The proton radius puzzle – 9 years later

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FCCP, August 2019

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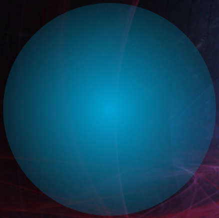
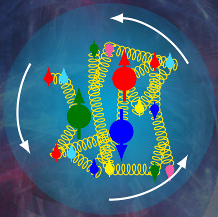
What is "stuff"?

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





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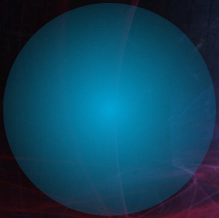

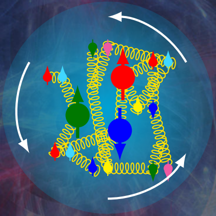

100 years of protons!

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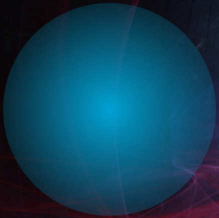
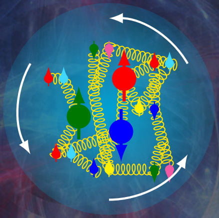
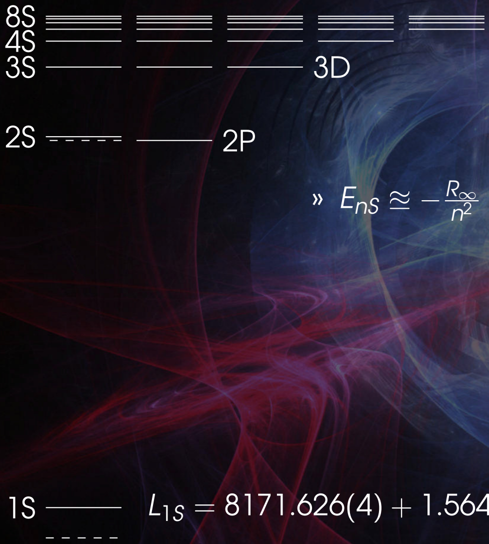




100 years of protons!
Proton is a composite system. It must have a size!

How big is it?

Motivation: "Normal" Hydrogen Spectroscopy



» $E_{nS} \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$

$$L_{1S} = 8171.626(4) + 1.5645 \left\langle r_p^2 \right\rangle \text{ MHz}$$

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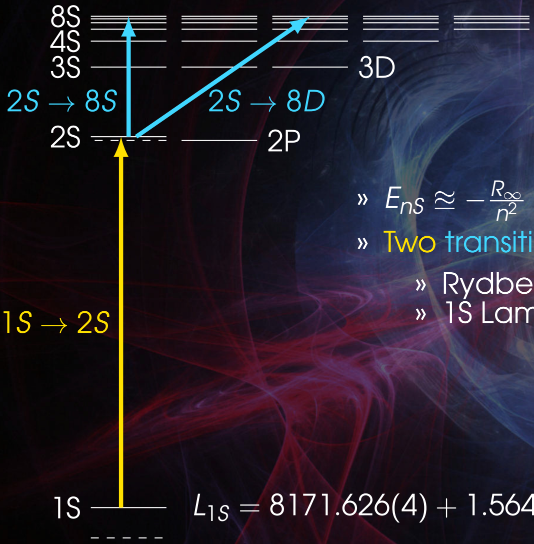

- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius

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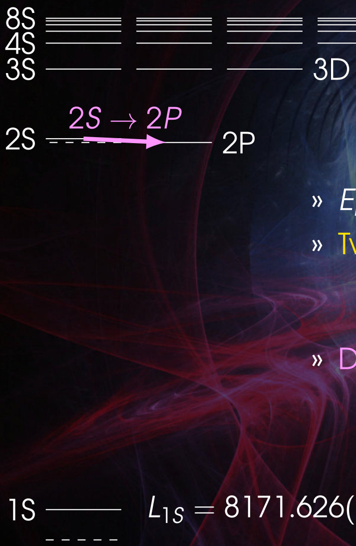


» $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$

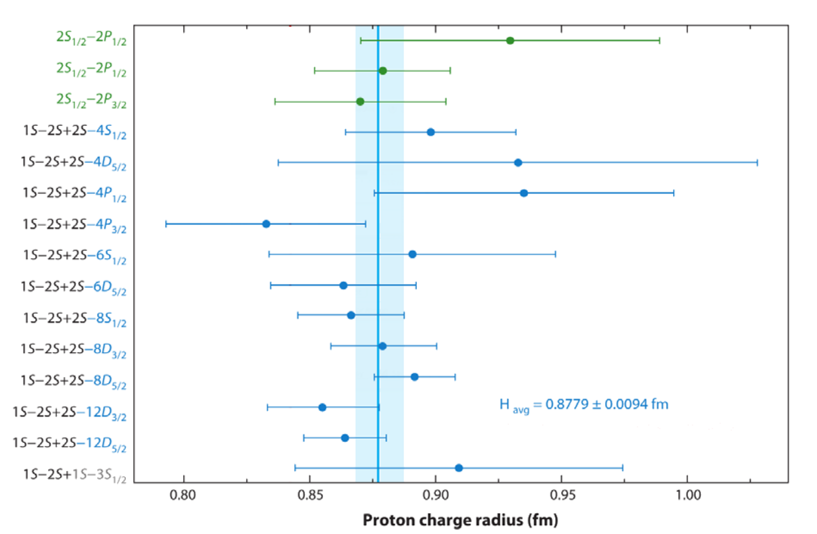
» Two transitions for two unknowns:

  » Rydberg constant R_∞
  » 1S Lamb shift $\Longrightarrow$ radius

» Direct Lamb shift $2S \rightarrow 2P$

$$L_{1S} = 8171.626(4) + 1.5645 \langle r_p^2 \rangle \text{ MHz}$$

“Normal” Hydrogen Spectroscopy Results



Elastic lepton-proton scattering

Method of choice: Lepton-proton scattering

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

e^-

Measure cross sections and reconstruct form factors.

Cross section for elastic scattering

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

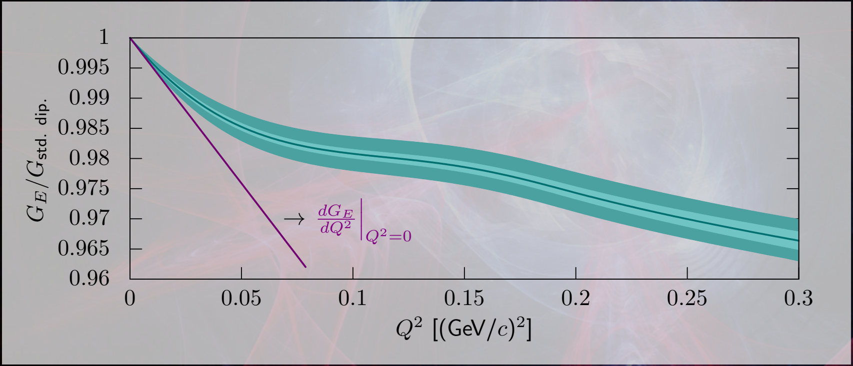
with:

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

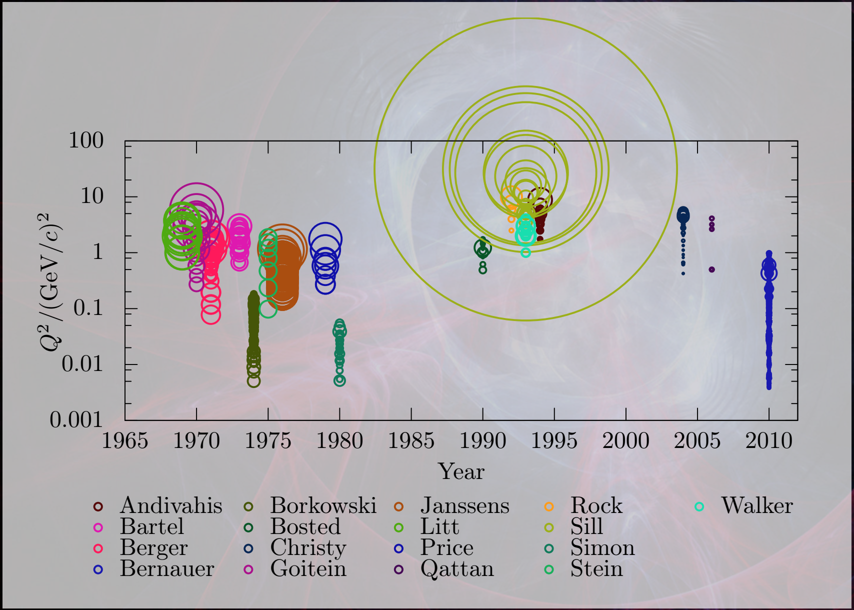
- Rosenbluth formula
- Electric and magnetic form factor encode the shape of the proton
- Fourier transform (almost) gives the spatial distribution, in the Breit frame

How to measure the proton radius

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



History of unpolarized electron-proton scattering



High-precision p(e,e′)p measurement at MAMI

High-precision p(e,e′)p measurement at MAMI

Mainz Microtron

- cw electron beam
- 10 $\mu\mathrm{A}$ polarized,
  100 $\mu\mathrm{A}$ unpolarized
- MAMI A+B: 180-855 MeV
- MAMI C: 1.6 GeV

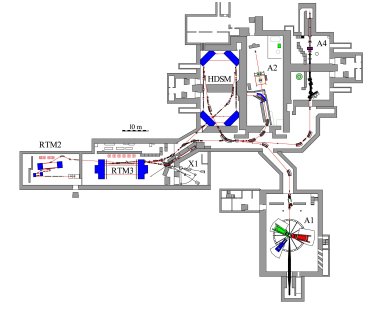
Johannes Gutenberg University of Mainz

Image © 2015 GeoBasis
Image © 2015 Digita
Image © 2015 Aero

3.97 mi

earth

Imagery Date: 7/31/2013 50°00'20.12" N 8°19'50.19" E elev 352 ft eye alt 17.20 mi



High-precision p(e,e′)p measurement at MAMI

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- cw electron beam
- 10 μA polarized,
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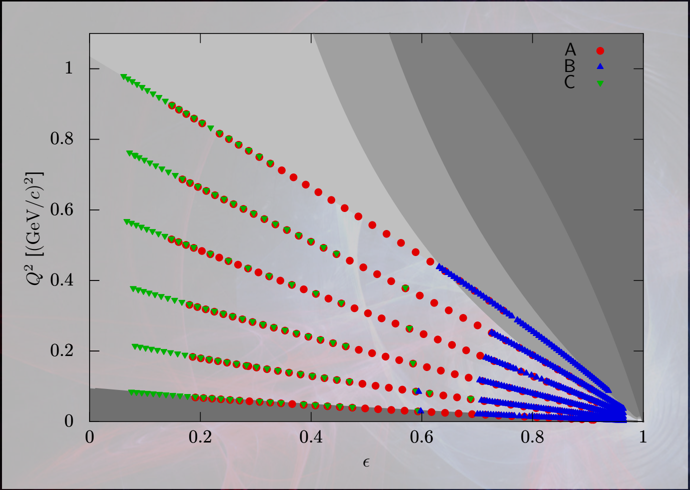
Johannes Gutenberg Univ

A1 3-spectrometer facility

- 28 msr acceptance
- angle resolution: 3 mrad
- momentum res.: 10^{-4}

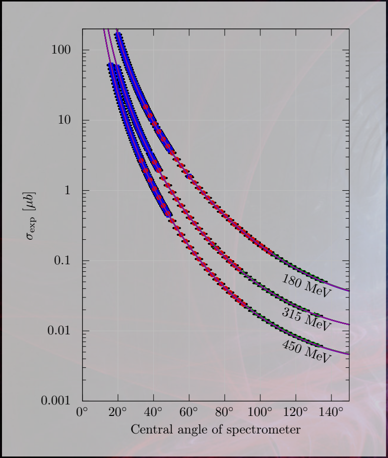
Measured settings

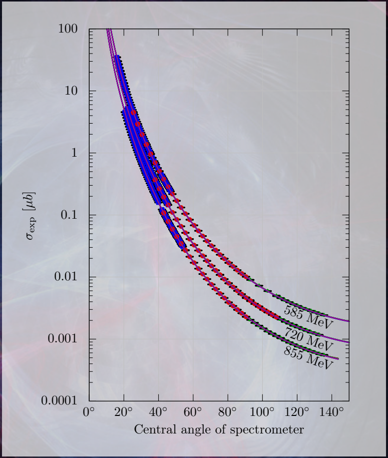


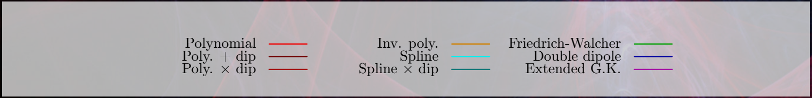
1422 settings

JCB et al., Phys. Rev. Lett. 105 (2010) 242001,
M. O. Distler, JCB, Th. Walcher, Phys. Lett. B 696, 343 (2011)
JCB et al., Phys. Rev. C90 (2014) 015206

Cross sections



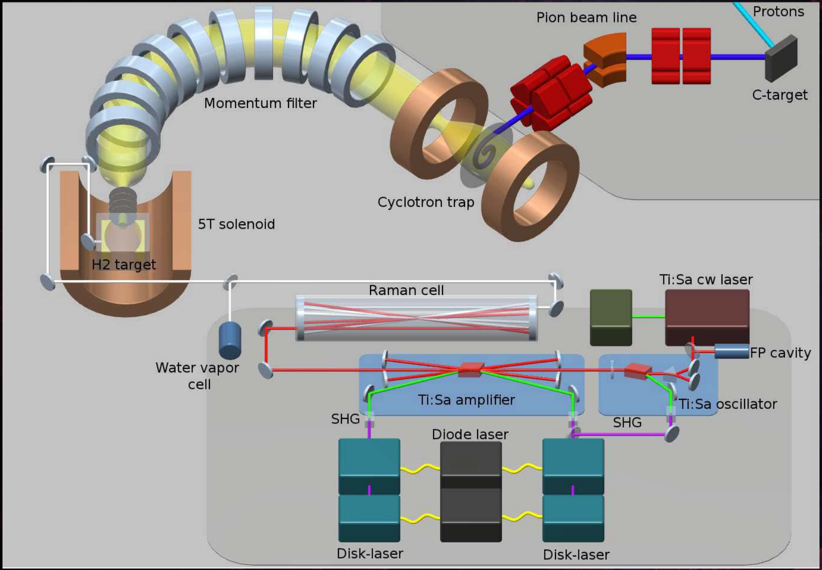




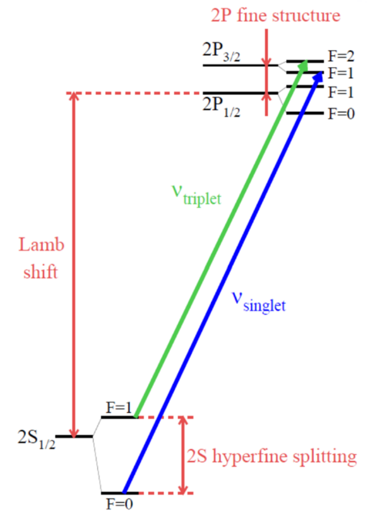
Muonic Hydrogen Spectroscopy

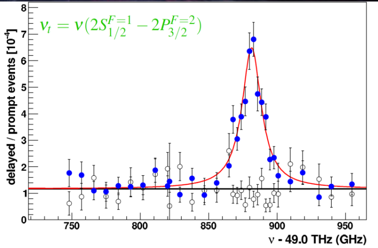
- Replace electron with muon
- 200 times heavier $\Longrightarrow$ 200 times smaller orbit
- Probability to be "inside" 200^3 higher!

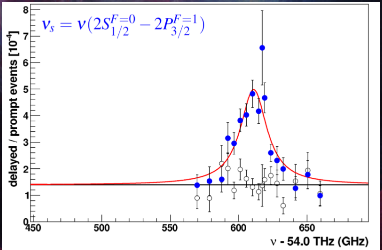
PSI setup (CREMA)



Muonic Hydrogen Spectroscopy Results







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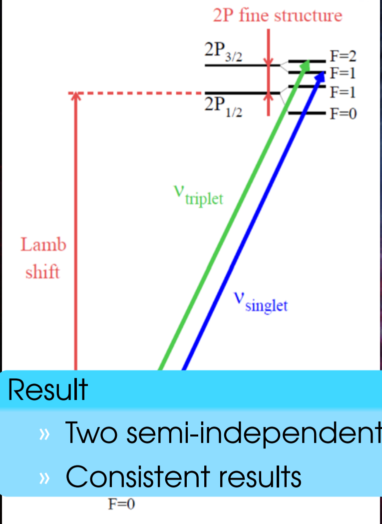

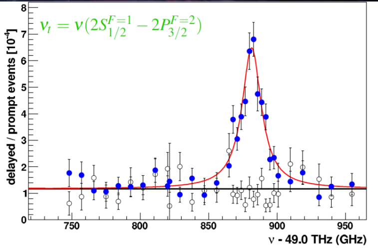

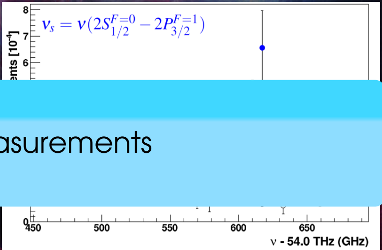

Result

- Two semi-independent measurements
- Consistent results

The Proton Radius puzzle

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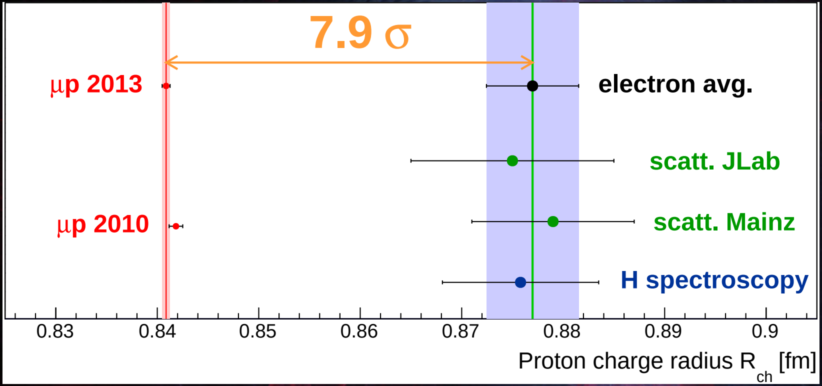

Theory / Fitting

- Many people have checked spectroscopy theory
  - generally seems robust, but few papers pop up with criticism
- We are sure we are measuring the same thing: G. Miller, Phys. Rev. C 99, 035202
- For scattering, radiative corrections might be problematic
- Fitting: Many people fit data and get different results.

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- For scattering, radiative corrections might be problematic
- Fitting: Many people fit data and get different results.
- 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

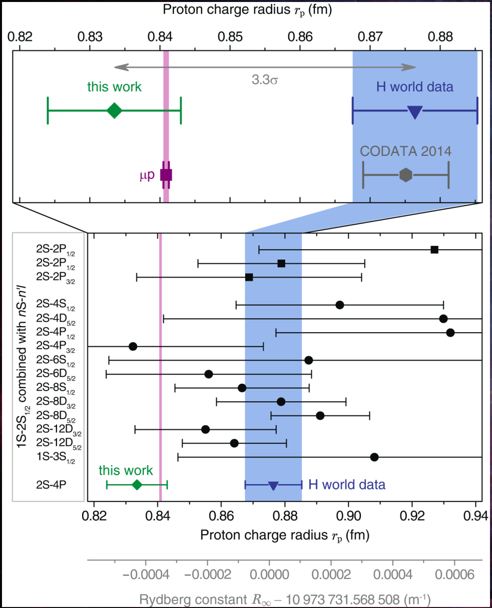
Spectroscopy:

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

Scattering:

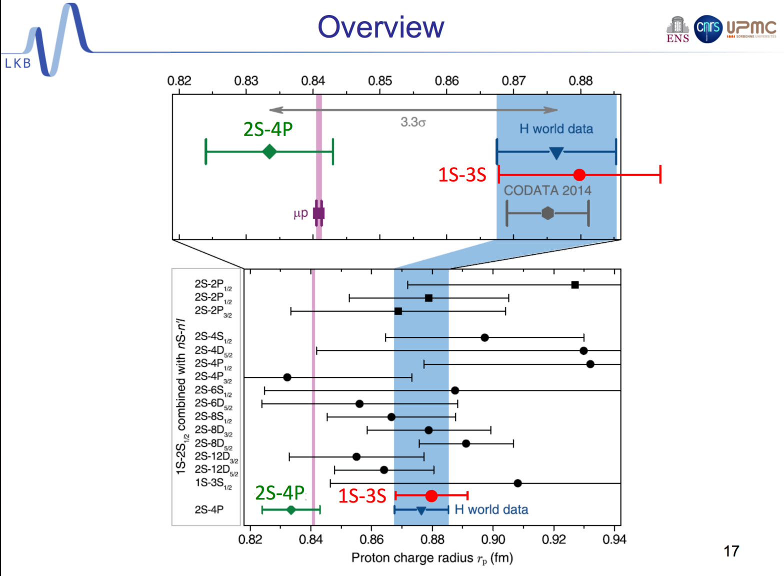
- PRad (Jefferson Lab)
- Mainz: ISR, H-TPC, Next-gen FF
- Muon Hydrogen-TPC, CERN
- PRAE Paris
- ELPH Japan
- MUSE

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



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

Overview



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More spectroscopy

There are more spectroscopy results coming.

- AFAIK, all give something in agreement with small radius!

More spectroscopy

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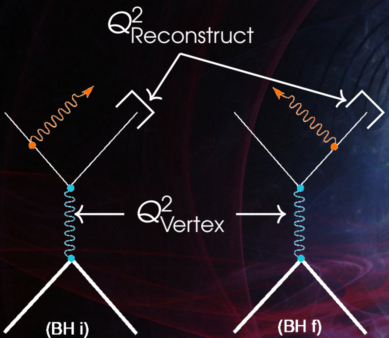
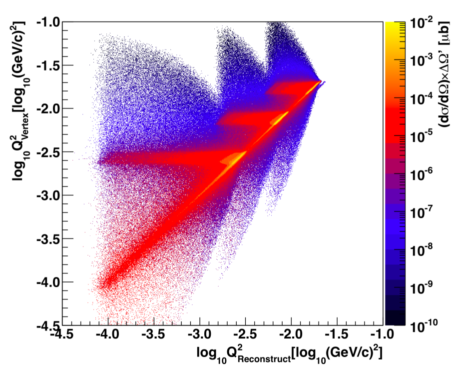
- AFAIK, all give something in agreement with small radius!
- Some ready to declare victory.
- I think it´s to early. We should at least understand want has gone wrong in Paris!

ISR method



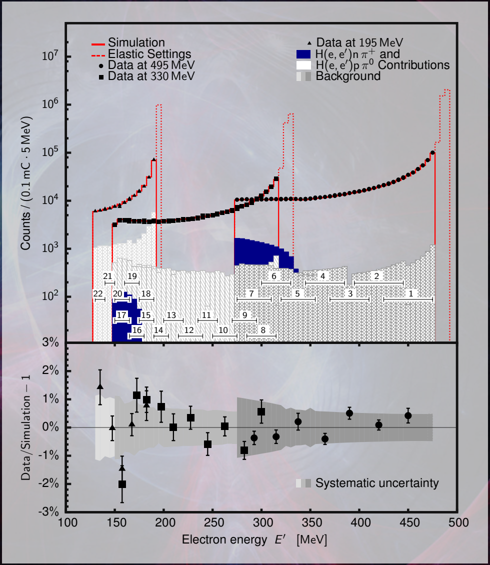


» Use initial state radiation to reduce effective beam energy

» Have to subtract FSR

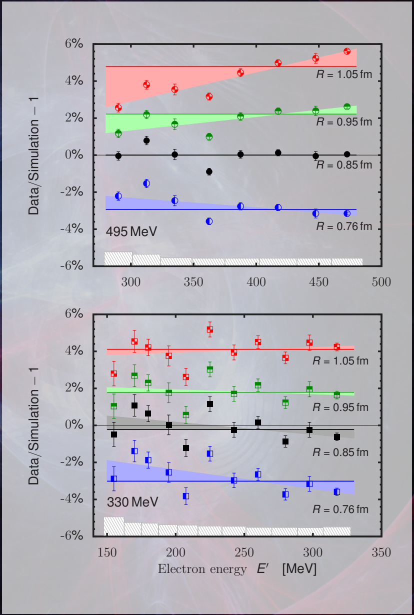
ISR at MAMI

- Published: PLB 771:194-198
- Radiative correction correct on the 1% level deep in the tail!
- Radius extraction not competitive in precision
- In principle: Larger scattering angle for G_M



Updated analysis of ISR

- arXiv:1905.11182
- Focuses on cs instead of FF
- $r_p = 0.870 \pm 0.014_{stat} \pm 0.024_{sys} \pm 0.003_{mod}$ fm
- Slightly prefers large radius



Slides provided by E. Pasyuk, presented at MENU 2019

PRAD slides removed on request of PRAD collaboration.

The missing piece

r_E (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060 or not?	????

Measure radius with muon-proton scattering!

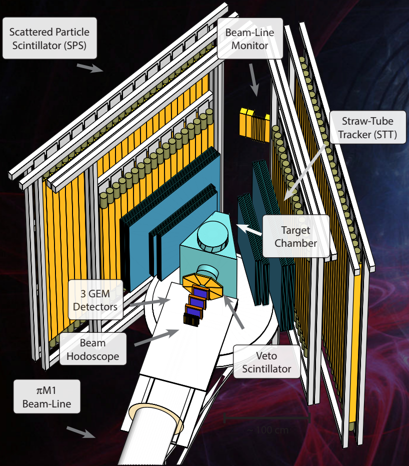
MUSE - Muon Scattering Experiment at PSI

World's most powerful low-energy $e/\pi/\mu$-beam:

Direct comparison of ep and μp!

- Beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on liquid H_2 target
  - Species separated by ToF, charge by magnet
- Absolute cross sections for ep and μp
- Ratio to cancel systematics
- Charge reversal: test TPE
- Momenta 115-210 MeV/c $\Rightarrow$ Rosenbluth G_E,G_M

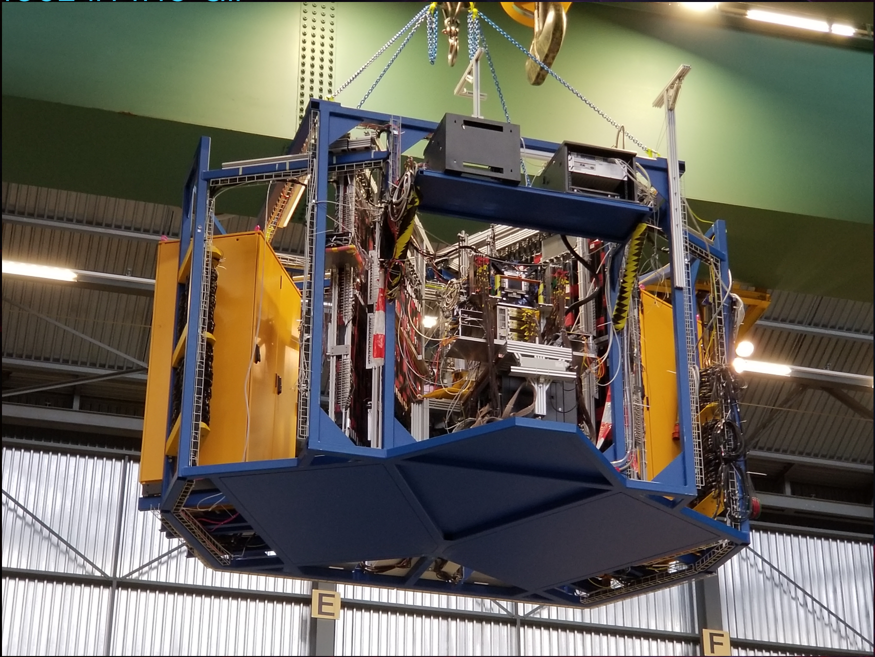
Experiment layout



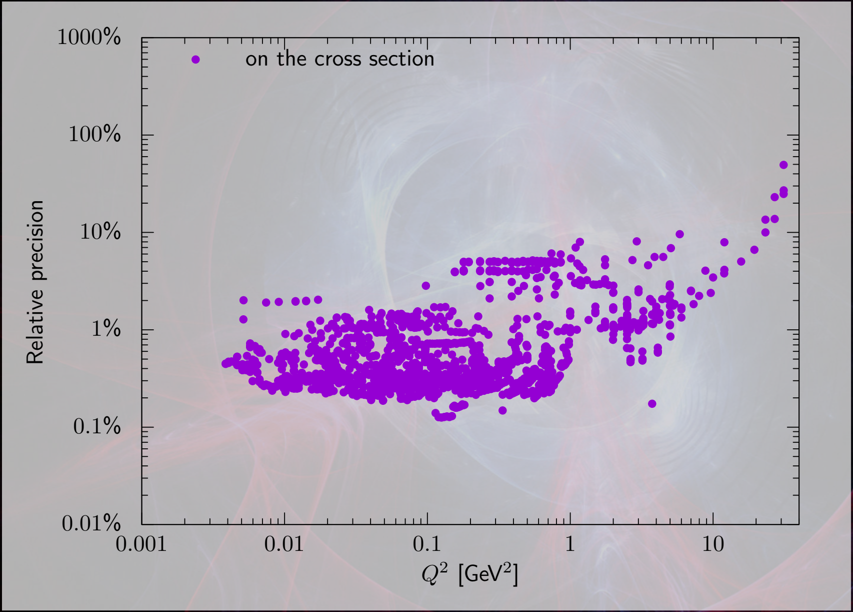
R. Gilman et al., arXiv:1303.2160 (nucl-ex)

- Secondary beam $\Longrightarrow$ track beam particles
- Low flux (5 MHz) $\Longrightarrow$ large acceptance
- Mixed beam $\Longrightarrow$ PID in trigger

MUSE in the air



What do we know about G_M



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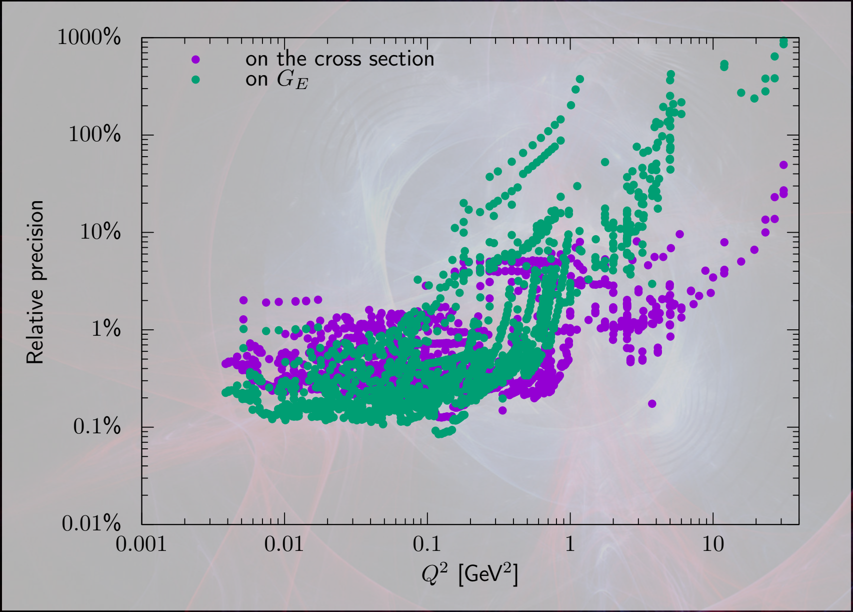

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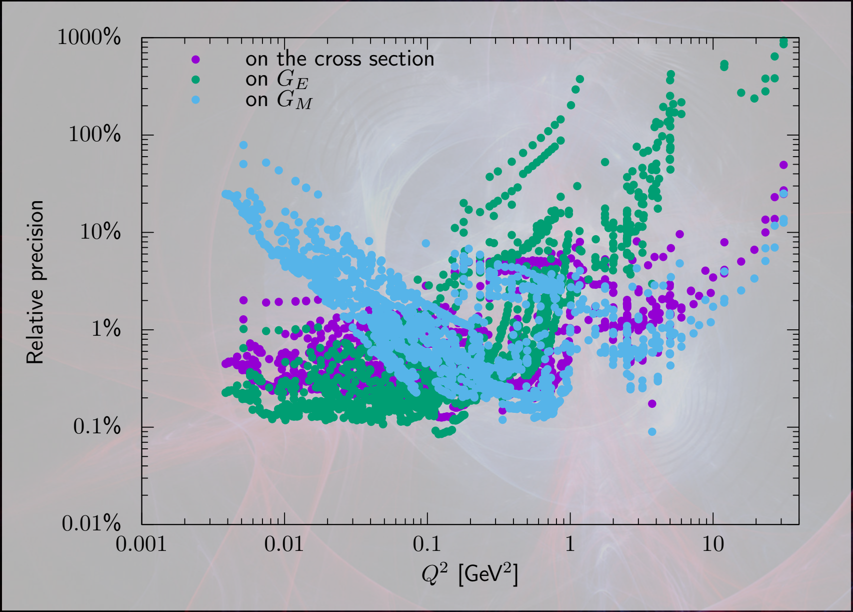
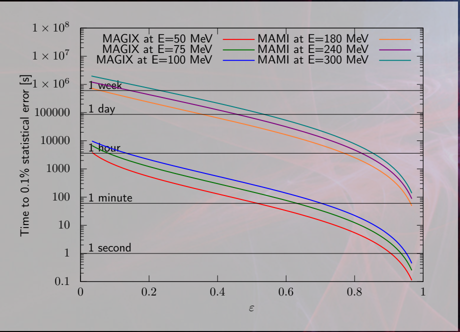


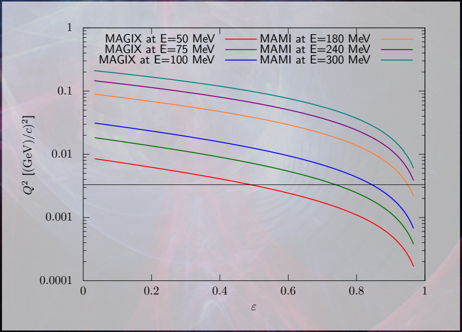
Next generation experiments at Mainz

- Initial State Radiation
- Next-gen Rosenbluth-type with improved systematics at MAMI and MESA
- Active target: high pressure Hydrogen TPC

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
- Already had test beam. Construct active veto and collimator for further background reduction



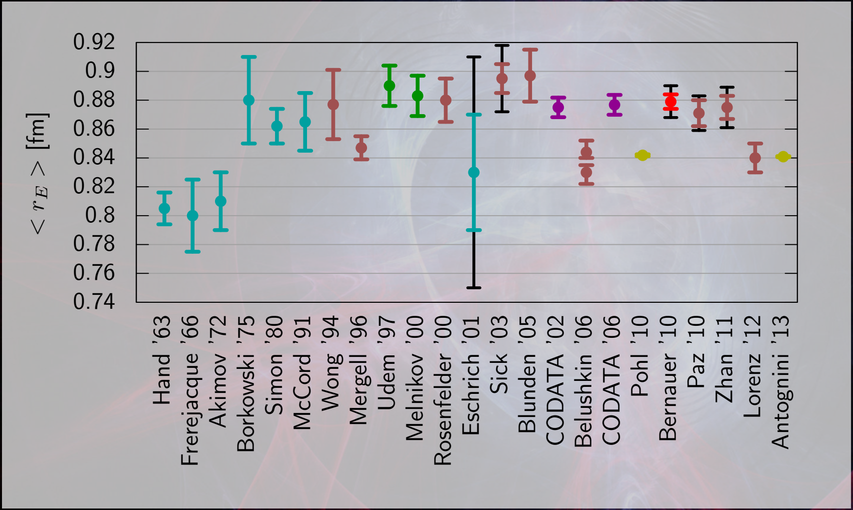


Summary

- After 9 years, the puzzle still stands
- Spectroscopy has many new results, mixed, but with weight behind the smaller radius
  - unknown what causes difference in spectroscopy results
- Scattering; First values released / about to be released. Situation still unclear
- More scattering data in the pipeline
- Don't forget about magnetic radius!

Backup slides

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

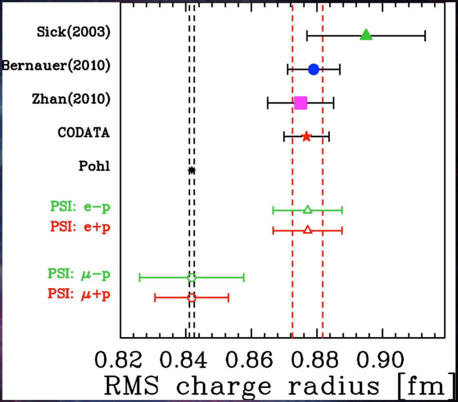
- Low-Q fits with low order don't work.

2018: XXX Yan/Higinbotham/...

- Small radius fraction finally does bias testing

MUSE: Predicted performance

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

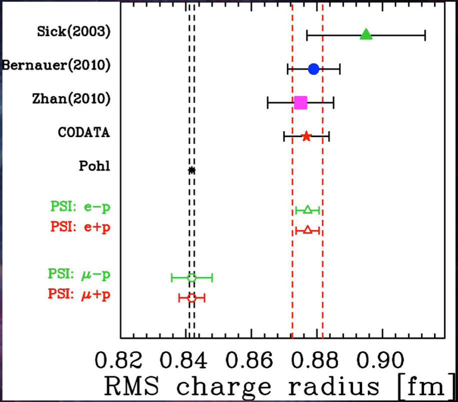


MUSE: Predicted performance

» 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