Charge Radii Measurements at JLab with Electrons and Positrons

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Mississippi State University

Workshop on NREC 2026
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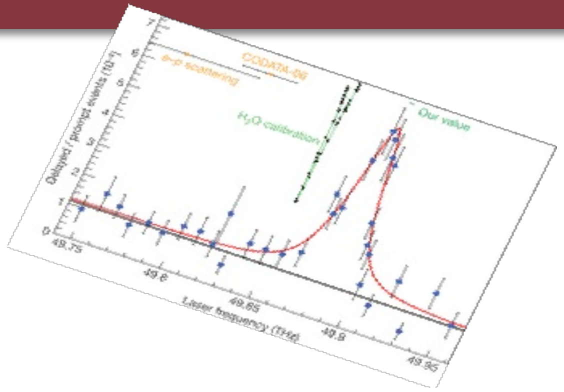
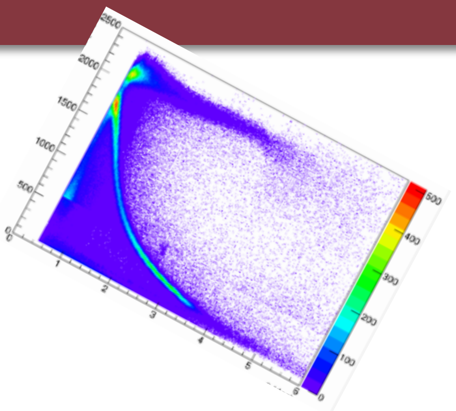
Stony Brook U.

Outline





1. The Proton/Deuteron Charge Radius Puzzles
2. The **PRad Method**
    - windowless target
    - high resolution calorimeter
    - simultaneous detection of elastic and M⌀ller

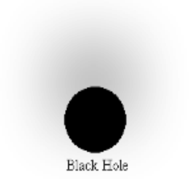
3. Why positrons?
4. Other experiments & prospects

The study of the proton has revolutionized physics

The proton is the primary, stable building block of all visible matter in the Universe.

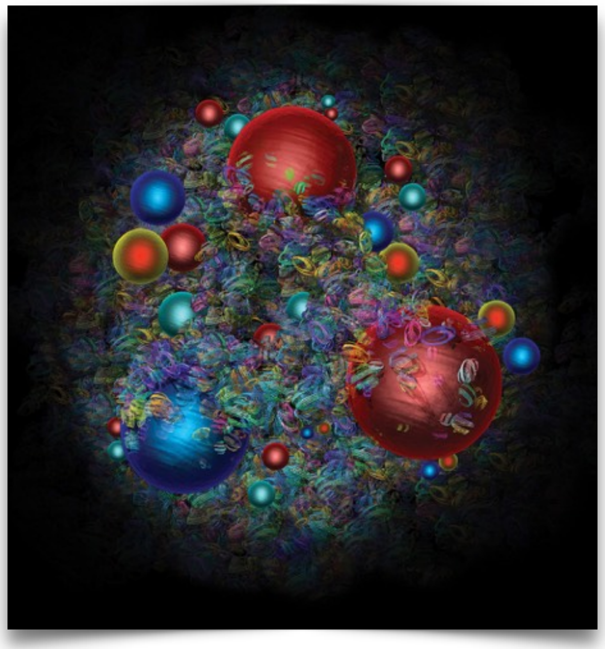
The proton played a leading role in the development of Quantum Chromo Dynamics (QCD): theoretical framework for strong interaction between quarks mediated by gluons.

In the last 100 yrs. since its discovery, the proton has evolved from



Positively charged structure-less point particle

to →



Glob of quarks and gluons, with ~90% of its mass due to the quark gluon interaction (and hence ~90% of the visible mass in the Universe).

The story of the proton has been in lock-step with many of the key advances in physics over the last 100 years.

It continues to surprise us time and again.

Proton's basic properties such as its RMS charge radius is interesting on its own right, but also needed for determining fundamental constants such as the Rydberg constant.

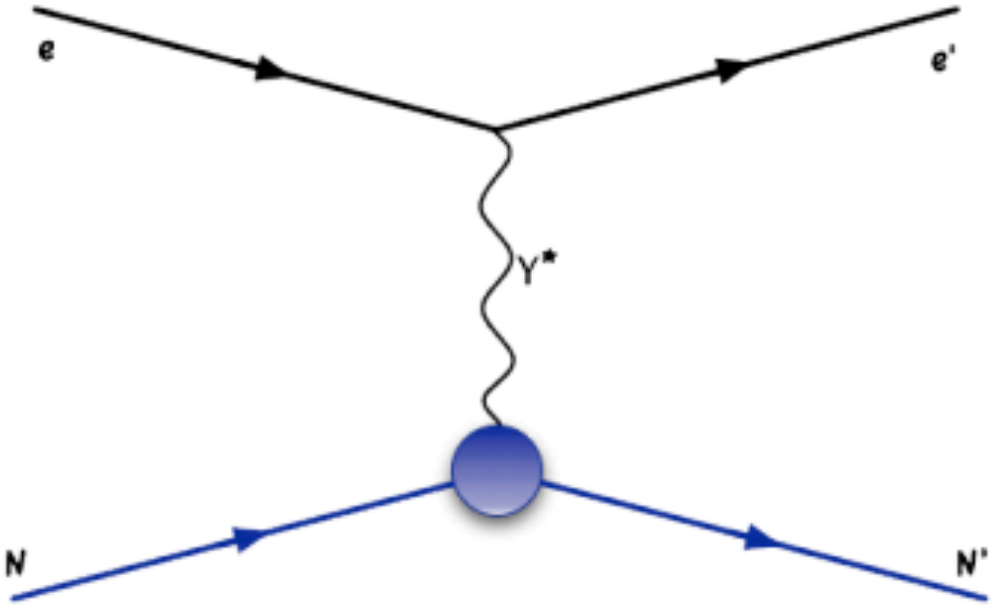
H - spectroscopy and elastic e-p scattering are the two traditional methods for determining proton charge radius

The forces defining the surface of a proton do not come to an abrupt end, its boundary is somewhat fuzzy.

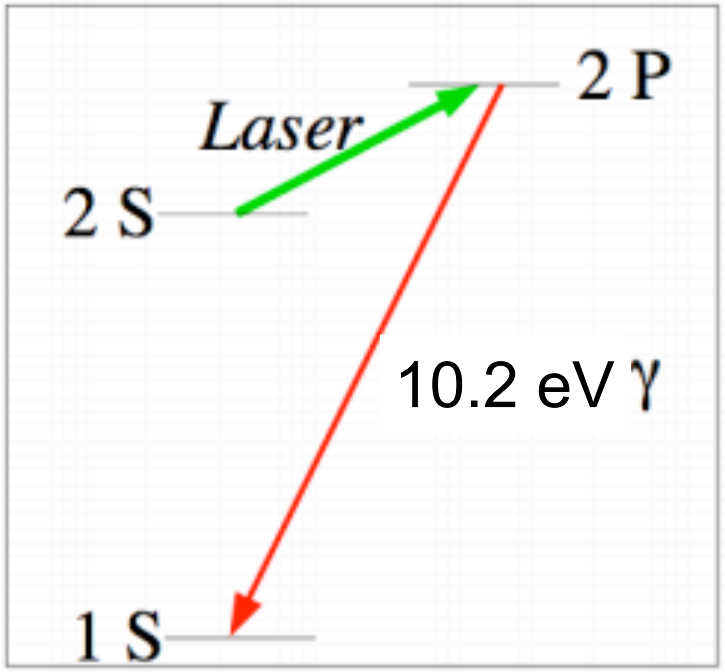
If the proton has no definite boundaries how do you define its radius?

RMS charge radius (r_p) is obtained from a consistent interpretation of hydrogen spectroscopy and electron-proton scattering experiments

e-p Scattering



H-spectroscopy

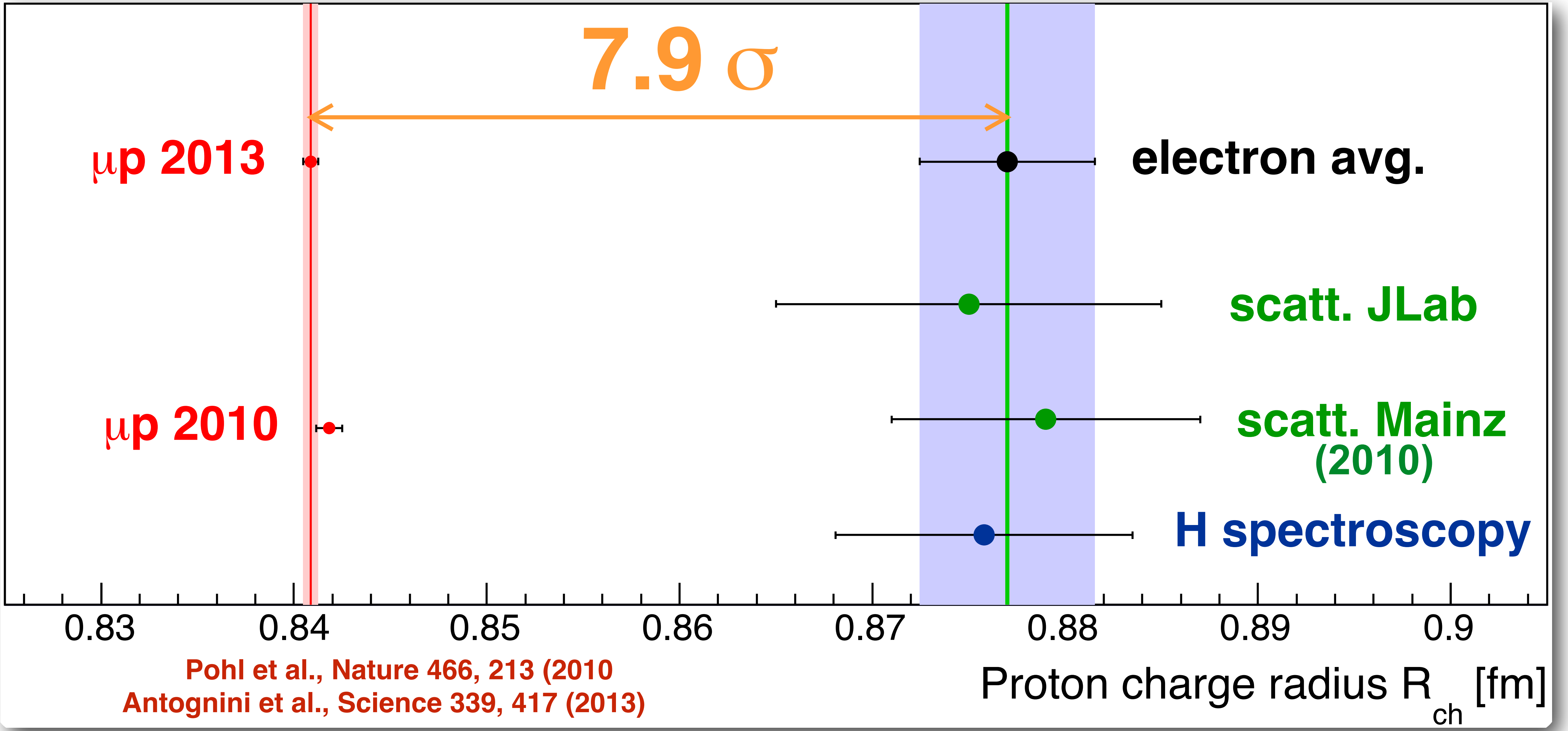


$$< \mathbf{r^2} > = -6 \left| \frac{dG_E^2}{dQ^2} \right|_{Q^2=0}$$

This definition has been rigorously shown to be consistent for all types of experimental measurements. G. Miller, Phys. Rev., C 99, 035202 (2019)

The results from the muonic hydrogen spectroscopy led to the so called "proton radius puzzle."

~8σ discrepancy between muon and electron based measurements



Pohl et al., Nature 466, 213 (2010
Antognini et al., Science 339, 417 (2013)

Proton rms charge radius measured using

electrons: 0.8770 ± 0.0045 (CODATA2010 + Zhan et al.)

muons: 0.8409 ± 0.0004

- unprecedented precision ~0.08%
  - $Q^2 \sim 10^{-6}$ GeV^2

There was a world wide effort to explore numerous possible resolutions to the “proton radius puzzle.”

★ **Are the state of the art QED calculations incomplete?**

- E. Borie, Phys. Rev. A 71, 032508 (2005)
- U. D. Jentschura, Ann. of Phys. 326, 500 (2011)
- F. Hagelstein, V. Pascalutsa, Phys. Rev. A 91, 040502 (2015)

★ **Are there additional corrections to the muonic Lamb shift due to proton structure (such as proton polarizability of $\mathcal{O}(\alpha^5)$?**

- C. E. Carlson, V. Nazaryan and K. Griffioen, Phys. Rev. A 83, 042509 (2011)
- R. J. Hill and G. Paz, Phys. Rev. Lett. 107, 160402 (2011)

★ **Are higher moments of the charge distribution accounted for in the extraction of rms charge radius?**

- M. O. Distler, J. C. Bernauer and T. Walcher, Phys. Lett. B 696, 343 (2011)
- A. de Rujula, Phys. Lett. B 693, 555 (2010), and 697, 264 (2011)
- I. Cloet, and G. A. Miller, Phys. Rev. C. 83, 012201(R) (2011)

★ **Is there an extrapolation problem in electron scattering data?**

- D. W. Higinbotham et al., Phys. Rev. C 93, 055207 (2016)
- K. Griffioen, C. Carlson, S. Maddox, Phys. Rev. C 93, 065207 (2016)
- Z-F. Cui, D. Binosi, C. D. Roberts, S. Schmidt, Phys. Rev. Lett. 127, 092001 (2021) (Continuum Schwinger Mtd.)

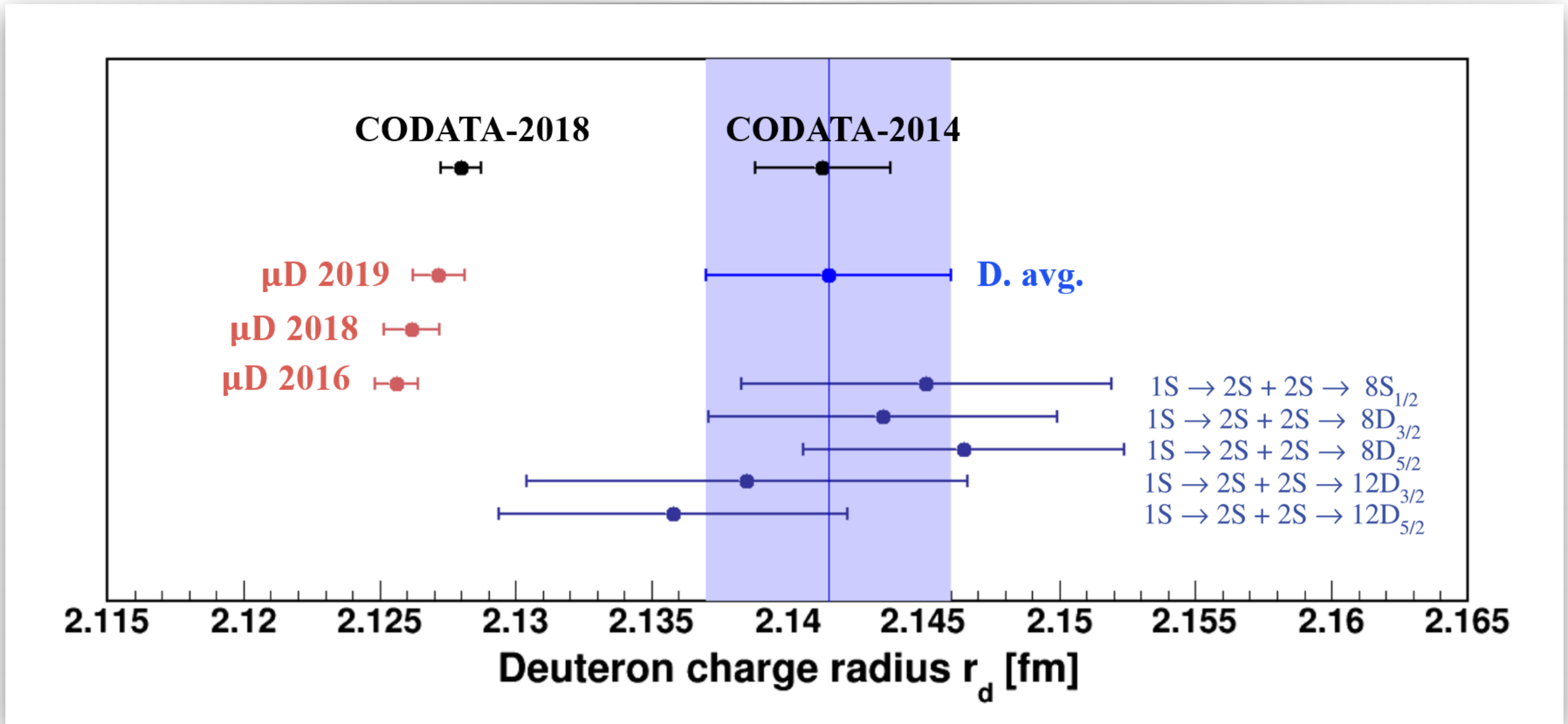
★ **Has new physics been discovered (violation of Lepton Universality)?**

- V. Barger, et al., Phys. Rev. Lett. 106, 153001 (2011)
- B. Batell, D. McKeen, M. Pospelov, Phys. Rev. Lett. 107, 011803 (2011)
- D. Tucker-Smith, I. Yavin, Phys. Rev. D 83, 101702 (2011).

★ **New force carriers?**

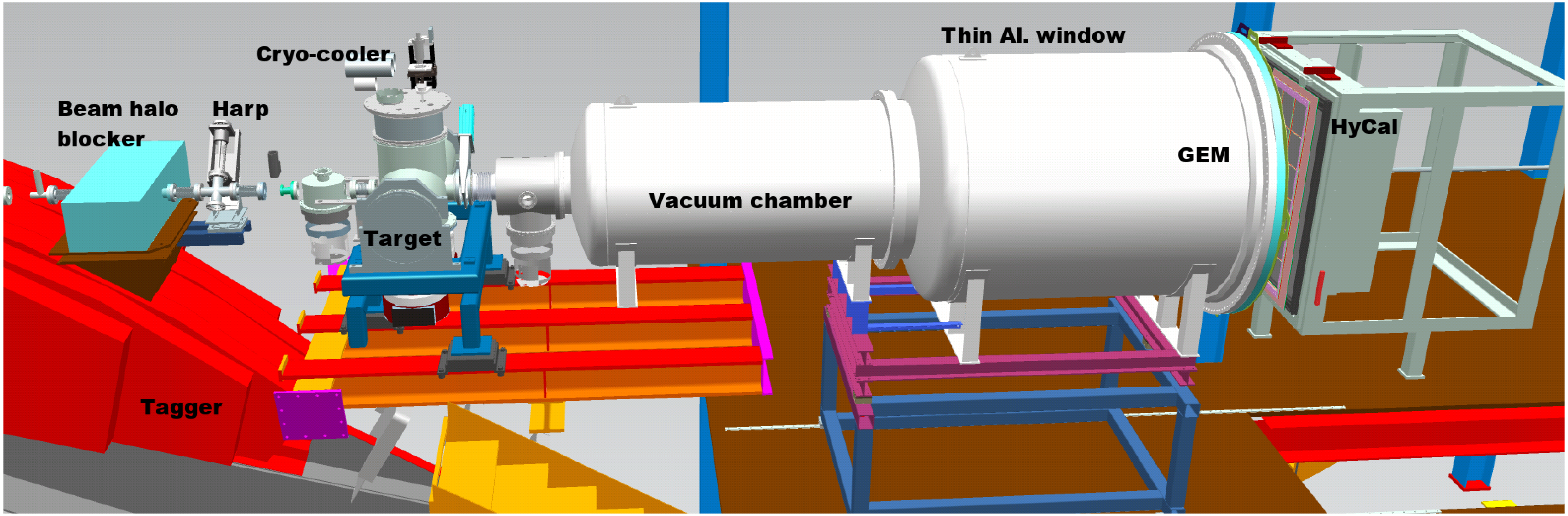
- C. E. Carlson, Prog. Part. Nucl. Phys. 82, 59–77 (2015).
- Y. S. Liu and G. A. Miller, Phys. Rev. D 96, 016004 (2017).

The "deuteron radius puzzle" unfolded soon after the "proton radius puzzle" but with less fanfare.



A ~6 σ discrepancy between r_D from ordinary D and μD spectroscopy was observed a few years after the "proton radius puzzle" came to the fore.

PRad: a novel electron scattering experiment



Spokesperson: A. Gasparian,
Co-spokespersons: D. Dutta, H. Gao, M. Khandaker

- **High resolution, Hybrid calorimeter** **(magnetic spectrometer free)**
- **Windowless, high density H_2 gas flow target** **(reduced backgrounds)**
- **Simultaneous detection of elastic and Møller electrons** **(control of systematics)**
- **Vacuum chamber, one thin window, large area GEM chambers** **(better resolution)**
- **Q^2 range of 10^{-4} – $6\text{x}10^{-2}$ GeV^2** **(lower than all previous electron scattering expts.)**

Ran in Hall-B at JLab in 2016, using 1.1 GeV and 2.2 GeV electron beam

talk by H. Gao on Tuesday 04/14

e-p elastic cross section extracted by normalizing to Møller cross section.

bin-by-bin normalization (double arm Møller)

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

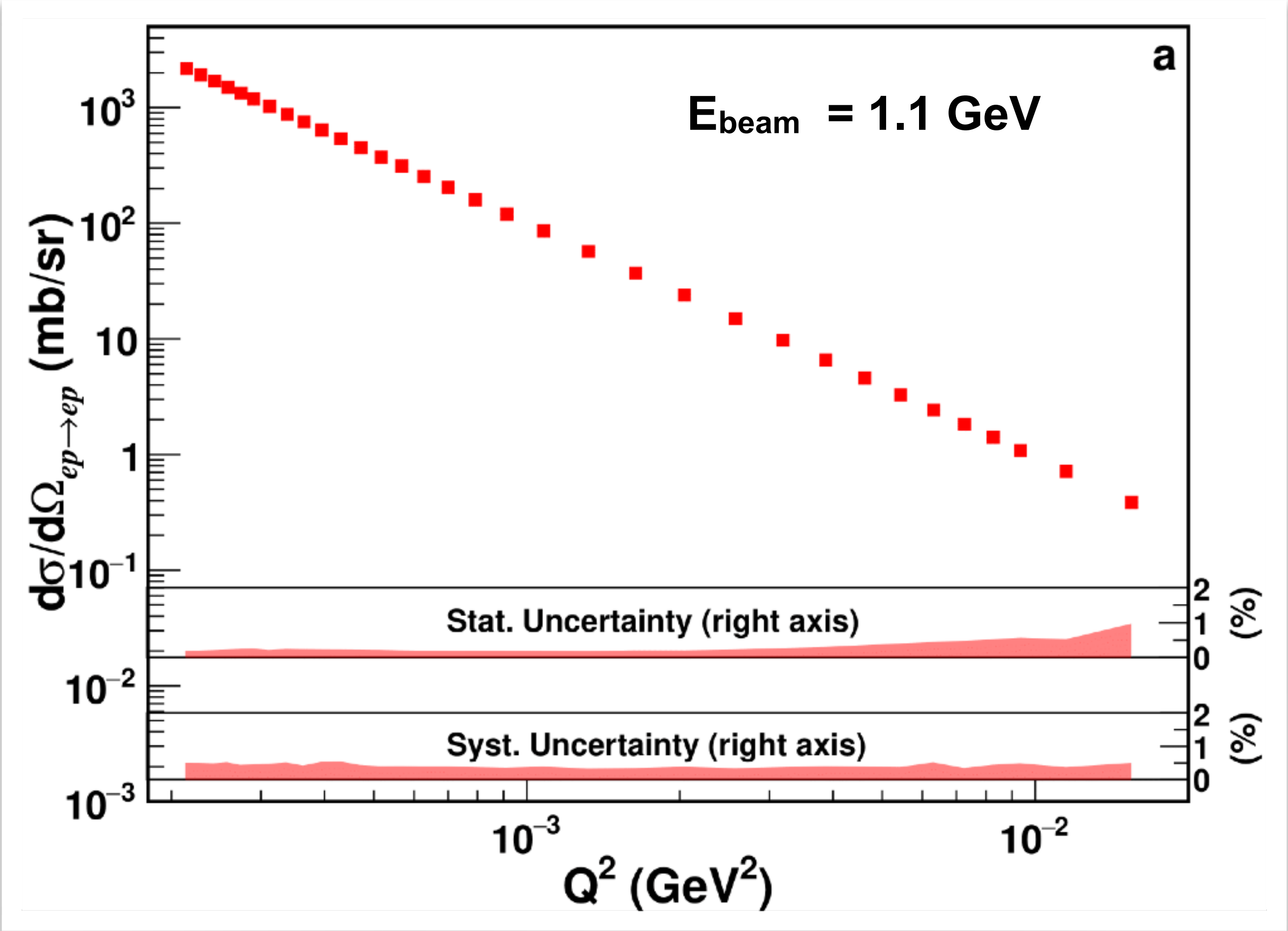
or

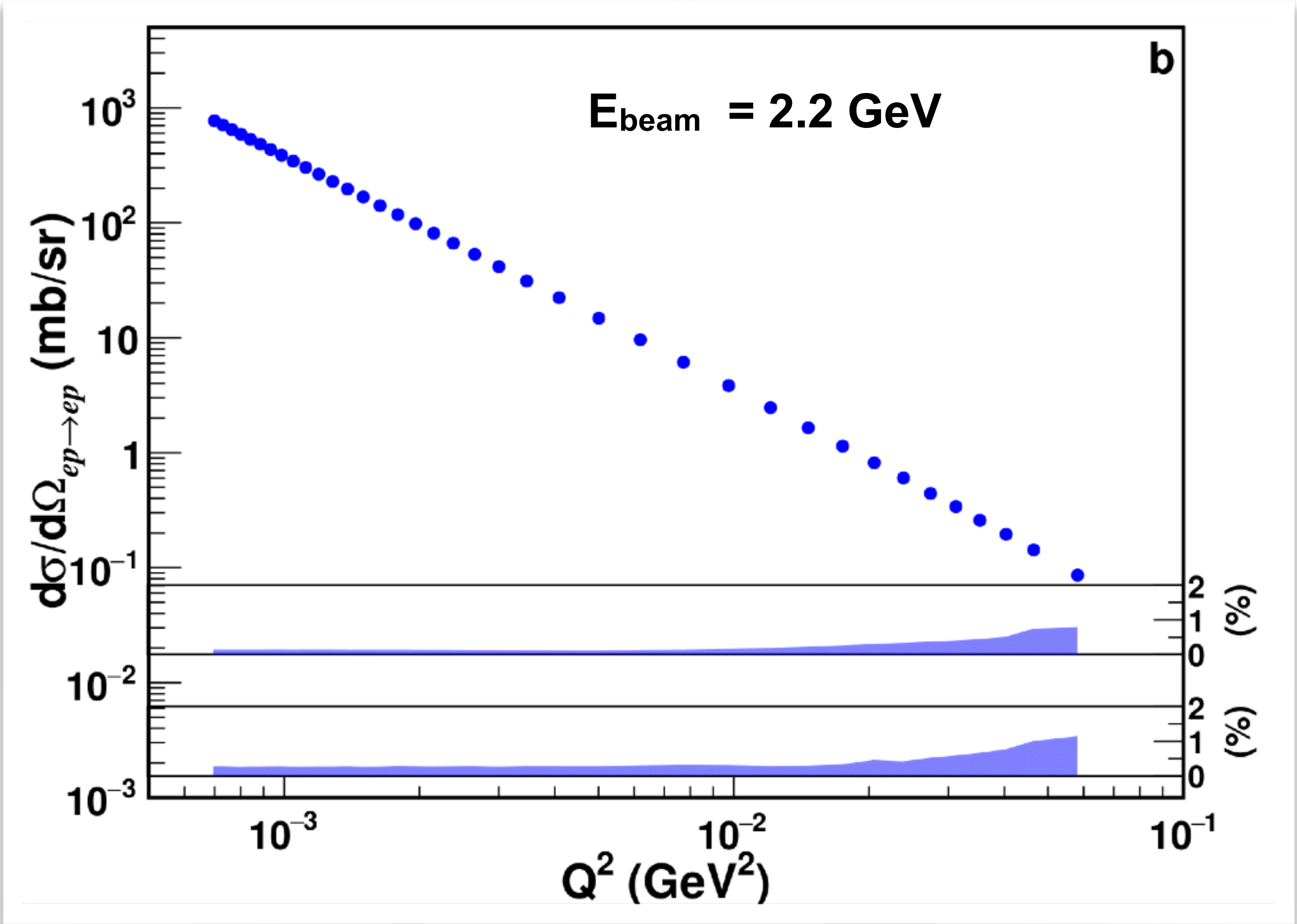
integrated over HyCal acceptance

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

Event generator for *e-p* elastic and Møller include radiative corrections beyond the ultra-relativistic approximation & two photon exchange **(used iteratively within a Geant4 simulation)**

1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41, 115001 (2014).
2. I. Akushevich et al., Eur. Phys. J. A 51, 1 (2015).
3. O. Tomalak, Few Body Syst. 59, 87 (2018). (two photon exchange formalism)

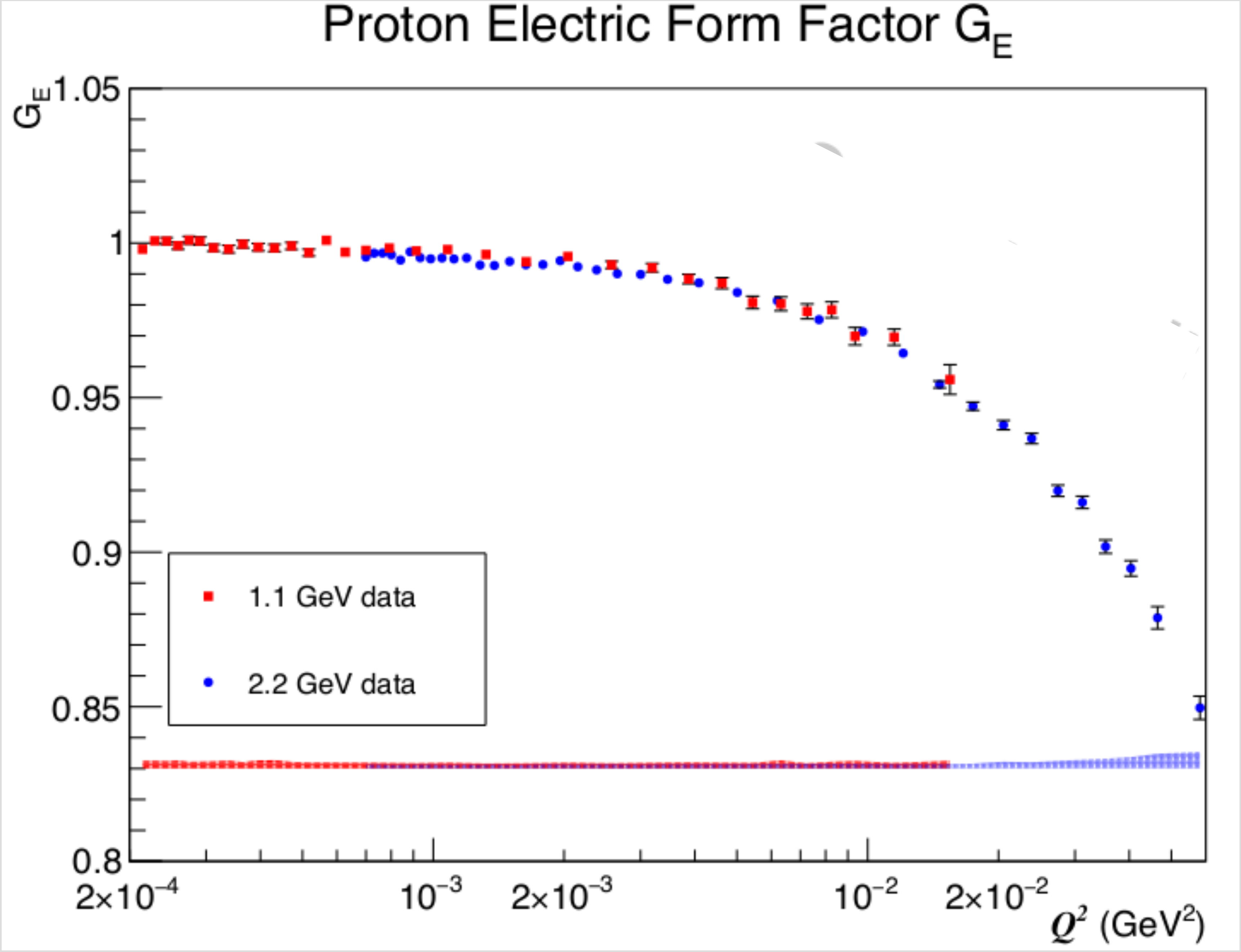




Systematic uncertainties: 0.3% - 0.5% at 1.1 GeV and 0.3% - 1.1% at 2.2 GeV

Figures courtesy of W. Xiong

The proton electric form factor was extracted at the lowest Q^2 ever achieved in electron scattering.



The slope of $G_E(Q^2)$ as $Q^2 \rightarrow 0$ is proportional to r_p^2.

Typically r_p is obtained by fitting $G_E(Q^2)$ to a functional form and extrapolating to $Q^2 = 0$.

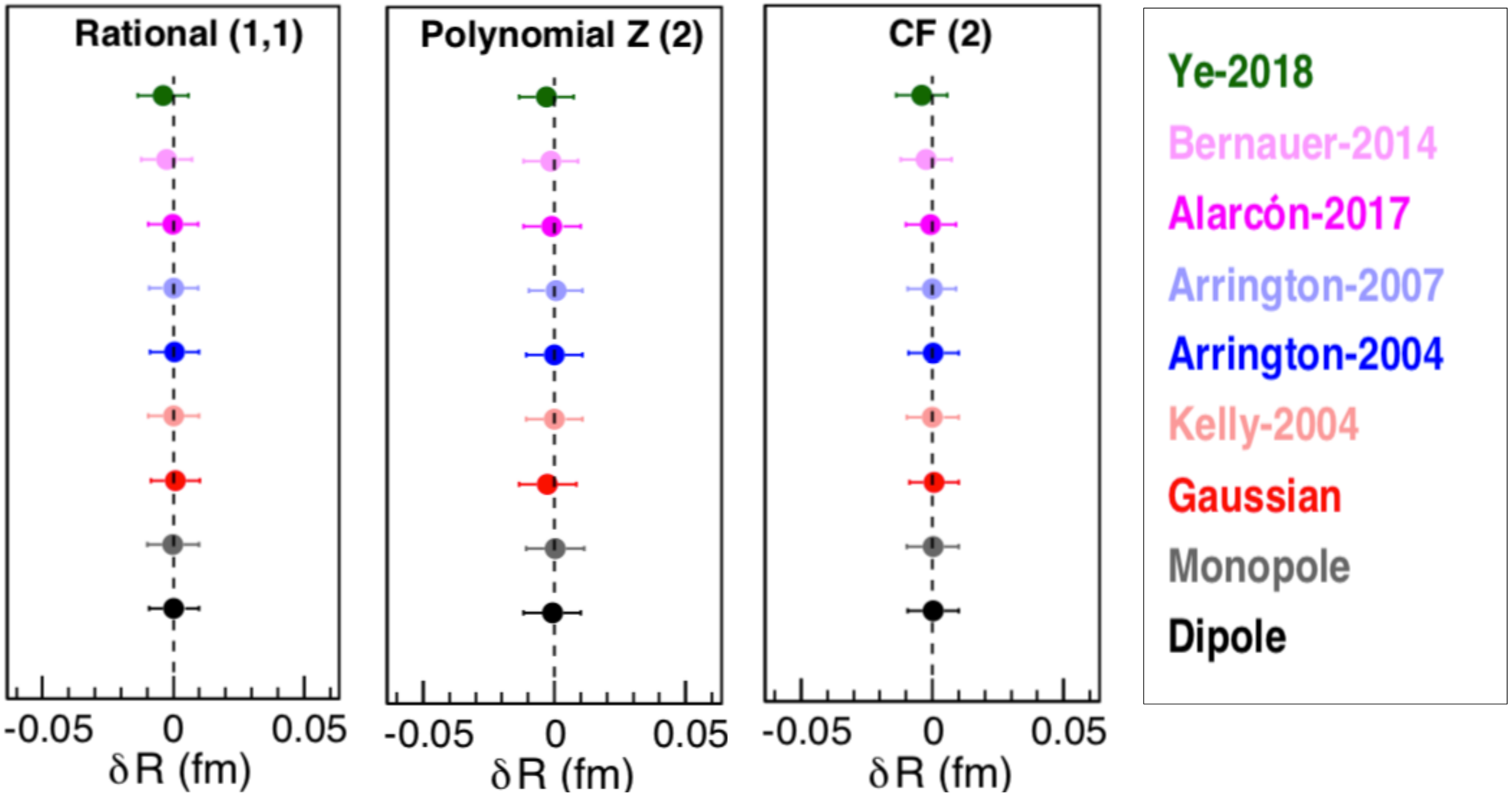
The truncation of the higher-order moments of $G_E(Q^2)$ introduces a model dependence which can bias the determination of r_p.

Figure courtesy of W. Xiong

A wide range of functional forms were systematically tested for their robustness in extracting r_p.

- **Numerous functional forms were tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties:** X. Yan *et al.* Phys. Rev. C98, 025204 (2018)

- **Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties**



Rational (1,1)

$$p_0 \frac{1+p_1Q^2}{1+p_2Q^2}$$

2nd order z transformation

$$p_0(1+p_1z+p_2z^2)$$

$$z = \frac{\sqrt{T_c+Q^2}-\sqrt{T_c-T_0}}{\sqrt{T_c+Q^2}+\sqrt{T_c-T_0}}$$

2nd order continuous faction

$$p_0 \frac{1}{1+\frac{p_1Q^2}{1+p_2Q^2}}$$

The robustness = root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{(\delta R)^2+\sigma^2},$$

δR = difference between the input and extracted radius
σ = statistical variation of the fit to the mock data

Estimated from >10,000 mock data sets smeared by systematic and statistical uncertainties.

Figure courtesy of W. Xiong

The rational (1,1) functional forms provides the most robust extraction of r_p from the PRad data.

- 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: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$
- PRad fit shown as $f(Q^2)$

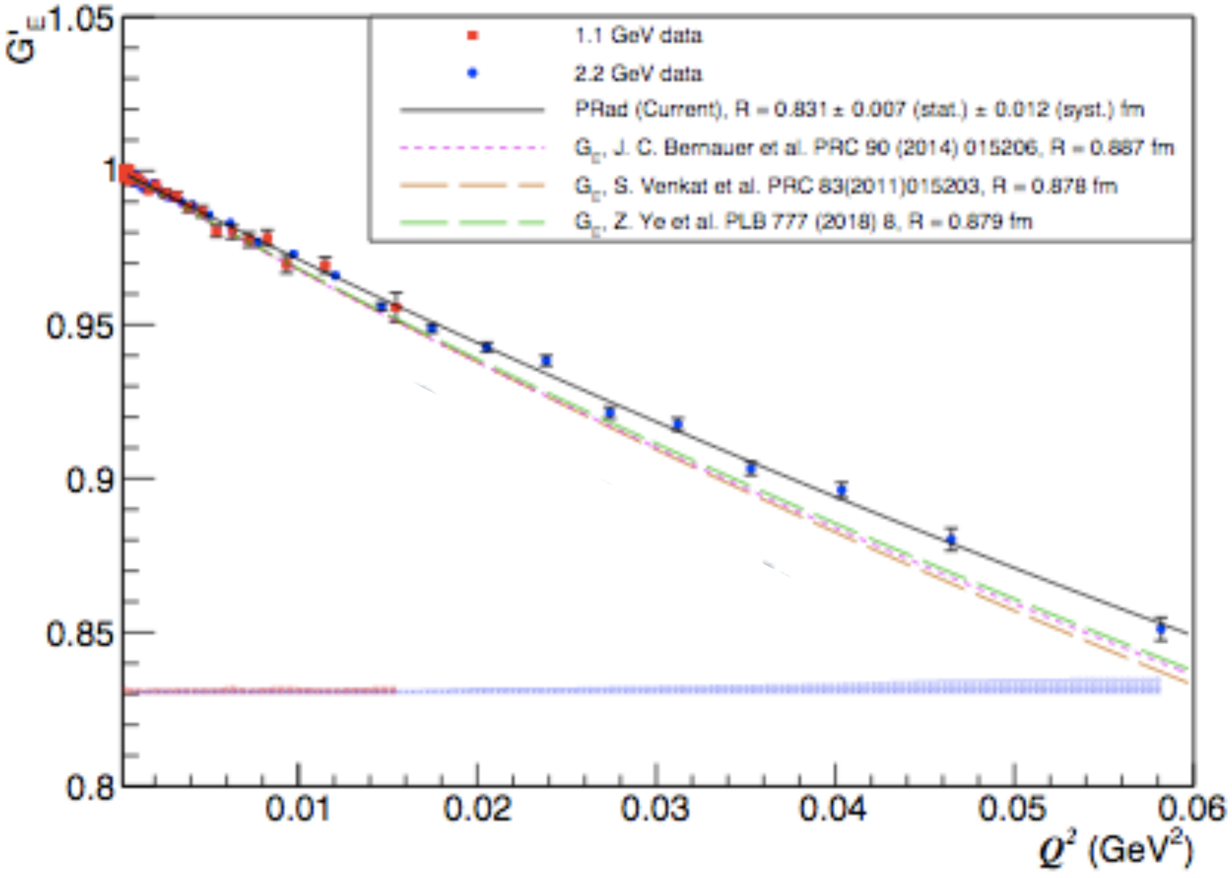
Using rational (1,1)

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

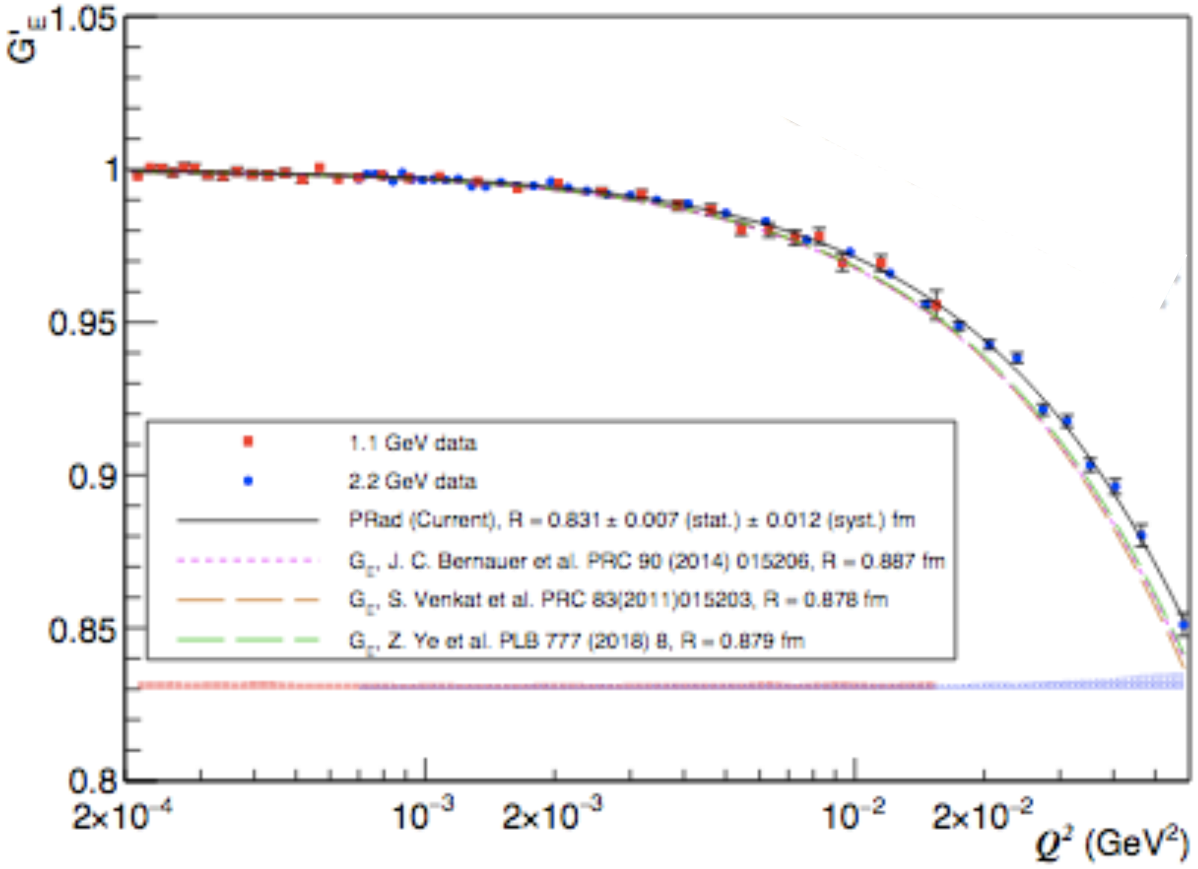
$$r_p = \sqrt{6(p_2 - p_1)}.$$

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

Proton Electric Form Factor G'_E



Proton Electric Form Factor G'_E



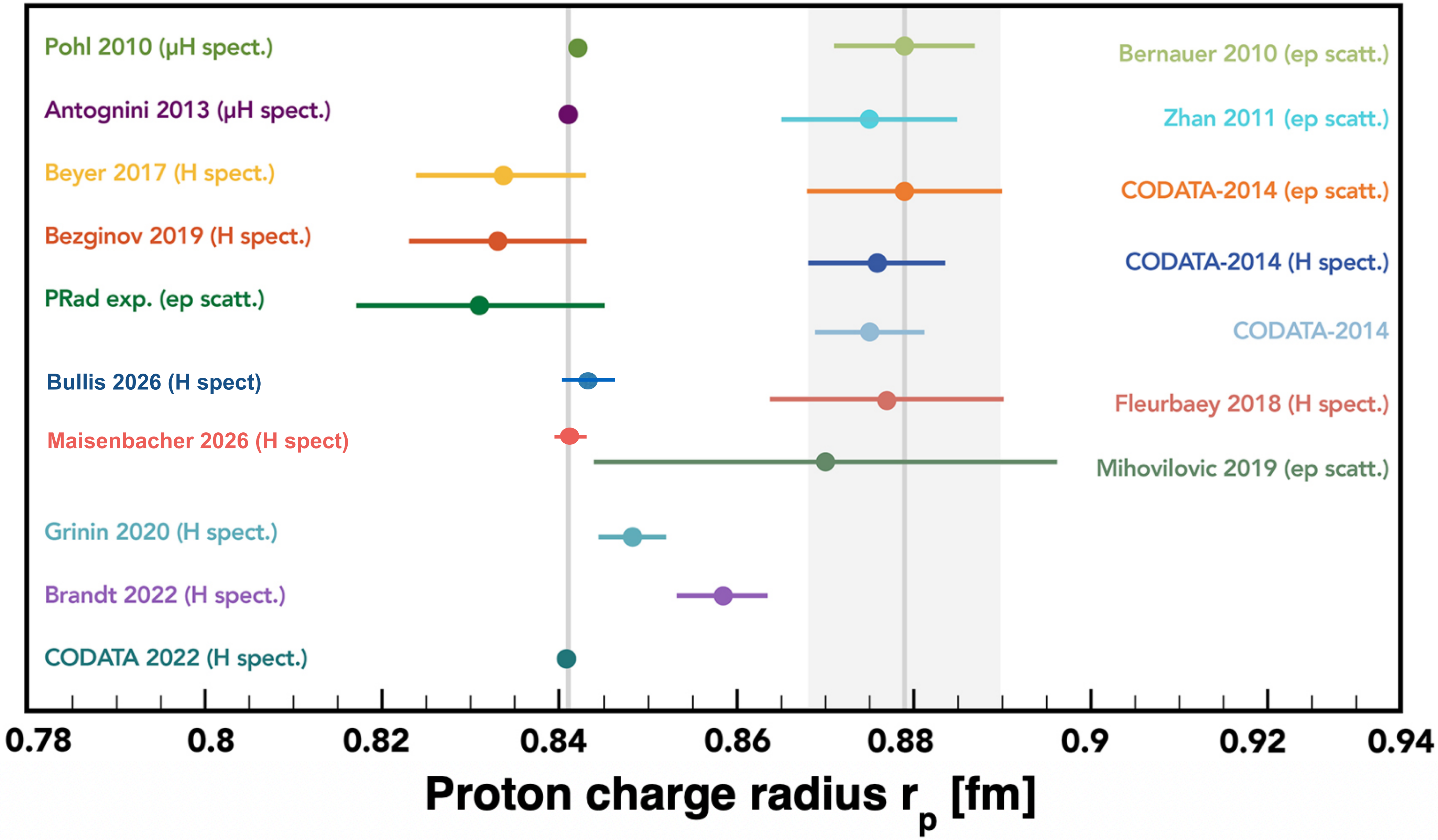
n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

W. Xiong et al., Nature, 575, 147 (2019)

Figures courtesy of W. Xiong

Since PRad there has been dramatic development over the last few years.

Several new H-spectroscopy results were reported



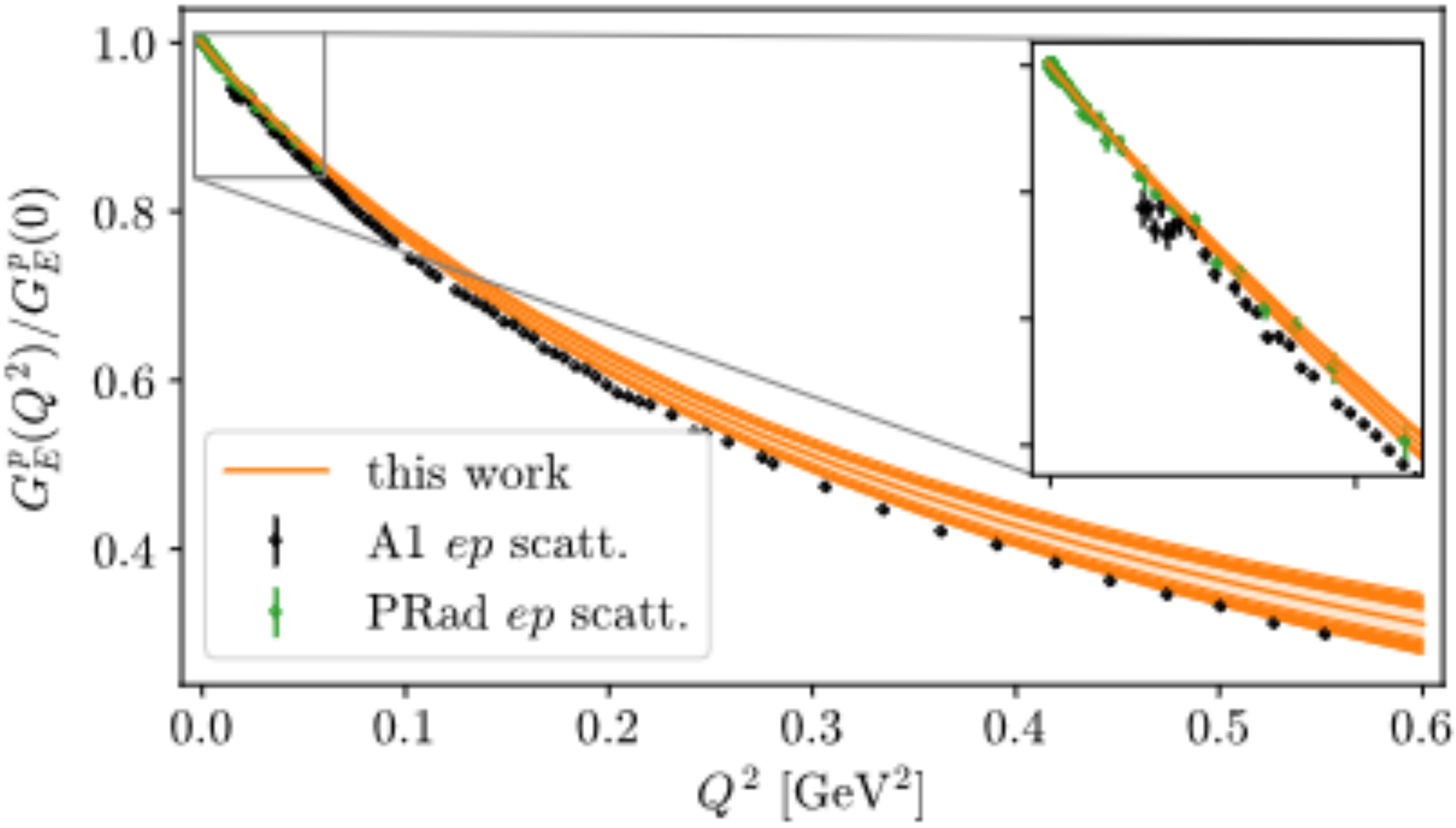
CODATA revised the value of r_p and the Rydberg constant.

2020 Review of Particle Physics claims - "…the puzzle appears to be resolved"

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

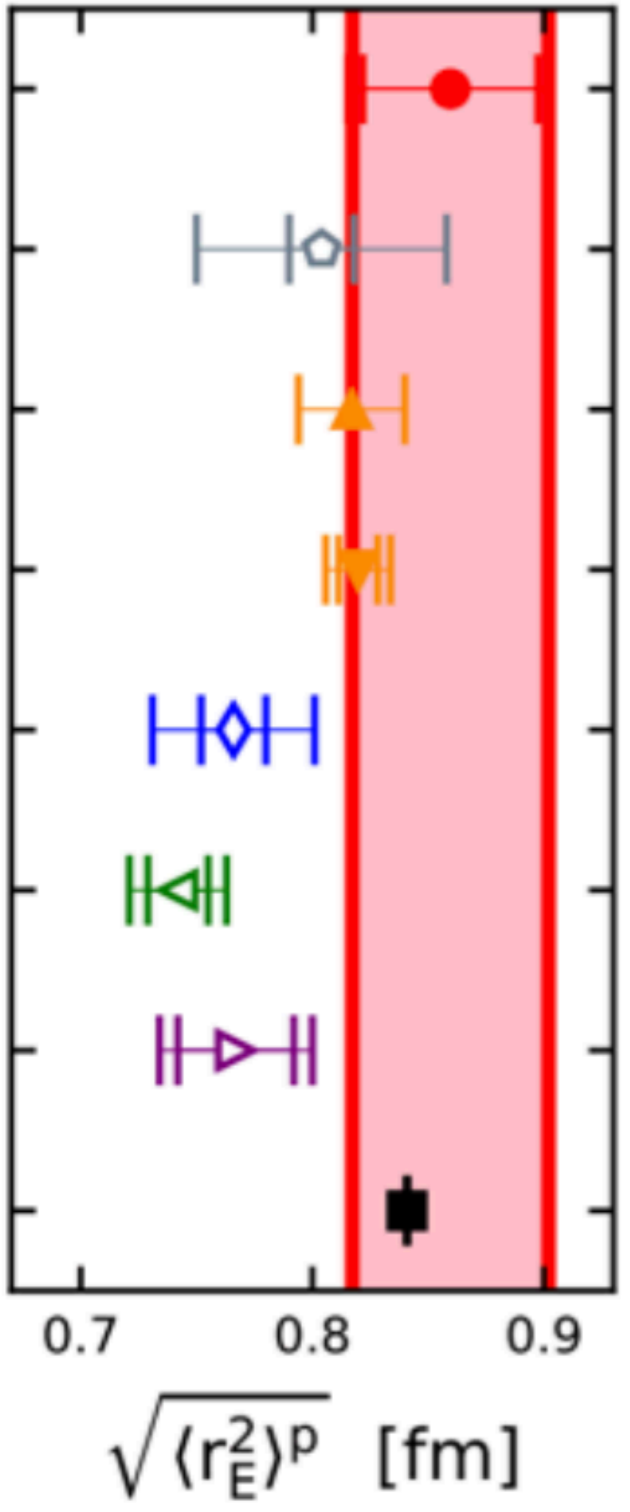
Latest Review Article: H. Gao & M. Vanderhaeghen, Rev. Mod. Phy. **94**, 015002 (2022).

New lattice results have also created a buzz.



D. Djukanovic et al. PRL, 132, 211901 (2024)

D. Djukanovic et al. PRD, 109, 094510 (2024)



talk by M. Constantinou on Wednesday 04/15

PRad-II is designed to address a new puzzle in hadronic physics.

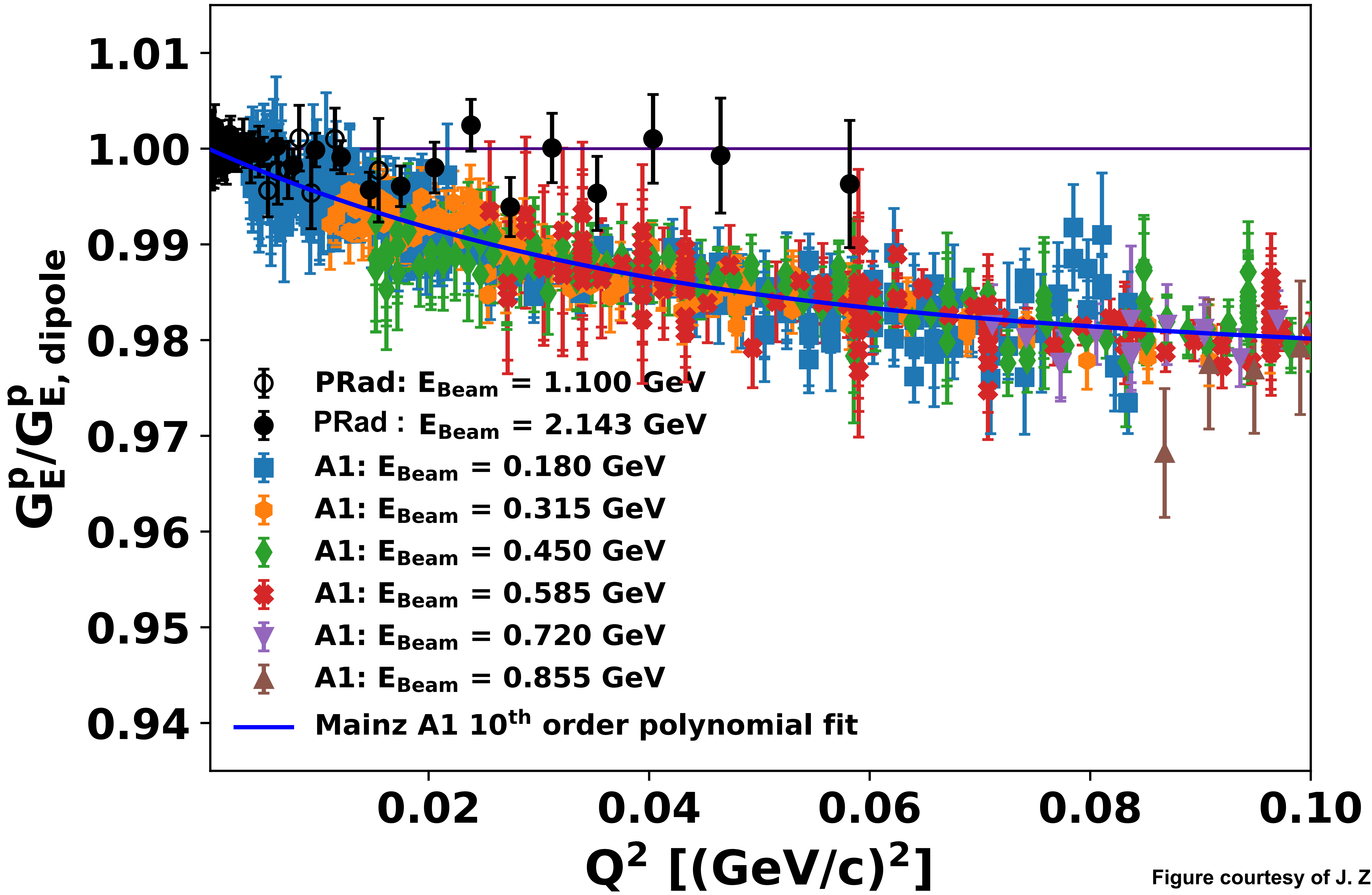
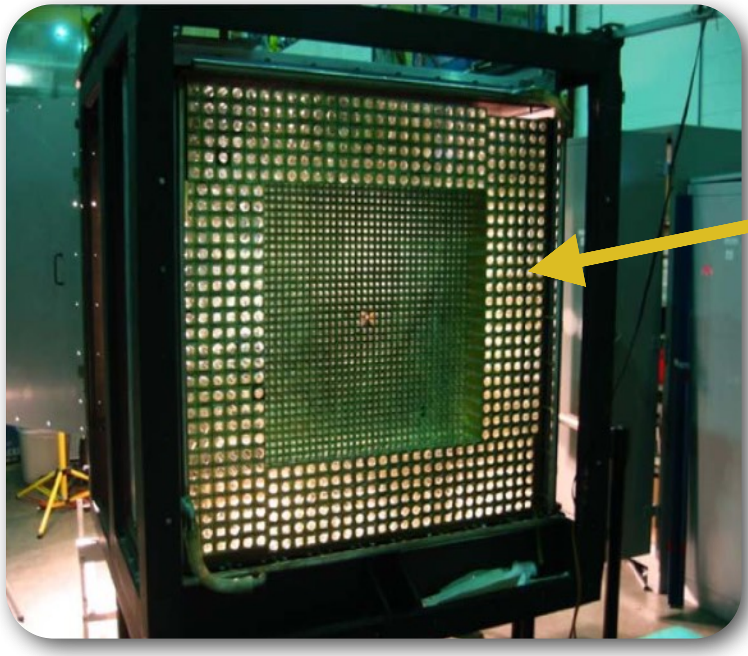


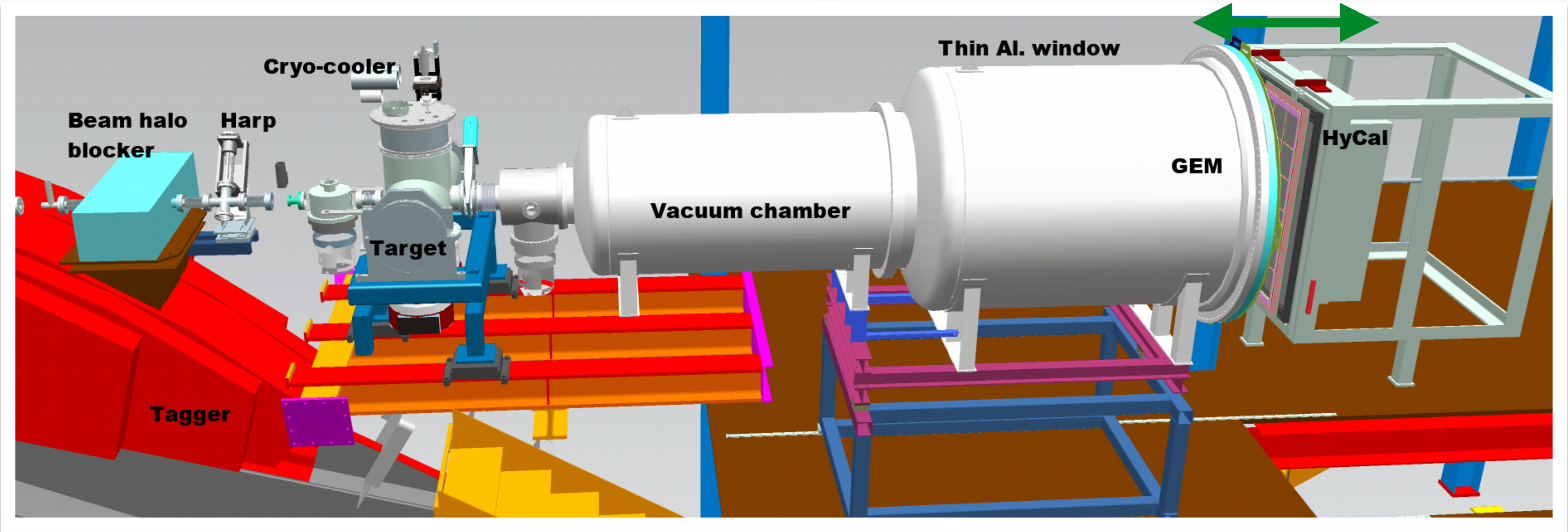
Figure courtesy of J. Zhou

A new experiment - PRad-II just started at JLab it will push the precision frontier of electron scattering.



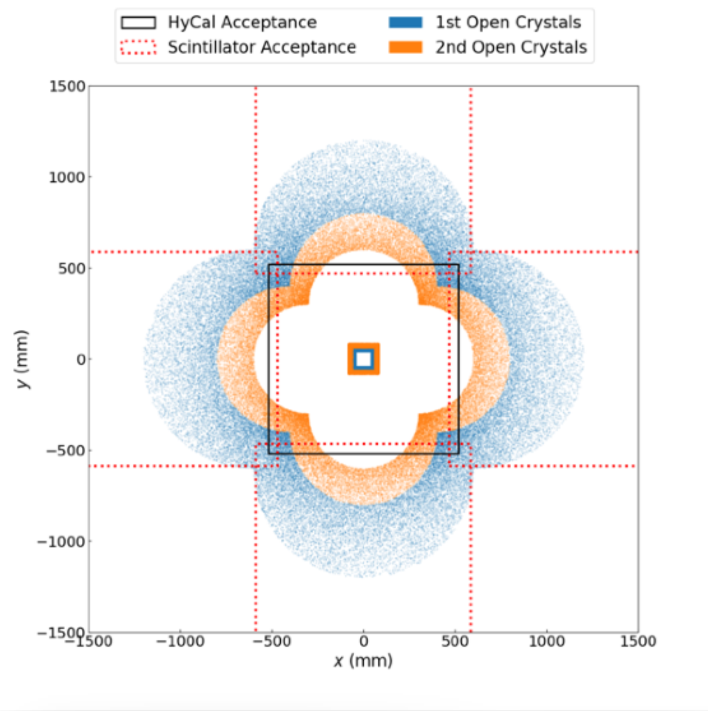
Upgrade HyCal to a FADC based readout (only the inner $PbWO_4$ crystals will be used)

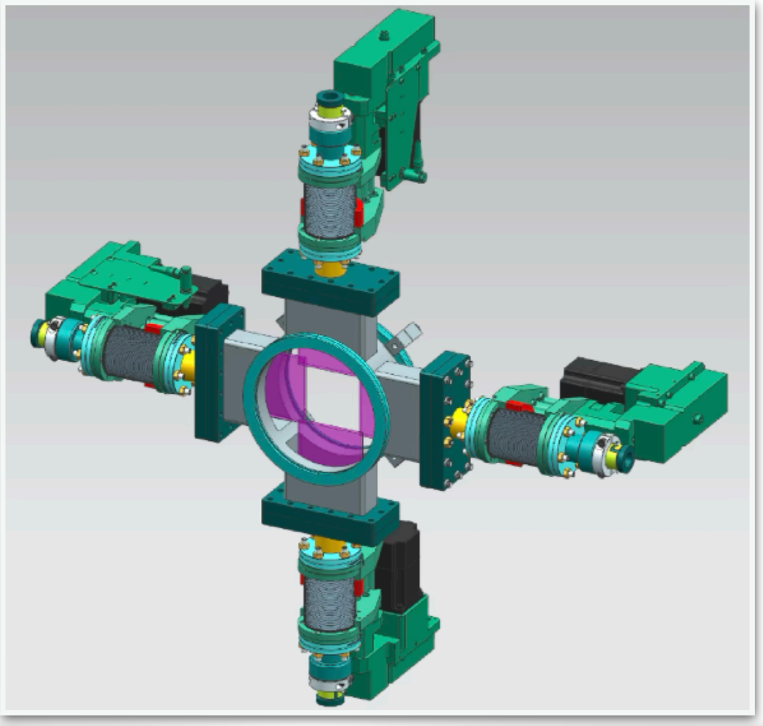
Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.



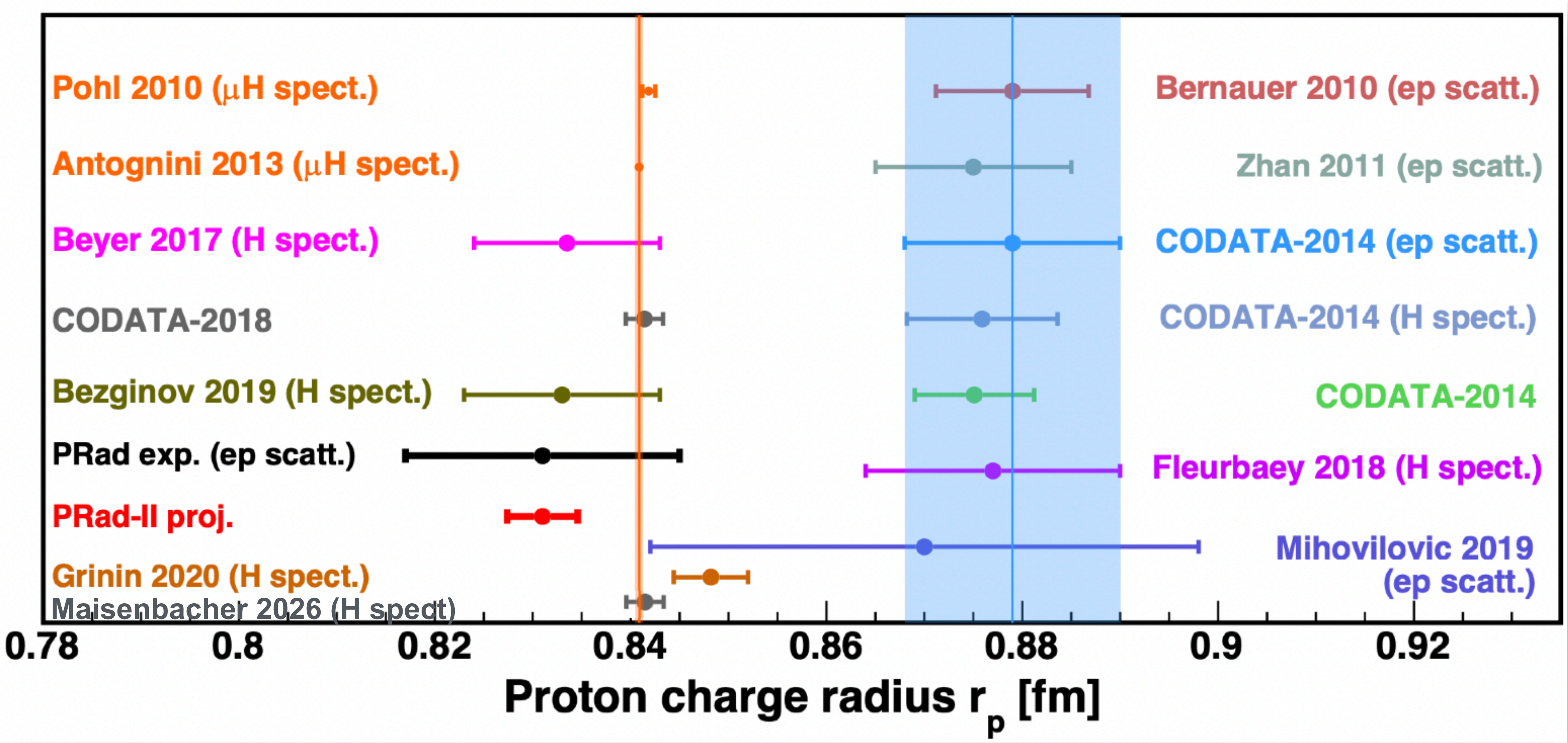
Will improve the precision of r_p measurements and start a new program of high precision measurements using the PRad method

PRad-II is projected to be ~3.5 times more precise than PRad with an uncertainty of 0.0043 fm.





A new scintillator detector will help reach the smallest scattering angles and the lowest Q^2 range (10^{-5} GeV^2) in lepton scattering.



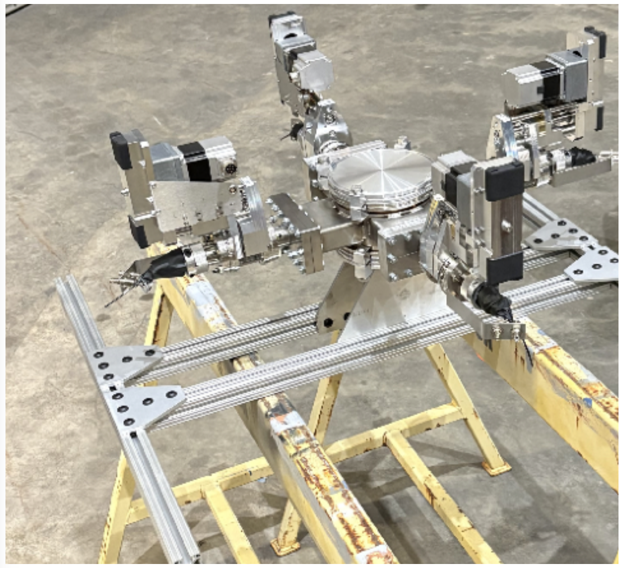
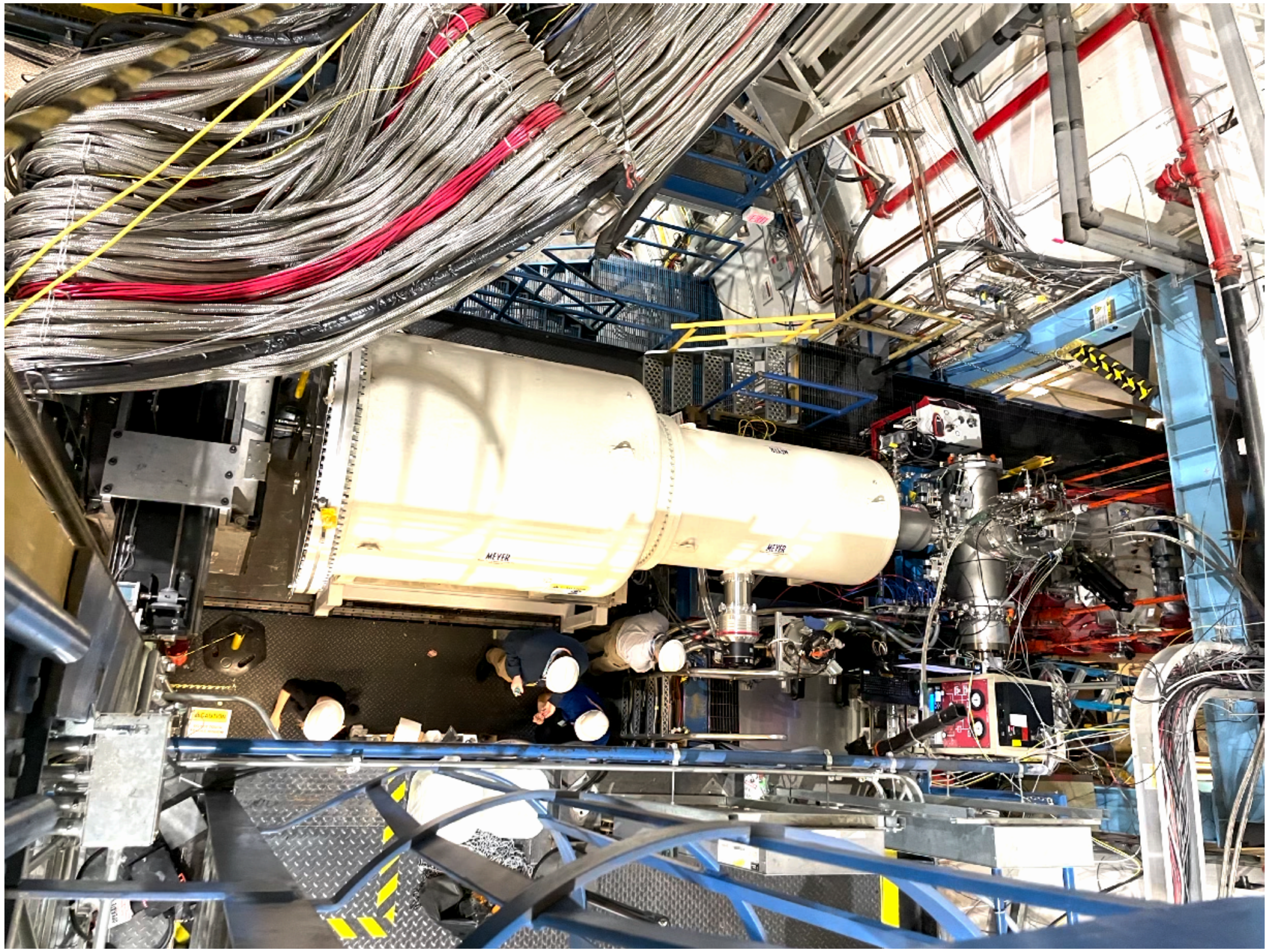
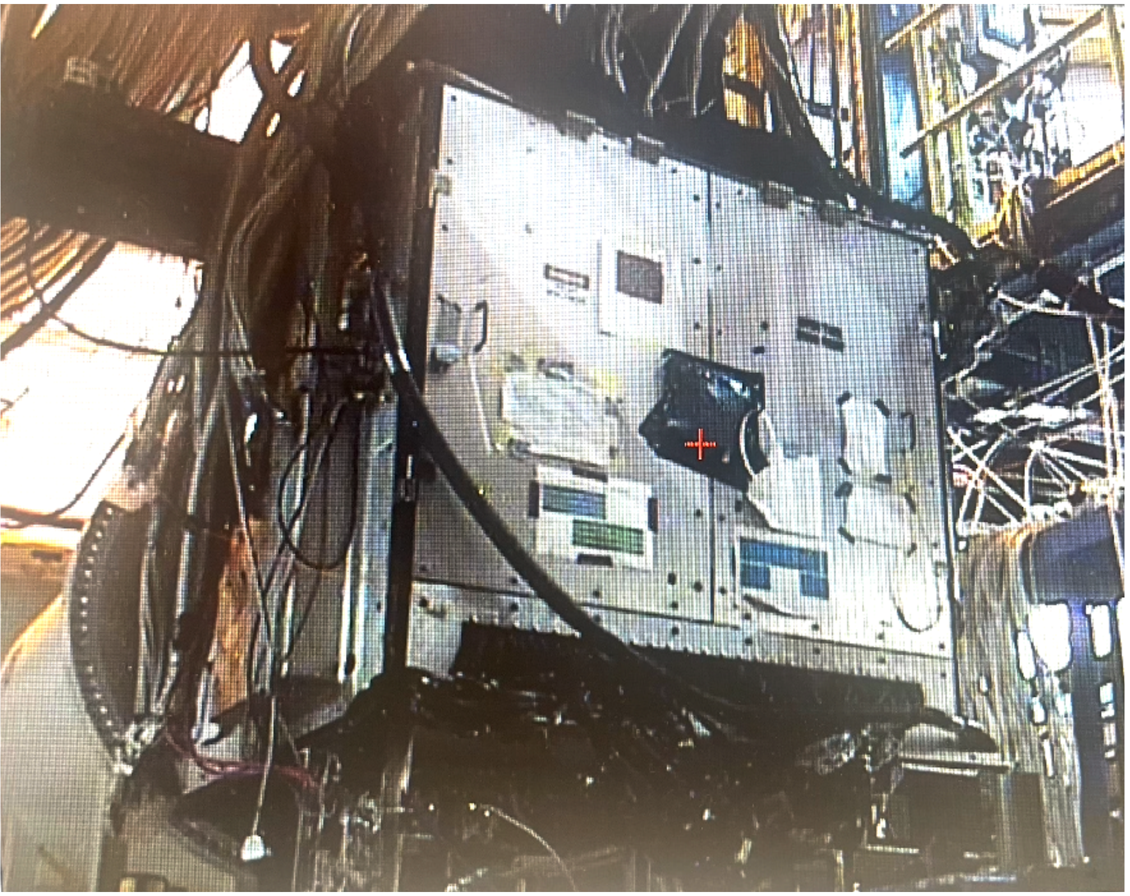


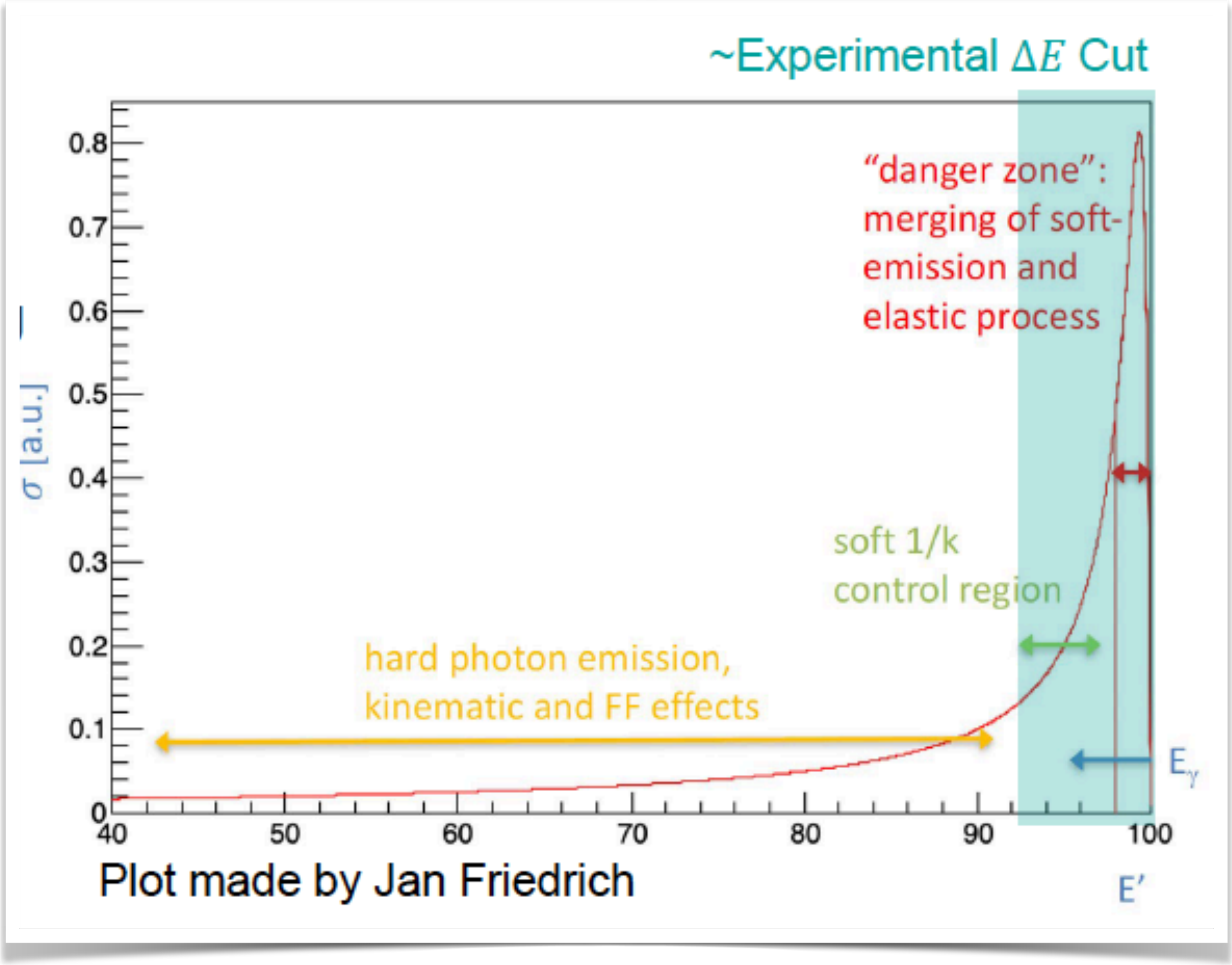
Figure courtesy of W. Xiong

PRad-II has just started collecting data at JLab





Radiative effects are an unwanted “background” in all electron scattering experiments



Plot made by Jan Friedrich

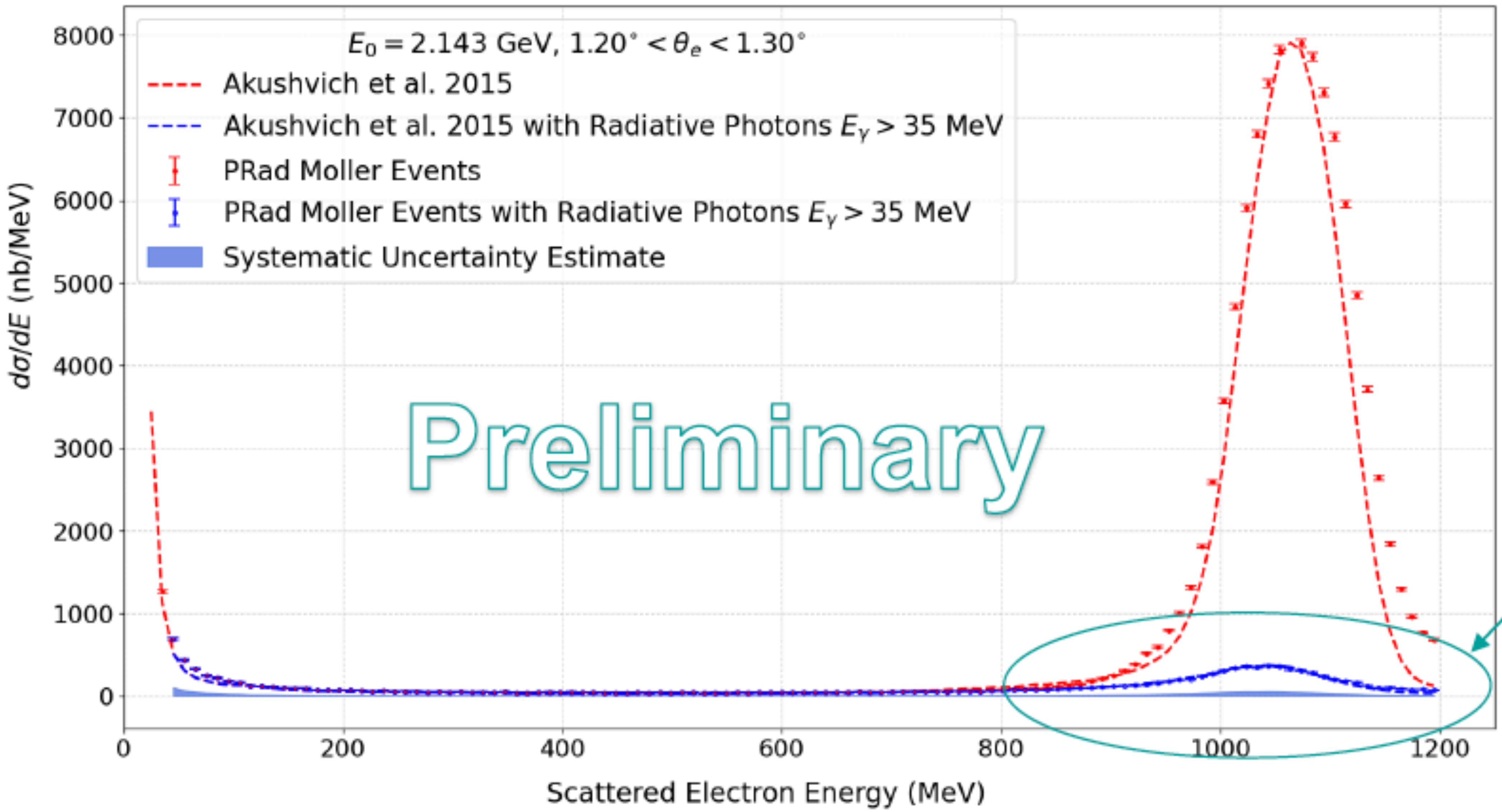
Ever-improving recipes for radiative corrections used to remove effects from experimental observables.

NNLO corrections available
(see talk by O. Tomalak,
I. Akushevich, and S. Strauch
on Thursday 04/16)

No direct measurements; only indirect test via un-folded spectra in “good” agreement with predictions

The PRad data was used for the first ever direct measurement of radiative photons in Møller scattering

Scattered electron energy distribution

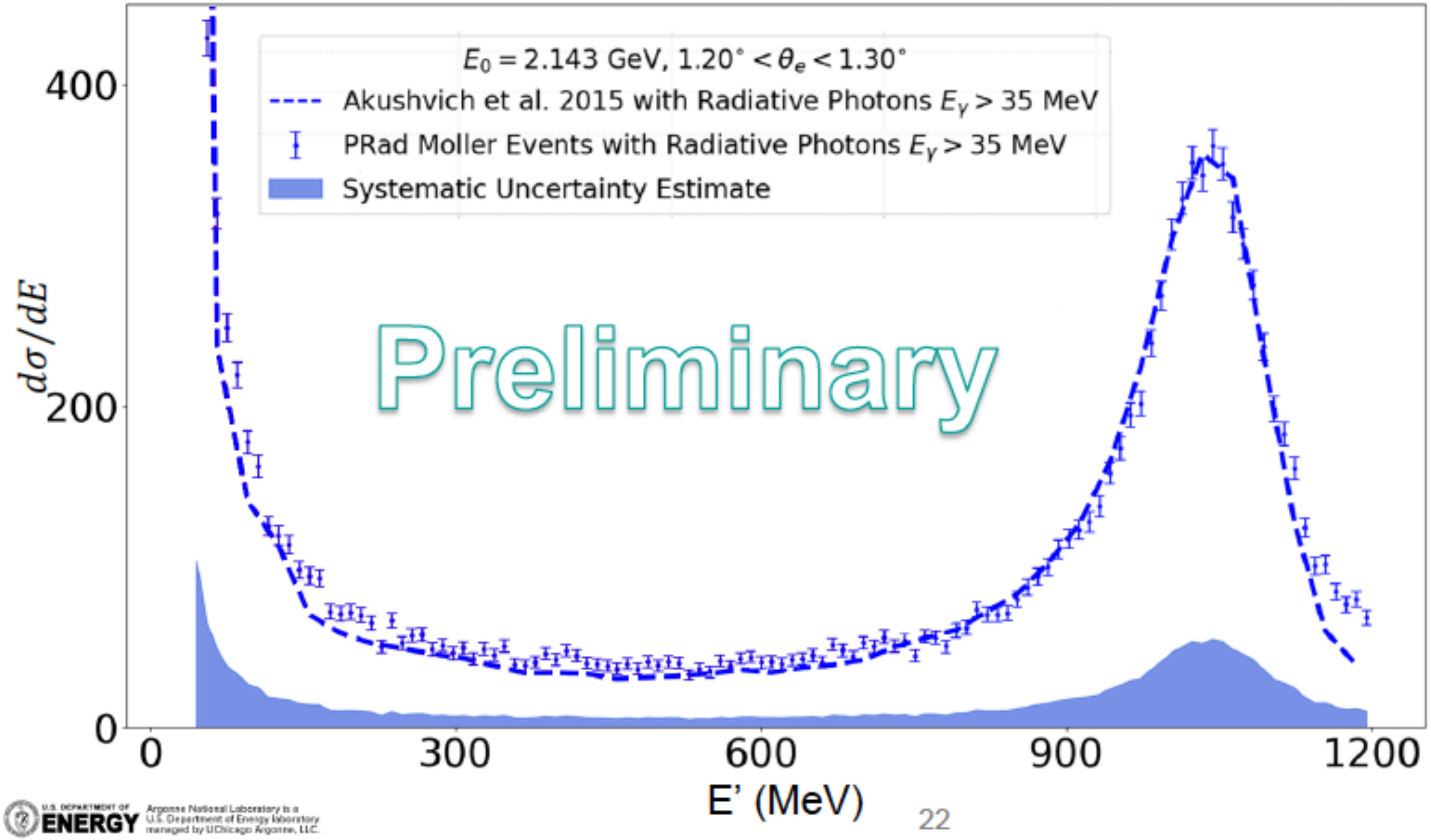


Bremsstrahlung buried under elastic (Moller) peak

Plot courtesy of C. Peng

The PRad data was used for the first ever direct measurement of radiative photons in Møller scattering

Scattered electron energy distribution



Two GEM detectors ⇒

improved efficiency measurement

better vertex resolution to reject upstream background

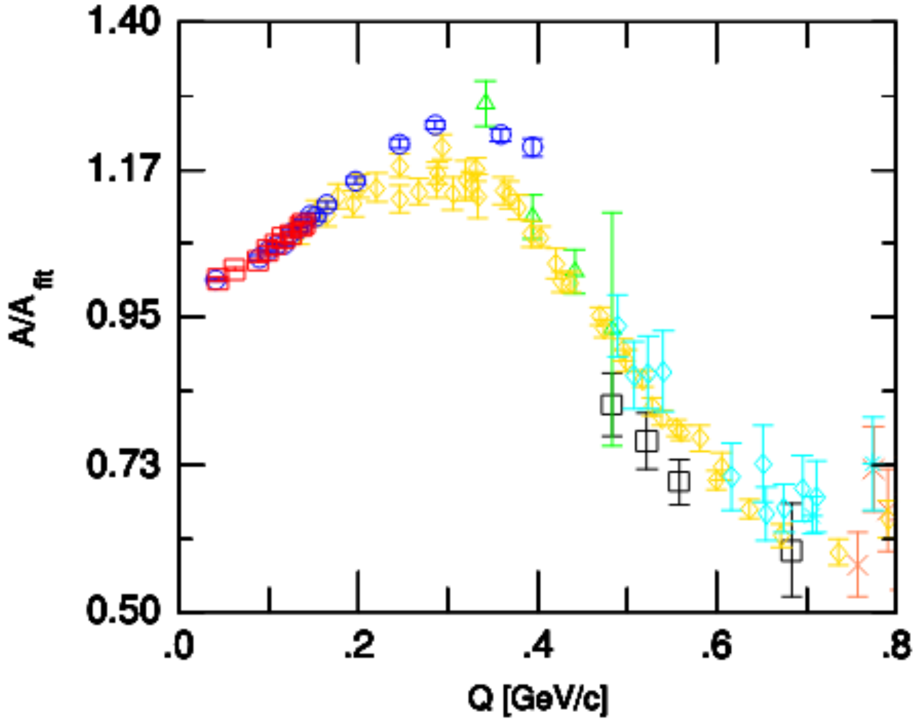
better photon identification

PRad-II will allow direct measurements of radiative photons in *ep* scattering

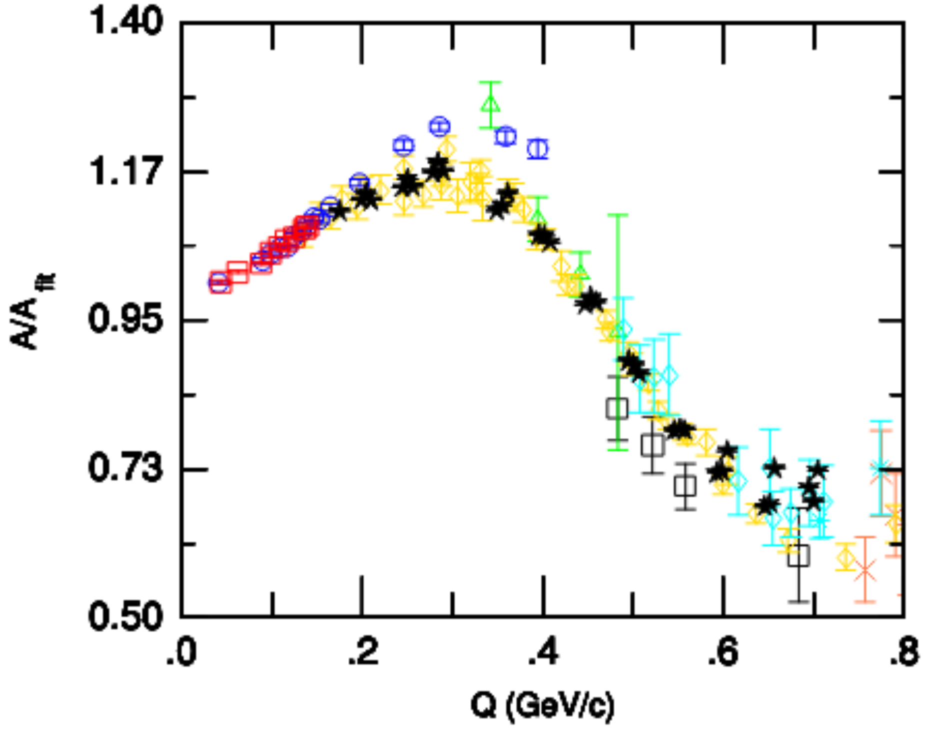
Plot courtesy of C. Peng

There is a urgent need for high precision *e-D* scattering cross section and charge form factor data

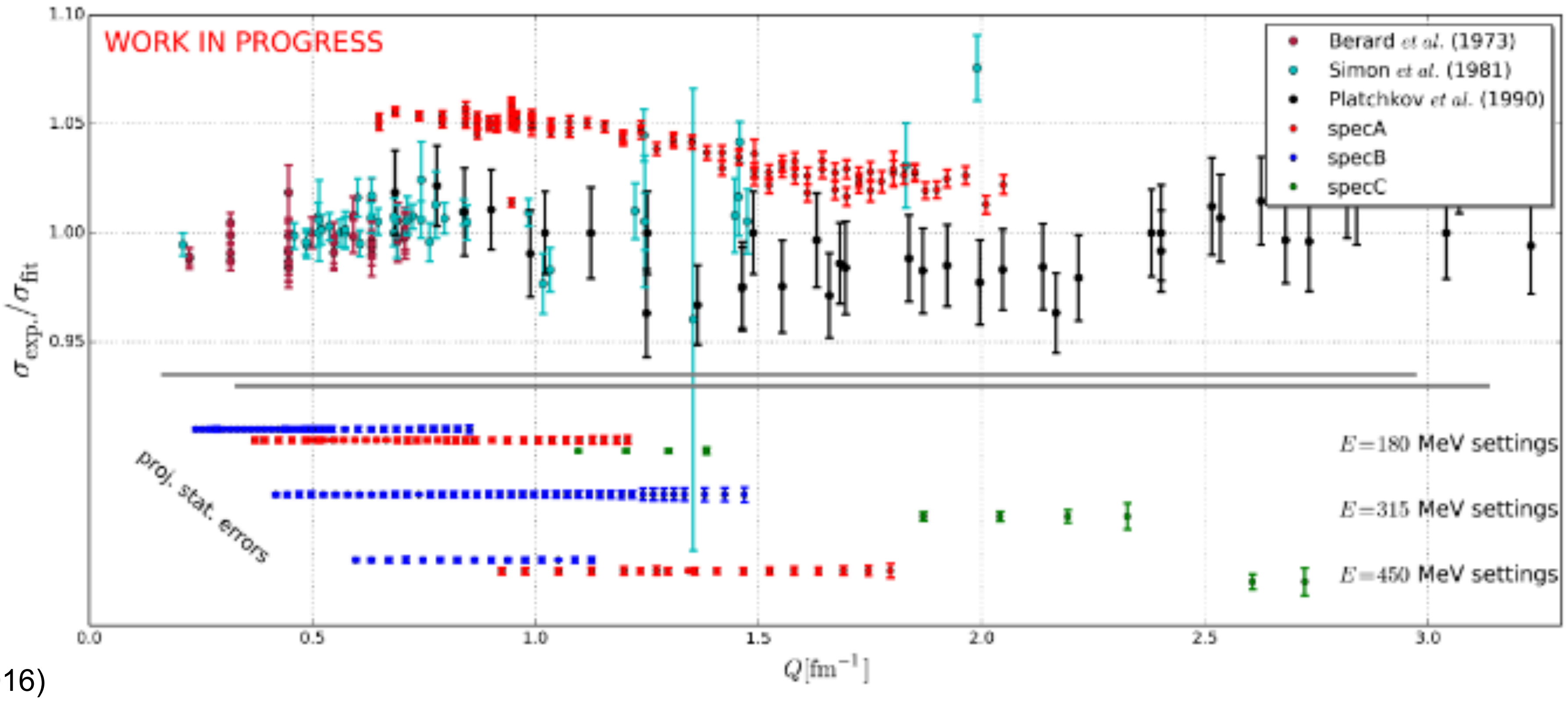
Figs. from Byungwuek Lee's PhD thesis (LEDEx experiment @ JLab)



Experiment	Q (GeV/c)	Symbol	Year and Reference
Monterey	0.04 - 0.14	□	1973 [8]
Mainz	0.04 - 0.39	○	1981 [9]
Saclay ALS	0.13 - 0.84	◇	1990 [10]
Orsay	0.34 - 0.48	△	1966 [11]
Stanford	0.48 - 0.88	□	1965 [12]
DESY	0.49 - 0.71	◇	1971 [13]
CEA	0.76 - 1.15	×	1969 [14]
JLab Hall C	0.81 - 1.34	★	1999 [15]
JLab Hall A	0.83 - 2.44	□	1999 [16]
SLAC E101	0.89 - 2.00	+	1975 [17]



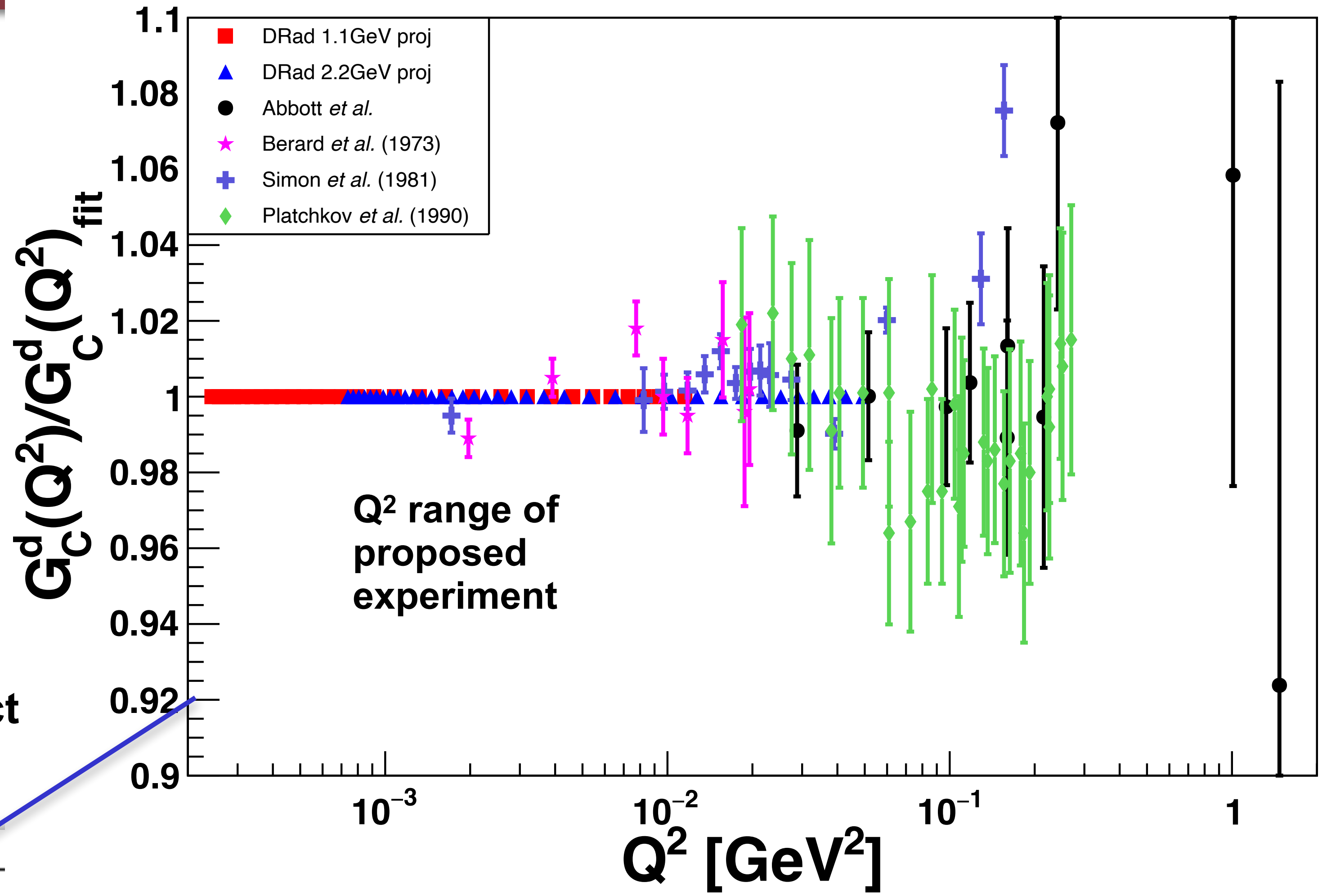
More recent experiment at Mainz



B.S. Schlimme, et al. EPJ W of C, 113, 04017 (2016)

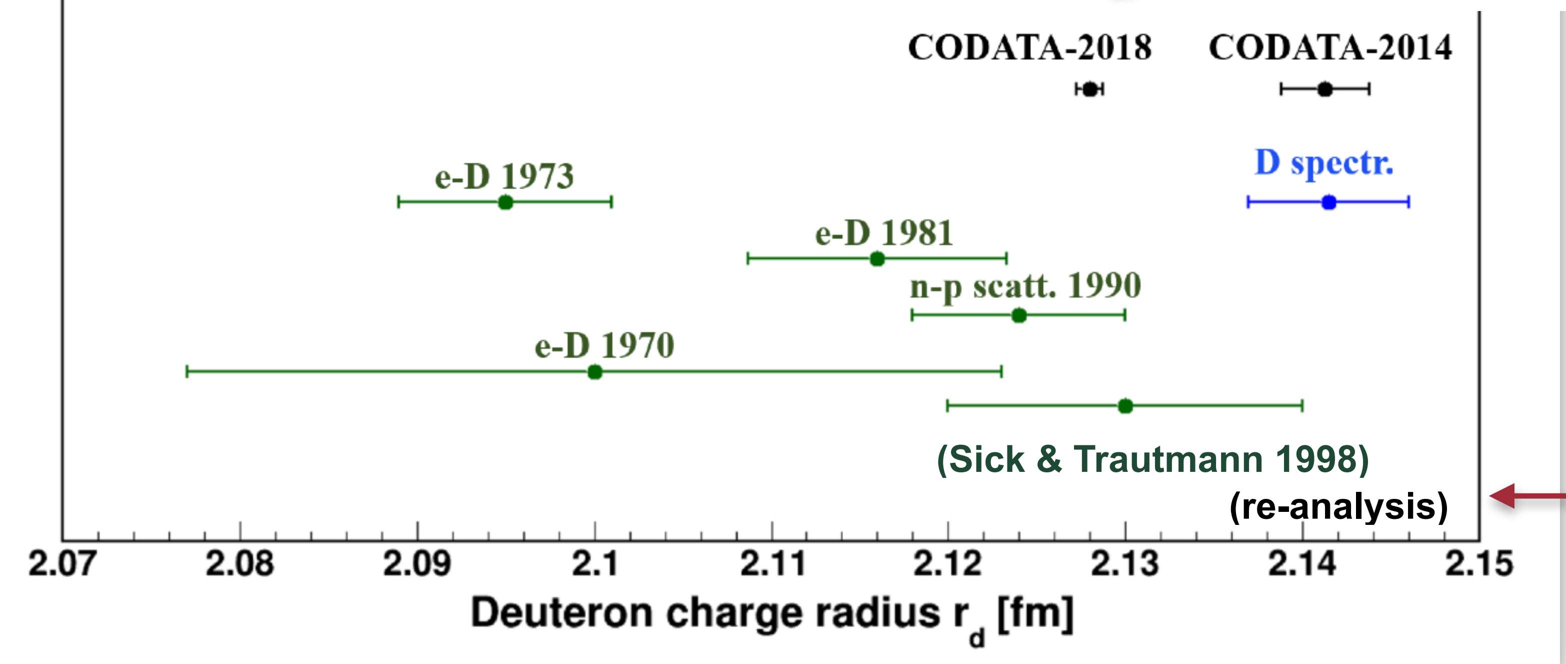
There is a urgent need for high precision *e-D* scattering cross section and charge form factor data

- existing data from old methods
- large uncertainty
- all used magnetic spectrometer method
- normalized ***eD*** to ***ep*** cross section
- large bgd. from target windows



Q^2 range of proposed experiment

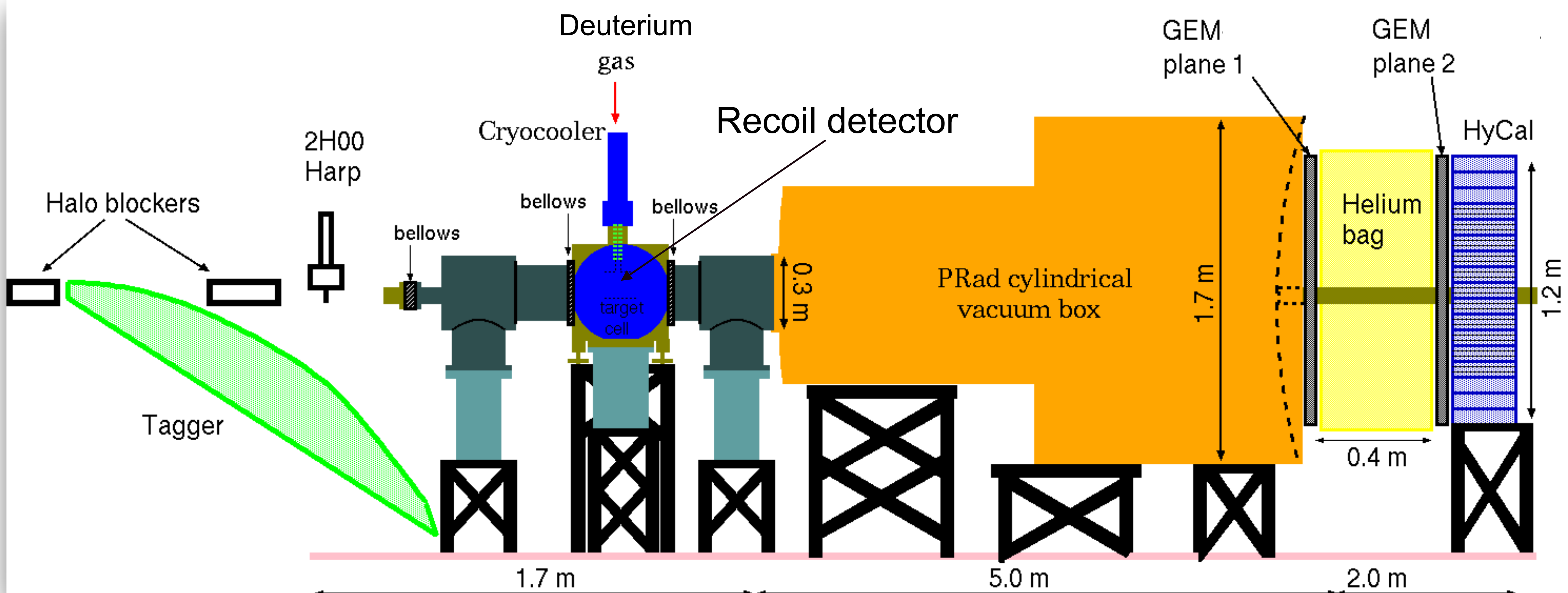
used to extract charge radius



Most recent extraction of charge radius is a reanalysis of old data.

Situation points to an urgent need for a new high precision *eD* experiment

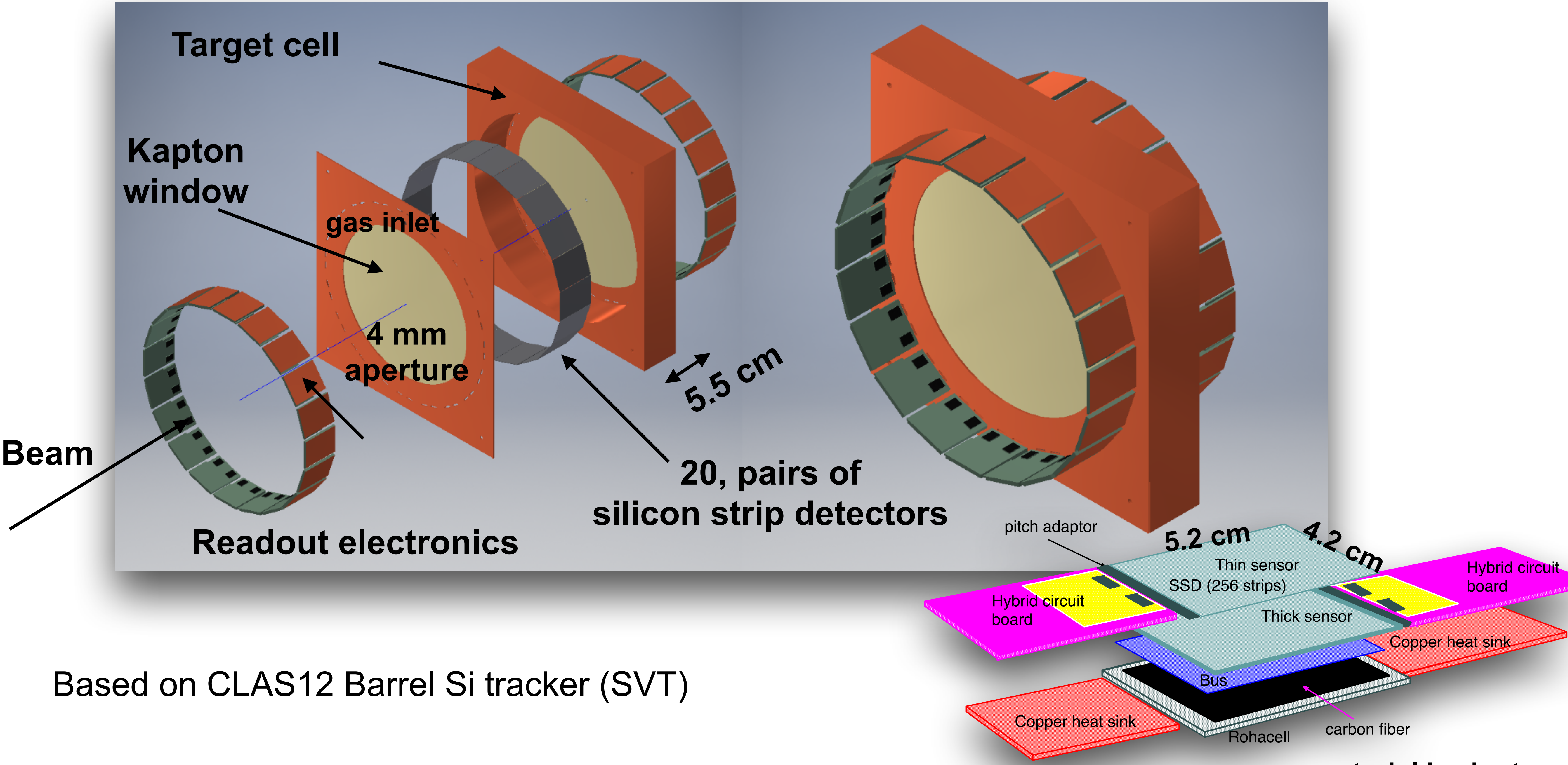
DRad: a novel electron scattering experiment



Will use the PRad-II setup with 1.1 GeV and 2.2 GeV electron beam

- **High resolution $PbWO_4$ calorimeter (magnetic spectrometer free)**
- **Windowless, high density gas flow target (reduced backgrounds)**
- **Simultaneous detection of elastic and Møller electrons (control of systematics)**
- **Vacuum chamber with one thin window, & two GEM chambers (better resolution)**
- **Q^2 range of $2\times10^{-4} – 5\times10^{-2}$ GeV^2 (lower than all previous electron scattering expts.)**
- **Add a cylindrical recoil detector for ensuring elasticity of reaction.**
- **Precise extraction of the charge form factor and charge radius r_D**

The elasticity of e-D scattering will be ensured with a cylindrical Si-strip-based recoil deuteron detector.

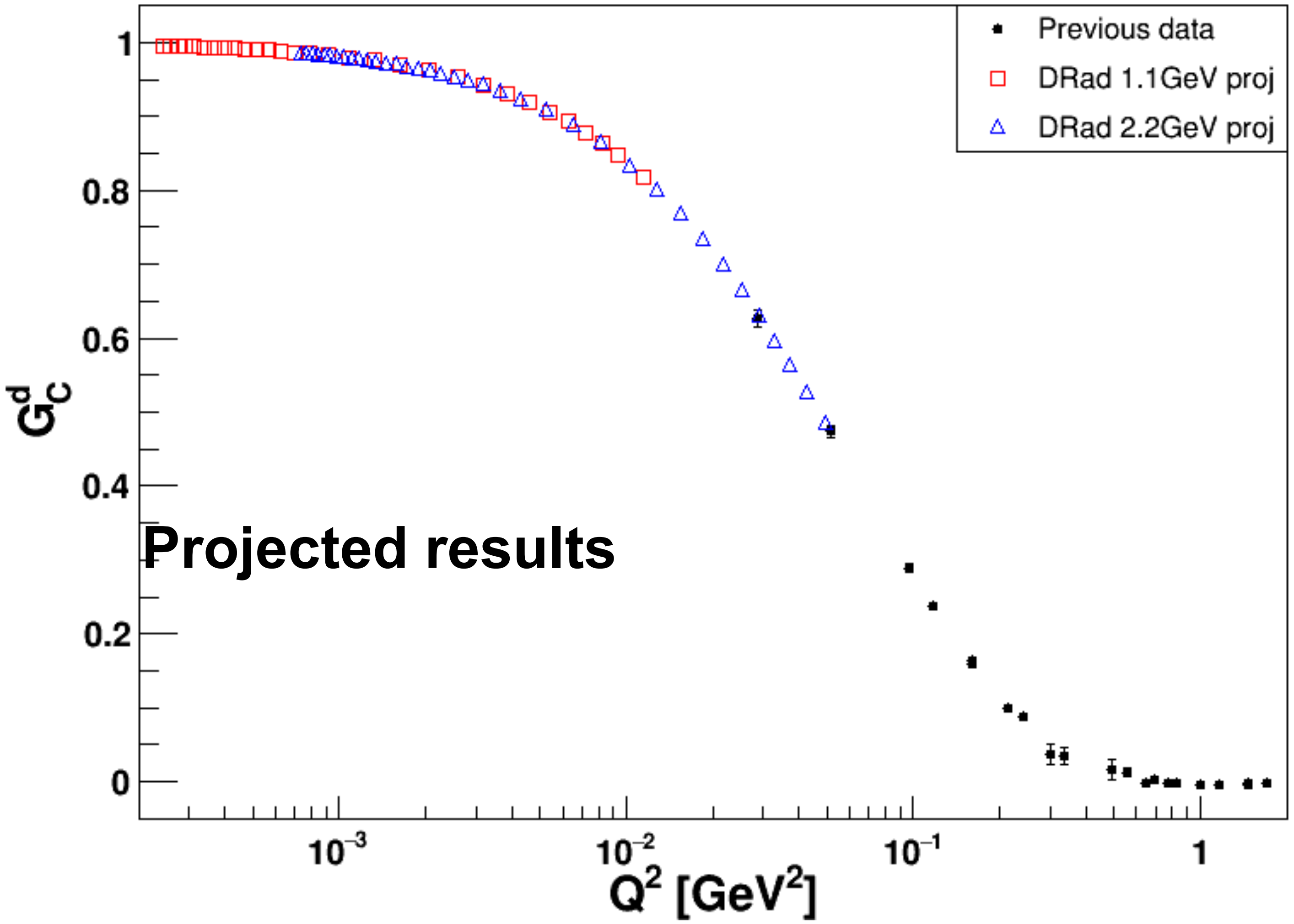


Based on CLAS12 Barrel Si tracker (SVT)

material budget < 1% r.l.

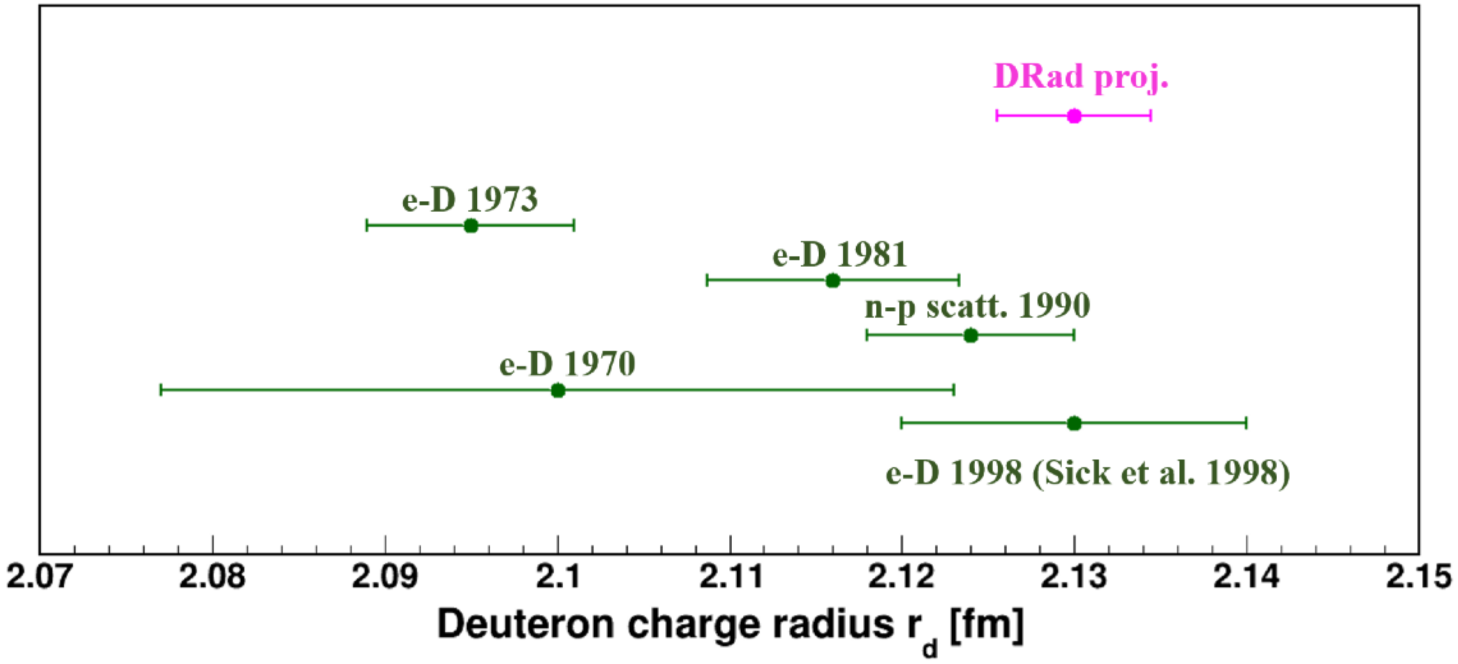
- consists of 20 panels of twin, single-sided Si-strip detectors (size; 42x52 mm^2);
- thickness: inner, ≈ 200 μm, outer ≈ 300 μm (to be optimized);
- 20 segment arrangement with R=13 cm radius (to be optimized);
- 256 strips on each segment, angular resolution: δφ ≤ 5 mrad, δθ ≤ 20 mrad
- Passivation layer ~ 0.1 μm (can be as low as 0.01 μm).

The estimated total uncertainties is about a factor of 2 better than the best extraction to date



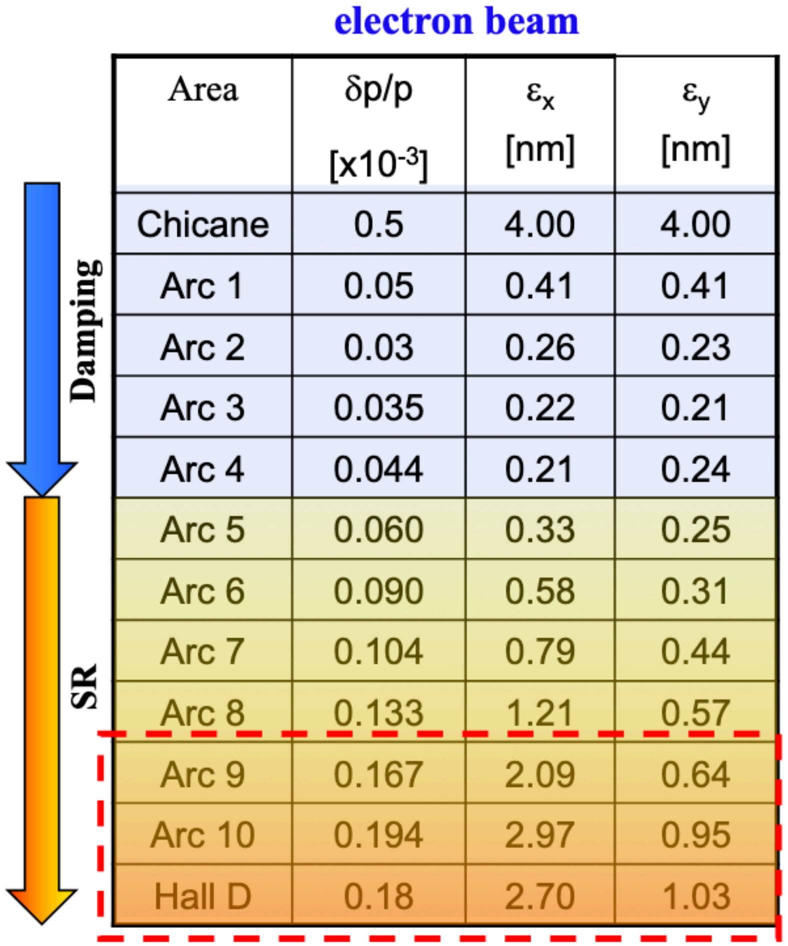
Estimated from 10,000 mock data sets smeared by systematic and statistical uncertainties.

systematic uncertainty = $(R_{smear} - R_{unsmear})/R_{unsmear}$

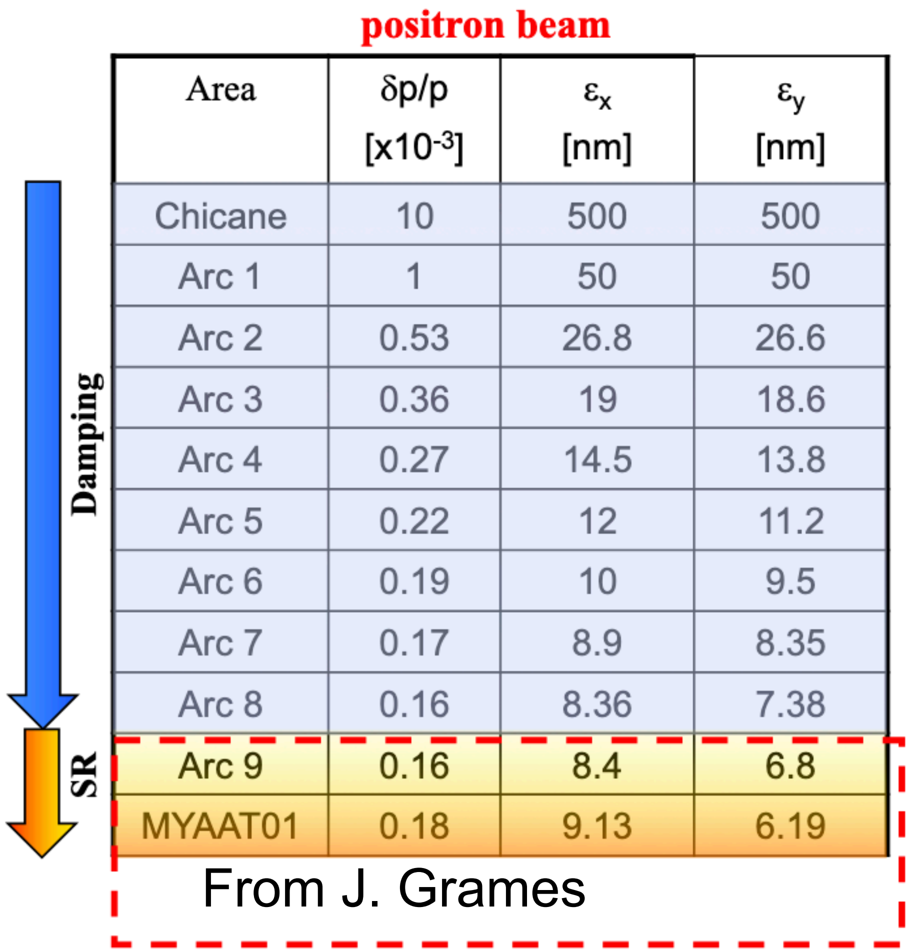


The PRad-II and DRad experiments can be repeated with the proposed positron beam

Machine Parameter	**Electrons**	**Positrons**
Hall Multiplicity	4	**1 or 2**
Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 µA	**> 1 µA**
Polarized Intensity	170 µA	**> 50 nA**
	%	**> 60%**
	Yes	1920 Hz/Yes


electron beam

Area	δp/p [x10^{-3}]	ε_x [nm]	ε_y [nm]
Chicane	0.5	4.00	4.00
Arc 1	0.05	0.41	0.41
Arc 2	0.03	0.26	0.23
Arc 3	0.035	0.22	0.21
Arc 4	0.044	0.21	0.24
Arc 5	0.060	0.33	0.25
Arc 6	0.090	0.58	0.31
Arc 7	0.104	0.79	0.44
Arc 8	0.133	1.21	0.57
Arc 9	0.167	2.09	0.64
Arc 10	0.194	2.97	0.95
Hall D	0.18	2.70	1.03


positron beam

Area	δp/p [x10^{-3}]	ε_x [nm]	ε_y [nm]
Chicane	10	500	500
Arc 1	1	50	50
Arc 2	0.53	26.8	26.6
Arc 3	0.36	19	18.6
Arc 4	0.27	14.5	13.8
Arc 5	0.22	12	11.2
Arc 6	0.19	10	9.5
Arc 7	0.17	8.9	8.35
Arc 8	0.16	8.36	7.38
Arc 9	0.16	8.4	6.8
MYAAT01	0.18	9.13	6.19

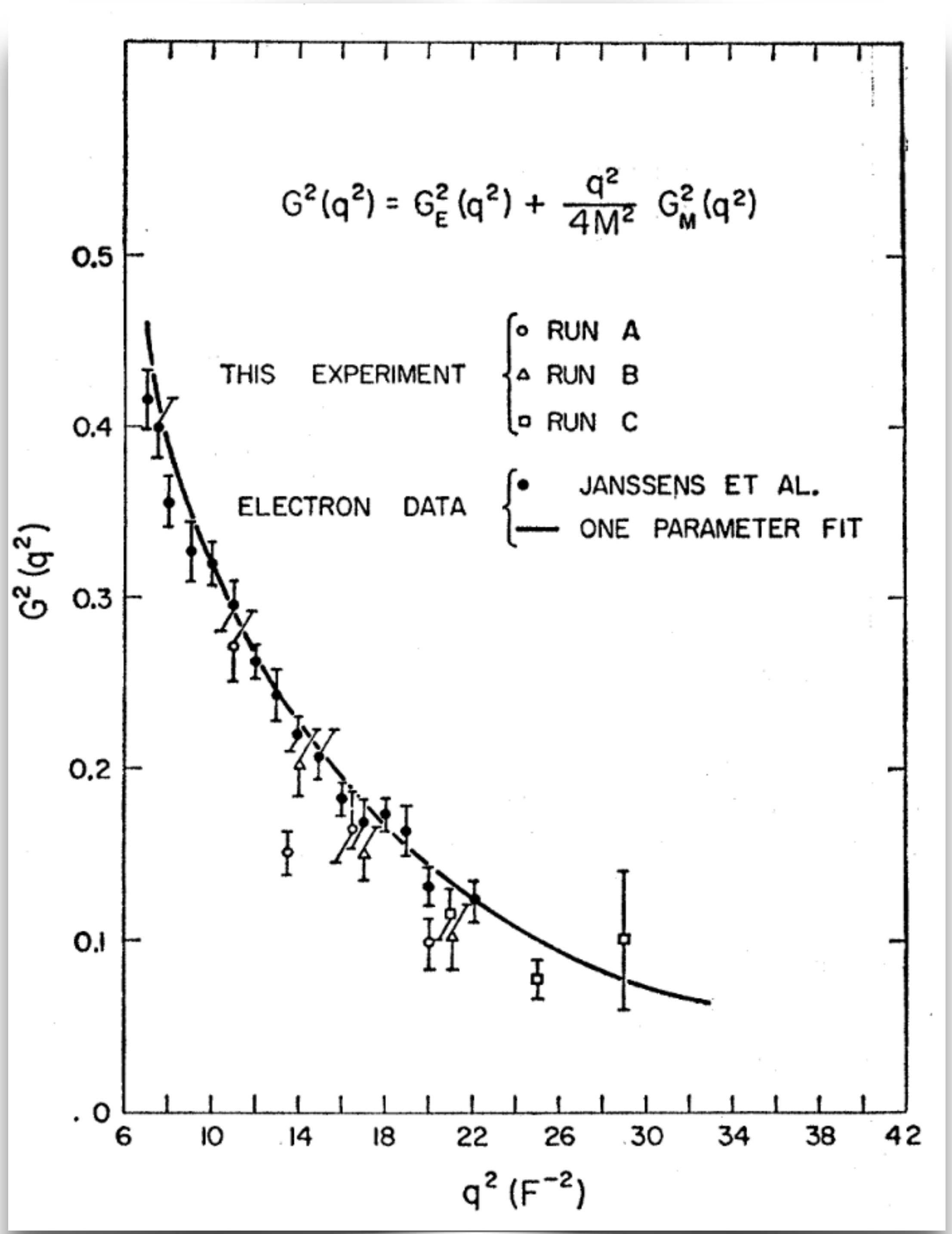
From J. Grames

Higher emittance of the positron beam will impact reconstruction and systematics

Must be paired with electron running with matching emittance

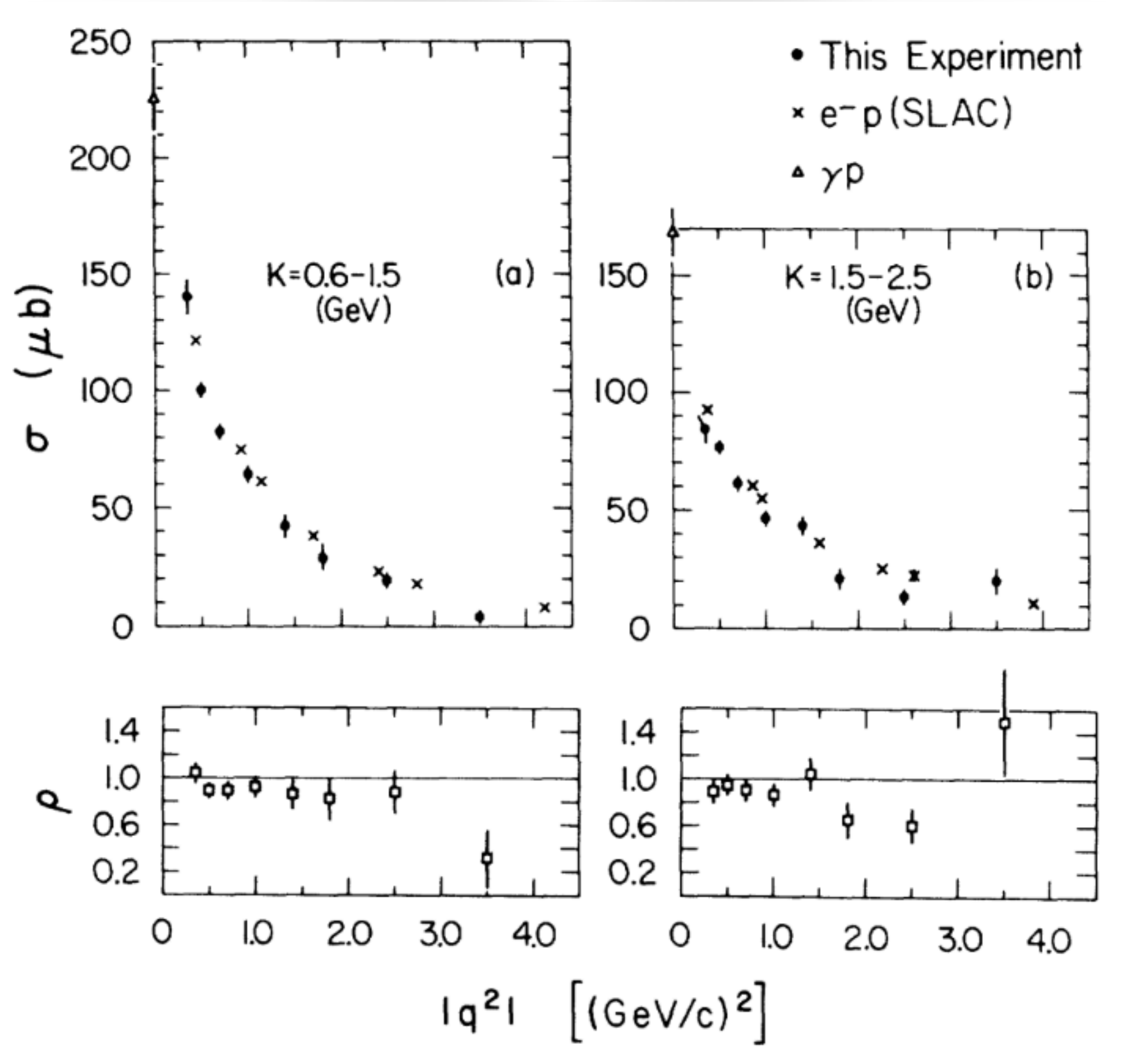
μ-p and e-p scattering have been compared to verify Lepton Universality at the ~10-15% level.

Elastic scattering



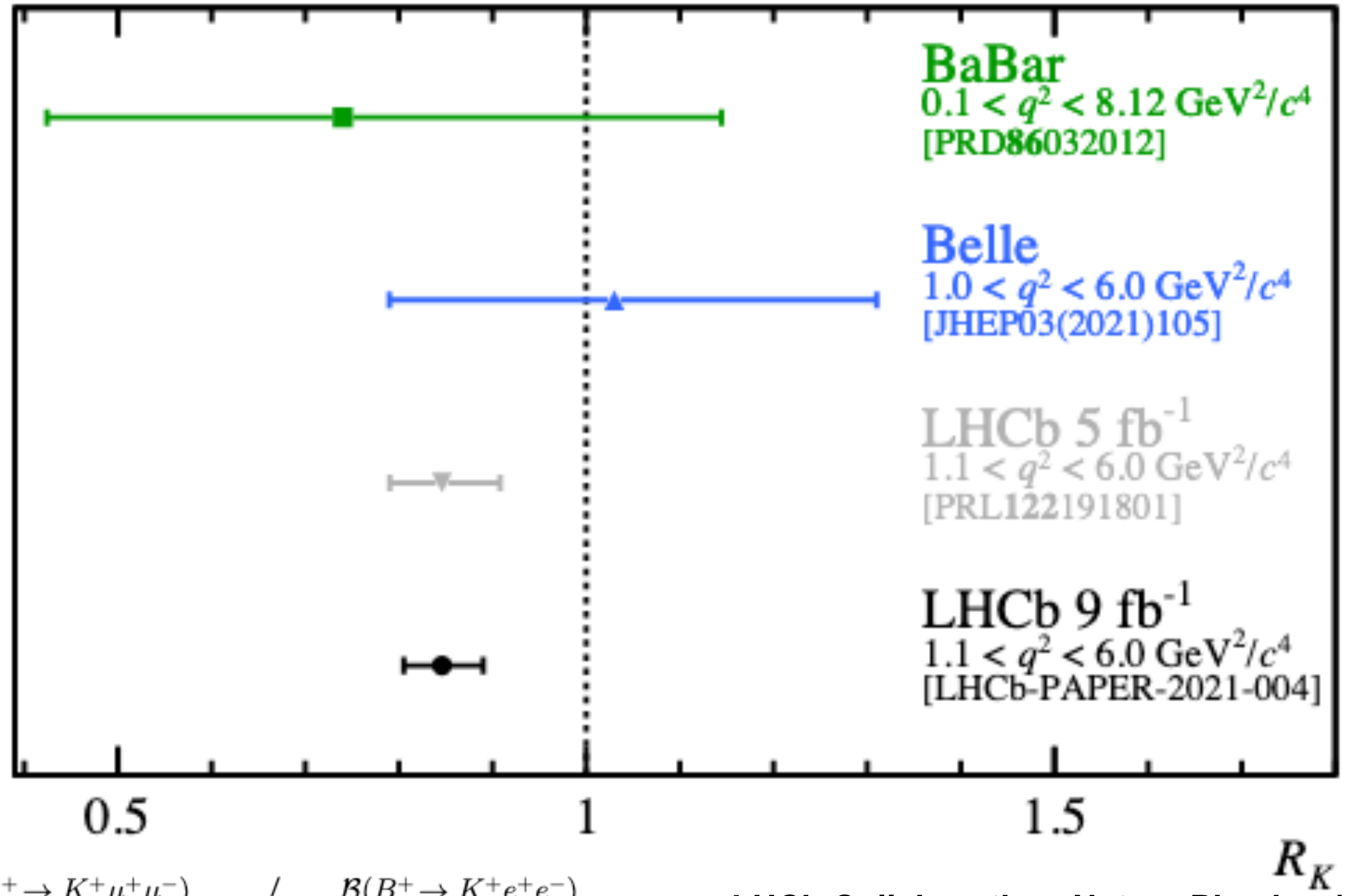
R. W. Ellsworth *et al.* Phys. Rev. 165, 1449 (1968)

Deep Inelastic scattering



T. J. Braunstein *et al.*, Phys. Rev.D, 6, 106 (1972)

Some recent results point to a possible violation of Lepton Universality



$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}.$$

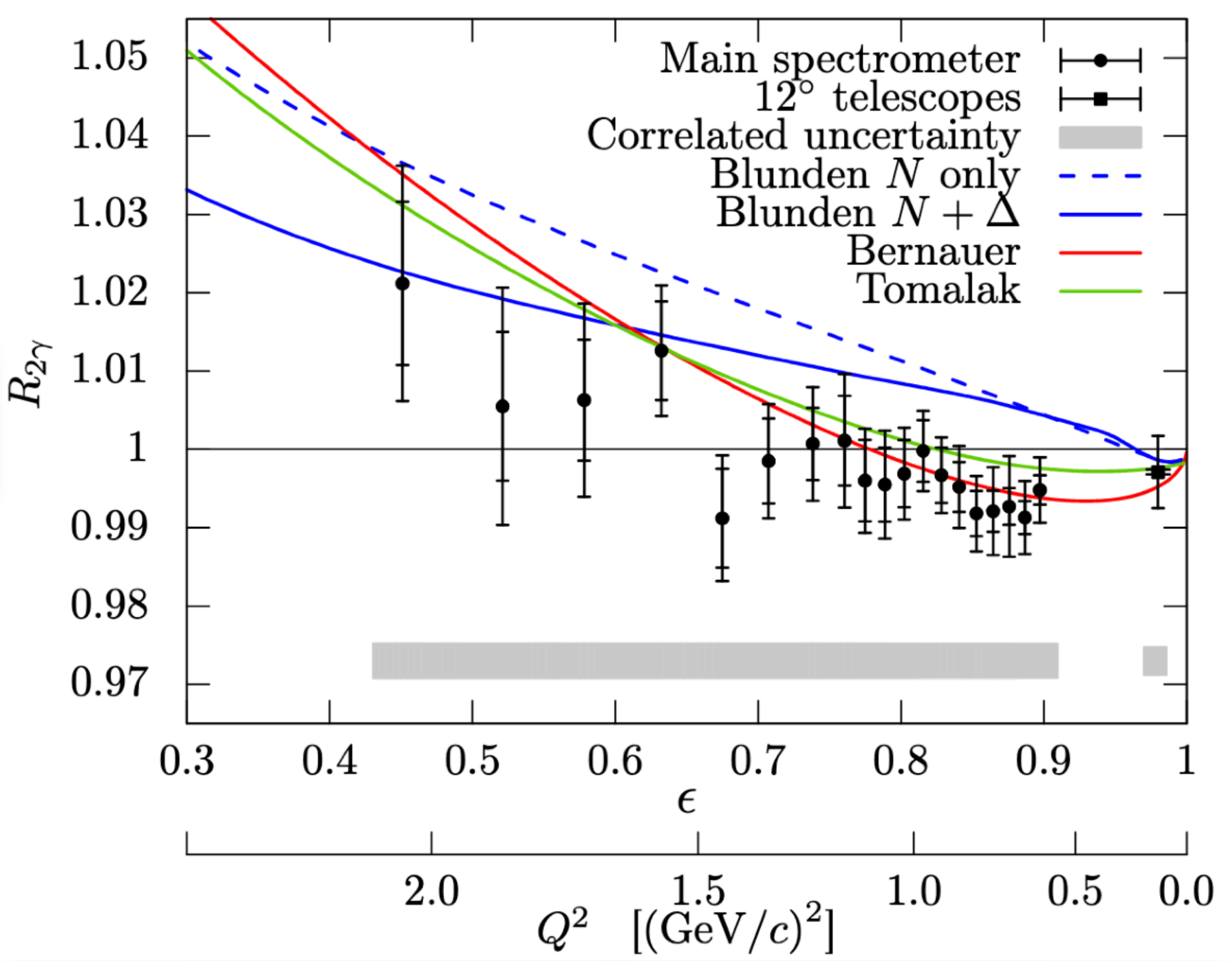
LHCb Collaboration: Nature Physics 18, 277 (2022)

Proton/Deuteron radius measured with positrons can contribute to tests of Lepton Universality

Measuring the two-photon contributions to the e^+p and e^-p cross sections is a major focus.

Results from most recent measurements

$$R_{2\gamma}(\varepsilon,Q^2) = \frac{\sigma_{e^+p}(\varepsilon,Q^2)}{\sigma_{e^-p}(\varepsilon,Q^2)} = 1 + \frac{4\Re\left[\mathcal{M}_{\gamma\gamma}\mathcal{M}_{\gamma}\right]}{\left|\mathcal{M}_{\gamma}\right|} + \mathcal{O}(\alpha^4)$$



Similar measurements over wide range of kinematics is one of the major focus of the positron program at JLab

B. S. Henderson *et al.* Phys. Rev. Lett. 118, 092501 (2017)

talk by P. Blunden on Thursday 04/16

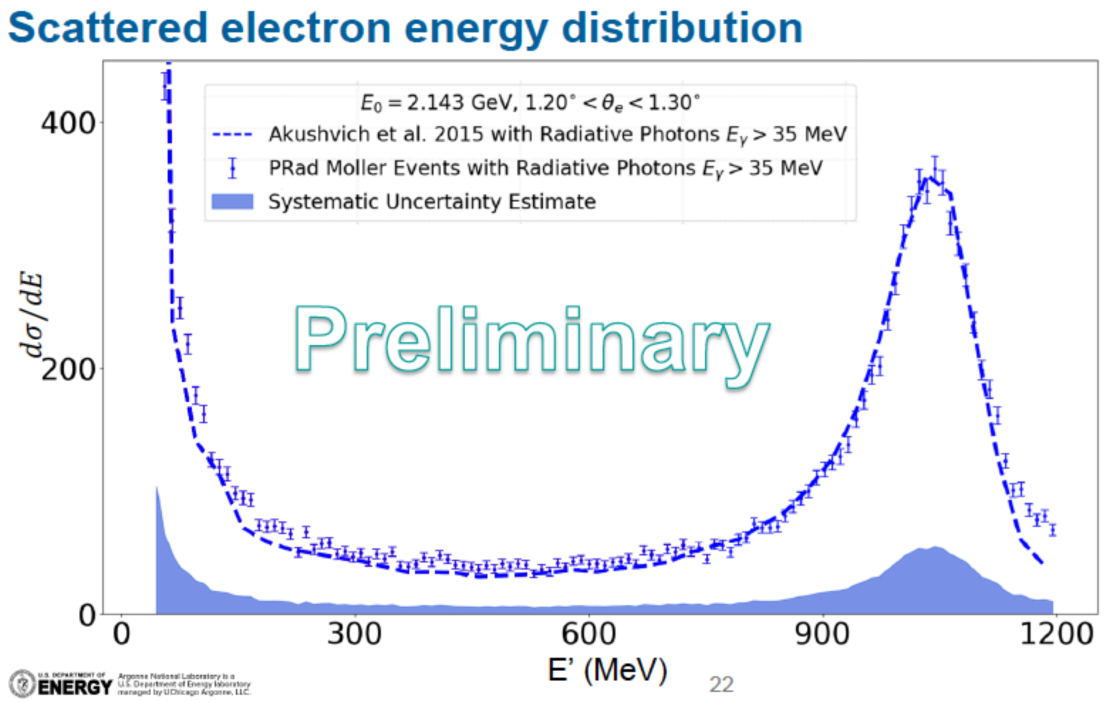
The PRad-II and DRad experiments with a positron beam will provide direct measurements of radiative photons

Two GEM detectors ⇒

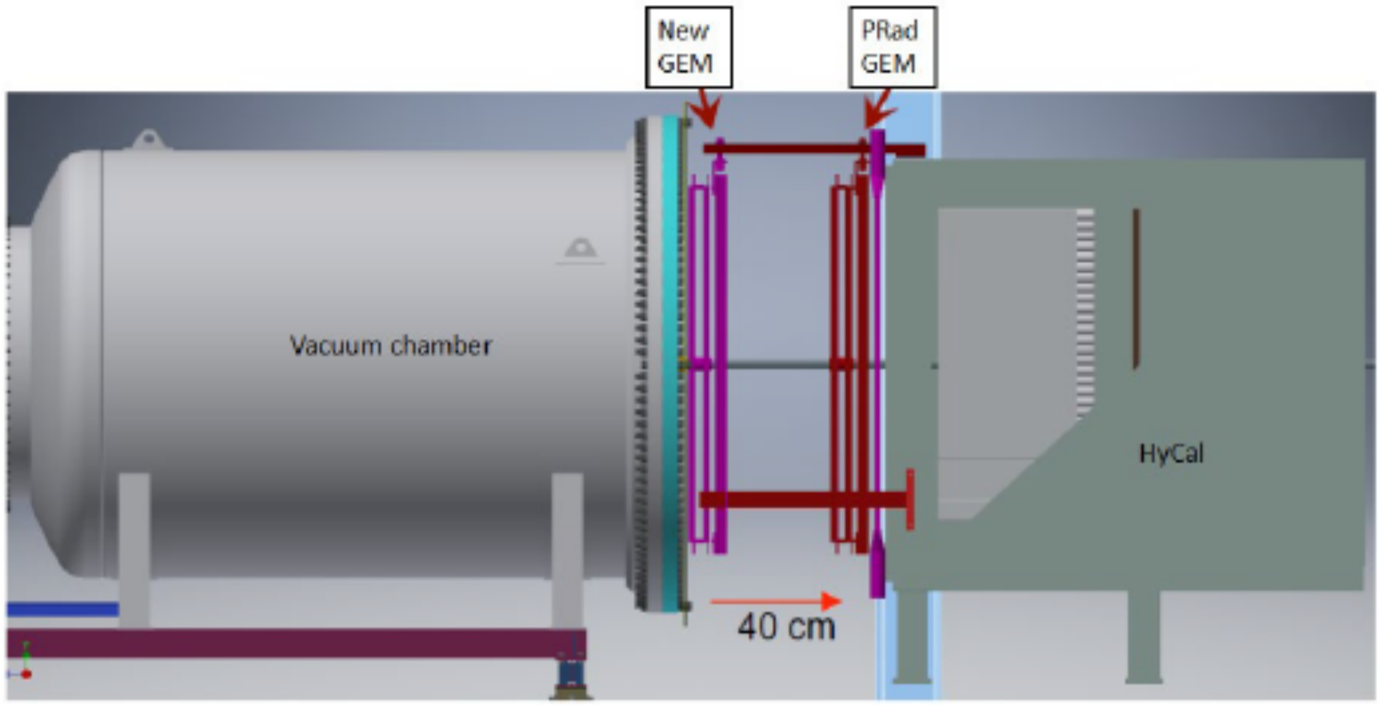
improved efficiency measurement

better vertex resolution to reject upstream background

better photon identification

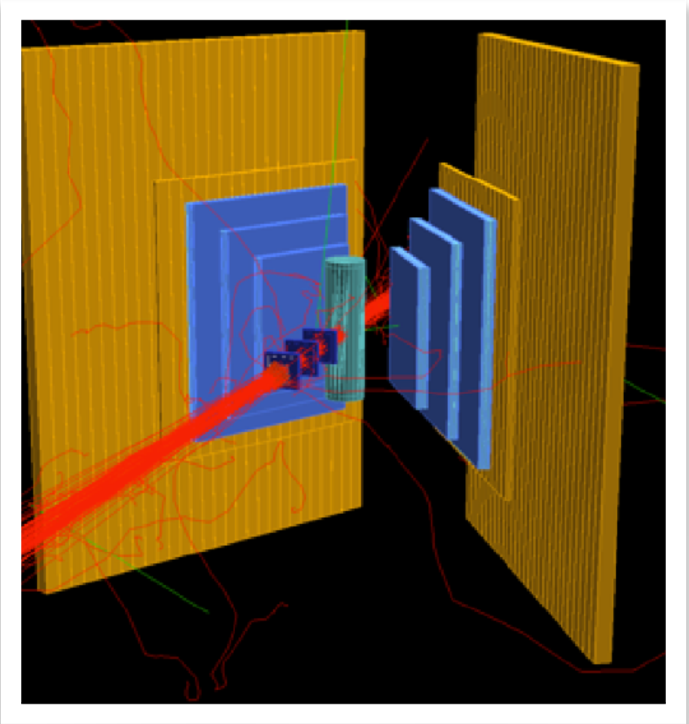


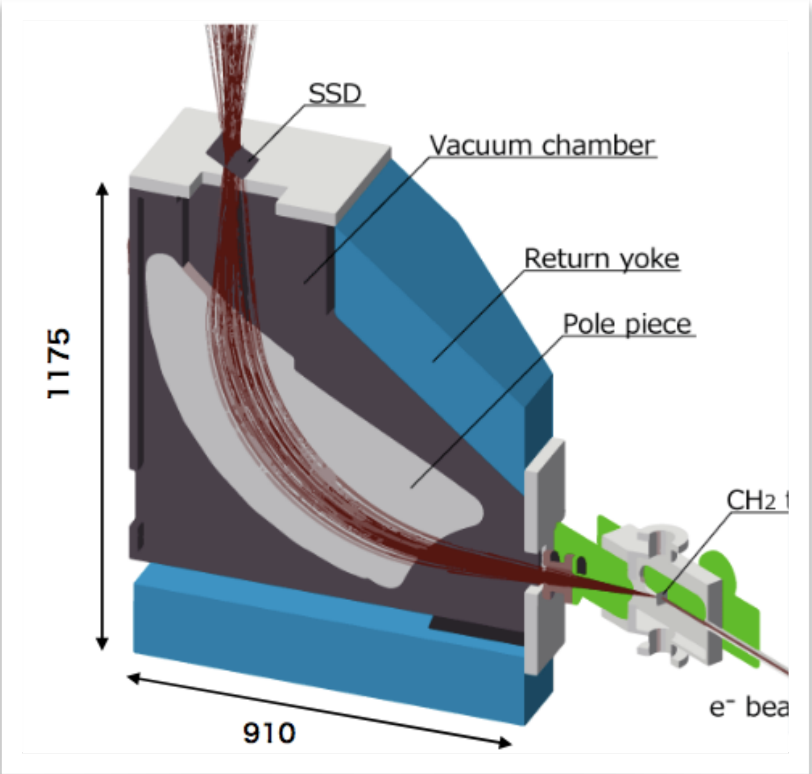
Similar quality results can be obtained for e⁻ p and e⁺ p scattering

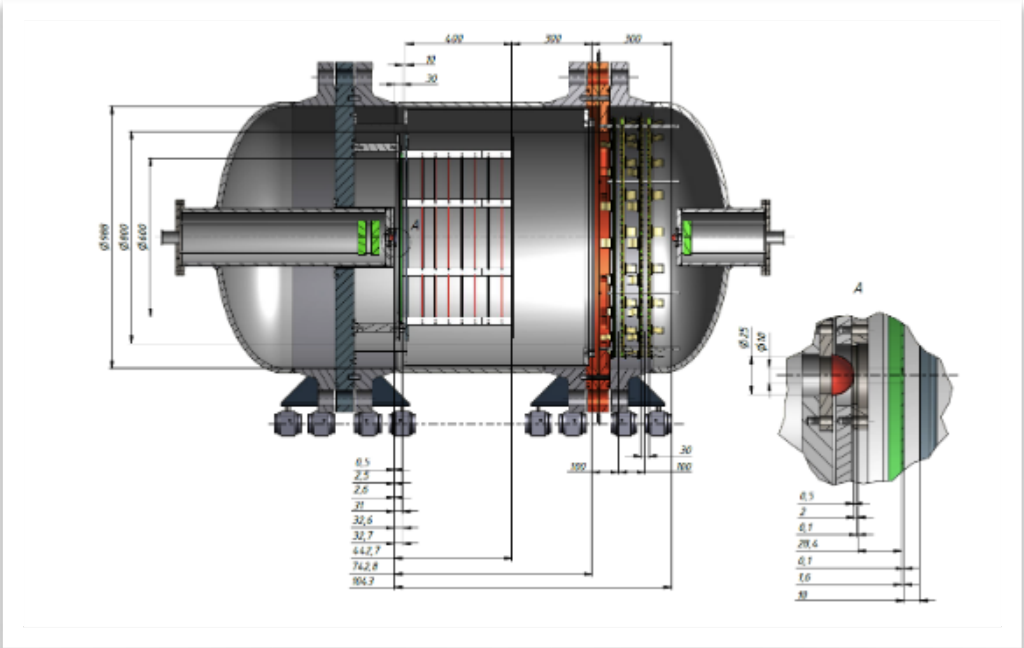


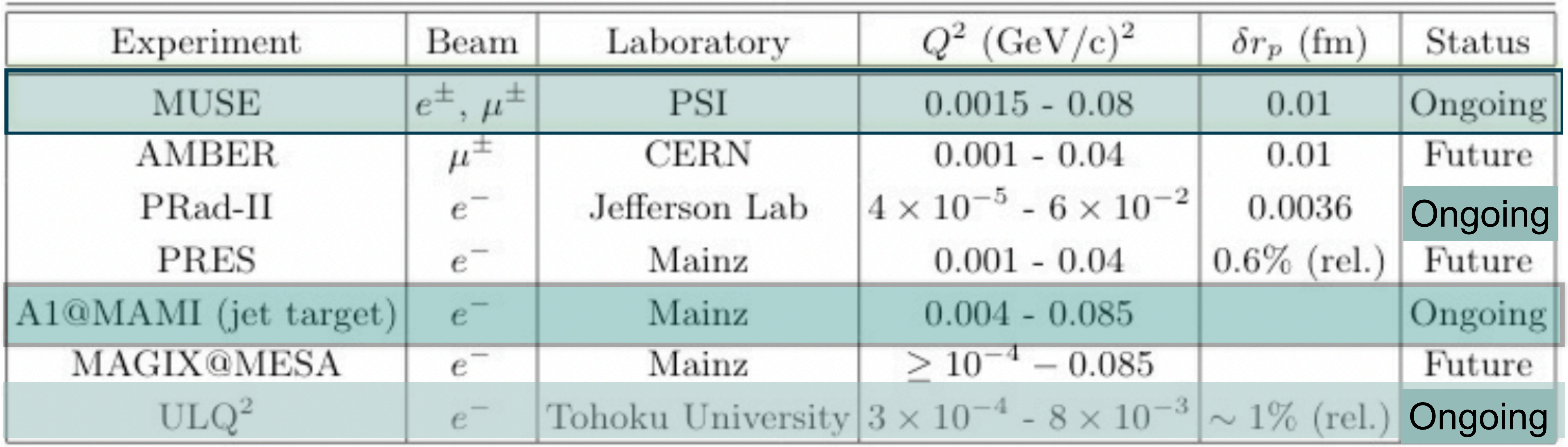
Direct measurement of radiative photon in e⁻ p and e⁺ p would give unique and high-precise access to the charge asymmetry and the 2- photon contribution (with different systematics)

Several lepton scattering experiments are currently running or being prepared.







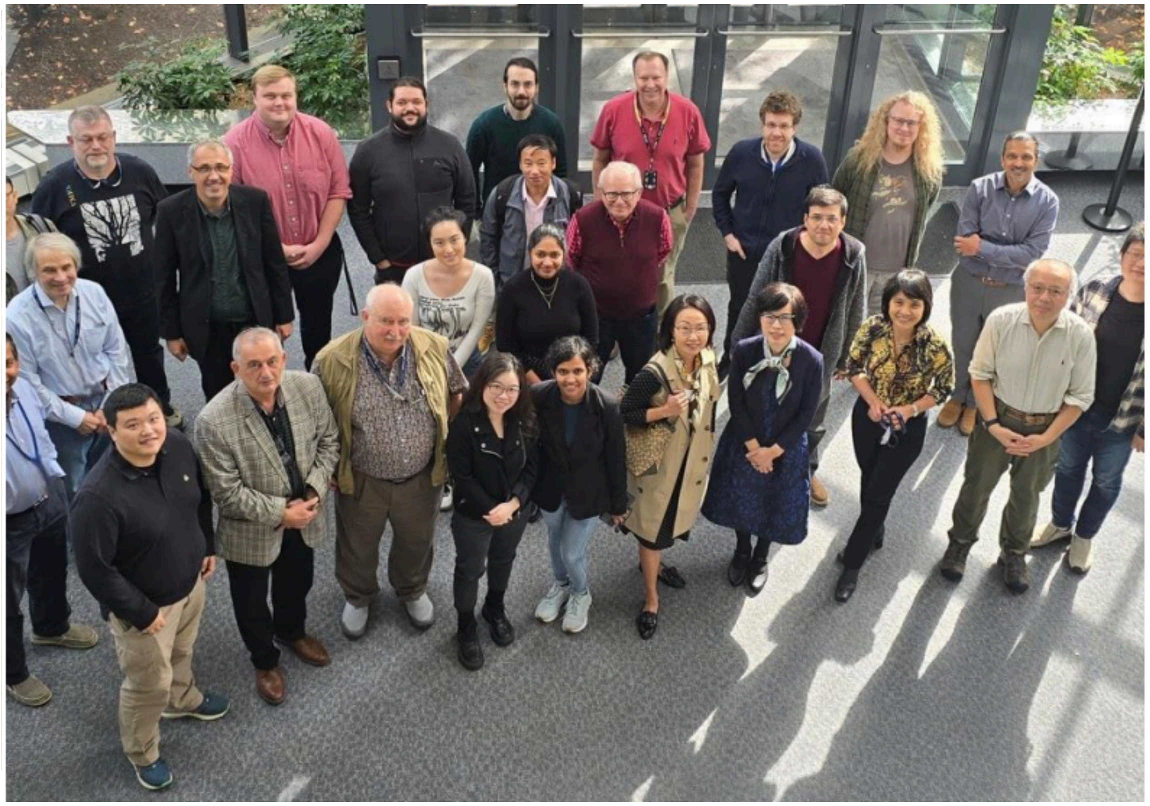


Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Ongoing
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)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

Proton/Deuteron radius measured with positrons can contribute to tests of Lepton Universality

Table courtesy of H. Gao

The PRad/PRad-II Collaboration



Duke University, NC A&T State University, Mississippi State University, Idaho State University, University of Virginia, Jefferson Lab, Argonne National Lab, University of North Carolina at Wilmington, Kharkov Institute of Physics and Technology, MIT, Old Dominion University, ITEP, University of Massachusetts, Amherst Hampton University, College of William & Mary, Norfolk State University, Yerevan Physics Institute Shandong University

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Yining Liu (Duke)
Nithya Kularatne (UVa)
Buddhiman Tamang (MSU)
Erik Wrightson (MSU)

Post-docs:
Aruni Nadeeshani (MSU)
Andrew Schick (Umass)
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PRad

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Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Latif-ul Kabir (MSU)

Summary

- The “proton radius puzzle” arose in 2010 with the first μH spectroscopy measurement of r_p.

- A novel electron scattering experiment (PRad) was completed at JLab Hall-B in 2016
  - ✓ lowest Q^2 ($\sim 2\text{x}10^{-4}$ GeV/C^2) in ep-scattering experiments was achieved;
  - ✓ simultaneous measurement of the Møller and elastic scattering processes was demonstrated to control systematic uncertainties;
  - ✓ data in a large Q^2 range ($2\text{x}10^{-4}$ - $6\text{x}10^{-2}$ GeV^2) was recorded in the same experimental setting, for the first time in ep-scattering experiments.

- Several new experiments are being prepared to help further establish these results. Including PRad-II & DRad

- PRad-II & DRad can be performed with positrons to help test Lepton Universality, validate radiative corrections, and give unique access to the two photon contribution

This work was supported by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-07ER41528

Backup Slides

PRad-II Rp uncertainty table

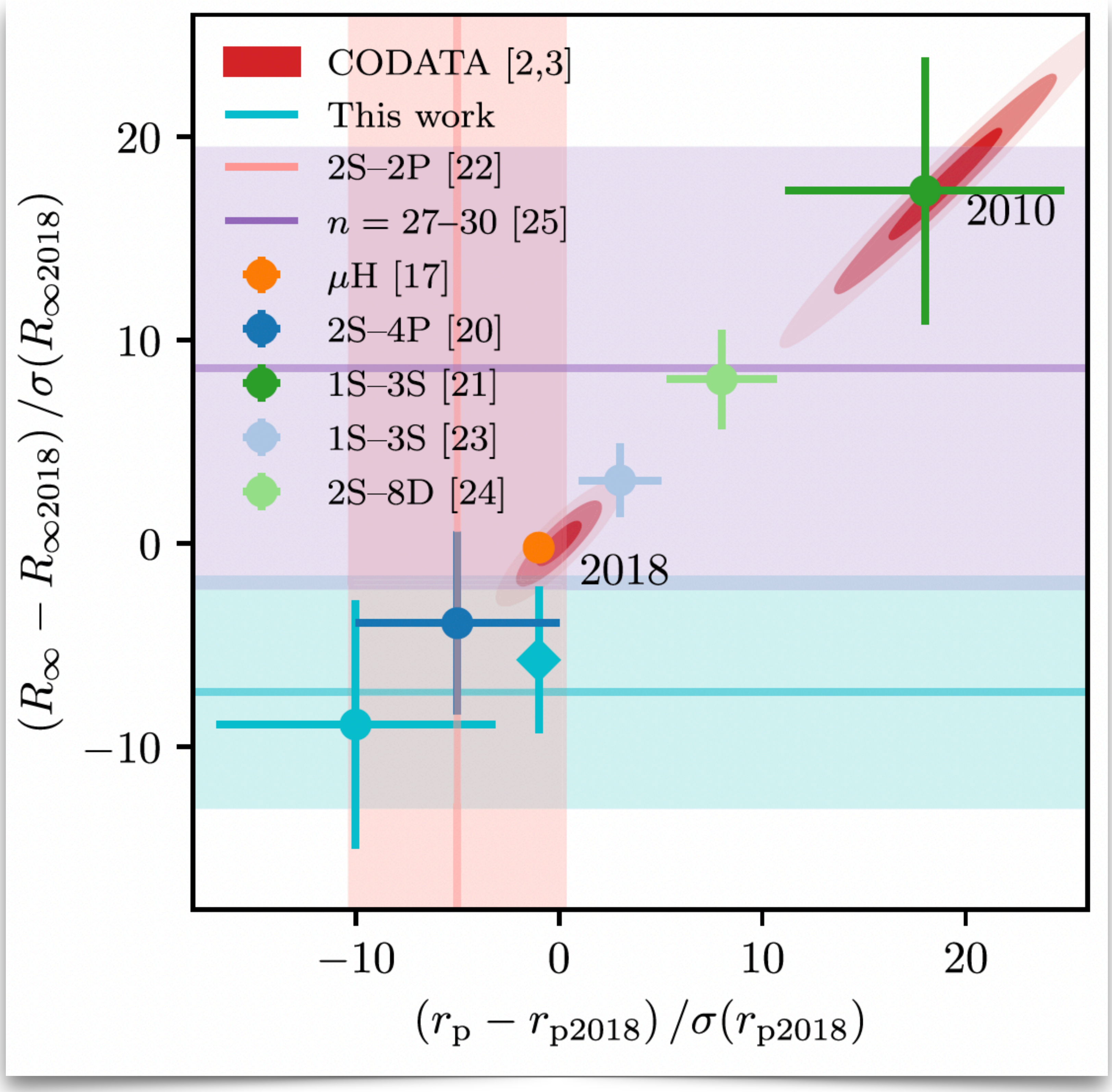
	PRad2 (current)
Stat. uncertainty	0.0014
GEM efficiency	0.0023
Acceptance	0.0002
Beam energy related	0.0002
Event selection	0.0027
HyCal response	0.0001
Beam background	0.0014
Radiative correction	0.0004
Inelastic ep	0.0002
Magnetic form factor model	0.0006
Total syst. uncertainty	0.0041
Total uncertainty	0.0043

- Assume regular GEMs with dead-area
- PRad-II uses only PbWO4 part of current HyCal

Production Run Plan

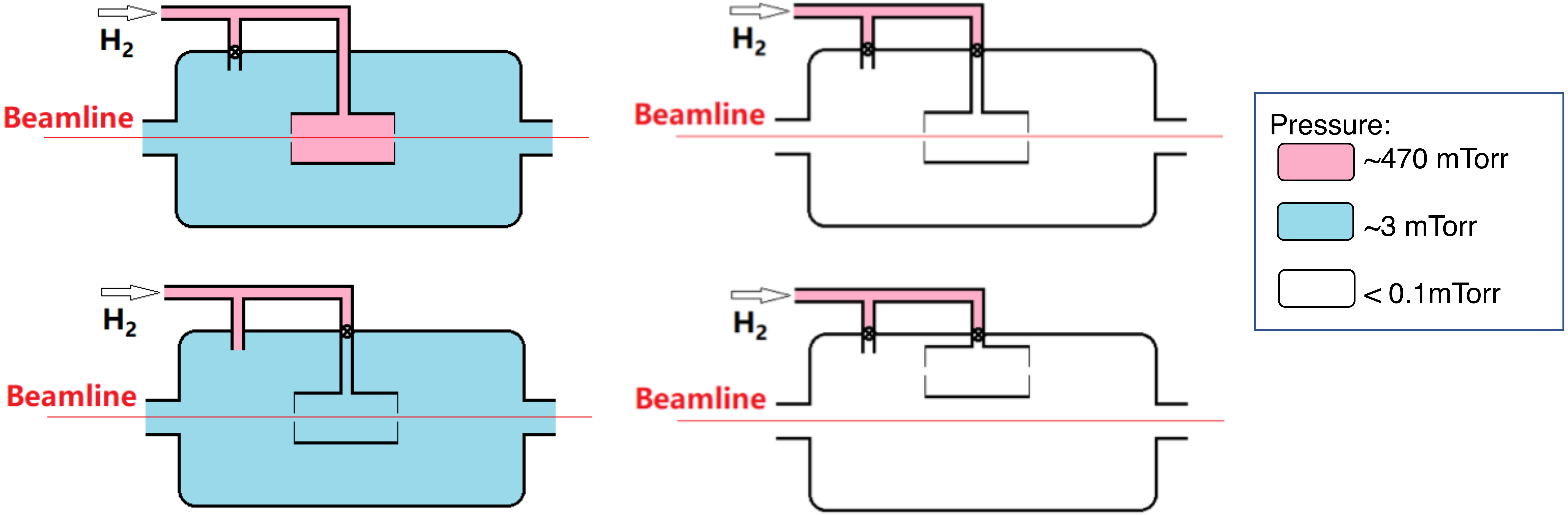
PRad-II
4 days, 700MeV, 20nA
5 days, 2100MeV, 150nA
15 days, 3500MeV, 150nA

The H-spectroscopy view has gotten even muddier in the last two years.



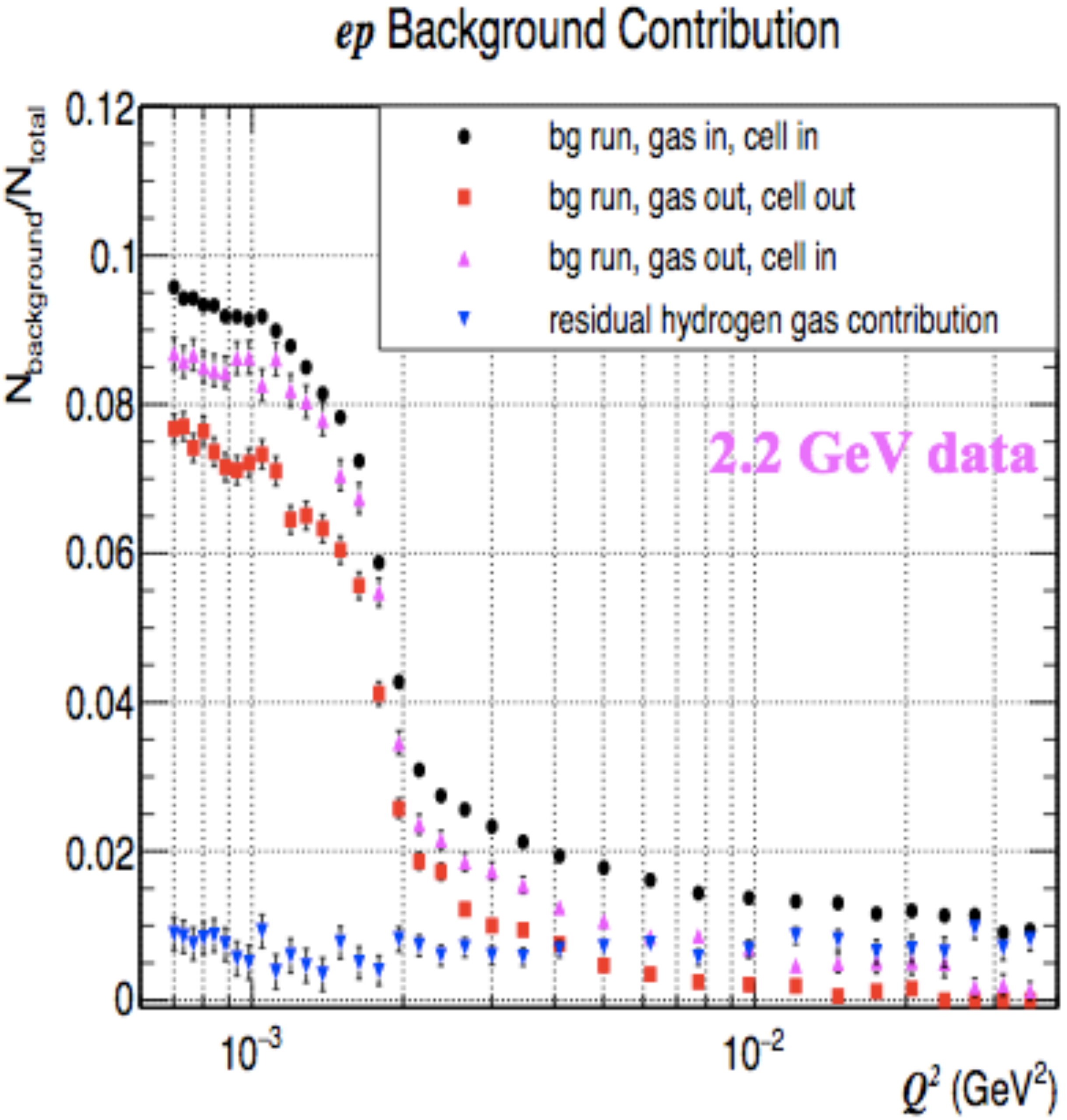
Background Subtraction

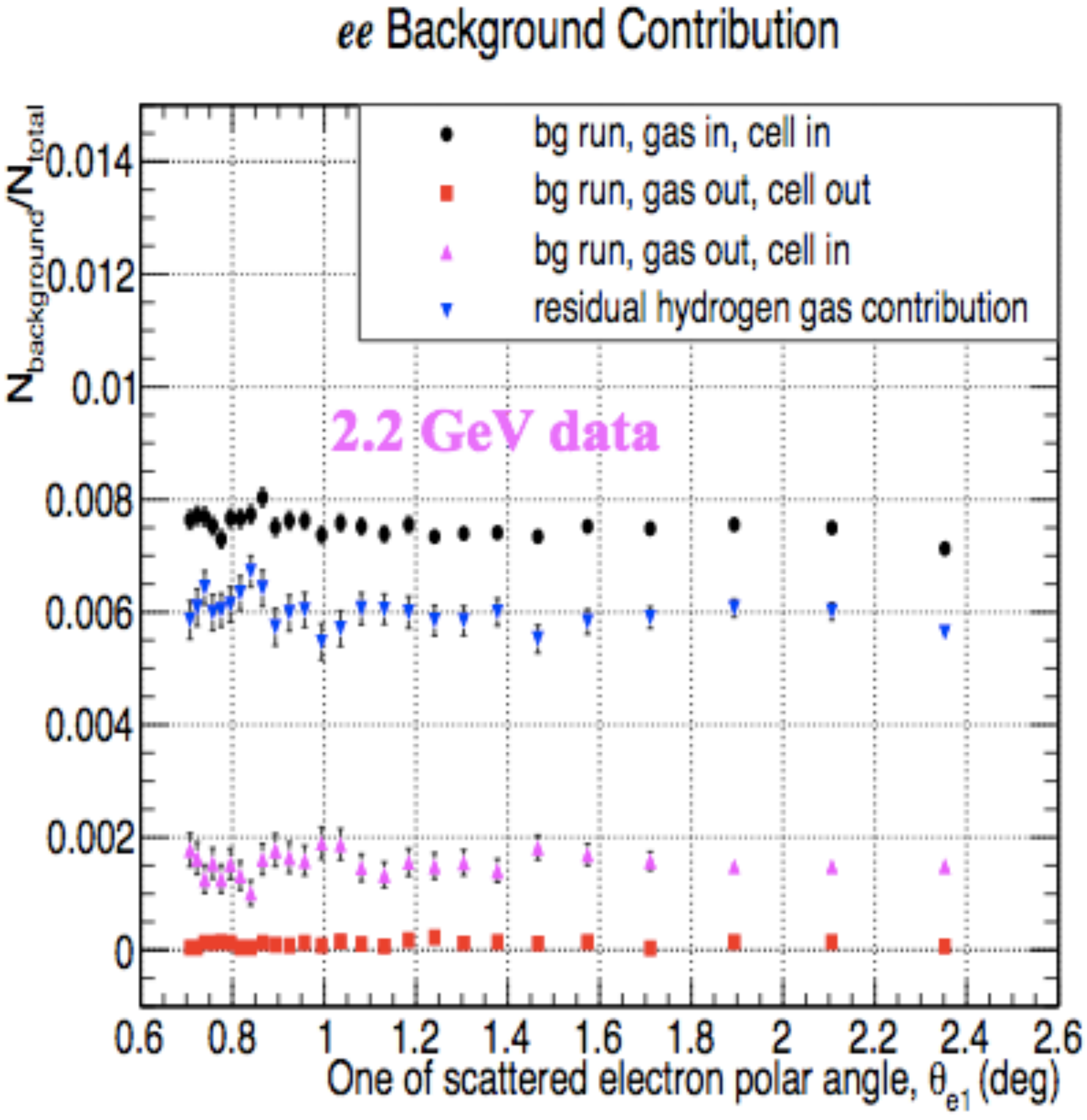
- **Runs with different target condition taken for background subtraction and studies for the systematic uncertainty**
- **Developed simulation program for target density (COMSOL finite element analysis)**



Background Subtraction

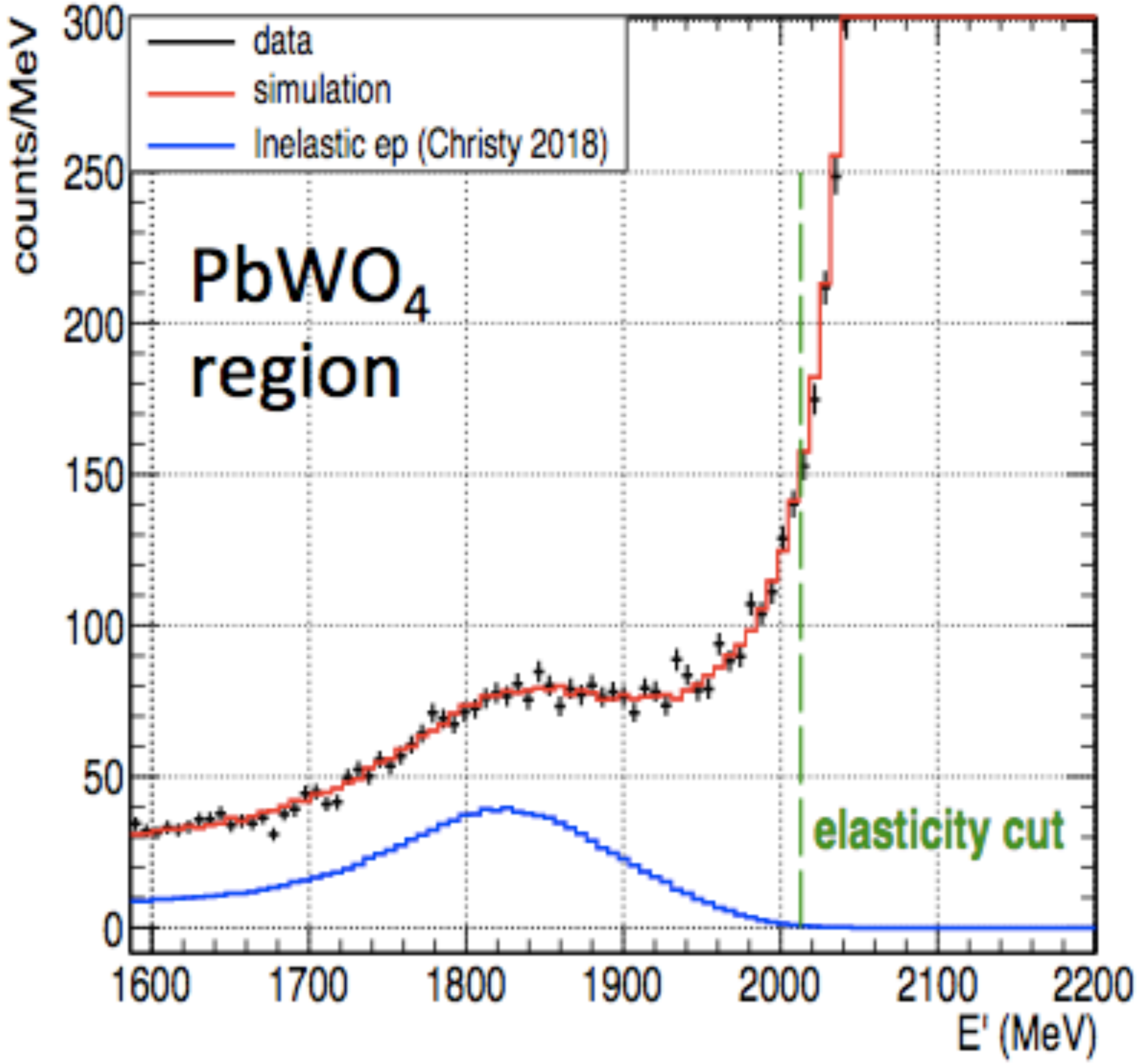
- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~ 0.8% at all angles



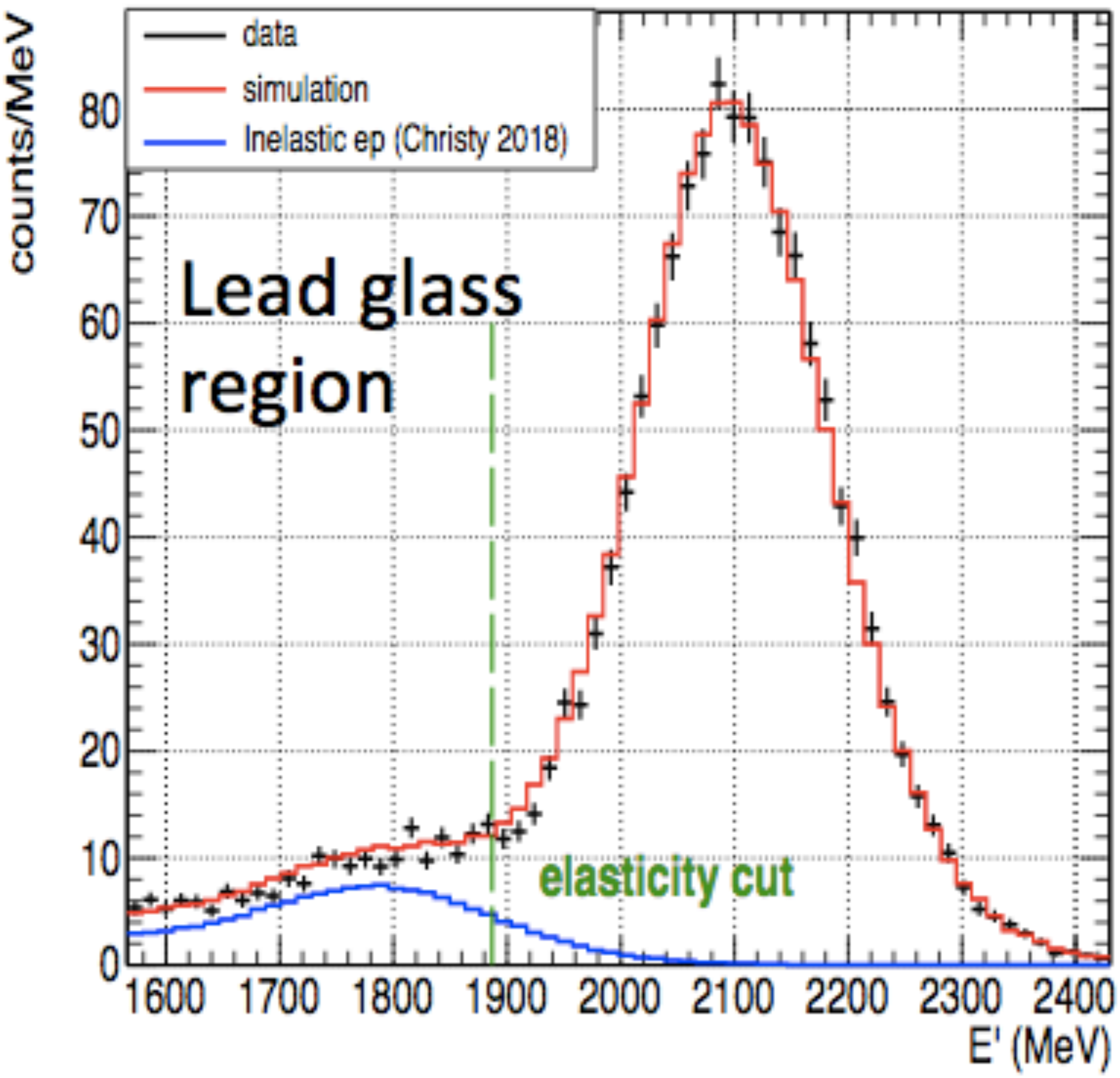


Elastic cut and inelastic contribution

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



spectrum for $3.0^{\circ} < \theta < 3.3^{\circ}$ ($Q^2 \sim 0.014\ \mathrm{GeV}^2$)



spectrum for $6.0^{\circ} < \theta < 7.0^{\circ}$ ($Q^2 \sim 0.059\ \mathrm{GeV}^2$)

M.E. Christy and P.E. Bosted. PRC 81, 055213 (2010)

There is a urgent need for high precision *e-D* scattering cross section and charge form factor data

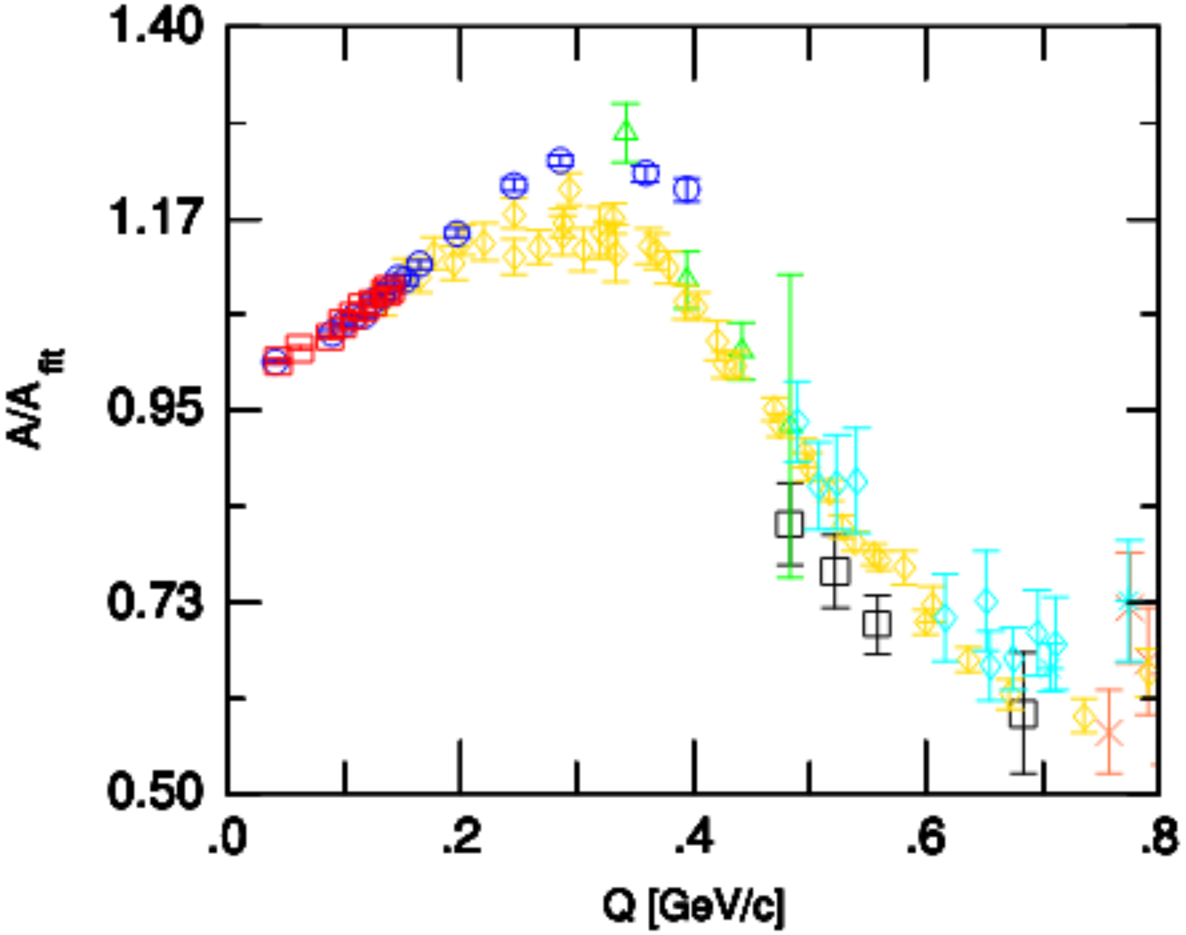
In the limit of first Born approximation, elastic *eD*- scattering is written in terms of the A(Q^2) and B(Q^2) structure functions.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{NS}[A(Q^2) + B(Q^2)\tan^2\theta/2]$$

$\frac{d\sigma}{d\Omega}|_{NS}$ is for elastic scattering from point-like spinless particle, & A(Q^2) and B(Q^2) are related to deuteron charge (G_{Cd}), electric quadrupole (G_{Qd}) and magnetic dipole (G_{Md}) form factors:

$$\begin{aligned} A(Q^2) &= G^2_{Cd}(Q^2) + \frac{2}{3}\eta G^2_{Md}(Q^2) + \frac{8}{9}\eta^2 G^2_{Qd}(Q^2) \\ B(Q^2) &= \frac{4}{3}\eta(1+\eta)G^2_{Md}(Q^2), \end{aligned}$$

$\eta = Q^2/4m_d^2$



Experiment	Q (GeV/c)	Symbol	Year and Reference
Monterey	0.04 - 0.14	□	1973 [8]
Mainz	0.04 - 0.39	○	1981 [9]
Saclay ALS	0.13 - 0.84	◇	1990 [10]
Orsay	0.34 - 0.48	△	1966 [11]
Stanford	0.48 - 0.88	□	1965 [12]
DESY	0.49 - 0.71	◇	1971 [13]
CEA	0.76 - 1.15	×	1969 [14]
JLab Hall C	0.81 - 1.34	★	1999 [15]
JLab Hall A	0.83 - 2.44	□	1999 [16]
SLAC E101	0.89 - 2.00	+	1975 [17]

Fig. from Byungwuek Lee's PhD thesis

Executive Summary

Using the PRad method, which has convincingly demonstrated the validit and advantage of the new calorimetric technique, we will measure the deuteron charge radius with a precision of 0.22%

We will cover the Q^2 range of $2\text{x}10^{-4}$ to $5\ \text{x}10^{-2}$ GeV^2 probing the lowest Q^2 reached by e-D scattering experiments.

We will use the PRad-II setup along with a new recoil detector.