Precision Measurement of the Proton Charge Radius

- PEB Workshop -

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Mehdi MEZIANE,
Duke University

On Behalf of the PRAD Collaboration

OUTLINE

- Introduction
- *ep* elastic scattering and nucleon form factors
- Proton Charge Radius Measurements
- Measurement of the proton charge radius at very low Q^2
- Radiative correction beyond the ultra relativistic approximation
- Conclusion

Introduction

- **High accuracy of the QED predictions and precise spectroscopy of simple atomic system allow the determination of fundamental quantities**

  - Fine structure constant α from the helium fine structure
  - The electron mass m_e from the *g* factor of hydrogen-like atoms
  - The Rydberg constant R_∞ and Lamb shift from the hydrogen spectrum

- **Proton charge radius r_p :**

  - Indirect measurements from spectroscopy of bound state proton-lepton (electronic or muonic transitions)
  - Direct measurement from extraction of G_{Ep} from *ep* elastic scattering experiments

Proton Charge Radius Extraction

❖ Unpolarized Cross Section of elastic ep->ep scattering:

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

where

$$\tau = Q^2/(4M_p^2)$$

❖ Polarization measurements (in the Born approximation):

Recoil

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

Double polarization (beam+target)

$$R = \frac{A_1}{A_2} = \frac{2\tau v_{T'}\cos\theta_1^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)}v_{TL'}\sin\theta_1^*\cos\phi_1^* G_M^p G_E^p}{2\tau v_{T'}\cos\theta_2^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)}v_{TL'}\sin\theta_2^*\cos\phi_2^* G_M^p G_E^p}$$

❖ RMS Proton Charge radius:

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

⇒

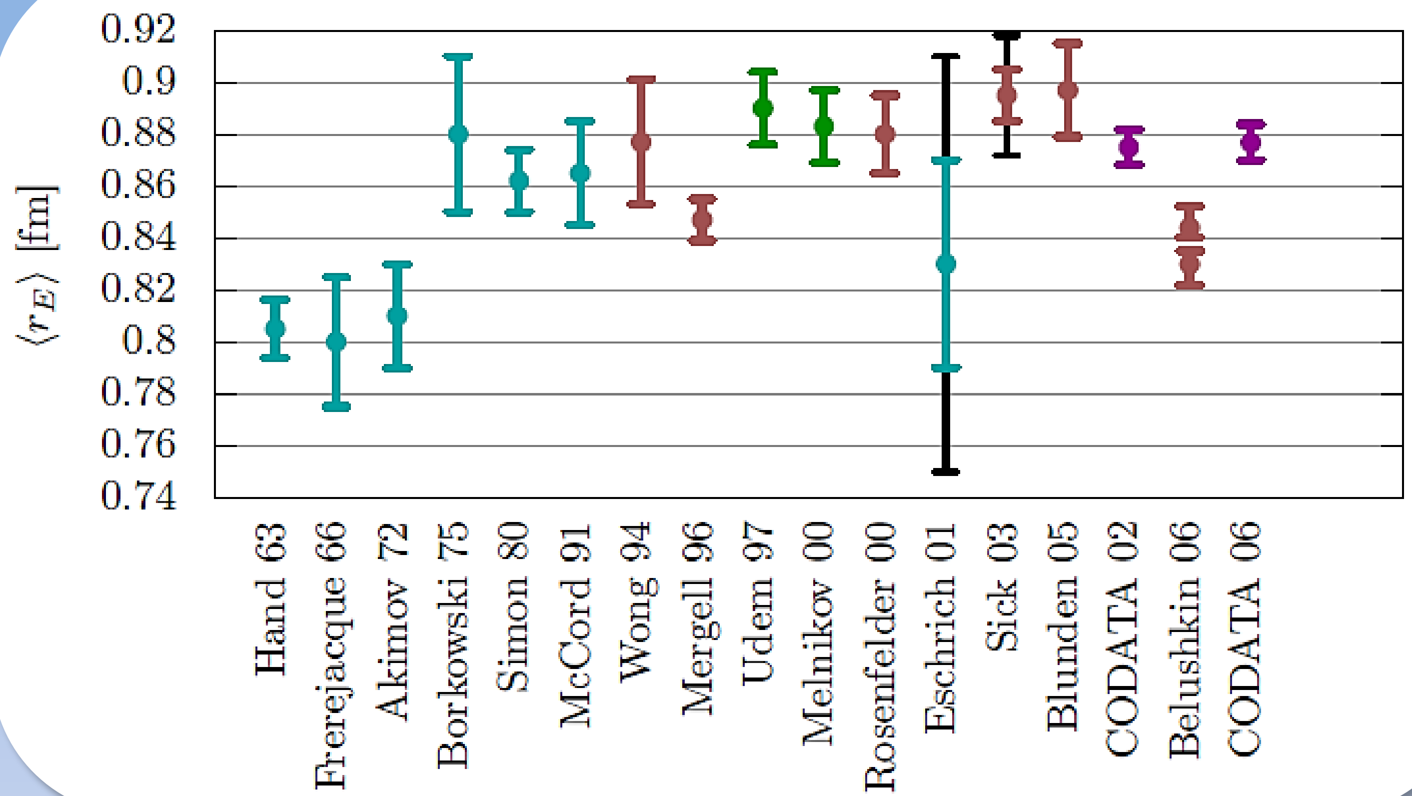
$$\langle r^2\rangle = -6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

Form Factors (FF)

Significance of low Q^2 measurements of FF:

- Sensitive to the pion cloud and provide test of effective field theories of QCD.
- Probe the strange quark contribution to the electromagnetic structure of the nucleon.
- In the limit $Q^2 \to 0$, FF are related to the charge and magnetic radii.
- Precise knowledge of the charge radius provides high precision test of QED based on hydrogen Lamb shift measurements.

Radius Data until 2006



Started with: $r_p \approx 0.81$ fm in 1963
Reached : $r_p \approx 0.88$ fm by 2006

Radius Data from ep scattering (and H spectroscopy)

- Re-analysis e-p scattering $r_p = 0.897 \pm 0.018$ fm

  I. Sick, Phys. Lett. B, vol. 576, no. 1–2, pp. 62 – 67, 2003.

- Hydrogen spectroscopy $r_p = 0.8768 \pm 0.0069$ fm

  P. J. Mohr et al. Rev. Mod. Phys., vol. 80, pp. 633–730, Jun 2008.

- *ep* scattering exp. at Mainz $r_p = 0.879 \pm 0.008$ fm

  J. Bernauer et al., PRL 105,242001, 2010

- ep scattering exp. at Jlab $r_p = 0.875 \pm 0.01$ fm, re-analysis including form factor ratio constraint obtained from recoil polarization

  X. Zhan et al., Phys. Lett. B, vol. 705, no. 1–2, pp. 59 – 64, 2011

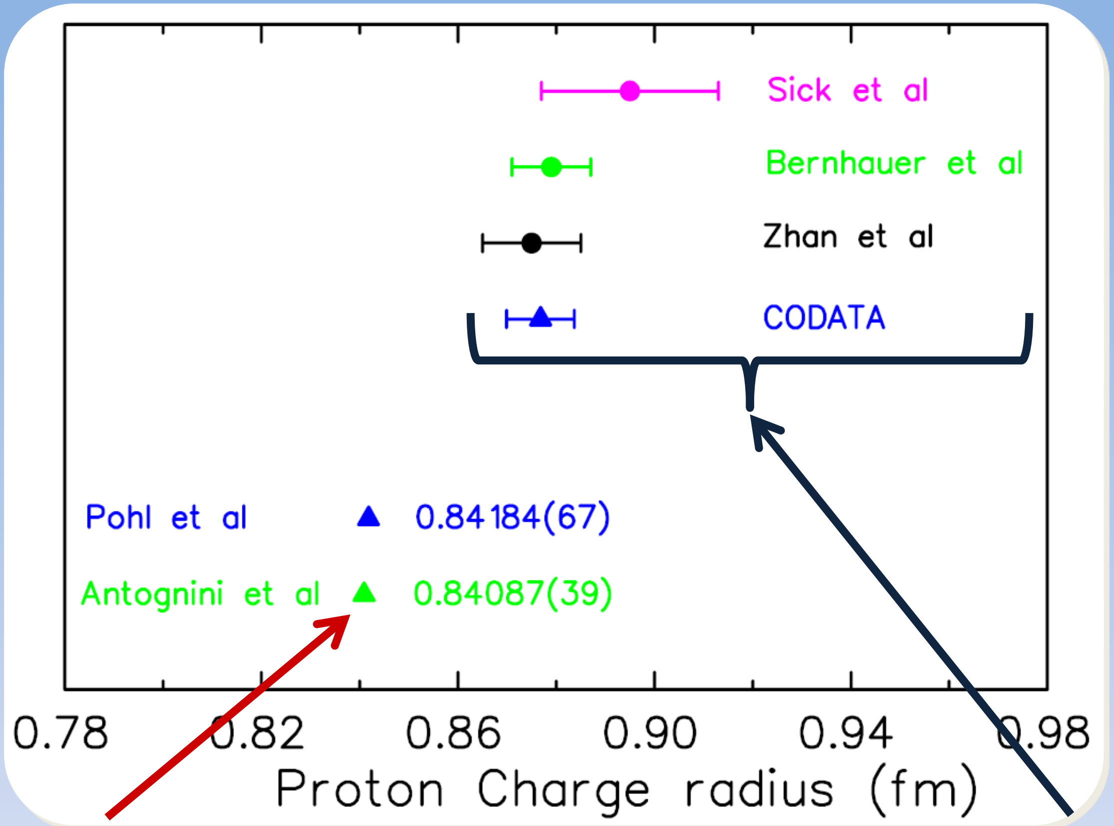
Proton Charge Radius Crisis

- Muonic hydrogen Lamb shift exp. at PSI

r_p = 0.84184(67) fm *Pohl, R. et al., Nature 466, 213-217 (2010)*

r_p = 0.84087(39) fm *Antognini. et al., Science 339, 417 (2013)*

Unprecedented precision



- 7σ discrepancy between muonic and average electronic measurements !
- Results from electronic and scattering measurements agree

Many Questions…

- **Is a new physics discovered?**
  - *V. Barger, et al., Phys. Rev. Lett.* ***106****, 153001 (2011)*
  - *C. Carlson , arXiv:1206.3587 (2012)…*

- **Are effects missing from the state-of-the-art calculations?**
  - *E. Borie, Phys. Rev. A* ***71****, 032508 (2005).*
  - *U.D. Jentschura, Annals of Physics* ***326****, 500 (2011)…*

- **Are there additional corrections to the muonic Lamb shift due to the proton structure?**
  - *G.Miller , arXiv:1209.4667 (2012)*
  - *C.E. Carlson, V. Nazaryan, K. Griffioen, Phys. Rev. A* ***83****, 042509 (2011).*
  - *R.J. Hill, G. Paz, arXiv:1103.4617 (2011)…*

- **Are the higher moments of the charge distribution taken into account correctly in the extraction of the rms charge radius?**
  - *M.O. Distler, J.C. Bernauer, T. Walcher, Phys. Lett. B* ***696****, 343 (2011).*
  - *A. De Rújula, arXiv:1008.4546 (2010), Phys. Lett. B* ***693****, 555 (2010), and* ***697****, 26 (2011).*
  - *I.C. Clöet, G.A. Miller, Phys. Rev. C* ***83****, 012201(R) (2011).*
  - *J.D. Carroll, A.W. Thomas, J. Rafelski, G.A. Miller, arXiv:1105.2384 , and 1101.40732 (2011)…*

Still to date an OPEN question!

⇒ **Need to carry out an additional measurement using a new technique**

Precision measurement of $<r_p>$

- Extract the rms proton charge radius using a novel magnetic spectrometer free method using *ep* elastic scattering at Jlab HallB

- Explore the lowest Q^2 ever reached: $[2.10^{-4} – 2.10^{-2}]$ GeV^2, equivalent to scattering angle range of : 0.7° – 3.8°

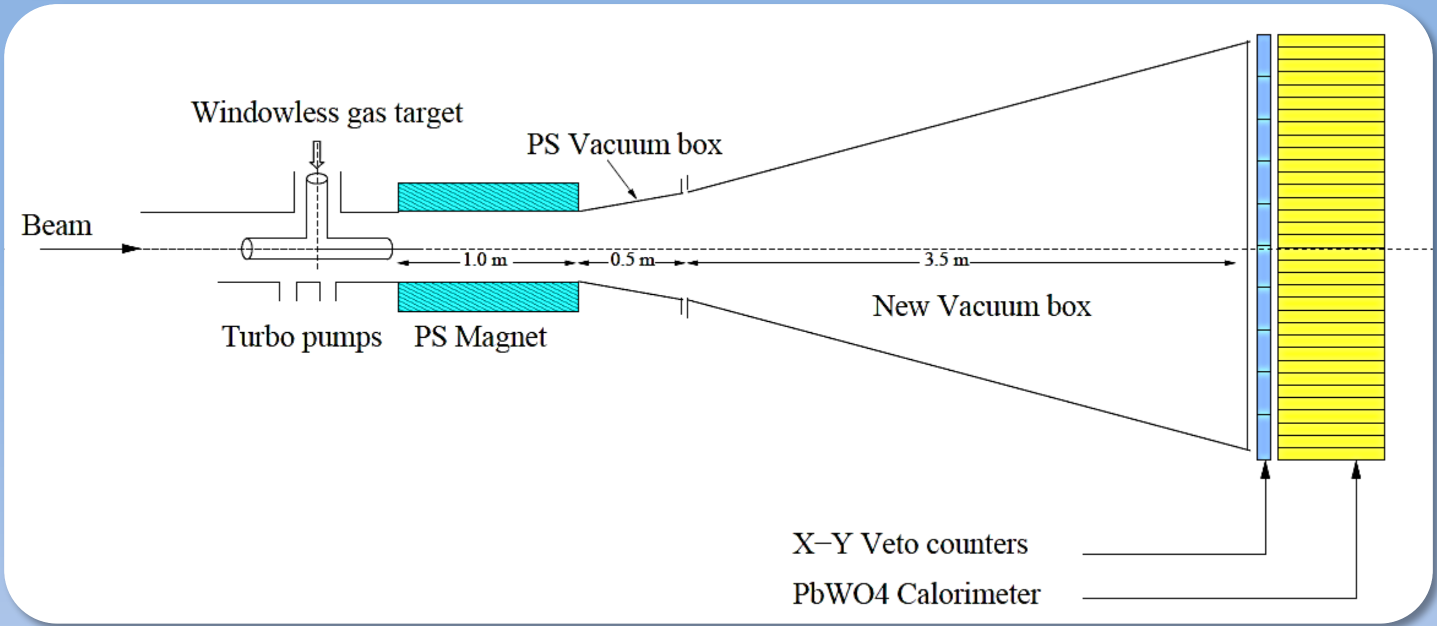
- Two energies 1.1 GeV and 2.2 GeV

- Reach a sub-percent precision. (low background +accurate knowledge of radiative corrections.)

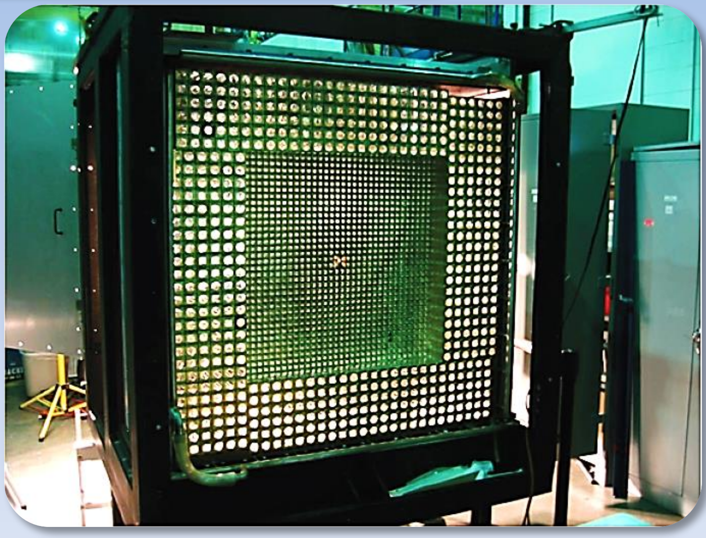
- Approved by PAC39 with A rating,
  running opportunities: end 2014- beginning 2015

- MRI proposal approved, items procurement on its way for a target test.

Experimental Setup with new windowless target



- Windowless H_2 gas flow target
- High energy and position resolutions and large acceptance 25 msr HyCal $PbWO_4$ calorimeter
- XY veto counters (veto for neutrals)
- Vacuum box, one thin window at HyCal only
- Good beam tune with σ=200μm and S/N ratio of 10^{-7} - 10^{-8} at 1 mm from the beam



Windowless Gas Flow targets

- Design and engineering of polarized and unpolarized internal gas flow target are well established and understood:

	Gas	Length (cm)	Cross section (mm×mm)	Thickness (atoms/cm^2)	Temperature (K)	Polarized
HERMES	H_2/D_2	40	8.9×21	$1\text{-}2\times10^{14}$	100	yes
BLAST	H_2/D_2	60	15×15	7×10^{13}	100	yes
OLYMPUS	H_2	60	9×27	3×10^{15}	25	no
VEPP-3	H_2	40	13×24	$\approx10^{15}$	-	no
Dark Light	H_2	25	2×2	$\approx10^{19}$	25	no
This proposal	H_2	4	4×4	$\approx10^{18}$	25	no

Proposed

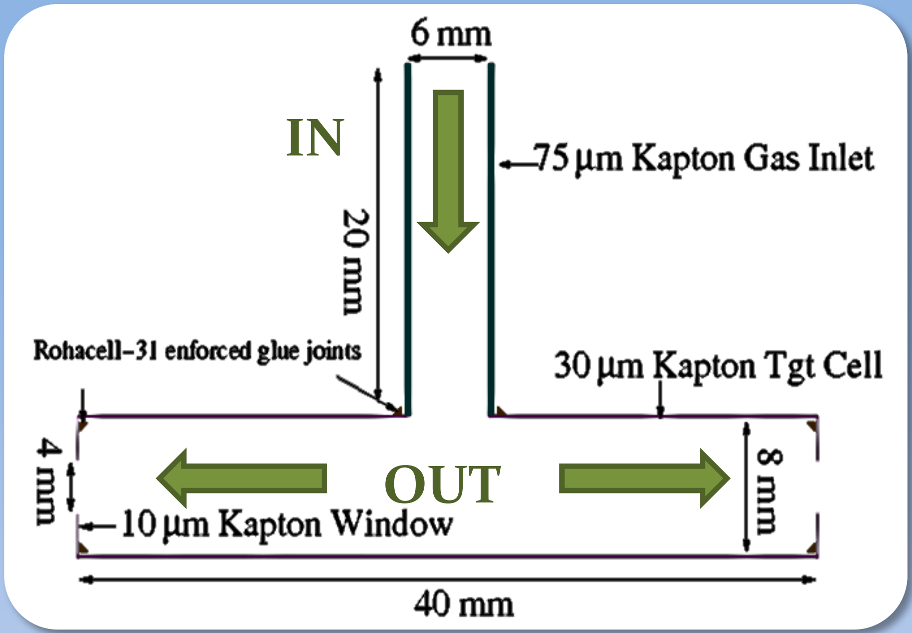
- List is not exhaustive , only focuses on electron/positron scattering experiments.

- Wide range of application, very good versatility and reliability.

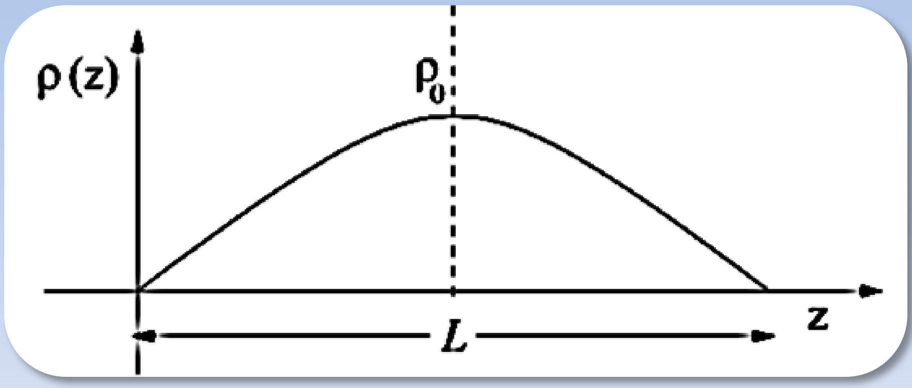
Windowless Gas Flow target

Target cell

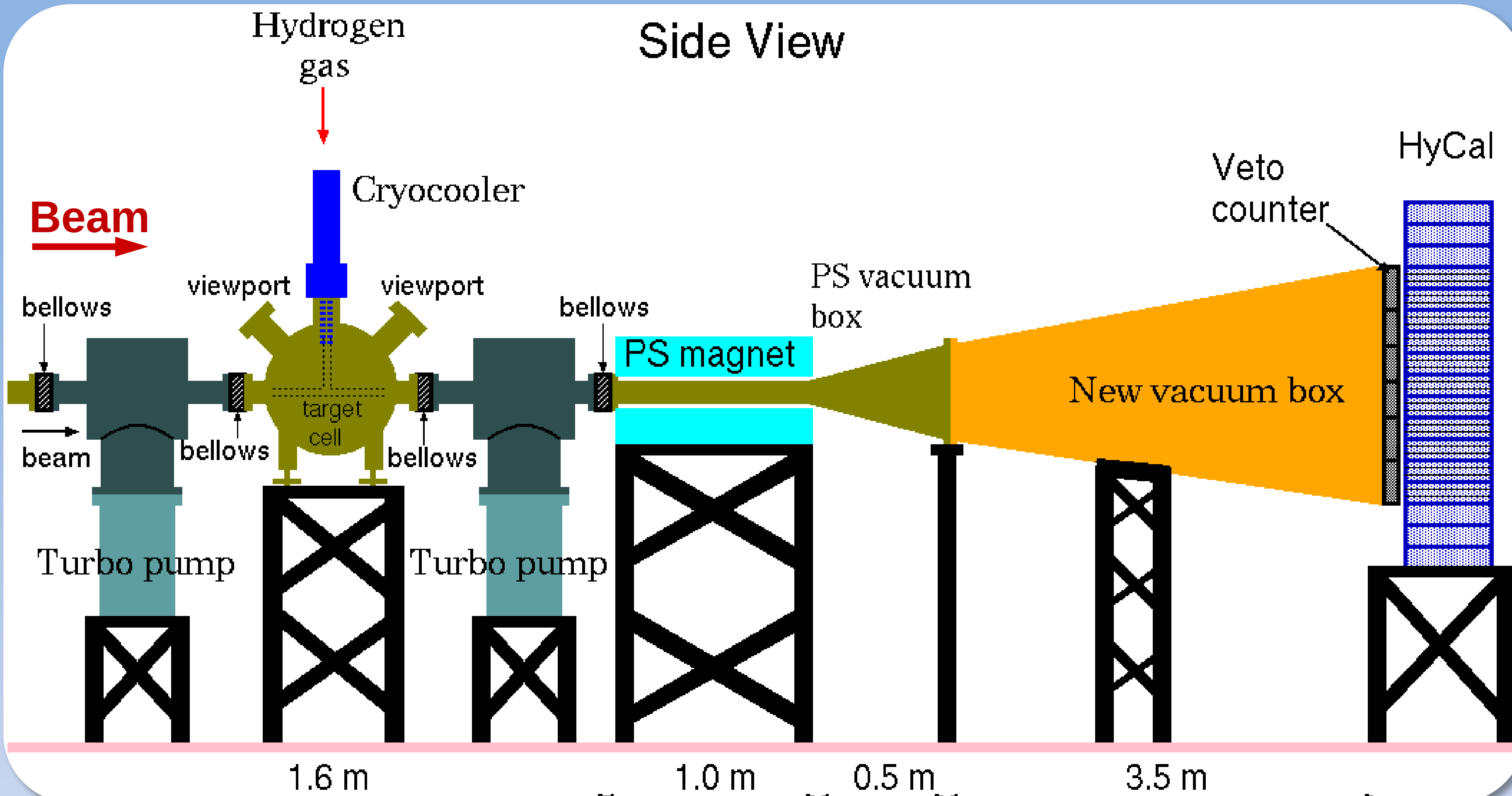
- cell length 4.0 cm
- cell diameter 8.0 mm
- cell material 30 μm Kapton
- input gas temp. 25 K
- target thickness $1x10^{18}$ H/cm^2
- average density $2.5x10^{17}$ H/cm^2
- gas mass-flow rate 6.3 Torr-l/s



In order to reach such density while keeping a manageable flow rate, cooling the H_2 becomes necessary

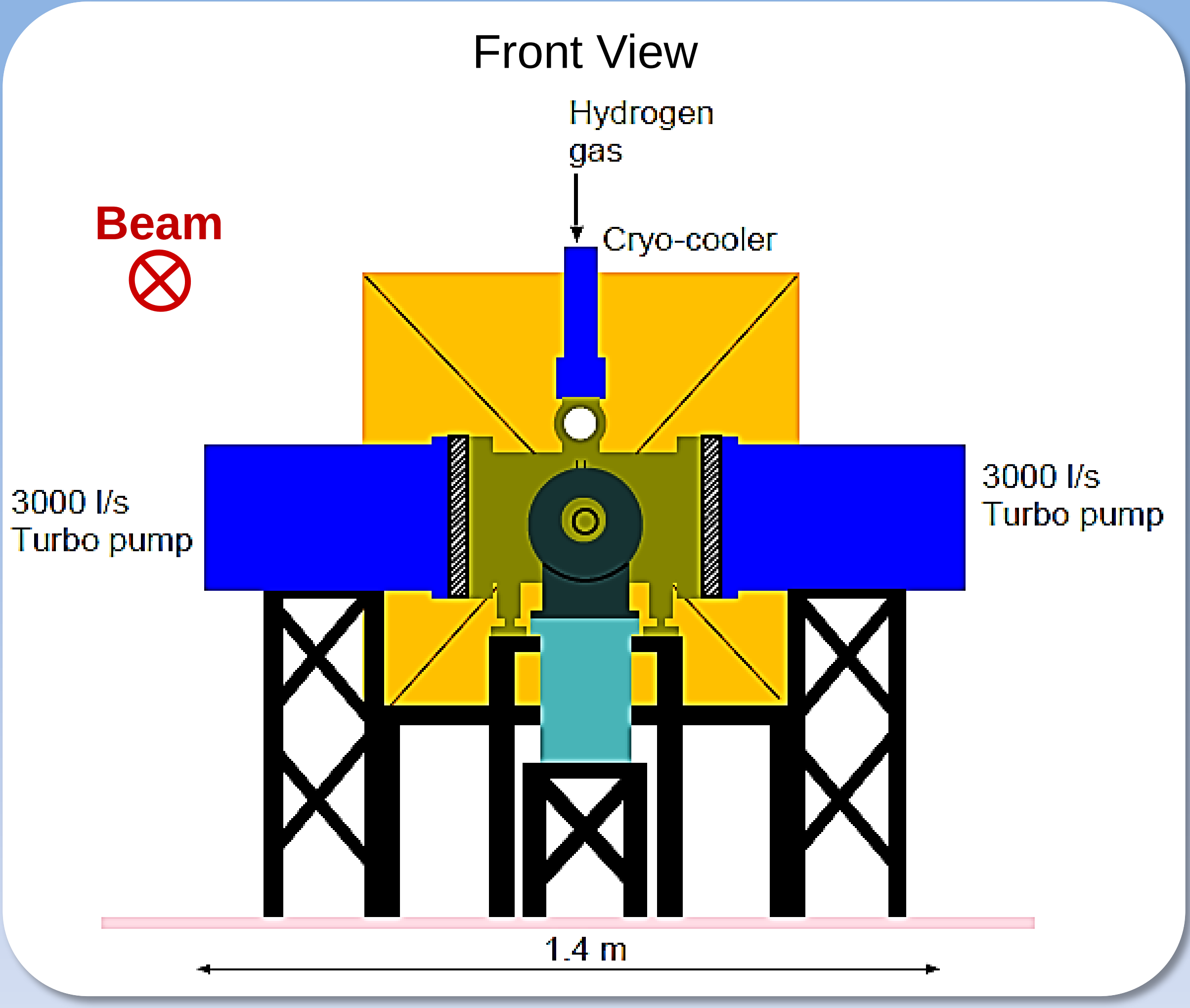


Windowless Gas Flow target



- Bellows will ensure a good conductance limit and stability of the system.
- Height of the target vacuum chamber will be adjusted using 100μm pitch screws.

Windowless Gas Flow target



Measurement Principle

- Will detect ep and Möller electrons simultaneously

- Extract ep->ep event yields

Same for ee->ee

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

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

- Normalizing the ep cross section to the Möller:

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

⇒ Main sources of systematic uncertainties N_{beam} and N_{tgt} typical for other cross section experiments cancel out in the normalization.

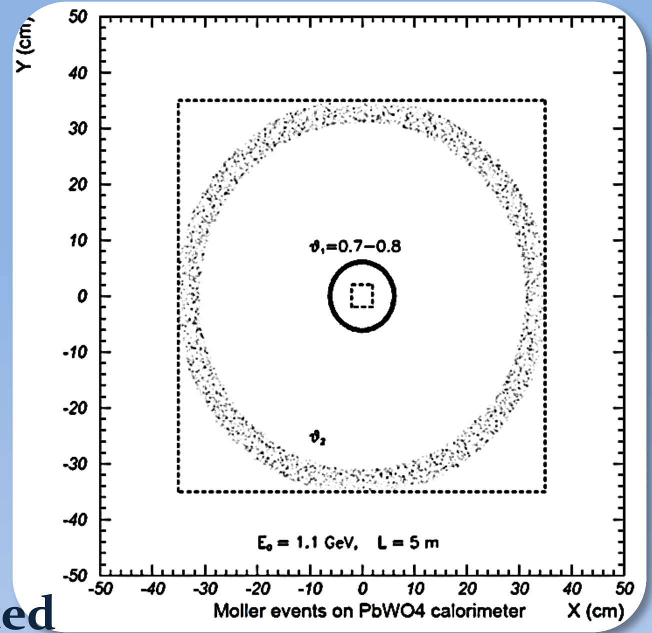
Measurement Principle

3 methods to analyze the Möller electrons:

❖ Single arm method: one Moller electron detected:

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

Only detection efficiencies and relative acceptance are needed.



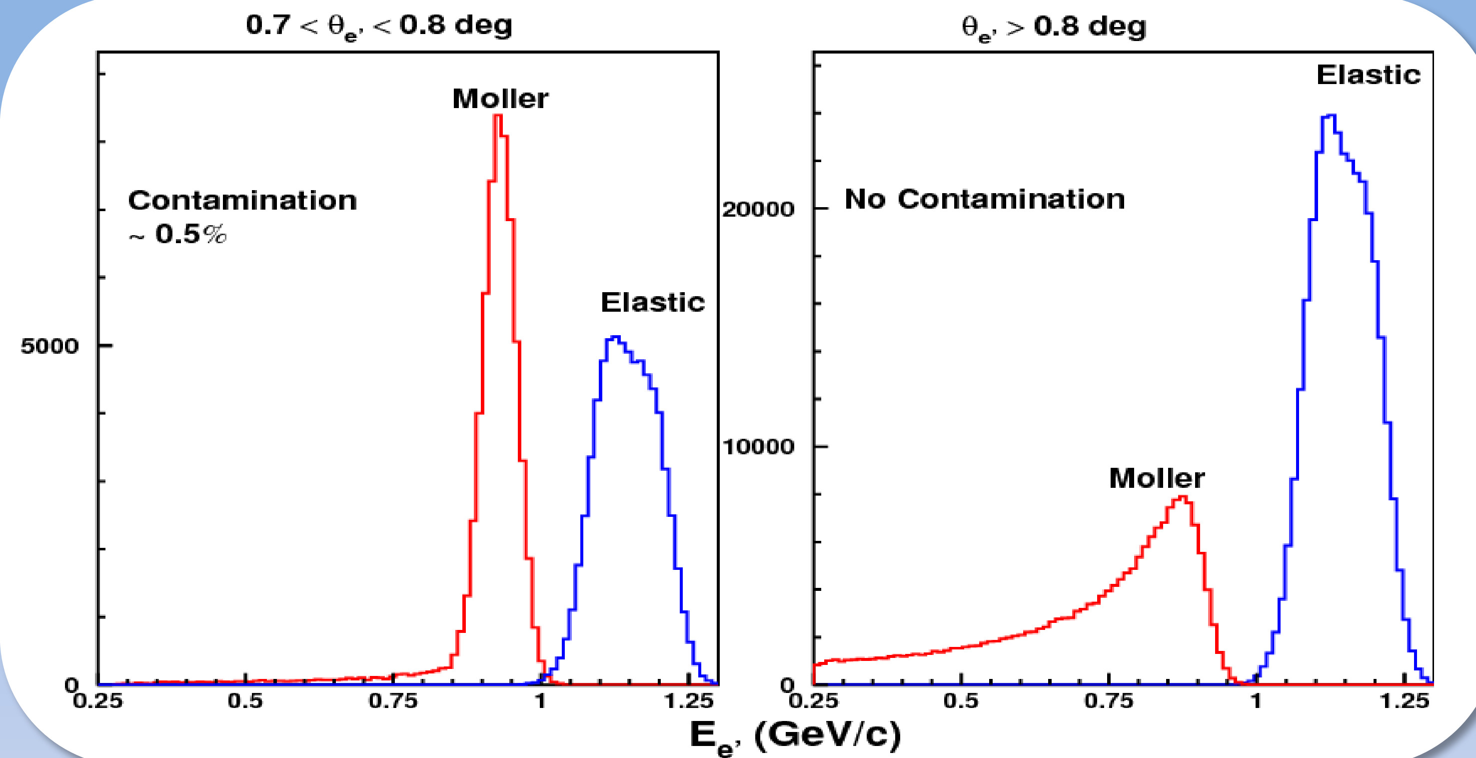
❖ Double arm method: both Möller electrons are detected

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

❖ Integrated Möller cross section method over all the HyCal acceptance

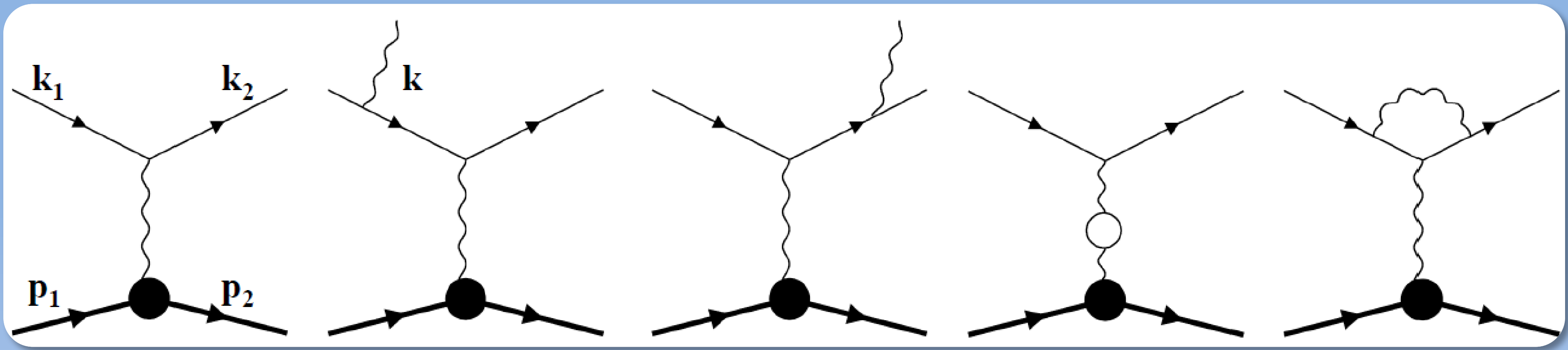
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep,\ \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^-,\ \text{on PbWO}_4)}\right]\frac{\varepsilon_{\text{geom}}^{e^-e^-}(\text{all PbWO}_4)}{\varepsilon_{\text{geom}}^{ep}(\theta_i \pm \Delta\theta)}\frac{\varepsilon_{\text{det}}^{e^-e^-}(\text{all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

Events Selection



Overlap of $E_{e'}$ spectra of radiative events ~0.5% contamination from Möller events (for $0.7° < \theta_{e'} < 0.8°$)

Radiative corrections



Born   Bremsstrahlung   Vacuum polarization   Vertex Correction

- Reaching $Q^2 \sim 10^{-4}$ $(GeV/c)^2$ requires precise knowledge of radiative corrections.

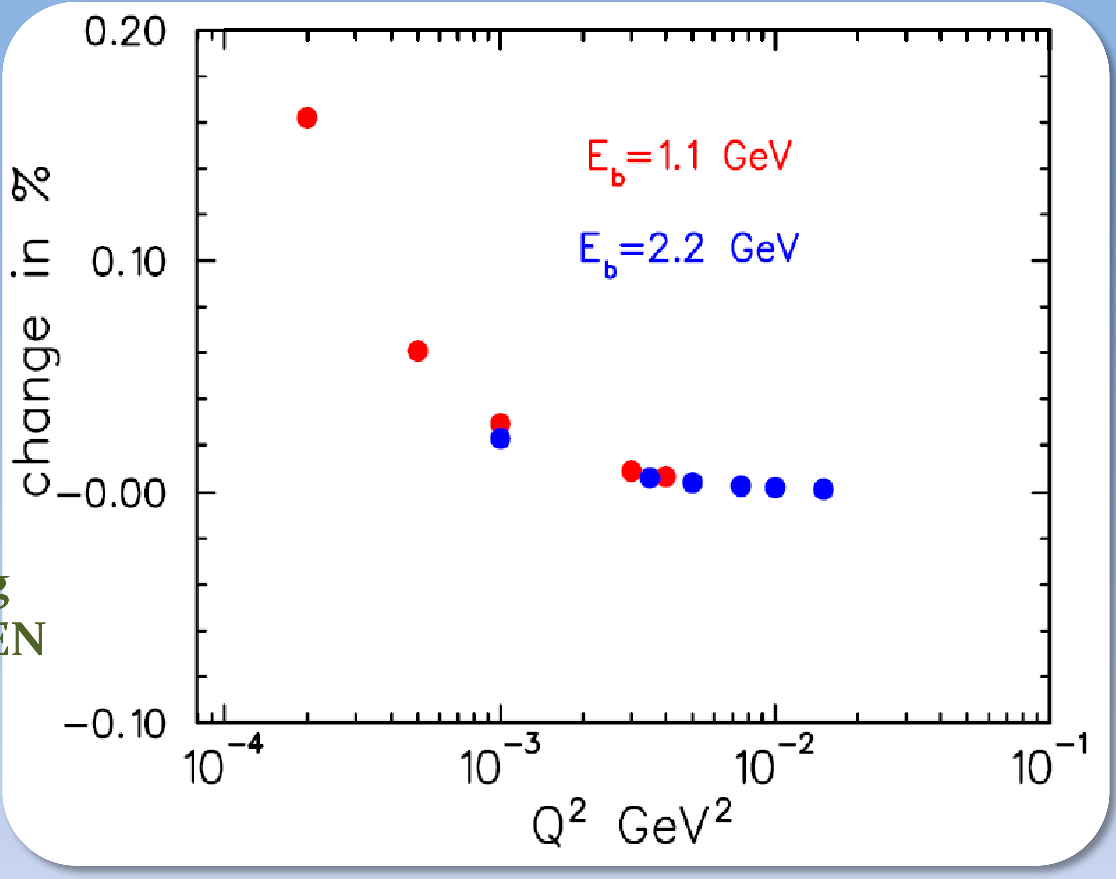
- Use Bardin-Shumeiko covariant formalism to calculate RC
  Nucl. Phys. ***B127*** *(1977) 242-258*

- Beyond the ultra relativistic approx. mass of the electron is NOT neglected

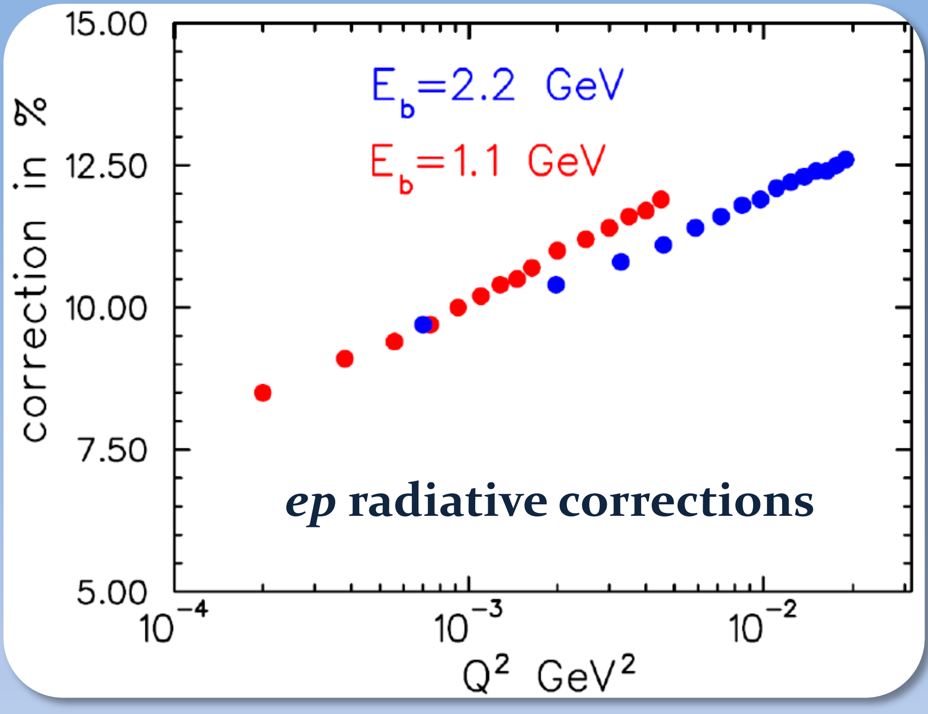
Radiative corrections

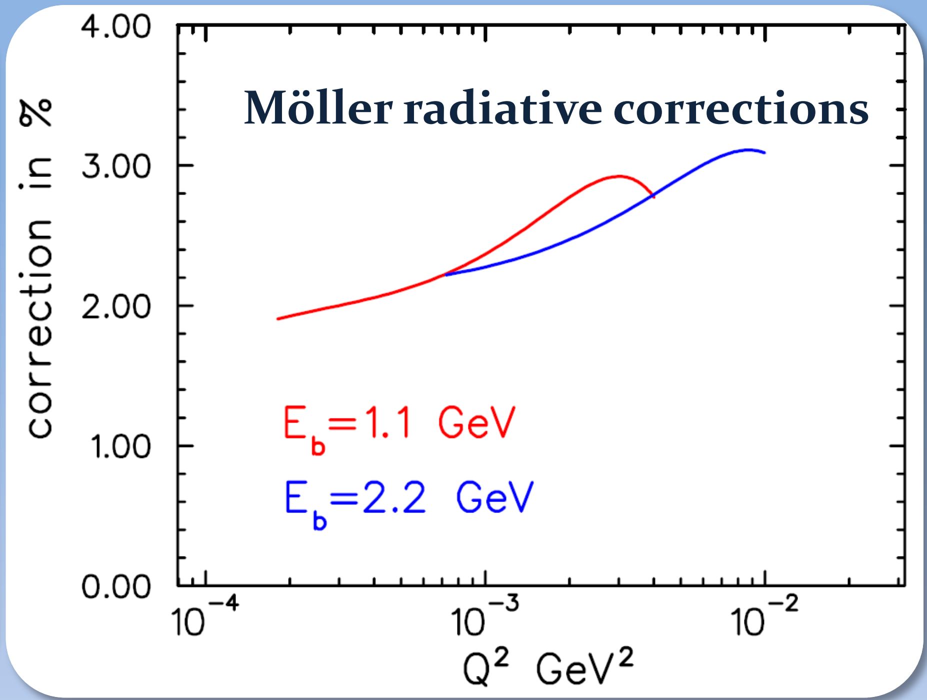
❖ The change in the cross section is less than 0.2% at the lowest Q^2 point

❖ Modified the elastic *ep* scattering codes ELRADGEN and MERADGEN accordingly



Radiative corrections





Corrections to the cross sections

ep **: ~8 -13%**
(ELRADGEN)

Möller : ~2-3%
(MERADGEN)

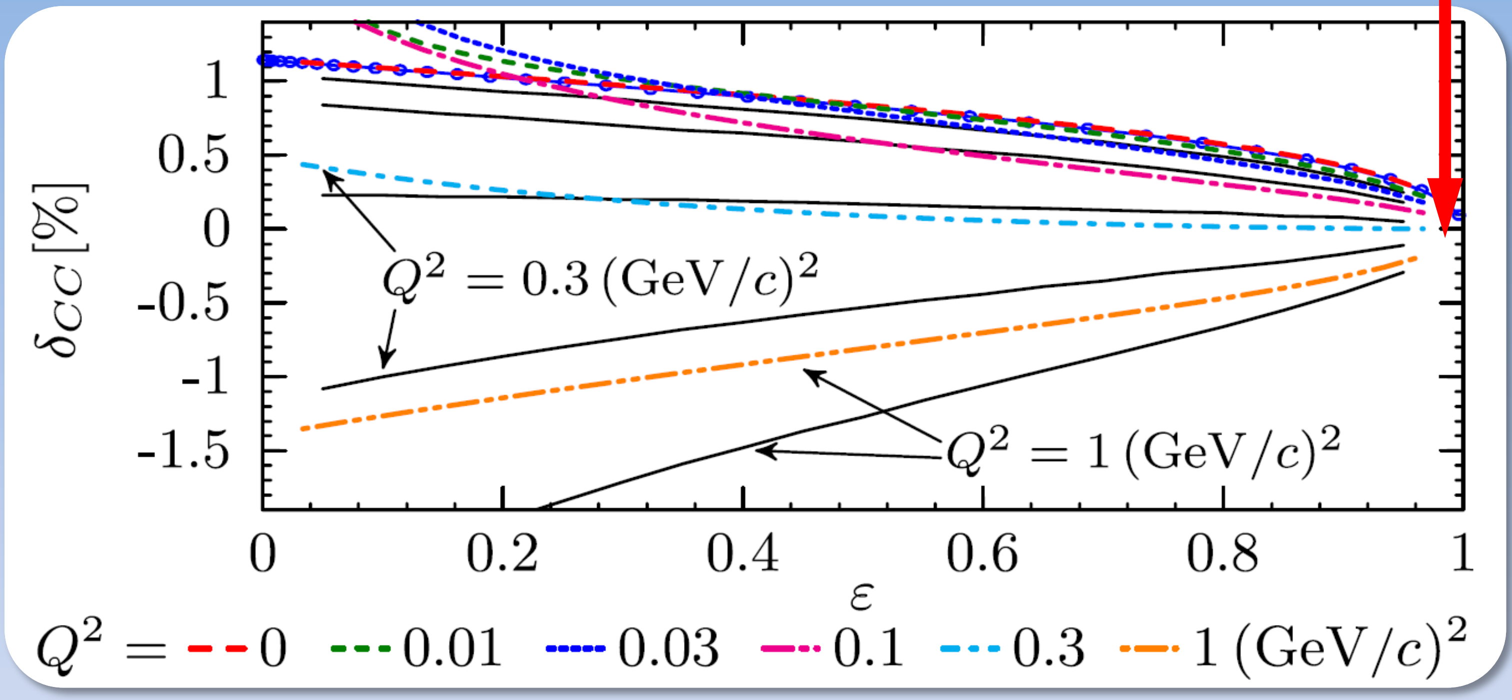
Radiative corrections

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

Largest ε of this experiment: 0.998

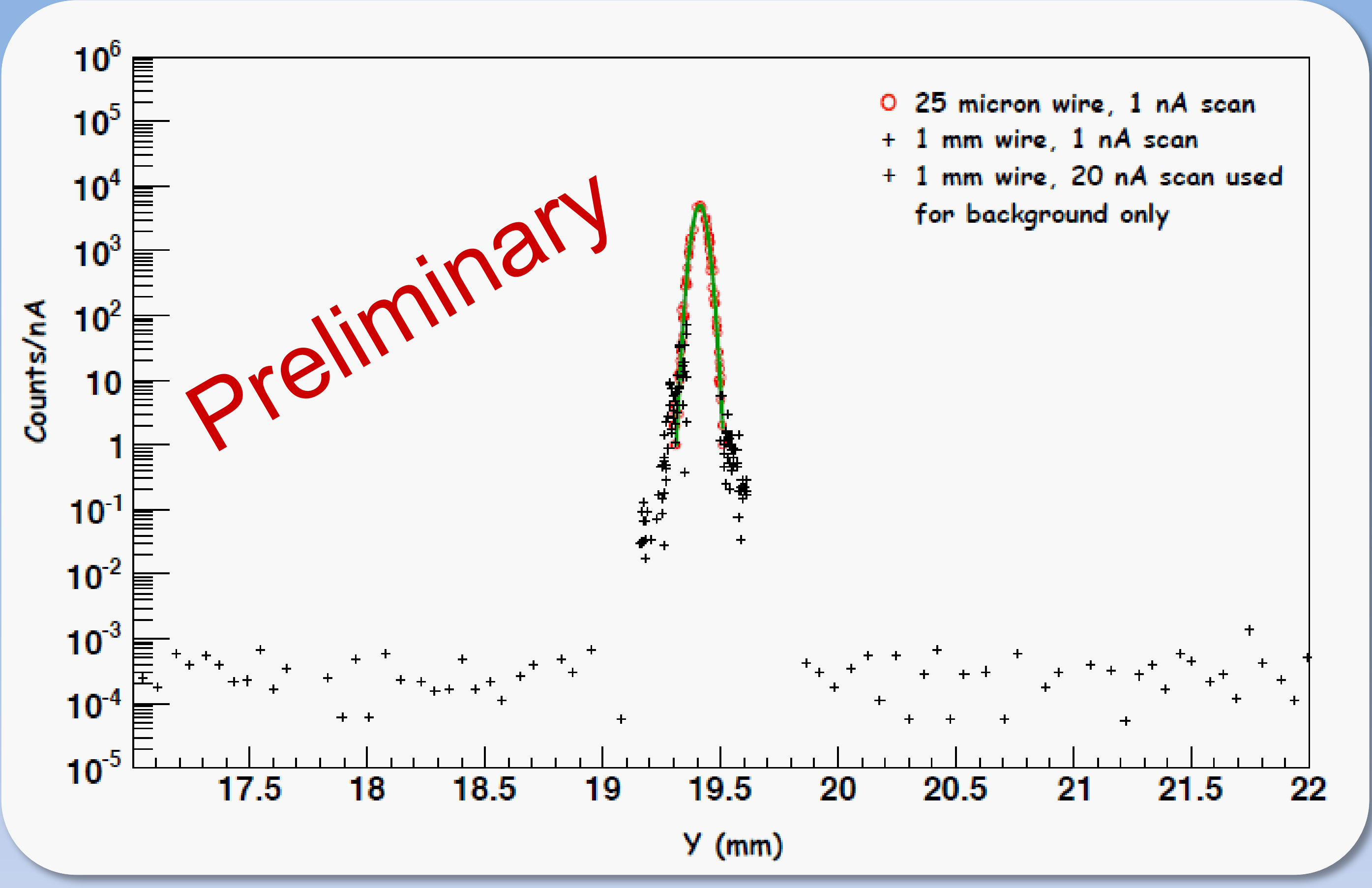
This experiment

Coulomb corrections



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

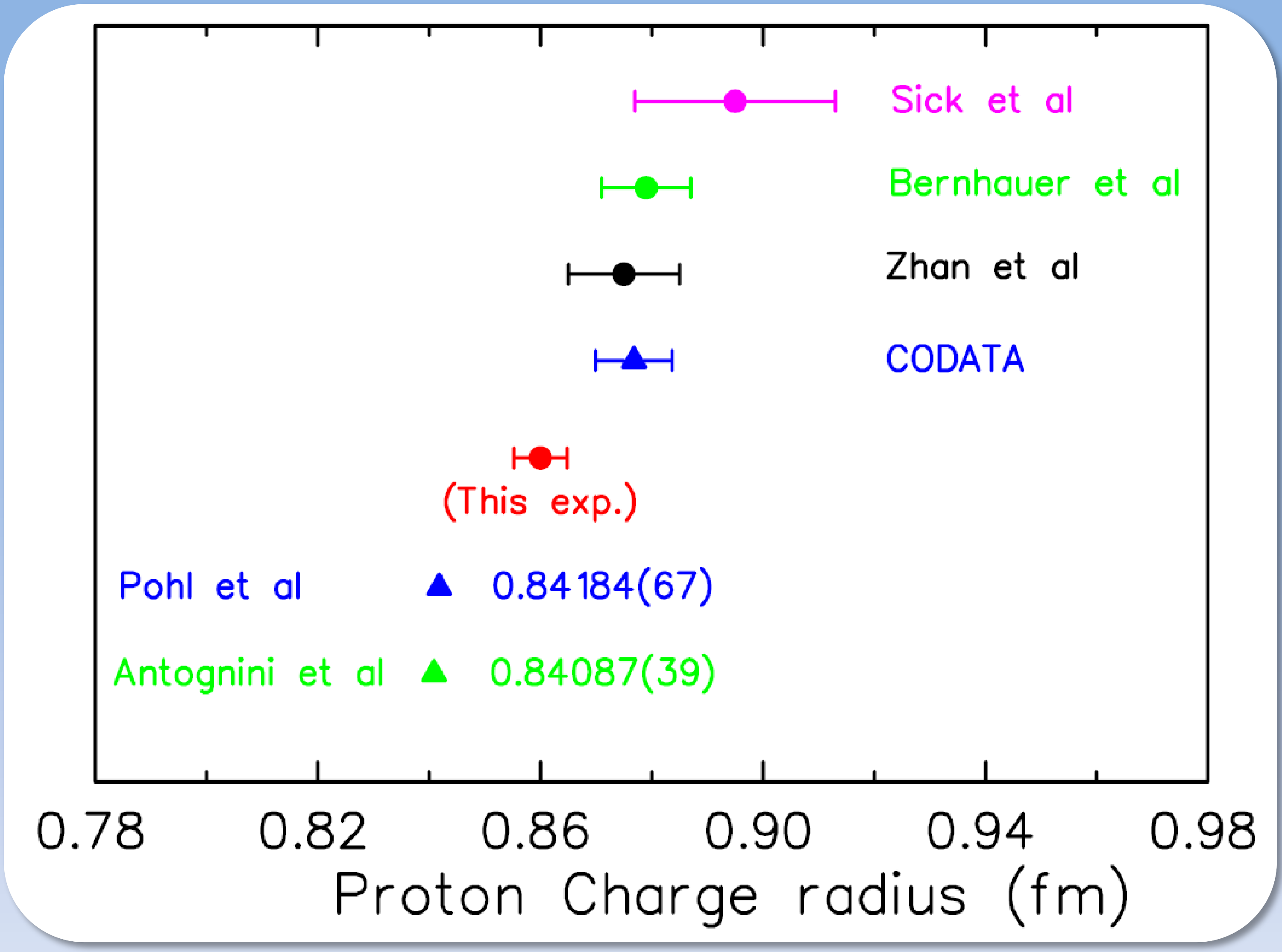
Beam Test Results



- Signal to noise ratio of at least 10^7.
- Can be improved improve with fine tuning of the accelerator

➡ Background situation is under control

Expected Results



Collaboration

A. Gasparian (spokesperson, contact person), R. Pedroni	NC A&T University
M. Khandaker (co-spokesperson)	Idaho State University
H. Gao (co-spokesperson), M. Meziane, I Akushevich, S. Jawalkar, C. Peng, M. Huang, G. Laskaris, Q.J. Ye, Y. Zhang, W. Zheng	Duke University
D. Dutta (co-spokesperson), J. Dunne	Mississippi State University
V. Punjabi, C. Salgado	Norfolk State University
A. Deur, E. Pasyuk, S. Stepanyan, V. Kubarovsky, D. Gaskell, M. Jones, D. Lawrence, S. Taylor, B. Wojtsekhowski, B. Zhilmann	Jefferson Laboratory
L. Gan	University of North Carolina Wilmington
G. Gavalian	Old Dominion University
C. Crawford	University of Kentucky
K. Slifer	University of New Hampshire

And growing...

Conclusion

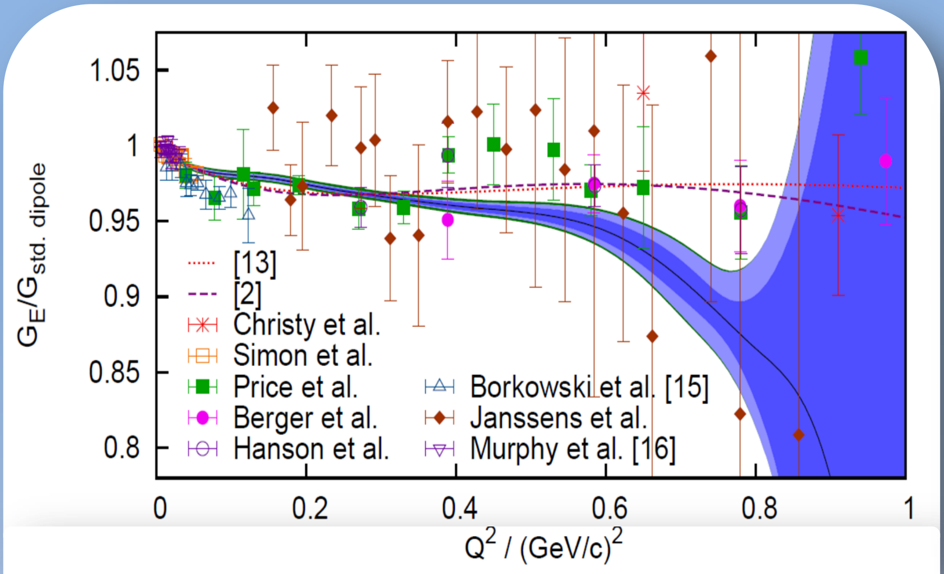
❖ Proton Radius is one of the fundamental quantities in physics

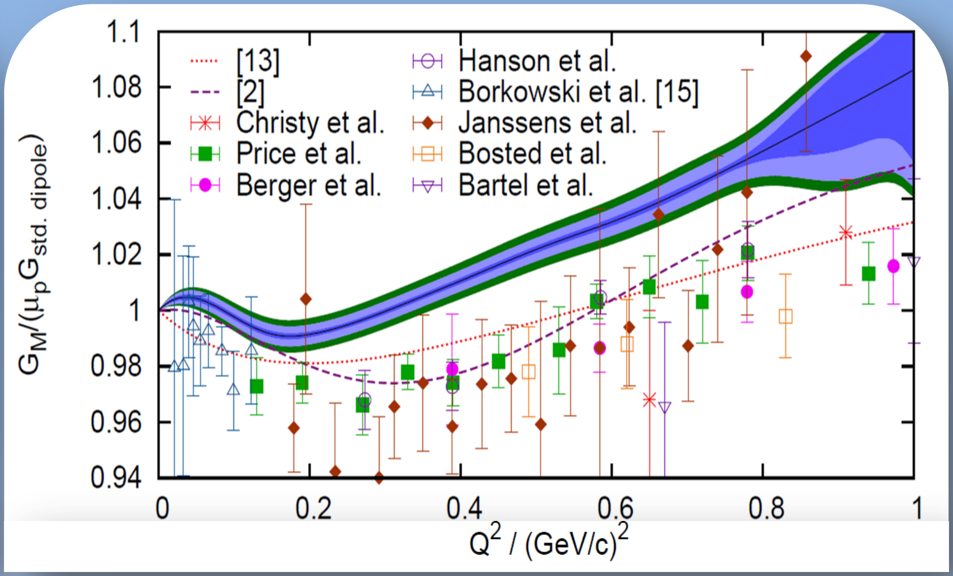
❖ 7 σ discrepancy between average electronic and muonic measurements

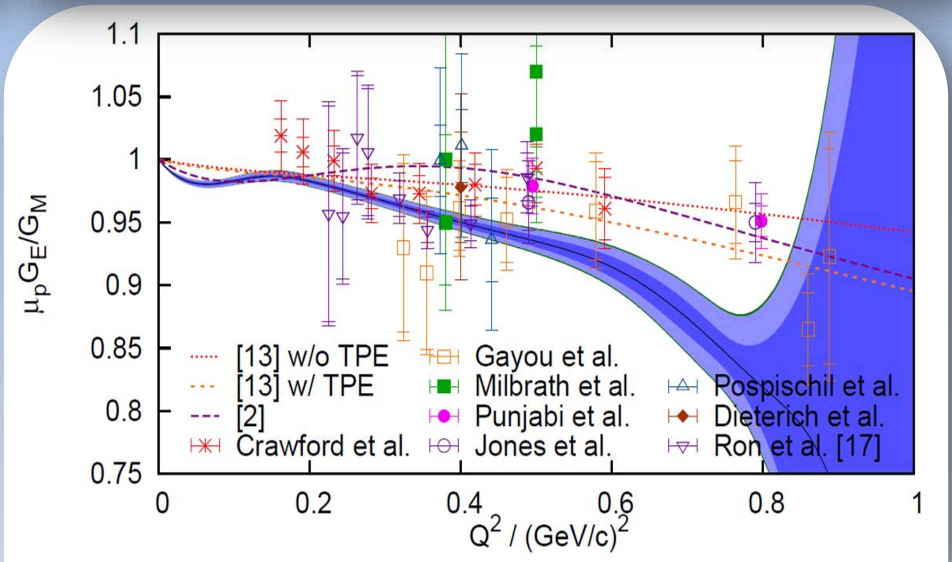
❖ Spectrometer free method using *ep* scattering to extract <r_p>

- ep->ep cross sections normalized to Möller scatterings
- Reach an unprecedented Q^2 range: [2.10^{-4} – 2.10^{-2}] GeV^2
- Windowless H_2 gas flow target
- Tight control of the systematics

Form Factors (FF)







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 charged point like particle for p+l → p+l :

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

Including q^2 corrections from proton structure:

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

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

with $m_r = m_\ell m_p/(m_\ell + m_p) \approx m_\ell$

Slide idea from Gil Paz

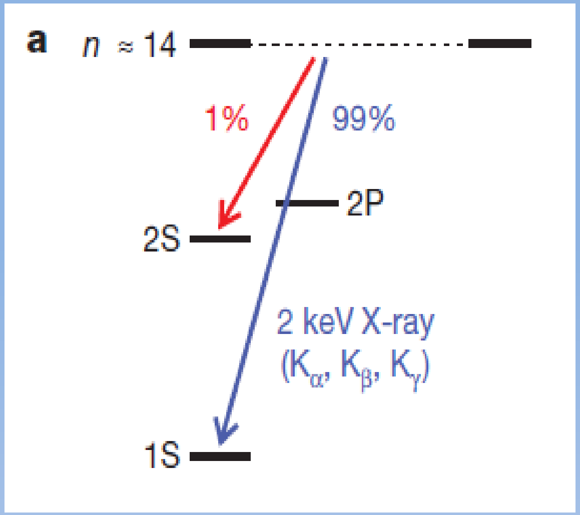
Muonic Hydrogen can give the best measurement of r_p

Muonic Hydrogen

- ❖ The MUON is about 200 heavier than the electron
- ❖ The atomic Bohr radius of muonic hydrogen is thus smaller than in ordinary hydrogen
- ❖ Muonic Hydrogen Lamb Shift will then be more sensitive to the finite size of the proton.

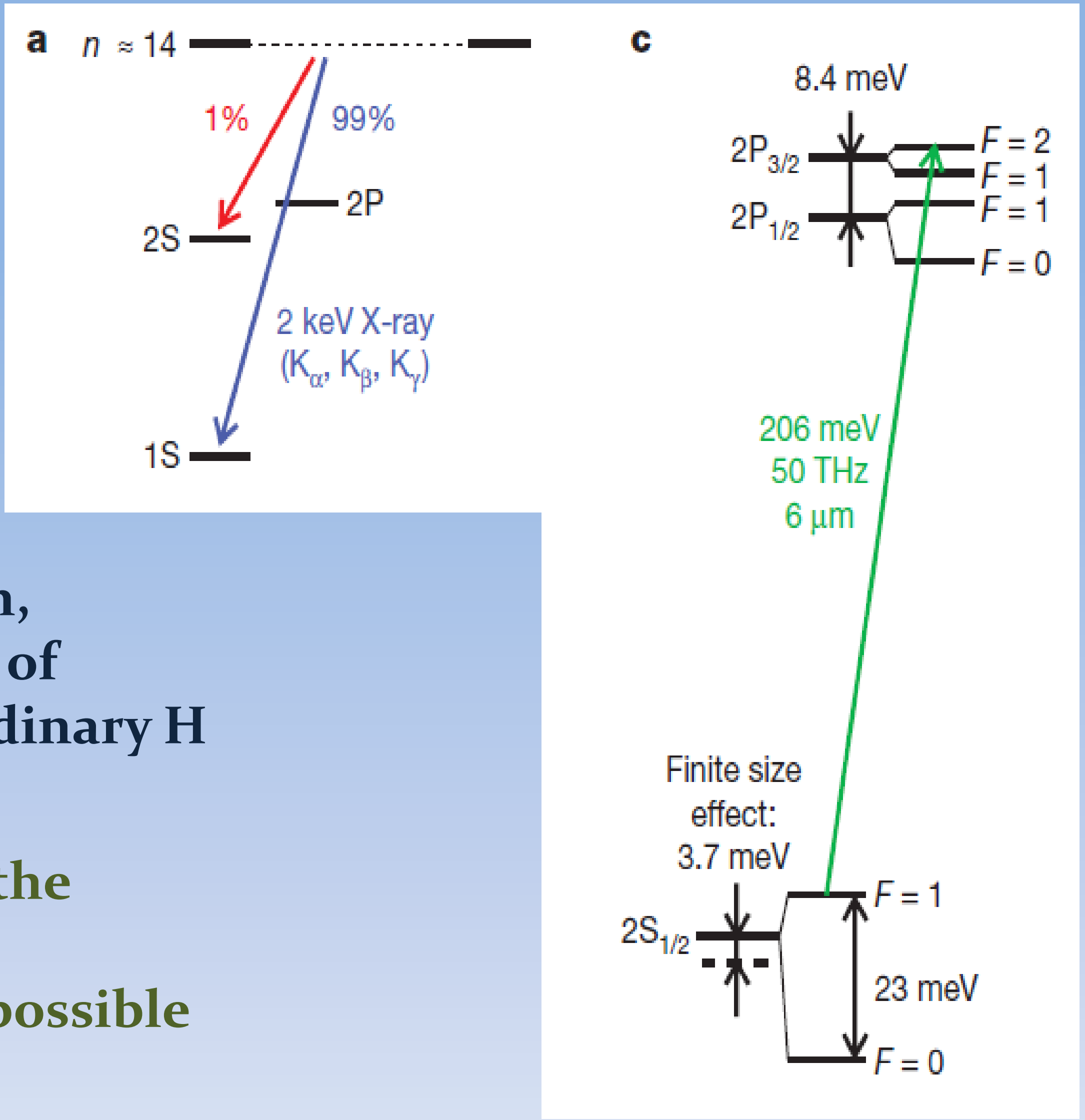
Muonic Hydrogen Measurement at PSI

- ❖ The nuonic hydrogen is highly excited when generated (n=14)
- ❖ Most of the atoms de-excite quickly to 1S but 1% reach the long lives 2S-state (~1μs)



Slides idea from Rebecca Boll

Muonic Hydrogen Measurement at PSI

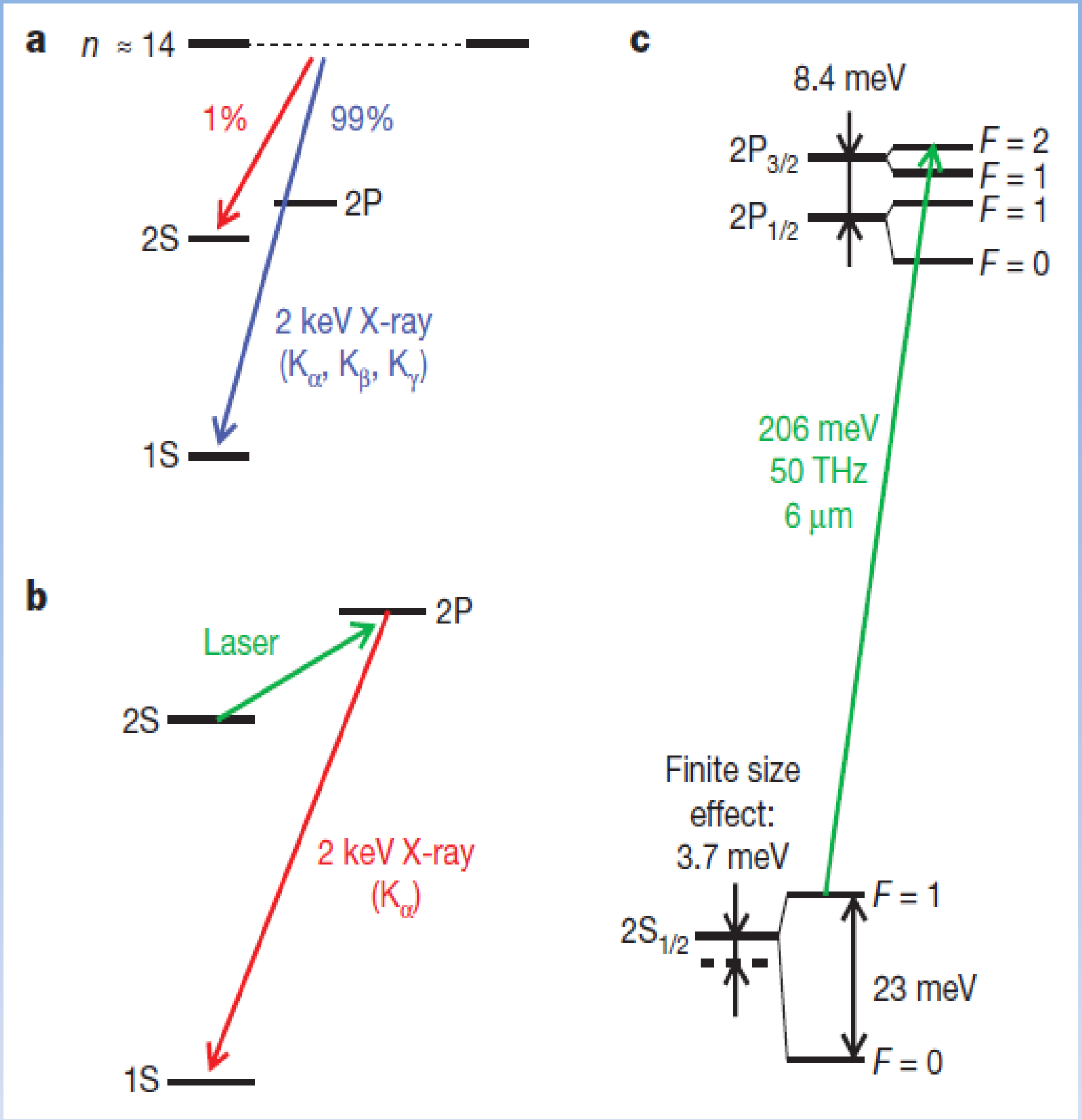


- For the $2S_{1/2} - 2P_{3/2}$ transition, finite size effect are two order of magnitude higher than for ordinary H

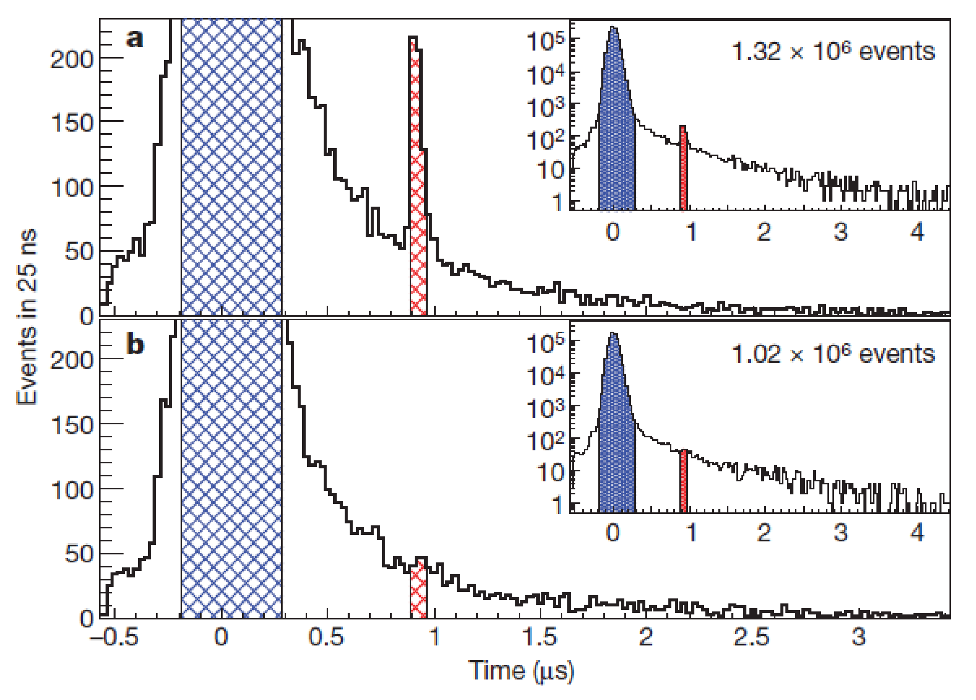
- A pulsed laser beam induces the excitation from $2S_{1/2}$ to $2P_{3/2}$ (gives the largest signal of all possible optical transitions)

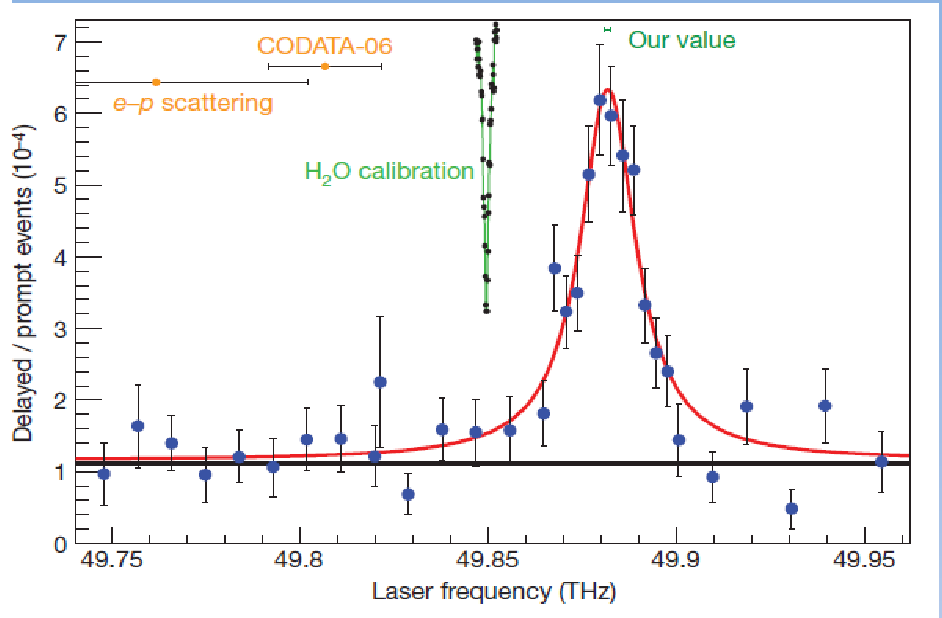
Muonic Hydrogen Measurement at PSI

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



Muonic Hydrogen Measurement at PSI





- Count the delayed X-rays and get a resonance curve by fine tuning of the laser frequency
- The transition frequency between $2P_{3/2}$ to $1S_{1/2}$ is $\Delta\nu$=49881.88(77) GHz corresponding to an energy difference of ΔE=206.2949(32) meV
- Theory predicts: $\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ meV

r_p= 0.84184(67) fm

Expected Uncertainties

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