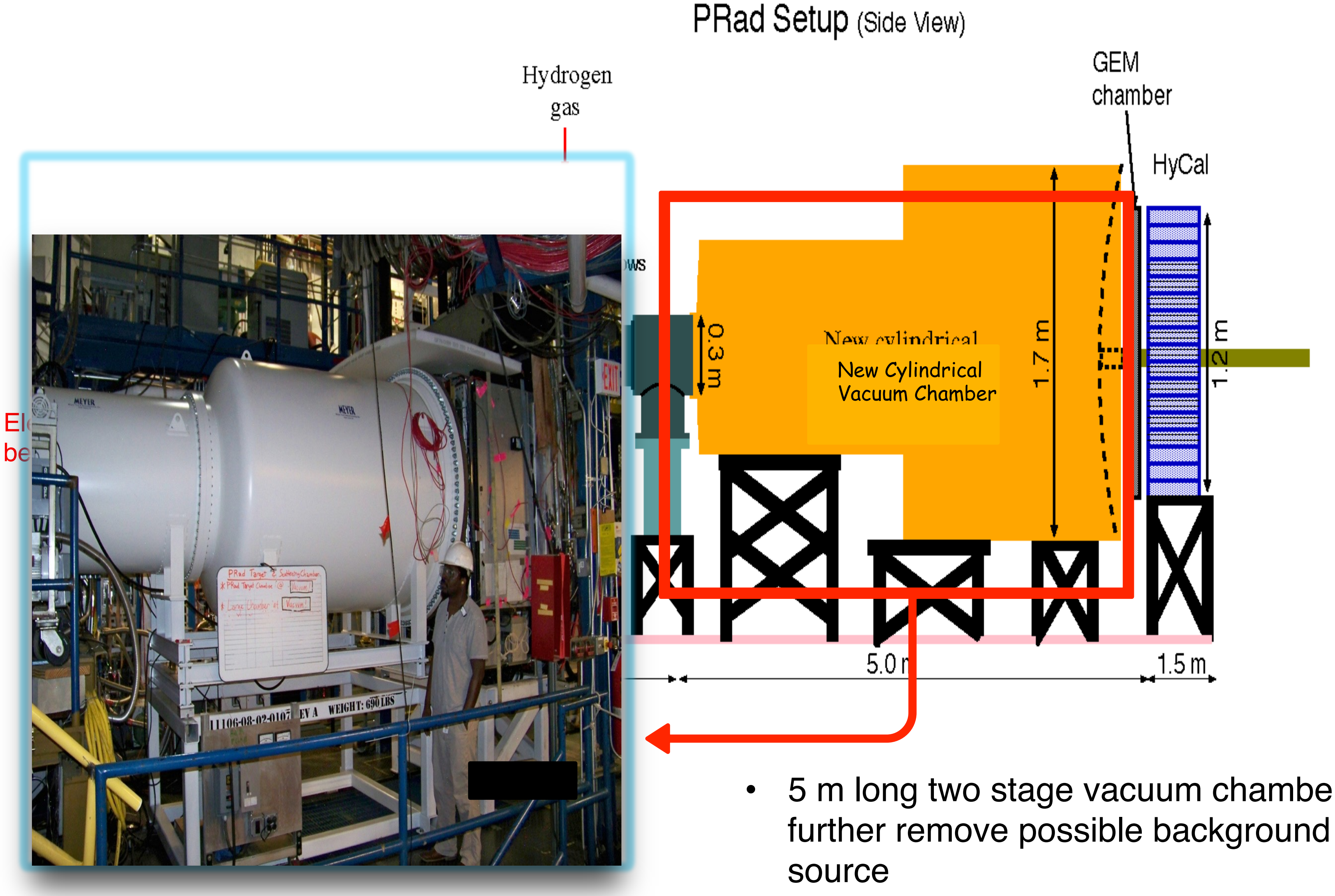
PRad Setup (Side View)





- 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 (cont.)



[redacted]

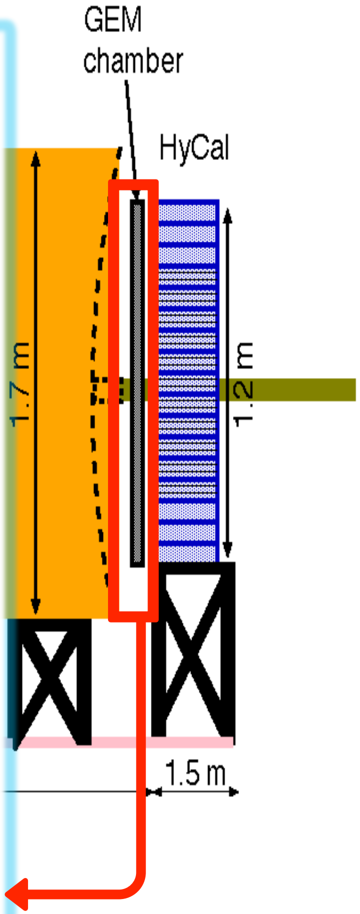
- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum chamber pressure: 0.3 mTorr

PRad Experimental Apparatus (cont.)

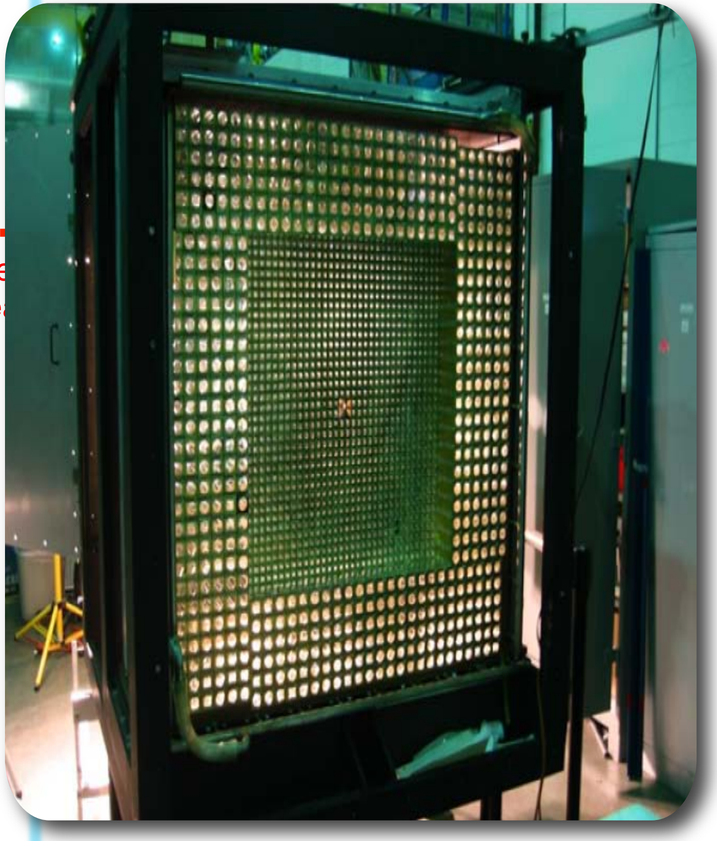
PRad Setup (Side View)

Ele
bea

- 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 improvements in Q^2 determination



PRad Experimental Apparatus (cont.)



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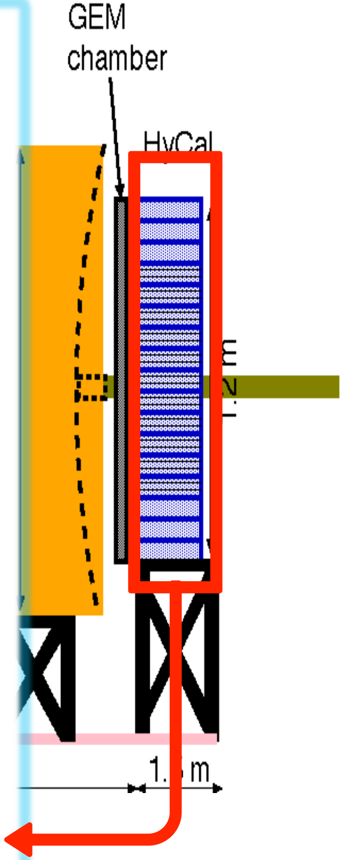
bea

PRad Setup (Side View)

- 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



Experimental Data Collected
(May/June 2016 Run)

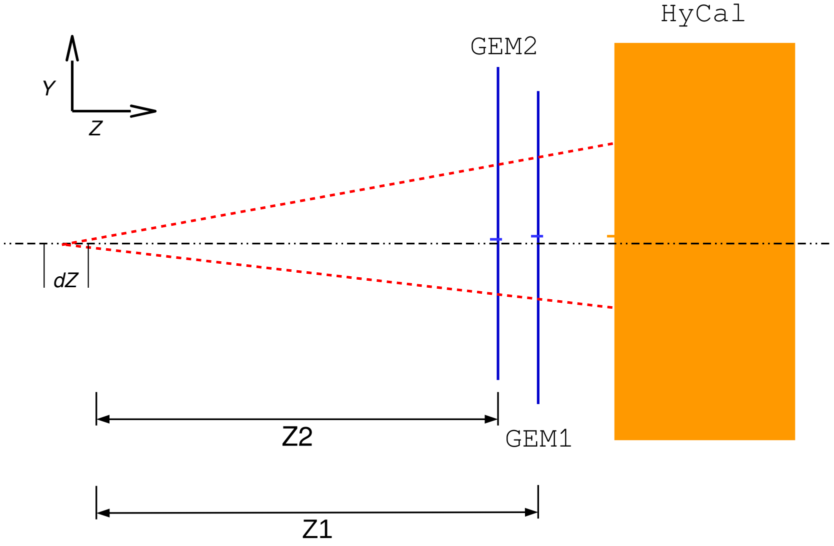
- with E_e = 1.1 GeV beam:
  - ✓ 4.2 mC (target areal density: $2 \times 10^{+18}$ H atoms/cm^2);
  - ✓ 604 M events with target;
  - ✓ 53 M events with “empty” target;
  - ✓ 25 M events with ^{12}C target for calibration.

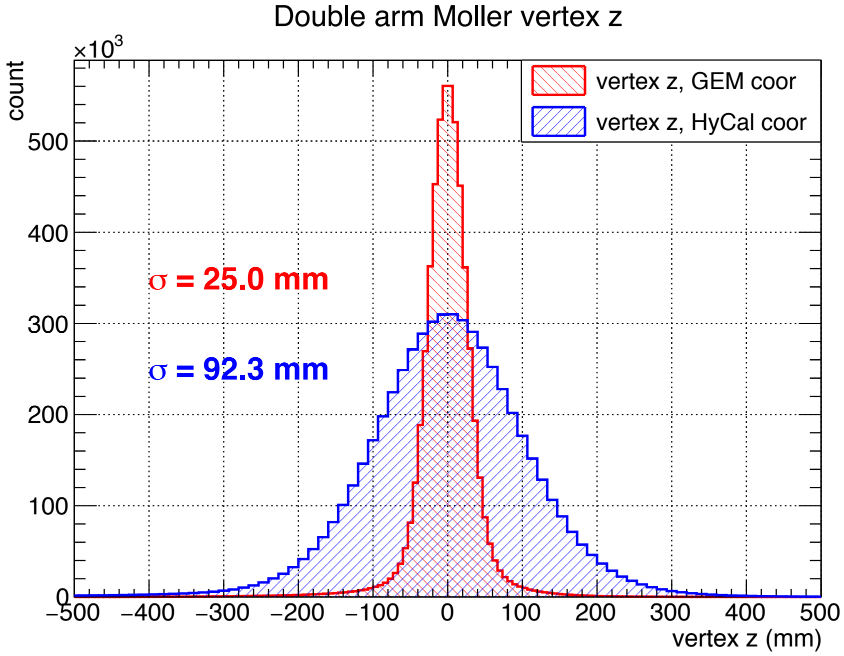
- with E_e = 2.2 GeV beam:
  - ✓ 14.3 mC (target areal density: $2 \times 10^{+18}$ H atoms/cm^2);
  - ✓ 756 M events with target;
  - ✓ 38 M events with “empty” target;
  - ✓ 10.5 M events with ^{12}C target for calibration.

Detectors Position Calibration

- Engineering survey.

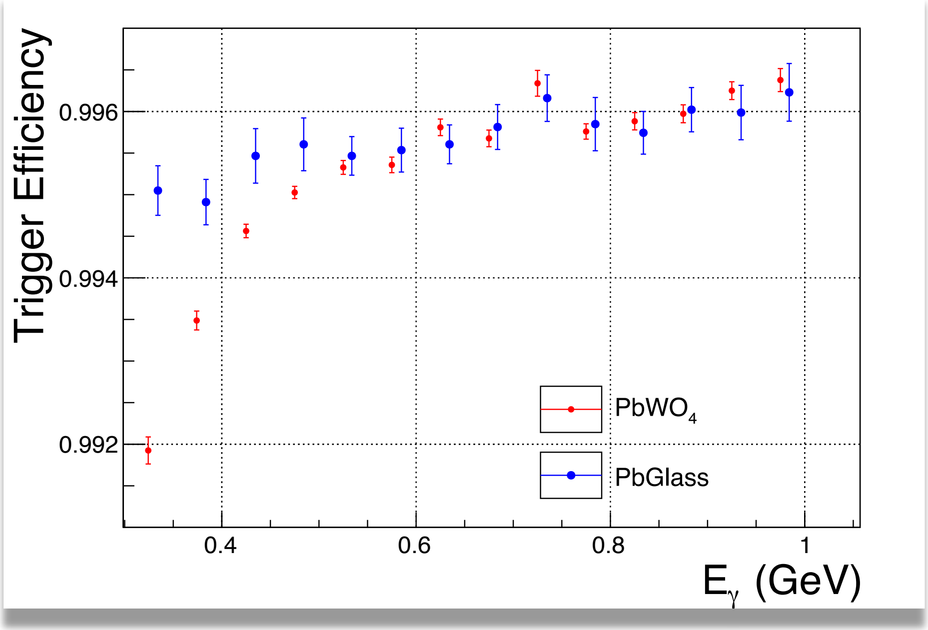
- Detector offsets and z position determined using double-arm Møller events:
  - co-planarity to determine offsets;
  - Møller kinematics to determine detector z position (cross check surveyed data);
  - offset with ~ 50 μm and z with ~ 1 mm precision;

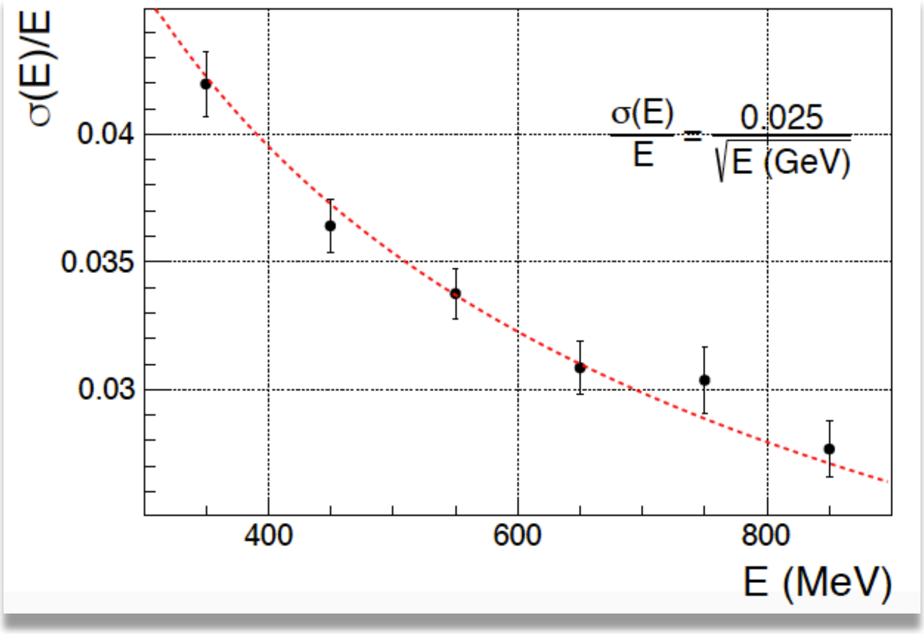




Trigger Efficiency and HyCal Resolution

- HyCal energy resolution and trigger efficiency extracted using high energy tagged photon beam from Hall B at Jlab
  - >99.5% trigger efficiency obtained for E_γ > 500 MeV, for various parts of HyCal
  - energy resolution ~2.5% at 1 GEV for PWO_4 , ~2.5 time worse for Pb-glass





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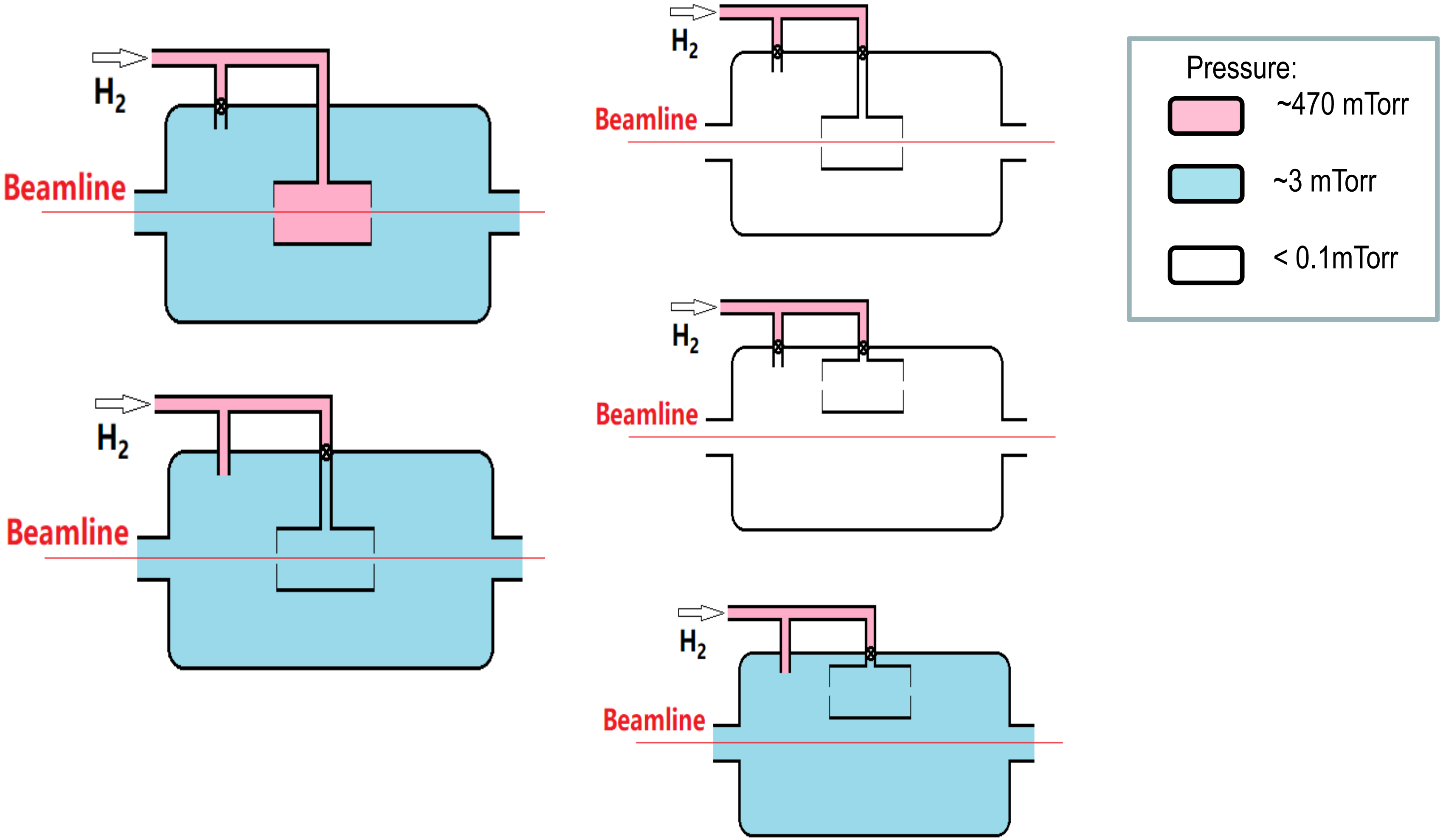
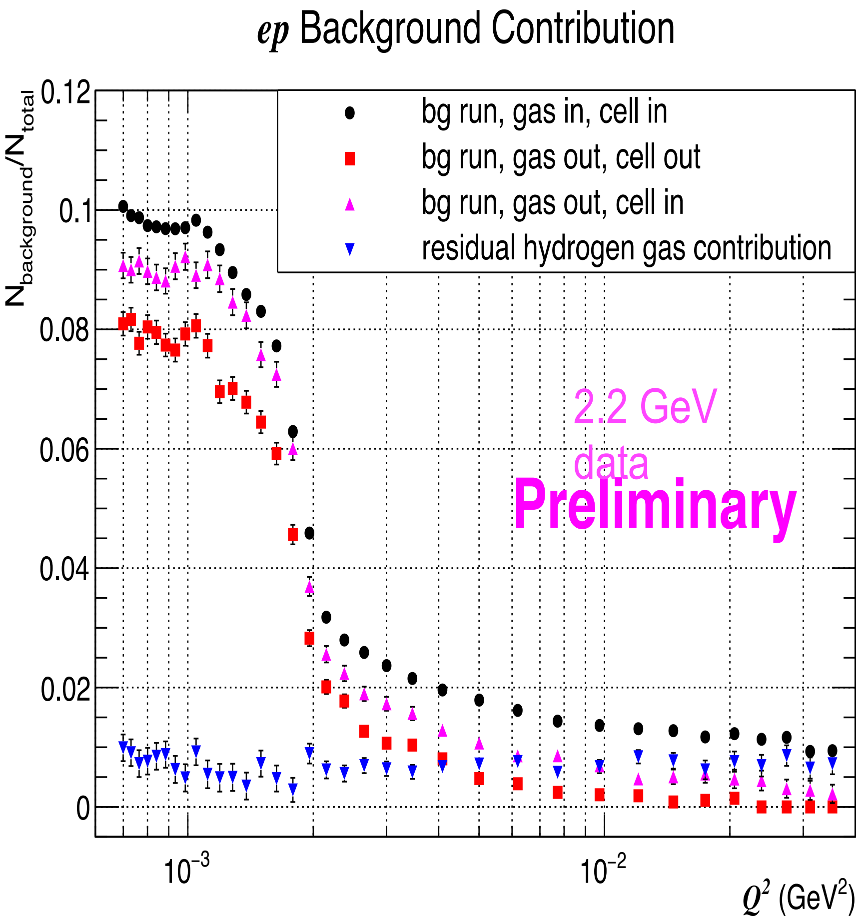
Data Analysis – Background Subtraction

- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty.
- Developed simulation program for target density distribution (COMSOL finite element analysis).

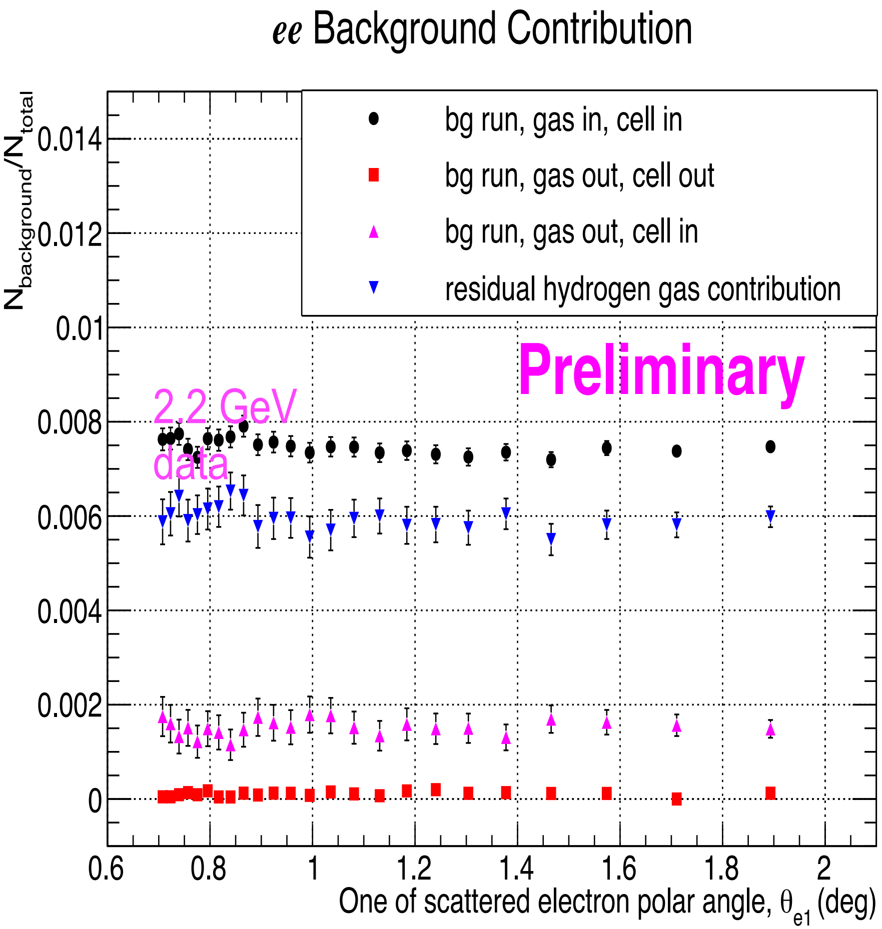


Data Analysis – Background Subtraction (2.2 GeV)

- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream “collimator”), less than 2% otherwise.
- ee background rate ~ 0.8% at all angles .



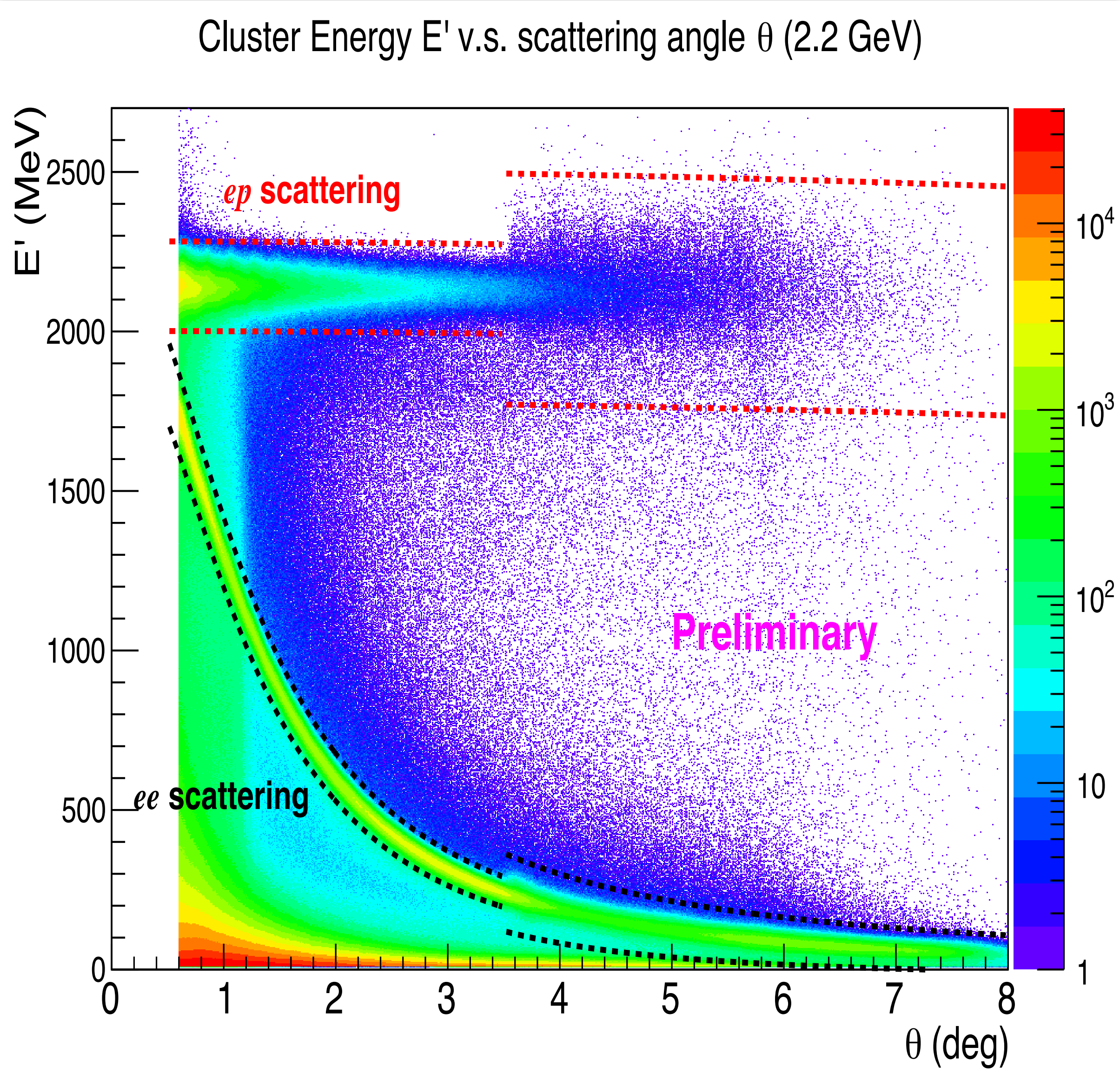
Residual hydrogen gas: hydrogen gas filled during background runs



Data Analysis – Event Selection

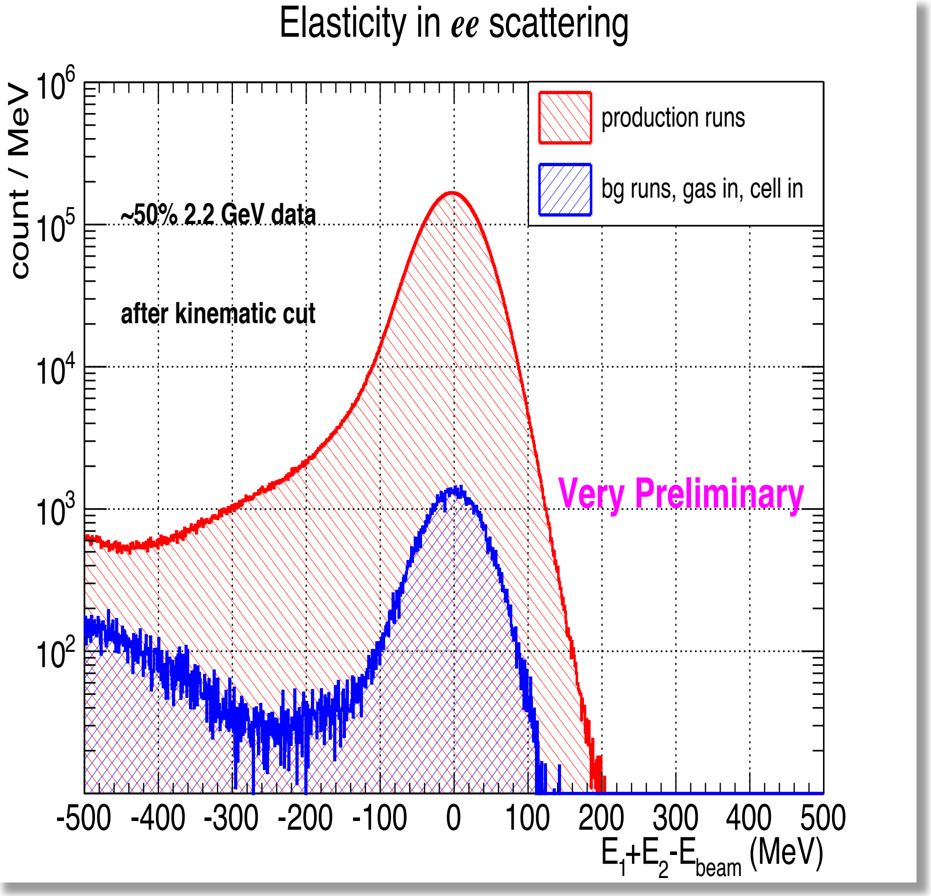
Event selection method

- ✓ Hit matching between GEMs and HyCal required
- ✓ Apply angle dependent energy cut based on kinematics:
  - cut size depend on local detector resolution (4σ).
- ✓ For *ee*, if requiring double-arm events, apply additional cuts:
  - elasticity;
  - co-planarity;
  - vertex z.

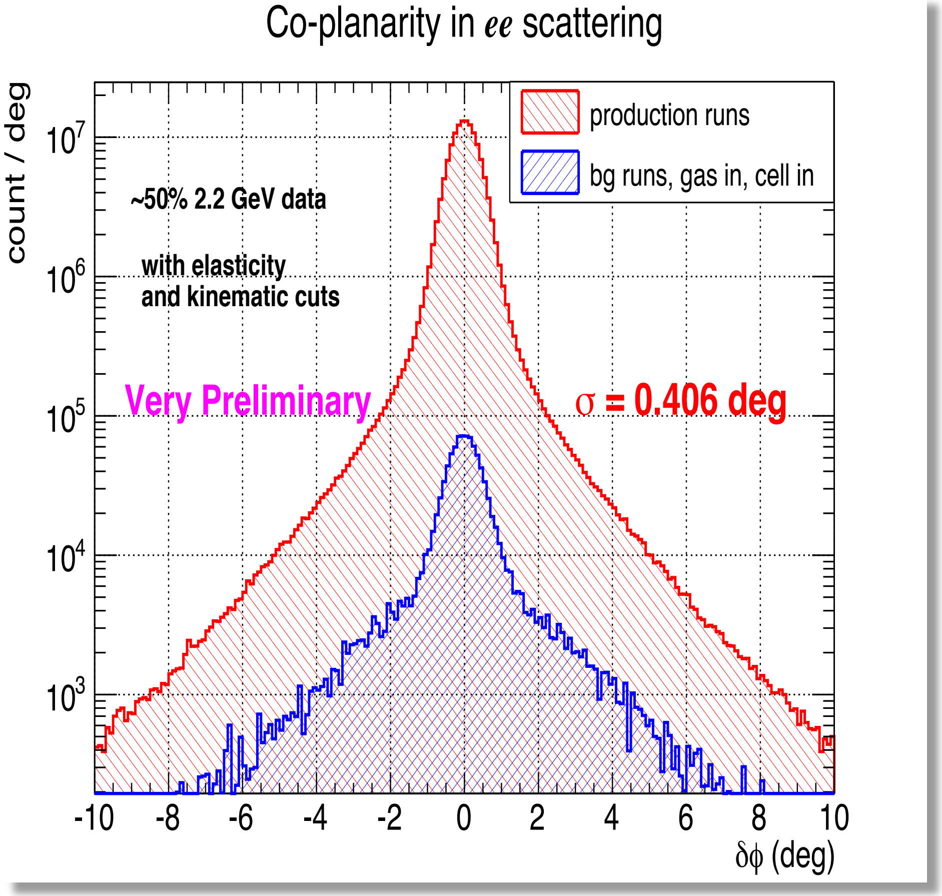


Data Analysis – Event Selection (cont.)

- Double-arm Møller event selection:



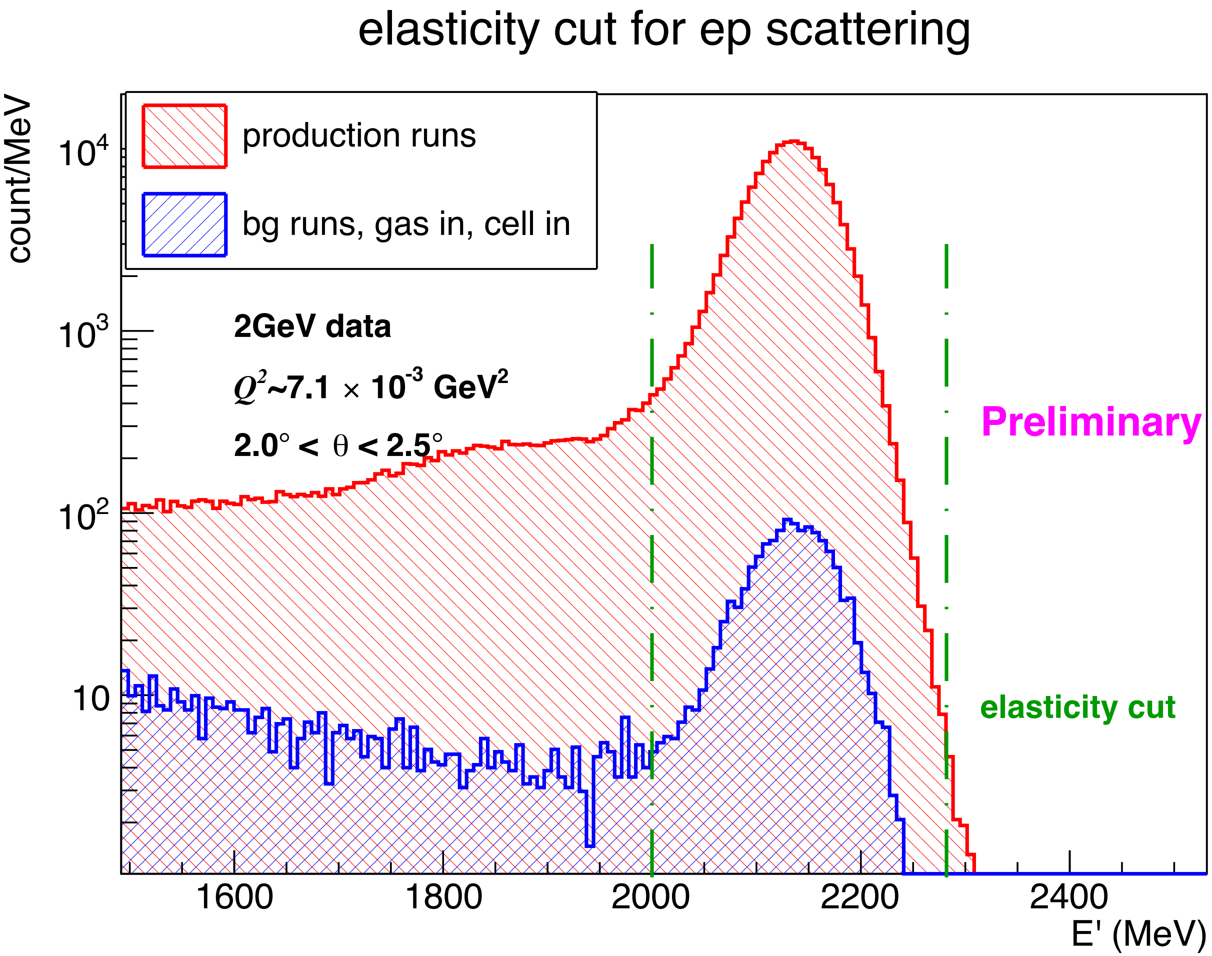
Elasticity in *ee* scattering



Co-planarity in *ee* scattering

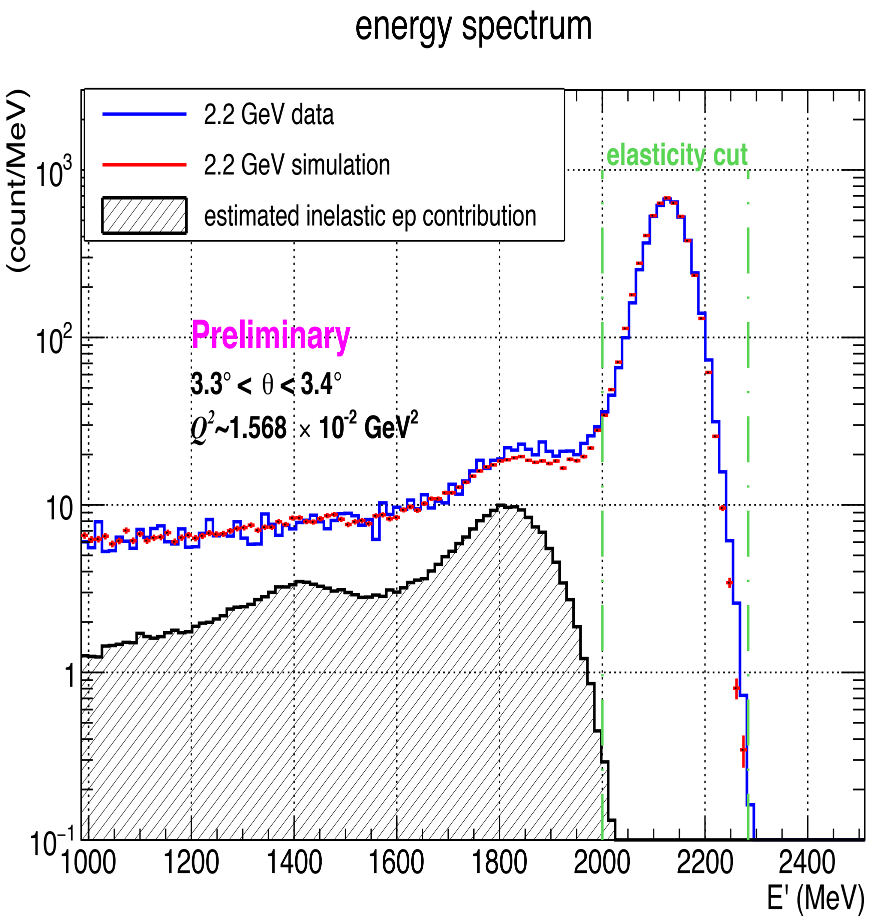
Data Analysis – Event Selection (cont.)

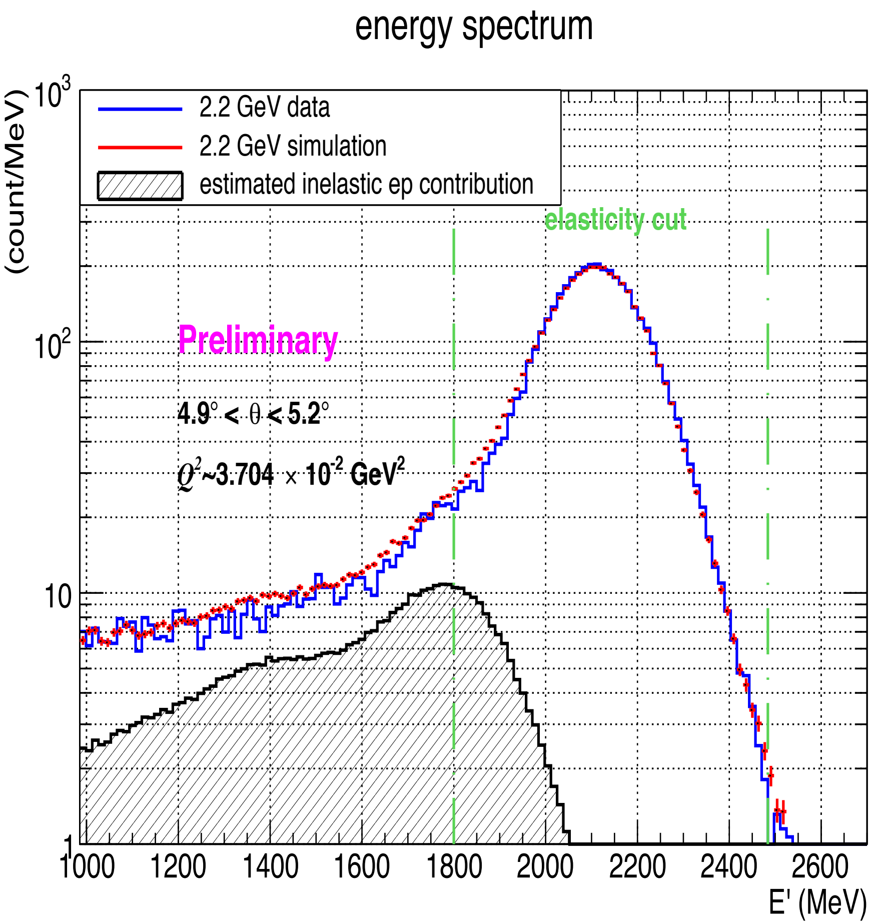
- *ep* - event selection:



Data Analysis – Inelastic *ep* Contribution

- Generator based on Peter Bosted model developed for inelastic ep (inclusive)
- Second generator being tested (based on MAID2007, including pions and photon)
- Contribution expected to be <0.1% in $PbWO_4$ region due to good resolution, not negligible in lead glass (increase with larger Q^2, maximum ~3.5% for 2.2 GeV, <1% for 1.1 GeV before subtraction)

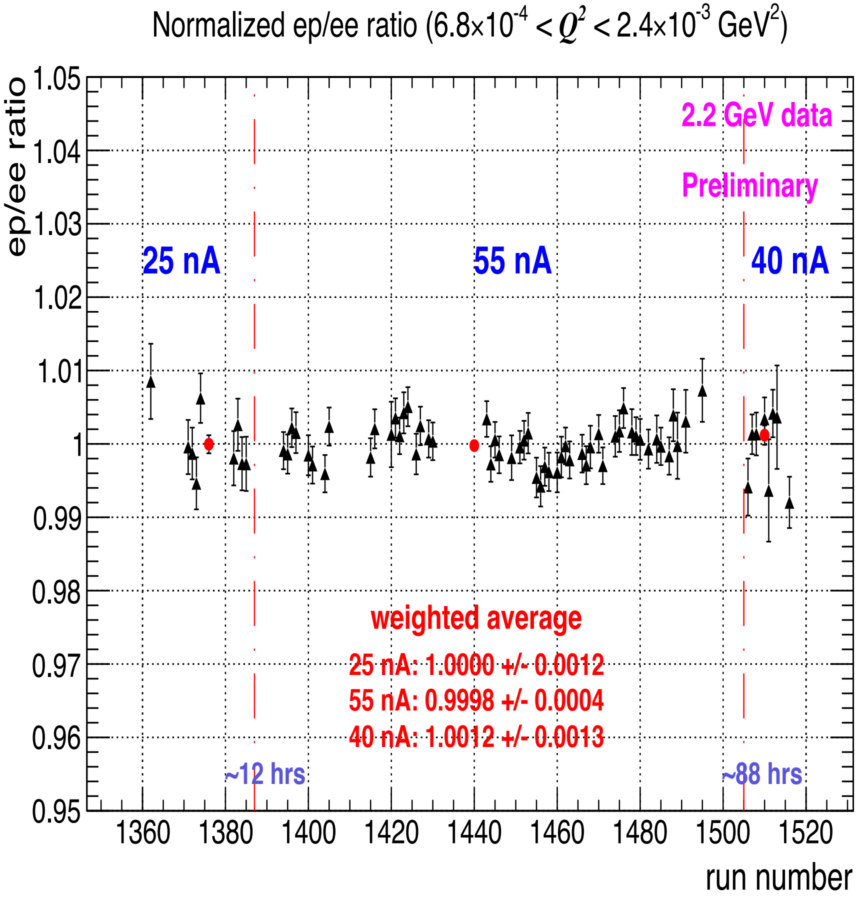

energy spectrum

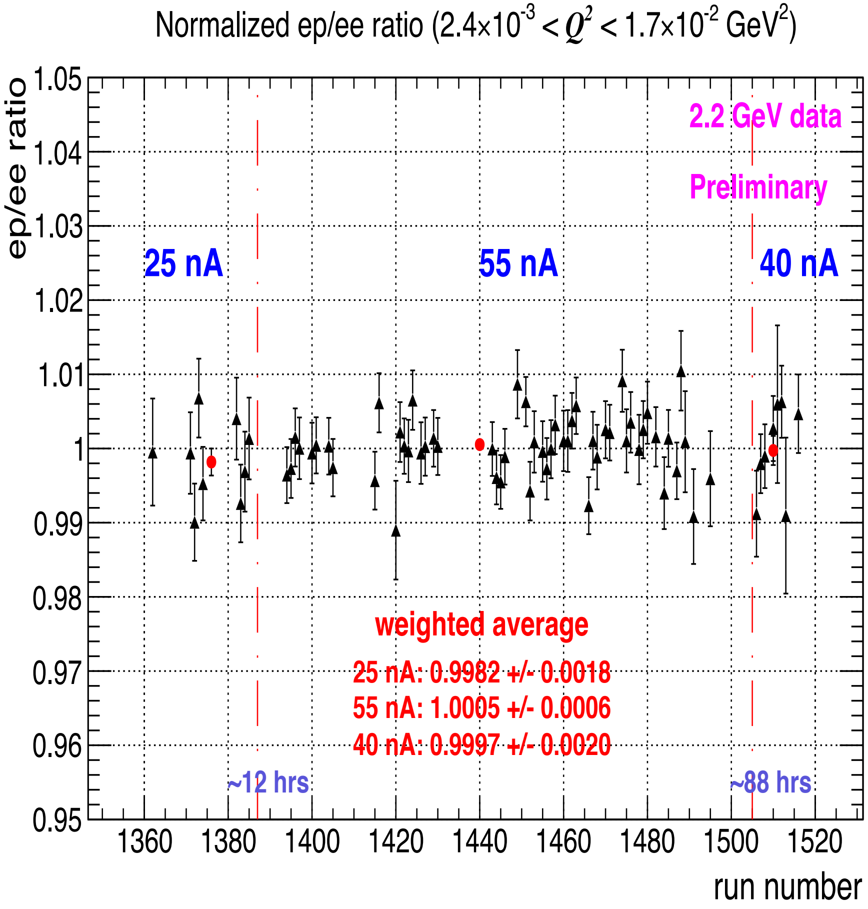

energy spectrum

Reference to Peter Bosted model: Phys. Rev. C81, 055213(2010), 0712.3731

Data Stability (2.2 GeV)

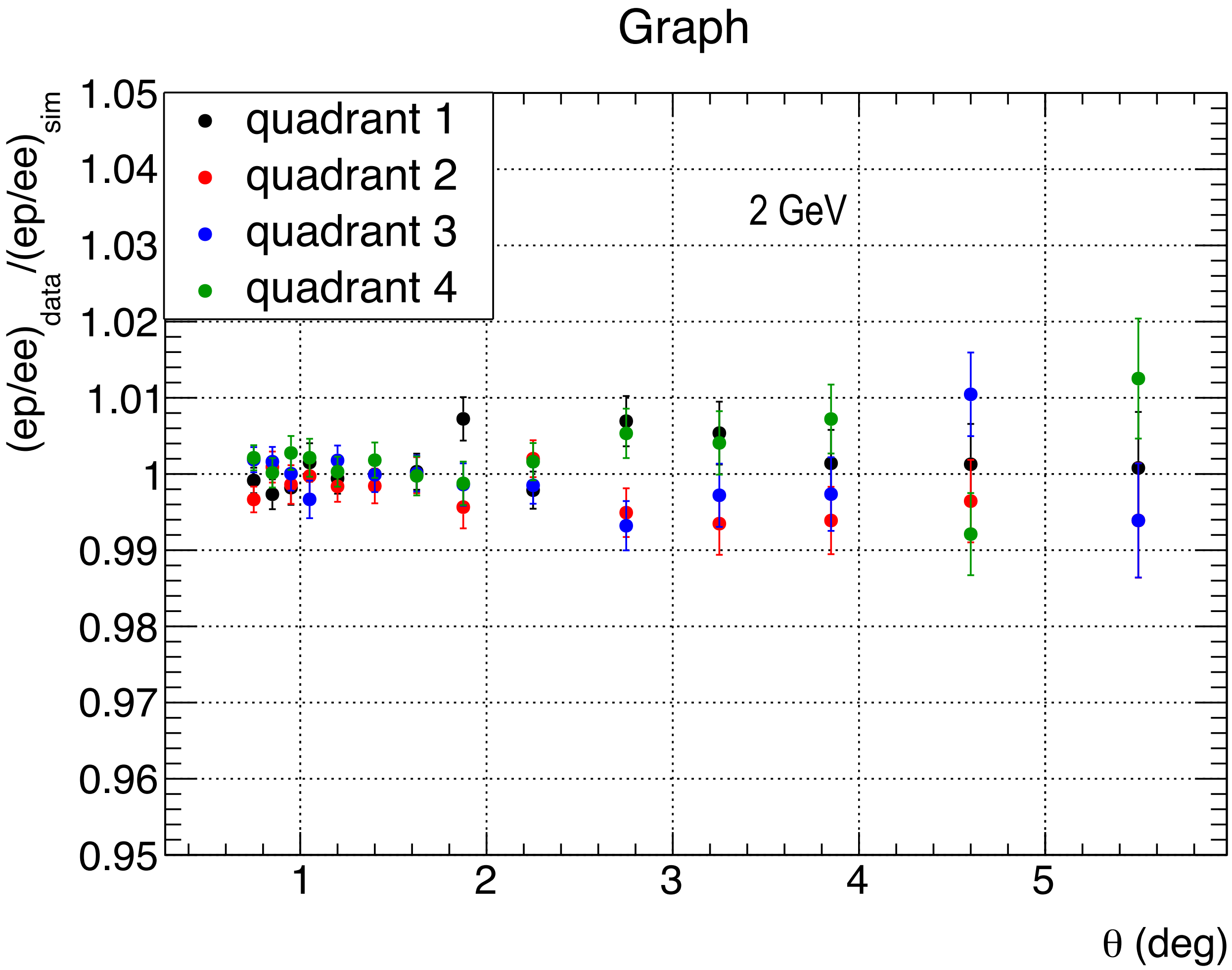
- Ratio *ep/ee* monitored run by run, background subtracted with neighboring empty target runs





Data Stability: Including the Simulation

- Ratio $(ep/ee)_{dat} / (ep/ee)_{sim}$ vs. azimuthal angle



Extraction of *ep* Elastic Scattering Cross Section

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

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

- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections:
  - *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 (fully beyond ultra relativistic approximation).*

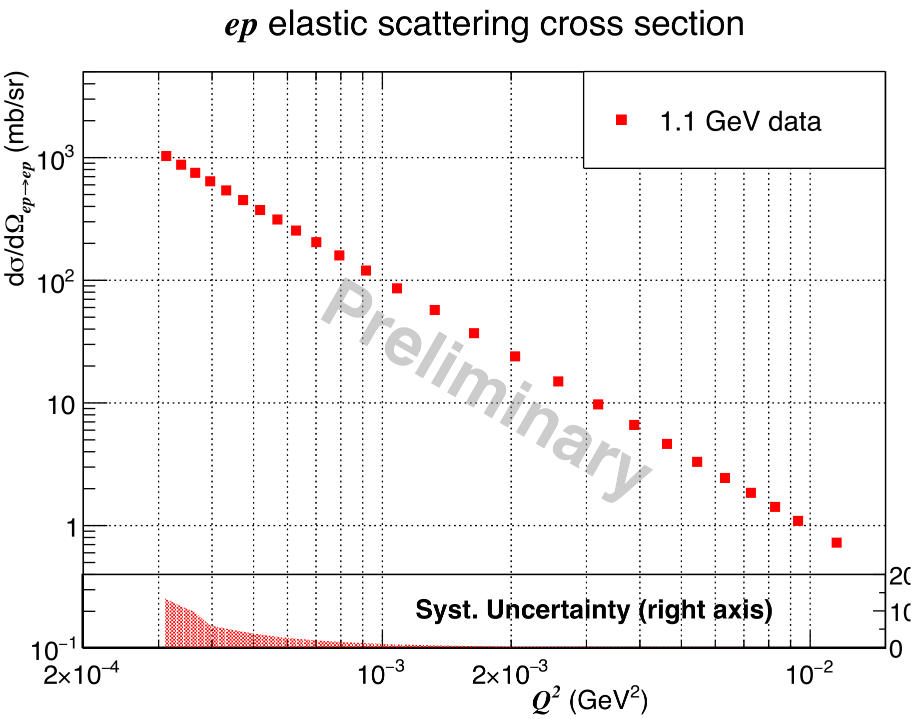
- A GEANT4 simulation package is used to study the radiative effects:

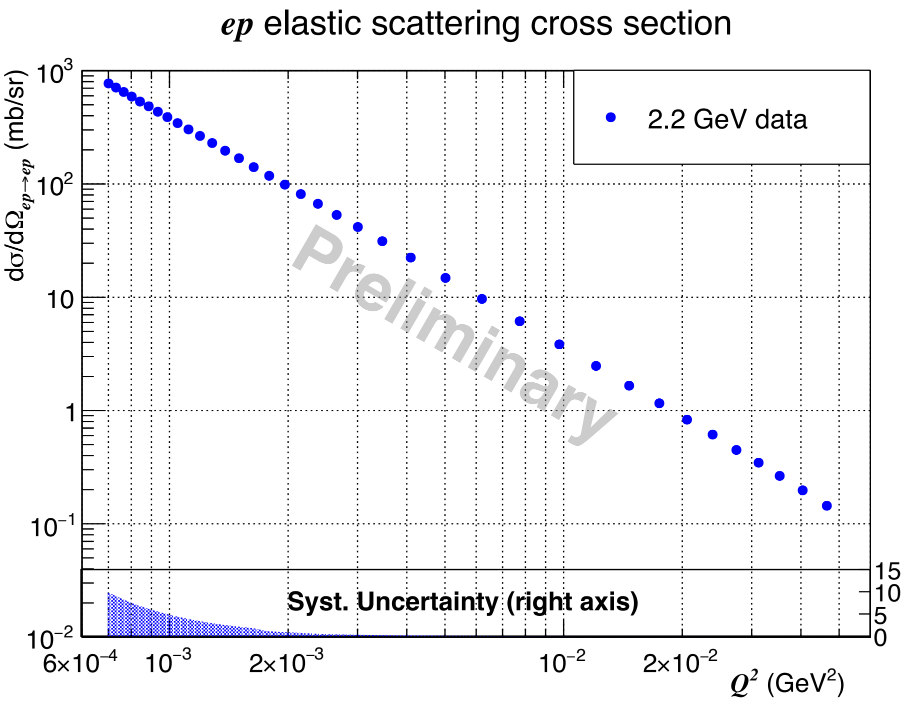
$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

- Iterative procedure applied for radiative correction.

Elastic *ep* Cross Section (Preliminary)

- Differential cross section vs. Q^2, with 2.2 (1.1) GeV data (preliminary).
- Statistical uncertainty at this stage: ~0.18% for 2 GeV, ~0.3% for 1 GeV per point.
- Systematic uncertainties at current stage: 0.8% ~ 2.0% for 2 GeV, 0.9% ~2.0% for 1 GeV (shown as shadow area).



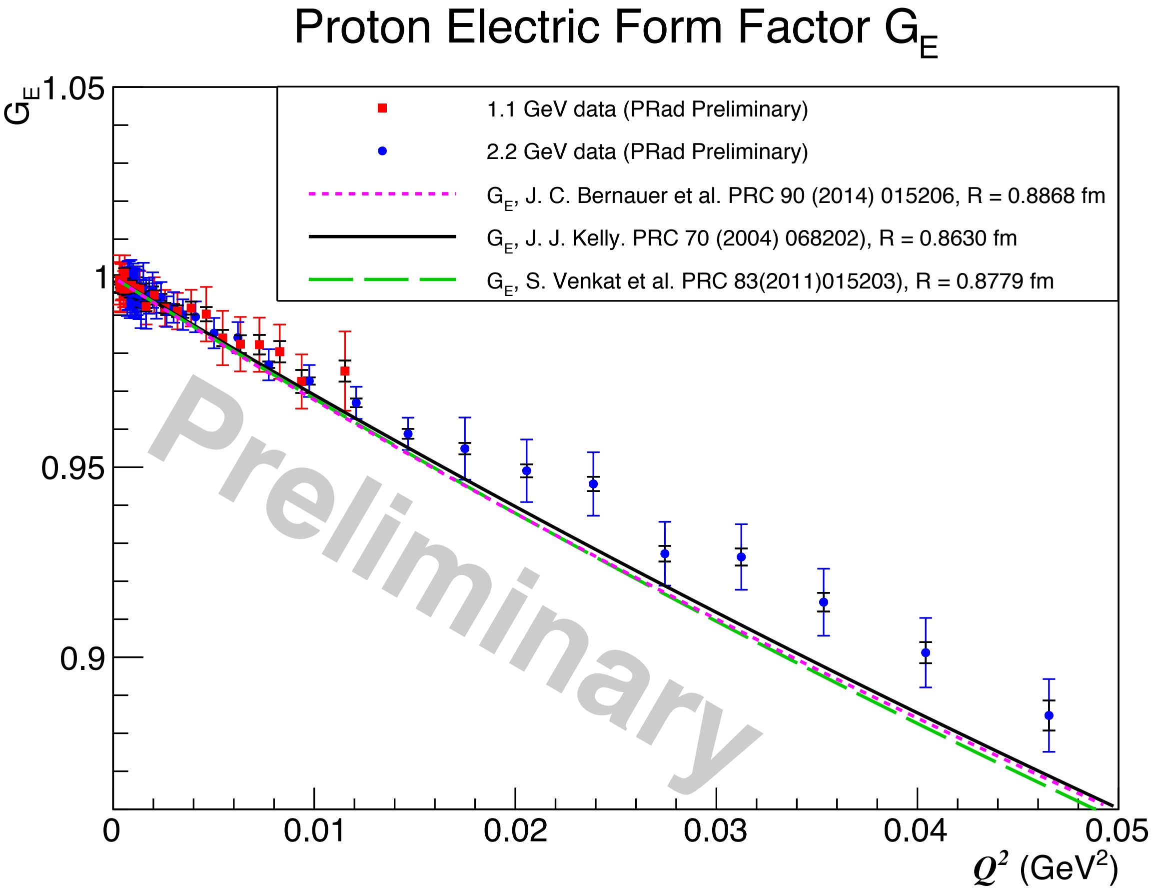


Proton Electric Form Factor: G_E (Preliminary)

- Proton electric form factor: G_E vs. Q^2 from 2.2 and 1.1 GeV data

(G_M used from J.J Kelly, PRC 70 (2004) 068202)

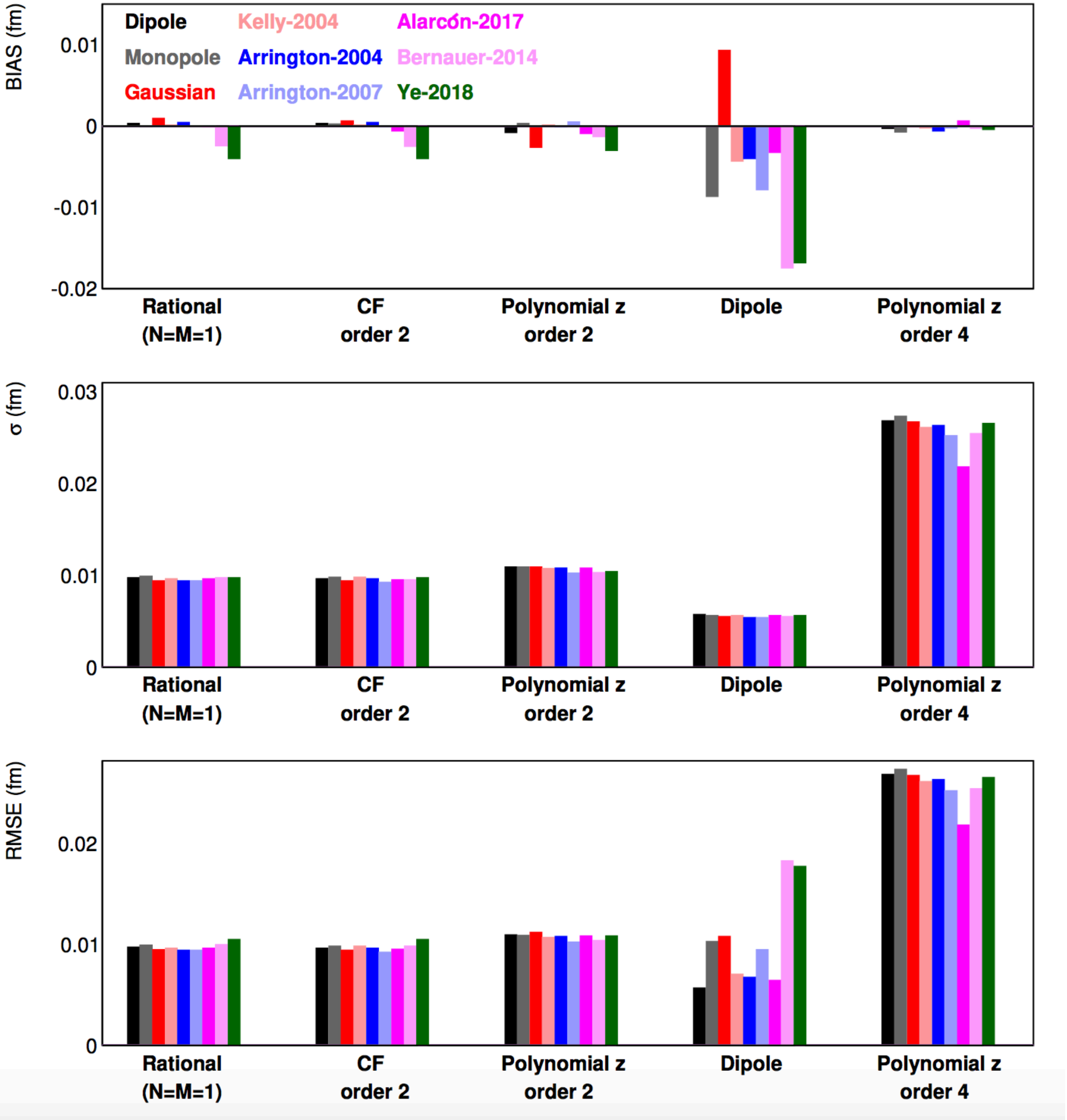
- Systematic uncertainties shown as colored error bars.
- Preliminary G_E slop seems to favor smaller radius.



Recent Developments in Fitting Procedures

- Xuefei Yan
  https://arxiv.org/abs/1803.01629

- Submitted to PRC (2018)



- RMSE = sqrt(bias^2 + σ^2)

A. Gasparian

Analysis Plan

- We are currently still working on number of corrections and systematic uncertainties:
  - background subtraction;
  - radiative corrections;
  - inelastic ep contribution;
  - trigger efficiency;
  - bremsstrahlung photons from target;
  - …

- Finalize cross sections for both energy runs (1.1 and 2.2 GeV), including full angular range: 0.7° ~ 6.0° (summer 2018).
- Preliminary extraction of radius (July/August 2018).
- Final extraction of proton charge radius (end of 2018).

PRad Collaboration Institutional List

- Currently 17 collaborating universities and institutions:

Jefferson Laboratory
NC A&T State University
Duke University
Idaho State University
Mississippi State University
Norfolk State University
University of Virginia
Argonne National Laboratory
University of North Carolina at Wilmington
University of Kentucky
Hampton University
College of William & Mary
Tsinghua University, China
Old Dominion University
ITEP, Moscow, Russia
Budker Institute of Nuclear Physics , Russia
MIT

- Graduate students:

Chao Peng (Duke)
Weizhi Xiong (Duke)
Li Ya (MSU)
Xinzhan Bai (Uva)
Abhisek Karki (MSU)

- Postdocs:

Chao Gu (Duke)
Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Zhihong Ye (Duke)
Maxime Lavilain (NC A&T)
Krishna Adhikari (MSU)
Rupesh Silwal (MIT)

Summary

- The *Proton Radius Puzzle* is still unresolved:
  - confirmation needed from other regular hydrogen spectroscopy experiments;
  - discrepancy between ep-scattering and muonic hydrogen experiments unchanged.

- PRad was uniquely designed and performed in May/June of 2016 to address the *Puzzle:*
  - ✓ lowest Q^2 data set ($\sim 10^{-4}$ GeV/C^2) has been collected for the first time in ep-scattering experiments;
  - ✓ simultaneous measurement of the Moller and Mott scattering processes has been demonstrated to control systematic uncertainties;
  - ✓ data in a large Q^2 range have been recorded with the same experimental settings, [$2x10^{-4} \div 6x10^{-2}$] GeV/C^2.

- Preliminary cross sections and G_E have been extracted covering Q^2 range from $3x10^{-4}$ to $5x10^{-2}$ GeV/c^2

- Preliminary G_E slop seems to favor smaller radius.

- PRad is supported in part by NSF MRI award #PHY-1229153 as well as DOE awards for GEM
- my research work is supported in part by NSF awards: PHY-1506388 and PHY-0855543

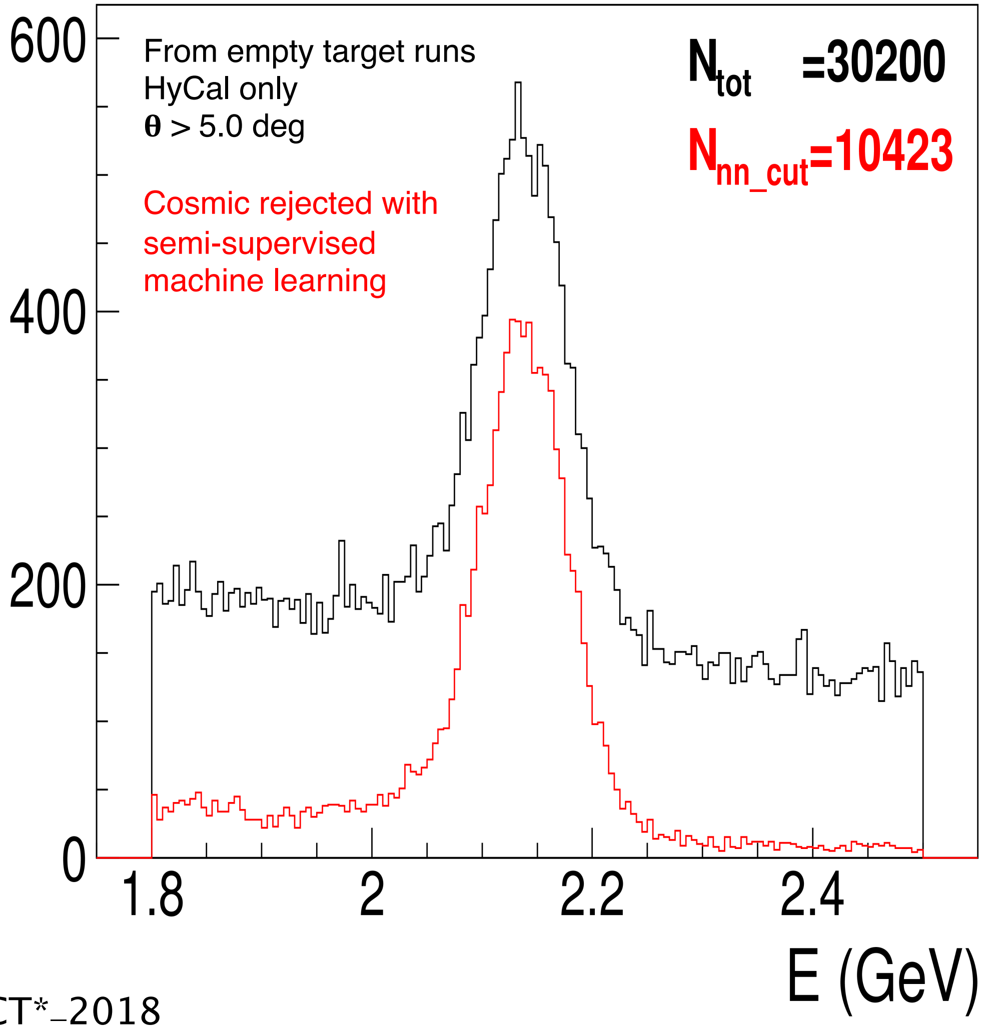
The End

Cosmic Background Events

- Most of the cosmic events are rejected by requiring matching hits between GEMs and HyCal

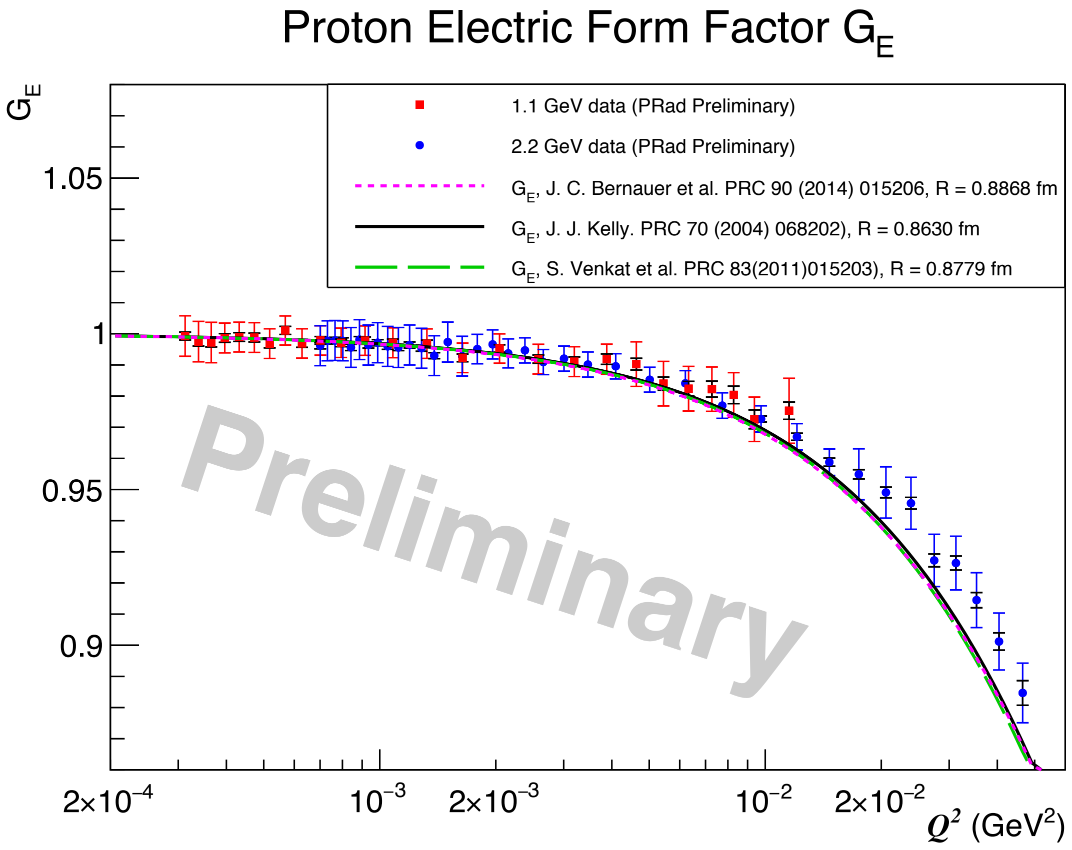
- Negligible at small angle due to high event rate

- Two algorithms developed for further cosmic event rejection
  - Empirical method: using cluster profile, cluster size…
  - Machine learning method: supervised and semi-supervised machine learning methods



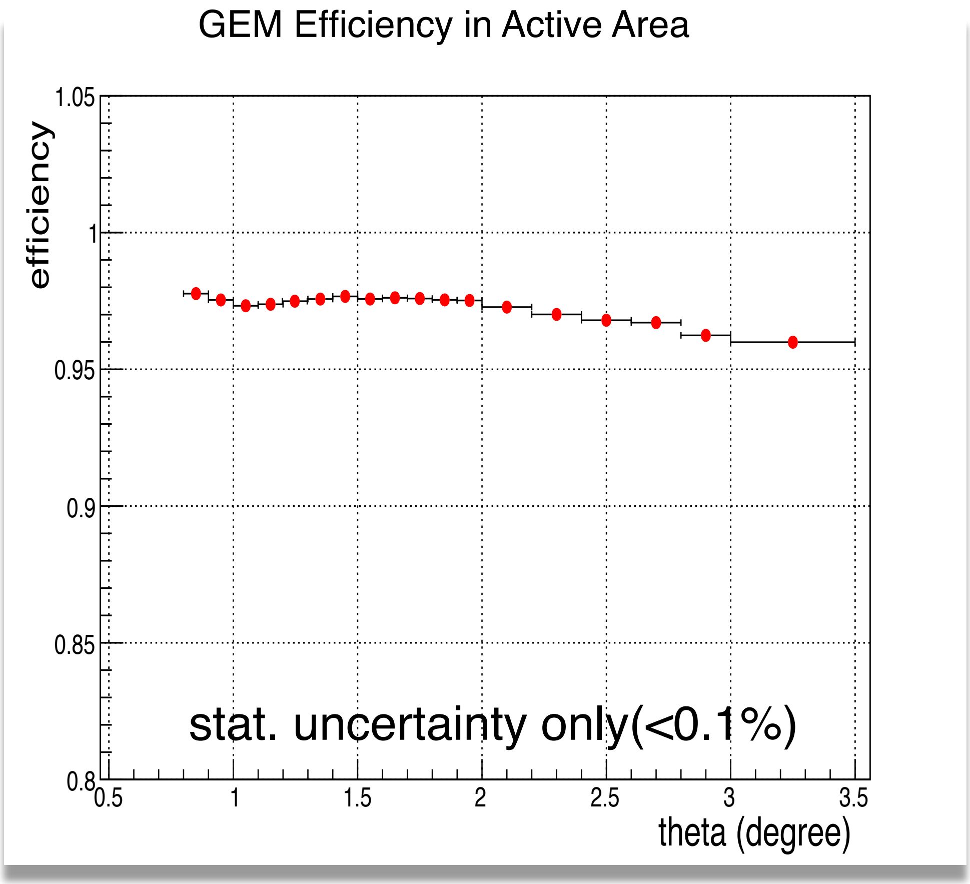
Proton Electric Form Factor: G_E (Preliminary)

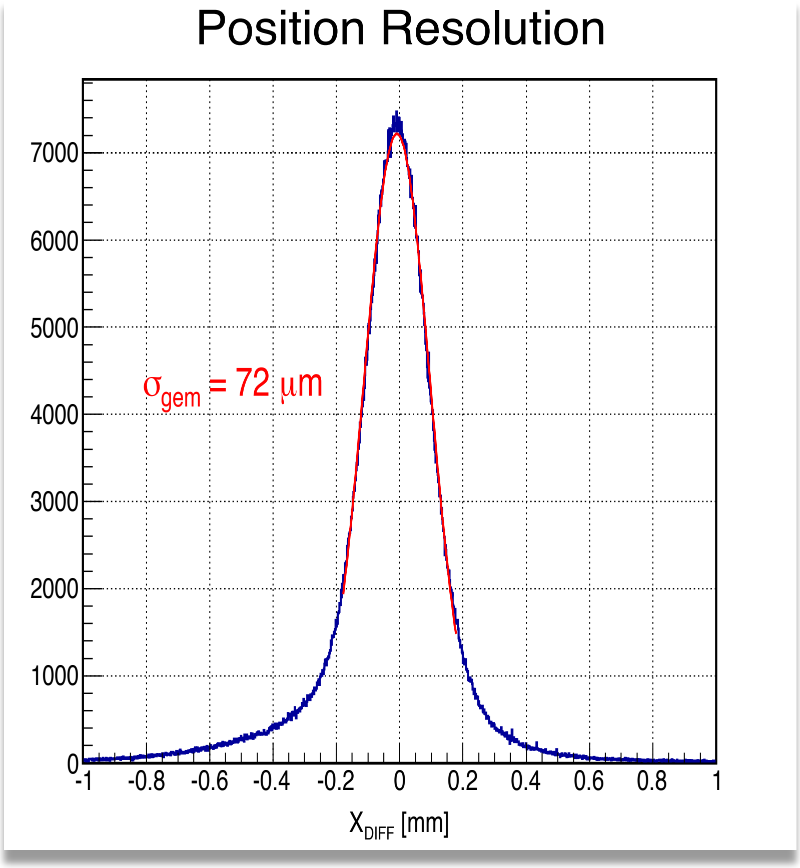
- G_E vs. Q^2, from 2.2 and 1.1 GeV data
  (G_M used from J.J Kelly, PRC 70 (2004) 068202)
- Q^2 range from 6×10^{-4} to 1.5×10^{-2} GeV^2 shown only.
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slop seems to favor smaller radius.



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)


GEM Efficiency in Active Area


Position Resolution

Plots courtesy of X. Bai

Radiative Correction

Two independent radiative correction calculations:

- 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 (fully beyond ultra-relativistic approximation)

- Two independent event generators has been developed based on these two cross section models