The latest on proton charge radius

Nuclear Physics Seminar
University of Virginia, Nov 8, 2011

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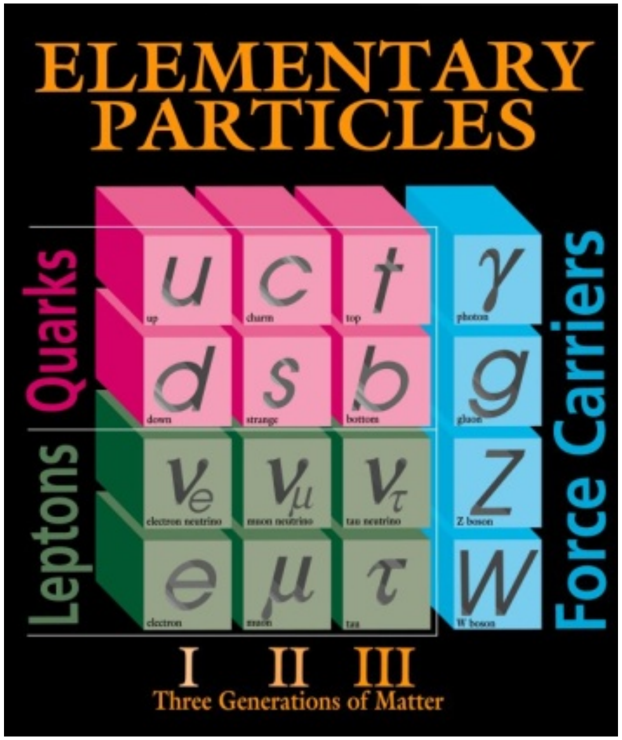
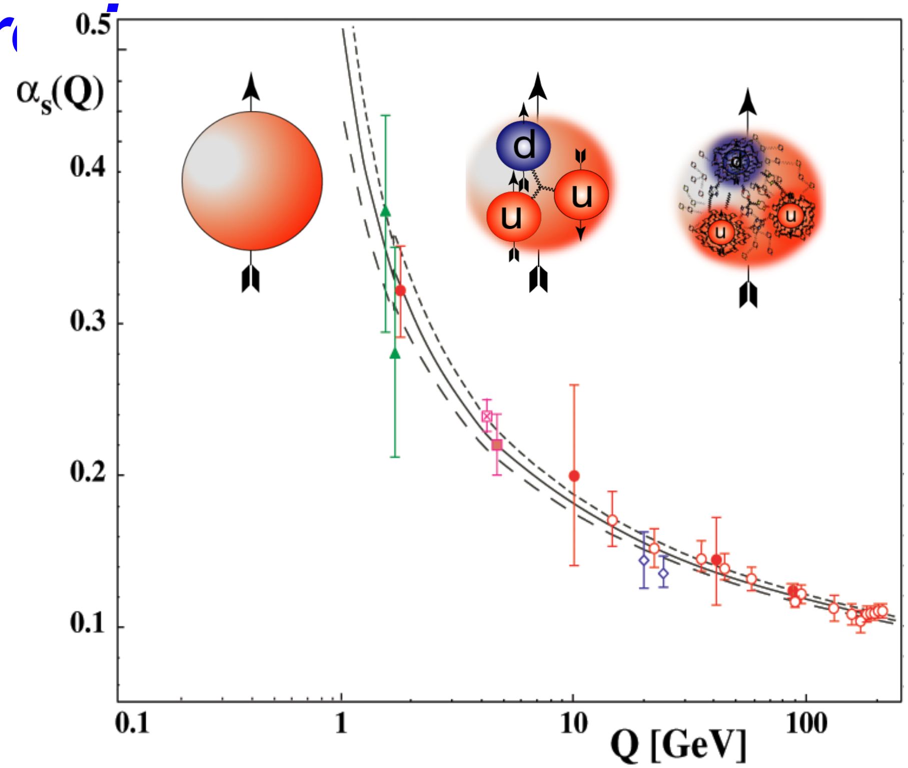
Outline

- Introduction
- Proton EM form factors and charge radius
- Proton charge radius from H Lamb shift
- A new experiment on proton charge radius
- Summary

QCD: still unsolved in non-perturbative r



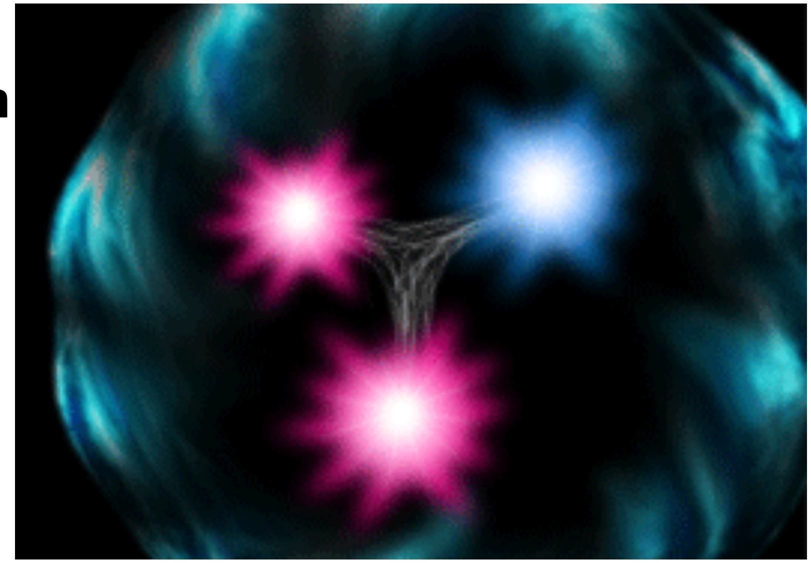


Gauge bosons: gluons (8)

- ***2004 Nobel prize for ``asymptotic freedom''***
- ***non-perturbative regime QCD ?????***
- ***One of the top 10 challenges for physics!***
- ***QCD: Important for discovering new physics beyond SM***
- ***Nucleon structure is one of the most active areas***

QCD ⟷ Nucleon Structure

- **Strong interaction, running coupling ~1**
  - **-- QCD: the theory of strong interaction**
  - **-- asymptotic freedom (2004 Nobel)**
    - **perturbation calculation works at high energy**
  - **-- interaction significant at intermediate energy**
    - **quark-gluon correlations**
  - **-- confinement**
    - **interaction strong at low energy**
    - **coherent hadron**
  - **-- Chiral symmetry**
  - **-- theoretical tools:**
    - **pQCD, OPE, Lattice QCD, ChPT**

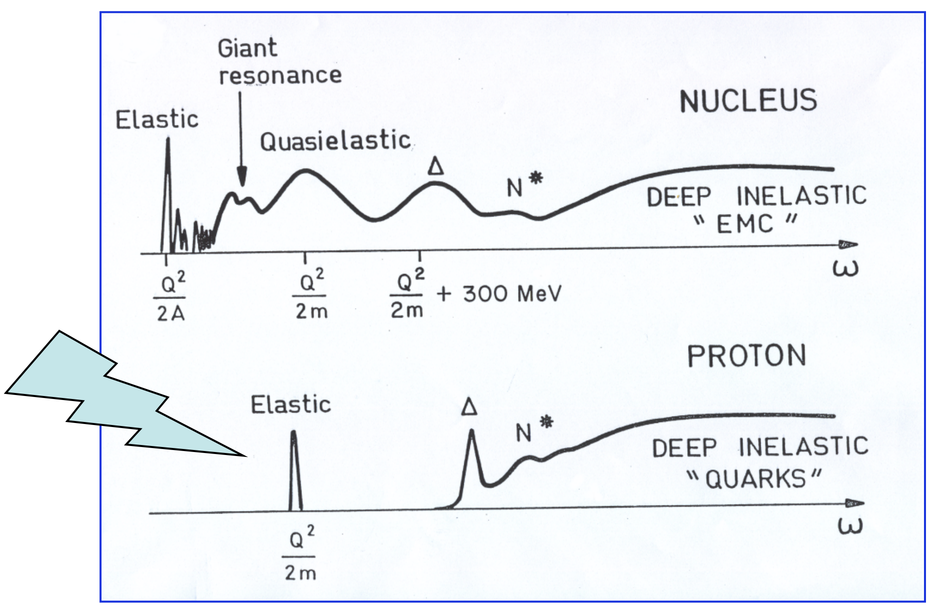


- *Charge and magnetism (current) distribution*
  - *Nucleon: Electric G_E and magnetic G_M form factor*
- *Spin distribution*
- *Quark momentum and flavor distribution*
- *Polarizabilities*
- *Strangeness content*
- *.....*

This talk focuses on proton charge radius

Lepton scattering: powerful microscope!

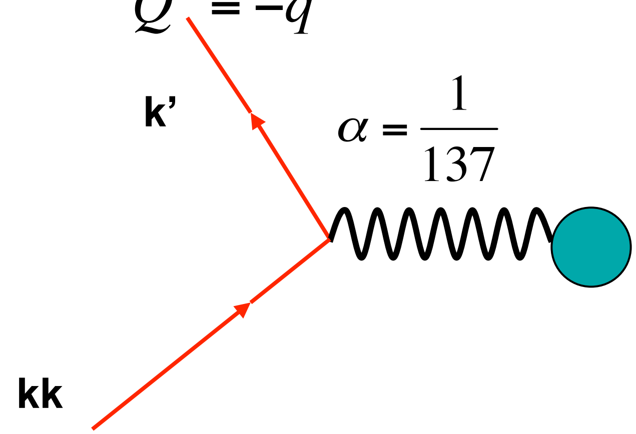
- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed***
- ***One can vary the wave-length of the probe to view deeper inside the hadron***



Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$

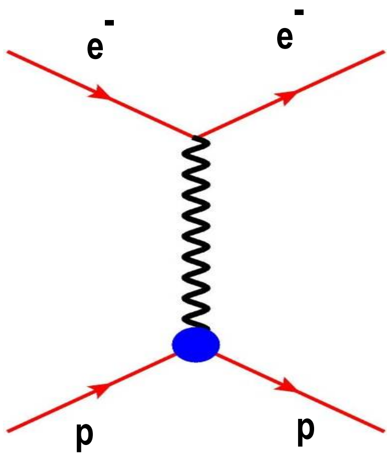


The Proton Charge Radius

- 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}: ➡

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

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

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

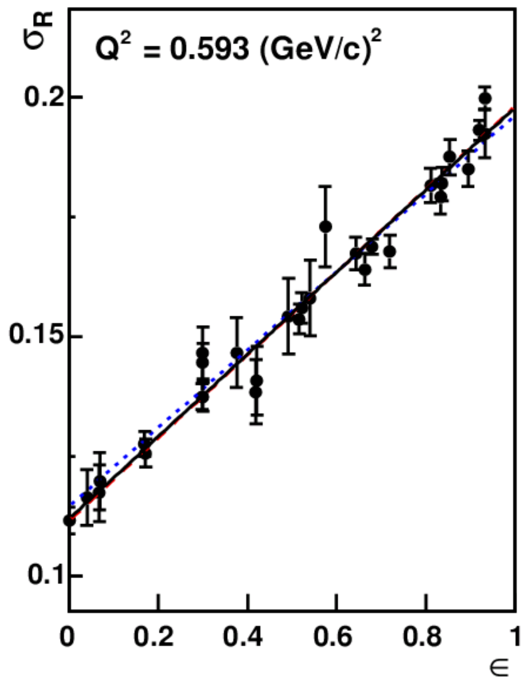
$$\langle r^2\rangle = -6 \left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

Size of the proton: unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- **Elastic e-p cross section**

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

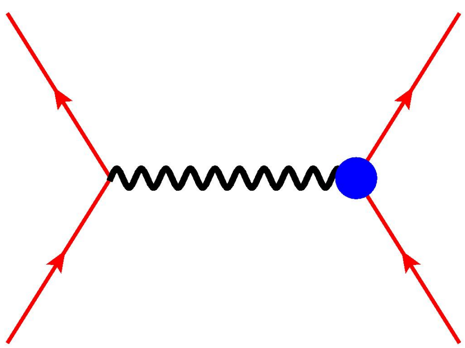


$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

- **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

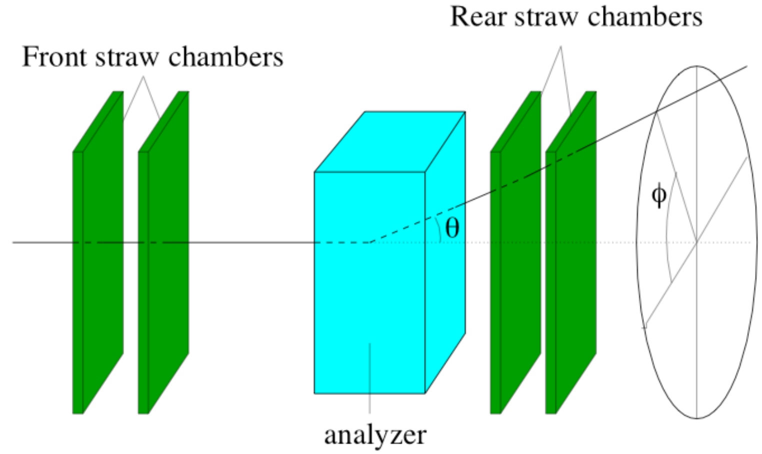
$$\tau = \frac{Q^2}{4M^2}$$

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



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

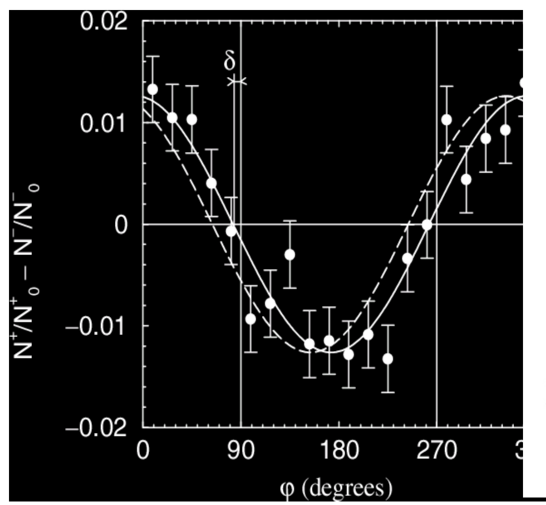
Polarization Transfer → $\dfrac{G_E^p}{G_M^p}$

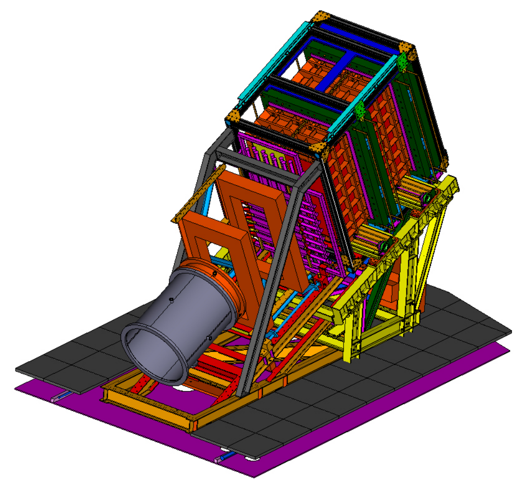


- **Recoil proton polarization**

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

- **Focal Plane Polarimeter**
  - **recoil proton scatters off secondary carbon target**
  - **P_t, P_l measured from φ distribution**
  - **P_b, and analyzing power cancel out in ratio**





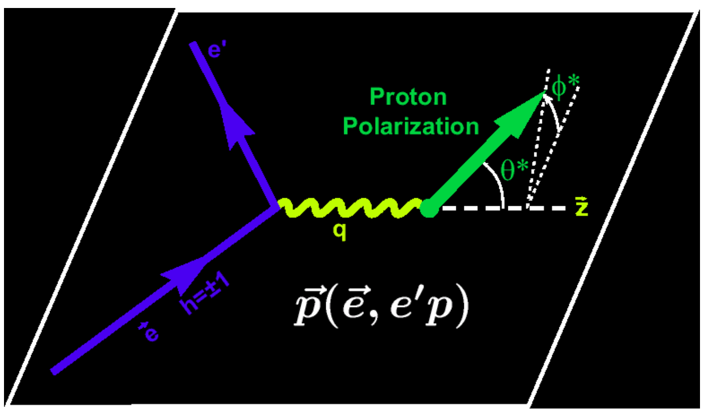
Focal-plane polarimeter

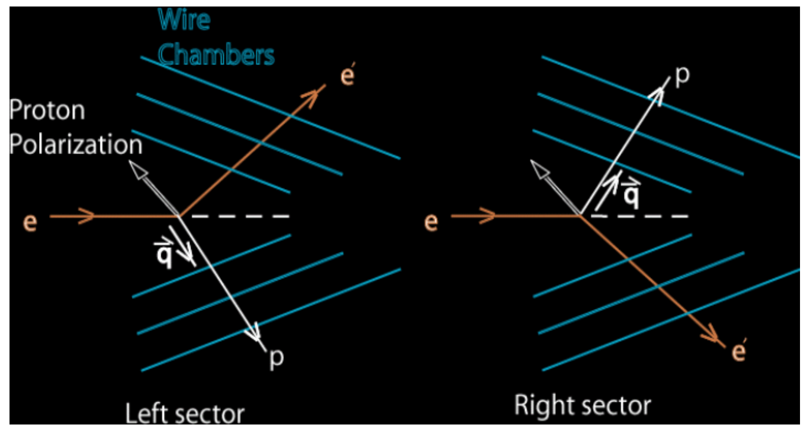
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

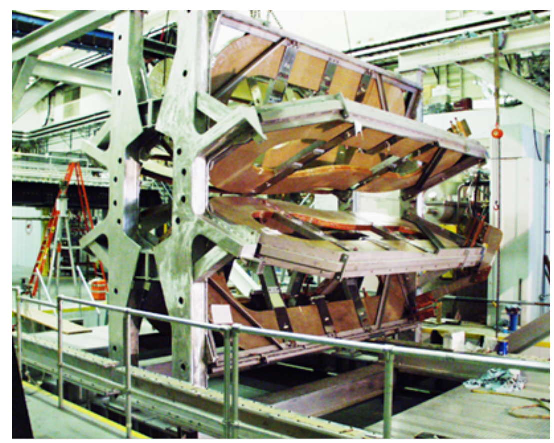
- **Polarized beam-target asymmetry**

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



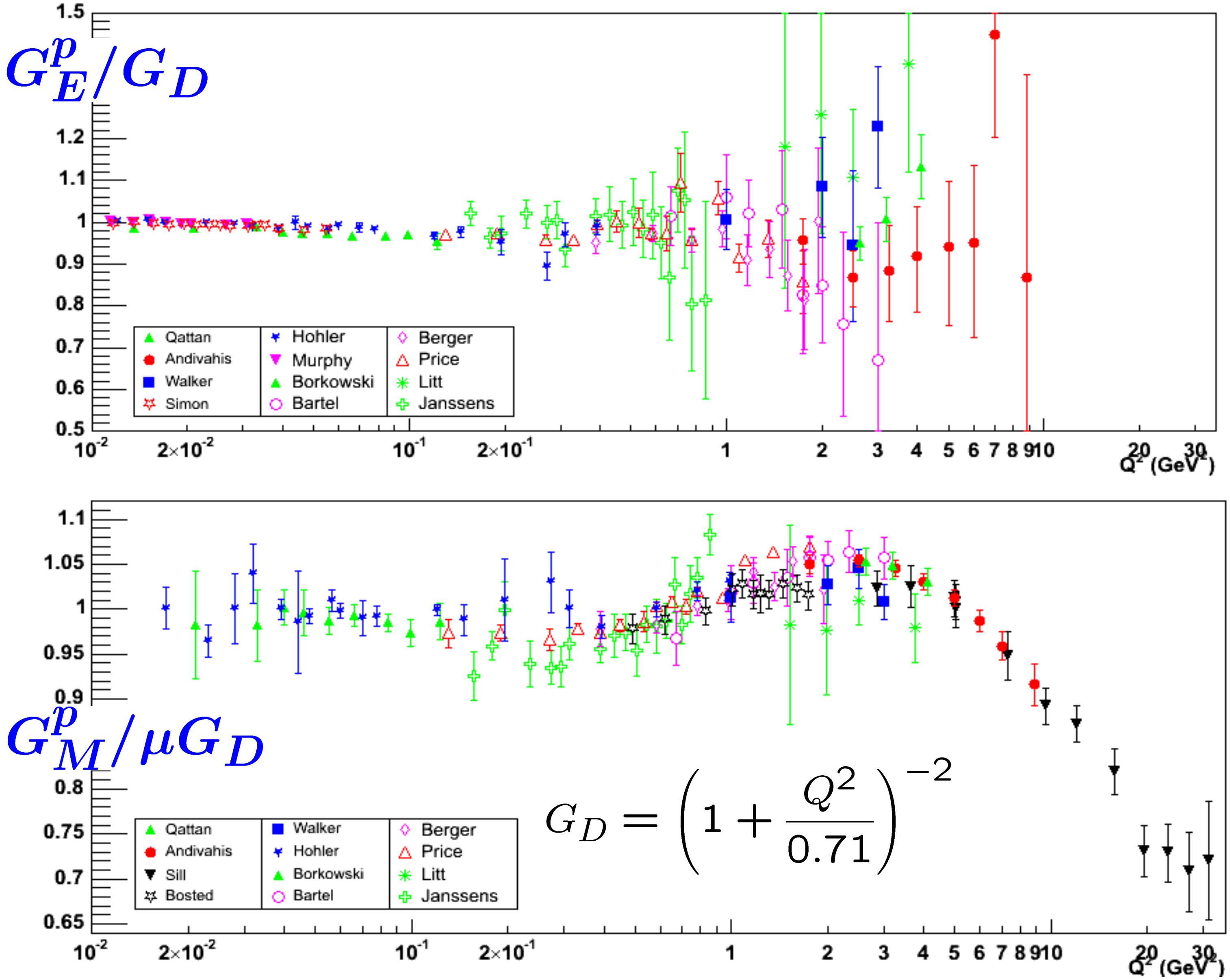


$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}$$

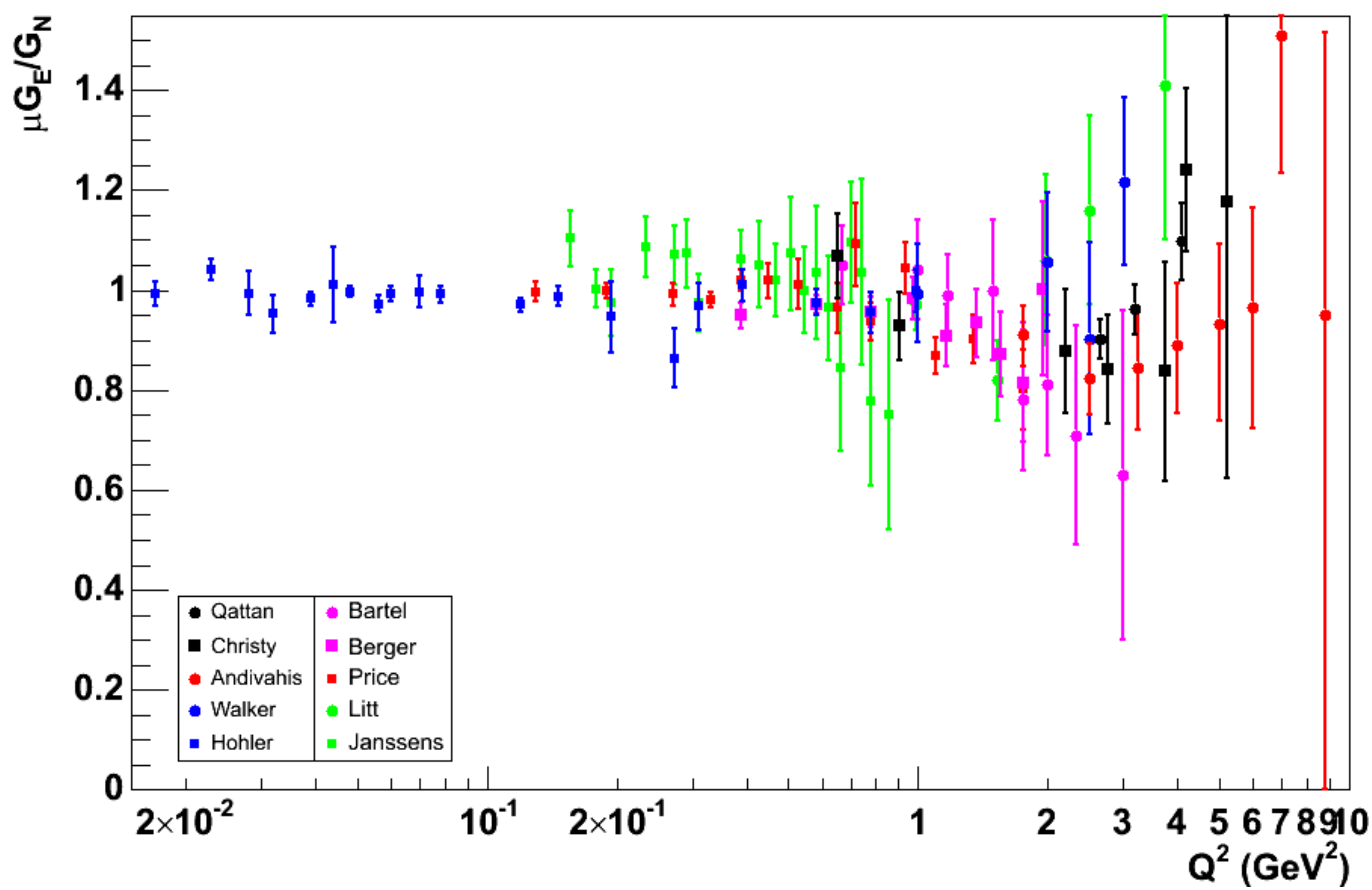


BLAST pioneered the technique, will be used in upcoming Jlab Hall A experiment

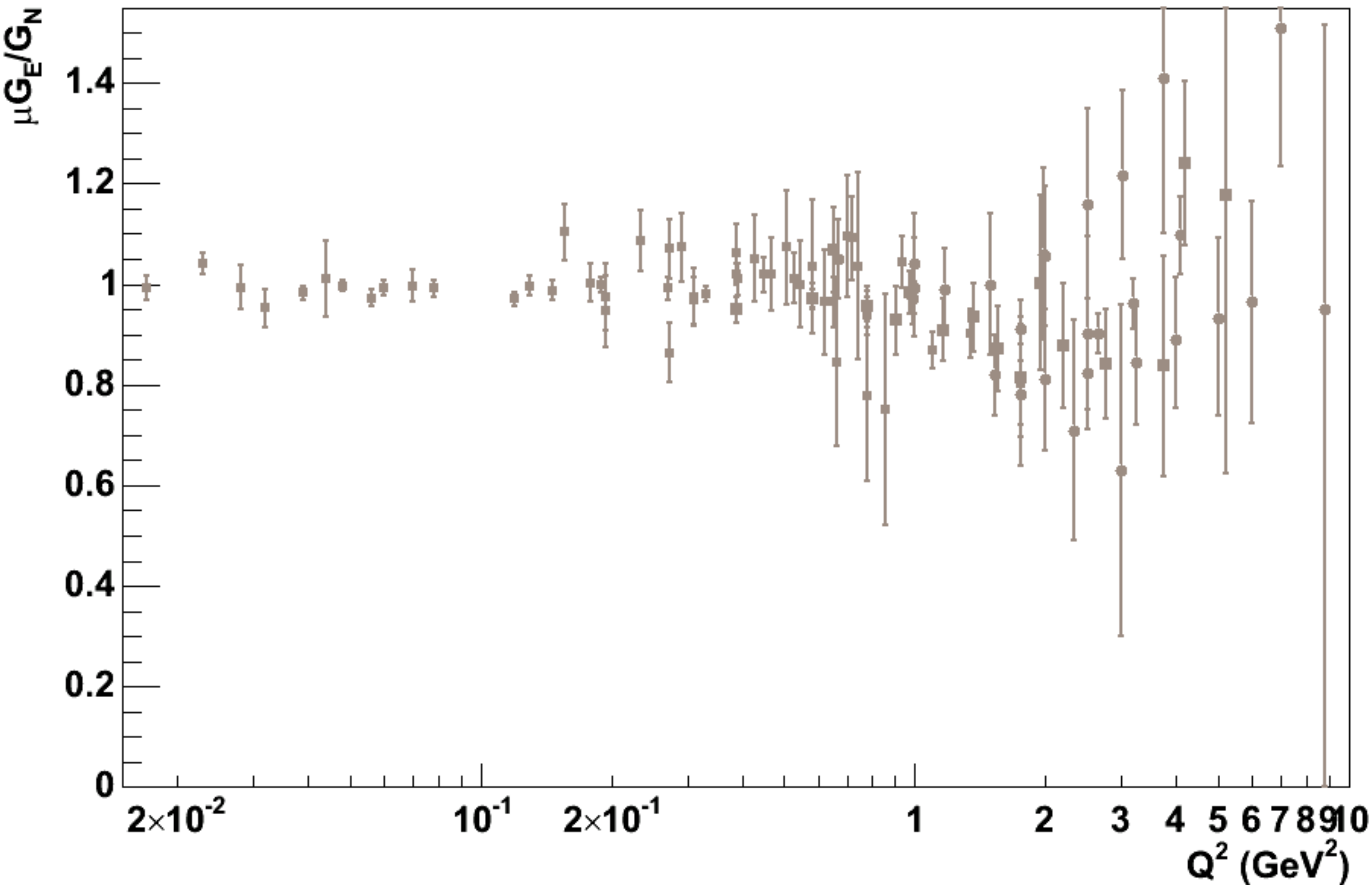
World Unpolarized Data



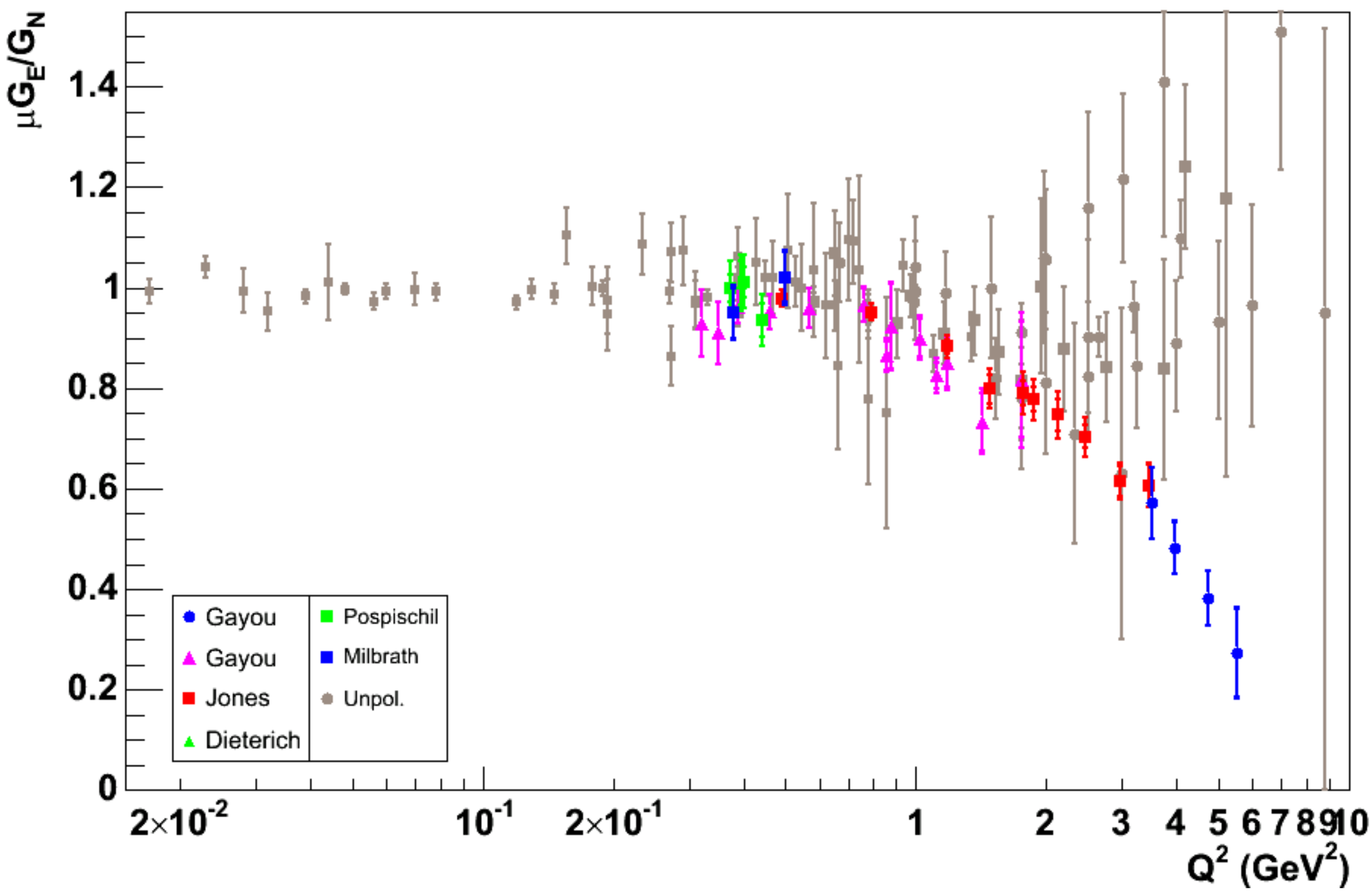
$\mu G_E/G_M$ — World Data



$\mu G_E/G_M$ — World Data



$\mu G_E/G_M$ — World Data

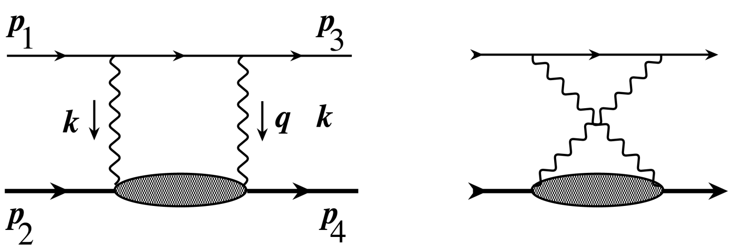


Two - Photon Exchange (TPE)

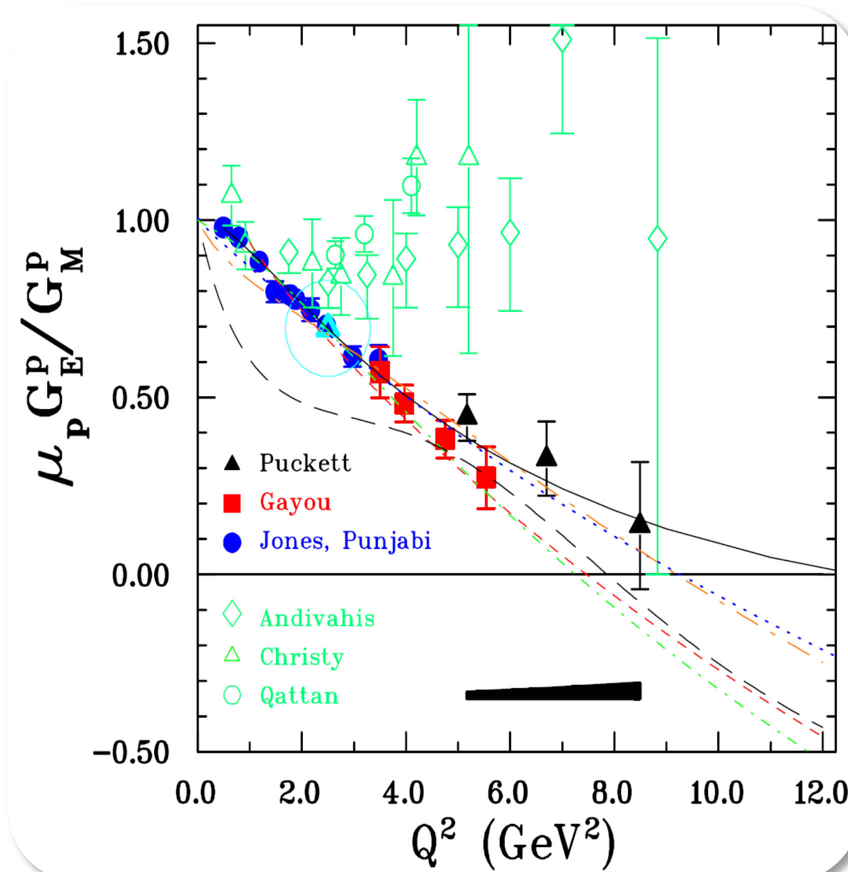
- **Proton form factor measurements**
  - Comparison of precise Rosenbluth and Polarization measurements of G_{Ep}/G_{Mp} show clear discrepancy at high Q^2

P.A.M.Guichon and M.Vanderhaeghen, PRL 91, 142303 (2003)

- **Two-photon exchange corrections believed to explain (part of) the discrepancy**

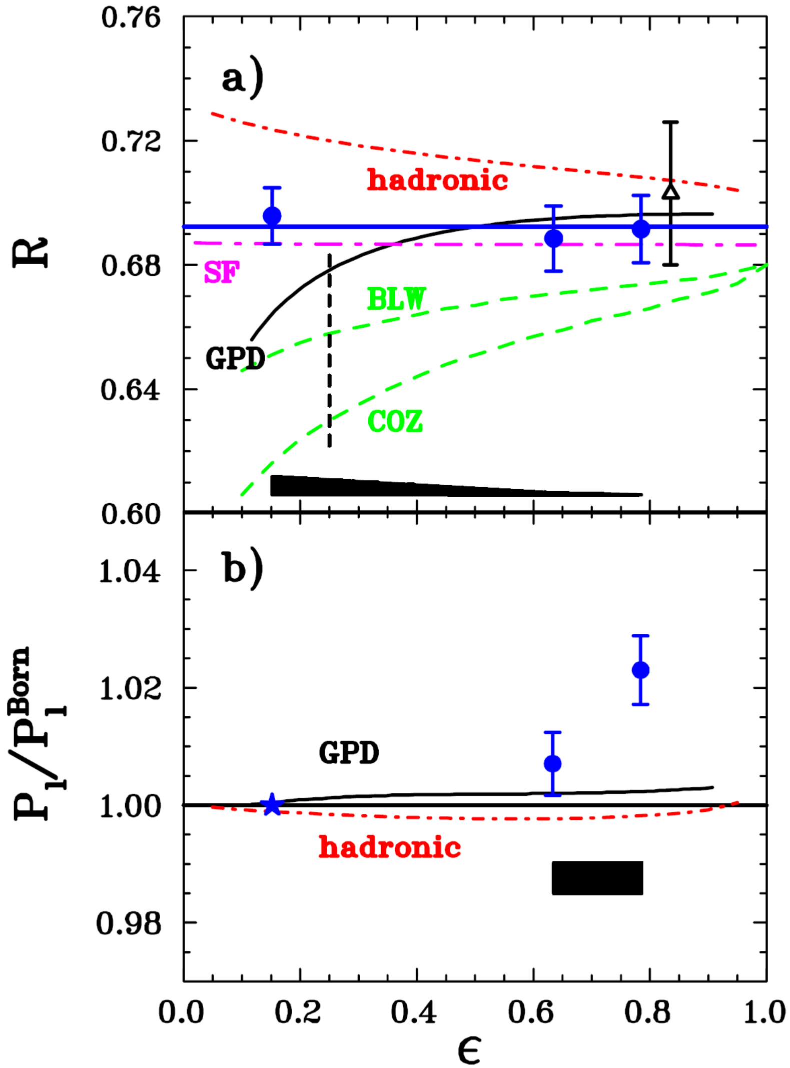


- **Have only limited direct evidence of effect on cross section**
  - **Active experimental, theoretical program to fully understand TPE effects**



Blunden et al (05); Afanasev et al (05); Arrington et al (07); Carlson and Vanderhaeghen (07) ,…..

Two-Photon Exchange

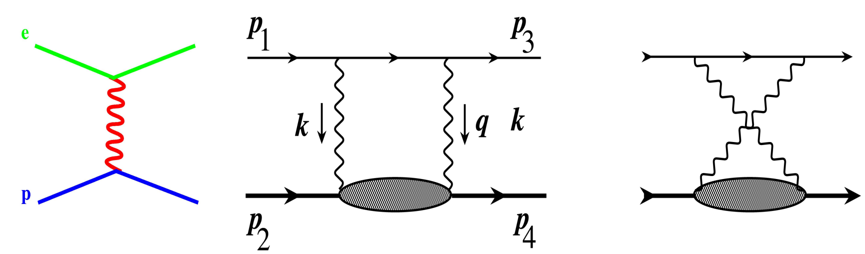


$$R = \mu_p G_E / G_M\,,\ Q^2 = 2.5\ \text{GeV}^2$$

ε, virtual photon polarization

M. Mehdi *et al*, PRL 106, 132501 (2011)

Golden mode: positron-proton vs. electron-proton elastic scattering



$$\frac{\sigma_{e^+}}{\sigma_{e^-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4 Re A_{2\gamma} A_{1\gamma}$$

Three new e+/e- experiments:

- **BINP Novosibirsk – internal target**
- **JLab Hall B – LH2 target, CLAS (2012)**
- **DESY (OLYMPUS) - internal target**

OLYMPUS Projected Results

Former BLAST experiment

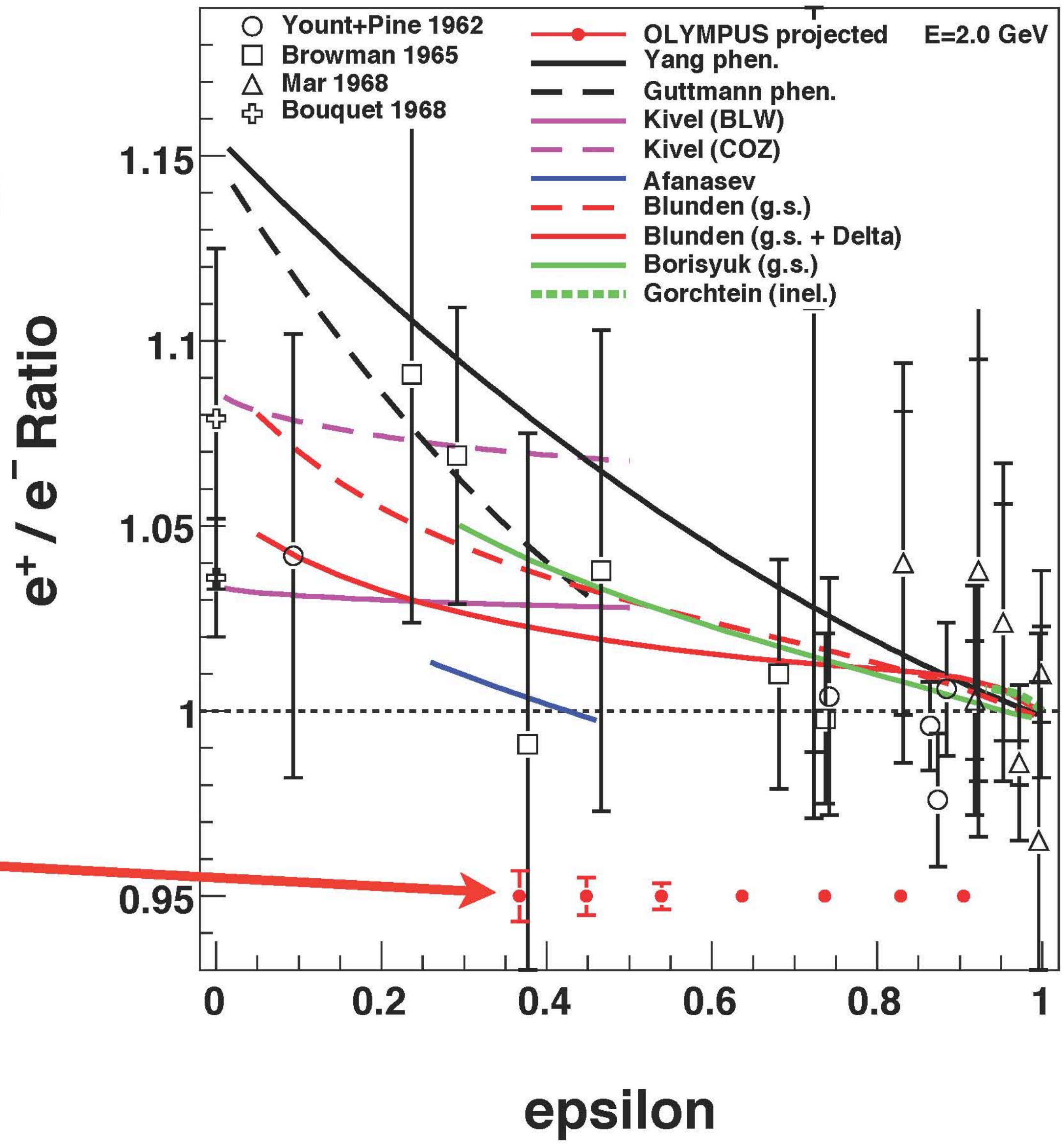
- windowless, internal gas target of pure hydrogen
- large acceptance
- left / right symmetric
- reversible magnetic field
- 1% luminosity measure

DORIS storage ring

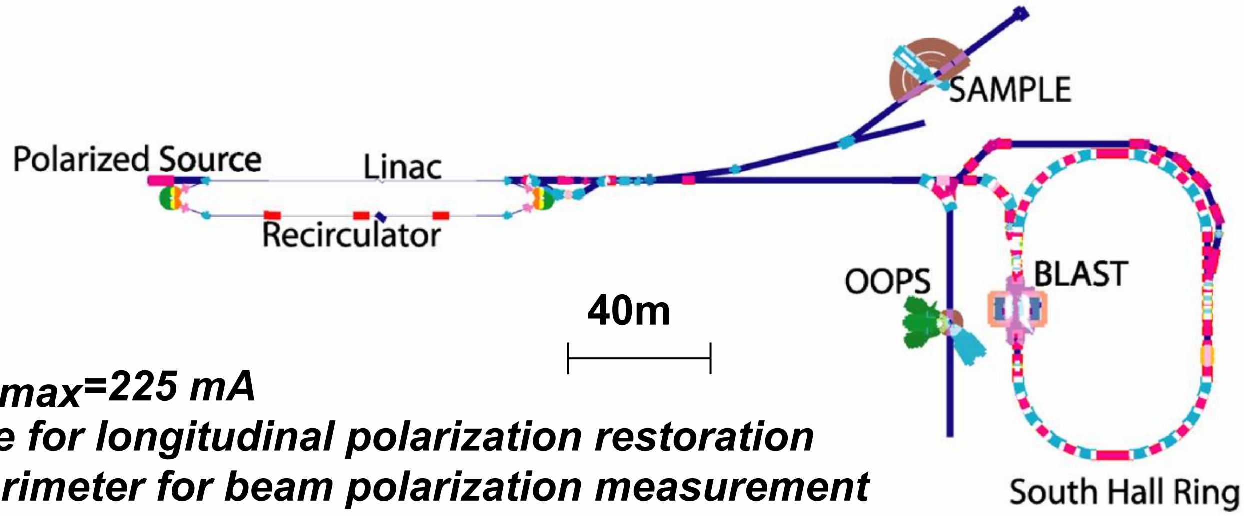
- switch e^- / e^+ frequently
- 2 GeV beam energy

Expected precision

- 2×10^{33} $cm^{-2}s^{-1}$
- 500 hours with e^+ and e^-

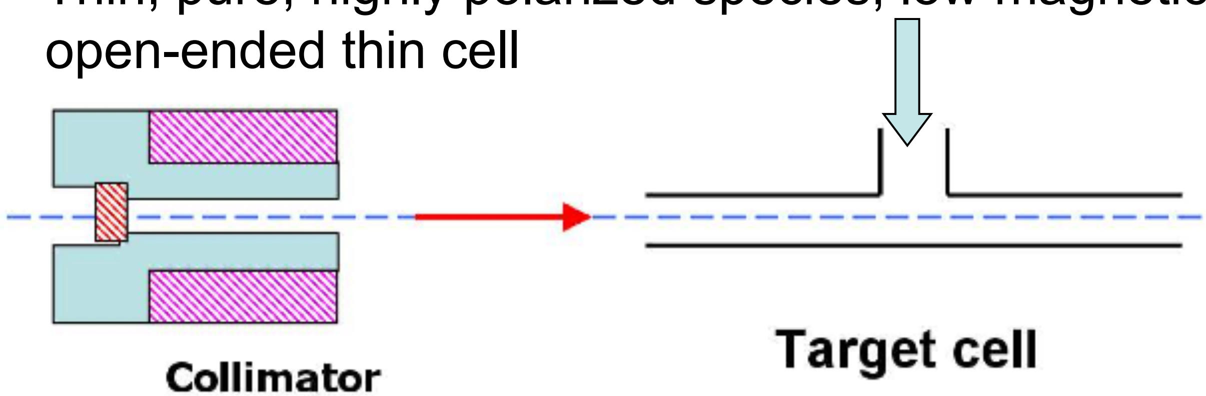


The BLAST Experiment

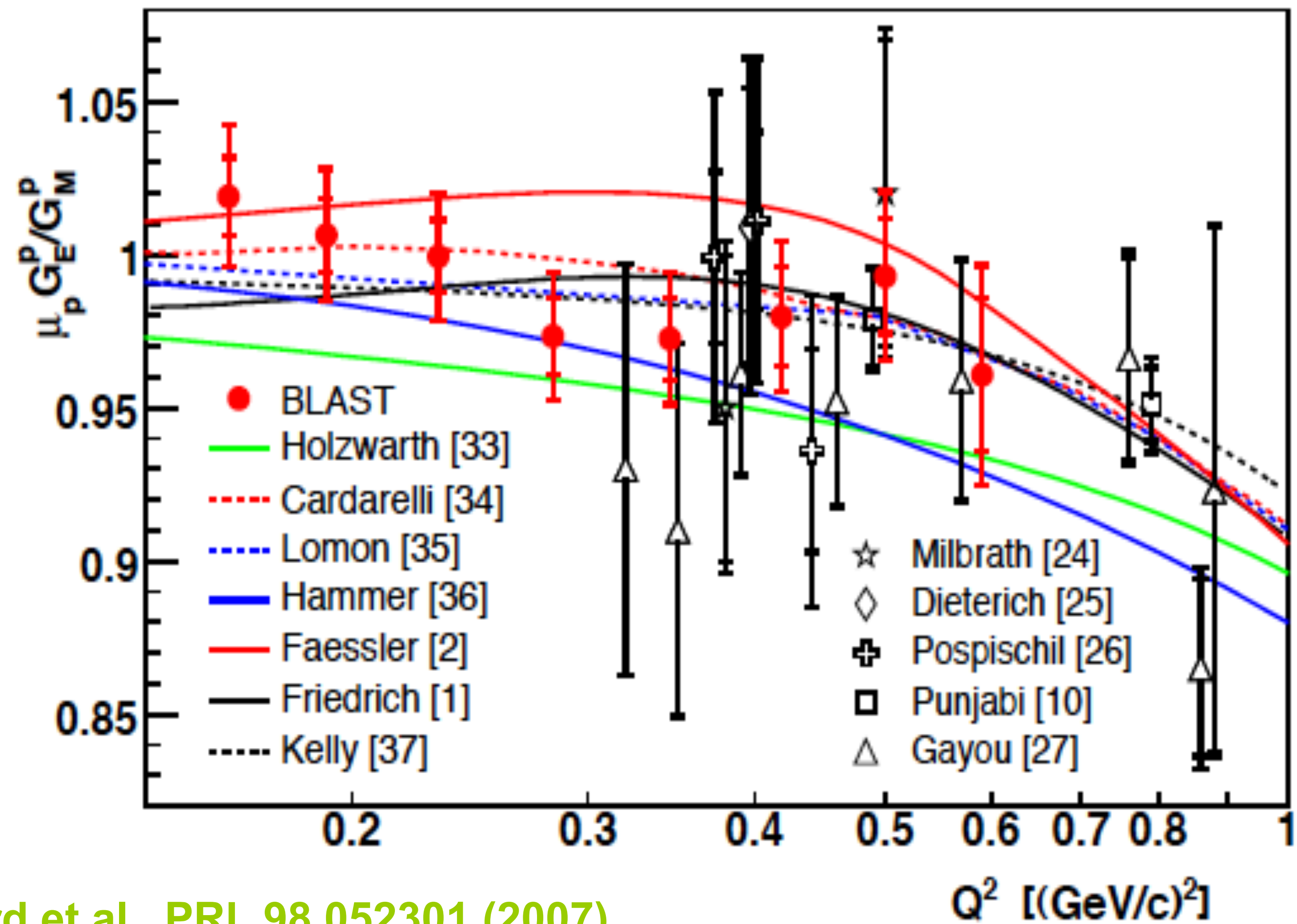


E_0=850 MeV I_{max}=225 mA
Siberian snake for longitudinal polarization restoration
Compton polarimeter for beam polarization measurement

- ***BLAST: internal target physics program***
  - ***Nucleon electromagnetic structure*** ← ***This talk***
  - Spin structure of few nucleon system,…….
  - Thin, pure, highly polarized species, low magnetic field, open-ended thin cell

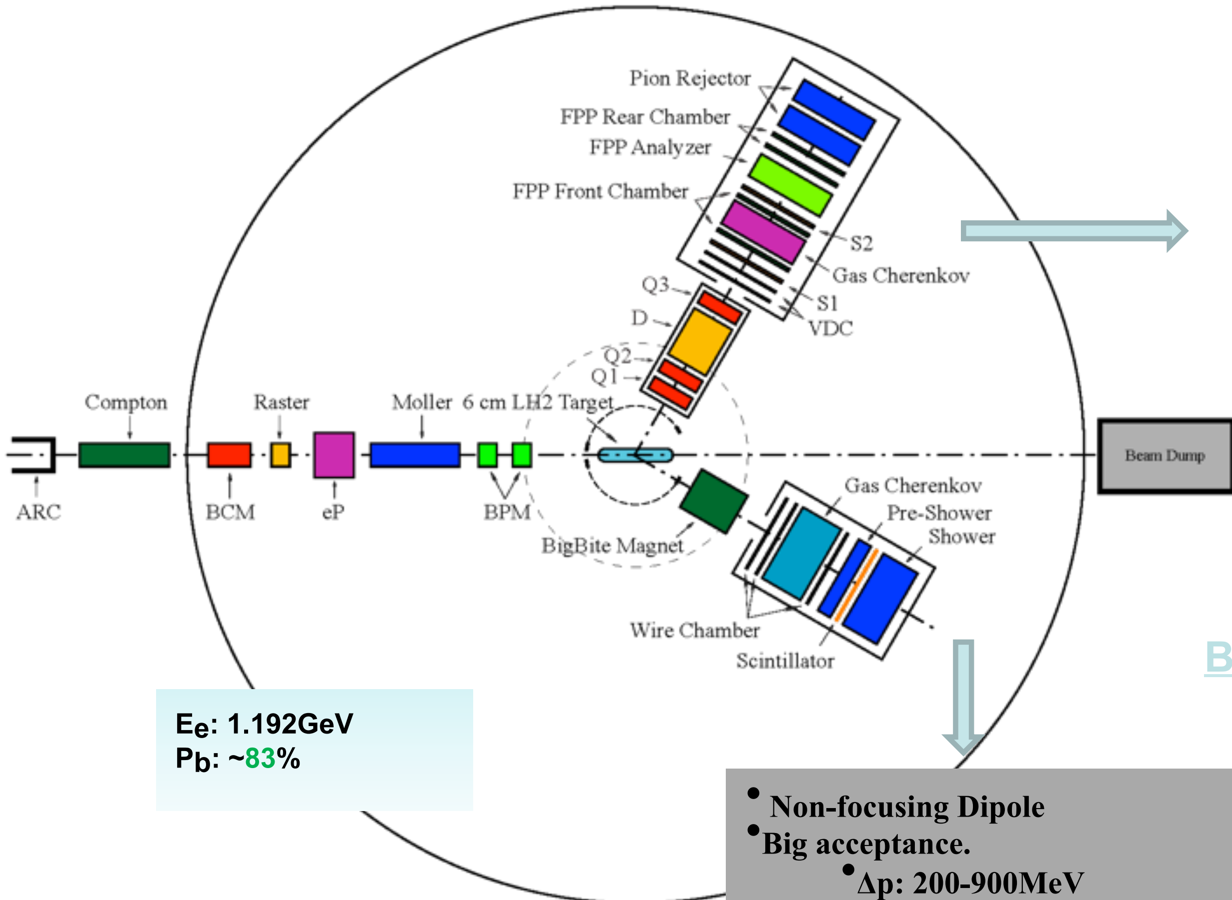


Results – G_E^p / G_M^p



C. Crawford et al., PRL 98 052301 (2007)

Experimental Setup



LHRS

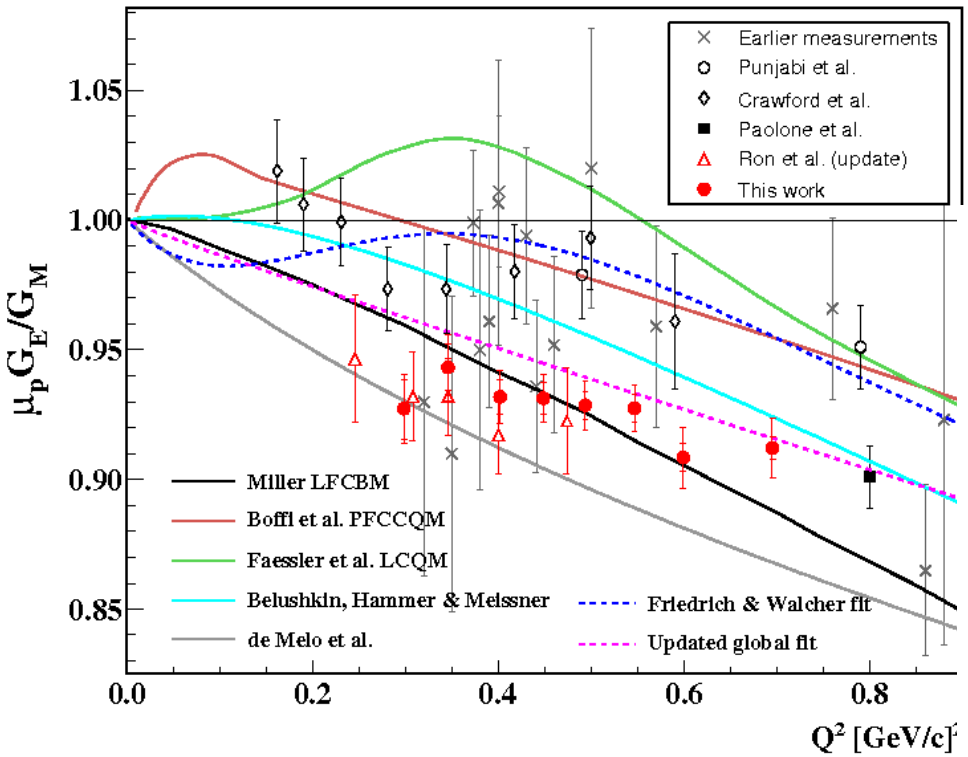
- **$\Delta p/p0$: ± 4.5% ,**
- **out-of-plane: ± 60 mrad**
- **in-plane: ± 30 mrad**
- **$\Delta\Omega$: 6.7msr**
- **QQDQ**
- **Dipole bending angle 45^{o}**
- **VDC+FPP**
- **P_p : 0.55 ~ 0.93 GeV/c**

E_e: 1.192GeV
P_b: ~83%

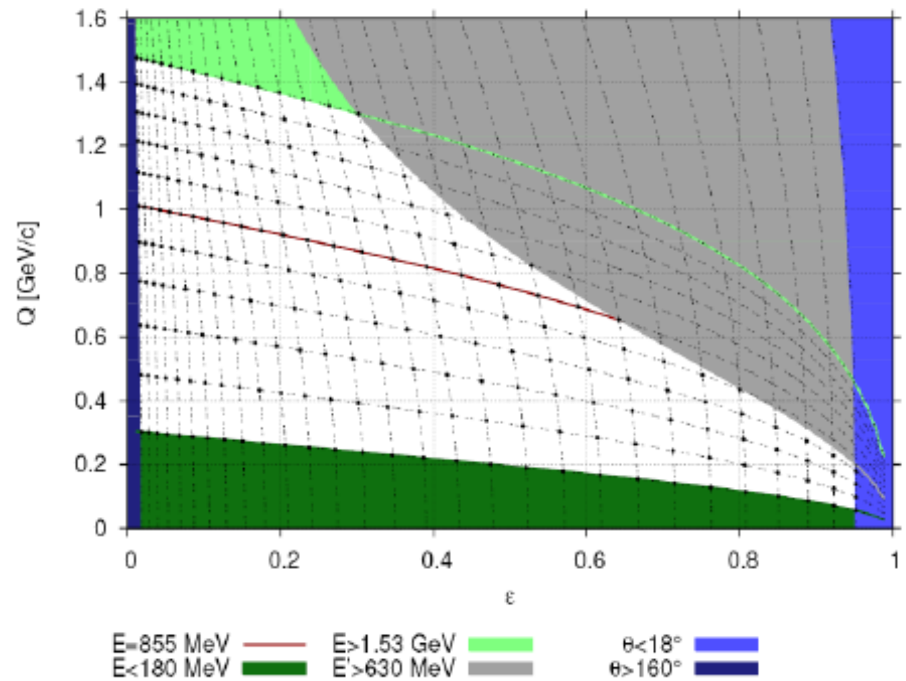
BigBite

- **Non-focusing Dipole**
- **Big acceptance.**
  - **Δp: 200-900MeV**
  - **$\Delta\Omega$: 96msr**
- **PS + Scint. + SH**

Electromagnetic form factor of nucleons at low Q^2



X. Zhan et al. (recoil polarization)
arXiv:1102.0318)
C. Crawford et al. (pol. Target)
PRL98, 052301 (2007)



In the limit of Q^2 goes to zero, the slope of the electric form factor determines the charge radius of the nucleon

Crucial for proton charge radius

$$r_p \propto \frac{d}{dQ^2} G_E(Q^2)|_{Q^2=0}$$

high precision unpolarized XS measurement at Mainz

($Q^2 \sim 0.004 - 1$ GeV^2)

J.C. Bernauer et al. PRL105, 242001 (2010)

Charge radius from atomic physics

$$\langle p(p_f)|\sum_q e_q\,\bar{q}\gamma^\mu q|p(p_i)\rangle = \bar{u}(p_f)\left[\gamma_\mu F_1^p(q^2) + \frac{i\sigma_{\mu\nu}}{2m}F_2^p(q^2)q_\nu\right]u(p_i)$$

- For a point particle amplitude for $p+\ell \to p+\ell$

$$\mathcal{M} \propto \frac{1}{q^2} \quad \Rightarrow \quad U(r) = -\frac{Z\alpha}{r}$$

- Including q^2 corrections from proton structure

$$\mathcal{M} \propto \frac{1}{q^2}q^2 = 1 \quad \Rightarrow \quad U(r) = \frac{4\pi Z\alpha}{6}\delta^3(r)(r_E^p)^2$$

- Proton structure corrections $\Big(m_r = m_\ell m_p/(m_\ell + m_p) \approx m_\ell\Big)$

$$\Delta E_{r_E^p} = \frac{2(Z\alpha)^4}{3n^3}m_r^3(r_E^p)^2\delta_{\ell 0}$$

- **Muonic hydrogen can give the best measurement of $\mathbf{r_E^p}$!**

Motivation for precise information on proton radius

- A fundamental static property of the nucleon
  - Important for understanding how QCD works
- 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?
- Turning things around one can determine proton radius using QED and Lamb shift measurements

Methods for measuring proton charge radius

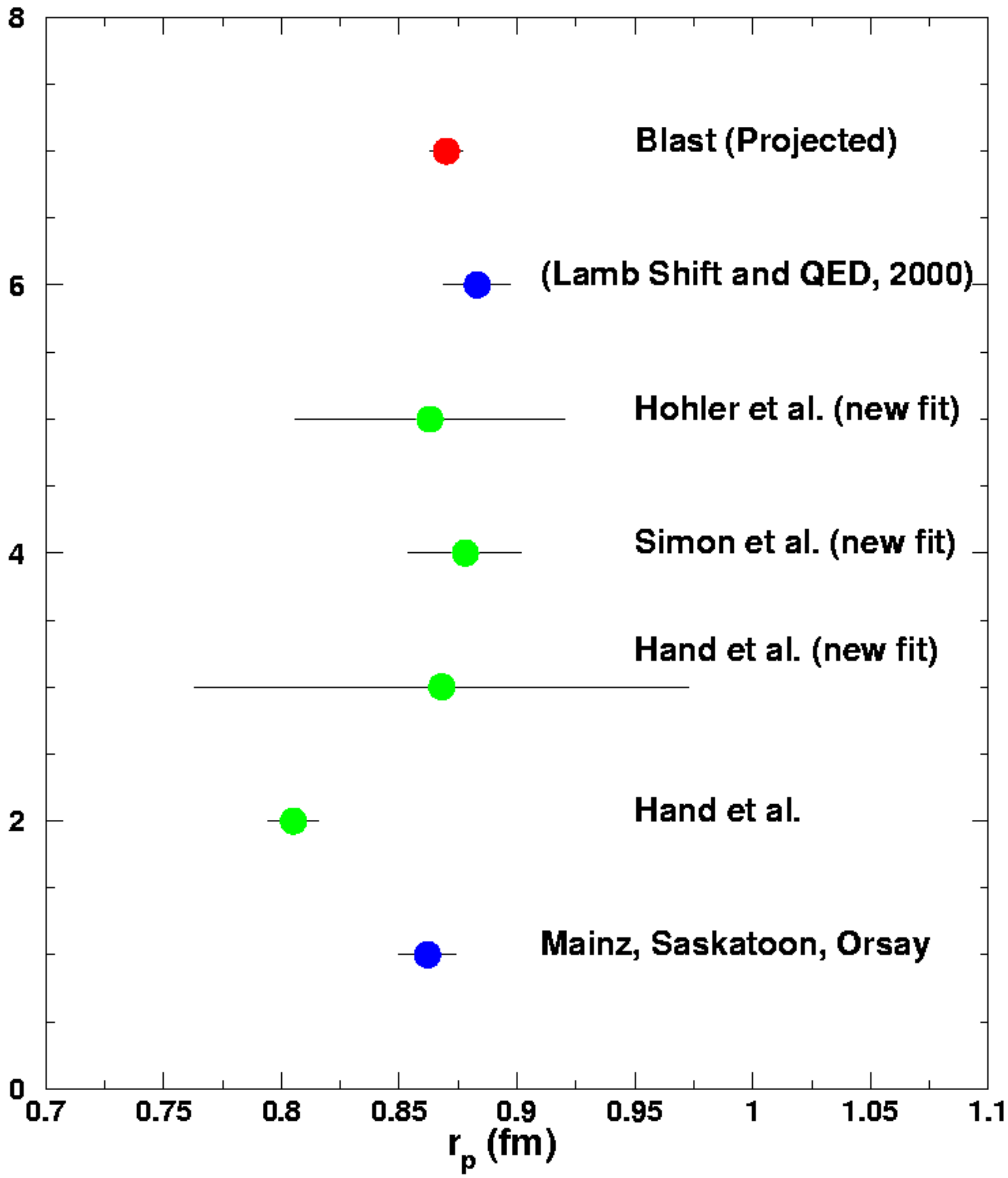
- Electron-proton elastic scattering to determine electric form factor

$$r_{rms} = \sqrt{< r^2 >} = -6 \frac{\partial G_E(Q^2)}{\partial (Q^2)} \Big|_{Q^2=0}$$

- Hydrogen spectroscopy (CODATA) (Lamb shift)

- Muonic Hydrogen (spectroscopy) (Lamb shift)

Personal story of proton charge radius before 2000



- *Motivated by discrepancy between Hand et al and Mainz, Saskatoon, Orsay results*
- *Discrepancy is a problem for H Lamb shift experiments*
- *Proposed a new experiment using BLAST and laser-driven polarized hydrogen target with sub percent precision*
- *Experiment did not happen – beam turned off*
- *No problem, PSI muonic hydrogen Lamb experiment will resolve everything*

Find out what happened ten years later soon

Muonic Hydrogen

- The **muon** is about 200 times heavier than the electron.

- Therefore, the atomic Bohr radius of muonic hydrogen is smaller than in ordinary hydrogen.

- This increases sensitivity of muonic hydrogen Lamb shift to the **finite size** of the proton.

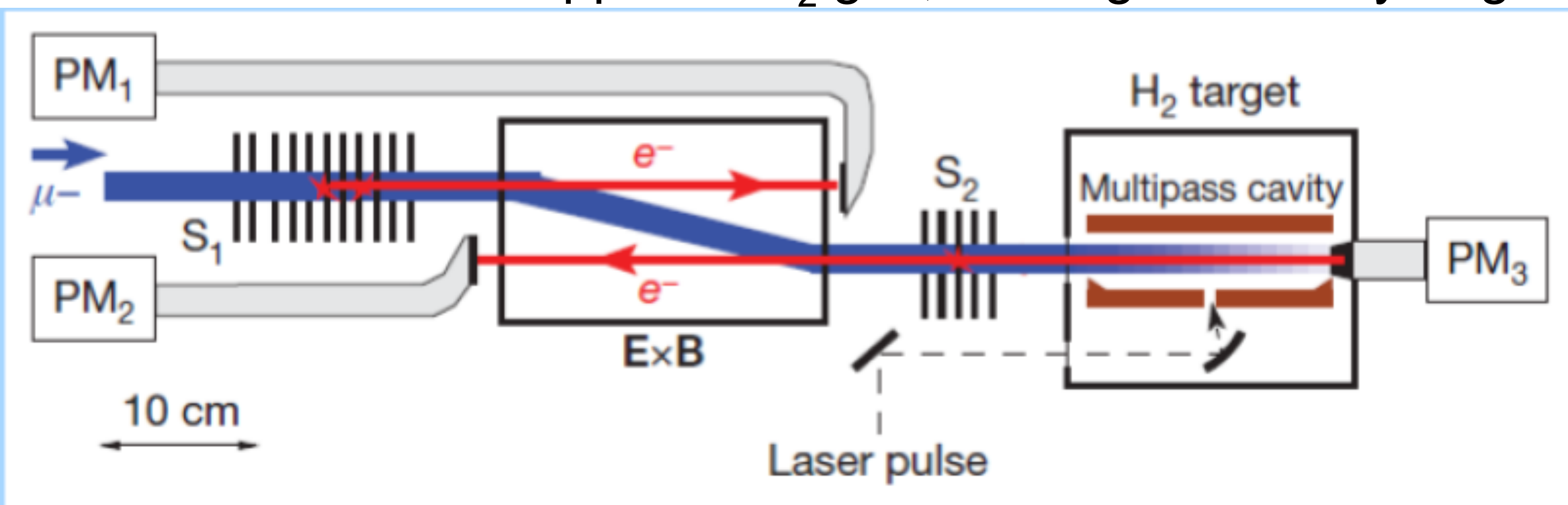
PSI Experiment

- Generation of muonic hydrogen
- X-ray time spectra
- Results
- Theoretical calculation

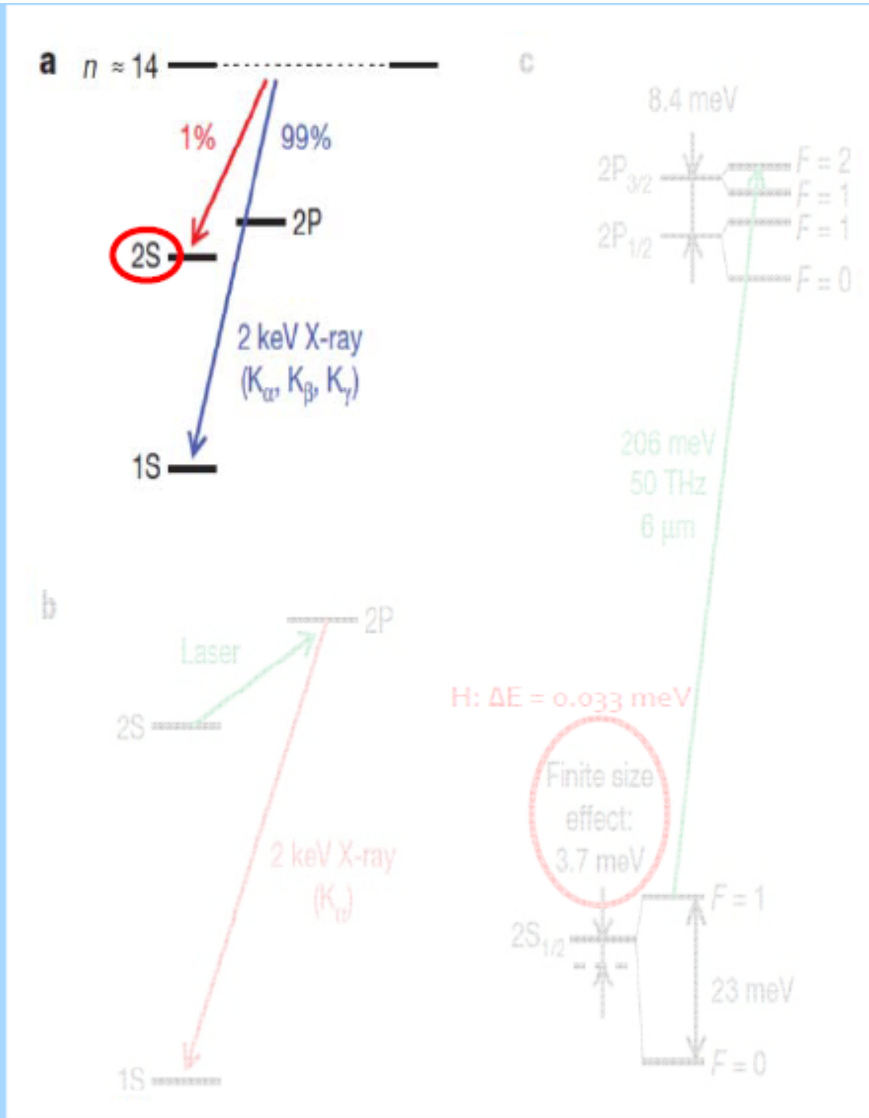
slides from Rebcca Boll

Generation of muonic hydrogen

- Slow muons pass two stacks of ultra-thin carbon foils (S1 , S2)
- The secondary electrons are detected in scintillators and read out by photomultipliers, acting as a trigger for the laser
- The muons are stopped in H_2 gas, forming muonic hydrogen

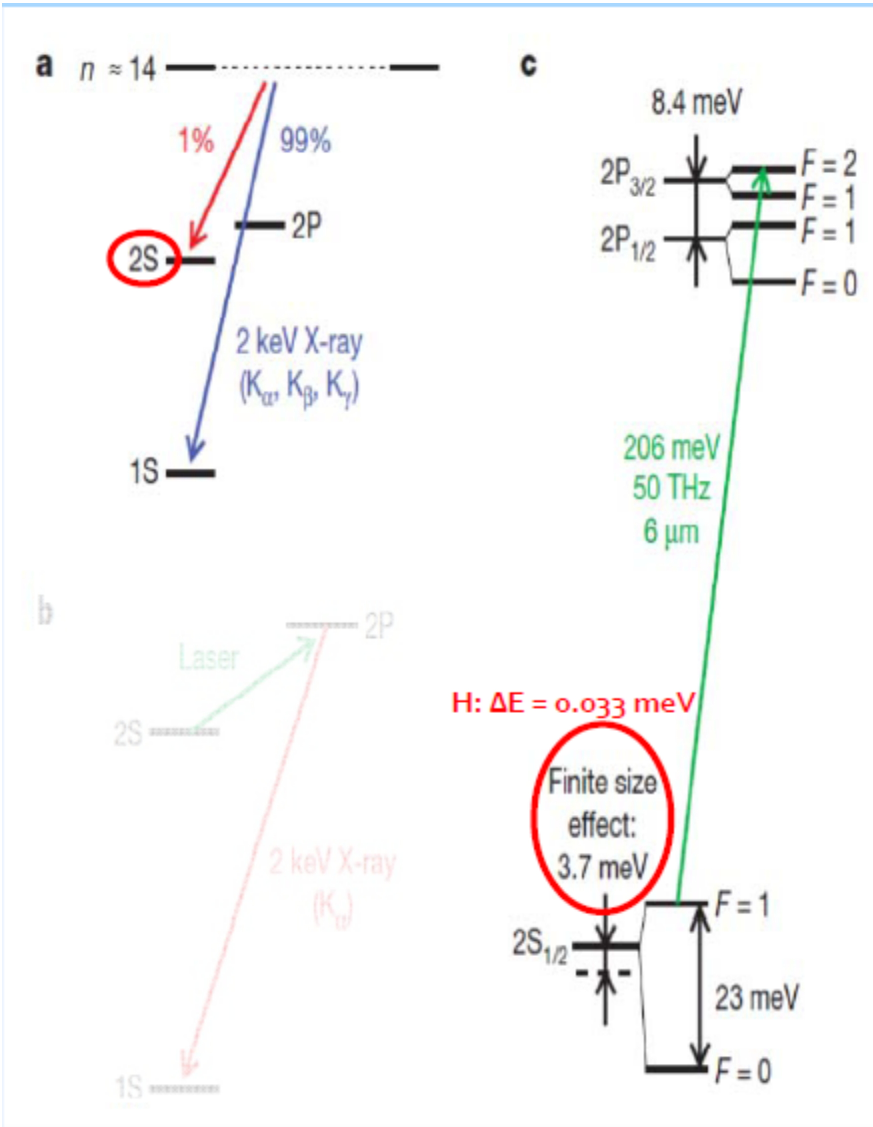


Energy levels and transitions



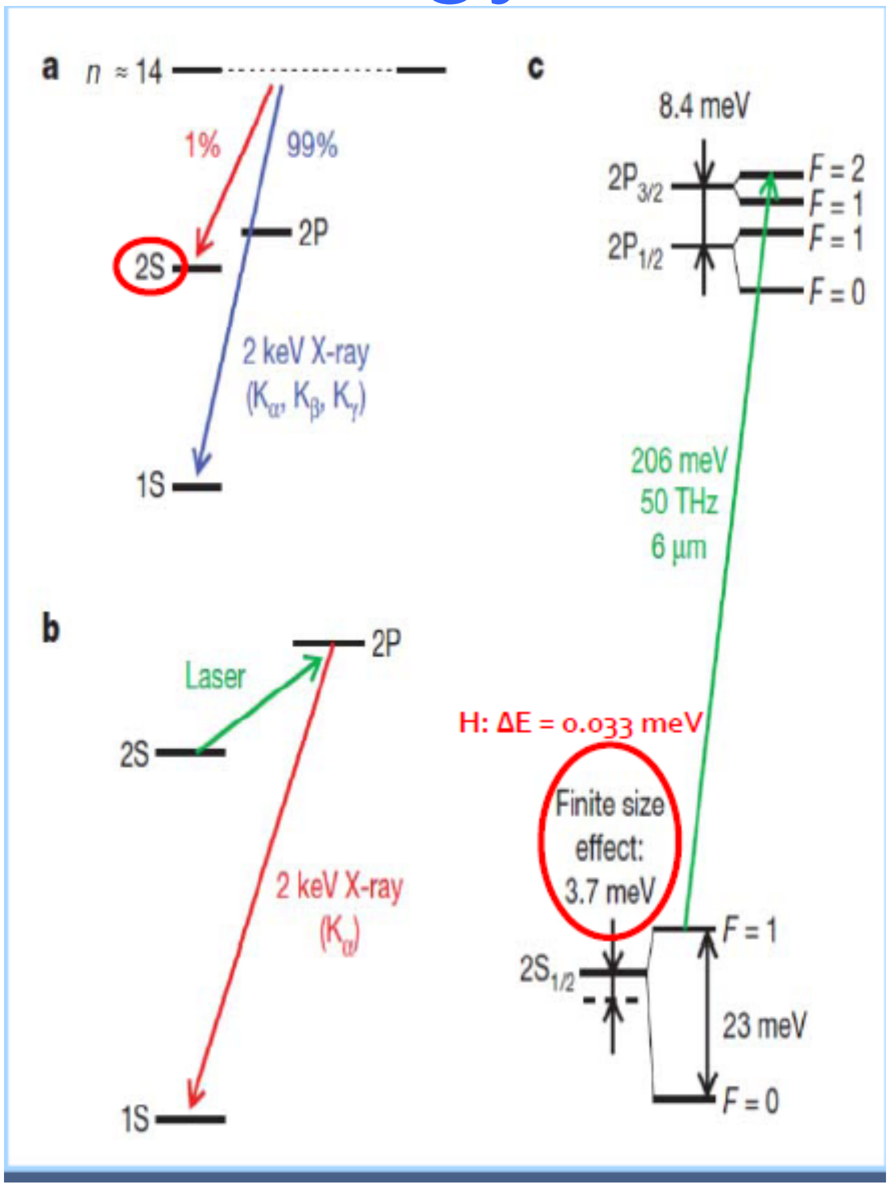
- The muonic hydrogen is **highly excited** when generated (n≈14)
- Most of the atoms de-excite quickly to 1S, but about 1% reach the **long-lived 2S-state** (lifetime about 1μs)

Energy levels and transitions



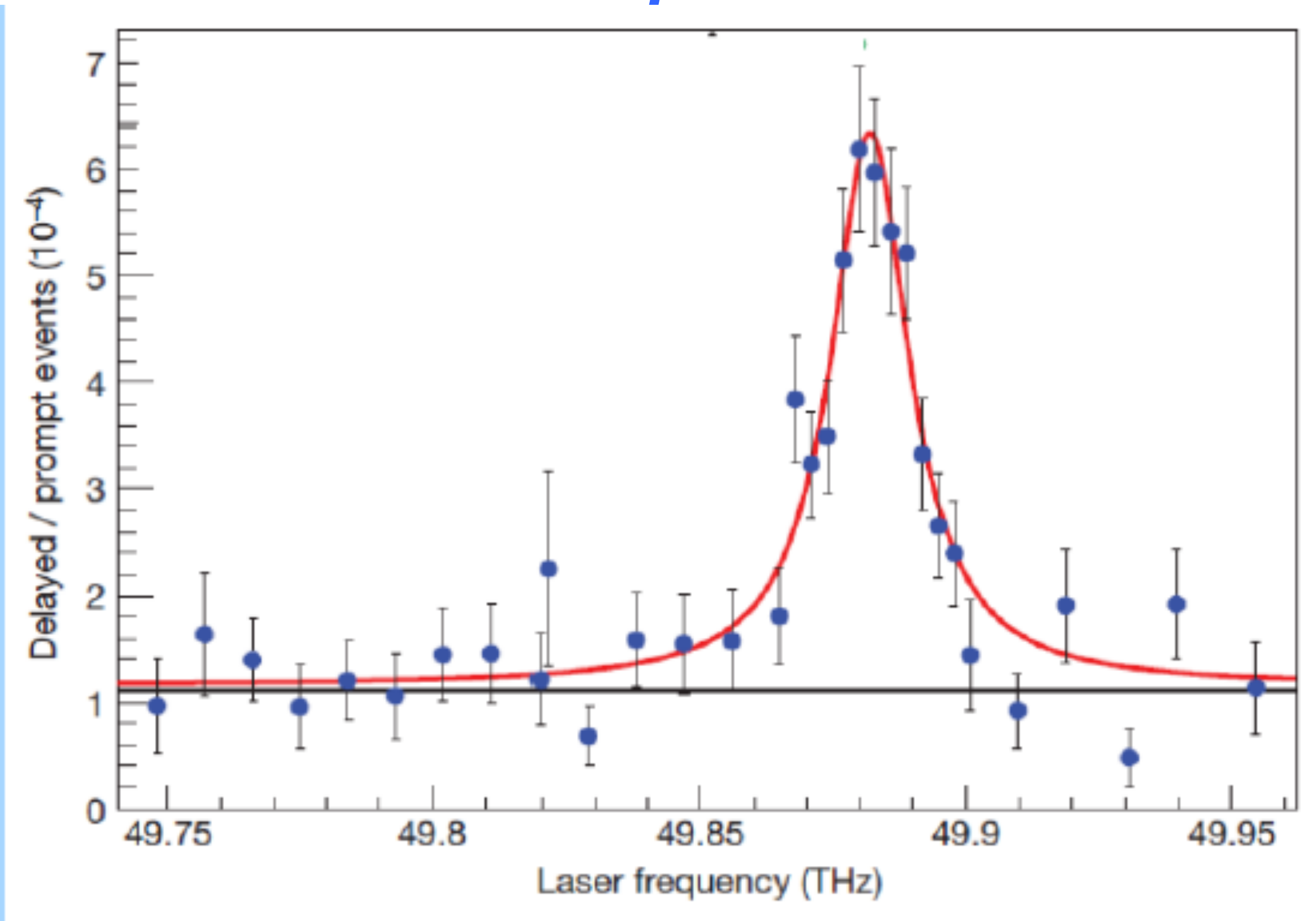
- For the $2S_{1/2}$ -$2P_{3/2}$ transition, **finite size effects** are two orders of magnitude higher than for ordinary H
- A **pulsed laser beam** (λ = 6μm) induces the excitation from $2S_{1/2}$ to $2P_{3/2}$ (gives the largest signal of all possible optical transitions)

Energy levels and transitions



- This is then followed by a de-excitation from $2P_{3/2}$ to $1S_{1/2}$ via **emission of an X-ray**

X-ray timing and 2S $_{1/2}$ - 2P $_{3/2}$ transition spectra



Result

- The transition frequency between $2P_{3/2}$ and $2S_{1/2}$ is obtained to be **$\Delta\nu$ = 49881.88(77) GHz** , corresponding to an energy difference of **ΔE = 206.2949(32) meV.**
- **Theory** predicts a value of

$$\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV}$$

- This results in a proton radius of **r_p = 0.84184(67) fm.**

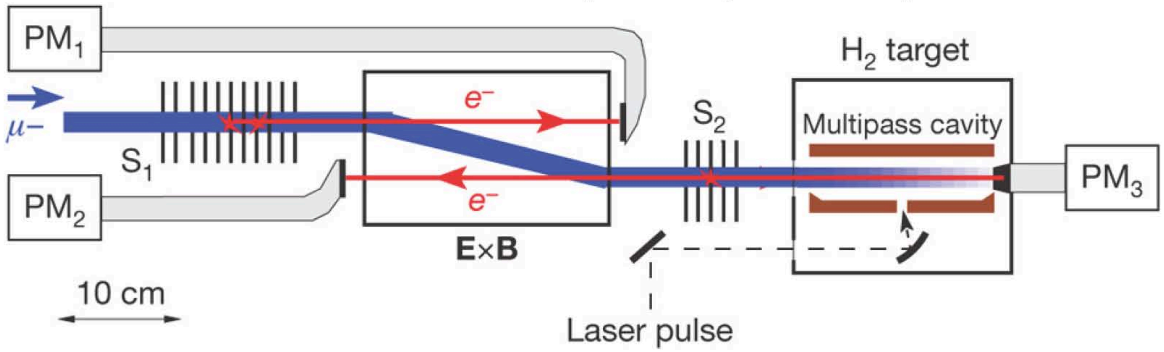
2005: Re-analysis electron-proton scattering **r_p = 0.897(18) fm**

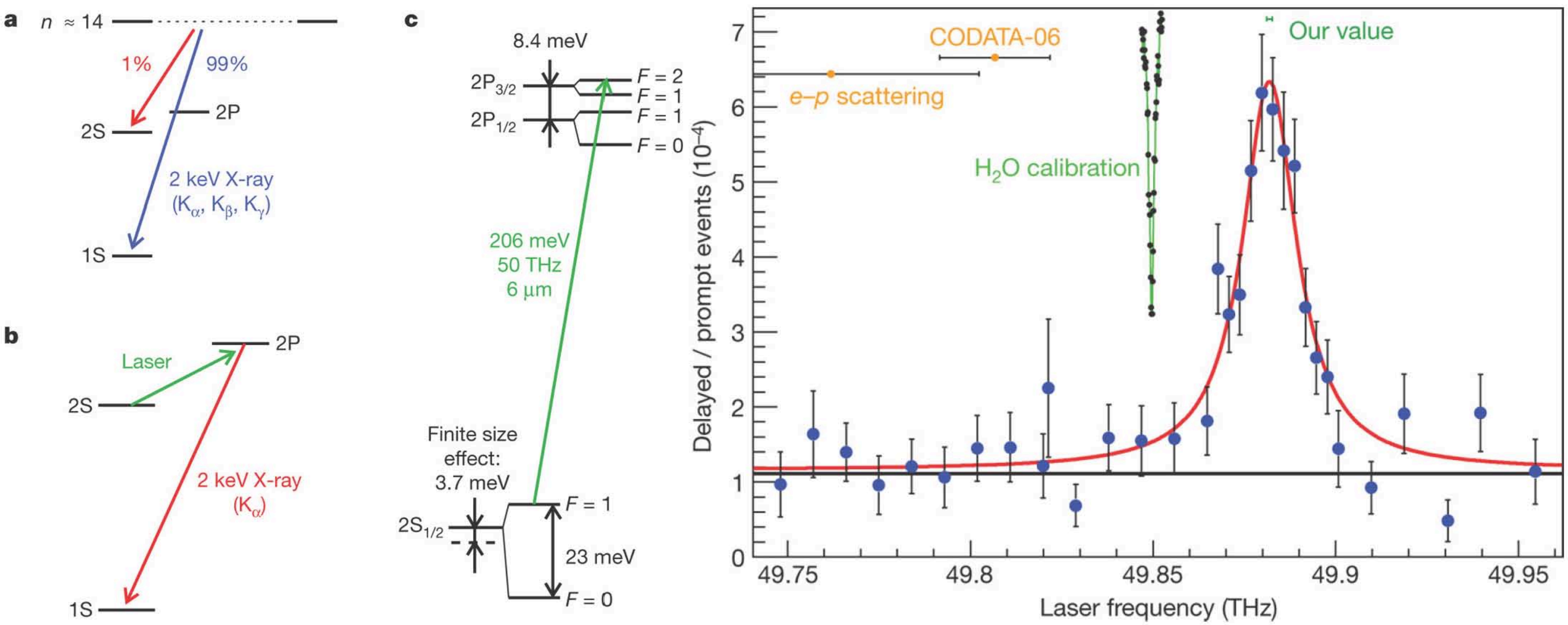
2008: Hydrogen spectroscopy (CODATA) **r_p = 0.8768(69) fm**

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

Muonic hydrogen Lamb shift experiment at PSI

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





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

unprecedented precision, great! But different from everybody else's value; Not quite!
M.A. Belushkin et al. (2007); T. Friedmann(2009)

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^{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 term 0.31 meV

to match CODATA value

Recent evaluation by Jentschura, Annals Phys. 326, 500 (2011)

Proton Polarizability contribution is 0.015(4) meV

Summary

2005: Re-analysis e-p scattering r_p = 0.897(18) fm (Sick 2003)

2008: Hydrogen spectroscopy (CODATA) r_p = 0.8768(69) fm (Mohr 2008)

2010: The new value is r_p = 0.84184(67) fm (muonic Lamb Shift)

2010: Mainz ep cross section r_p =0.879(5)$_{stat}$(4)$_{sys}$(2)$_{mod}$(4)$_{group}$

Magnetic radius: r_p =0.777(13)$_{stat}$(9)$_{sys}$(5)$_{mod}$(2)$_{group}$

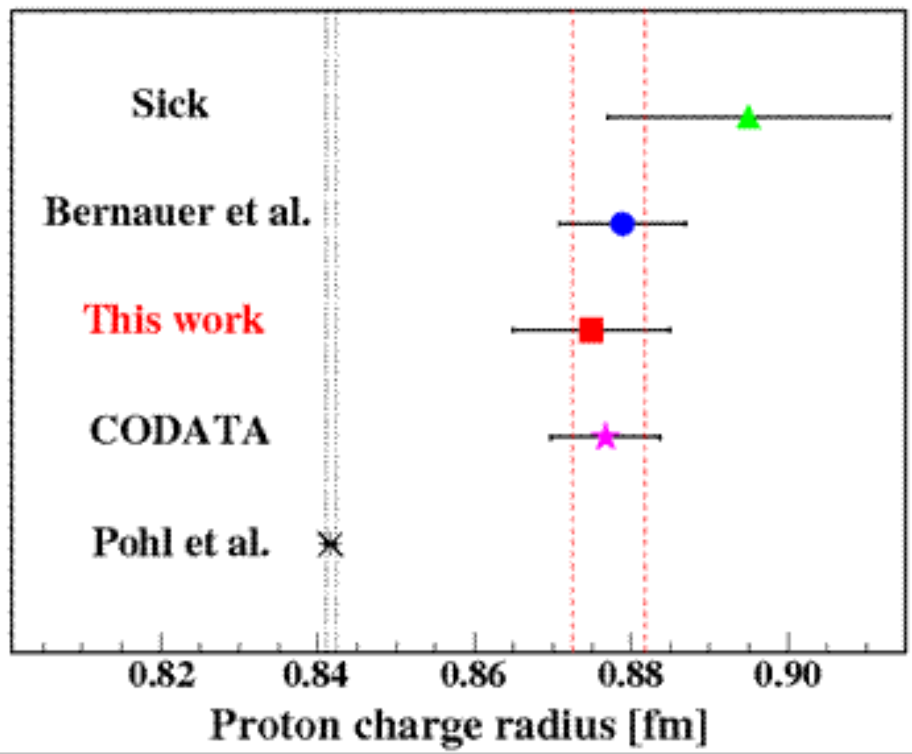
2010: Model independent analysis Paz and Richard, PRD82,113005 (2010)

$$r_E^p = 0.877^{+0.031}_{-0.049} \pm 0.011 \text{ fm}$$

2011: JLab r_p =0.875(10),

r_p =0.867(20) (magnetic)

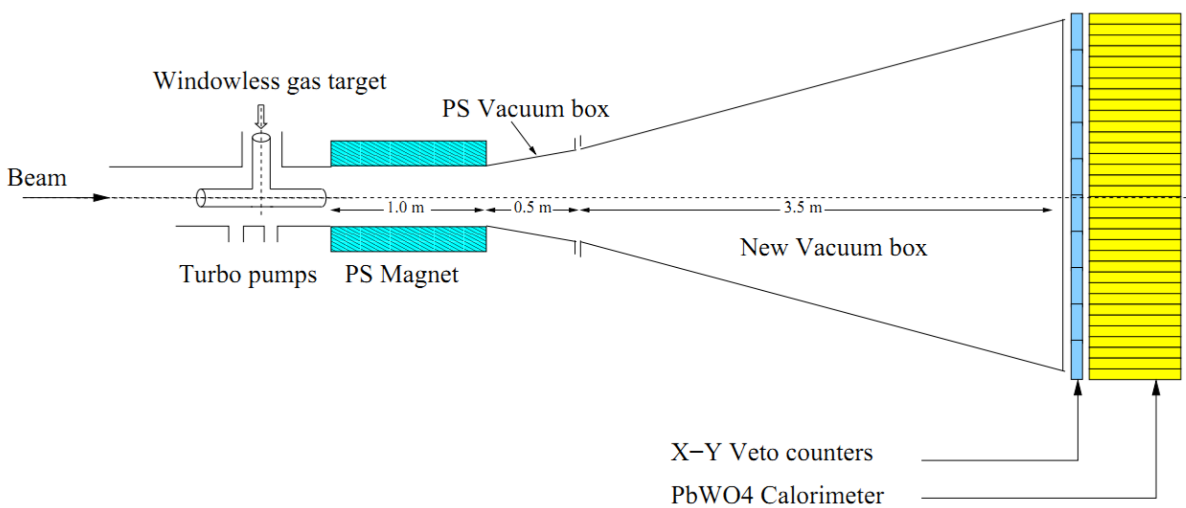
Zhan et al. arXiv:1102.0318

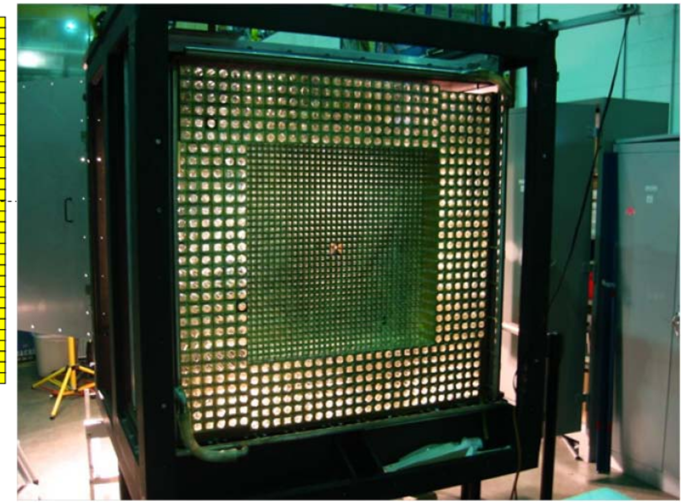


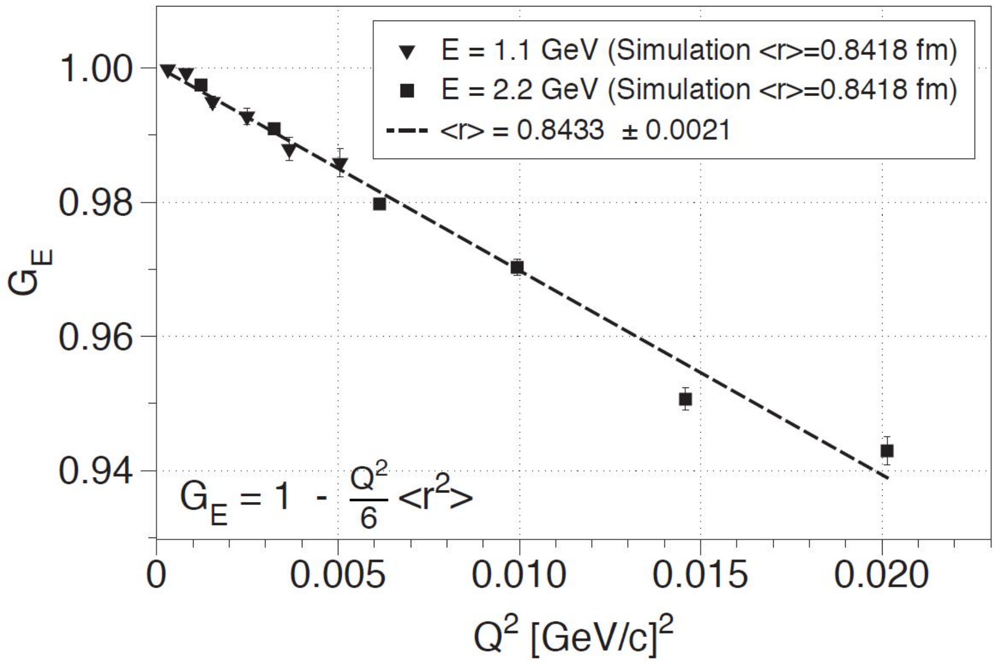
Partial summary

- **Exotic partcles, e.g. Barger et al. PRL106,153001 (2011) and references**
- **New PV muonic force, Batell et al. PRL 107 (011803) 2011**
- **Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen, arXiv:1101.5965, Jentschura, Annals Phys. 326, 500 (2011), Borie, arXiv: 1103:1772, Carroll et al, arXiv:1108.5785,….**
- **Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher, PLB696, 343(2011),..**
- **New experiments: Mainz, Jlab, PSI, …**

A new ep experiment on charge radius



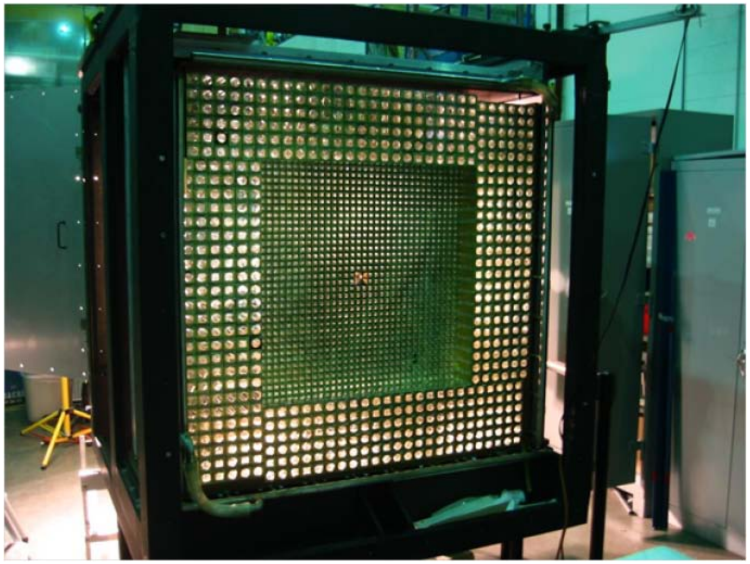


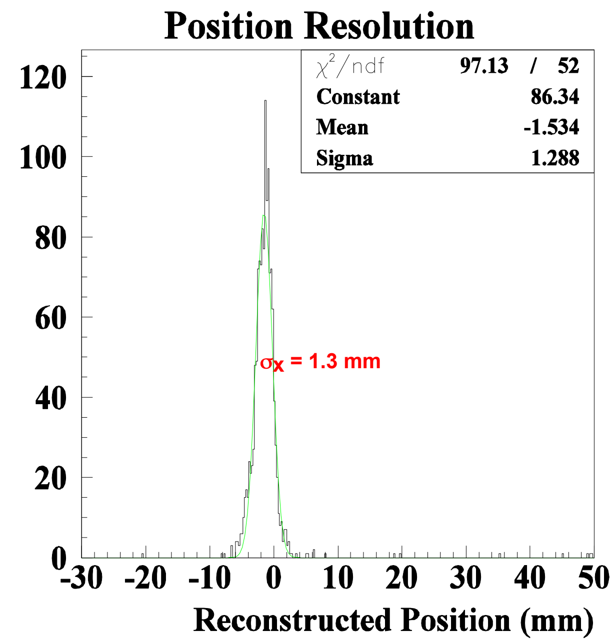


- EM calorimeter
- Windowless target, Low background
- QED moller process as normalization by ep and ee at the same time
- extremely low Q^2 : 10^{-2}- 10^{-4} GeV^2
- Sub % overall precision

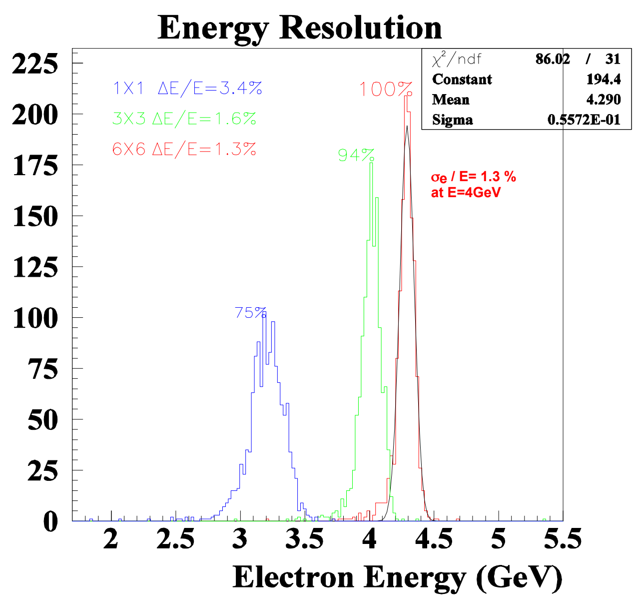
Gasparian, Khandaker, Gao, Dutta to JLab PAC38 (conditionally approved)

Electromagnetic HyCal calorimeter





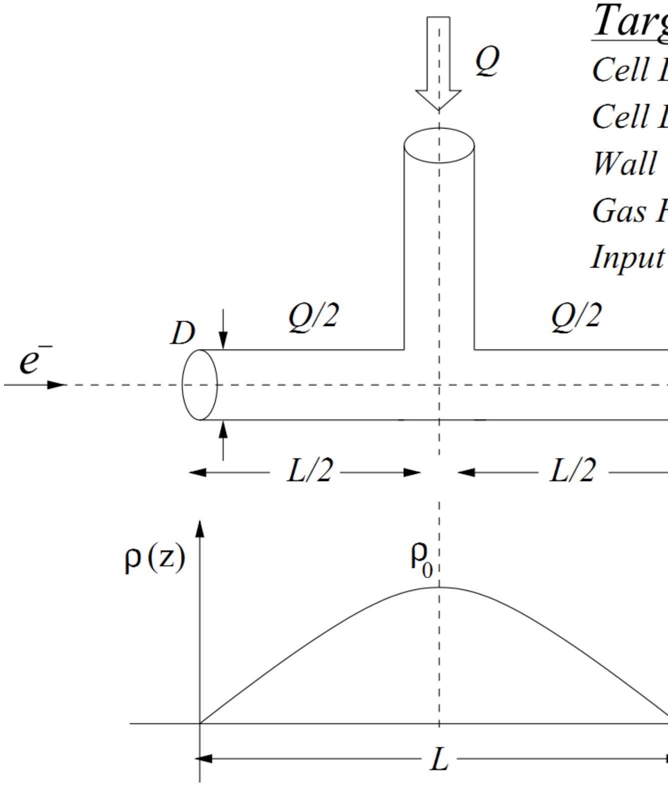
- High resolution, large acceptance HyCal calorimeter ($PbWO_4$ part only)
- Windowless H_2 gas flow target
- XY – veto counters
- Vacuum box, one thin window at HyCal only
- Harp scanner for beam profile

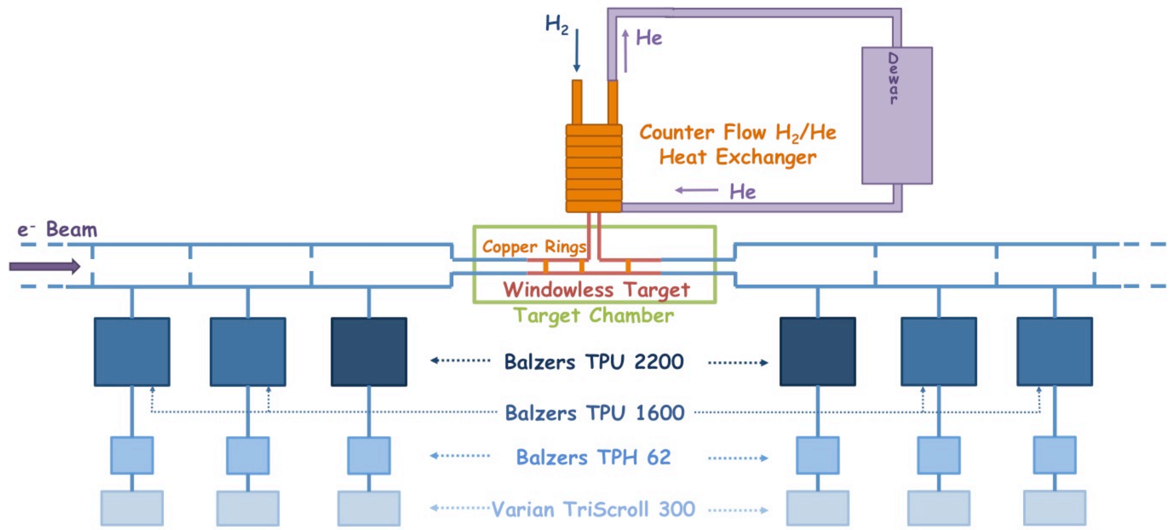


Windowless Gas Flow H_2 Target

Target Parameters:

Cell Diameter = 4 mm
Cell Length = 4 cm
Wall Thickness = 30 um Kapton
Gas Flow rate = 6 Torr−l/s
Input Gas Temp = 25 K





- Major background for typical magnetic spectrometer experiments is from target window material.
- This proposed experiment is essentially a background-free measurement.

- **Similar targets in OLYMPUS and HERMES at DESY.**

Control of Systematic Errors

- Major improvements over past 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: [$2x10^{-4}$ – $2x10^{-2}$] (GeV/c)^2 ➡ Model independent r_p extraction

- **Extracted diff. cross sections for *ep* ⟶ *ep***

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

- **… and for *ee* ⟶ *ee*, Moller**

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

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

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

- **Two major sources of systematic errors, N_e and N_{tgt}, typical for all previous experiments, are canceling out.**

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

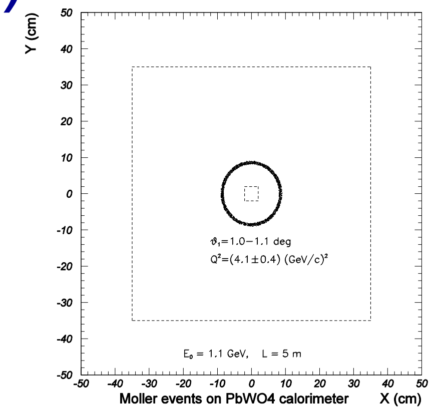
Will analyze Moller events in 3 different ways:

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

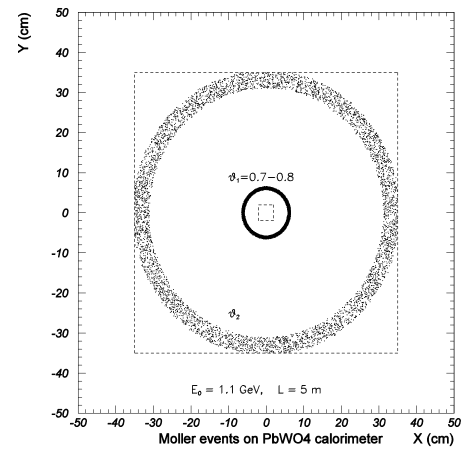
Relative ε_{det} are needed for this experiment

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



2) Coincident Method

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



3) Integrated over HyCal acceptance

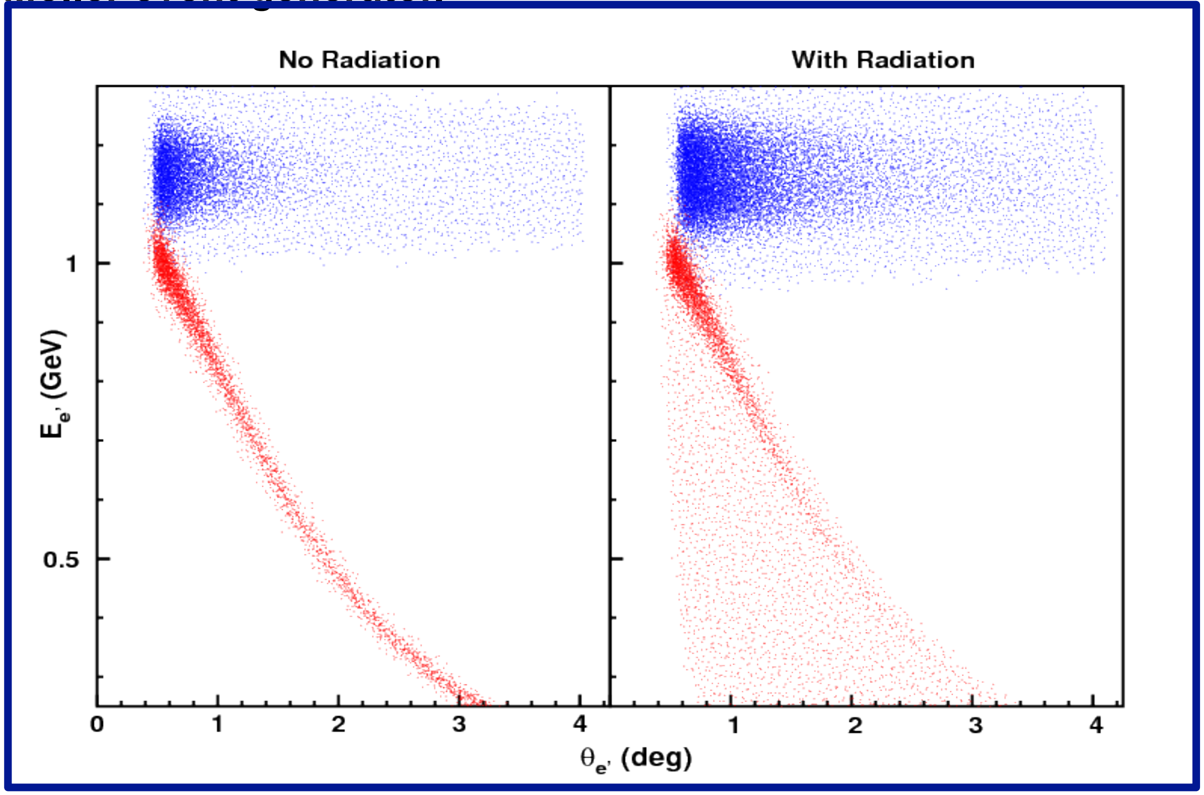
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep,\ \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^-,\ \text{on PWO})}\right]\frac{\varepsilon_{\text{geom}}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\text{geom}}^{ep}(\theta_i \pm \Delta\theta)}\,\frac{\varepsilon_{\text{det}}^{e^-e^-}(\text{all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

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 Selection and Radiative Corrections

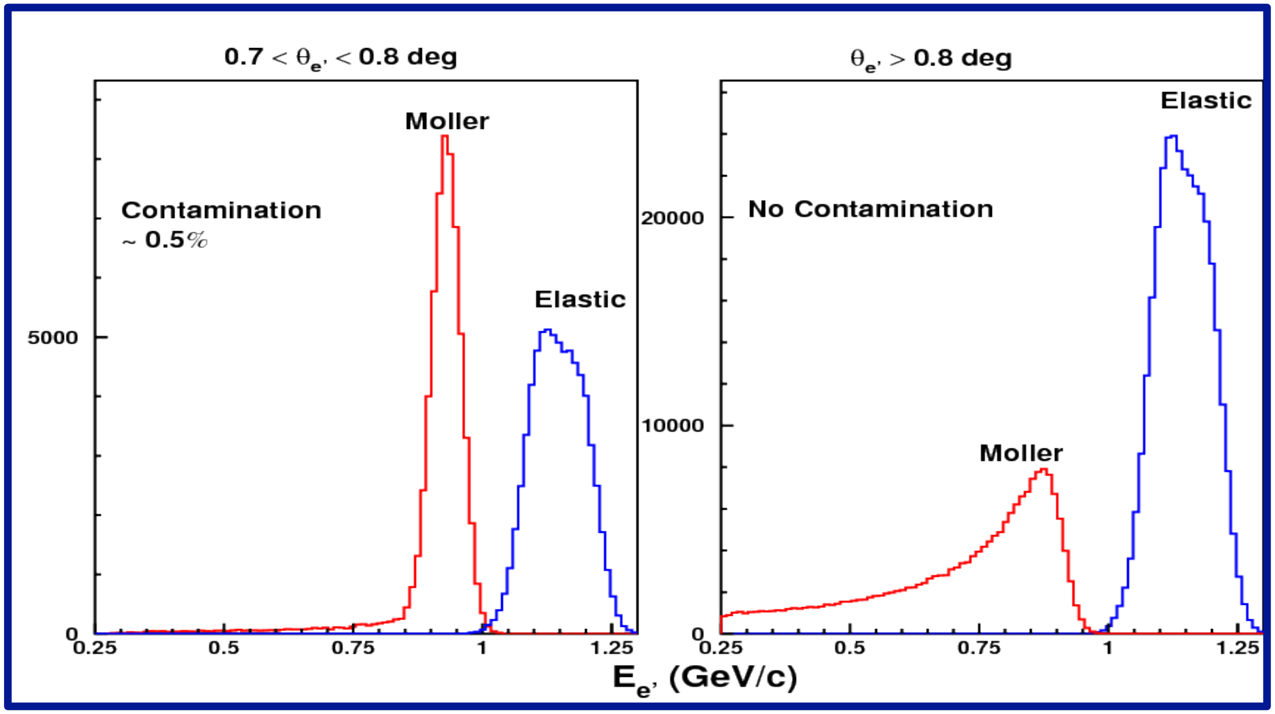
- ***ep* elastic** radiative corrections were simulated using ELRADGEN[1] within an *ep* elastic event generator (in consultation with I. Akushevich)
- Moller radiative corrections were simulated using MERADGEN[2] within a Moller event generator.



[1] I. Akushevich, O. Filoti, A. Ilyichev, and N. Shumeiko, arXiv:hep-ph/1104.0039v1, (2011).
[2] A. Afanasev, E. Chudakov, V. A. Zukunov and A. N. Ilyichev, Comp. Phy. Comm, 176, 218 (2007)

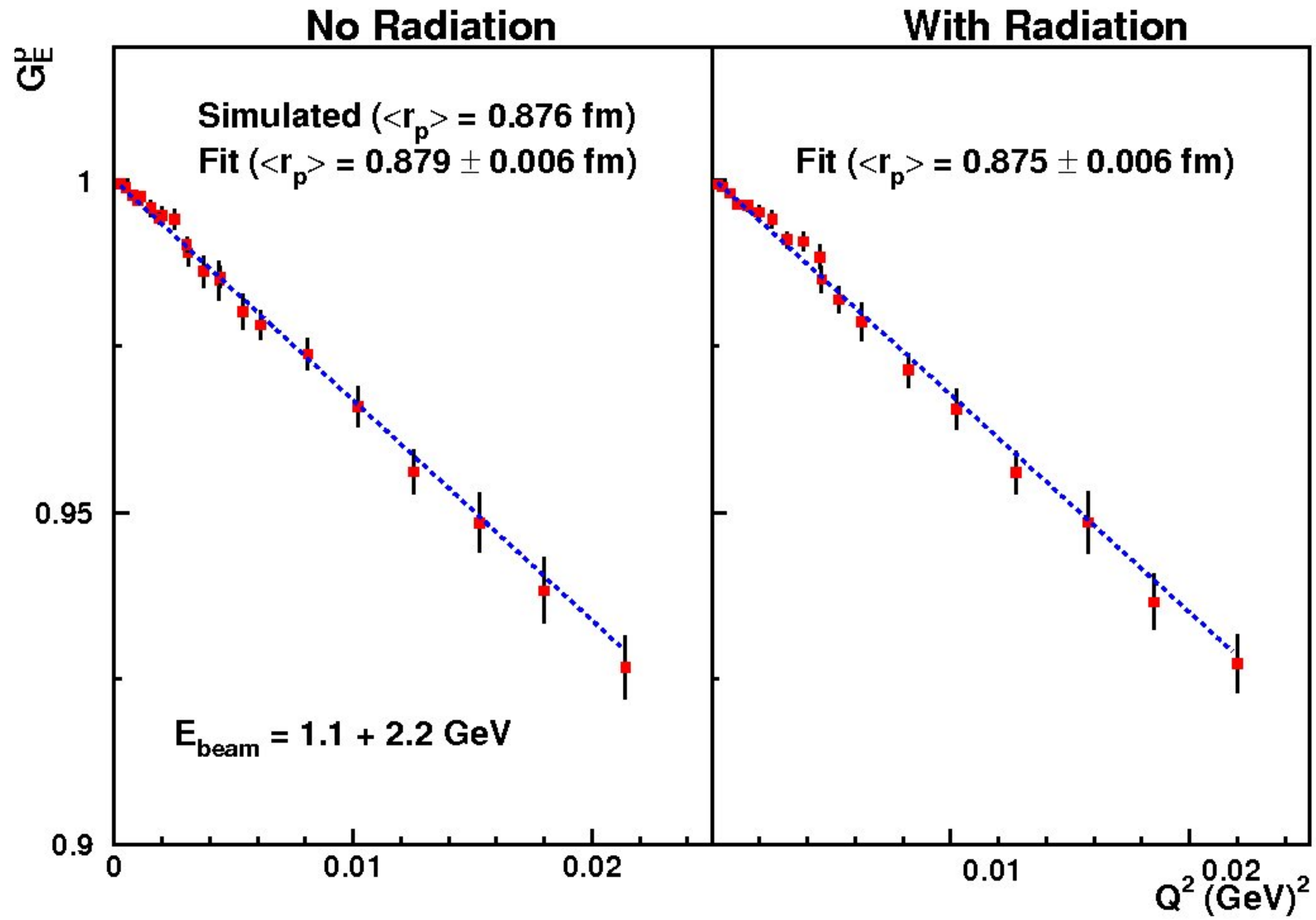
Elastic/Moller Overlap

- Overlap of $E_{e'}$ spectra of radiated events ~0.5% contamination from Moller events (for $0.7 < \theta_{e'} < 0.8$ deg)



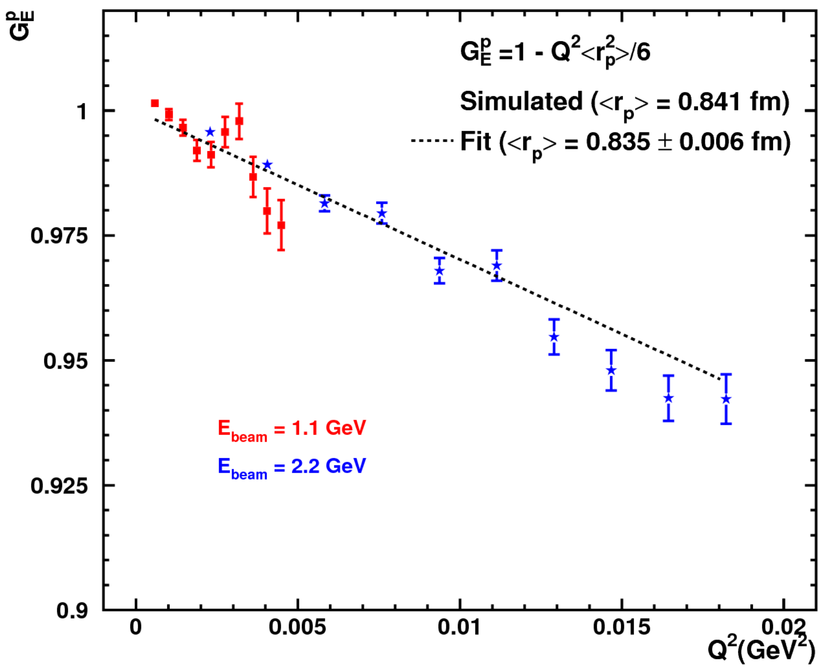
- Addresses TAC's concerns about possible overlap of Moller and Elastic events at the smallest angles.

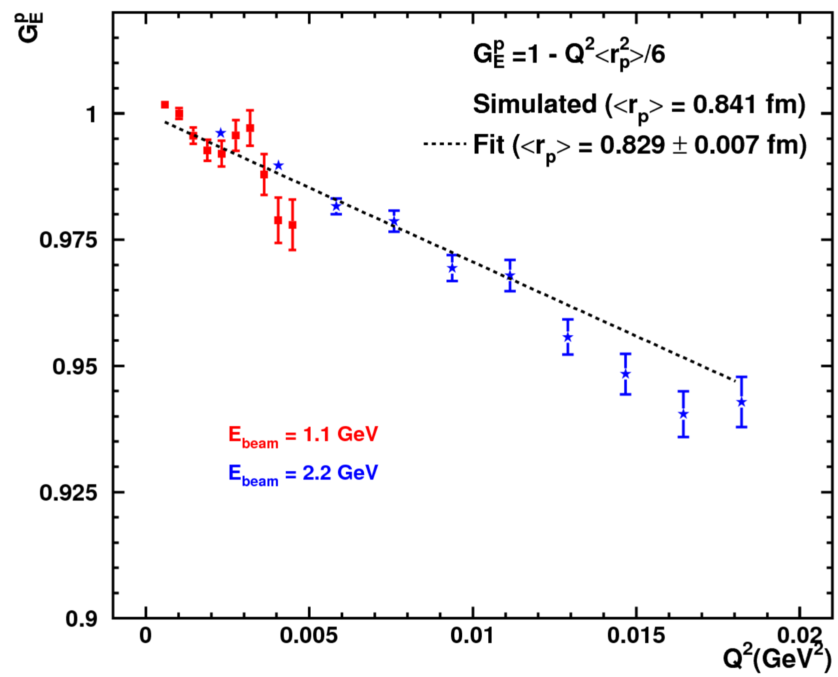
Radiative Corrections



- **Extracting r_p from simulations with and without radiation we have estimated the systematic uncertainty from radiative corrections to be < 0.3%**

Control of Systematic Errors (Calorimeter Misalignment)





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

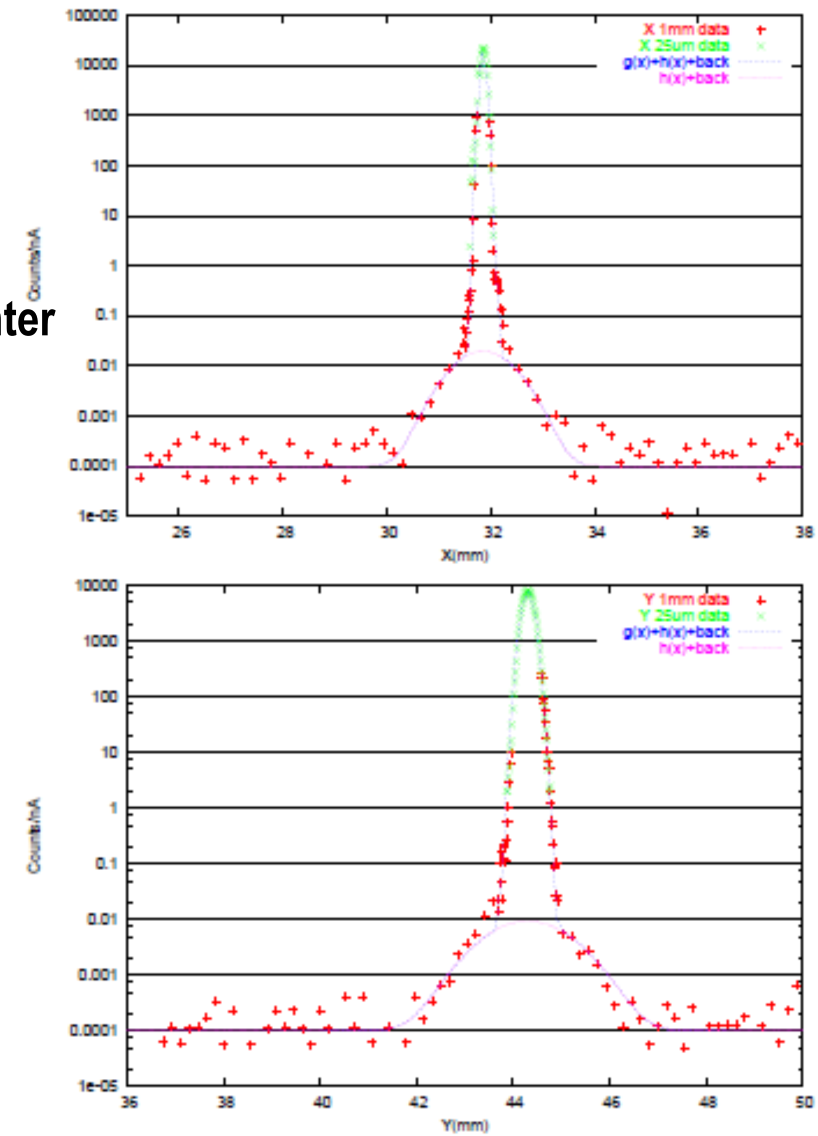
1mm shift $r_p = 0.829 \pm 0.007$ fm

- 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

HPS Quality Electron Beam Test

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



Beam Time Request and Estimated Error Budget

- **Beam time**

	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

- **Estimated error budget** (added quadratically)

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%

Summary and outlook

- Two frontiers for discovering new physics
  - High energy such as LHC
  - Low energy high precision (intensity) frontier
- Surprise on proton charge radius from muonic hydrogen atom Lamb shift measurement due to high precision
- New precision measurement using different experimental technique from electron scattering is **a MUST**
- New experiment using EM calorimeter and windowless gas target will reach unprecedented low Q^2 region
- New physics or not will dependent on new precision results from electron scattering, and new Lamb shift measurements on H, D and He

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