The Incredible Shrinking Proton and the Proton Radius Puzzle

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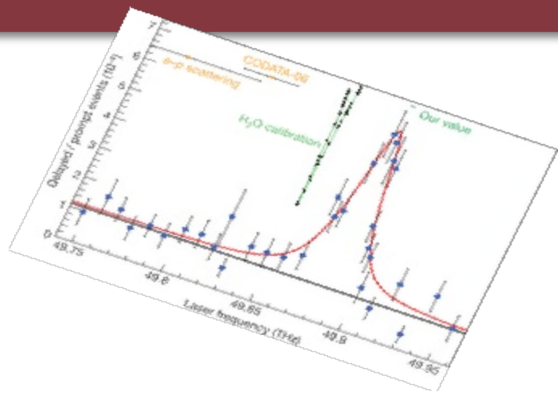
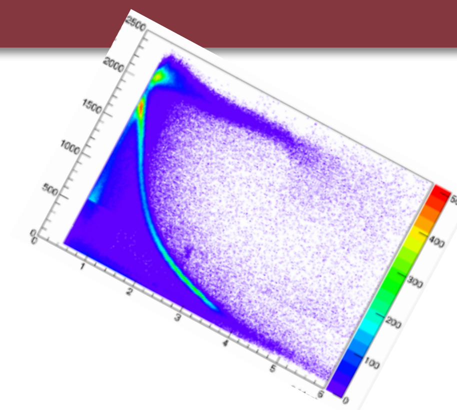
Outline





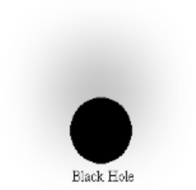
1. Introduction
2. The Proton Charge Radius Puzzle
3. The PRad Experiment
   - windowless target
   - high resolution calorimeter
   - simultaneous detection of elastic and Møller
4. Other recent experiments & future prospects

The study of the proton has revolutionized physics

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

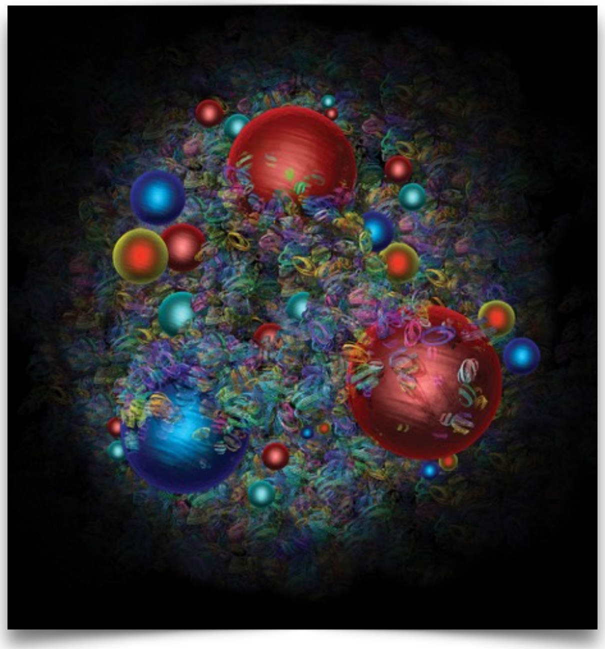
The proton played a leading role in the development of Quantum Chromo Dynamics (QCD): theoretical framework for strong interaction between quarks medicated by gluons.

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



Positively charged structure-less point particle

to



Bag 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.

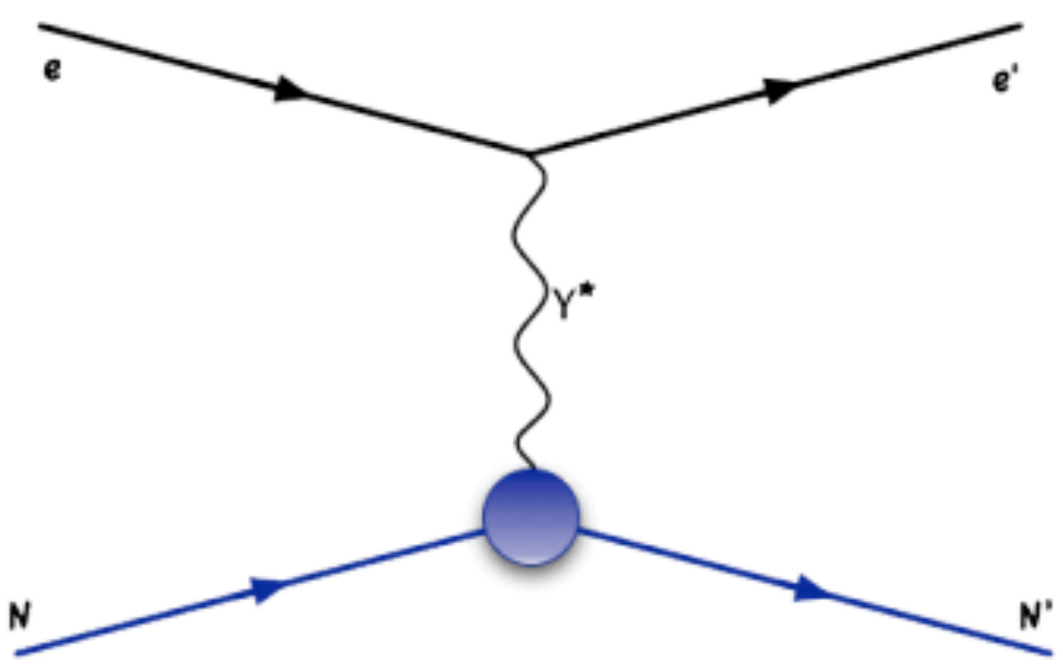
H - spectroscopy and elastic e-p scattering are the two traditional methods for determining proton charge radius

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

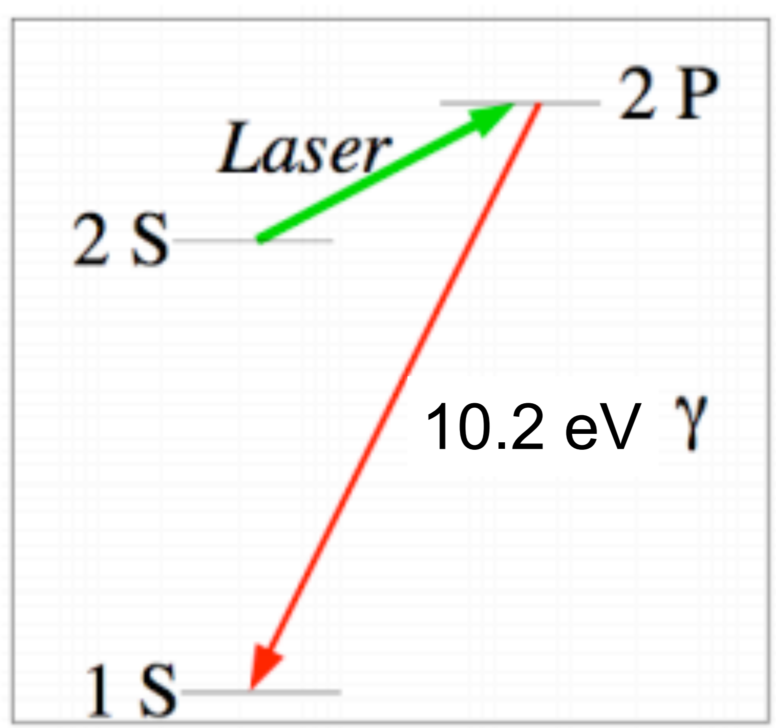
If the proton has no definite boundaries how do you define its radius?

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

e-p Scattering

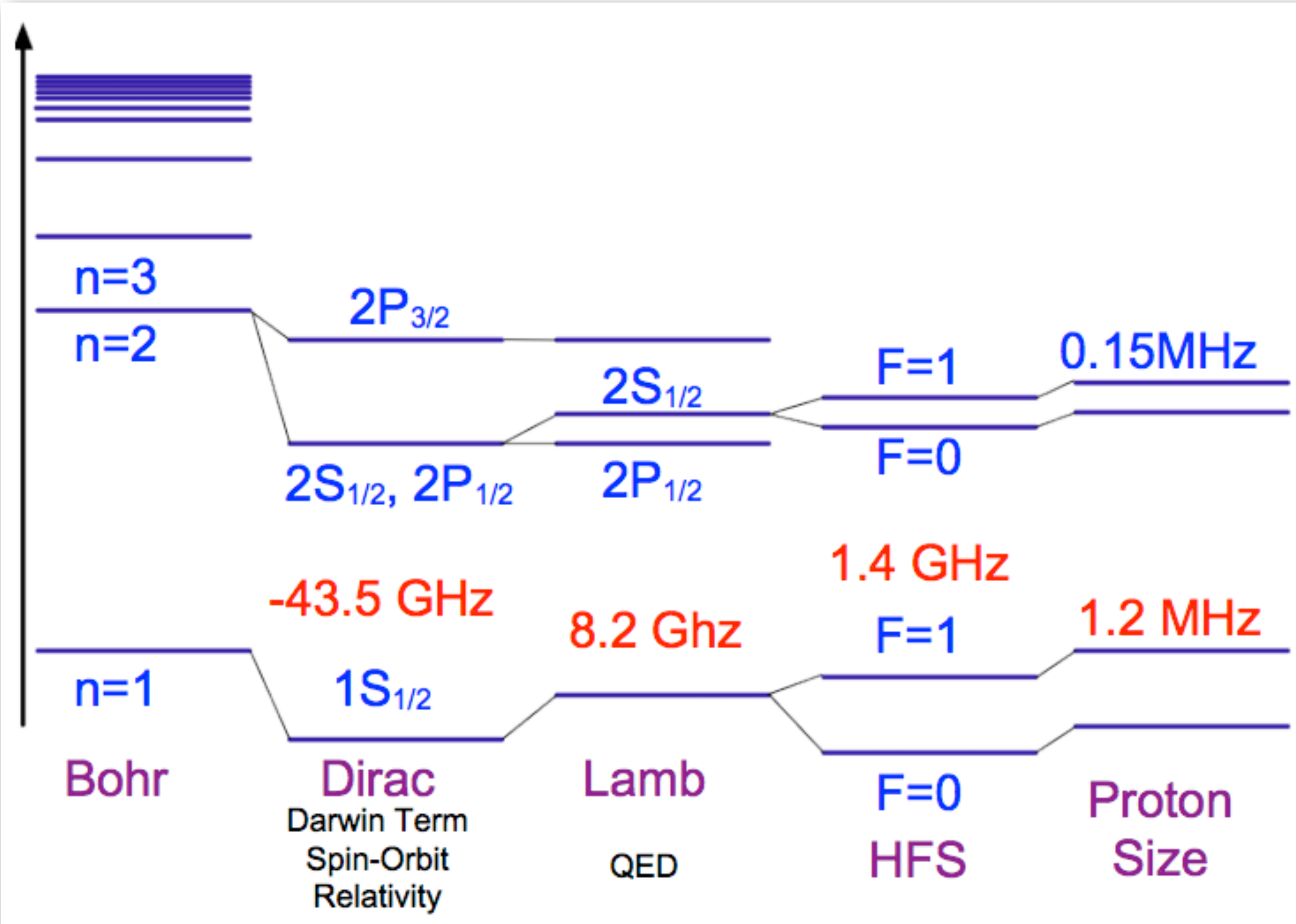


H-spectroscopy



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

Corrections to H - spectroscopy due to the extended charge distribution of the proton used to extract r_p



The absolute frequency of H energy levels has been measured with an accuracy of

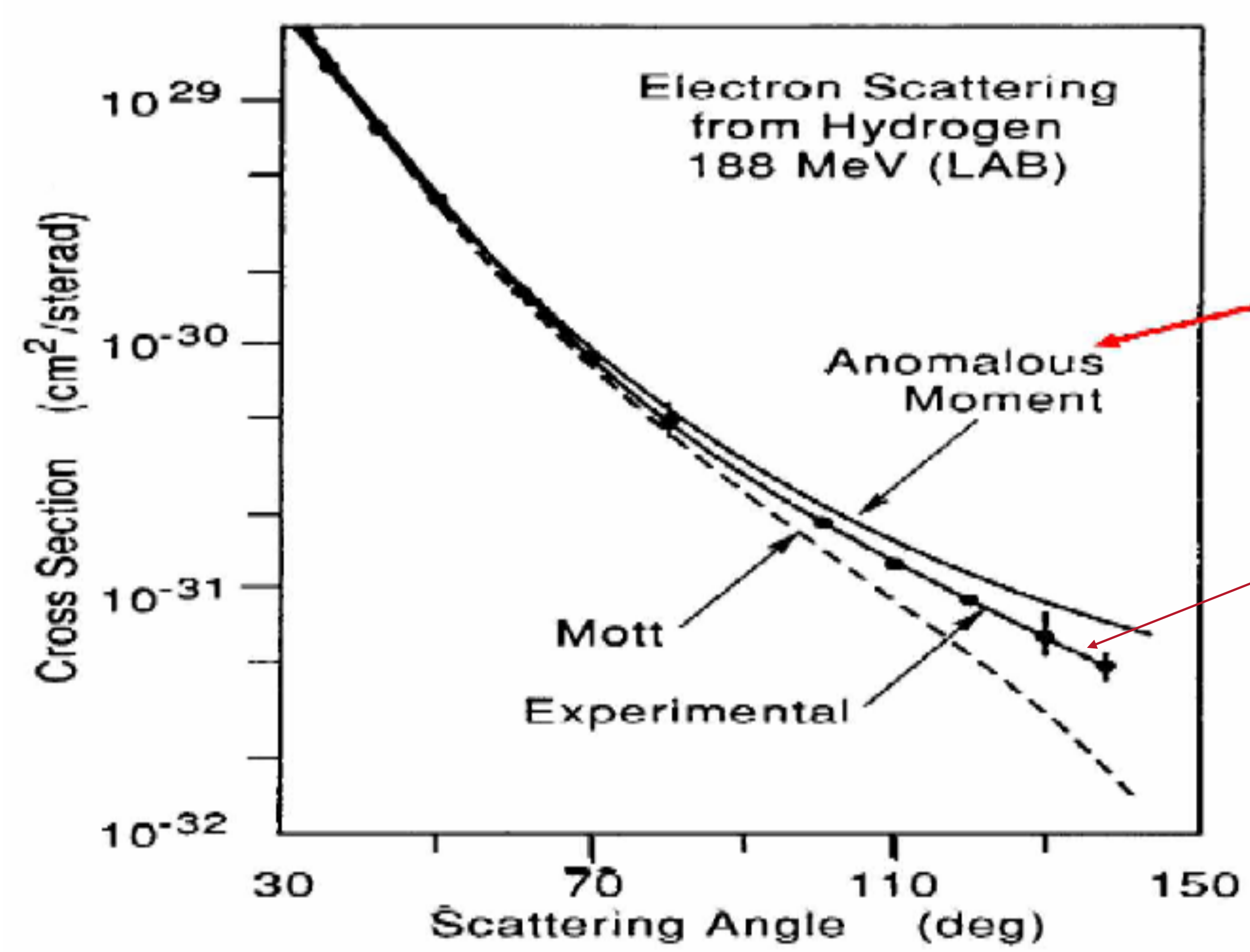
1.4 part in 10^{14}

via comparison with an atomic Cs fountain clock as a primary frequency standard.

Comparing measurements to QED calculations that include corrections for the finite size of the proton provide a precise value of the rms proton charge radius.

Also, yields R_∞ (the most precisely known constant in Physics)

The slope of the electric form factor down to zero Q^2 used to extract r_p from elastic e-p scattering.



Point like proton with G_E = 1 and $G_M = \mu_p$ = 2.79

Data show proton Has finite size

R. Hofstadter and R. W. McAllister, Phys. Rev., 98 (1955)

At very low Q^2, cross section dominated by G_E:

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

$$\mathbf{G}_{\mathbf{E}}(\mathbf{Q}^2) = 1 - \frac{Q^2}{6} < r^2 > + \frac{Q^4}{120} < r^4 > + \ldots$$

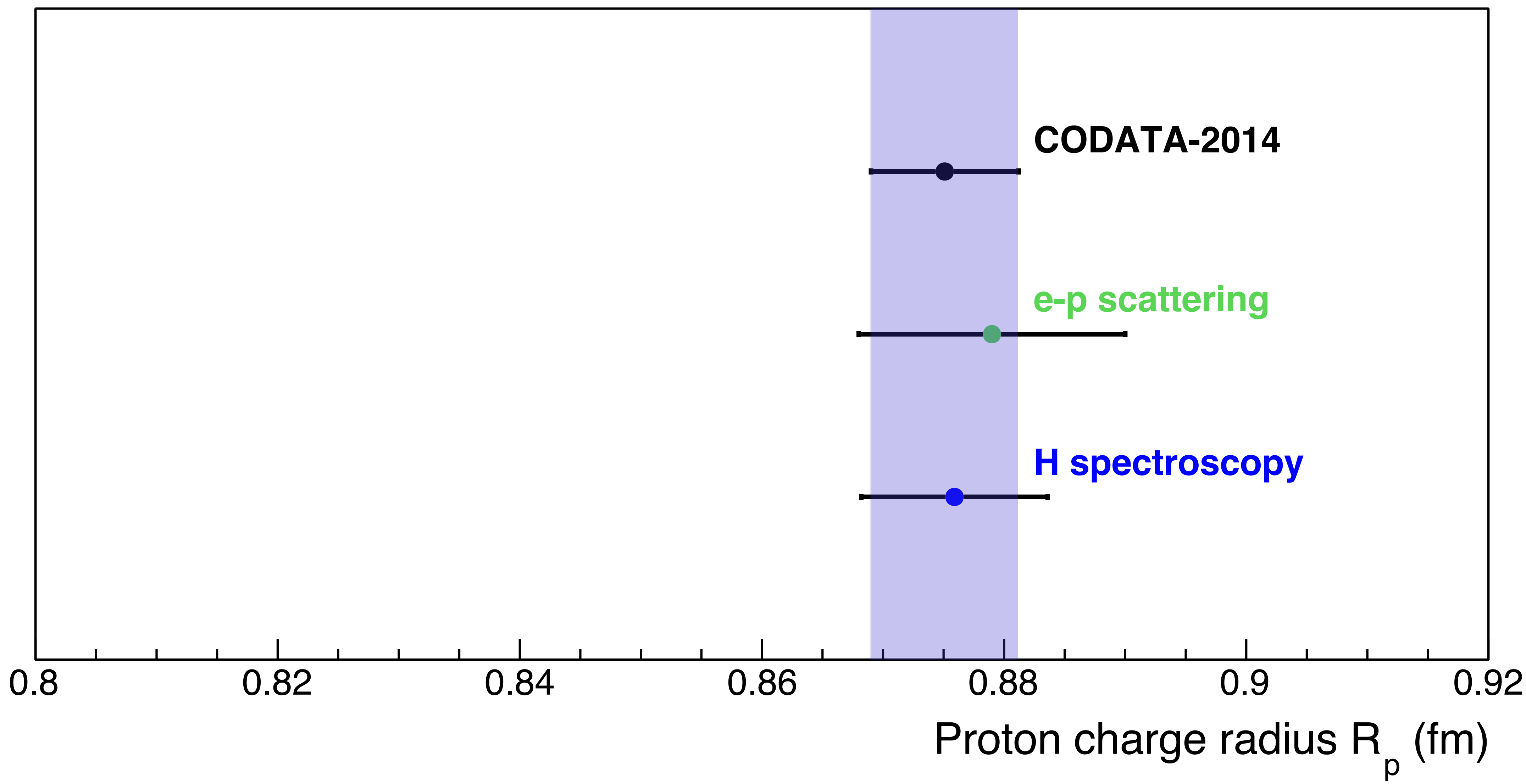
Charge radius given by the slope at $Q^2 = 0$:

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

This definition has been rigorously shown to be consistent with all experimental measurements.

G. Miller, Phys. Rev., C 99, 035202 (2019)

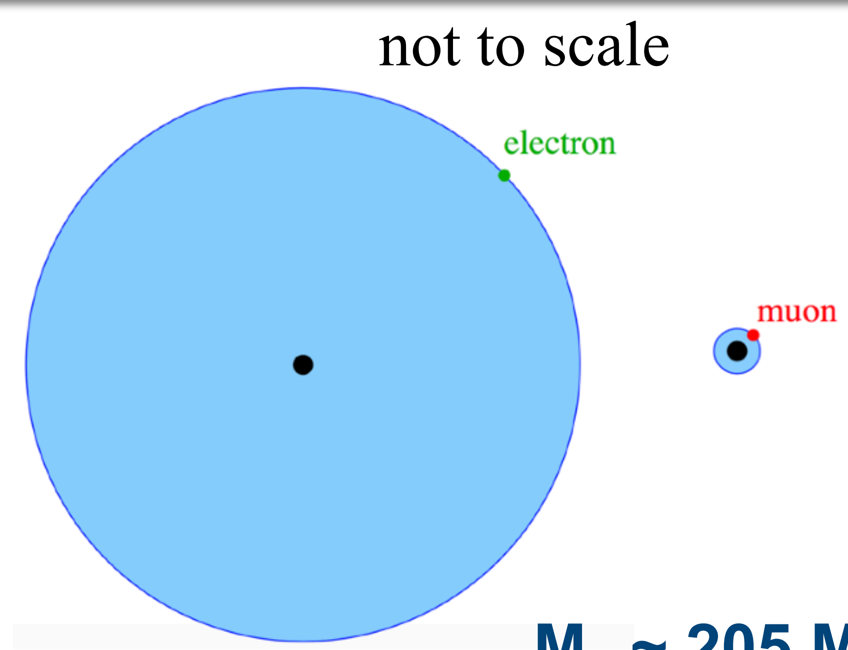
Prior to 2010 the r_p extracted from H - spectroscopy and elastic e-p scattering were consistent with each other.



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

The charge radius of the proton was considered a settled question.

A new method based on muonic hydrogen spectroscopy was used to extract r_p for the first time in 2010.



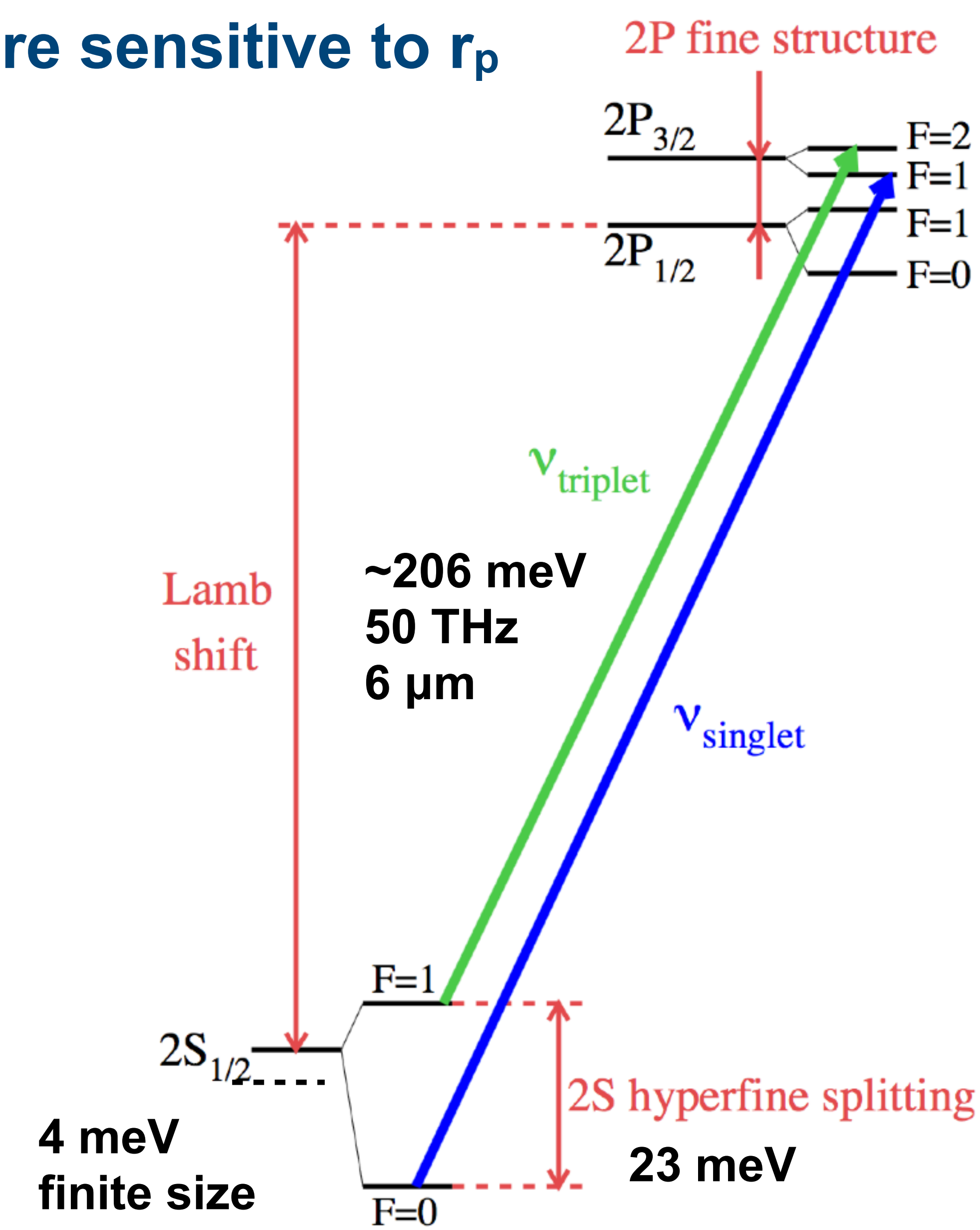
$M_\mu \sim 205\ M_e$

Probability of lepton to be inside proton

$$\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p\alpha)^3 m^3$$

m = reduced mass
$\sim 186\ M_e$

μH is ~ 6×10^6 times more sensitive to r_p

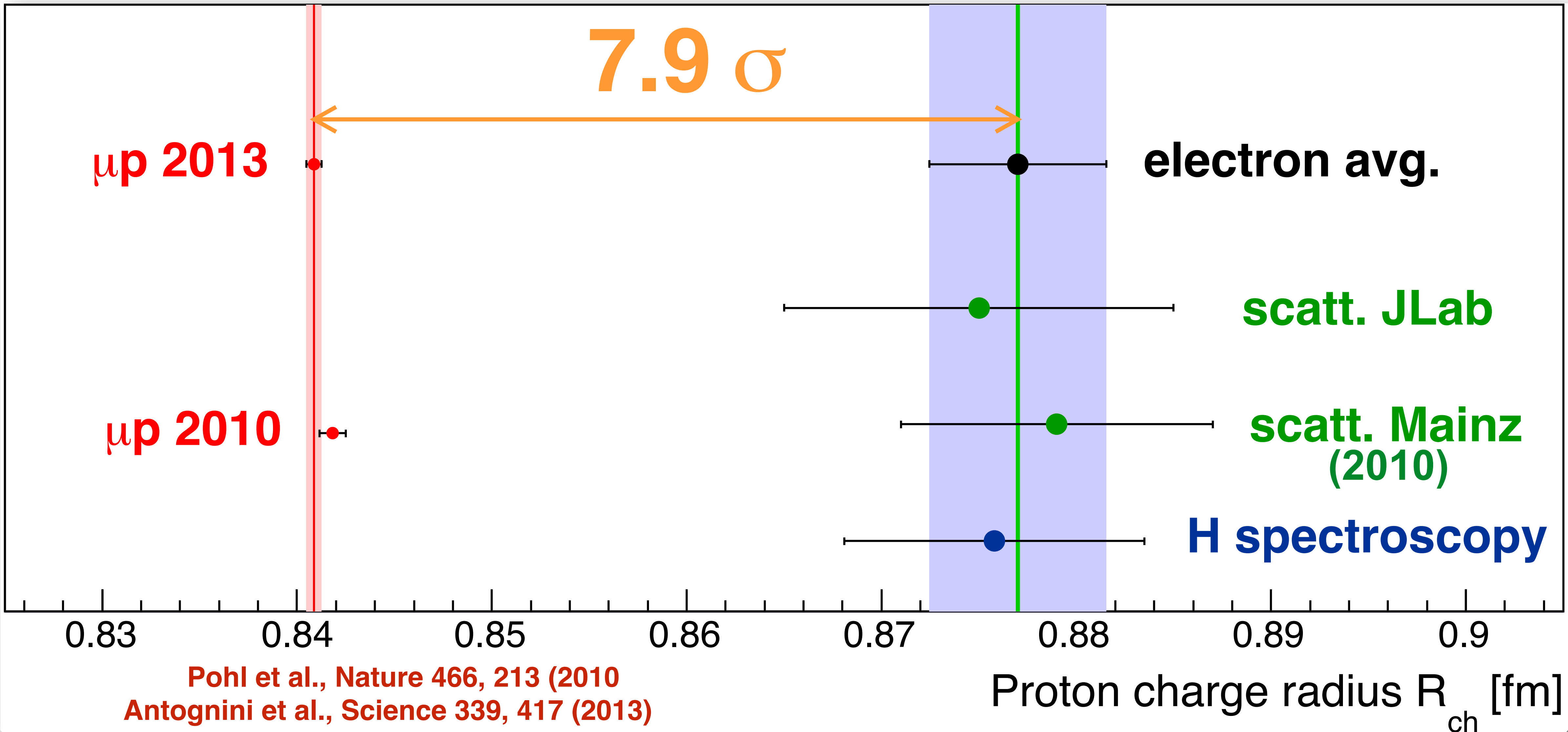


Lamb shift in μH:
$\Delta E = 206.0668(25) - 5.2275(10)\ r_p^2$ [meV]
finite proton size is ~2% correction to μH Lamb shift

r_p was extracted with
10 times higher precision (~0.1 %)
compared to all previous measurements

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)

★ **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).

Clearly more experiments were needed !

- Redo atomic hydrogen spectroscopy (3 different groups)
- Muon-proton scattering (MUSE, AMBER)
- Electron scattering experiments (PRad, ISR, MAGIX, ULQ², PRad-II, …)

(2016)

The status of "proton radius puzzle" in 2018

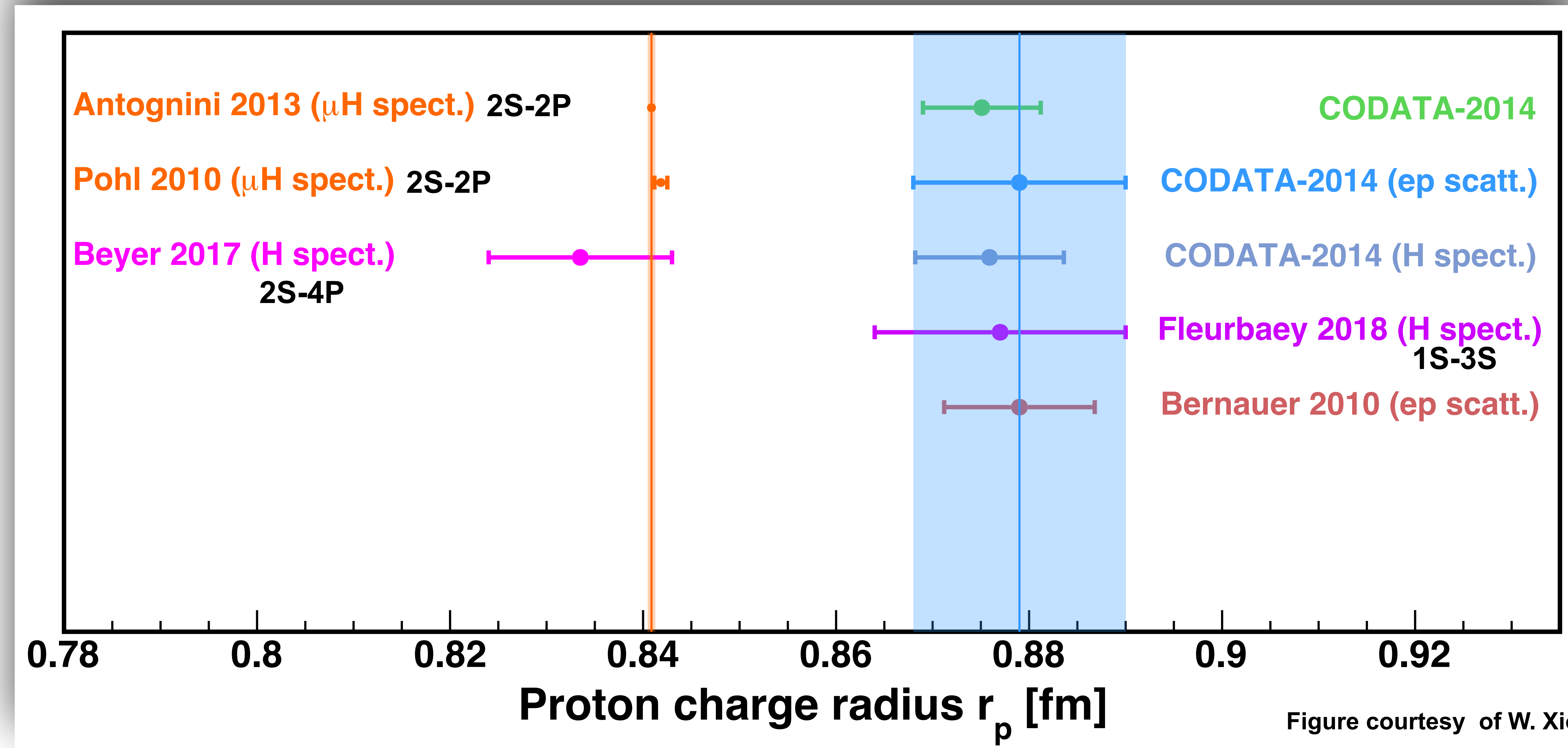
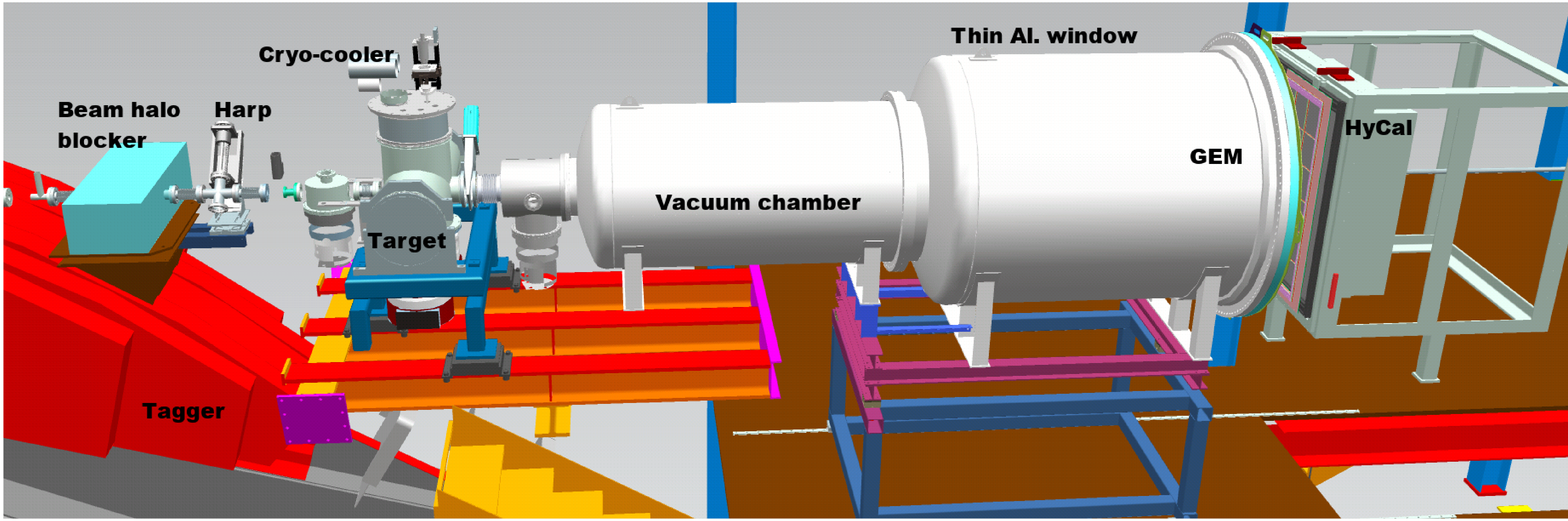


Figure courtesy of W. Xiong

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} – 6×10^{-2} GeV^2 (lower than all previous electron scattering expts.)**

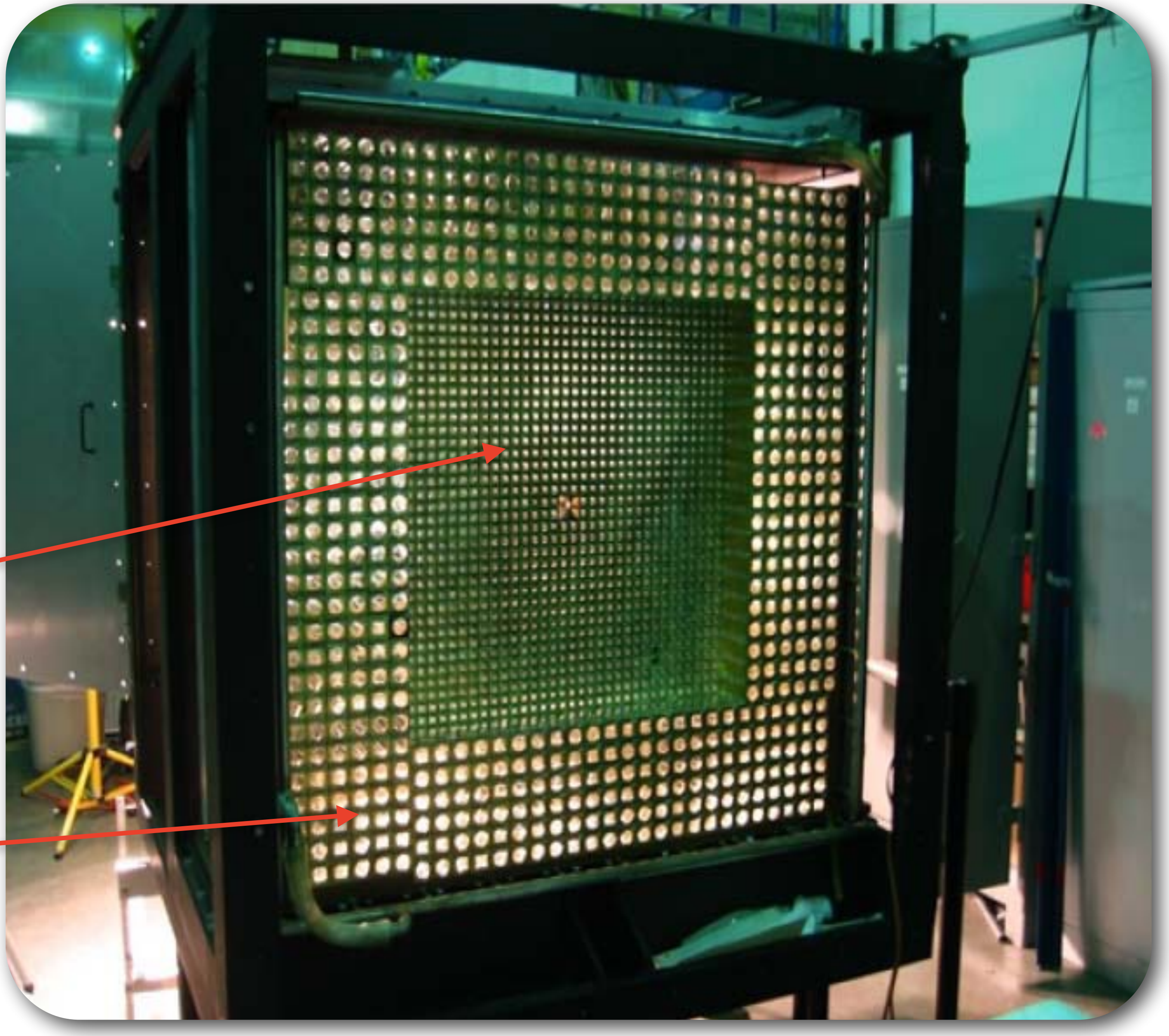
Ran in Hall-B at JLab in 2016, using 1.1 GeV and 2.2 GeV electron beam

The first experiment to use a magnetic spectrometer free method to measure r_p

Reused PrimEx Hybrid Calorimeter

- $PbWO_4$ and Pb-glass calorimeter (118x118 cm^2)
- 34x34 matrix of 2.05 x 2.05 cm^2 x18 cm $PbWO_4$
- 576 Pb-glass detectors (3.82x3.82 cm^2 x45 cm)
- 5.5 m from the target,
- 0.5 sr acceptance

Allows coverage of extreme forward angle (0.7^o - 7.5^o) in a single setting and complete azimuthal angle coverage



$PbWO_4$ resolution:
$\sigma_E/E = 2.6\%/\sqrt{E}$
$\sigma_{xy} = 2.5$ mm/$\sqrt{E}$

Pb-glass:

2.5 times worse

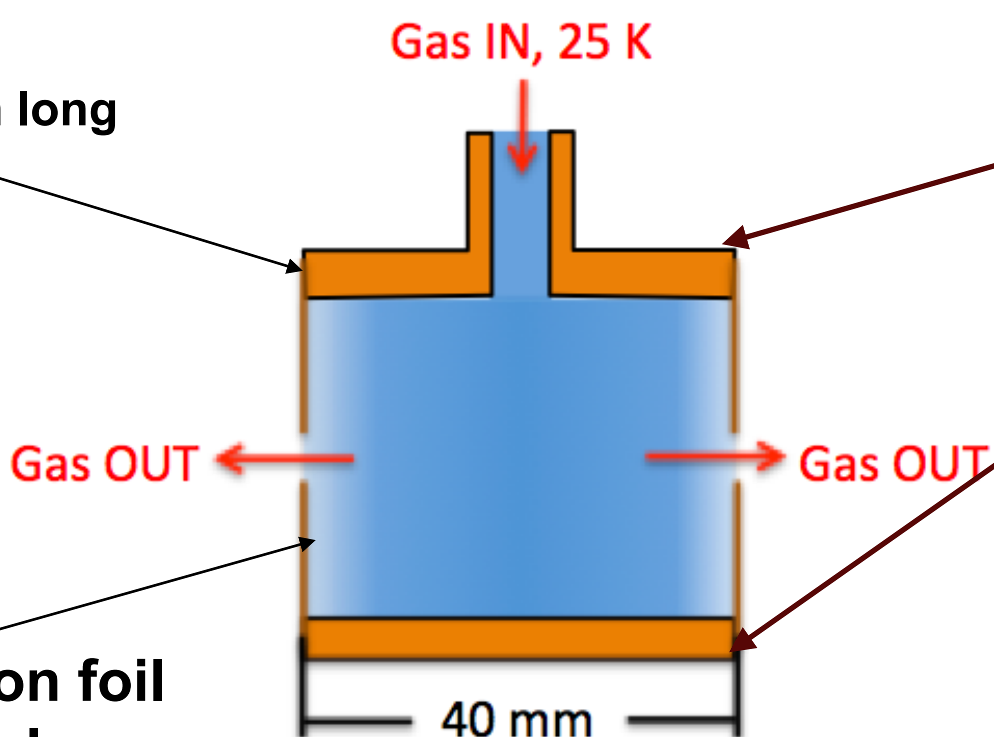
The first experiment to use a windowless target to measure r_p

Used a cryo-cooled windowless gas flow hydrogen target.

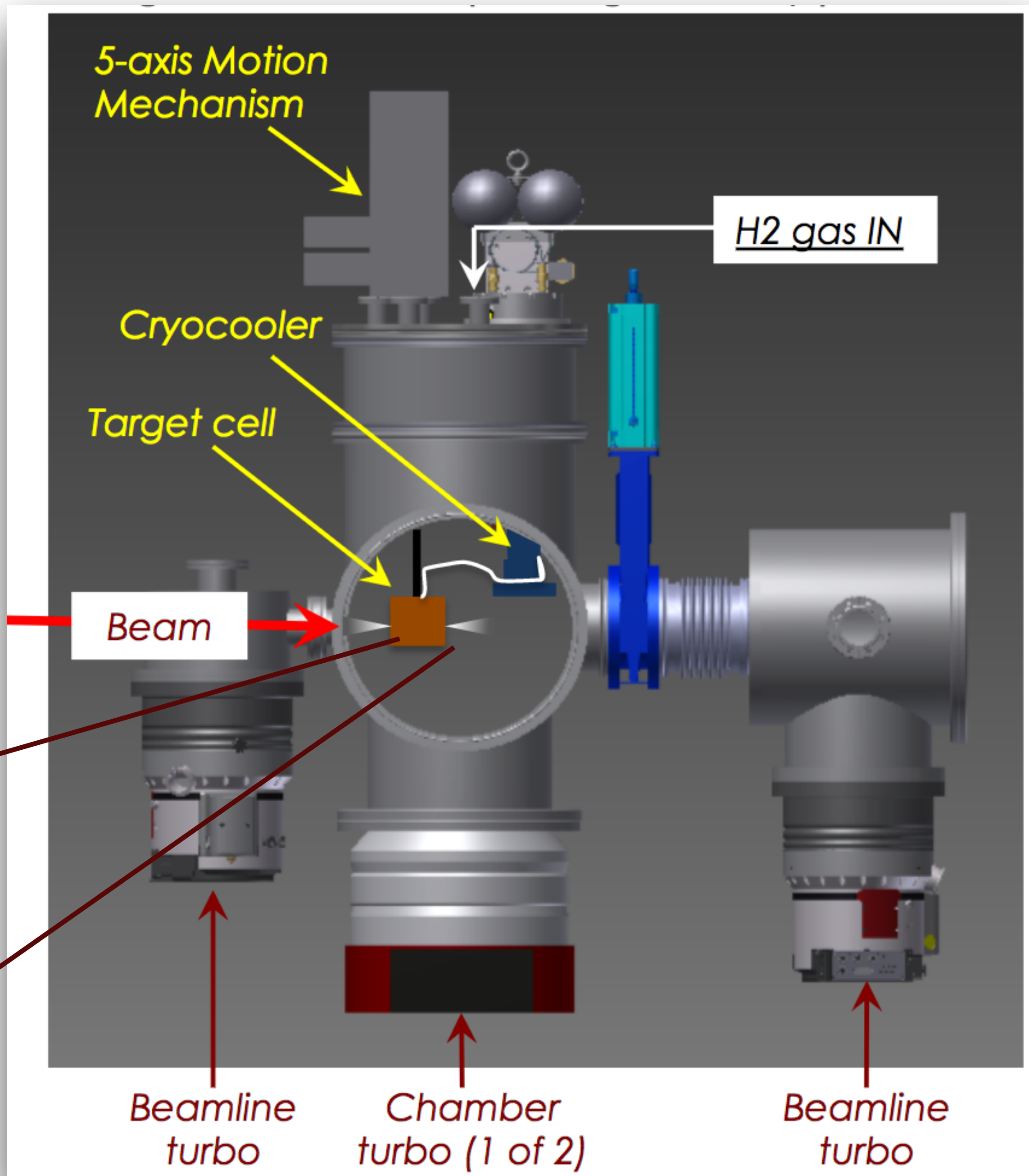
density:
~2x10^{18} atoms/cm^2

cell / chamber/ tank pressure:
470 / 2.3 / 0.3 mtorr

Target cell
(8 cm dia x 4 cm long copper)



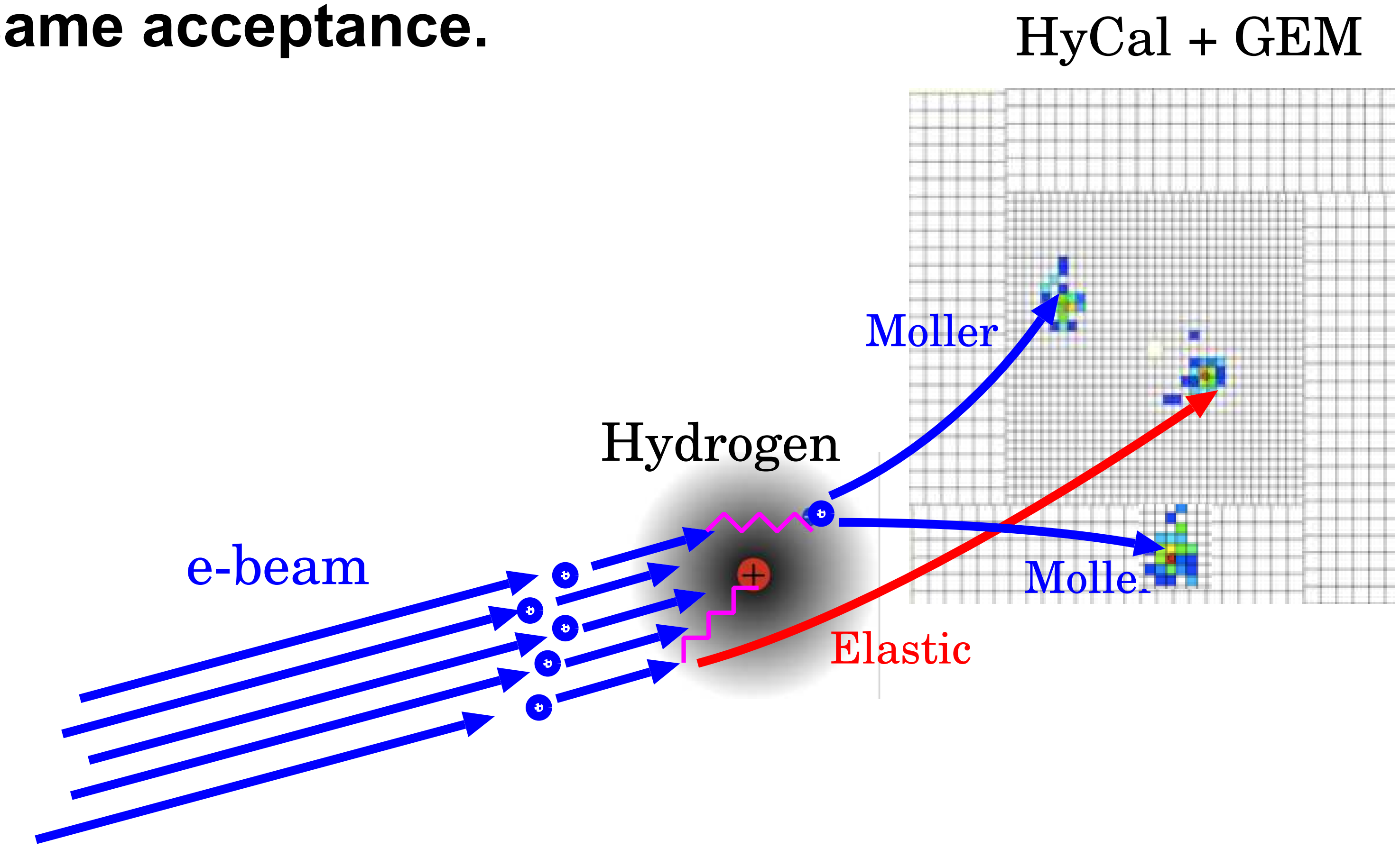
7.5 μm kapton foil with 2mm hole



Empty target runs used to subtract background

Key innovations in the design allowed a unique high precision measurement.

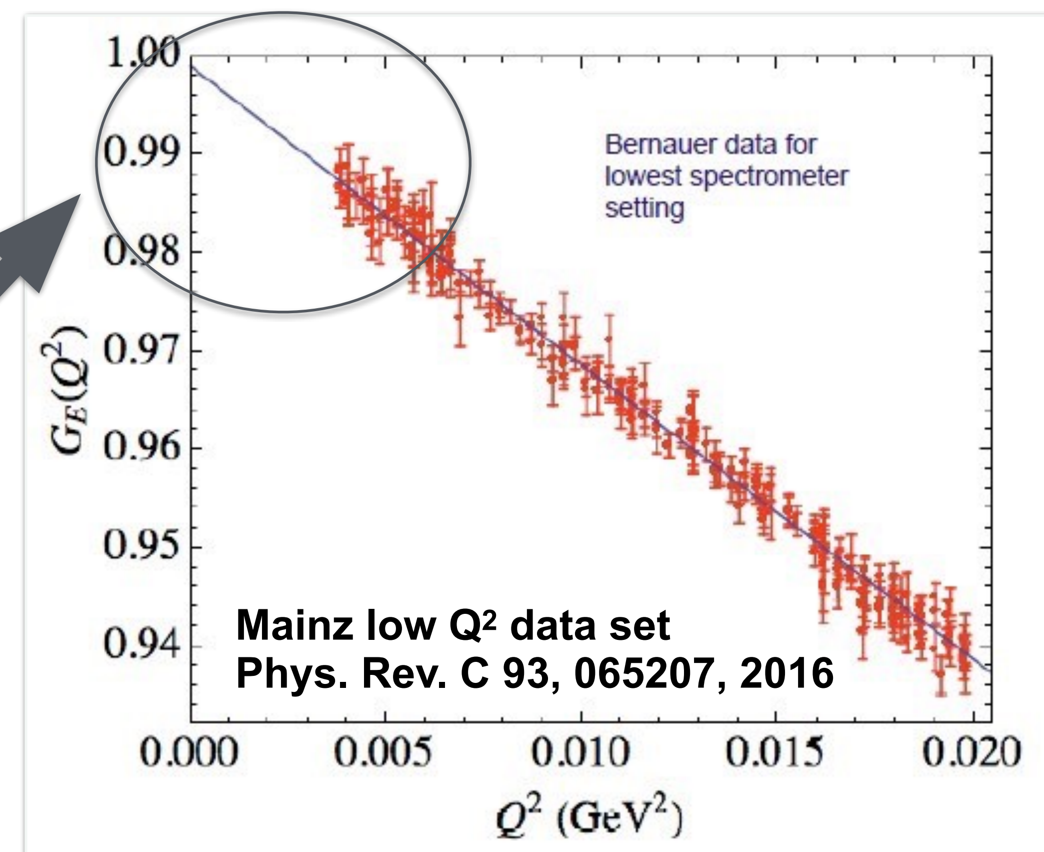
Simultaneous detection of the Møller *(e-e)* and *e-p* elastic events within the same acceptance.



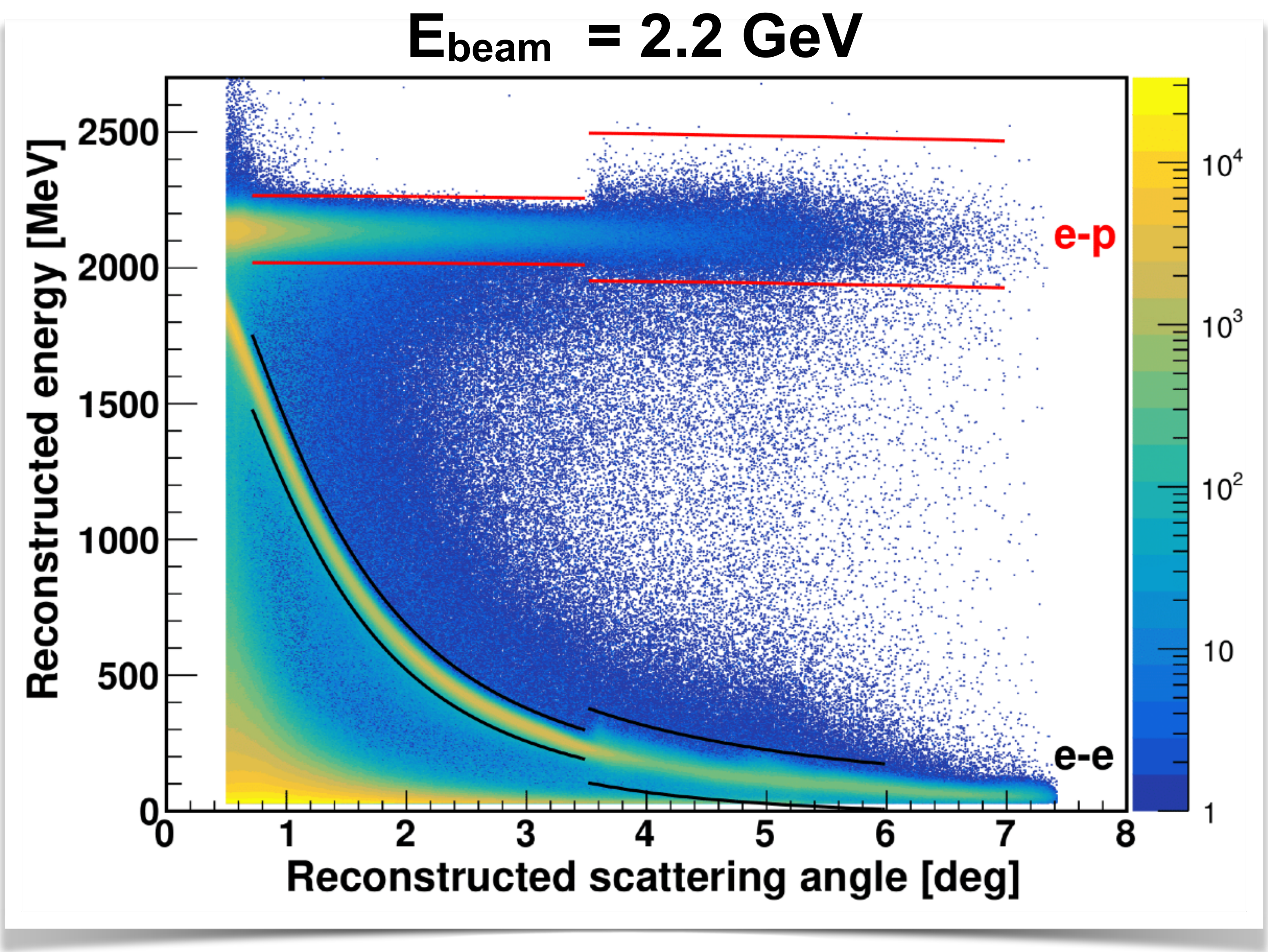
- **Experimental design allows:**
  - ➢ **control of systematics**
  - ➢ **eliminates need to monitor luminosity**

Large forward angle acceptance with high energy resolution (HyCal) and 72 µm position resolution (GEM).

- **Experimental design allows:**
  - ➢ **fill in the very low Q^2 range**
  - ➢ **large Q^2 range in a single setting (~$2x10^{-4}$ - $6x10^{-2}$ GeV^2)**

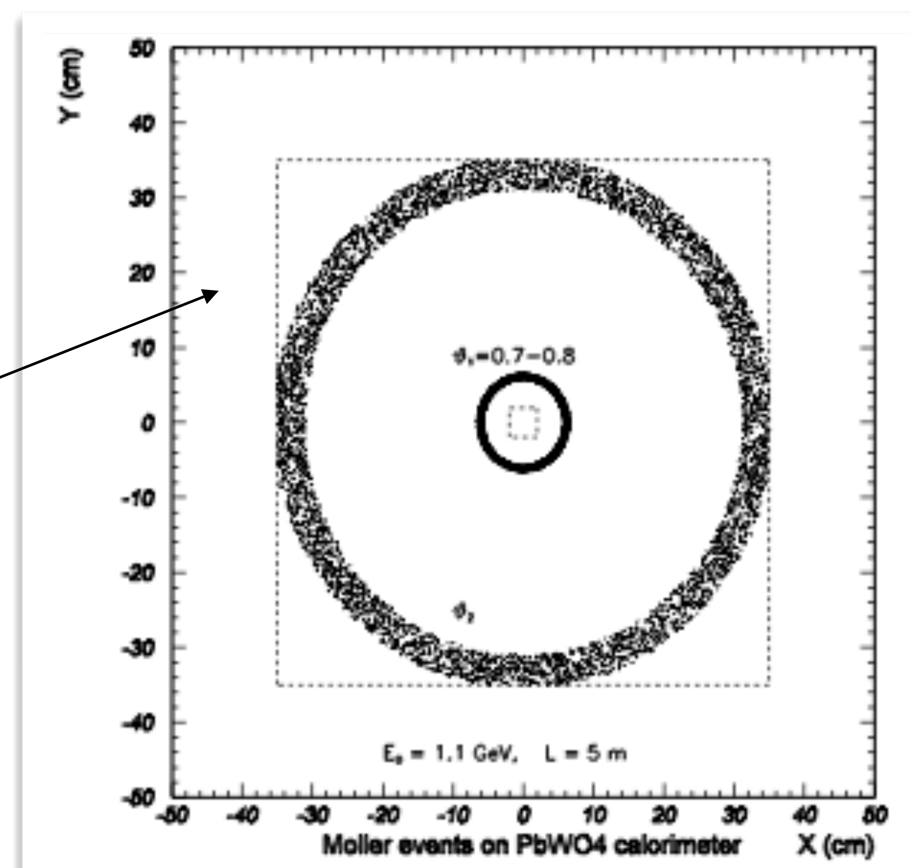


Angle dependent energy cuts are used to select the Møller (*e-e*) and *e-p* elastic events.



GEM and HyCal detector hits must match for all (*e-p*) and (*e-e*) events

Angle dependent energy cuts for (*e-p*) and (*e-e*) events based on kinematics with the cut size based on local resolution.



Additional constraints for double arm Møller events on: co-planarity, elasticity, z-vertex

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

bin-by-bin normalization (double arm Møller)

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

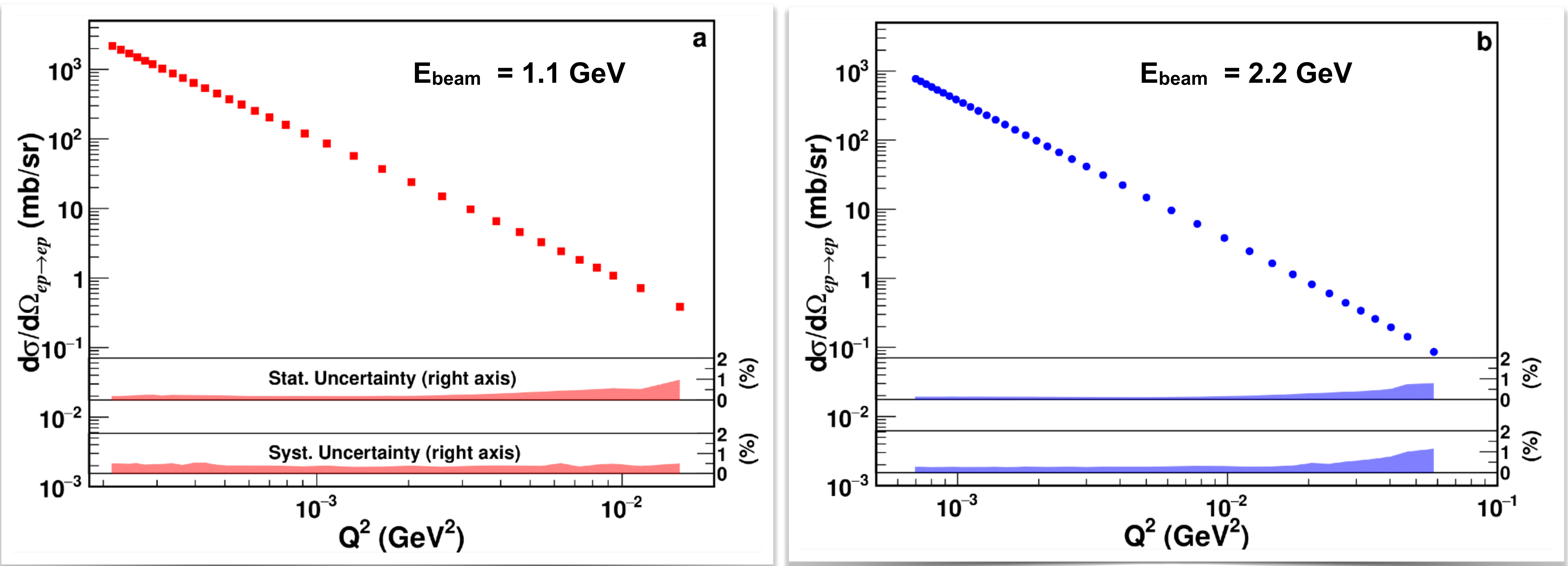
or

integrated over HyCal acceptance

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

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)**

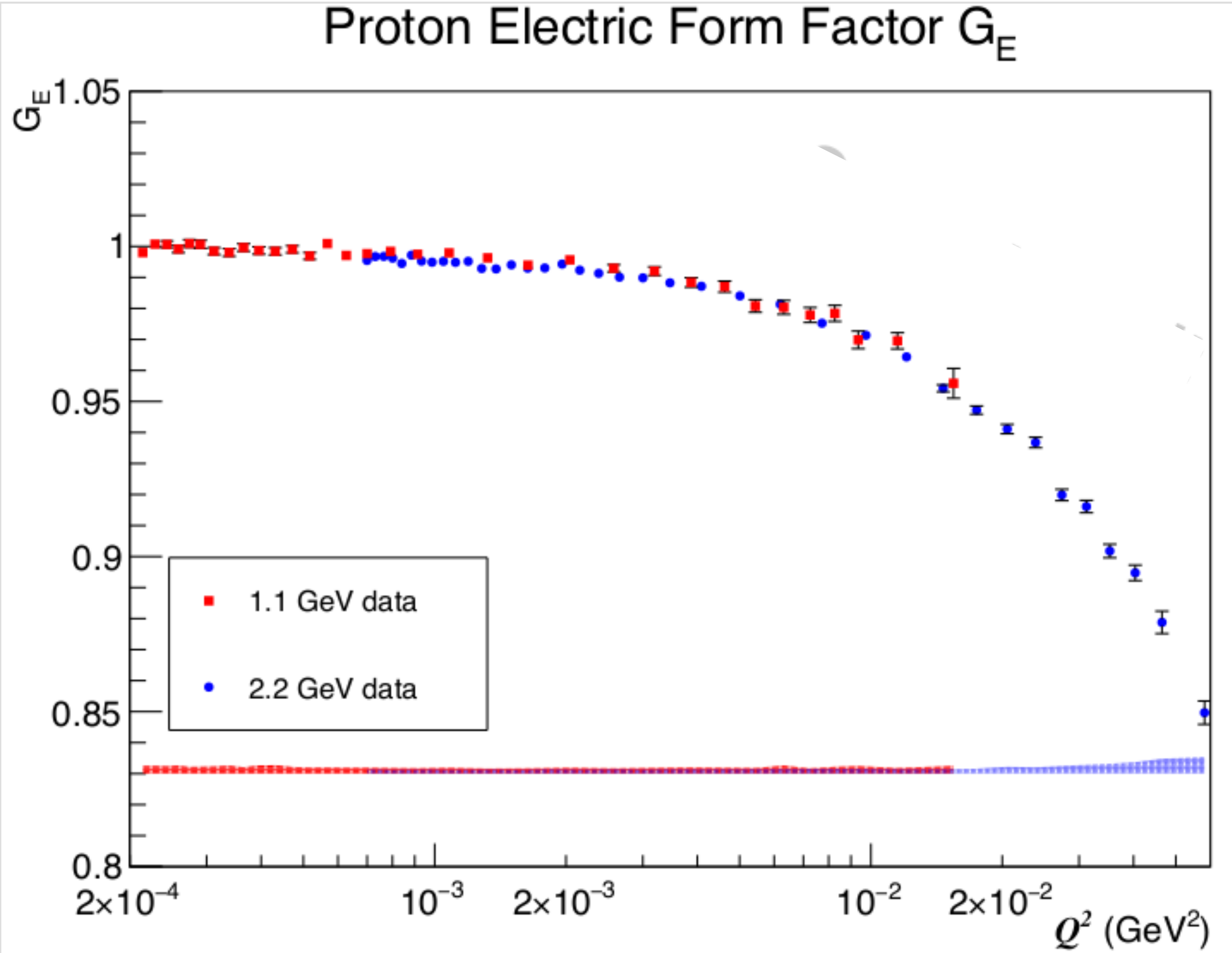
1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41, 115001 (2014).
2. I. Akushevich et al., Eur. Phys. J. A 51, 1 (2015).
3. O. Tomalak, Few Body Syst. 59, 87 (2018). (two photon exchange formalism)



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 $Q^2 = 0$.

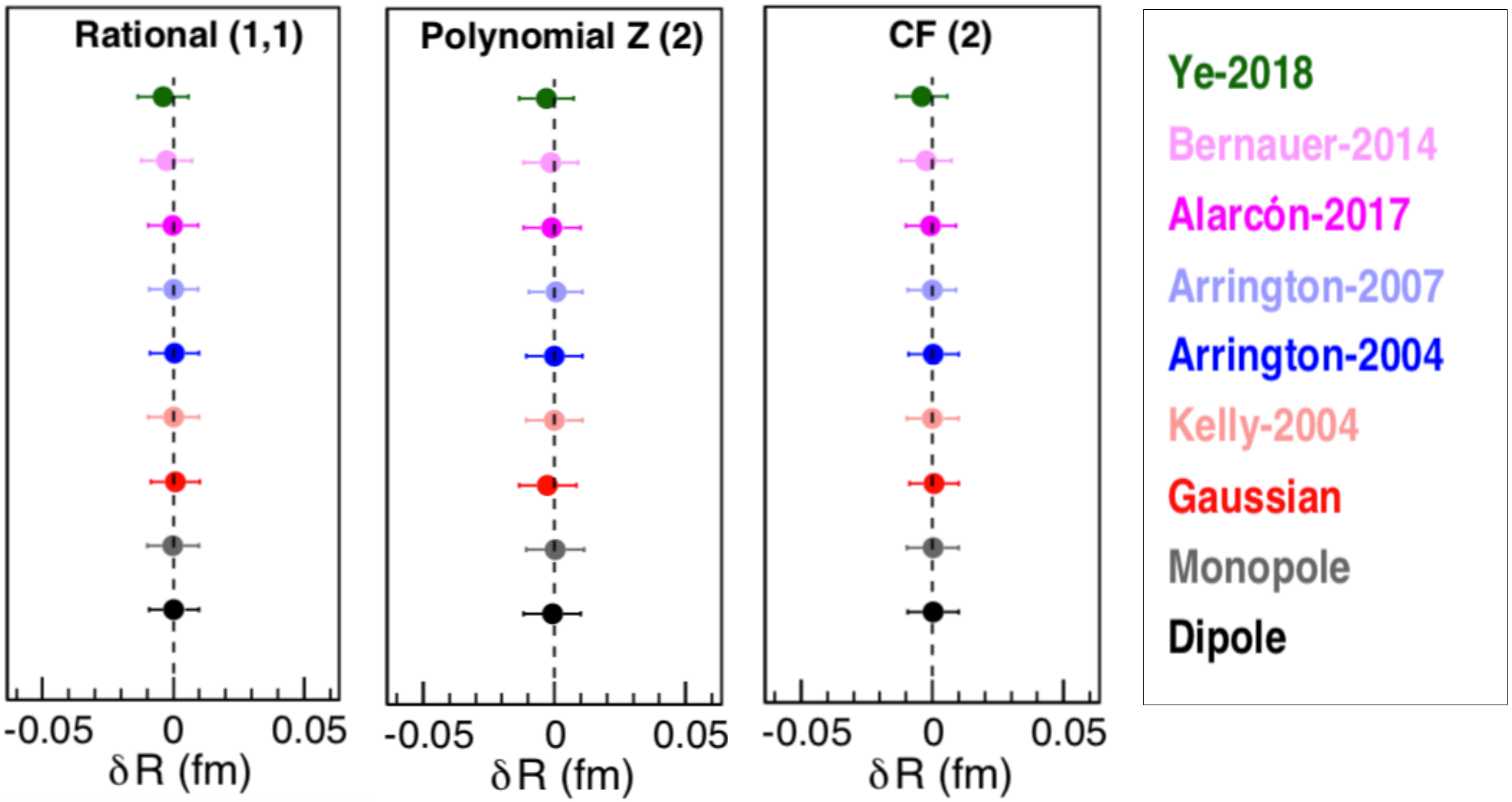
The truncation of the higher-order moments of $G_E(Q^2)$ introduces a model dependence which can bias the determination of r_p.

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)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order z transformation

$$p_0(1 + p_1 z + p_2 z^2)$$

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

2nd order continuous faction

$$p_0 \frac{1}{1 + \frac{p_1 Q^2}{1 + p_2 Q^2}}$$

Figure courtesy of W. Xiong

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

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

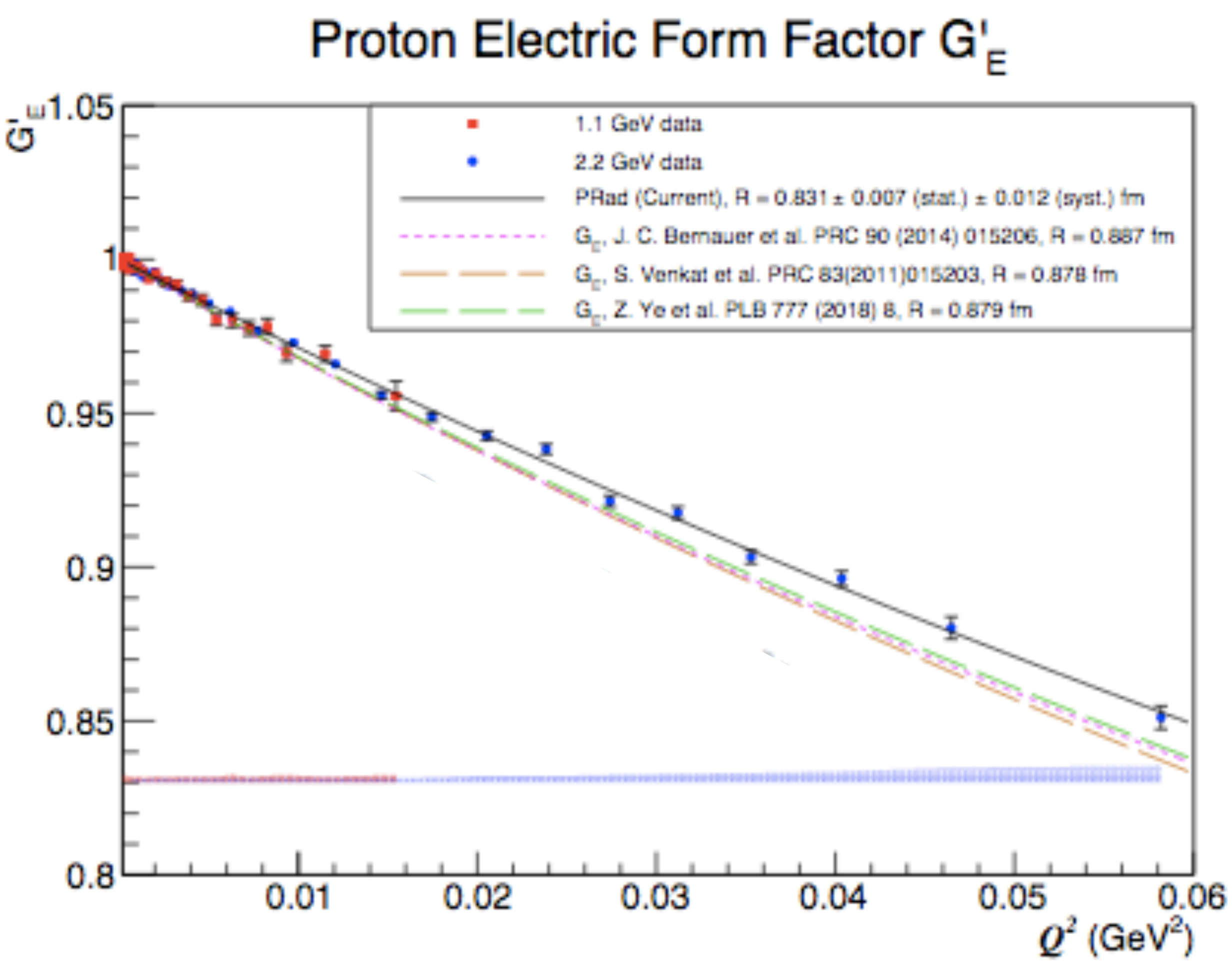
- n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$
- G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$
- PRad fit shown as $f(Q^2)$

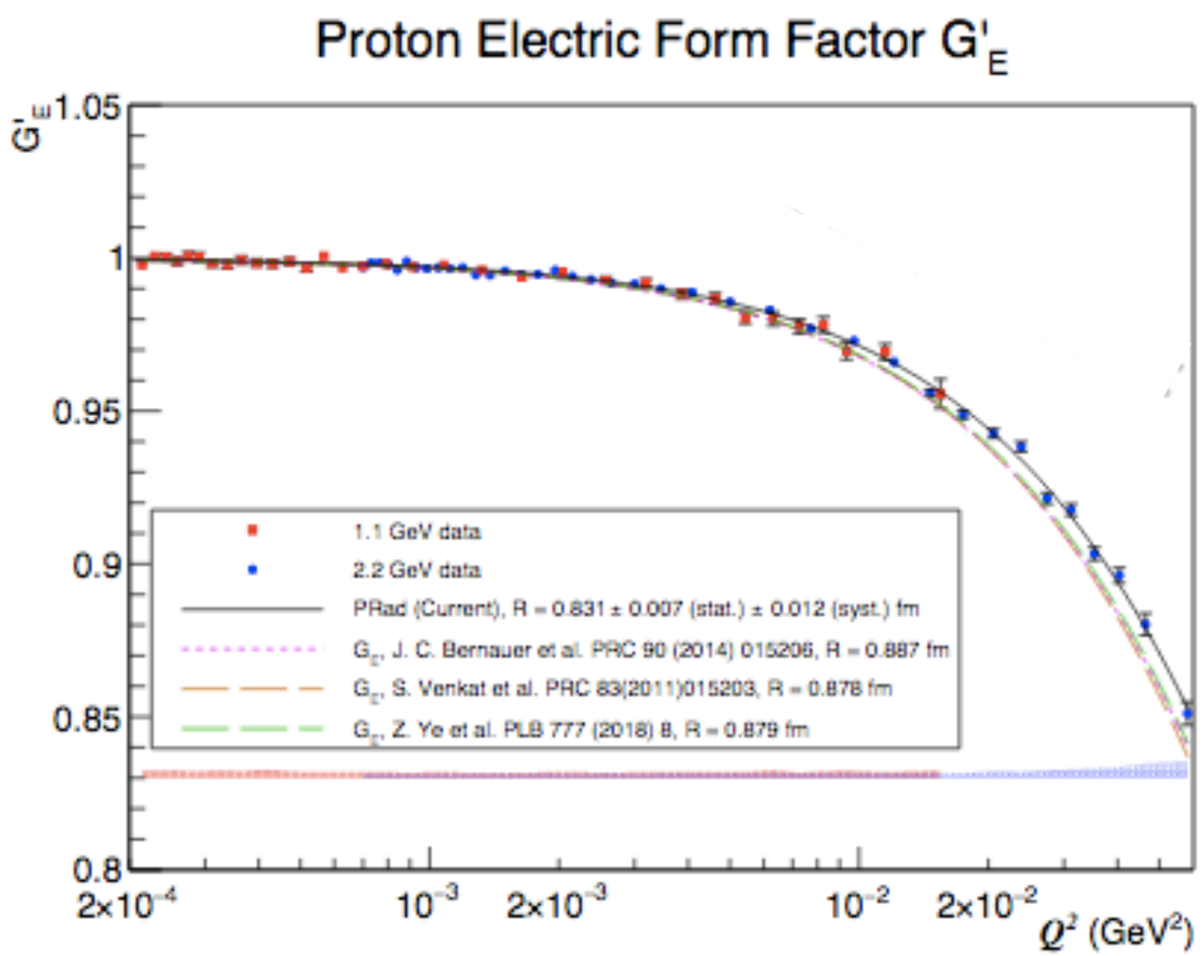
Using rational (1,1)

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

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

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



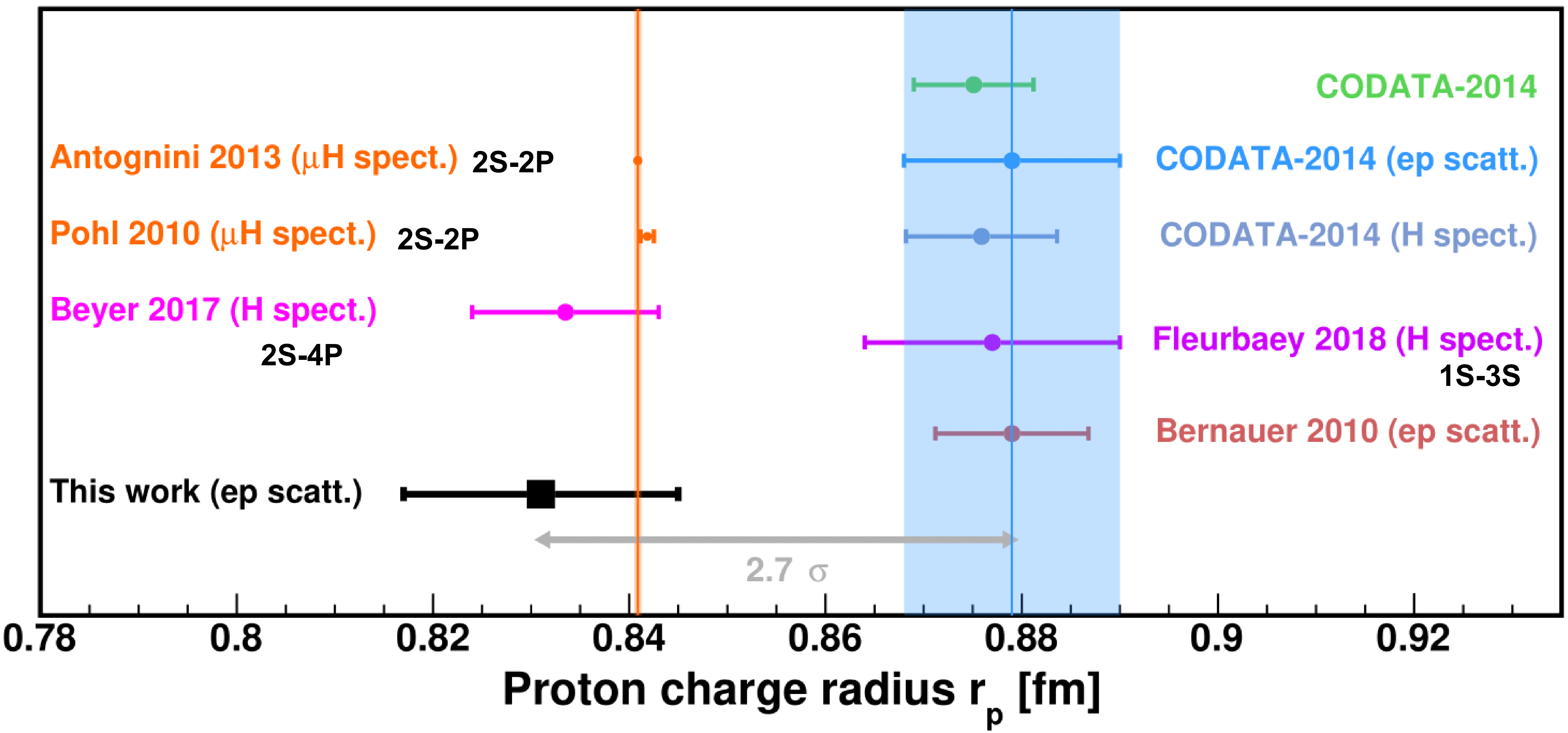


n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

Figures courtesy of W. Xiong

The PRad result for the proton charge radius.

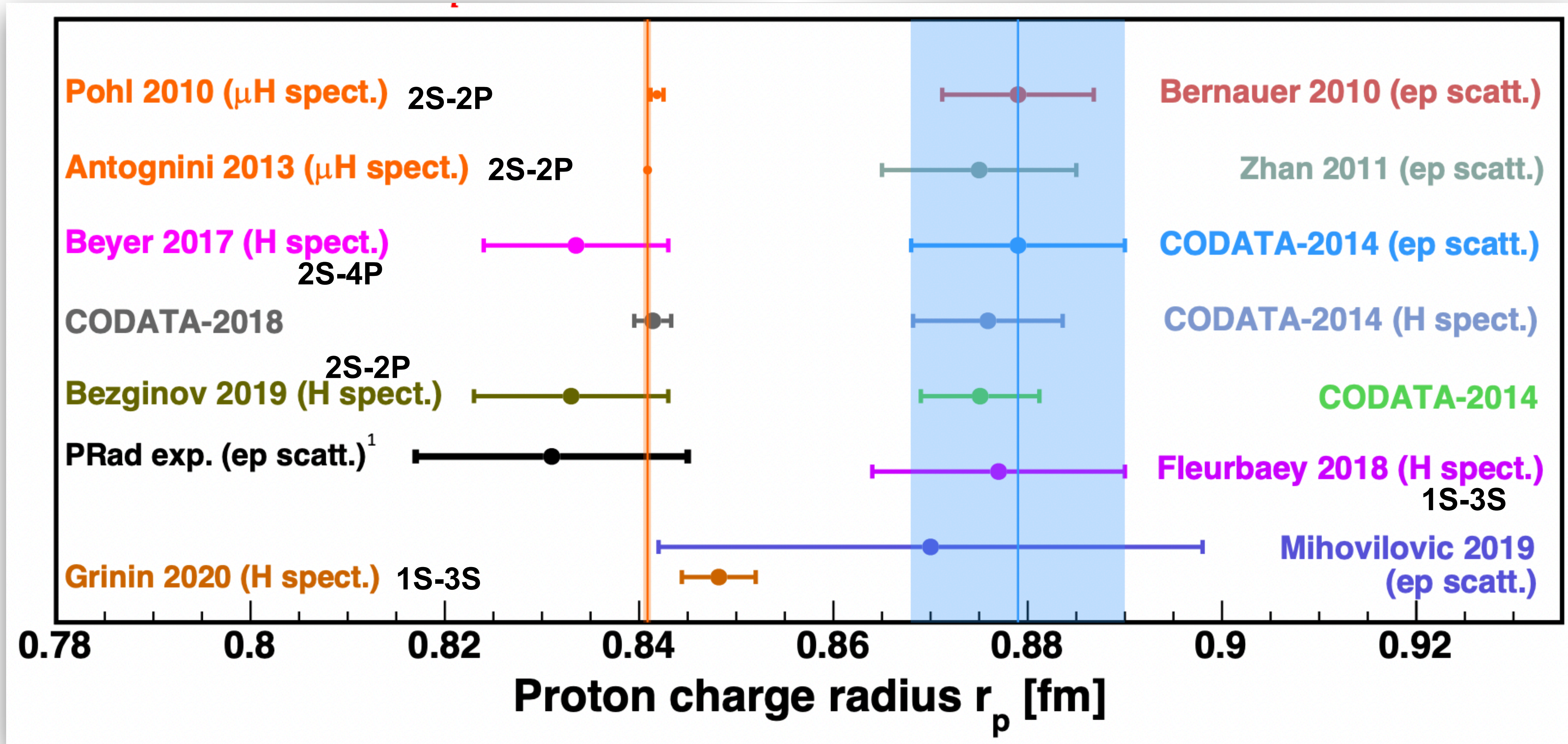
PRad result: 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm



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

There has been some rapid and dramatic development over the last few years.

Two new H-spectroscopy results were reported in Science Magazine



CODATA revised the value of r_p and the Rydberg constant.

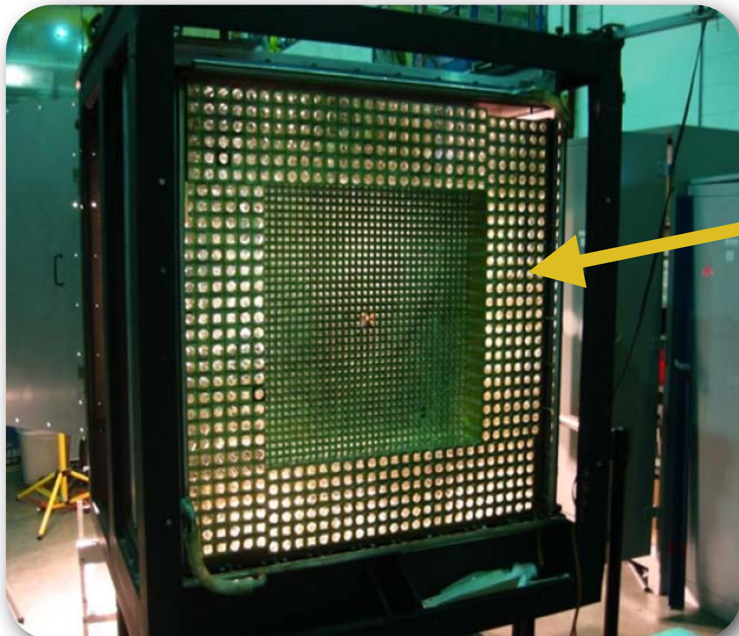
2020 Review of Particle Physics claims - "…the puzzle appears to be resolved"

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).

Figure courtesy of W. Xiong

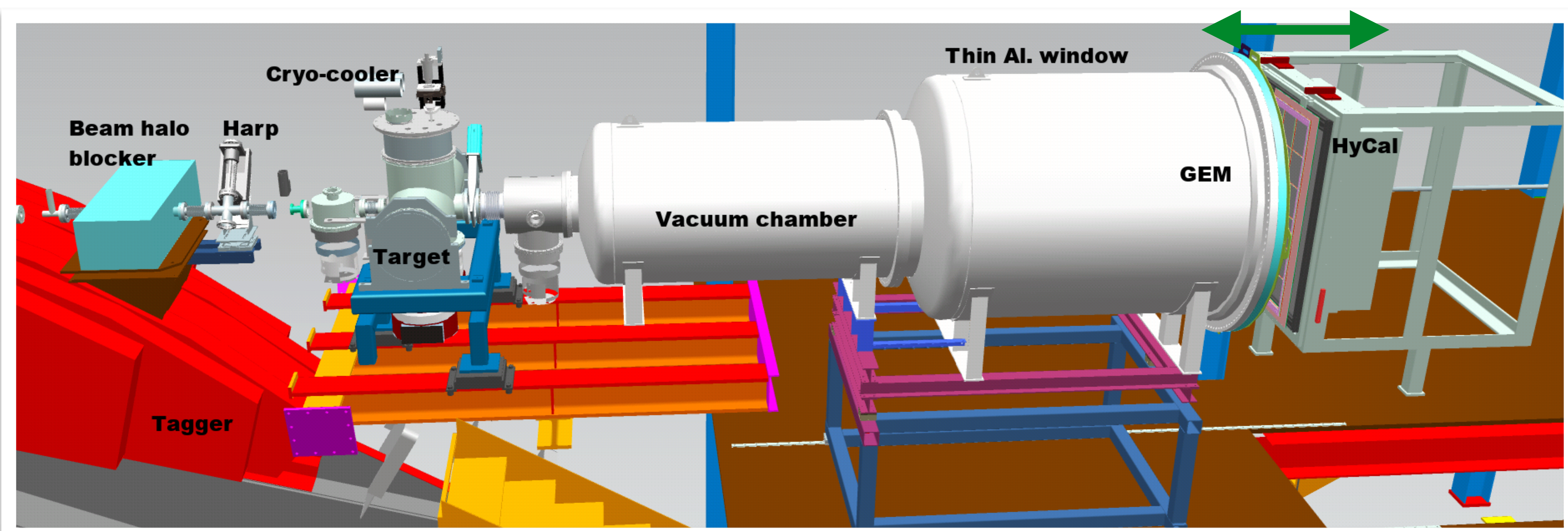
A new proposal - PRad-II was approved in 2020 to push the precision frontier of electron scattering.



Upgrade HyCal to be replace all lead-glass modules with $PbWO_4$ modules to have uniform high resolution.

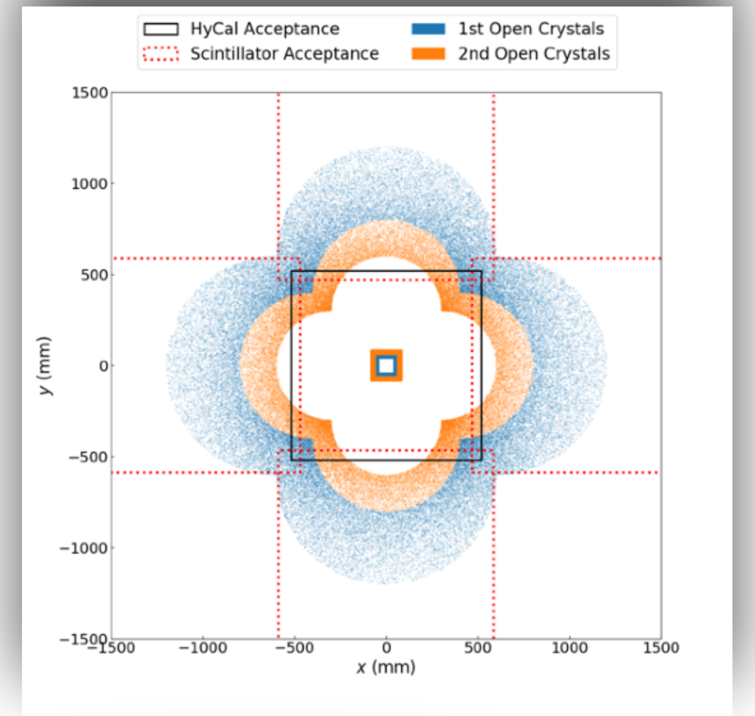
Convert to FADC based readout of HyCal

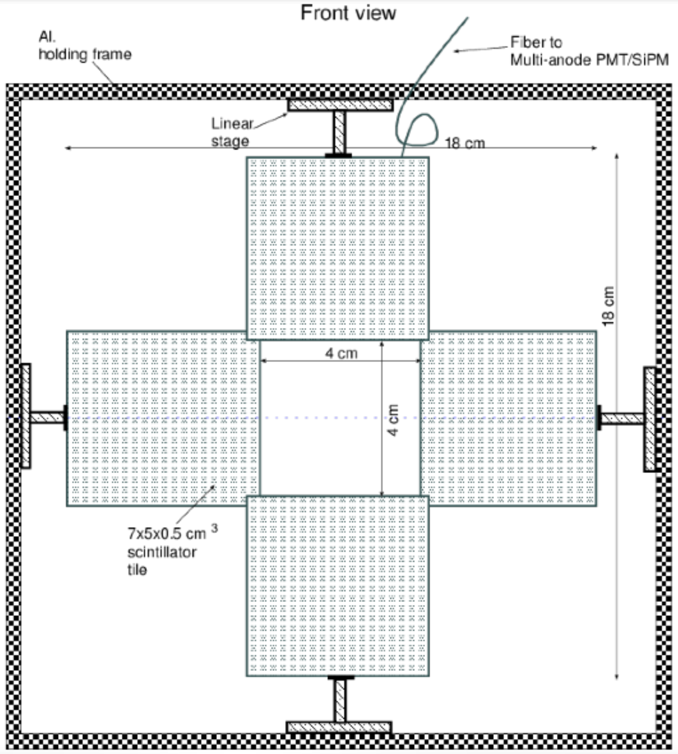
Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.



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 ~4 times more precise than PRad with an uncertainty of 0.0036 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.

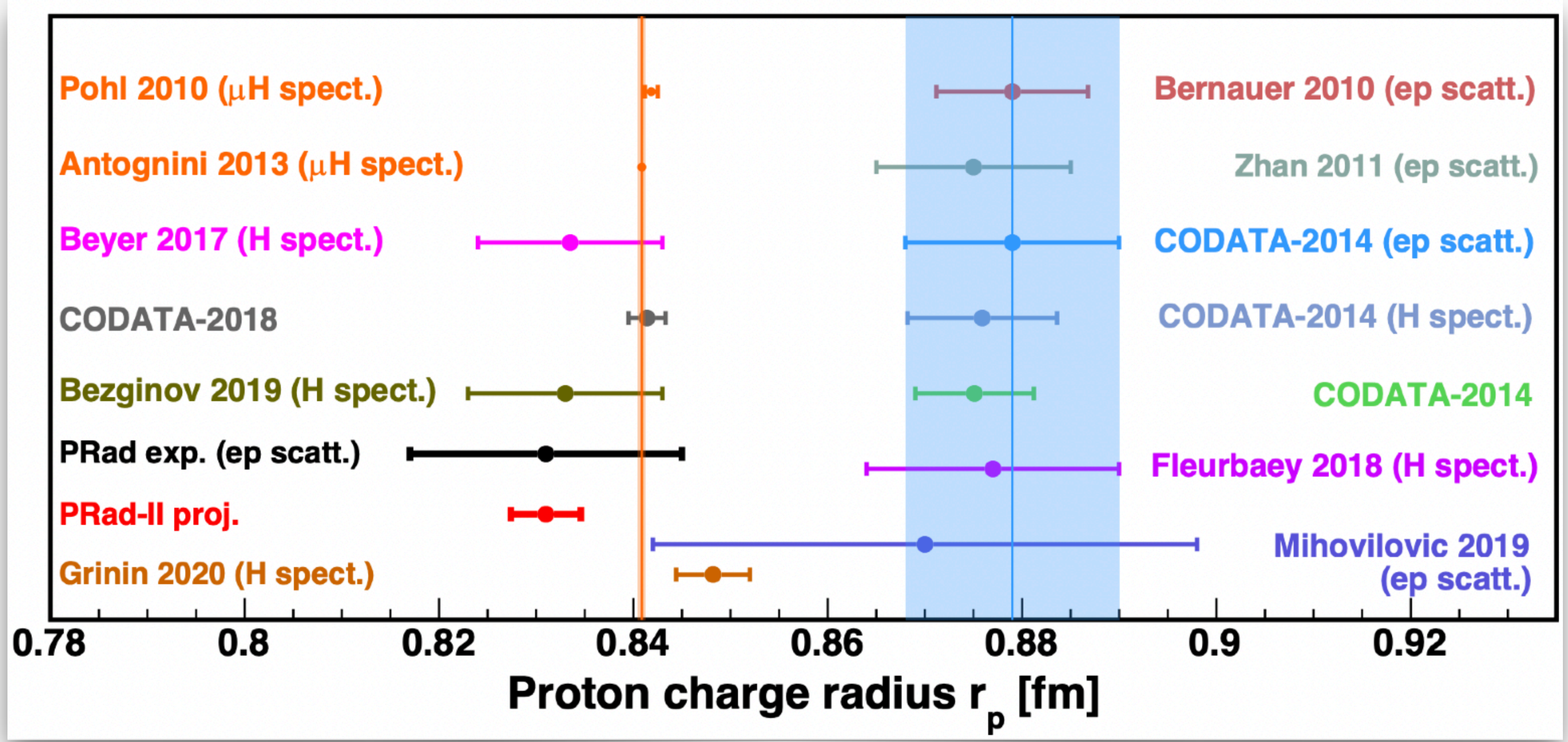
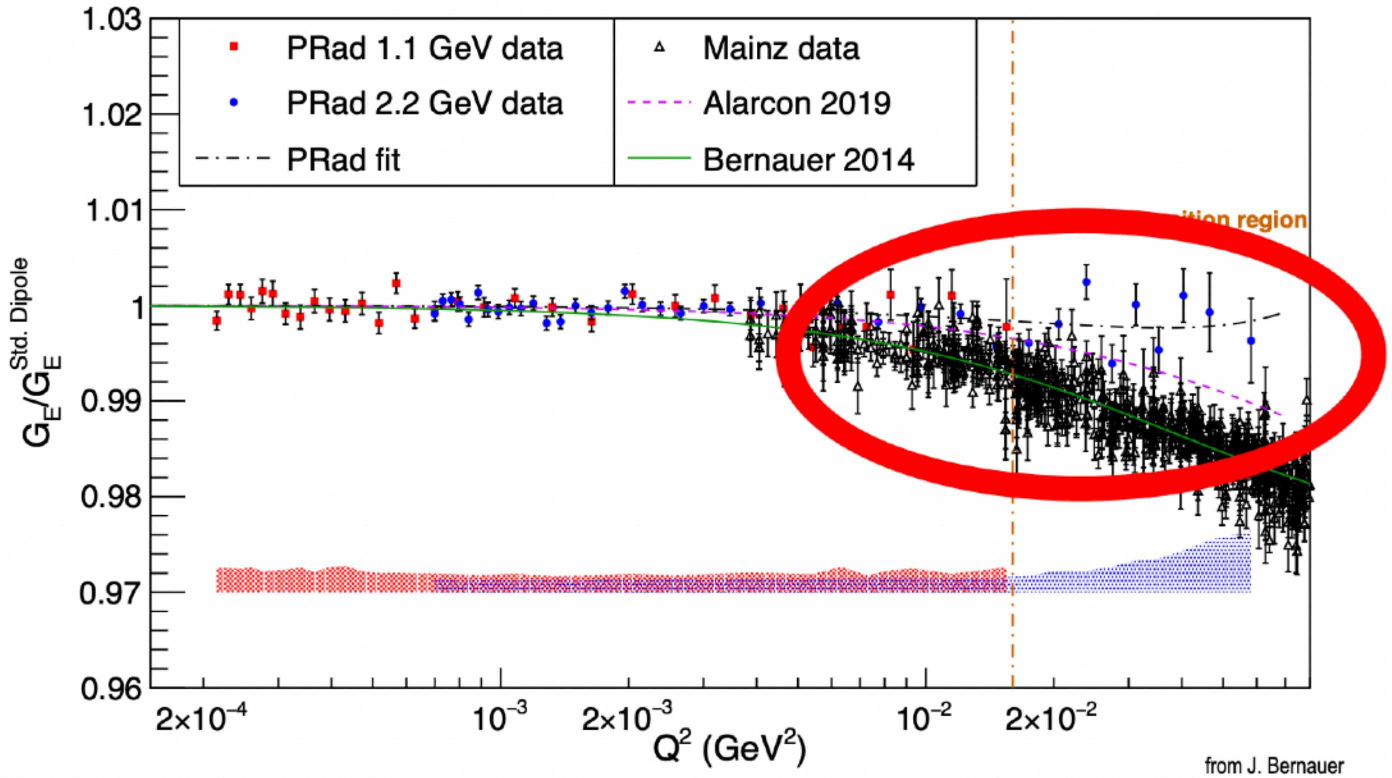


Figure courtesy of W. Xiong

Several new experiments are currently being prepared and some are already running.



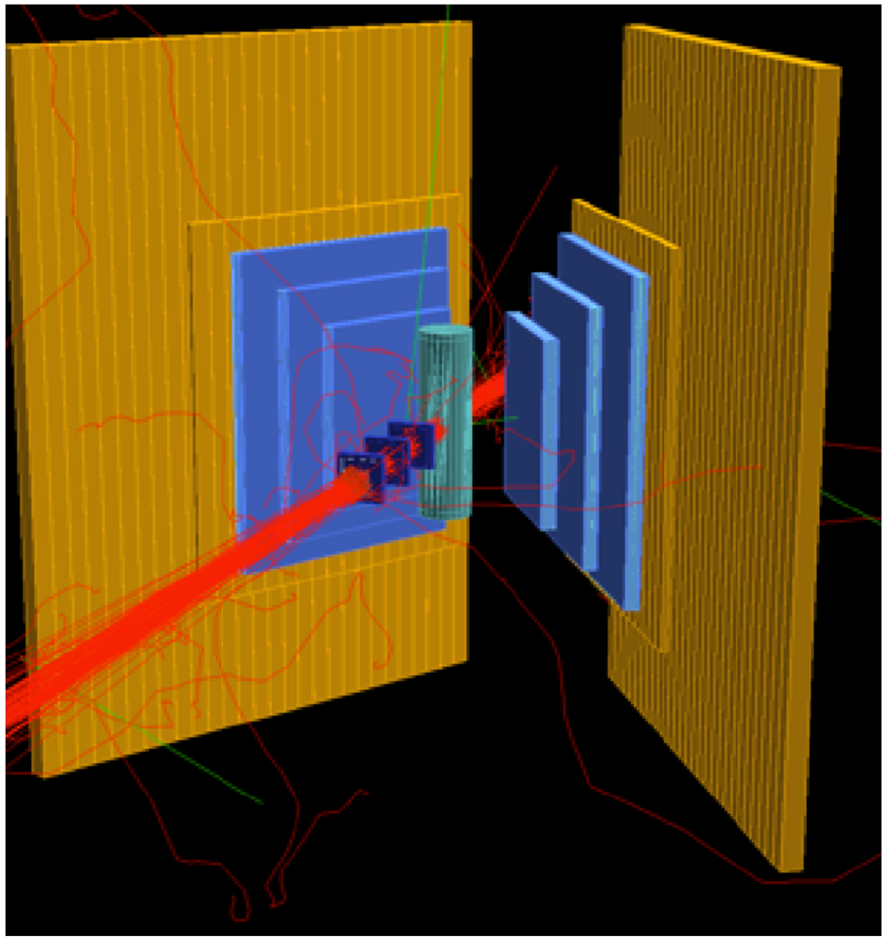
PRad-II is designed to address this new puzzle in hadronic physics.

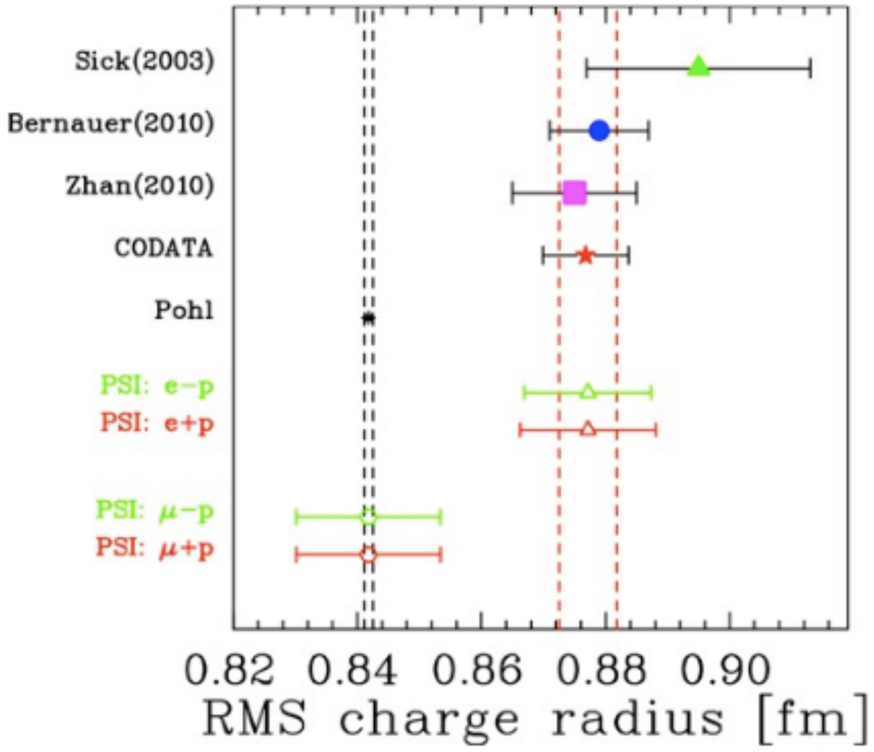
Experiment	Beam	Laboratory	Q^2 (GeV/c)^2	δr_p (fm)	Status
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-	Mainz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

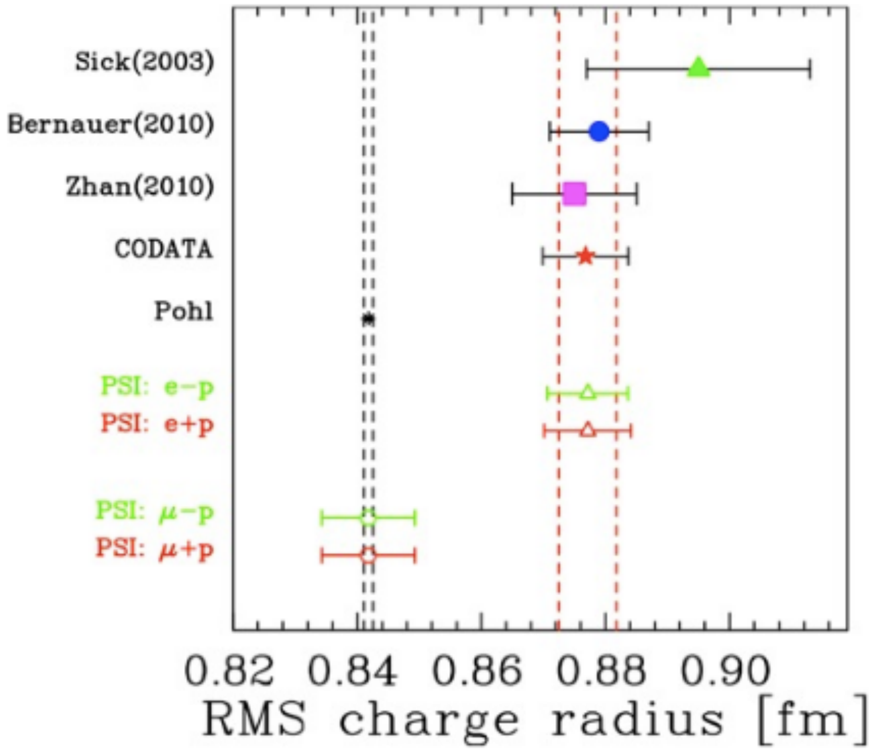
Table courtesy of H. Gao

The MUon proton Scattering *Experiment* (*MUSE*) at the PSI will simultaneous measure elastic $\mu^{\pm}$-p and elastic $e^{\pm}$-p scattering to determine r_p.

Spokespersons: R. Gilman, E. Downie, & G. Ron







θ ≈ 20° – 100°
$Q^2 \approx 0.002$ - 0.07 GeV^2
3.3 MHz total beam flux
≈ 2-15% μ's
≈ 10-98% e's
≈ 0-80% π's

Absolute errors **Relative errors**

Individual radius extractions from e±, μ± each to 0.01 fm

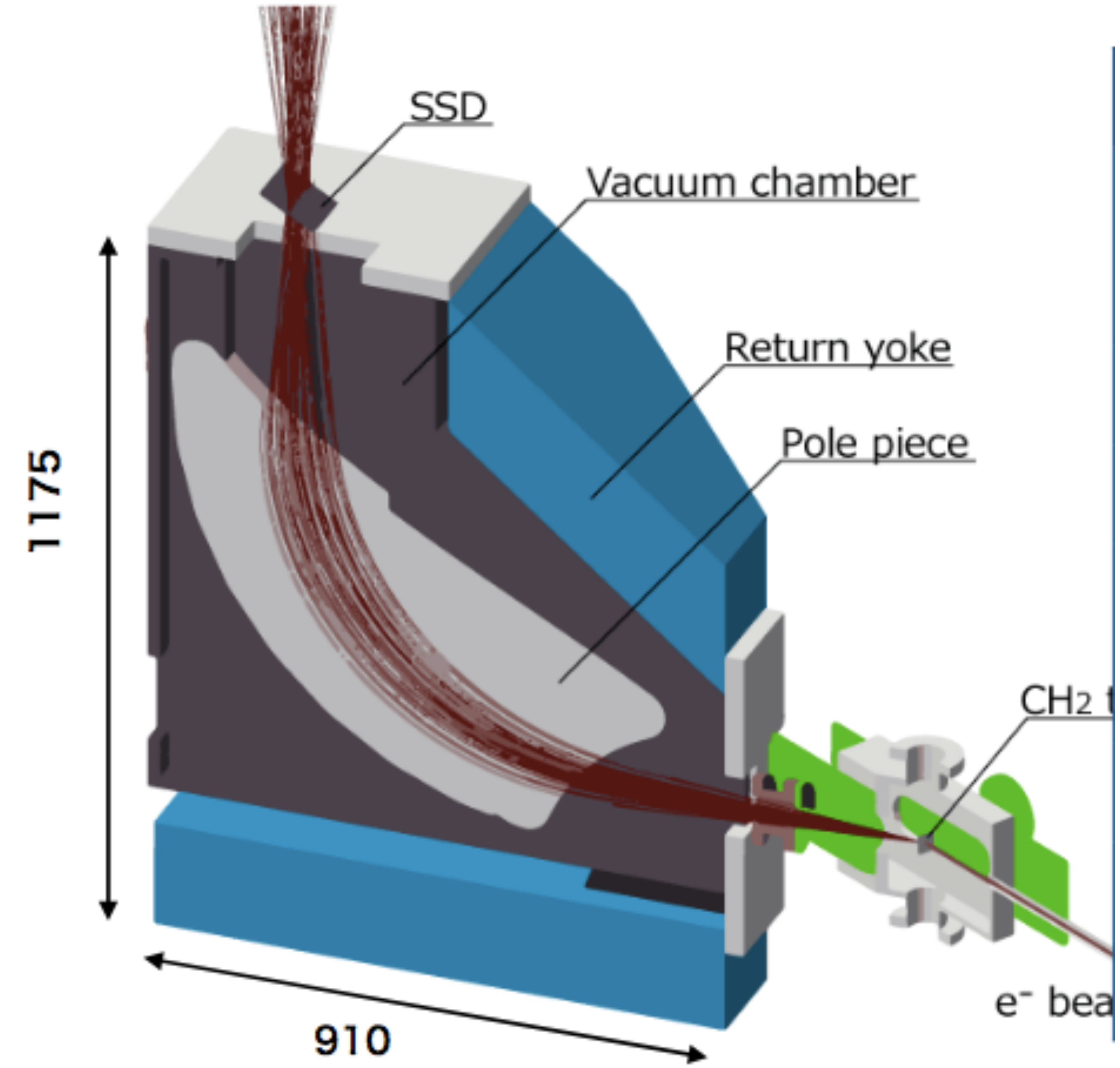
➔ Test of lepton universality
➔ Determination contribution of two-photon exchange in μ-p scattering.

Friday, November 19, 2021
5:30PM - 5:45PM

O01.00003: Status of the MUSE experiment at PSI
Alexander Golossanov

Figures courtesy of J. Arrington and PSI

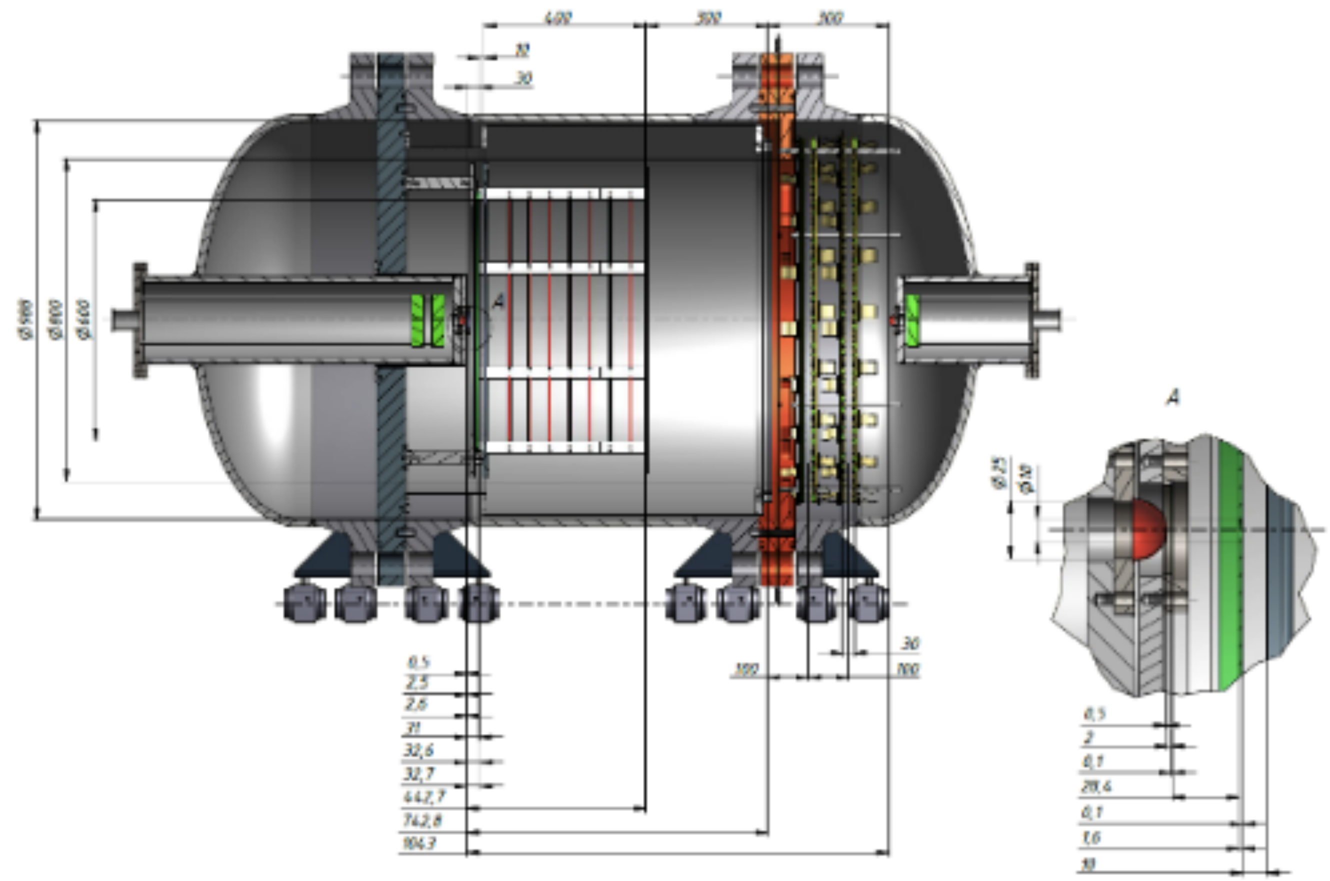
The ULQ^2 experiments will use very low energy electron beams to reach ultra low Q^2.



ULQ^2 collaboration at Tohoku U, will use a **20-60 MeV** electron beam on a CH_2 target to measure the cross section in the **30^o - 150^o** angular range with double arm high resolution spectrometers.
ULQ^2 plans to cover a Q^2 range of **3x10^{-4} - 8x10^{-3}** (GeV/c)^2.
Spokesperson: **T. Suda**

Proton charge radius will be measured at AMBER and at Mainz using a hydrogen gas TPC.

μ^--p scattering will used to measure r_p at COMPASS using a high pressure hydrogen gas TPC as an active target and recoil proton detector. COMPASS plans to cover a Q^2 range of **10^{-4} - 1** $(GeV/c)^2$.



The same high pressure hydrogen gas TPC will be used as an active target and recoil proton detector for an *e-p* scattering experiment at Mainz to determine r_p

Summary

- **The proton charge radius is a fundamental quantity in Physics**
  - ✓ Important for precision atomic spectroscopy
  - ✓ Precision tests of future lattice QCD calculations
  - ✓ "New Physics"

- **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 (~2×10^{-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 (2×10^{-4} - 6×10^{-2} GeV^2) was recorded in the same experimental setting, for the first time in ep-scattering experiments.

- **The PRad current result points to a small proton charge radius.**
- **Several other recent results seem to confirm the small proton radius.**
- **Several new experiments are being prepared to help further establish these results.**

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

The PRad Collaboration

Graduate students (Thesis students)
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Li Ye (MSU)
Weizhi Xiong (Duke)
Xinzhan Bai (UVa)

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

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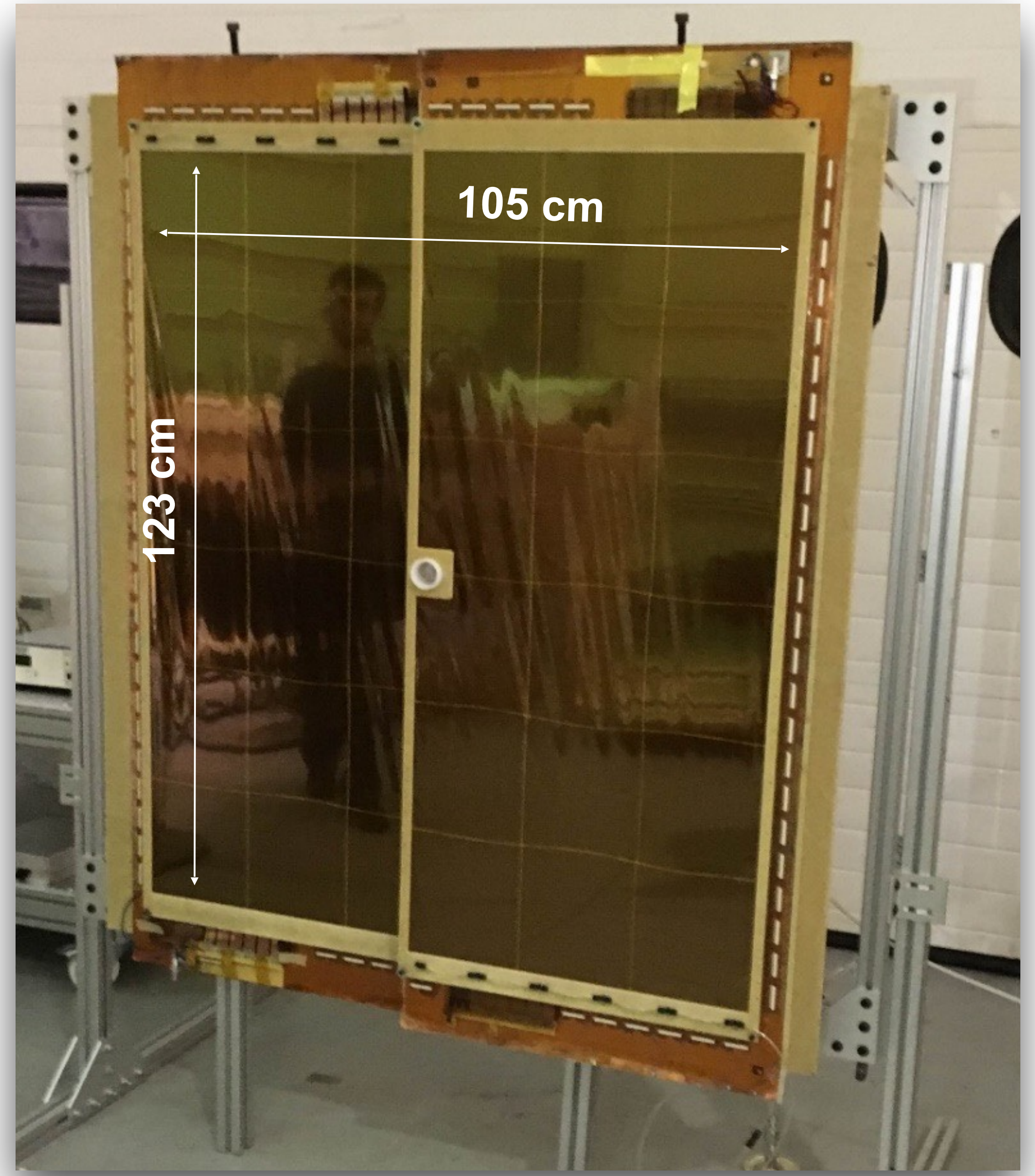
Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Latif-ul Kabir (MSU)

Backup Slides

Large area GEM coordinate detectors

- **Two large GEM based X and Y- coordinate detectors with 100 μm position resolution**

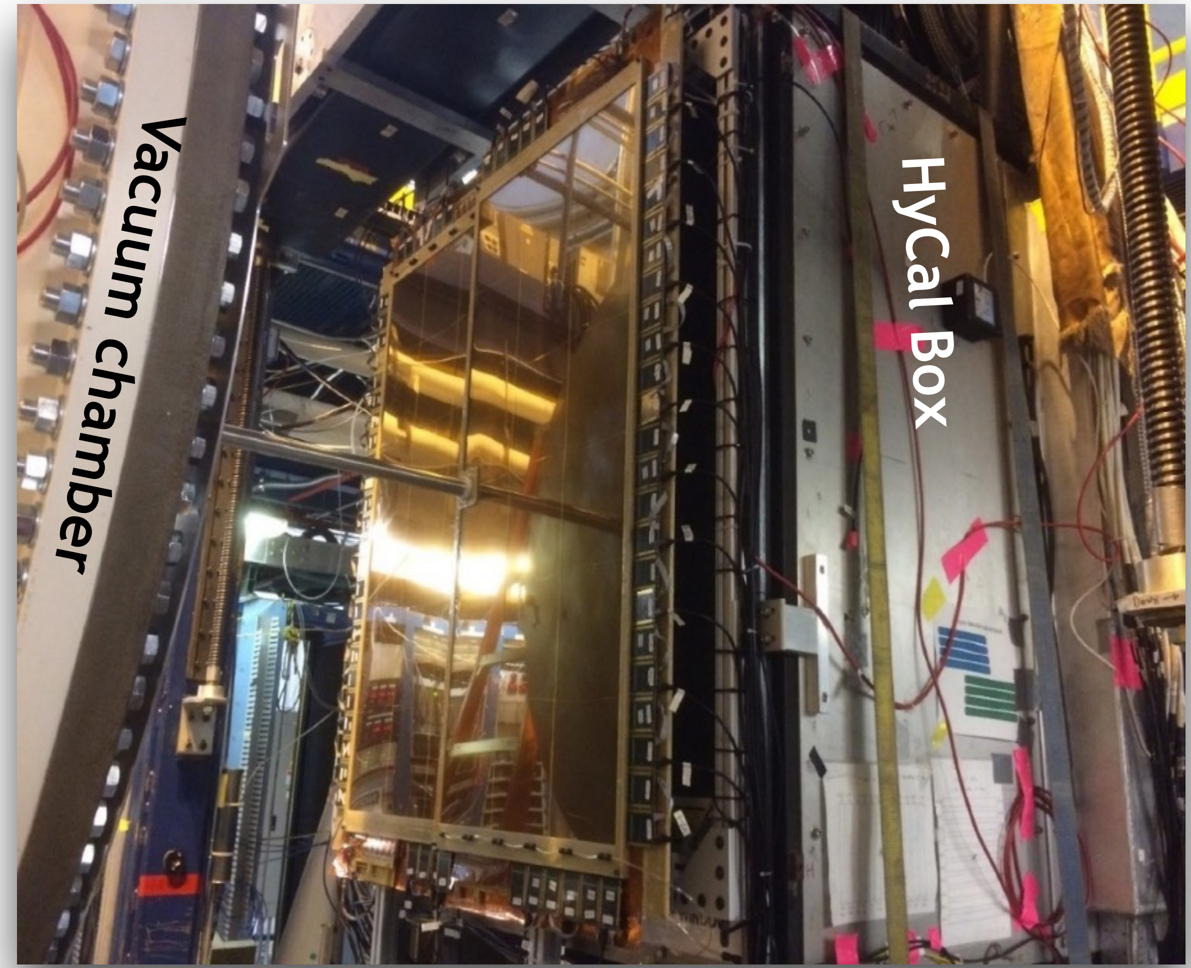
- **Designed and built at University of Virginia (UVa)**



- **The GEM detectors provided:**
  - factor of **>20 improvements in coordinate resolutions**
  - similar improvements in Q^2 resolution
  - unbiased coordinate reconstruction (including HyCal transition region)
  - increase Q^2 range by enabling use of Pb-glass part of calorimeter

HyCal and GEMs on the beamline

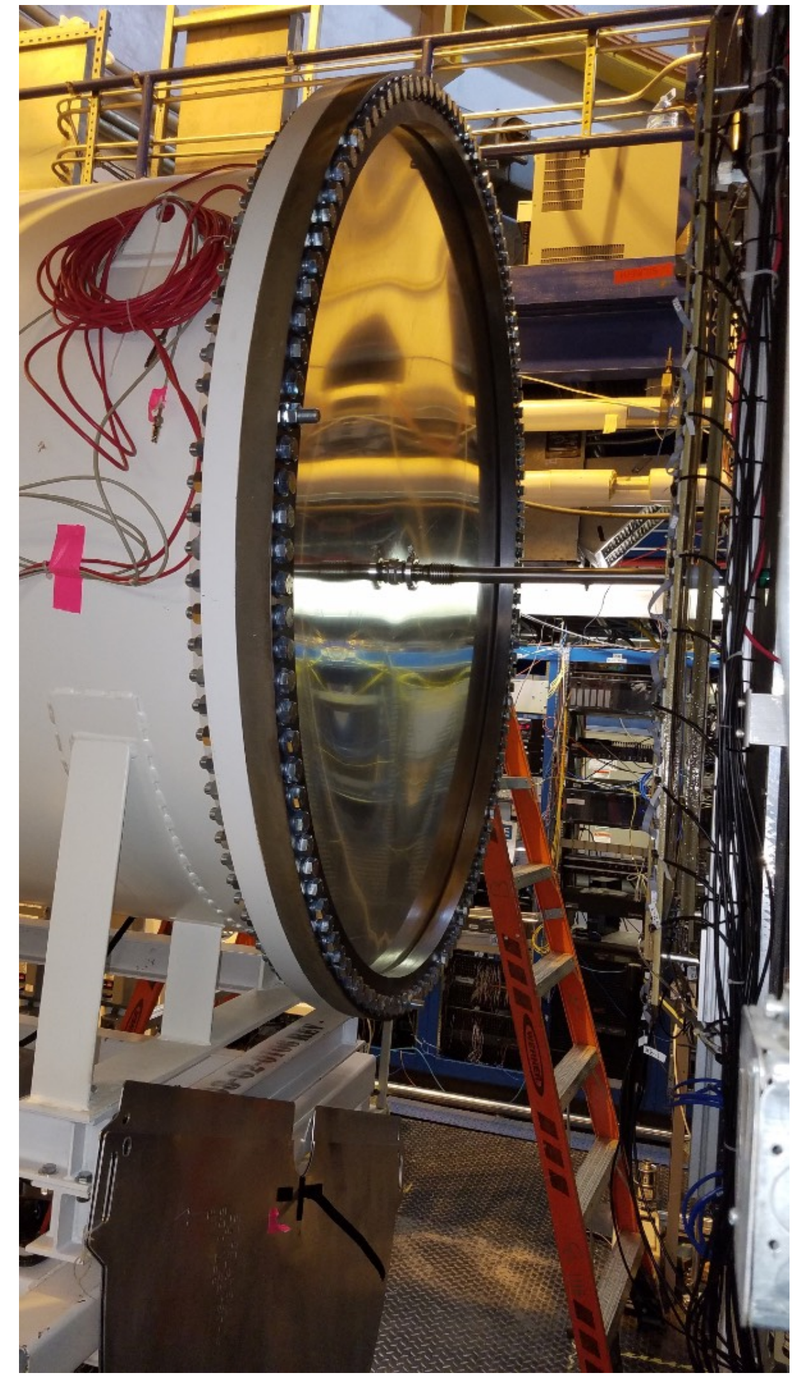
beam view



downstream view

Vacuum chamber with one thin window

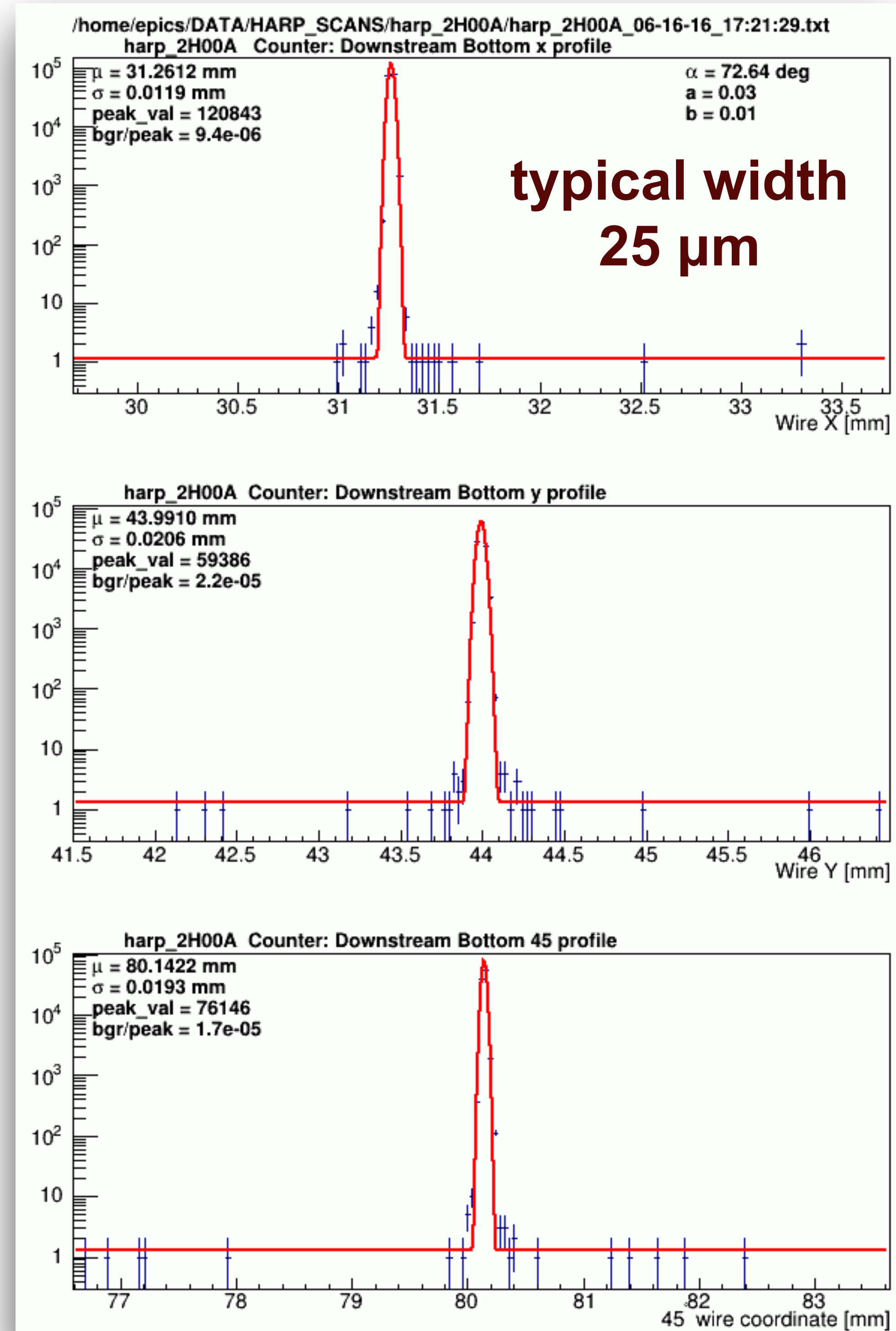
two stage, 5 m long vacuum box



1.7 m dia, 2 mm thick
Al window

High quality, stable CEBAF electron beam

electron beam profile at target
(measured with harp scan)



position stability : ± 250 µm

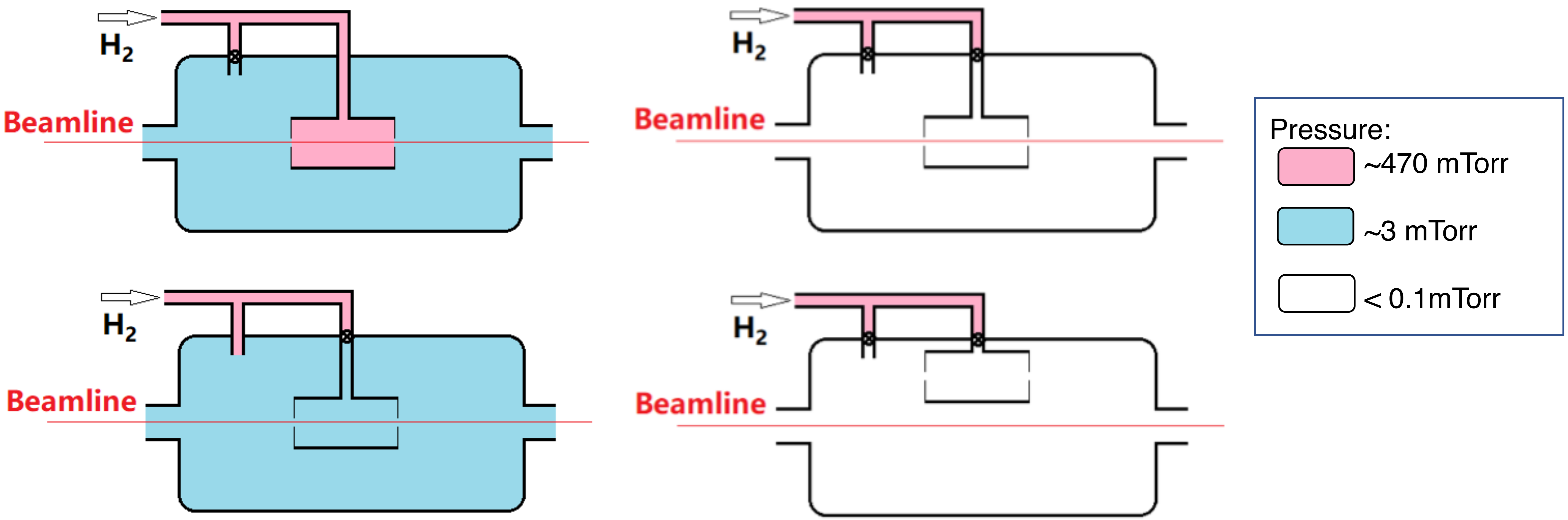
Experiment ran during May/June 2016

With E_e = 1.1 GeV beam
collected 4.2 mC on target (2×10^{18} H atoms/cm^2)
604 M events with H and
53 M events without H in target
25 M events on 1µm Carbon foil target

With E_e = 2.2 GeV beam
collected 14.3 mC on target (2×10^{18} H atoms/cm^2)
756 M events with H and
38 M events without H in target
10.5 M events on 1µm Carbon foil target

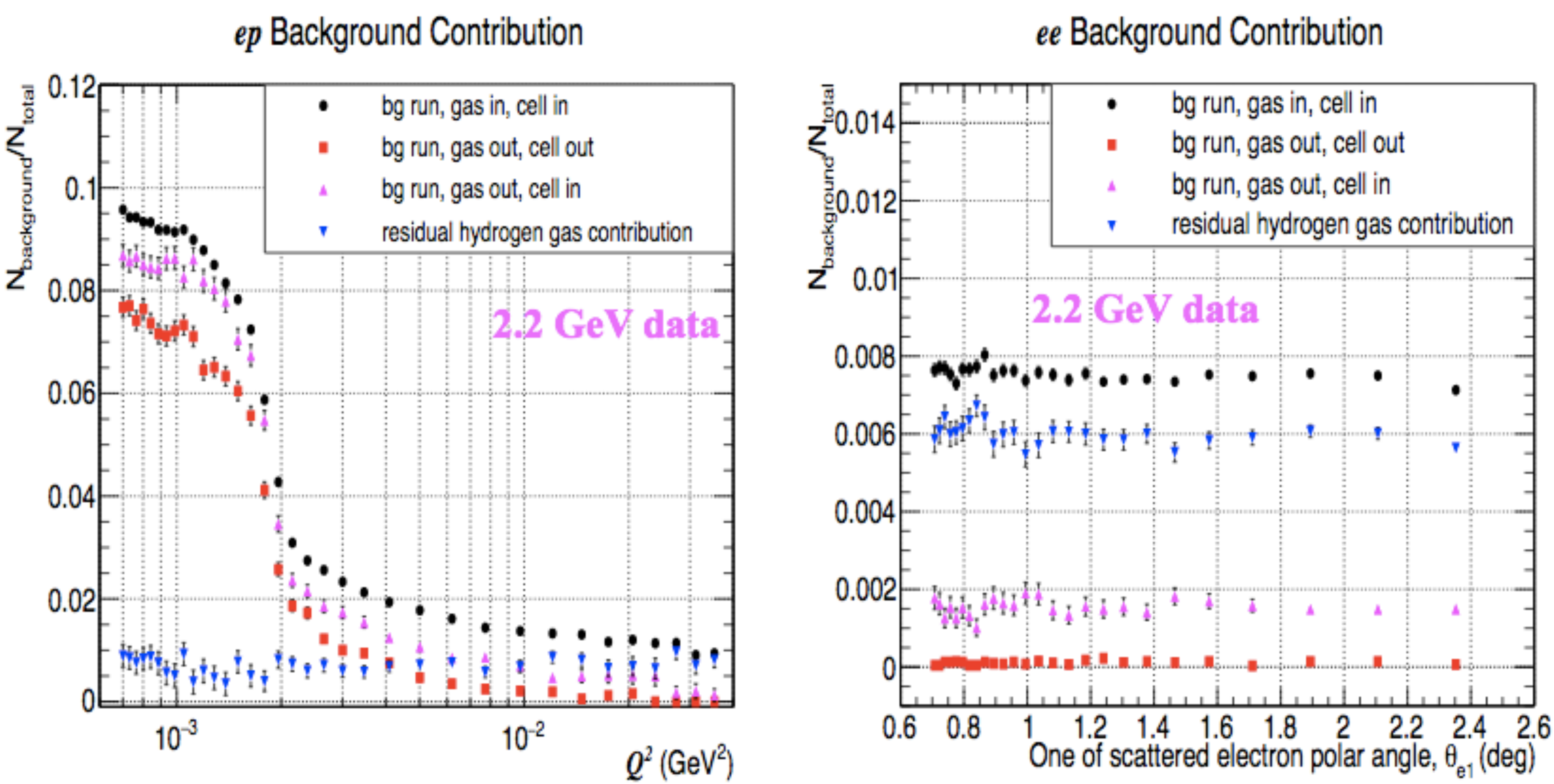
Background Subtraction

- 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)



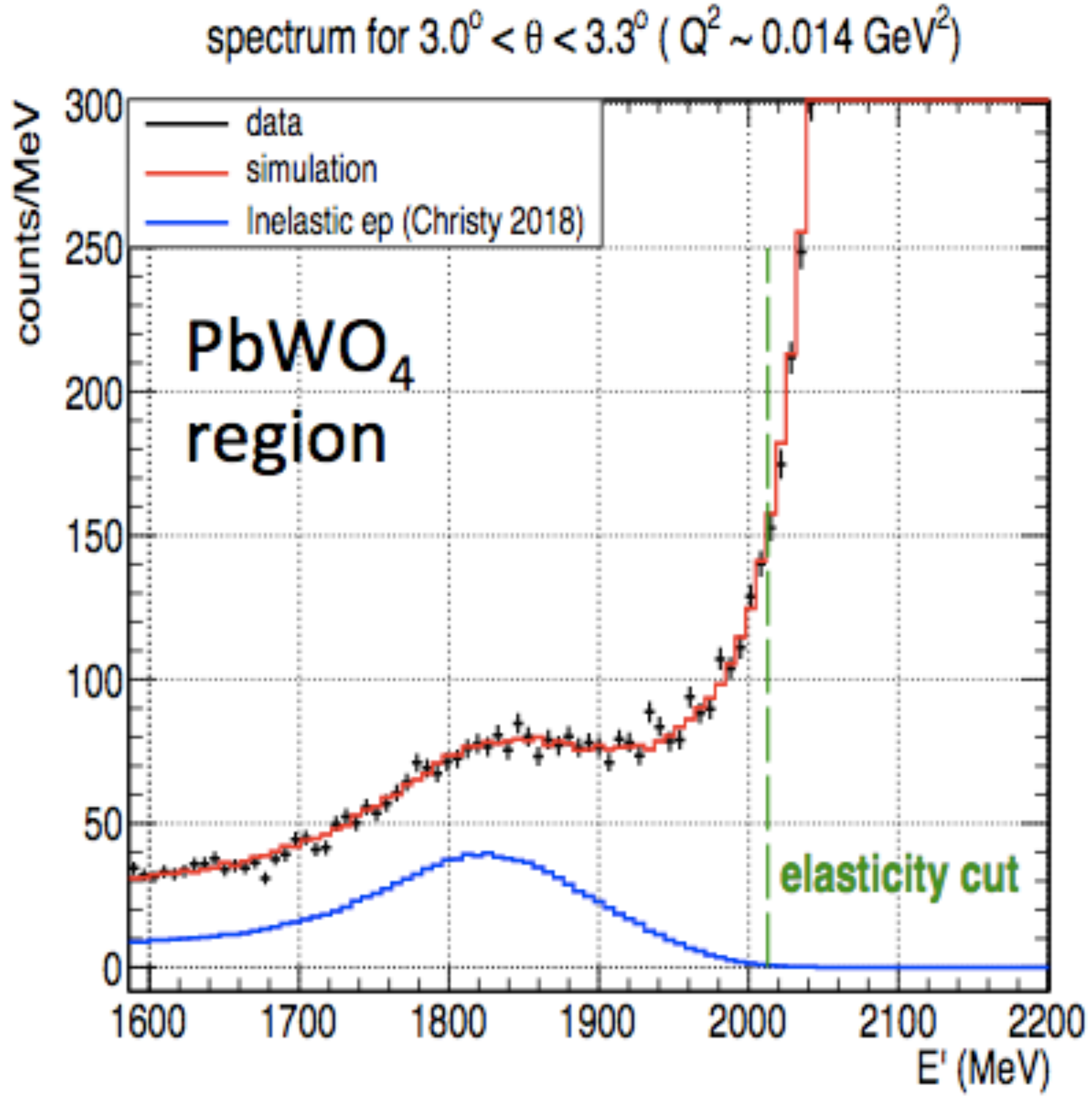
Background Subtraction

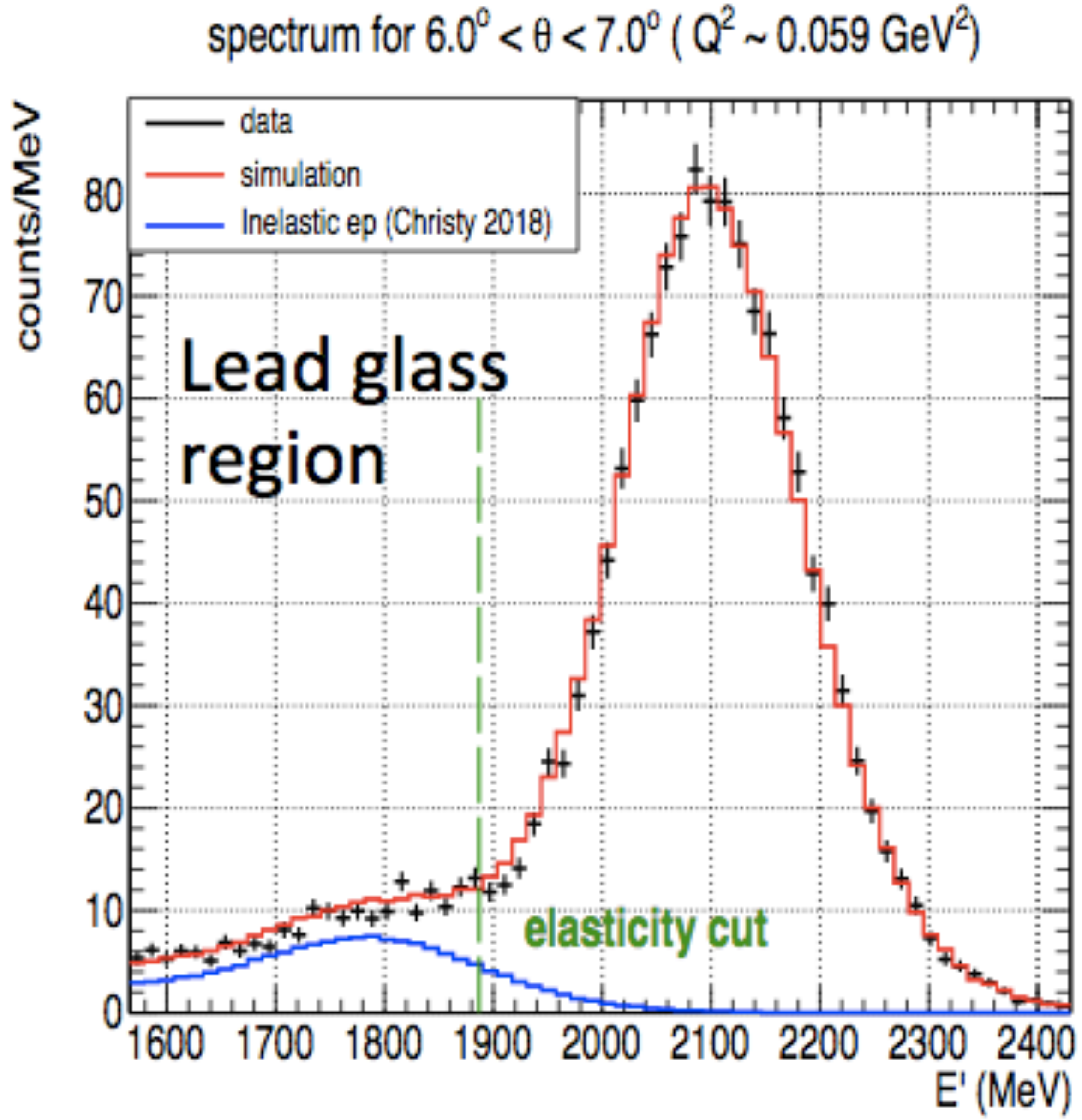
- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~ 0.8% at all angles



Elastic cut and inelastic contribution

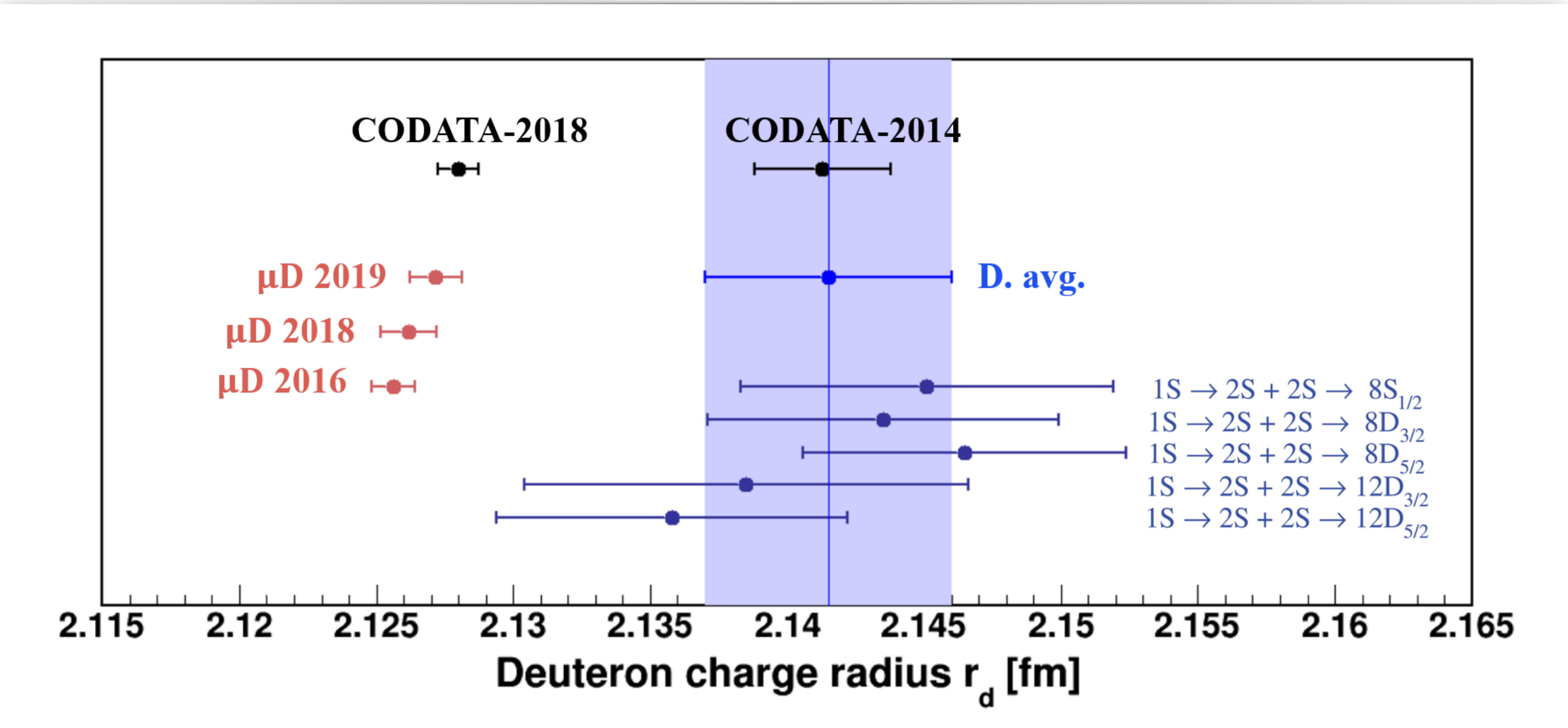
- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region





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

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.

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 2×10^{-4} to 5×10^{-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**.