The Proton Radius Puzzle and MUSE

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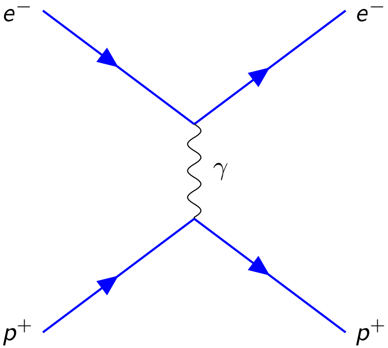
Measuring the Proton Radius with Elastic Scattering

Historically r_p measured via ep scattering

$(\frac{d\sigma}{d\Omega})_{red} = \frac{\tau}{\epsilon(1+\tau)}[G_M^2(Q^2) + \frac{\epsilon}{\tau}G_E^2(Q^2)]$

- G_E related to charge distribution, $G_E(0) = 1$
- G_M related to magnetic distribution, $G_M(0) = \mu_p$

$$\langle r_p^2 \rangle \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

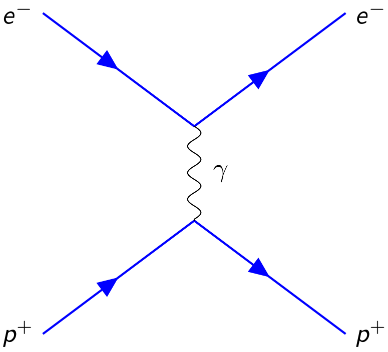


Measuring the Proton Radius with Elastic Scattering

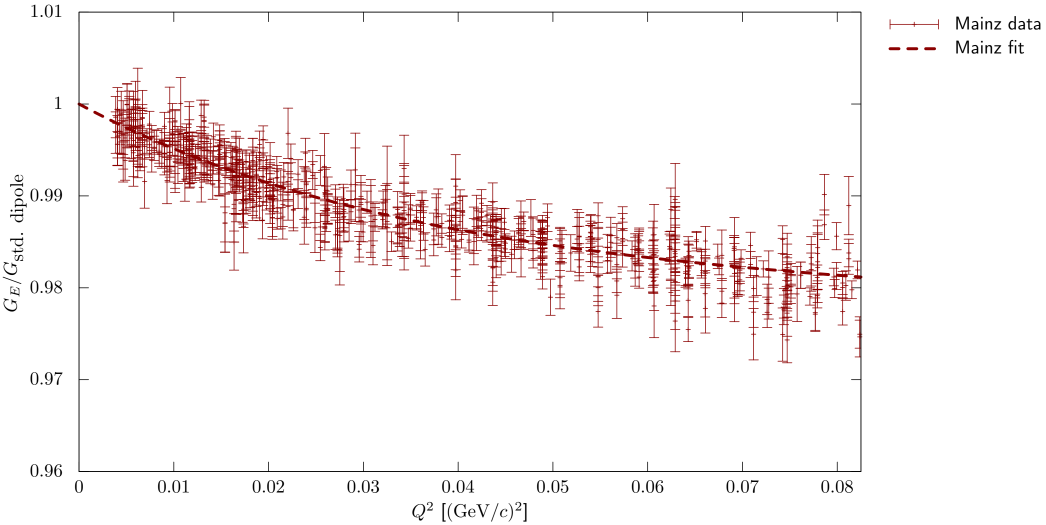
For elastic scattering, with a known beam energy, we only have one independent variable, Q^2

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

- Q^2 totally determined by θ
- At low Q^2 measuring θ determines $G_E(Q^2)$
- $G_M(Q^2)$ enters into cross section $\propto Q^2$

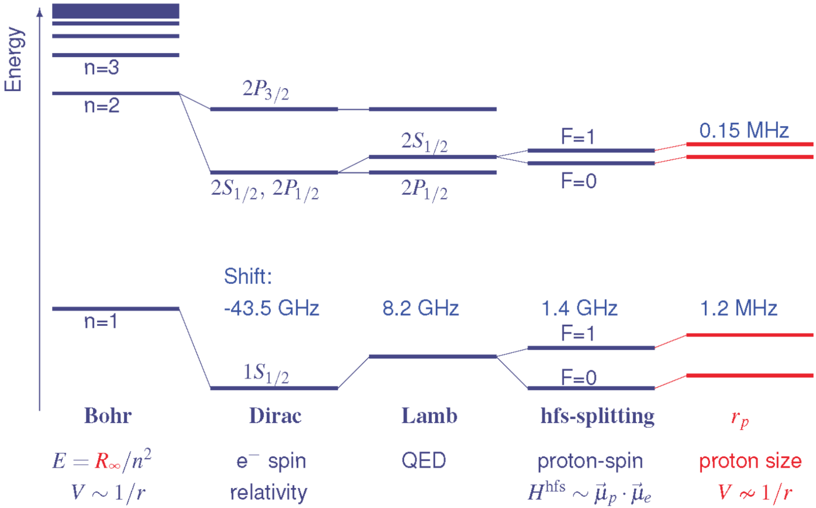


Extracting the Proton Radius



Sample G_E behavior

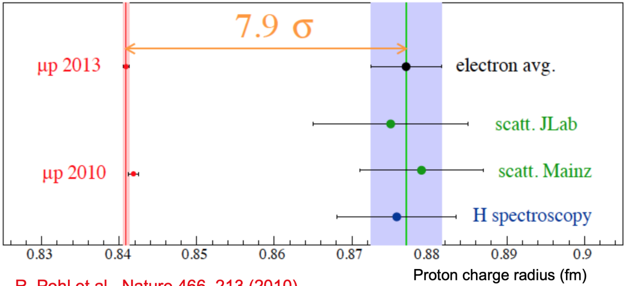
Spectroscopic Measurements



Energy levels in Hydrogen

The Original Proton Radius Puzzle

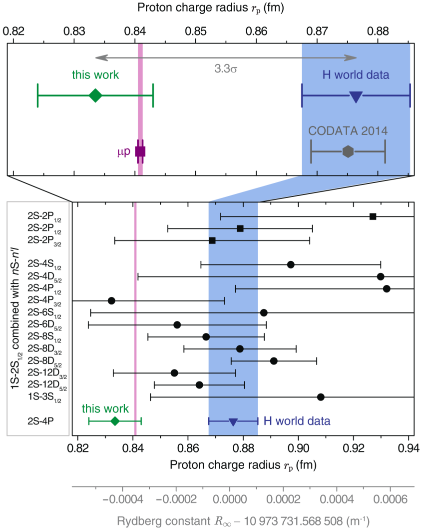
electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)
muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

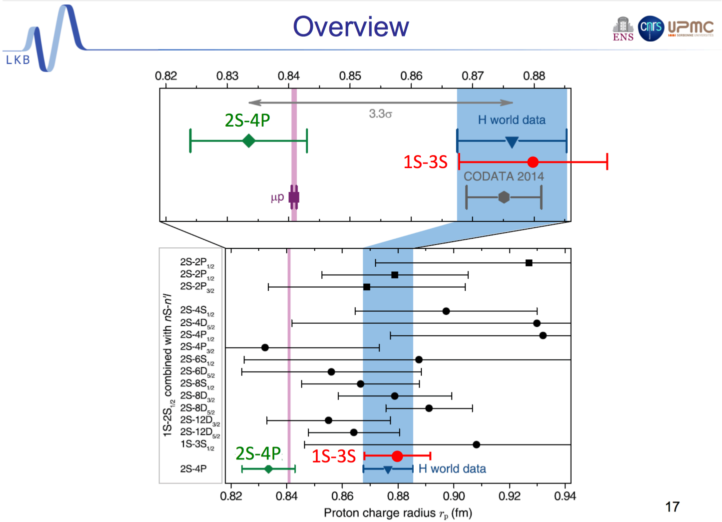
"Although the uncertainty of the muonic hydrogen value is significantly smaller than the uncertainties of these other values, its negative impact on the internal consistency of the theoretically predicted and experimentally measured frequencies . . . was deemed so severe that the only recourse was to not include it in the final least-squares adjustment on which the 2010 recommended values are based." - https://physics.nist.gov/cuu/Constants/Preprints/lsa2010.pdf

The Garching Result



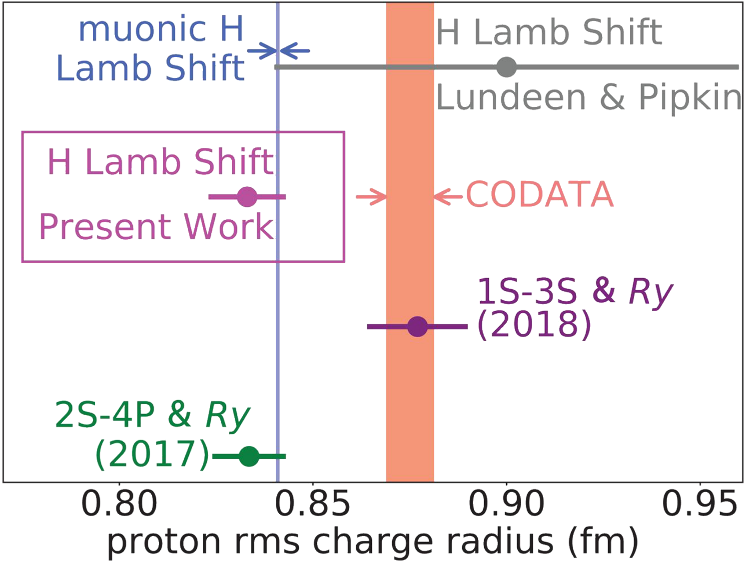
A. Beyer *et al.*, Science 358, 79 (2017)

The Paris Result



Fleurbaey *et al.*, Phys. Rev. Lett. 120, 183001 (2018)

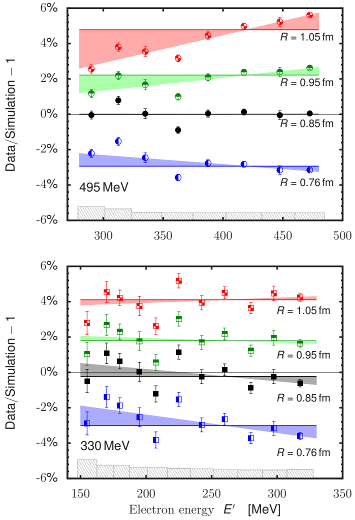
The York Result



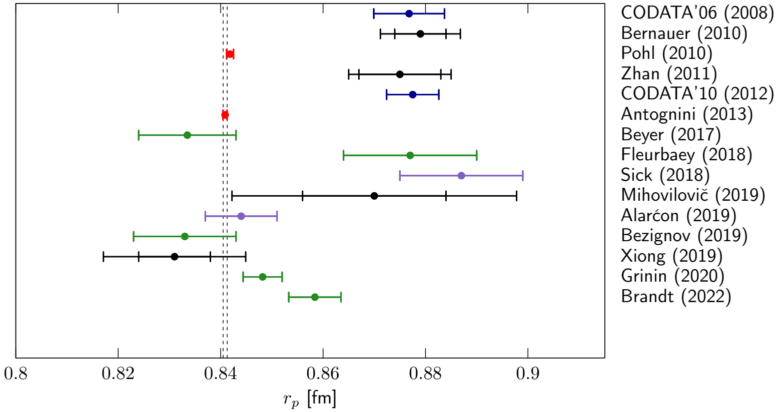
Bezginov *et al.*, Science 365, 6457 1007-101 2019

ISR @ MAMI

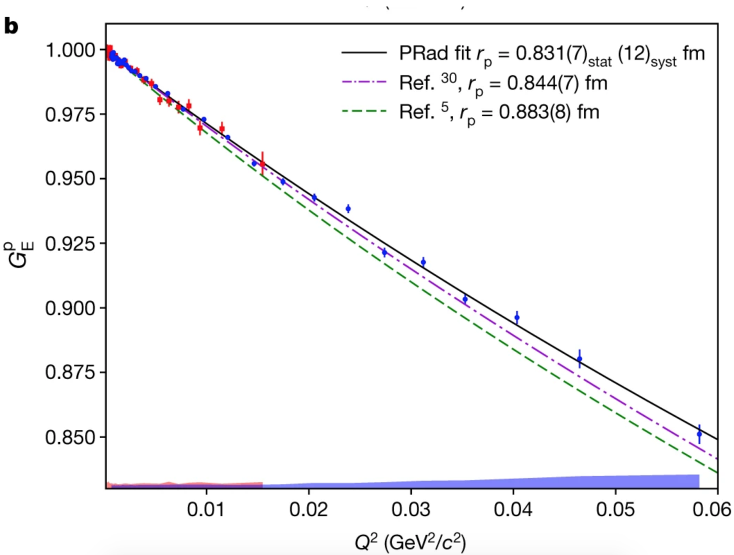
- Miha Mihovilovič, *et al.*
- Published: PLB 771:194-198
- Updated version on arXiv:1905.11182
- $r_p = 0.870 \pm 0.014_{stat} \pm 0.024_{sys} \pm 0.003_{mod}$ fm
- Follow up experiment planned



The Puzzle Deepens

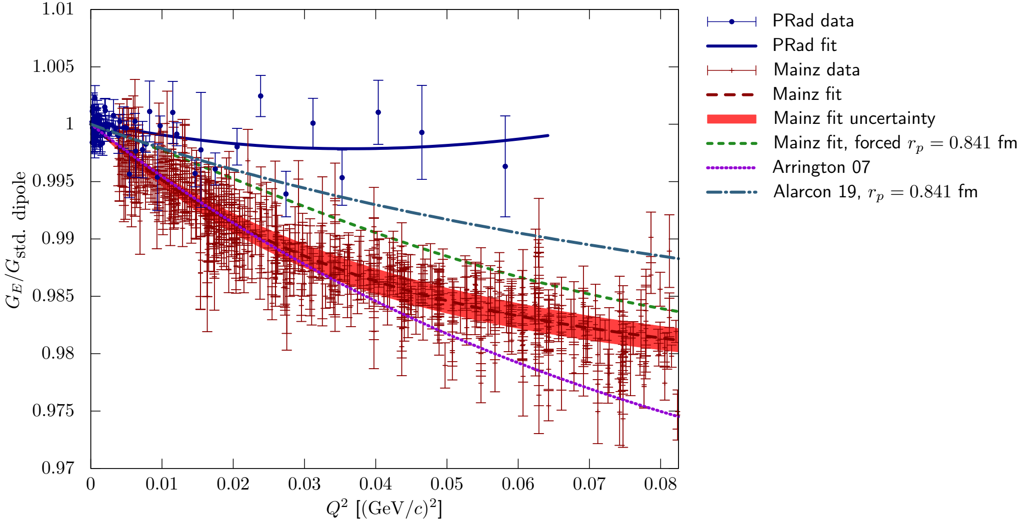


An Aside on PRad



W. Xiong, *et al.*, Nature, 2019

PRad Compared to Mainz



What's the Next Experiment?

r_p (fm)	ep	μp
Spectroscopy	0.877 ± 0.007	0.841 ± 0.0004
Scattering	0.875 ± 0.006	**??**

- No high precision muon-proton scattering experiment to date
- Highly desirable to perform another electron-proton scattering experiment
- Measure two-photon exchange in muons and electrons
- MUSE!

MUSE

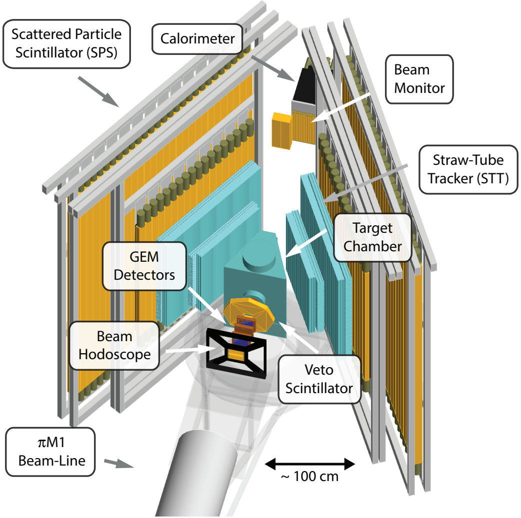
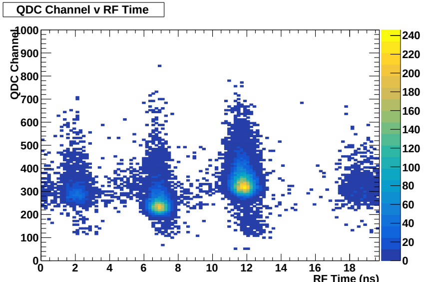


Figure from S. Strauch

- Secondary beam line
- Measure incoming beam event by event
- Beam contains e's, μ's, and π's
- Can select positive or negative charge polarities
- Veto to reject beam halo and decay events
- Use RF signal for PID via TOF
- Veto π's in the trigger



Kinematics of MUSE

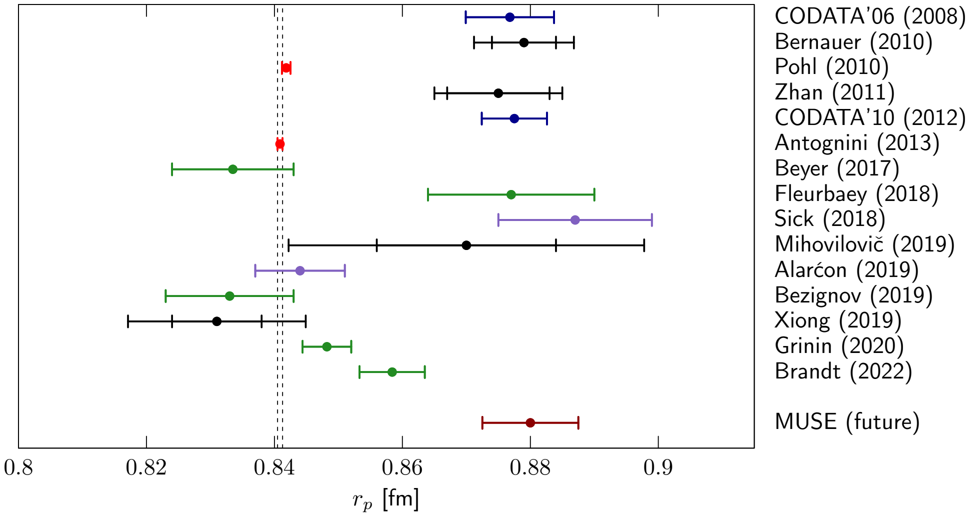
Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle range	20° - 100°
Azimuthal coverage	30% of 2π typical
ε	0.26 – 0.94
Q^2 range for electrons	0.0016 GeV^2 - 0.0820 GeV^2
Q^2 range for muons	0.0016 GeV^2 - 0.0799 GeV^2

- Simultaneous elastic ep and μp scattering $\rightarrow$ can test lepton universality
- Can measure both lepton charge polarities $\rightarrow$ direct test of two photon exchange effect
- Some systematic uncertainties cancel in comparisons
- Precisely capture difference in cross sections and in radii

Physics Coverage of MUSE

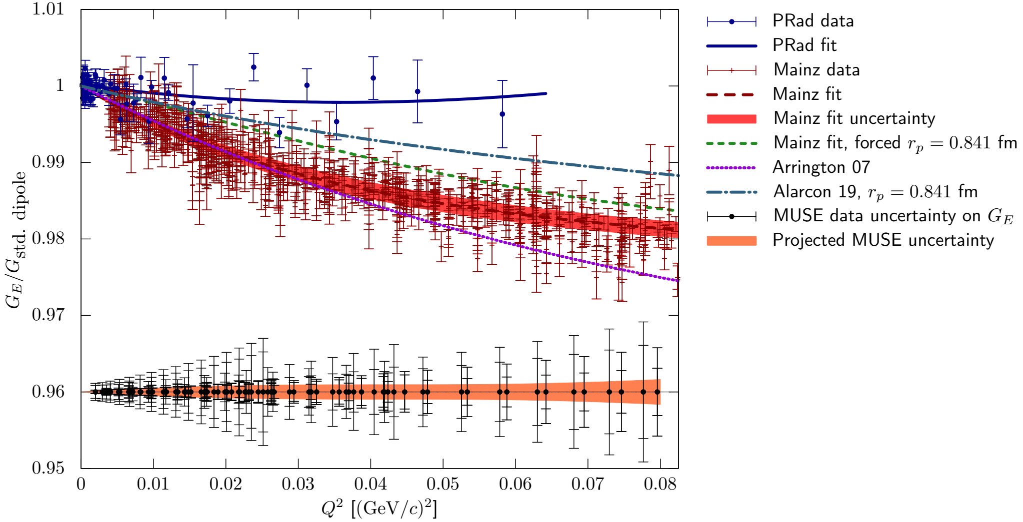
- First high precision measurement of μp scattering for TPE and at precision necessary to inform PRP
- Direct comparison between *ep* and μp scattering at cross section level to test rad. corr. and lepton universality
- Low energy πp scattering important for χPT
- Search for $\sigma(\pi^+ p)/\sigma(\pi^- p)$ resonances

Projected Resolution of MUSE



MUSE value arbitrarily placed at 0.88 fm for visualization

Comparing PRad and MUSE

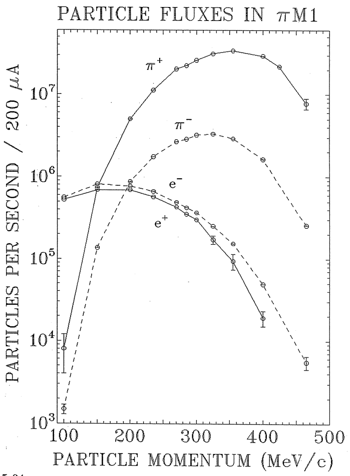


Thank You!

Questions?

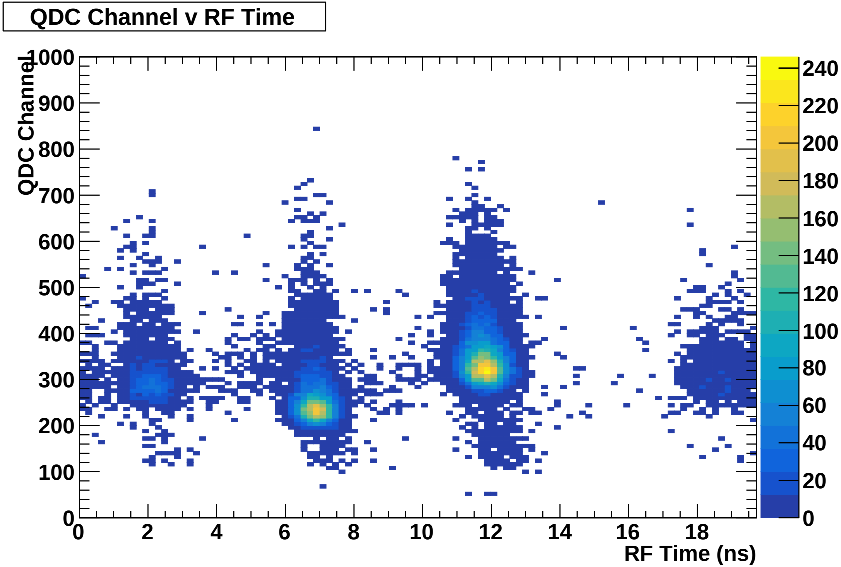
Back up

Particle Flux



Time: 30–JUN–87 18:35:01

RF V QDC



QDC Channel v RF Time
QDC Channel
RF Time (ns)
0
100
200
300
400
500
600
700
800
900
1000
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240

PiM1 TRANSPORT