High Precision Measurement of the Proton Charge Radius

(C12-11-106)

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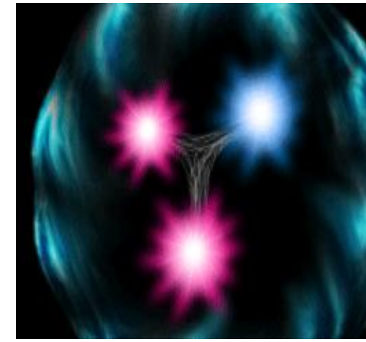
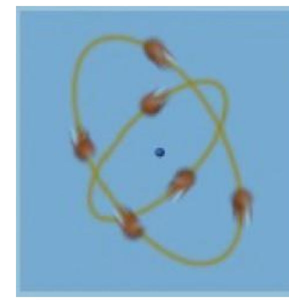
Outline

- Motivation of the experiment
- Proposed experiment
  - windowless hydrogen gas flow target
  - beam background
  - radiative corrections at very low Q^2
- Summary

Motivation of the Experiment

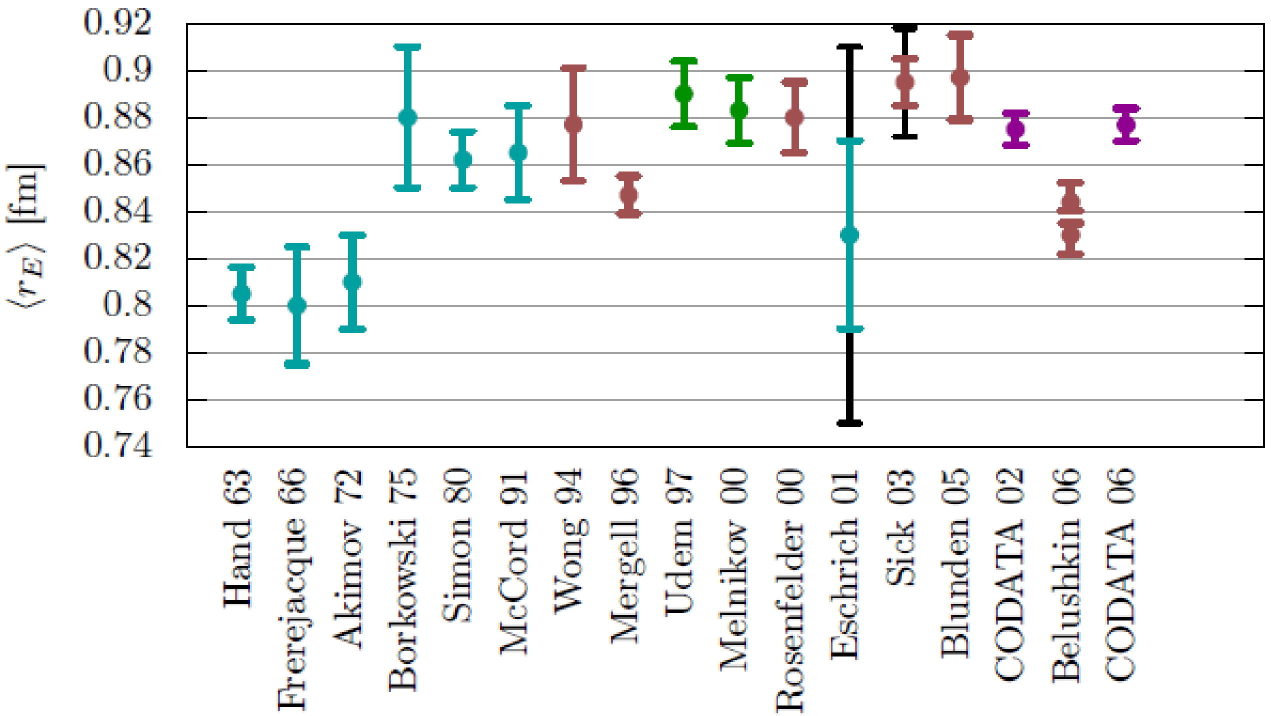
- Proton charge radius (r_p) is one of the fundamental quantities in physics
  - Important for nuclear physics:
    - long range structure of hadrons
    - test of upcoming lattice calculation
  - Critically important for atomic physics:
    - spectroscopy of atomic hydrogen
    - determination of Rydberg constant
      (the most accurately known constant in physics)
  - Connects nuclear and atomic physics
  - Arguably, the most referred quantity from outside of nuclear physics





- Three different ways to measure r_p
  - $ep \rightarrow ep$ elastic scattering at low Q^2
  - electronic-hydrogen spectroscopy (Lamb shift)
  - Muonic-hydrogen spectroscopy (Lamb shift)

Motivation of the Experiment (cont'd)
(r_p data before 2010)



(J. Bernauer)

CODATA → atomic Lamb shift

- More different analysis results than actual experiments
- Started with: $r_p \approx$ 0.81 fm in 1963
- Reached to: $r_p \approx$ 0.88 fm by 2006

Recent New Experimental Developments

- Muonic hydrogen Lamb shift experiment at PSI in 2010 (R. Pohl, et al., Nature 466, 213-217, 2010)
  - Spectroscopic measurement with unprecedented error:

The result: $\mathbf{r_p = 0.84184(67)}$ **fm** $< 0.1\%$ total error

✓ ***Different from most of previous experimental results !!!***

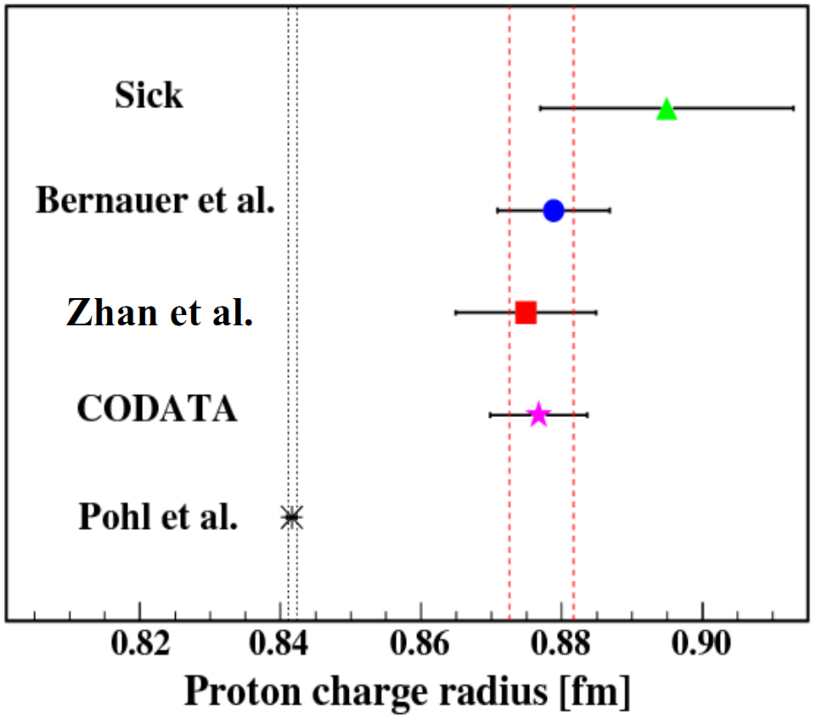
- High statistics $ep \rightarrow ep$ experiment at Mainz in 2010 (J. C.Bernauer, et al. PRL 105, 242001, 2010)
  - Relatively small Q^2 range: $Q^2 = [0.004 – 1.0]$ $(GeV/c)^2$
  - Statistical error $\leq 0.2\%$

The result: $\mathbf{r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}}$

✓ Confirms the previous results from ep- scattering;
✓ Consistent with CODATA06 value: (r_p=0.8768(69) fm)
✓ ***No change in r_p average value !***

- Plans for muonic-deuterium and muonic-helium Lamb shift measurements by same group
- New experimental proposal for $\mu p \rightarrow \mu p$ scattering at PSI

Summary of Current r_p Status



- <u>Open questions (after 2 years):</u>
  - additional corrections to muonic-hydrogen … ?
  - missing contributions to electronic-hydrogen … ?
  - higher moments in electric form factor …?
  - different ep and μp interactions … ?
  - new physics beyond SM … ?
- many models, discussions …
- no conclusions !

- 5 – 7 σ discrepancy between muonic and electronic measurements!
  current "proton charge radius crisis"

- A novel high precision experiment performed with an independent method is needed to address this crisis.

The Proposed Experiment

- Proposed to PAC38 for high precision $ep \rightarrow ep$ scattering experiment:
  with:
  - high resolution, large acceptance crystal calorimeter (HyCal)
    non-magnetic-spectrometer method
    - ✓ simultaneous detection of Moller process
      (best control of systematic errors)
    - ✓ reach smaller scattering angles: ($\theta = 0.8^0 - 3.8^0$)
      Q^2 = [$2x10^{-4}$ – $2x10^{-2}$] GeV^2 first time for ep-experiments
      essentially, model independent r_p extraction
  - use high density windowless H_2 gas flow target
    - ✓ lowest background experiment
    - ✓ beam background fully under control with high quality CEBAF beam

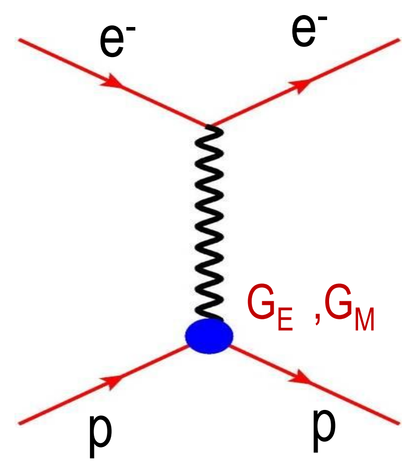
- Two energies E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision
- Conditionally approved by PAC38 to finalize and address:
  - Full target design
  - Radiative corrections at very low Q^2
  - Full background simulations

The Proton Charge Radius from $ep \rightarrow ep$ Scattering Experiments

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

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

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



- Structure less proton:

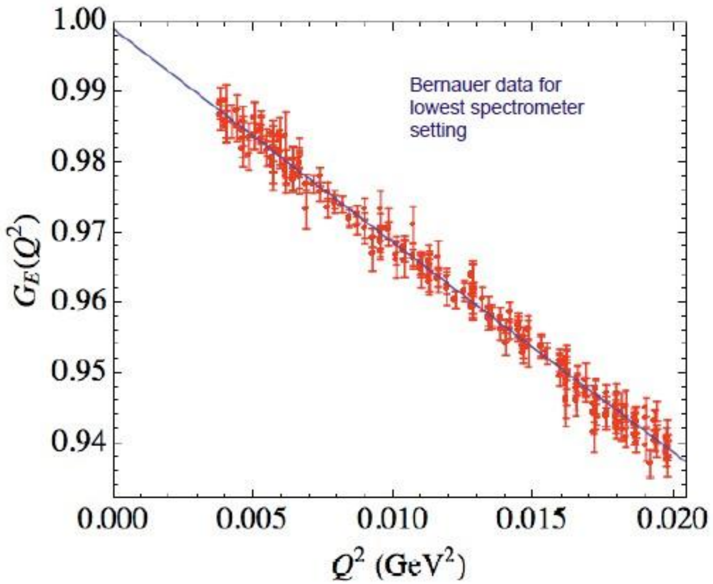
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2 \left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

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

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

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

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



Example of recent Mainz *e-p* experiment (2010)

Control of Systematic Errors

- Major improvements over previous experiments:
  1) Simultaneous detection of two processes
     - *ep* → *ep*
     - *ee* → *ee* Moller scattering → Tight control of systematic errors
  2) Windowless H_2 gas target → Low beam background
  3) Very low Q^2 range: $[2\text{x}10^{-4} – 2\text{x}10^{-2}]$ $(\text{GeV/c})^2$ → Model independent r_p extraction

- Extracted yield for *ep* → *ep*

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

- … and for *ee* → *ee*, Moller

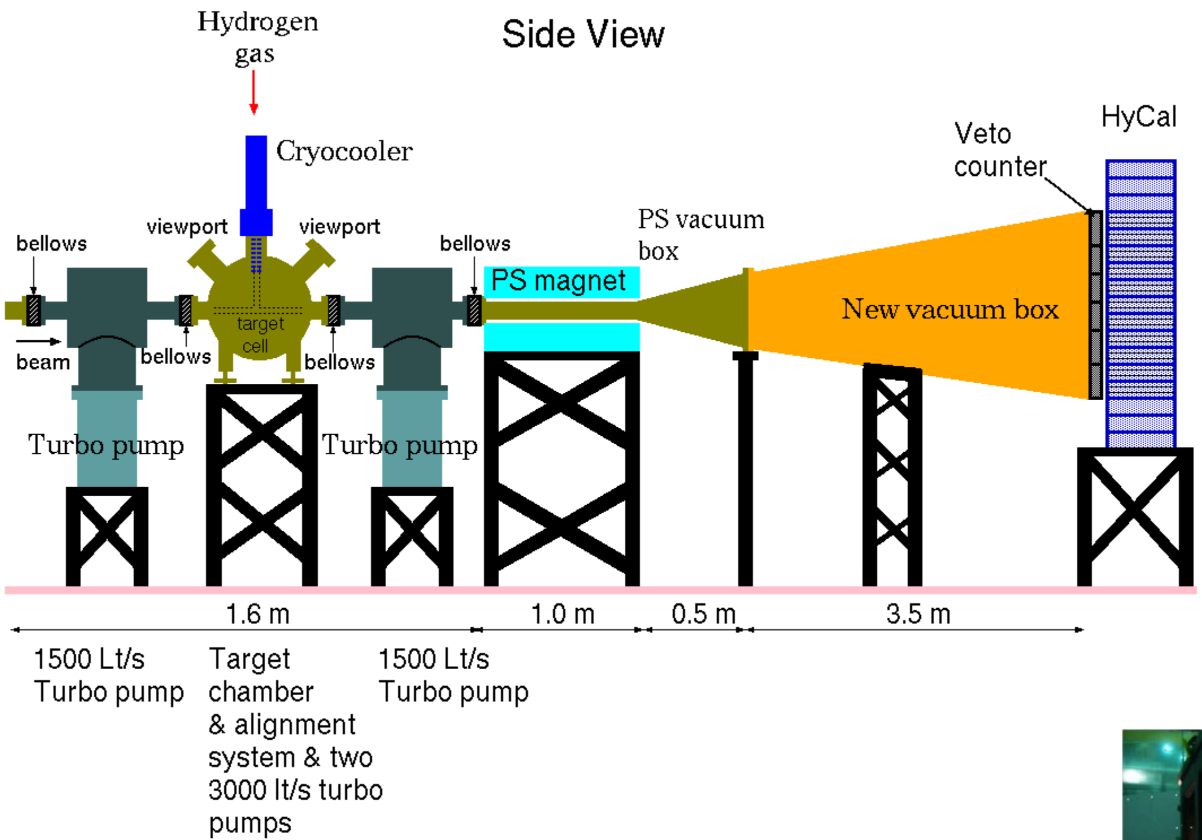
$$N_{\text{exp}}^{\text{yield}}(e^-e^- \rightarrow e^-e^-) = \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-} \times N_{\text{beam}}^{e^-} \cdot N_{\text{tgt}}^{\text{H}} \cdot \varepsilon_{\text{geom}}^{e^-e^-} \cdot \varepsilon_{\text{det}}^{e^-e^-}$$

- Then, *ep* cross section is related to Moller:

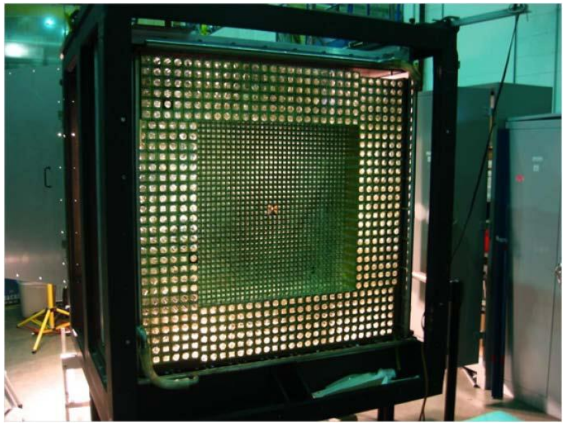
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep \rightarrow ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^- \rightarrow e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{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

- Two major sources of systematic errors, N_e and N_{tgt}, typical for all previous experiments, cancel out.
- Moller scattering will be detected in coincident mode in HyCal acceptance

Proposed Experimental Setup in Hall B



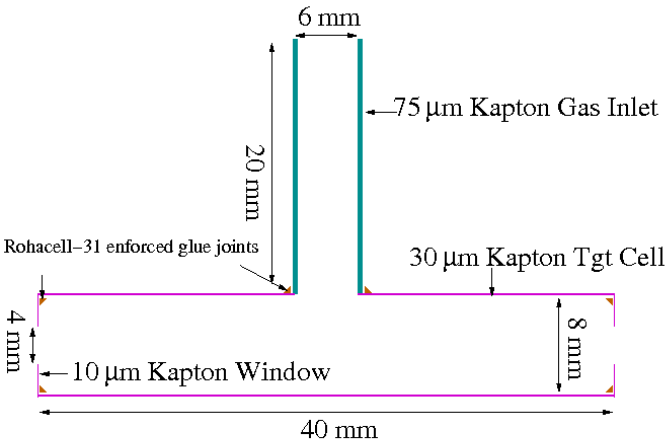
- High resolution, large acceptance HyCal calorimeter ($PbWO_4$ part only)
- Windowless H_2 gas flow target
- XY – veto counters
- Vacuum box, one thin window at HyCal only

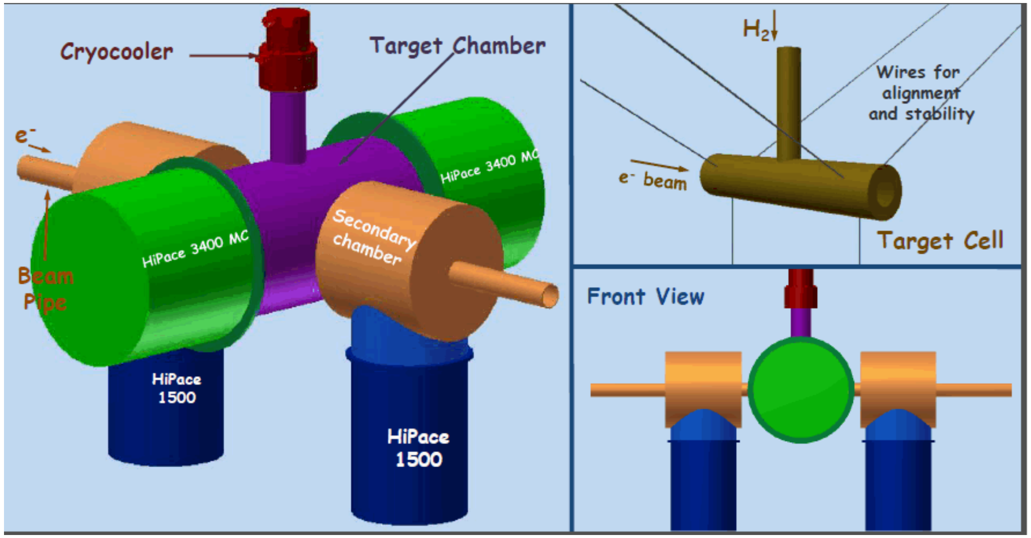


HyCal

Windowless H_2 Gas Flow Target

cell length	4.0 cm
cell diameter	8.0 mm
cell material	30 μm Kapton
input gas temp.	25 K
target thickness	$1x10^{18}$ H/cm^2
average density	$2.5x10^{17}$ H/cm^2
gas mass-flow rate	6.3 Torr-l/s





- Pre-engineering design finalized
- NSF MRI proposal developed and submitted for target construction

Beam Background Simulations

- GEANT based MC code developed with realistic experimental setup, including current windowless H_2 target

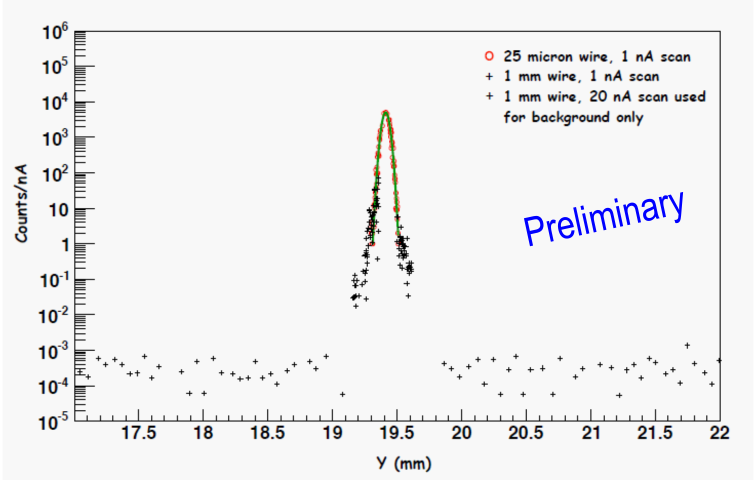
- Beam test successfully performed in Hall B
  - ✓ Thanks to Hall B management, staff and Accelerator group

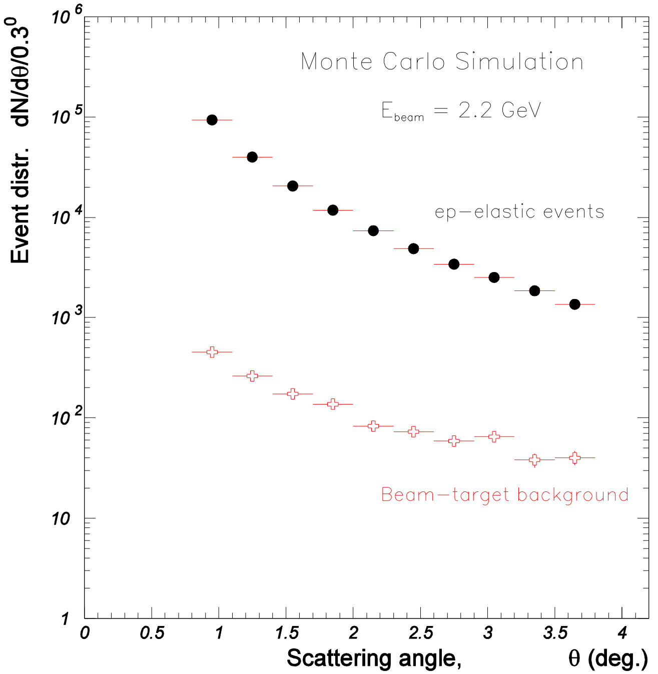
- high quality CEBAF beam parameters:
  - ✓ Signal/Noise $> 10^7$
  - ✓ beam size at target: ~ 100 μm

- Target design optimized to minimize beam background

- Beam background estimated to be at percent level
  - ✓ Major contribution from 30 μm Kapton cell

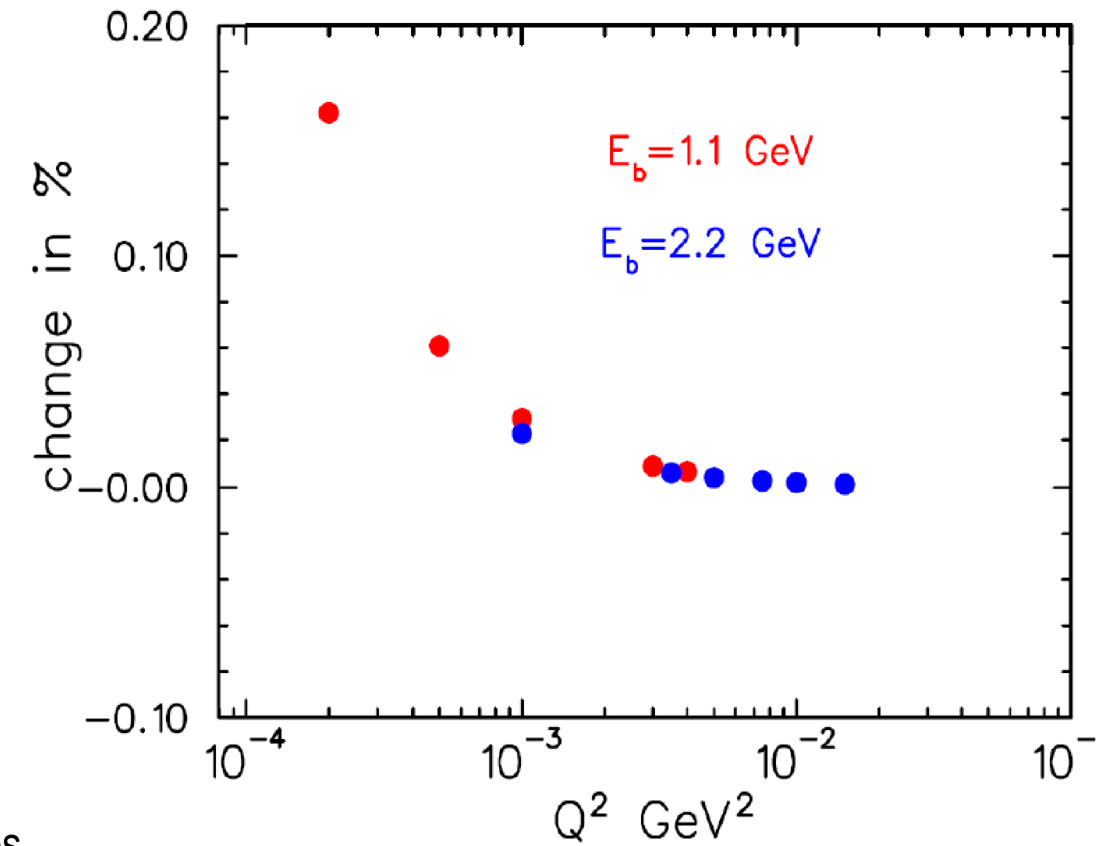
- periodic "empty target" measurements to control background on sub-percent level.



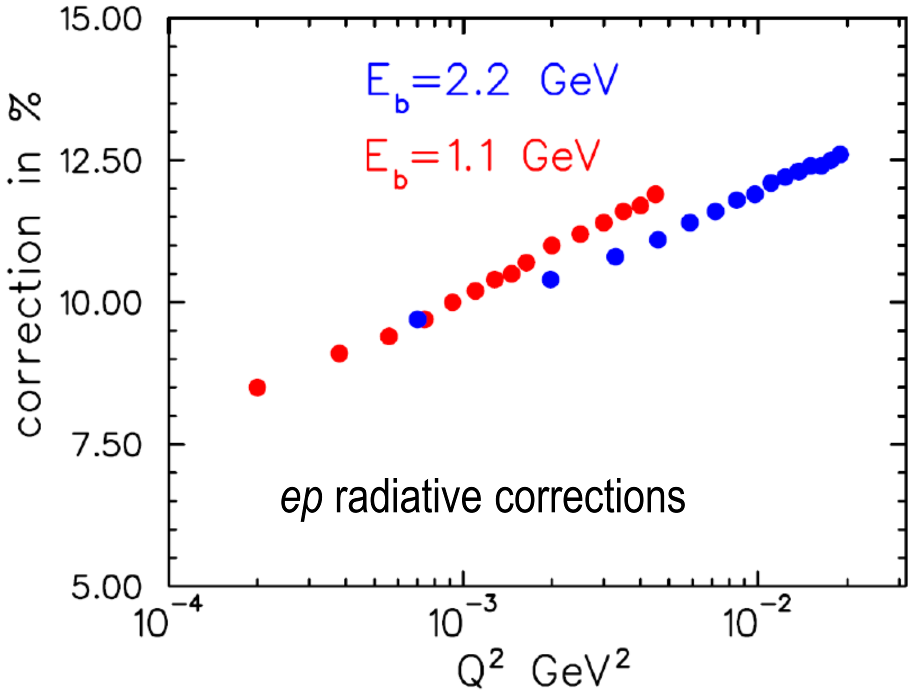


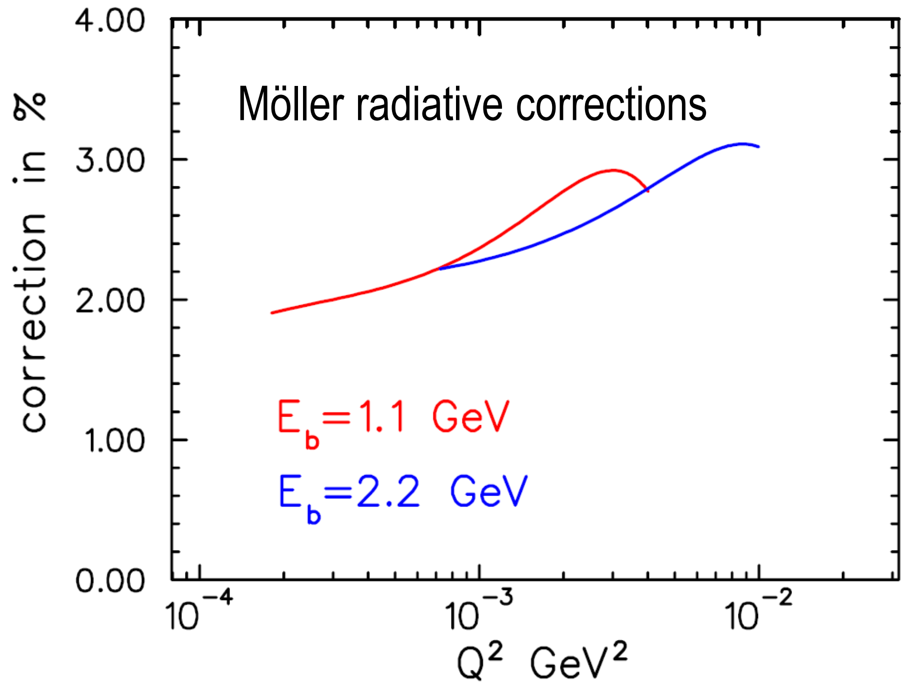
Radiative Corrections

- Use Bardin-Shumeiko covariant formalism to calculate RC
- Beyond the ultra relativistic approx. mass of the electron is not neglected
- The change in the cross section is less than 0.2% at the lowest Q^2 point
- Modified the elastic *ep* scattering codes ELRADGEN and MERADGEN accordingly



Radiative Corrections (cont'd)



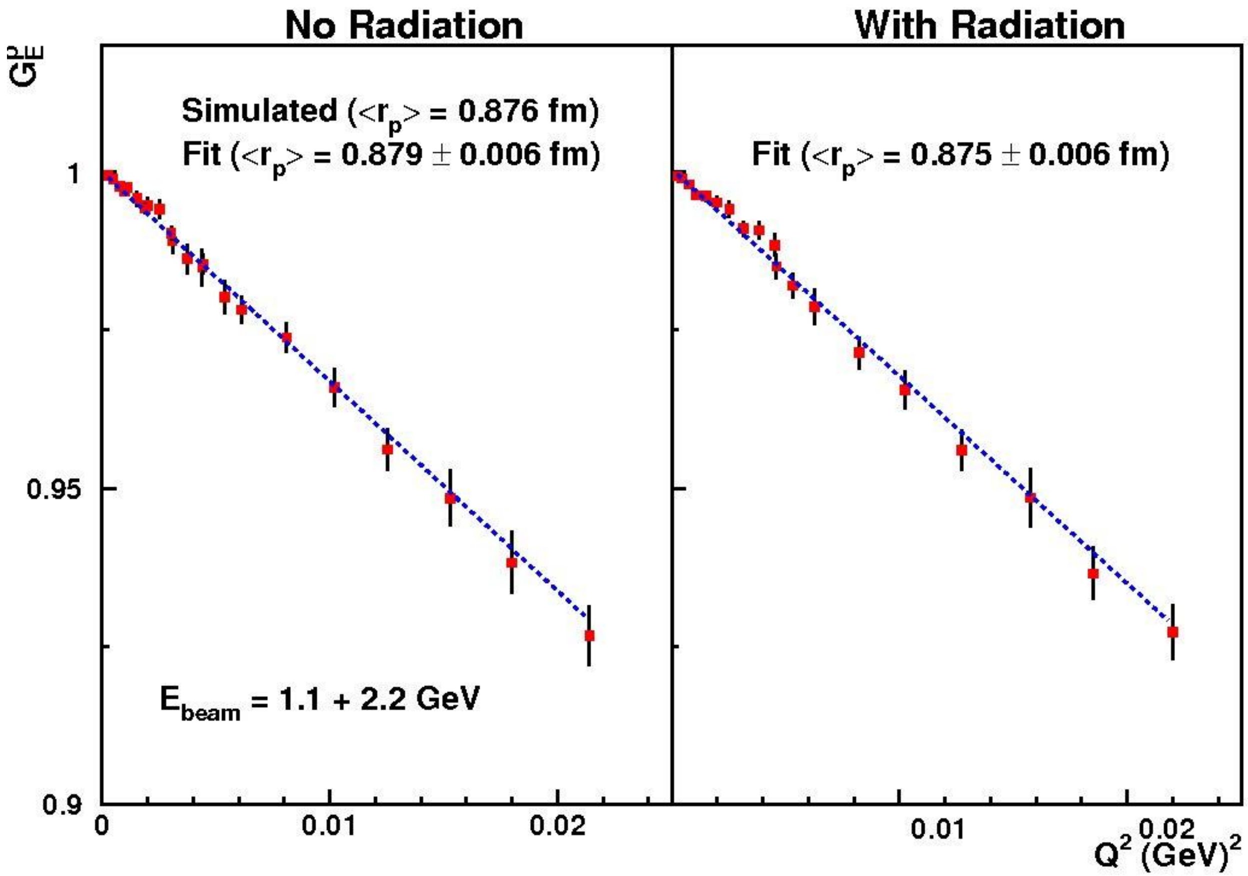


Corrections to the cross sections

ep : ~8 -13% (ELRADGEN)

Möller : ~2-3% (MERADGEN)

Extraction of Proton Charge Radius



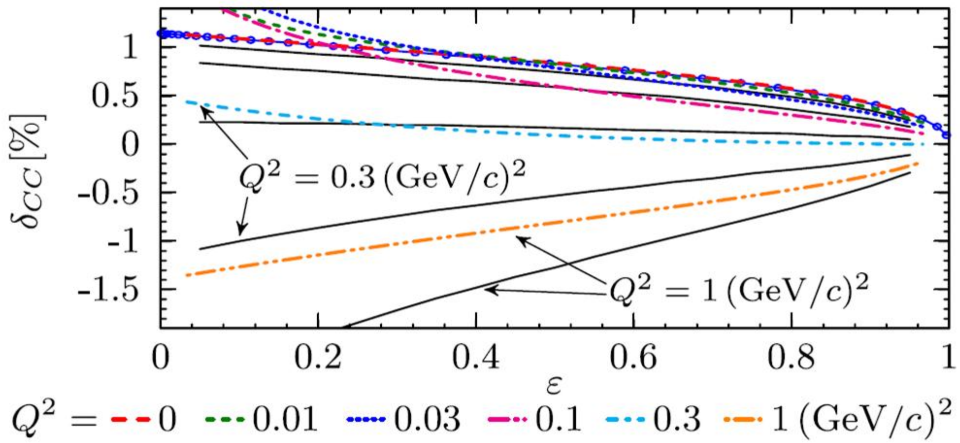
- Extraction of r_p from MC simulations with and without radiation
- Estimated systematic uncertainty < 0.3%

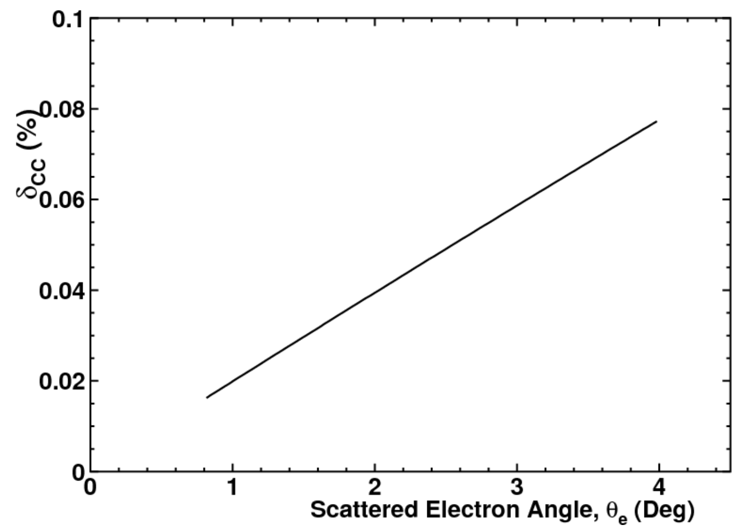
Responses to Theory Comments

- Theory comment:

1) *“…The* Coulomb corrections *should be re-discussed (they were in the original proposal) to convincingly show they will cause no problems for the data analysis. … ”*

✓ full Coulomb simulations performed for our kinematics (Fig. right)
✓ compared with other modern calculations (Fig. left).
✓ Coulomb corrections for our Q^2 range and $\varepsilon \approx 1$ are smaller than the sensitivity of this experiment.





- J. Arrington, PRL 107, 119101, 2011
- J.C. Bernauer, et al. PRL 107, 119102, 2011

Responses to TAC Comments

- TAC comments:

1) *"…coordinate with JLab engineers during the design and construction of the target to ensure that it meets the lab's stringent safety requirements …"*

   ✓ We agree with this comment and already from the pre-engineering design phase of the target we have closely worked with Jlab engineers. We will continue this during the entire period of the full engineering design, construction and installation of the target.

2) *"… A plan should be devised of how the focal plane will be maintained and calibrated after the Hall upgrade to 12 GeV operation …"*

   ✓ The photon tagger will be used for the

   (a) gain equalizing to make an effective trigger and

   (b) energy calibration of HyCal.

   For this, only a small part (upper ~20%) of the focal plane is needed.

   We will continue discussions and work out all possible tagger related options with Hall B management.

Beam Time Request and Error Budget

- target thickness: N_{tgt} = 1x10^{18} H atoms/cm^2
  I_e : ~10nA (N_e = 6.25x10^{10} e$^-$/s)

- for E_0= 1.1 GeV, Total rate for *ep → ep*
  $N_{ep} = N_e \times N_{tgt} \times \Delta\sigma \times \varepsilon_{geom} \times \varepsilon_{det}$
  ≈ 150 events/s ≈ 12.8 M events/day

Rates are high, however, for 0.5% stat. error for the last Q^2= 5x10^{-3} (GeV/c)^2 bin, 2 days are needed

	Time (days)
Setup checkout, calibration	3.5
H_2 gas target commission	5
Statistics at 1.1 GeV	2
Energy change	0.5
Statistics at 2.2 GeV	2
Empty target runs	2
Total	15

- Beam time

Contributions	Estimated Error (%)
Statistical error	0.2
Acceptance (including Q^2 determination)	0.4
Detection efficiency	0.1
Radiative corrections	0.3
Background and PID	0.1
Fitting error	0.2
Total Systematics	0.6%

- Estimated error budget (added quadratically)

Summary

- A novel experiment for the proton size measurement with an independent method is required to address the current "proton charge radius crisis". Jlab is in a position to make a long lasting impact on this important quantity in a timely and unique way

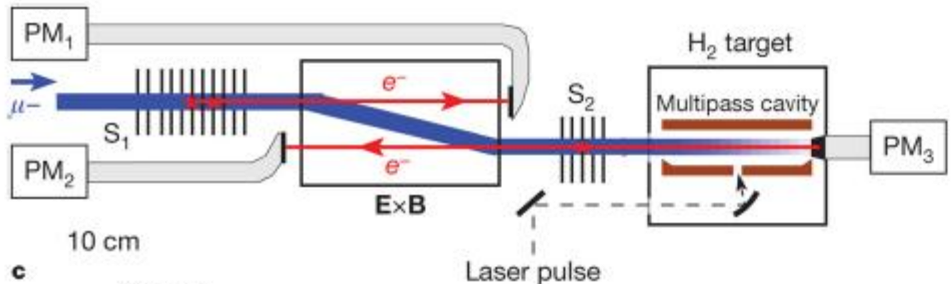
- New magnetic-spectrometer-free experiment with tight control of systematic errors:
  - ✓ ep→ep cross sections normalized to Moller scattering
  - ✓ reach very low Q^2 range: $[2\times10^{-4} – 2\times10^{-2}]$ GeV^2
  - ✓ windowless hydrogen gas flow target

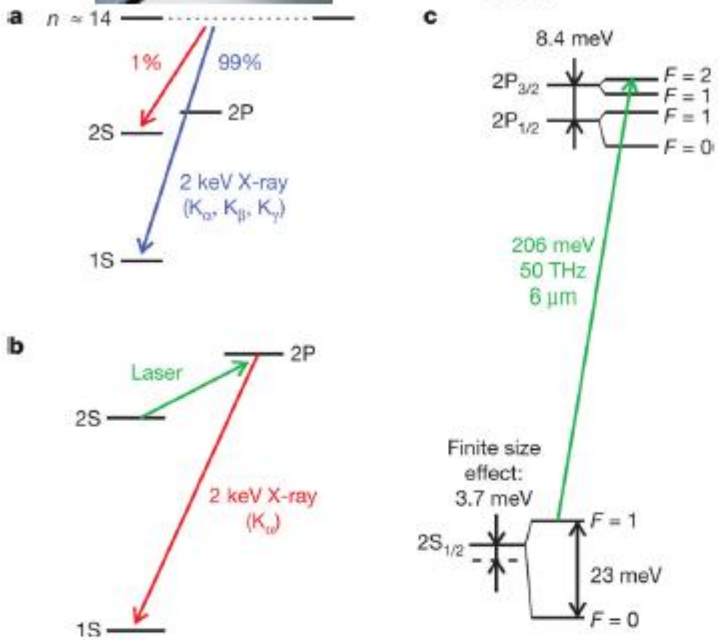
- Questions raised by PAC38 addressed:
  - ✓ Pre-engineering design of the new target is completed
  - ✓ Radiative correction codes improved at this Q^2 to provide less than 0.3% uncertainty
  - ✓ Full Monte Carlo simulation code developed for the experiment. Backgrounds are at percent level

- Requesting 15 days of beam time to measure r_p with sub-percent precision

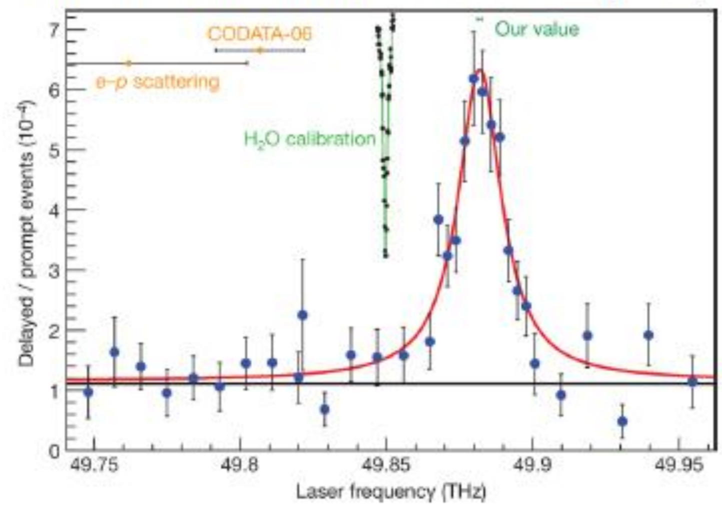
The End

Muonic Hydrogen Experiment (2010)





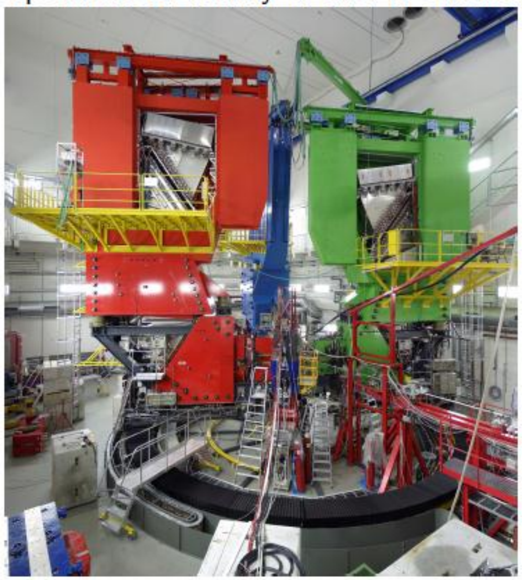
Pohl, R. et al. Nature 466, 213-217 (2010)

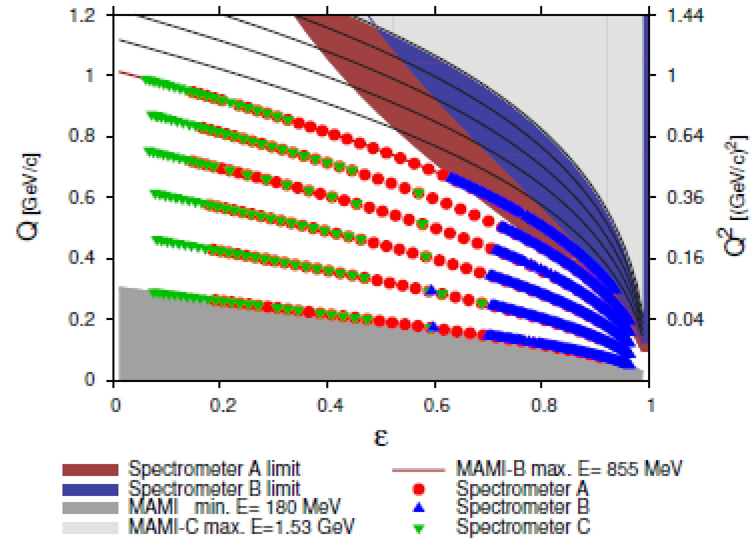


- Muonic hydrogen Lamb shift experiment at PSI
- **r_p = 0.84184(67) fm ➡ Unprecedented less than 0.1% precision**
- **Different from most of previous experimental results and analysis**

Recent Mainz High Precision $ep \rightarrow ep$ Experiment

Three spectrometer facility of the A1 collaboration:





- Large amount of overlapping data sets
- Statistical error ≤ 0.2%
- Luminosity monitoring with spectrometer
- Additional beam current measurements

- Q^2 = [0.004 – 1.0] (GeV/c)^2 range

J. Bernauer, PRL 105,242001, 2010

- Many form factor models, fit to all cross sections.

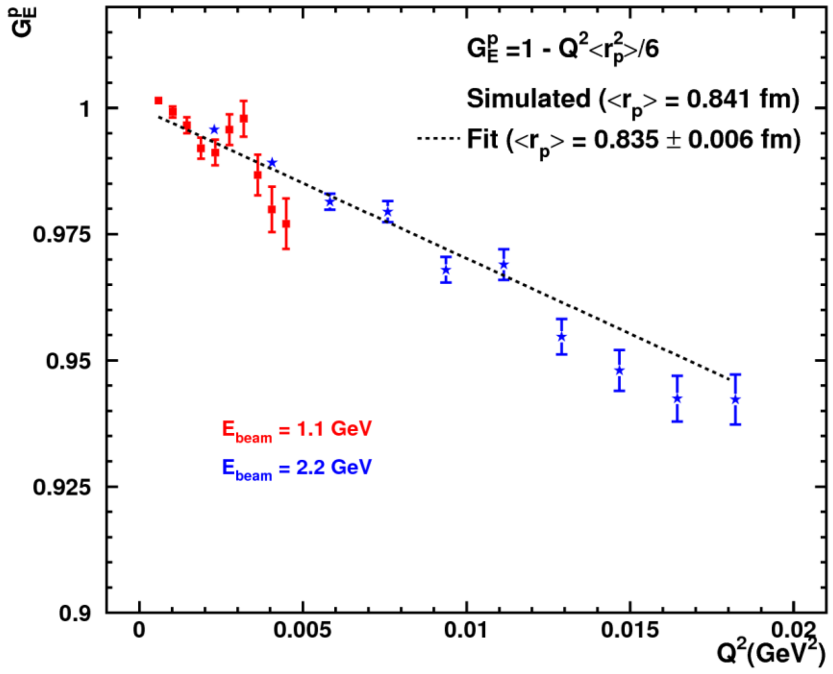
The result:

$\mathbf{r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}}$

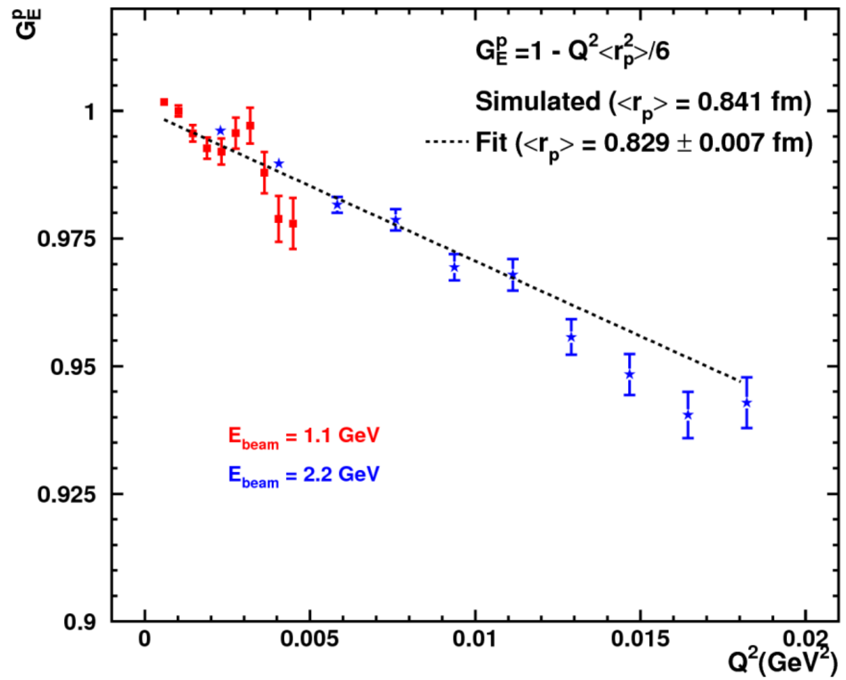
✓ Confirms the previous results from *ep→ep* scattering;
✓ Consistent with CODATA06 value: (r_p=0.8768(69) fm)

✓ No change in r_p average value !

Control of Systematic Errors (Calorimeter Misalignment)



0 mm shift $r_p = 0.835 \pm 0.006$ fm



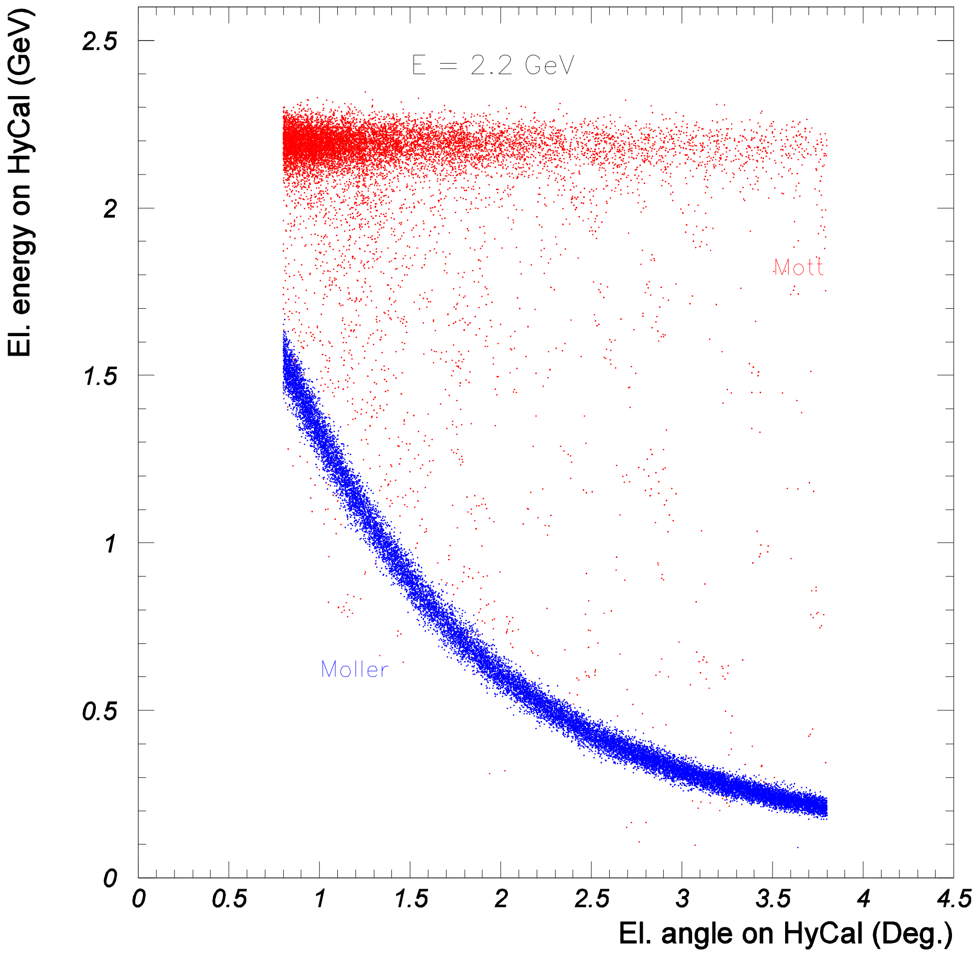
1 mm shift $r_p = 0.829 \pm 0.007$ fm

- accuracy of engineering survey: 0.7 mm
- Off-line check with co-planarity of Moller events (done in PrimEx experiments with Compton)

➢ HyCal misalignment is not a problem for r_p extraction

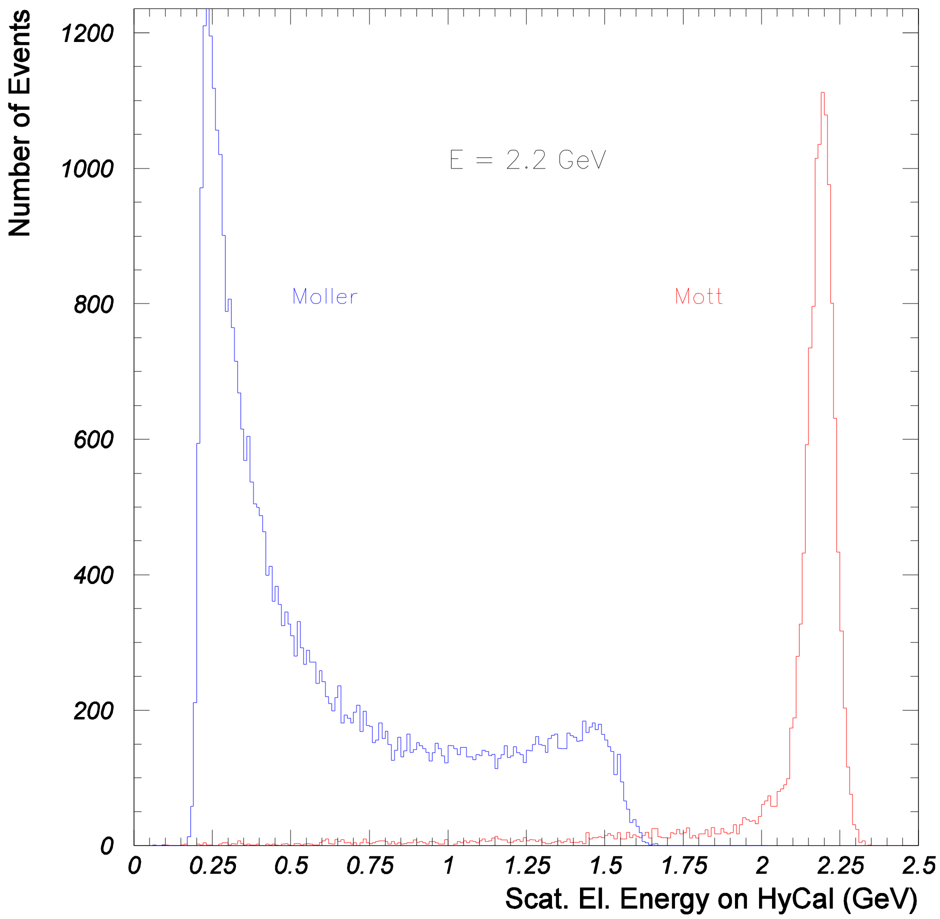
Elastic/Moller Overlap

- Overlap of $E_{e'}$ spectra of radiated events



Elastic/Moller Overlap

- Overlap of $E_{e'}$ spectra of radiated events contamination from Moller events (for $0.8 < \theta_{e'} < 3.8$ deg)



Control of Systematic Errors (cont'd)
(Moller event selection)

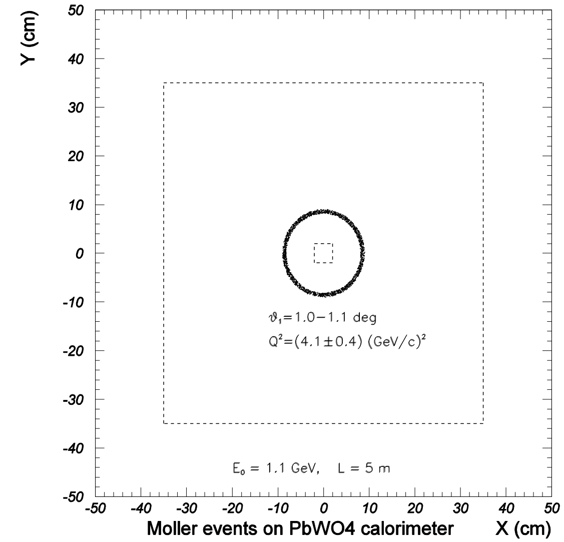
Will analyze Moller events in 3 different ways:

1) Single-arm method: one Moller e^- is in the same Q^2 range

ε_{det} will be measured for [0.5 – 2.0] GeV range

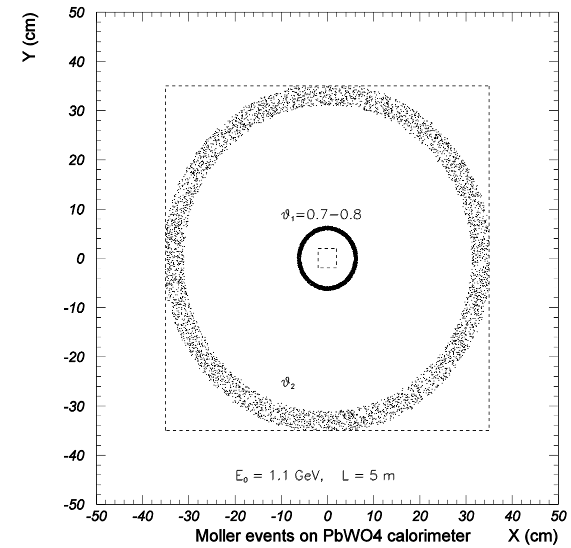
Relative ε_{det} are needed for this experiment

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



2) Coincident Method

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



3) Integrated over HyCal acceptance

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

Relative ε_{det} will be measured with high precision.

Contribution of ε_{det} and ε_{geom} in cross sections will be on second order only.

Event Rate and Statistics

With hydrogen gas target thickness: $N_{tgt} = 1\text{x}10^{18}$ H atoms/cm^2
Electron beam intensity: ~10nA ($N_e = 6.25\text{x}10^{10}$ e^-/s)

- For E_0= 1.1 GeV run
  - Total rate for *ep → ep*

    $N_{ep} = N_e \text{ x } N_{tgt} \text{ x } \Delta\sigma \text{ x } \varepsilon_{geom} \text{ x } \varepsilon_{det}$
    $= 6.25\text{x}10^{10} \text{ x } 1.10^{18} \text{ x } 3.14\text{x}10^{-26} \text{ x } 0.75 \text{ x } 1.$
    ≈ 150 events/s
    $\approx$ 12.8 M events/day

Rates are high, however, for 0.5% stat. error for the last Q^2= $5\text{x}10^{-3}$ (GeV/c)^2 bin, 2 days are needed

  - Rate for *ee → ee* cross sections are higher, but geometrical acceptance is less:

    $N_{ee} = 6.25\text{x}10^{10} \text{ x } 1.10^{18} \text{ x } 6.8\text{x}10^{-26} \text{ x } 0.005 \text{ x } 1.$
    ≈ 200 events/s
    $\approx$ 17.3 M events/day High rate will provide good statistics

- For E_0 = 2.2 GeV run:
  - The *ee → ee* $\sigma_{ee} \approx 1/E_0$ But, ε_{geom} is increasing, the rate is ≈ constant
  - The *ep → ep* $\sigma_{ep} \approx 1/E_0^2$ However, only last bin: $Q^2 = 2.\text{x}10^{-2}$ (GeV/c)^2 will have ≈1% stat. error for the same 2 days of run

HPS Quality Electron Beam Test

- Signal/Noise ≈ 10^8 level reached starting from ± 2 mm from beam center
- Electron beam size ≈ 25 μm