The Proton Charge Radius (PRad) Experiment at JLab

Haiyan Gao

Duke University and TUNL

For the PRad Collaboration

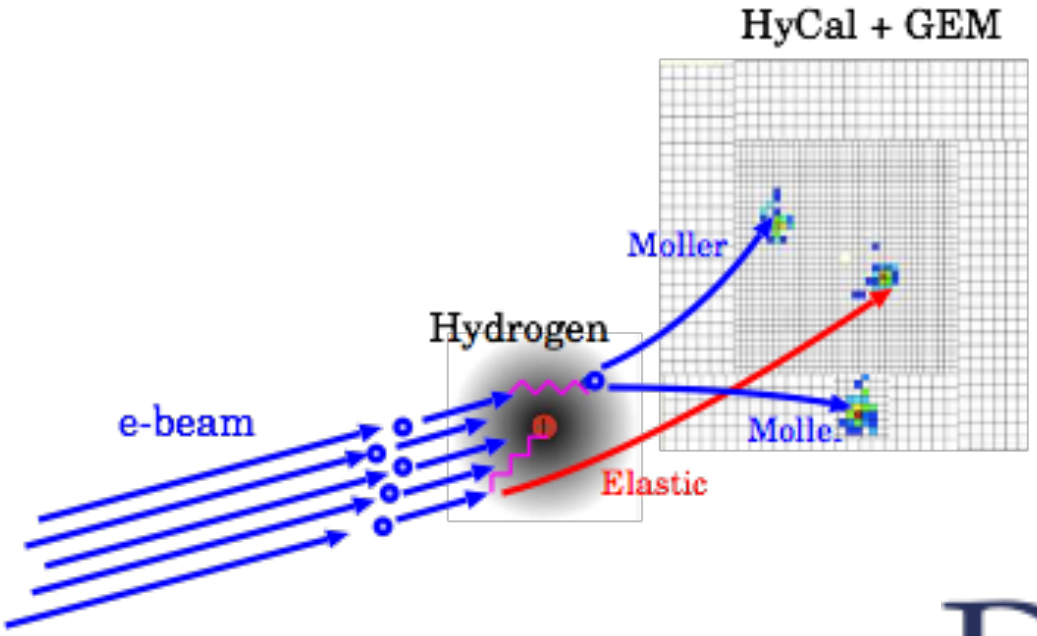


Image credit: Dipangkar Dutta

The Art of the Proton

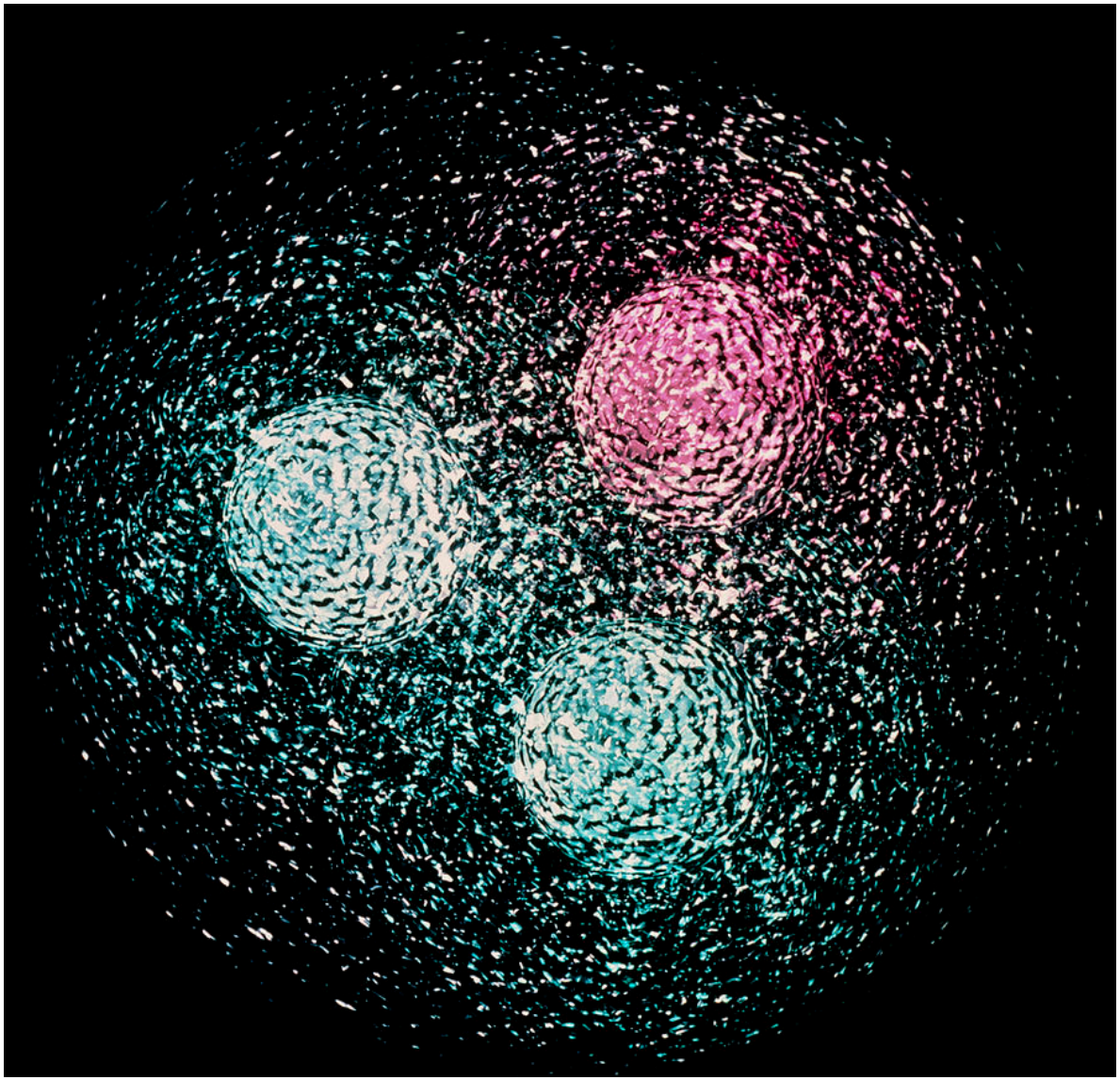
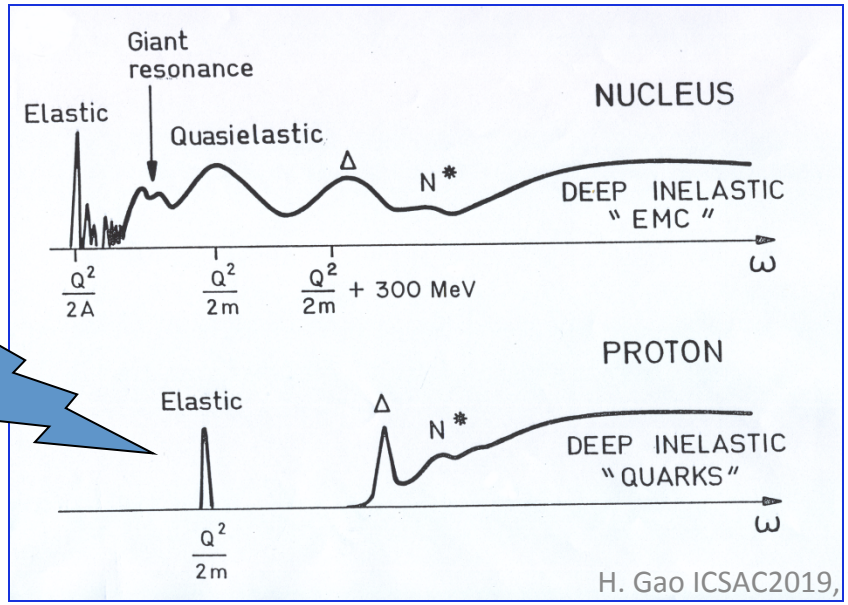


Image credit: fineartamerica.com

Lepton scattering: powerful microscope!

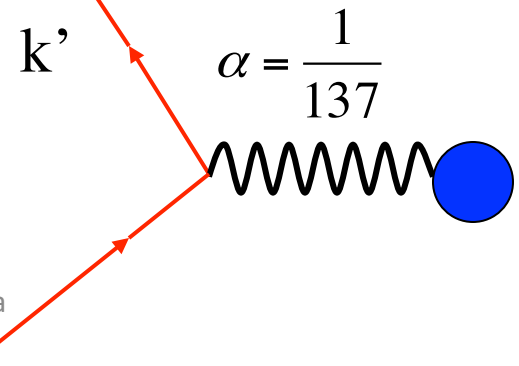
- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***One can vary the wave-length of the probe to view deeper inside the hadron***



Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$



What is inside the proton/neutron?

1933: Proton's magnetic moment

Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic moment of the proton".

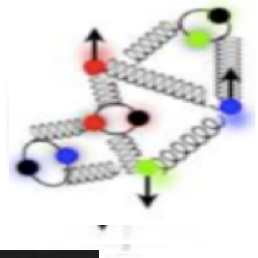
$$g \neq 2$$

1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

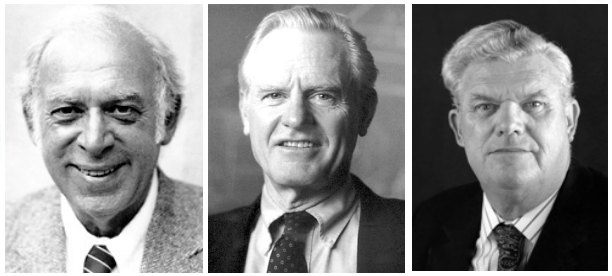
Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"



Form factors → Charge distributions

1969: Deep inelastic e-p scattering



Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

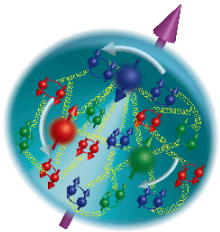
1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Nucleon Spin Puzzle



Proton spin puzzle

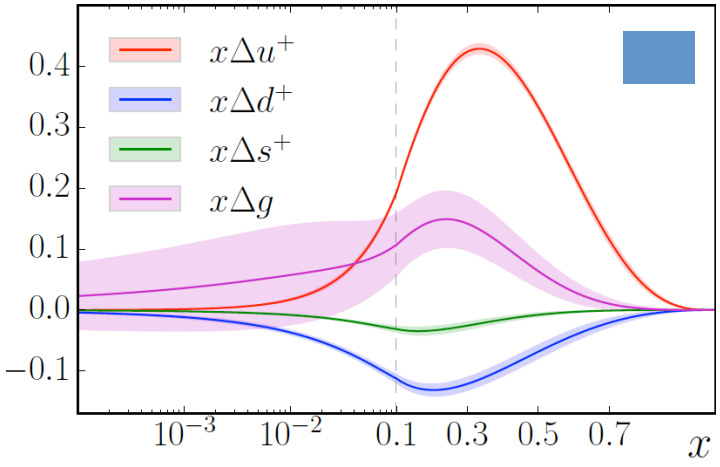
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

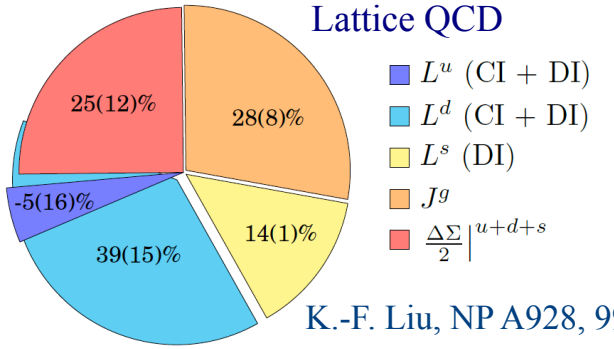
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PRD (2016).



K.-F. Liu, NP A928, 99 (2014).

Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

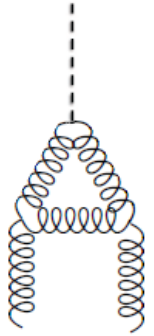
3D imaging of the nucleon.

Latest Lattice QCD results suggest 50% from gluon spin (Phys. Rev. Lett. 118, 102001)

Proton Mass Puzzle

- **Connecting**
  - **Trace of energy momentum tensor**
  - **"Beta" function** energy evolution of strong interaction coupling constant

$$G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta}$$



$$< N | \frac{\beta(g)}{2g} G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta} + \sum_{u,d,s,} m_q \bar{q} q | N >= M_N$$

$$H_{QCD} = H_q + H_m + Hg + H_a$$

$H_q =$ Quark energy $\int d^3x \; \psi^\dagger (-i\mathbf{D} \cdot \alpha) \psi$

$H_m =$ Quark mass $\int d^3x \; \bar{\psi} m \psi$

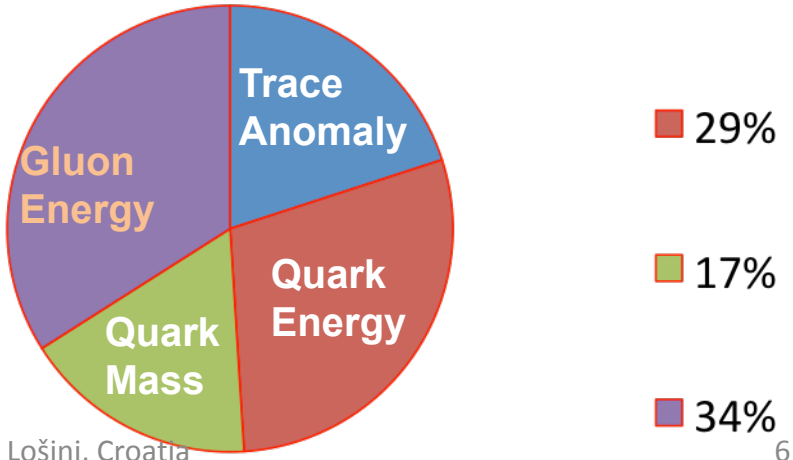
$H_g =$ Gluon energy $\int d^3x \; \frac{1}{2} (\mathbf{E^2} + \mathbf{B^2})$

$H_a =$ Trace anomaly $\int d^3x \; \frac{9\alpha_s}{16\pi} (\mathbf{E^2} - \mathbf{B^2})$

Sets the scale for the Hadron mass!

Proton Mass Budget

(Proton rest frame)



X. Ji PRL 74 1071 (1995)

The Committee on U.S.-Based Electron Ion Collider Science Assessment

- **Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?

citation: National Academies of Sciences, Engineering, and Medicine. 2018. *An Assessment of U.S.-Based Electron-Ion Collider Science.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25171

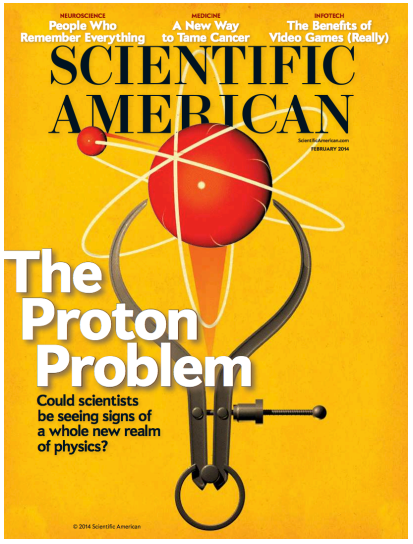
The Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Progress made on lattice
  - An important physics input to the bound state QED calculations, affects muonic H Lamb shift $(2S_{1/2} - 2P_{1/2})$ by as much as 2%

- **Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)**

$$\sqrt{< r^2 >} = \sqrt{-6 \frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0}}$$

- **Spectroscopy (Atomic physics)**
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

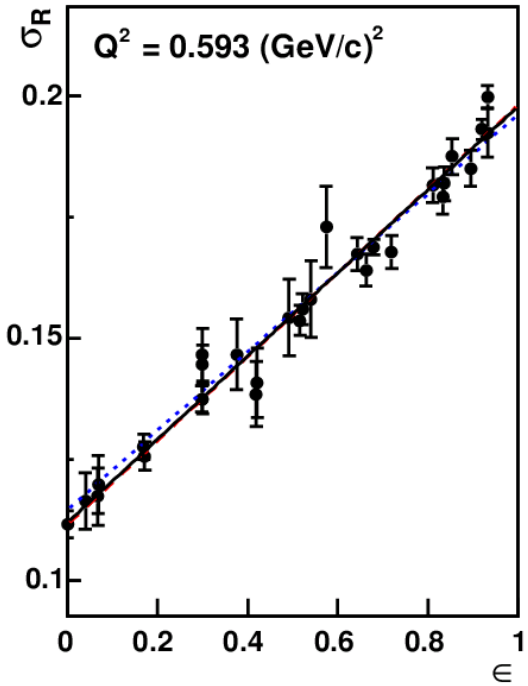


Unpolarized electron-nucleon scattering (Rosenbluth Separation)

- Elastic e-p cross section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^{p\,2} + \tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2} \tan^2\frac{\theta}{2} \right)$$

$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2\frac{\theta}{2} \right)$$



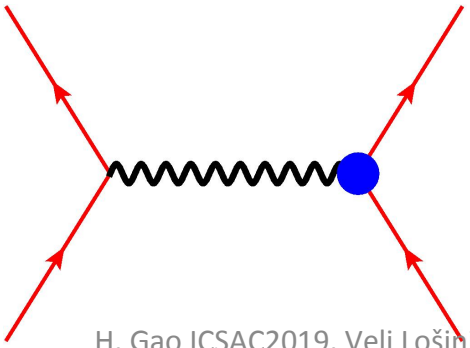
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - Low Q^2 by G_E
    - High Q^2 by G_M

$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$

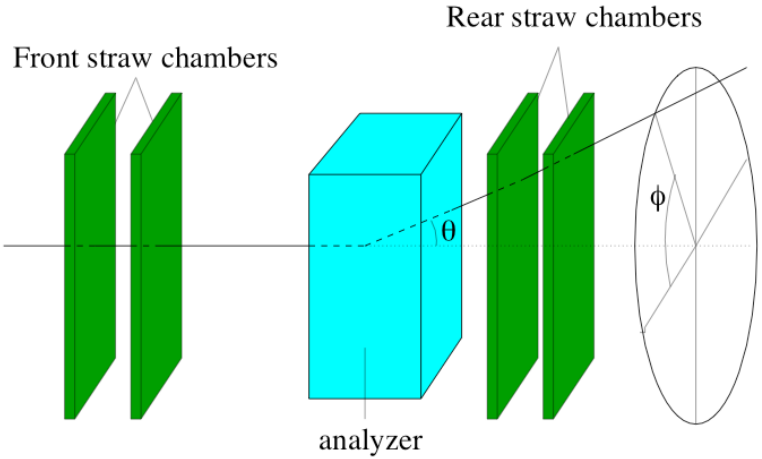
G_E or G_M



One-photon-exchange diagram

Elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

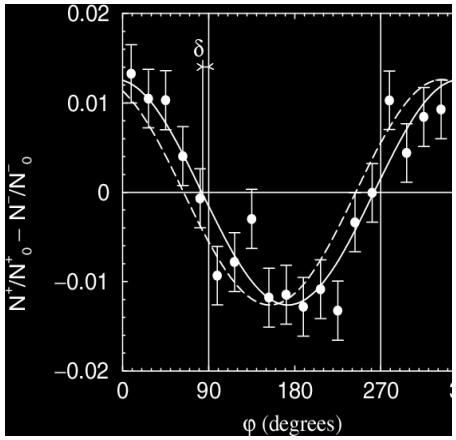
Polarization Transfer → $\frac{G_E^p}{G_M^p}$

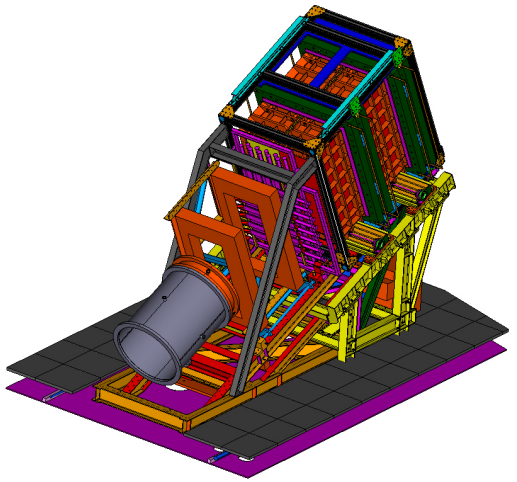


- Recoil proton polarization

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}$$

- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio





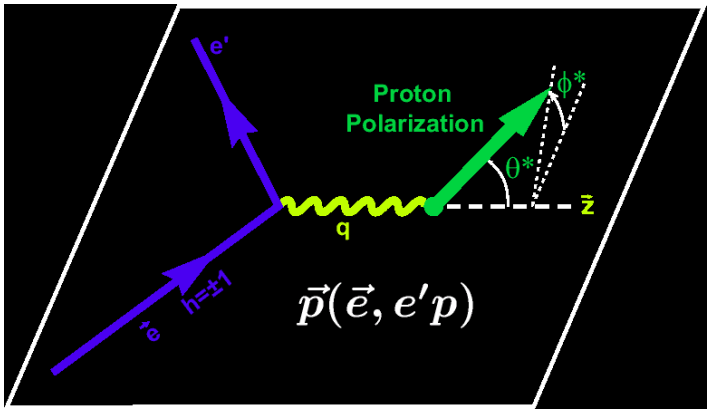
Focal-plane polarimeter

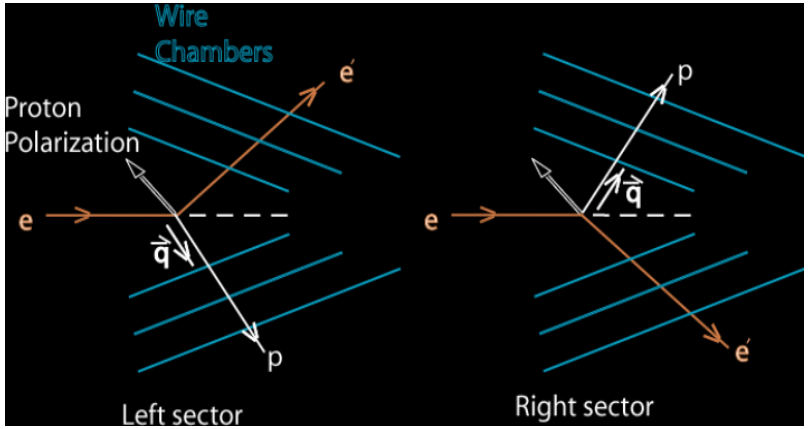
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

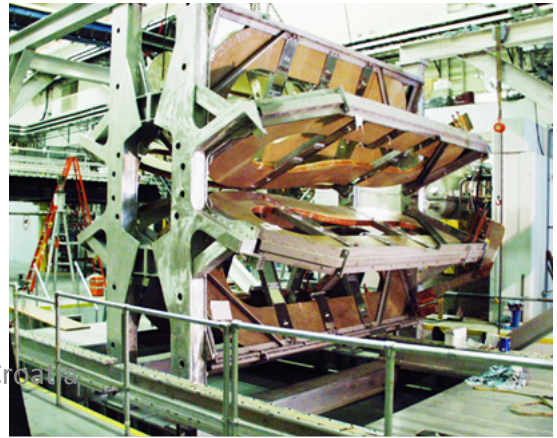
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





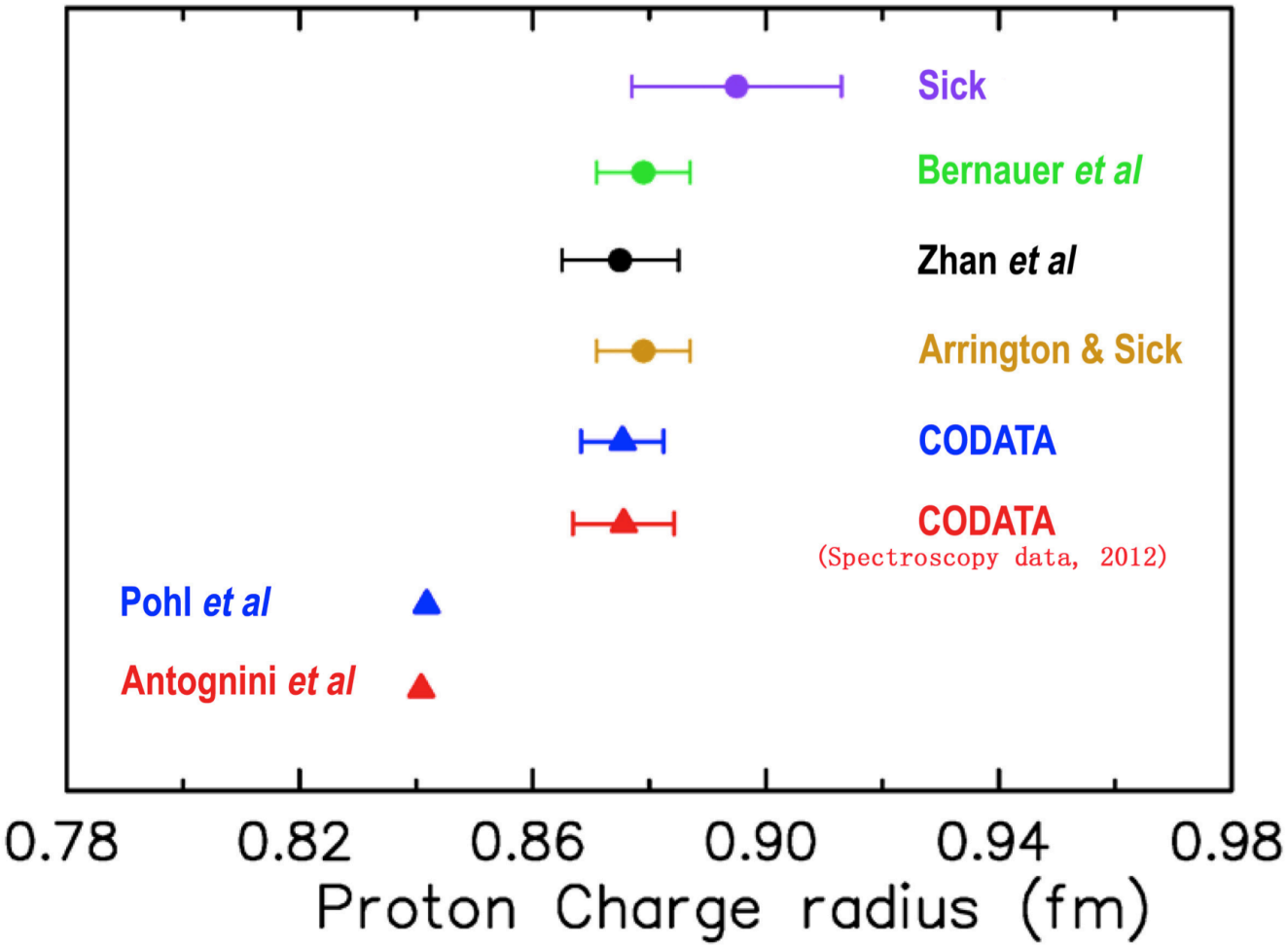
- Super-ratio

$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}$$



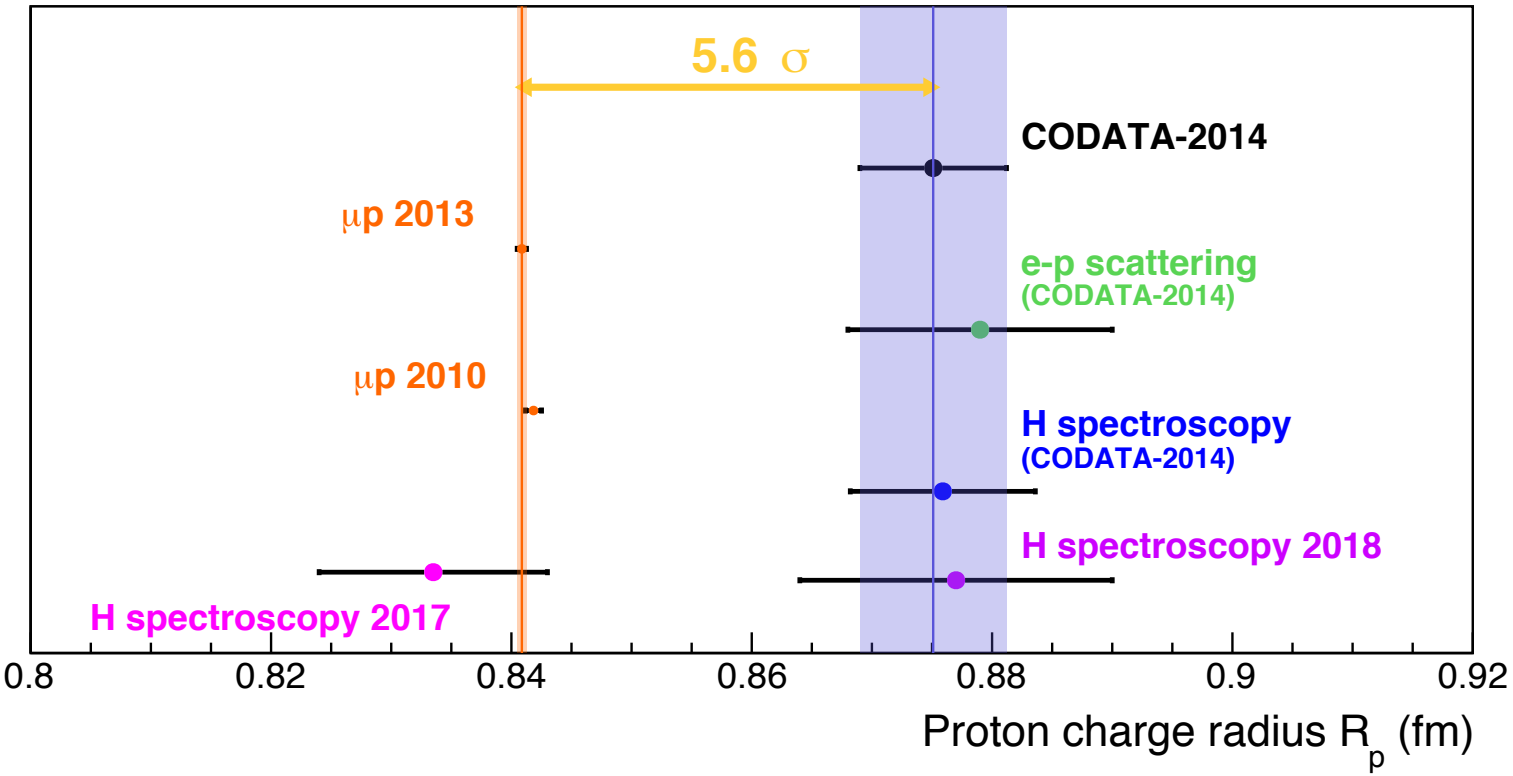
BLAST pioneered the technique, later also used in JLab Hall A experiment

The situation on the Proton Charge Radius in 2013



This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so

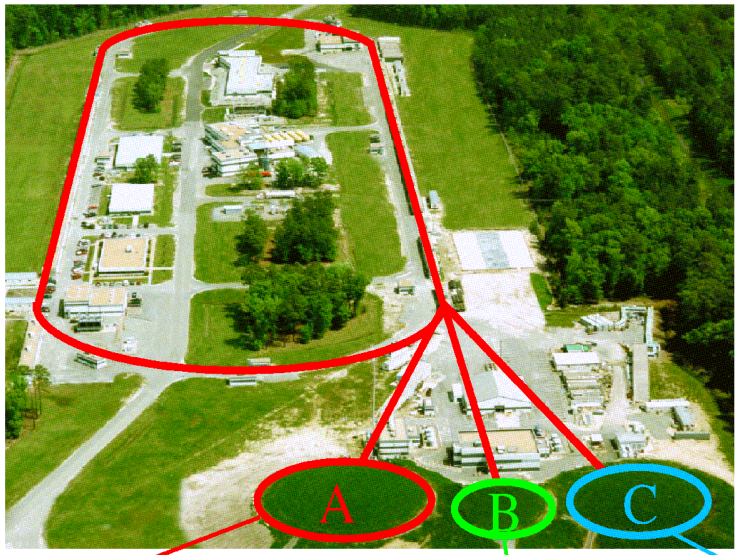
The Proton Charge Radius Puzzle in 2018

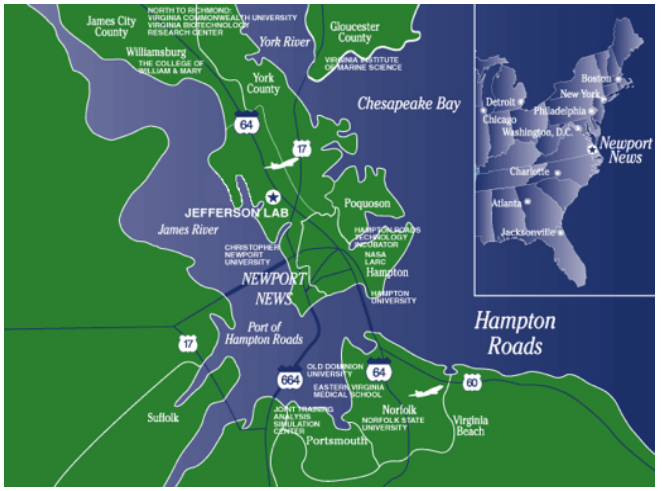


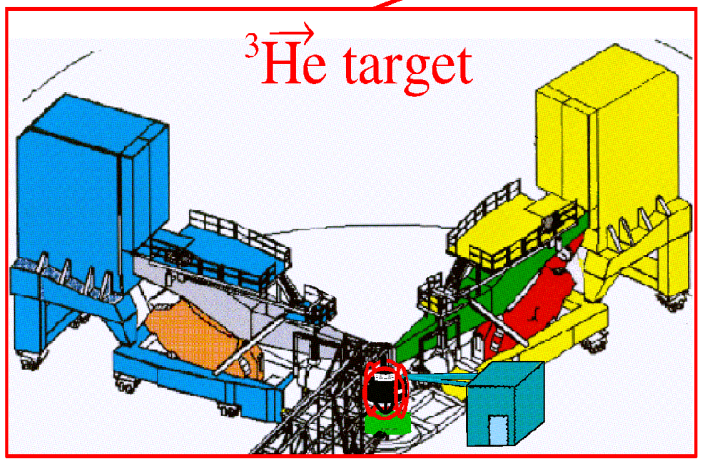
Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)
H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

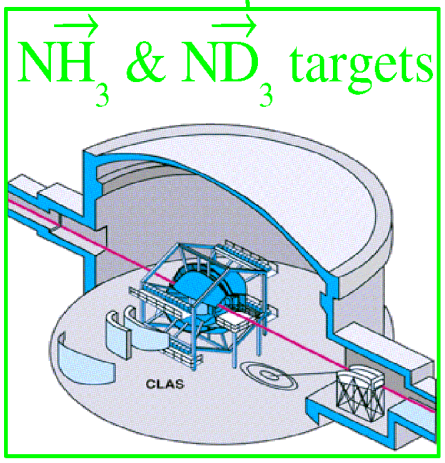
Jefferson Lab in Pre-12 GeV Era

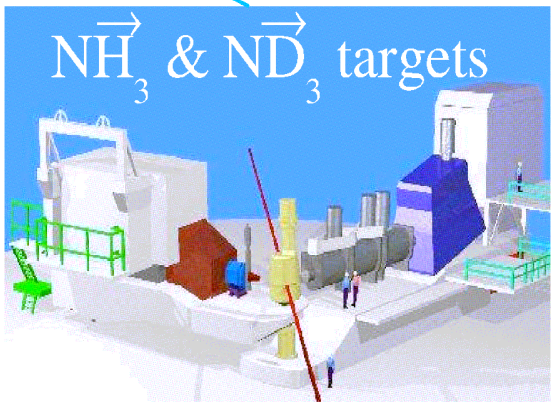
6 GeV polarized
CW electron beam
Pol=85%, 180μA









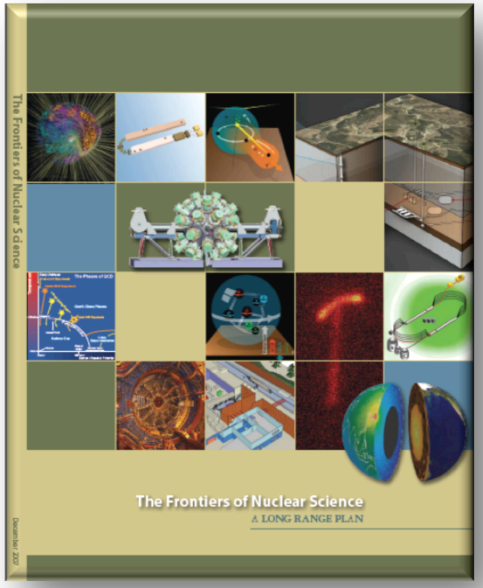


HallA: two HRS'

Hall B:CLAS

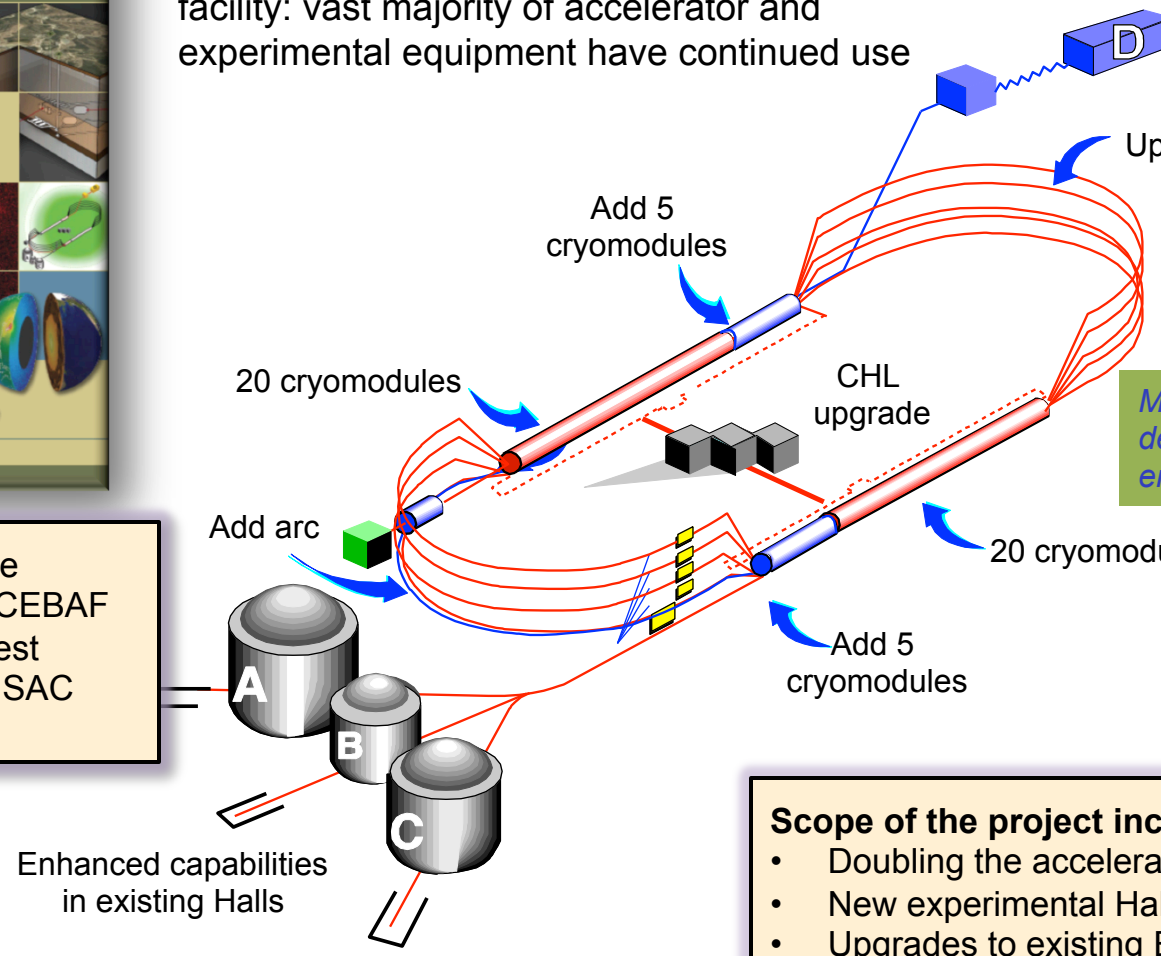
Hall C: HMS+SOS

Energy Upgraded JLab at 12 GeV



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade was designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



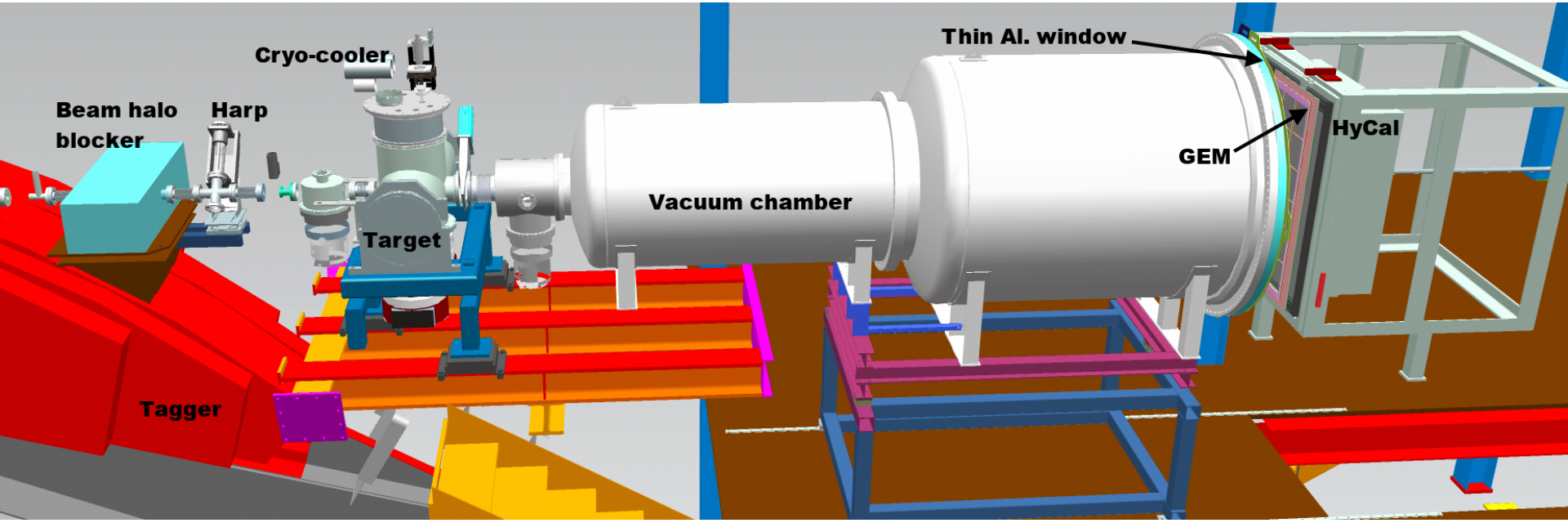
*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

Scope of the project includes:

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

PRad was the first experiment to complete following the 12-GeV upgrade

PRad Experimental Setup in Hall B at JLab



- **High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2×10^{-4} – 0.06 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum chamber**

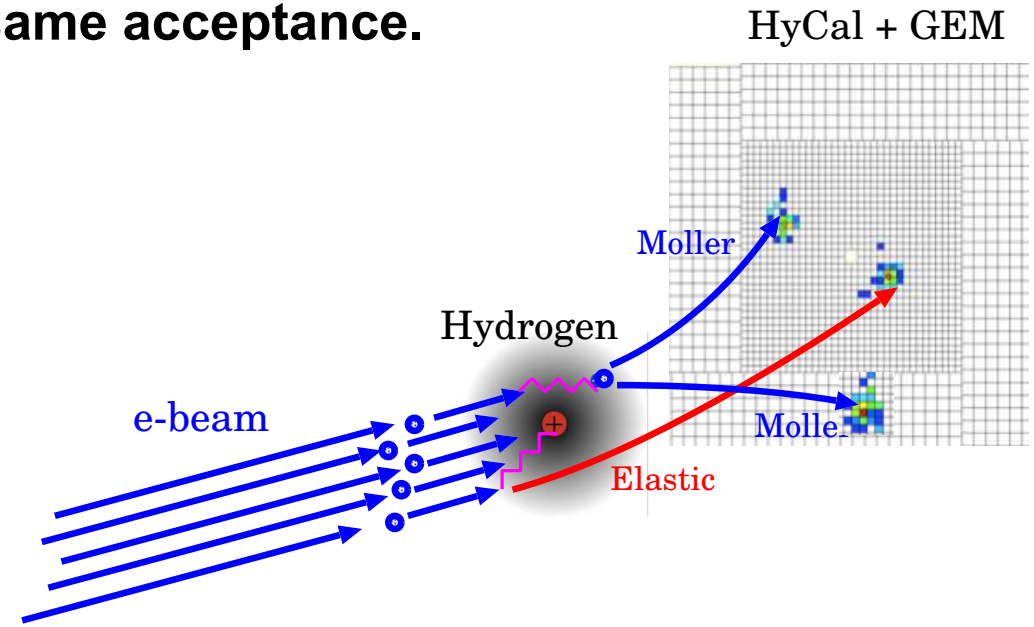
Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker

Electron/muon scattering measurements:
(1) ep elastic scattering at JLab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz, and more
(4) New experiments in France, Japan and at CERN

Review by J. Bernauer

Key innovations in the design allowed a unique high precision measurement.

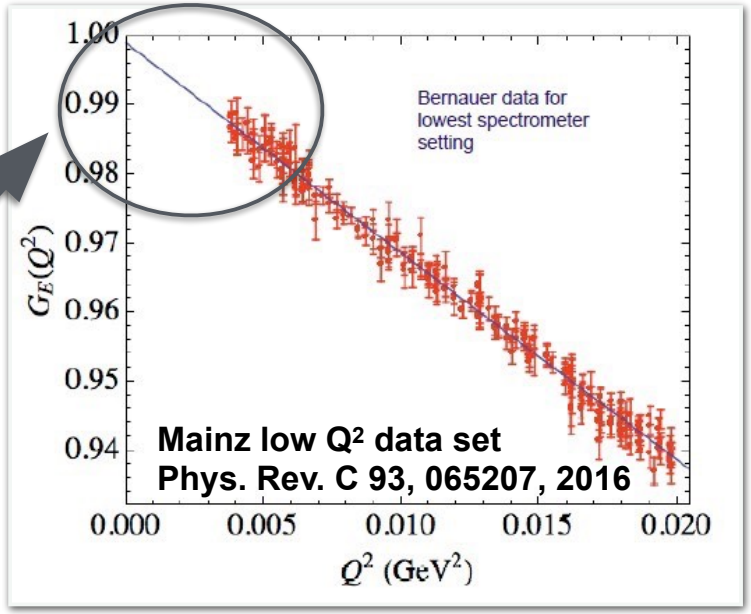
Simultaneous detection of the Møller *(e-e)* and *e-p* elastic events within the same acceptance.



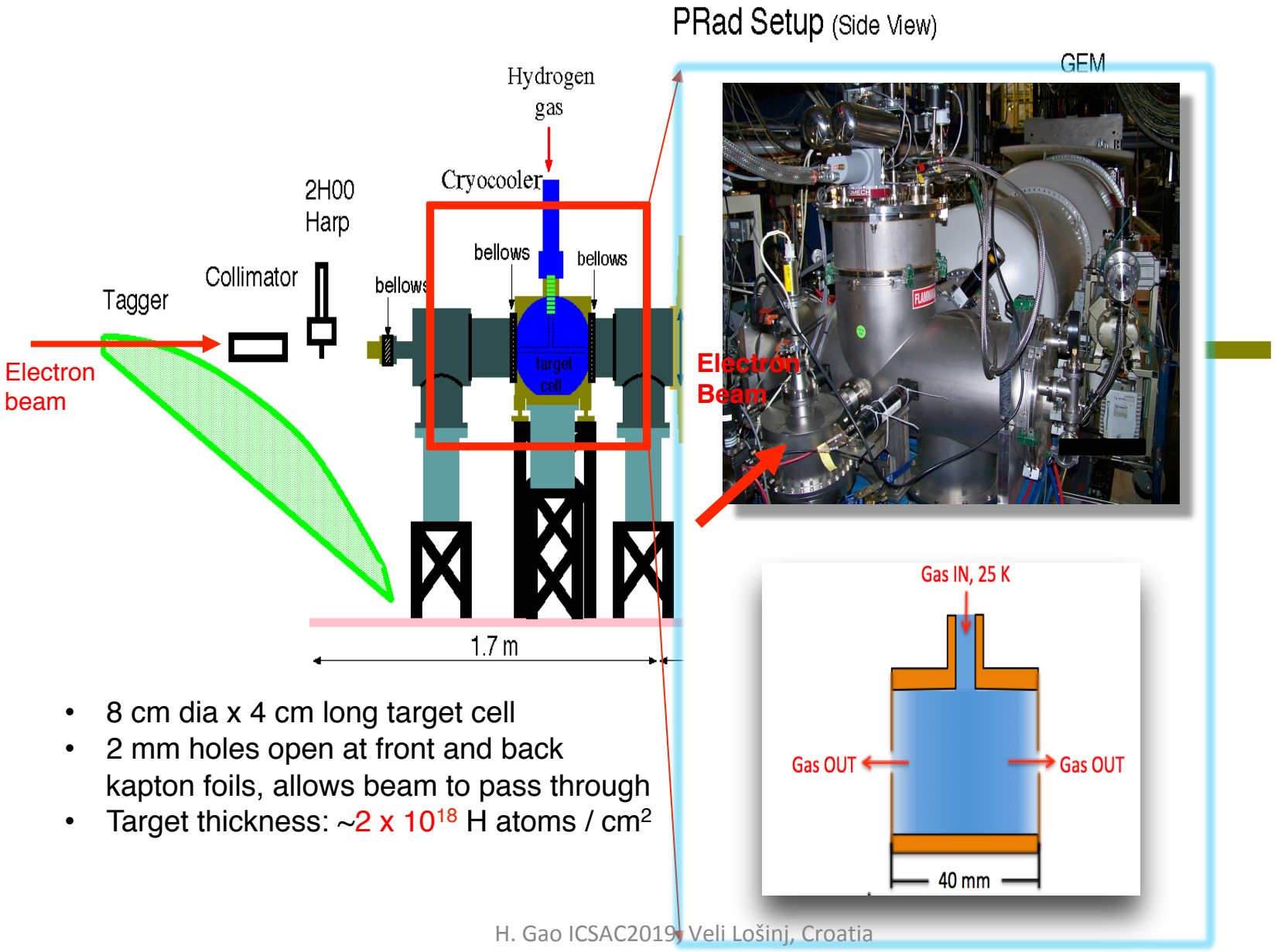
- **Experimental design allows:**
  - **control of systematics**
  - **eliminates need to monitor luminosity**

Large forward angle acceptance with high energy resolution (HyCal) and 72 μm position resolution (GEM).

- **Experimental design allows:**
  - **fill in the very low Q^2 range**
  - **large Q^2 range in a single setting (~2×10^{-4} - 6×10^{-2} GeV^2)**

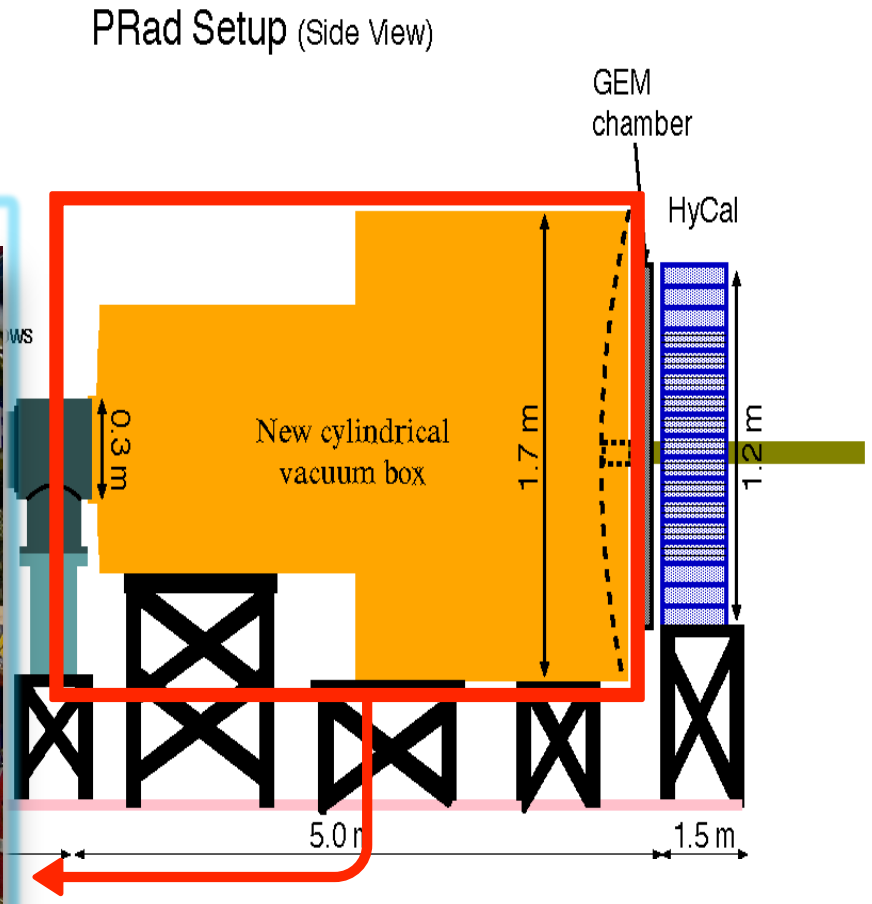


PRad Experimental Apparatus



- 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

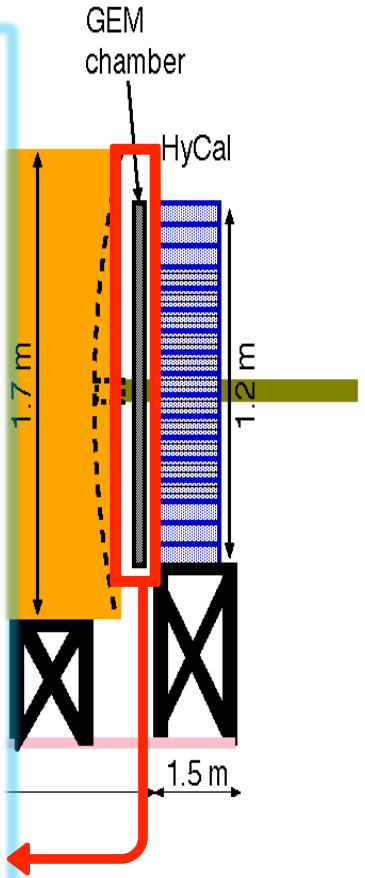


- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum tank pressure: 0.3 mTorr

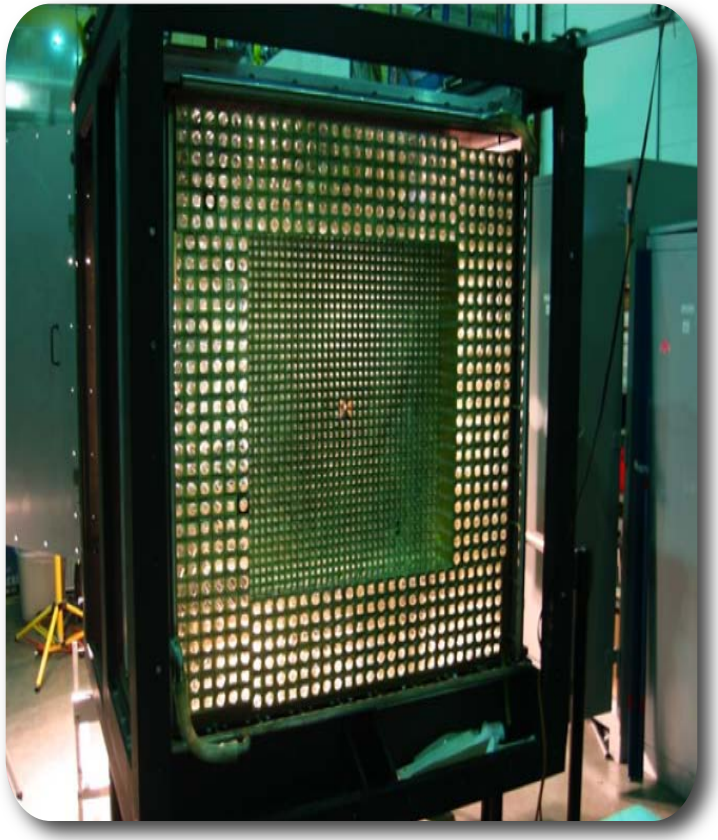
PRad Experimental Apparatus

- 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
- Similar improvement for Q^2 determination at small angle

PRad Setup (Side View)

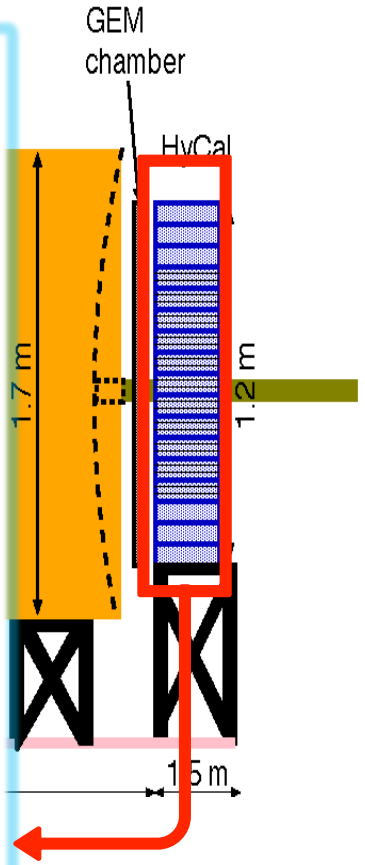


PRad Experimental Apparatus



- 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)



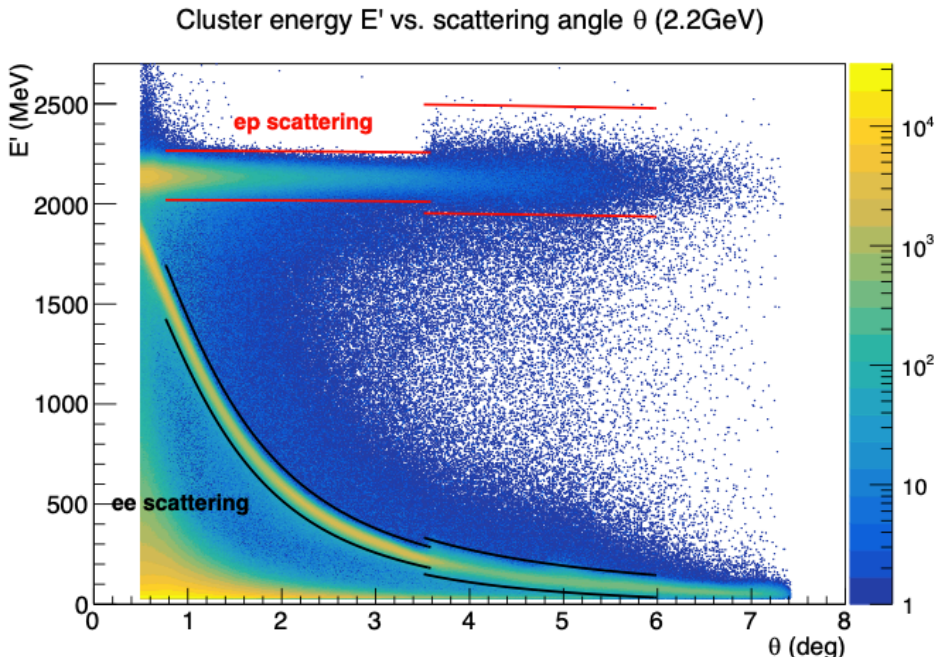
Analysis – Event Selection

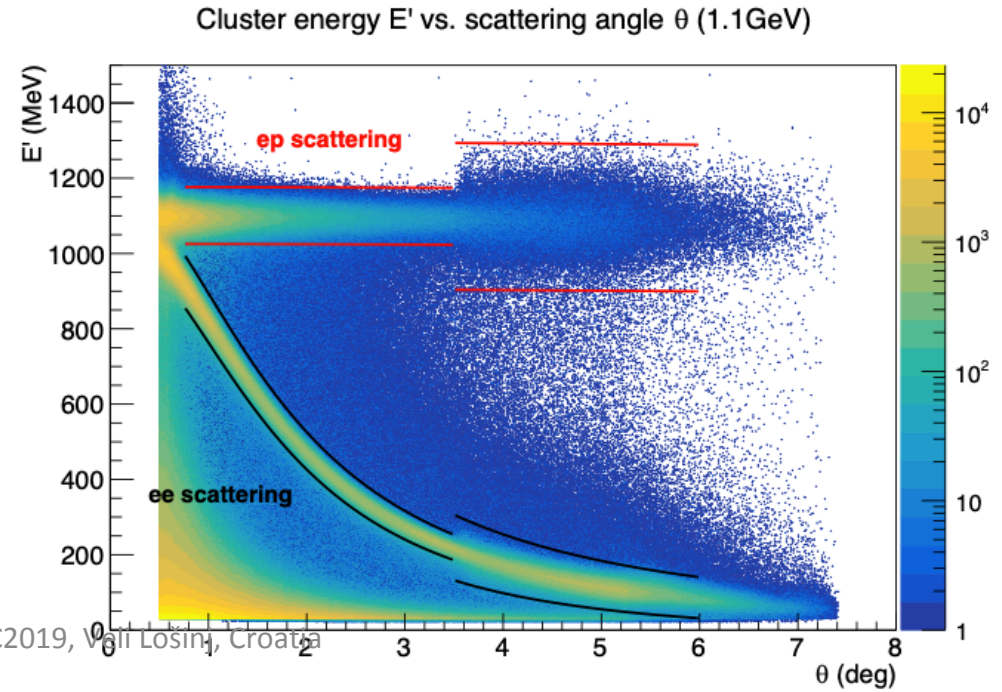
Event selection method

1. For all events, require hit matching between GEMs and HyCal

2. For *ep* and *ee* events, apply angle dependent energy cut based on kinematics
   1. Cut size depend on local detector resolution

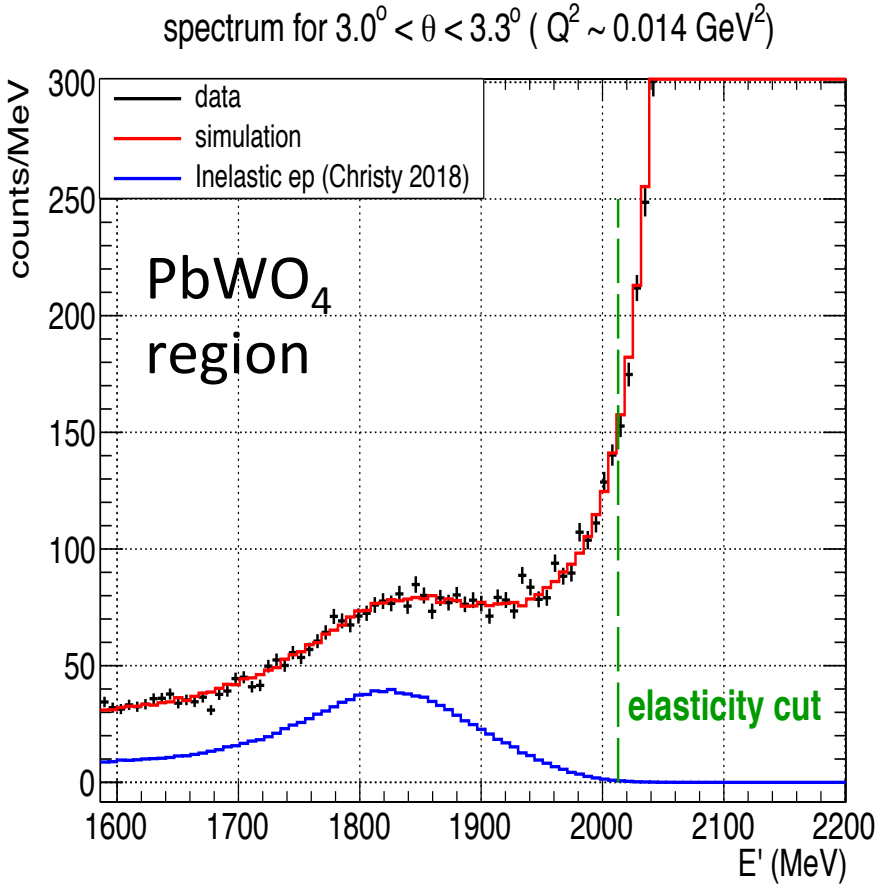
3. For *ee*, if requiring double-arm events, apply additional cuts
   1. Elasticity
   2. Co-planarity
   3. Vertex z

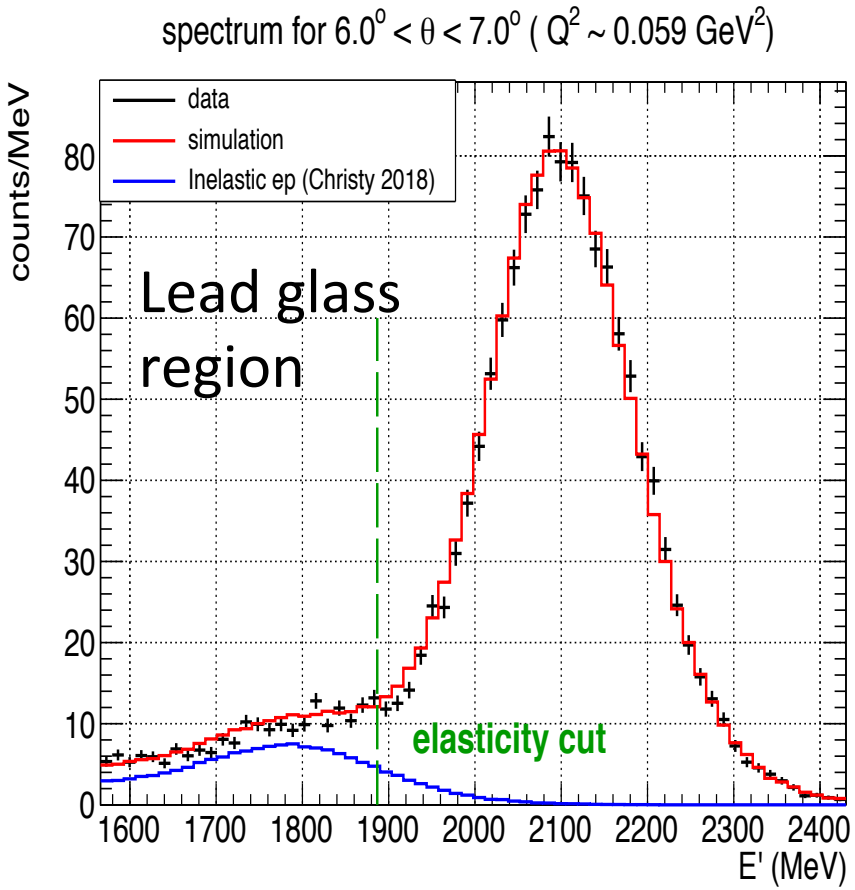




Analysis – elastic cut and inelastic contribution

- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region

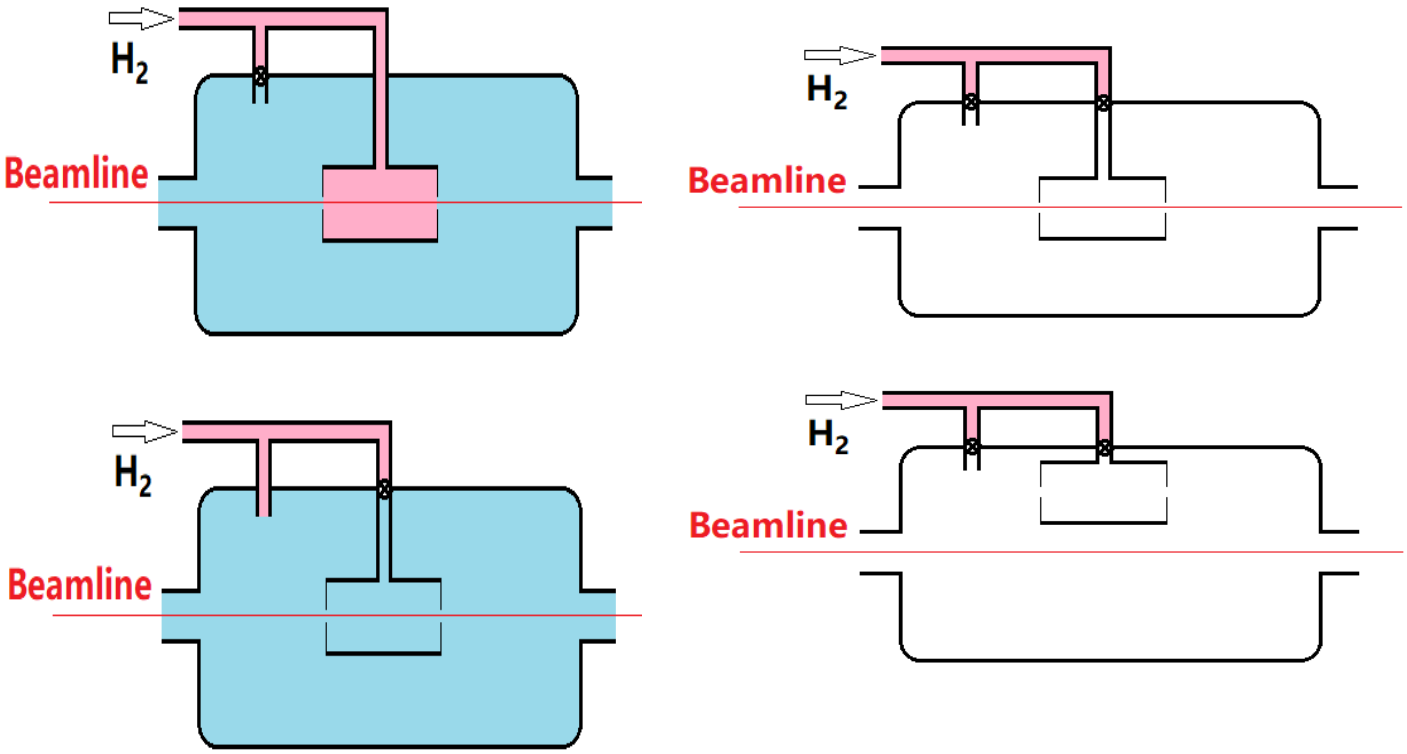




M.E. Christy and P.E. Bosted. PRC 81, 055213 (2010)

Analysis – Background Subtraction

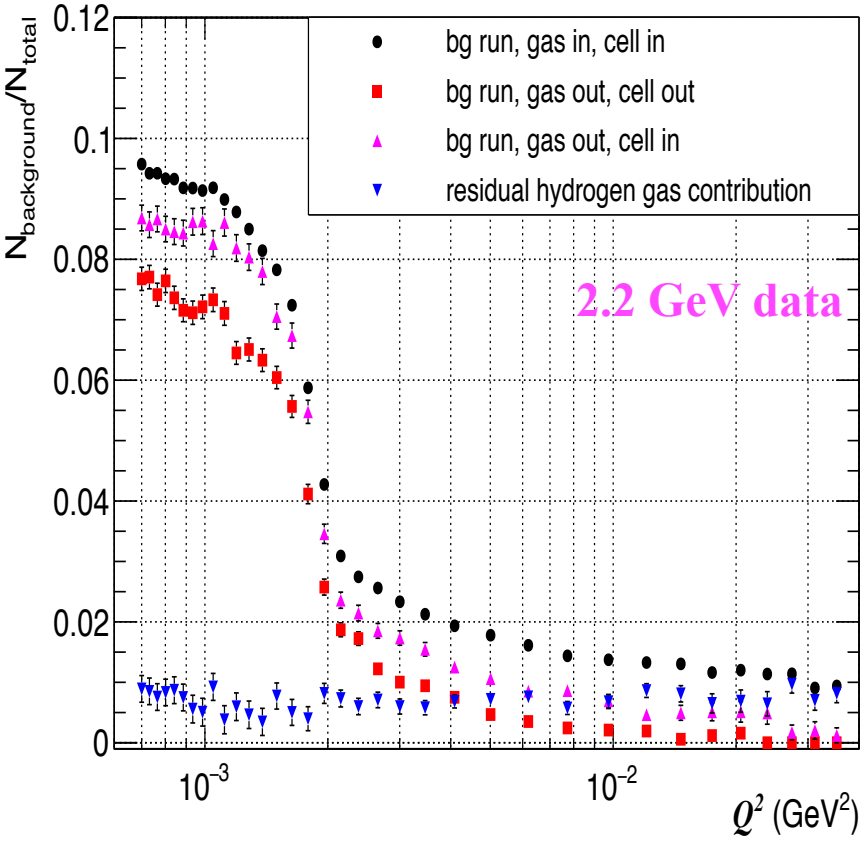
- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)



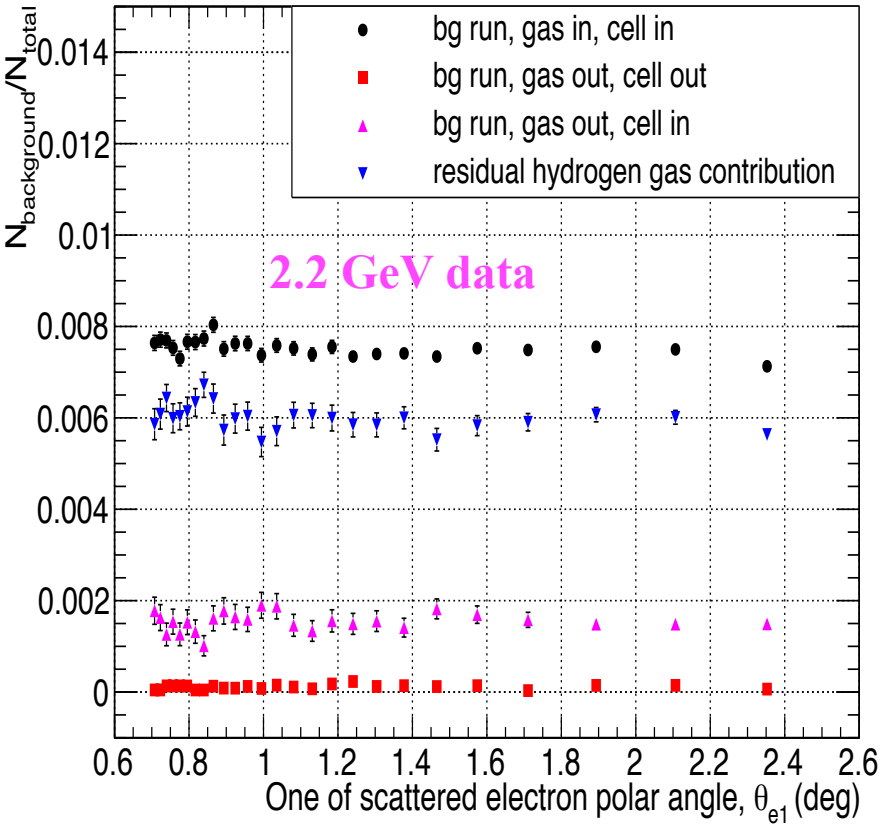
Analysis – Background Subtraction at 2.2 GeV

- *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

ep Background Contribution



ee Background Contribution



Extraction of *ep* Elastic Scattering Cross Section

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

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

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

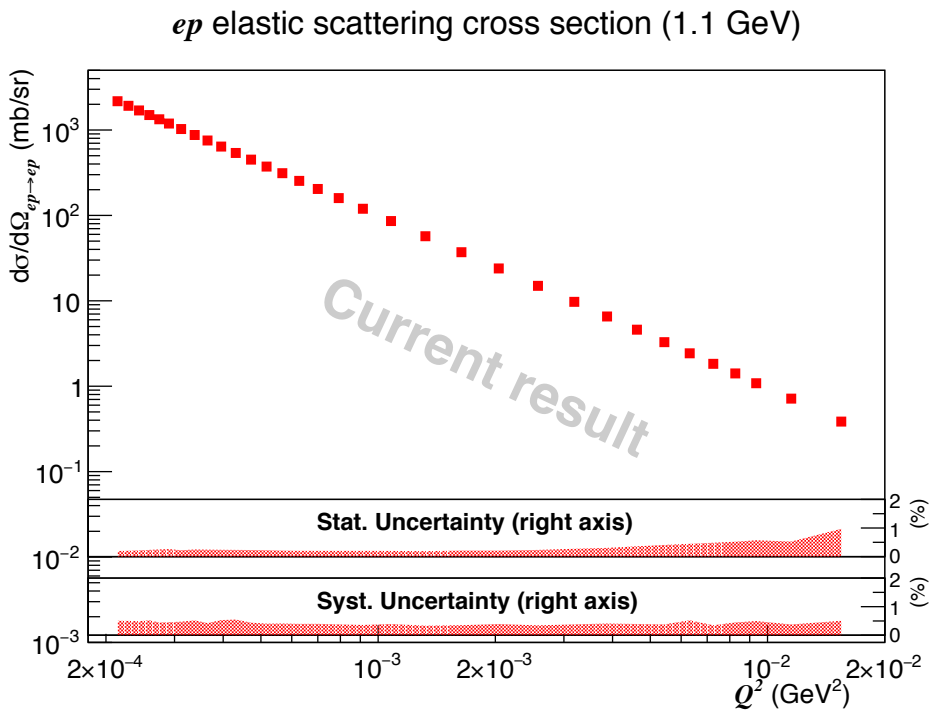
- A Geant4 simulation package is used to study the radiative effects:

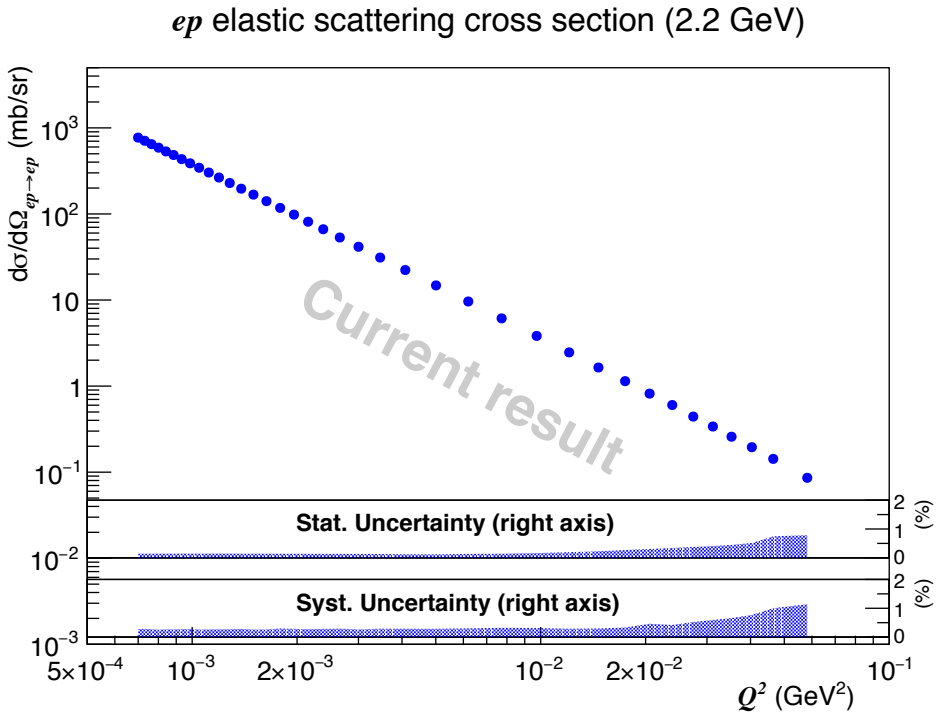
$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

- Iterative procedure applied for radiative correction

Elastic ep Cross Sections (Current)

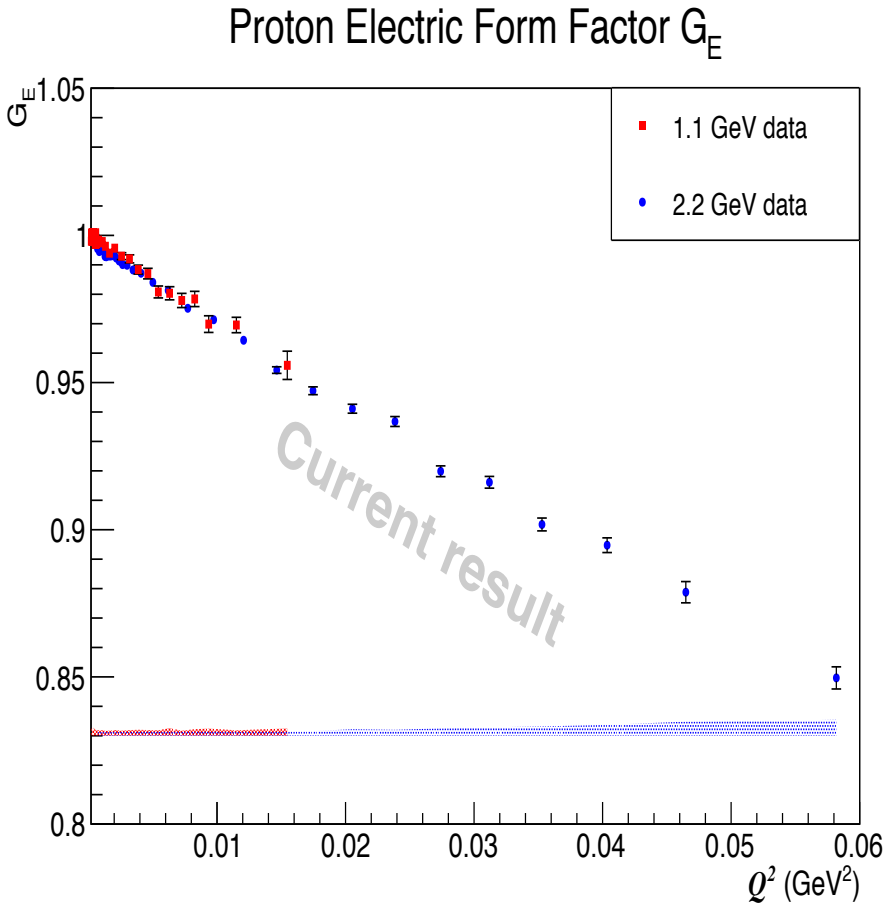
- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data (current)
- Statistical uncertainties at current stage: ~0.15% for 2GeV, ~0.2% for 1GeV per point
- Systematic uncertainties at current stage: 0.3%~1.1% for 2GeV, 0.3%~0.5% for 1GeV (shown as shadow area)

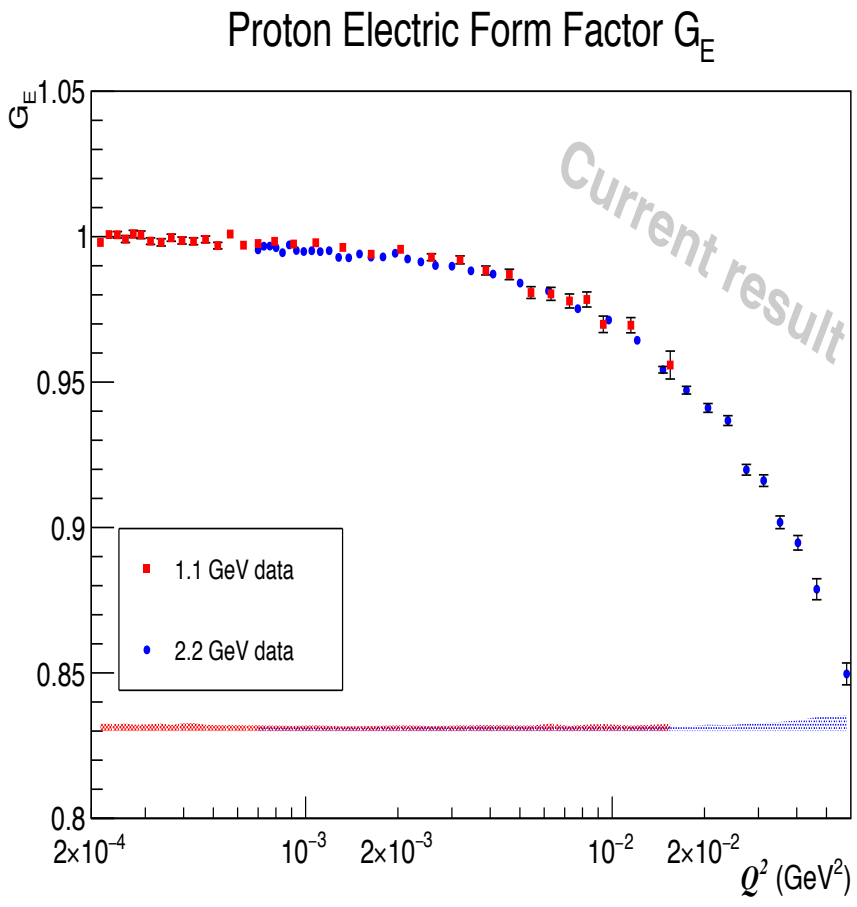




Systematic uncertainties shown as bands

Proton Electric Form Factor G_E

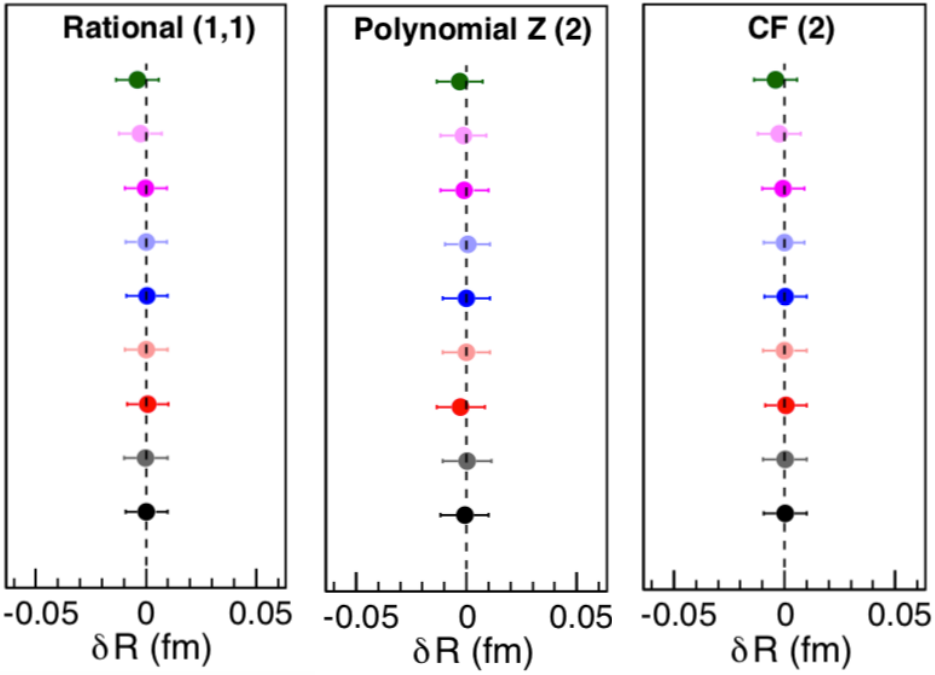




Lowest Q^2 ever achieved from ep elastic scattering

Searching the Robust fitters

- Various fitters tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties:
  - X. Yan *et al.* Phys. Rev. C98, 025204 (2018)
- Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties



Ye-2018
Bernauer-2014
Alarcón-2017
Arrington-2007
Arrington-2004
Kelly-2004
Gaussian
Monopole
Dipole

Rational (1,1)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order *z* transformation

$$p_0(1 + p_1 z + p_2 z^2)$$

$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

2nd order continuous faction

$$p_0 \frac{1}{1 + \frac{p_1 Q^2}{1 + p_2 Q^2}}$$

Rapid Progress

- The latest result published in Science on September 9, 2019 from H Lamb Shift: 0.833 +/- 0.010 fm

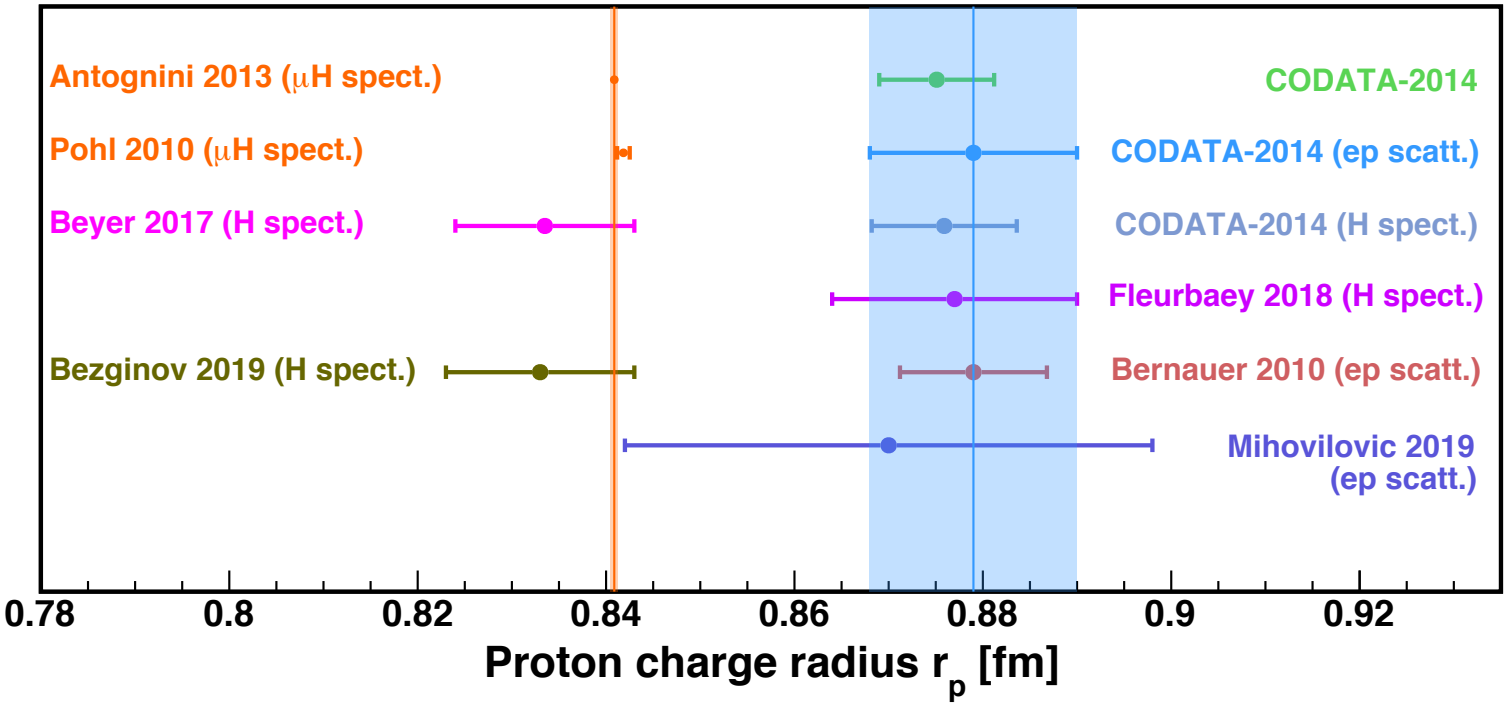


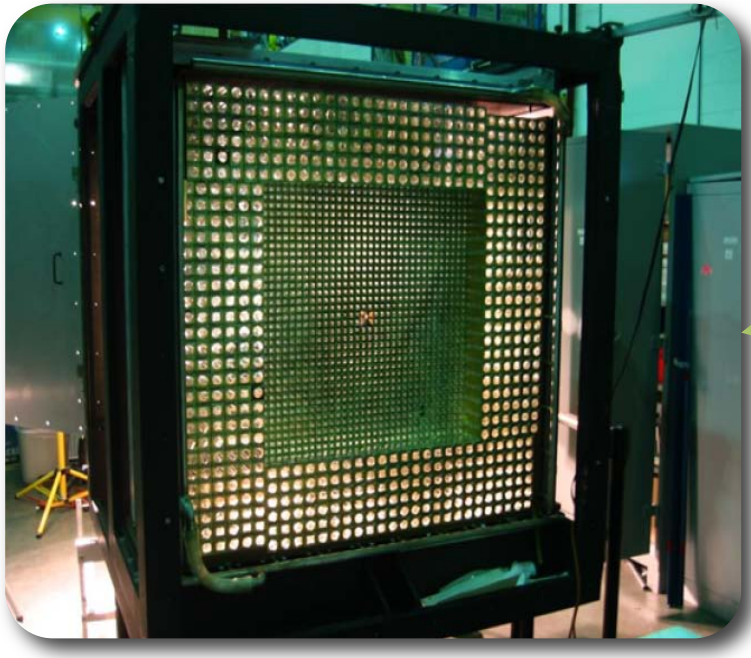
Figure Credit: Weizhi Xiong

Bezginov *et al.*, *Science* **365**, 1007-1012 (2019)

Systematic uncertainties (current)

Item	R_p uncertainty (fm)	n_1 uncertainty (1GeV)	n_2 uncertainty (2GeV)
Event selection	0.0070	0.0002	0.0006
Radiative correction	0.0069	0.0010	0.0011
Detector efficiency	0.0042	0.0000	0.0001
Beam background	0.0039	0.0017	0.0003
HyCal response	0.0029	0.0000	0.0000
Acceptance	0.0026	0.0001	0.0001
Beam energy	0.0022	0.0001	0.0002
Inelastic ep	0.0009	0.0000	0.0000
Total	0.0116	0.0020	0.0013

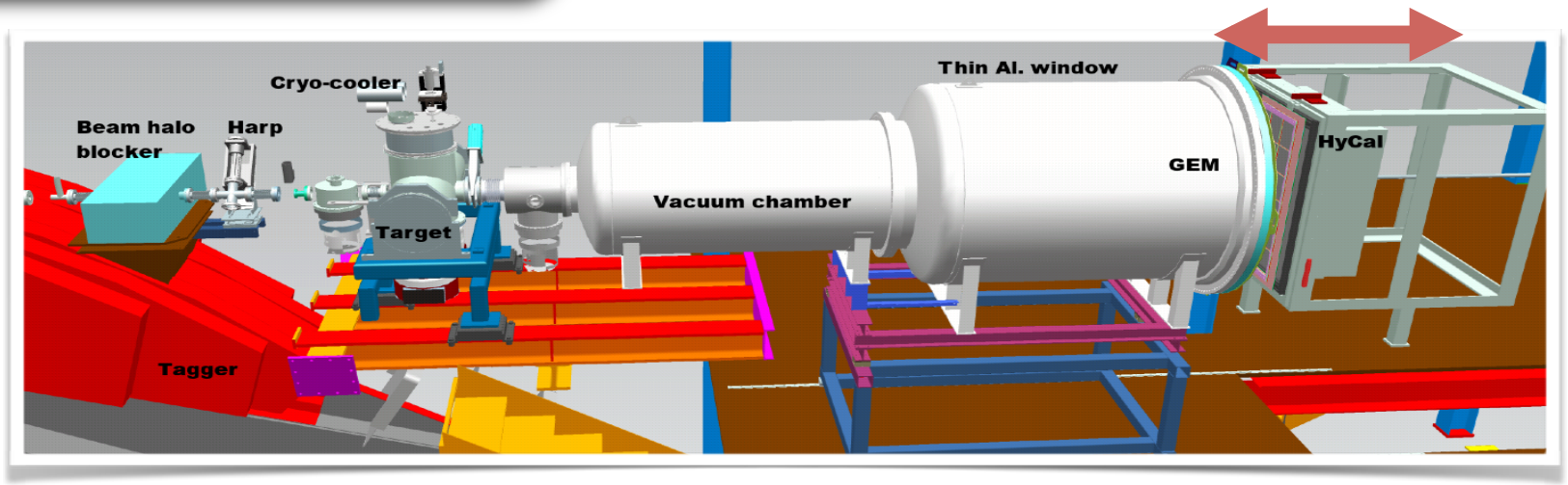
Future Outlook for PRad – PRad-II



Upgrade HyCal to be replace all lead-glass modules with $PbWO_4$ modules to have uniform high resolution (desired)

Convert to FADC based readout of HyCal

Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.



Goals: improve the precision of r_p measurements and start a new program of high precision measurements using the PRad method

PRad Collaboration Institutional List

- 17 collaborating universities and institutions:

Thomas Jefferson National Accelerator Facility
North Carolina A&T State University
Duke University and TUNL
Idaho State University
Mississippi State University
University of Virginia
Argonne National Laboratory
University of North Carolina at Wilmington
Kharkov Institute of Physics and Technology
MIT
Old Dominion University
ITEP, Moscow, Russia
University of Massachusetts Amherst
Hampton University
College of William & Mary
Norfolk State University
Yerevan Physics Institute

- Graduate students (inclusive):

Chao Peng (Duke)
Weizhi Xiong (Duke)
Li Ye (MSU)
Xinzhan Bai (UVa)
Abhisek Karki (MSU)

- Postdocs (inclusive):

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

Summary and outlook

- **After almost 10 years, major progress made in resolving the proton radius puzzle**
- **The PRad collaboration carried out a first electron-scattering experiment using a non magnetic spectrometer approach – calorimeter and GEM**
  - **Lowest 4-momentum transfer squared ever reached 10^{-4} $(GeV/c)^2$**
  - **Novel use of an internal cryogenically cooled hydrogen gas target**
  - **Simultaneous measurements of ep and ee scattering to reduce systematics**
- **The PRad result supports the smaller value of the proton charge radius and consistent with the latest H Lamb Shift result!**

Acknowledgement: JLab Hall B, target group, Physics Division, Accelerator Division and the JLab management, the PRad Collaboration, supported in part by NSF MRI PHY-1229153 and the U.S. Department of Energy under contract number DE-FG02-03ER41231