Overview on electromagnetic form factors and radii from lepton scattering

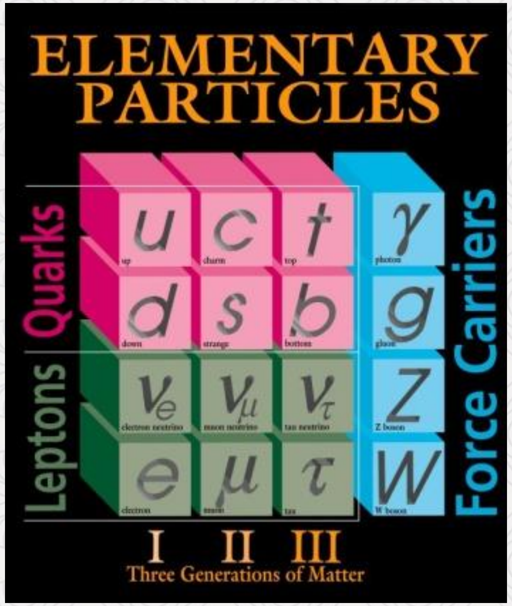
Haiyan Gao

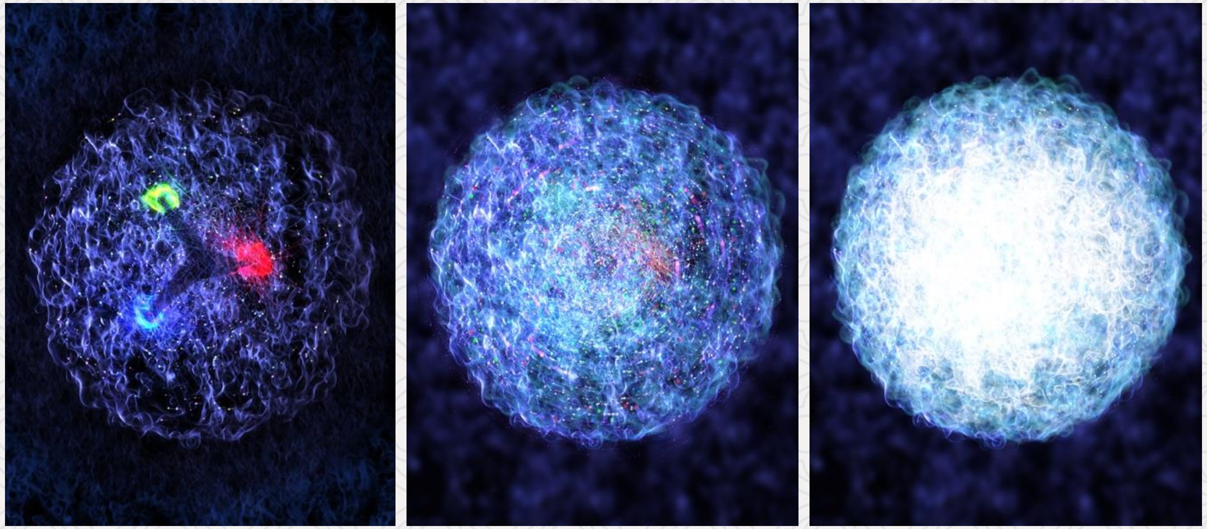
Duke University

Workshop on NREC 2026 (the second workshop on Nuclear Radius Extraction Collaboration)

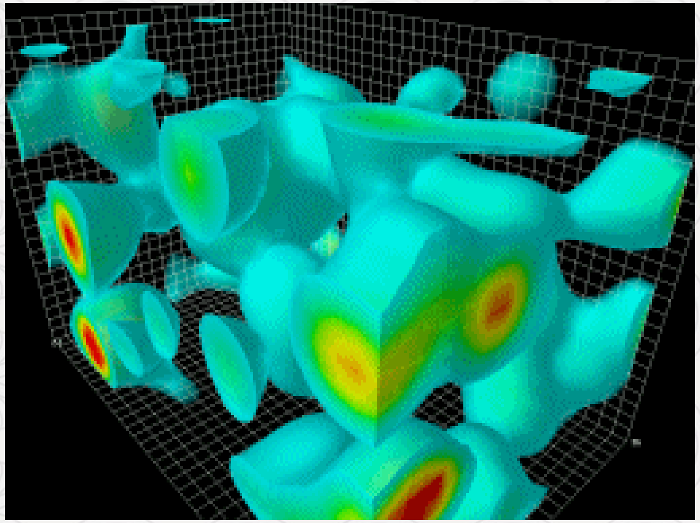
Stony Brook, April 13-17, 2026

Structure of visible matter





Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.

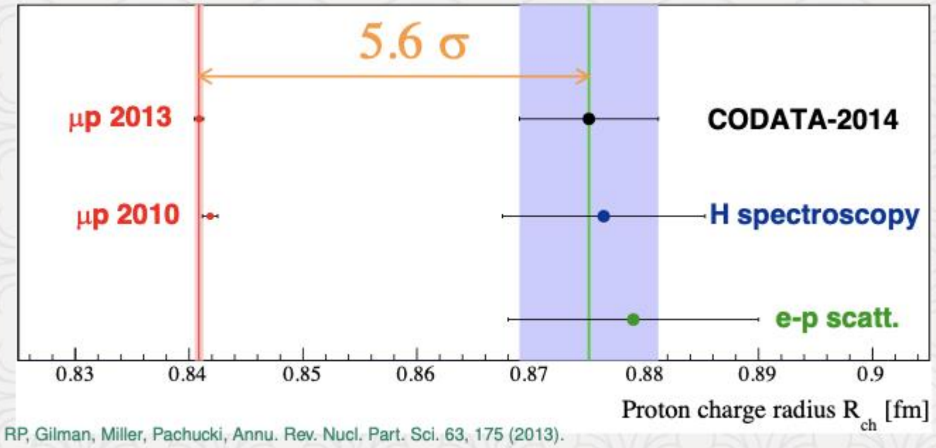


Credit: D. Leinweber

- ***Charge and magnetism (current) distribution***
- ***Spin and mass decomposition***
- ***Quark momentum and flavor distribution***
- ***Polarizabilities***
- ***Strangeness, charm content***
- ***Three-dimensional tomography***
- ***more***

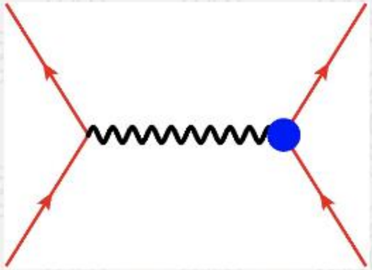
Proton Charge Radius and the Puzzle

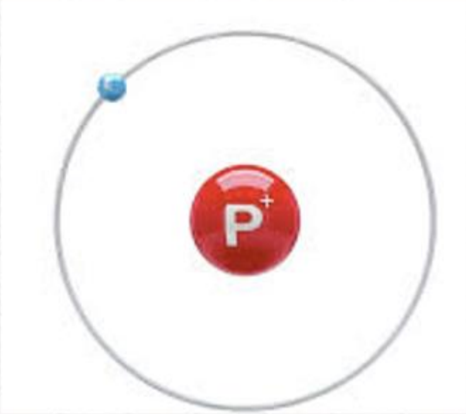
- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - Ordinary hydrogen
     - Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics)
     - *ep* elastic scattering (like PRad)
     - *μp* elastic scattering (like MUSE, COMPASS++/AMBER)

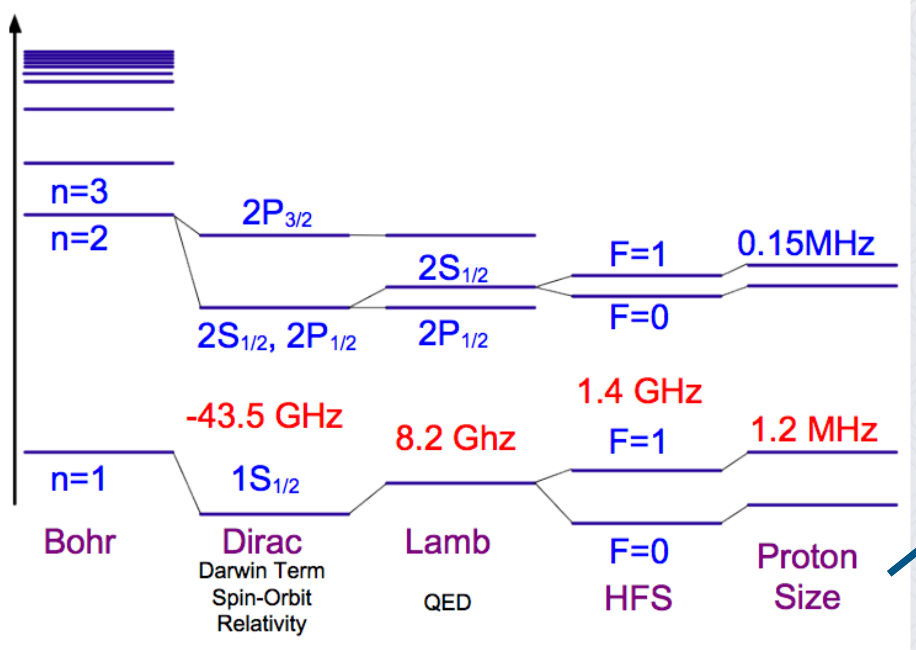




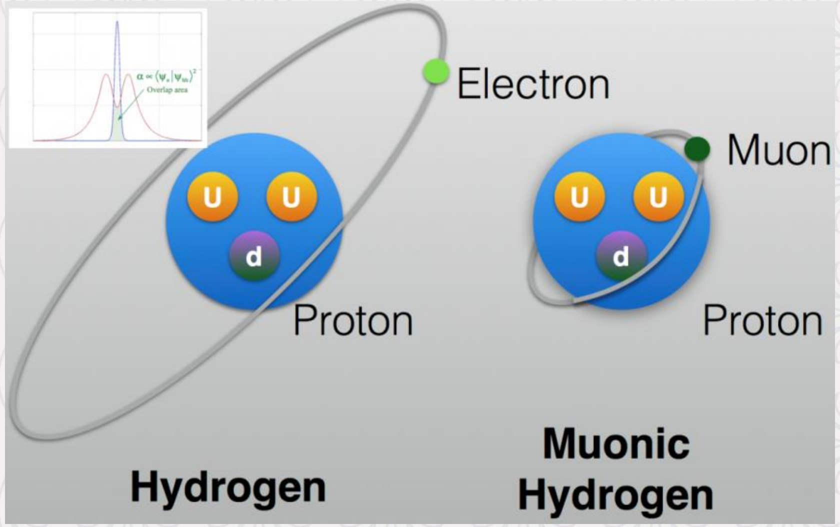
➢ Important point: the proton radius measured in lepton scattering is defined in the same way as in atomic spectroscopy (G.A. Miller, 2019)

$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}|_{q^2=0}}$$

Hydrogen Spectroscopy



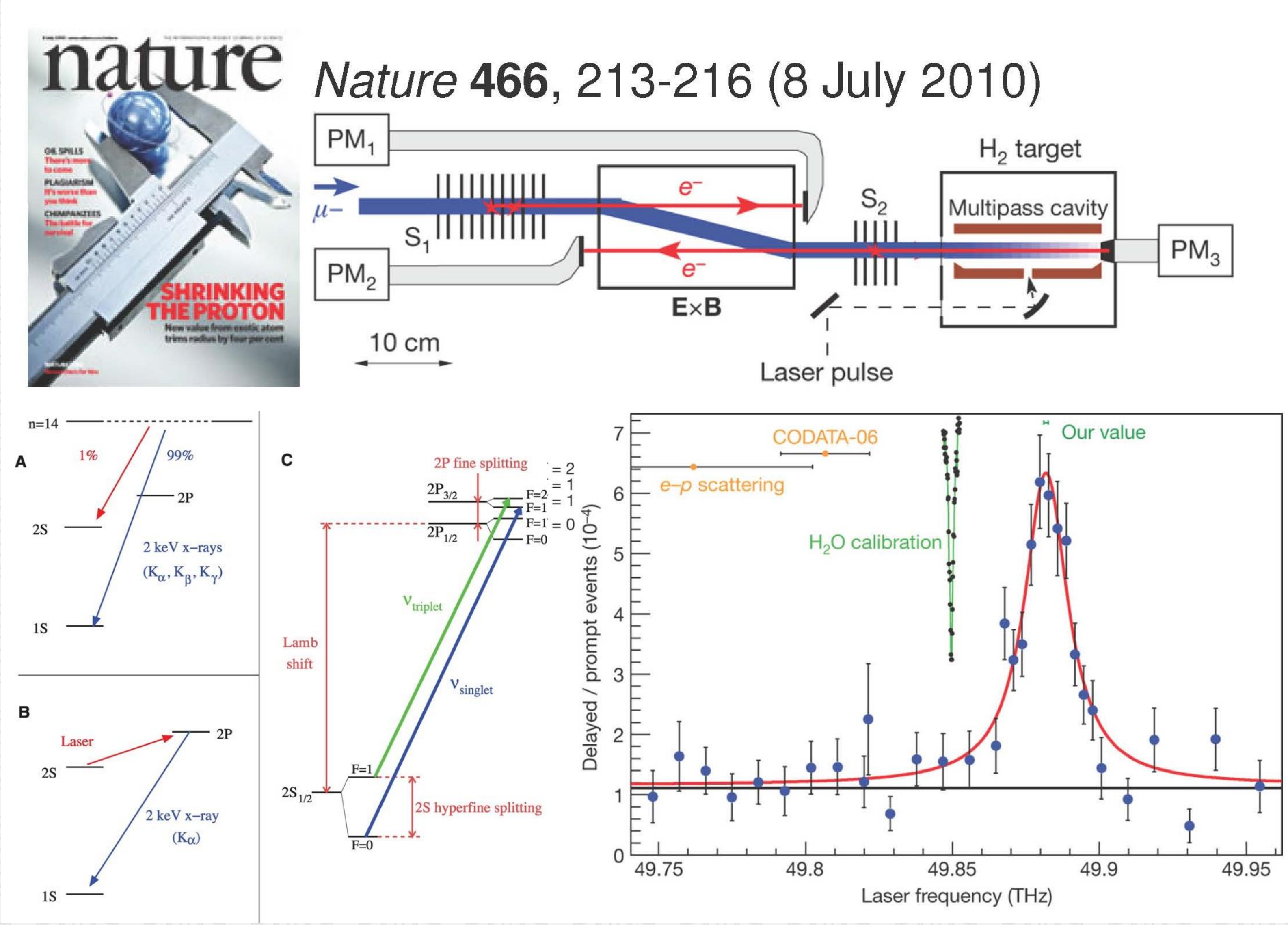
$$\Delta E_{\text{fin size}} = \frac{2\pi\alpha}{3}\langle r_{Ep}^2\rangle|\psi_{nl}(0)|^2 = \frac{2\alpha^4}{3n^3} m_r^3 \langle r_{Ep}^2\rangle \delta_{l0}.$$



The absolute frequency of H energy levels has been measured with a fractional frequency uncertainty of 4.5×10^{-15} via comparison with an atomic cesium fountain clock as a primary frequency standard.
Yields Rydberg constant R_∞ (one of the most precisely known constants)

Comparing measurements to QED calculations that include corrections for the finite size of the proton can provide very precise value of the rms proton charge radius
Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

Muonic hydrogen Lamb shift at PSI (2010, 2013)



2010 value is r_p = 0.84184(67) fm **r_p = 0.84087(39) fm, A. Antognini *et al*., Science 339, 417 (2013)**

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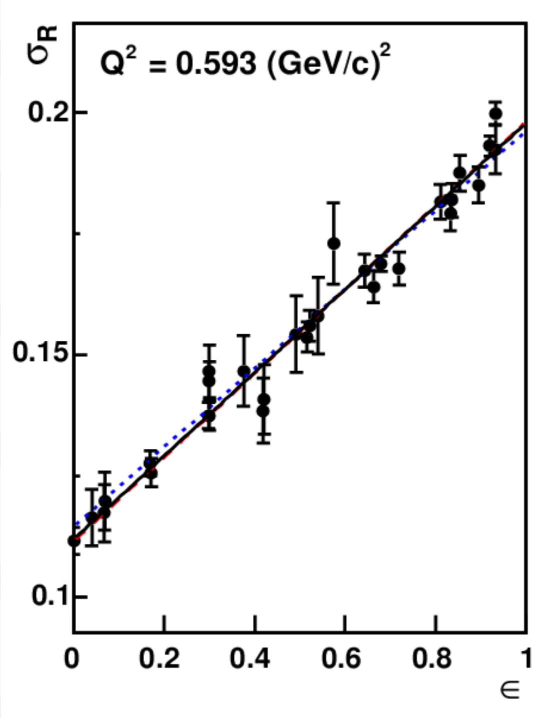
Unpolarized electron-nucleon scattering
(Rosenbluth Separation)

- Elastic e-p cross section

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

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

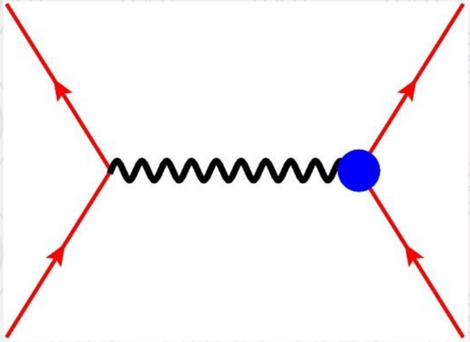


$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

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

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

G_E or G_M



One-photon-exchange diagram

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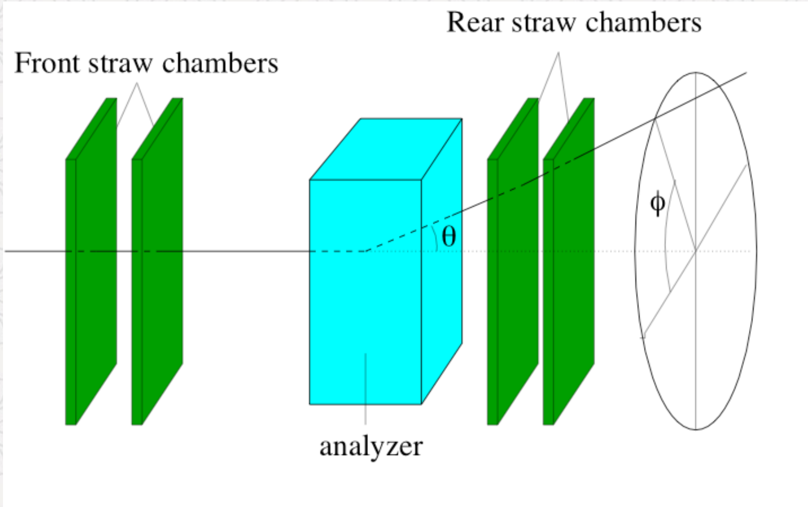
Polarization Transfer Measurement in Electron-Proton Elastic Scattering

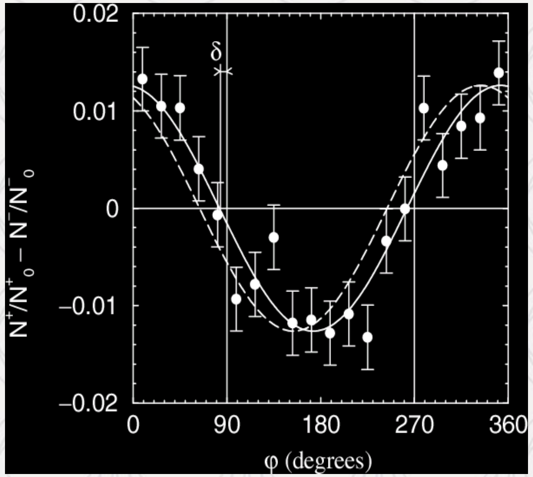
Polarization Transfer

Longitudinally polarized electron beam and recoil proton polarization measurement → $\frac{G_E^p}{G_M^p}$

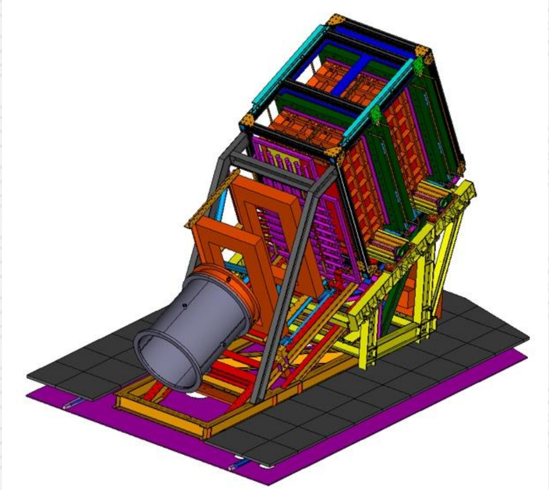


- Recoil proton polarization

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



- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio



Punjabi *et al.*, EPJA (2015)

Focal-plane polarimeter

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PRL **104,** 242301 (2010) PHYSICAL REVIEW LETTERS week ending 18 JUNE 2010

Recoil Polarization Measurements of the Proton Electromagnetic Form Factor Ratio to $Q^2 = 8.5$ GeV^2

A. J. R. Puckett,[1,*] E. J. Brash,[2,3] M. K. Jones,[3] W. Luo,[4] M. Meziane,[5] L. Pentchev,[5] C. F. Perdrisat,[5] V. Punjabi,[6] F. R. Wesselmann,[6] A. Ahmidouch,[7] I. Albayrak,[8] K. A. Aniol,[9] J. Arrington,[10] A. Asaturyan,[11] H. Baghdasaryan,[12] F. Benmokhtar,[13] W. Bertozzi,[1] L. Bimbot,[14] P. Bosted,[3] W. Boeglin,[15] C. Butuceanu,[16] P. Carter,[2] S. Chernenko,[17] E. Christy,[8] M. Commisso,[12] J. C. Cornejo,[9] S. Covrig,[3] S. Danagoulian,[7] A. Daniel,[18] A. Davidenko,[19] D. Day,[12] S. Dhamija,[15] D. Dutta,[20] R. Ent,[3] S. Frullani,[21] H. Fenker,[3] E. Frlez,[12] F. Garibaldi,[21] D. Gaskell,[3] S. Gilad,[1] R. Gilman,[3,22] Y. Goncharenko,[19] K. Hafidi,[10] D. Hamilton,[23] D. W. Higinbotham,[3] W. Hinton,[6] T. Horn,[3] B. Hu,[4] J. Huang,[1] G. M. Huber,[16] E. Jensen,[2] C. Keppel,[8] M. Khandaker,[6] P. King,[18] D. Kirillov,[17] M. Kohl,[8] V. Kravtsov,[19] G. Kumbartzki,[22] Y. Li,[8] V. Mamyan,[12] D. J. Margaziotis,[9] A. Marsh,[2] Y. Matulenko,[19] J. Maxwell,[12] G. Mbianda,[24] D. Meekins,[3] Y. Melnik,[19] J. Miller,[25] A. Mkrtchyan,[11] H. Mkrtchyan,[11] B. Moffit,[1] O. Moreno,[9] J. Mulholland,[12] A. Narayan,[20] S. Nedev,[26] Nuruzzaman,[20] E. Piasetzky,[27] W. Pierce,[2] N. M. Piskunov,[17] Y. Prok,[2] R. D. Ransome,[22] D. S. Razin,[17] P. Reimer,[10] J. Reinhold,[15] O. Rondon,[12] M. Shabestari,[12] A. Shahinyan,[11] K. Shestermanov,[19,†] S. Širca,[28] I. Sitnik,[17] L. Smykov,[17,†] G. Smith,[3] L. Solovyev,[19] P. Solvignon,[10] R. Subedi,[12] E. Tomasi-Gustafsson,[14,29] A. Vasiliev,[19] M. Veilleux,[2] B. B. Wojtsekhowski,[3] S. Wood,[3] Z. Ye,[8] Y. Zanevsky,[17] X. Zhang,[4] Y. Zhang,[4] X. Zheng,[12] and L. Zhu[1]

[1]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Christopher Newport University, Newport News, Virginia 23606, USA*
[3]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[4]*Lanzhou University, Lanzhou 730000, Gansu, People's Republic of China*
[5]*College of William and Mary, Williamsburg, Virginia 23187, USA*
[6]*Norfolk State University, Norfolk, Virginia 23504, USA*
[7]*North Carolina A&T State University, Greensboro, North Carolina 27411, USA*
[8]*Hampton University, Hampton, Virginia 23668, USA*
[9]*California State University Los Angeles, Los Angeles, California 90032, USA*
[10]*Argonne National Laboratory, Argonne, Illinois, 60439, USA*
[11]*Yerevan Physics Institute, Yerevan 375036, Armenia*
[12]*University of Virginia, Charlottesville, Virginia 22904, USA*
[13]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[14]*Institut de Physique Nucléaire, CNRS/IN2P3 and Université Paris-Sud, Orsay Cedex, France*
[15]*Florida International University, Miami, Florida 33199, USA*
[16]*University of Regina, Regina, Saskatchewan S4S OA2, Canada*
[17]*JINR-LHE, Dubna, Moscow Region, Russia 141980*
[18]*Ohio University, Athens, Ohio 45701*
[19]*IHEP, Protvino, Moscow Region, Russia 142284*
[20]*Mississippi State University, Starkville, Mississippi 39762, USA*
[21]*INFN, Sezione Sanità and Istituto Superiore di Sanità, 00161 Rome, Italy*
[22]*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08855, USA*
[23]*University of Glasgow, Glasgow G12 8QQ, Scotland, United Kingdom*
[24]*University of Witwatersrand, Johannesburg, South Africa*
[25]*University of Maryland, College Park, Maryland 20742, USA*
[26]*University of Chemical Technology and Metallurgy, Sofia, Bulgaria*
[27]*University of Tel Aviv, Tel Aviv, Israel*
[28]*University of Ljubljana, SI-1000 Ljubljana, Slovenia*
[29]*DSM, IRFU, SPhN, Saclay, 91191 Gif-sur-Yvette, France*

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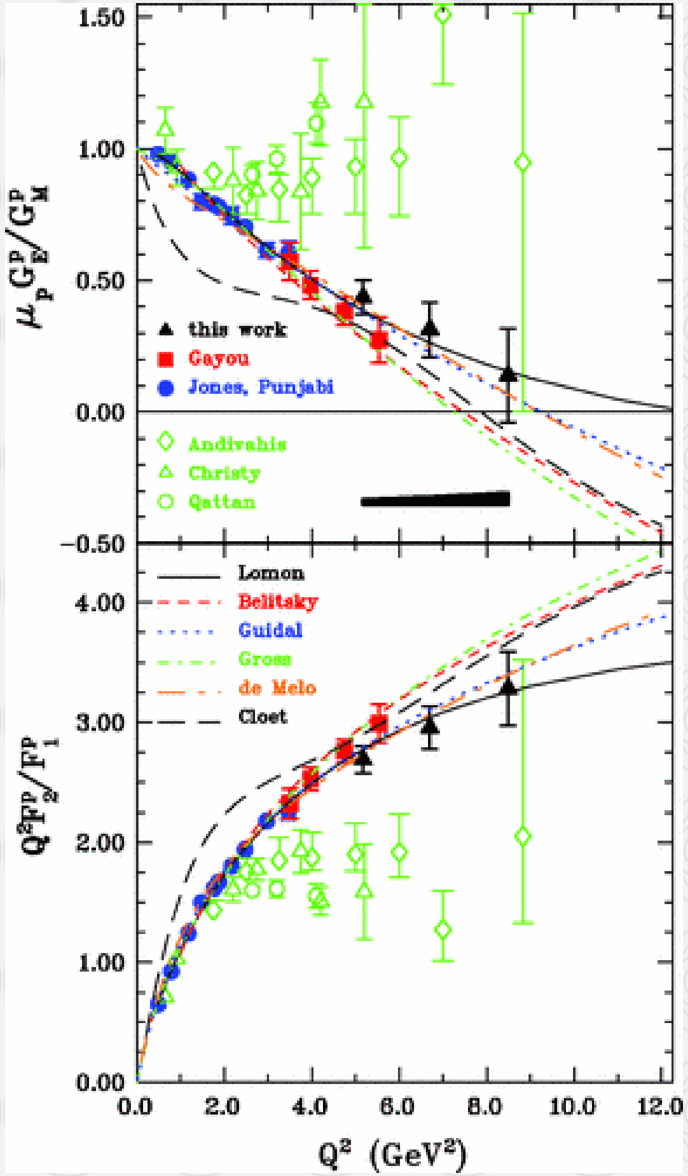
Among the most fundamental observables of nucleon structure, electromagnetic form factors are a crucial benchmark for modern calculations describing the strong interaction dynamics of the nucleon's quark constituents; indeed, recent proton data have attracted intense theoretical interest. In this Letter, we report new measurements of the proton electromagnetic form factor ratio using the recoil polarization method, at momentum transfers $Q^2 = 5.2$, 6.7, and 8.5 GeV^2. By extending the range of Q^2 for which G_E^p is accurately determined by more than 50%, these measurements will provide significant constraints on models of nucleon structure in the nonperturbative regime.

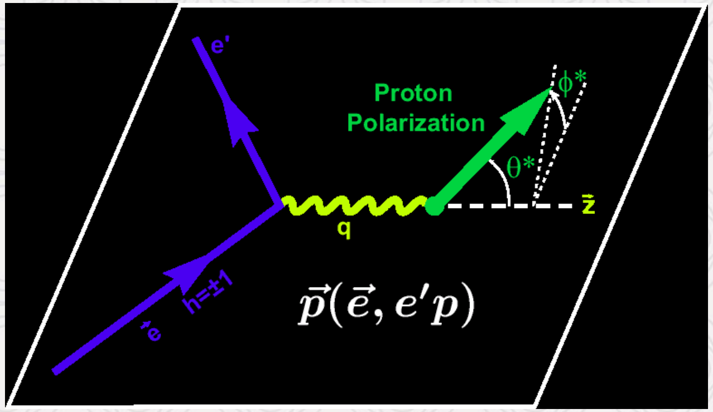


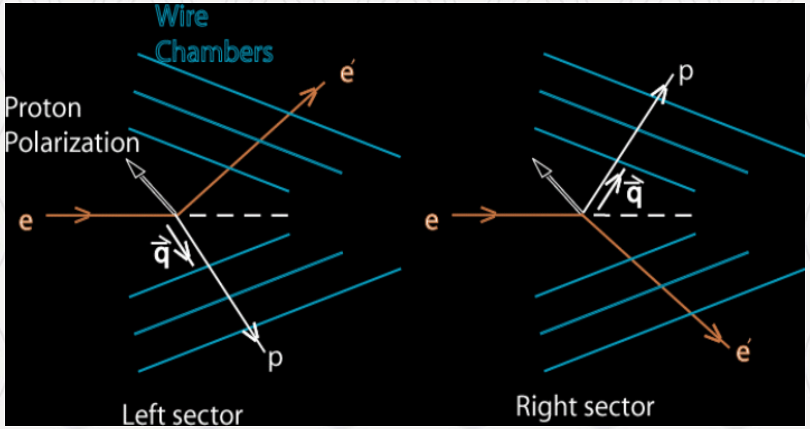
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

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





- Super-ratio

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

BLAST pioneered the technique, later also used in JLab Hall A experiment C. Crawford *et al*. PRL98, 052301 (2007)

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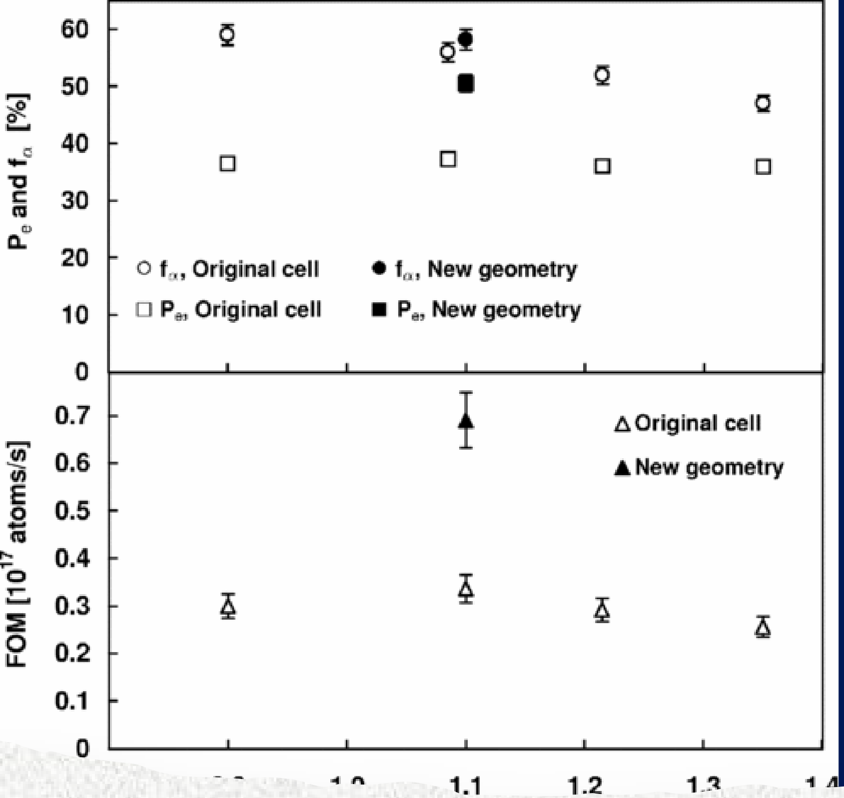
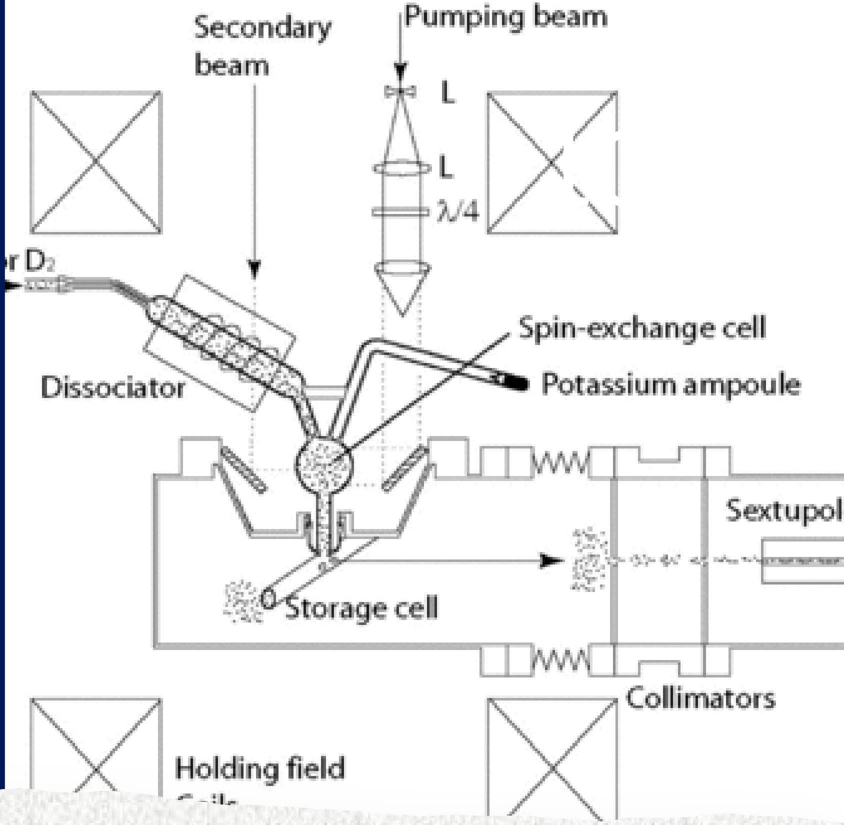
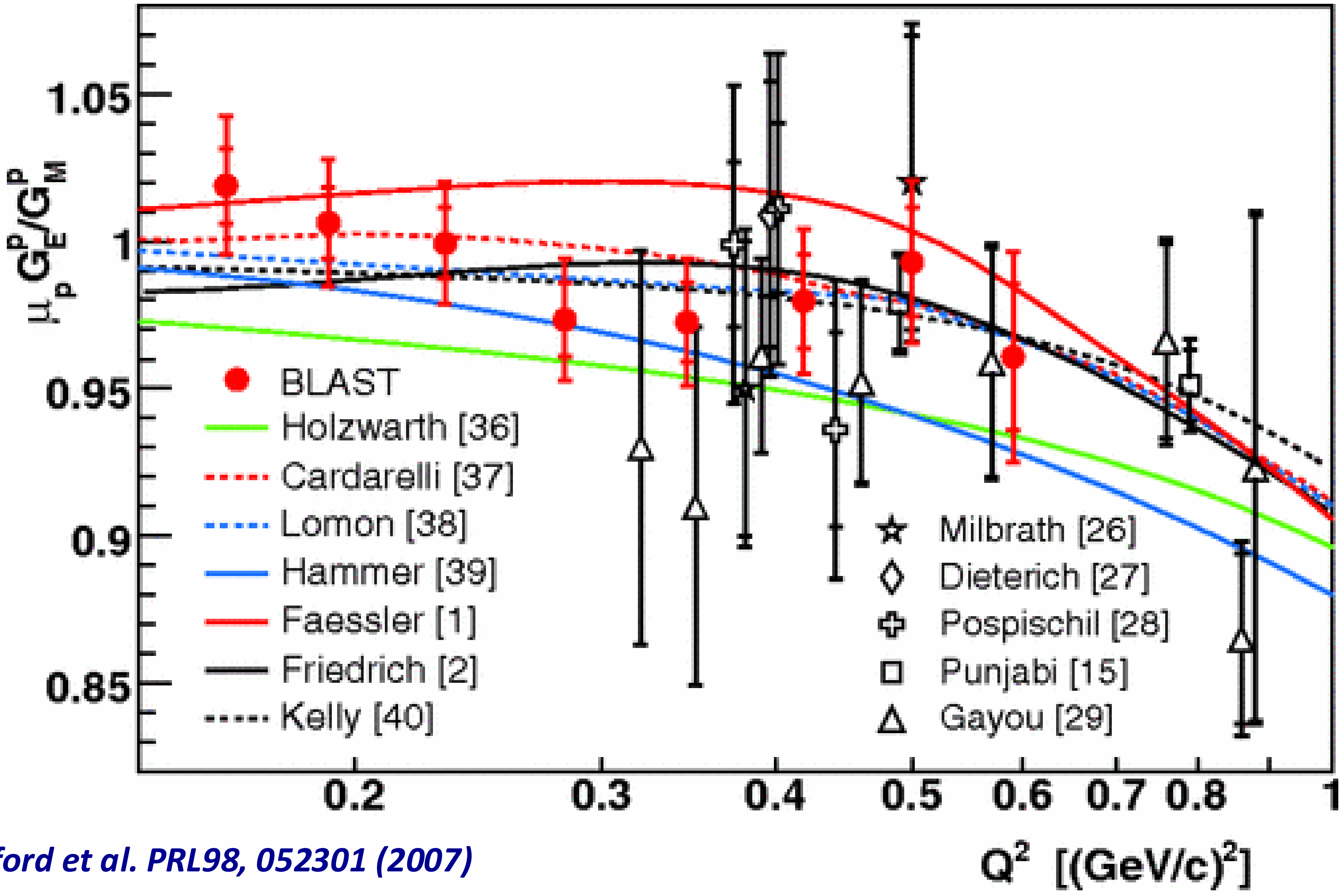
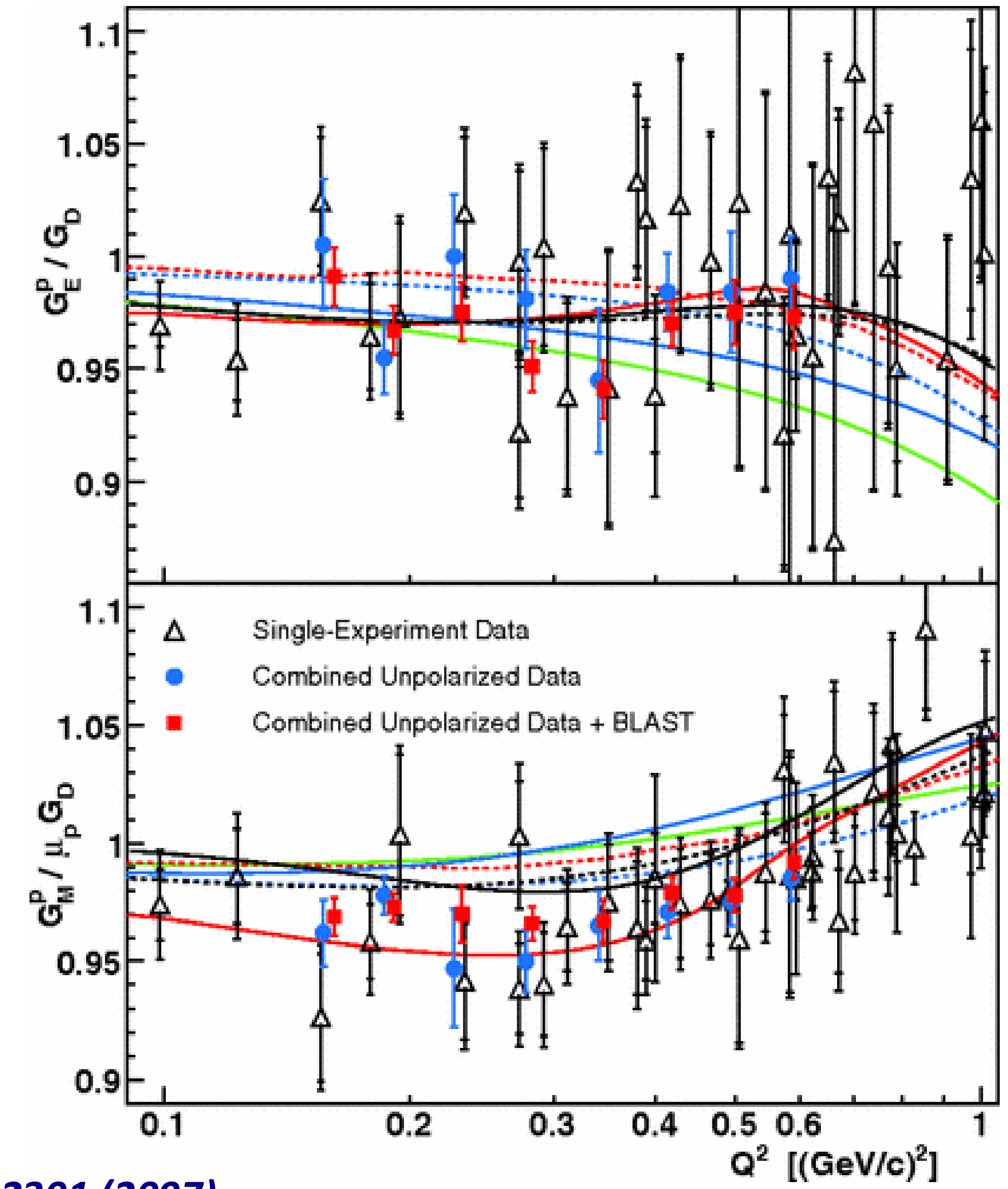




- ***A little bit of History***



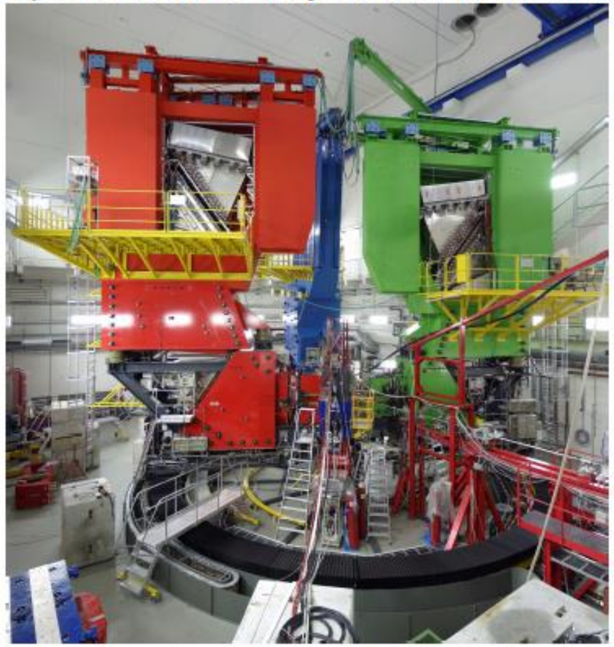
C. Crawford et al. PRL98, 052301 (2007)

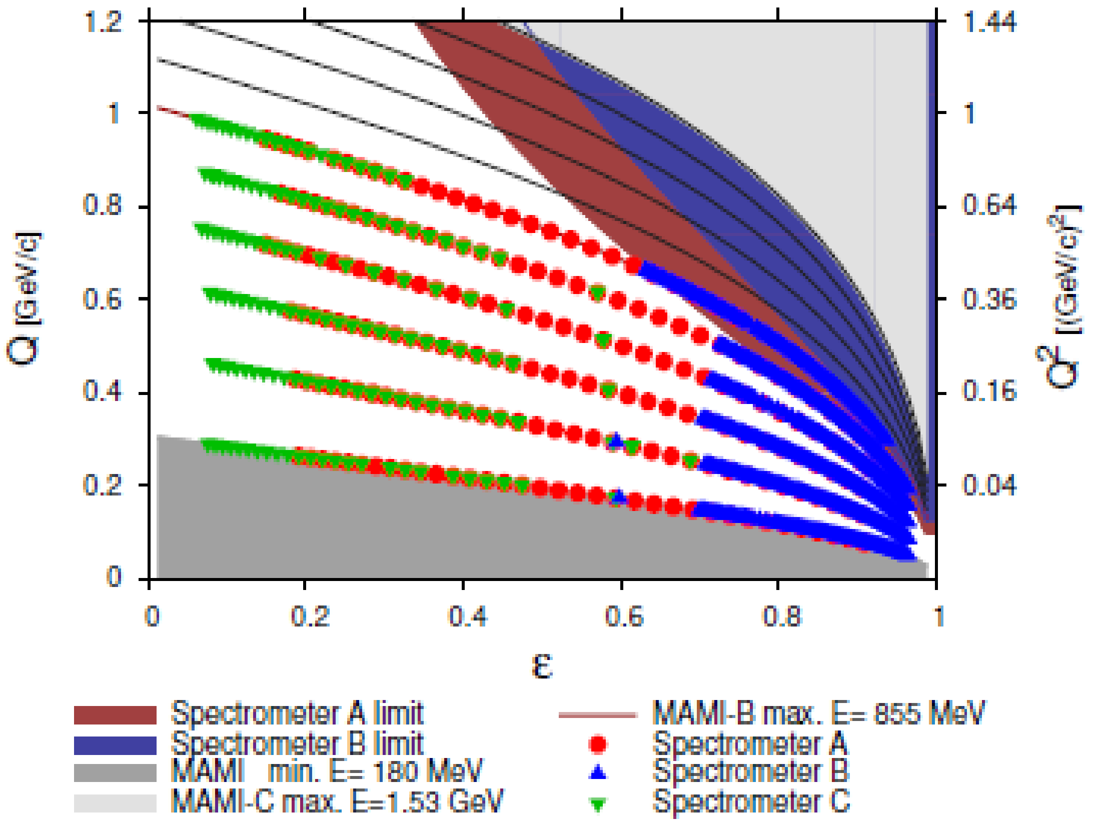


C. Crawford et al. PRL98, 052301 (2007)

Electron-proton Scattering – Mainz A1 experiment

Three spectrometer facility of the A1 collaboration:





– Large amount of overlapping data sets
– Cross section measurement
– Statistical error ≤ 0.2%
– Luminosity monitoring with spectrometer

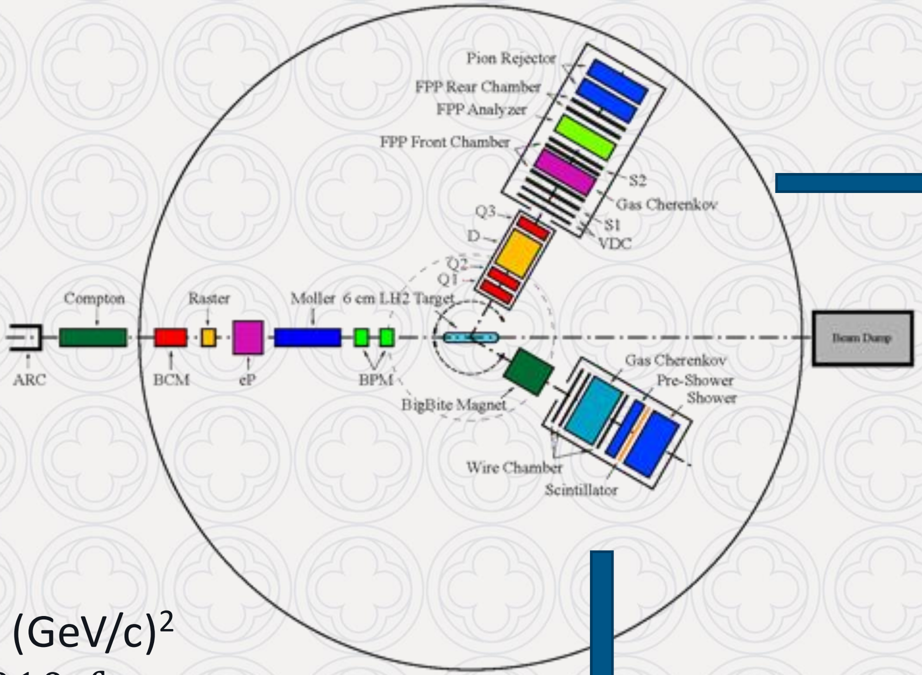
- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

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

5-7σ higher than muonic hydrogen result !

J. Bernauer, PRL 105, 242001 (2010)

JLab Recoil Proton Polarization Experiment



LHRS

- Δp/p0: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

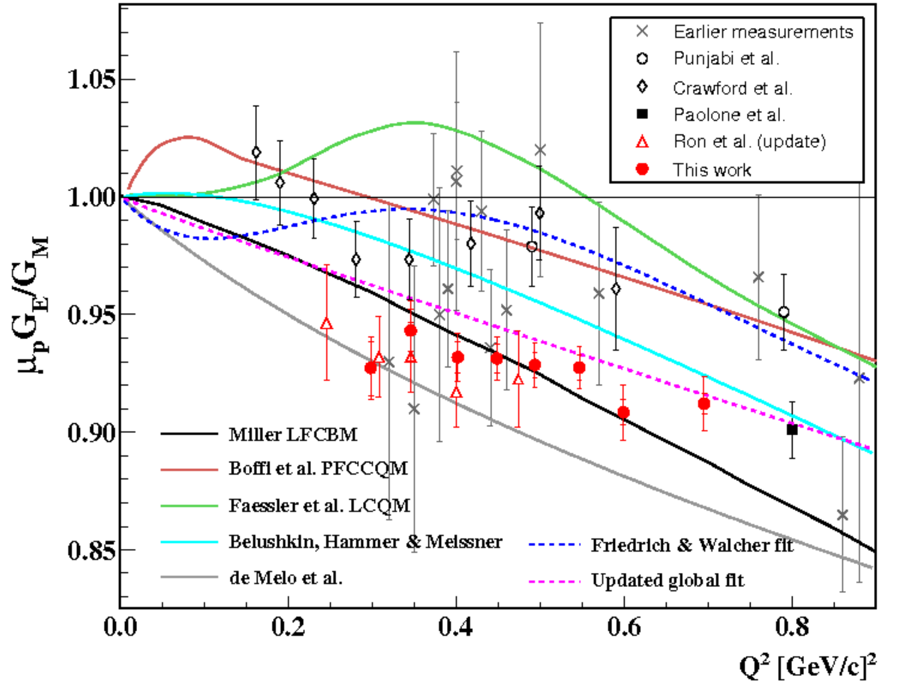
- Q^2 = 0.3 – 0.7 $(GeV/c)^2$
- r_p =0.875±0.010 fm

(global analysis not including Mainz A1)

E_e: 1.192GeV
P_b: ~83%

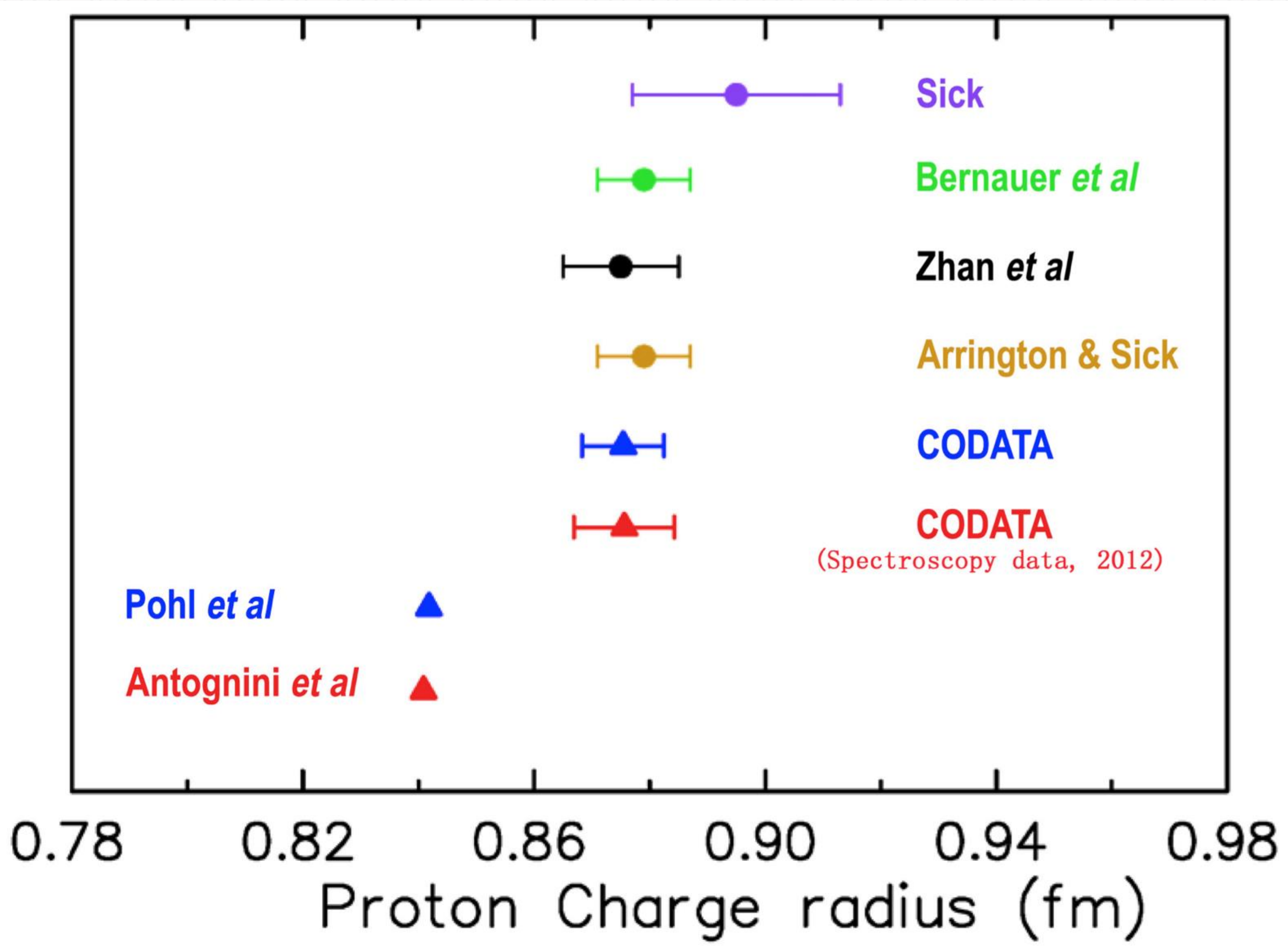
BigBite

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - ΔΩ: 96msr
- PS + Scint. + SH



X. Zhan et al. Phys. Lett. B 705 (2011) 59-64

The situation on the Proton Charge Radius in 2013



This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so

How to resolve the puzzle? - Incomplete list

- Revisit of the state-of-the-art QED calculations: E. Borie (2005), Jentschura (2011), Hagelstein and Pascalutsa (2015),..
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher (2011), de Rujula (2010, 2011), Cloet and Miller (2011),…
- Extrapolation in electron scattering: Higinbotham et al. (2016), Griffioen, Carlson and Maddox (2016)
- Reanalysis of ep elastic data: Distler, Walcher, and Bernauer (2015), Arrington (2015), Horbatsch and Hessels (2015), T. Hayward, K. Griffioen (2018),…..
- Discrepancy explained/somewhat explained by some authors, but not all agree: Lorenz et al., Ronson, Donnelly et al., Alarcón, Weiss, et al
- Consistency re radius defined in ep and atomic experiments: Miller (2019)
- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller, Alvarado, Aranda and Bonilla….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio,…..
- **Exps: Mainz, JLab (PRad), MUSE at PSI, ULQ2 in Japan, Amber@CERN; H spectroscopy (Germany, France, Canada, U.S.), …**

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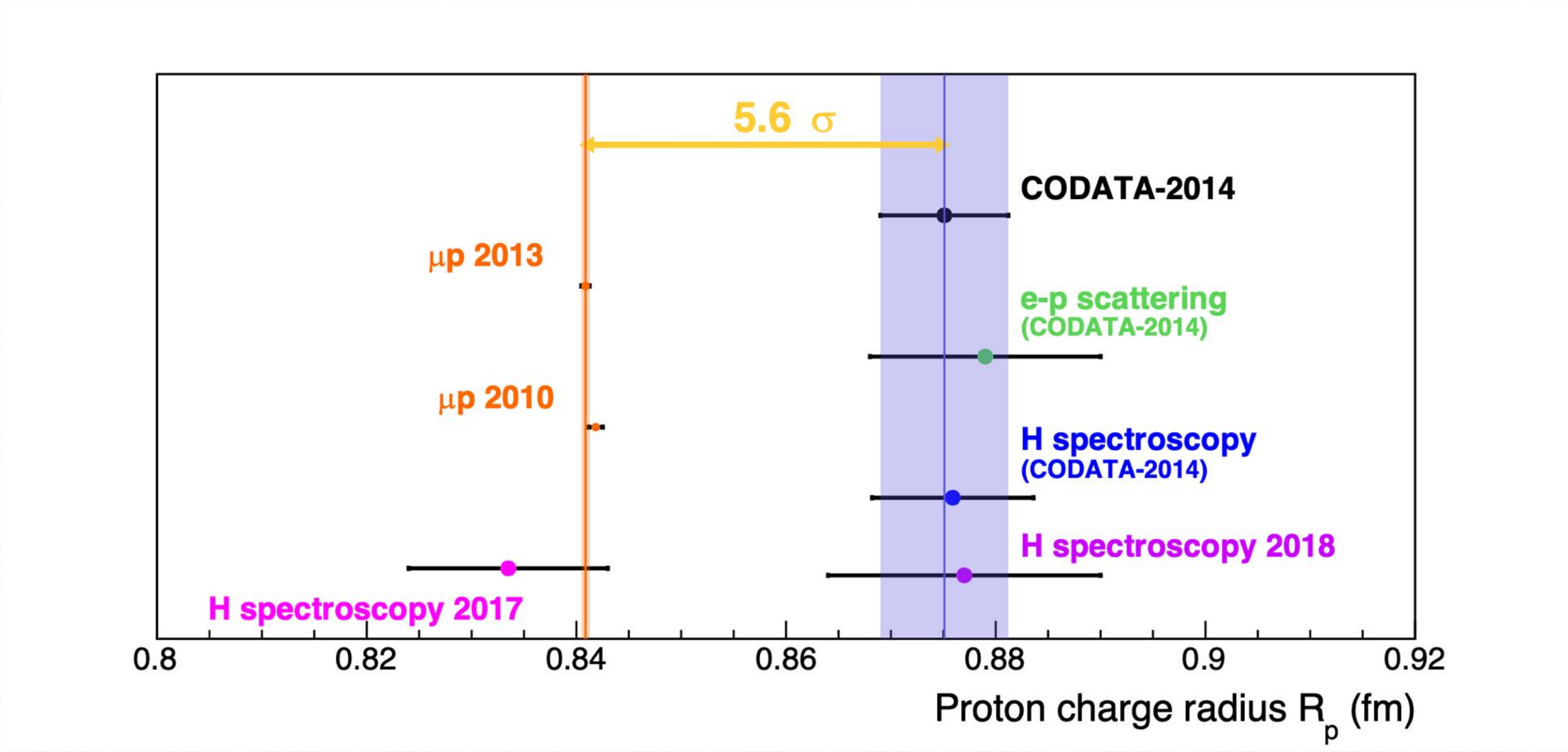
The Proton Charge Radius Puzzle in 2018



Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)

Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)

H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)

H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

Not shown: ep scattering (ISR, 2017): $0.810 \pm 0.035_{stat.} \pm 0.074_{syst.} \pm 0.003$ (delta_a, delta_b) (Mihovilovic PLB 771 (2017); $0.878 \pm 0.011_{stat.} \pm 0.031_{syst.} \pm 0.002_{mod.}$ (Mihovilovic 2021))

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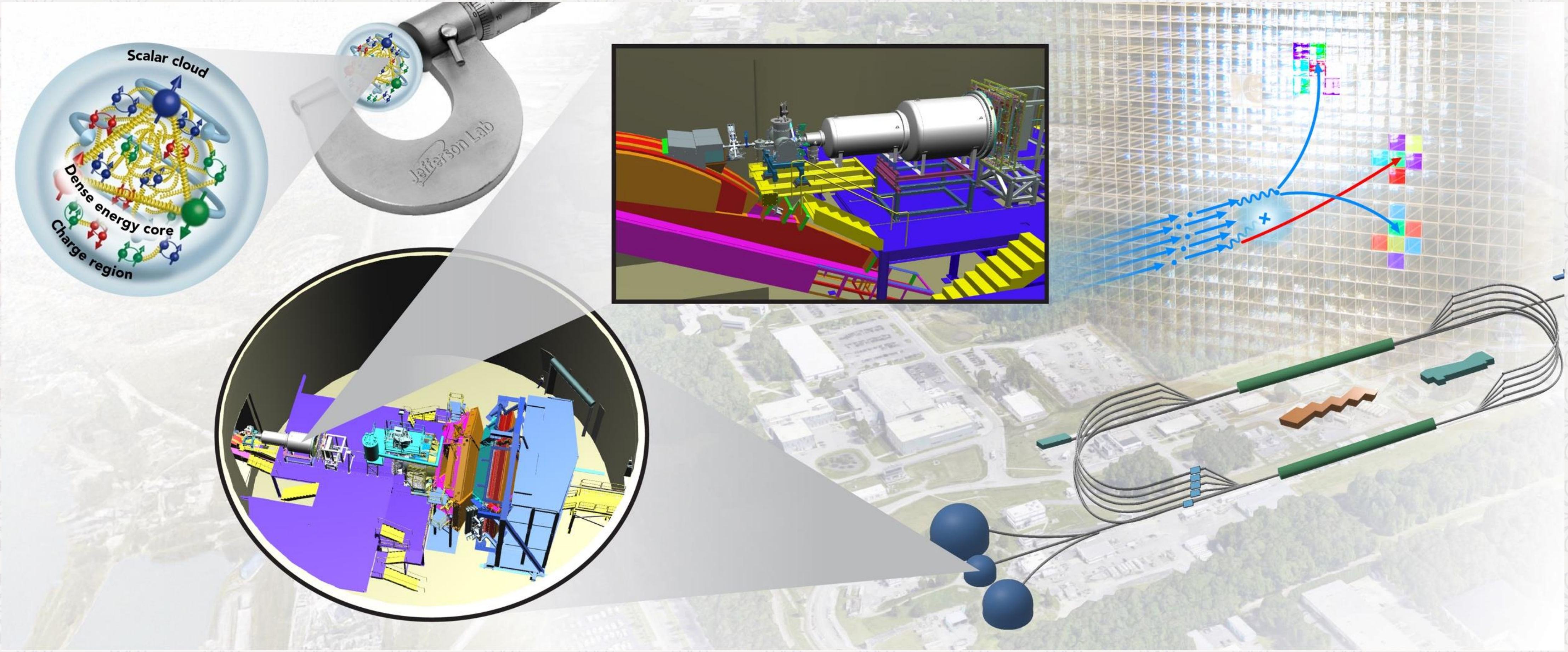
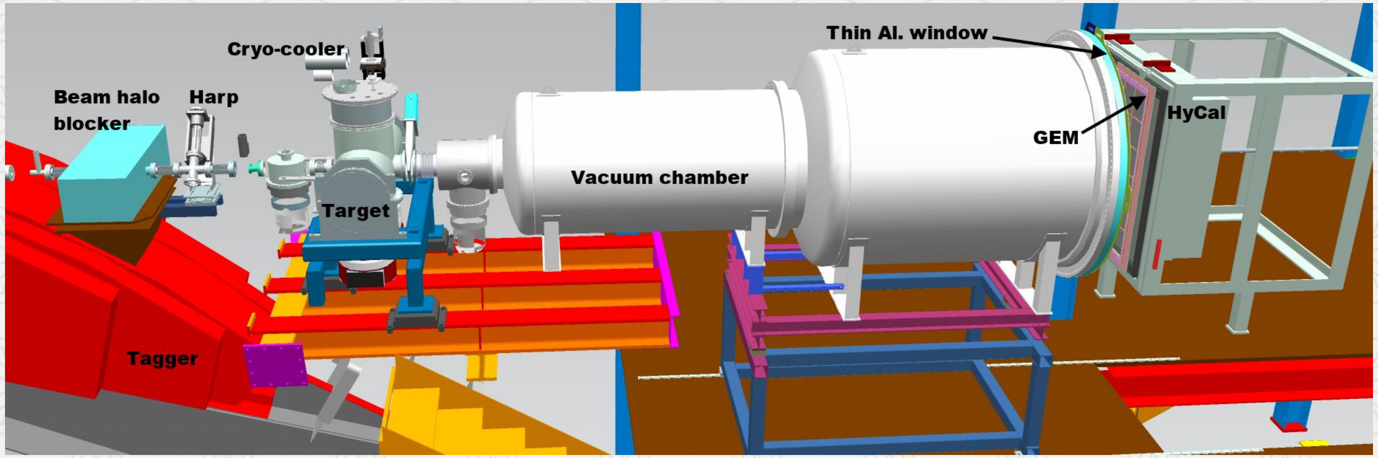
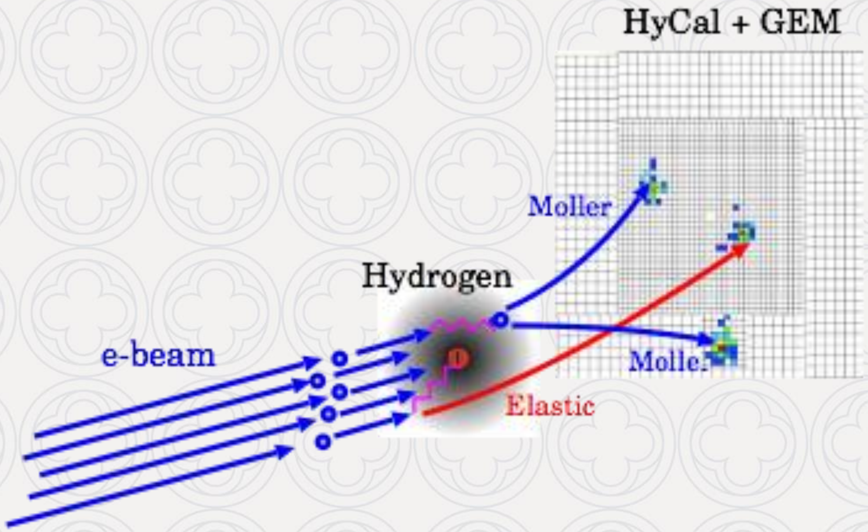
Proton Charge Radius at JLab (PRad & PRad-II)



https://www.innovationnewsnetwork.com/how-large-is-the-proton-how-do-we-measure-it/61615/

The PRad Experiment in Hall B at JLab

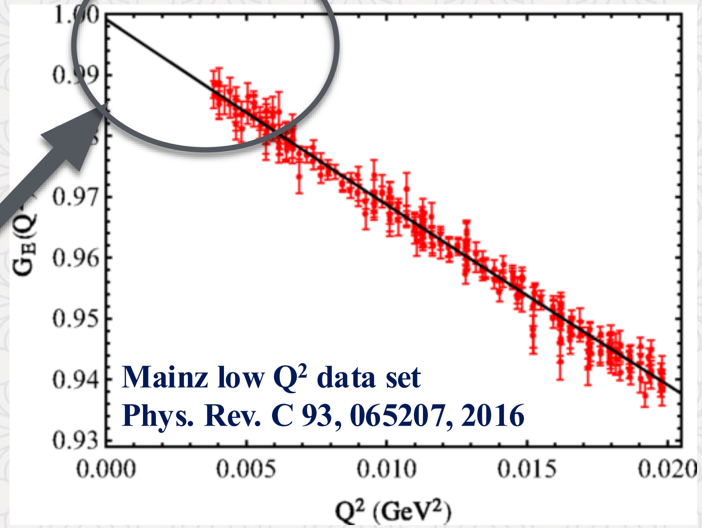




- High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb-Glass)
- Windowless H_2 gas flow target
- Simultaneous detection of elastic e-p and Moller electrons
- Q^2 range of $2 \times 10^{-4} – 0.06$ GeV^2
- XY – veto counters replaced by GEM detector
- Vacuum chamber

Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker

PRad result r_p : 0.831 +/- 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*



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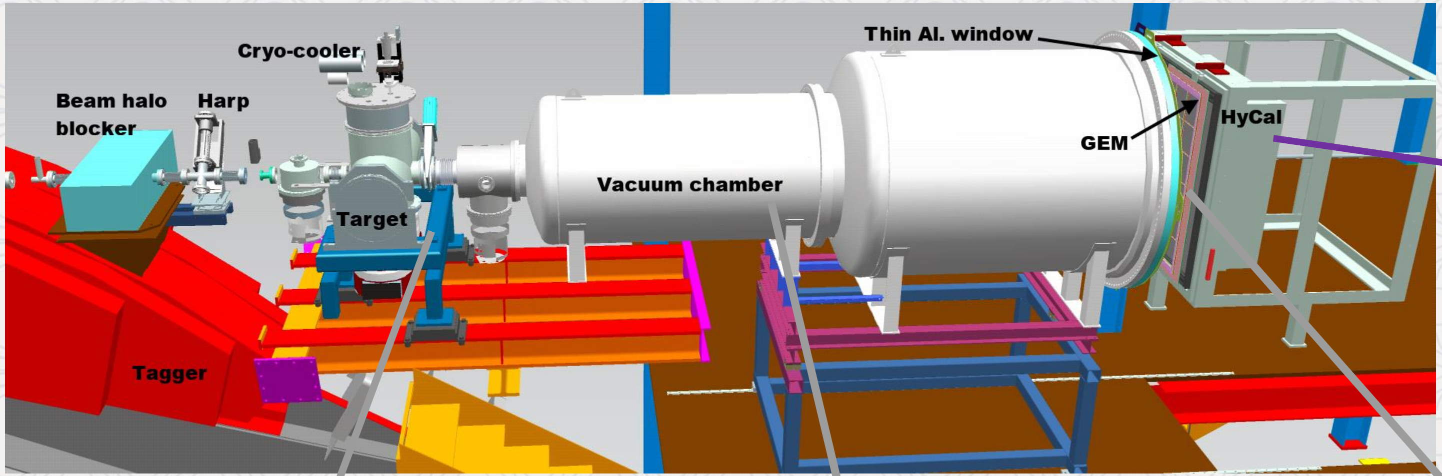
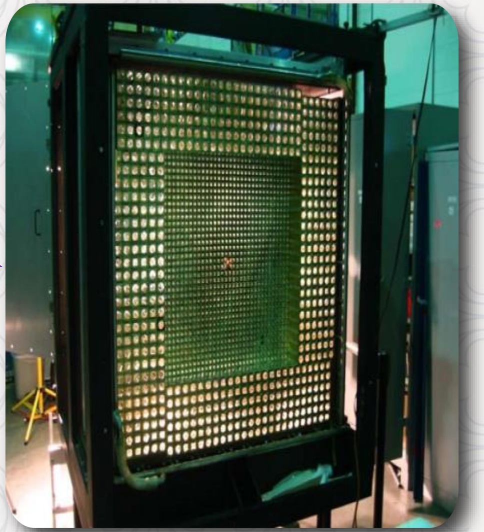
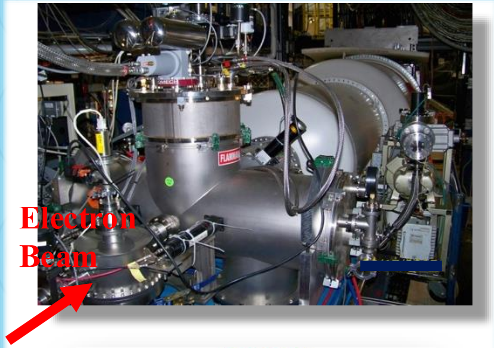
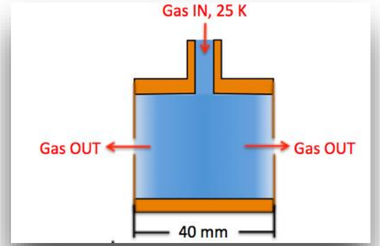
The PRad Experimental setup





I Larin, Y Y. Zhang, *et al.*, Science 6490, 506



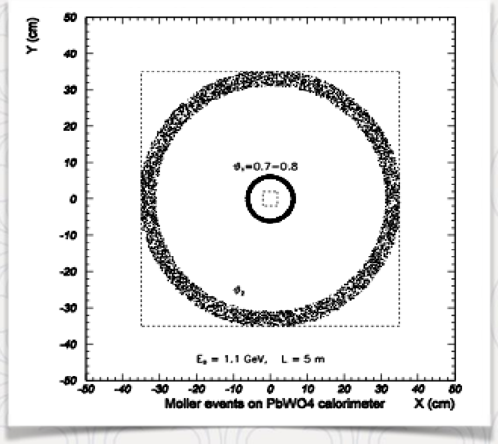


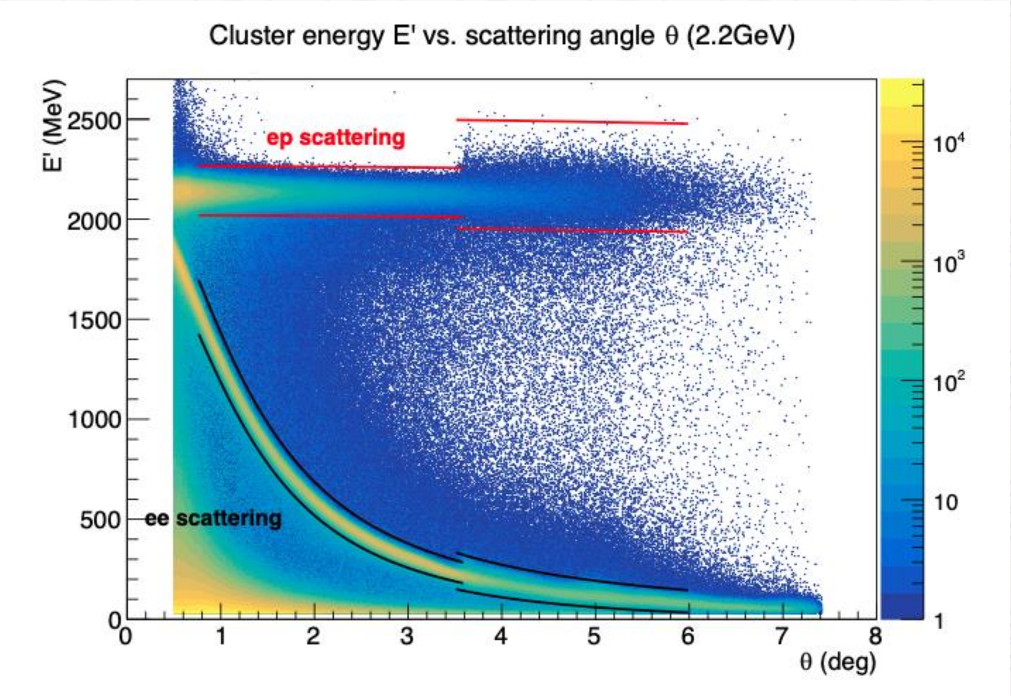
J. Pierce *et al.*, NIMA **1003**, 165300 (2021)

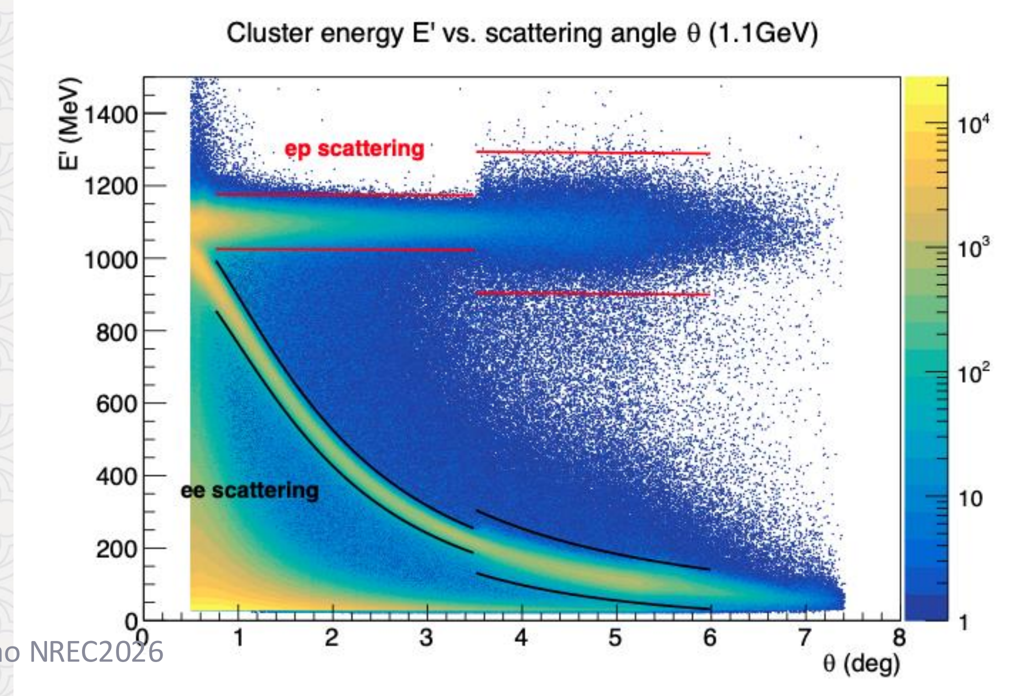
Analysis – Event Selection

Event selection method

1. For all events, require hit matching between GEMs and HyCal
2. For *ep* and *ee* events, apply angle-dependent energy cut based on kinematics
    1. Cut size depend on local detector resolution
3. For *ee*, if requiring double-arm events, apply additional cuts
    1. Elasticity
    2. Co-planarity
    3. Vertex z

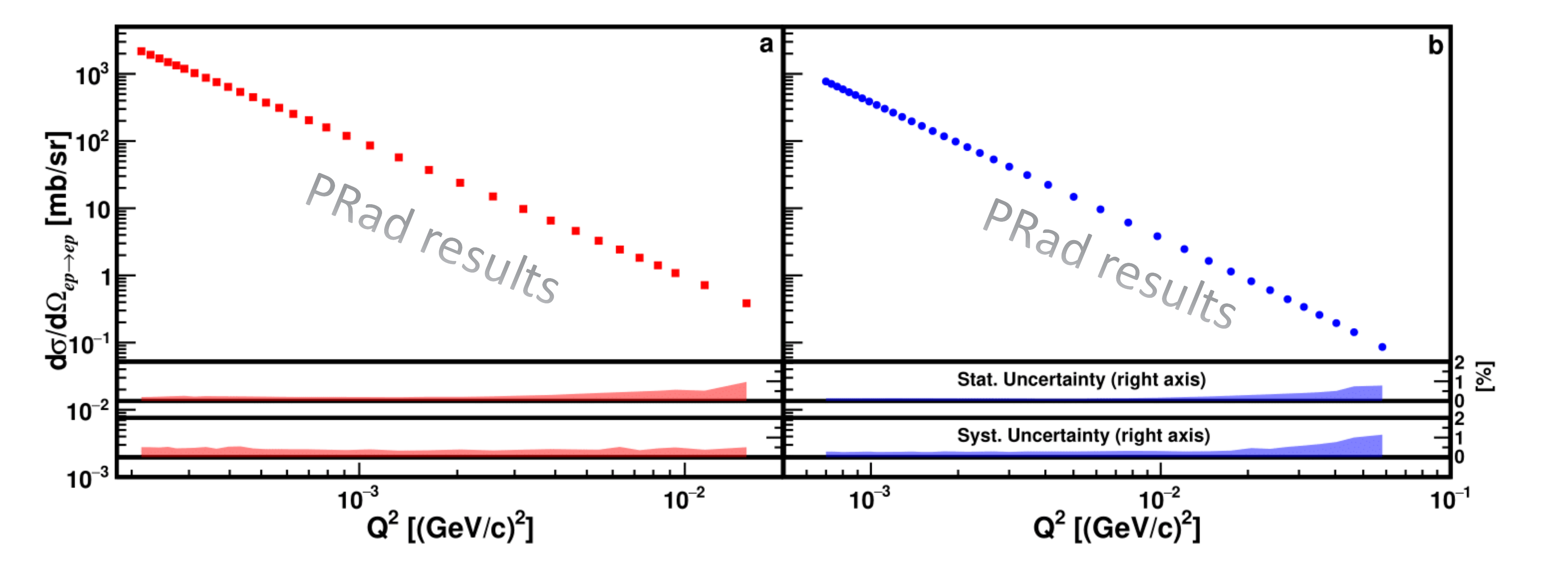






Elastic ep Cross Sections

- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data
- Statistical uncertainties: ~0.15% for 2.2 GeV, ~0.2% for 1.1 GeV per point
- Systematic uncertainties: 0.3%~1.1% for 2.2 GeV, 0.3%~0.5% for 1.1 GeV (shown as shadow area)



Systematic uncertainties shown as bands *Xiong et al., Nature 575, 147–150 (2019)*

Duke

Proton Electric Form Factor G'_E (Normalized)

- n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

- G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

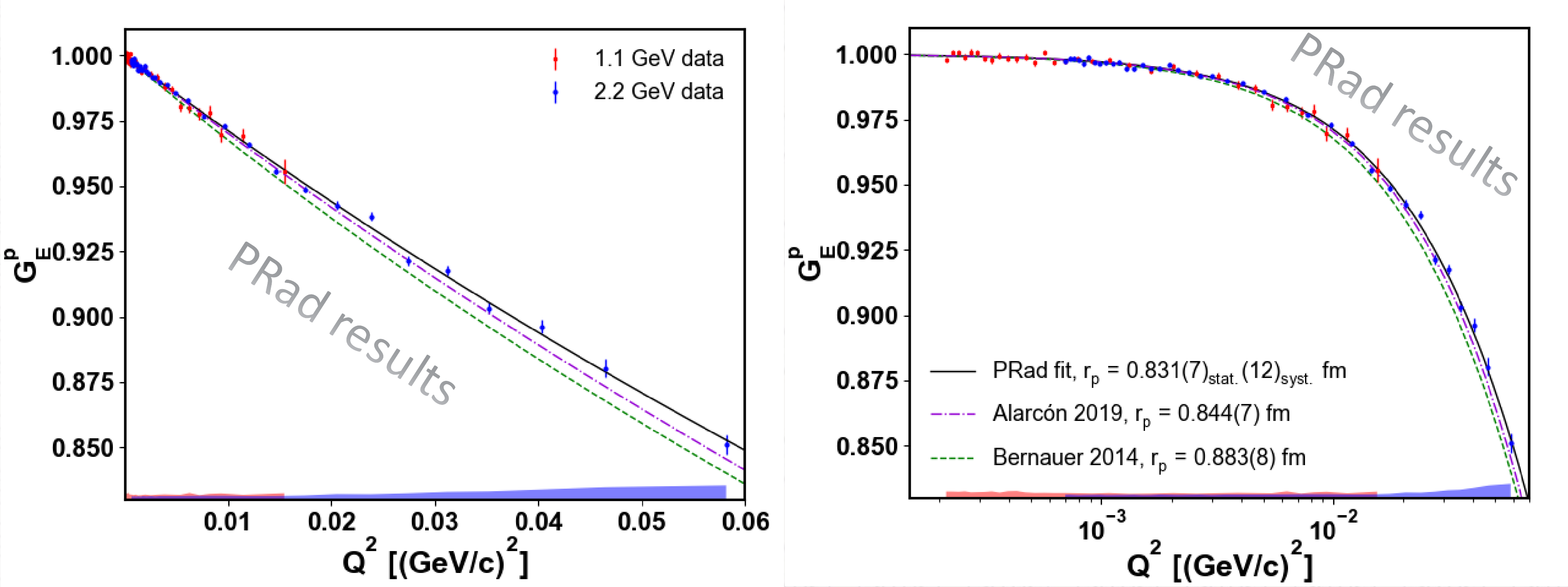
Using rational (1,1)

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

Yan *et al*. PRC98,025204 (2018)

  - PRad fit shown as $f(Q^2)$

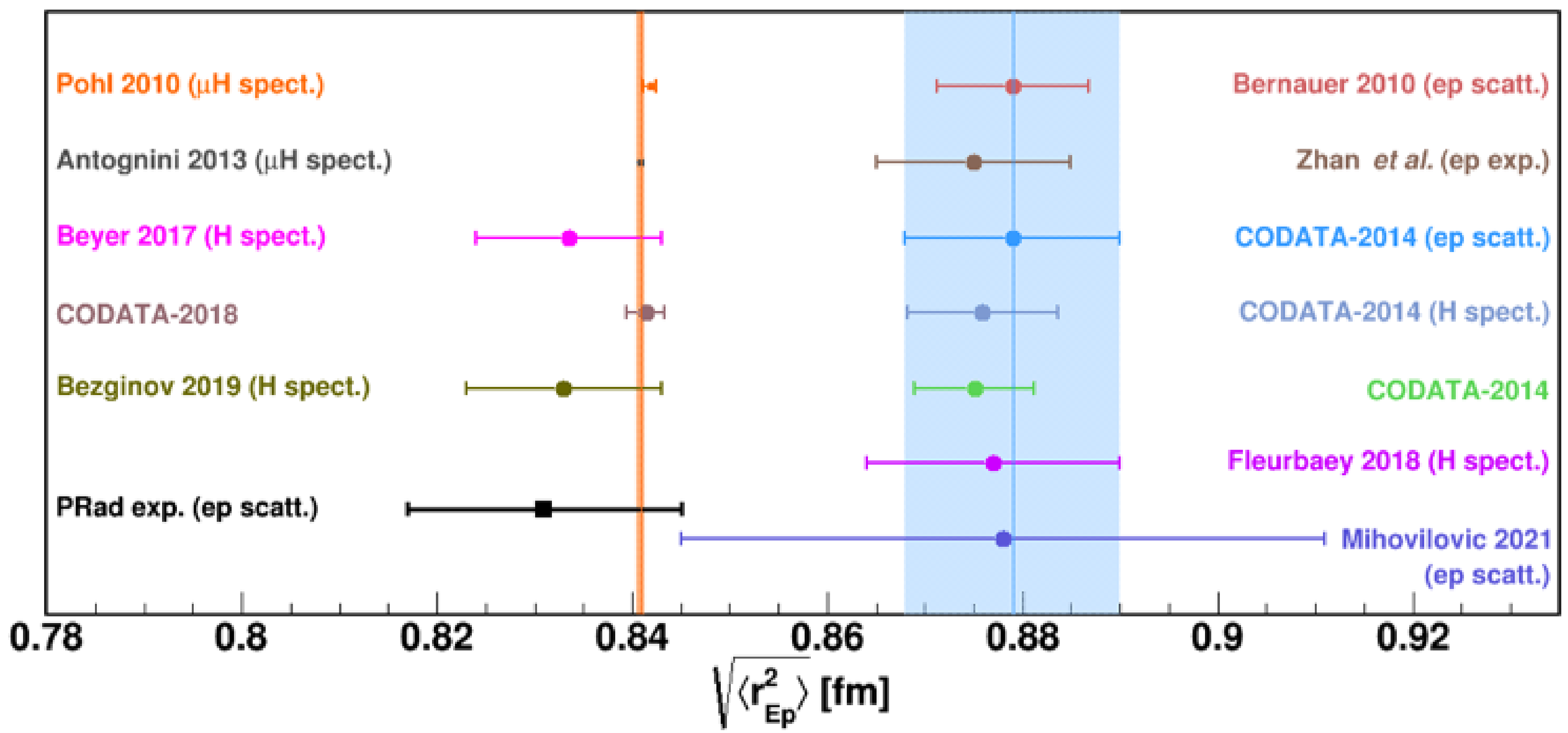
r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

Proton radius at the time of PRad publication

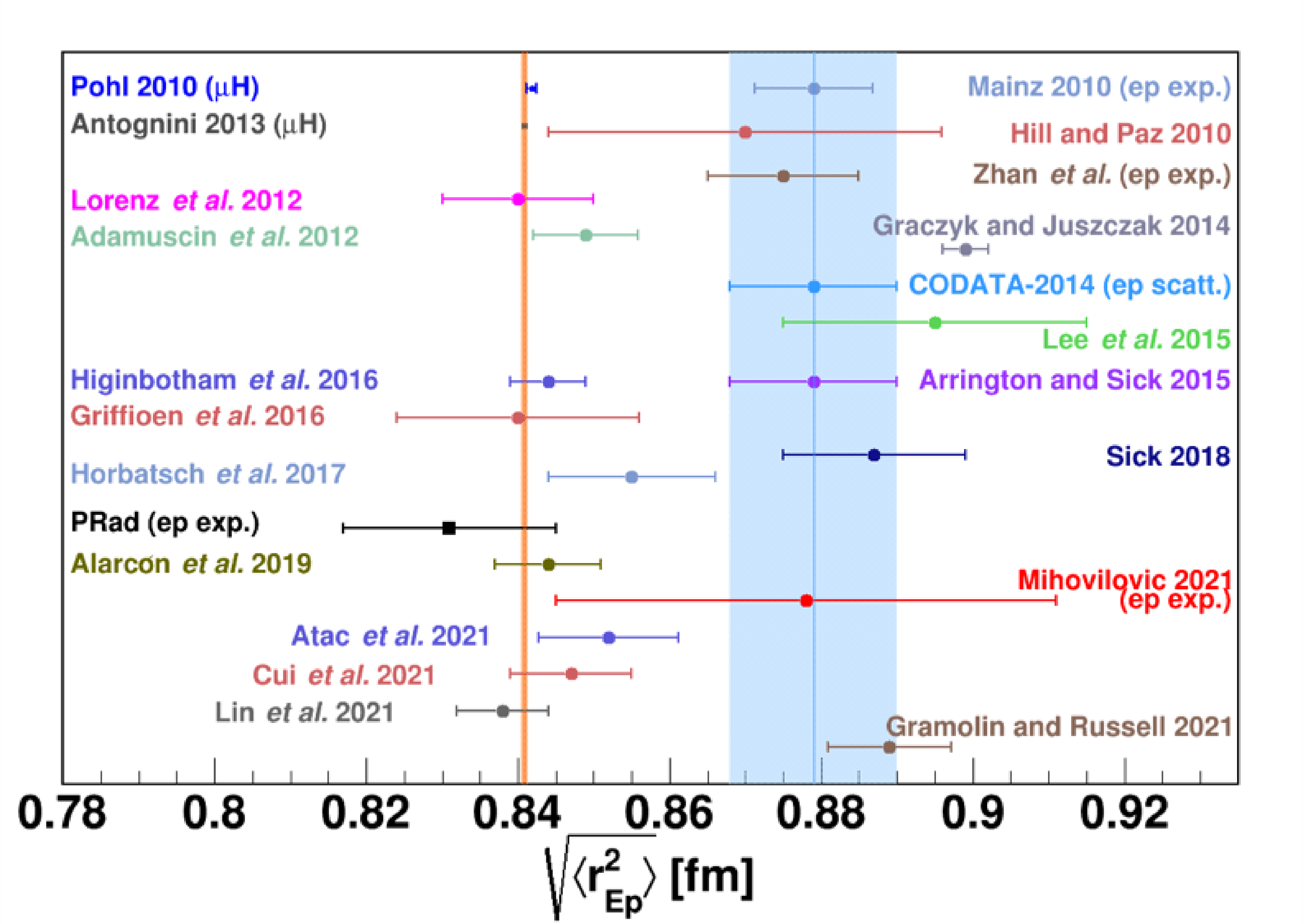
- PRad result r_p : 0.831 +/- 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*
- H Lamb Shift: 0.833 +/- 0.010 fm Bezginov *et al., Science* **365**, 1007-1012 (2019)
- CODATA 2018 value of r_p: 0.8414 +/- 0.0019 fm, *E. Tiesinga et al., RMP 93, 025010(2021)*



CODATA has also shifted the value of the Rydberg constant.

Duke

(Re)analyses of e-p scattering data



Gao and Vanderhaeghen,
Rev. Mod. Phys. 94, 015002 (2022)

Some more recent work:

Cui *et al* 2022 Chinese Phys. *C* **46** 122001;

G. Paz *Mod.Phys.Lett.A* 36 (2021) 20, 2150143;

Qattan (PRC 2025);
Goharipour *et al*. (PLB 2025)

PHYSICAL REVIEW LETTERS **128,** 052002 (2022)

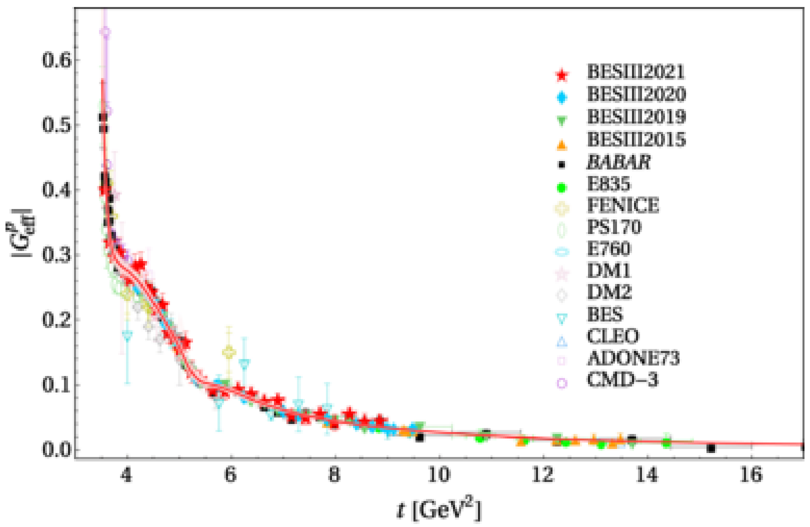
New Insights into the Nucleon's Electromagnetic Structure

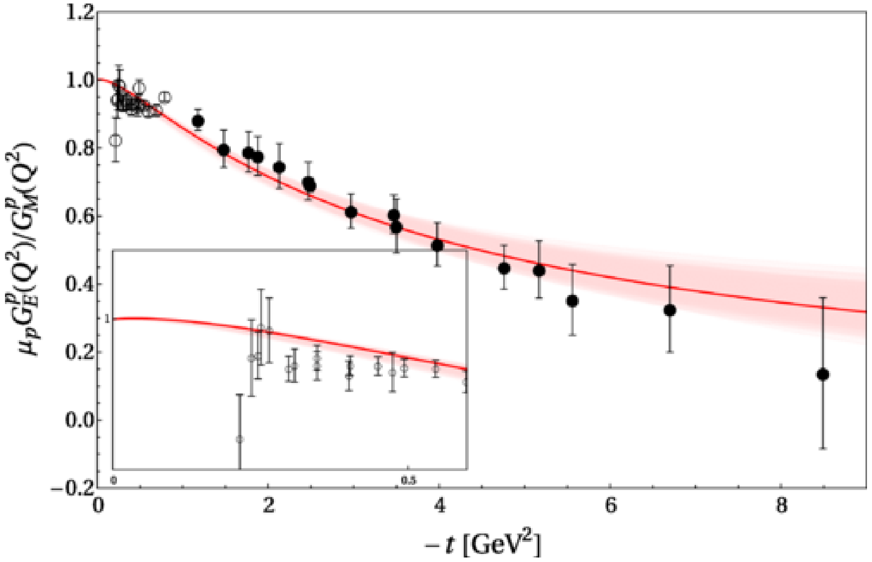
Yong-Hui Lin[1] Hans-Werner Hammer[2,3] and Ulf-G. Meißner[1,4,5]
[1]*Helmholtz Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[2]*Department of Physics, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[3]*Extreme Matter Institute EMMI and Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[4]*Institute for Advanced Simulation and Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[5]*Tbilisi State University, 0186 Tbilisi, Georgia*

(Received 8 October 2021; accepted 18 January 2022; published 3 February 2022)

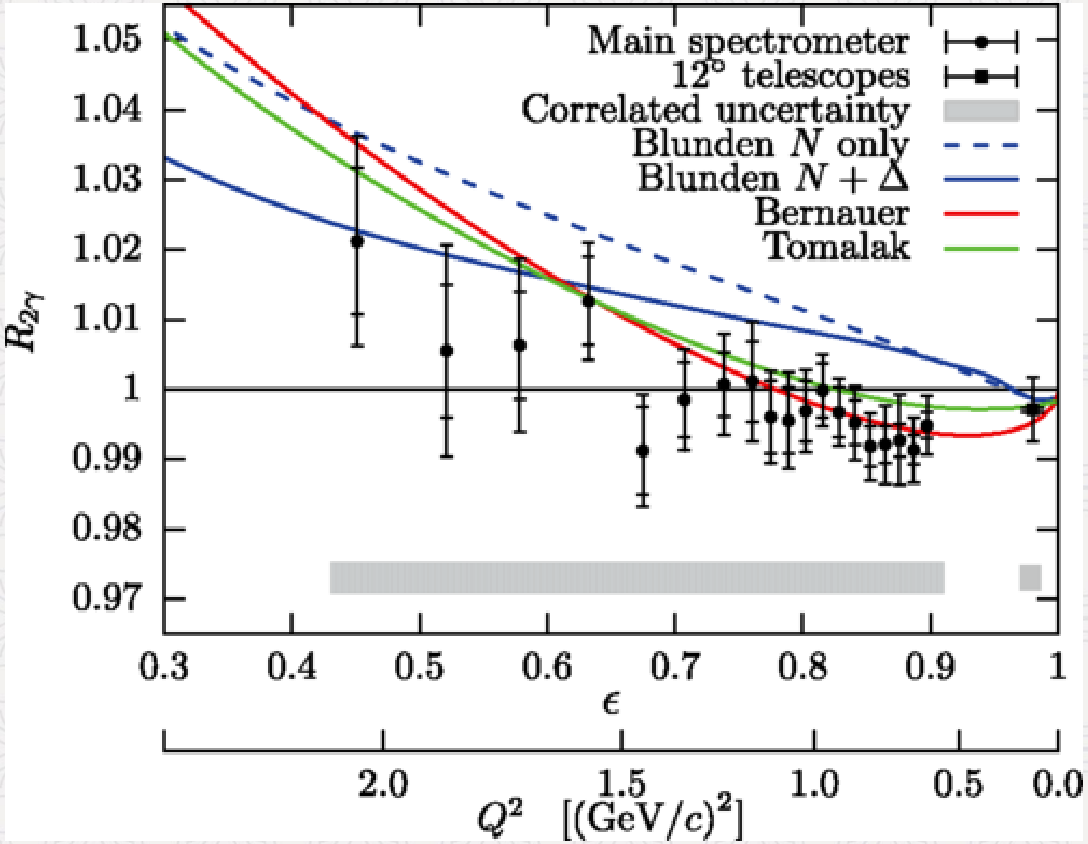
We present a combined analysis of the electromagnetic form factors of the nucleon in the space- and timelike regions using dispersion theory. Our framework provides a consistent description of the experimental data over the full range of momentum transfer, in line with the strictures from analyticity and unitarity. The statistical uncertainties of the extracted form factors are estimated using the bootstrap method, while systematic errors are determined from variations of the spectral functions. We also perform a high-precision extraction of the nucleon radii and find good agreement with previous analyses of spacelike data alone. For the proton charge radius, we find $r_E^p = 0.840^{+0.003}_{-0.002}{}^{+0.002}_{-0.002}$ fm, where the first error is statistical and the second one is systematic. The Zemach radius and third moment are in agreement with Lamb shift measurements and hyperfine splittings. The combined dataset of space- and timelike data disfavors a zero crossing of $\mu_p G_E^p/G_M^p$ in the spacelike region. Finally, we discuss the status and perspectives of modulus and phase of the form factors in the timelike region in the context of future experiments, as well as the onset of perturbative QCD.

DOI: 10.1103/PhysRevLett.128.052002





How about two-photon exchange?



PRL **118,** 092501 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Hard Two-Photon Contribution to Elastic Lepton-Proton Scattering Determined by the OLYMPUS Experiment

B. S. Henderson,[1] L. D. Ice,[2] D. Khaneft,[3] C. O'Connor,[1] R. Russell,[1] A. Schmidt,[1] J. C. Bernauer,[1,*] M. Kohl,[4,†] N. Akopov,[5] R. Alarcon,[2] O. Ates,[4] A. Avetisyan,[5] R. Beck,[6] S. Belostotski,[7] J. Bessuille,[1] F. Brinker,[8] J. R. Calarco,[9] V. Carassiti,[10] E. Cisbani,[11] G. Ciullo,[10] M. Contalbrigo,[10] R. De Leo,[12] J. Diefenbach,[4] T. W. Donnelly,[1] K. Dow,[1] G. Elbakian,[5] P. D. Eversheim,[6] S. Frullani,[11] Ch. Funke,[6] G. Gavrilov,[7] B. Gläser,[3] N. Görrissen,[8] D. K. Hasell,[1] J. Hauschildt,[8] Ph. Hoffmeister,[6] Y. Holler,[8] E. Ihloff,[1] A. Izotov,[7] R. Kaiser,[13] G. Karyan,[8,‡] J. Kelsey,[1] A. Kiselev,[7] P. Klassen,[6] A. Krivshich,[7] I. Lehmann,[13] P. Lenisa,[10] D. Lenz,[8] S. Lumsden,[13] Y. Ma,[3] F. Maas,[3] H. Marukyan,[5] O. Miklukho,[7] R. G. Milner,[1] A. Movsisyan,[5,§] M. Murray,[13] Y. Naryshkin,[7] R. Perez Benito,[3] R. Perrino,[12] R. P. Redwine,[1] D. Rodríguez Piñeiro,[3] G. Rosner,[13] U. Schneekloth,[8] B. Seitz,[13] M. Statera,[10] A. Thiel,[6] H. Vardanyan,[5] D. Veretennikov,[7] C. Vidal,[1] A. Winnebeck,[1] and V. Yeganov[5]

(OLYMPUS Collaboration)

[1]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Arizona State University, Tempe, Arizona 85281, USA*
[3]*Johannes Gutenberg-Universität, 55099 Mainz, Germany*
[4]*Hampton University, Hampton, Virginia 23668, USA*
[5]*Alikhanyan National Science Laboratory (Yerevan Physics Institute), 0036 Yerevan, Armenia*
[6]*Rheinische Friedrich-Wilhelms-Universität, 53113 Bonn, Germany*
[7]*Petersburg Nuclear Physics Institute, Gatchina 188300, Russia*
[8]*Deutsches Elektronen-Synchrotron, 22603 Hamburg, Germany*
[9]*University of New Hampshire, Durham, New Hampshire 03824, USA*
[10]*Università degli Studi di Ferrara and Istituto Nazionale di Fisica Nucleare sezione di Ferrara, 44122 Ferrara, Italy*
[11]*Istituto Nazionale di Fisica Nucleare sezione di Roma and Istituto Superiore di Sanità, 00185 Rome, Italy*
[12]*Istituto Nazionale di Fisica Nucleare sezione di Bari, 70126 Bari, Italy*
[13]*University of Glasgow, Glasgow G12 8QQ, United Kingdom*

(Received 14 November 2016; revised manuscript received 19 December 2016; published 3 March 2017)

The OLYMPUS Collaboration reports on a precision measurement of the positron-proton to electron-proton elastic cross section ratio, $R_{2\gamma}$, a direct measure of the contribution of hard two-photon exchange to the elastic cross section. In the OLYMPUS measurement, 2.01 GeV electron and positron beams were directed through a hydrogen gas target internal to the DORIS storage ring at DESY. A toroidal magnetic spectrometer instrumented with drift chambers and time-of-flight scintillators detected elastically scattered leptons in coincidence with recoiling protons over a scattering angle range of $\approx 20°$ to $80°$. The relative luminosity between the two beam species was monitored using tracking telescopes of interleaved gas electron multiplier and multiwire proportional chamber detectors at 12°, as well as symmetric Møller or Bhabha calorimeters at 1.29°. A total integrated luminosity of 4.5 fb^{-1} was collected. In the extraction of $R_{2\gamma}$, radiative effects were taken into account using a Monte Carlo generator to simulate the convolutions of internal bremsstrahlung with experiment-specific conditions such as detector acceptance and reconstruction efficiency. The resulting values of $R_{2\gamma}$, presented here for a wide range of virtual photon polarization $0.456 < \epsilon < 0.978$, are smaller than some hadronic two-photon exchange calculations predict, but are in reasonable agreement with a subtracted dispersion model and a phenomenological fit to the form factor data.

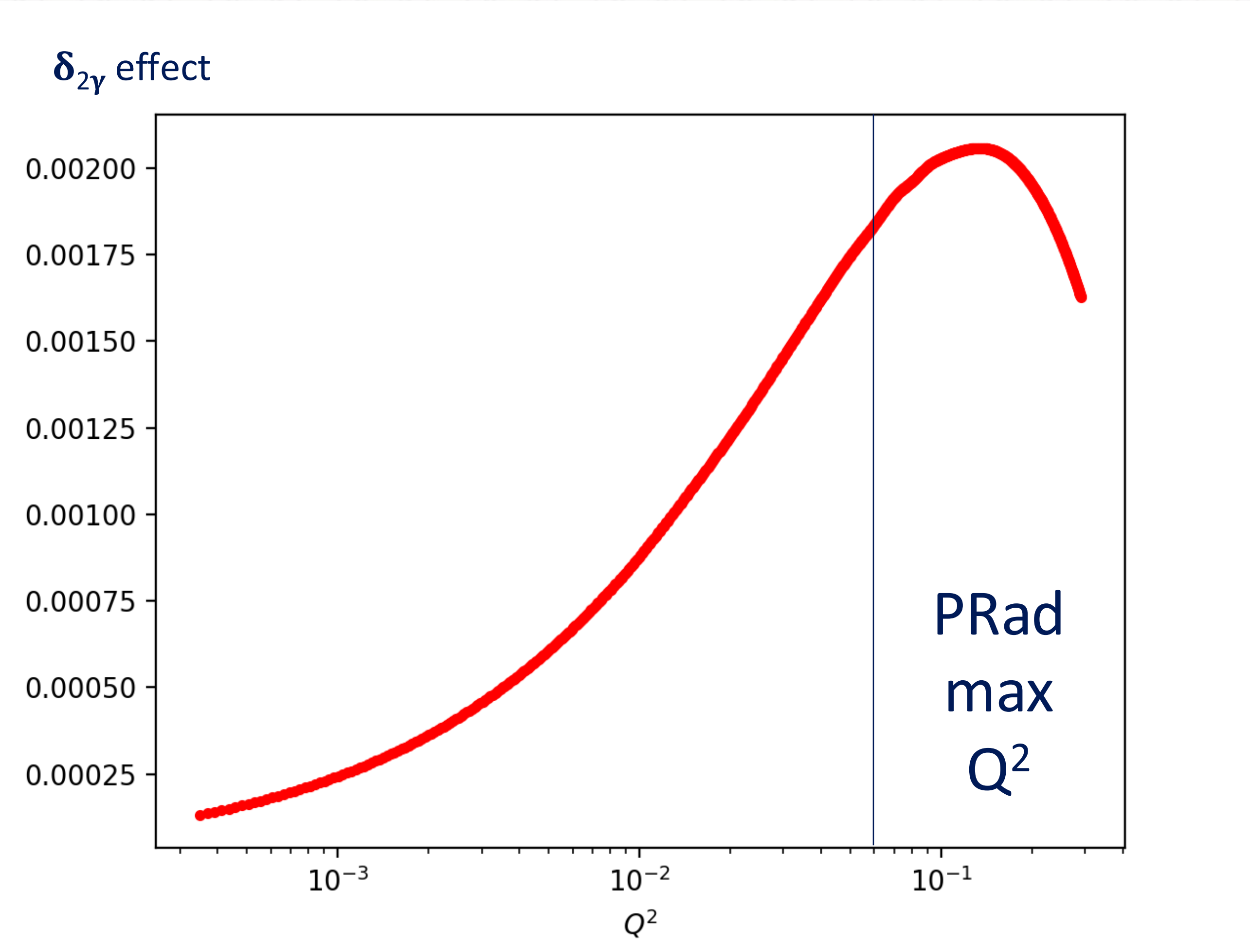
DOI: 10.1103/PhysRevLett.118.092501

Next frontier: MUSE experiment

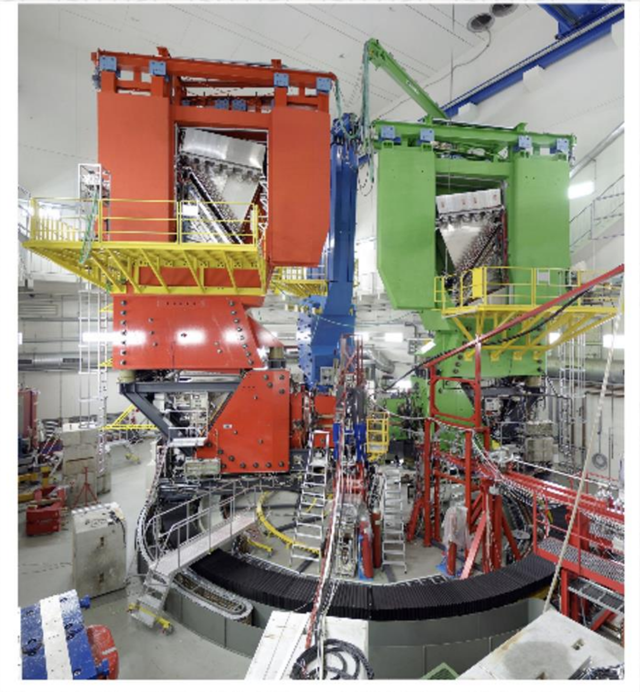
Two-photon Exchange

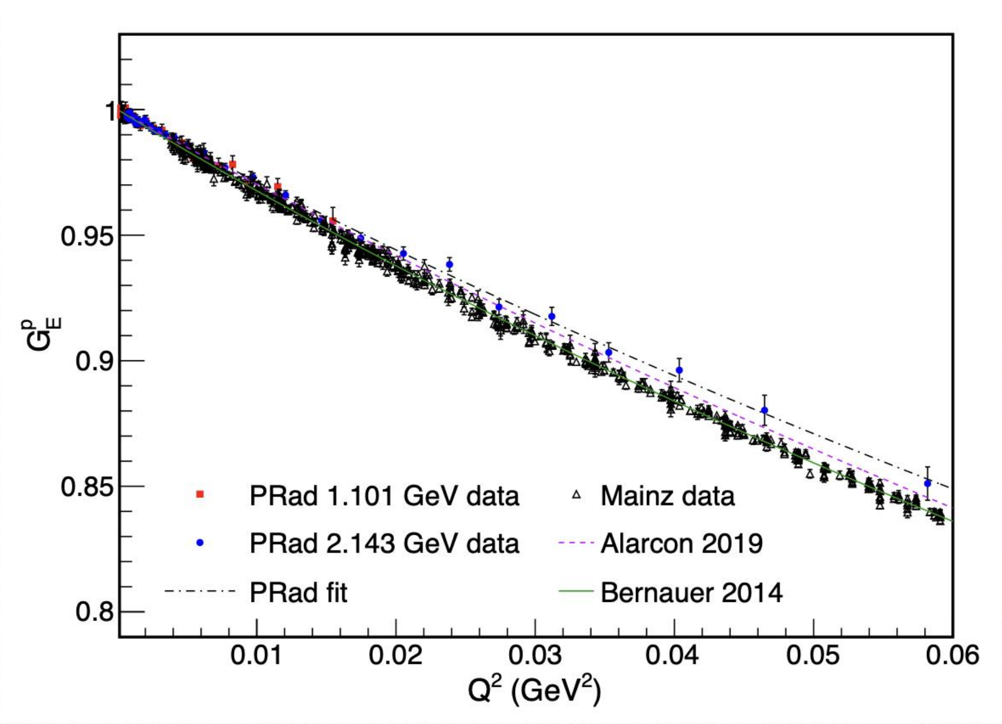
- TPE effect based on calculation of Oleksandr Tomalak
  - O. Tomalak, Few Body Syst. **59**, no. 5, 87 (2018)
  - O. Tomalak and M. Vanderhaeghen, PRD **93** (2016) no.1, 013023
  - O. Tomalak and M. Vanderhaeghen, EPJA **51** (2015) no.2, 24
- Less than 0.2% effect on the cross section within PRad kinematic range

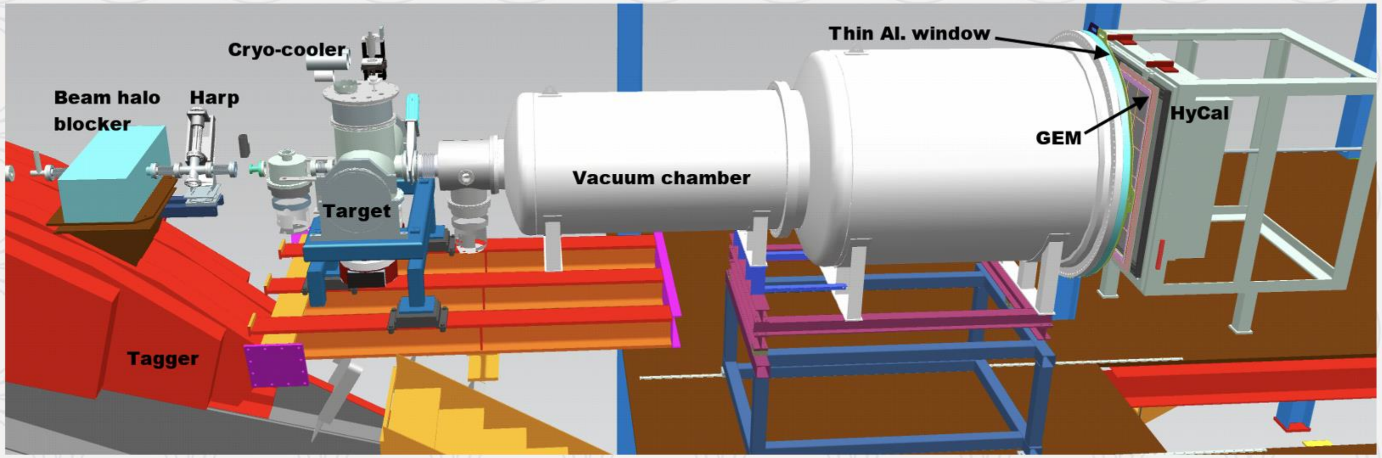
U. Raha, P. Blunden at this workshop



e-p scattering: magnetic spectrometer and calorimetric method



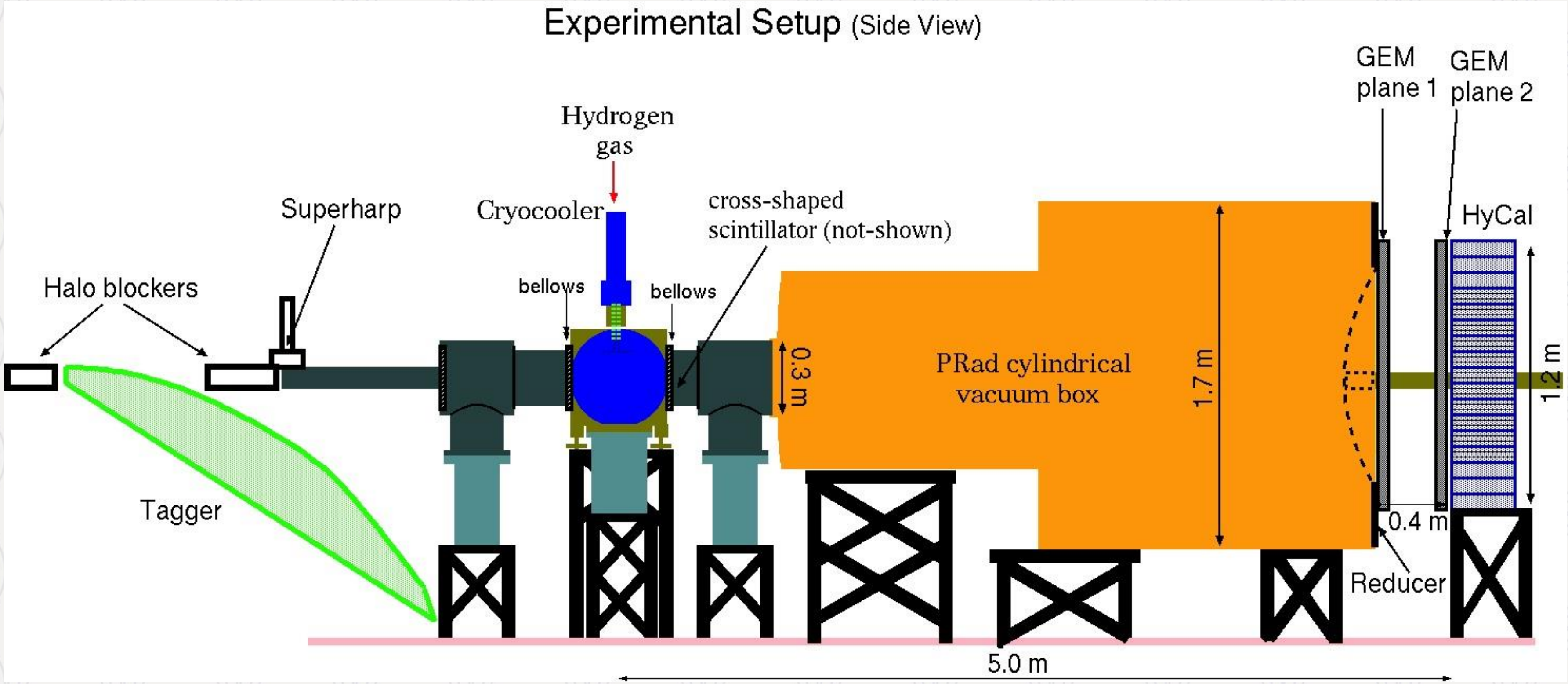


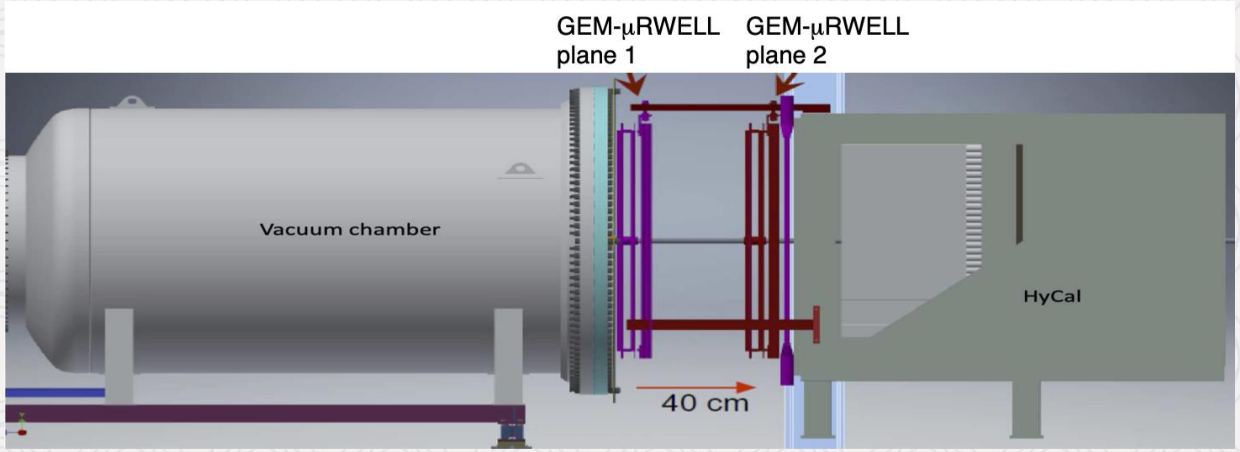


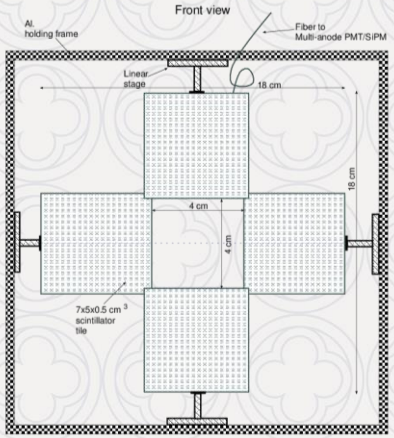
PRad-II: goals and approaches

- Reduce the uncertainty of the r_p measurement by a factor of **3!**
- Precise measurement of G_E to investigate the difference between the Mainz data and PRad
- Reach an unprecedented low values of Q^2 : 4×10^{-5} $(GeV/c)^2$
- How?
  - Improving tracking capability by adding a second plane of tracking detector
  - Adding new rectangular cross shaped scintillator detectors to separate Moller from ep electrons in scattering angular range of 0.5^0- 0.8^0
  - Upgrading HyCal electronics for readout
    - Converting to FADC based readout
  - Suppressing beamline background
    - Improving vacuum
    - Adding second beam halo blocker upstream of the tagger
  - Reducing statistical uncertainties by a factor of 4 compared with PRad
  - Three beam energies: 0.7, 2.1, 3.5 GeV – ***0.7 GeV is critical to reach the lowest Q^2 (4×10^{-5} $(GeV/c)^2$)***
  - Improve radiative correction calculations by going to NNL order
  - Potential target improvement (***not used in projection***)

D. Dutta at this workshop


Experimental Setup (Side View)
GEM plane 1
GEM plane 2
Hydrogen gas
Superharp
Cryocooler
cross-shaped scintillator (not-shown)
HyCal
Halo blockers
bellows
bellows
0.3 m
PRad cylindrical vacuum box
1.7 m
1.2 m
Tagger
0.4 m
Reducer
5.0 m


GEM-μRWELL plane 1
GEM-μRWELL plane 2
Vacuum chamber
HyCal
40 cm


Front view
Al. holding frame
Fiber to Multi-anode PMT/SiPM
Linear stage
18 cm
18 cm
4 cm
4 cm
7x5x0.5 cm 3 scintillator tile

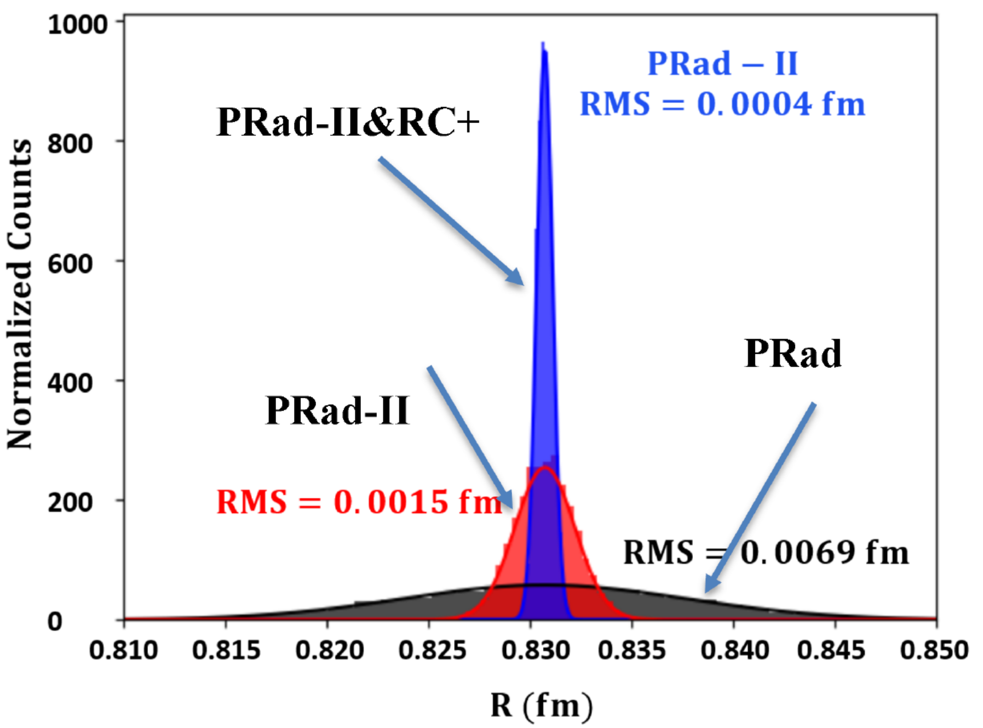
RC effect and improvement from PRad to PRad-II

RC studies for PRad-II

- Improvement of the RC associated syst. uncertainty on r_p
  - Black spectrum $\rightarrow$ RC δr_p for PRad

Akushevich, H. Gao, A. Ilyichev, and M. Meziane, Eur. Phys. J. A 51, 1 (2015)

  - Red spectrum $\rightarrow$ projected RC δr_p with two planes of coordinate tracking detectors plus current RC calculations
  - Blue spectrum $\rightarrow$ projected RC δr_p with two planes of coordinate tracking detectors plus improved RC calculations at NNLO



- Synergistic activities
  - Whitepaper on Radiative Corrections: *arXiv:2012.0997*
  - Synergy with ongoing RC-related studies for the JLab SoLID SIDIS and the planned studies for the proposed DRad experiment
- McMule+PRad/PRad-II (ongoing)

I. Akushevich, A. Signer, S. Strauch, O. Tomalak at this workshop

McMule: Monte Carlo for MUons and other LEptons

- A high-precision framework for theoretical calculations in QED
- Core Function
  - Calculates physical cross-sections for various scattering processes
  - Provides predictions for direct comparison with experimental data
- Processes supported:
  - All leptonic 2 → 2 scattering processes
  - Other processes, i.e. particle decay

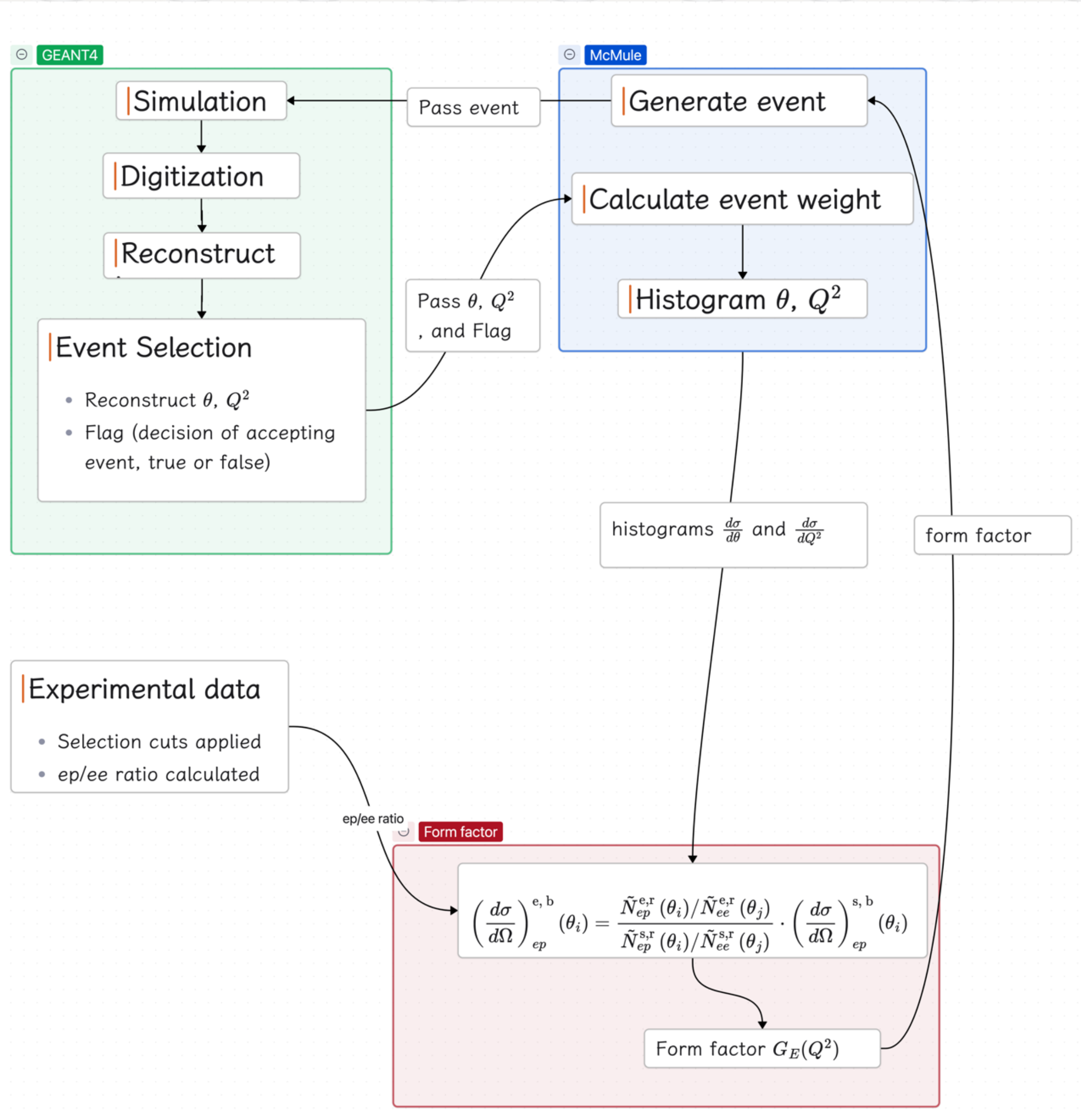
process	experiment	physics motivation	order
$e\mu \to e\mu$	MUonE	HVP to $(g-2)_\mu$	NNLO+
$\ell p \to \ell p$	P2, Muse, Prad, QWeak, ...	proton radius and weak charge	NNLO
$eN \to eN$	PRad, ULQ2	background	+
$e^-e^- \to e^-e^-$	Prad 2	normalisation	NNLO
	MOLLER, ...	$\sin^2\theta_W$ at low Q^2	
$e^+e^- \to e^+e^-$	any e^+e^- collider	luminosity measurement	NNLO
$ee \to \ell\ell$	VEPP, BES, Daphne, ...	R-ratio	NNLO±
	Belle	τ properties	
$ee \to \gamma\gamma$	Daphne	dark searches	NNLO−
	any e^+e^- collider	luminosity measurement	
$e\nu \to e\nu$	DUNE	flux & $\sin^2\theta_W$	NNLO−
$\mu \to \nu\bar{\nu}e$	MEG	ALP searches	NNLO+
	DUNE	beam-line profiling	

Part of processes supported by McMule

f.l.t.r.: S.Kollatzsch (Zurich & PSI), A.Signer (Zurich & PSI), V.Sharkovska (Zurich & PSI), S.Gündogdu (Zurich & PSI), D. Moreno (PSI), A.Coutinho (IFIC), Y.Ulrich (Liverpool), D. Radic (Zurich & PSI), L.Naterop (Zurich & PSI), M.Rocco (Turin)
not shown: F.Hagelstein (Mainz), N.Schalch (Oxford), T.Engel (Freiburg), A.Gurgone (Pavia), P.Banerjee (Cosenza)

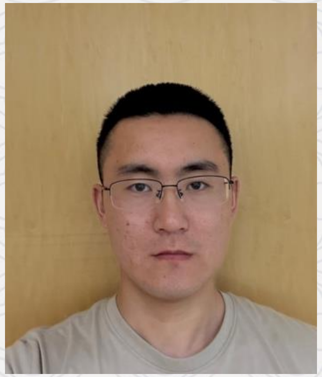
codes: https://mule-tools.gitlab.io/
docs: https://mcmule.readthedocs.io/

Current strategy for the NNLO RC Correction



Event generation and processing at event level

1. Event generation and processing
   a. McMule passes an event to GEANT4 (Interfaces required)
   b. GEANT4 performs simulation, digitization, reconstruction, and event selection
   c. GEANT4 returns event accepting flag and reconstructed θ, Q^2 to McMule (Interfaces required)
   d. McMule fills histograms $d\sigma/d\theta$, $d\sigma/dQ^2$ with such info
   e. Repeat a→d for required statistics (event loop controlled by McMule)
2. Form super ratio and extract form factor
   a. McMule outputs the final histograms
   b. PRad2 calculates the super ratio and extract the form factor
   c. Update the form factor in McMule with the new fit (Interfaces required)
3. Repeat 1→2 for the next iteration

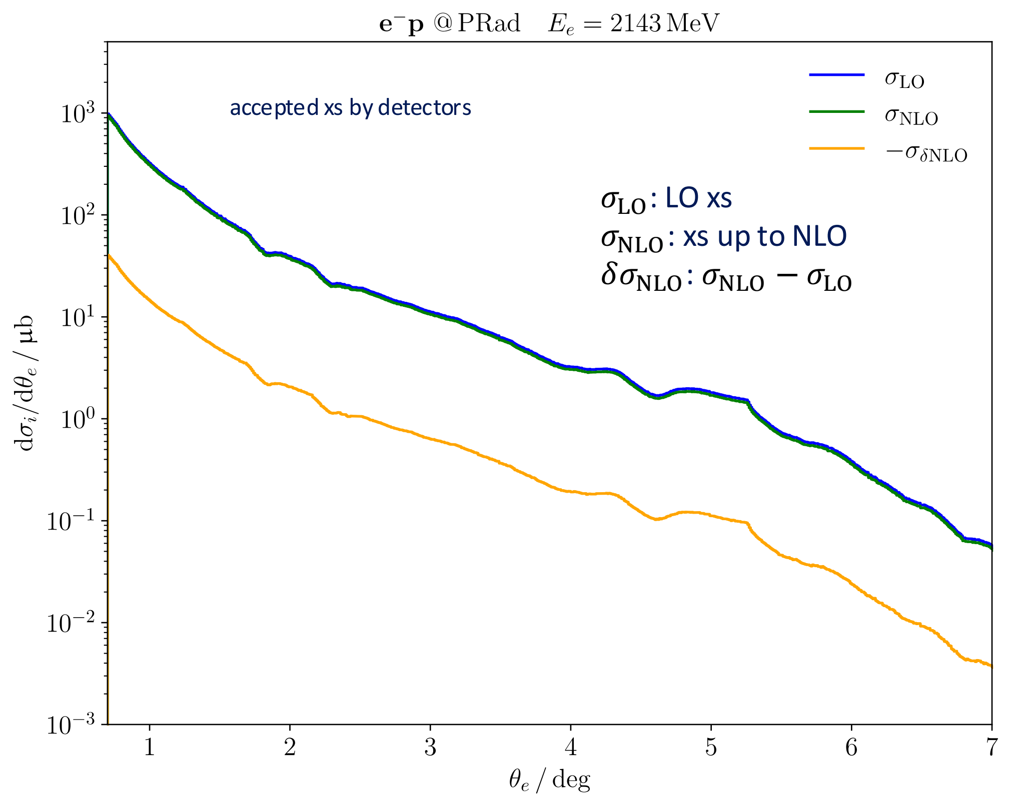


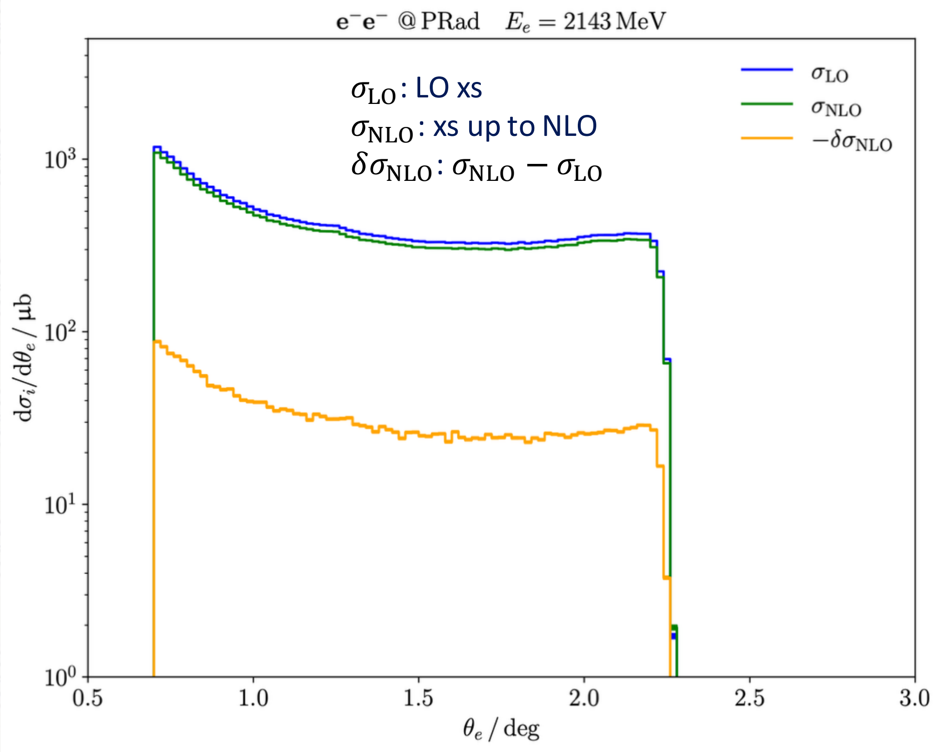
Dr. Yi Yu

Duke

Current status on e-p elastic and Moller cross sections with McMule up to NLO

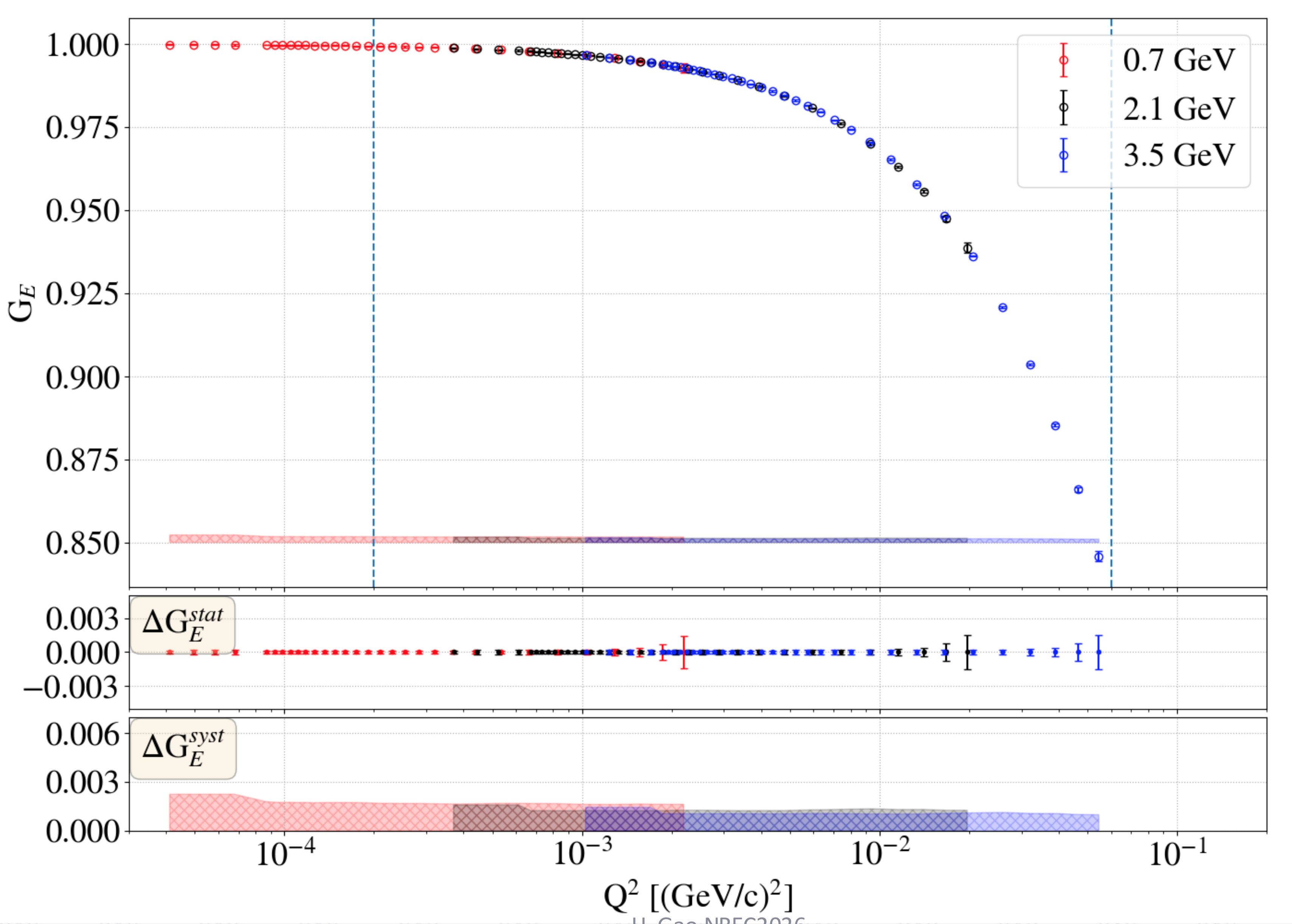
- Cross sections are calculated with detector effects implemented
- The up-and-down structures are coming from the detector effects (ep)
- Double-arm Moller electrons required
- $\delta\sigma_{\mathrm{NLO}}$ corrections still have some fluctuations and more statistics needed (Moller)



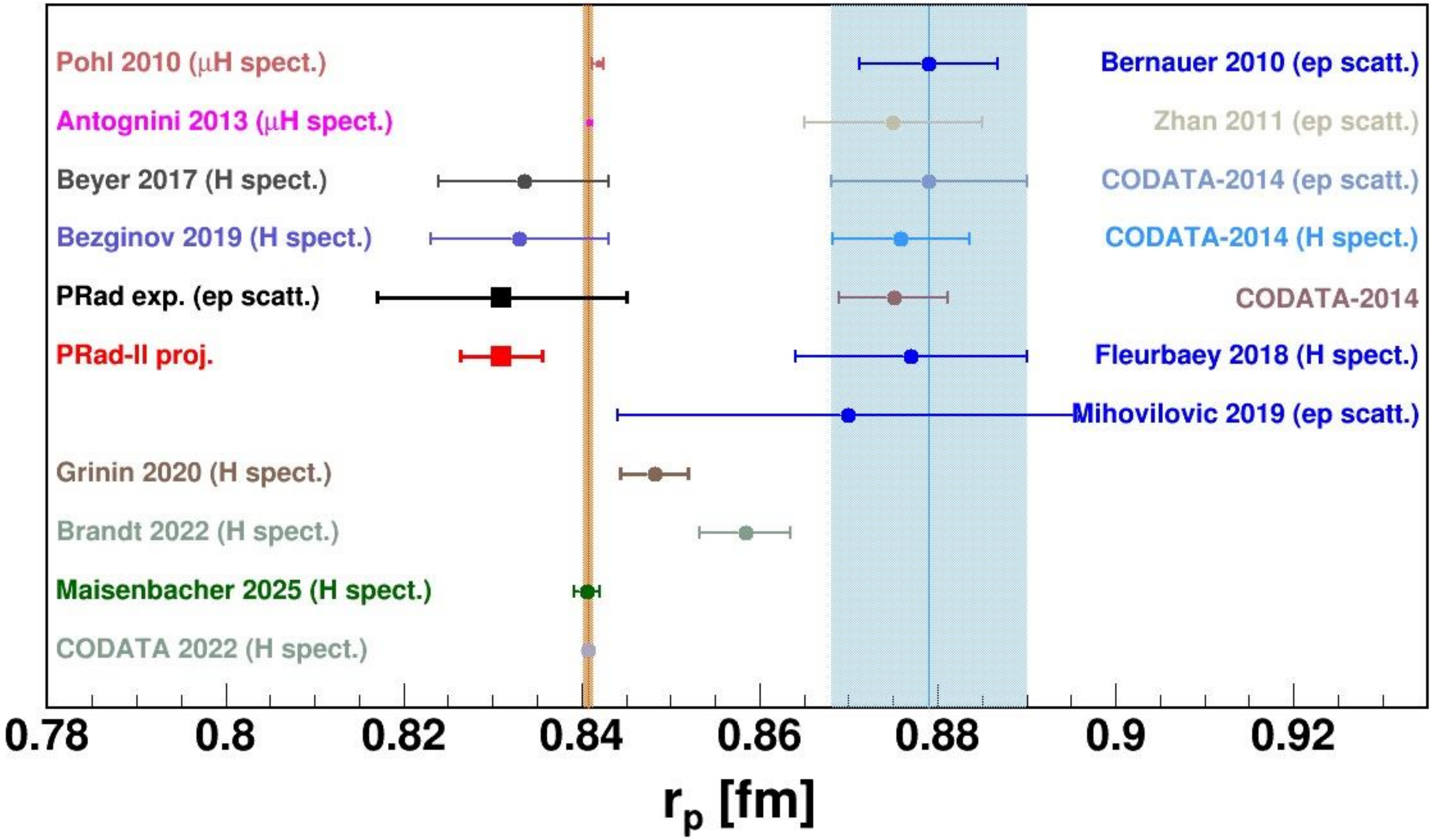


Duke

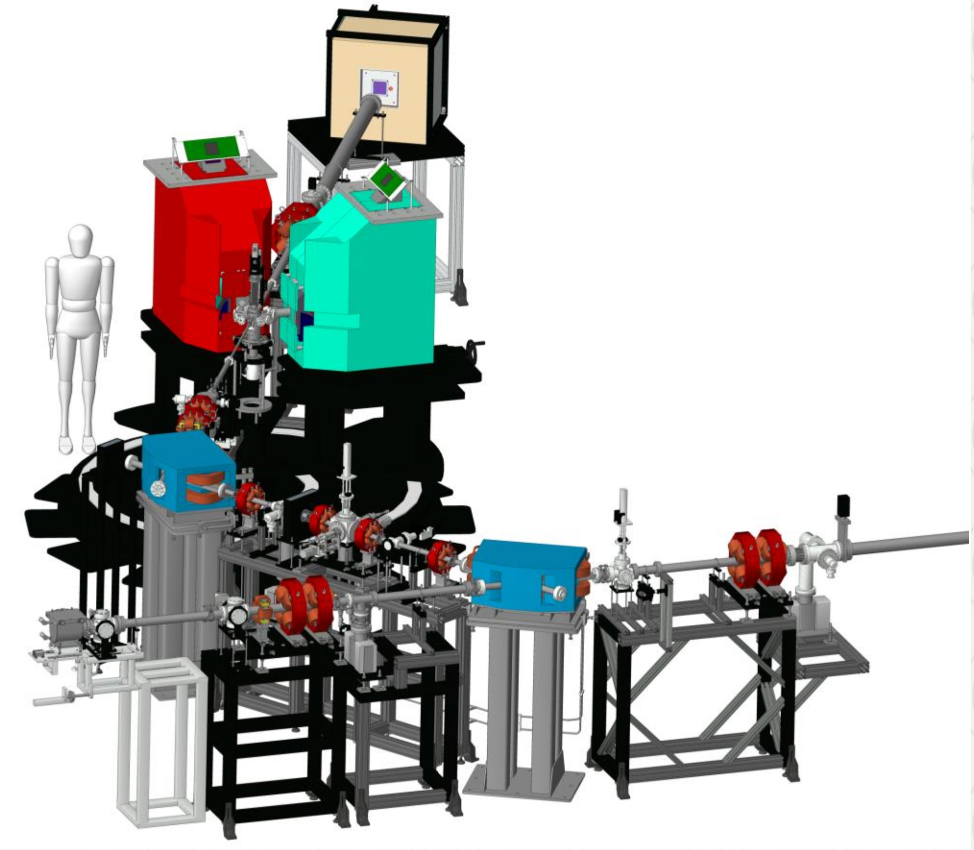
Simulated PRad-II Uncertainties on G_E



Projected PRad-II on r_p



L. Maisenbacher at this workshop



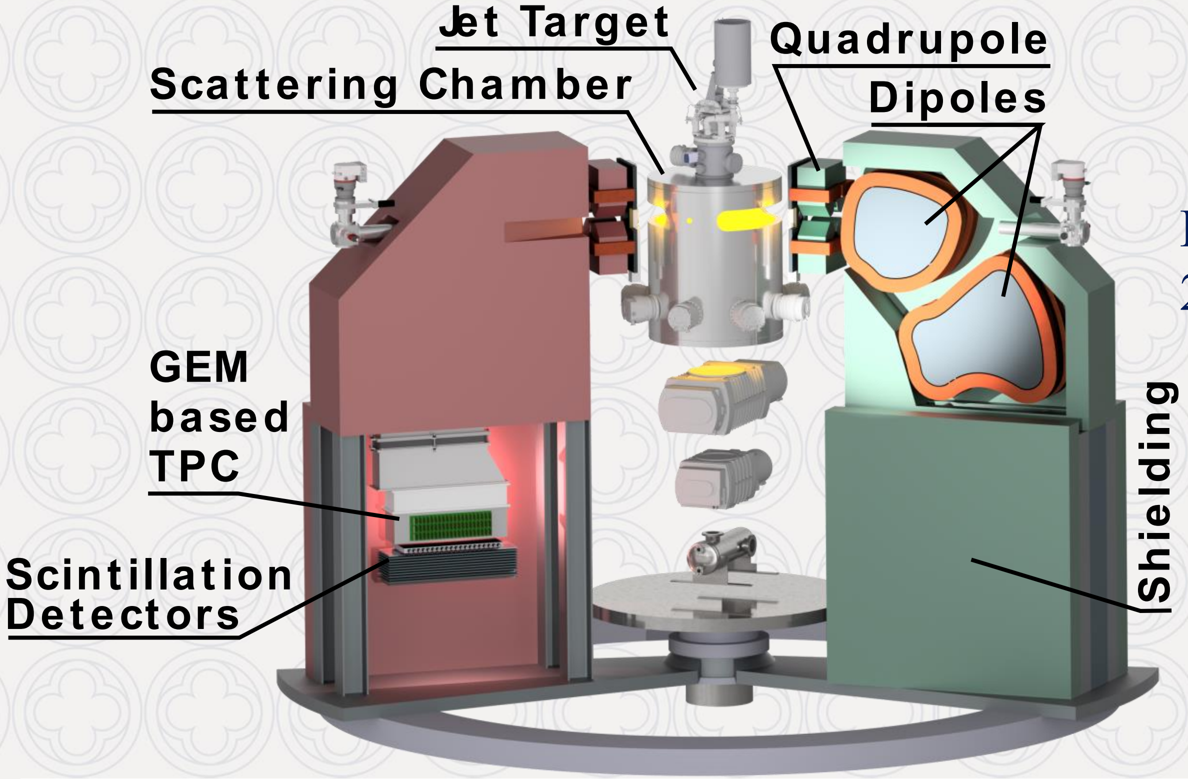
The ULQ^2 Experiment at Tohoku University

Beam momentum values:
20-60 MeV/c
Scattering angle: 30^0 -150^0
Target CH_2
Focal plane detector:
Single-sided Silicon Detectors

C. Legris at this workshop

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status	
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing	
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future	Ongoing
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future	Ongoing
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future / Uncertain	Uncertain
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing	
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future	
ULQ^2	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim 1\%$ (rel.)	Future	Ongoing

The MAGIX@MESA Experiment at Mainz

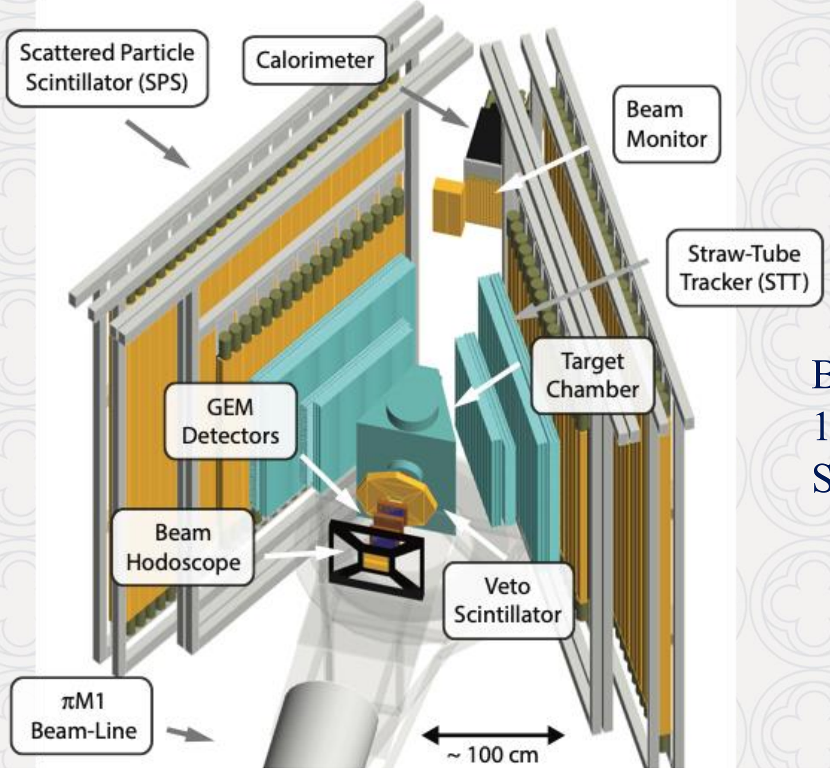


Electron beam momentum:
20-105 MeV/c

P. Achenbach at this workshop

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future
ULQ^2	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim 1\%$ (rel.)	Future

The MUSE Experiment at PSI



Beam momentum values:
115, 153, 210 MeV/c
Scattering angle: 20^0 -100^0

T. Krahulik at this workshop

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future
ULQ^2	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim$ 1% (rel.)	Future

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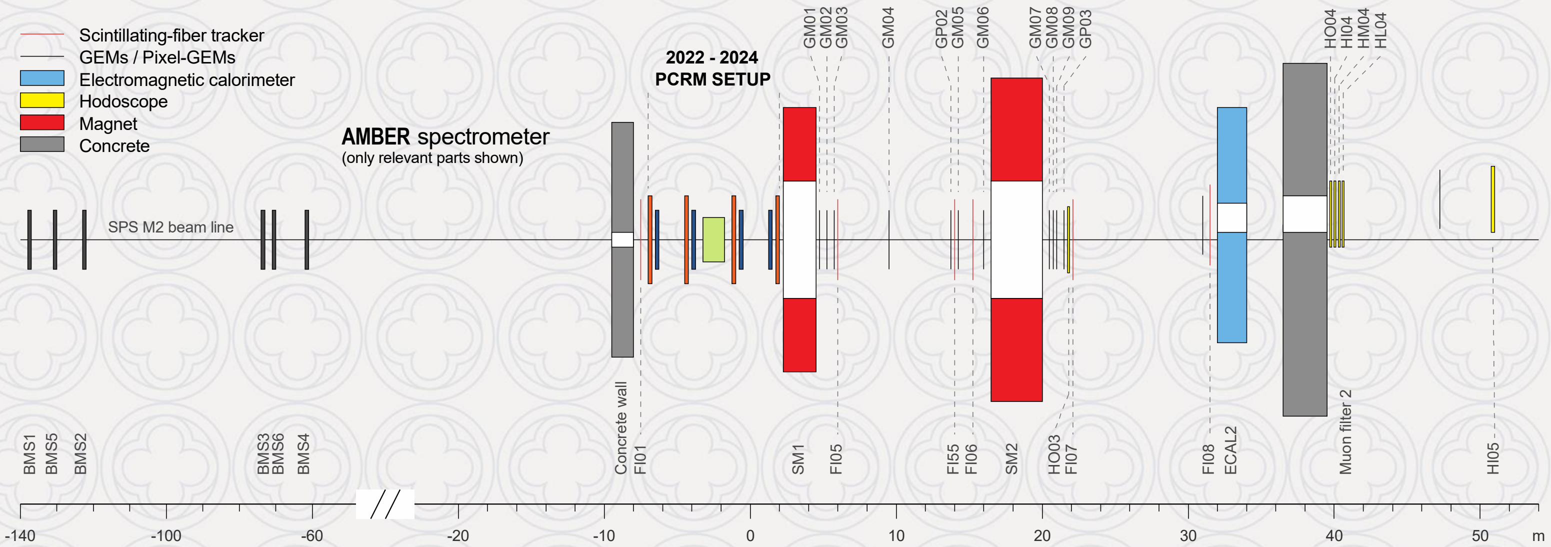
The Amber Experiment at CERN

M2 Beam-line:
100 GeV muons



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J. Friedrich at this workshop

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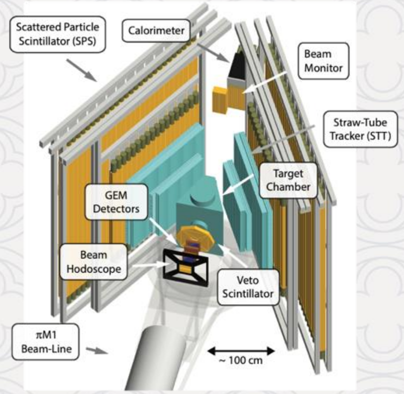
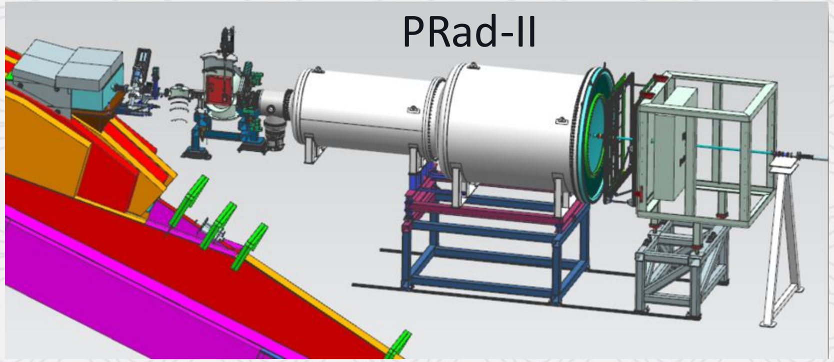
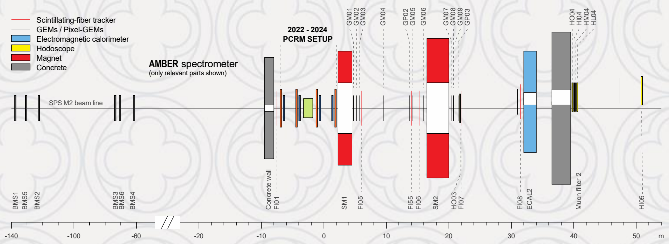
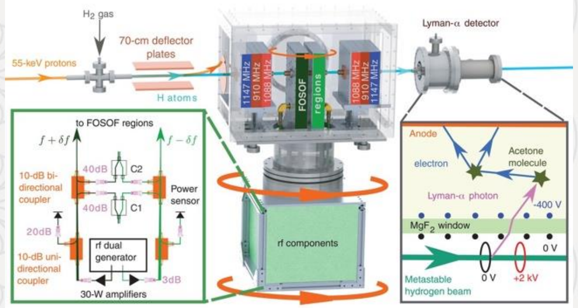
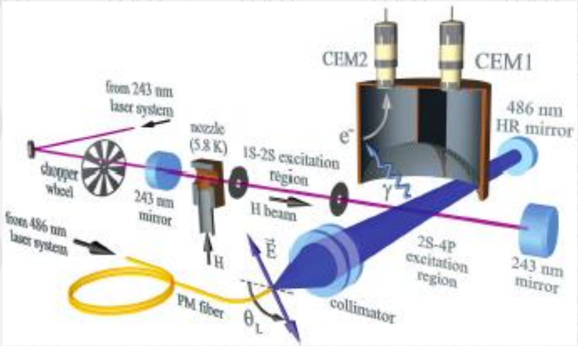
World-wide effort in Nuclear and Atomic Physics on Proton Charge Radius

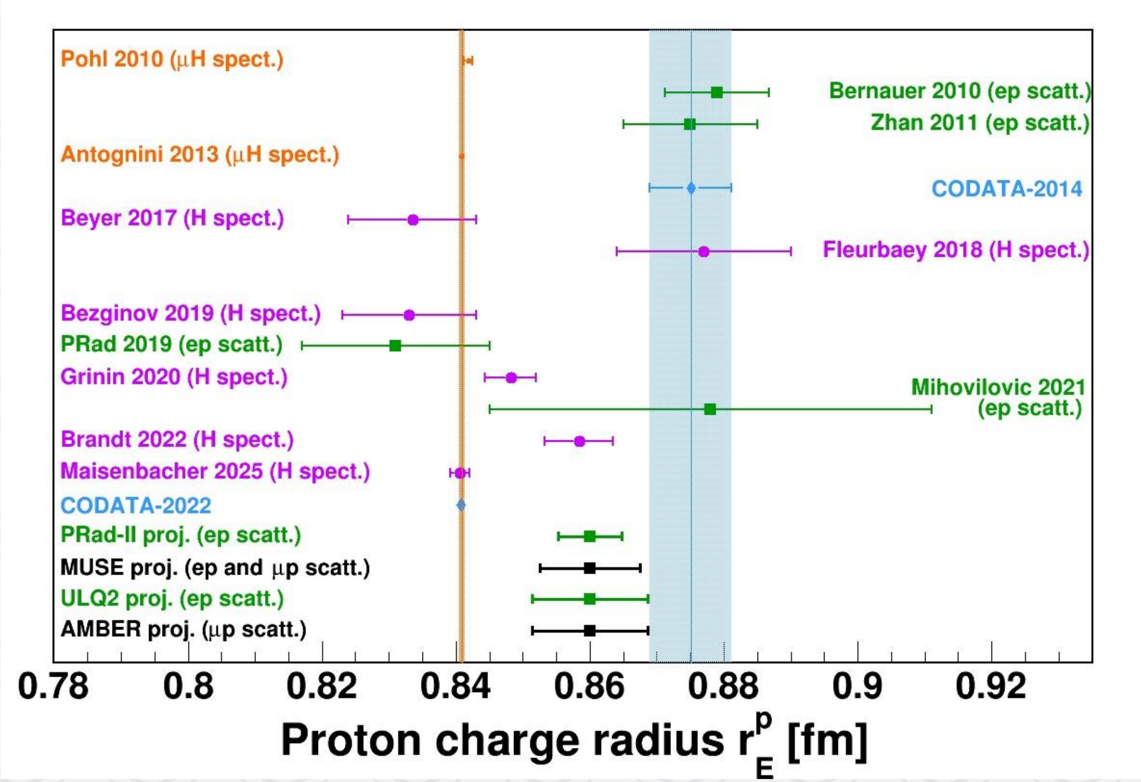




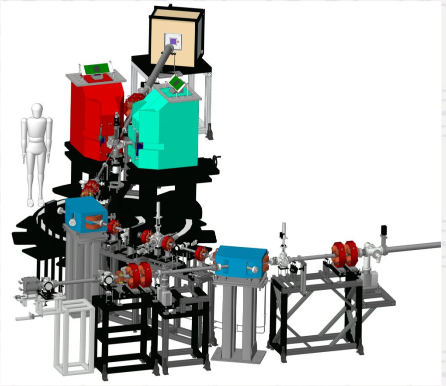


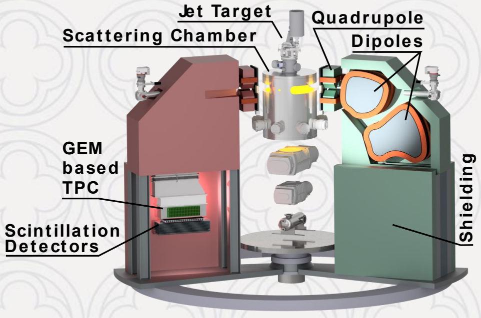






Gao & Vanderhaeghen Rev. Mod. Phys. 94, 015002 (2022)





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Summary

- The proton charge radius puzzle not resolved yet, but major progress made
- The PRad – a first ep scattering experiment using a non-magnetic spectrometer – obtained a result consistent with muonic hydrogen measurements
- Most of the recent ordinary hydrogen spectroscopy measurements are consistent with muonic results
- New results expected from lepton scattering including PRad-II

Acknowledgment: The PRad Collaboration (some collaborators are not shown in the picture)

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