The Proton Radius: ~~Preliminary~~ Final Result from the PRad Experiment

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for the PRad collaboration

PRoton Radius

University of Virginia

Jefferson Lab
Exploring the Nature of Matter

Outline

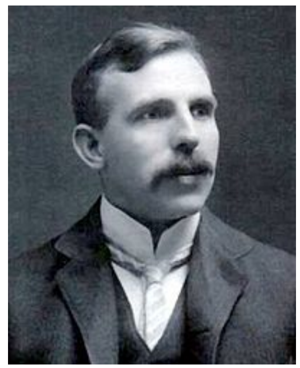
- The proton
- Proton Radius Puzzle: current status
- Our approach for a new ep scattering experiment: Prad
- ~~Preliminary~~ Final results
- Summary and outlook

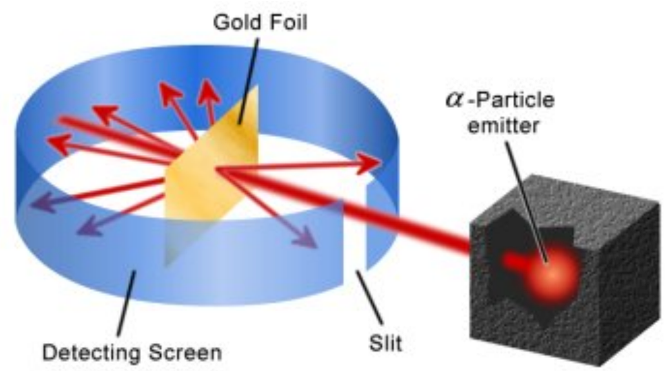
Randolph Pohl et al.

Story of the Proton

Proton is the most studied sub-atomic particle

- It has been over hundred years since Rutherford postulated the existence of the proton

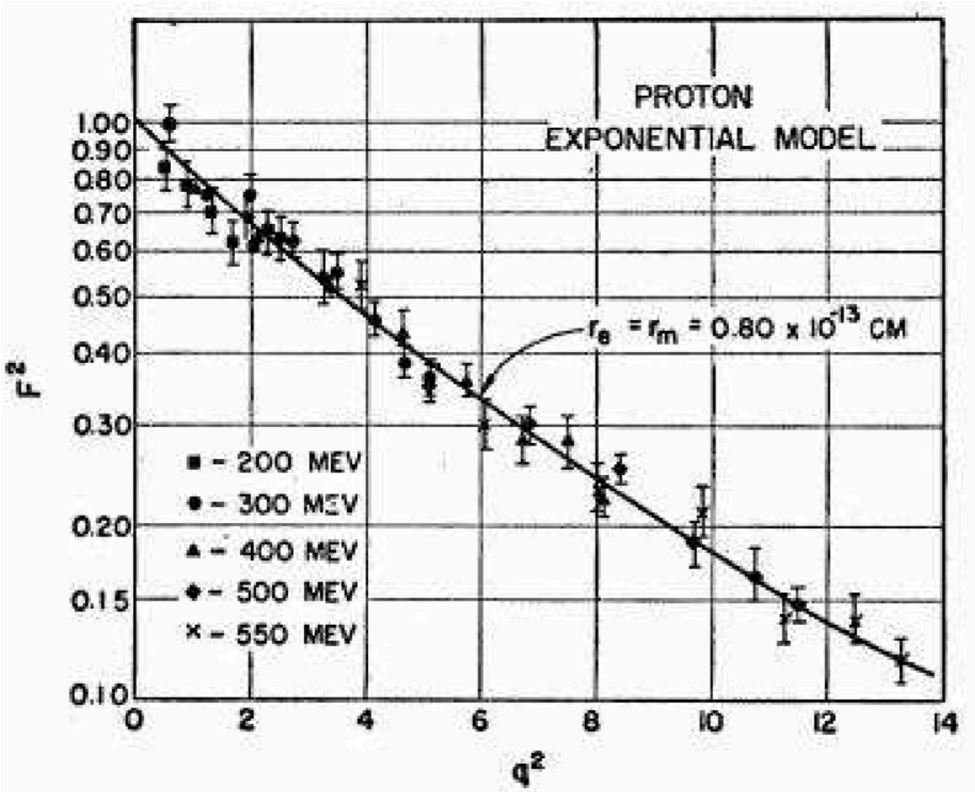




- In 1933 Stern measured the anomalous magnetic moment of the proton to show that proton is NOT an elementary point like particle.

Electron Scattering to Probe the Proton

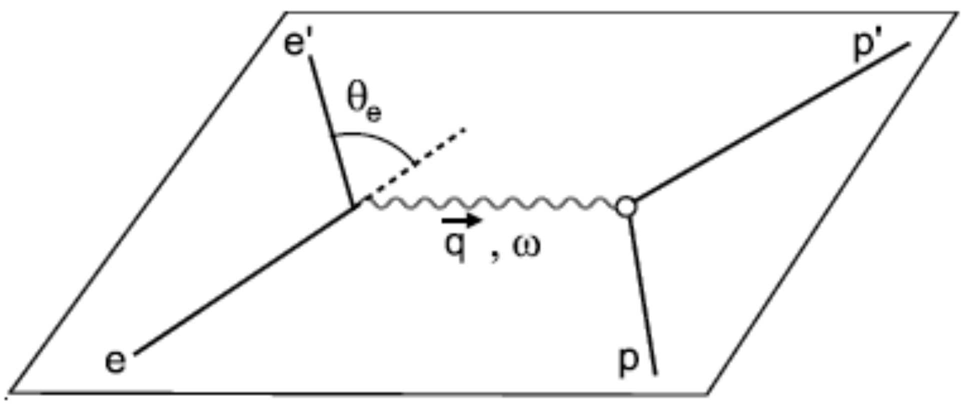
Hofstadter 1958: electron scattering to measure proton radius ~ 0.8 fm.



Electron Scattering to Probe the Proton

Hofstadter used the charge form factor to describe the charge distribution of the proton:

$$F(q) = \int_{volume} \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3 r$$



F(q) is the probability amplitude for the proton to absorb the exchanged photon

So the probability of elastically scattering off the proton:

$$\sigma(\theta_e) = \sigma_{Mott} |F(\mathrm{q})|^2 \Rightarrow [F(\mathrm{q})]^2 = \frac{\sigma(\mathrm{q})}{\sigma_{Mott}(\mathrm{q})}$$

Story of the Proton, continued….

MIT-SLAC experiments 1967: Deep Inelastic electron Scattering off protons to confirm the quarks inside the proton.

Kendall, Friedman and Taylor et al.

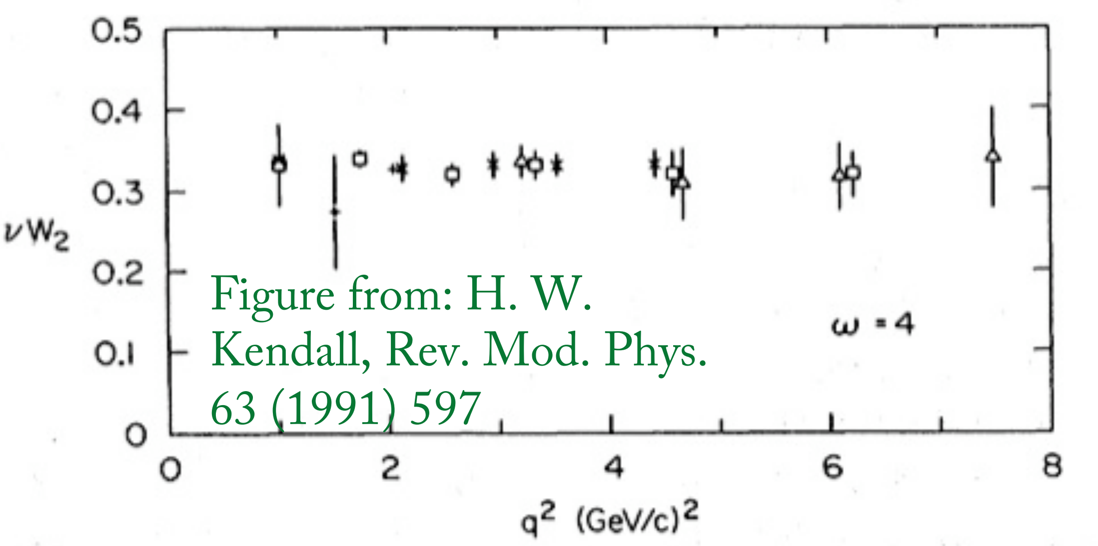
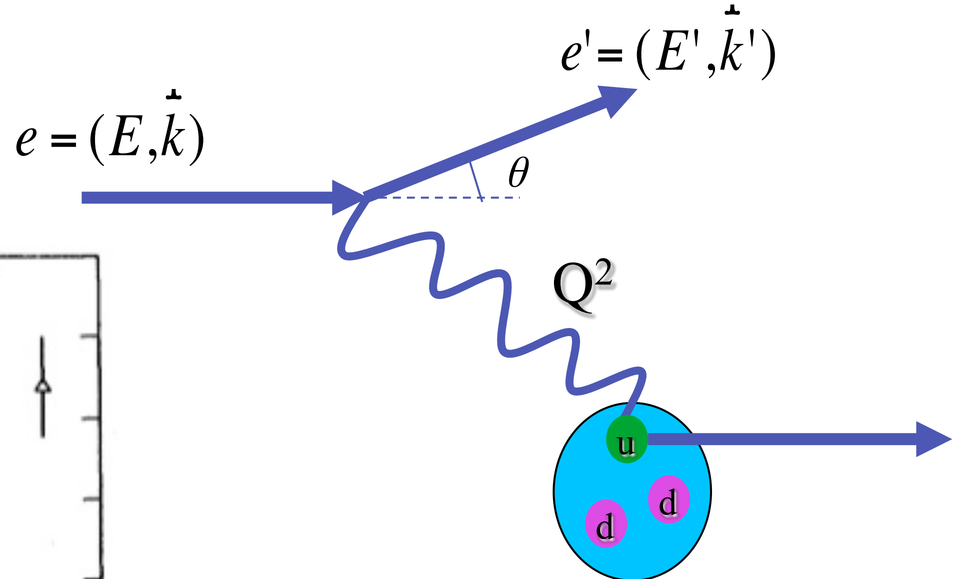
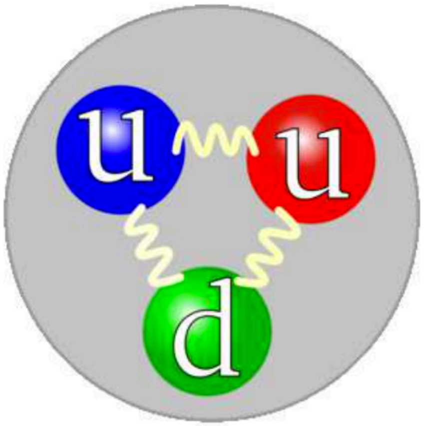


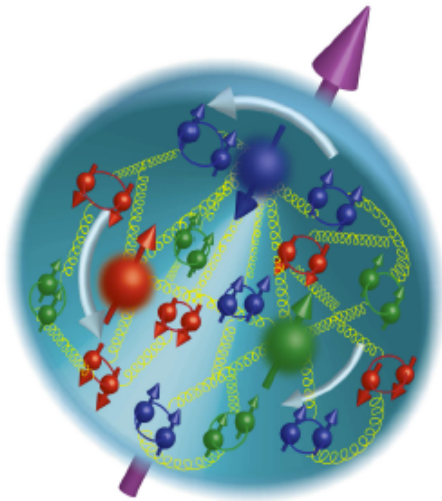
Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597



Story of the Proton, continued….

- 1970's: Quantum Chromo Dynamics (QCD): theoretical framework for strong interaction between quarks medicated by gluons.
- 1980's – Today: Looking deep inside the proton





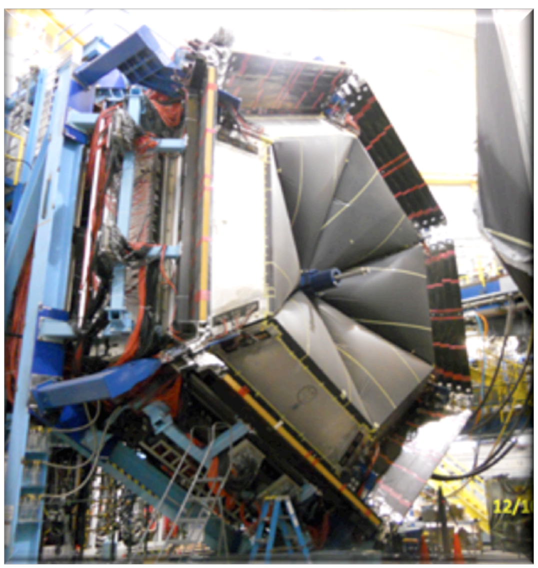
Proton: an ideal laboratory to understand strong interaction

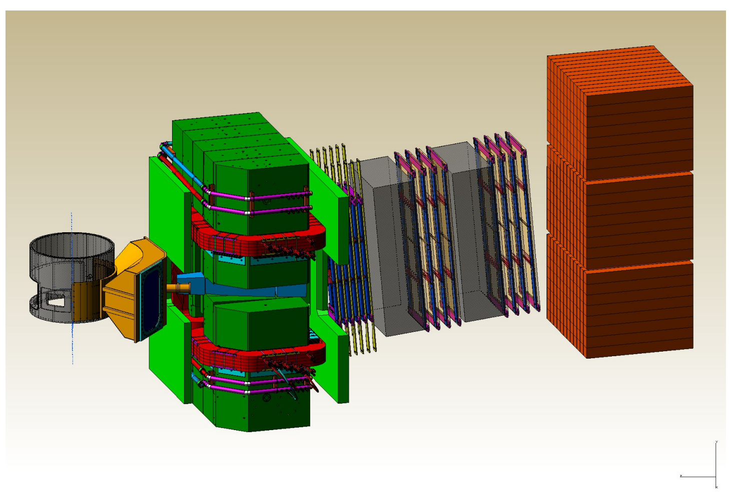
Many deep questions to answer

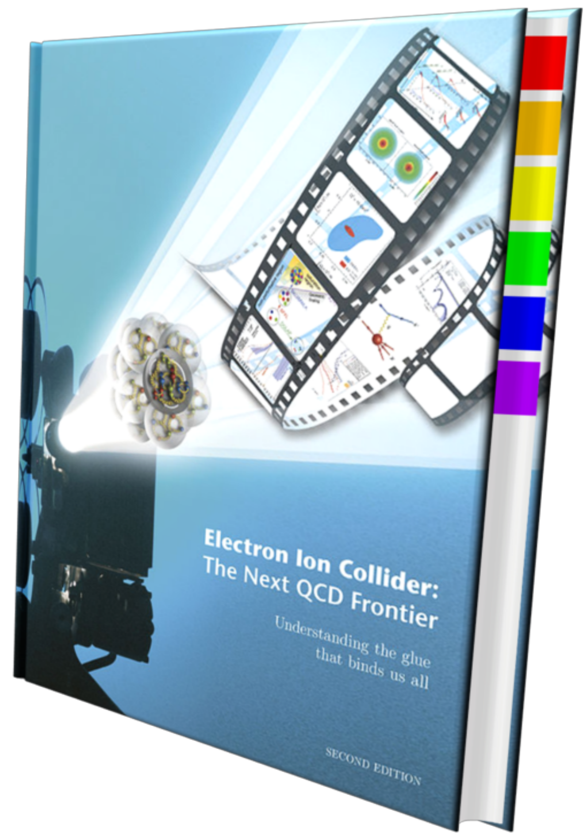
- How does proton acquire its mass: only ~1% of proton mass comes from Higgs.
- What are the different contributions to nucleon spin ?
- How does the confinement come about ?
- What role does the gluon play in all these ??

Exciting times ahead for the proton

- Jefferson Lab 12 GeV
  - 3D structure of the proton: GPDs
  - Ground stated properties with high resolution: high Q^2 FF.
- Electron Ion Collider
  - Understand the role of gluon

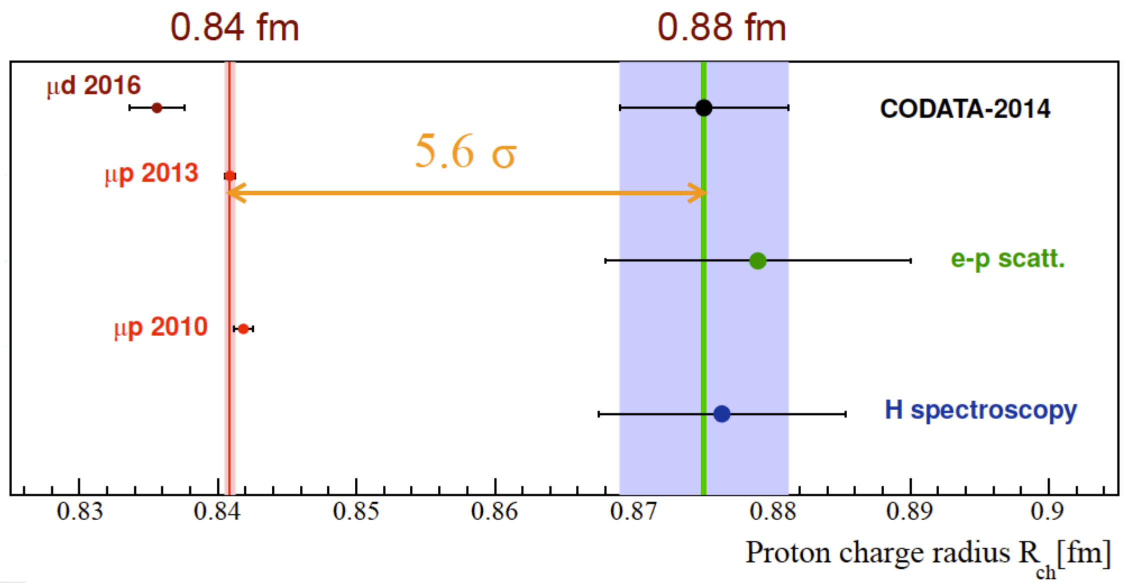


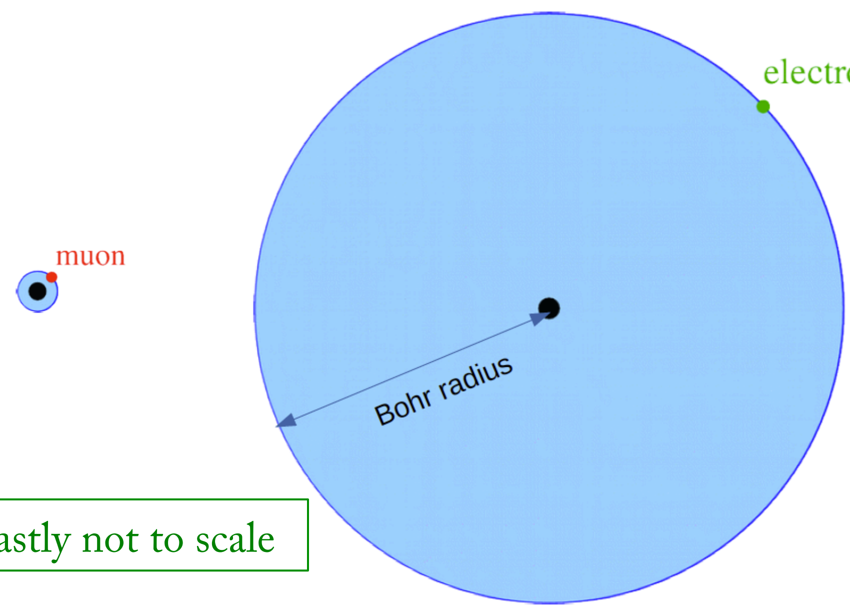




Surely, there is a lot to learn about the proton, …

But we thought we at least understood the ground state bulk properties of the proton well, until….

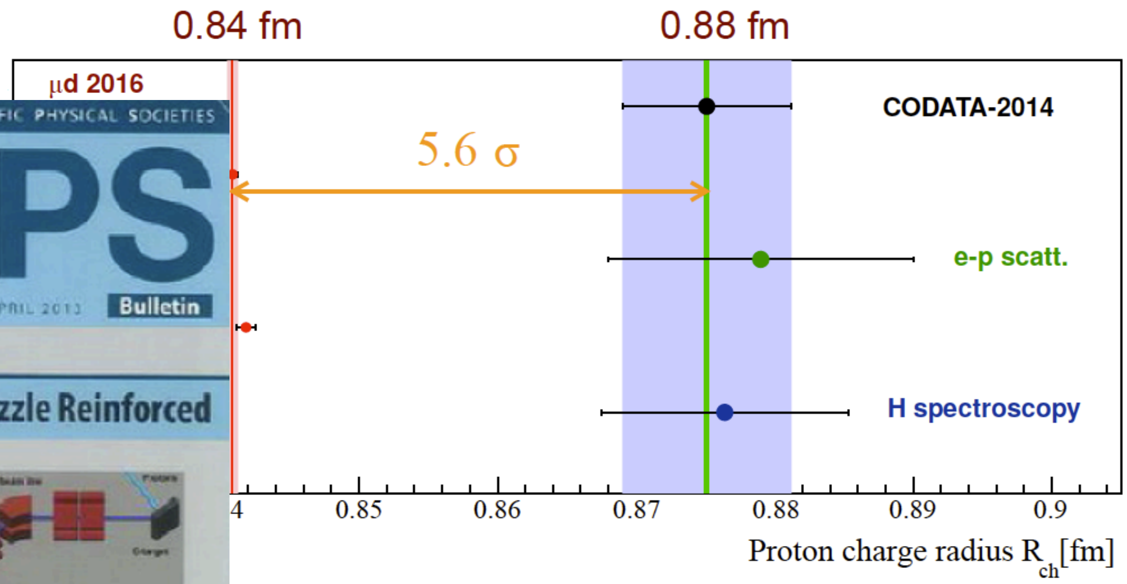




vastly not to scale

Surely, there is a lot to learn about the proton, …

But we thought we at least understood the ground state bulk properties of the proton well, until….

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8 July 2010 | www.nature.com/nat
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First hints of how their
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TINY PARTICL BIG PROBLEI
The humble proton i
nothing like we exp
EVOLUTION
IN MINIAT
It works differently if y
People Who Remember Everything
A New Way to Tame Cancer
The Benefits of Video Games (Really)
SCIENTIFIC AMERICAN
The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?


SCIENTIFIC AMERICAN
O enigma do
Próton
环球科学 SCIENTIFIC AMERICAN
2013年度创新榜:
最具影响力研发中心
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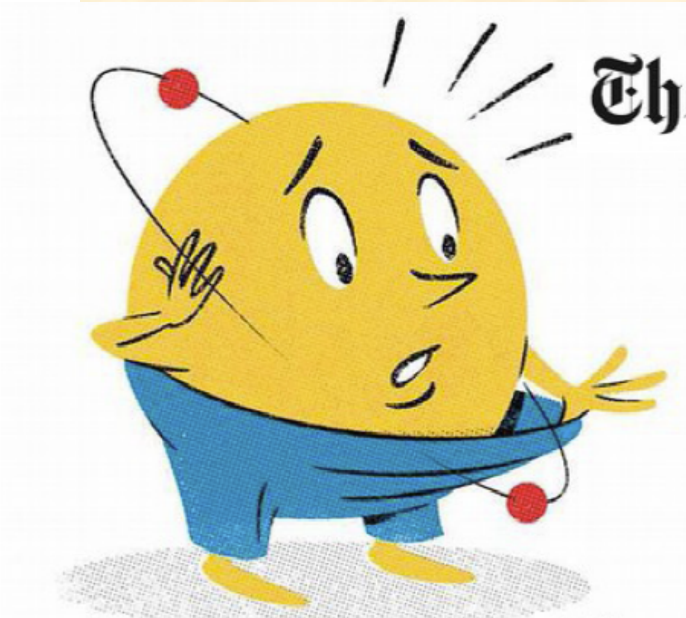
The Big deal about the Proton Radius



The New York Times

OK, the proton may be ~5% smaller than we thought, so what's the big deal ?

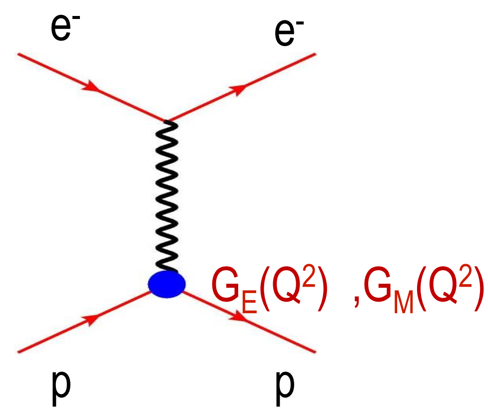
- Important bench-mark quantity for many calculations.
  - nuclear physics (QCD, Lattice, …)
  - atomic physics (QED, Lamb shifts, …)
- directly correlated to the Rydberg constant (most accurately known constant in physics)
- potential for "New Physics"
  - Lepton universality in question ??? !!
  - Coupling to unknown particles ?

Elastic electron-proton Scattering Formalism

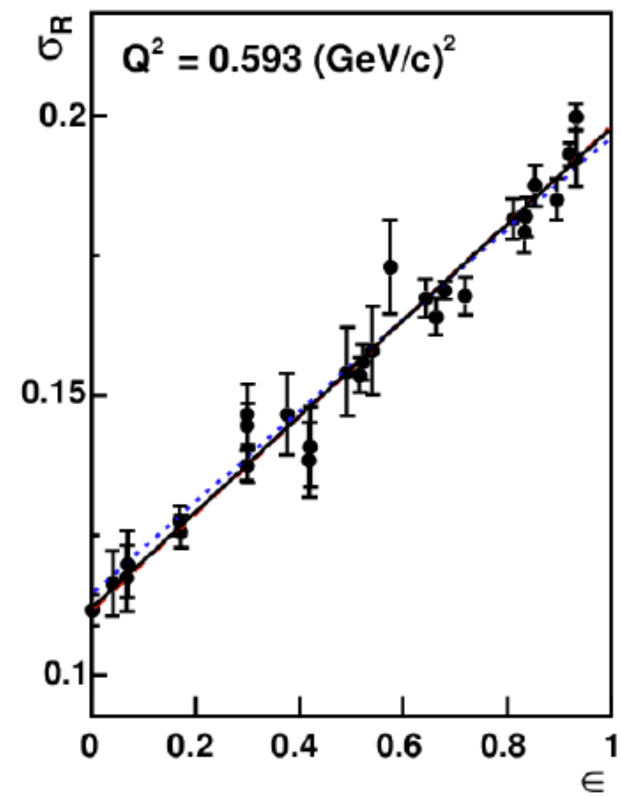
In one photon approximation the elastic *ep* scattering

$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

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



- $G_E(Q^2)$ and $G_M(Q^2)$ extracted using Rosenbluth separation
- Measure the reduced cross section at several values of ε while keeping Q^2 fixed.
- Extract G_E from the slope
- At extremely low Q^2 the G_M contribution is small, like in the PRad experiment



Proton Mean Square Charge Radius

Classically:

$$\langle r^2 \rangle = \int \rho(r) r^2 d^3 r$$

Using the QED formalism: with the

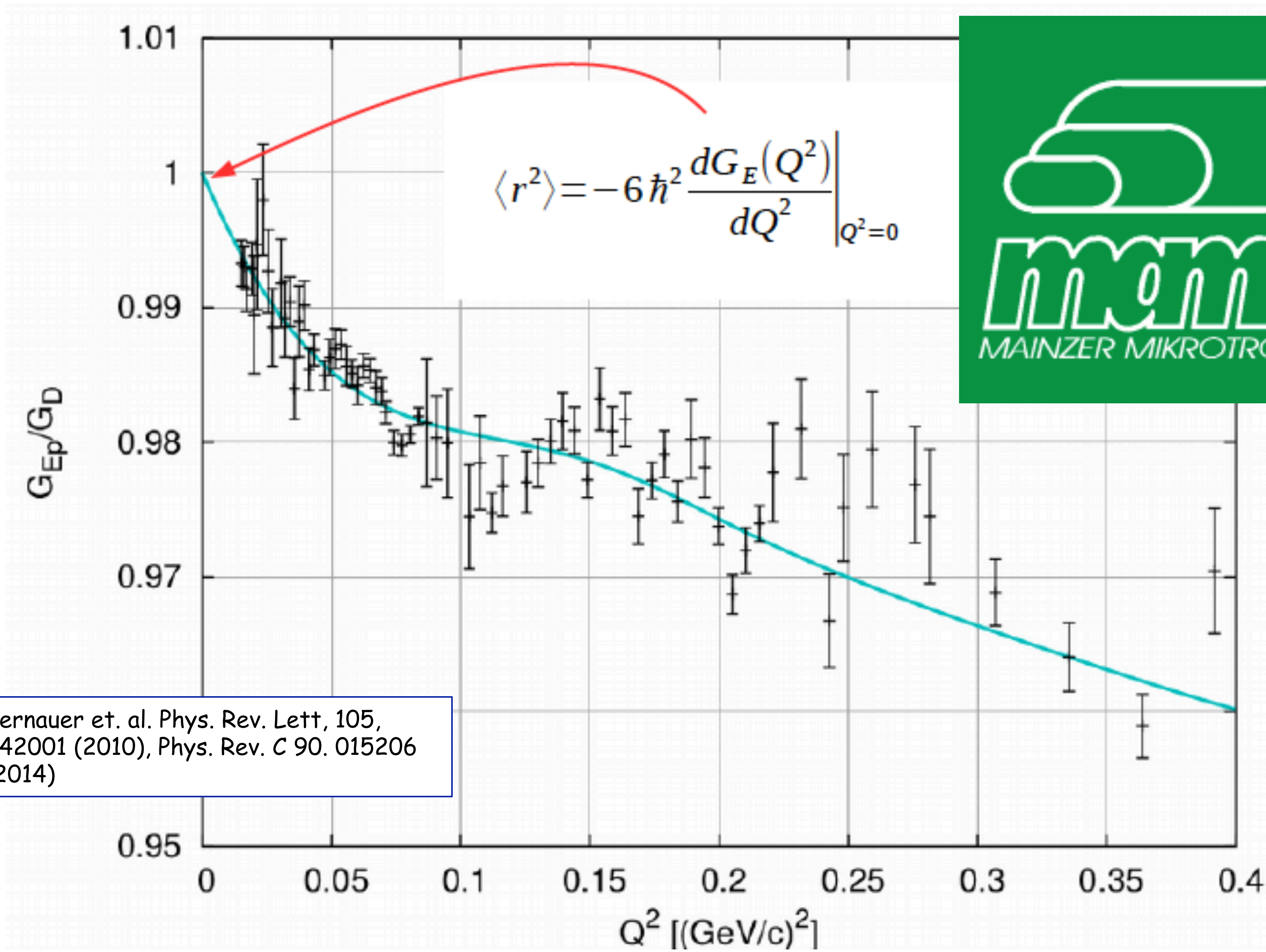
Expanding Electric FF $G_E(Q^2)$ in Taylor series:

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

We have:

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

Proton Mean Square Charge Radius

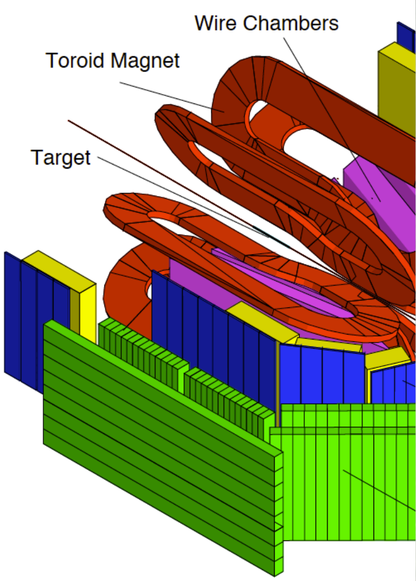


$$\langle r^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

MAMI
MAINZER MIKROTRON

Bernauer et. al. Phys. Rev. Lett, 105, 242001 (2010), Phys. Rev. C 90. 015206 (2014)

Proton Radius from electron-proton Scattering



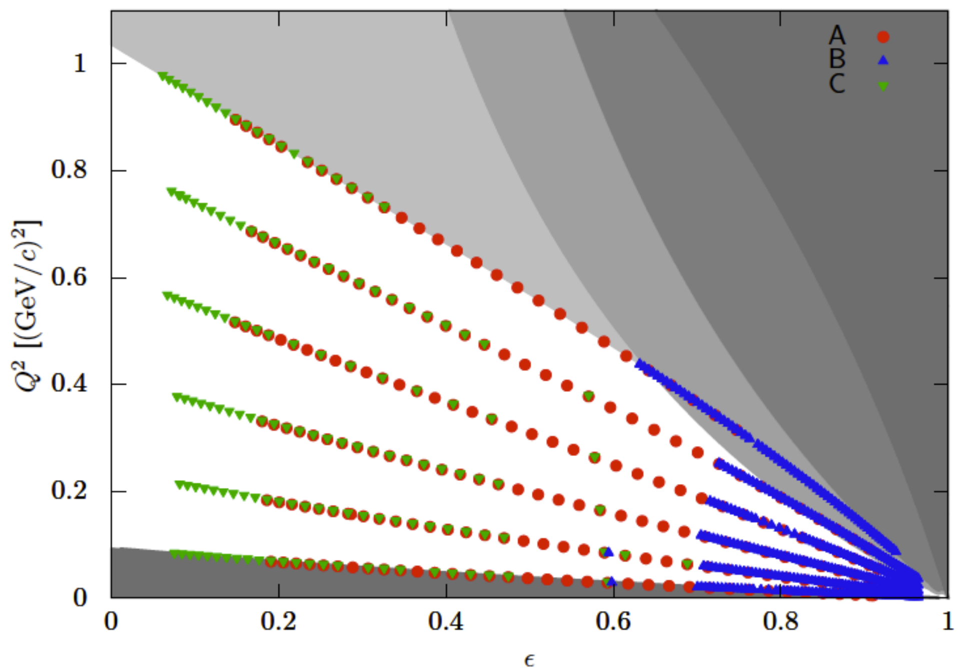
Mainz Microtron

- cw electron beam
- 10 μA polarized,
  100 μA unpolarized
- MAMI A+B: 180-855 MeV
- MAMI C: 1.6 GeV

A1 3-spectrometer facility

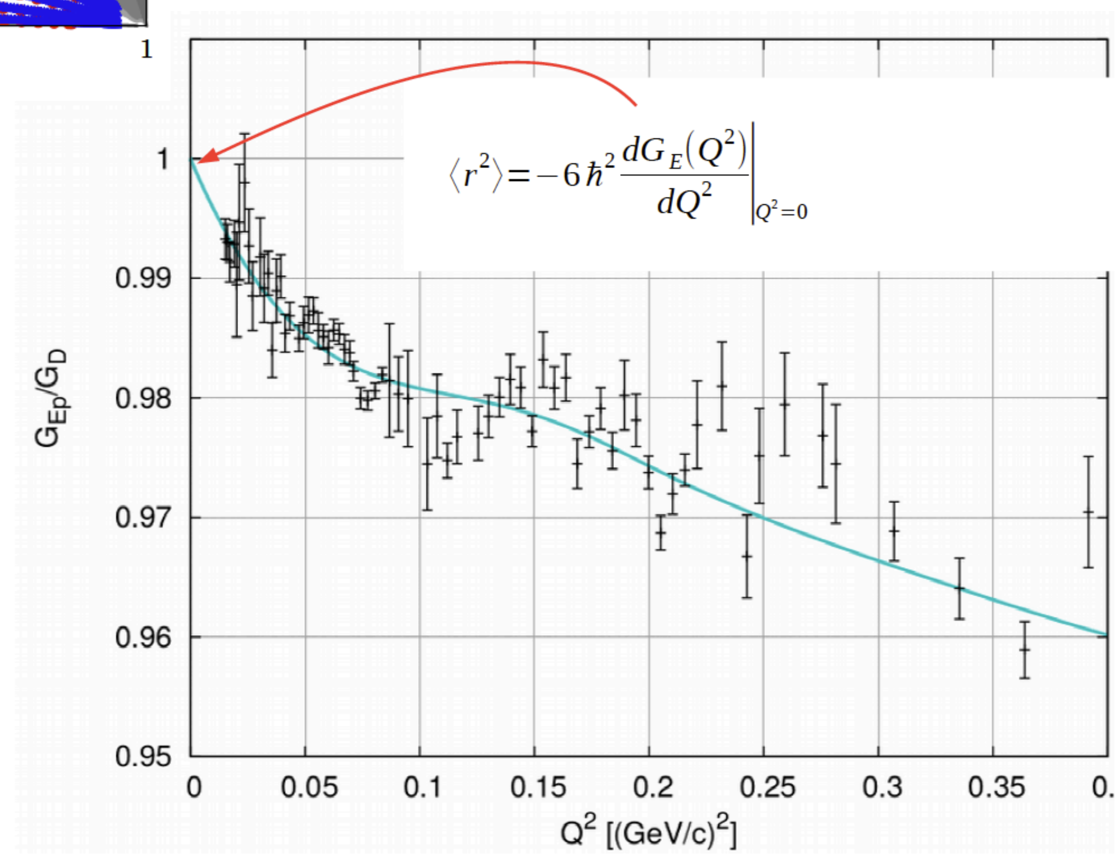
- 28 msr acceptance
- angle resolution: 3 mrad
- momentum res.: 10^{-4}

electron-proton Scattering data from Mainz

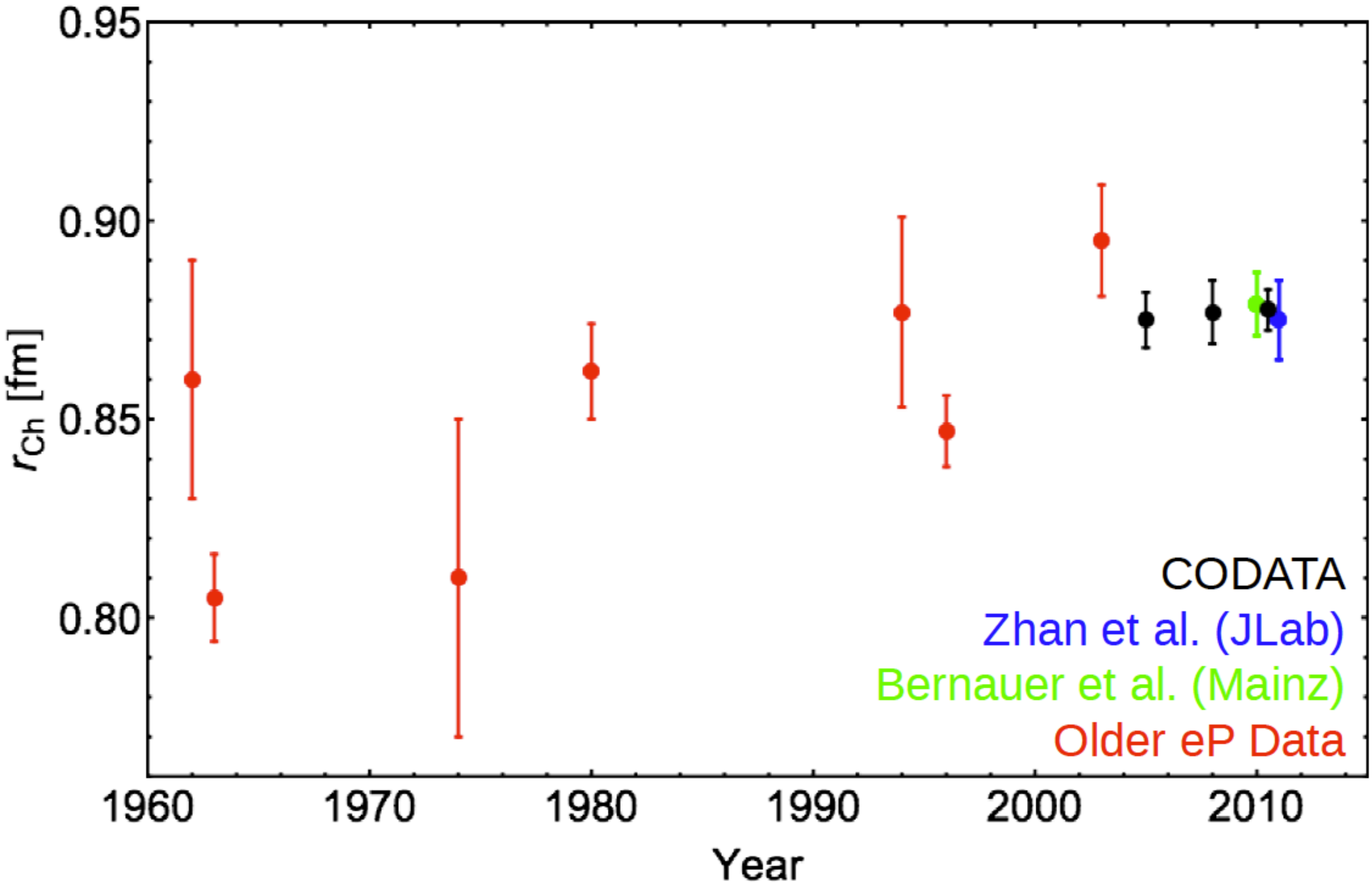


Bernauer et. al. Phys. Rev. Lett, 105, 242001 (2010), Phys. Rev. C 90. 015206 (2014)

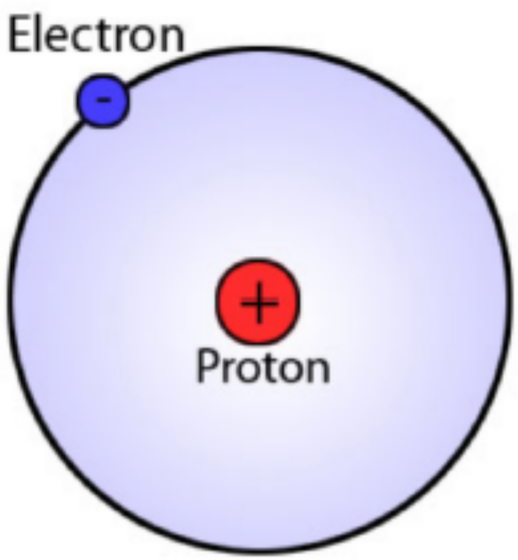
- Mainz data come from a wide range of beam energies and spectrometer angles: required separation of G_E from G_M
- Mainz G_E agrees with G_E from Jlab Hall A; but G_M disagrees

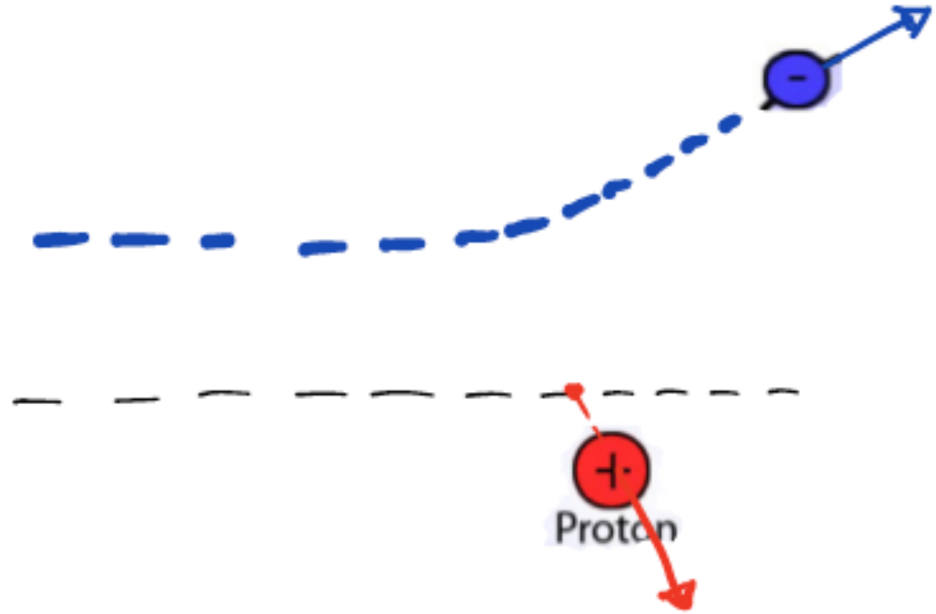


Time evolution of Proton Radius from e-p Scattering



How is the same $<r^2>$ measured in Atomic Physics ?





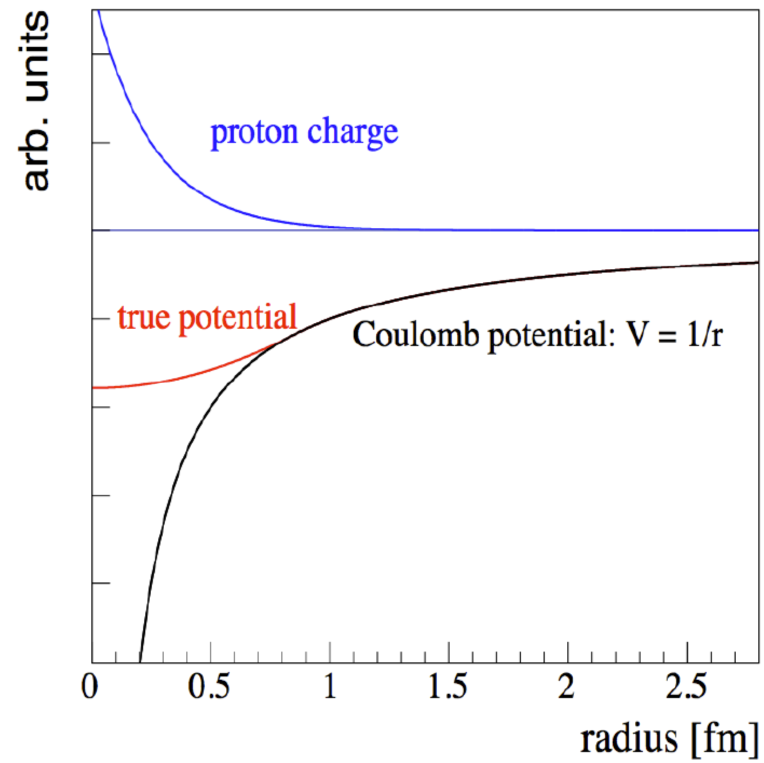
e-p bound state:
Atomic Physics

e-p scattering state:
Nuclear Physics

In either case electron interacting with proton through Coulomb interaction,

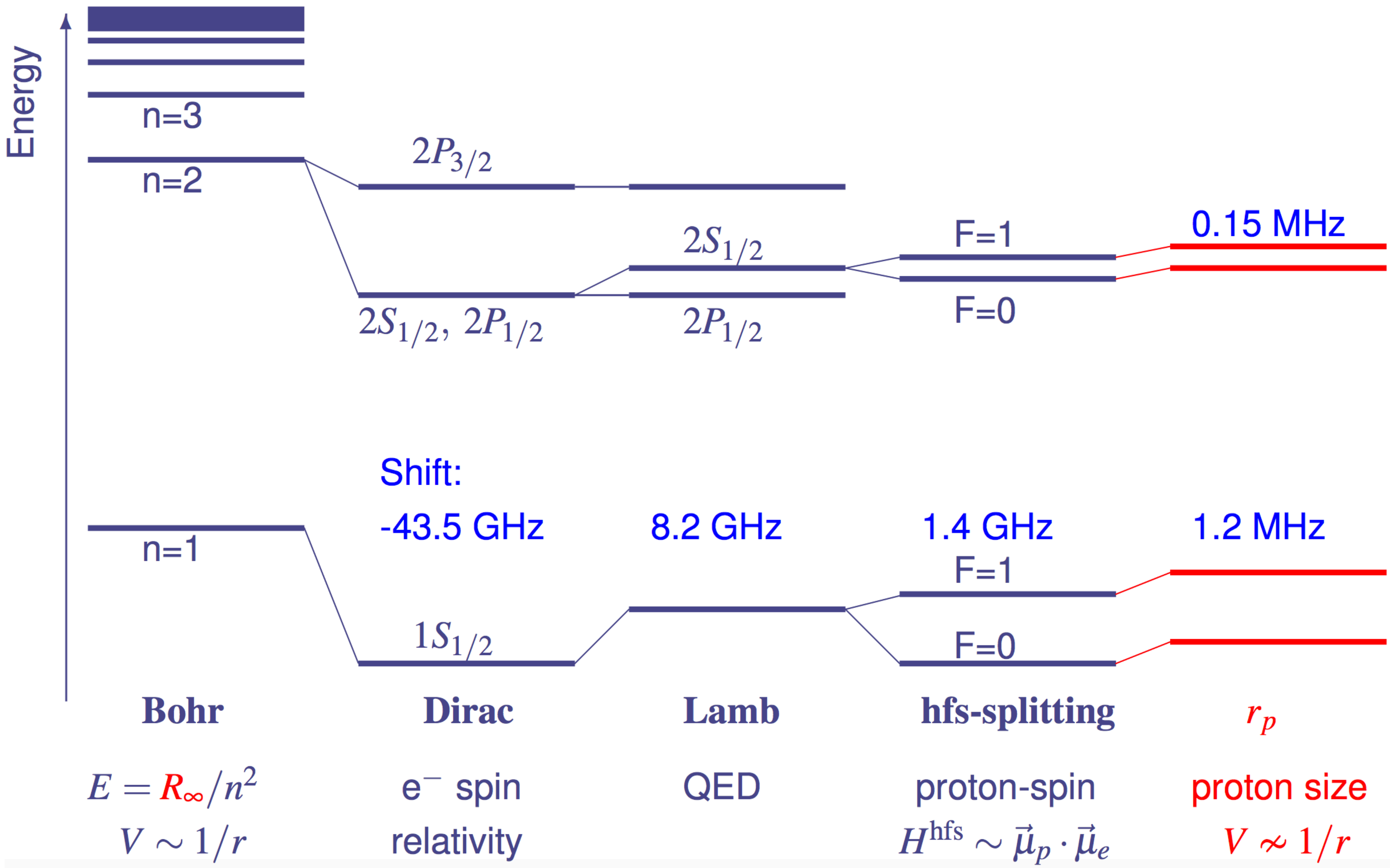
Coulomb interaction which is modified due to the extended charge distribution of the proton

The difference between true proton potential and the potential for a point like proton

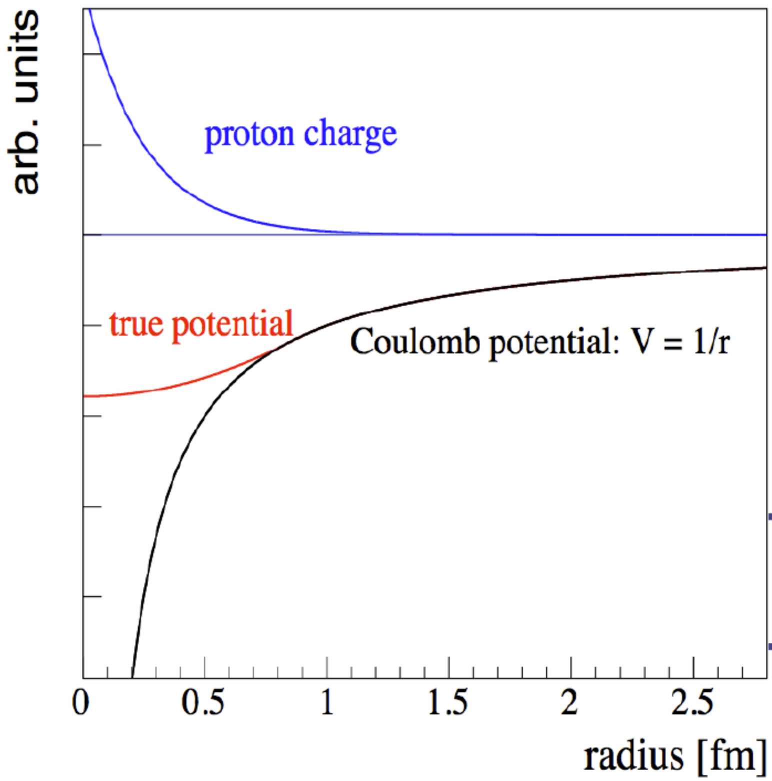


$$\delta V(\mathbf{r}) \equiv V_C(\mathbf{r}) - V_C^{\mathrm{pt}}(\mathbf{r}) = -4\pi\alpha \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{[G_{\mathrm{E}}(\mathbf{q}^2) - 1]e^{-i\mathbf{q}\cdot\mathbf{r}}}{\mathbf{q}^2}.$$

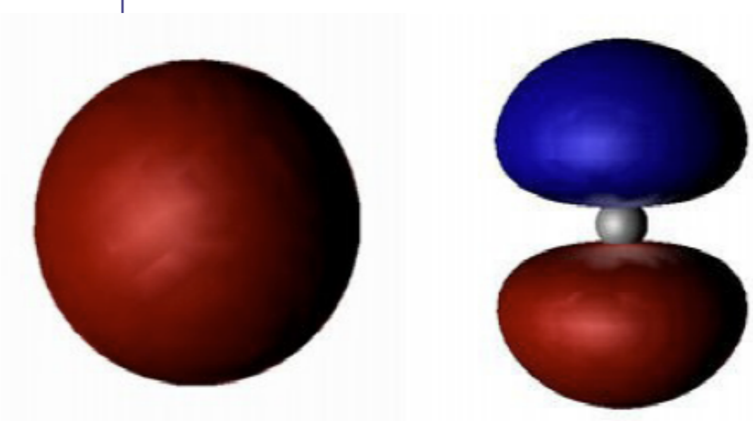
Regular Hydrogen spectroscopy

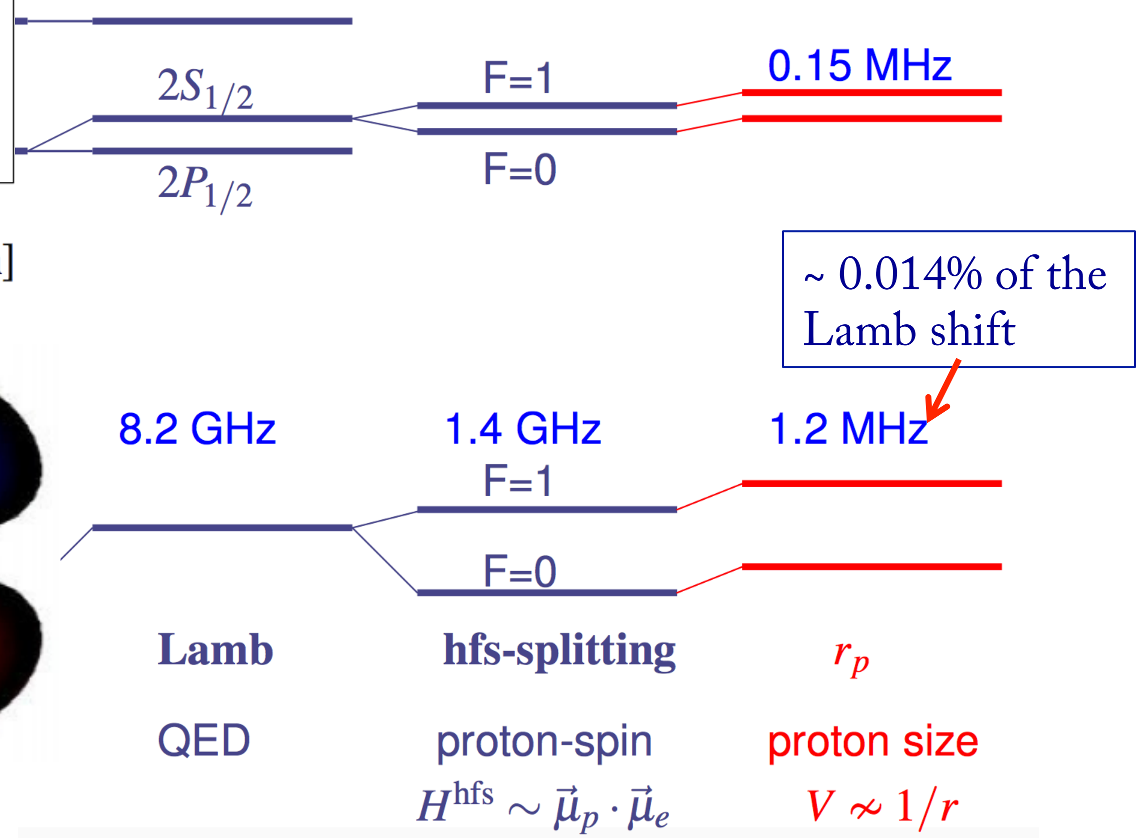


R. Pohl



- While electron is inside the proton attractive potential is lower.
- Strongly affects the S orbital, much less so the P.





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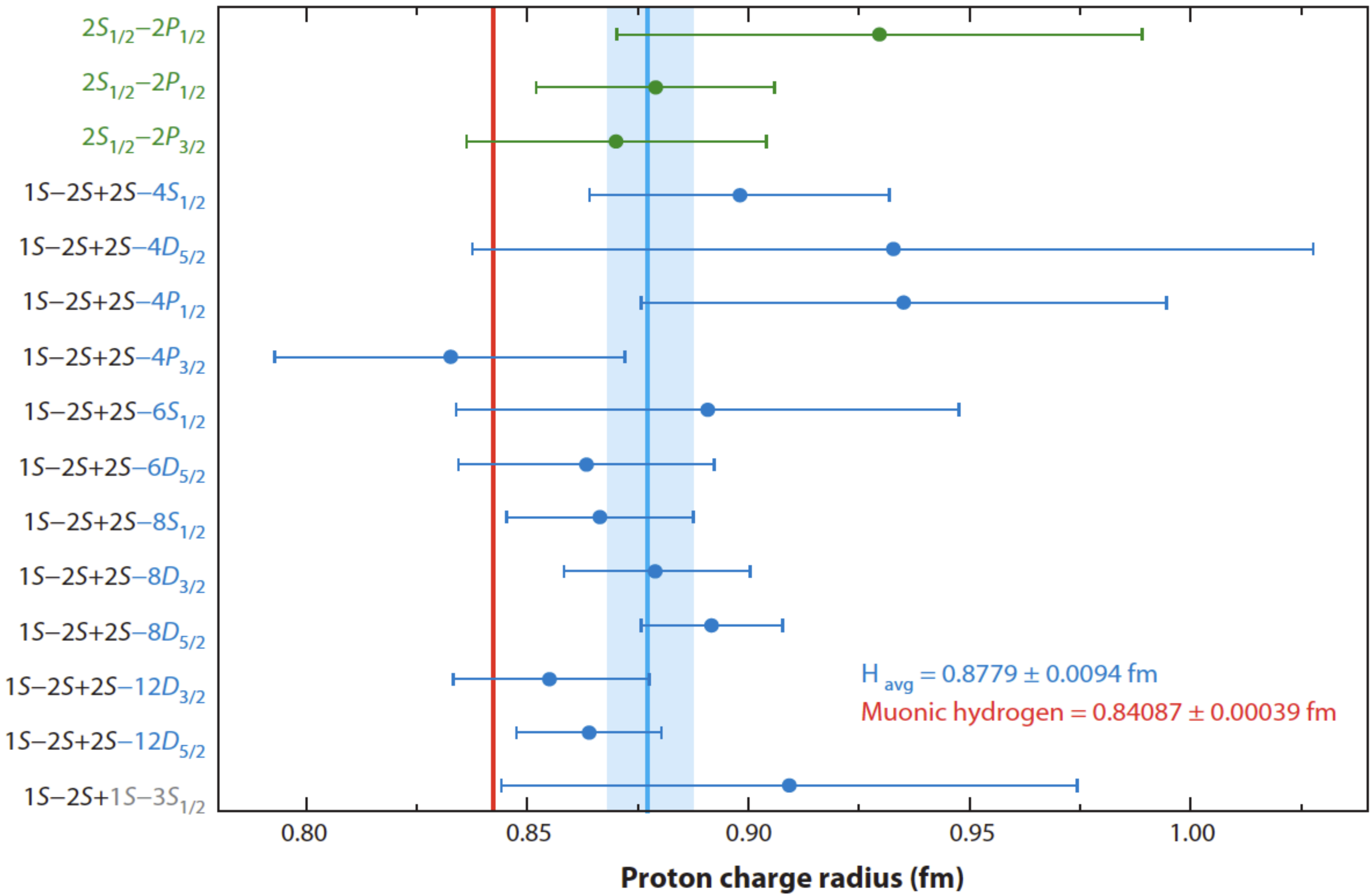
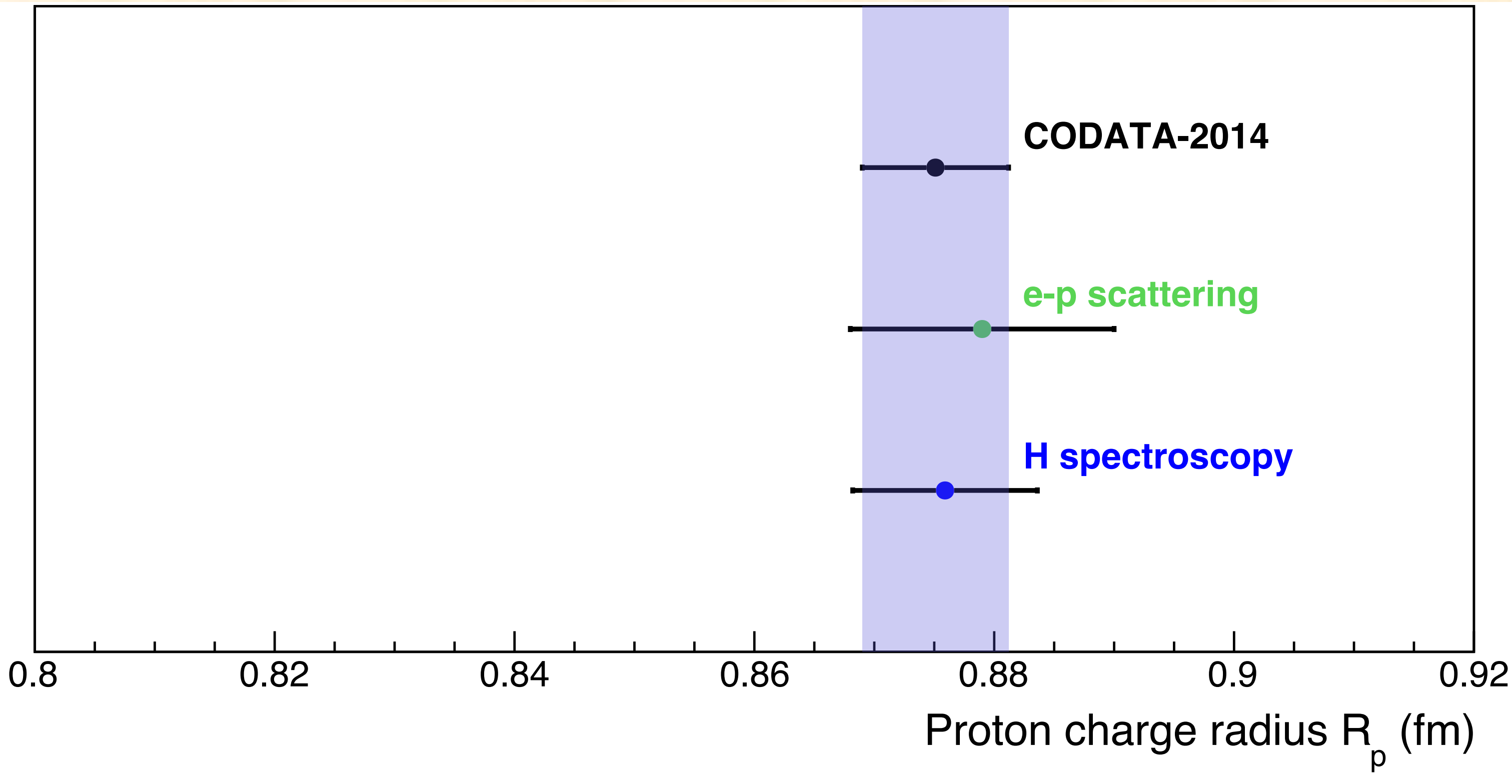


$2S_{1/2}$–$2P_{1/2}$
$2S_{1/2}$–$2P_{1/2}$
$2S_{1/2}$–$2P_{3/2}$
1S–2S+2S–$4S_{1/2}$
1S–2S+2S–$4D_{5/2}$
1S–2S+2S–$4P_{1/2}$
1S–2S+2S–$4P_{3/2}$
1S–2S+2S–$6S_{1/2}$
1S–2S+2S–$6D_{5/2}$
1S–2S+2S–$8S_{1/2}$
1S–2S+2S–$8D_{3/2}$
1S–2S+2S–$8D_{5/2}$
1S–2S+2S–$12D_{3/2}$
1S–2S+2S–$12D_{5/2}$
1S–2S+1S–$3S_{1/2}$
H_{avg} = 0.8779 ± 0.0094 fm
Muonic hydrogen = 0.84087 ± 0.00039 fm
0.80
0.85
0.90
0.95
1.00
Proton charge radius (fm)

Proton Radius Before 2010



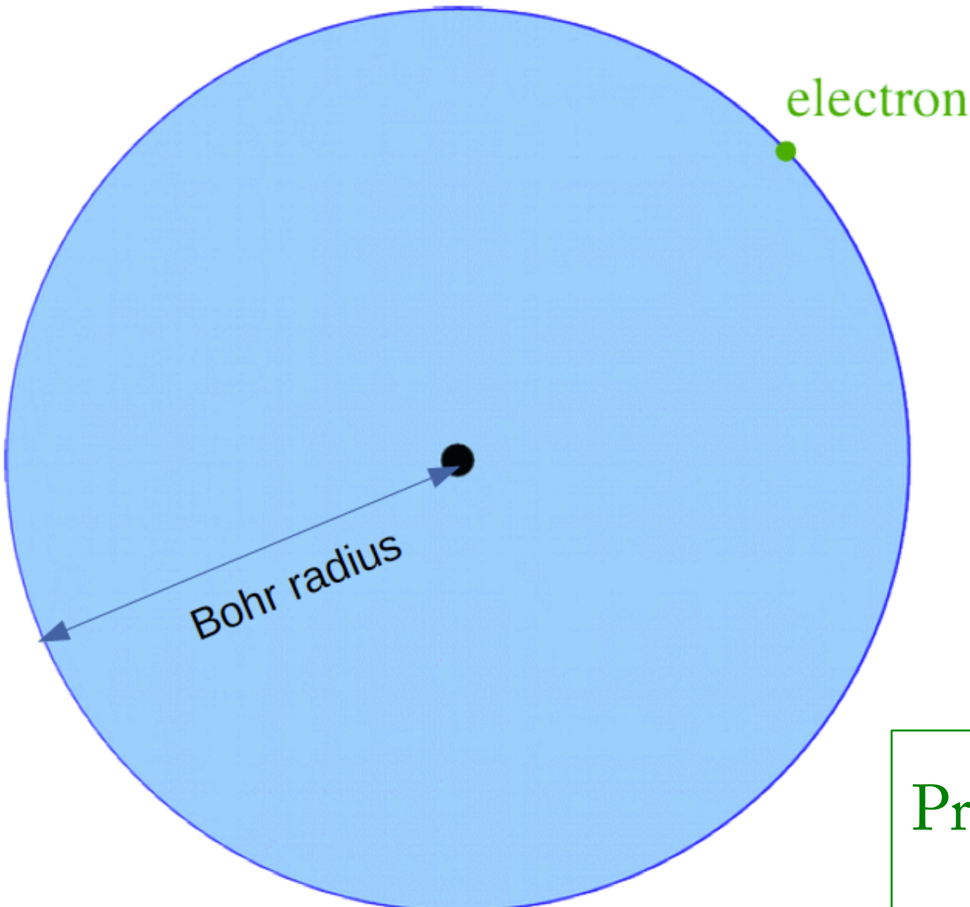
CODATA average:	0.8751 ± 0.0061 fm
ep-scattering average (CODATA):	0.879 ± 0.011 fm
Regular H-spectroscopy average (CODATA):	0.859 ± 0.0077 fm

Very good agreement between ep-scattering and H-spectroscopy results !

Electronic and Muonic Hydrogen

Regular hydrogen:

Proton + Electron



Muonic hydrogen:

Proton + Muon

Muon **mass** = **200** * electron mass

Bohr **radius** = **1/200** of H

200^3 = a **few million times** more sensitive to proton size

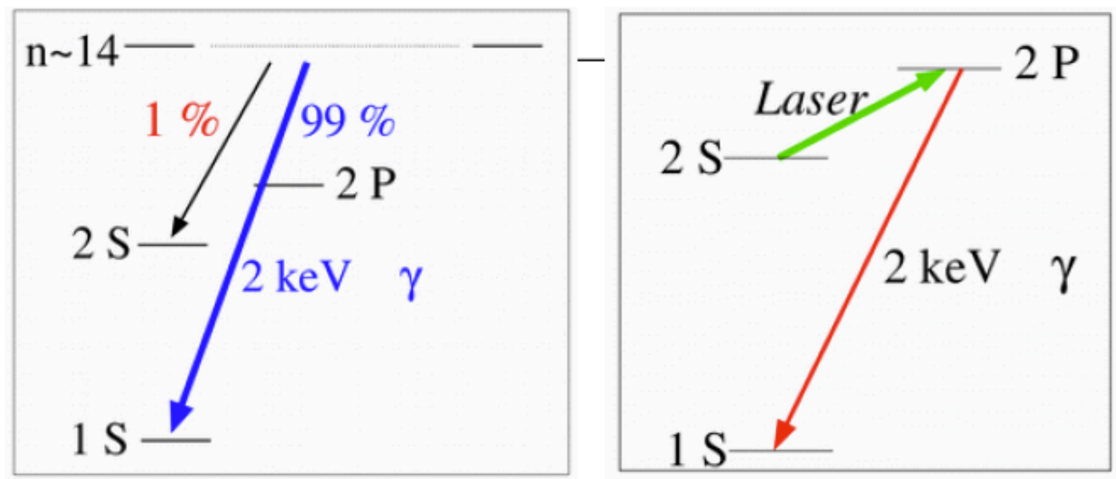
Probability for lepton inside proton
~ volume of proton / volume of atom

R. Pohl

Vastly not to scale

Muonic Hydrogen Spectroscopy Experiment

- Form μH* (n~14) by firing muon beam on 1 mbar H_2 target.
- 99% decay to 1S emitting prompt 2 keV photons.
- 1% decay to long lived 2S state.
- Excite from 2S to 2P using tuned laser: decay from 2P to 1S emitting delayed 2 keV photons.
- Vary laser frequency, find 2S-2P resonance.

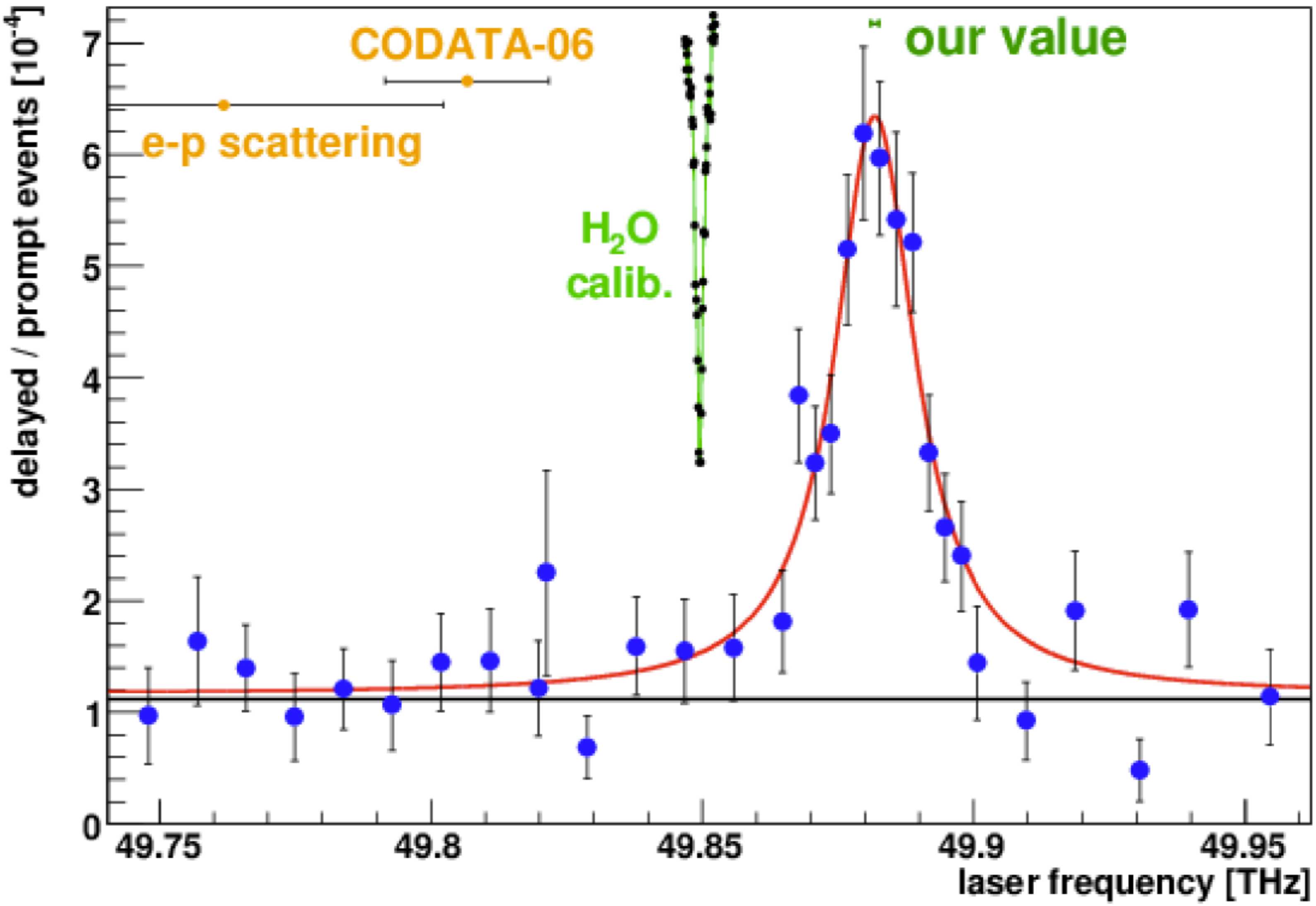


prompt (t=0)   “delayed” (t = 1 μs)

Plots from R. Pohl

Muonic Hydrogen Spectroscopy Experiment

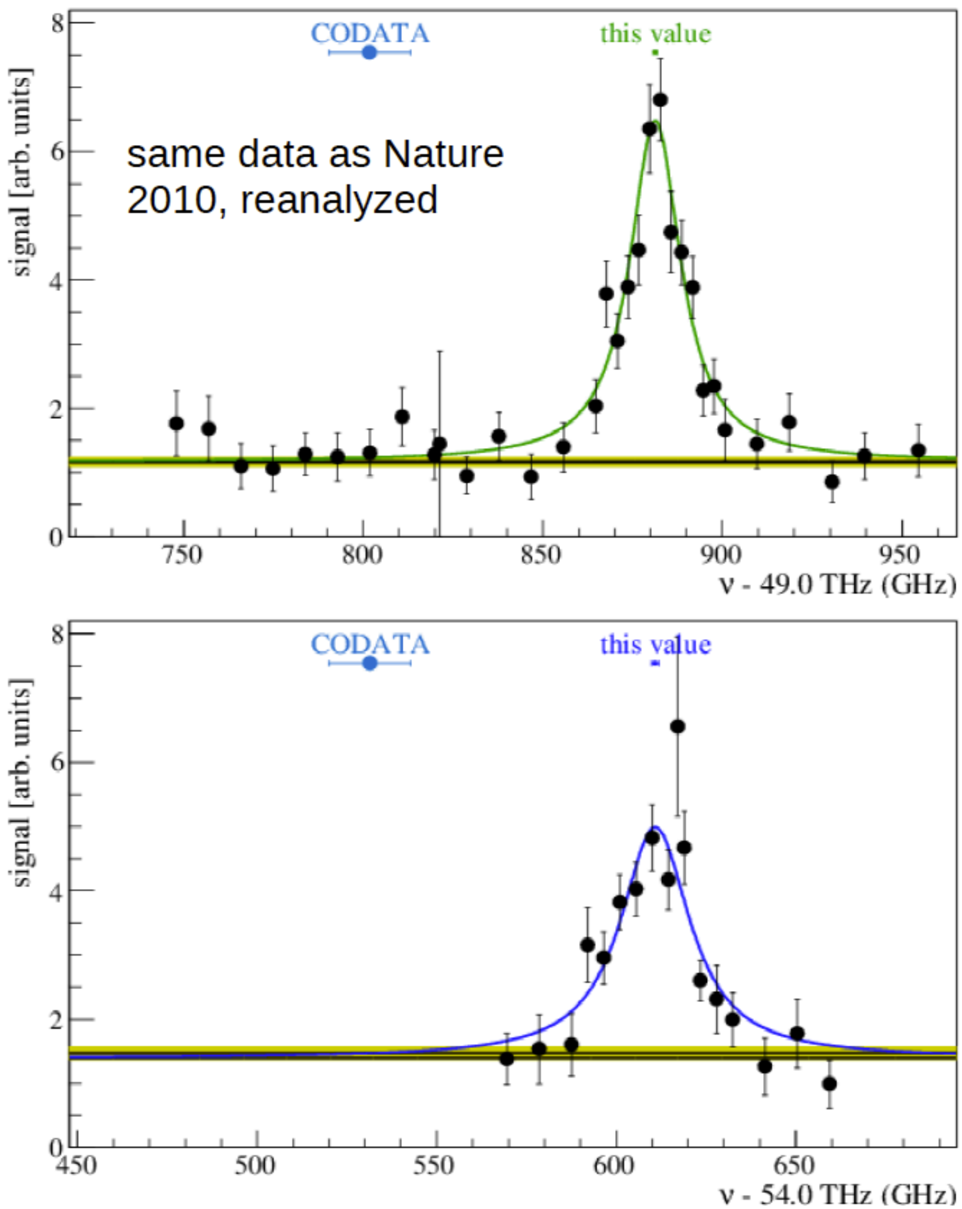
Resonance in muonic hydrogen



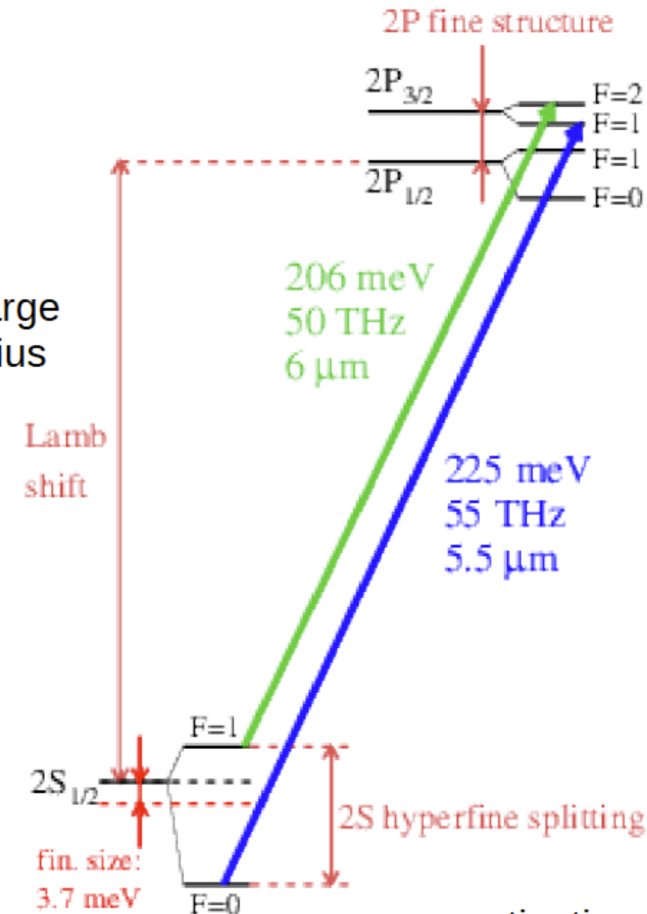
Pohl et al. (CREMA Coll.), Nature 466, 213 (2010)

Muonic Hydrogen Spectroscopy Experiment

2 transitions in muonic H



charge radius



magnetization distribution (Zemach radius)

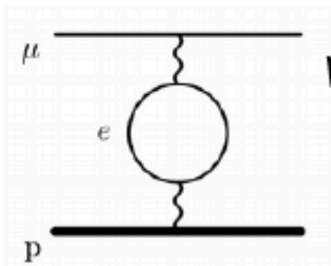
R. Pohl

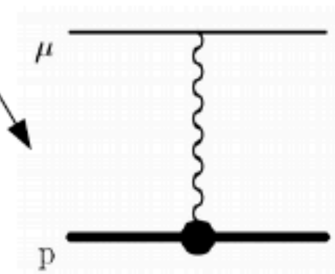
Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

Theory in muonic H

$$\Delta E_{Lamb} = 206.0336\ (15)\ meV_{QED} + 0.0332\ (20)\ meV_{TPE} - 5.2275\ (10)\ meV/fm^2 * R_p^{\ 2}$$

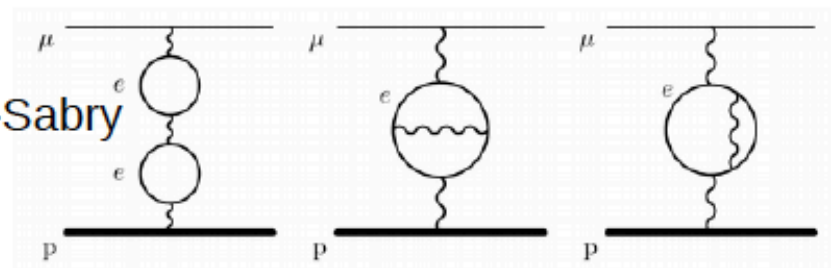
Uehling

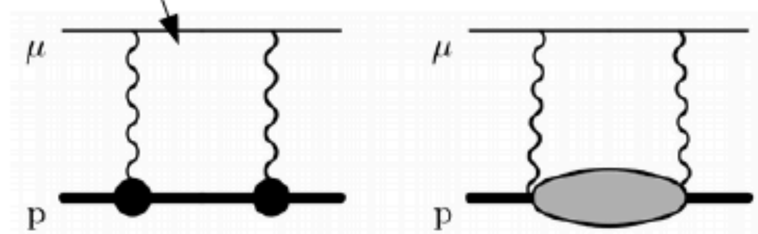




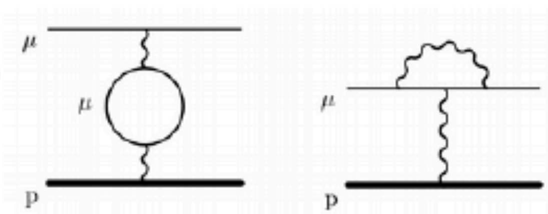
Proton form factor

Källen-Sabry





Muon SE+VP



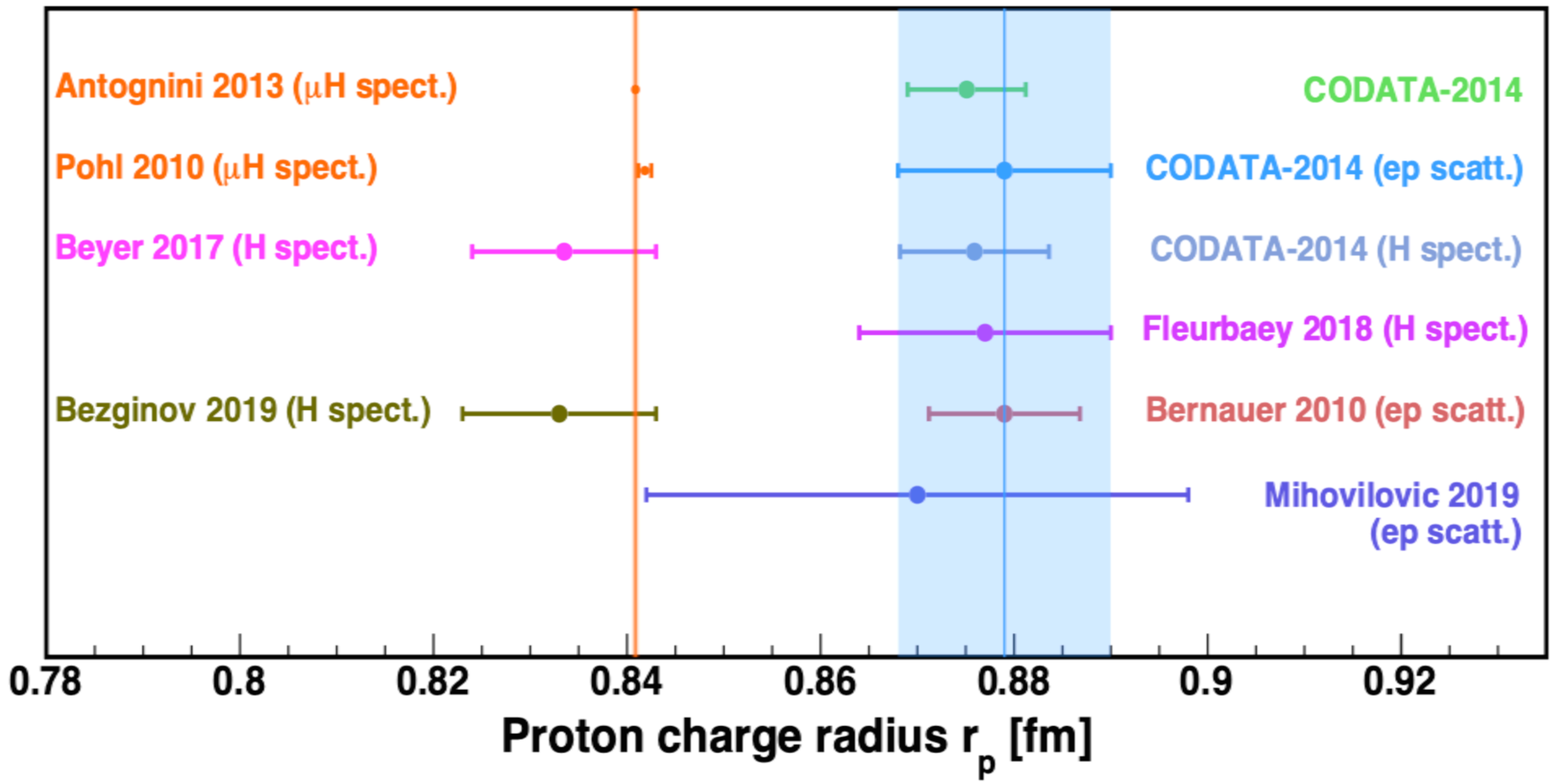
and 20 more….

elastic and inelastic two-photon exchange
(Friar moment and polarizability)

So, how do we resolve this puzzle ?

	ep	μp
Spectroscopy	New measurements with ▪ lower systematics ▪ new transitions	✔
Scattering	New measurements with ▪ lower systematics ▪ reaching lower Q^2 ProRAD, ULQ2, ISR @ MESA, PRad	No data yet. MUSE at PSI coming soon

Proton Radius Puzzle, getting even more puzzling……



Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll.):	0.8409 ± 0.0004 fm
Regular H (2S ➔ 4P, CREMA coll.):	0.8335 ± 0.0095 fm
Regular H (1S ➔ 3S, LKB, Paris):	0.877 ± 0.013 fm

Regular H-spectr. (2S ➔ 2P, York Univ. Canada, Just published in Science)

So, how do we resolve this puzzle ?

	ep	μp
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A New ep Scattering Experiment?

A 1% level *Rp* measurements requires

- Q^2 down to 10^{-4} GeV^2 level or lower
- Measurements over wide enough Q^2 range for a fit
- ~< 0.5% accuracy in absolute cross section
- ~< 0.2 mrad in scattering angle determination

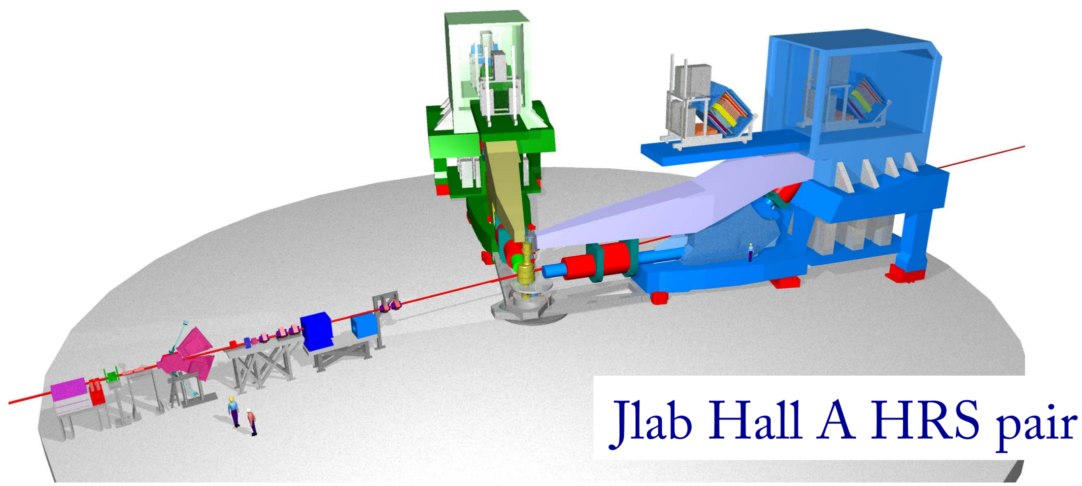
These conditions are VERY difficult to achieve with the standard methods used for *ep* scattering experiments

Difficulties with traditional ep Scattering Experiments

Practically all *ep*-scattering experiments have been performed with magnetic spectrometers and LH_2 targets.

- many experimental settings to cover the Q^2 range!
  - angle (Θ_e) , energies (E')
- limitation on minimum Q^2: 10^{-3} GeV/C^2

Mainz magnetic spectrometers



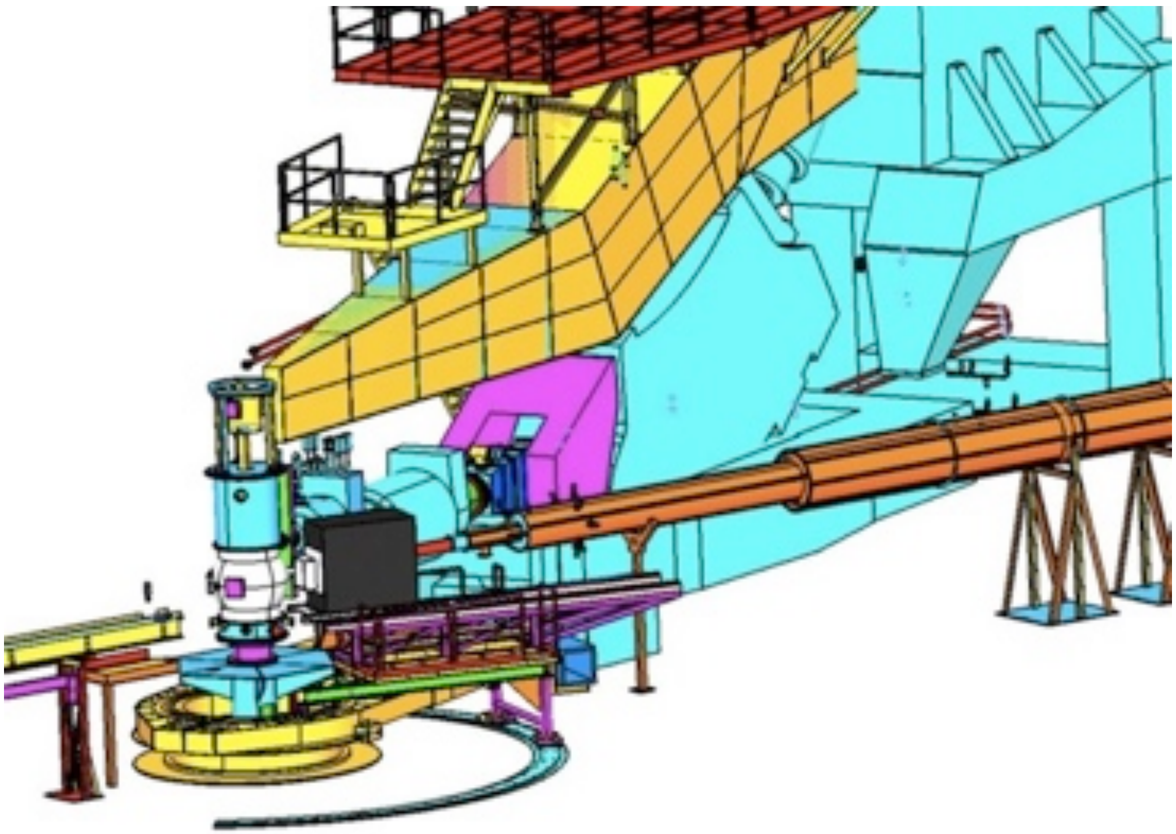
Jlab Hall A HRS pair

limitation on minimum Q^2: 10^{-3} GeV/C^2

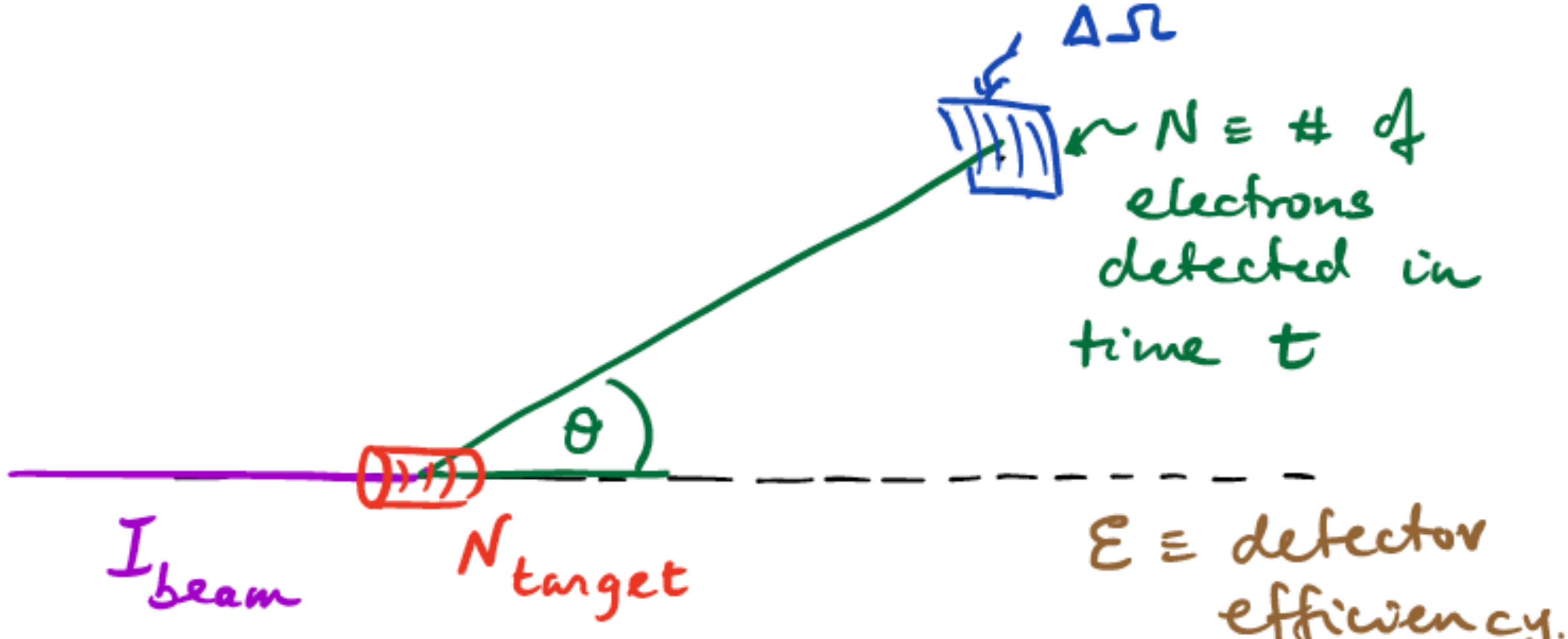
min. scattering angle: $\theta_e \approx 5^0$

beam energies: ~ 0.1 ÷1 GeV

Jlab Hall A HRS



A New ep Scattering Experiment?



$$N_{beam} = \int I_{beam}\, dt / e$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{N\,\delta}{N_{beam} \cdot N_{target}\, \Delta\Omega\, \varepsilon}$$

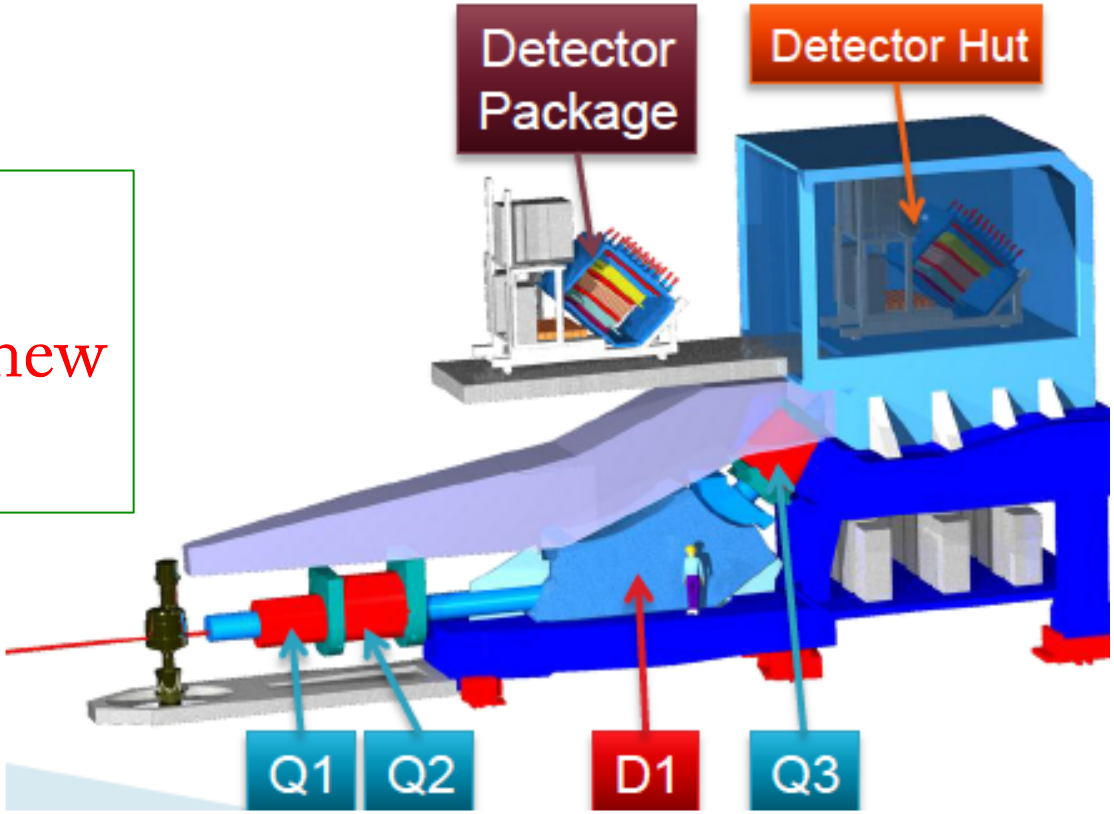
$\delta \equiv$ other corrections. (radiative etc.)

A New ep Scattering Experiment?

limitation on absolute cross sections (dσ/dΩ): ~ 2 ÷ 3%

- statistics is not a problem (<0.2%)
- control of systematic errors???
- beam flux, target thickness, windows,
- acceptances, detection efficiencies,
- ...

A new high precision measurement requires a new experimental method.



The PRad Experimental Approach

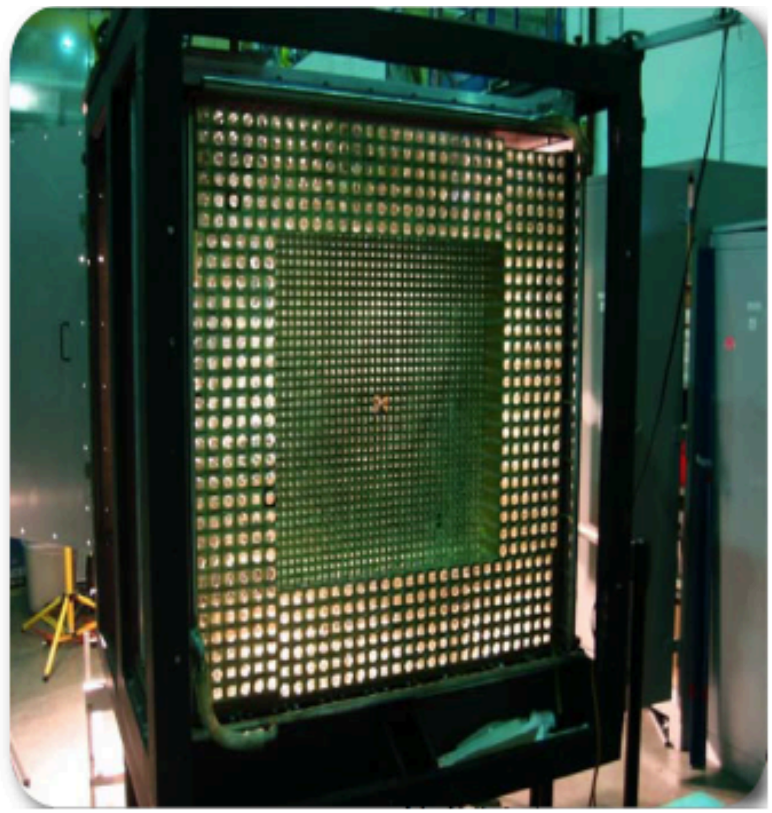
PRad initial goals:

- large Q^2 range in one experimental setting
- reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
- reach to sub-percent precision in cross section

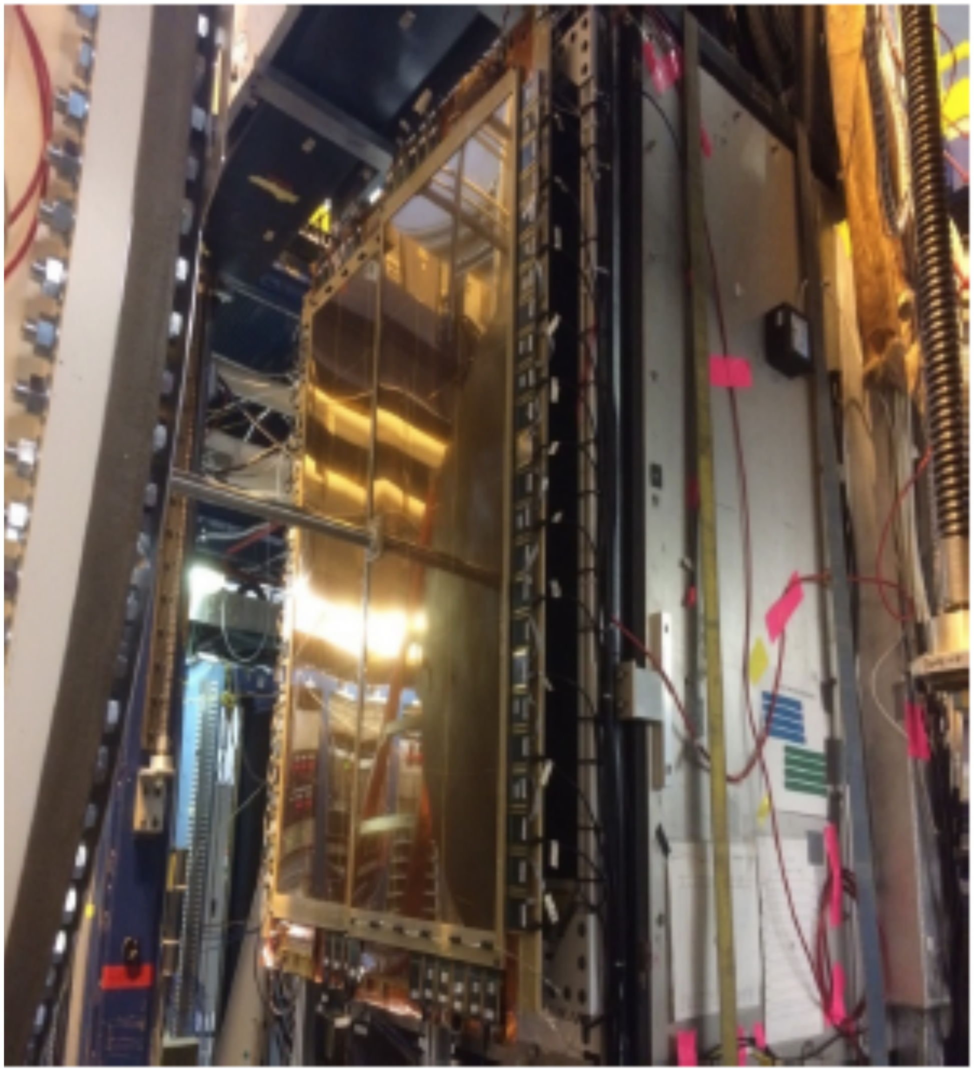
PRad suggested solutions

use high resolution high acceptance calorimeter:

- ✓ reach smaller scattering angles: ($\theta_e = 0.7^0 - 7.0^0$):
  ($Q^2 = 2x10^{-4} \div 6x10^{-2}$) GeV/c^2 ;
- ✓ large Q^2 range in one experimental setting!;



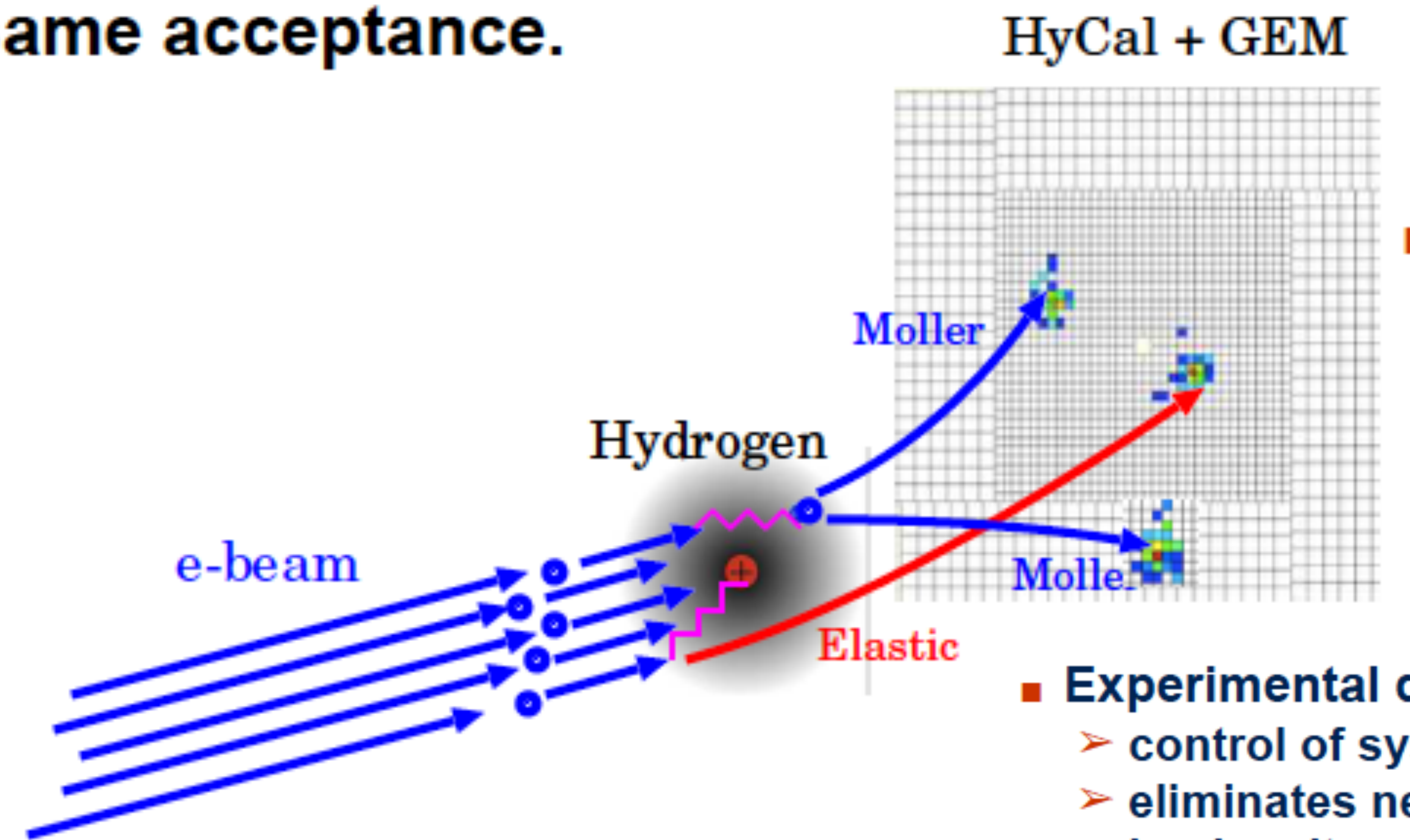
PRad Experimental Apparatus: GEM coordinate detectors



- Two large area GEM detectors (largest GEM detectors in the world at the time)
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Large improvements in Q^2 determination

Our setup also allowed simultaneous detection of $ee \rightarrow ee$ Moller scattering (best known control of systematics).

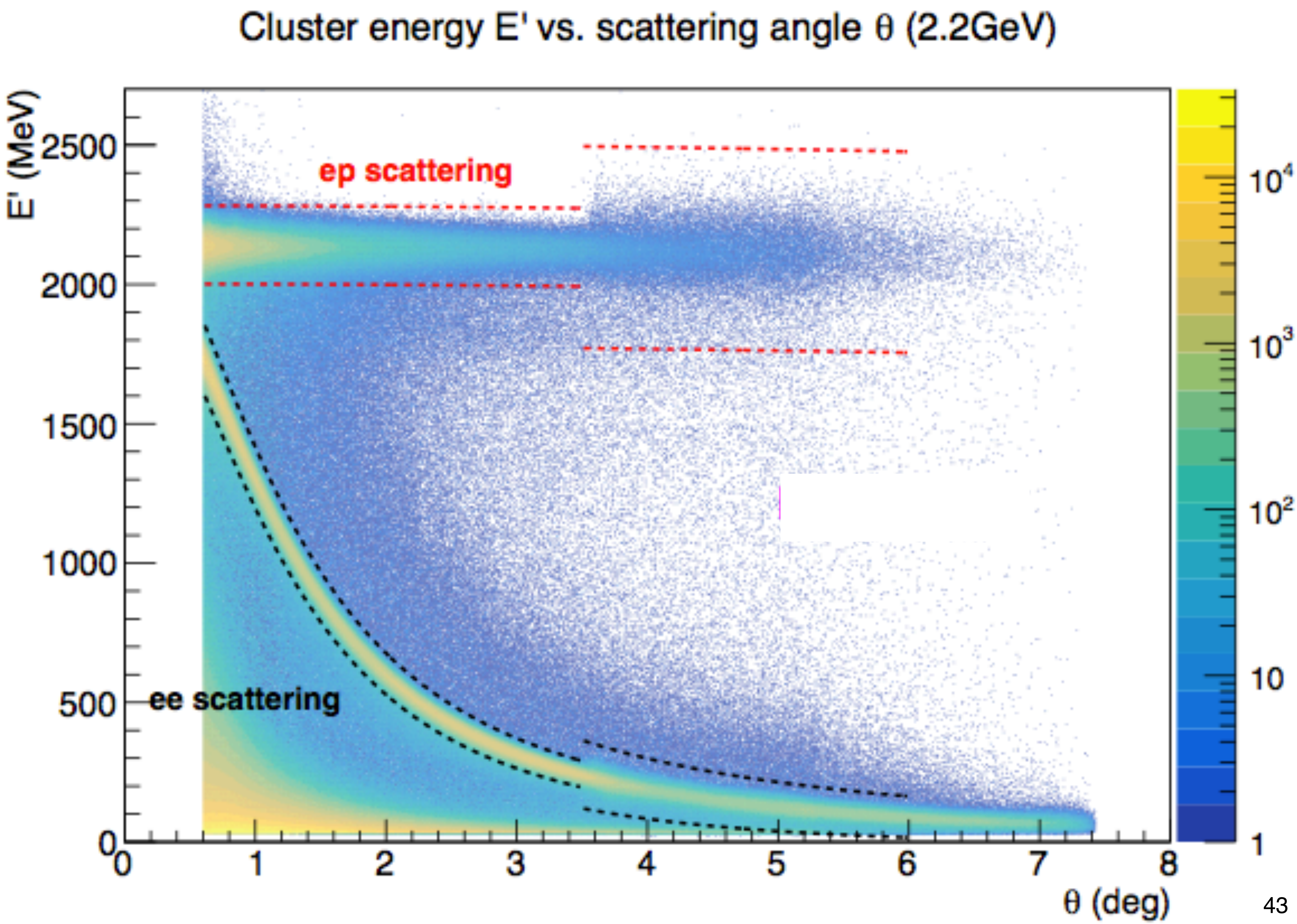
same acceptance.



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

$ee \rightarrow ee$ Moller scattering cross section is known with very high accuracy from QED

PRad data

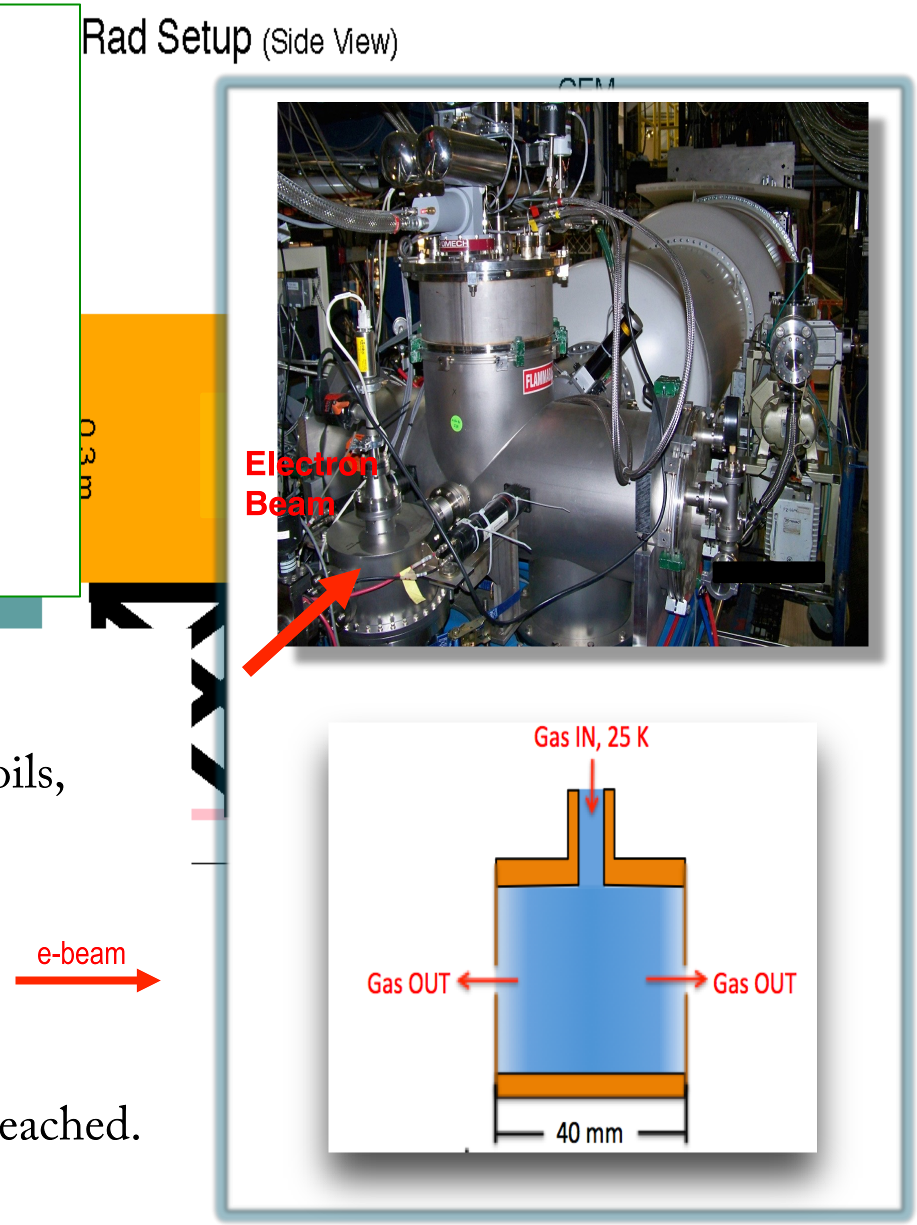


Cluster energy E' vs. scattering angle θ (2.2GeV)
E' (MeV)
2500
2000
1500
1000
500
0
ep scattering
ee scattering
0
1
2
3
4
5
6
7
8
θ (deg)
1
10
10²
10³
10⁴

Windowless Gas Flow Target

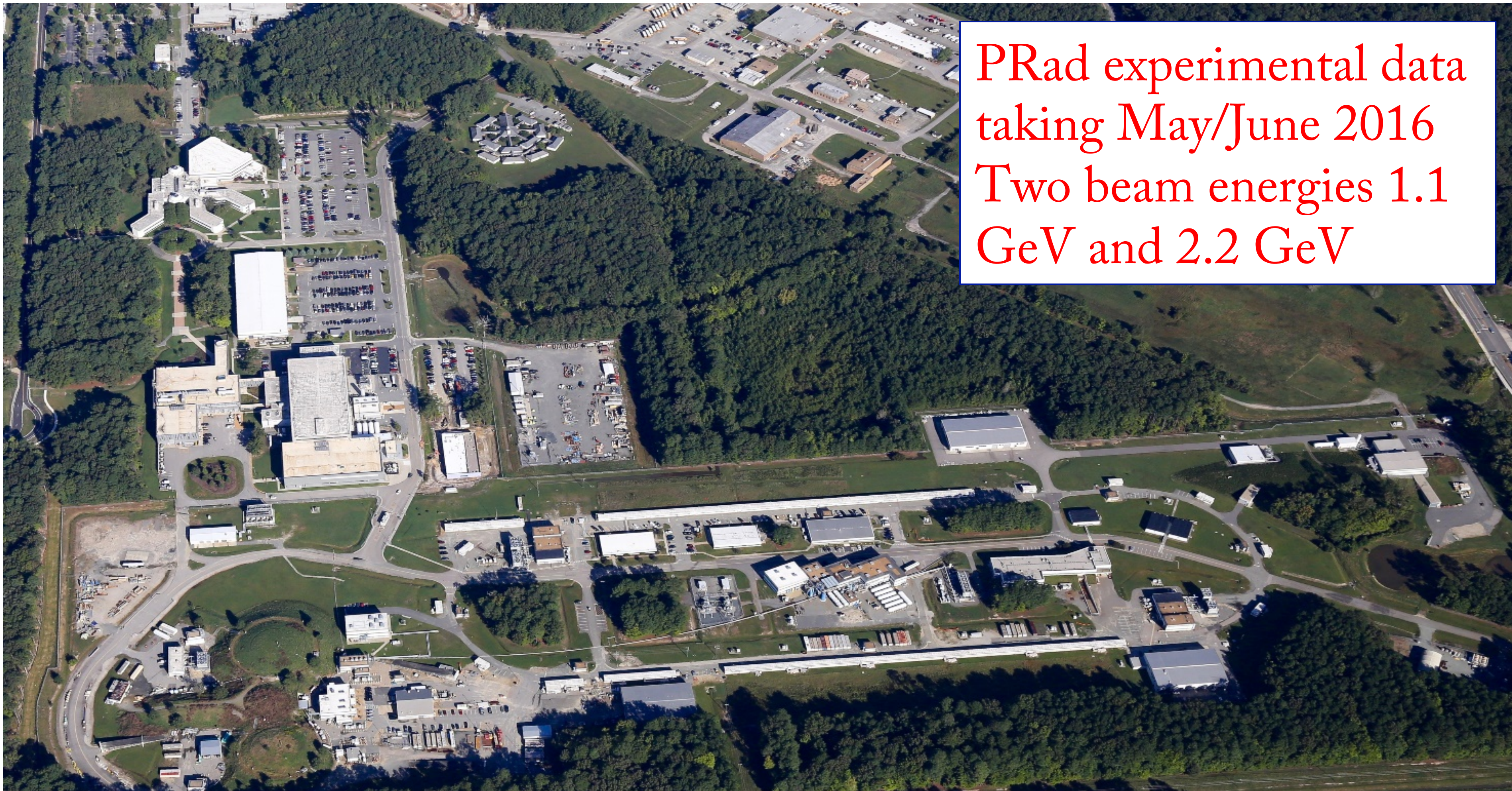
use high density windowless H_2 gas flow target:

- ✓ beam background under control;
- ✓ minimize experimental background.



- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Areal density: $1.8 \times 10^{+18}$ H atoms/cm^2
  - cell pressure: 471 mtorr
  - chamber pressure: 2.34 mtorr
  - cell vs. chamber pressures: 200:1 was reached.
- Gas temperature: 19.5 K

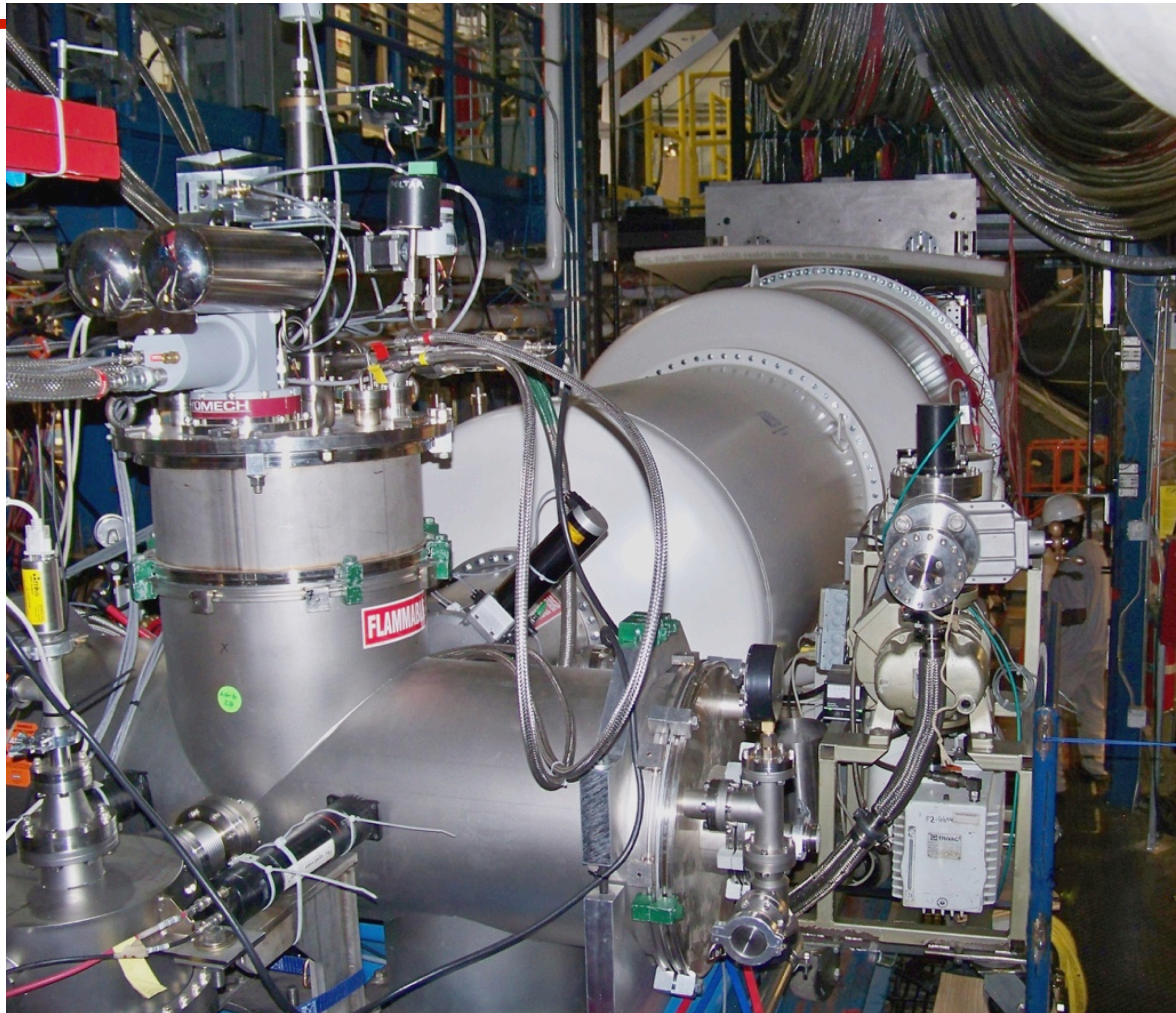
PRad experiment was carried out at Jefferson lab, located in Virginia



PRad experimental data taking May/June 2016
Two beam energies 1.1 GeV and 2.2 GeV

PRad was one of the first experiments to run at Jefferson lab after its major upgrade

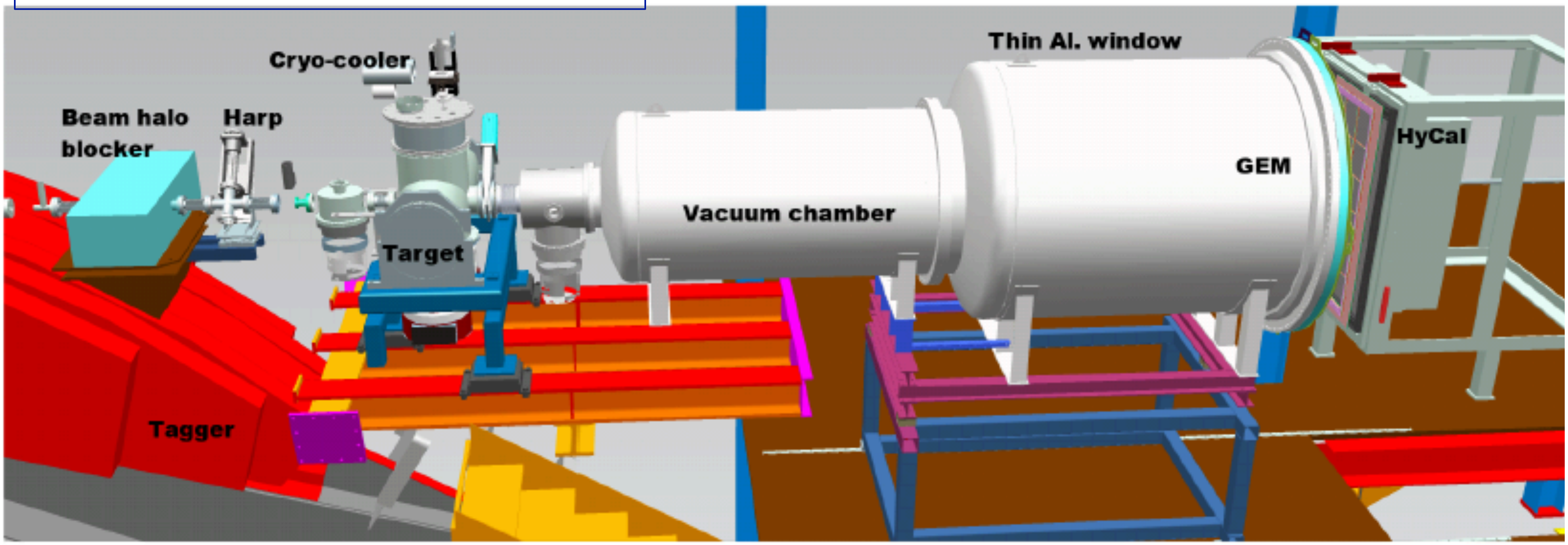
PRad Experimental in Hall B



PRad Experimental Setup in Hall B at JLab (schematics)

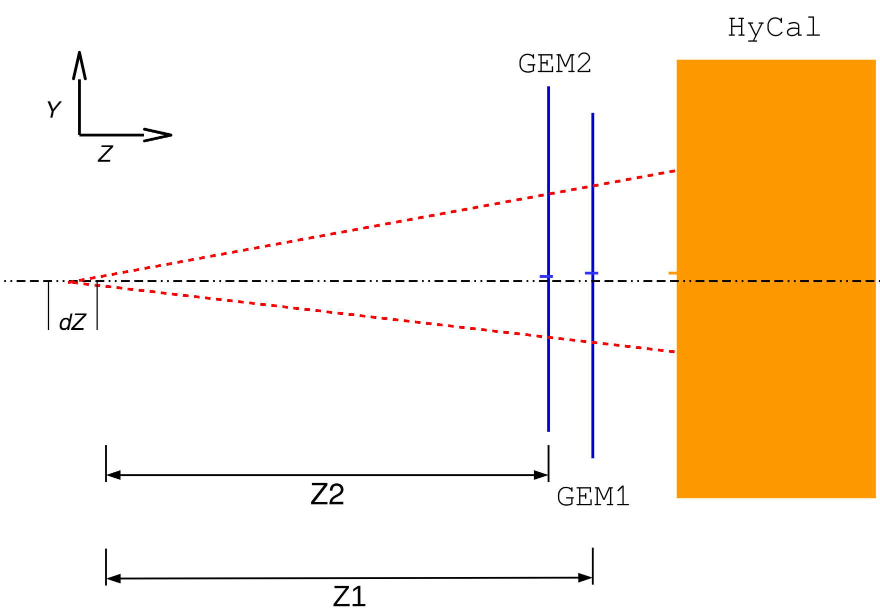
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal
- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo "cleanup")
  - Harp 2H00
  - pipe connecting Vacuum Window through HyCal

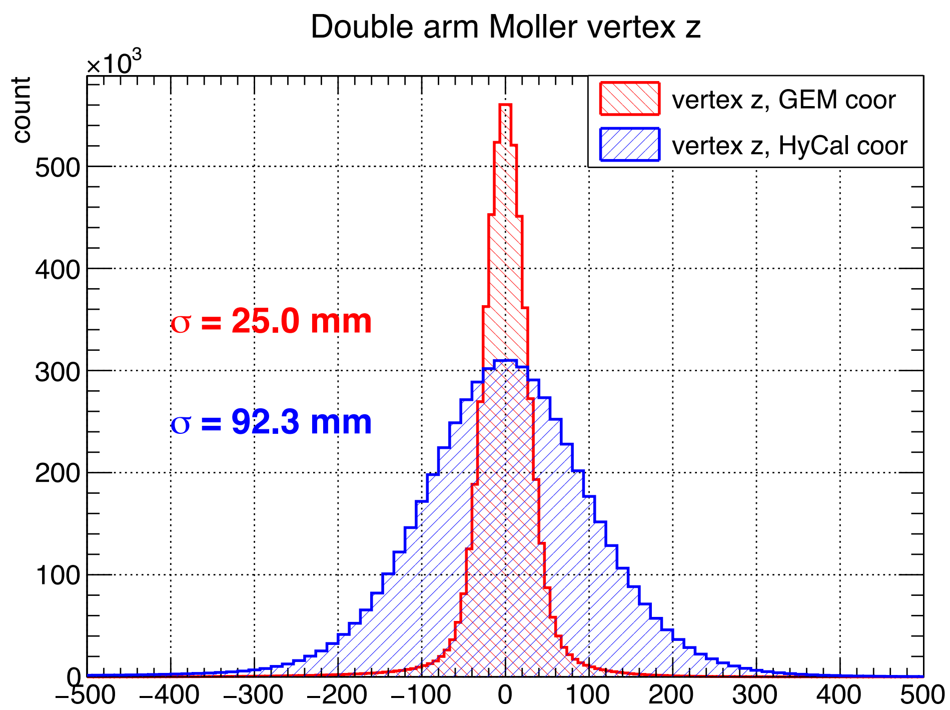
PRad experimental data taking May/June 2016: Two beam energies 1.1 GeV and 2.2 GeV



Detector Position Calibration

- Engineering survey, done before the experiment.
- Detector offsets and z position from double-arm Moller events:
  - co-planarity to determine offsets;
  - Møller kinematics to determine detector z position (cross check surveyed data);
  - offset with ~ 50 μm and z with ~ 1 mm precision;

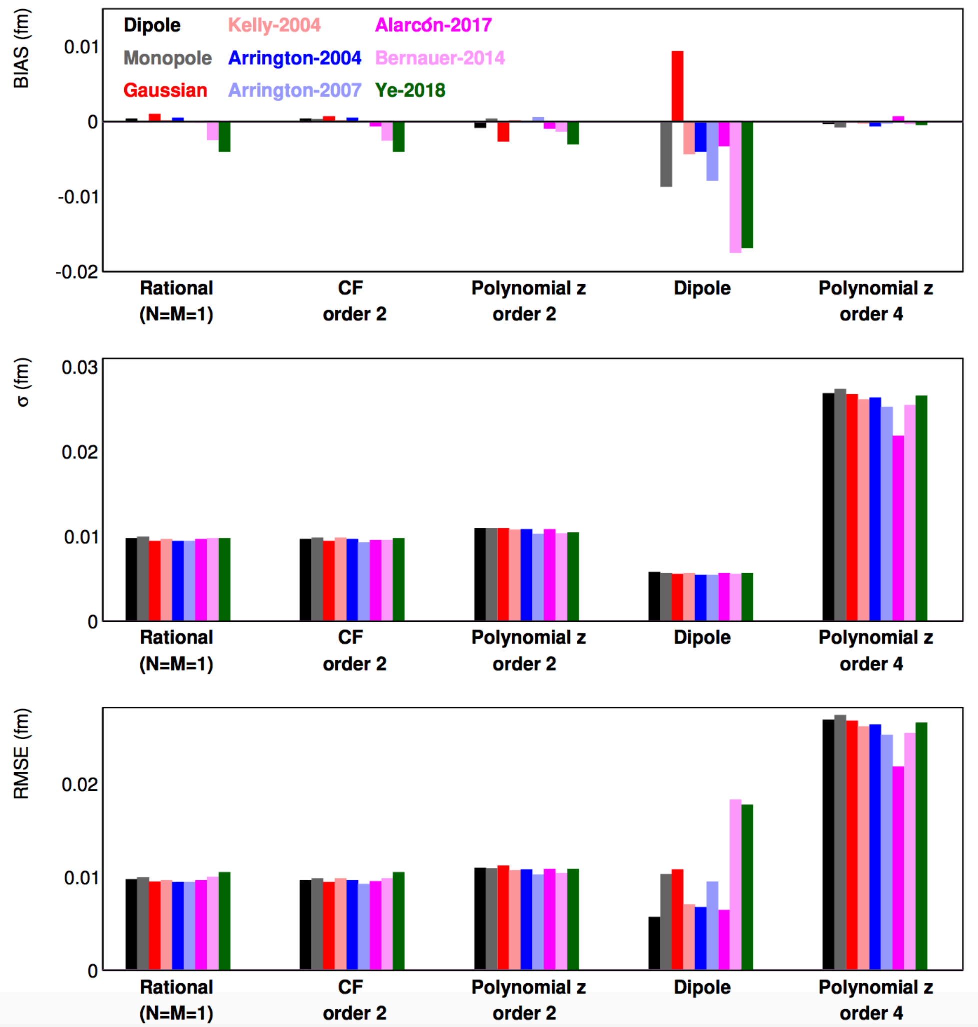




Recent Developments in Fitting Procedures

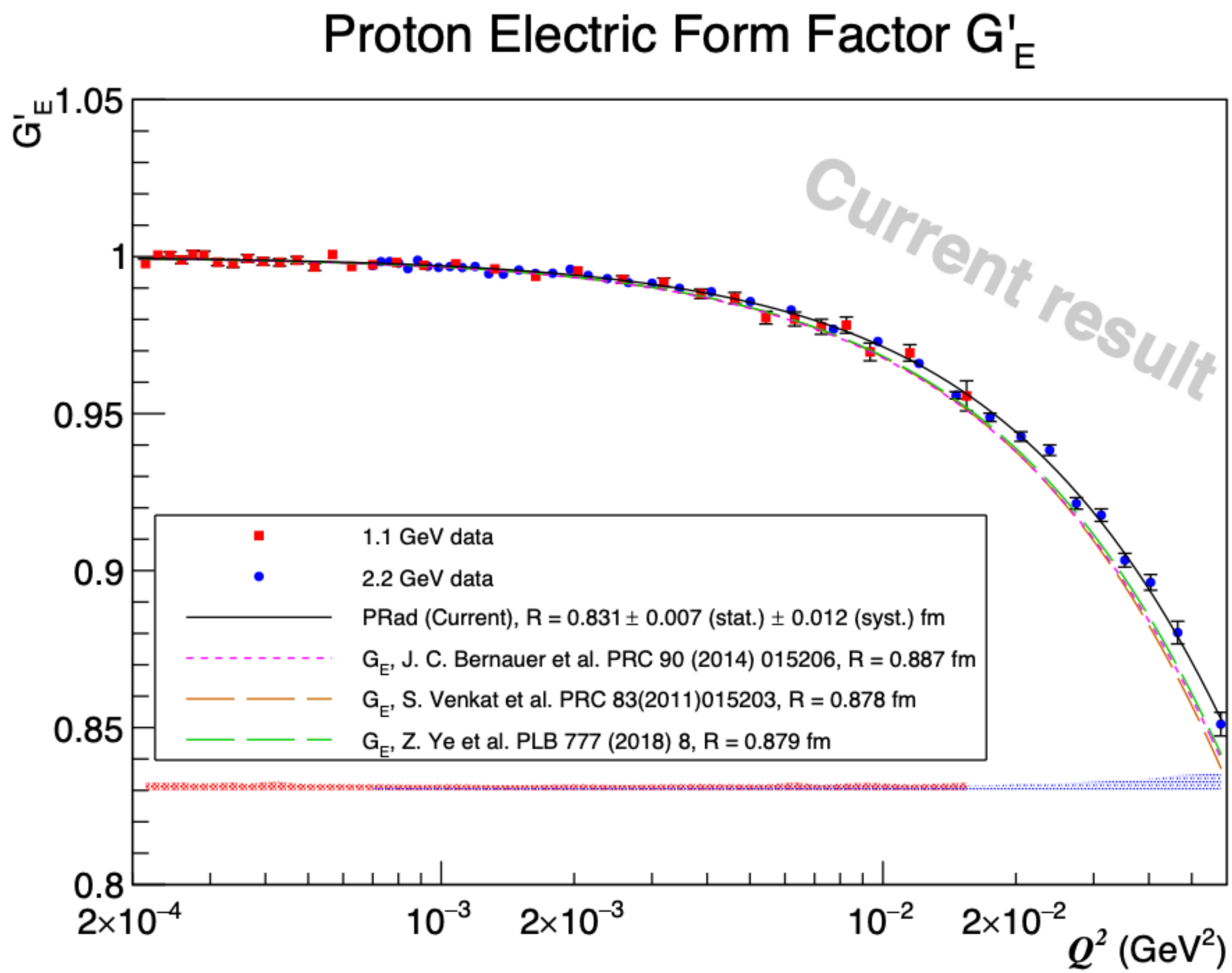
✓ X. Yan, D.W. Higinbotham, D. Dutta et al. "*Robust extraction of the proton charge radius from electron-proton scattering data*" Published in: *PRC 98, 2, 025204, 2018*

- The input form factors (with known Rp) are used to generate pseudodata with fluctuations mimicking the binning and random uncertainty of a set of real data.
- All combinations of input functions and fit functions can then be tested repeatedly against regenerated pseudodata.
- Since the input radius is known, this allows us to find fitting functions that are robust for proton radius extractions in an objective fashion.
- … we find that a two-parameter rational function, a two-parameter continued fraction, and the second-order polynomial expansion of z can extract the input radius regardless of the input charge form factor function that is used.



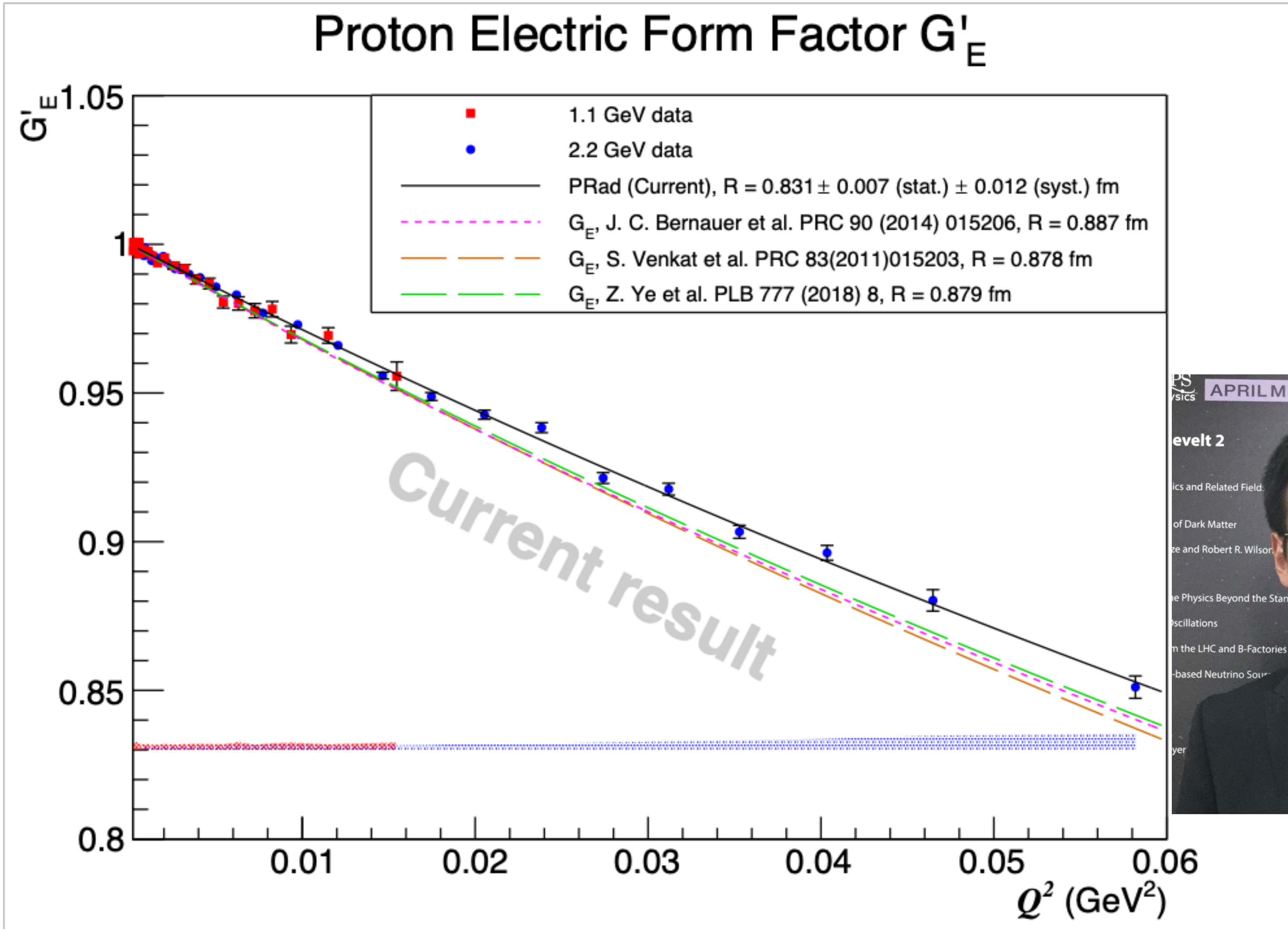
$$f_{\text{rational}}(Q^2) = p_0 G_E(Q^2) = p_0 \frac{1 + \sum_{i=1}^{N} p_i^{(a)} Q^{2i}}{1 + \sum_{j=1}^{M} p_j^{(b)} Q^{2j}},$$

Proton Electric Form Factor with Recent Models



Plots courtesy of Weizhi Xiong

PRad result from Duke analysis

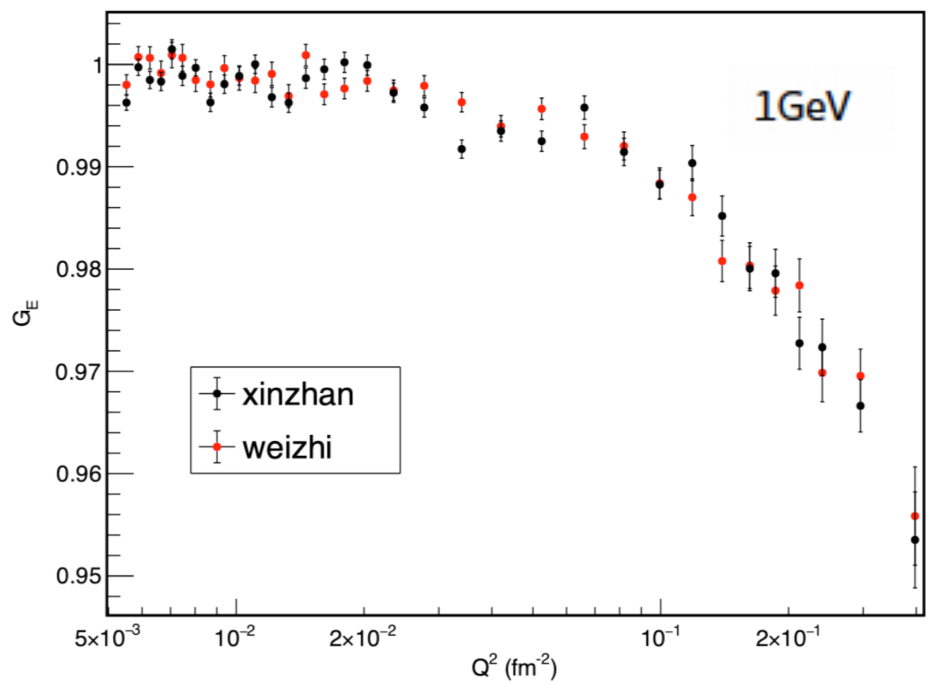


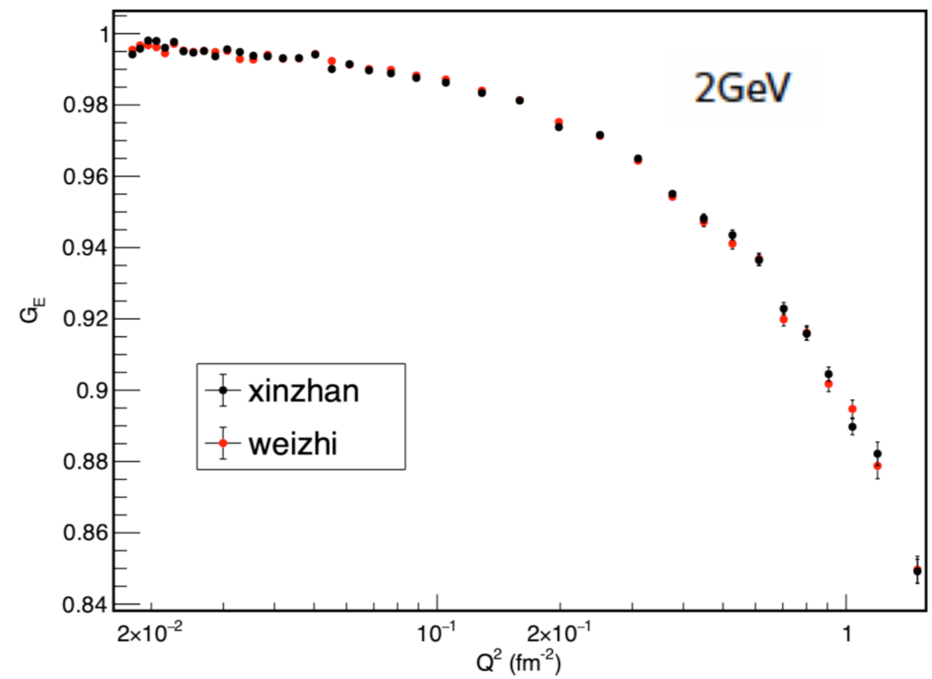
Prad result:
R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

Plots courtesy of Weizhi Xiong

PRad result from UVa analysis

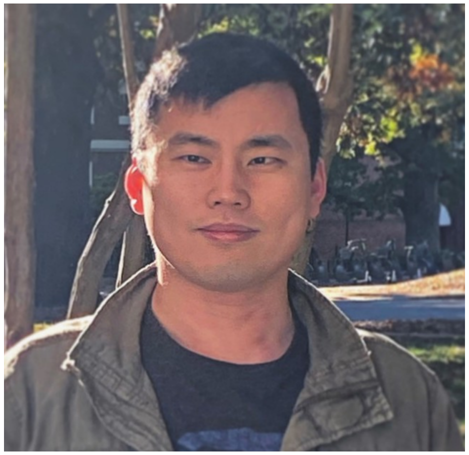
courtesy of Xinzhan Bai





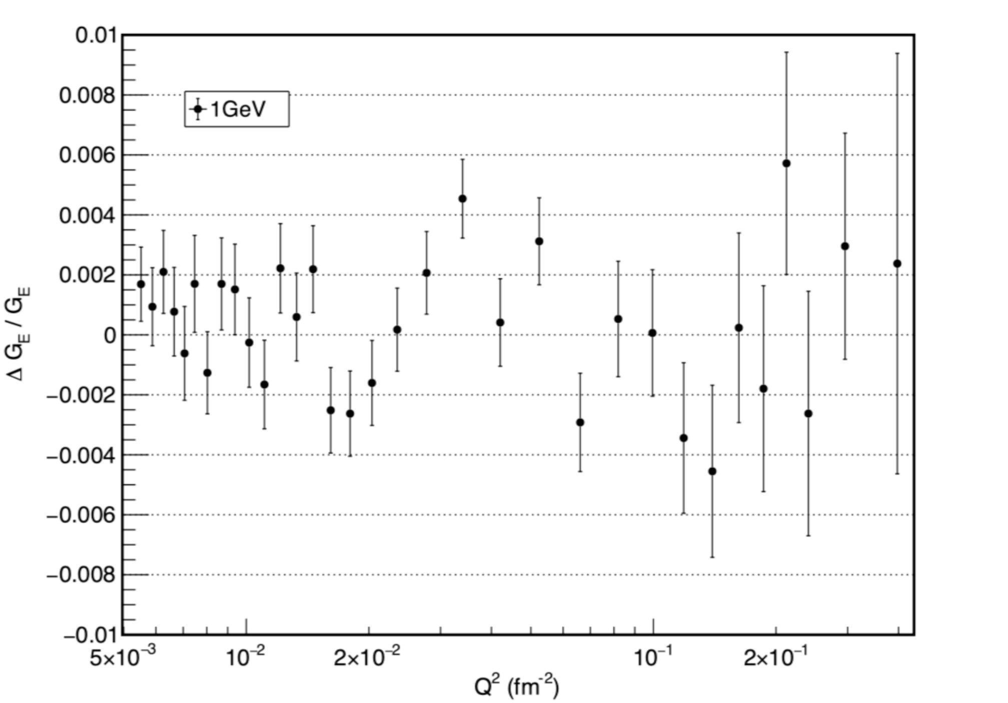
Prad result from Duke:
R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

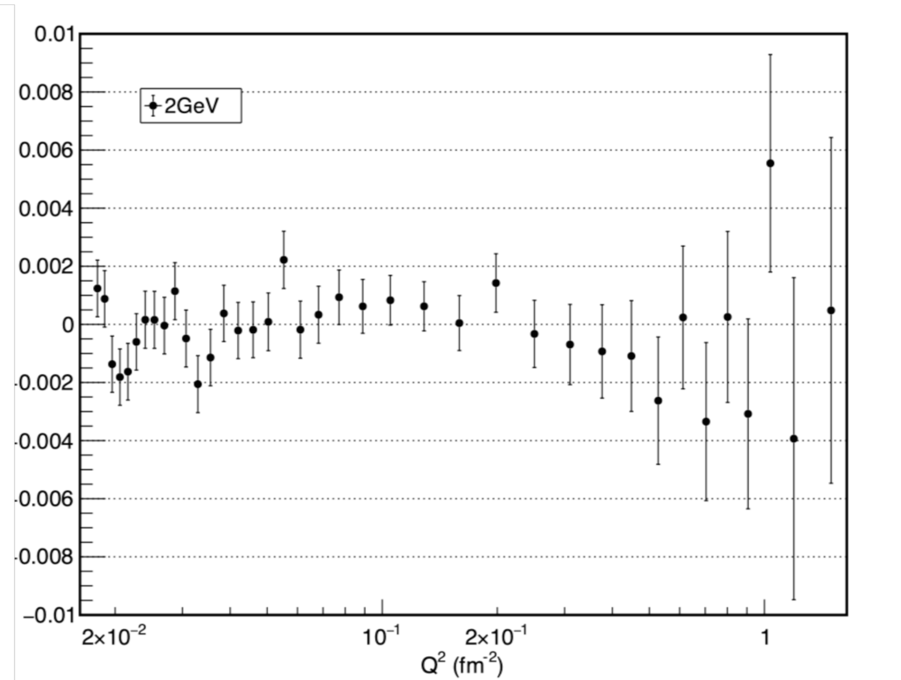
Prad result from UVa :
R_p = 0.833 ± 0.007 (stat.) ± 0.012 (syst.) fm



PRad result: UVa analysis compared to Duke analysis.

courtesy of Xinzhan Bai





Prad result from Duke:
R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

Prad result from UVa :
R_p = 0.833 ± 0.007 (stat.) ± 0.012 (syst.) fm

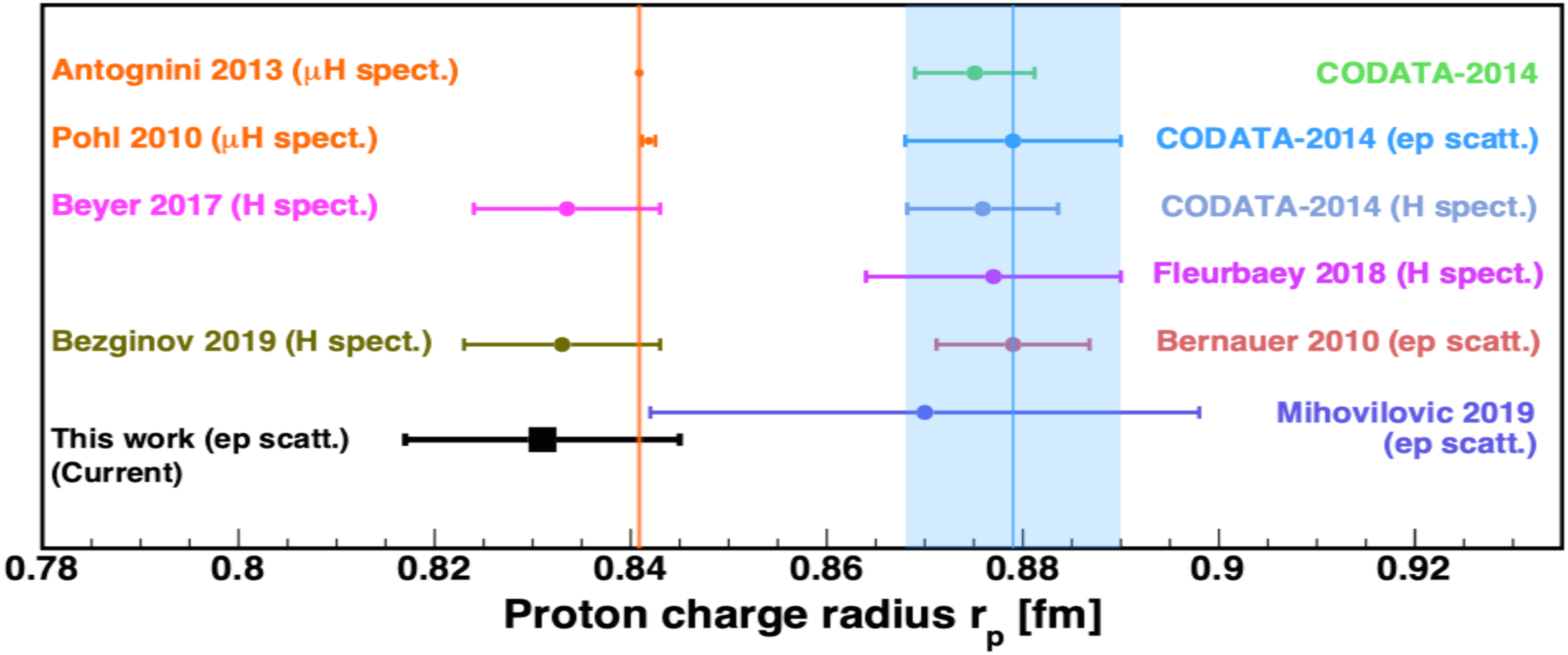
Systematic Uncertainties on Rp (Preliminary)

Showing only major items

Item	R_p uncertainty (fm)	n_1 uncertainty (1GeV)	n_2 uncertainty (2GeV)
Event selection	(0.0052)0.0092	(0.0002)0.0008	(0.0005)0.0011
Acceptance	(0.0024)0.0054	(0.0001)0.0001	(0.0001)0.0001
Beam background	(0.0038)0.0039	(0.0017)0.0020	(0.0003)0.0003
Detector efficiency	(0.0038)0.0045	(0.0001)0.0001	(0.0001)0.0001
Beam energy	(0.0022)0.0084	(0.0001)0.0001	(0.0002)0.0003
HyCal response	(0.0020)0.0032	(0.0000)0.0000	(0.0000)0.0001
Inelastic ep	(0.0009)0.0051	(0.0000)0.0001	(0.0000)0.0000
Radiative corrections	(0.0070)0.0070	(0.0011)0.0009	(0.0011)0.0009
Total	(0.0109)0.0175	(0.0020)0.0023	(0.0013)0.0015

(Current numbers in brackets)

Proton Radius from PRad



Prad result:
R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

Nature paper in print: will come out on Nov 7

What's Next ?

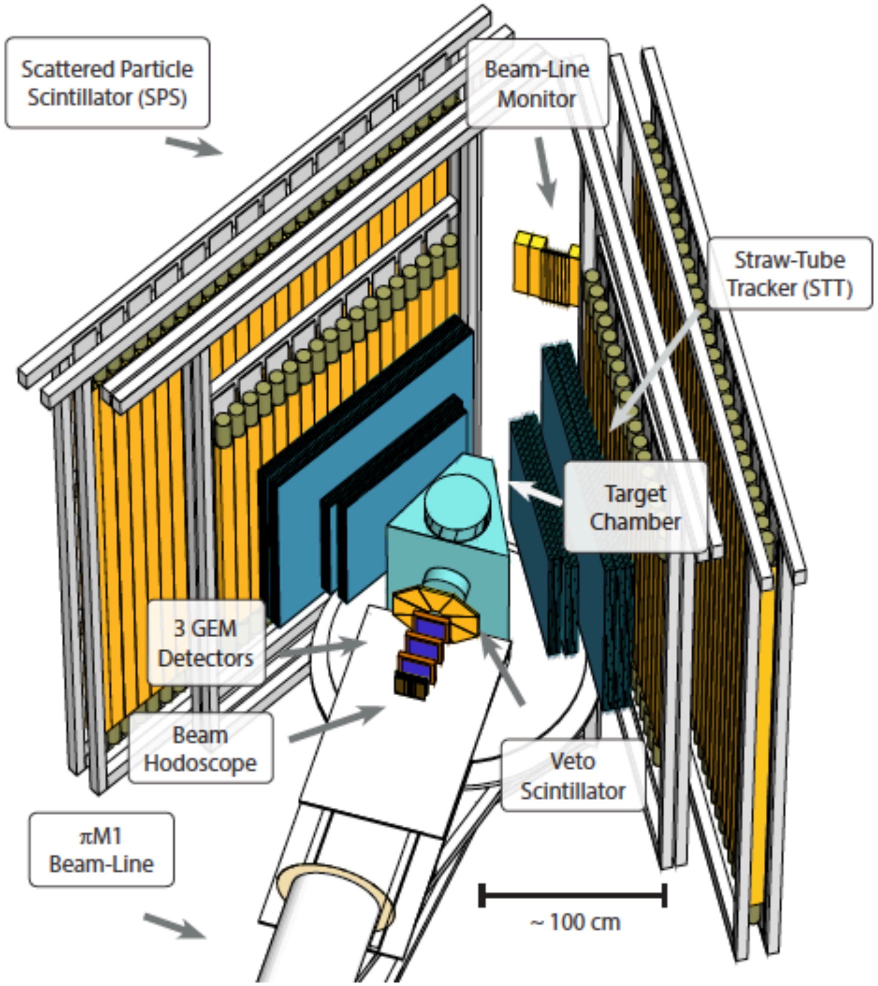
- Several other experiments around the world.
  - μP scattering: MUSE at PSI
  - ProRad at Grenoble
  - ULQ2 at Tokohu
  - ISR measurement at MESA @ Mainz
- DRad and an even more precise PRad

MUSE @ PSI

Paul Scherrer Institute πM1 Beam

- 590 MeV proton beam, 2.2mA, 1.3MW beam, 50.6MHz RF frequency
- World's most powerful proton beam
- Converted to $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ in piM1 beamline
- Separate out particle species by timing relative to beam RF
- Cut as many pions as possible, trigger on $e^{\pm}$, $\mu^{\pm}$

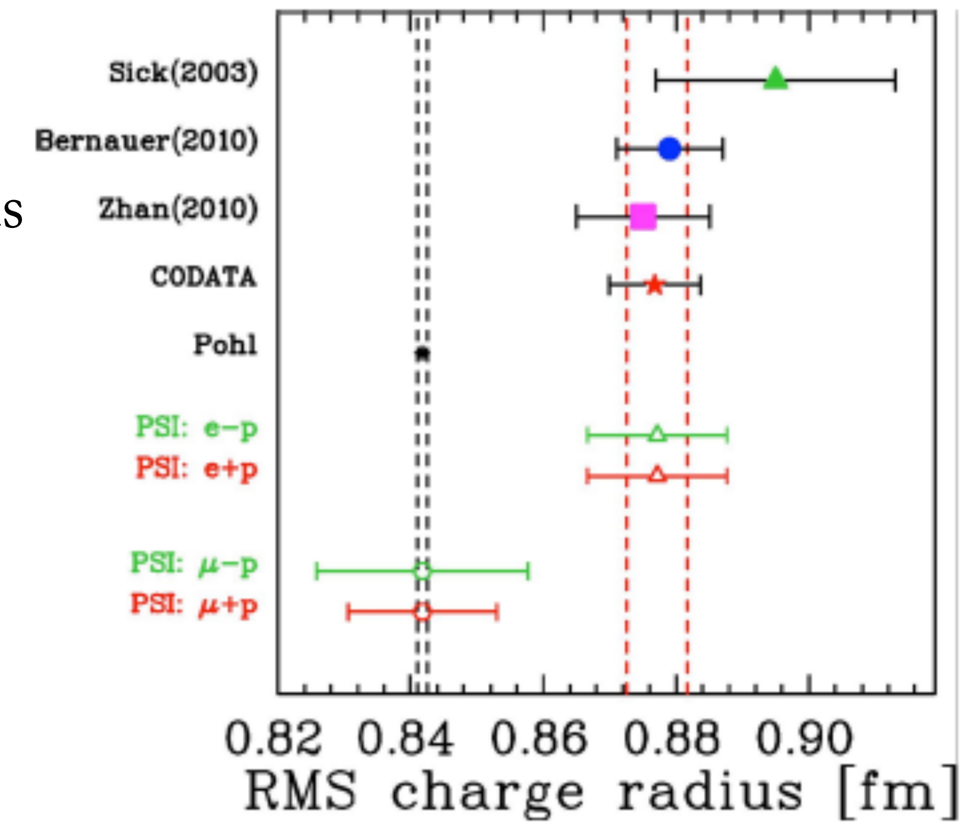
MUSE Experiment



- Low beam flux. → Large angle, non-magnetic detectors.
- Secondary beam. → Tracking of beam particles to target.
- Mixed beam. → Identification of beam particle in trigger.

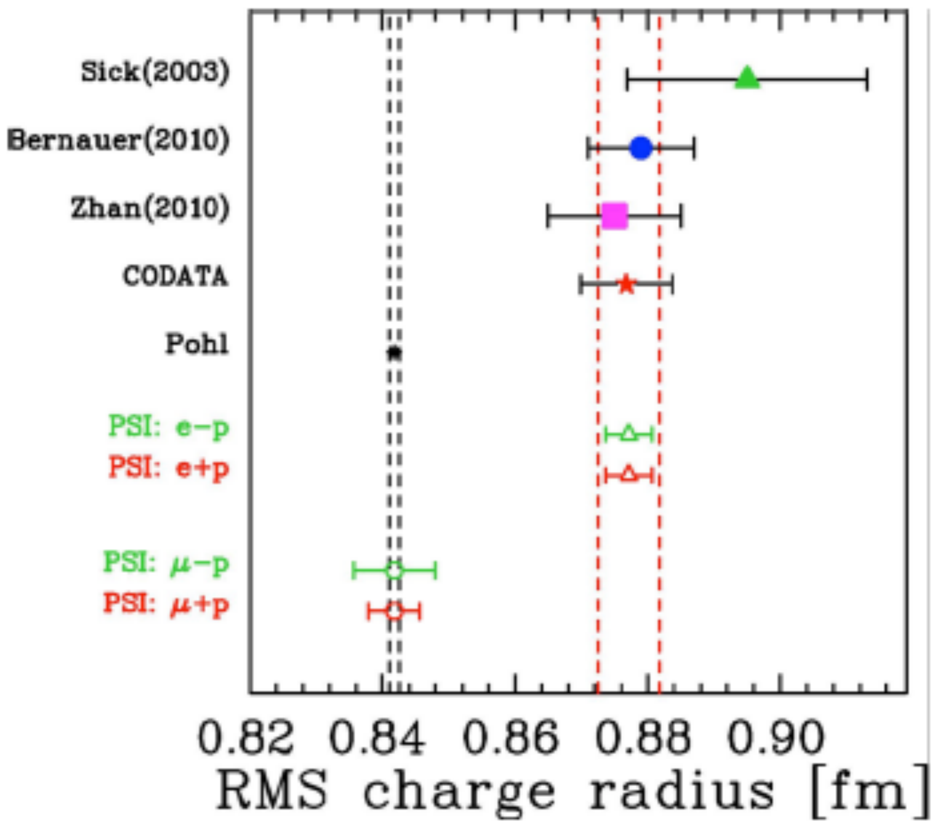
MUSE expected results

Absolute radius extraction uncertainties similar to previous experiments

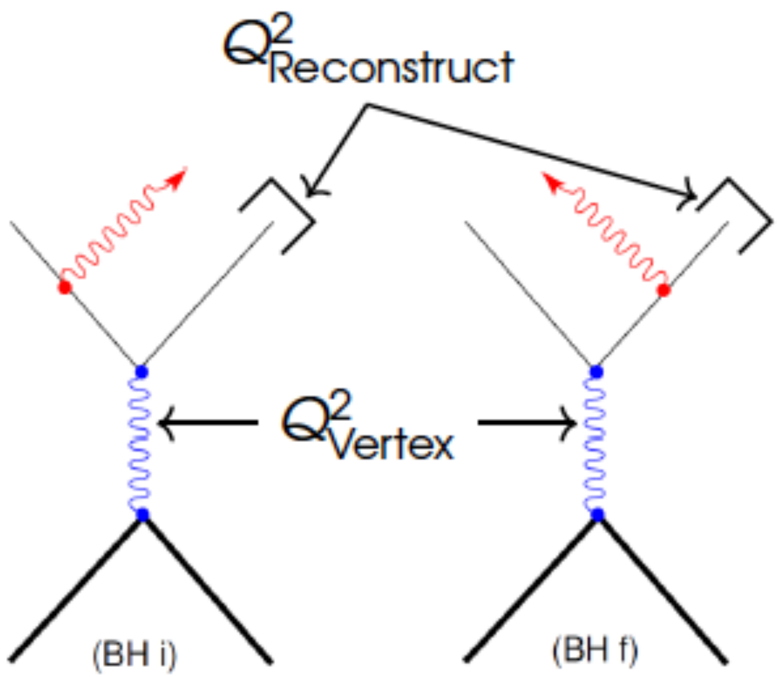


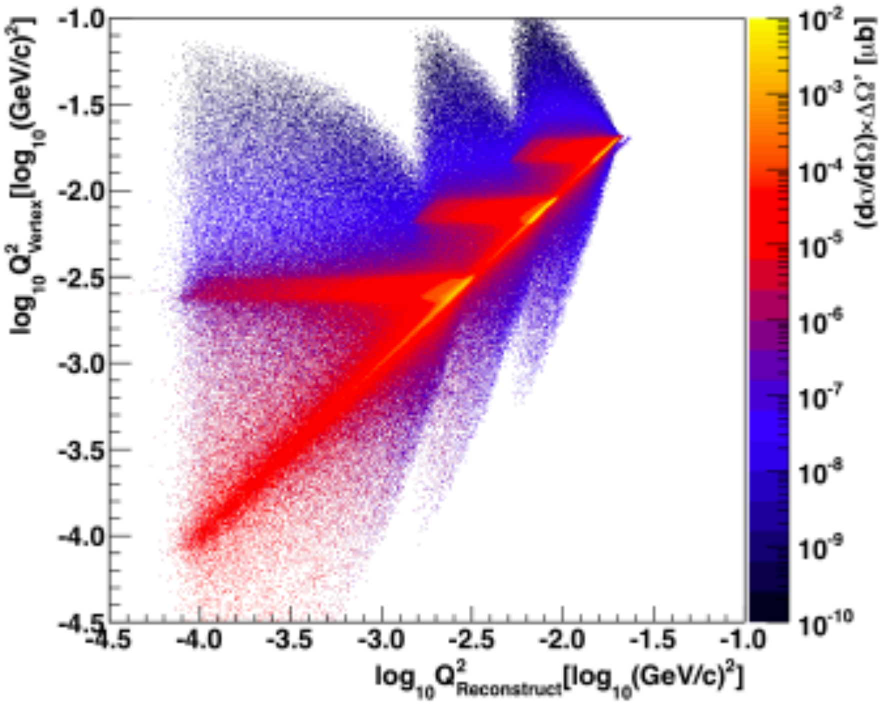
MUSE expected results

- Absolute radius extraction uncertainties similar to previous experiments
- However, common uncertainties cancel



Mainz ISR

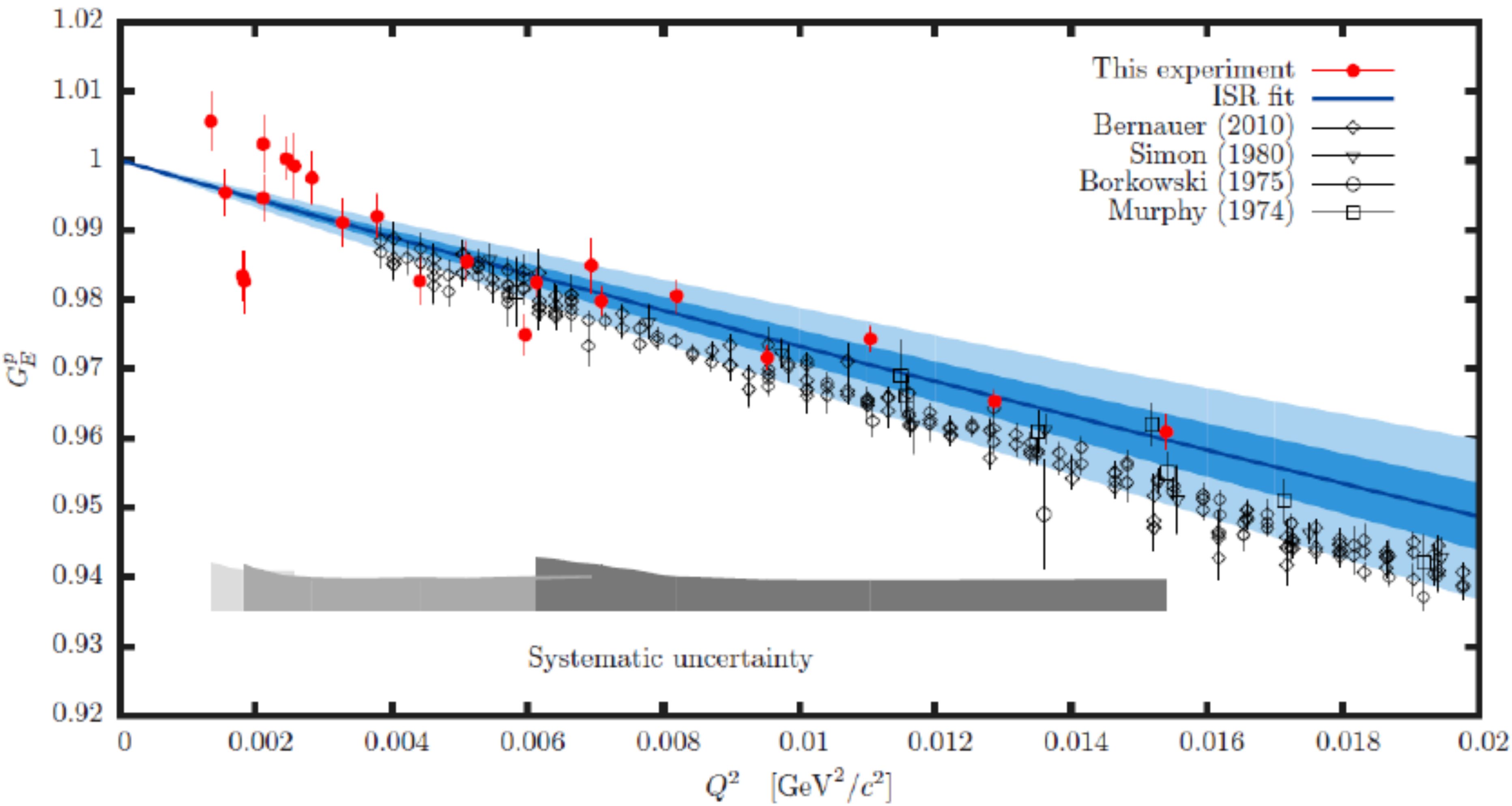




- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

Jan Bernauer

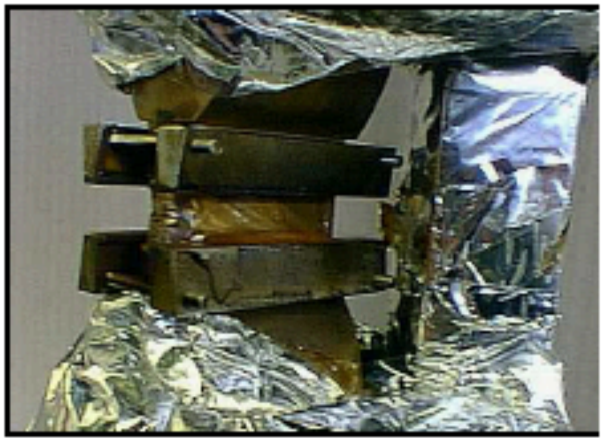
Mainz ISR



- Result from the pilot measurement: R_p = 0.810 ± 0.035 (stat.) ± 0.074 (syst.) fm
- Not competitive
- New measurement planed with MESA with the Jet target

Mainz ISR

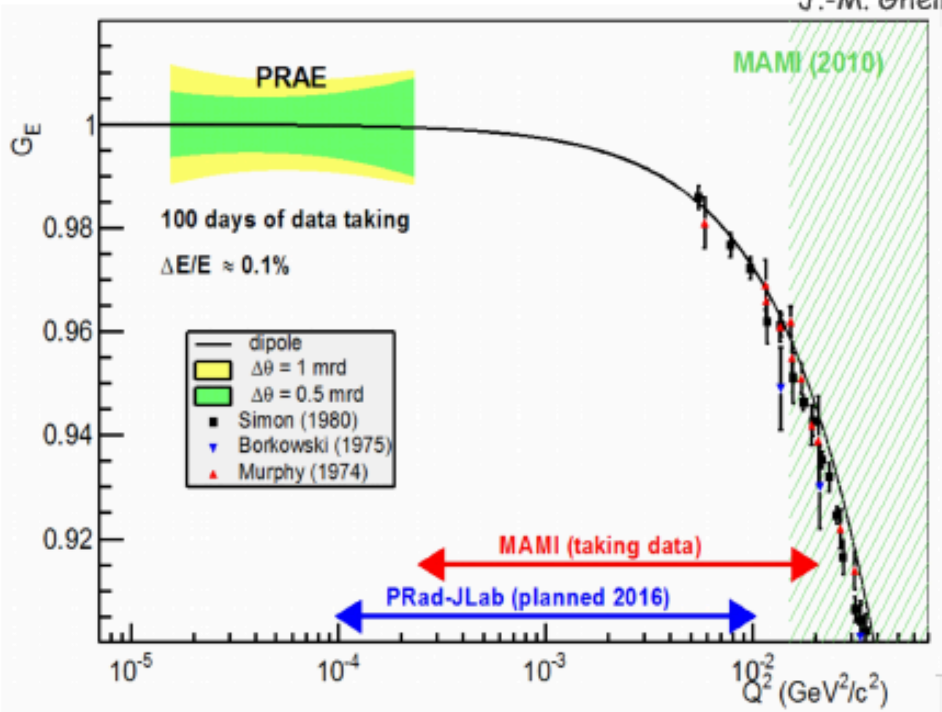
- For Mainz data, systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target
- Eliminate with jet target
  - point-like
  - no walls
  - but less density
- Rinse, repeat with D,^{3}He,^{4}He, ...

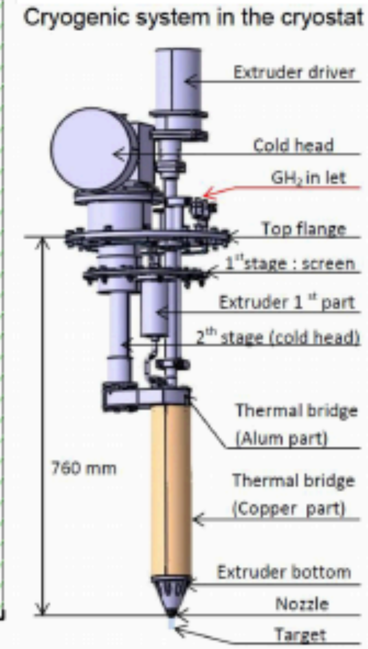


⇓

Platform for Research and Applications with Electrons: ProRad

J.-M. Gheller et al. AIP Conf. Proc. 1573 (2014) 58



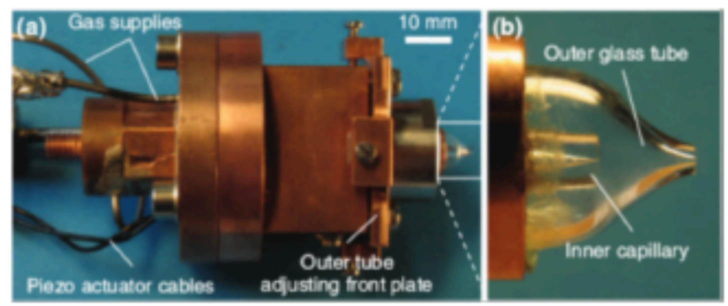


CHyMENE

Details from Eric Voutier LPSC, Grenoble (France).

Bi-national ANR proposal with Francfort University submitted.

Droplet Sream



- New accelerator to be built in France,
- Beginning measurement 2020
- Measurements in unexplored Q^2-range

  → $1.5\times10^{-5} - 3\times10^{-4}\ (GeV/c^2)^2$
- Constrain Q^2-dependence of G_E and extrapolation to zero
- Non-magnetic spectrometer, frozen hydrogen wire / film target

ULQ² @ Sendai

ULQ² collaboration
(Ultra-Low Q²)

1) elastic e+p scattering at ultra-low Q^2 region

2) $G_E(Q^2)$ at $0.0003 \leq Q^2 \leq 0.008$ $(GeV/c)^2$

3) G_E is extracted by Rosenbluth separation

4) Absolute cross section measurement

relative to $^{12}C(e,e)^{12}C$: sys. err. ~3×10^{-3}

5) Ee = 20 - 60 MeV, θ = 30 - 150°

6) the new beam line, and spectrometer are under construction

7) the experiments will start in 2019

PRad Nature publication will appear on Nov 7.

Article

A small proton charge radius from electron–proton scattering experiments

https://doi.org/10.1038/s41586-019-1721-2

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Elastic electron–proton scattering (e–p) and the spectroscopy of hydrogen atoms are the two methods traditionally used to determine the proton charge radius, r_p. In 2010, a new method using muonic hydrogen atoms[1] found a substantial discrepancy compared with previous results[2], which became known as the 'proton radius puzzle'. Despite experimental and theoretical efforts, the puzzle remains unresolved. In fact, there is a discrepancy between the two most recent spectroscopic measurements conducted on ordinary hydrogen[3,4]. Here we report on the proton charge radius experiment at Jefferson Lab (PRad), a high-precision e–p experiment that was established after the discrepancy was identified. We used a magnetic-spectrometer-free method along with a windowless hydrogen gas target, which overcame several limitations of previous e–p experiments and enabled measurements at very small forward-scattering angles. Our result, $r_p = 0.831 \pm 0.007_{stat} \pm 0.012_{syst}$ femtometres, is smaller than the most recent high-precision e–p measurement and 2.7 standard deviations smaller than the average of all e–p experiment results[6]. The smaller r_p we have now measured supports the value found by two previous muonic hydrogen experiments[5,7]. In addition, our finding agrees with the revised value (announced in 2018) for the Rydberg constant[8]—one of the most accurately evaluated fundamental constants in physics.

Q2

The proton is the dominant ingredient of visible matter in the Universe. Consequently, determining the proton's basic properties—such as its root-mean-square charge radius, r_p—is of interest in its own right. Accurate knowledge of r_p is also important for the precise determination of other fundamental constants, such as the Rydberg constant (R_∞)[2]. The value of r_p is also required for precise calculations of the energy levels and transition energies of the hydrogen atom—for example, the Lamb shift. In muonic hydrogen (μH atoms), in which the electron in the H atom is replaced by a 'heavier electron' (a muon), the extended proton charge distribution changes the Lamb shift by as much as[1] 2%. The first-principles calculation of r_p from the accepted theory of the strong interaction (quantum chromodynamics, QCD), is notoriously challenging and currently cannot reach the accuracy demanded by experiments, but lattice QCD calculations are on the cusp of becoming precise enough to be tested experimentally[9]. Therefore, the precise measurement of r_p is critical not only for addressing the proton radius puzzle but also important for determining certain fundamental constants of physics and testing lattice QCD.

Prior to 2010 the two methods used to measure r_p were ep → ep elastic scattering measurements, in which the slope of the extracted proton (p) electric (E) form factor, G_E^p, as the four-momentum transfer squared (Q^2) approaches zero is proportional to r_p^2; and Lamb shift (spectroscopy) measurements of ordinary H atoms, which, along with state-of-the-art calculations, can be used to determine r_p. Although the e–p results can be somewhat less precise than the spectroscopy results, until 2010 the values of r_p obtained from these two methods[2,5] mostly agreed with each other[10]. Since that year, two new results based on Lamb shift measurements in μH were reported[5,7]. The Lamb shift in μH is several million times more sensitive to r_p because the muon in a μH atom is about 200 times closer to the proton than is the electron in a H atom. To the surprise of both the nuclear and atomic physics communities, the two μH results[1,7], displaying unprecedented precision with an estimated error

Q3

Q4

Q5

Q6

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Rupesh Silwal (MIT)

Summary

- PRad was uniquely designed and performed in May/June of 2016 to address the *"Proton Radius Puzzle"*:
  - data in a large Q^2 range have been recorded with the same experimental settings, $[2\times10^{-4} \div 6\times10^{-2}]$ GeV/C^2.
  - lowest Q^2 data set ($\sim 10^{-4}$ GeV/C^2) has been collected for the first time in ep-scattering experiments;
  - simultaneous measurement of the Moller and Mott scattering processes has been demonstrated to control systematic uncertainties.

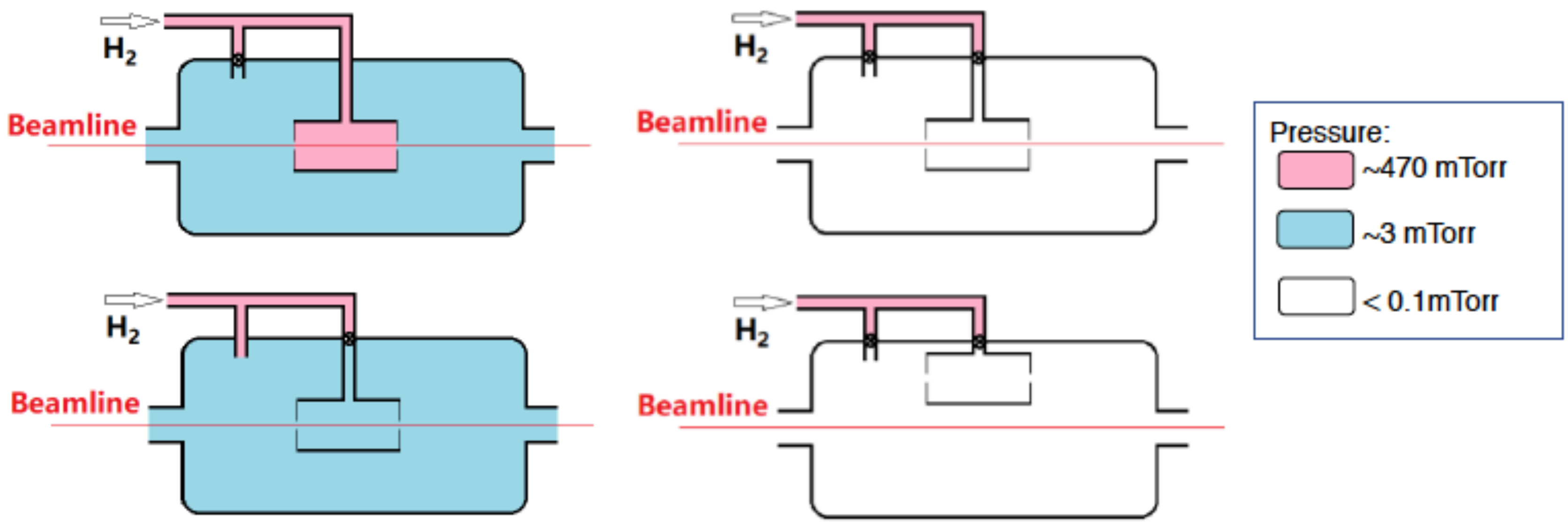
- The final result from the PRad experiment is:

  $R_p = 0.831 \pm 0.007$ (stat.) ± 0.012 (syst.) fm

- The article with the Final result will appear online in a few days.
- Stay tuned for PRad-II and DRad

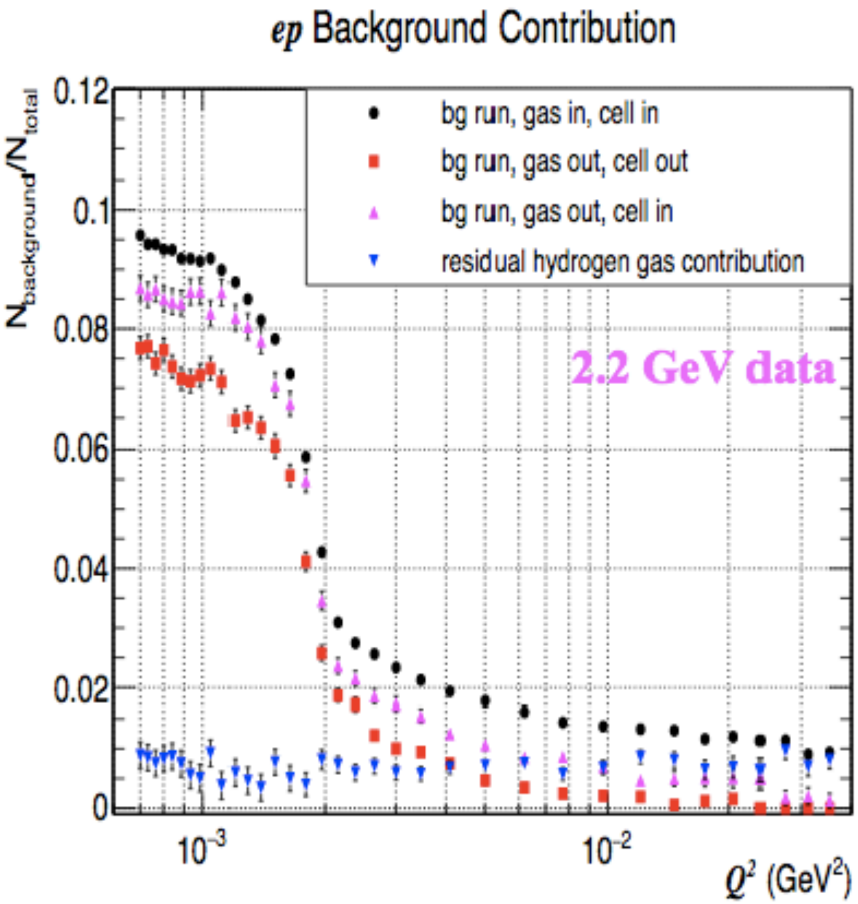
Background Subtraction

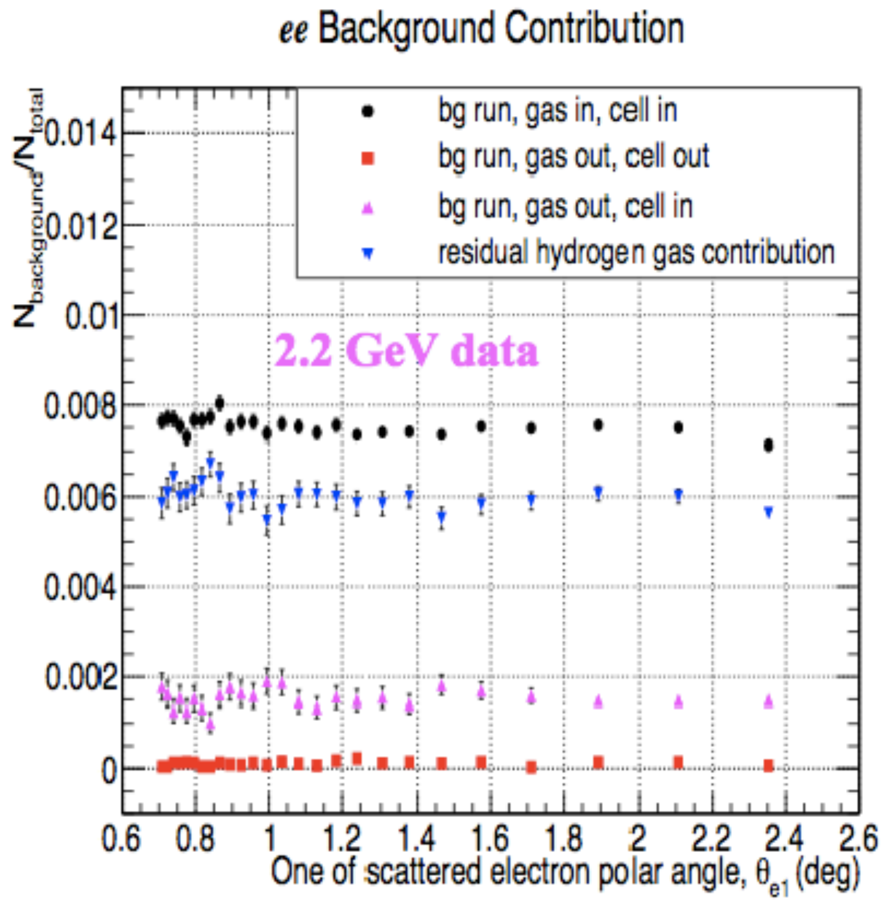
- **Runs with different target condition taken for background subtraction and studies for the systematic uncertainty**
- **Developed simulation program for target density (COMSOL finite element analysis)**



Background Subtraction

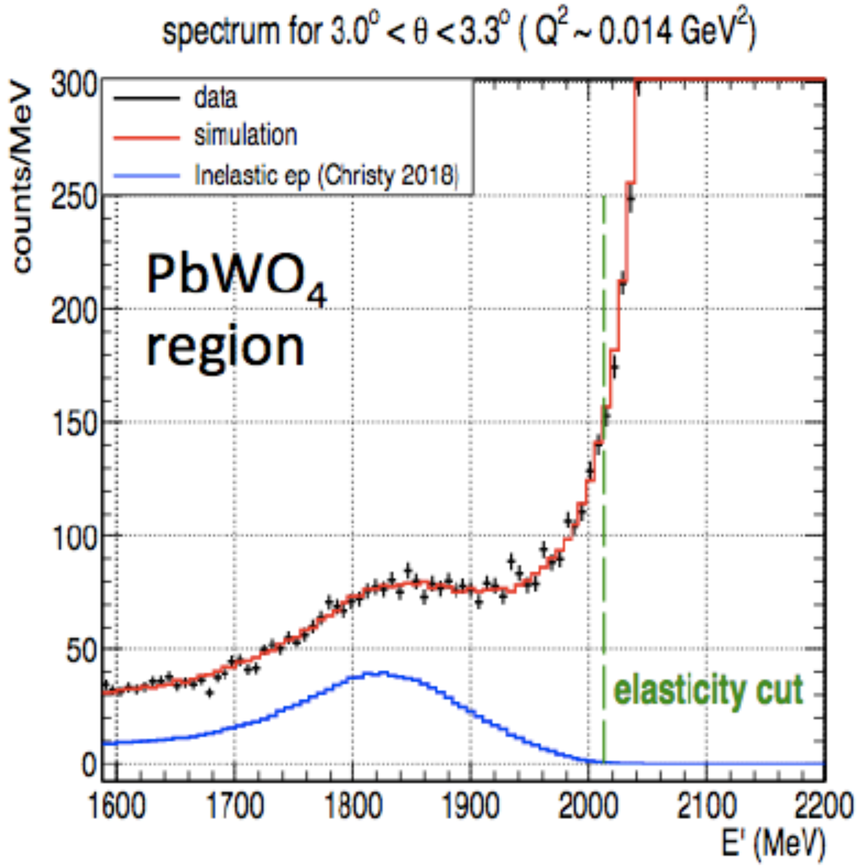
- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~ 0.8% at all angles

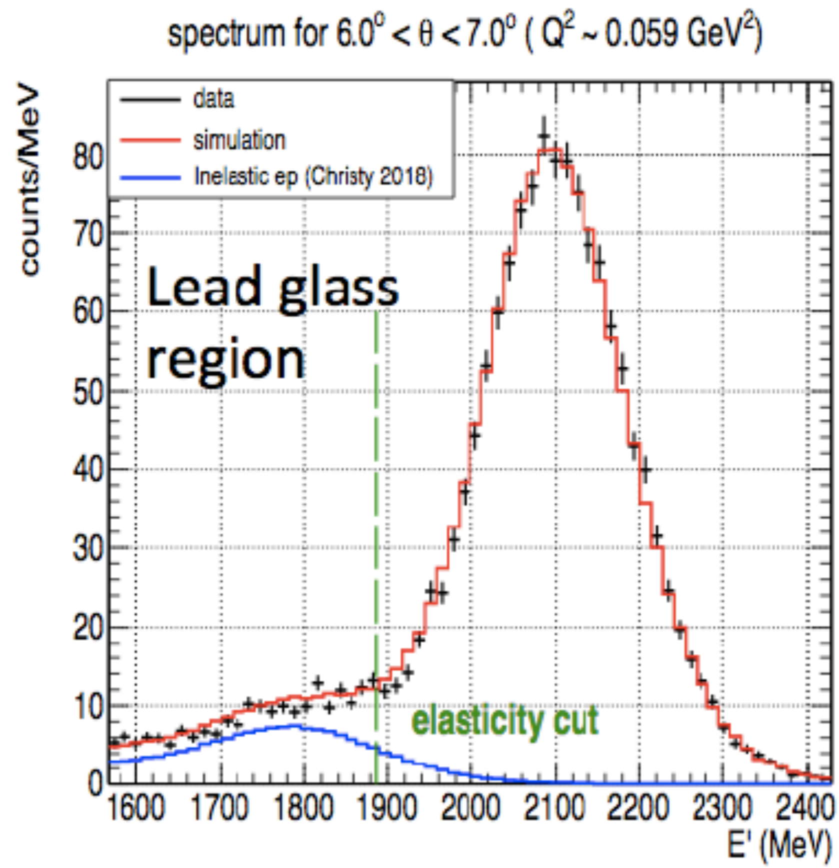




Elastic cut and inelastic contribution

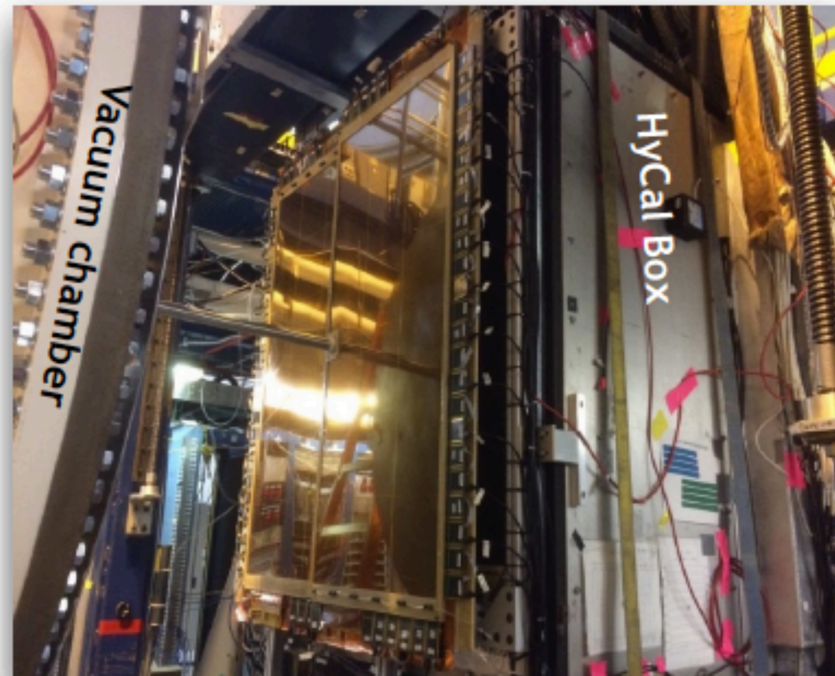
- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region





HyCal and GEMs on the beamline

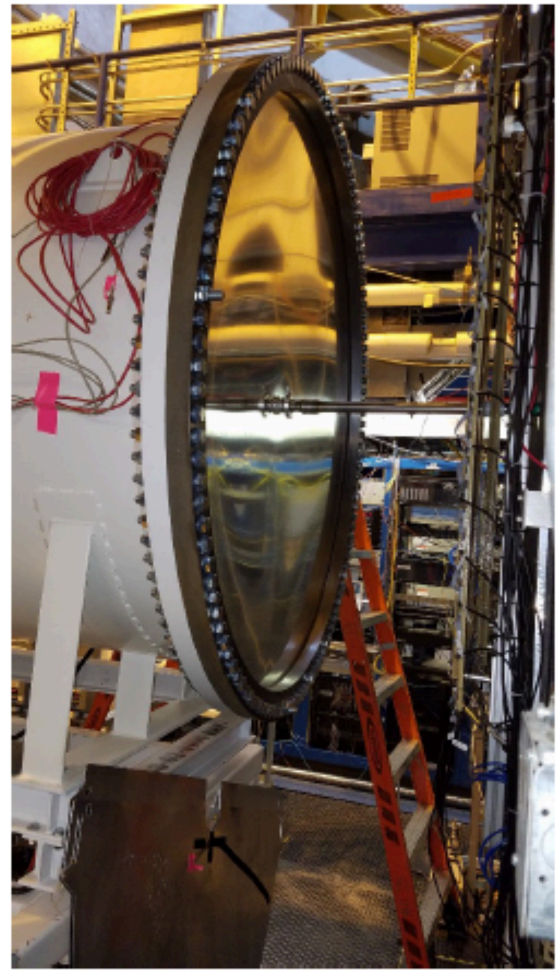
beam view



downstream view

Vacuum chamber with one thin window

two stage, 5 m long vacuum box



1.7 m dia, 2 mm thick
Al window

Extraction of *ep* Elastic Scattering Cross Section

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

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

- 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 (fully beyond ultra relativistic approximation)

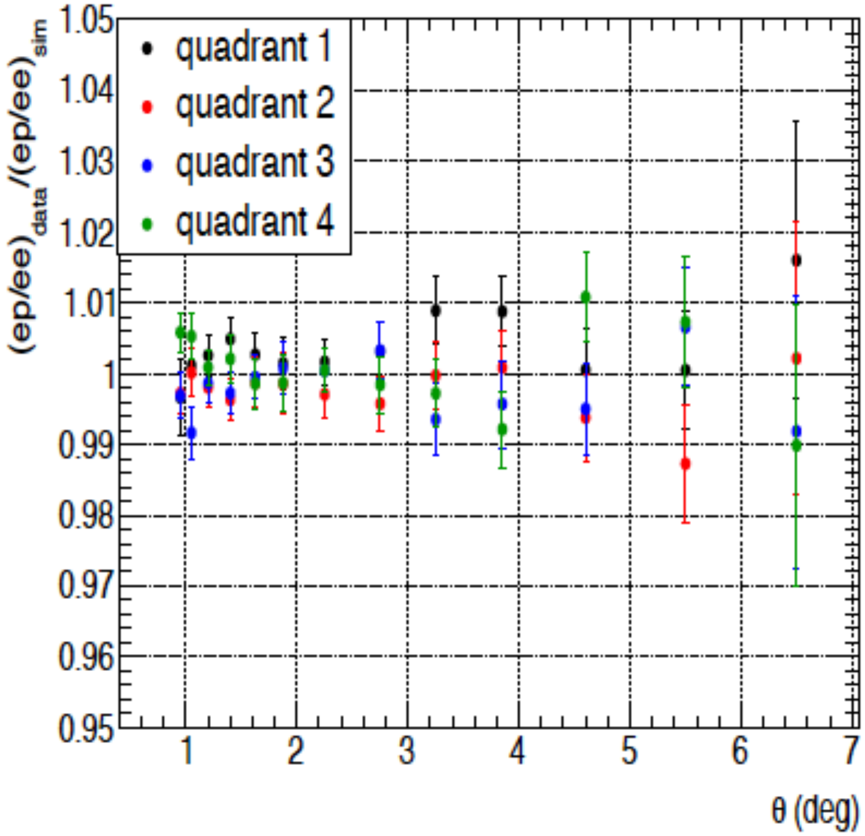
- A Geant4 simulation package is used to study the radiative effects:

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

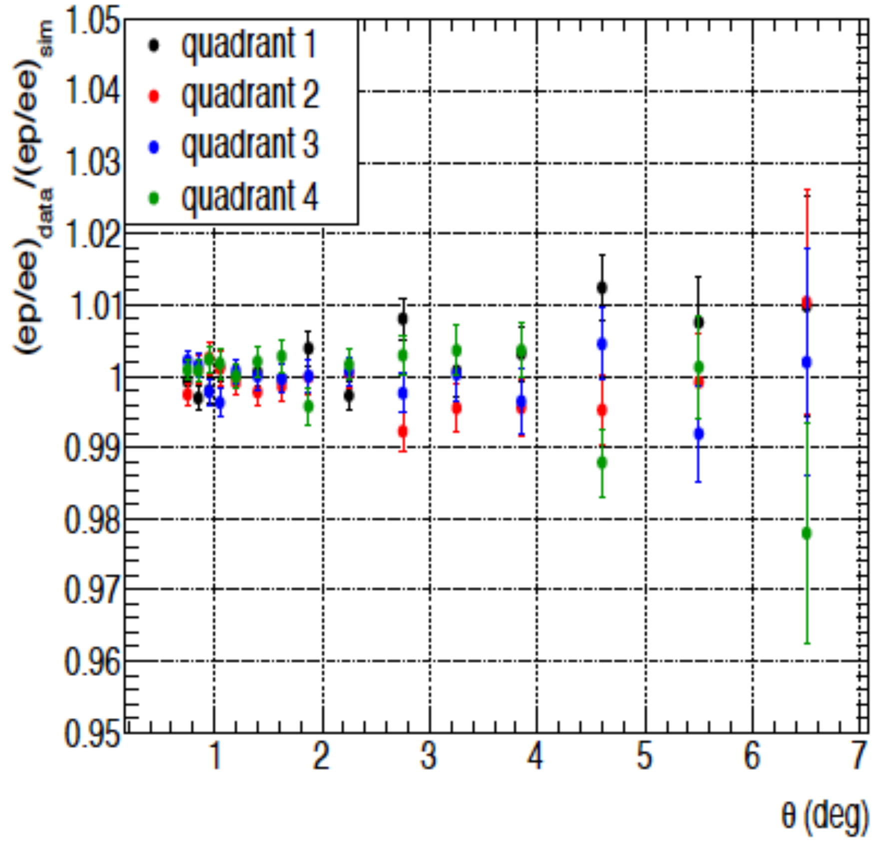
- Iterative procedure applied for radiative correction

Normalized super ratio by quadrants

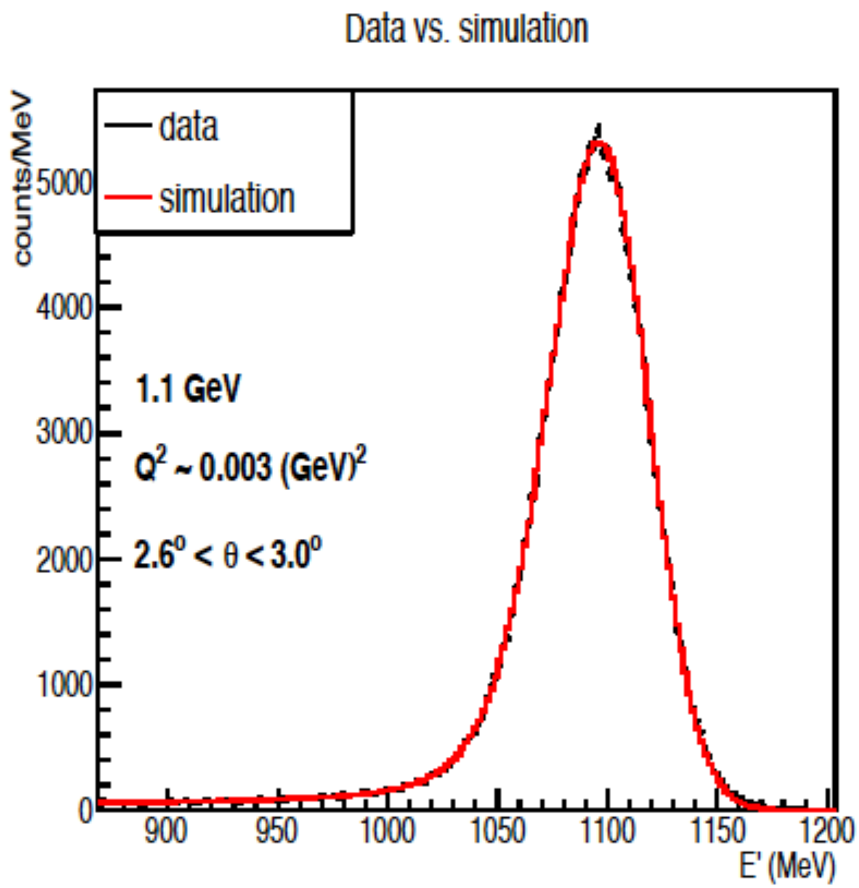
1GeV

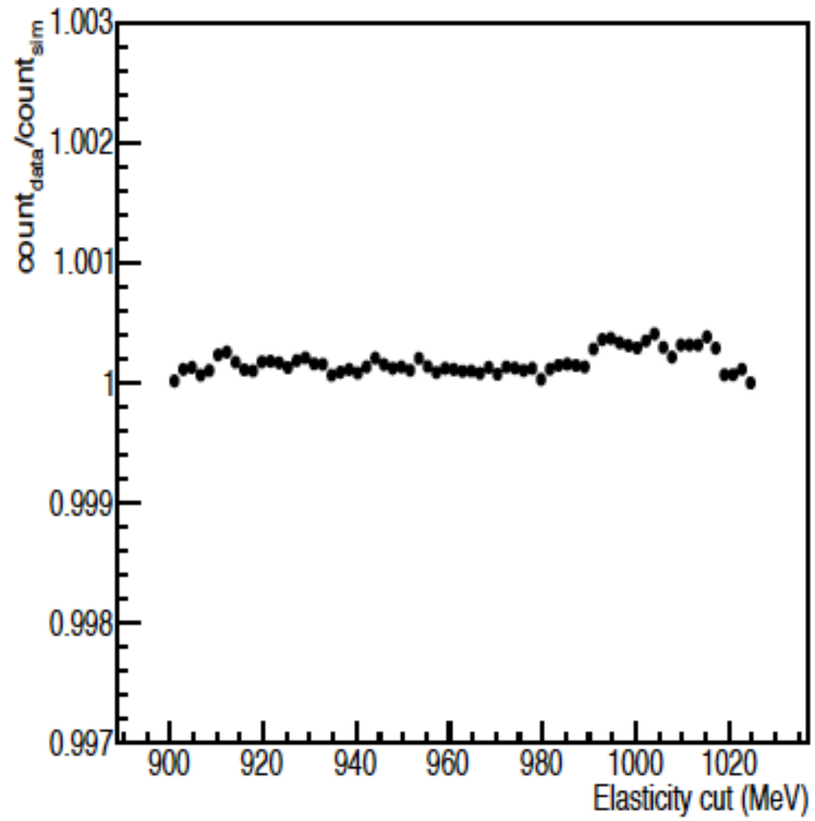


2GeV

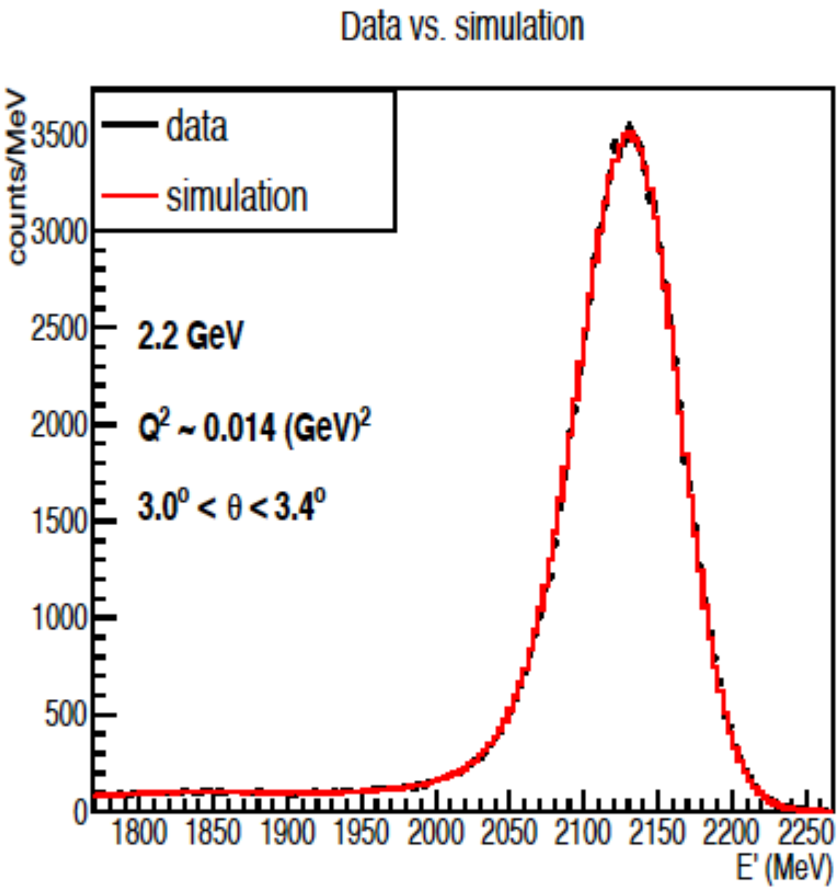


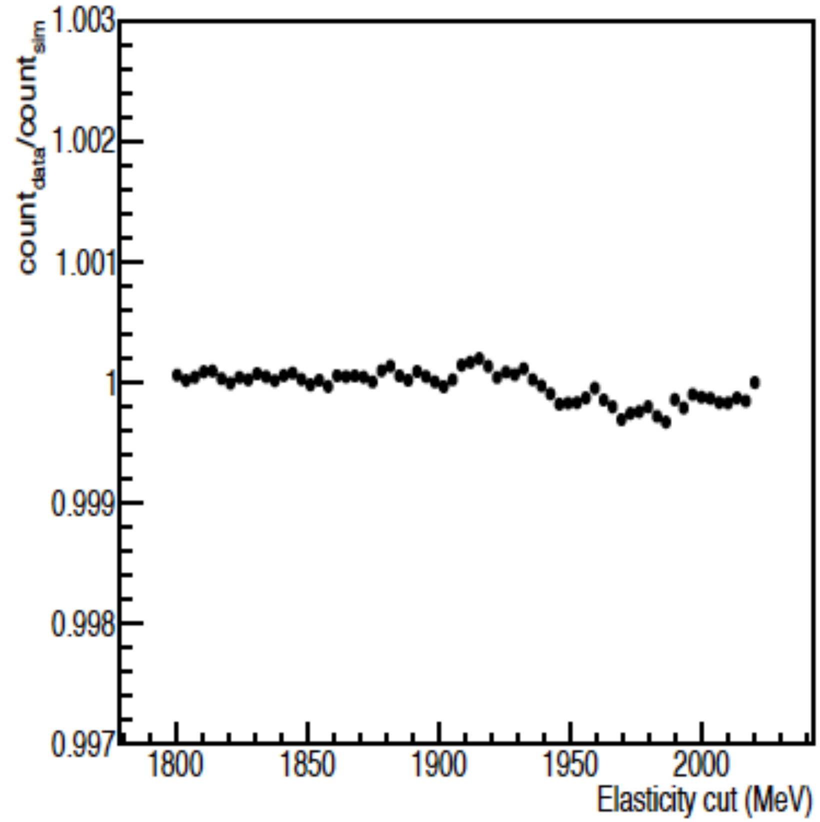
1GeV elasticity cut sensitivity





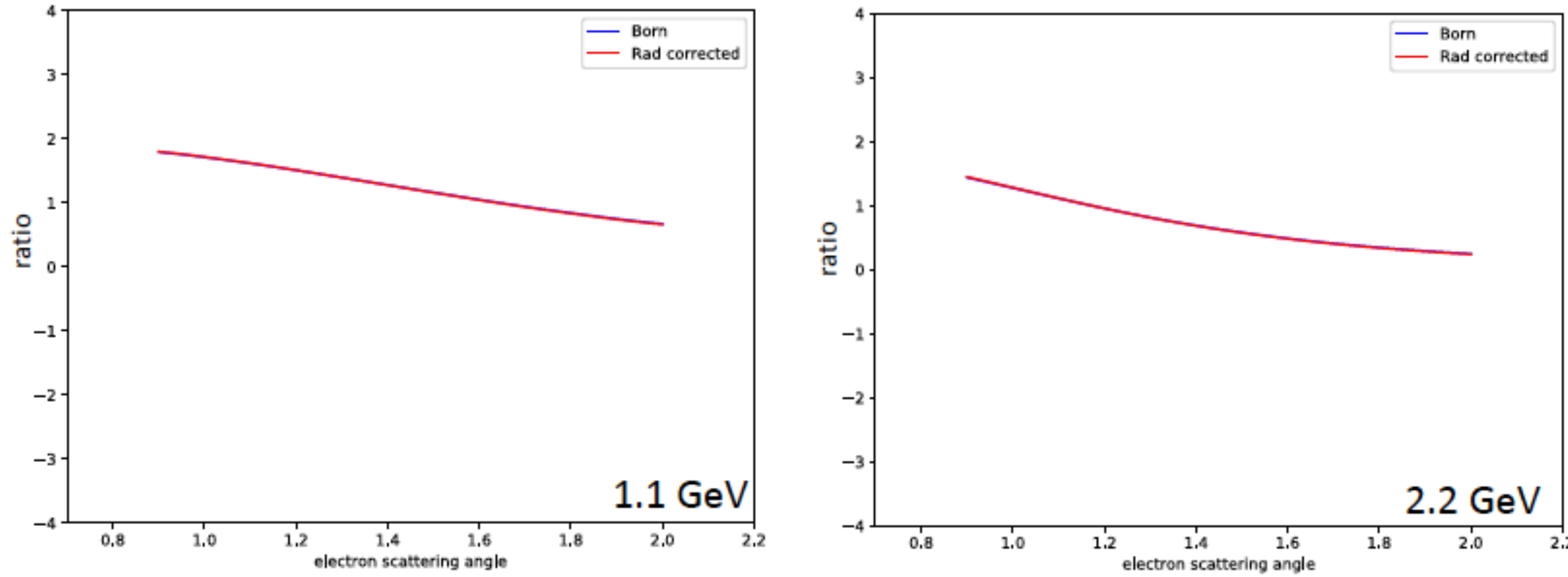
2GeV elasticity cut sensitivity





Radiative corrections

ep cross section / *ee* cross section

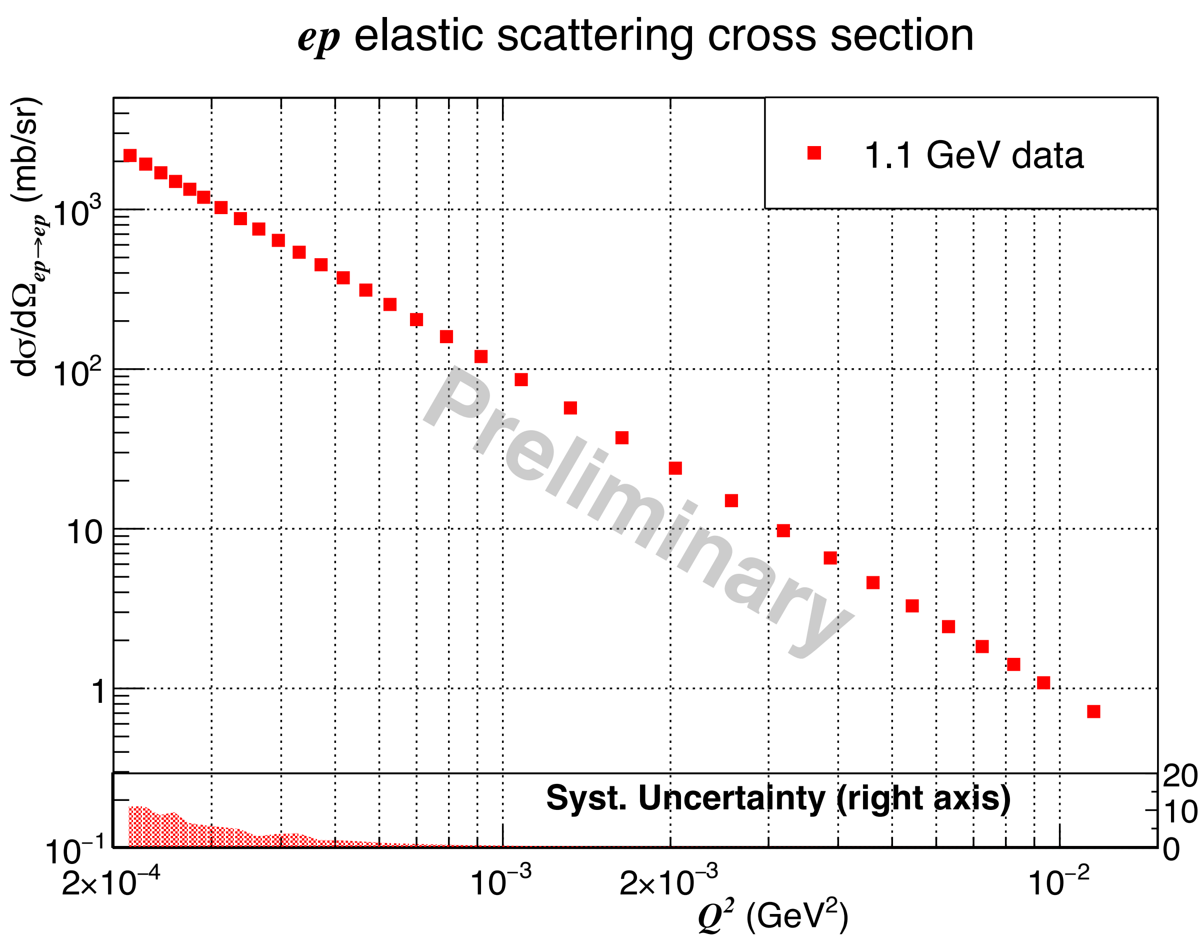


- Event generators for *ep* and *ee* elastic scattering developed based on complete calculation of radiative correction beyond URA[1]
- Cross checked with results from second generator[2]
- Include hard emission radiative photons for full correction of radiative effect with HyCal
- Include effect from two photon exchange[3]

1. I. Akushevich et al., Eur. Phys. J. A 51(2015)1
2. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
3. O. Tomalak, Few Body Syst. **59**, no. 5, 87 (2018)

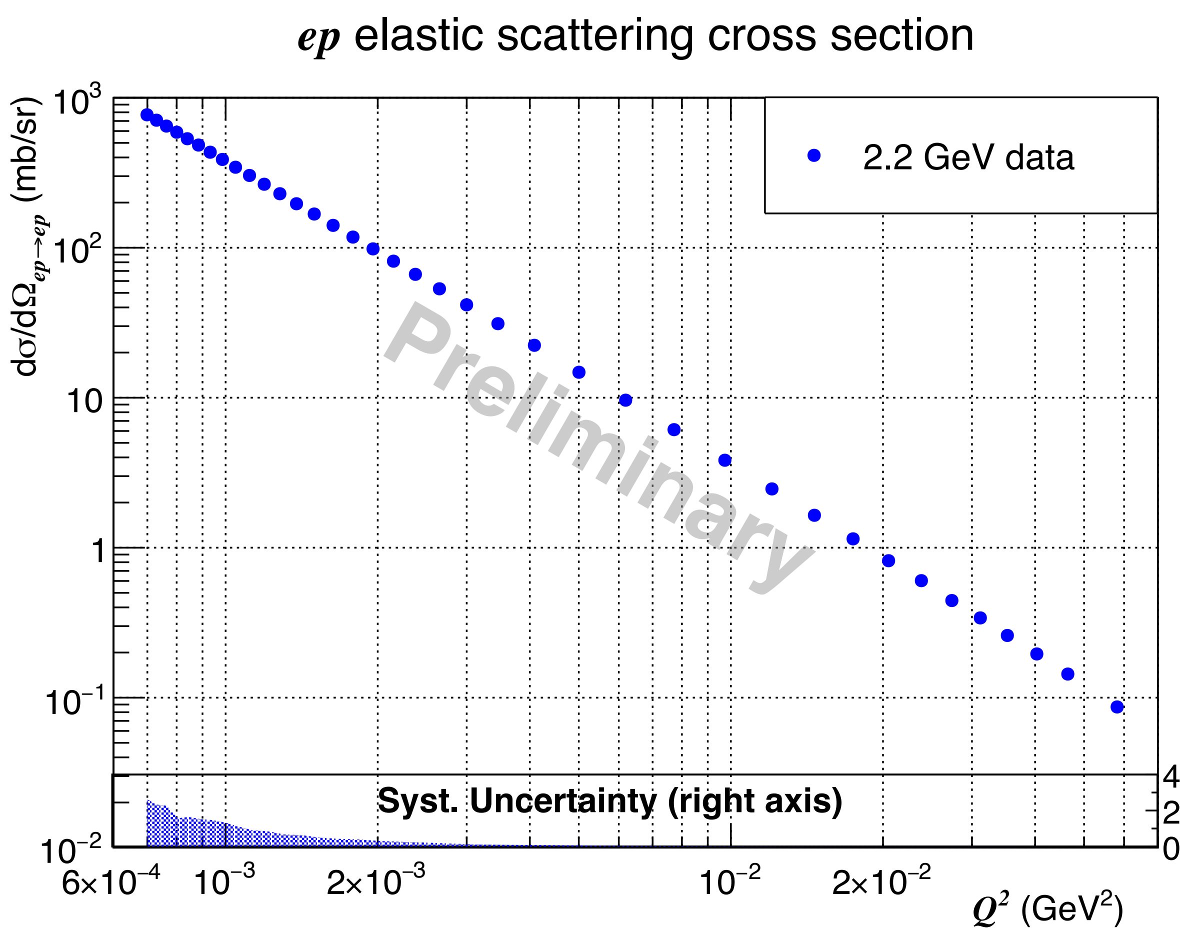
Elastic ep→ep Cross Sections, 1.1 GeV (Preliminary)

- Differential cross section vs. Q^2, with 1.1 GeV data (preliminary).
- Statistical uncertainty at this stage: ~0.2% per point.
- Systematic uncertainties at current stage: 0.3% ~0.6% (shown as shadow area).



Elastic ep→ep Cross Sections, 2.2 GeV (Preliminary)

- Differential cross section vs. Q^2, with 2.2 GeV data.
- Statistical uncertainty at this stage: ~0.18% , per point.
- Systematic uncertainties at current stage: 0.3% ~ 1.3% (shown as shadow area).

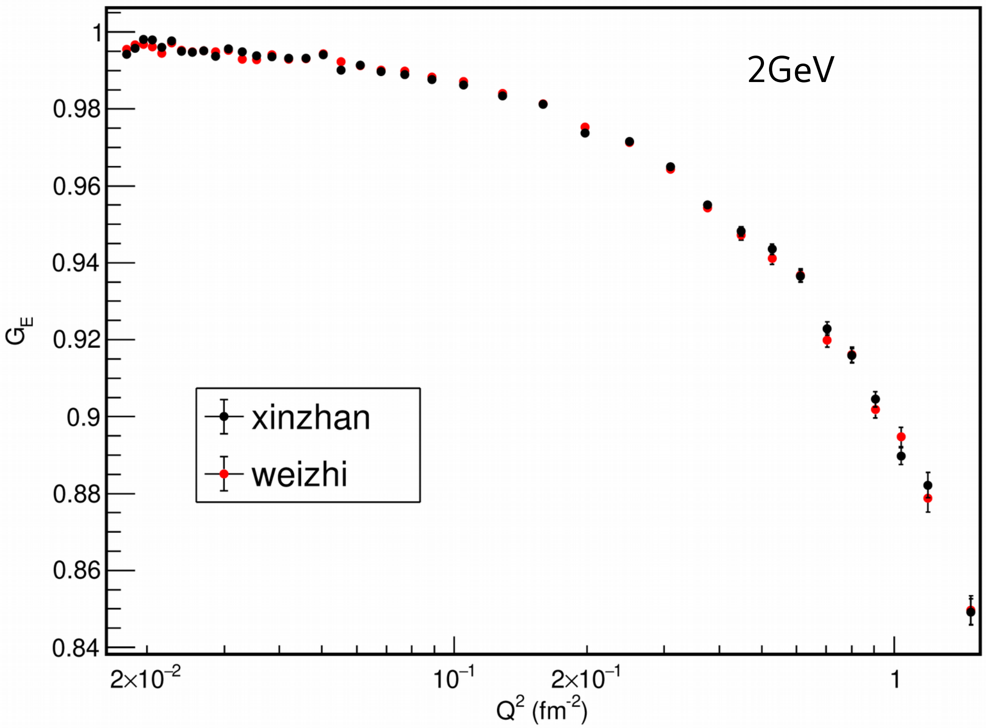


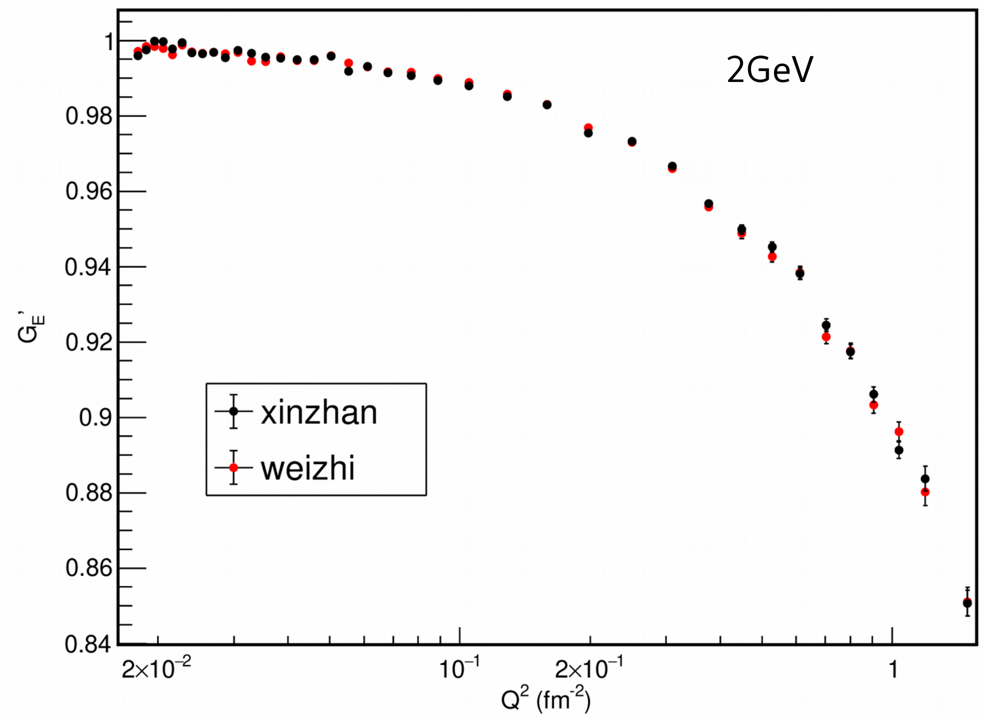
GE compare

- 1.1 GeV data fit to: $n_1 f(Q^2)$
- 2.2 GeV data fit to: $n_2 f(Q^2)$

$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

$$G'_E = G_E/n$$





- Fit 1.1 GeV data only: $R_p = 0.845802\ fm \pm 0.0248939\ fm;$ $n_1 = 0.999835 \pm 0.000226$
- Fit 2.2 GeV data only: $R_p = 0.82863\ fm \pm 0.00529776\ fm;$ $n_2 = 0.995738 \pm 0.000151314$
- Fit 1.1GeV and 2.2GeV data: $R_p = 0.833086\ fm \pm 0.0070957\ fm;$ $n_1 = 0.99694 \pm 0.00019$ $n_2 = 0.995816 \pm 0.00017$