

PRad-II and the Proton Radius Puzzle

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On behalf of the PRad Collaboration

 Jefferson Lab

U.S. Department of
ENERGY



The Proton Radius Puzzle

How big is the proton?

It depends on who you ask!



How big is the proton?

It depends on who you ask!

ChatGPT

What is the radius of the proton

The radius of a proton is approximately:

0.84 to 0.88 femtometers (fm)
 (1 femtometer = 10^{-15} meters)

More specifically:

- Electron scattering experiments often give a value around **0.88 fm**
- Muonic hydrogen measurements suggest a smaller value around **0.84 fm**

This discrepancy is known as the **proton radius puzzle**, and it's an active area of research in particle physics. The precise value depends on the method used to measure it.

Gemini 2.5 Flash

What is the radius of the proton

Google Search

The accepted value for the proton's root mean square charge radius is approximately **0.84-0.87 femtometers (fm)**.

To give you a more precise figure, recent measurements and re-analyses of older data, particularly from 2019, have converged around **0.833 fm** with an uncertainty of ± 0.010 fm. The 2018 CODATA recommended value is **0.8414(19) fm**.

It's worth noting that there was a "proton radius puzzle" for several years, as different measurement techniques (electron-proton scattering, atomic hydrogen spectroscopy, and muonic hydrogen spectroscopy) initially yielded slightly different values. However, more recent experiments and analyses have largely resolved this discrepancy, with results now agreeing on the smaller radius.

Sources



Microsoft Copilot

What is the radius of the proton

The proton's radius is most commonly defined by its charge distribution and is on the order of **0.84 to 0.87 femtometers (fm)** ($1 \text{ fm} = 10^{-15}$ meters). In particular, measurements using muonic hydrogen—where a muon (about 200 times heavier than an electron) orbits the proton—yield a value very near 0.84 fm. Traditional electron scattering experiments, on the other hand, often indicate a slightly larger value, around 0.88 fm. This discrepancy between different experimental approaches is known as the "**proton radius puzzle**" and has spurred extensive research in both experimental and theoretical physics.

It's important to note that these values refer to an effective "size" determined by how the proton's positive charge is distributed. Because a proton is a dynamic, quantum mechanical object composed of quarks and gluons, this effective radius isn't fixed in the classical sense but is derived from the way its electric field falls off with distance.

The ongoing research to resolve the proton radius puzzle not only refines our understanding of one of nature's most fundamental particles but also tests the limits of quantum electrodynamics (QED) and the standard model of particle physics. Advanced experiments and novel theoretical approaches continue to bridge the gap between the different measurement techniques.

Beyond just the number, you might be interested in how these measurements are performed in practice. For instance, the muonic hydrogen measurements involve detecting tiny shifts in energy levels (specifically the Lamb shift) as the muon orbits close to the proton—a process that is significantly more sensitive to the proton's charge distribution than traditional electron-based experiments. Additionally, clarifying the proton's size has broader implications, influencing the determination of fundamental constants and the precision of modern physics experiments.

If you're curious about diving deeper, we could explore how these measurement techniques work, the current experimental strategies to solve the proton radius puzzle, or even how similar challenges arise in determining the sizes of other subatomic particles.

Edit this response

XAI Grok 3

What is the radius of the proton

The radius of a proton is approximately **0.84 to 0.87 femtometers (fm)**, or about 0.84×10^{-15} to 0.87×10^{-15} meters. This value, often referred to as the proton's charge radius, is determined through experiments like electron-proton scattering and muonic hydrogen spectroscopy. The precise value can vary slightly depending on the measurement method, with recent studies favoring the lower end of this range.

How big is the proton?

It depends on who you ask!

ChatGPT

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0.84-0.87 fm (maybe 0.88 fm included?)

Better ask a physicist!

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What is the radius of the proton

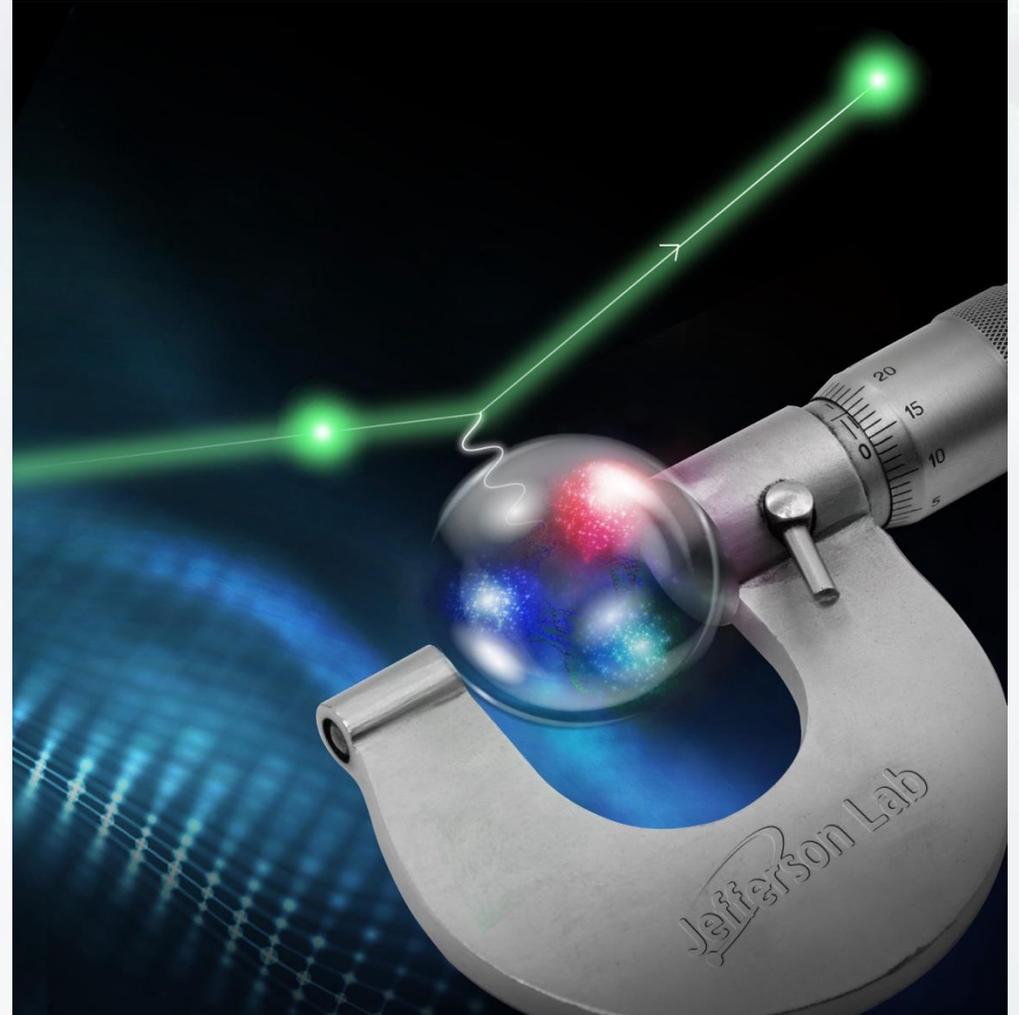
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698ms

But really, *what* is the radius of the proton?

- More properly stated as the “root mean square charge radius”
- Related to the non-relativistic charge distribution*
- Most accurately, though perhaps less satisfactorily, it is a fundamental property of the proton proportional to the first derivative of the Sachs form factor at zero four-momentum transfer

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



*See G. Miller *Phys.Rev.C* 99 (2019) 3, 035202 for a detailed discussion of what the radius is and is not

How do we *measure* the radius?

ℓ -p Scattering

- The elastic lepton-proton scattering cross section is related to the electric and magnetic form factors
- Measure data at very low Q^2 , fit it, then extrapolate to $Q^2 = 0$

Hydrogen Lamb Shift

- The energy difference between excited S and P states is directly related to the slope of the Sachs form factor at $Q^2 = 0$
- Radiative effects that contribute are well known allowing for high precision measurements
- Muonic hydrogen (replacing the electron with a muon) is even more sensitive to the proton radius due to the larger muon mass

The Proton Radius Puzzle

- The proton radius was always 0.88 fm



The Proton Radius Puzzle

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Until it wasn't



The Proton Radius Puzzle

- The proton radius was always 0.88 fm
Until it wasn't
- Muonic hydrogen results from R. Pohl *et al.* *Nature* 466 (2010) reported a radius of 0.84 fm

A discrepancy of $>5\sigma$!

- Many efforts since have aimed to explain the cause of this discrepancy as well as to determine the *true* radius value

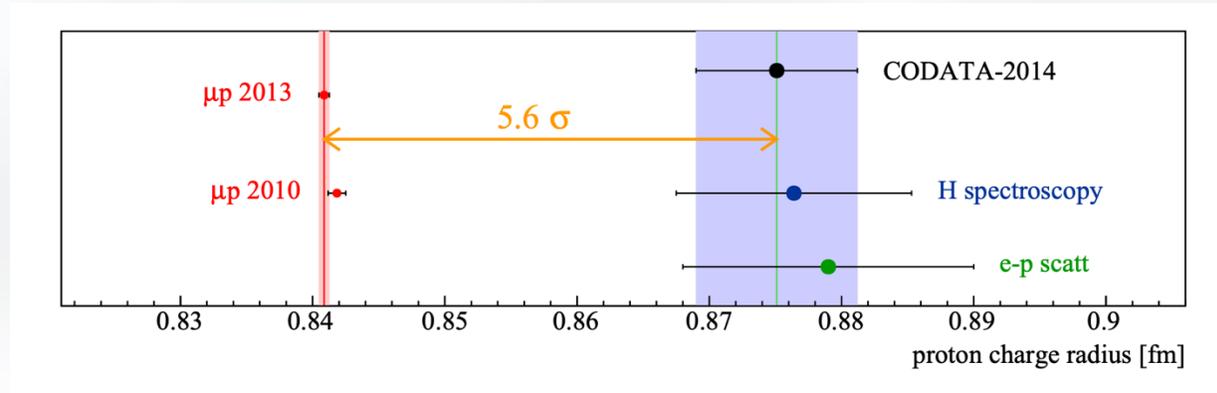


Figure from J.J. Krauth *et al.* arXiv:1706.00696

Possible Explanations

New Physics?

Could lepton universality be violated?

MUSE is working on this (See P. Reimer talk, Wed. @ 19:00)*

Improper e-p Extraction?

Extraction relies on extrapolating a fit

Choice of fit function can bias extraction

Explored in S. Barcus *et al. PRC 102*
(2020)

Inconsistent Definitions?

Is the definition of r_p consistent between the measurement techniques?

G. Miller *PRC 99* (2019) derives that definitions are consistent

Incorrect Rydberg Constant?

Could help explain atomic and muonic hydrogen differences

CODATA updated Rydberg constant in 2018

Past Measurements

Atomic Hydrogen Spectroscopy

- Energy shifts in the hydrogen atom are sensitive to proton finite size effects (i.e. the proton is not point-like)
- In fact, they are directly related to the slope of the electric form factor at $Q^2 = 0$ by virtue of a Taylor expansion around $Q^2 = 0$ allowed by the vanishingly small four-momentum transfer in spectroscopy measurements
- Historically extracted a radius of ~ 0.88 fm (a few more recent measurements have gotten ~ 0.84 fm)

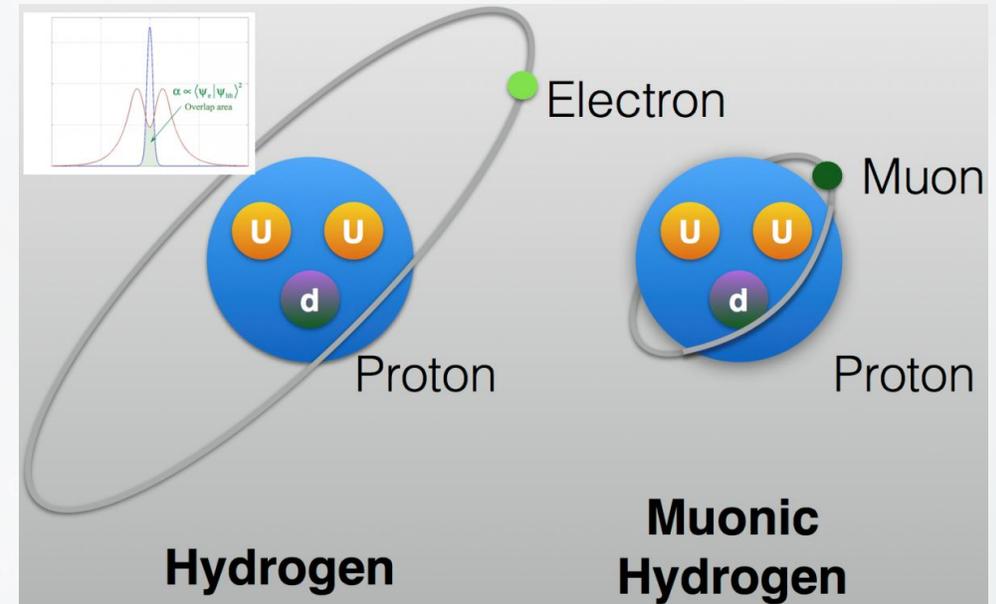
$$\begin{aligned}\Delta E &= -4\pi\alpha G_E^{\prime p}(0)|\psi_{n0}(0)|^2\delta_{l0} \\ &= 4\pi\alpha\frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.\end{aligned}$$

Muonic Atomic Hydrogen Spectroscopy

- Energy shifts in the hydrogen atom are sensitive to proton finite size effects (i.e. the proton is not point-like)
- In fact, they are directly related to the slope of the electric form factor at $Q^2 = 0$ by virtue of a Taylor expansion around $Q^2 = 0$ allowed by the vanishingly small four-momentum transfer in spectroscopy measurements
- Historically extracted a radius of ~ 0.88 fm (a few more recent measurements have gotten ~ 0.84 fm)
- Typical Q^2 values are inversely related to the Bohr radius
- Muons are 200x heavier than electrons
 - 200x smaller Bohr radius
 - $\geq 10^2$ x enhancement to proton finite size effect
 - Very high accuracy measurement of ~ 0.84 fm

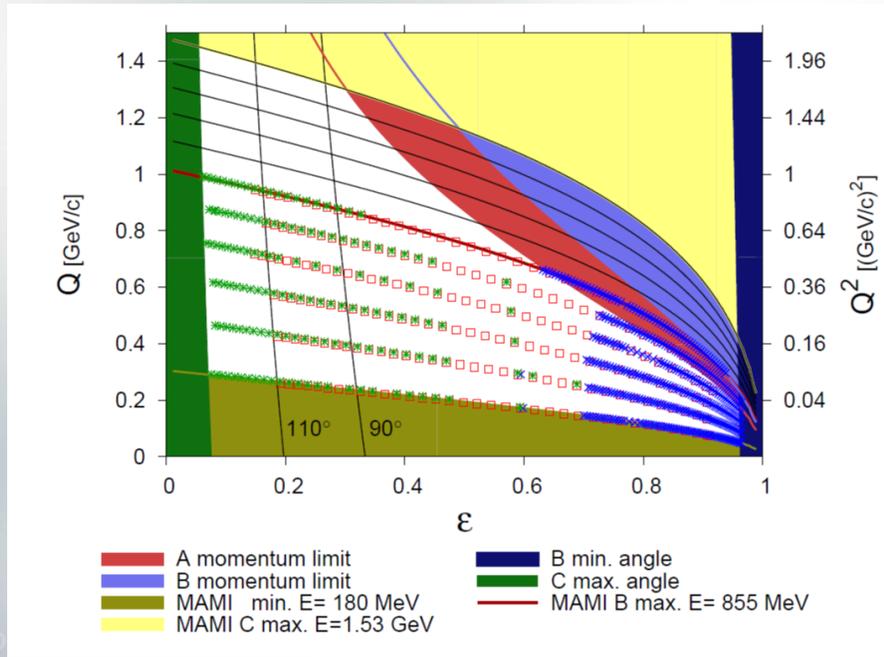
$$\Delta E = -4\pi\alpha G_E^{\prime p}(0) |\psi_{n0}(0)|^2 \delta_{l0}$$

$$= 4\pi\alpha \frac{r_p^2}{6} |\psi_{n0}(0)|^2 \delta_{l0}.$$



A1 at Mainz

- Many overlapping data sets
- Small statistical uncertainty $\leq 0.2\%$
- Large Q^2 coverage (0.004 - 1.0 GeV^2)
- $r_p = 0.879 \pm 0.008 \text{ fm}^*$



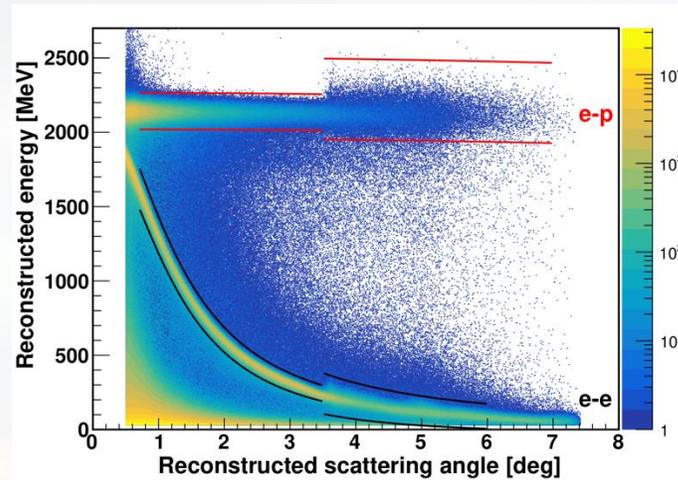
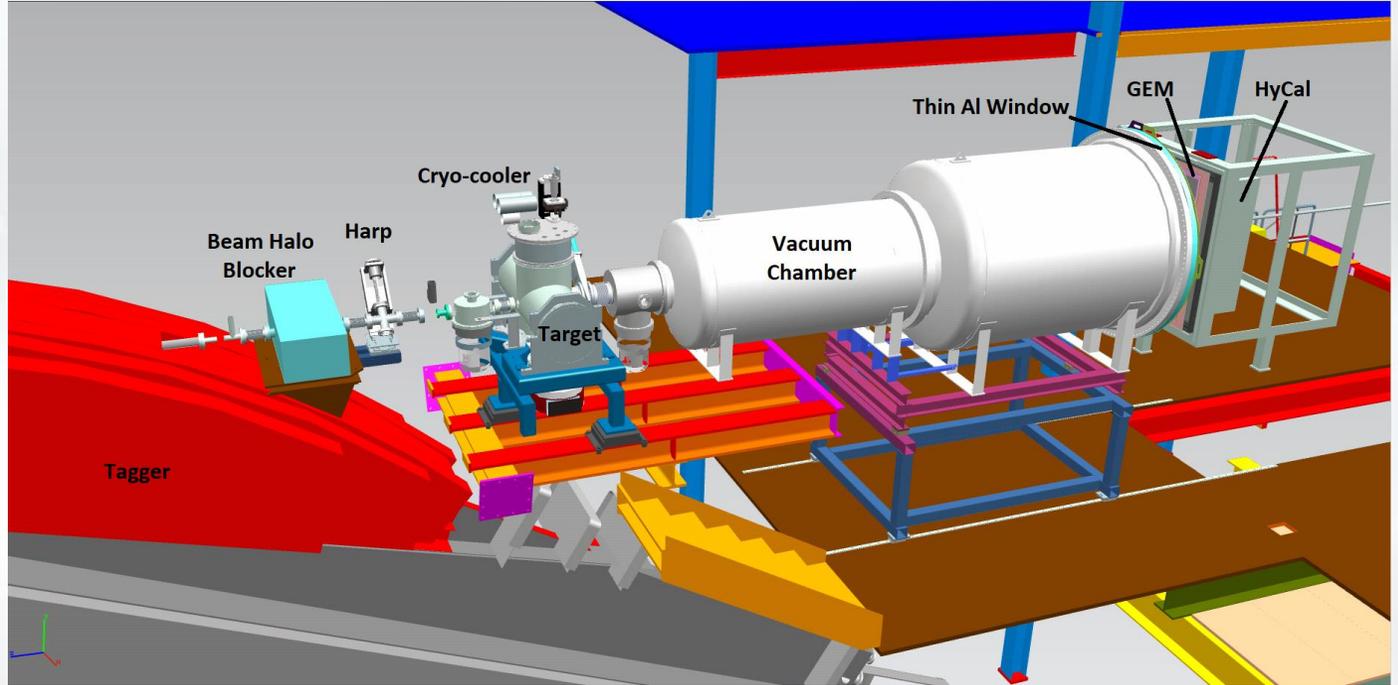
Three spectrometer facility of the A1 collaboration:



*J.C. Bernauer *Ph.D. Thesis*

PRad at JLab

- Large acceptance, far forward, magnet free spectrometer
- Windowless gas-flow target to minimize non-target background
- Ran in Jefferson Lab Hall B in 2016
- Used two beam energies, 1.1 GeV and 2.1 GeV, to cover a wide Q^2 range
- Simultaneously measured Møller scattering to normalize data
- Published test extractions on pseudodata to benchmark fit functions prior to extraction*
- Reported $r_p = 0.831 \pm 0.014 \text{ fm}^{**}$



*X. Yan *et al.* PRC 98 (2018) **W. Xiong *et al.* Nature 98 (2019)

Is the puzzle resolved?

It depends on who you ask!

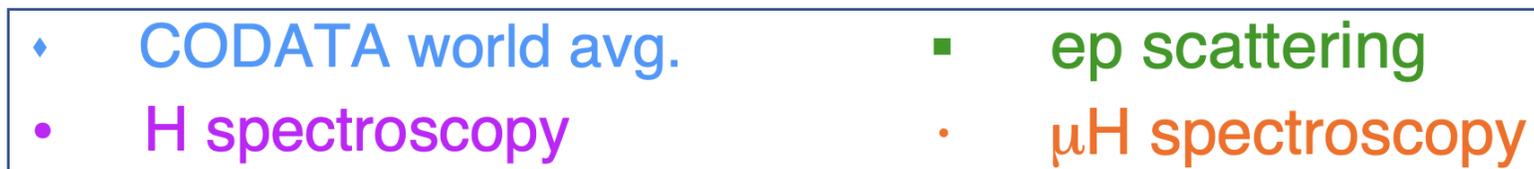
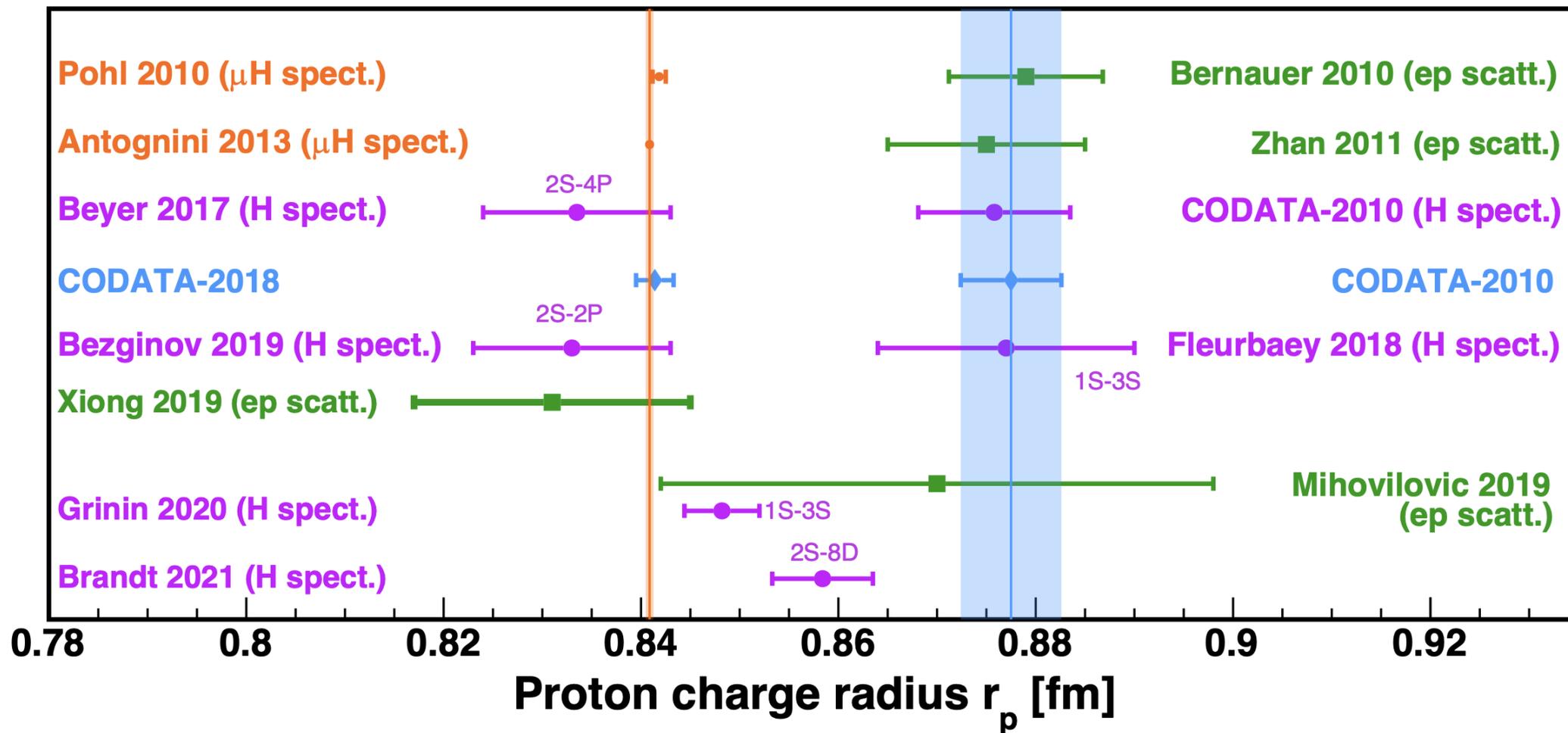


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Just kidding. No more chatbots.

Proton Charge Radius Puzzle



Current Status of the Puzzle

- Is it resolved? ***Partially***

New data and reanalysis of past scattering data *seems* to support the small radius

It is still unknown why past atomic hydrogen spectroscopy measurements are larger

- What questions still need work? (*disclaimer: list is non-exhaustive*)

Do we now have the Rydberg constant correct?

Is lepton universality violated?

Why is there a form factor discrepancy between PRad and A1 results?

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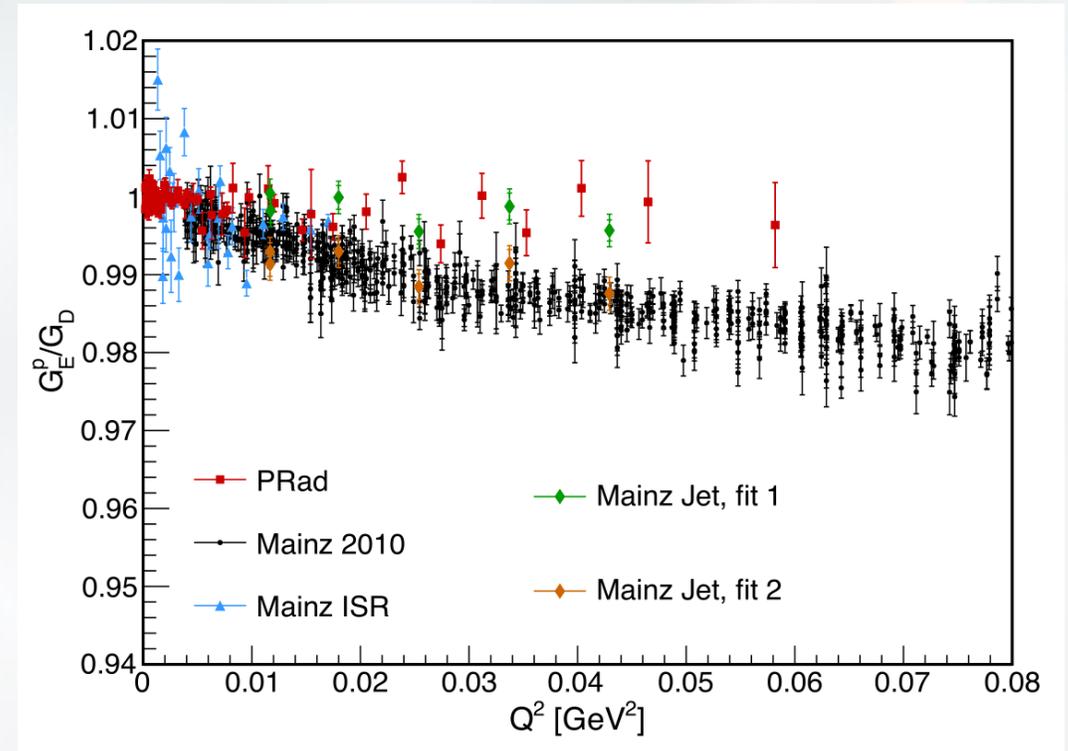
Why is there a form factor discrepancy between PRad and A1 results?

PRad-II can help with that last one!

Motivation for a New Proton Radius Measurement

PRad - A1 Form Factor Discrepancy

- The PRad and A1 Experiments have a $>1\%$ difference in G_E^p at the high end of their Q^2 ranges
- Both data sets have similar precision in the region of difference
- PRad-II will remeasure this region with greatly improved precision to rectify this
- Recent Mainz data with a jet target were unable to resolve the discrepancy



A More Precise Normalization

- Fits to data include a normalization parameter for each data set
- This allows both internal consistency to be enforced and for physically motivated fit constraints to be applied
- It is defined that $G_E^p(Q^2 = 0) \equiv 1$
- By going closer to this limit, we can better constrain the normalization of the data over the entire Q^2 range
- Recent Mainz gas jet target results show that data restricted to the discrepancy region are incapable of resolving the normalization tension

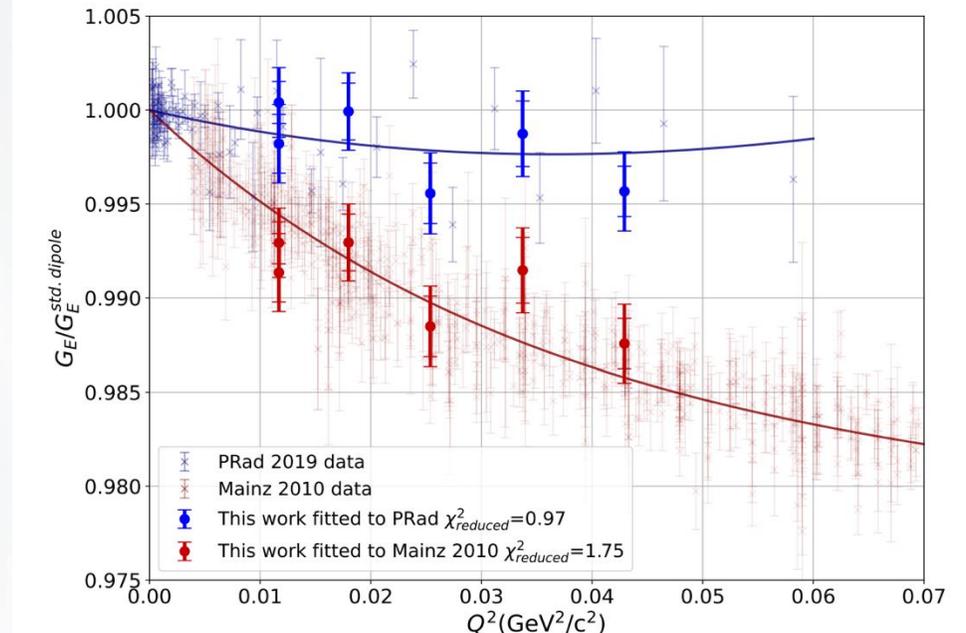
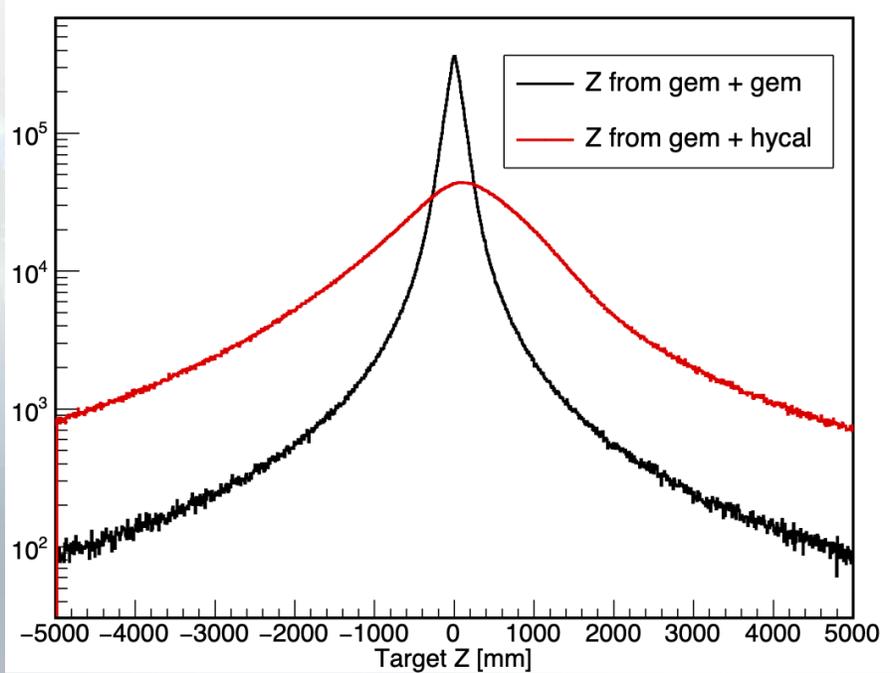


Figure from Y. Wang *et al.* *PRC* 106 (2022)

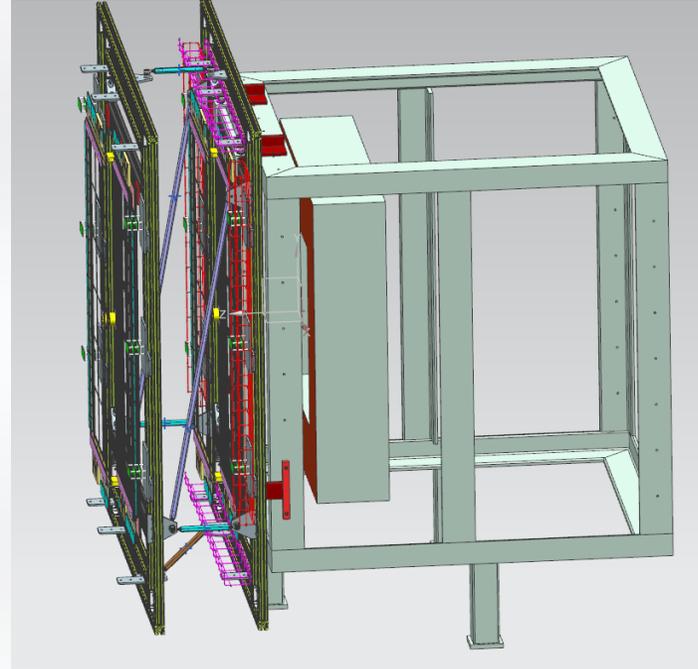
The PRad-II Experiment

The *Upgraded* PRad-II Spectrometer

- Two GEM planes
 - Improved non-target background rejection
 - Improved Q^2 resolution

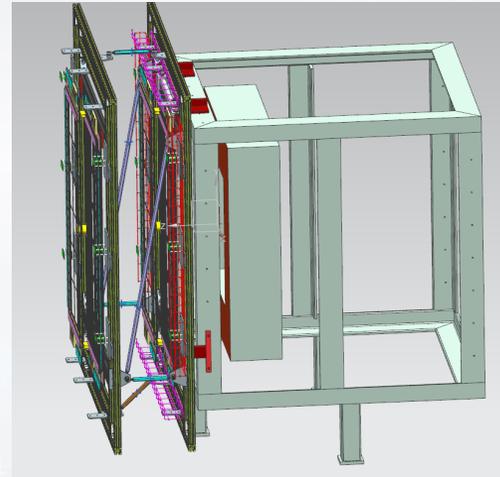
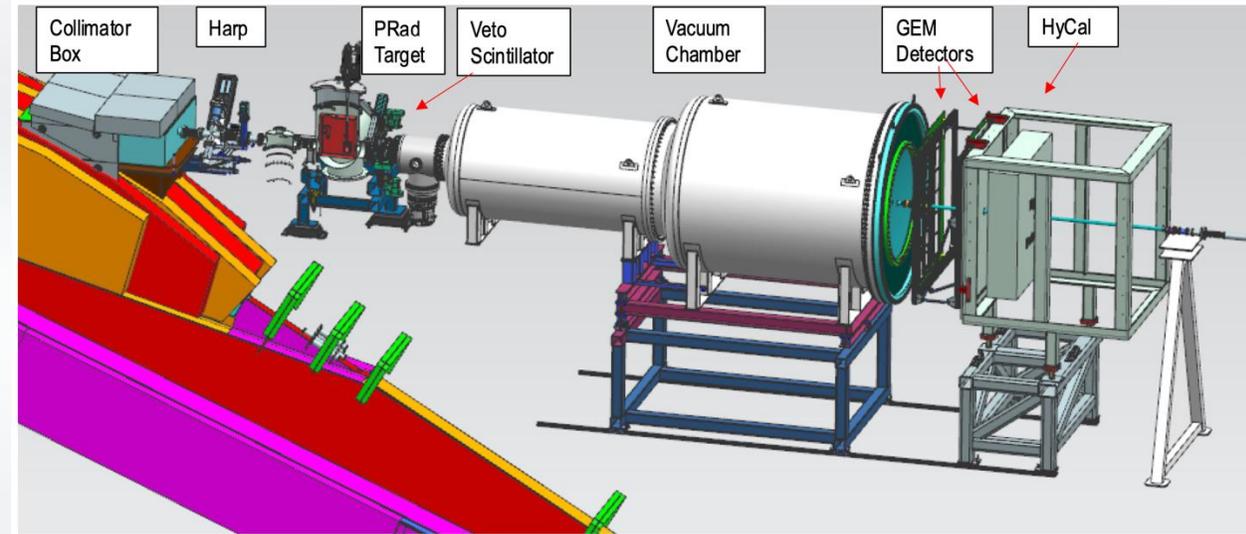


PRad target is 4 cm long



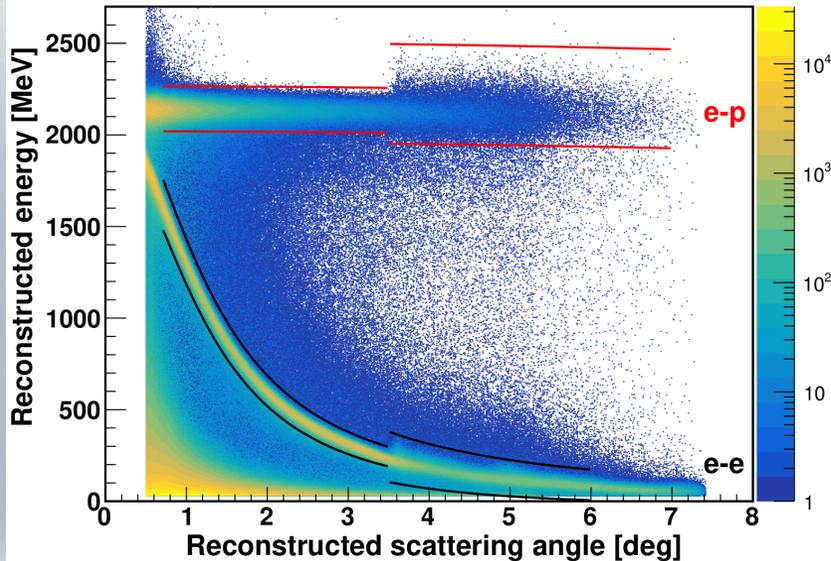
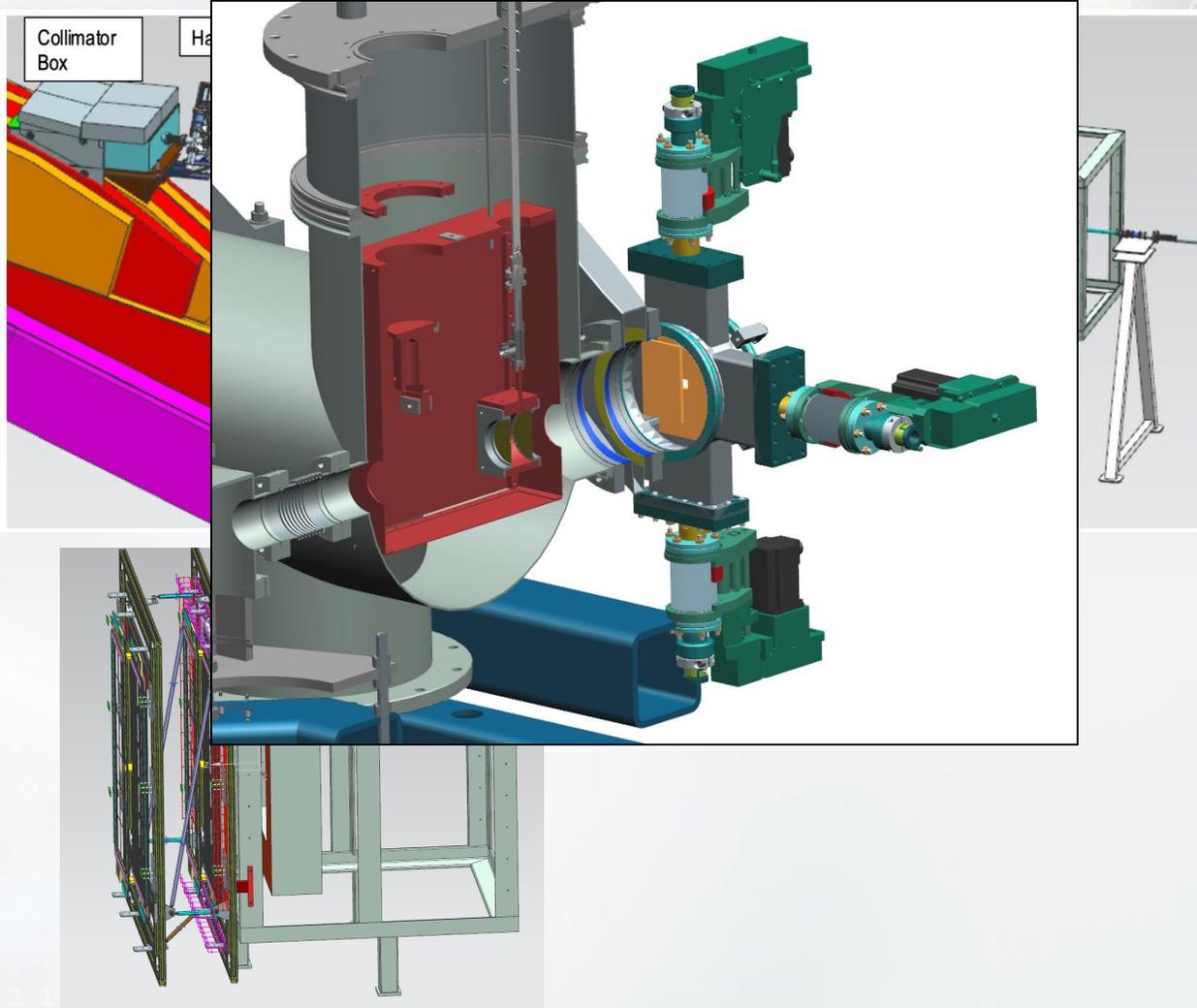
The *Upgraded* PRad-II Spectrometer

- *Two* GEM planes
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 - Reduced deadtime
 - Real-time cluster finding



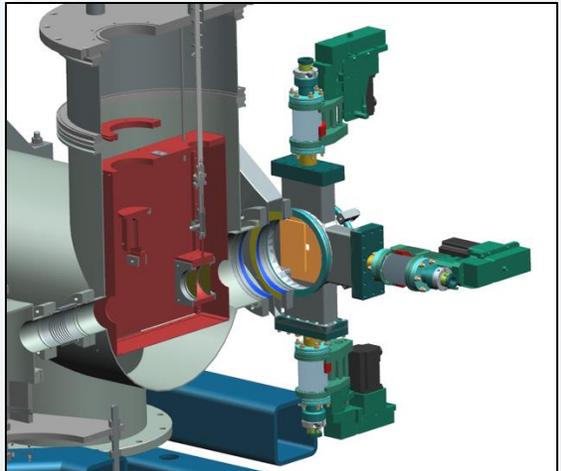
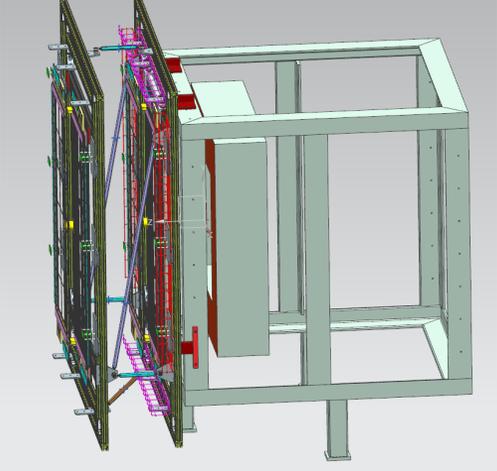
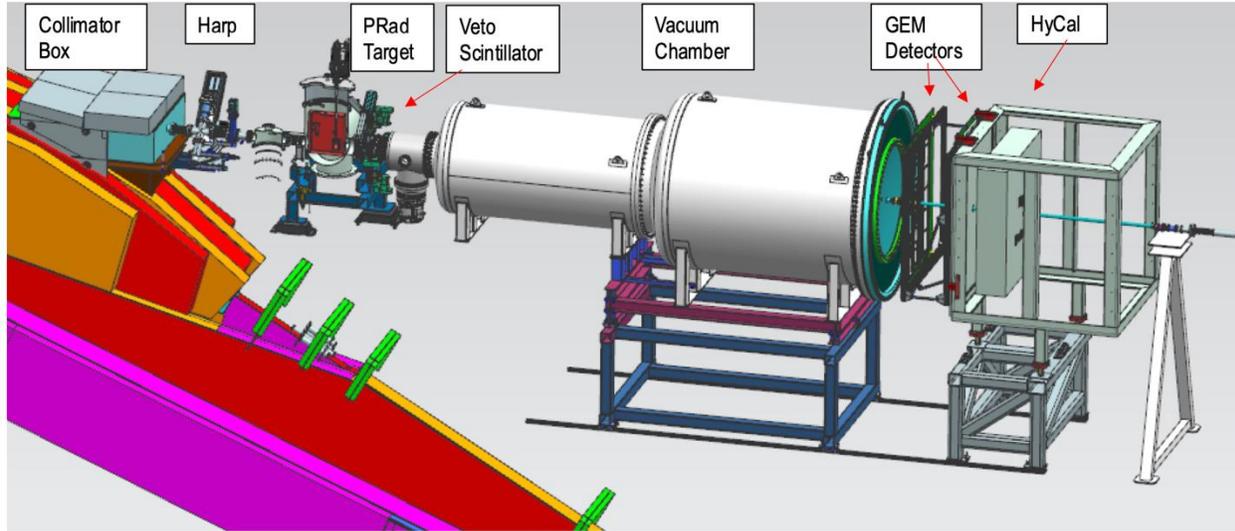
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 - Better separation of Møller events \rightarrow Improved normalization



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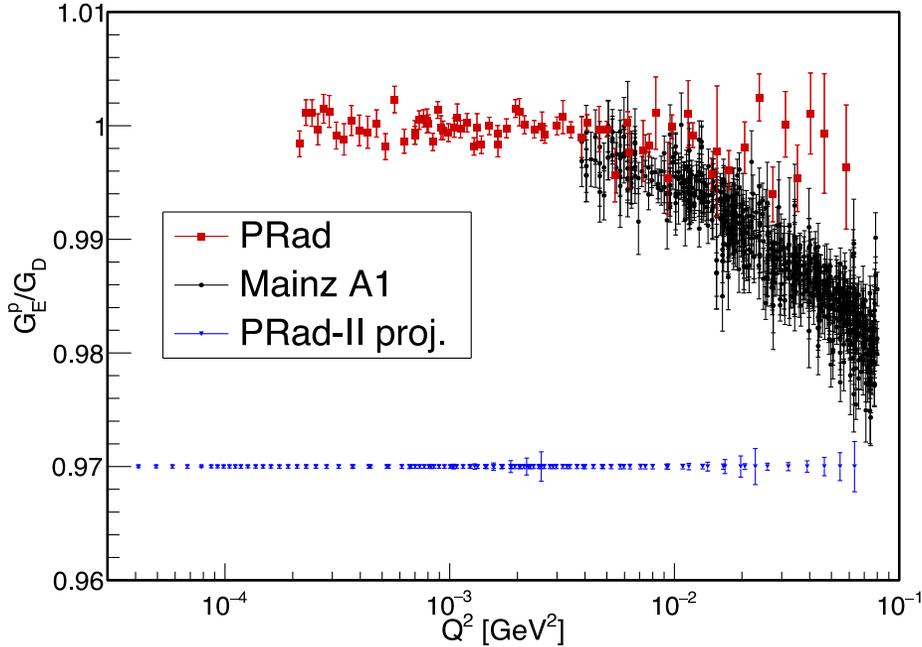
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 - Better separation of Møller events → Improved normalization
- All of this earned an “A” rating for the proposal by the JLab Program Advisory Committee



E12-20-004	A	B	PRad-II: A New Upgraded High Precision Measurement of the Proton Charge Radius	A. Gasparian* D. Dutta H. Gao D. Higinbotham N. Liyanage E. Pasyuk C. Peng	NCAT State U Mississippi State Duke U JLab U of Virginia JLab ANL	40	A	48	Proposal
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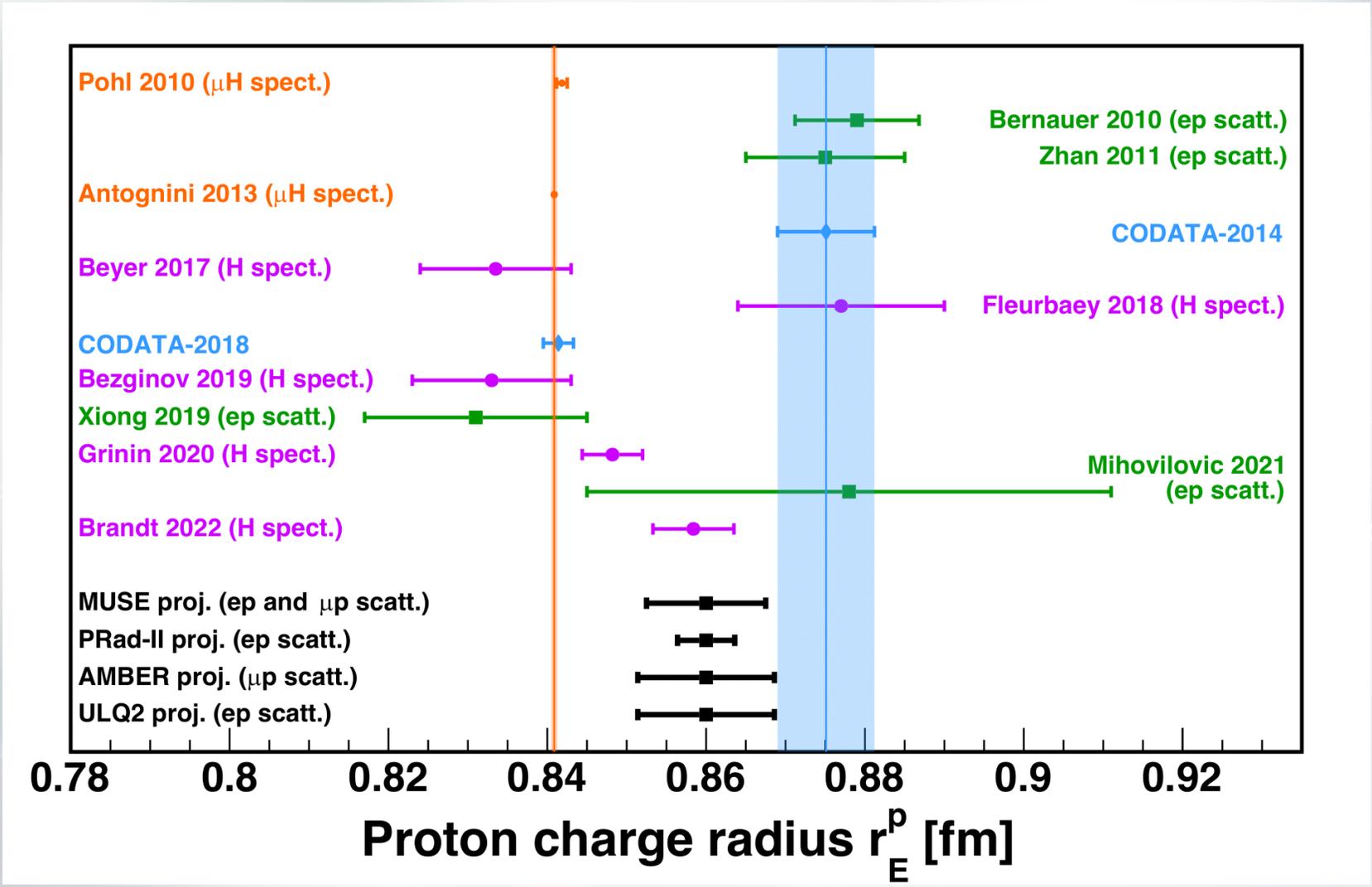
Kinematics and Projected Data

- Three beam energies: 0.7, 2.1, and 3.5 GeV
- Unprecedentedly low $Q^2 \sim 10^{-5} \text{ GeV}^2$
- Ultra-high precision for a more than 3x reduction in uncertainty on the extracted radius



Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0015
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0025
Beam background	0.0039	0.0014
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p model	0.0006	0.0005
Total syst.	0.0115	0.0043
Total uncertainty	0.0137	0.0046

Projected Future Lepton Scattering Results



Summary

- Progress has been made on the proton radius puzzle
- Tensions between data sets require further measurements and studies
- Some pieces remain untested (e.g. lepton universality)
- PRad-II improves upon the successful PRad experiment
- The experiment aims to be the most precise lepton scattering result for the proton radius with a projected uncertainty of $\delta_r \sim 0.0046$ fm

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🎉 PRad-II had a successful Experimental Readiness Review a month ago 🎉

📅 Anticipate to begin data taking in early 2026! 📅

QUESTIONS?