The Proton Radius Puzzle and Experiment

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The Proton Radius Puzzle

What is the proton radius?

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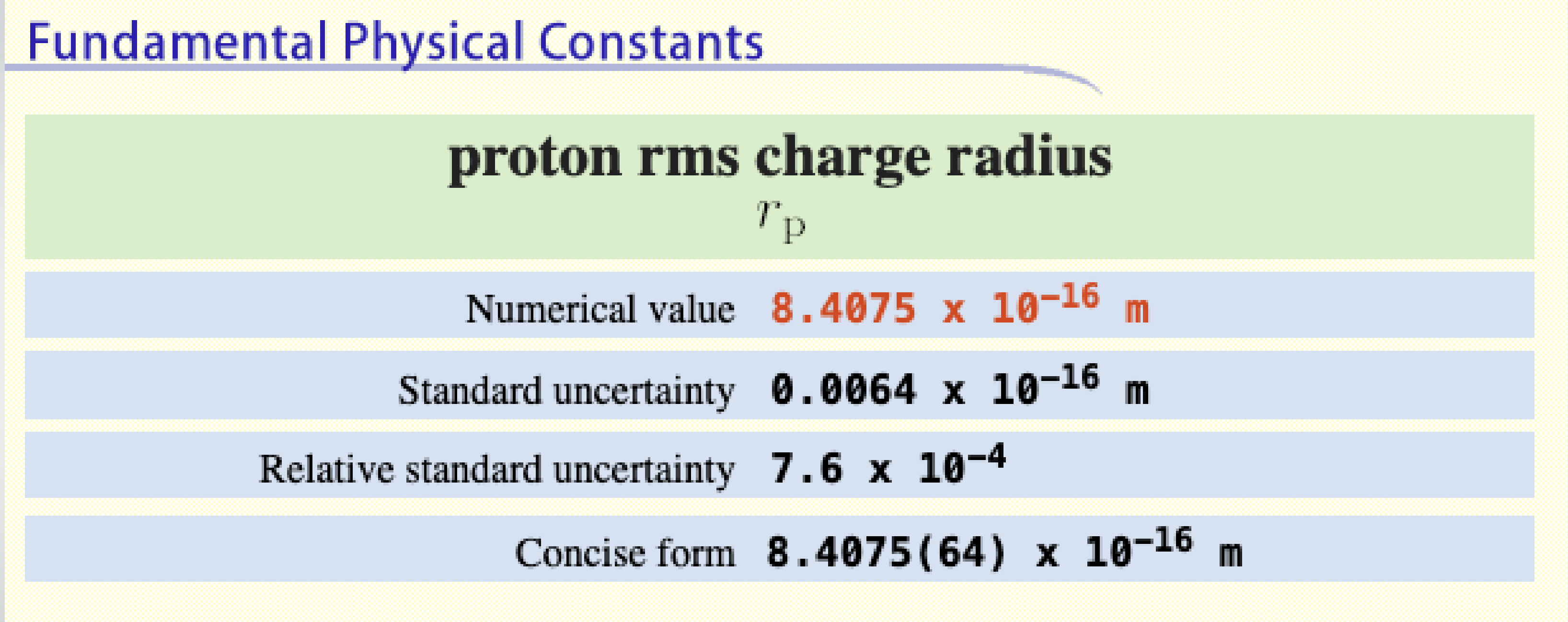


Fundamental Physical Constants

proton rms charge radius

r_p

Numerical value	8.4075 x 10^{-16} m
Standard uncertainty	0.0064 x 10^{-16} m
Relative standard uncertainty	7.6 x 10^{-4}
Concise form	8.4075(64) x 10^{-16} m

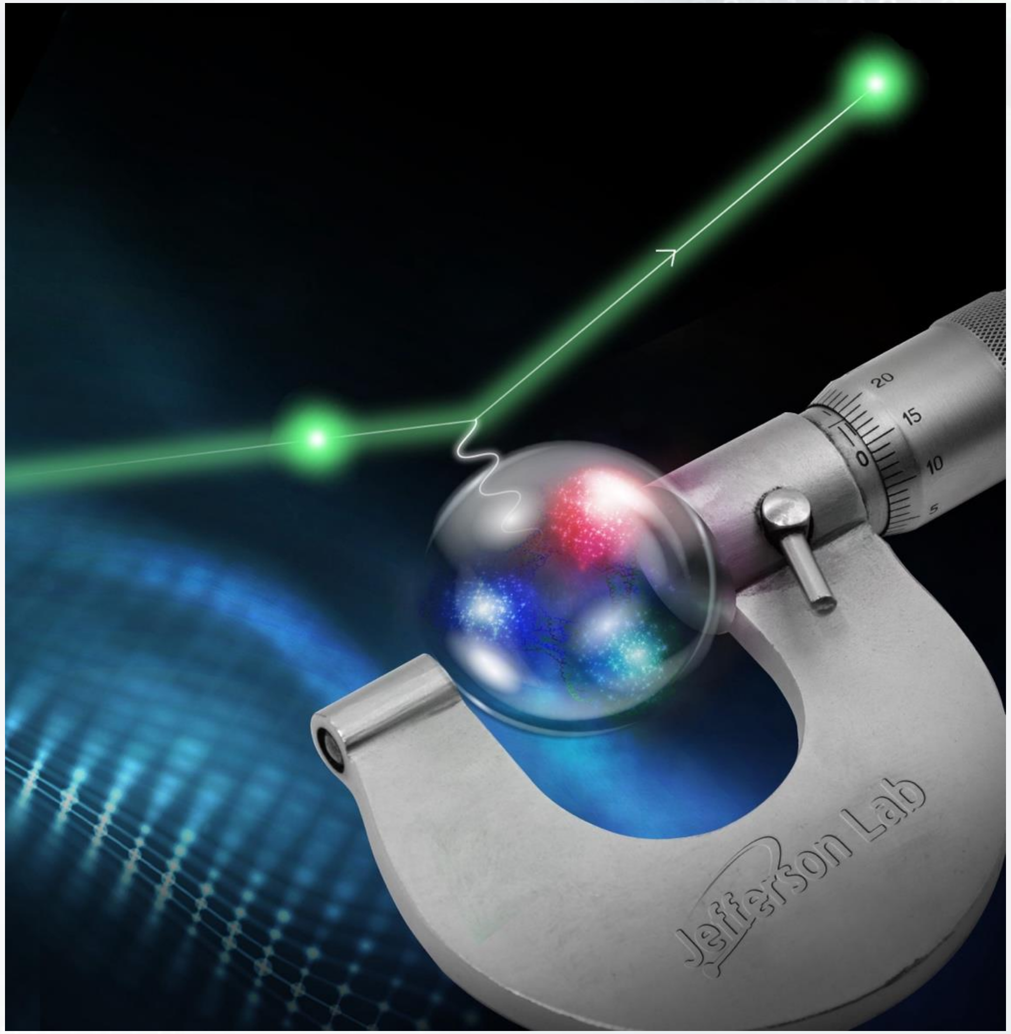
0.84075 +/- 0.00064 fm

Image from NIST, reflecting the current CODATA value

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

The *Proton Radius Puzzle*

- The proton radius was always 0.88 fm

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Until it wasn't

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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 >5σ!

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

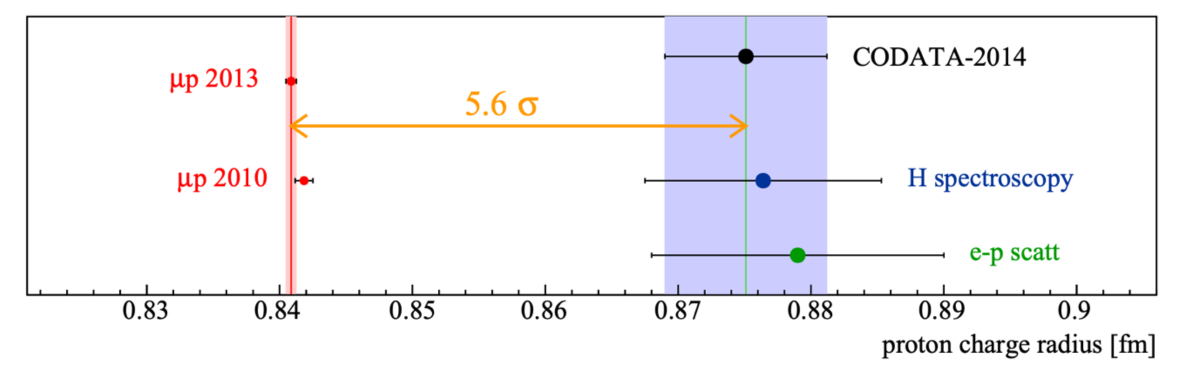

Figure from J.J. Krauth *et al.* arXiv:1706.00696

And why should I care?

And why should I care?

New Physics?

Could lepton universality be violated?

MUSE is working on this

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

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

Spectroscopy 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)

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

Muonic
~~Atomic~~ Hydrogen Spectroscopy

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- 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
  - → ≥10^2x enhancement to proton finite size effect
  - → Very high accuracy measurement of ~0.84 fm

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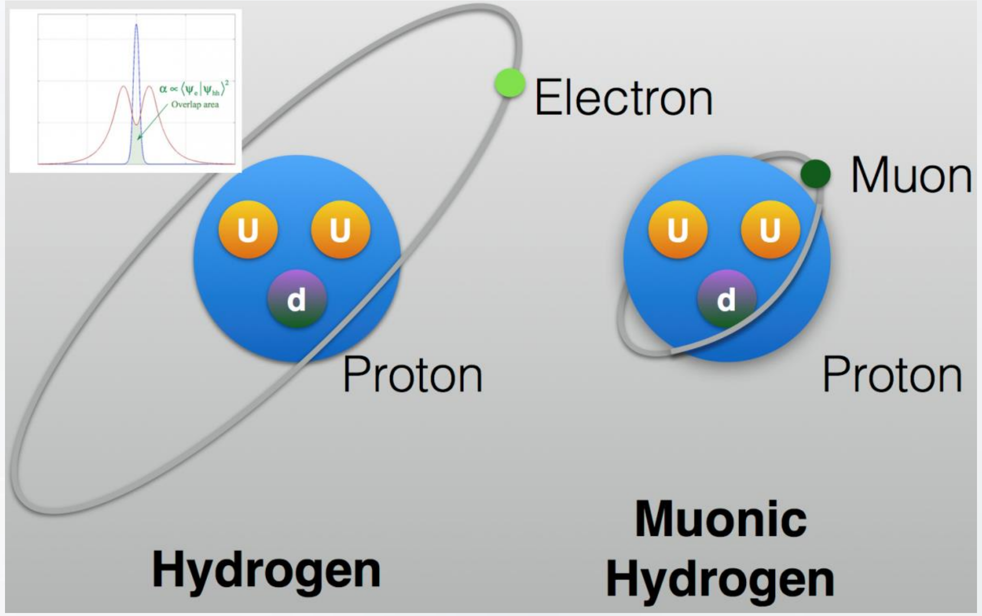


Designing a Scattering Measurement

What do we need to measure?

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

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

$$\mathrm{Q}^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right) \qquad \tau = \frac{\mathrm{Q}^2}{4\mathrm{M}_{\mathrm{p}}^2} \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1} \qquad \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} = \frac{\alpha^2\left[1 - \beta^2 \sin^2\left(\frac{\theta}{2}\right)\right]}{4\mathrm{k}^2 \sin^4\left(\frac{\theta}{2}\right)}$$

What does an experiment and spectrometer need to do?

- Particle Identification
- Energy measurement
- Tracking (angle measurement)
- Identify/Mitigate Backgrounds
- Create minimal backgrounds itself
- Measure the luminosity (how much beam you use and how much target you have)

What are *your* ideas for this measurement?

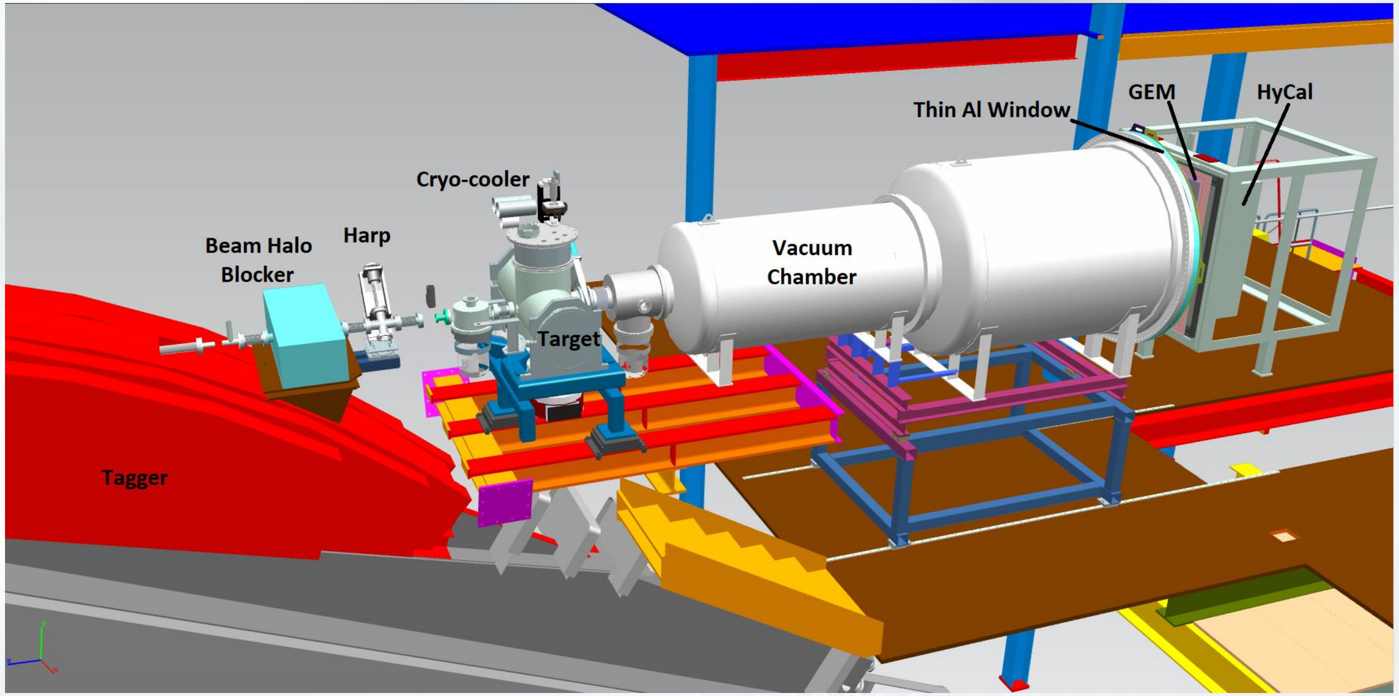
- We need the slope of G_E as Q^2 goes to 0
- How do we deal with G_M?
- What about backgrounds?
- Luminosity?

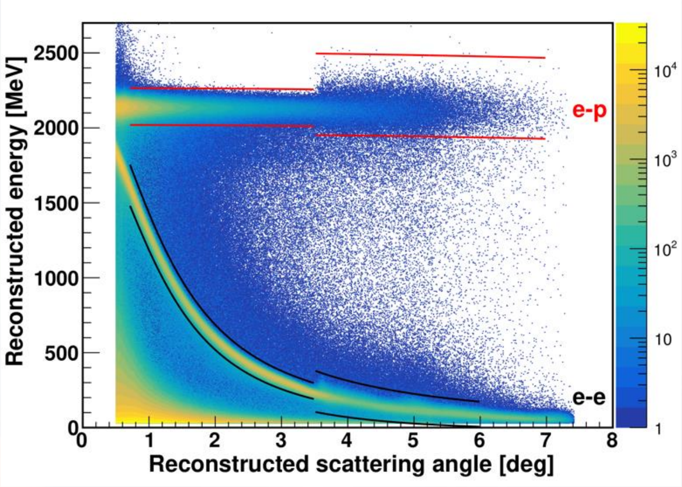
$$\mathrm{Q}^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

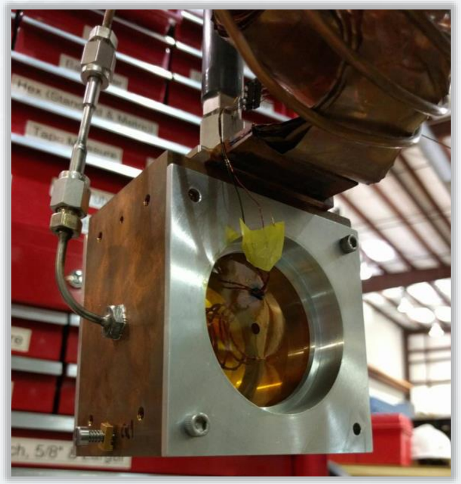
- (Meant to be interactive, let’s talk through ideas)

How did PRad do it?

- Particle ID
  - Electron proton scattering has well defined kinematics
  - GEMs only detect charged particles
- Energy Measurement
  - High resolution PbWO4 calorimeter blocks in the region of lowest Q^2
- Tracking
  - GEM tracker for high resolution position detection
- Identify backgrounds
  - Anything that doesn't match e-p scattering kinematics is background
- Create Minimal backgrounds
  - Vacuum chamber minimizes rescattering
- Measure Luminosity
  - Uses Møller scattering as a luminosity check

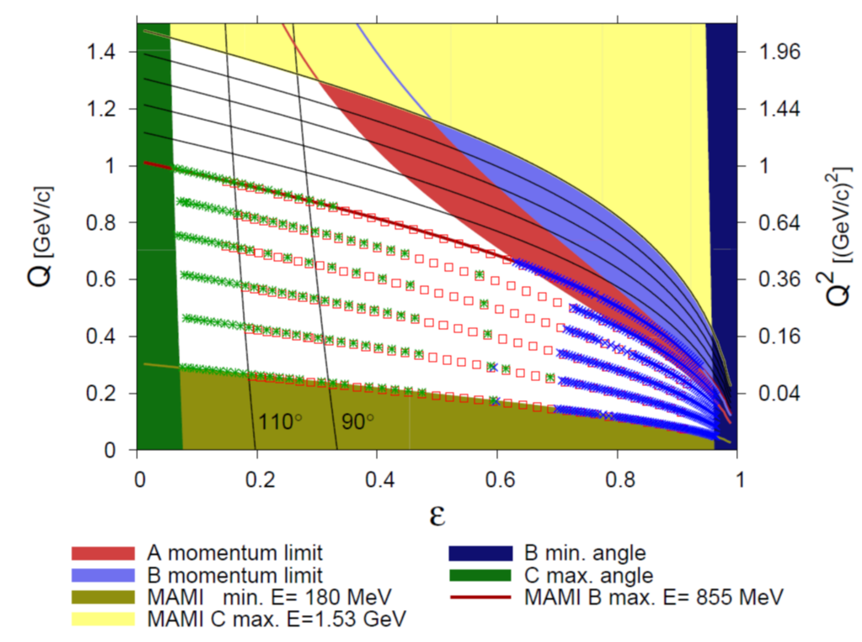


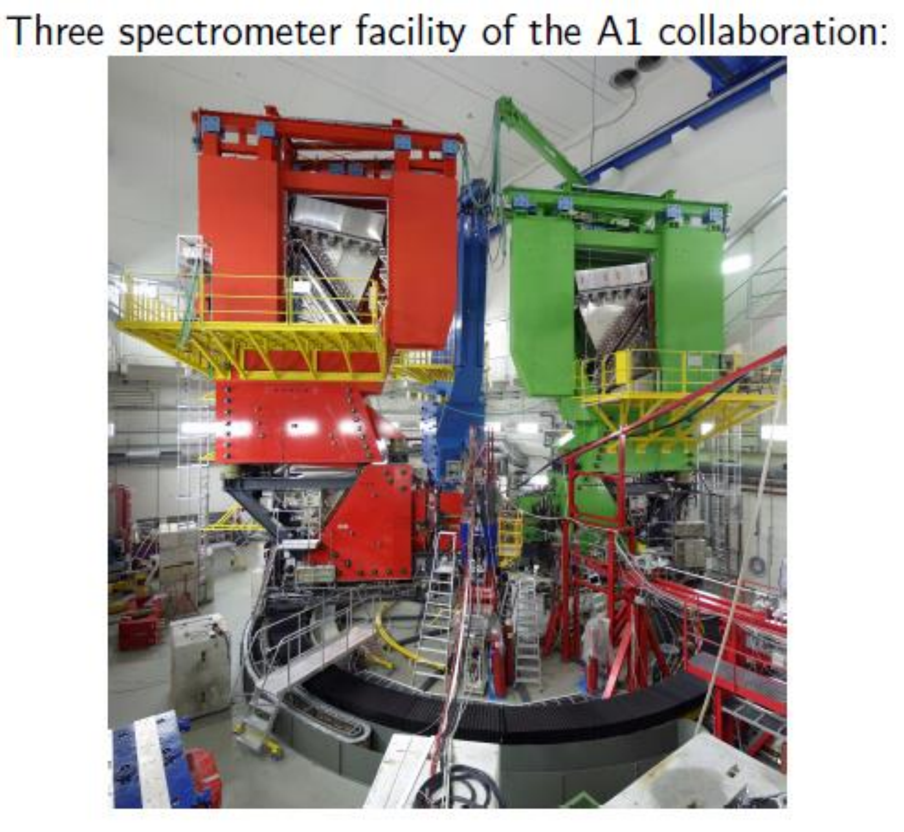




A1 at Mainz

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

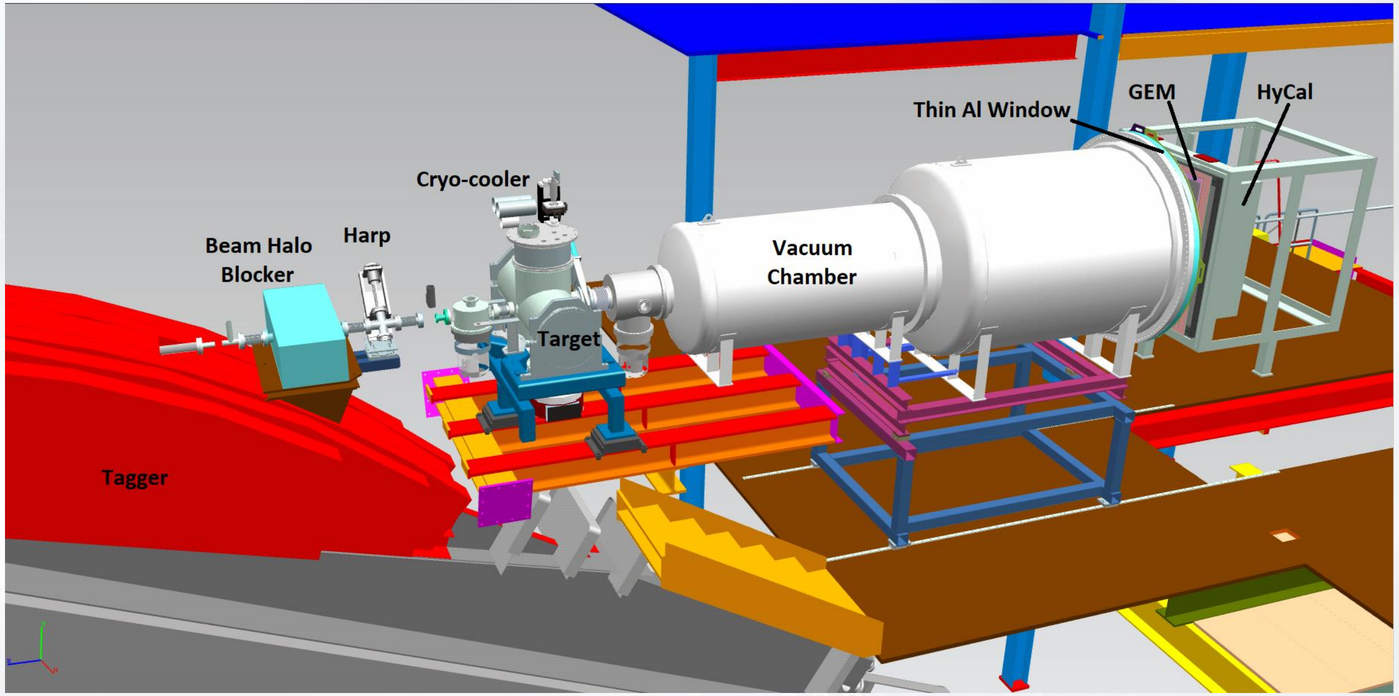


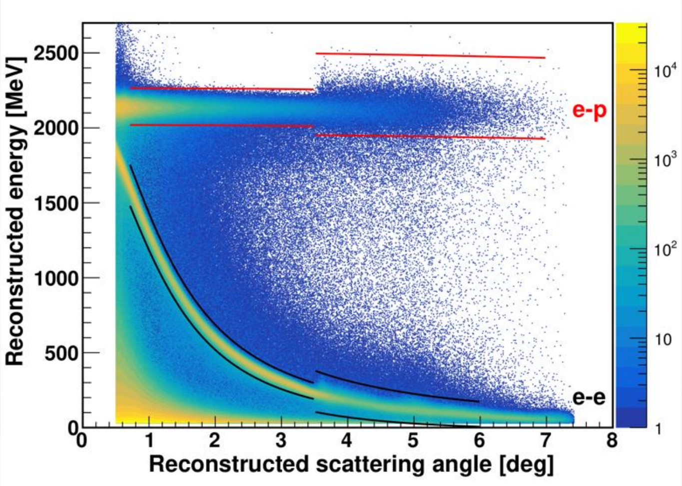

Three spectrometer facility of the A1 collaboration:

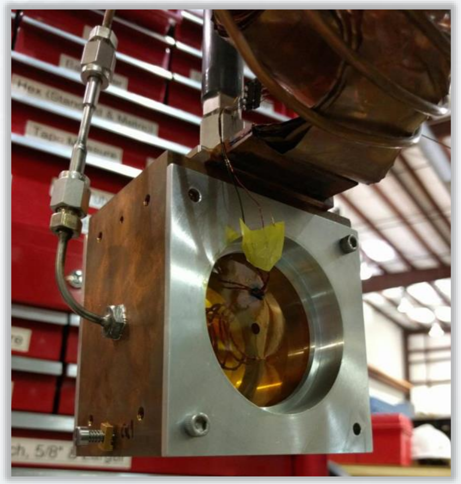
*J.C. Bernauer *Ph.D. Thesis*

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 $r_p = 0.831 \pm 0.014$ fm**







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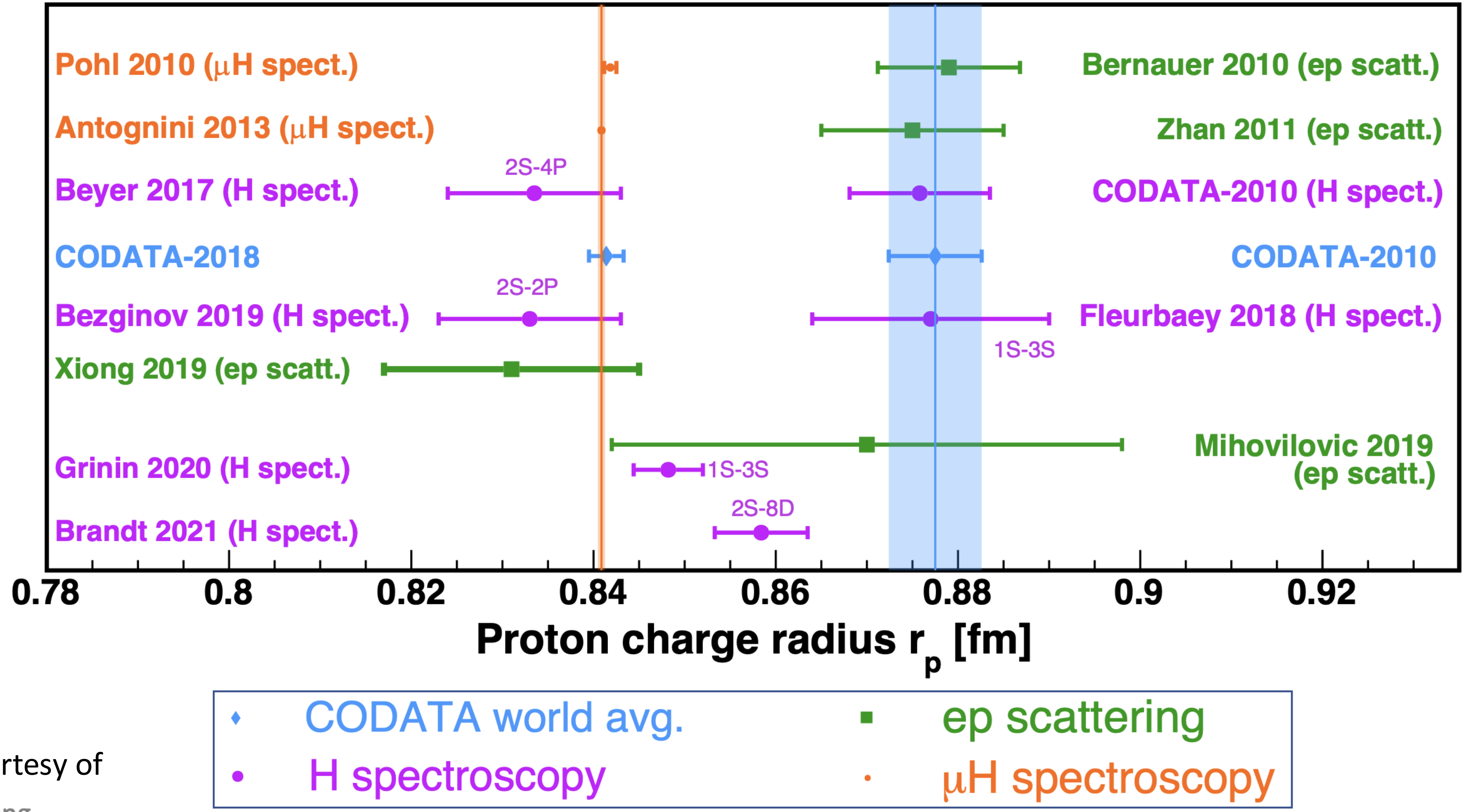
*X. Yan *et al. PRC* 98 (2018) **W. Xiong *et al. Nature* 98 (2019)

Is the puzzle resolved?

- It’s getting there
- The current consensus largely trends towards a small radius, but it’s not definitive
- New data and techniques will help

Proton Charge Radius Puzzle



Slide courtesy of

Weizhi Xiong

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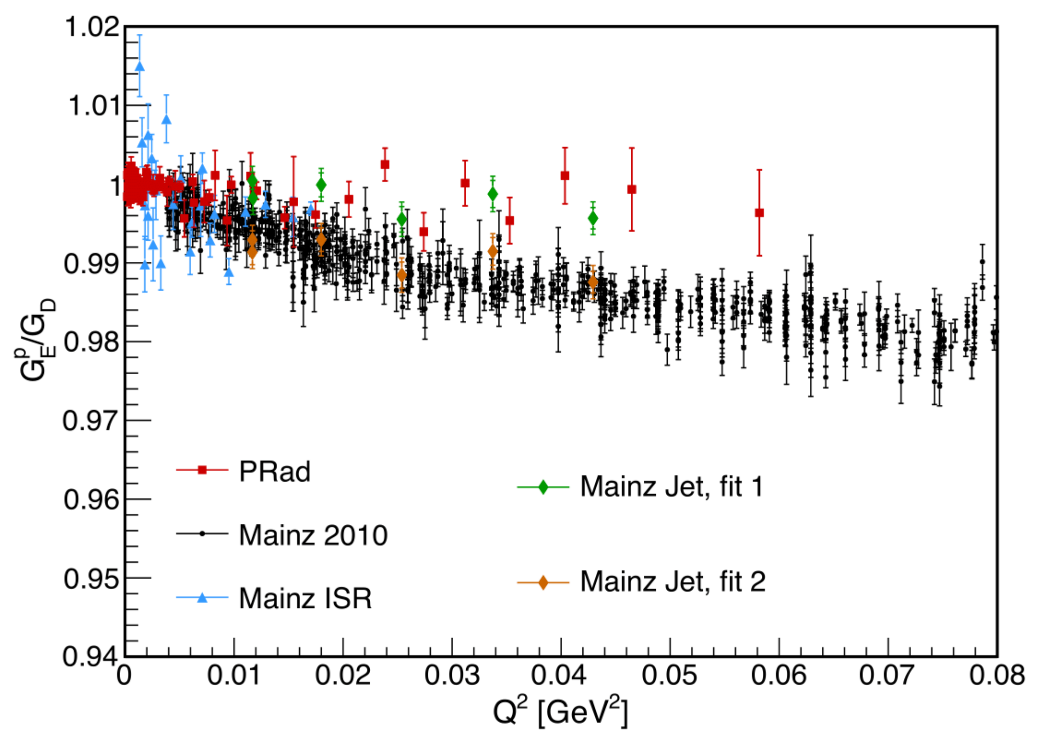
    - Why is there a form factor discrepancy between PRad and A1 results?

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

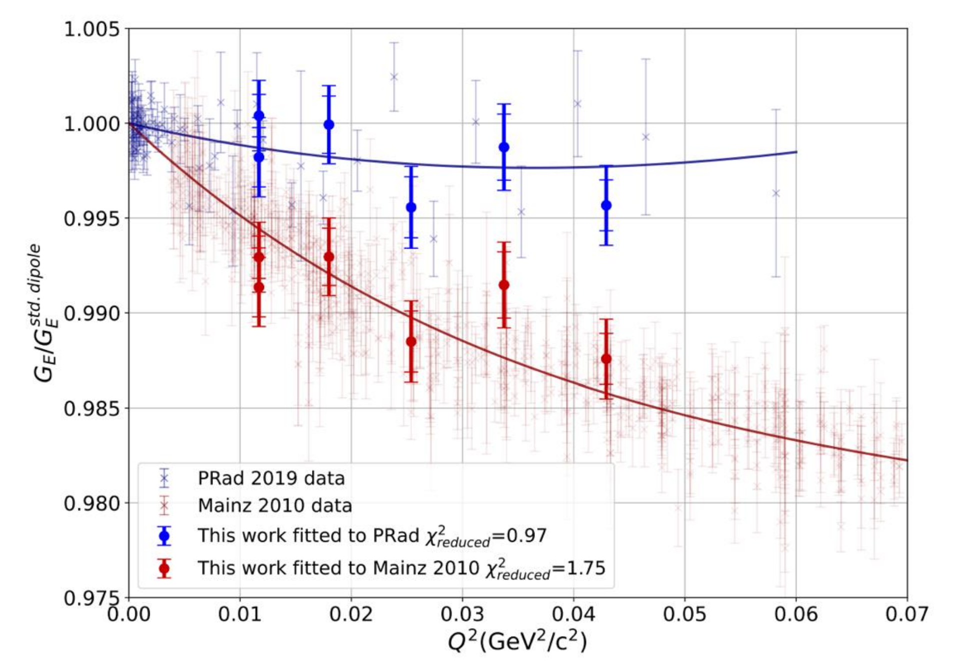


Figure from Y. Wang *et al. PRC 106* (2022)

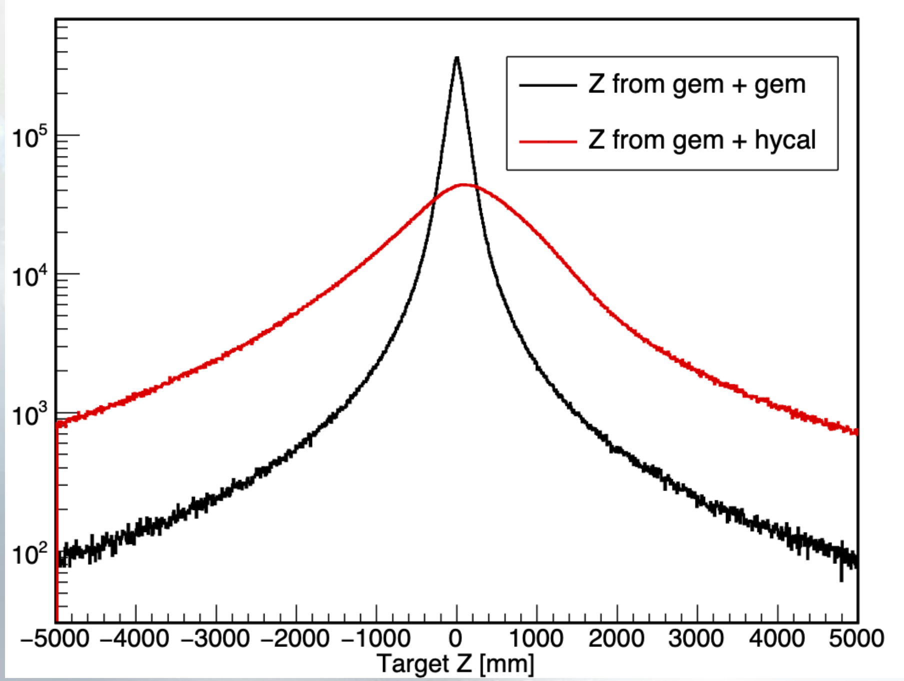
The PRad-II Experiment

What can we do to improve on PRad?

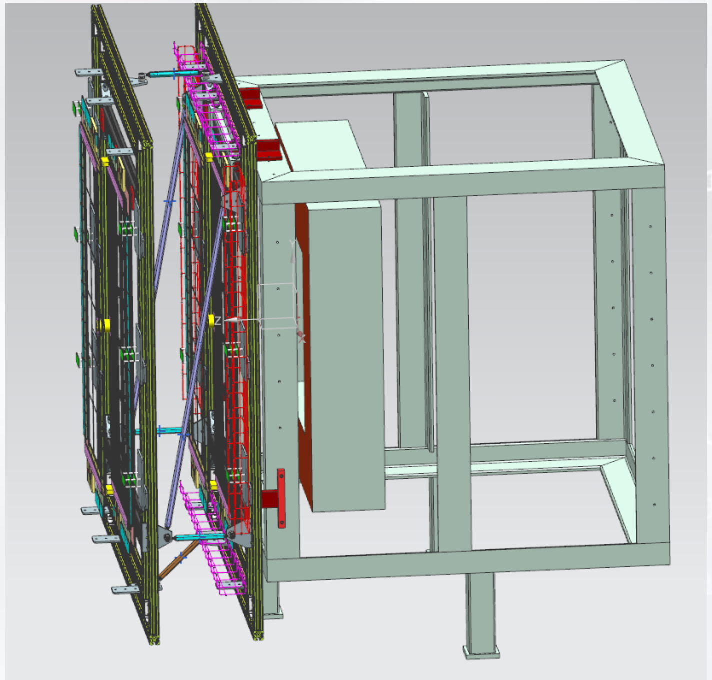
- Do it again, but better
- What were the tradeoffs with the first design and how can we reduce their impact?

The *Upgraded* PRad-II Spectrometer

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

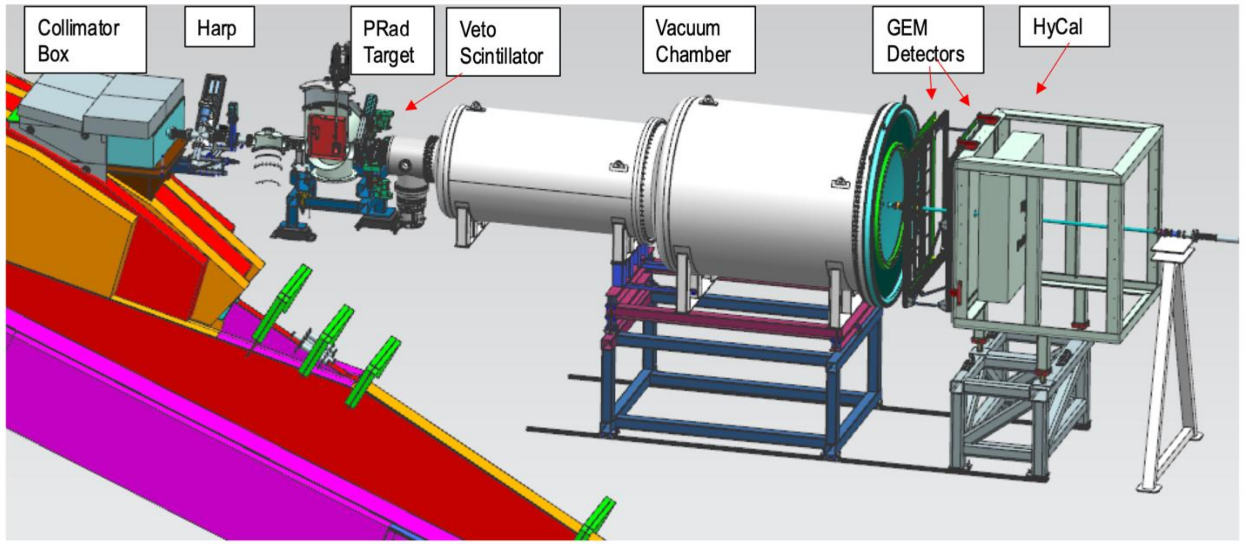


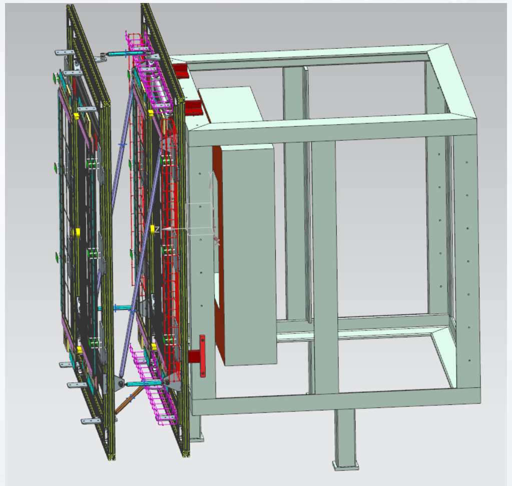
PRad target is 4 cm long



The *Upgraded* PRad-II Spectrometer

- *Two* GEM planes
    - Improved non-target background rejection
    - Improved Q^2 resolution
- Full DAQ and readout system upgrade
    - Reduced deadtime
    - Real-time cluster finding





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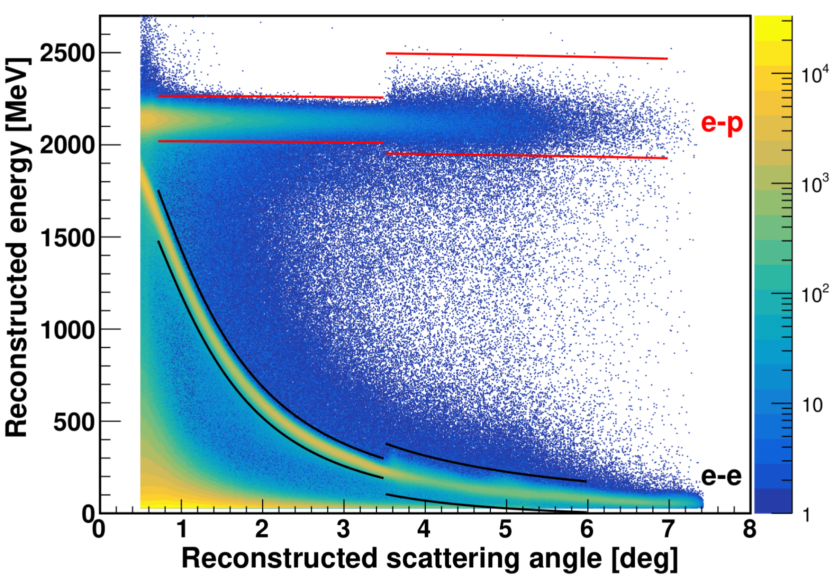
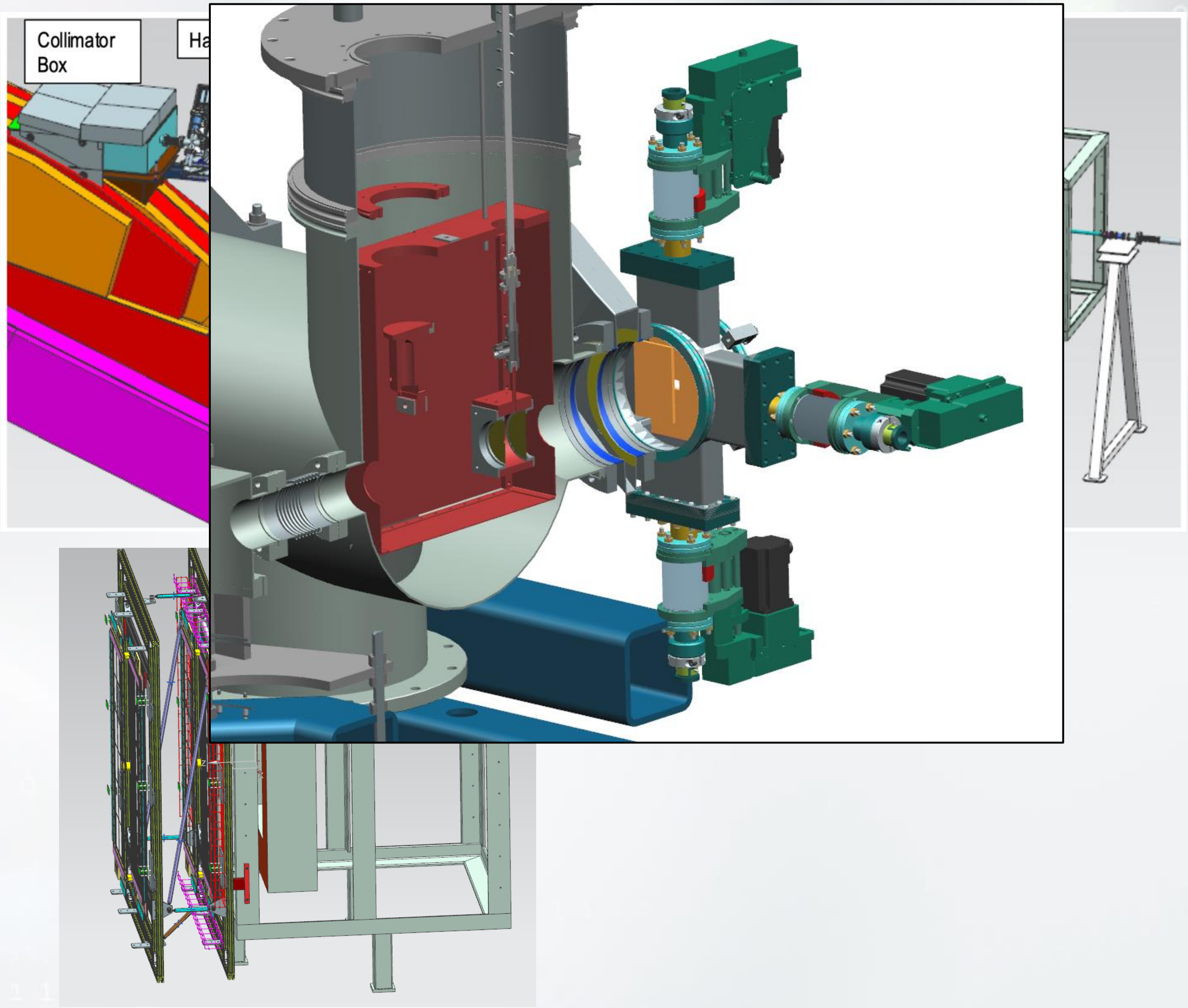
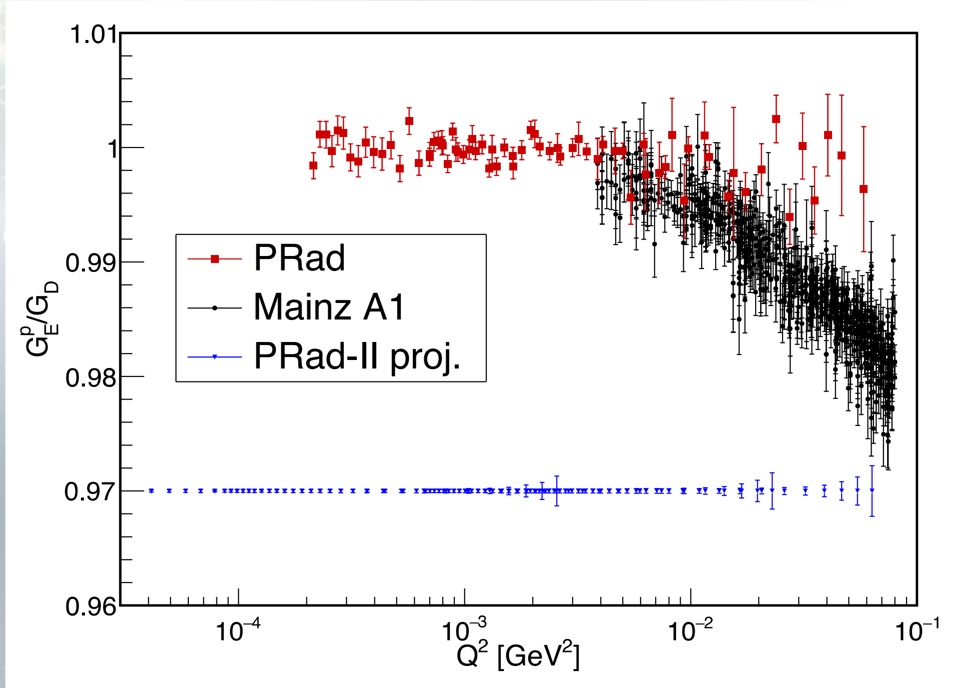
  - Improved non-target background rejection
  - Improved Q^2 resolution
- Full DAQ and readout system upgrade
  - Reduced deadtime
  - Real-time cluster finding
- New scintillator detector
  - Better separation of Møller events → Improved normalization





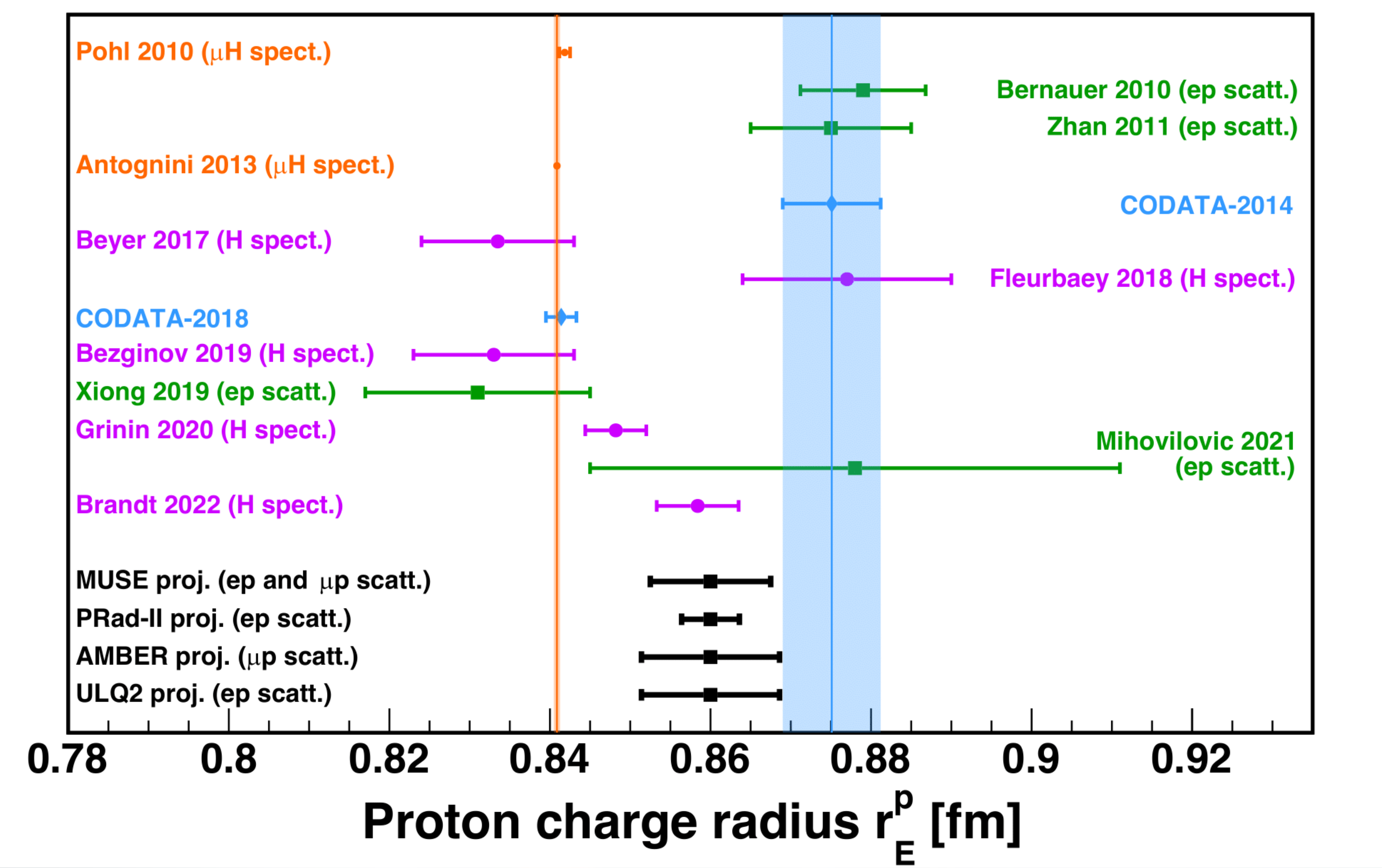
Kinematics and Projected Data

- Three beam energies: 0.7, 2.1, and 3.5 GeV
- Unprecedentedly low $Q^2 \sim 10^{-5}$ 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

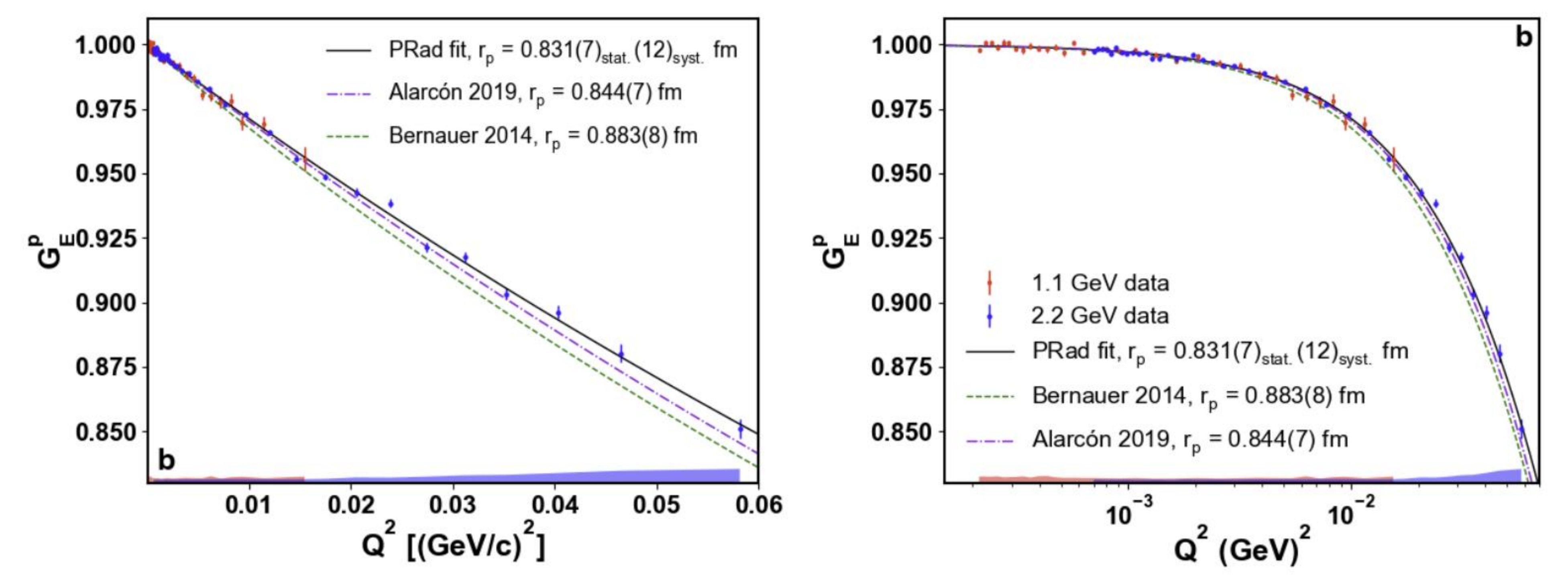
Projected Future Lepton Scattering Results



We have our data…
Now what?

We need to slope at 0 GeV^2

- 0 GeV^2 is the limit of “no scattering”
- We can’t get there, so we have to extrapolate
- How do you think we should do this?



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)

- Experiment design requires tradeoffs that are best assessed by having well defined goals

- PRad-II improves upon the successful PRad experiment
- PRad-II is actively running to better understand electron scattering results
- 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

QUESTIONS?