# *The PRad experiment at JLab*

***The 6th Workshop on Hadron Physics in China and Opportunities in US***

***July 21-24, 2014***
***IMP, Lanzhou, China***

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***Duke University***

Duke
UNIVERSITY

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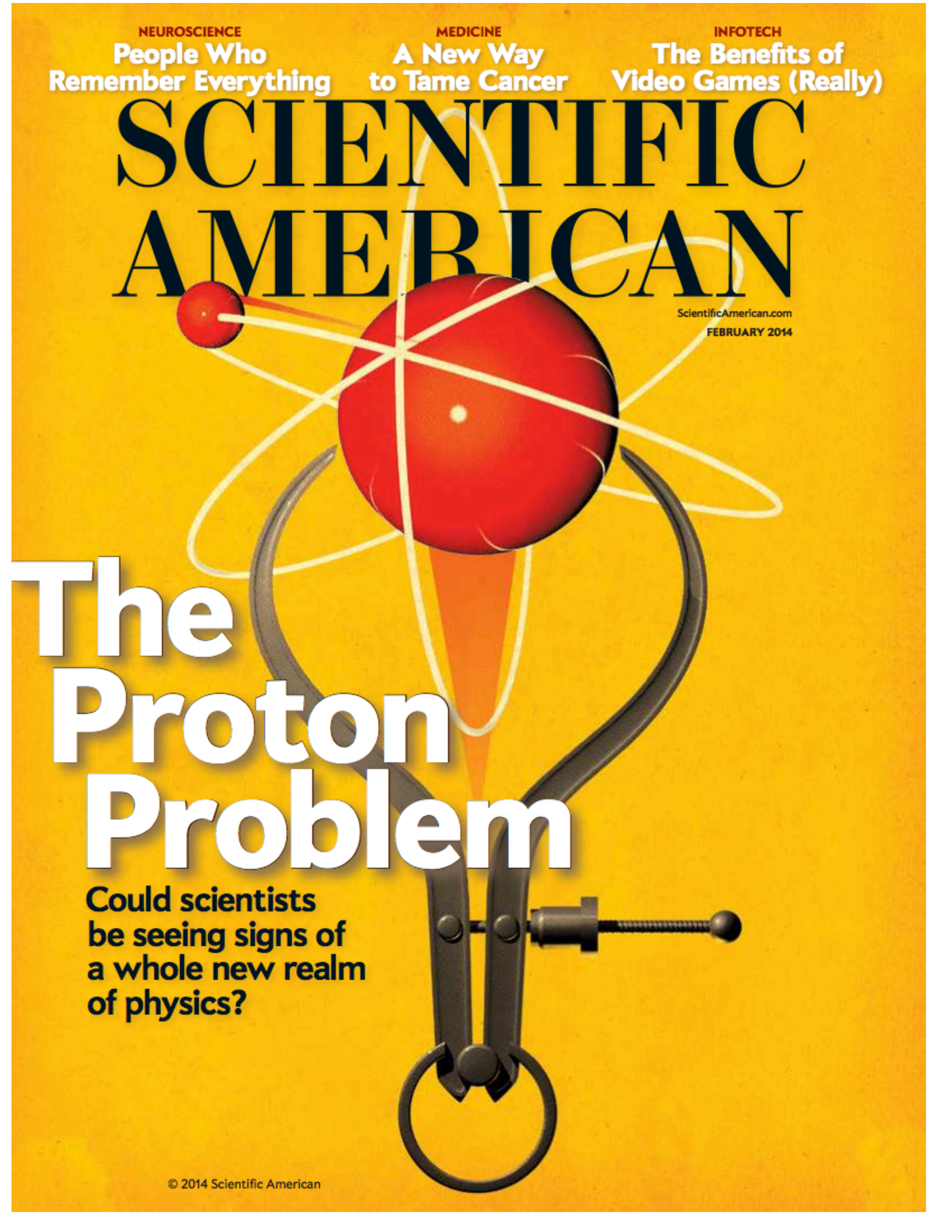
# *Proton Radius Puzzle*

# *Motivation for precise information on proton radius*

- A fundamental static 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%
- Lamb Shift ($2S_{1/2} - 2P_{1/2}$) measurements are becoming more and more precise
- High precision tests of QED?
  - Needs inputs from electron scattering experiments on proton radius
- Turning things around one can determine proton radius using QED and Lamb shift measurements

# *Methods for measuring proton charge radius*

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

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

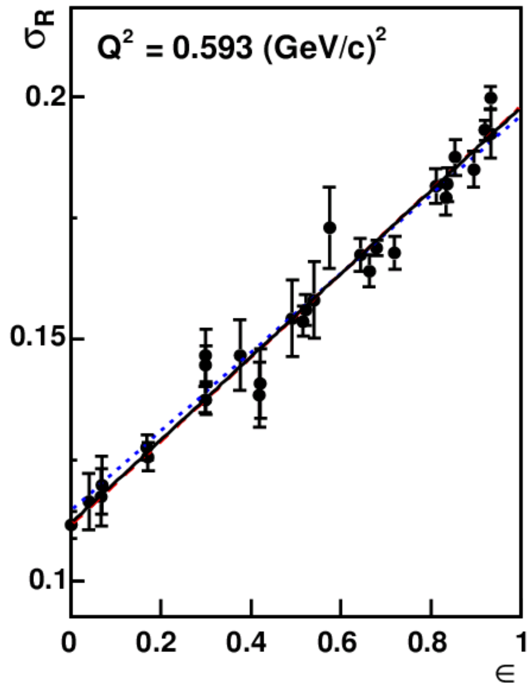
- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

# Unpolarized electron-nucleon scattering

## (Rosenbluth Separation)

- Elastic e-p cross section

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

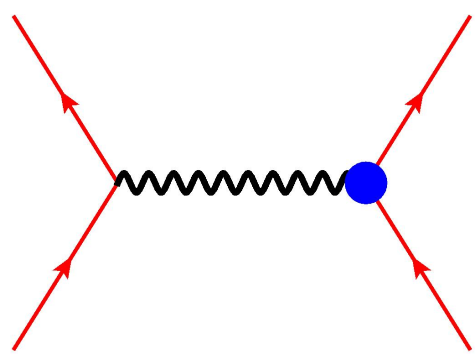



$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

- 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 $G_M$

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

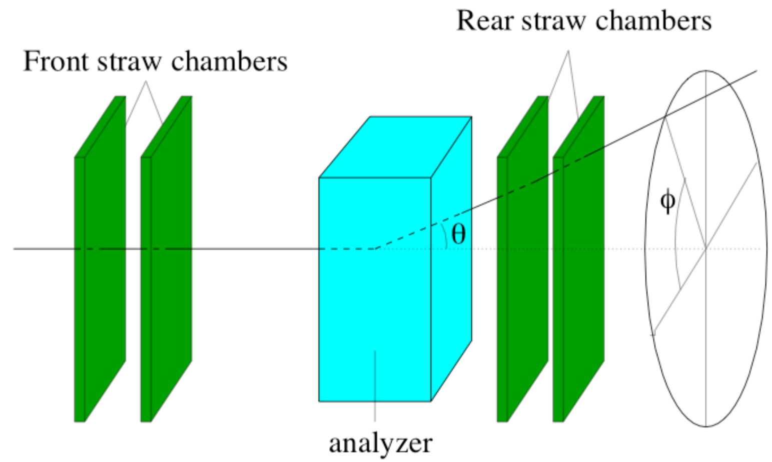
$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$



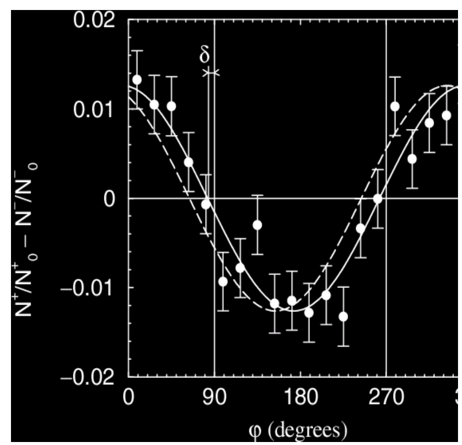
super Rosenbluth Separation

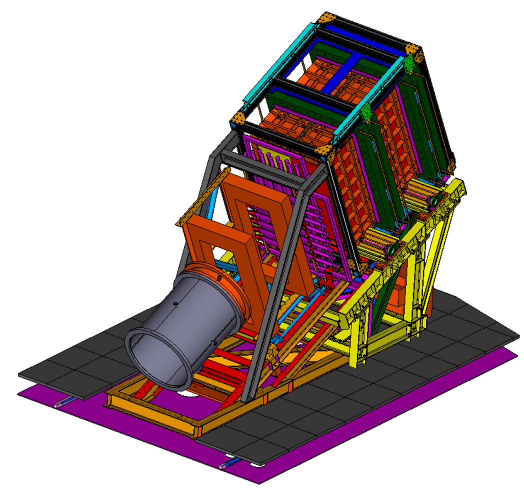
# *Recoil proton polarization measurement from e-p elastic scattering*

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




- Recoil proton polarization
- $$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}$$
  - recoil proton scatters off secondary $^{12}C$ target
  - $P_t$, $P_l$ measured from $\varphi$ distribution
  - $P_b$, and analyzing power cancel out in ratio



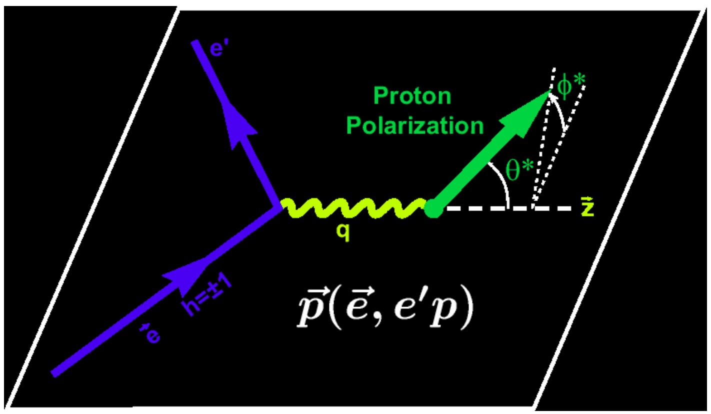
**Focal-plane polarimeter**

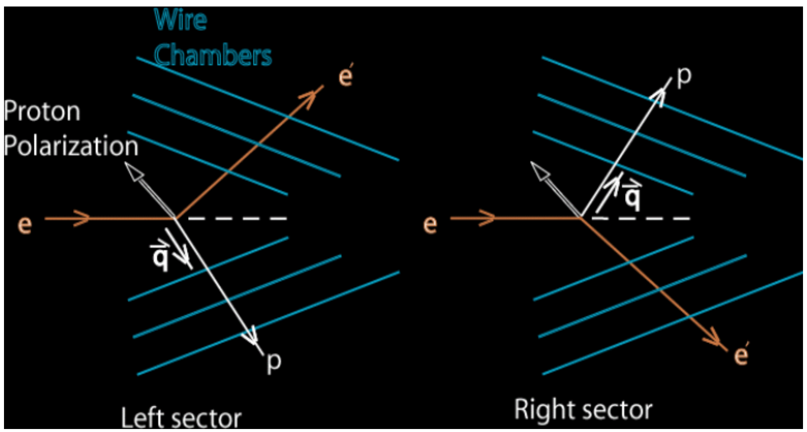
# Asymmetry Super-ratio Method

*Polarized electron-polarized proton elastic scattering*

- Polarized beam-target asymmetry

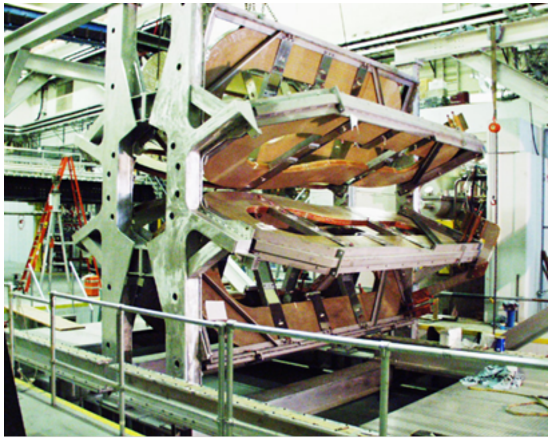
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$



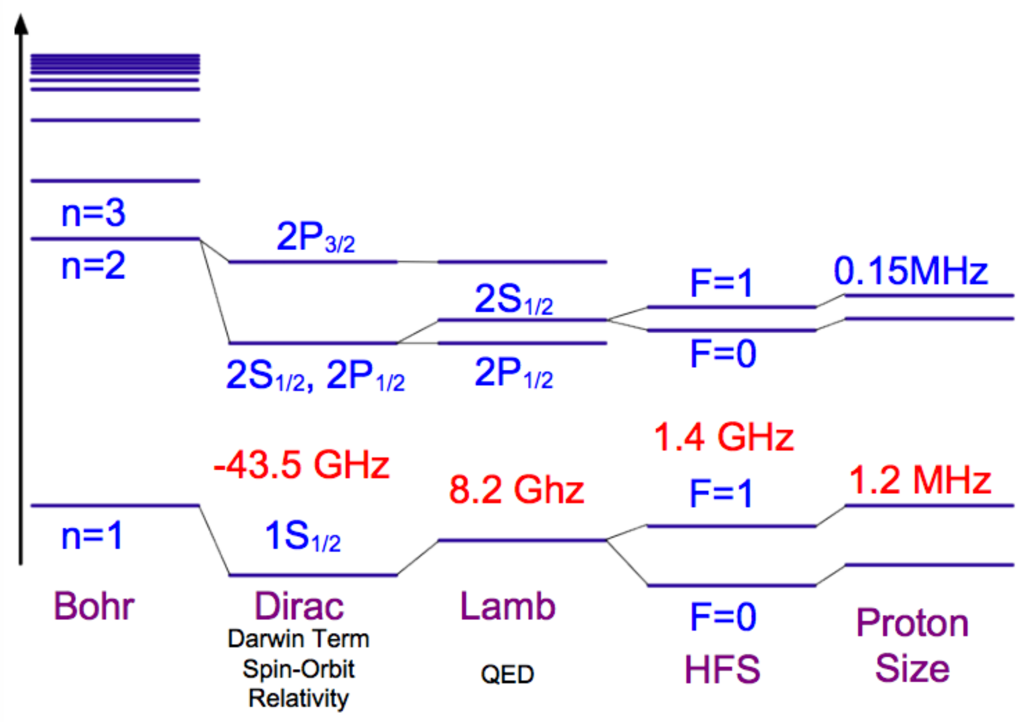

- Super-ratio

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



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

# *Hydrogen Spectroscopy*



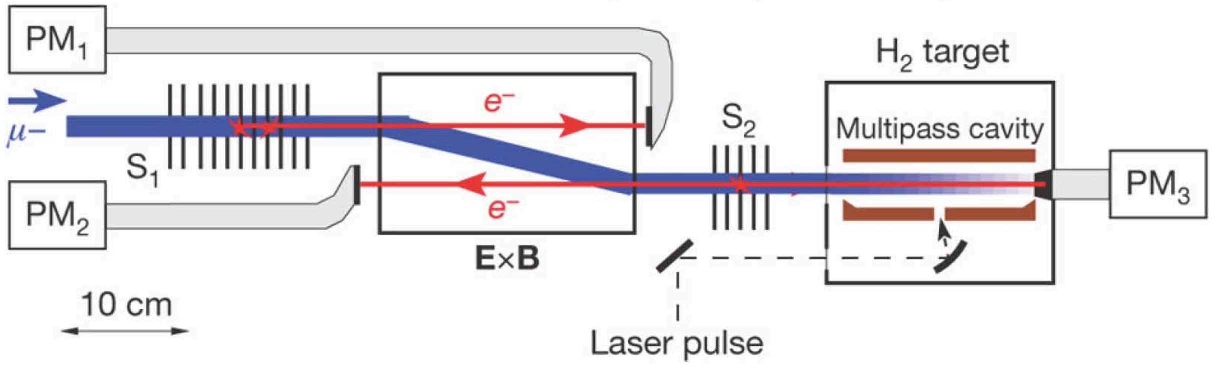

The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in $10^{14}$ via comparison with an atomic cesium fountain clock as a primary frequency standard.

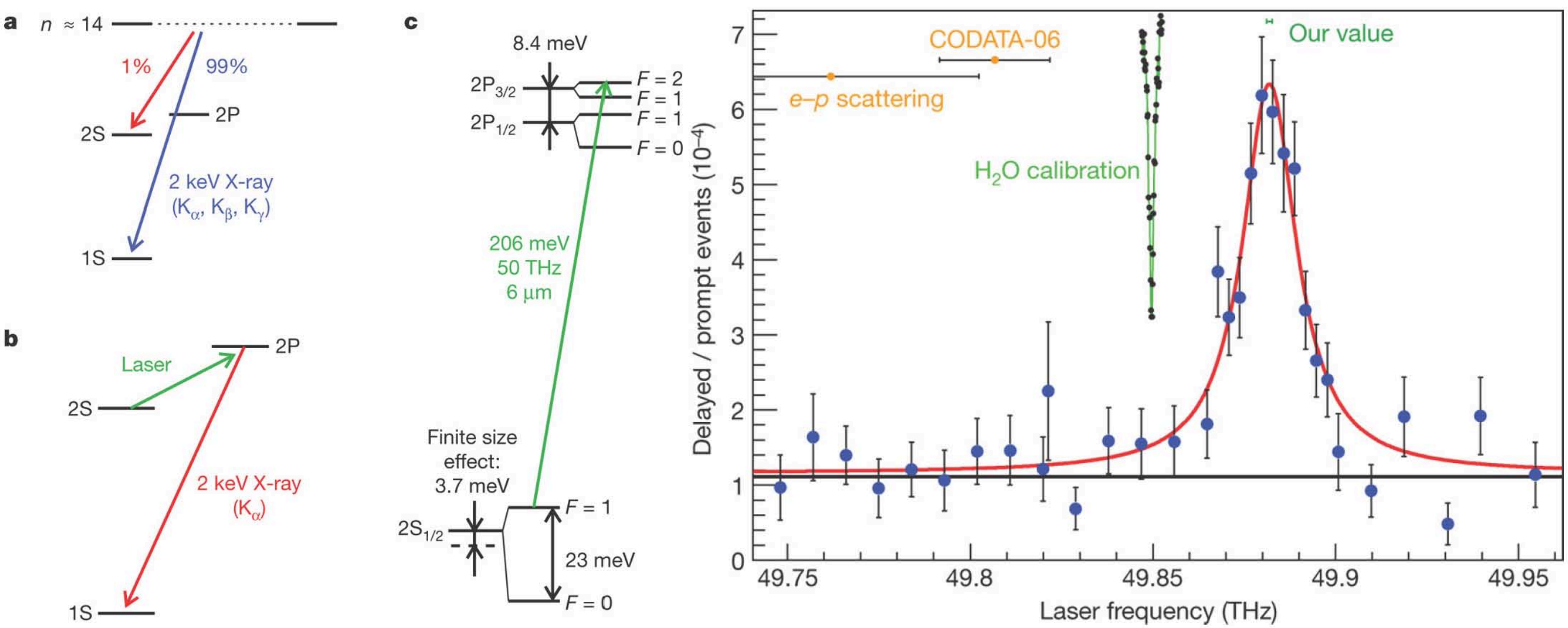
Yields $R_\infty$ (the most precisely known constant)

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

# *Muonic hydrogen Lamb shift experiment at PSI*

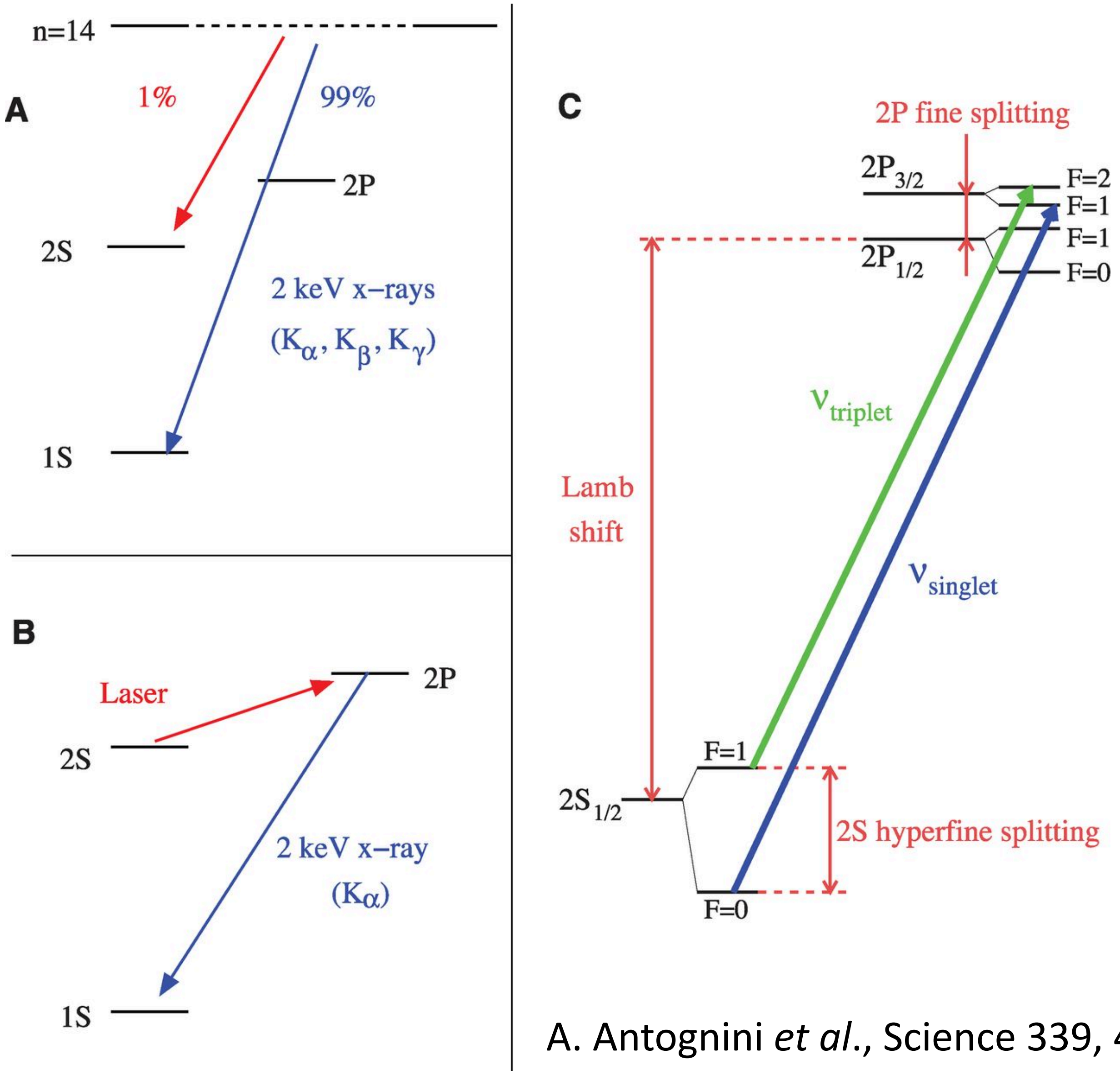

*Nature* **466**, 213-216 (8 July 2010)



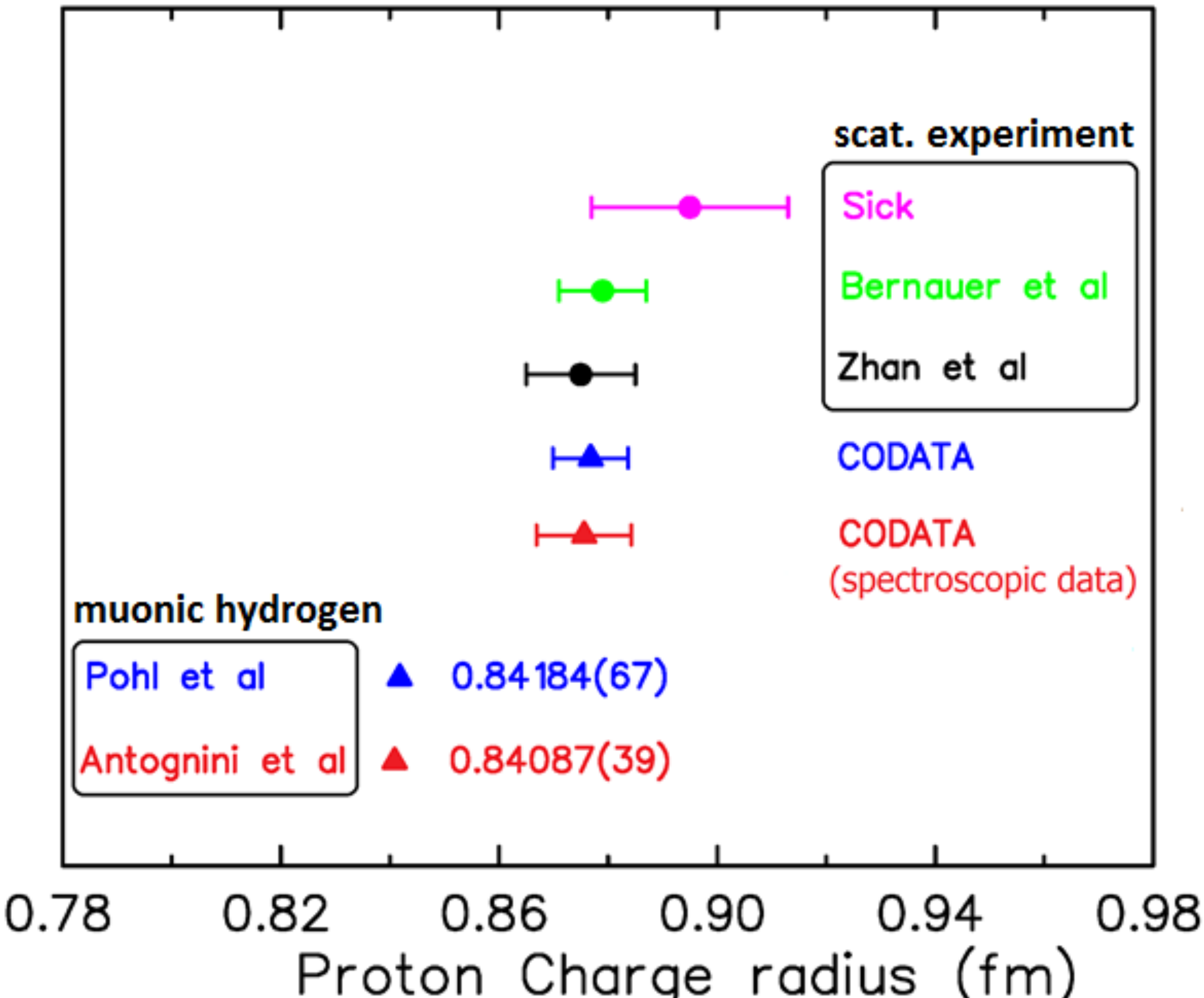

2010: new value is $r_p$ = 0.84184(67) fm

# *New PSI results reported in Science 2013*




A. Antognini *et al*., Science 339, 417 (2013)

# *The proton radius puzzle intensified, more intrigued by muonic helium result*




Maybe not (talks by Griffioen, Lorenz)

# Calculations

| Contribution | | Value [meV] | Uncertainty [$10^{-4}$ meV] |
|---|---|---|---|
| Uehling | | 205.0282 | |
| Källen–Sabry | | 1.5081 | |
| VP iteration | | 0.151 | |
| Mixed $\mu - e$ VP | | 0.00007 | |
| Hadronic VP [21,23] | | 0.011 | 20 |
| Sixth order VP [24] | | 0.00761 | |
| Whichmann–Kroll | | −0.00103 | |
| Virtual Delbrück | | 0.00135 | |
| Light–by–light | | – | 10 |
| Muon self–energy and muonic VP ($2^{\mathrm{nd}}$ order) | | −0.66788 | |
| Fourth order electron loops | | −0.00169 | |
| VP insertion in self energy [17] | | −0.0055 | 10 |
| Proton self–energy [18] | | −0.0099 | |
| Recoil [17,43] | | 0.0575 | |
| Recoil correction to VP (one–photon) | | −0.0041 | |
| Recoil (two–photon) [19] | | −0.04497 | |
| Recoil higher order [19] | | −0.0096 | |
| Recoil finite size [32] | | 0.013 | 10 |
| Finite size of order $(Z\alpha)^4$ [32] | $-5.1975(1)\, r_p^2$ | −3.979 | (620) |
| Finite size of order $(Z\alpha)^5$ | $0.0347(30)\, r_p^3$ | 0.0232 | (20) |
| Finite size of order $(Z\alpha)^6$ | | −0.0005 | |
| Correction to VP | $-0.0109\, r_p^2$ | −0.0083 | |
| Additional size for VP [19] | $-0.0164\, r_p^2$ | −0.0128 | |
| Proton polarizability [18,33] | | 0.015 | 40 |
| Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$ | | 8.352 | 10 |
| $2P_{3/2}^{F=2}$ hyperfine splitting | | 1.2724 | |
| $2S_{1/2}^{F=1}$ hyperfine splitting [42], (−22.8148/4) | | −5.7037 | 20 |

An additional 0.31 meV to match CODATA value

Evaluation by Jentschura, Annals Phys. 326, 500 (2011)
Recent summary by A. Antognini et al., arXiv:1208.2637

Birse and McGovern, arXiv:1206.3030
0.015(4) meV (proton polarizability)

J.M. Alarcon, et al. 1312.1219
0.008 meV

G.A. Miller, arXiv:1209.4667

New experiments at HIGS and Mainz on proton polarizabilities

# *Partial Summary*

- New physics: new particles, Barger et al. PRL106,153001 (2011), Carlson and Rislow, arXiv:1206.3587;

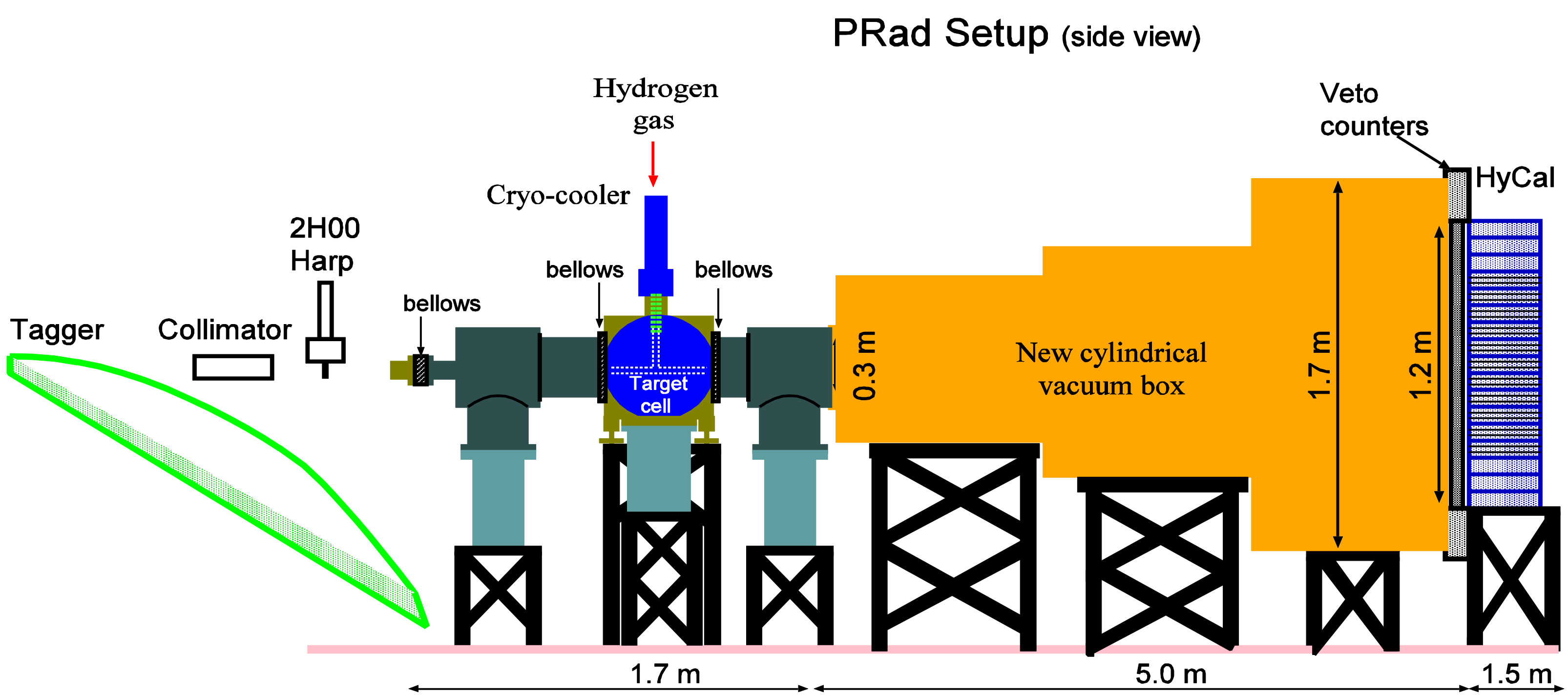
  New PV muonic force, Batell et al. PRL 107 (011803) 2011; quantum gravity at the Fermi scale R. Onofrio, arXiv:1312.3469;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen, arXiv:1101.5965, arXiv:1109.3779; Jentschura, Annals Phys. 326, 500 (2011), Borie, arXiv:1103:1772, Carroll et al, arXiv:1108.5785, Hill and Gaz, PRL107, 160402(2011); Birse and McGovern, arXiv1206.3030, G.A. Miller 1209.4667, J.M. Alarcon, et al. 1312.1219,….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher, PLB696, 343(2011),..
- Dispersion relations: Lorentz et al. arXiv:1205.6628
- ……………
- New experiments: Mainz (e-d, ISR, Jlab (PRad), PSI (Lamb shift, mu-p scattering), H Lamb shift, ***PRad*** …

# *How to resolve the proton charge radius puzzle?*

***Focus on experiments here***

- ✦ Redo atomic hydrogen spectroscopy
- ✦ Muonic deuterium and helium (PSI)
- ✦ Muon-proton scattering (MUSE experiment)
- ✦ Electron scattering experiments (Jlab and Mainz)
  (preferably with completely different systematics)

# PRad Experimental Setup in Hall B

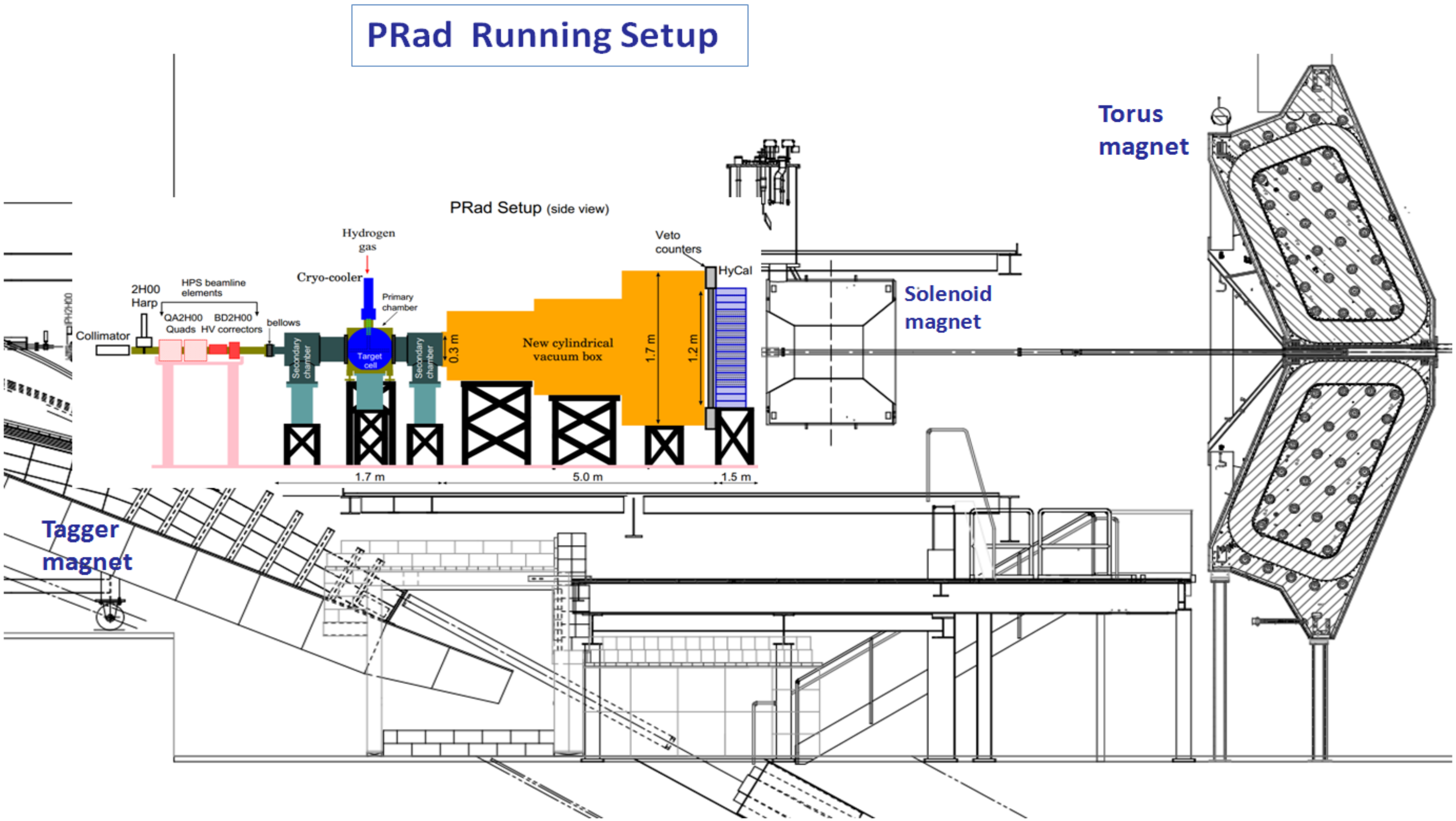



- **High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb)**
- **Windowless $H_2$ gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **$Q^2$ range of $2x10^{-4}$ – 0.14 $GeV^2$**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

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

Approved with A rating

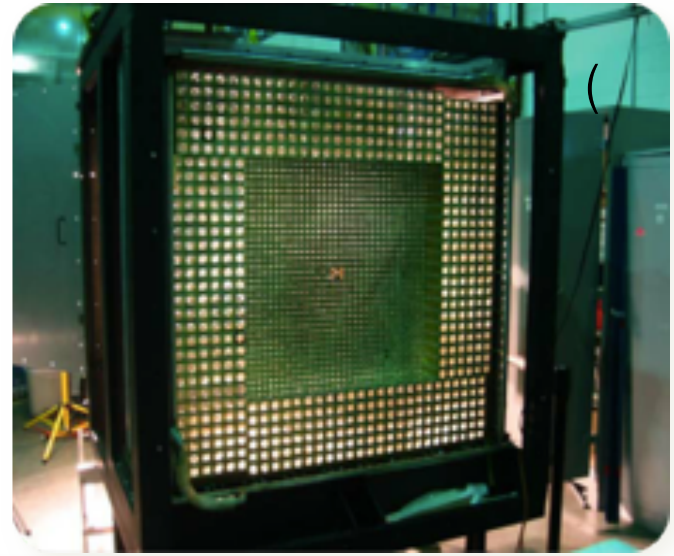
# PRad Layout in Hall B at Jefferson Lab

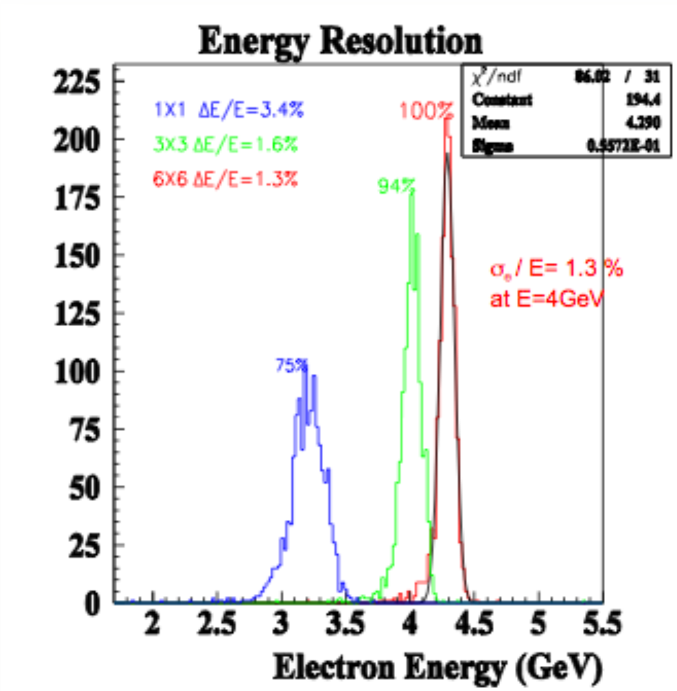


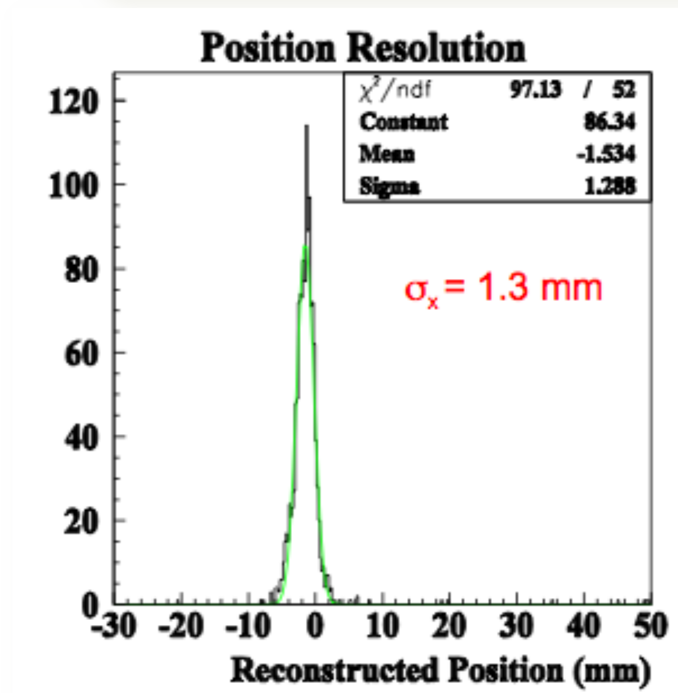

Distance between the HPS Quads' girder and the center of the Hall is ~10.5 m

# *High Resolution Calorimeter*

- HyCal is a $PbWO_4$ and Pb-glass calorimeter
- 2.05 x 2.05 $cm^2$ x18 cm (20 rad. Length)
- 1152 modules arranged in 34x34 matrix
- ~5 m from the target,
- 0.5 sr acceptance

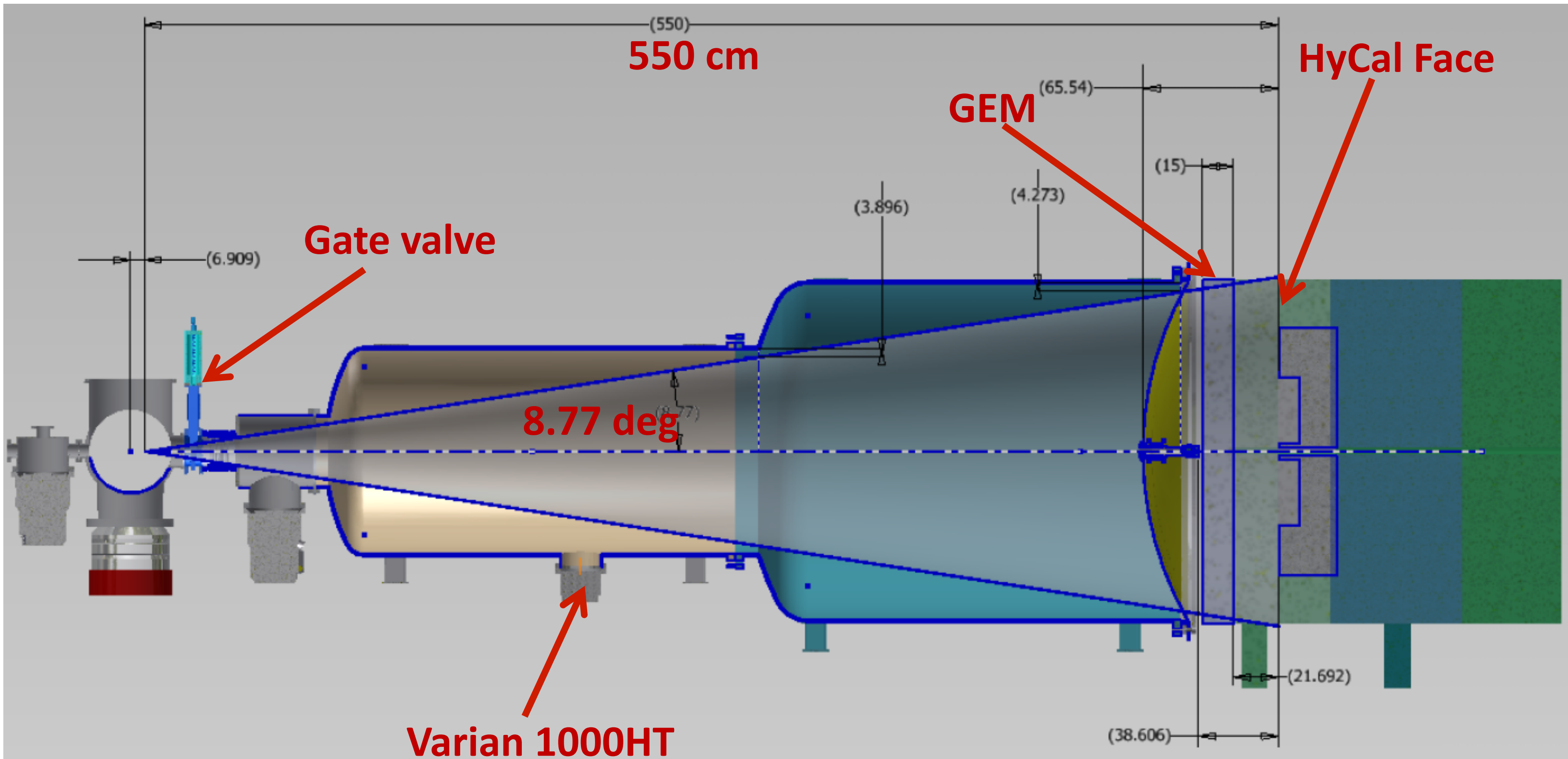




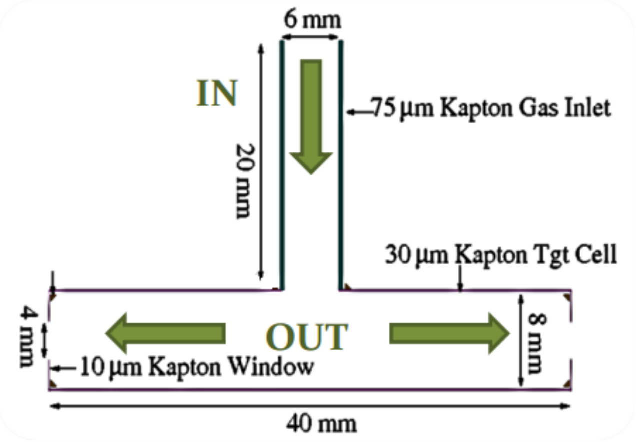



# *Vacuum Box and GEM*

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

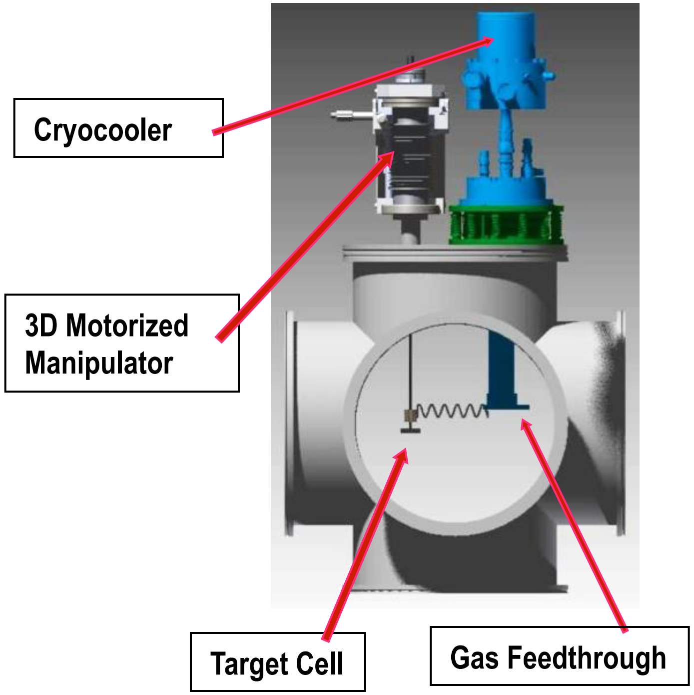


# *Windowless $H_2$ Gas Flow Target*




- **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 — $1\times10^{18}$ H/cm$^2$
  - average density — $2.5\times10^{17}$ H/cm$^3$
  - gas mass-flow rate — 6.3 Torr-l/s ≈ 430 sccm

- **Target parts:**
  - pumping system — (all parts at Jlab)
  - cryocooler — (at Jlab)
  - motorized Manipulator — (at Jlab)
  - chillers for pumps and cryocooler — (at Jlab)
  - Target and secondary chambers — (at JLab)

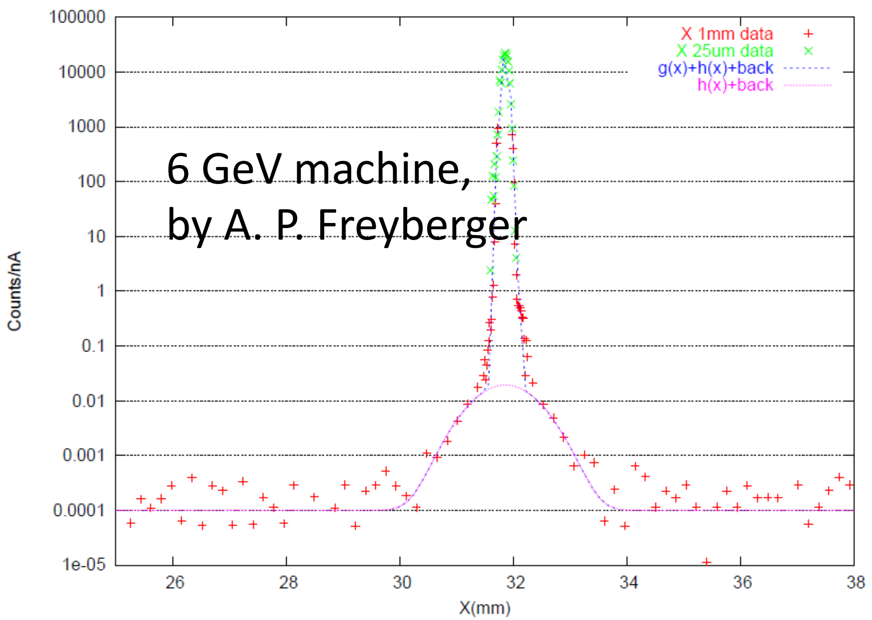



- **Kapton cell: work in progress**

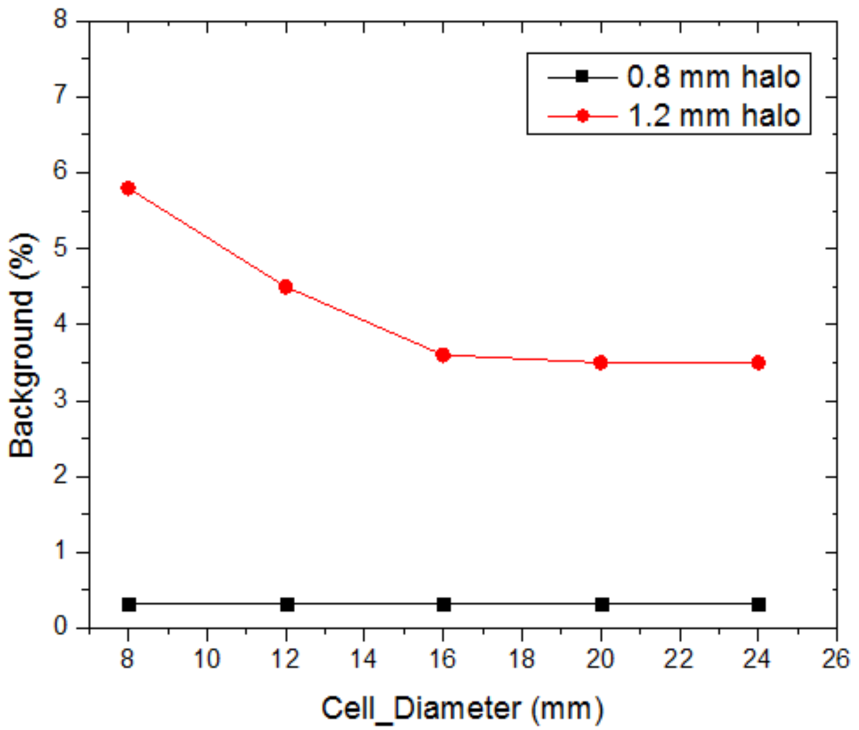
**Target supported by NSF - MRI grant**

# Background due to beam halo

- Beam halo is the main background source, it may hit the cell structure
- This background will be subtracted by empty target run
- The cell design is also changed to reduce the background level



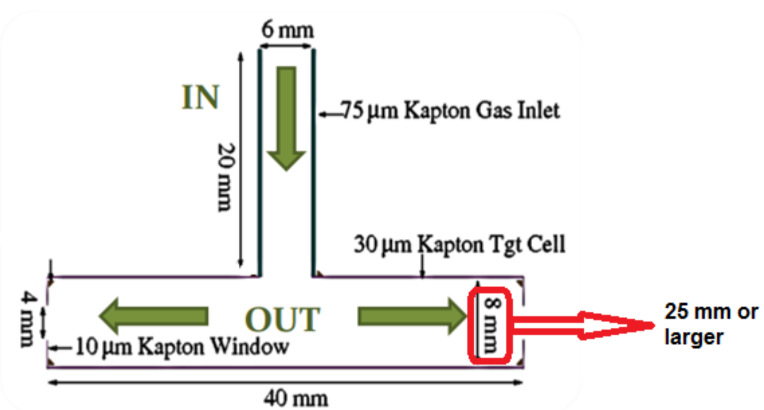

Halo $\sigma_{x,y}$ = 0.38 – 0.95 mm

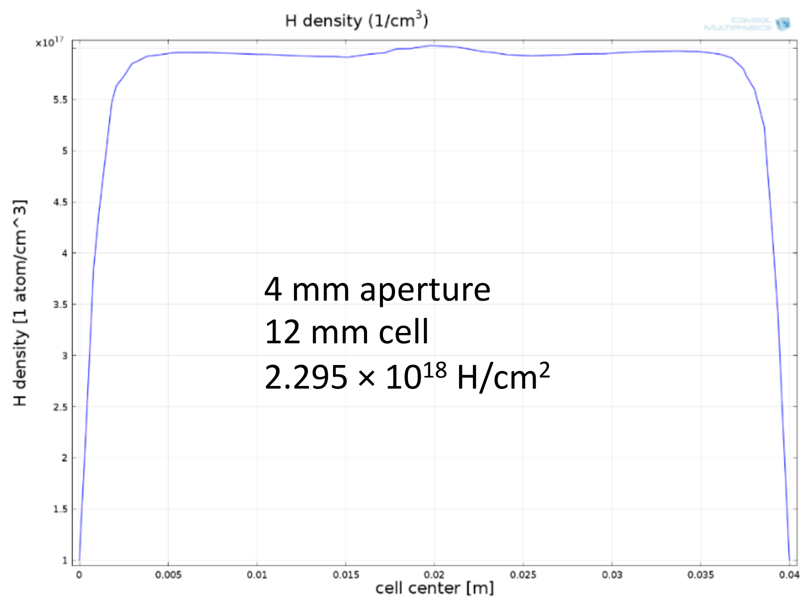


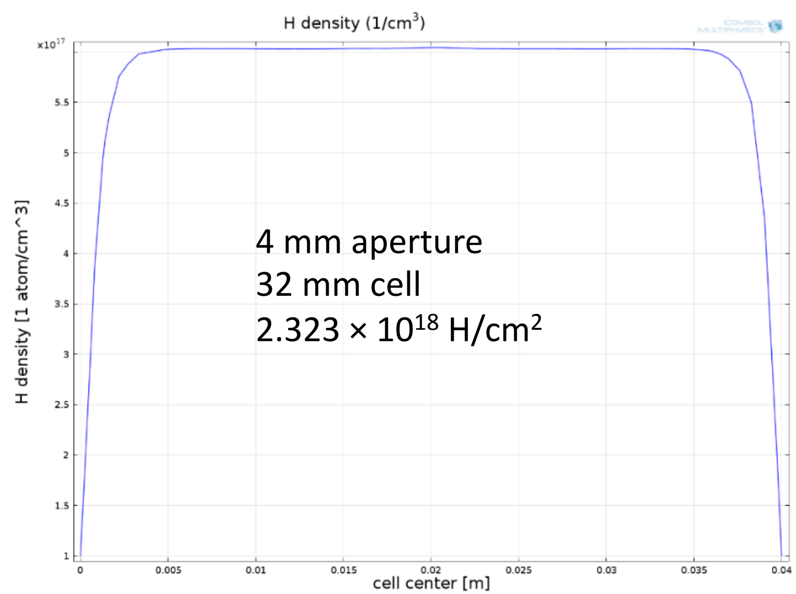

Target cell aperture diameter 4 mm

# *Background due to beam halo*

- The aperture of cell is fixed at 4 mm, and the cell diameter increases
- The new design maintains the target thickness, and reduces the background from halo

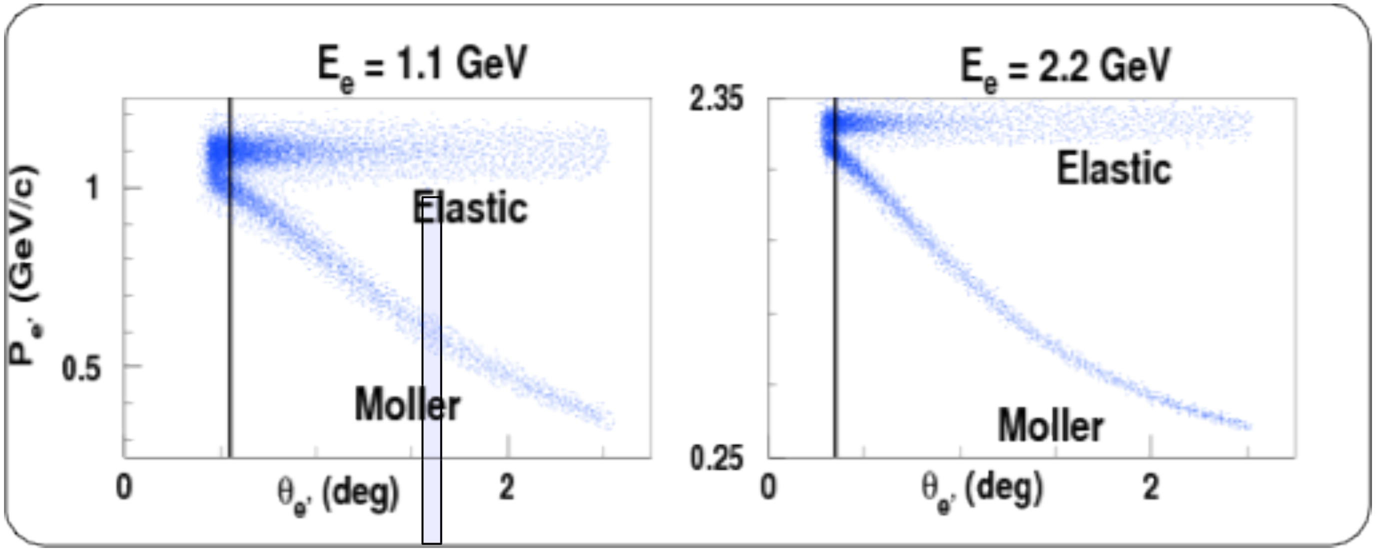


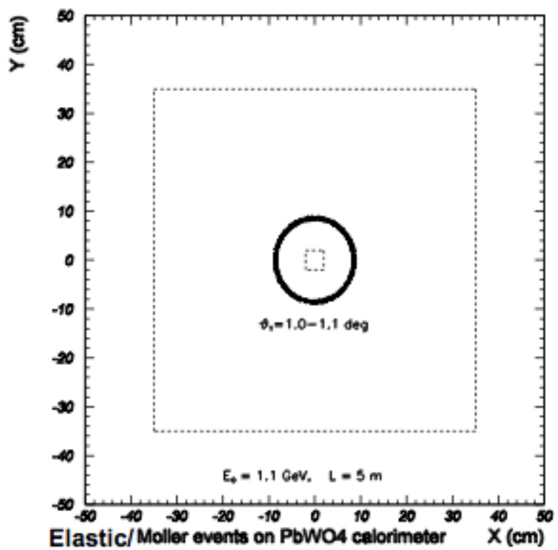



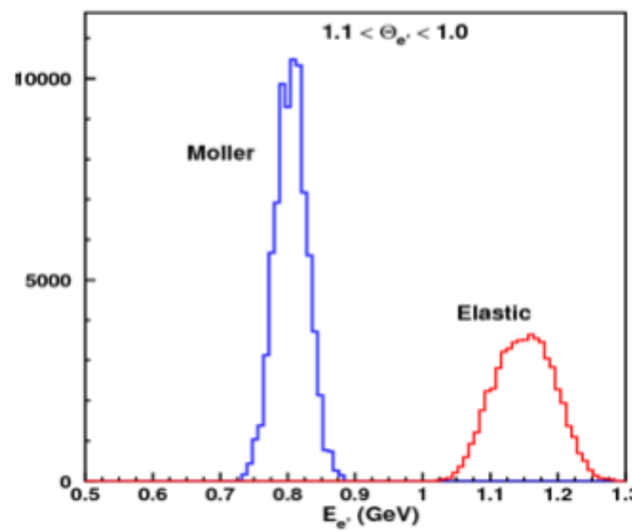



# *Normalization with Moller Scattering*

Simultaneous detection of ep elastic and ee Moller events



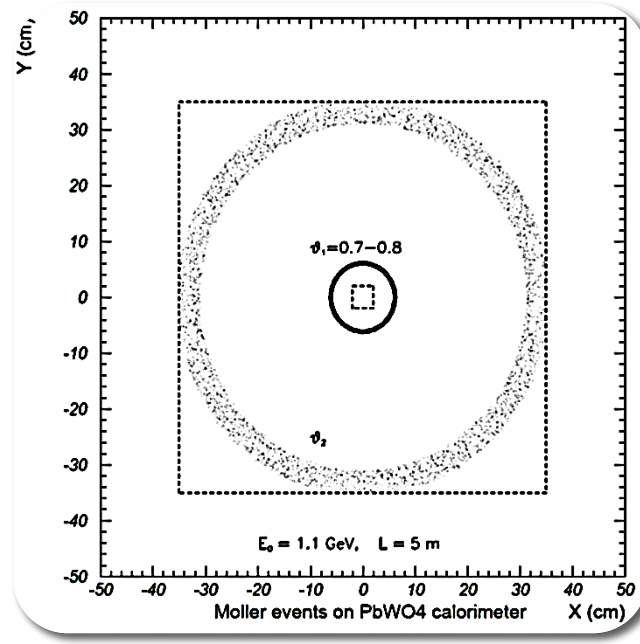
# Measurement Principle

## 3 methods to analyze the Möller electrons:

❖ **Single arm method: one Moller electron detected:**

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^- \to e^-e^-)}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

**Only detection efficiencies and relative acceptance are needed.**




❖ **Double arm method: both Möller electrons are detected**

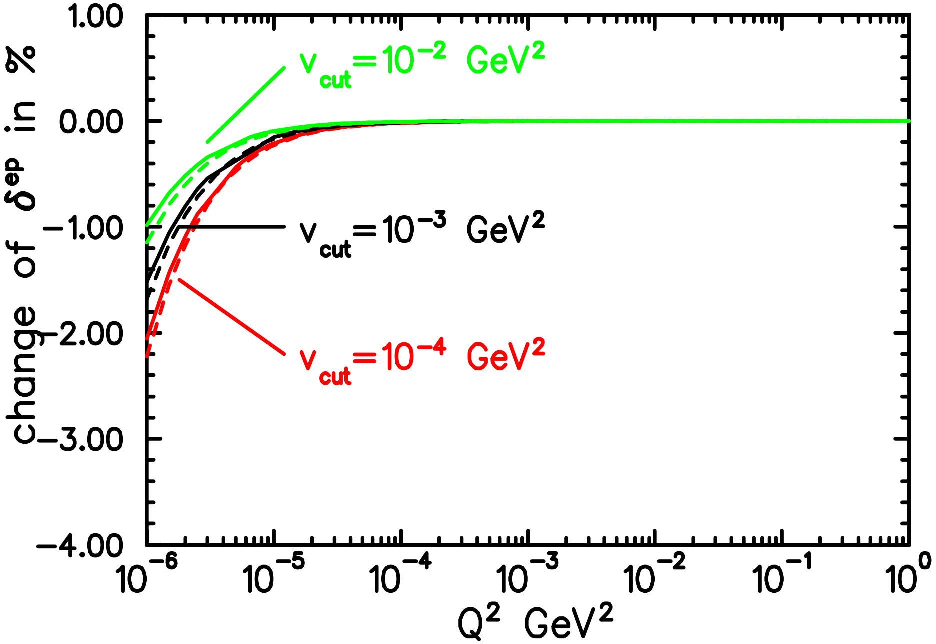
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{ep}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

❖ **Integrated Möller cross section method over all the HyCal acceptance**

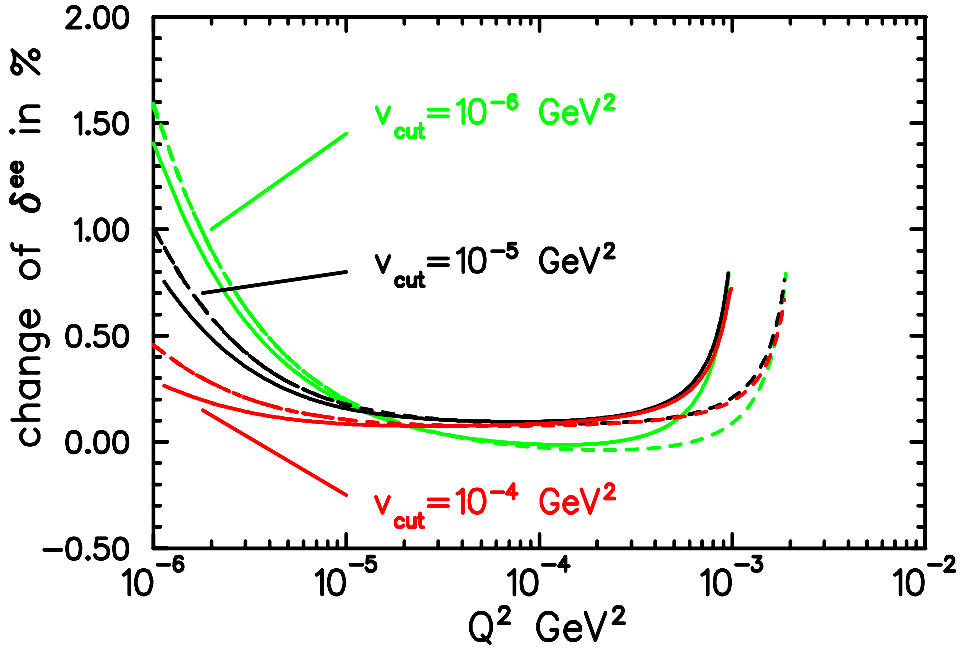
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep,\ \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^-,\ \text{on PbWO}_4)}\right]\frac{\varepsilon_{\text{geom}}^{e^-e^-}(\text{all PbWO}_4)}{\varepsilon_{\text{geom}}^{ep}(\theta_i \pm \Delta\theta)}\frac{\varepsilon_{\text{det}}^{e^-e^-}(\text{all PbWO}_4)}{\varepsilon_{\text{det}}^{ep}(\theta_i \pm \Delta\theta)} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

# *Radiative Corrections at low $Q^2$ for the PRad Experiment*

***ep* case**




**Møller case**




**Updated ep radiative corrections code MASCARAD**

*A. **Afanasev** et al. Phys.Rev.D vol. **64**, p. 113009 (2001).*

**Updated Møller radiative corrections code MERA**

*A. Ilyichev et al. Phys.Rev.D vol. **72**, p. 033013 (2005).*

Two studies within PRad collaboration:

(1) Akushevich, Gao, Ilyichev and Meziane

(2) Gasparian and Gramolin

Solid line: 1.1 GeV

Dashed line: 2.2 GeV

Inelasticity cut: 0.05 GeV$^2$ for ep and $10^{-5}$ GeV$^2$ for Moller

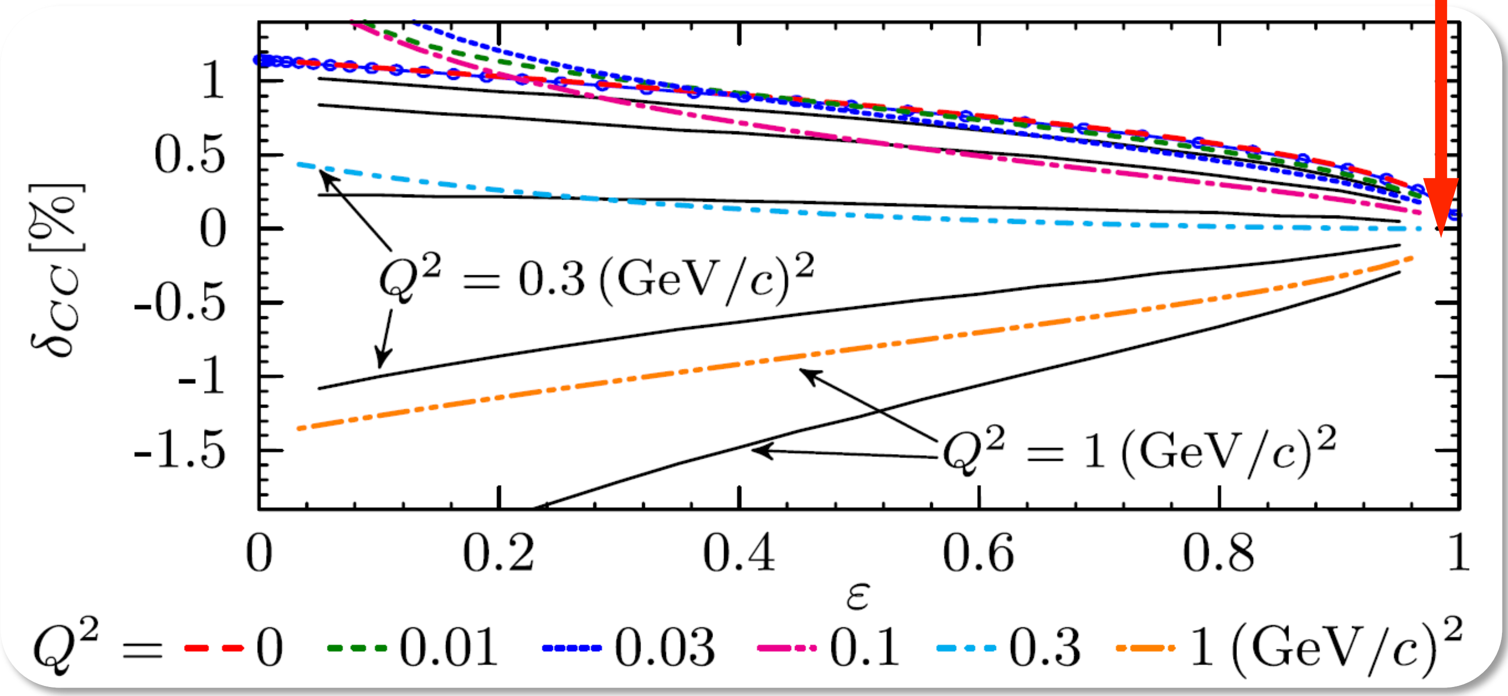
# Coulomb corrections

**Both latest Arrington (solid lines) and Bernauer et al. (color lines) give Coulomb corrections significantly less than 0.1% to the unpolarized cross section for ε->1**

**Largest ε of this experiment: 0.998**

**This experiment**

**Coulomb corrections**




*Bernauer et al. Phys. Rev. Lett. 105, 242001 (2010)*
*Arrington: Phys. Rev. Lett. 107, 119101 (2011)*

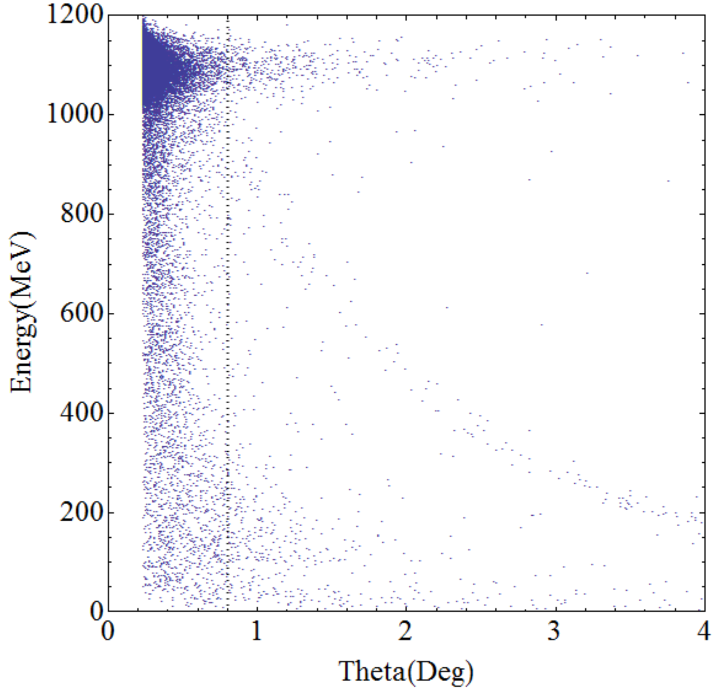
TPE: M. Gorshteyn

# *Full Simulation of the Experiment*

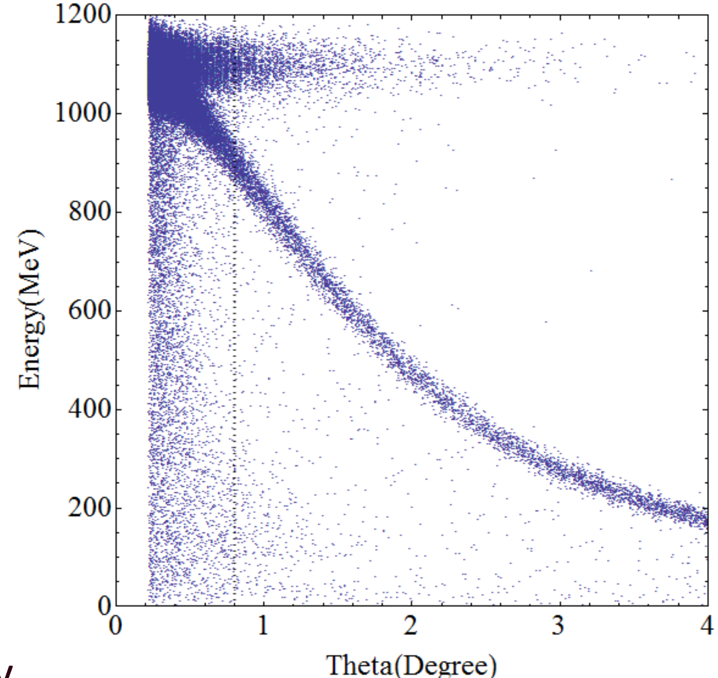
**A Geant4 based simulation of the entire experiment has been developed**

***A detailed study of backgrounds and background subtraction has been performed using this simulation (need 20% beam time for empty target runs)***

***Empty target***




***Full target***



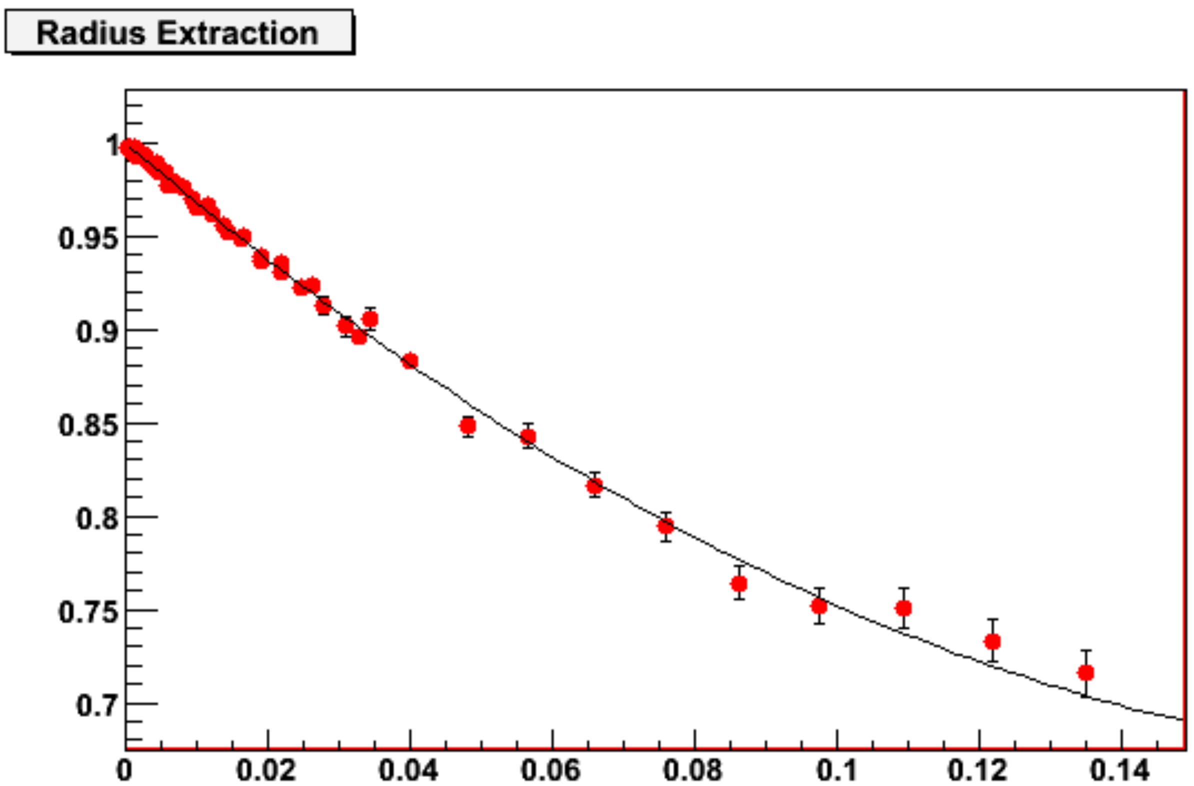

Simulations by
C. Peng (Duke)

# *Full Simulation and projection of the Experiment*

$Q^2$ range using full HyCal, and adding GEM position detector, statistical and sys. uncertainties included

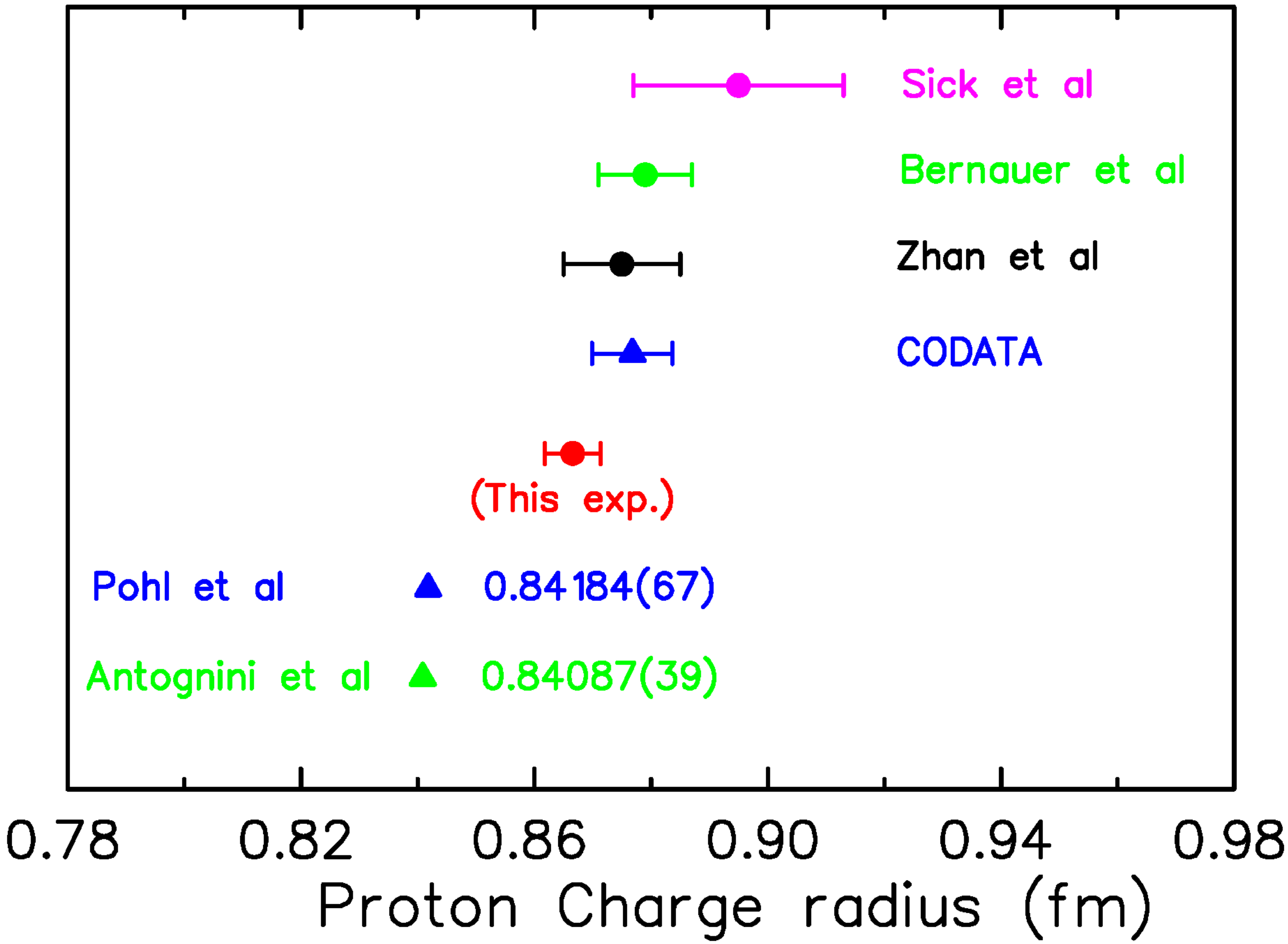
$r_p$ = 0.8768 fm (input)

$r_p$ = 0.8758(58) fm (extracted)

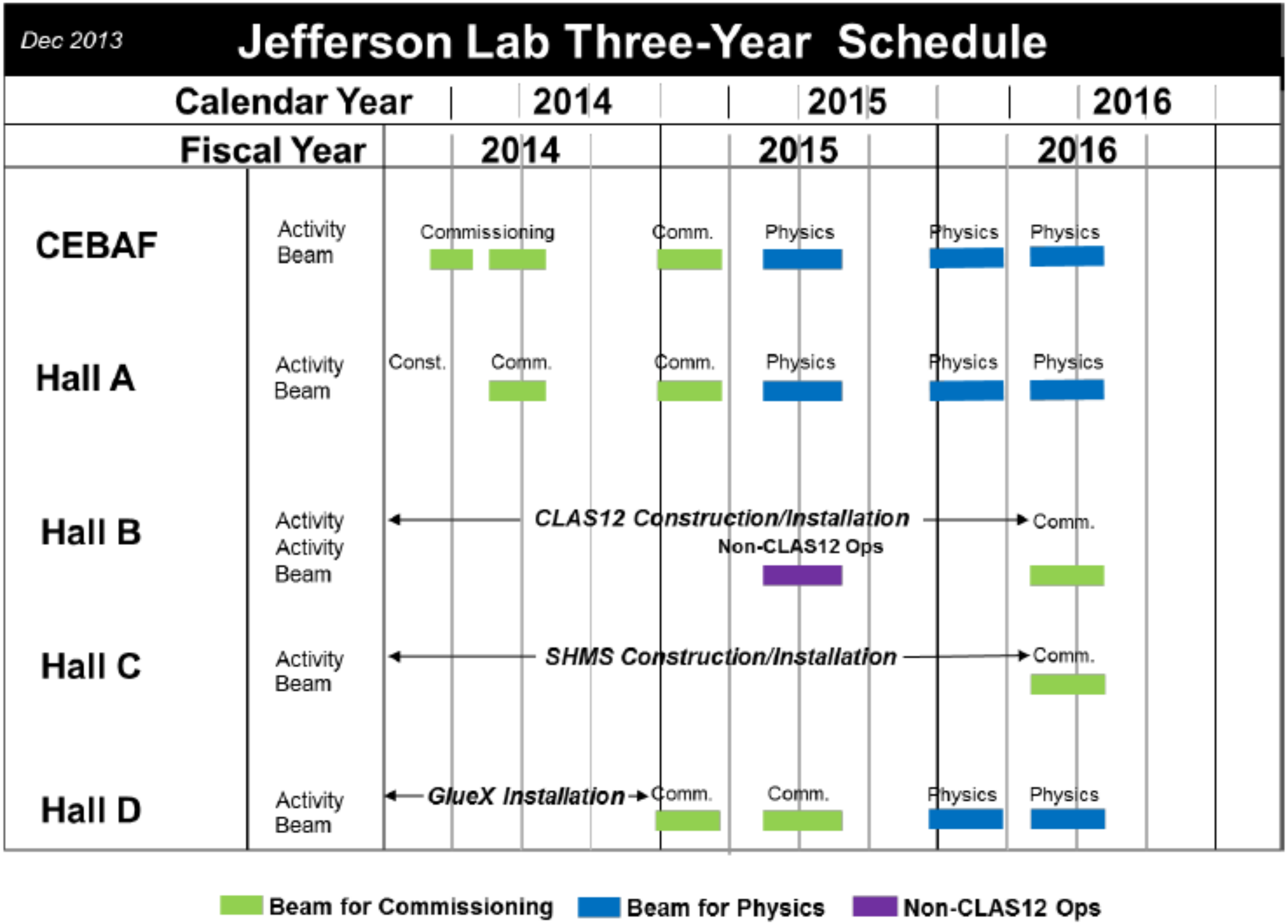



Simulations by C. Peng

# Projected Result



# *JLab Three-Year Run Plan*



# *PRad Collaboration Institutional List*

- ***Currently 16 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**

- ***Welcome new collaborators and institutional groups***

# *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 is **a MUST**
- **PRad: new experiment on e-p elastic scattering will use novel experimental techniques**
- Stay tuned for more news about proton charge radius

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## The 21st INTERNATIONAL SYMPOSIUM on Spin Physics (SPIN2014), Beijing, China


**Dates: October 20-24, 2014**
**Place: Peking University**
**Beijing, China**
**Conference co-chairs:**
**Bo-Qiang Ma and Haiyan Gao**

Symposium website
http://www.phy.pku.edu.cn/spin2014/
Poster competition with prizes
http://www.phy.pku.edu.cn/spin2014/poster.html
**Deadline: August 30, 2014**

# 11th European Research conference on "Electromagnetic interactions with nucleons and nuclei

- 2-7 Nov. 2015, Paphos, Cyprus, http://www.cyprusconferences.org/einn2015/
- Annabelle Hotel (Official Rating – 5*) http://www.cyprusconferences.org/einn2015/?page_id=292
- Scientific program will include:
  - Nucleon form factors and low-energy hadron structure
  - Partonic structure of nucleons and nuclei
  - Precision electroweak physics with searches for dark photons
  - Meson spectroscopy and  structure
  - Baryon and light-meson spectroscopy
  - Nuclear effects and few-body physics