The proton radius puzzle: a status update

Jan C. Bernauer

LEES 2024, Sendai

Center for Frontiers in Nuclear Science
Stony Brook University

Dr. Bernauer is partially supported by NSF grants PHY 2012114/2412703

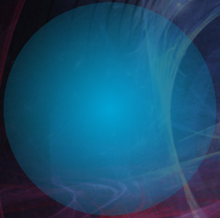
What is "stuff"?

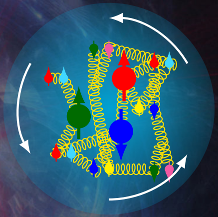
The matter around us is described by non-perturbative quantum chromodynamics. npQCD is hard.

Simplest QCD system to study: Protons

What is "stuff"?

The matter around us is described by non-perturbative quantum chromodynamics. npQCD is hard.
Simplest QCD system to study: Protons





100 years of protons!

What is "stuff"?

The matter around us is described by non-perturbative quantum chromodynamics. npQCD is hard.

Simplest QCD system to study: Protons

100 years of protons!

Proton is a composite system. It must have a size!

How big is it?

Three ways to measure the proton charge radius

- Normal hydrogen spectroscopy
- Muonic hydrogen spectroscopy
- Lepton-proton scattering

Elastic lepton-proton scattering

Method of choice: Lepton-proton scattering

- » Point-like probe
- » No strong force
- » Lepton interaction "straight-forward"

e^-

Cross section for elastic scattering

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}} = \frac{1}{\varepsilon\left(1+\tau\right)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

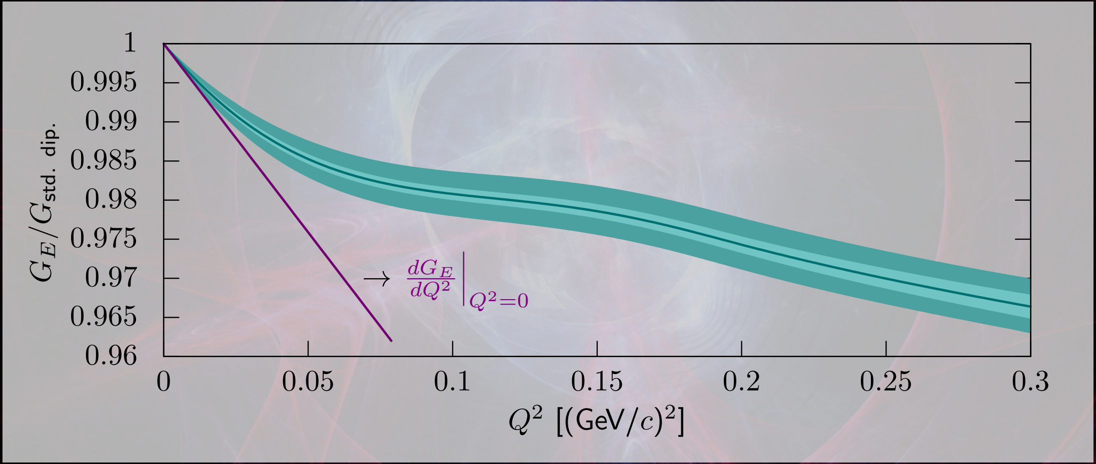
with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\left(1+\tau\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

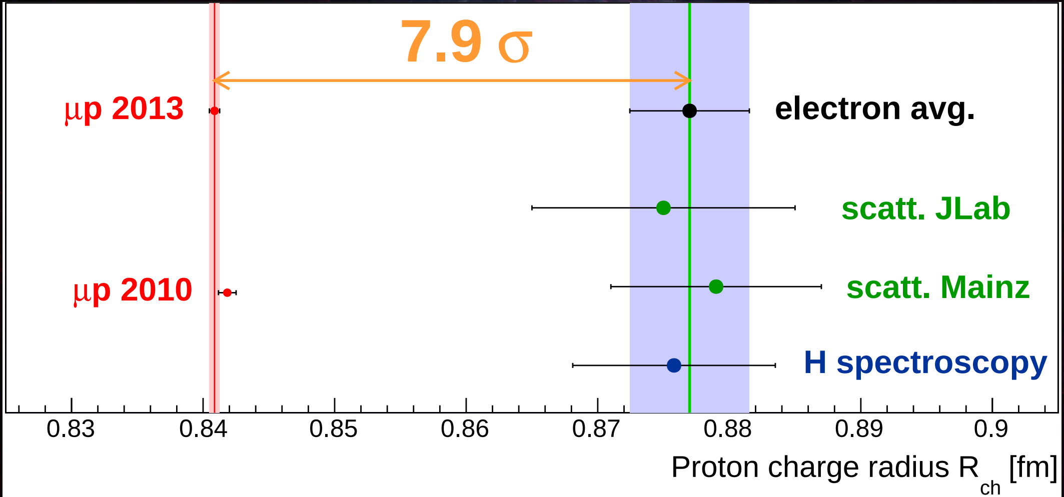
- Rosenbluth formula
- Electric and magnetic form factor encode the shape of the proton
- Fourier transform (almost) gives the spatial distribution, in the Breit frame

Proton radius from scattering

$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$



The Proton Radius puzzle



The Proton Radius puzzle

What's going on?

- Are we measuring the same thing: Yes! G. Miller, Phys. Rev. C 99, 035202
- Muon spectroscopy wrong?
  - Data is robust
  - A lot of theory required! Checked extensively.
- Electron data wrong?
  - Spectroscopy and scattering?
  - Data or theory? Or fit?
- BSM physics? Still alive and kicking, E.g.: Liu, Cloet, Miller Nucl. Phys. B 944 114638 (also explains $g_\mu - 2$)

The ~~face~~ puzzle that launched a thousand ~~ships~~ experiments

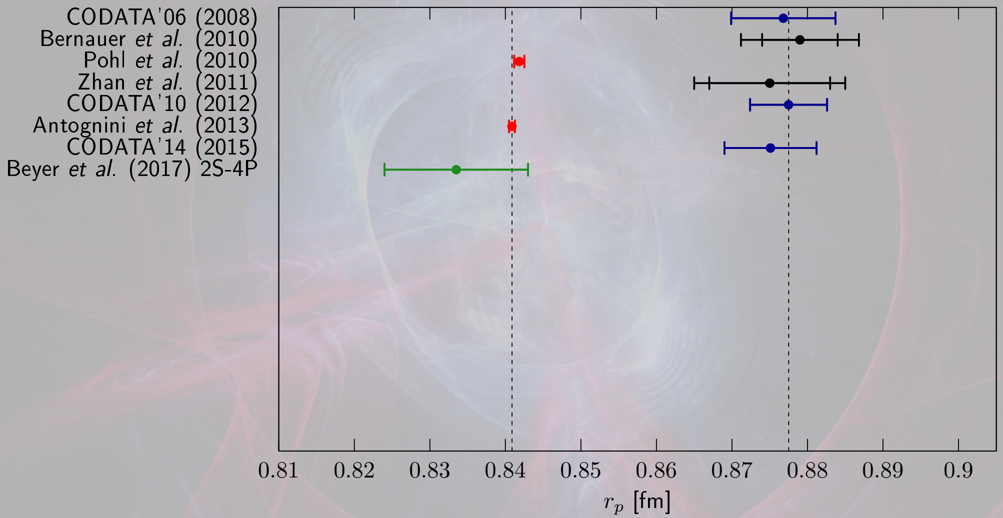
Spectroscopy:

- MPQ
- York University
- Paris
- + measurements on $d, {}^3He, {}^4He, \ldots$

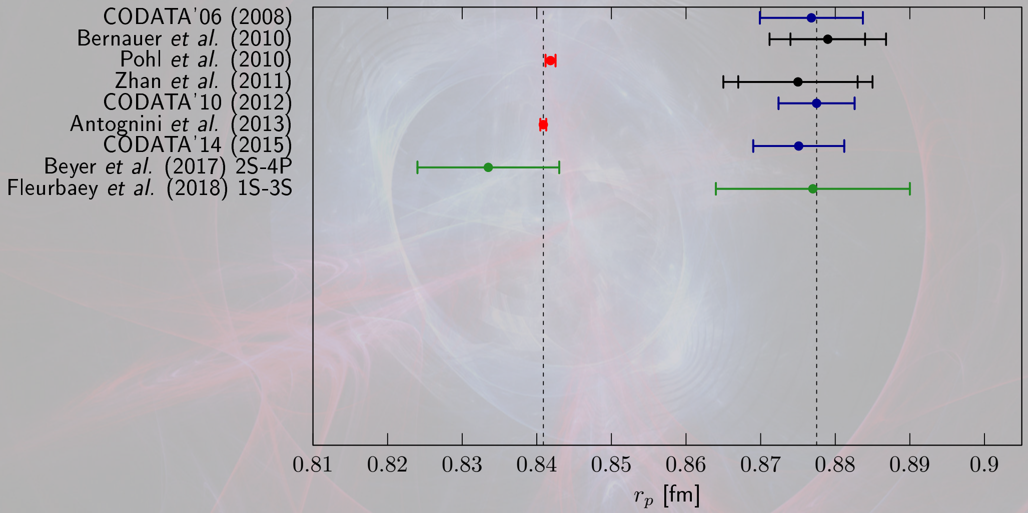
Scattering:

- PRad (Jefferson Lab)
- Mainz:
  - ISR,
  - Next-gen FF
- ULQ2 Sendai
- MUSE
- AMBER@CERN

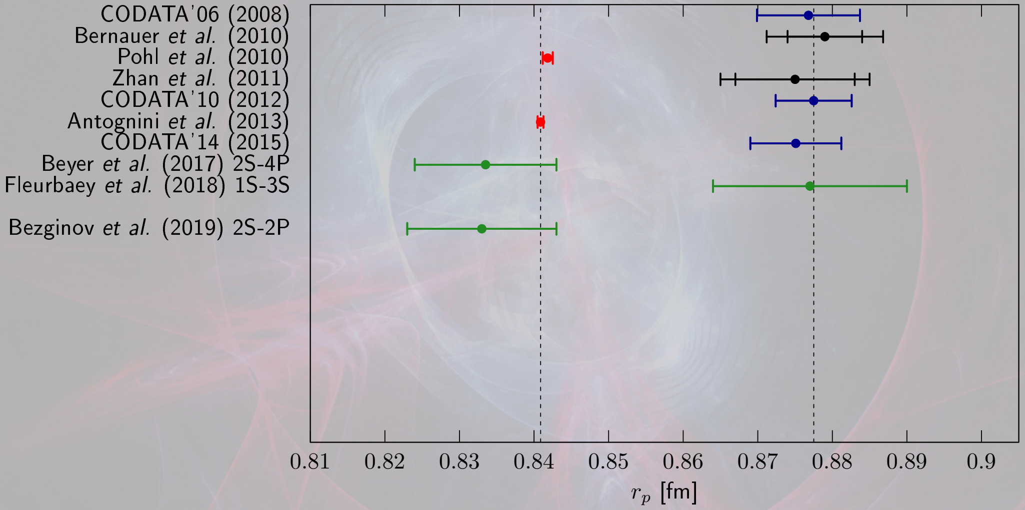
New results: MPQ (A. Beyer et al., Science 358, 79 (2017))



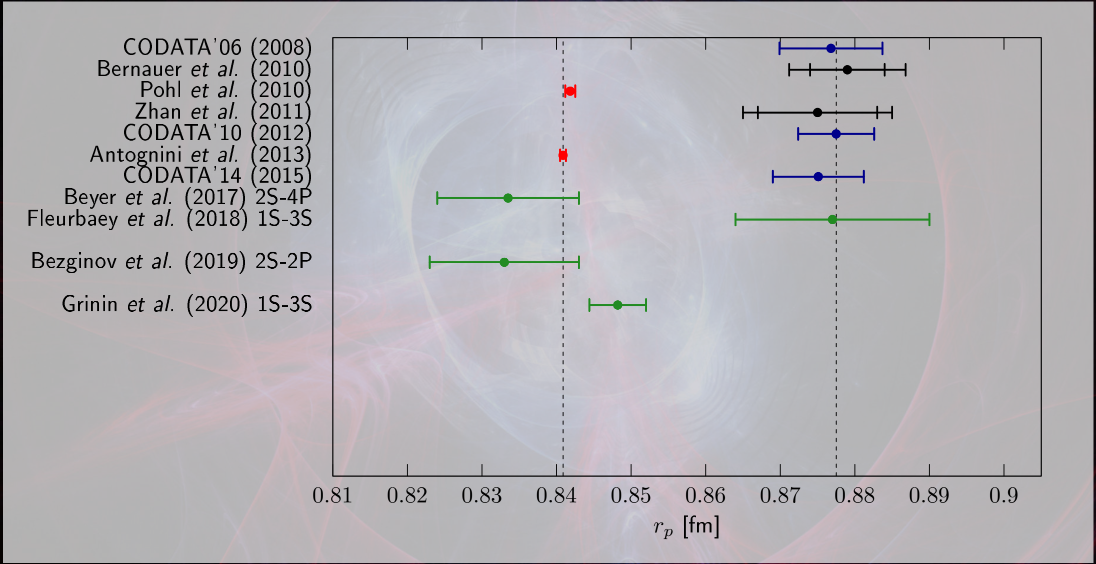
New results: Paris (Fleurbaey et al., Phys. Rev. Lett. 120, 183001 (2018))



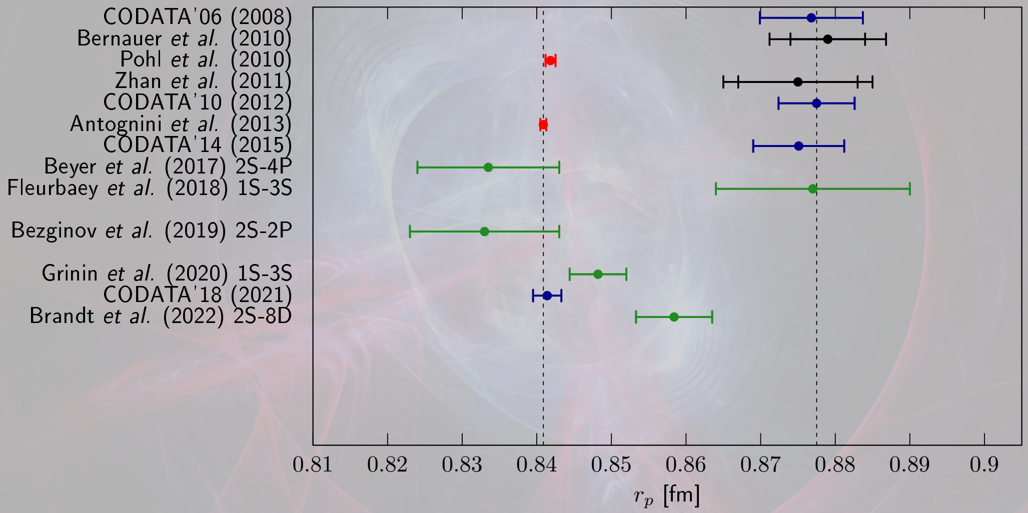
New results: York (Bezginov et al., Science 365, 1007–1012 (2019))



New results: MPQ again (Grinin et al., Science 370, 1061-1066 (2020))



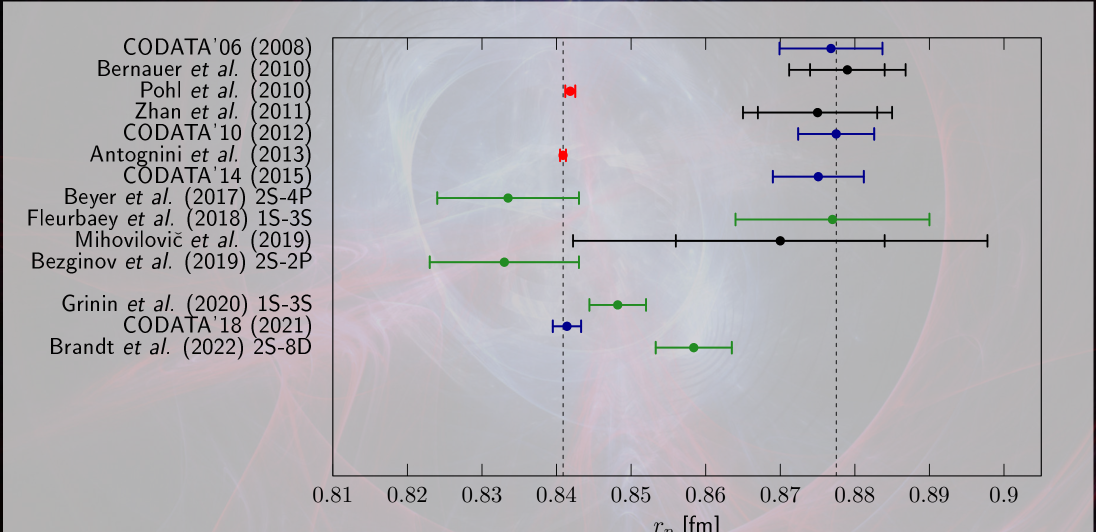
New results: CSU (Brandt et al., Phys. Rev. Lett. 128, 023001 (2022))



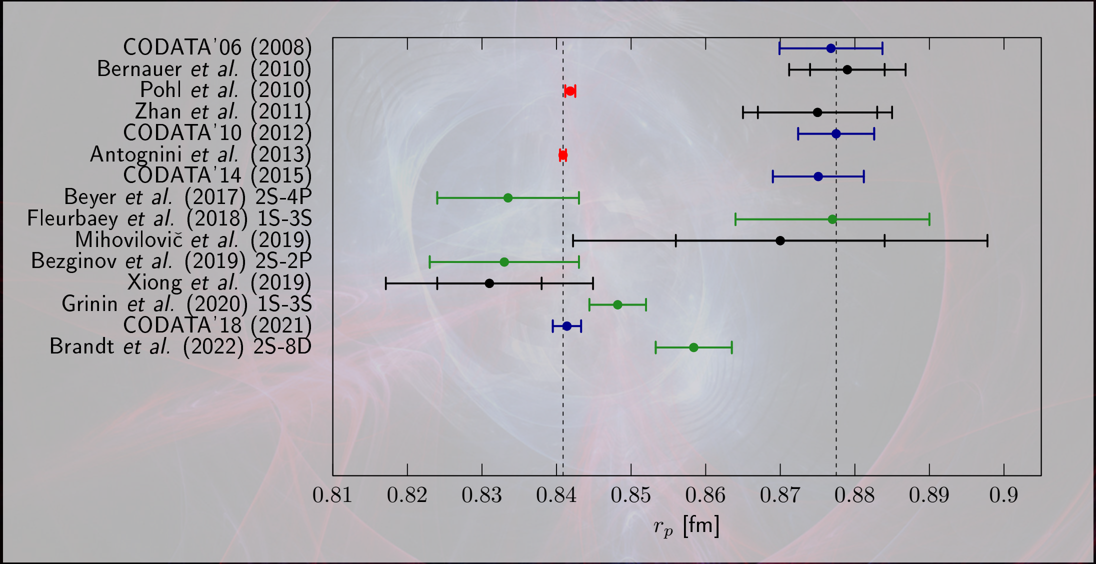
Focus for scattering: test extrapolation

- Require data at smaller Q^2
- How can we get to smaller Q^2?
  - Smaller scattering angle
  - Smaller beam momentum

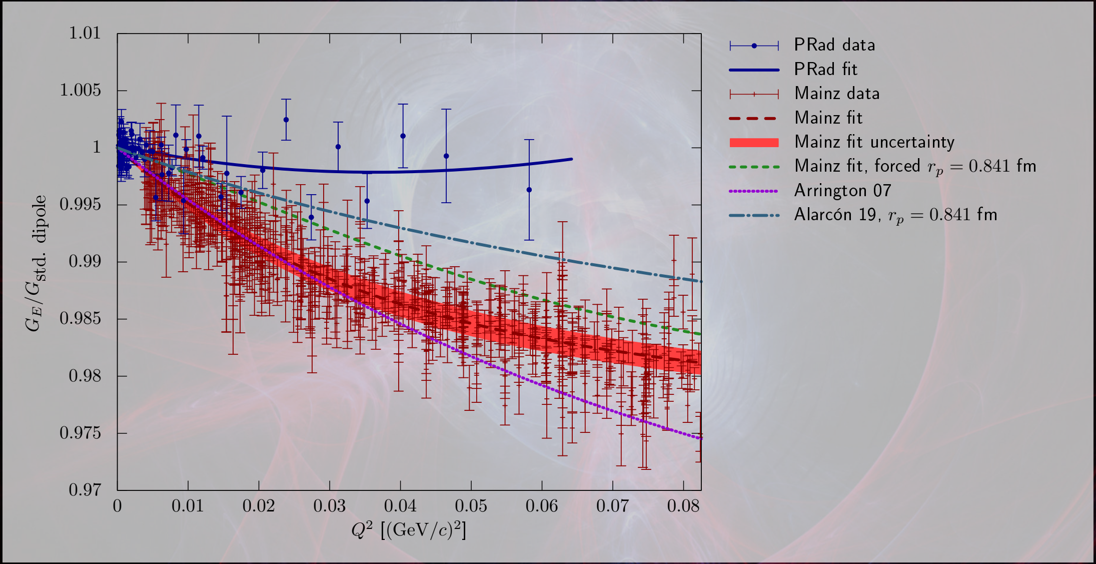
New results: Mainz ISR (Mihovilovič et al., Eur.Phys.J.A 57 (2021) 3, 107)



New results: PRad (Xiong et al., Nature 575 7781, 147-150 (2019))



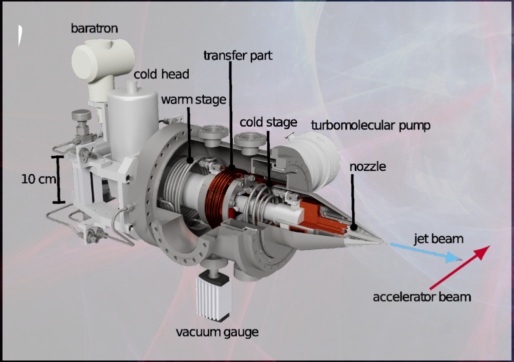
A new puzzle



$G_E/G_{\text{std. dipole}}$
1.01
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Q^2 [(GeV/c)^2]
PRad data
PRad fit
Mainz data
Mainz fit
Mainz fit uncertainty
Mainz fit, forced $r_p = 0.841$ fm
Arrington 07
Alarcón 19, $r_p = 0.841$ fm

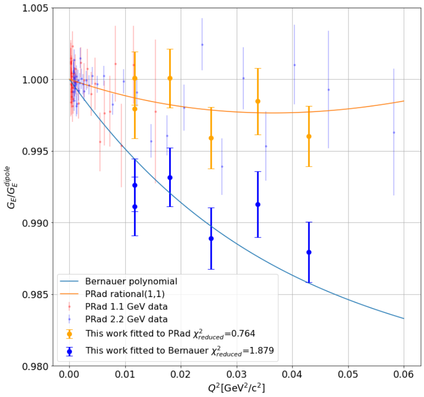
Upgraded target at Mainz

- Gas-Jet target: pure hydrogen target, point-like. Eliminate major background.
- Designed for MAGIX, but run at A1 as a prototype exp.



Upgraded target at Mainz

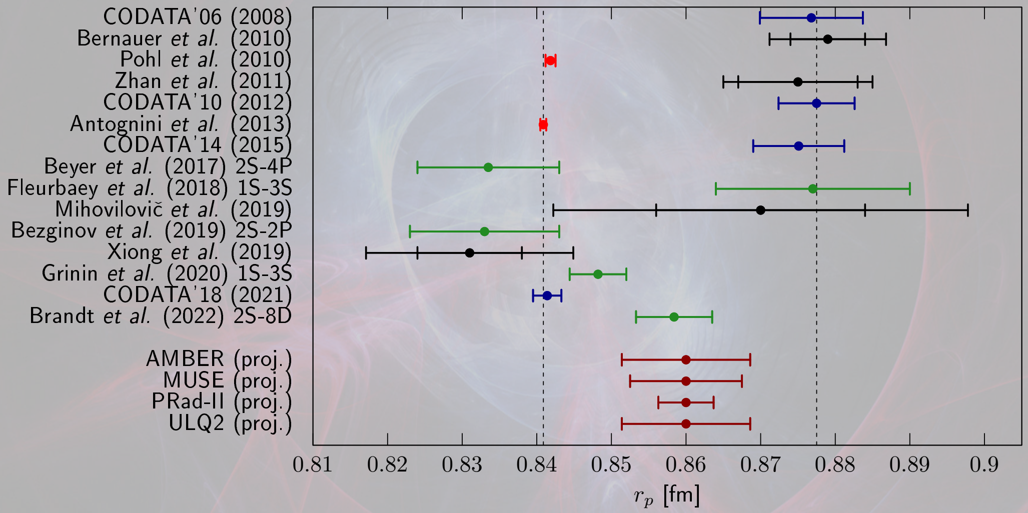
- Gas-Jet target: pure hydrogen target, point-like. Eliminate major background.
- Designed for MAGIX, but run at A1 as a prototype exp.
- COVID limited reach: Prefers PRad, but not decisive.



Ongoing/future experiments

- ULQ2@Sendai: *ep* with CH2 target. (see talks by Honda and Legris today at 11, 11:30)
- AMBER@CERN: μp, detecting proton, at many-GeV beam energies (see talk by Friedrich on Thursday at 3pm)
- MUSE@PSI: $e/\mu p$, direct lepton universality check (see talk by Kohl on Thursday at 2:30pm)
- PRad-II: larger momentum range (see talk by Xiong today at 10)
- MAGIX@MESA: gas-jet, also measure G_M and magnetic radius (see next talk)

Projections



Complementarity: Kinematical Regime

- Small Q^2
  - Large angles, small momentum. Also access G_M
  - Large momentum, small angle. $\epsilon = 1$, negligible G_M
- Tests different part of radiative corrections.
- N.B.: Size of radiative corrections do not inform uncertainty. Cancellations of two large corrections!

Complementarity

Exp	Regime				Comments
PRAD2@JLAB	small angle				
ULQ2@TOHOKU	large angle				
MAGIX@MESA	large angle				
AMBER@CERN	small angle				
MUSE@PSI	large angle				

Settings

- Cover Q^2 range. Always: different energies
- Angle coverage:
  - Large acceptance (“few”)
    - Need to control position dependence
  - Small acceptance (“many”)
    - Need to control time dependence

Complementarity

Exp	Regime	Settings			Comments
PRAD2@JLAB	small angle	few			
ULQ2@TOHOKU	large angle	many			
MAGIX@MESA	large angle	many			
AMBER@CERN	small angle	few			
MUSE@PSI	large angle	few			

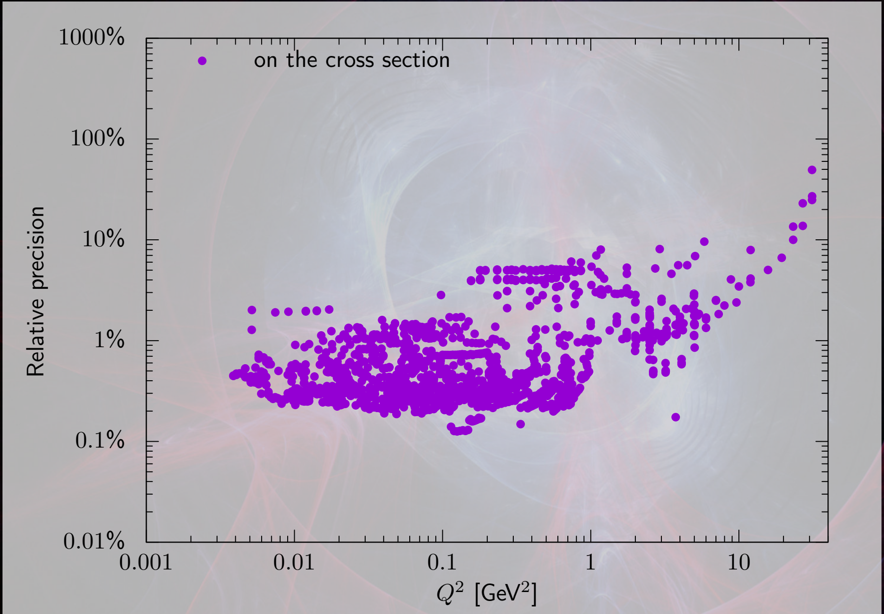
Particle types

- e/μ:
  - Muons: Different, typically smaller radiative corrections
  - Test lepton universality
- Antiparticles:
  - Test Two-Photon-Exchange and odd orders of radiative corrections. (believed to be understood, but large Q^2 TPE data different from Theory)

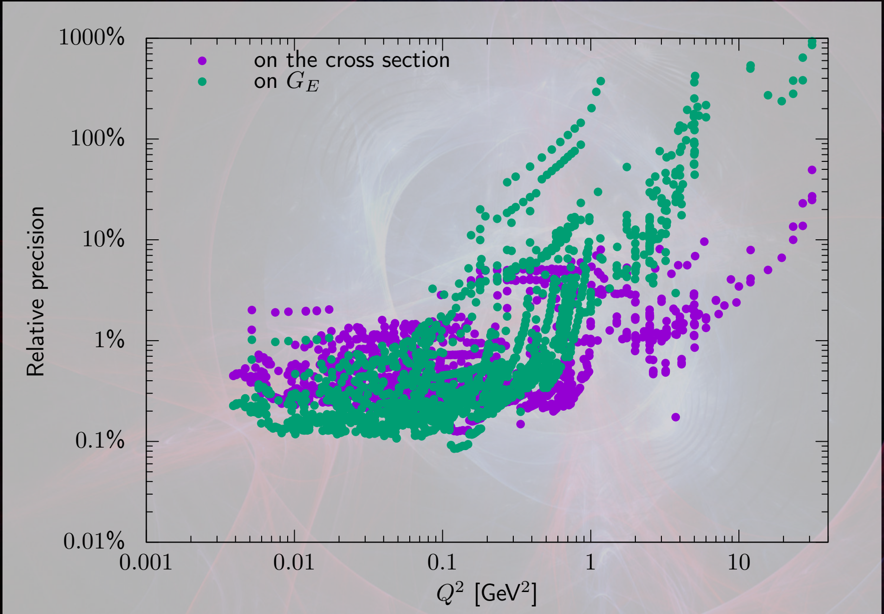
Complementarity

Exp	Regime	Settings	e/μ	Antiparticle	Comments
PRAD2@JLAB	small angle	few	e^-	no	
ULQ2@TOHOKU	large angle	many	e^-	no	G_M, light nuclei
MAGIX@MESA	large angle	many	e^-	no	G_M, light nuclei
AMBER@CERN	small angle	few	μ	yes	measure p!
MUSE@PSI	large angle	few	e/μ	yes	measure π

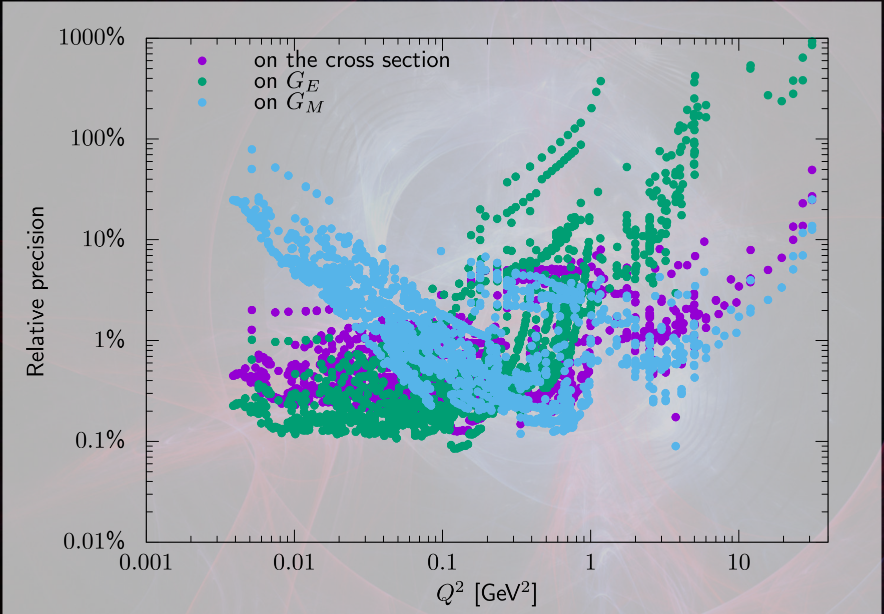
What do we know about G_M



What do we know about G_M

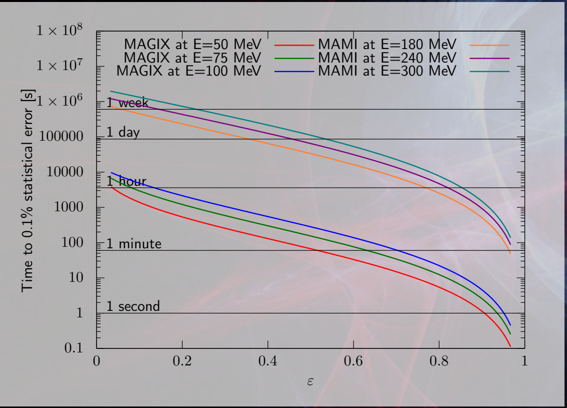


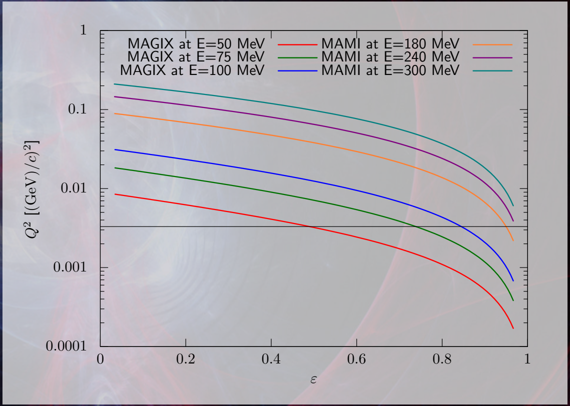
What do we know about G_M



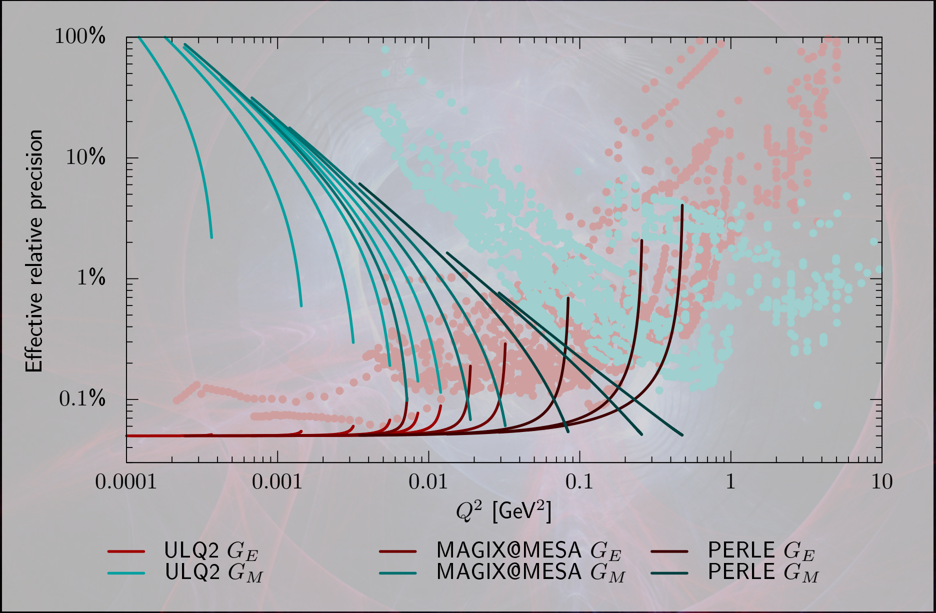
Mainz future plans

- Cluster jet target to kill major contributions to systematic errors
- Repeat ISR with new target (mainly G_E)
- Use new target also for classical approach





What we will know about G_M



Summary

» After 14 years, the puzzle still stands, but has changed shape

» Spectroscopy has many new results, mixed, but with weight behind the smaller radius

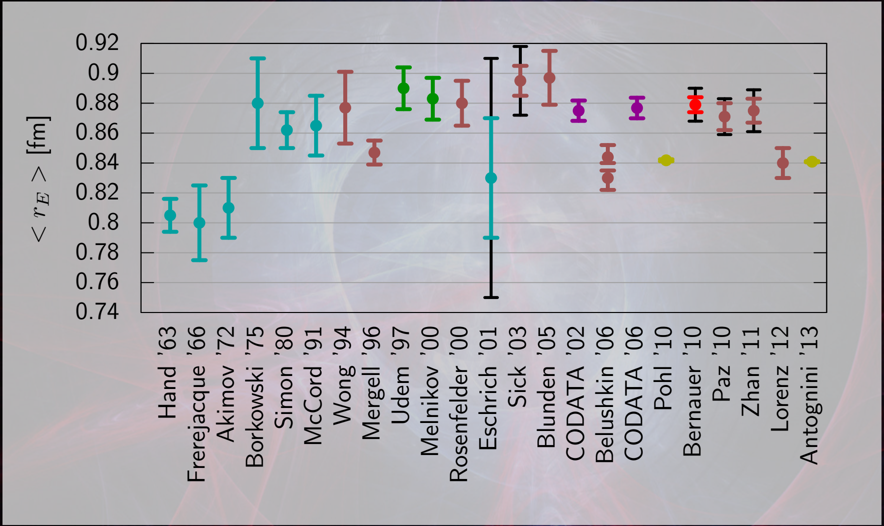
  » unknown what causes difference in spectroscopy results

» Scattering; Values disagreeing Situation still unclear

» More scattering data in the pipeline

» Don't forget about magnetic radius!

Timeline of proton radius results



Comments on some newer fitting results

2010: >0.870 Hill, Paz: old data, z expansion with disp. bounds

- Bounds on infinite exp. $\rightarrow$ bounds for truncated exp.?

2012: 0.840(10) Lorenz, Hammer, Meissner: Disp. relation fit.

- Same value but a lot more data. Probably model dominated.

2014: 0.84 Lorenz, Meissner: z expansion without bounds

- Fit did not converge. In real minimum, large radius is found.

2014: 0.8989(1) Gracyk/Juszczak: Bayesian estimation

- Interesting technique, unbelievable? small errors

2016: 0.84? Higinbotham: F-Test to select max. order

- Misunderstood F-test. Absence of proof $\neq$ proof of absence.

2016: 0.84? Horbatsch/Hessels/Griffioen/Carlson/Maddox... Low-Q

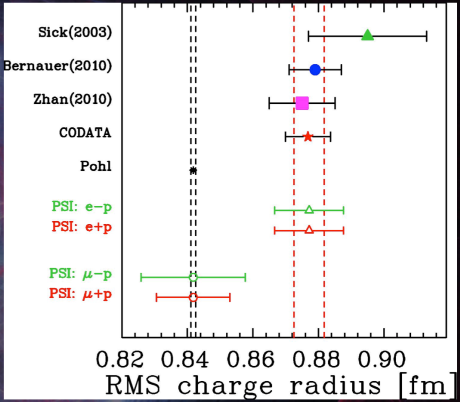
- Low-Q fits with low order don't work.

2018: XXX Yan/Higinbotham/...

- Small radius fraction finally does bias testing

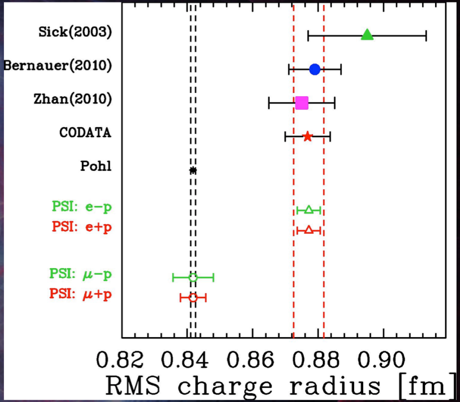
MUSE: Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.



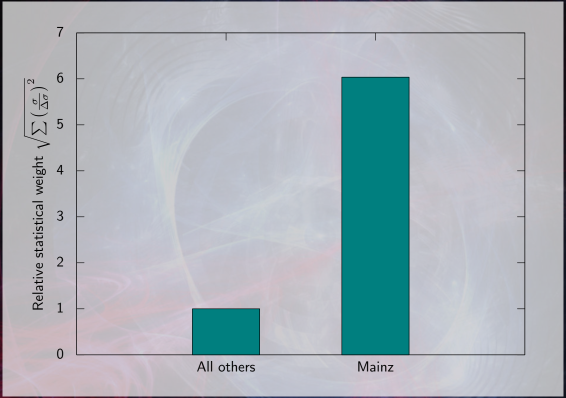
MUSE: Predicted performance

- Absolute radius extraction uncertainties similar to current exp's.
- Difference: Common uncertainties cancel!
- $\longrightarrow$ factor two more sensitivity

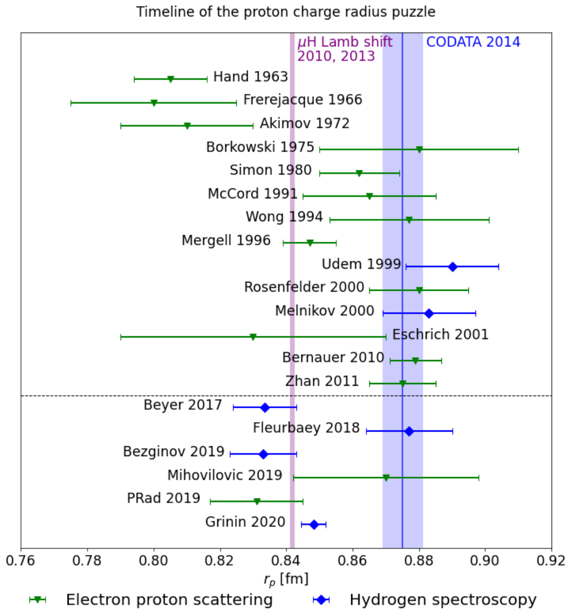


MUSE can verify 7σ effect with similar significance!

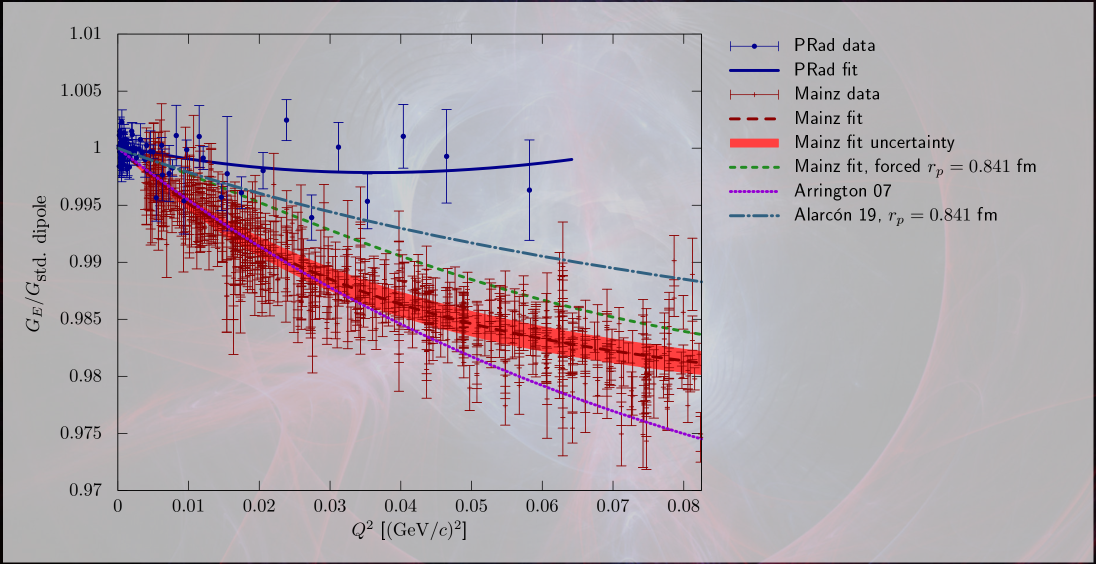
Mainz: Volume of Data



New results


Timeline of the proton charge radius puzzle
μH Lamb shift 2010, 2013
CODATA 2014
Hand 1963
Frerejacque 1966
Akimov 1972
Borkowski 1975
Simon 1980
McCord 1991
Wong 1994
Mergell 1996
Udem 1999
Rosenfelder 2000
Melnikov 2000
Eschrich 2001
Bernauer 2010
Zhan 2011
Beyer 2017
Fleurbaey 2018
Bezginov 2019
Mihovilovic 2019
PRad 2019
Grinin 2020
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
r_p [fm]
Electron proton scattering
Hydrogen spectroscopy

A different puzzle?



Magnetic form factor structures