The PRad experiment and the Proton Radius Puzzle

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The Proton Radius Puzzle

What is the Proton Radius Puzzle?

Prior to 2010, the proton radius was believed to be 0.88 fm

[1] Krauth et al., "The proton radius puzzle".
[2] Pohl et al., "The size of the proton".

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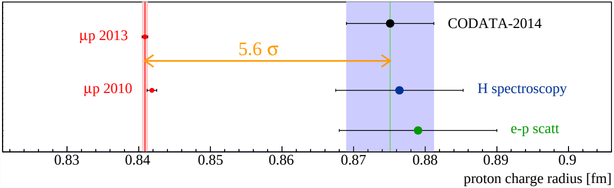

Figure from[1]

A new μH spectroscopy measurement[2] upended this with a measurement of 0.84 fm boasting unprecedented precision.

A $> 5\sigma$ discrepancy!

[1] Krauth et al., "The proton radius puzzle".
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How is the Proton Radius Measured?

$e - p$ Scattering

- The "proton radius" is defined as a moment of the of the proton electric form factor, G_E^p, and is proportional to the slope of G_E^p as $Q^2 \to 0$
- Through a Taylor-expansion of G_E^p around $Q^2 = 0$, we find:

$$G_E^p\left(Q^2\right) = 1 - \frac{Q^2\left\langle r_p^2\right\rangle}{6} + \frac{Q^4\left\langle r_p^4\right\rangle}{120} - \dots \tag{1}$$

- By fitting G_E^p data and extrapolating to 0 Q^2 the proton radius, r_p, can be extracted as $r_p = \sqrt{6\frac{dG_E^p}{dQ^2}}$

How is the Proton Radius Measured?

Hydrogen Lamb Shift

- The energy difference between excited S and P states of Hydrogen is directly related to the proton radius
- While it relies on (and is dominated by) radiative effects of the Hydrogen atom, precision measurements and improved calculations leave r_p as the limiting factor
- The increased mass of the muon make μH even more sensitive to r_p

Proposed Explanations

New Physics?

- Could lepton universality be violated?

Inconsistent Definitions?

- Is the definition of r_p consistent between the two measurement techniques?

Improper Extraction from $e - p$ Data?

- Extraction relies on extrapolation
- Poor choice of fit function can bias the extraction

Incorrect Rydberg Constant?

- Would explain difference with standard Hydrogen spectroscopy

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PRad

The PRad Experiment

- Experiment designed to achieve the most precise proton radius extraction from $e - p$ scattering
- Aimed to record the lowest Q^2 achieved in $e - p$ scattering (from 2.1×10^{-4} to 6×10^{-2} GeV^2)
- Simultaneously measure Møller Scattering to fix the normalization

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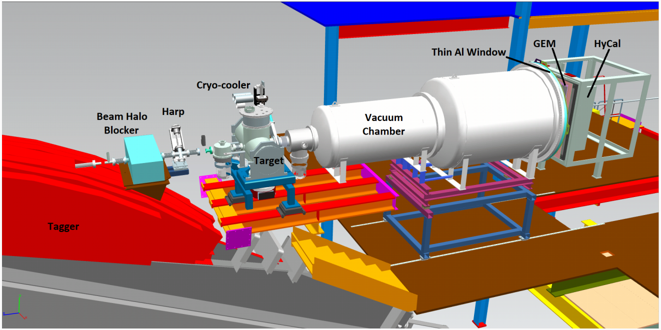
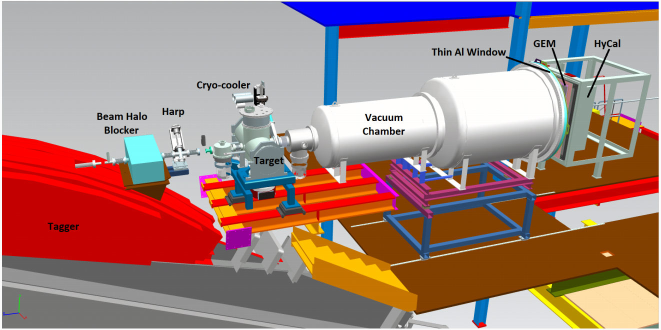
Experimental Setup



- Magnet-free setup
- Large area vacuum chamber
- Large acceptance forward hybrid calorimeter (HyCal) to cover entire Q^2 range in a single setting
- GEM for neutral particle rejection and tracking
- Window-less gas flow target

Experimental Setup



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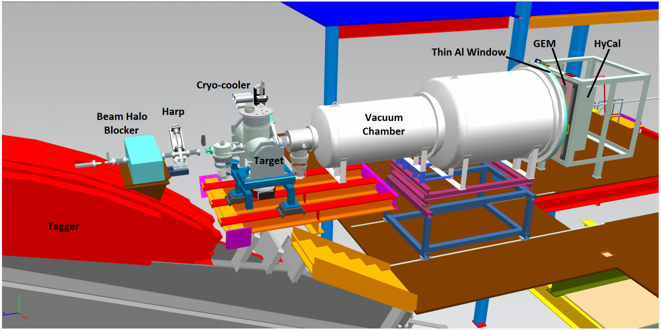

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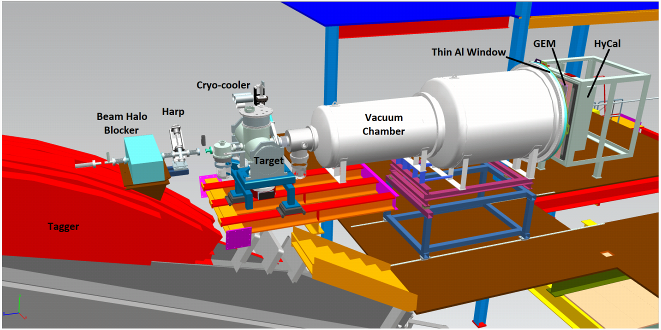

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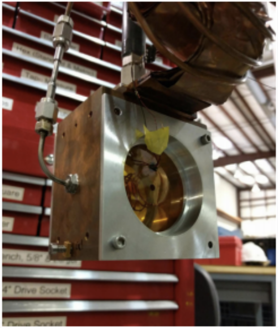

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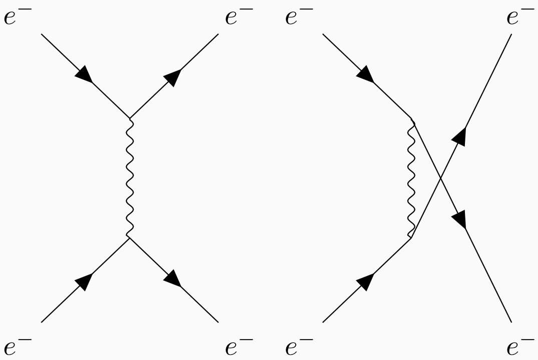
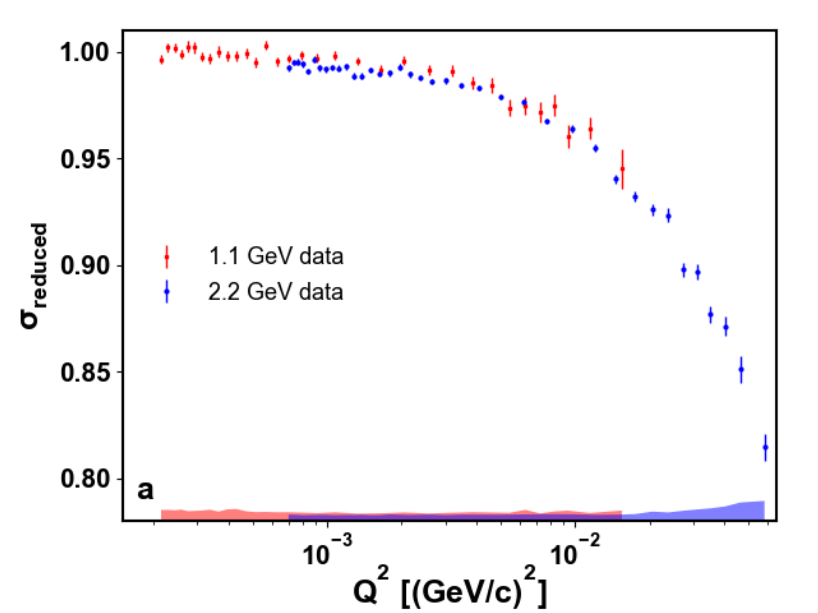
Møller Scattering Normalization



- Detect single arm Møller scattered electrons
- Møller Scattering is exactly calculable in QED
- Simultaneous measurement minimizes normalization uncertainty

Cross Section Results



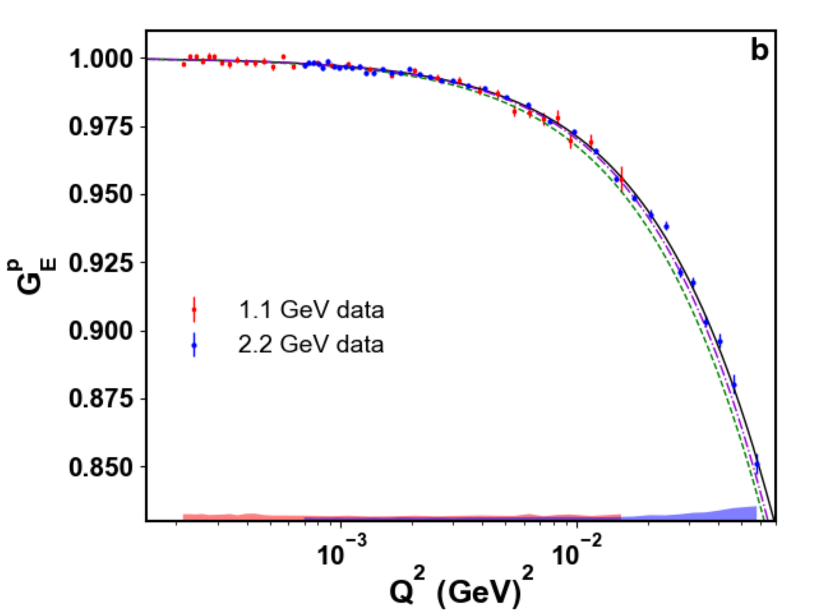
But that's not G_E^p!

- The cross section can be turned into G_E^p through the Rosenbluth equation (below) and a parameterization of the proton magnetic form factor, G_M^p

$$\sigma = \sigma_{\mathrm{Mott}} \times \left[\frac{G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)}{1+\tau} + 2\tau G_M^2\left(Q^2\right) \tan^2\left(\frac{\theta}{2}\right) \right]$$

- The extraction is largely independent of the parameterization chosen
  - In testing several parameterizations, G_E^p varied by no more than 0.2% at high Q^2 to less than 0.01% at the lowest Q^2

We have G_E^p!


b
1.000
0.975
0.950
0.925
0.900
0.875
0.850
G_E^p
1.1 GeV data
2.2 GeV data
10^{-3}
10^{-2}
Q^2 (GeV)^2

Now... How do we extract the radius?[3]

- Fit the data and extrapolate to $Q^2 = 0$
- But what fit function?
- The functional form of G_E^p is unknown, so assumptions must be made
- Prior to recording data, PRad tested several functional forms for robustness
- Robustness was determined by trial fits of mock data across the PRad Q^2 range
- RMSE was used as the robustness metric, defined as $\sqrt{\text{bias}^2 + \sigma^2}$

[3] Yan et al., “Robust extraction of the proton charge radius from electron-proton scattering data”.

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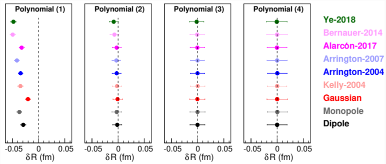

Polynomial Fits

$$\mathrm{Polynomial}\,(n) = a_0 \left(1 + \sum_{i=1}^{n} a_i Q^{2i}\right)$$

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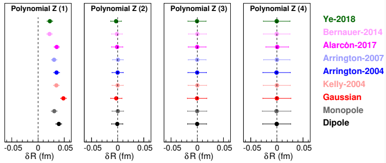
Now... How do we extract the radius?[3]



Polynomial Fits with conformal mapping

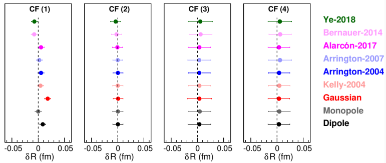
$$\text{Polynomial Z}\,(n) = a_0 \left(1 + \sum_{i=1}^{n} a_i Z^{2i}\right)$$

$$Z\left(Q^2, Q^2_{\text{cut}}\right) = \frac{\sqrt{Q^2_{\text{cut}} - Q^2} - \sqrt{Q^2_{\text{cut}}}}{\sqrt{Q^2_{\text{cut}} - Q^2} + \sqrt{Q^2_{\text{cut}}}}$$

[3]Yan et al., "Robust extraction of the proton charge radius from electron-proton scattering data".

Now... How do we extract the radius?[3]

$$\mathrm{CF}(n) = \frac{a_0}{1 + \frac{a_1 Q^2}{1 + \frac{a_2 Q^2}{1 + \cdots}}}$$

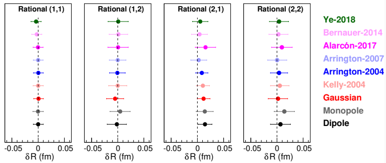


Continued Fraction Fits

[3] Yan et al., “Robust extraction of the proton charge radius from electron-proton scattering data”.

Now... How do we extract the radius?[3]

$$\text{Rational}\,(N,M) = a_0 \frac{1 + \sum_{i=1}^{N} a_i^{(a)} Q^{2i}}{1 + \sum_{j=1}^{M} a_j^{(b)} Q^{2j}}$$



Rational Function Fits

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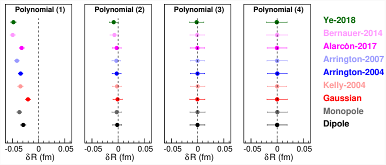

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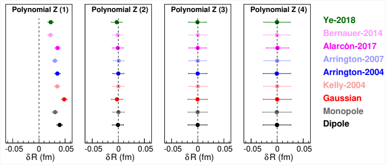

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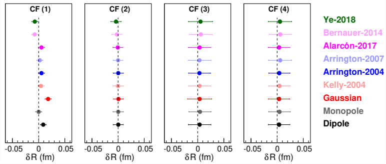

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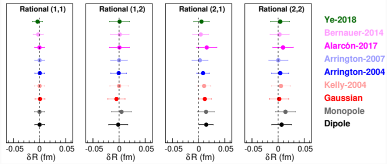


Rational Function Fits

[3] Yan et al., "Robust extraction of the proton charge radius from electron-proton scattering data".

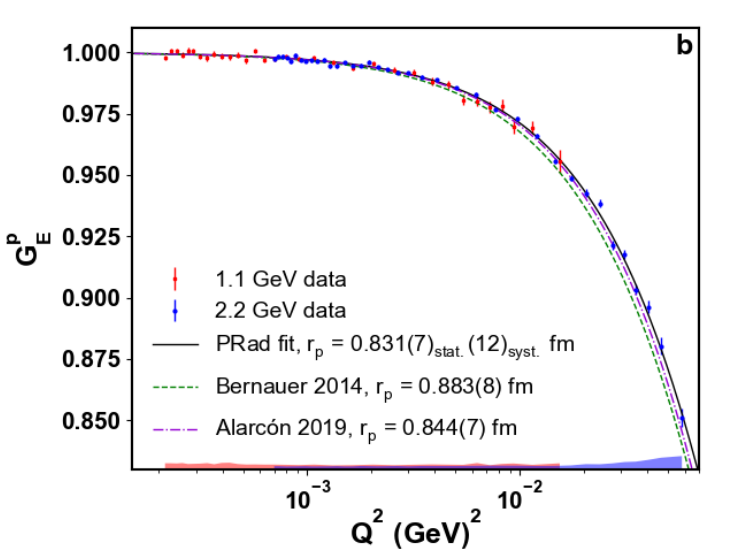
Let's be Rational$(1, 1)$

- Ultimately the Rational(1,1) function was chosen

$$f\left(Q^2\right) = n\frac{1 + aQ^2}{1 + bQ^2}$$

- This form is approximately monotonic, ensuring that the function does not vary wildly when extrapolated beyond the bounds of data
- The radius is then extracted as $r_p = \sqrt{6\left(b - a\right)}$
- n is a normalization factor that is unique to each beam energy data set

The Fit



b
1.000
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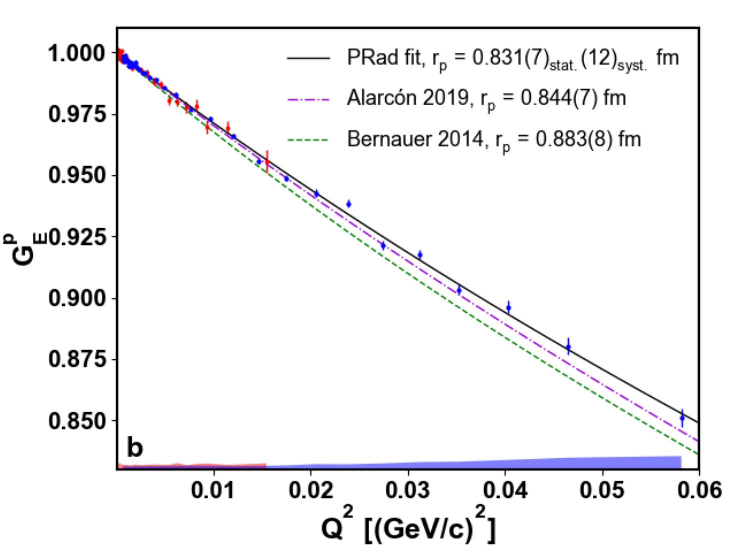
G_E^p
1.1 GeV data
2.2 GeV data
PRad fit, r_p = 0.831(7)$_{stat.}$ (12)$_{syst.}$ fm
Bernauer 2014, r_p = 0.883(8) fm
Alarcón 2019, r_p = 0.844(7) fm
10^{-3}
10^{-2}
Q^2 $(GeV)^2$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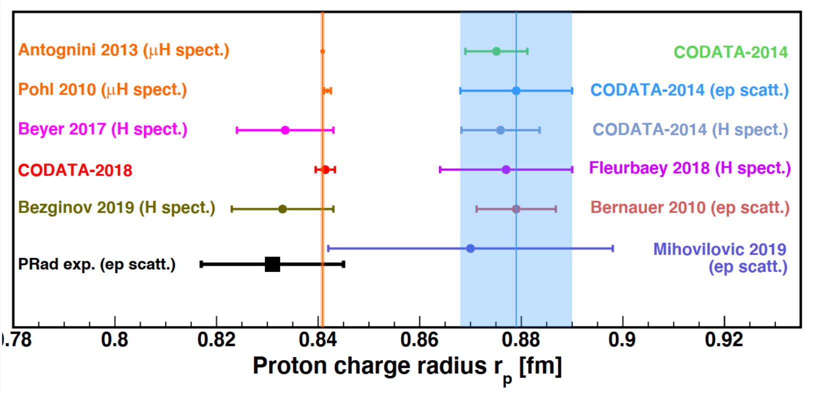
G^p_E
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0.01
0.02
0.03
0.04
0.05
0.06
Q^2 [(GeV/c)^2]

Yes!

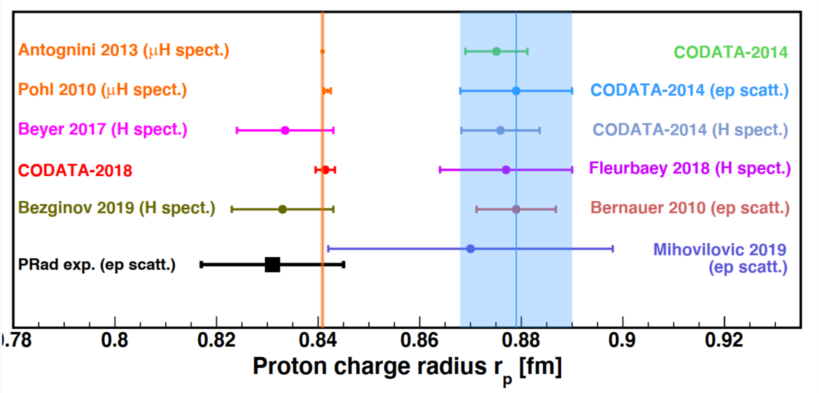
The PRad result agrees with μH!



But no...

That's only one measurement and many others disagree

It also doesn't explain the disagreeing atomic spectroscopy results



Is the puzzle solved?

Maybe?

Reanalysis suggests that other data is, in fact, consistent with a small radius, but...

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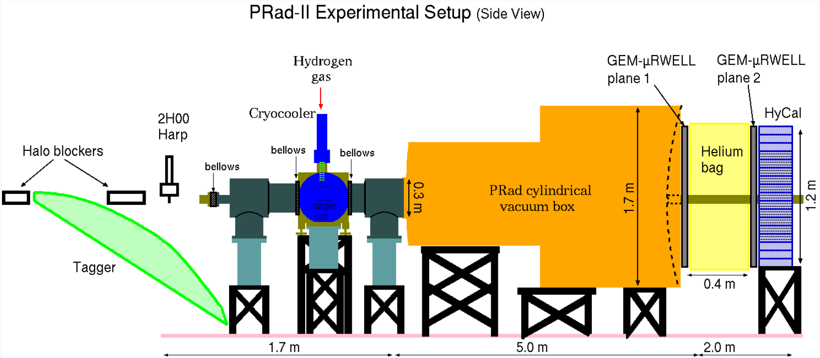
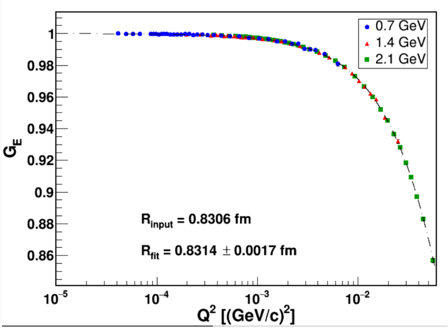
PRad-II

The PRad-II Setup



What's different?

- Lower beam energy for lower Q^2 reach (from $\sim 10^{-5}$ to 6×10^{-2} GeV^2)
- New scintillators to descern $e - p$ from Møller at low Q^2
- Second GEM plane to reject non-target background
- HyCal upgrade for improved resolution at high Q^2



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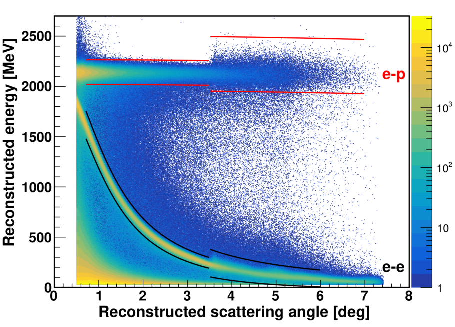

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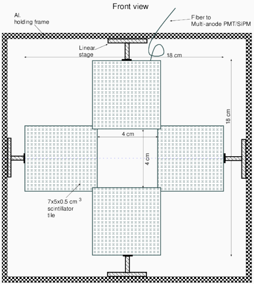

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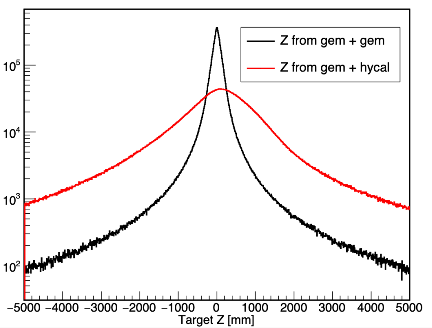

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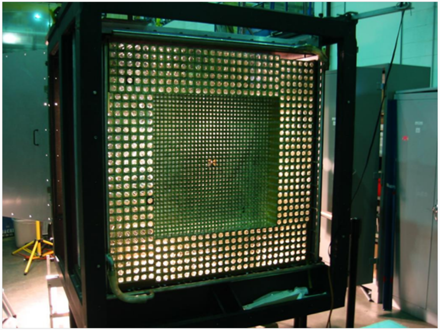


Culmination

Nearly 4x precision!

Lowest Q^2 ever recorded!

Item	PRad δr_p [fm]	PRad-II δr_p [fm]	Reason
Stat. uncertainty	0.0075	0.0017	more beam time
GEM efficiency	0.0042	0.0008	2nd GEM detector
Acceptance	0.0026	0.0002	2nd GEM detector
Beam energy related	0.0022	0.0002	2nd GEM detector
Event selection	0.0070	0.0027	2nd GEM + HyCal upgrade
HyCal response	0.0029	negligible	HyCal upgrade
Beam background	0.0039	0.0016	better vacuum 2nd halo blocker vertex res. (2nd GEM)
Radiative correction	0.0069	0.0004	improved calc.
Inelastic *ep*	0.0009	negligible	-
G_M^p parameterization	0.0006	0.0005	HyCal upgrade
Total syst. uncertainty	0.0115	0.0032	
Total uncertainty	0.0137	0.0036	

Current Status

Full Approval

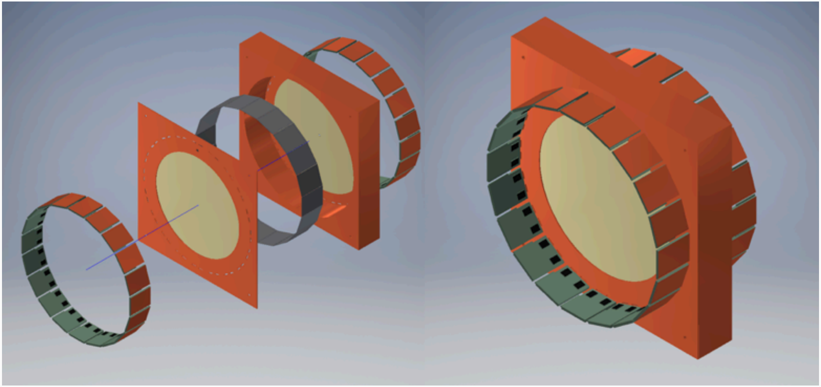
	E12-20-004	A	B	PRad-II: A New Upgraded High Precision Measurement of the Proton Charge Radius	A. Gasparian* D. Dutta H. Gao D. Higinbotham N. Liyanage E. Pasyuk C. Peng	NCAT State U Mississippi State Duke U JLab U of Virginia JLab ANL	40	A	48	Proposal

Currently, the collaboration is actively seeking funding for the HyCal upgrade

We expect to be ready to run in the next few years

Other PRad Family Experiments

The deuteron radius can be accurately calculated with the proton radius as an input[4], so a shift in r_p results in a shift in r_D



[4] Pohl et al., "The size of the proton and the deuteron".

π^0 Transition Form Factor

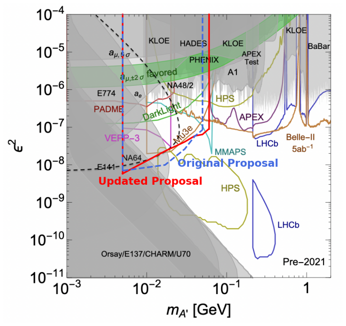
Approved with **A-** rating in JLab PAC 50

Will measure the π^0 transition form factor using the PRad-II setup

π^0's will be produced through the Primakoff mechanism ($e^- A \rightarrow e^- A \pi^0$) and the recoil electron and two decay photons of the π^0 will be simultaneously detected.

Approved with **A** rating in JLab PAC 50

A hidden sector search, with particular emphasis on resolving the X17 anomaly[5]

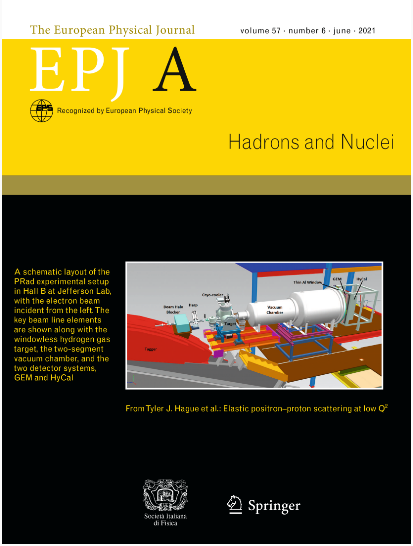


[5]Krasznahorkay et al., "Observation of Anomalous Internal Pair Creation in Be8 : A Possible Indication of a Light, Neutral Boson".

PRad+[6]

Experiment idea to run PRad-II with the proposed positron beam upgrade

This measurement could assess charge-odd radiative corrections (particularly Bremsstrahlung) when combined with electron scattering data



[6] Hague et al., “Elastic positron–proton scattering at low Q^2”.