Proton Charge Radius and the PRad Experiment at JLab

Workshop on New Vistas in Low-Energy Precision Physics
Mainz, April 4-7, 2016

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Duke UNIVERSITY

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

What is inside the proton/neutron?

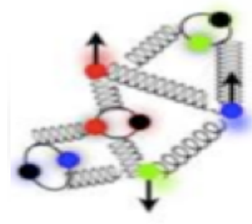
1933: Proton’s magnetic moment

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

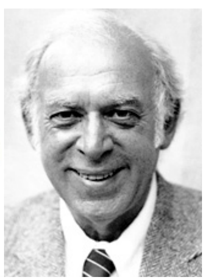
Nobel Prize
In Physics 1961

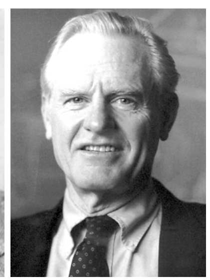
Robert Hofstadter

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

Form factors $\rightarrow$ 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

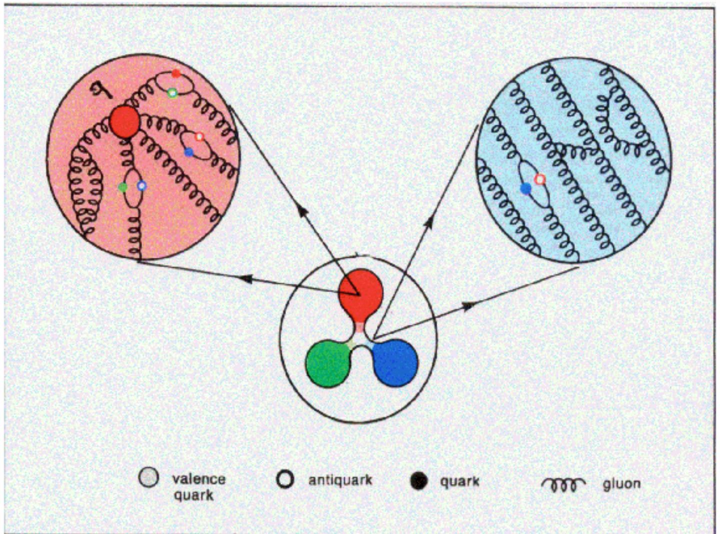
Nobel Prize in Physics 2004

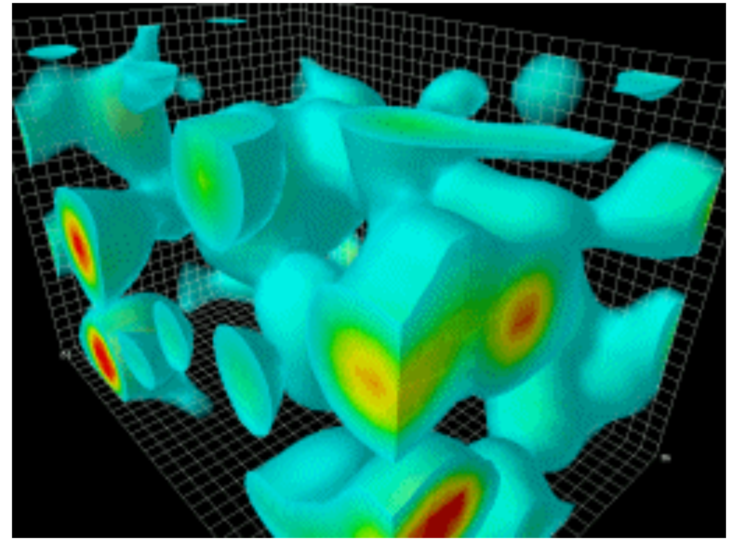
David J. Gross, H. David Politzer, Frank Wilczek

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

Proton: a fascinating many-body relativistic system

Higgs discovery almost irrelevant to proton mass





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

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

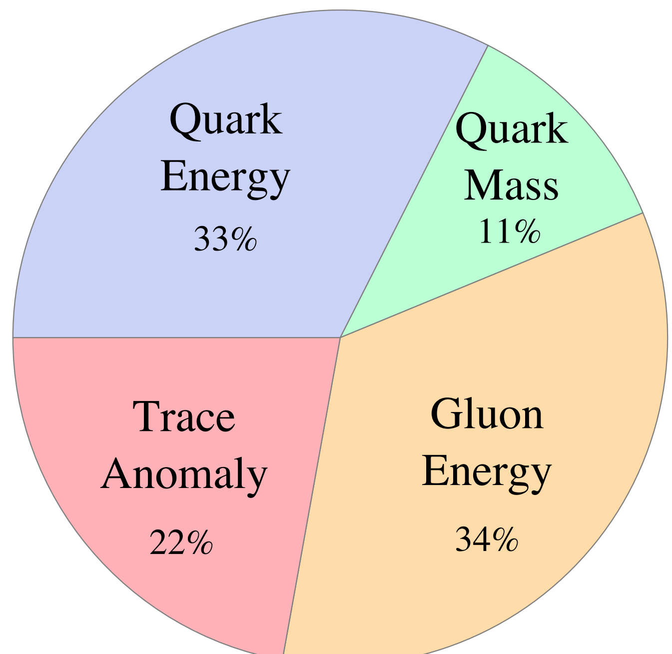
$H_m =$ Quark mass $\int d^3x\, \bar{\psi}m\psi$

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

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

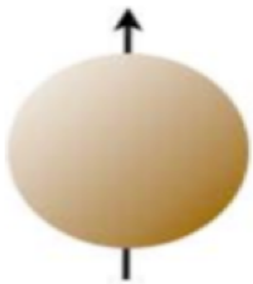
Sets the scale for the Hadron mass!

X. Ji PRL 74 1071 (1995)



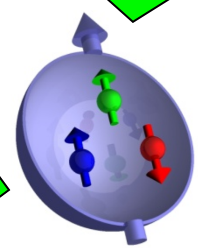
The incomplete nucleon: spin puzzle

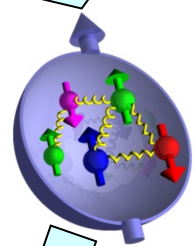
Jaffe-Manohar, 90
Ji, 96

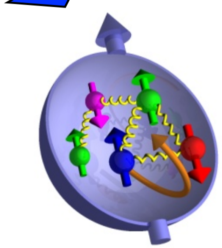


Proton Spin

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







Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

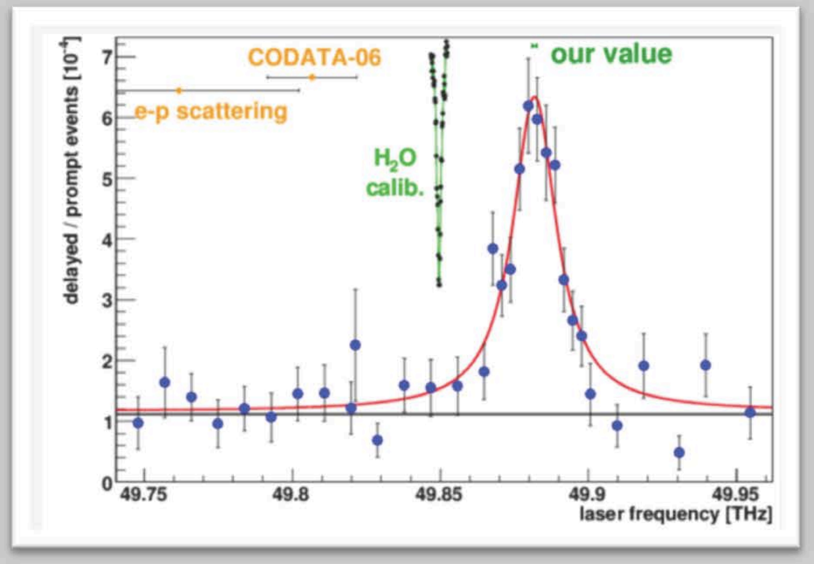
$$\Delta G = \int dx \Delta g(x)$$

$$\sim 20\% (\mathrm{STAR\ Data})$$

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

The Proton Size Puzzle



The New York Times

Süddeutsche Zeitung

DIE ZEIT

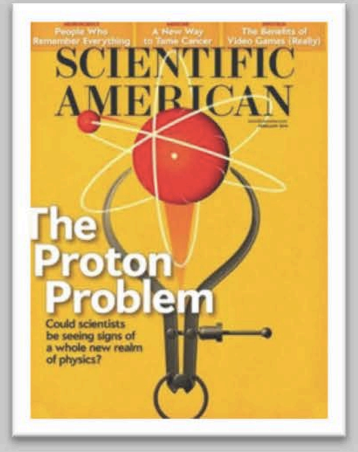
SPIEGEL ONLINE

la Repubblica

Neue Zürcher Zeitung

NATIONAL GEOGRAPHIC

Los Angeles Times



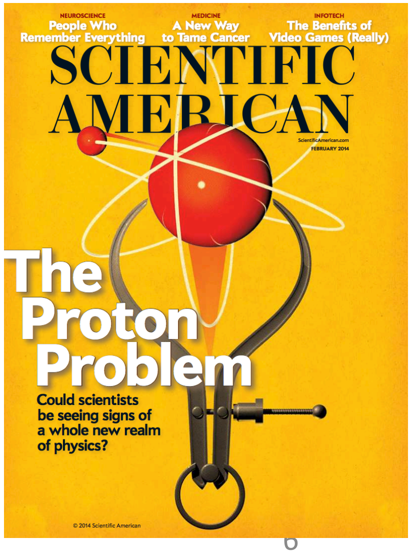
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  - 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)

$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}|_{q^2=0}}$$

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



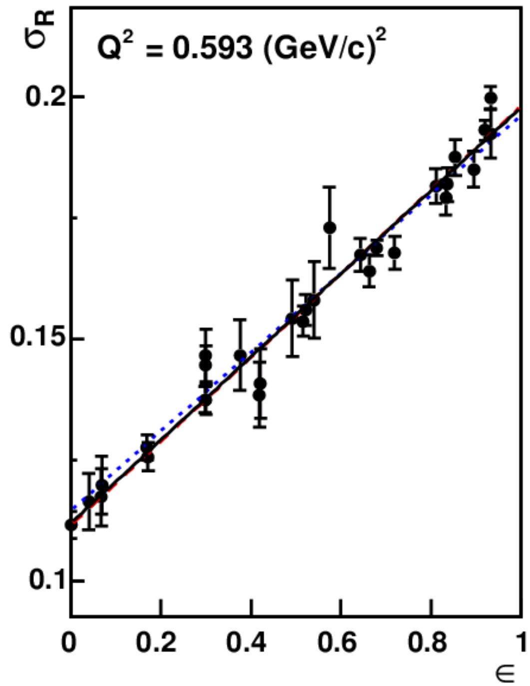
Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section

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

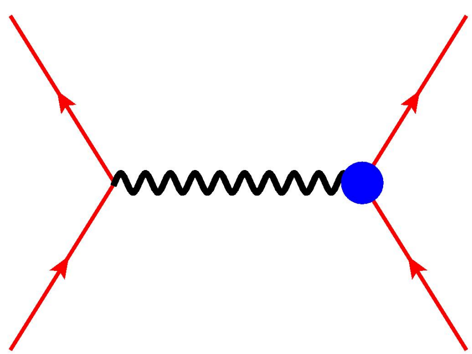
$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2\frac{\theta}{2} \right)$$



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

- 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

G_E or G_M

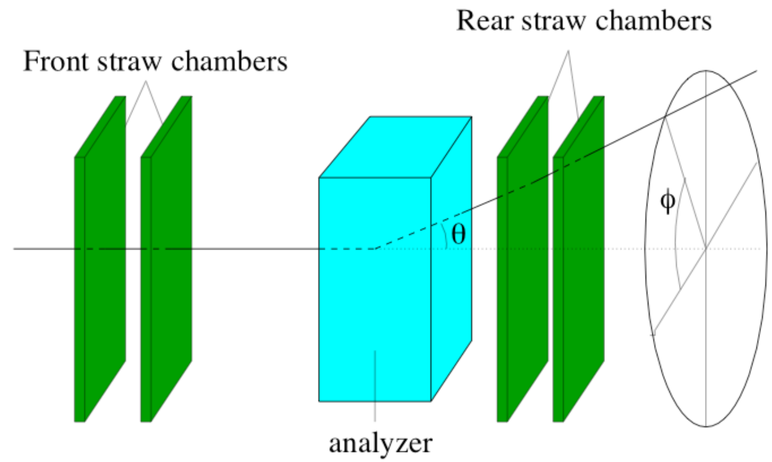


$$\tau = \frac{Q^2}{4M^2}$$

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

Electron-proton elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

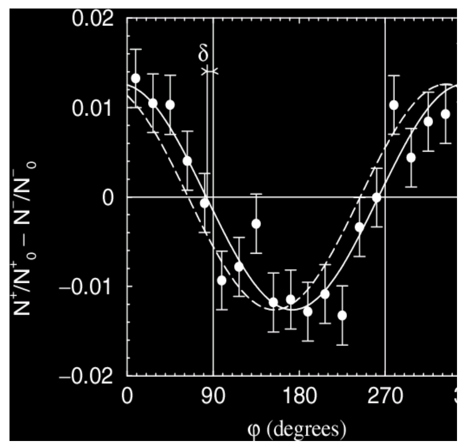
Polarization Transfer → $\dfrac{G_E^p}{G_M^p}$

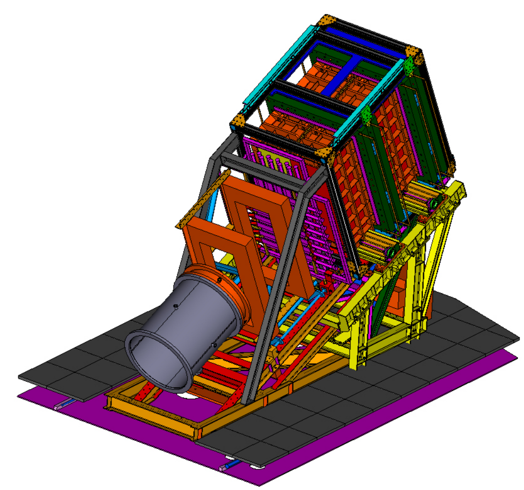


- Recoil proton polarization

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

- 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





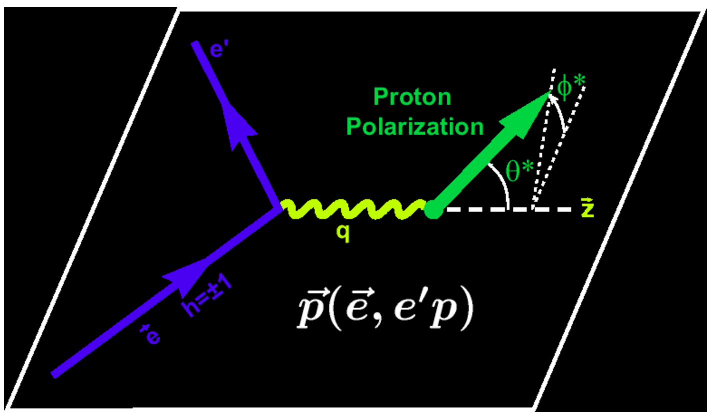
Focal-plane polarimeter

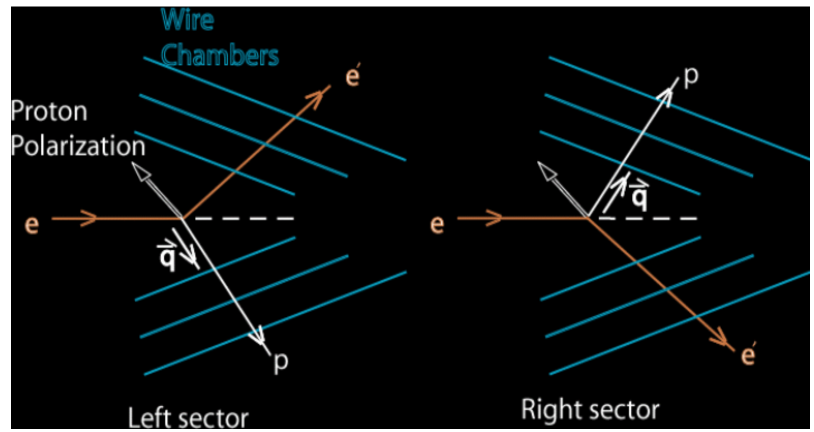
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

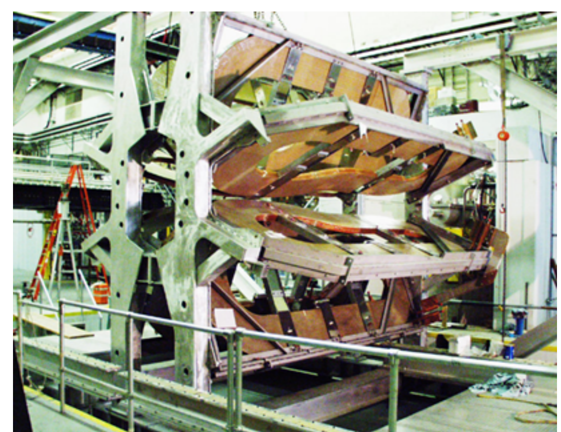
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)}\, v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





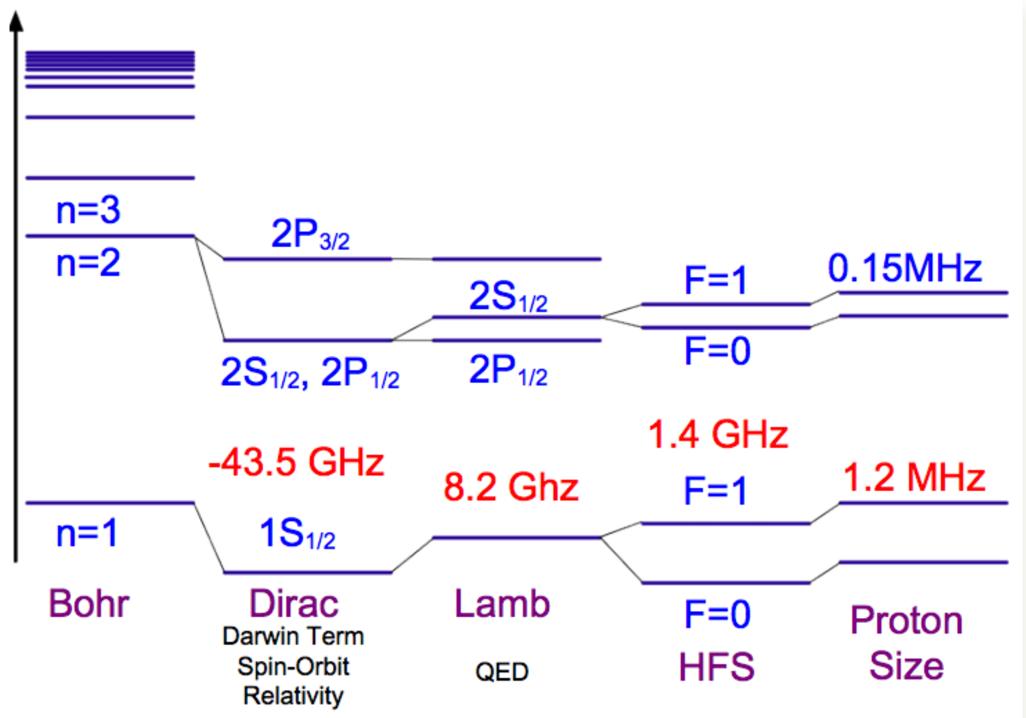
- Super-ratio

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



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

Hydrogen Spectroscopy



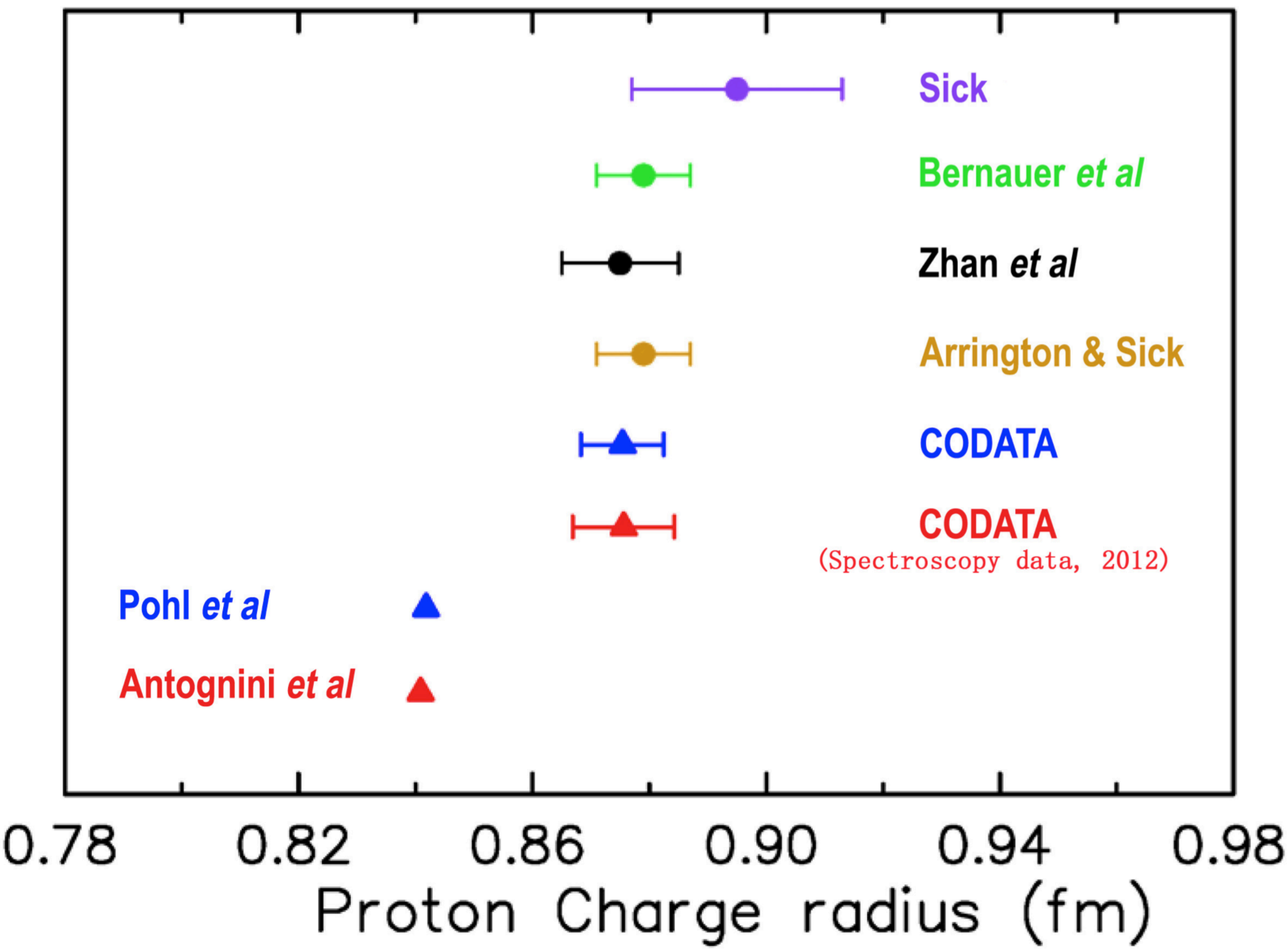
The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in 10^{14} via comparison with an atomic cesium fountain clock as a primary frequency standard.

Yields R_∞ (the most precisely known constant)

Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius

Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

Proton Charge Radius from recent experiments and analyses



Revisits of e-p scattering data (just 2015)

- Re-analysis of existing proton form factor data
  - D. W. Higinbotham, arXiv:1510.01293: two parameter dipole form fit describes the data at both low Q^2 and high Q^2 well, and the result is consistent with PSI value
  - K. Griffioen, C. Carson, S. Maddox, arXiv:1509.06676: re-analysis of Mainz data, focusing on the low Q^2 part with a polynomial form fit.
  - M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, simple fits (one-parameter model, dipole model, linear model) for low Q2 data, and spline extension to high Q2 data, these fits can all describe data well, but the extracted radius varies from 0.84 ~ 0.89 fm. So current data is not able to resolve the puzzle.
  - J. Arrington, arXiv:1506.00873: re-analysis of world data, found the previous scattering results might underestimate the uncertainty.
  - **Distler, Walcher, and Bernauer, arXiv1511.00479**

All these studies emphasize even more the importance of low Q^2 e-p scattering data

New Physics or what? - Incomplete list

- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher,…..
- J.A. Arrington, G. Lee, J. R. Arrington, R. J. Hill discuss systematics in extraction from ep data, no resolution on discrepancy
- Donnelly, Milner and Hasell discuss interpretation of ep data,………

Discrepancy explained by some but others disagree

- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift**

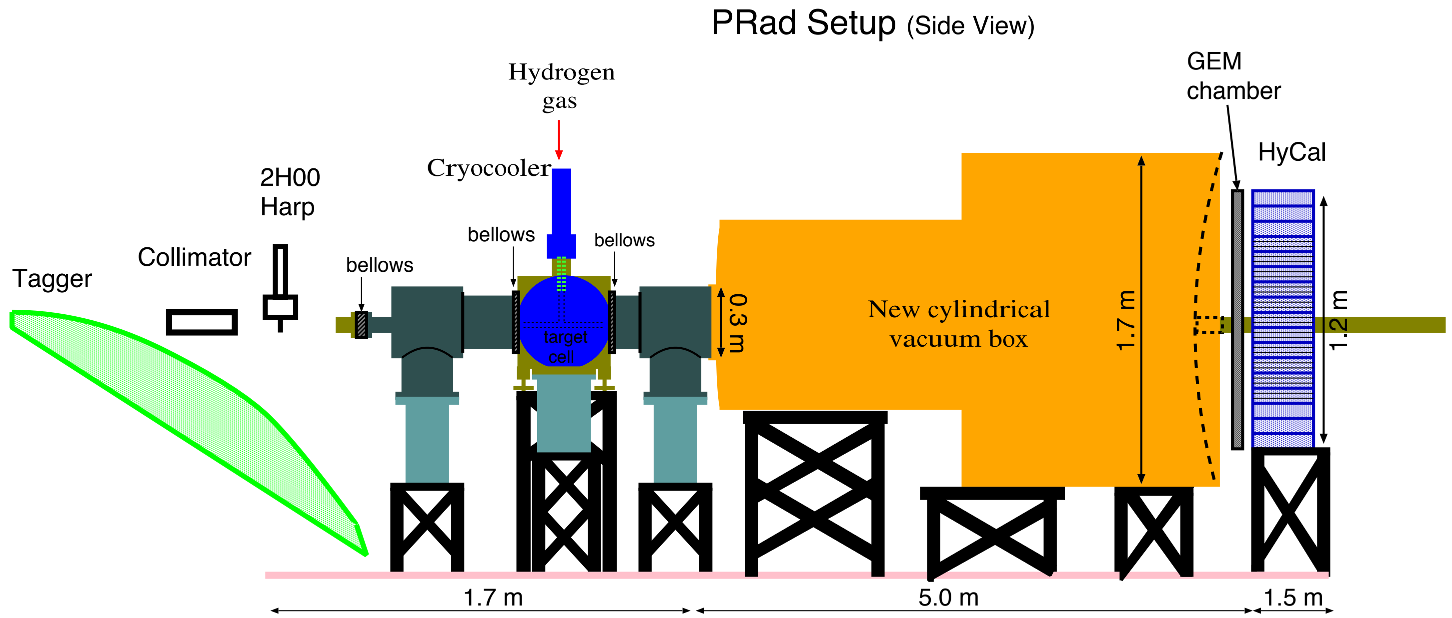
Update on proton radius puzzle

- F. Hagelstein and V. Pascalutsa, http://arxiv.org/pdf/1502.03721v2.pdf
  - Breakdown of the expansion of finite-size corrections to the hydrogen Lamb shift in moments of charge distribution
  - They show that if there is a non-smooth region of charge distribution near the Bohr radius, then the expansion in the moments is not valid, thus the Lamb shift calculation is not correct.
  - They claimed a small bump in GE at very low Q2 would explain the proton radius puzzle

- J. Arrington, http://arxiv.org/pdf/1602.01461v1.pdf
  - Comment on previous paper "Breakdown of the expansion of finite-size corrections to the hydrogen Lamb shift in moments of charge distribution"
  - He pointed out the effect due to the "small bump" is significant, and thus resulted in unphysical form factors.

- F. Hagelstein and V. Pascalutsa, http://arxiv.org/pdf/1602.01978v1.pdf
  - Reply to the comment
  - They accepted the bump is not physical, and present another modification for very low Q2 GE that resolves the discrepancy on proton radius
  - But they also emphasize such an ad hoc modification is not considered as the solution to the puzzle

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} – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

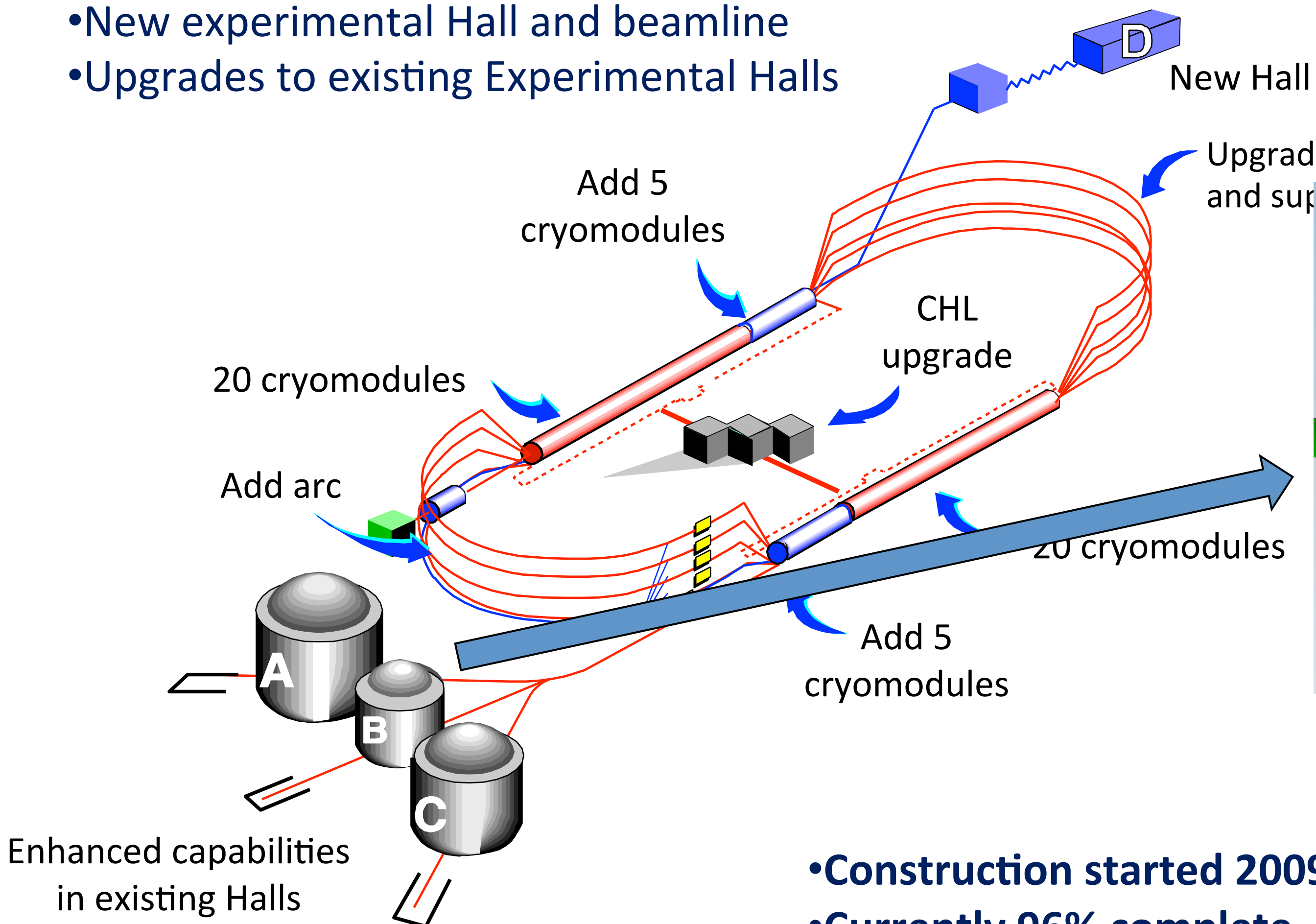
Spokespersons: D. Dutta, H. Gao, A. Gasparian, M. Khandaker

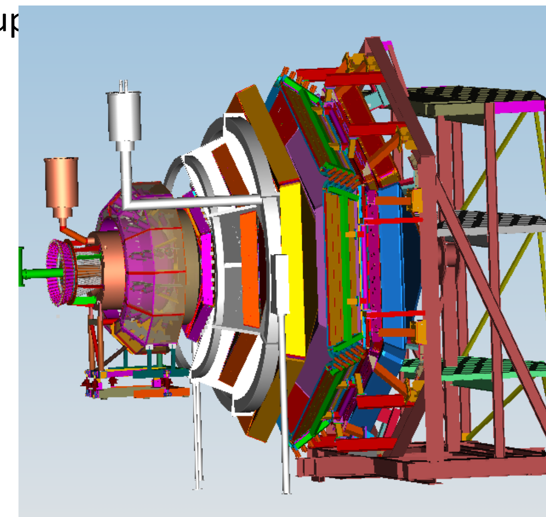
Future sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

12 GeV Upgrade Project

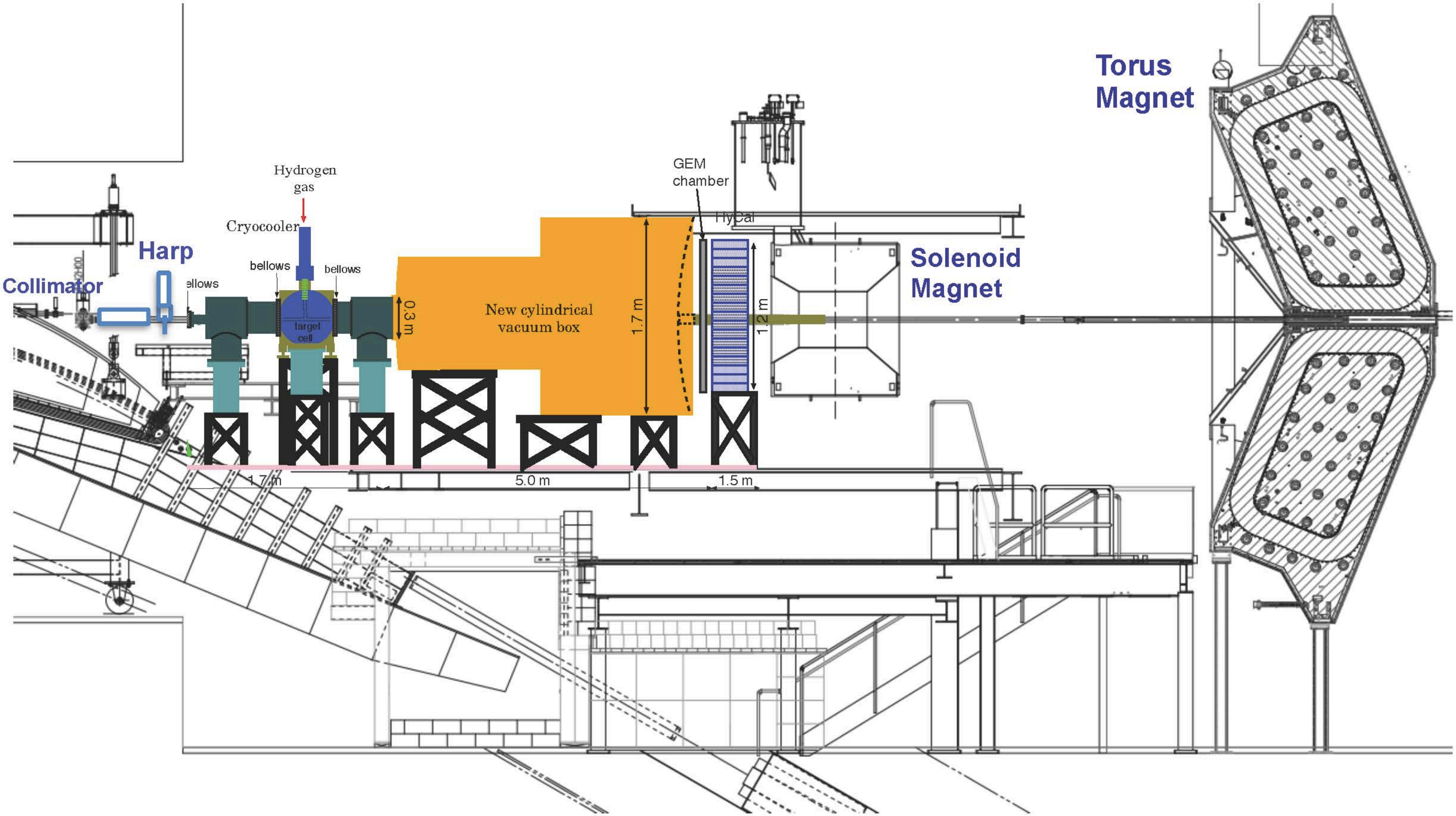
Scope of the project includes:
- Doubling accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls





- **Construction started 2009**
- **Currently 96% complete**
- **Beams in Hall A and Hall D already**

PRad Running Setup



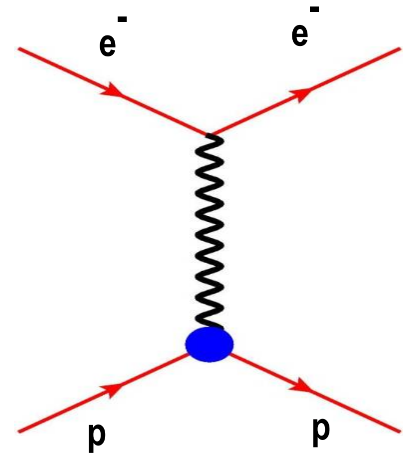
Distance: 2H00 wire harp to Solenoid support frame ~13.7 m

The Proton Charge Radius

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

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

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



- Structure less ``proton":

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

- At very low Q^2, cross section dominated by G_{Ep}:

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

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

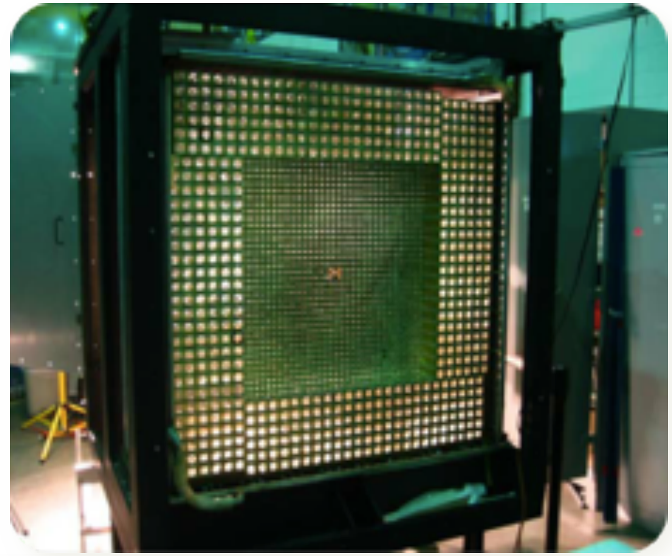
- r.m.s. charge radius given by the slope:

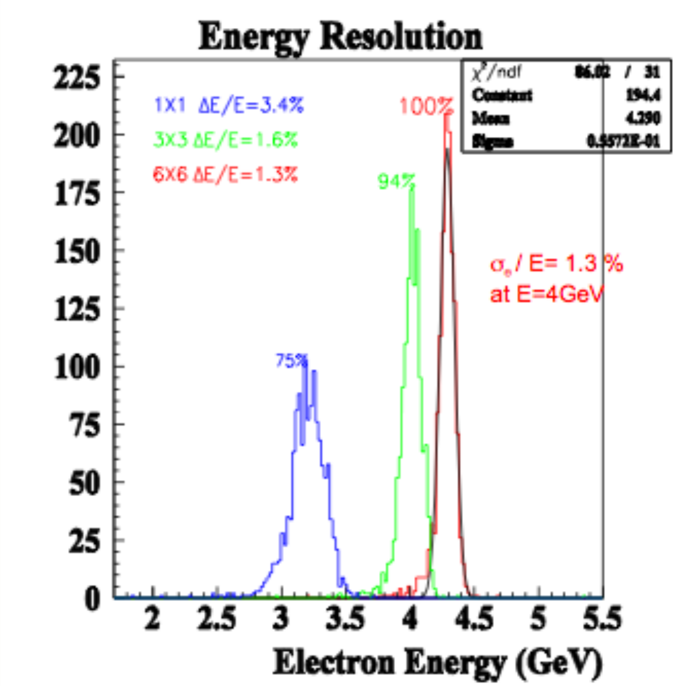
$$\boxed{\langle r^2\rangle = -6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}}$$

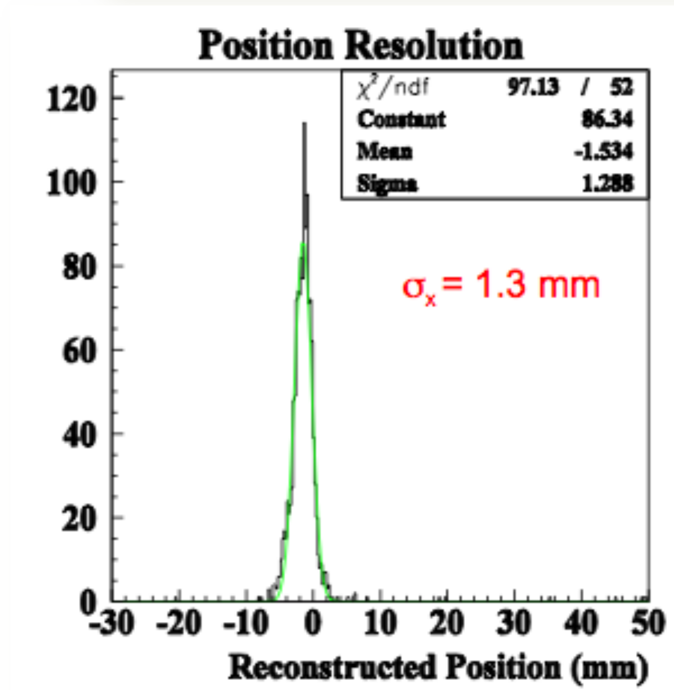
- **Simultaneous detection of elastic and Moller electrons**

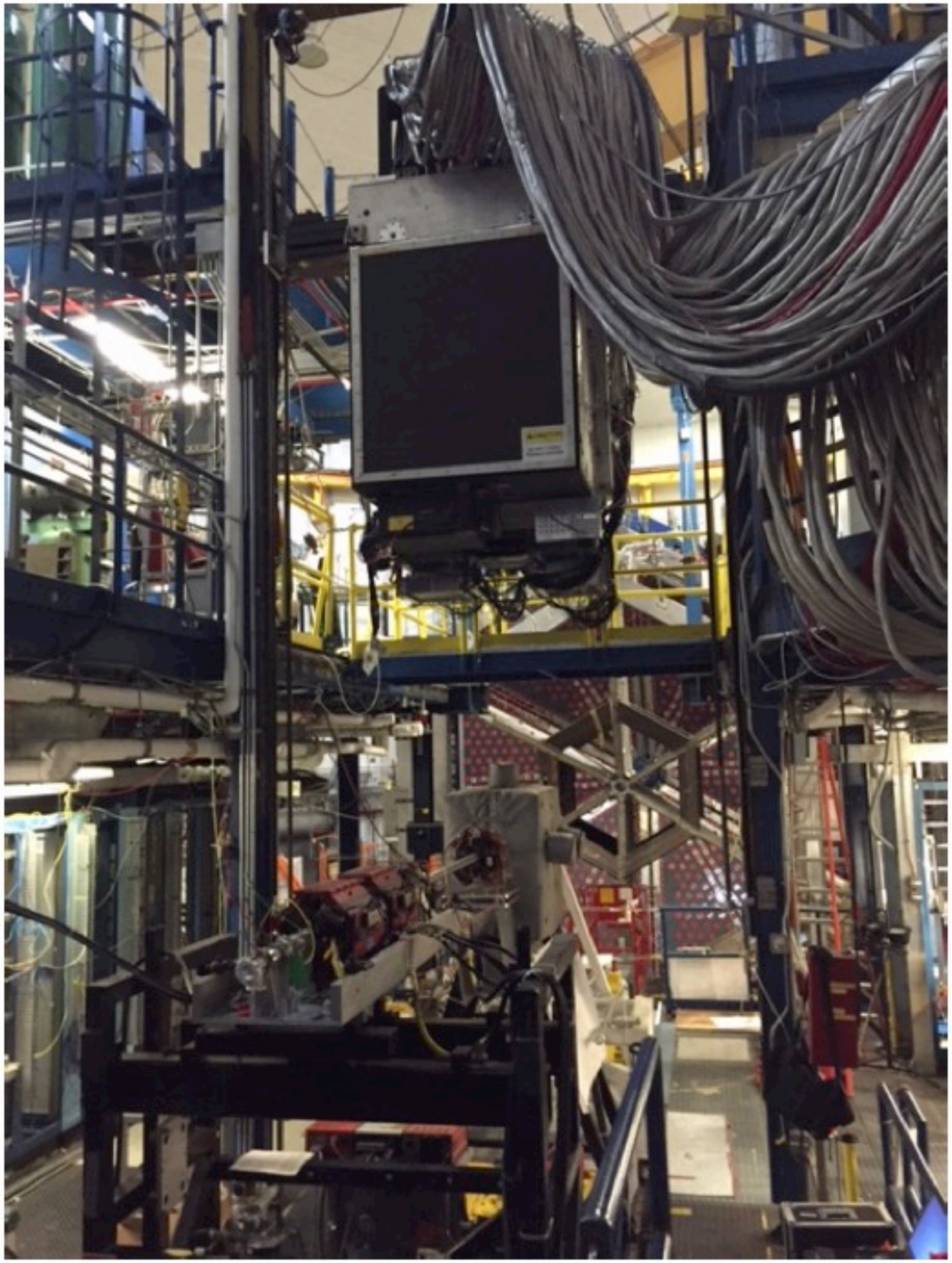
High Resolution Calorimeter

- HyCal calorimeter: 1152 $PbWO_4$ modules arranged in 34x34 matrix in the center, 576 outer Pb-glass modules
- 2.05 x 2.05 cm^2 x18 cm (20 rad. Length)
- ~5.5 m from the target,
- 0.5 sr acceptance



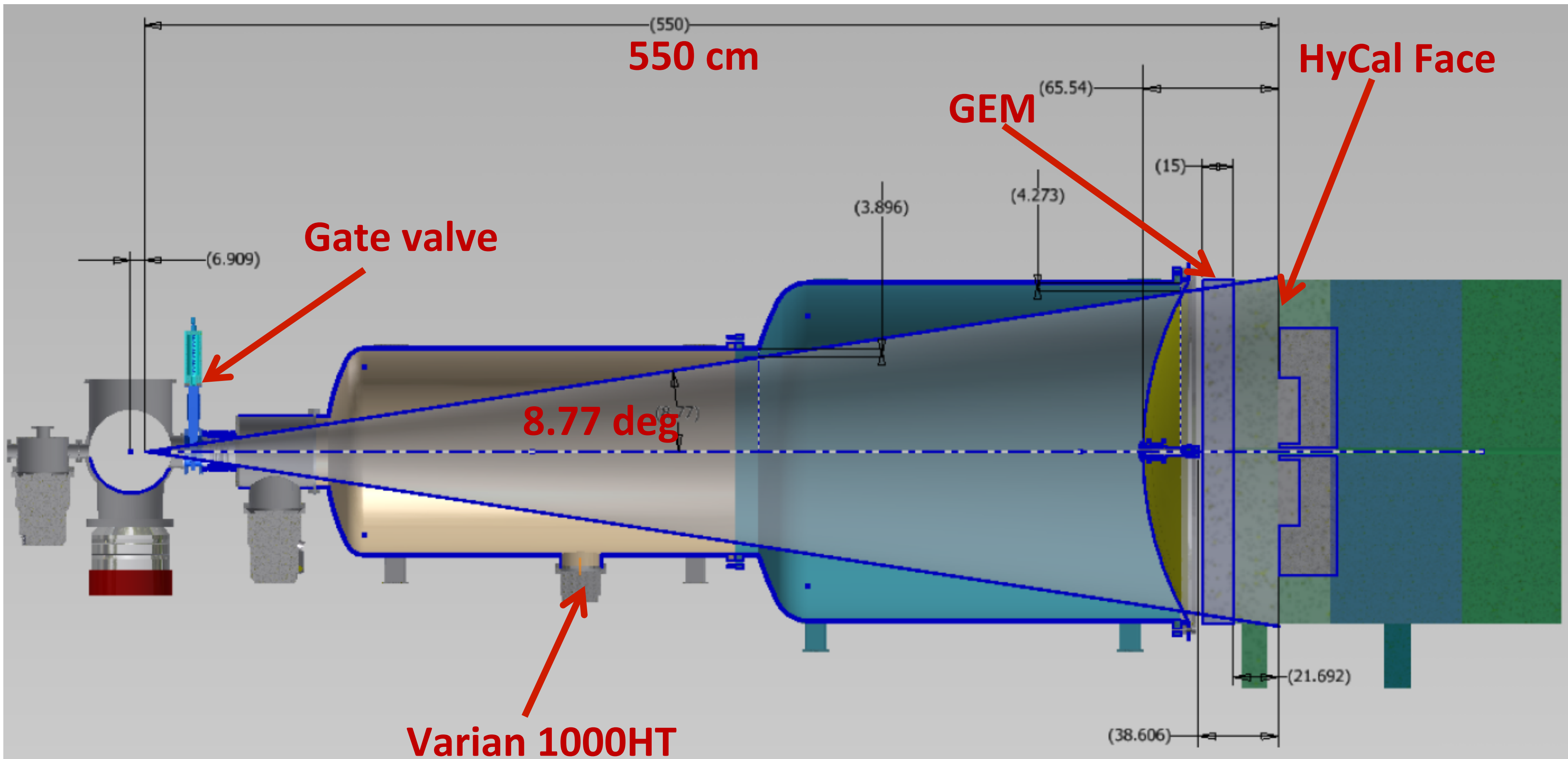






Vacuum Box and GEM

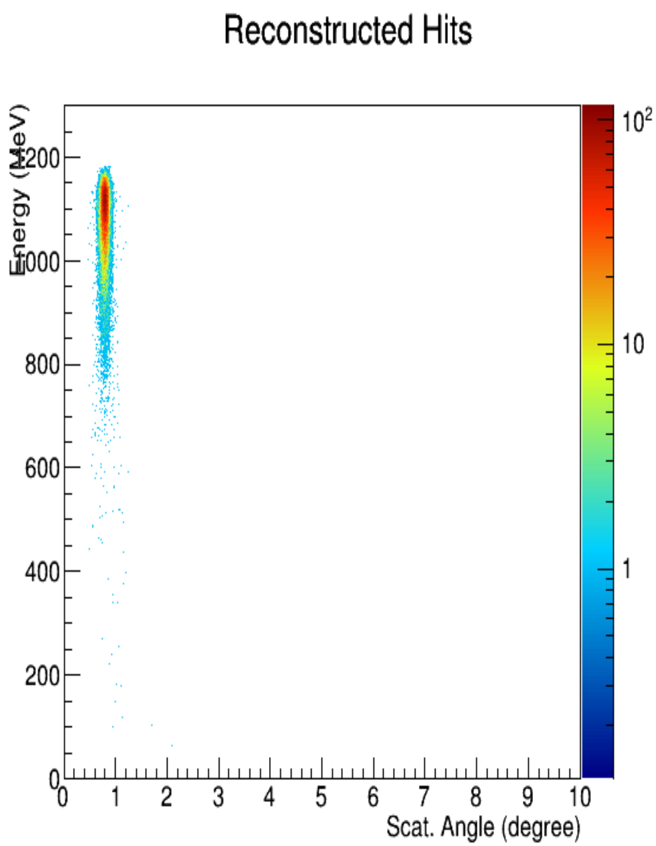
Two-cylinder design for vacuum box
GEM detector to replace veto counter to improve Q2 resolution (particularly with using lead blocks)

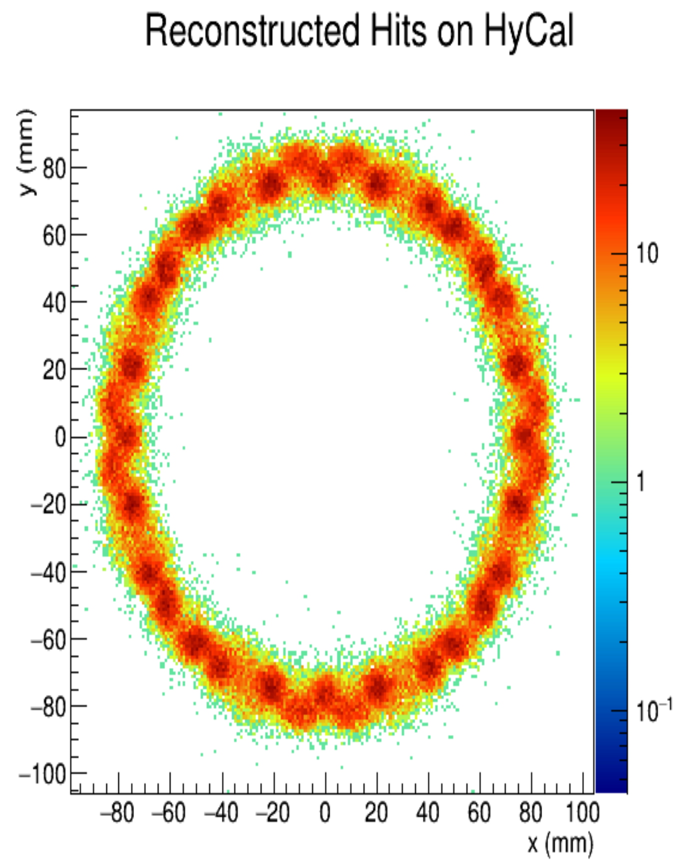


- **GEM detector funded by DOE**

Vacuum Box

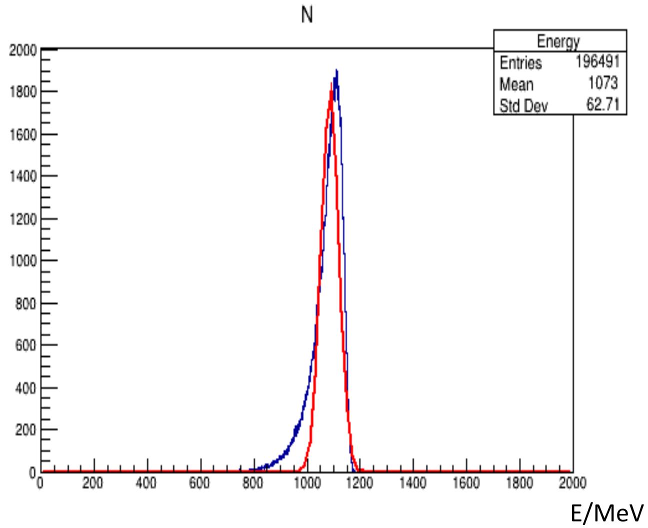
The GEM detectors in the test lab



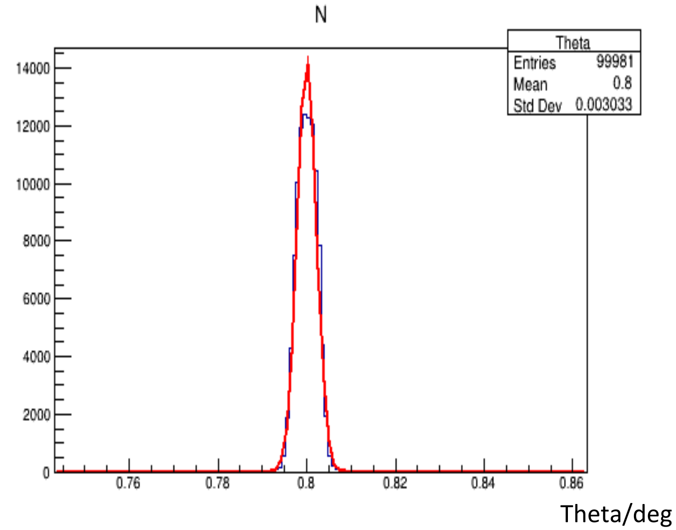


The reconstruction of 0.8 degree ring with only HyCal detector

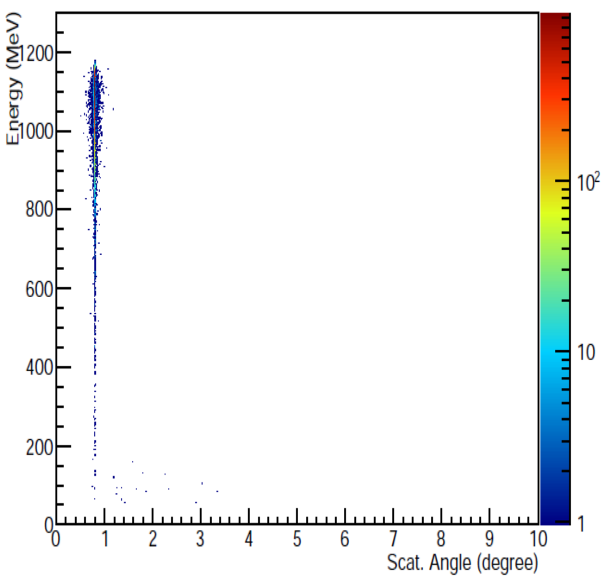
HyCal and GEM detectors (frame + foils)



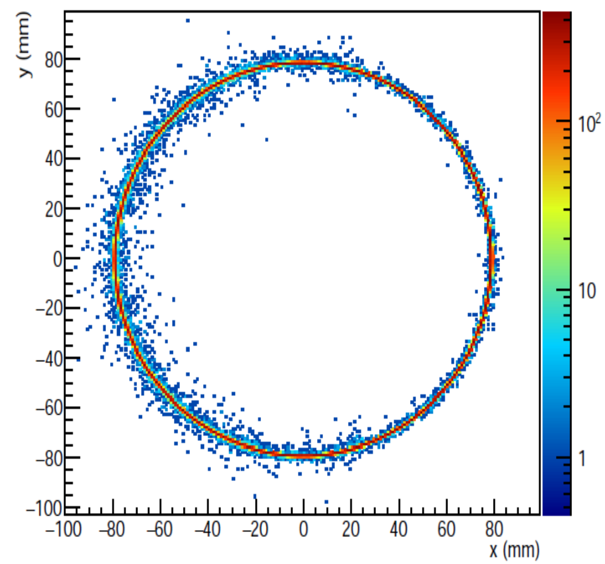
HyCal + GEM, energy resolution ~ 26 MeV



HyCal + GEM, angular resolution 0.0025 degree



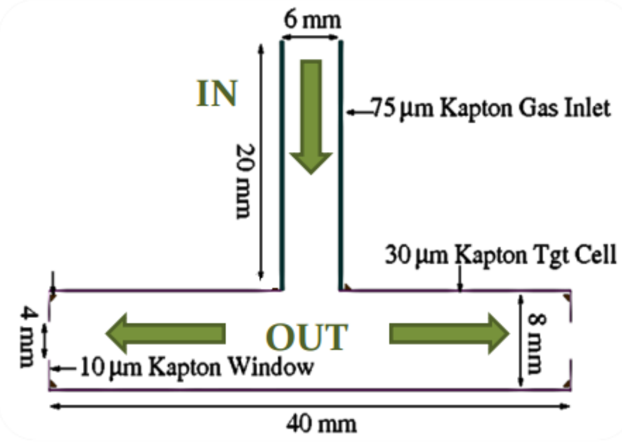
Energy vs. angle, reconstructed hits



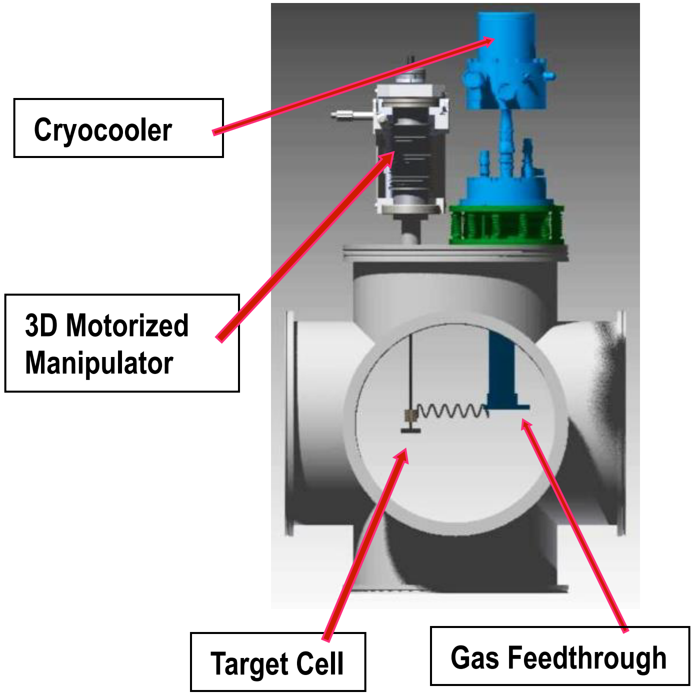
Reconstructed theta ring (0.8 degree)

Windowless H_2 Gas Flow Target

- **Target cell (original design):**
  - cell length 4.0 cm
  - cell diameter 8.0 mm
  - cell material 30 µm Kapton
  - input gas temp. 25 K
  - target thickness 1×10^{18} H/cm^2
  - average density 2.5×10^{17} H/cm^3
  - gas mass-flow rate 6.3 Torr-l/s ≈ 430 sccm

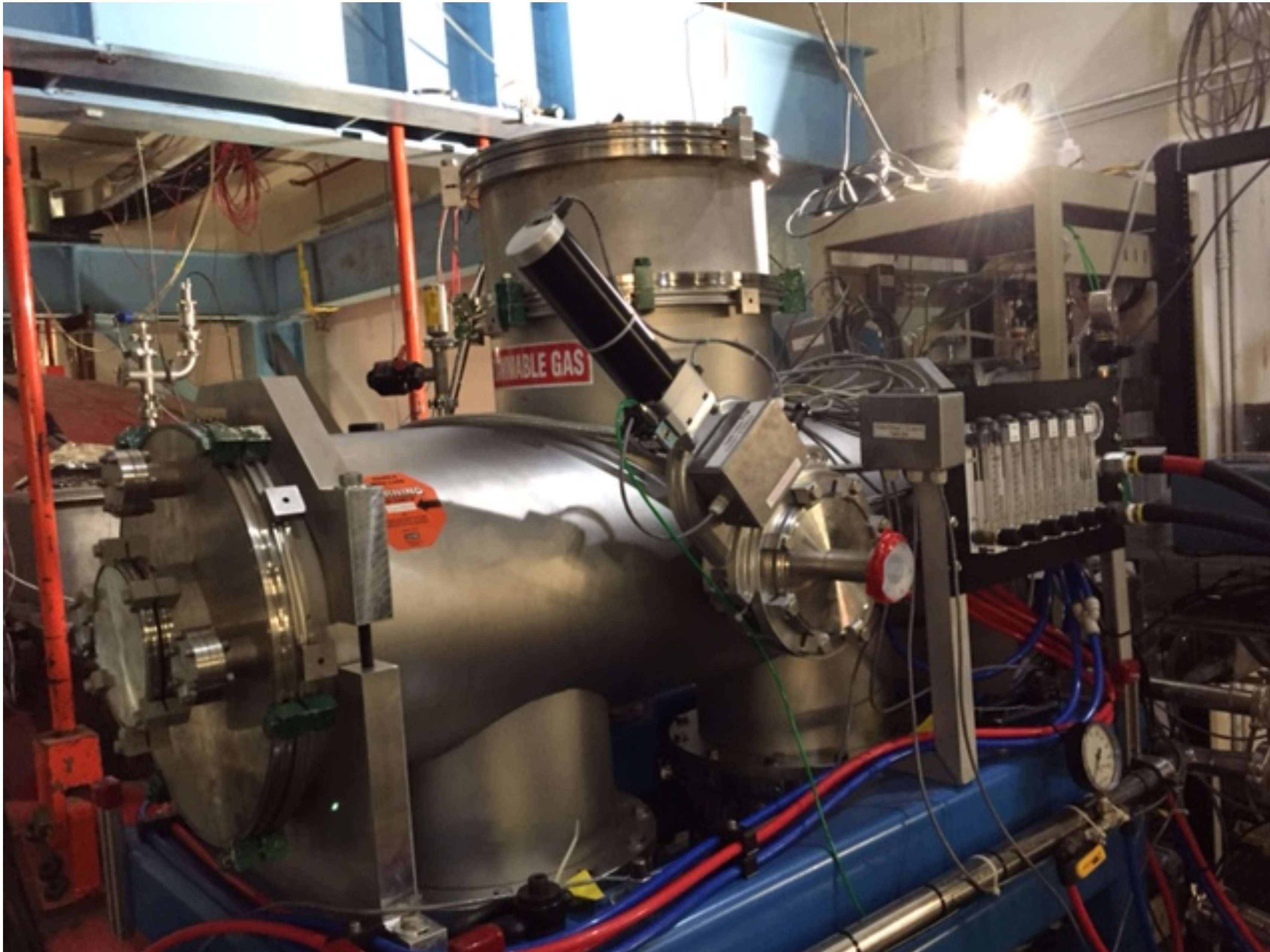


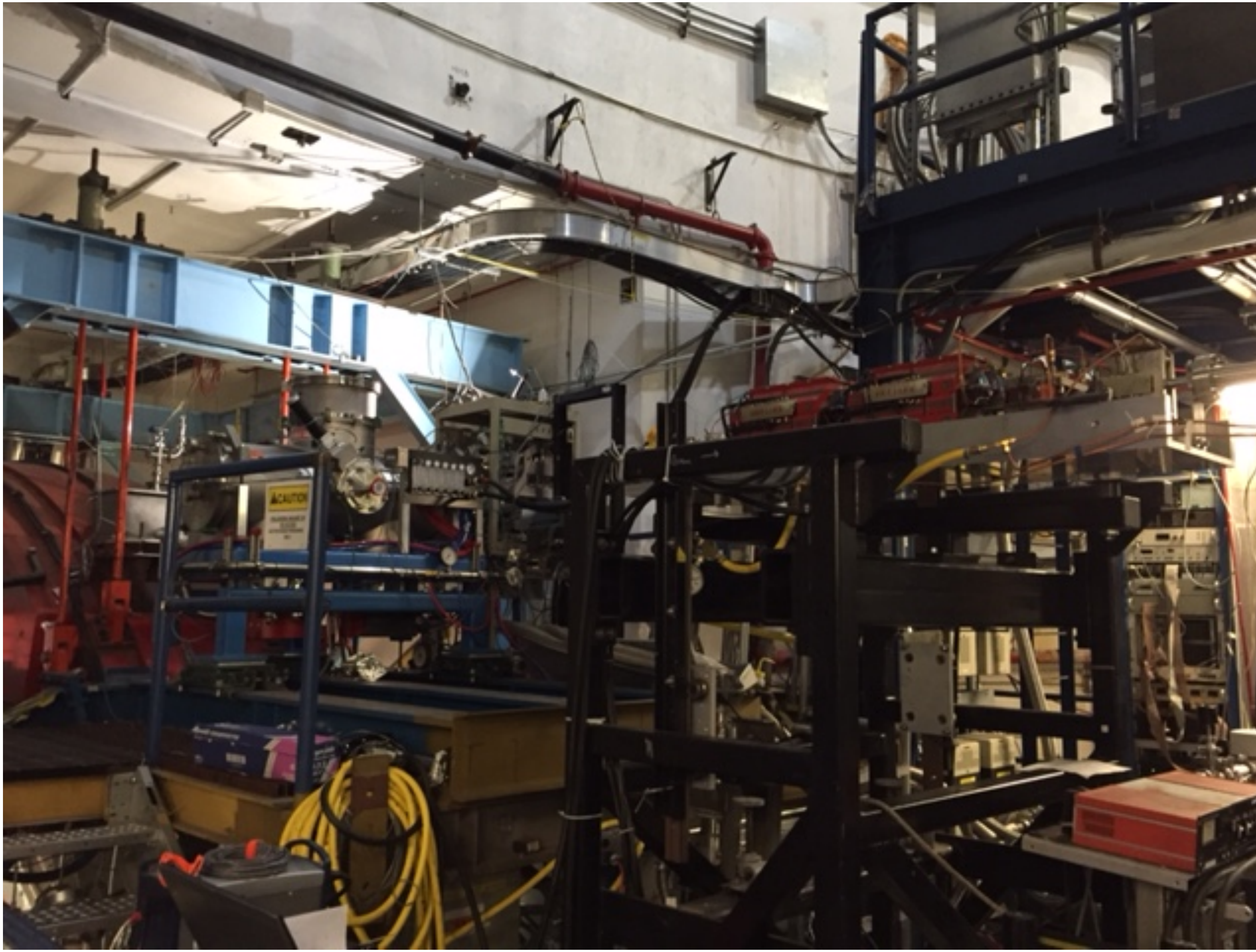
- **Target components:**
  - pumping system
  - cryocooler
  - motorized Manipulator
  - chillers for pumps and cryocooler
  - Target and secondary chambers



- **Kapton cell**

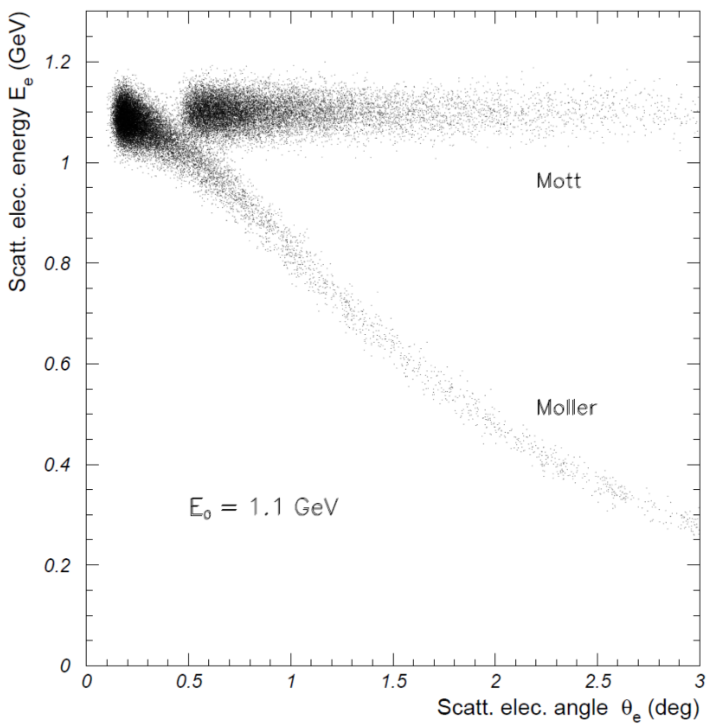
Target supported by NSF - MRI grant

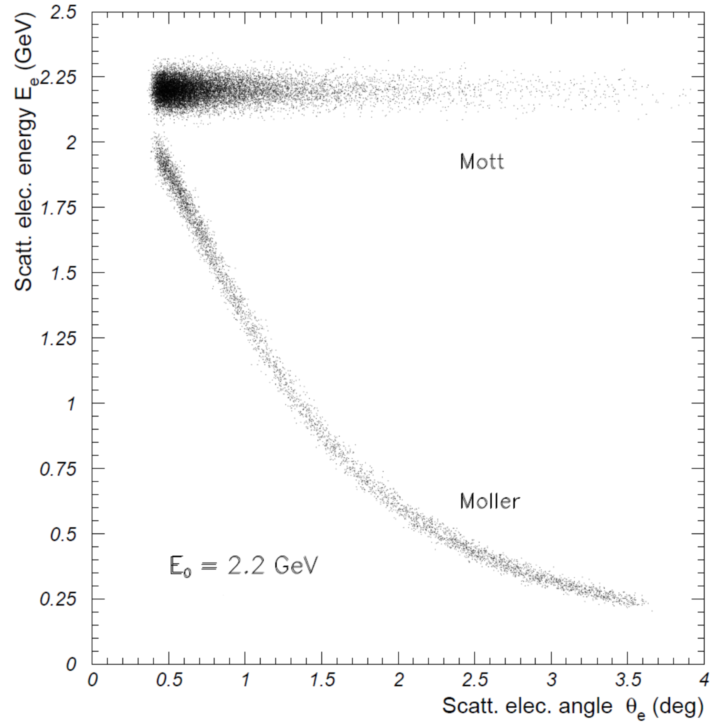



CAUTION

Events separation

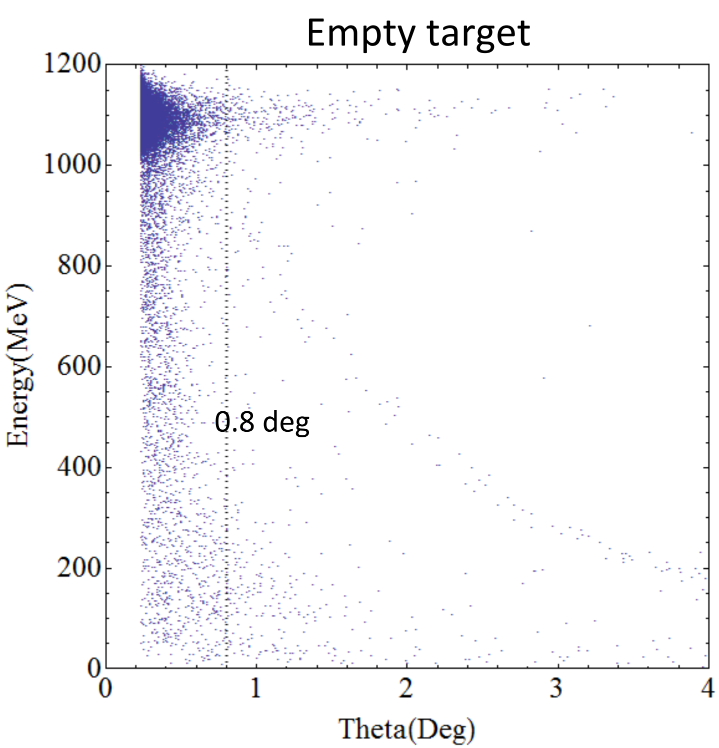
- In our kinematics, the Møller and ep elastic events can be separated by a 2D cut
  - Due to radiation effects, the two types of events cannot be perfectly separated, but this effect will be corrected during radiative corrections.

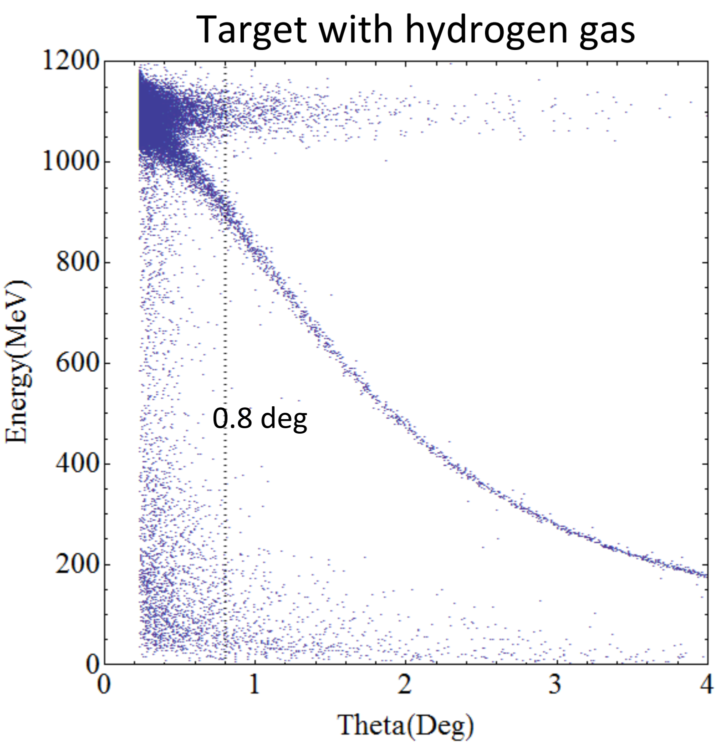




Empty target subtraction

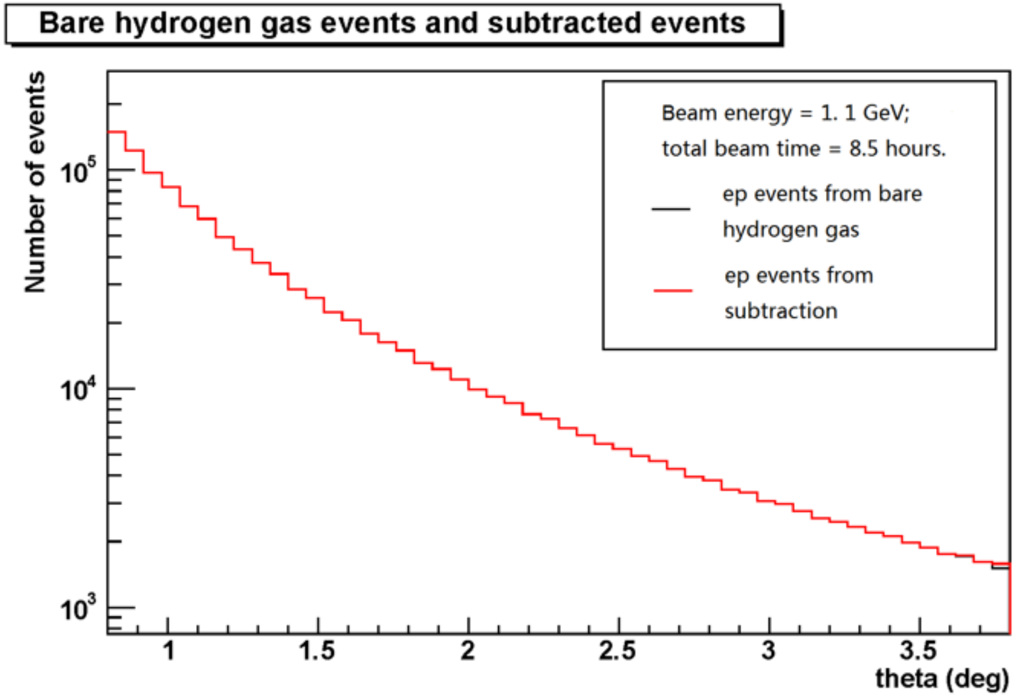
- An empty target run will be performed, and the events will be subtracted from production run.
- The subtraction minimizes the background from target cell structure and residual gas.





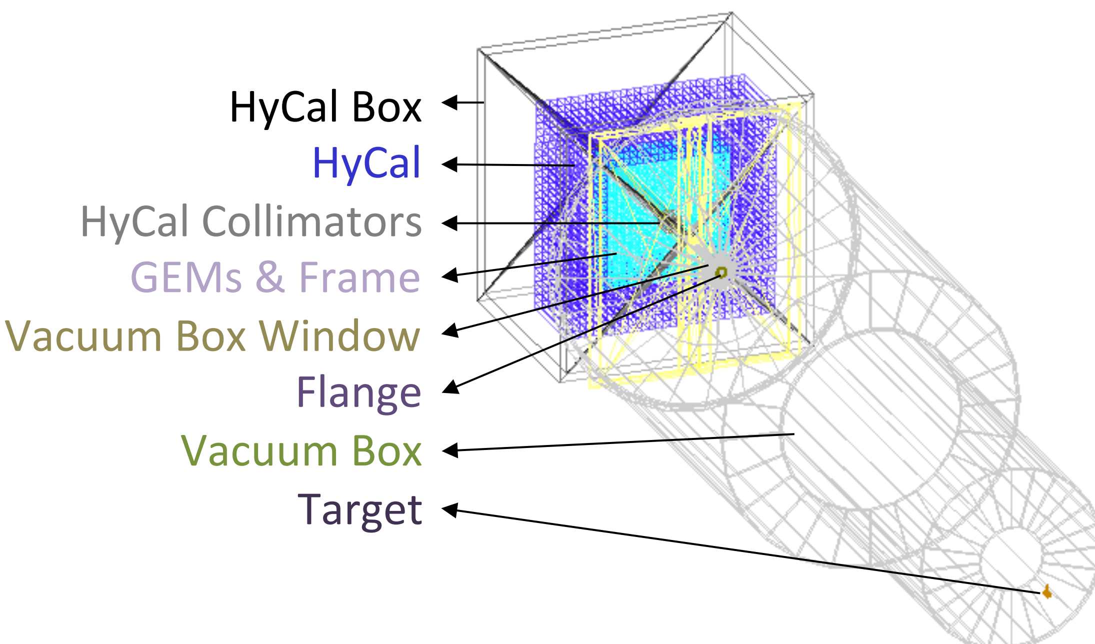
Empty target subtraction

- Comparison between subtracted events and bare hydrogen target events:
  - 3 days of beam time, 20% beam time is for empty target run
  - uncertainty 0.06% ~ 0.5% for 12 angular bins from 0.8 degree to 3.8 degree



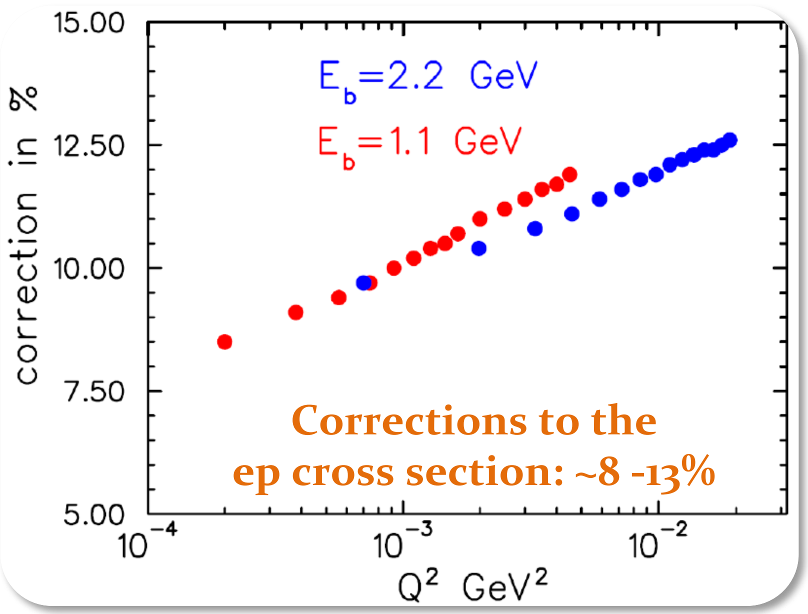
Radiative corrections

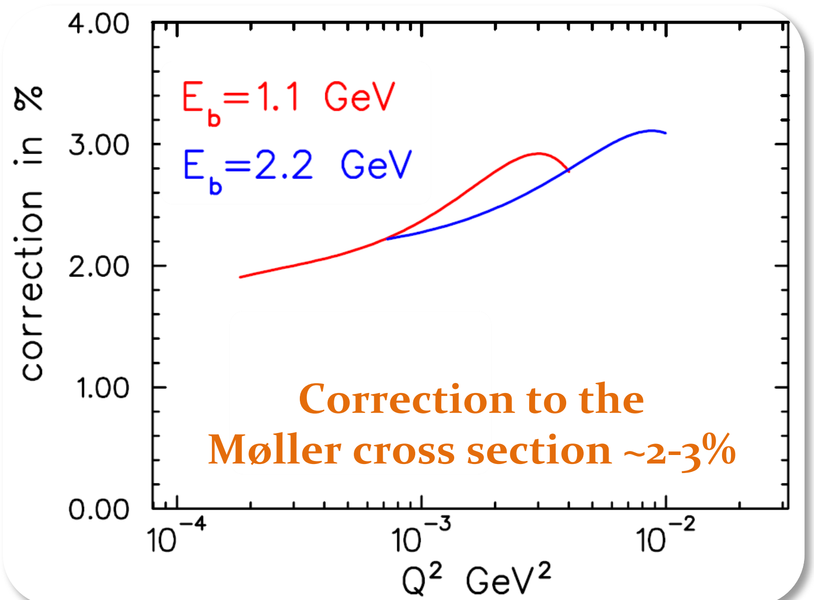
- External corrections
  - GEANT4 simulation, current geometry in code is shown below



Radiative corrections

- Internal corrections
  - Event generators including radiation effects of e-p and e-e scattering were developed
  - For very low Q^2, go beyond the ultra-relativistic approximation (URA, $m^2 << Q^2$)





I. Akushevich, H. Gao, A. Ilyichev, and M. Meziane, Eur. Phys. J. A 51, 1 (2015)

Form factor extraction

- Rosenbluth formula

$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{\sigma_{Mott}}{\epsilon}\frac{\tau}{1+\tau}\right) = \frac{\epsilon}{\tau} G_E^{p\,2} + G_M^{p\,2}$$

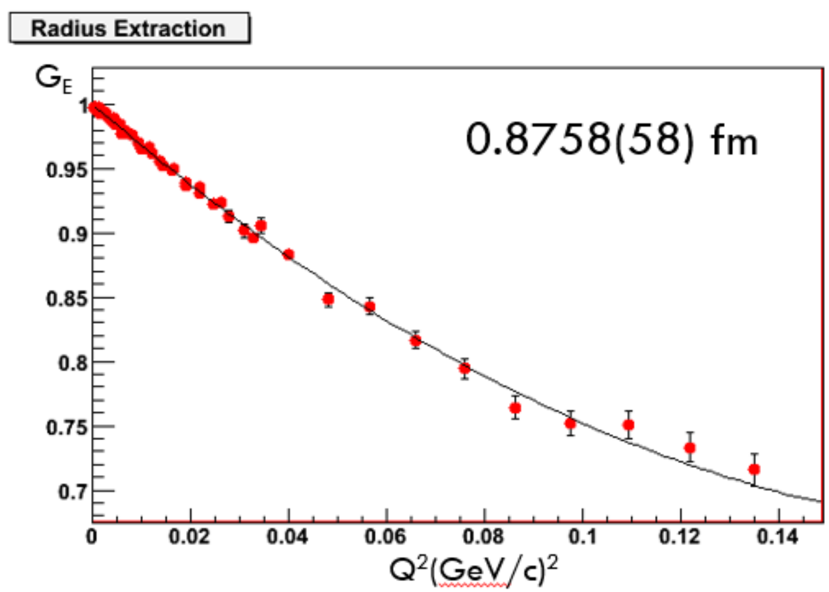
- At 1.1 GeV, G_M contribution is 0.015% ~ 0.06%, can be neglected
- High Q^2 part at 2.2 GeV, G_E is still dominating, G_M contribution can be simply determined by existing data with a reasonable uncertainty

Extraction of proton radius

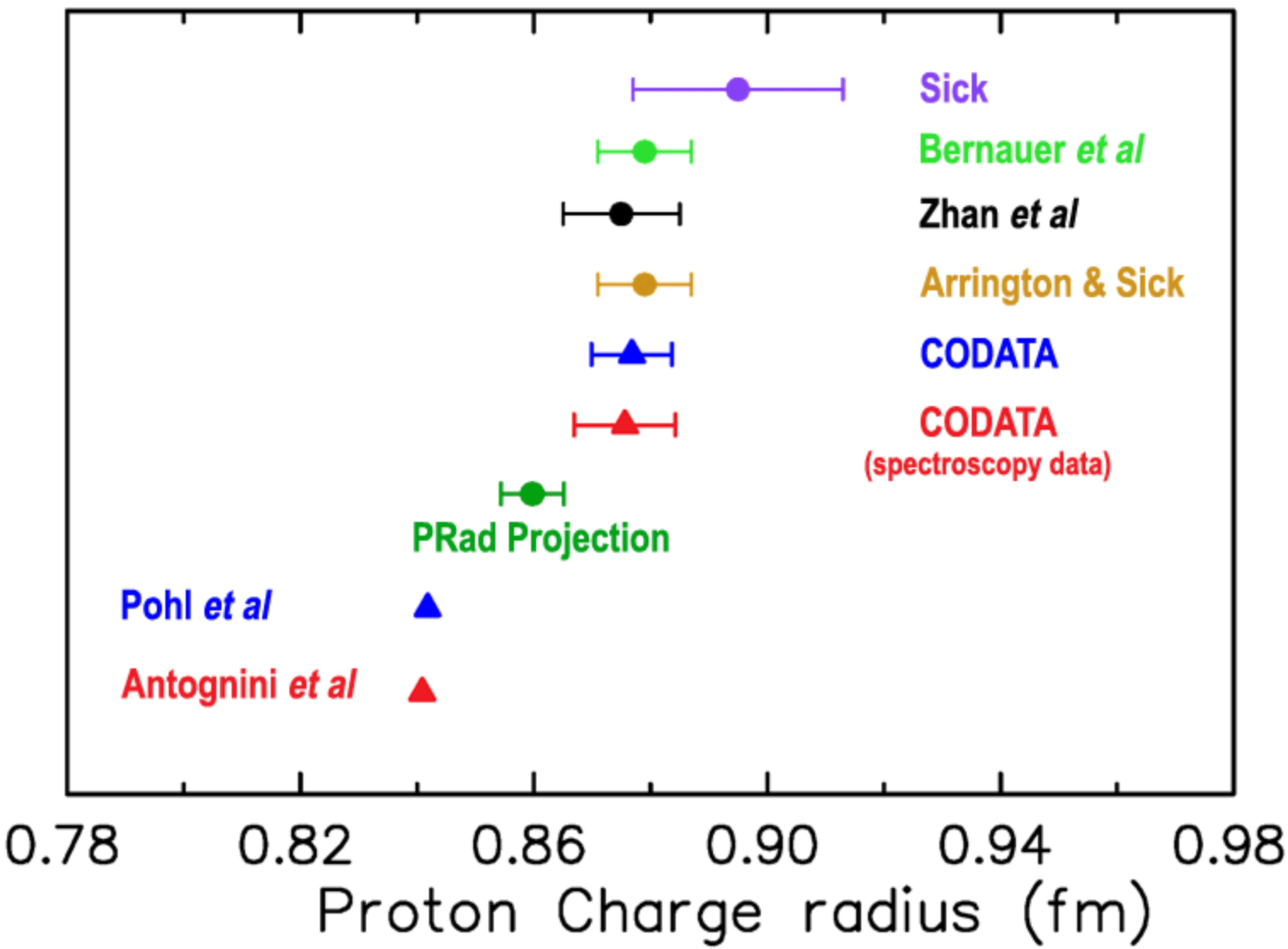
- Rms proton charge radius, slope of G_E at Q^2 close to 0

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

- The slope is extracted through fitting
  – Linear fit, polynomial fit, dipole fit and continuous fraction fit were tested with simulation data (dipole fit is shown)



PRad Projected Result with world data



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
  Argonne National Laboratory
  University of North Carolina at Wilmington
  University of Kentucky
  Hampton University
  College of William & Mary
  University of Virginia
  Tsinghua University, China
  Old Dominion University
  ITEP, Moscow, Russia
  Budker Institute of Nuclear Physics , Novosibirsk, Russia
  MIT

- ***Experiment scheduled for data taking May-June 2016***

Summary and outlook

- Proton charge radius: fundamental quantity important to atomic, nuclear, and particle physics
- Proton charge radius puzzle triggered by muonic hydrogen atom Lamb shift measurements motivated extensive theoretical and experimental activities
- New precision measurement from electron scattering at low Q^2 is **a MUST**
- **PRad: new experiment on e-p elastic scattering will use novel experimental techniques – data taking scheduled for May-June 2016**
- Stay tuned for more news about proton charge radius

Acknowledgement: the PRad Collaboration
Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231, NSF MRI PHY-1229153

Kunshan 昆山

- Population 1.647 million (by 2010)
- Household population is 730,000
- 6,500 foreign companies in the city and 4,200 of them belong to Taiwanese owners
- More than 100,000 Taiwaneses live and work in the city
- GDP in 2013 of 292 billion yuan (US$47.45 billion)
- capital of the world's notebook and tablet sector

Located in Jiangsu Province between Shanghai and Suzhou, 15-18 mins high-speed train to Shanghai