The PRad experiment at JLab

MITP Proton Radius Puzzle Workshop

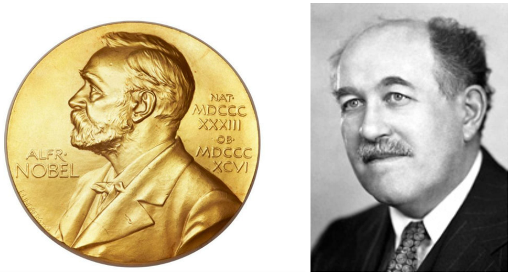
Waldthausen Castle near Mainz

June 2-6, 2014

Haiyan Gao
Duke 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".

$g \neq 2$

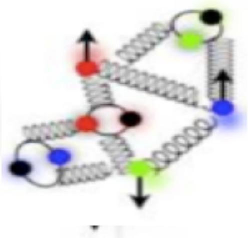
1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

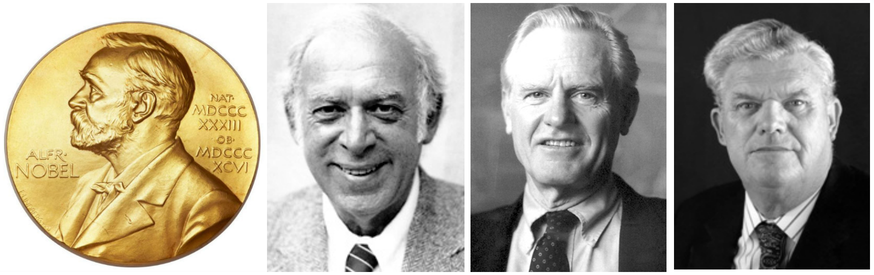
Robert Hofstadter

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

Form factors → 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".

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)
- 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 as you have heard extensively

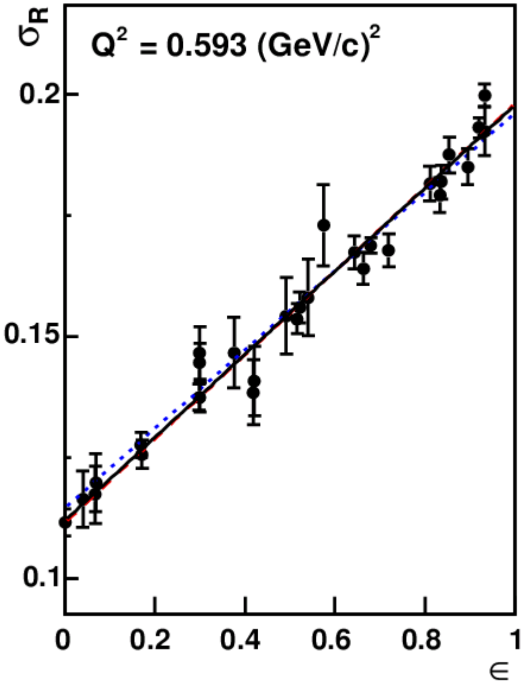
Unpolarized electron-nucleon scattering
(Rosenbluth Separation)

- Elastic e-p cross section

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

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

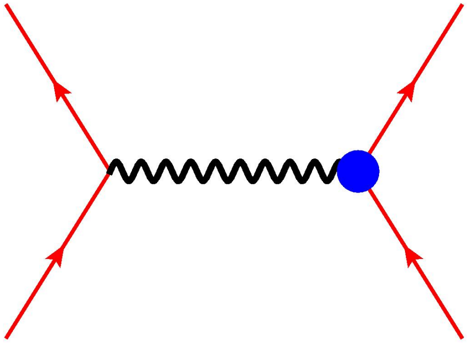
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - **Low Q^2 by G_E**
    - **High Q^2 by G_M**



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

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

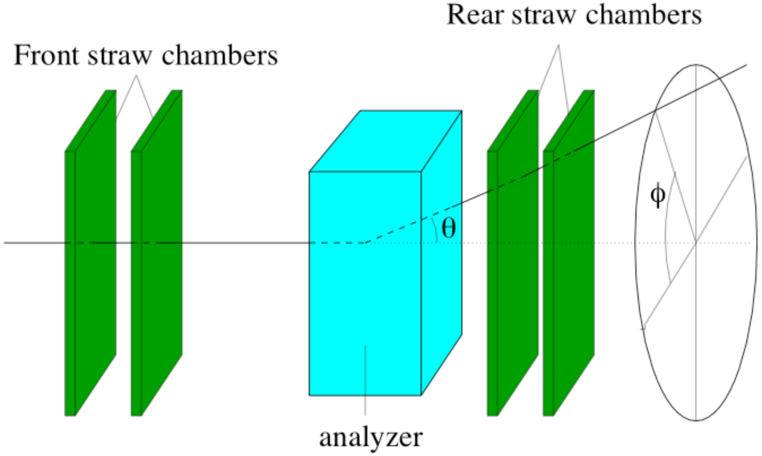
$$\varepsilon = \left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$



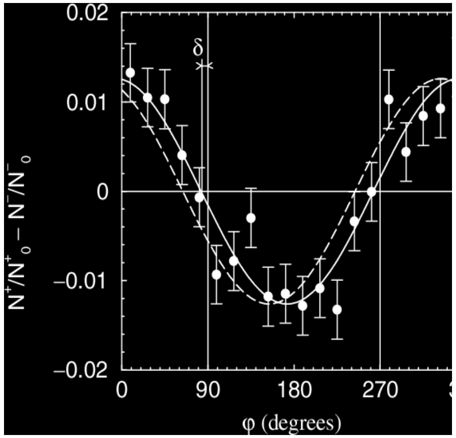
super Rosenbluth Separation

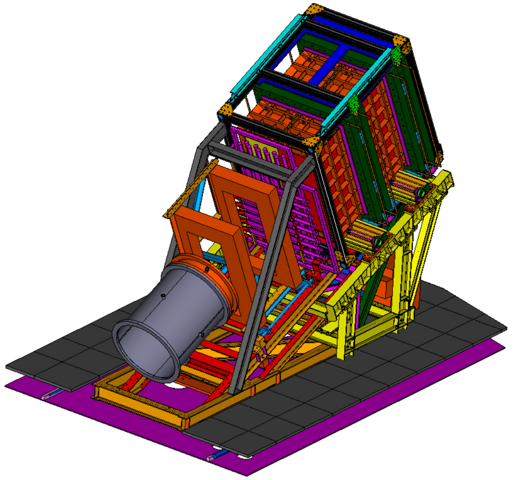
Recoil proton polarization measurement from e-p elastic scattering

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 φ distribution
  - P_b, and analyzing power cancel out in ratio





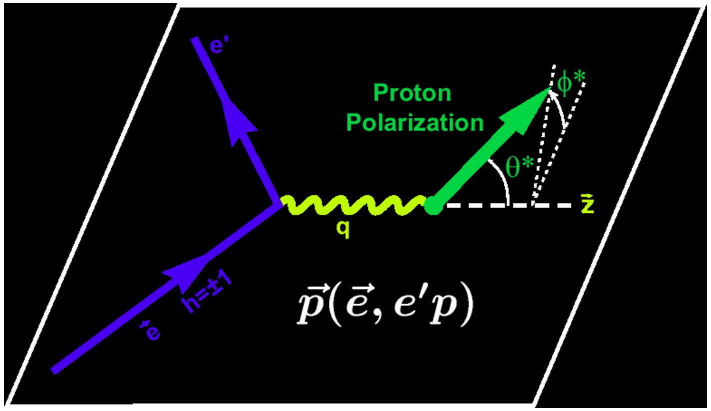
Focal-plane polarimeter

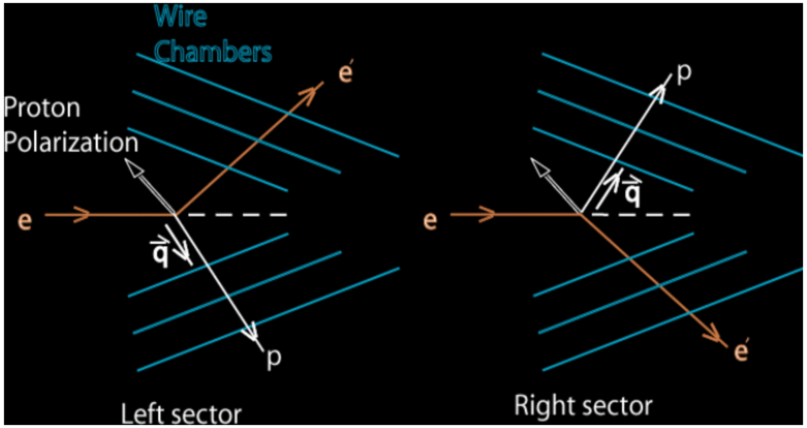
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

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

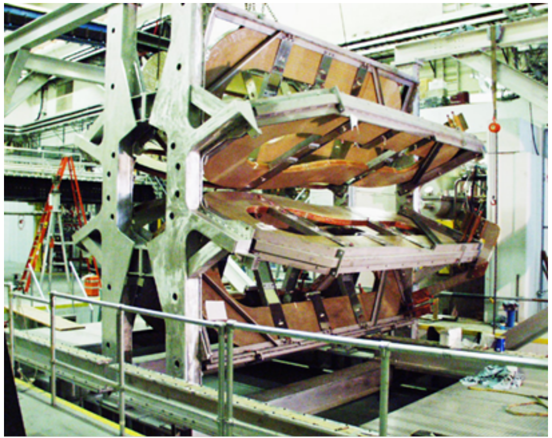




- Super-ratio

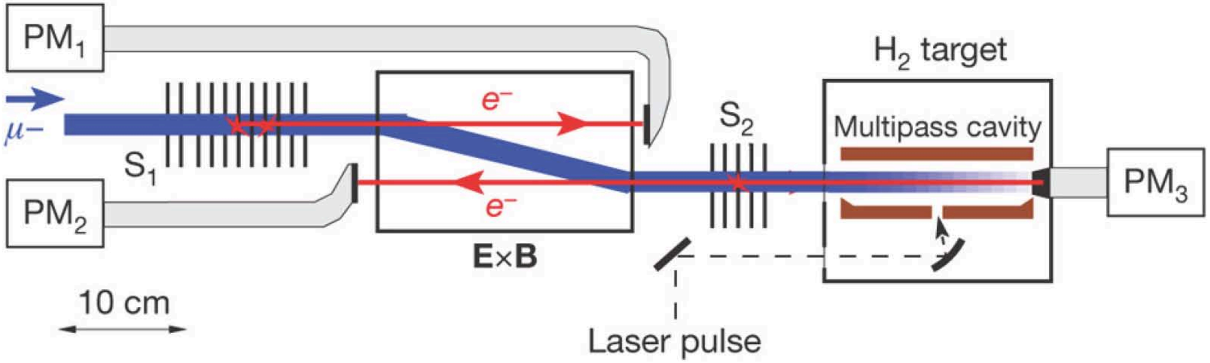
$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p/G_M^p}{a_2 - b_2 \cdot G_E^p/G_M^p}$$

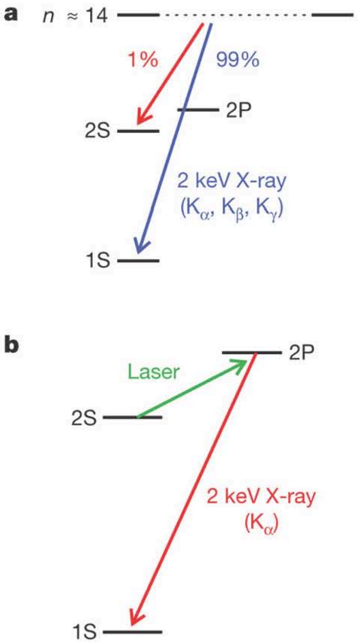
BLAST pioneered the technique, later also used in Jlab Hall A experiment (Gilman's talk)

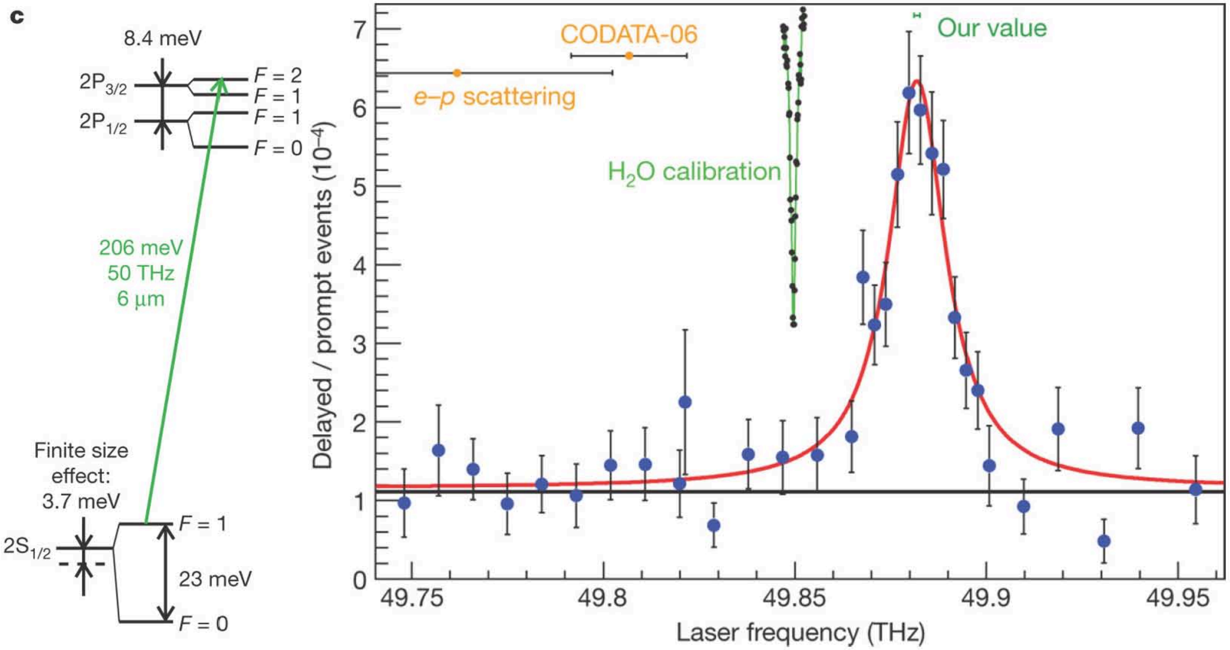


Muonic hydrogen Lamb shift experiment at PSI

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



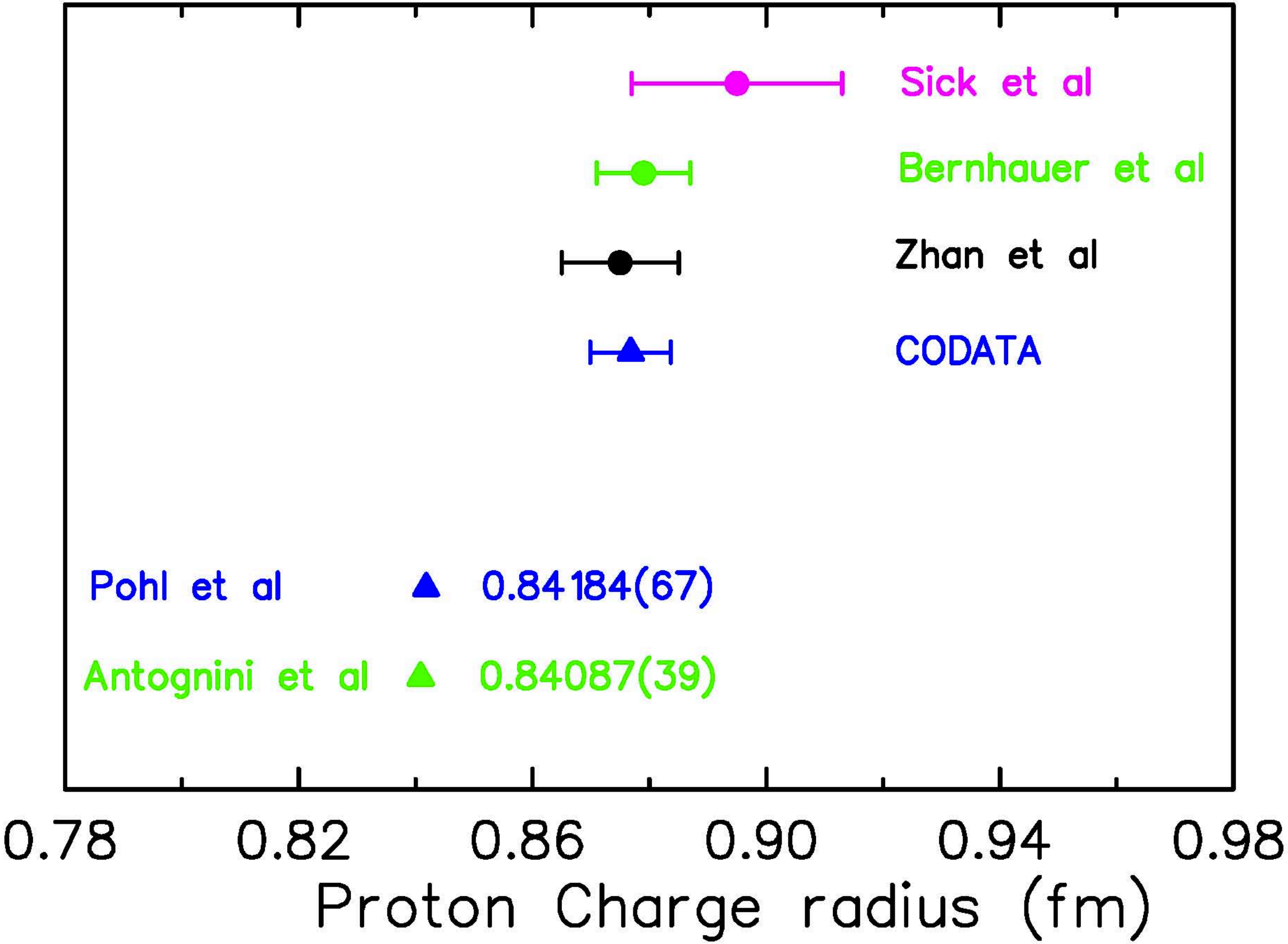




2010: new value is r_p = 0.84184(67) fm

The proton radius puzzle intensified, more intrigued by muonic helium

Maybe not (talks by Griffioen, Lorenz)

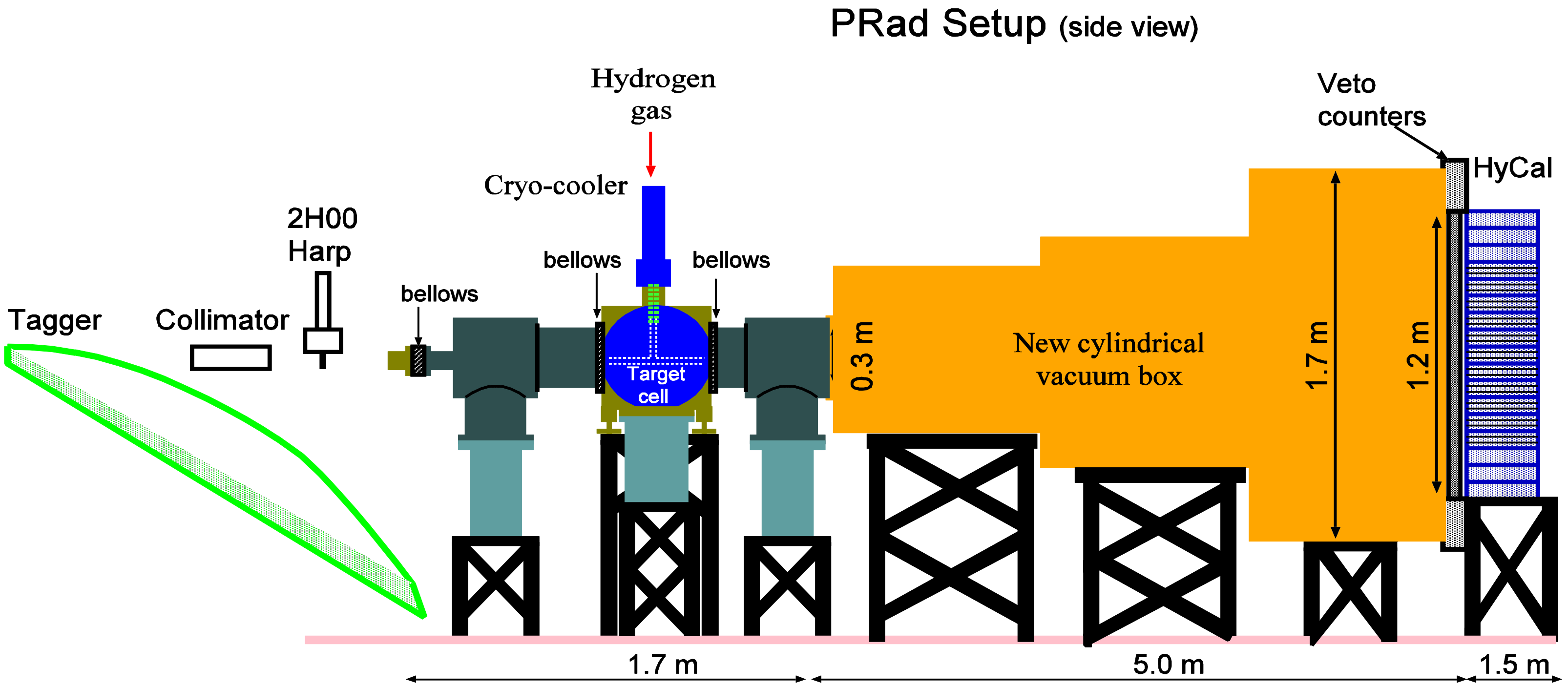


How to resolve the proton charge radius puzzle?

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



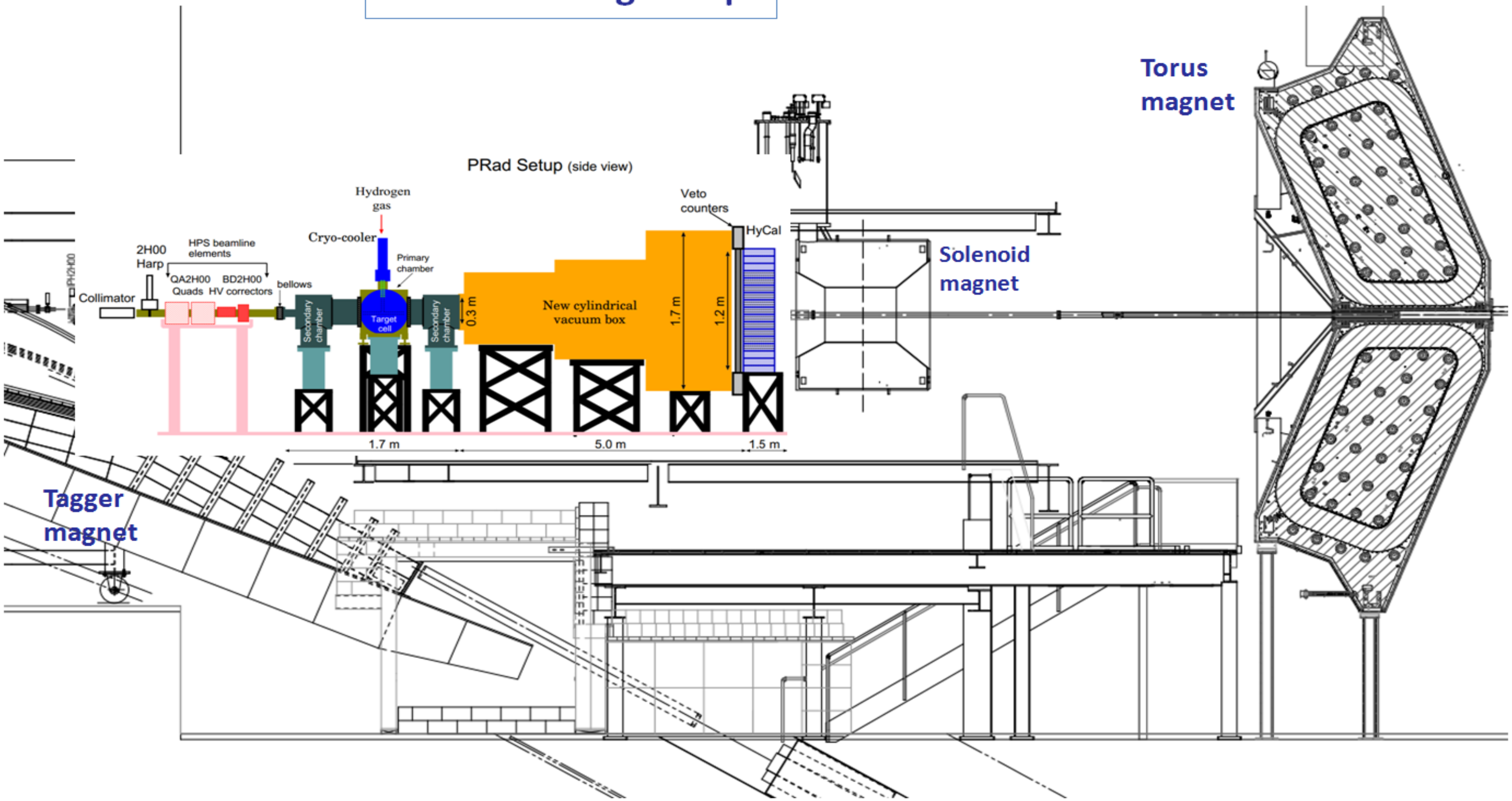
- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb)**
- **Windowless H$_2$ gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2x10^{-4} – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

Spokesperson: A. Gasparian, Co-spokespersons: D. Dutta, H. Gao, M. Khandaker

Approved with
A rating

PRad Layout in Hall B at Jefferson Lab

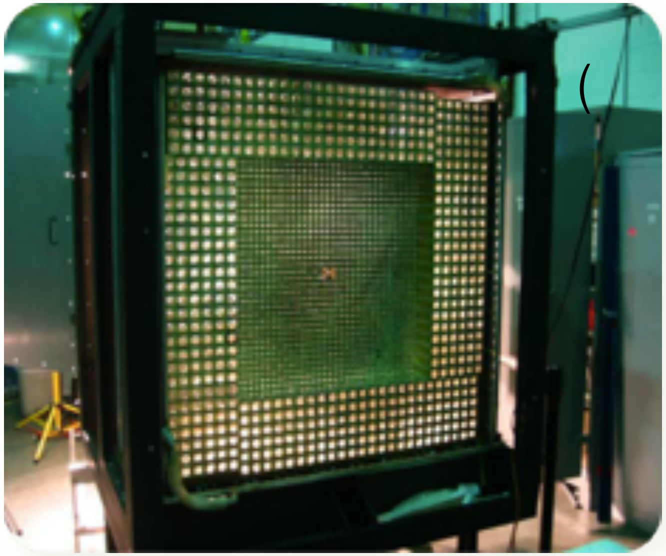
PRad Running Setup

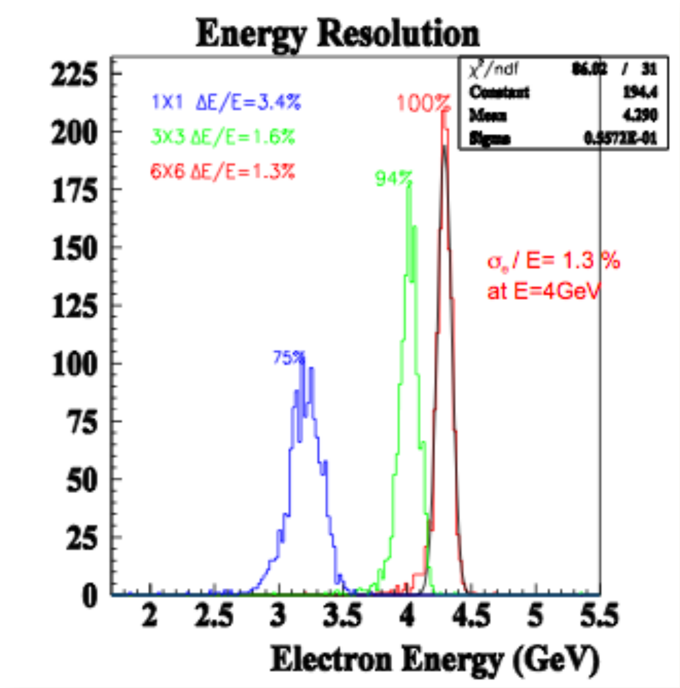


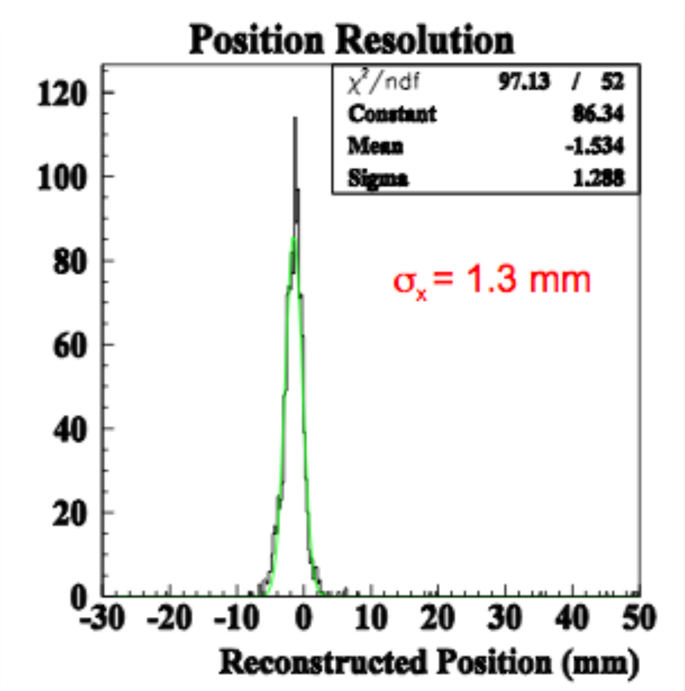
Distance between the HPS Quads' girder and the center of the Hall is ~10.5 m

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

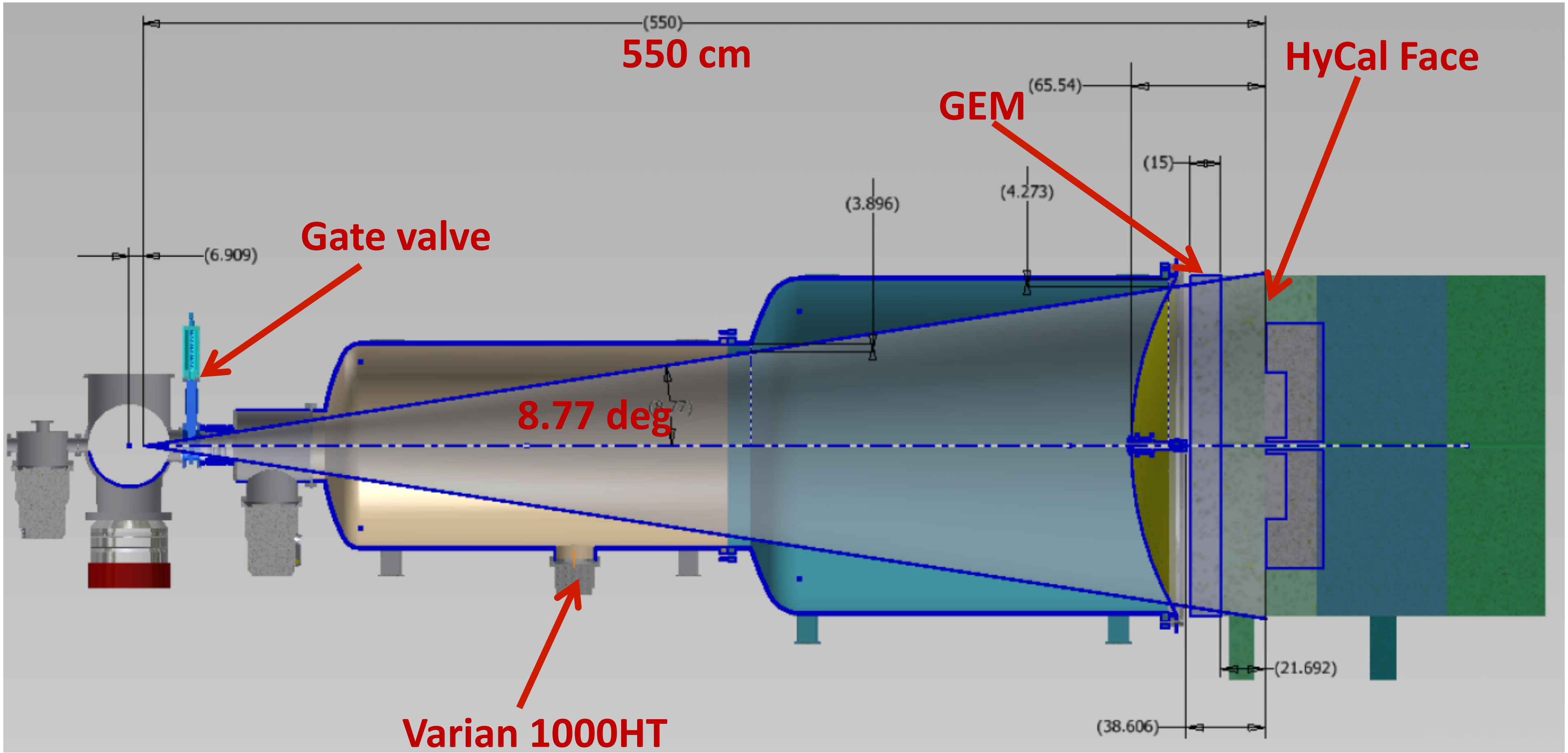




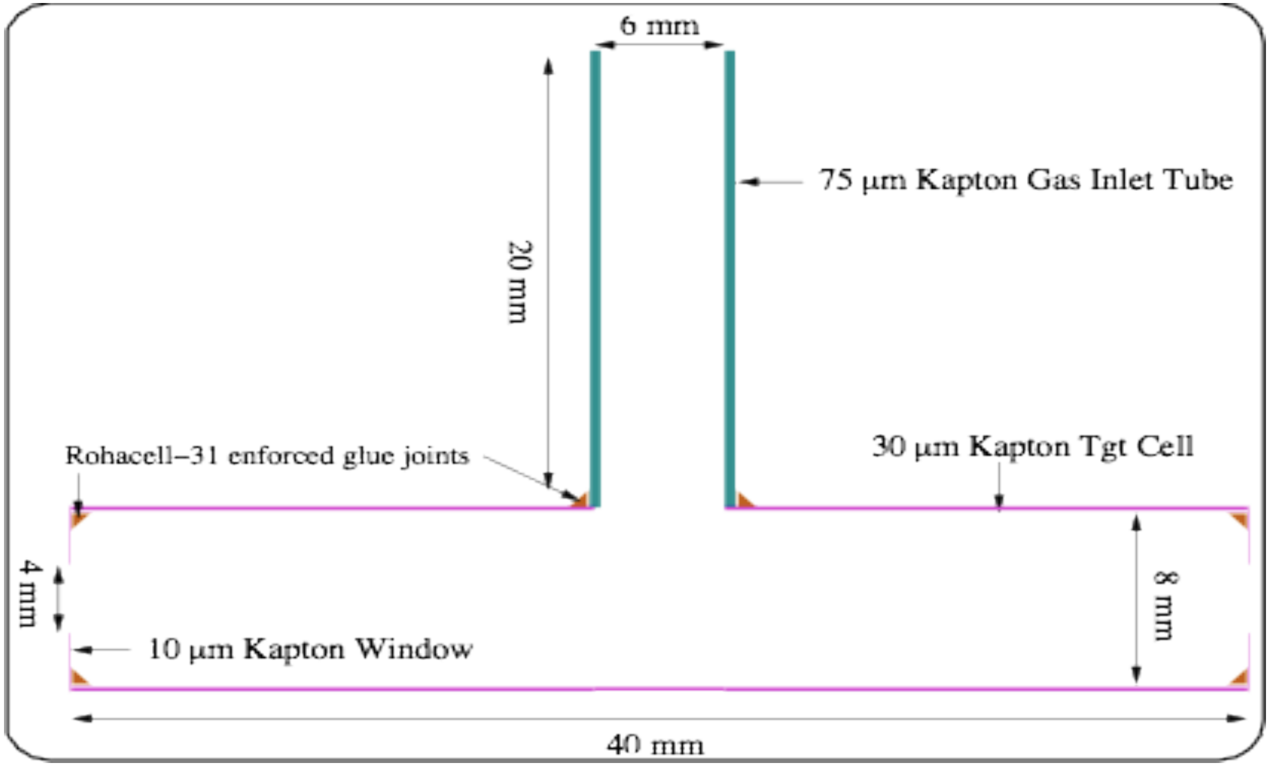


Vacuum Box and GEM

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



Windowless Gas Flow Target



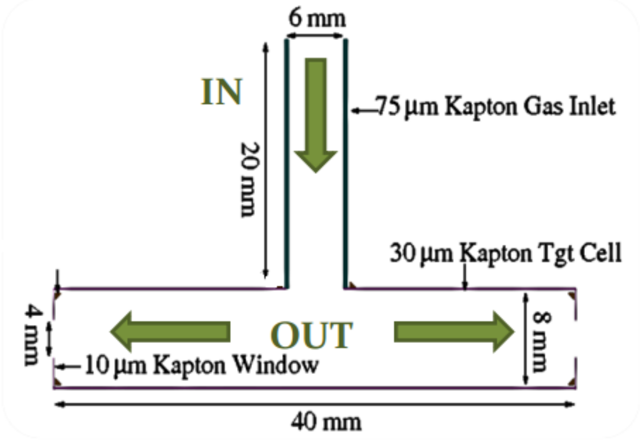
- target windows are a major source of background for typical magnetic spectrometer experiments

- PRad will avoid this background using windowless target

Target thickness
1.0×10^{18} atoms/cm^2
at 25K

Target supported by NSF - MRI grant

Windowless H_2 Gas Flow Target

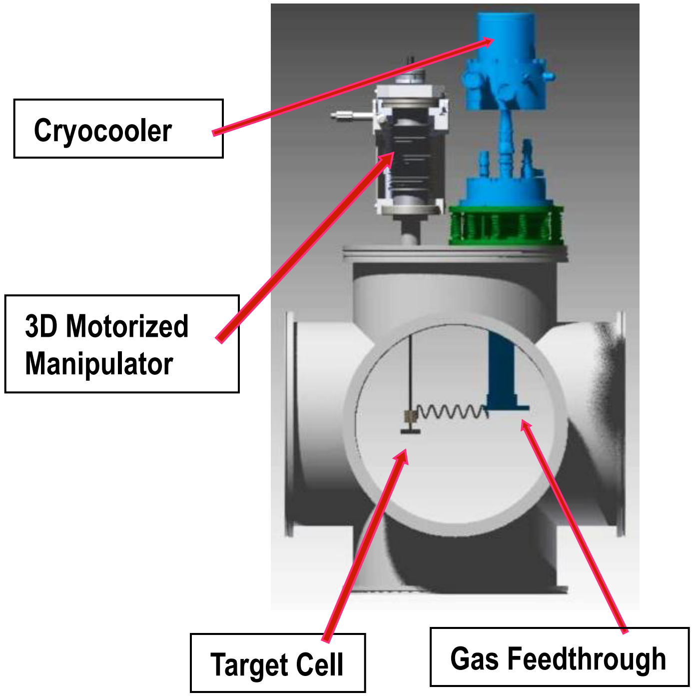


Target cell (original design):

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

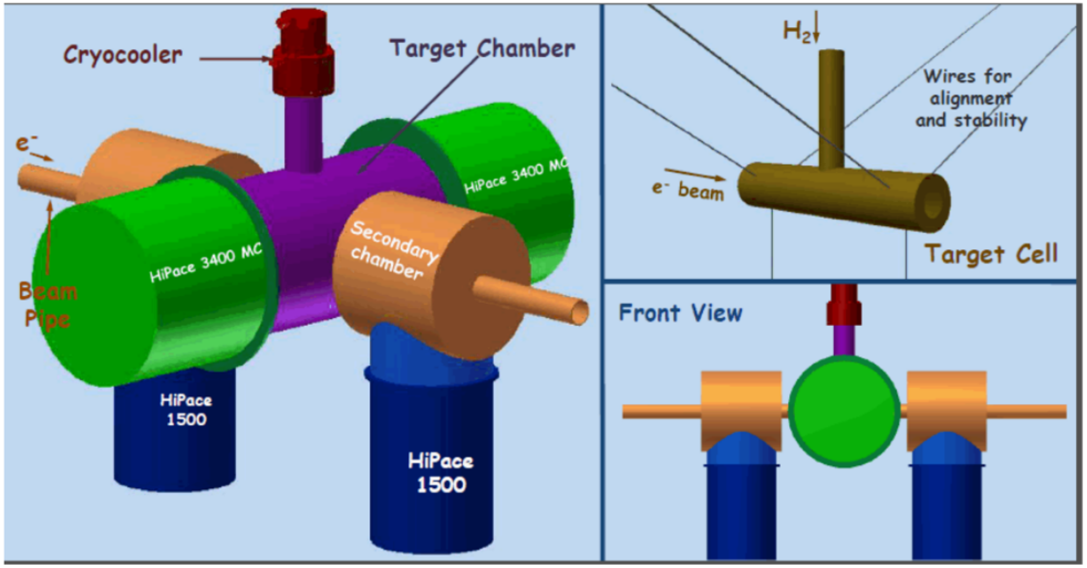
Target parts:

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)

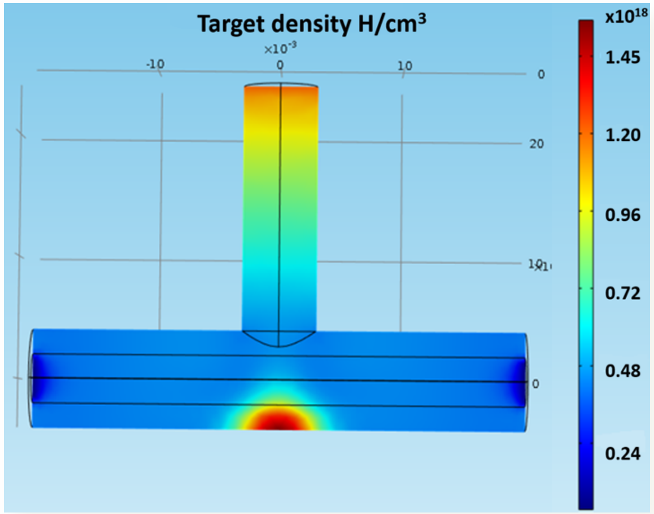


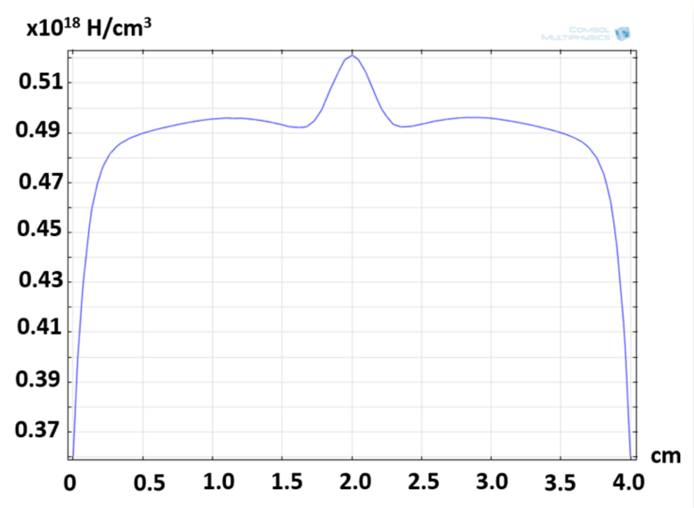
Kapton cell: work in progress

Windowless Gas Flow Target



Simulations show that the desired densities can be achieved.

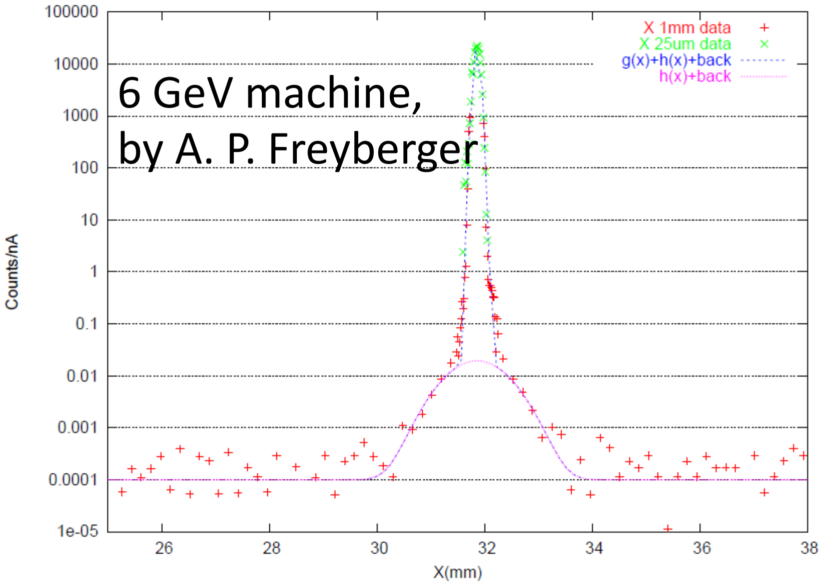




simulations by Y. Zhang

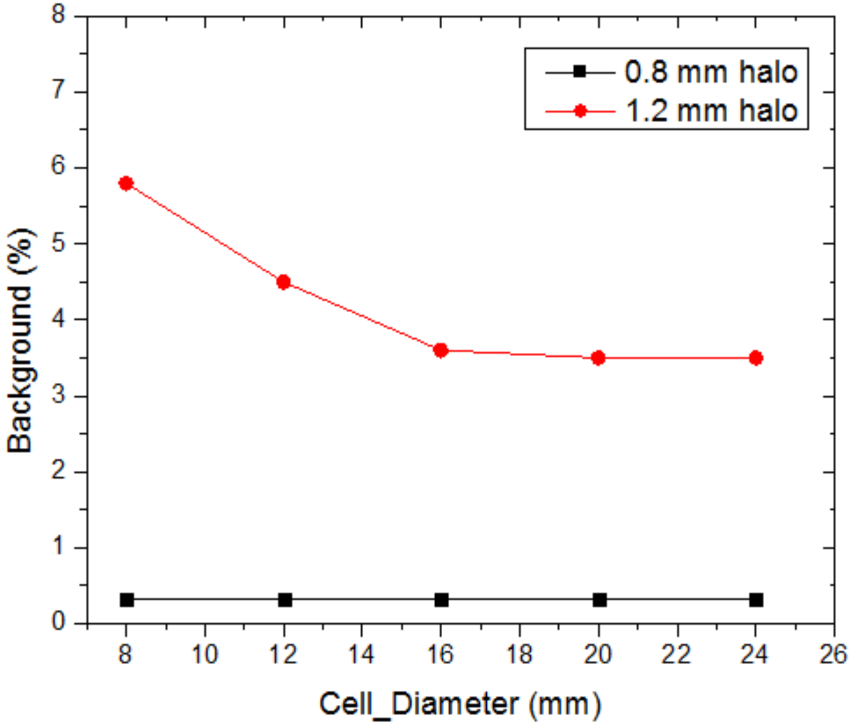
Background due to beam halo

- 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



6 GeV machine,
by A. P. Freyberger

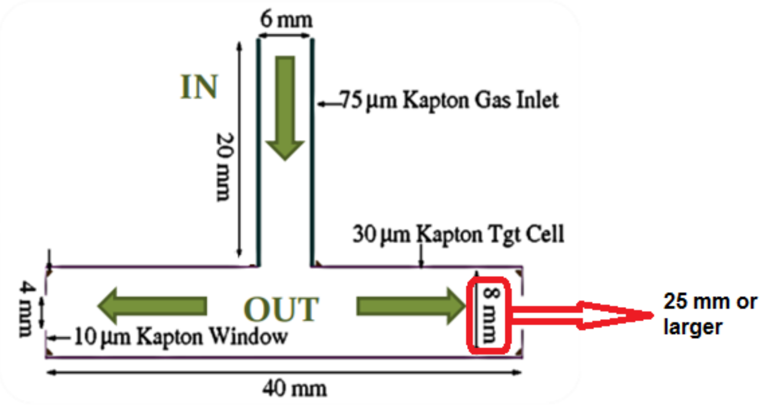
Halo $\sigma_{x,y}$ = 0.38 – 0.95 mm

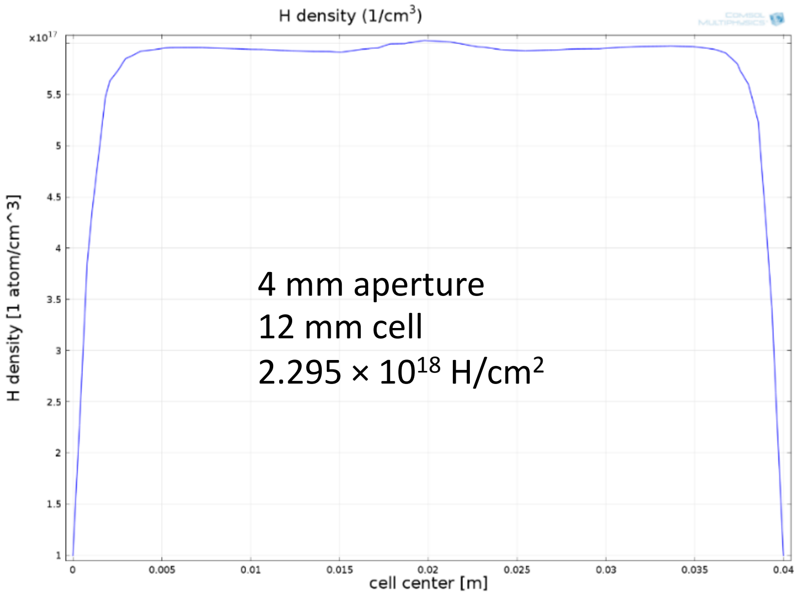


Target cell aperture diameter 4 mm

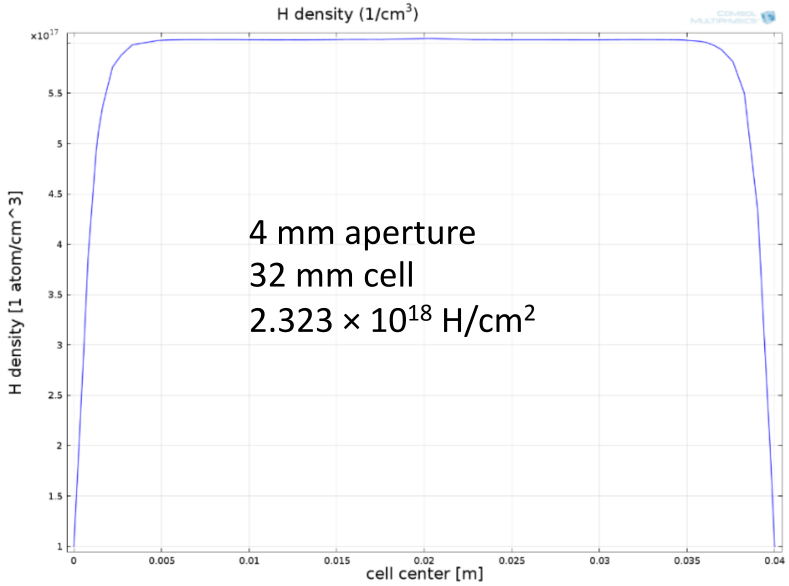
Background due to beam halo

- 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





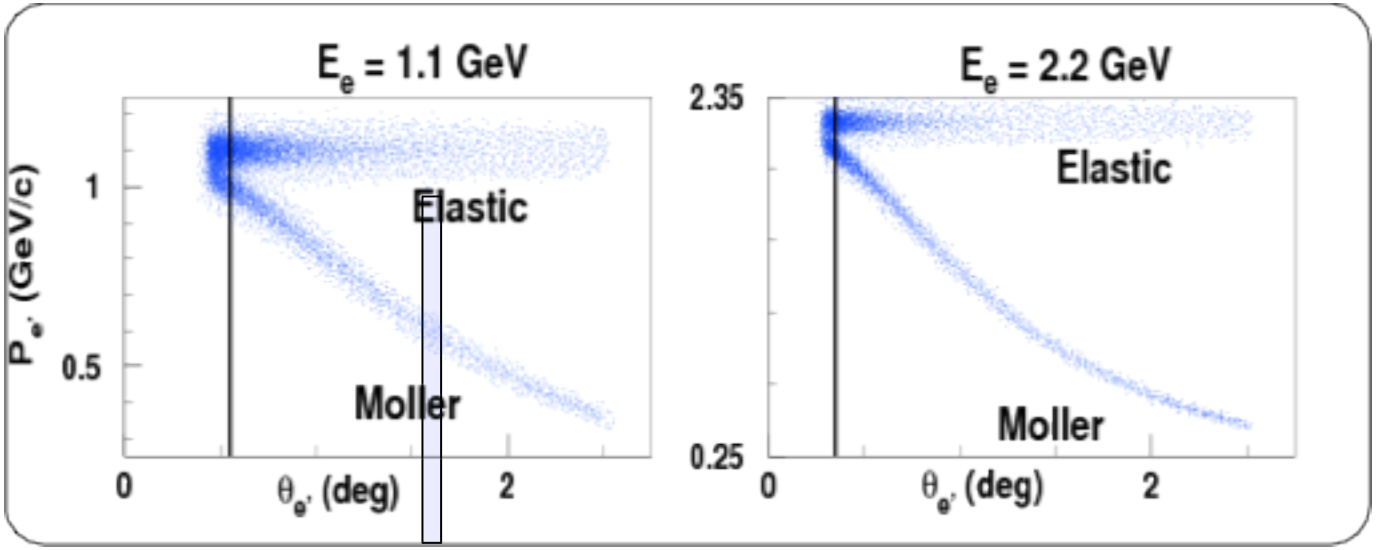
4 mm aperture
12 mm cell
2.295×10^{18} H/cm^2

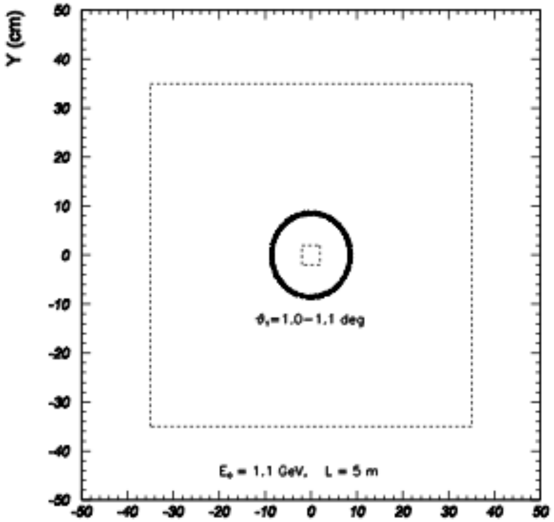


4 mm aperture
32 mm cell
2.323×10^{18} H/cm^2

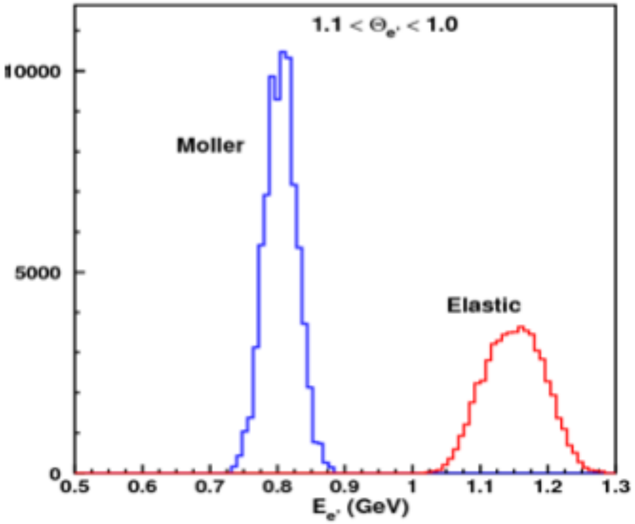
Normalization with Moller Scattering

Simultaneous detection of ep elastic and ee Moller events





Elastic/ Moller events on PbWO4 calorimeter



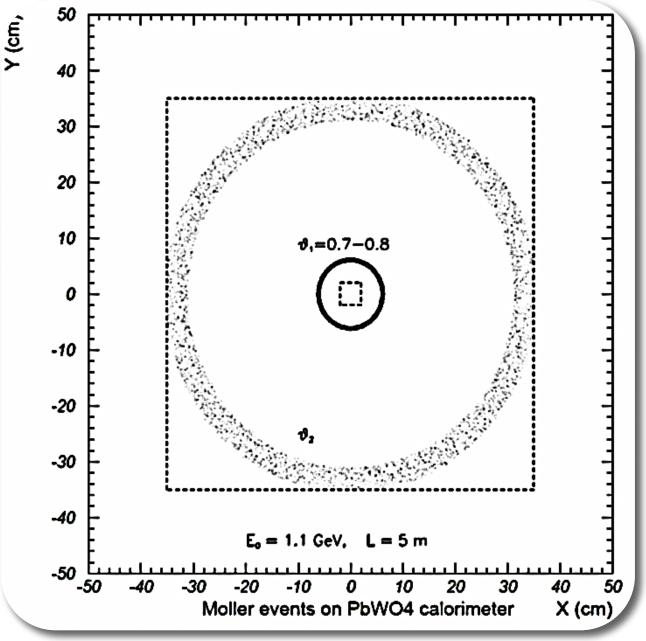
Measurement Principle

3 methods to analyze the Möller electrons:

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

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

Only detection efficiencies and relative acceptance are needed.



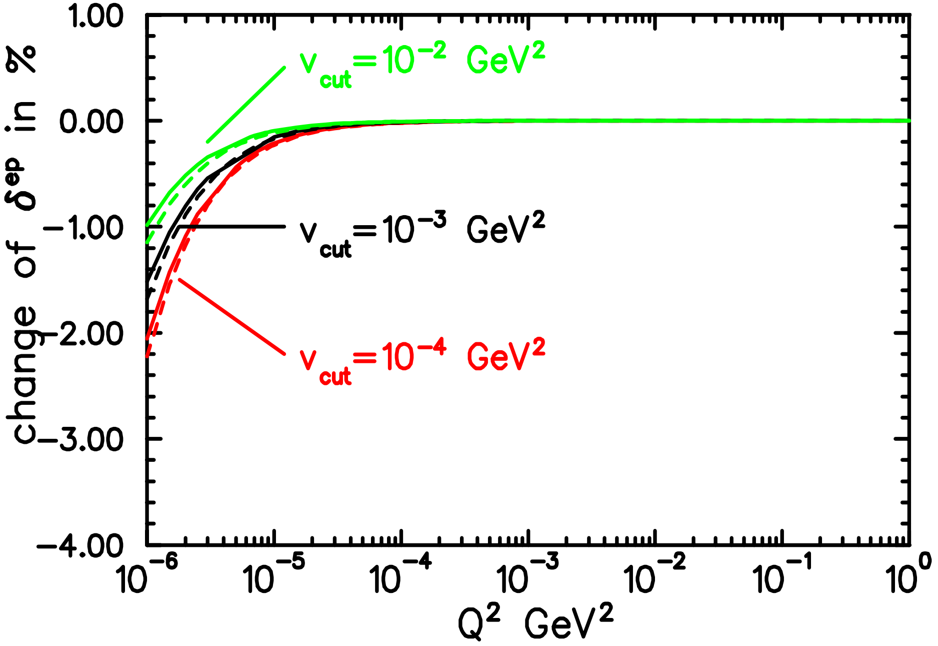
- **Double arm method: both Möller electrons are detected**

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

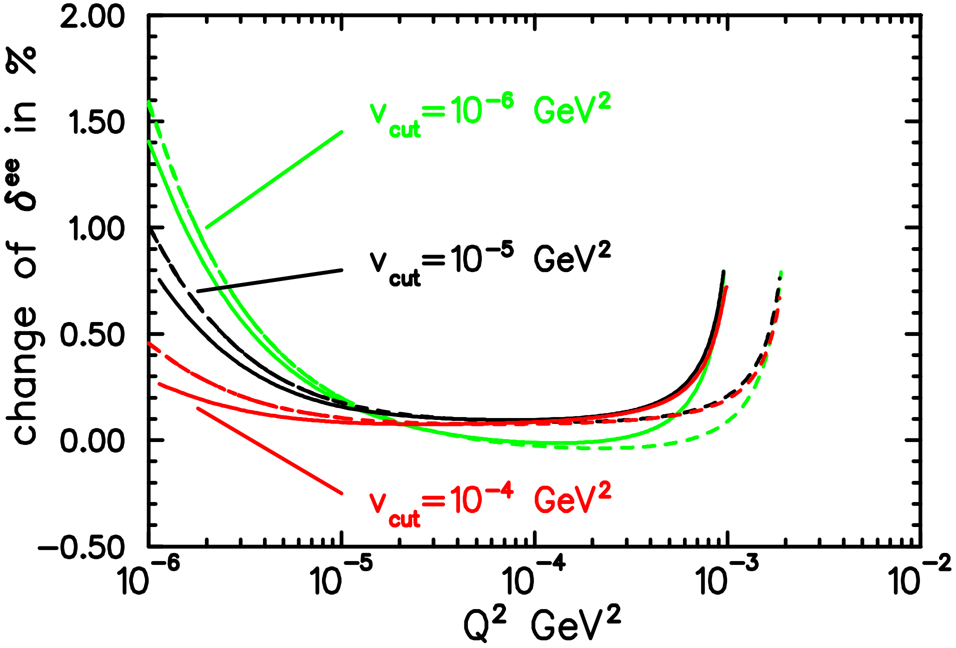
- **Integrated Möller cross section method over all the HyCal acceptance**

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

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

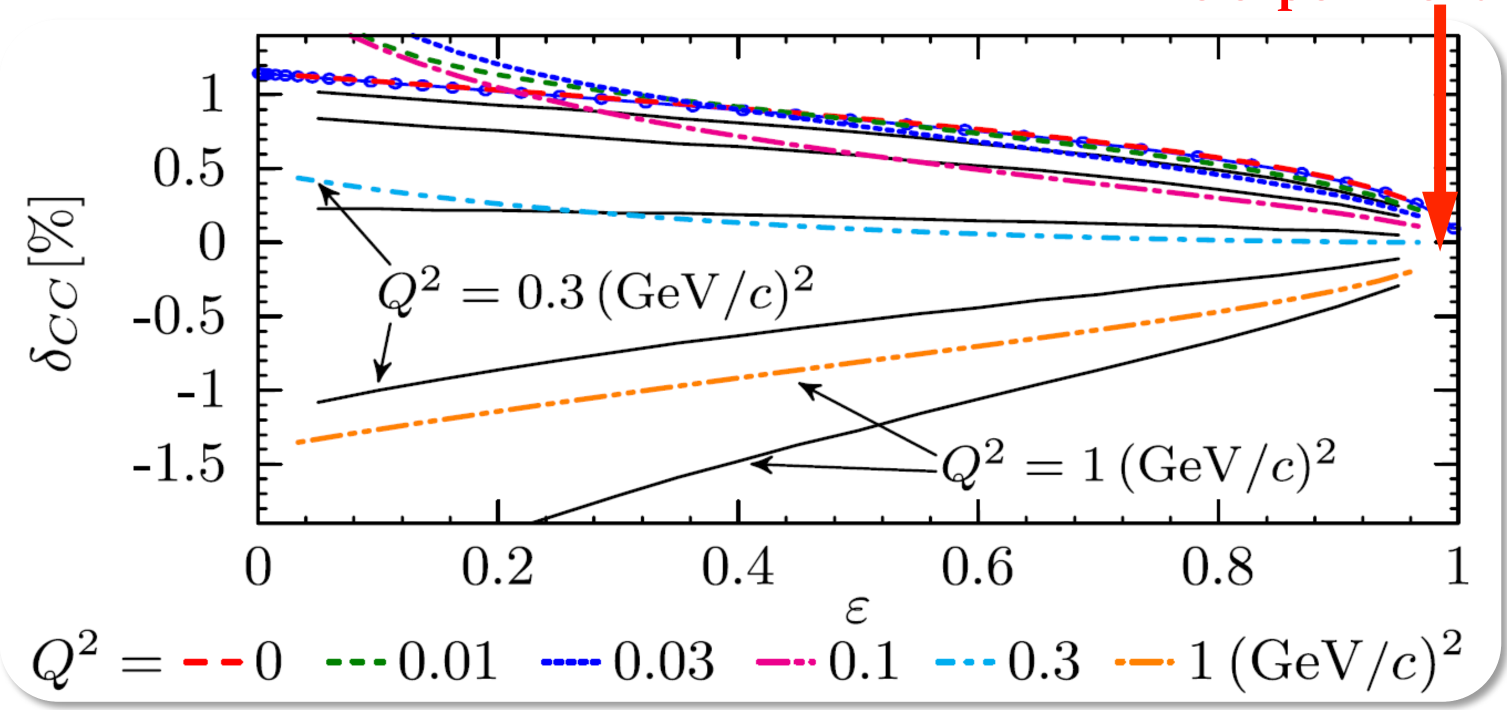
Solid line: 1.1 GeV
Dashed line: 2.2 GeV
Inelasticity cut: 0.05 GeV^2
For ep and 10^{-5} GeV^2 for Moller

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

Coulomb corrections



This experiment

Bernauer et al. Phys. Rev. Lett. 105, 242001 (2010)

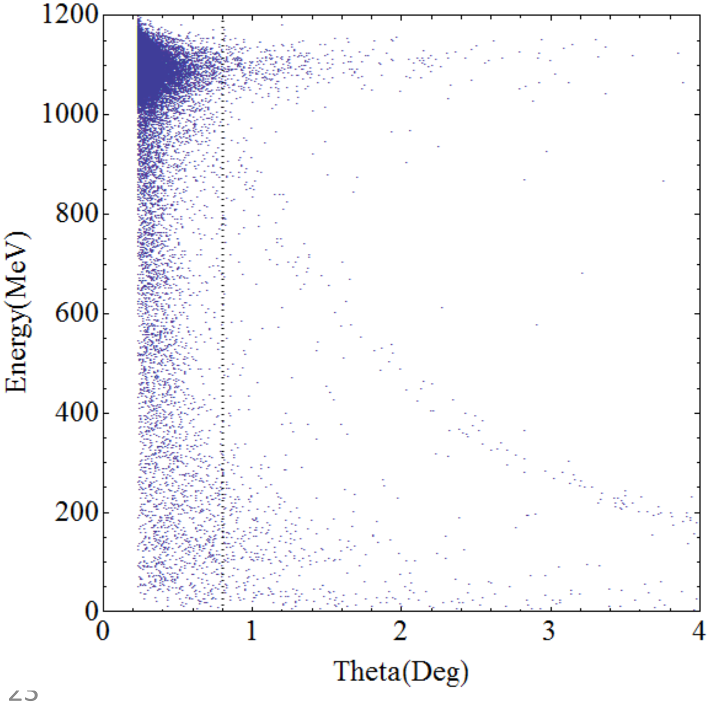
Arrington: Phys. Rev. Lett. 107, 119101 (2011)

TPE: M. Gorshteyn

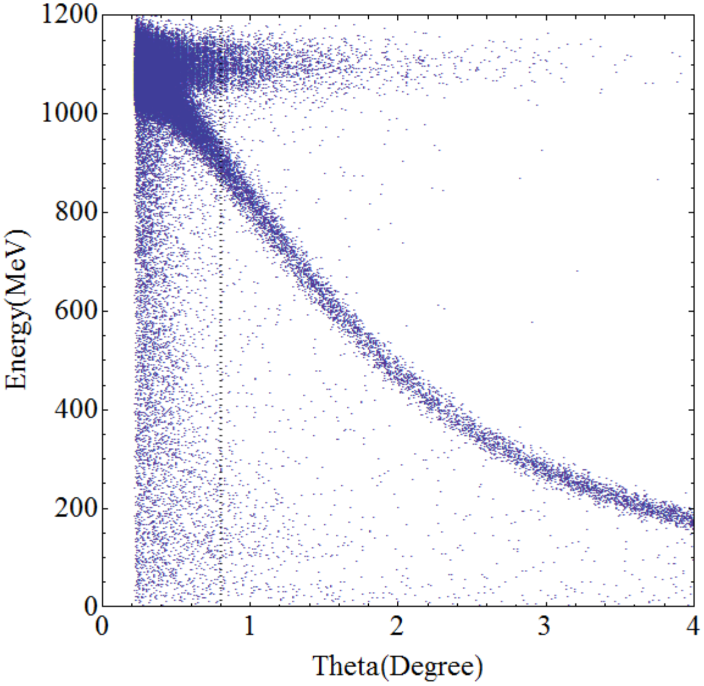
Full Simulation of the Experiment

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)

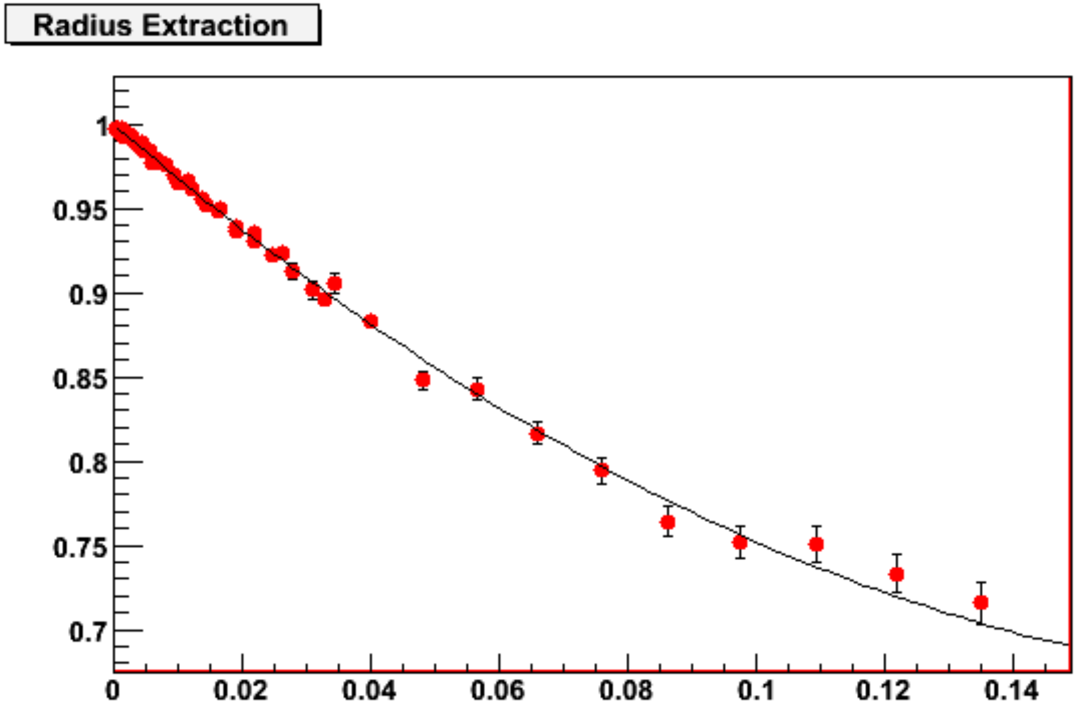
Full Simulation of the Experiment

A Geant4 based simulation of the
entire experiment has been developed

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

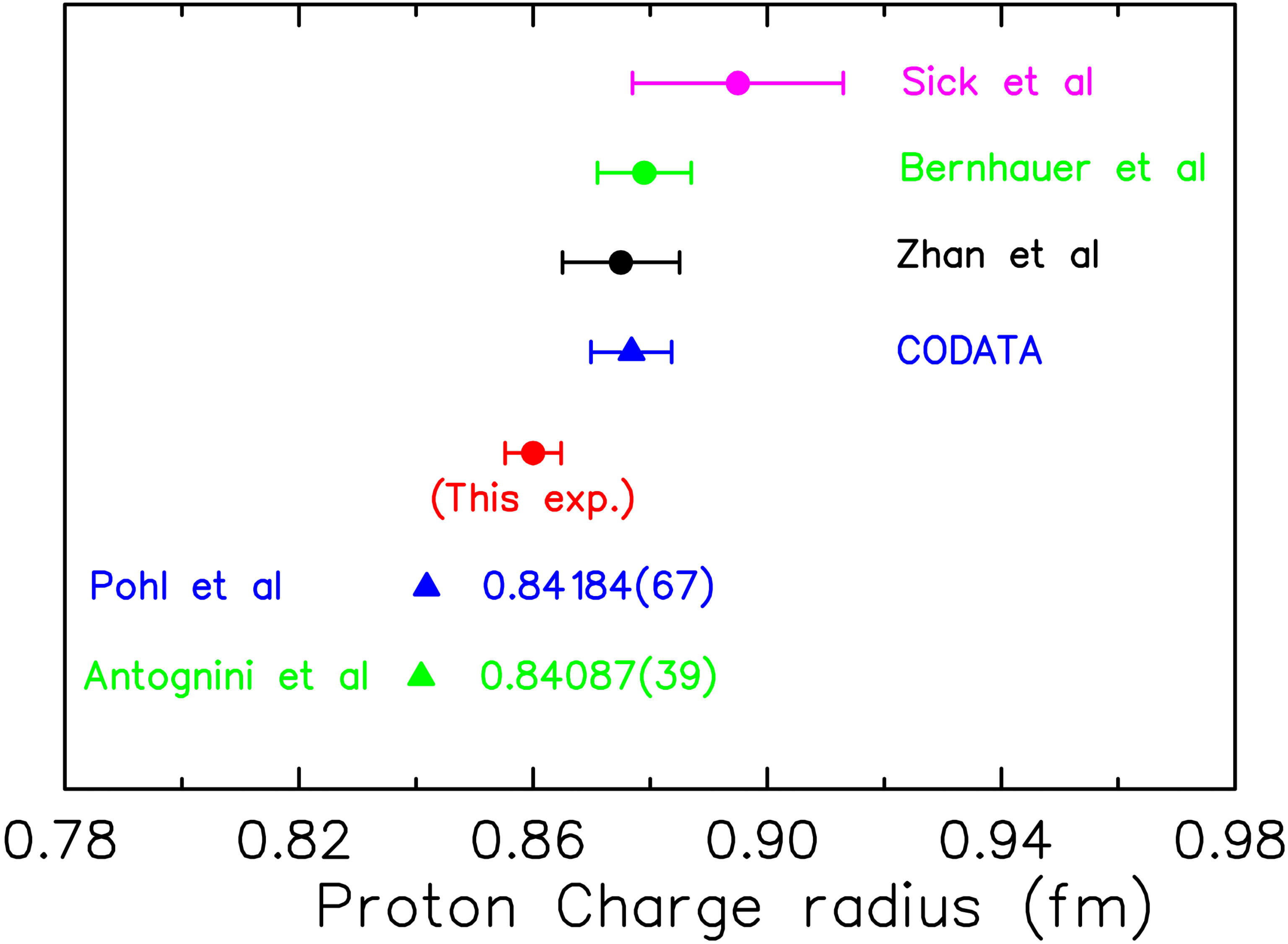
r_p = 0.8768 fm (input)

r_p = 0.8758(58) fm (extracted)

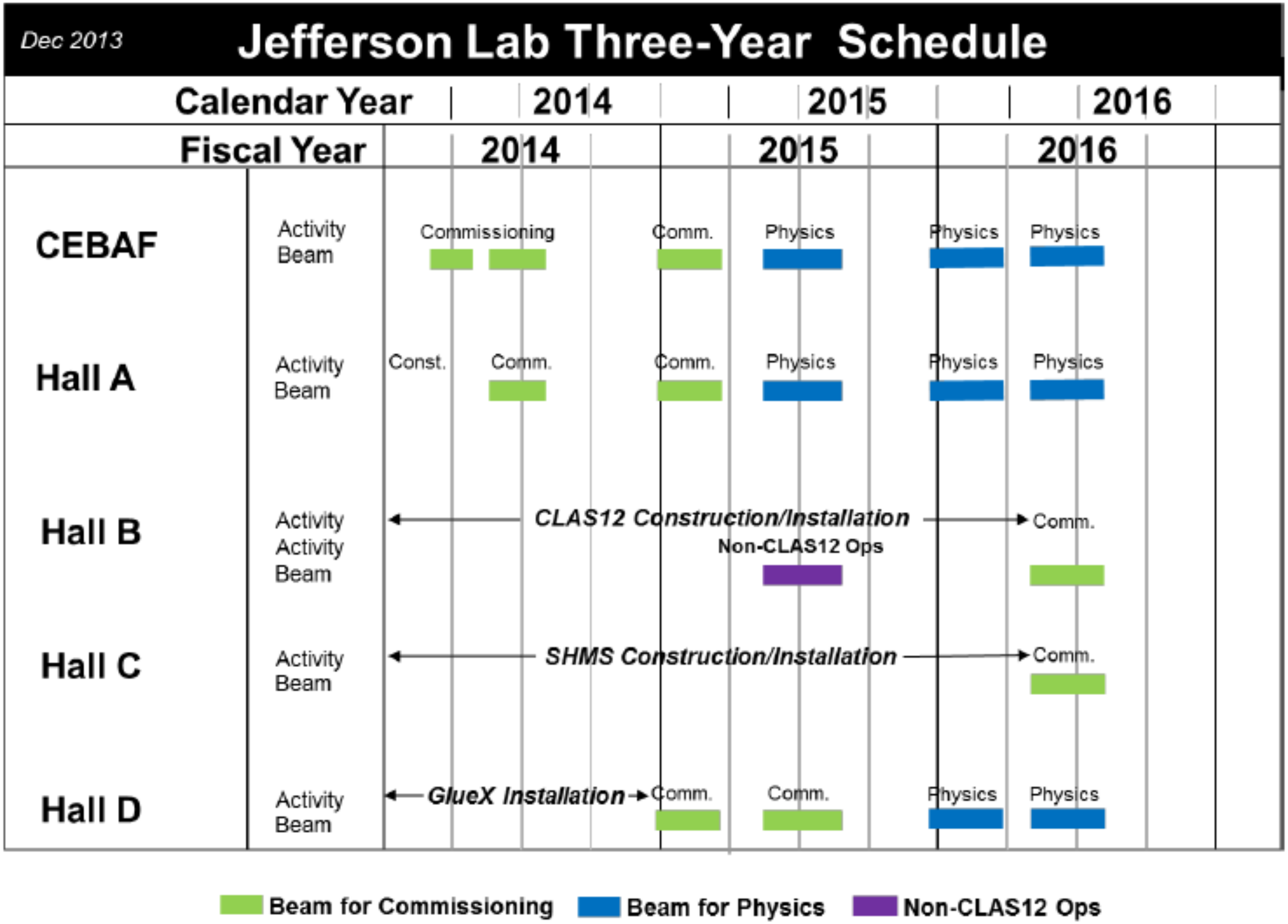


Simulations by
C. Peng

Projected Result



JLab Three-Year Run Plan



Dec 2013

Jefferson Lab Three-Year Schedule

Calendar Year 2014 2015 2016

Fiscal Year 2014 2015 2016

CEBAF
Activity: Commissioning, Comm., Physics, Physics, Physics
Beam

Hall A
Activity: Const., Comm., Comm., Physics, Physics, Physics
Beam

Hall B
Activity: *CLAS12 Construction/Installation* → Comm.
Activity: Non-CLAS12 Ops
Beam

Hall C
Activity: *SHMS Construction/Installation* → Comm.
Beam

Hall D
Activity: *GlueX Installation* → Comm., Comm., Physics, Physics
Beam

🟩 **Beam for Commissioning** 🟦 **Beam for Physics** 🟪 **Non-CLAS12 Ops**

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**
- New experiments at Mainz and PSI
- 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