The MUSE experiment:

addressing the proton radius puzzle via elastic muon scattering

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SLAC seminar
(26-June-2018)

- The Proton Radius Puzzle
    - What is a radius ? How do we measure it ?
- What is the problem ?
- How do we solve it: MUSE ?

This work is supported by NSF

The Proton Radius Problem

July 2010

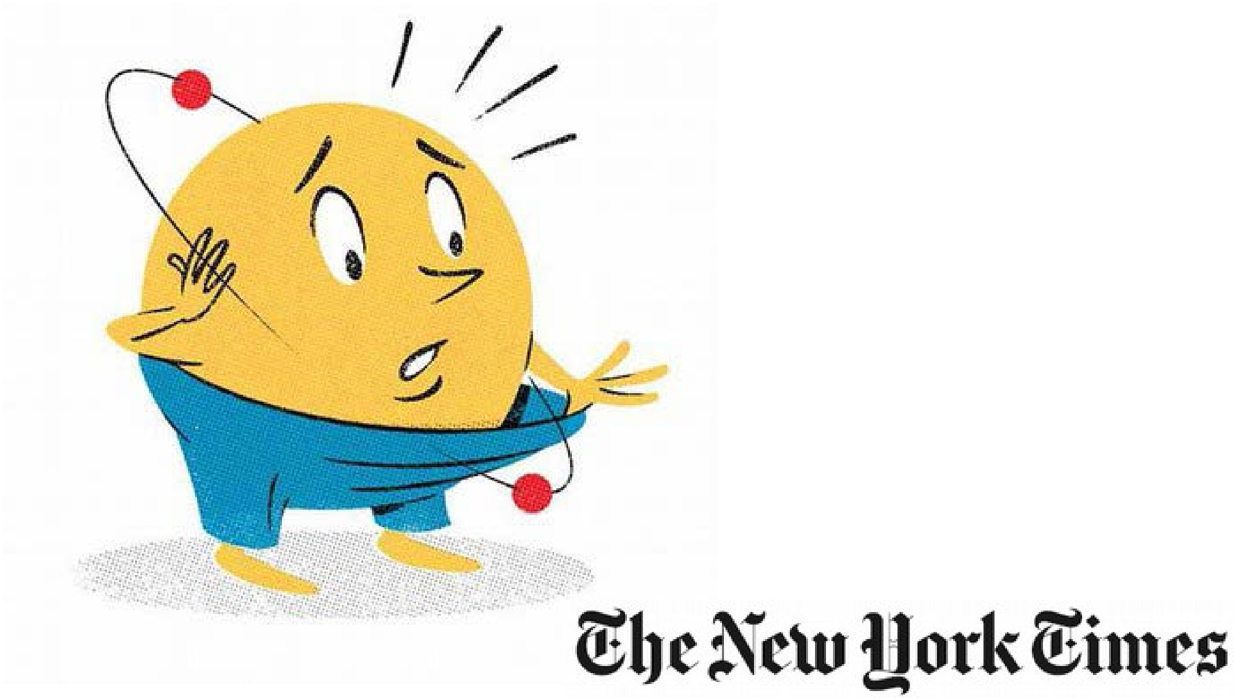
April 2013

July 2013

January 2014

The Proton Radius Problem

The Proton Radius Problem



- The Proton Radius Puzzle (PRP) has garnered a lot of interest!
- Not just interesting:
  - Tests our theoretical understanding of proton
  - Radius of proton is dominant uncertainty in many QED processes
- What exactly is the puzzle ?

The Proton Radius

- Classical physics (sphere of charge density $\rho(r)$):

$$\langle r^2 \rangle = \int \rho(r) r^2 d^3 r$$

- Non-relativistic QM (w.f. of density of target $\psi(r)$):

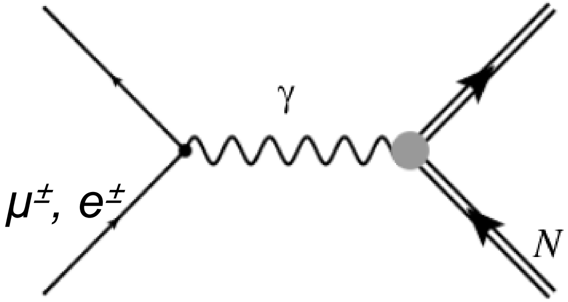
$$\langle r^2 \rangle = \int \langle \psi^*(r) | r^2 | \psi(r) \rangle d^3 r$$

- Relativistic QM (form factor $G(Q^2)$):

$$\langle r^2 \rangle = -6 \left. \frac{dG(Q^2)}{dQ^2} \right|_{Q^2=0}$$

The Proton Radius - II

- Lepton scattering



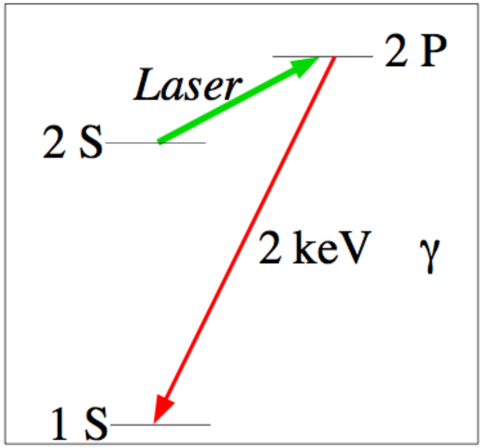
Non-relativistic scattering off extended proton:

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{point} \times \left(G(Q^2)\right)^2$$

$(G(Q^2) = \int \rho(r) e^{iQ\cdot r} d^3r$ is Fourier transform of $\rho(r)$

Fit form factor trend with Q^2, fit to data, find slope as $Q^2 \to 0$

- Atomic Energy Levels

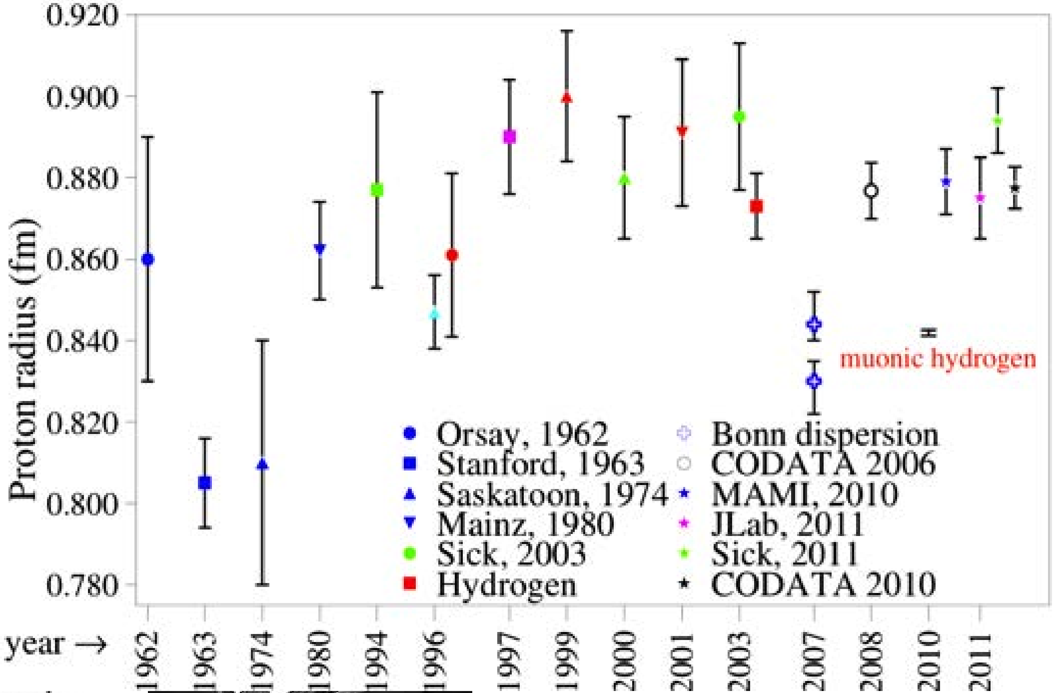


Non-relativistic (Schwinger 1952):

$$\Delta E_1 = \frac{2\pi\alpha}{3} \left|\phi^2(0)\right| \left\langle r_E^2 \right\rangle$$

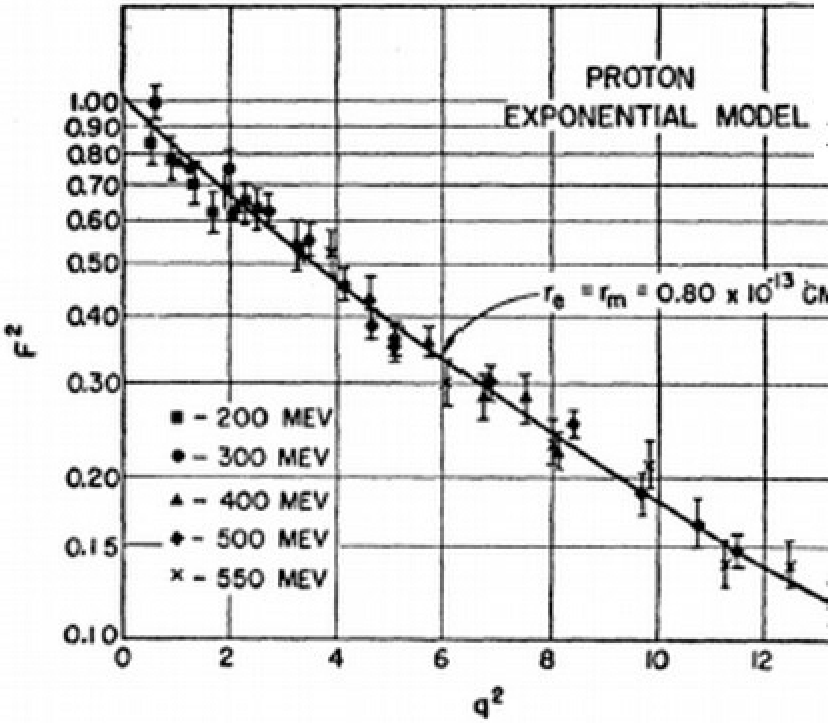
Finite size of proton perturbs energies of S states – $r_p << r_{atomic}$, so effect proportional to electron wavefunction $\phi^2(r=0)$

The Proton Radius vs Time



From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, Ann.Rev.NPS, modified

Chambers and Hofstadter, Phys Rev 103, 1454 (1956)



Electron Scattering Measurements

$$\sigma_R\left(\approx\frac{(d\sigma/d\Omega)}{(d\sigma/d\Omega)_{Mott}}\right)=\tau G_M^2+\varepsilon G_E^2\;;\;\text{with}\;\;\tau=\frac{Q^2}{4M^2}\;;\;\varepsilon=\left[1+2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

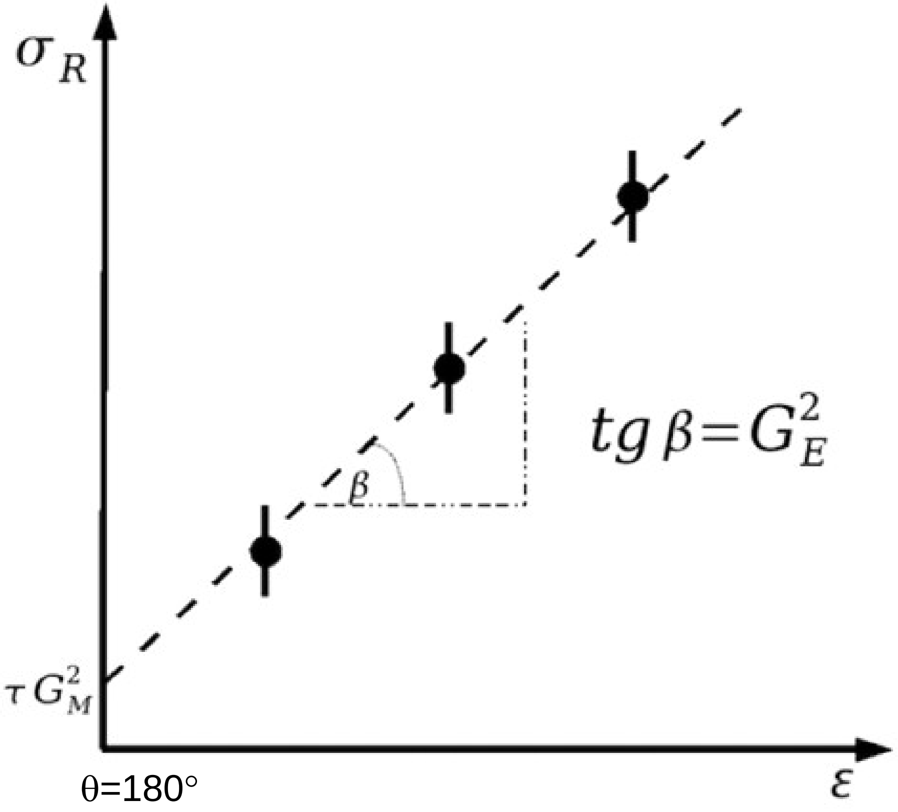
current distr.

charge distr.

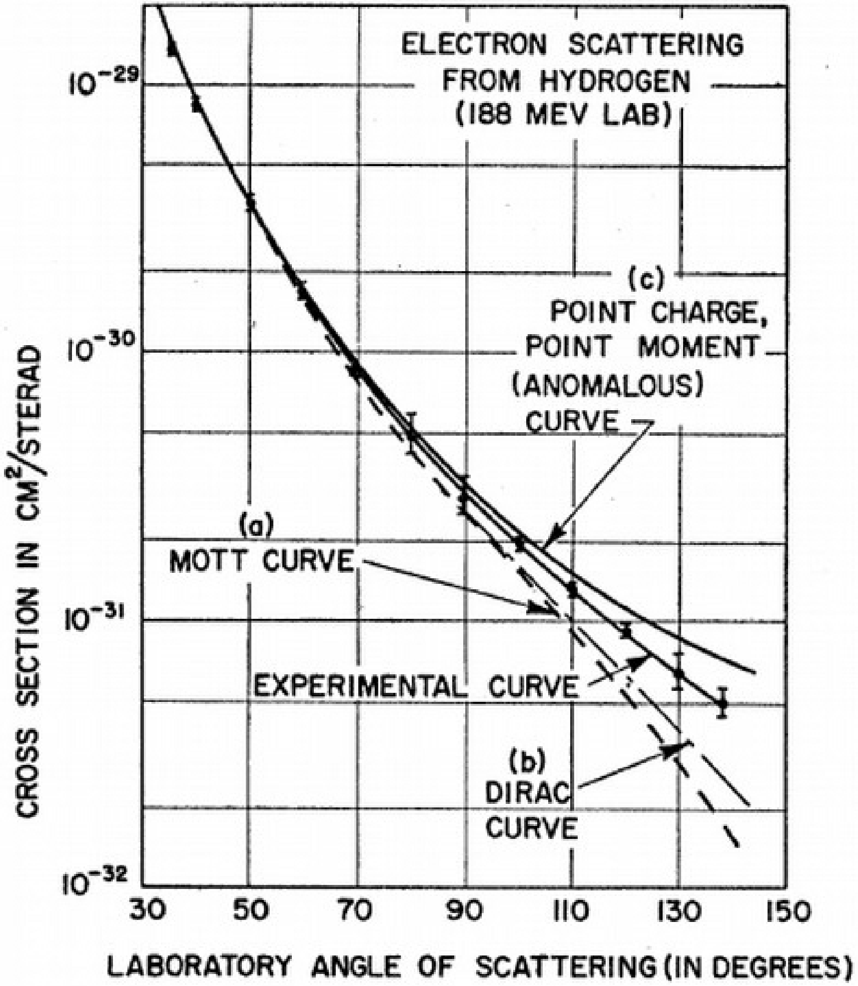
$$G_E^2(0)=1;\quad G_M^2(0)=\mu_p$$

- In **one-photon** exchange (or Born approximation), form factors are related to elastic e-p scattering cross section

- Classical **Rosenbluth separation**
- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed
- Linear fit to get intercept and slope



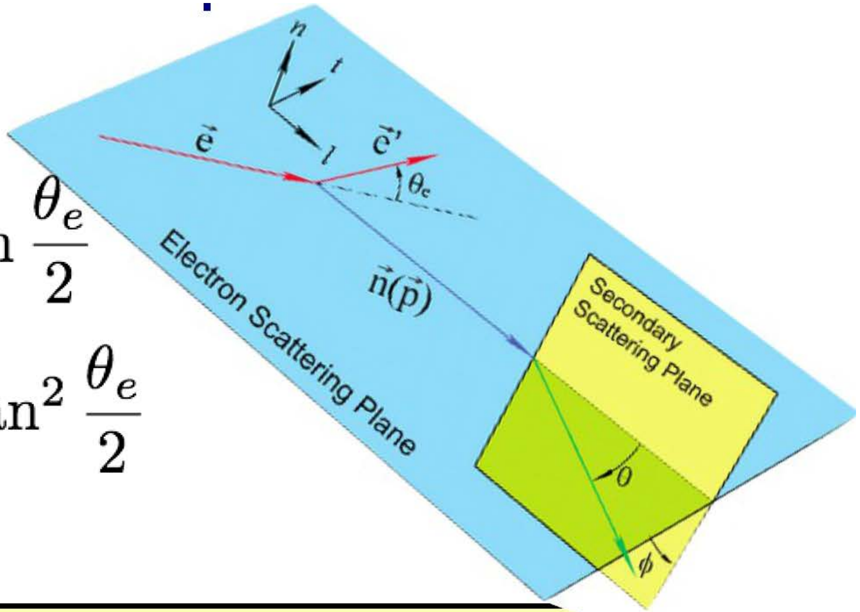
Electron Scattering Measurements (1950s)



$$\langle r_E \rangle = 0.74(24)\ fm$$

- fit to RMS radius Stanford 1956
- R.W. McAllister and R. Hofstadter, Phys. Rev. **102**, 851 (1956)

Electron Scattering Measurements w/ polarization



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

$$P_n = 0 \ (1\gamma)$$

$$\boxed{\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}}$$

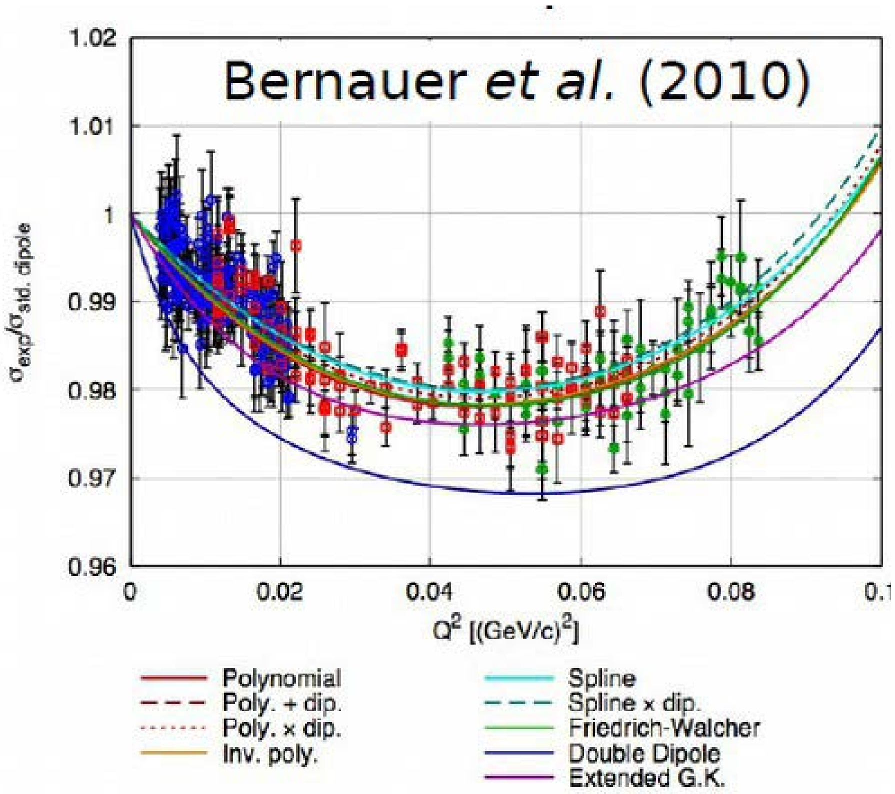
- Double polarization in elastic e-p scattering
  - measure recoil polarization or with (vector) polarized target

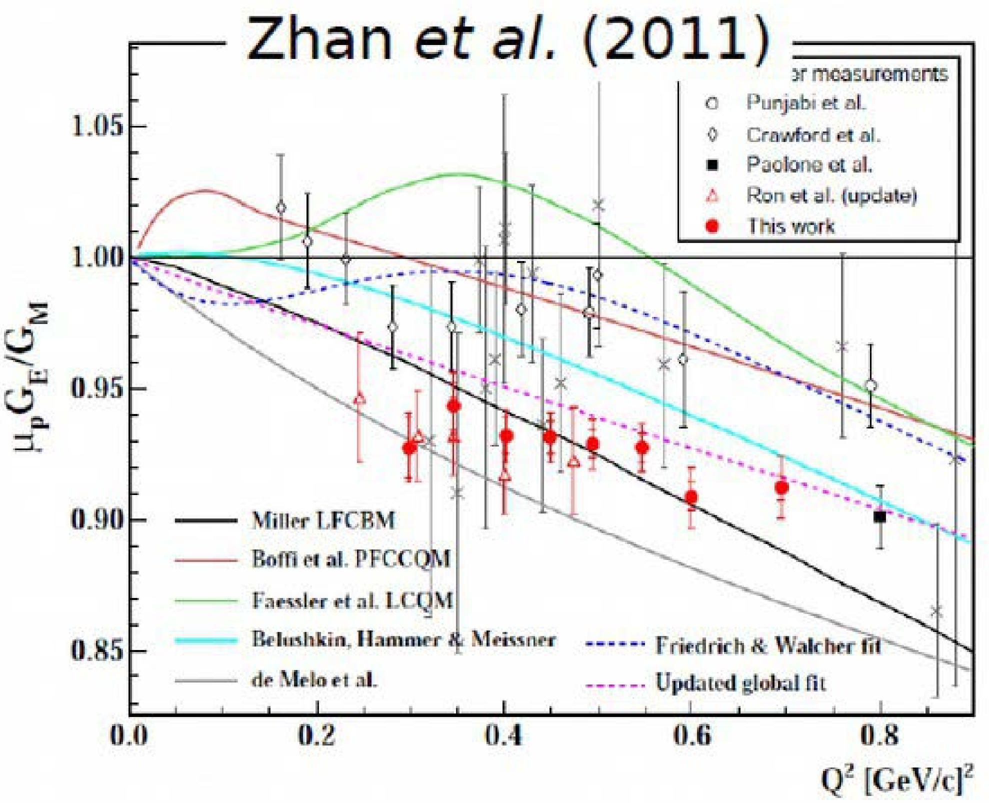
$${}^1H(\vec{e},e'\vec{p}), \quad {}^1\vec{H}(\vec{e},e'p)$$

- A single measurement gives ratio of form factors

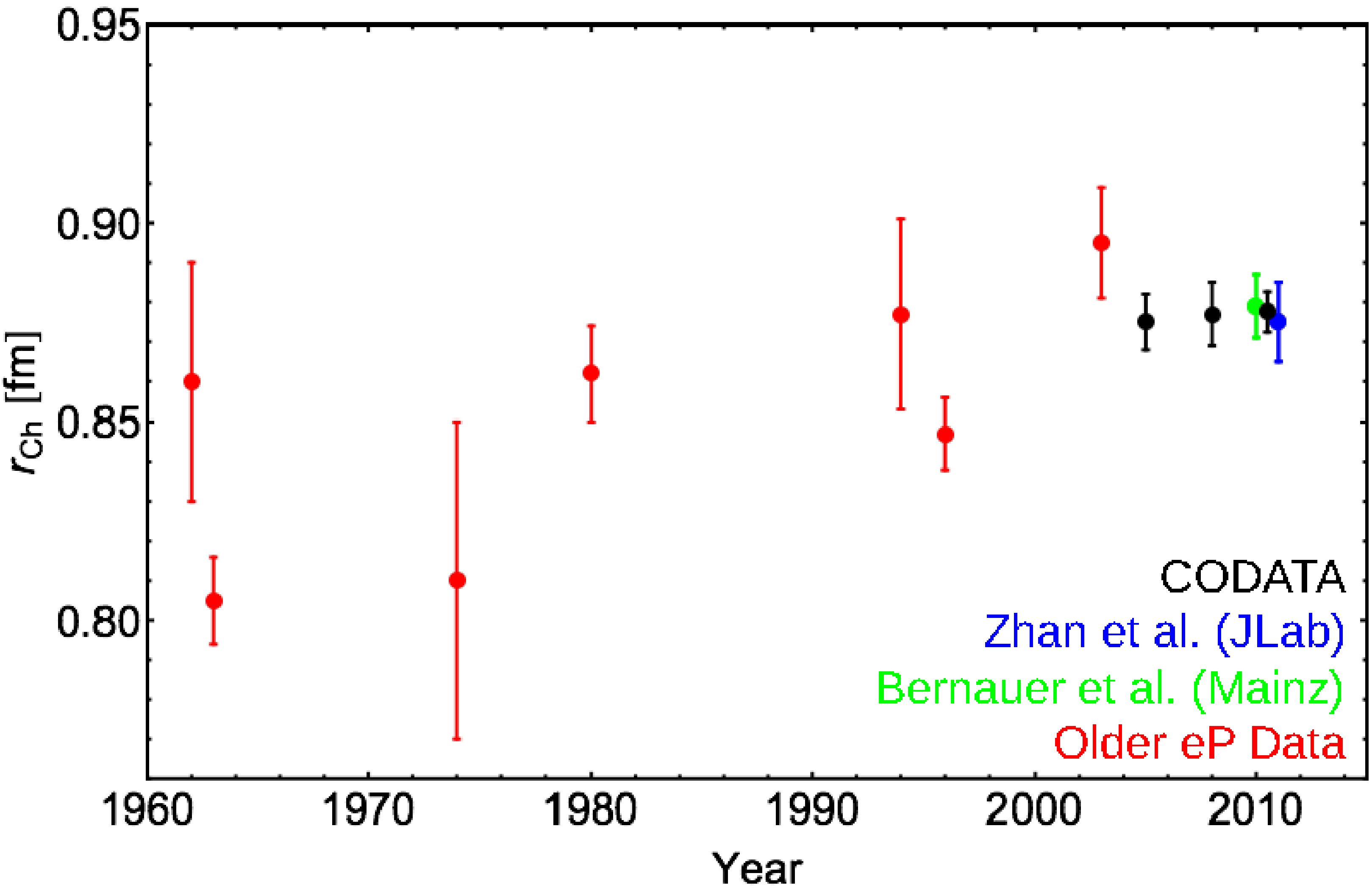
Electron Scattering Measurements (2010s)

- Bernauer et al. PRL 105, 242001: world's largest data set
  - fit functional forms to data rather than Rosenbluth separation
- Zhan *et al.* PLB 705 (2011) 59-64: Polarization measurements to get G_E/G_M, valuable over a large Q^2 range
  - fit(Jlab + world – Bernauer) gives radius compatible with Bernauer





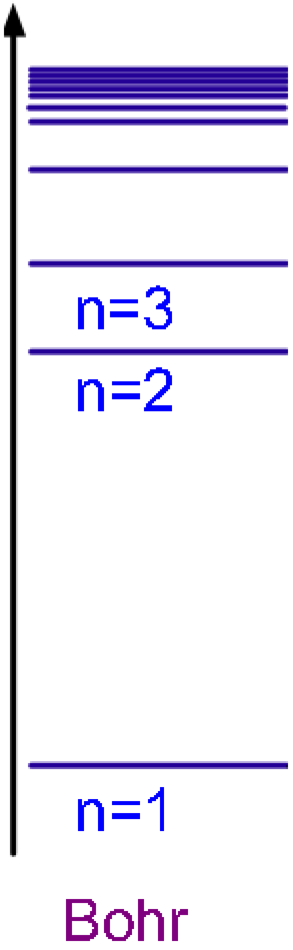
The Proton Radius vs Time from ep data



CODATA: Committee on Data for Science and Technology, the international group which publishes the recommended values for fundamental physical constants every four years.

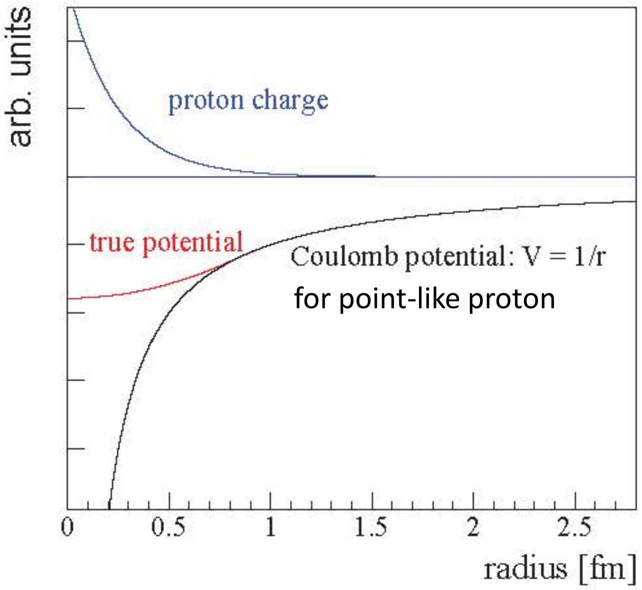
The Proton Radius from H Lamb Shift

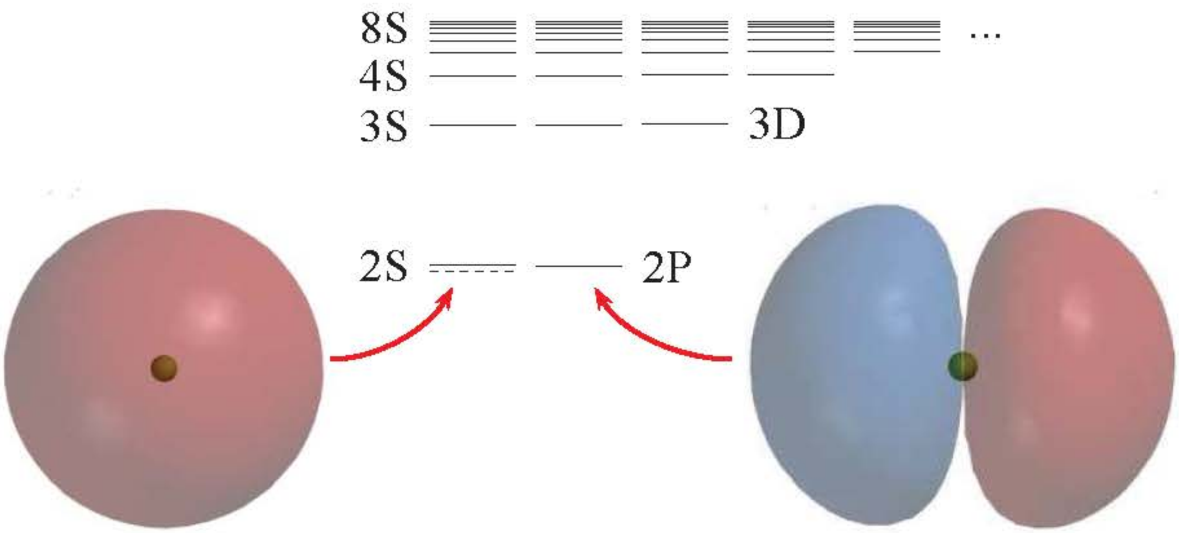
Components of the Hydrogen Energy Levels



0.014% of the Lamb Shift!

Finite-size shift of atomic energy levels





S states: max. at r=0

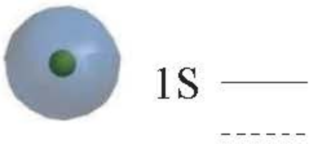
P states: zero at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

size of the proton



Electron is not inside the proton.

Orbital pictures from Wikipedia

Pictures: R. Pohl

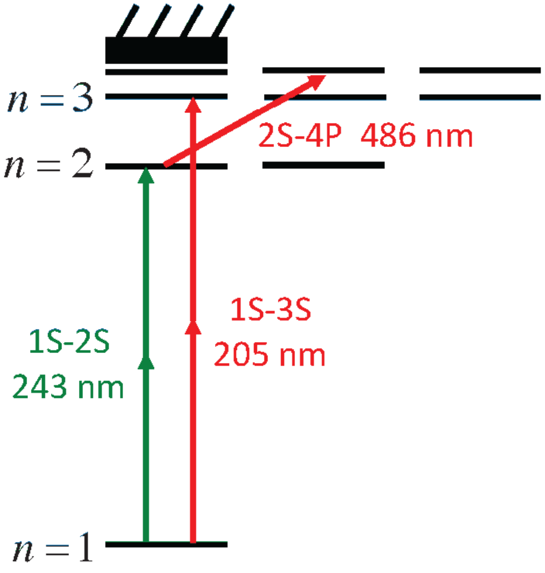
Hydrogen Atom Spectroscopy

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

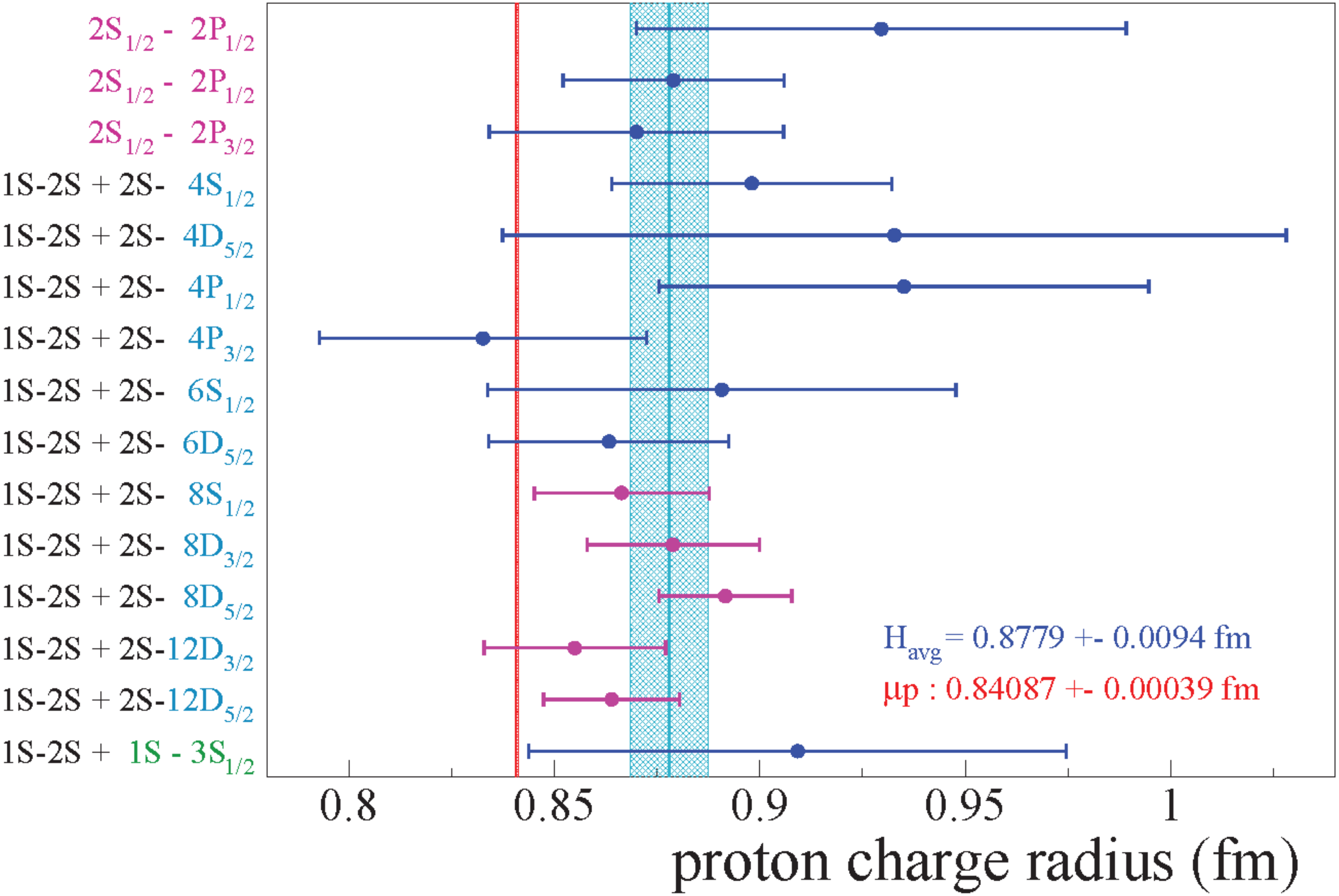
$$\text{Lamb shift}: \quad L_{1S}(r_\text{p}) = 8171.636(4) + 1.5645 \langle r_\text{p}^2 \rangle \text{ MHz}$$

- 2 measurements required to determine R_∞ and r_p
  - A **single** narrow transition: 1S-2S ($\Delta\nu$ = 1.3 Hz) measured with high accuracy.
  - Other transitions: natural width ~ MHz.

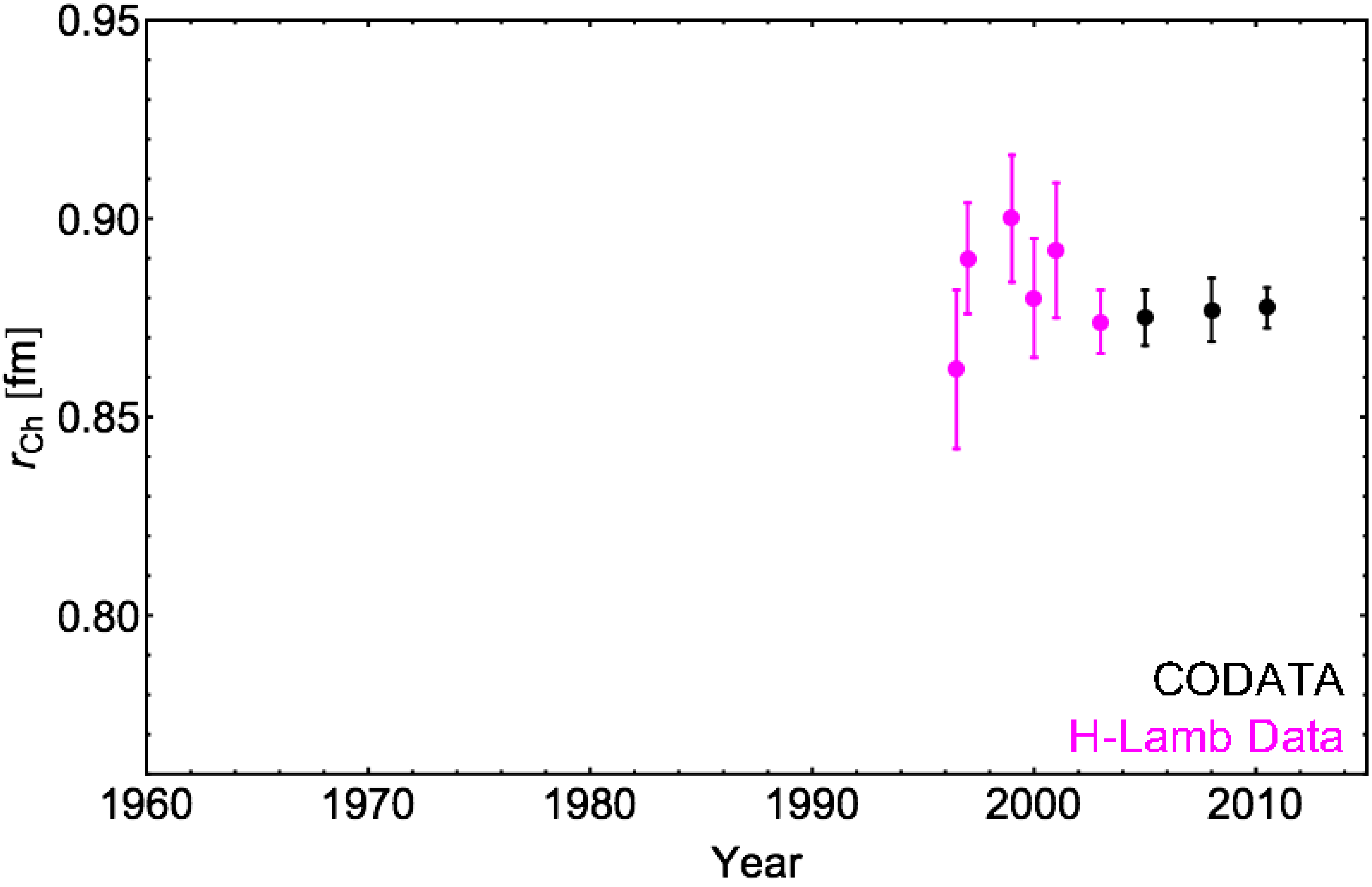
  Each measurement, combined with 1S-2S, yields a correlated pair (R_∞, r_p).



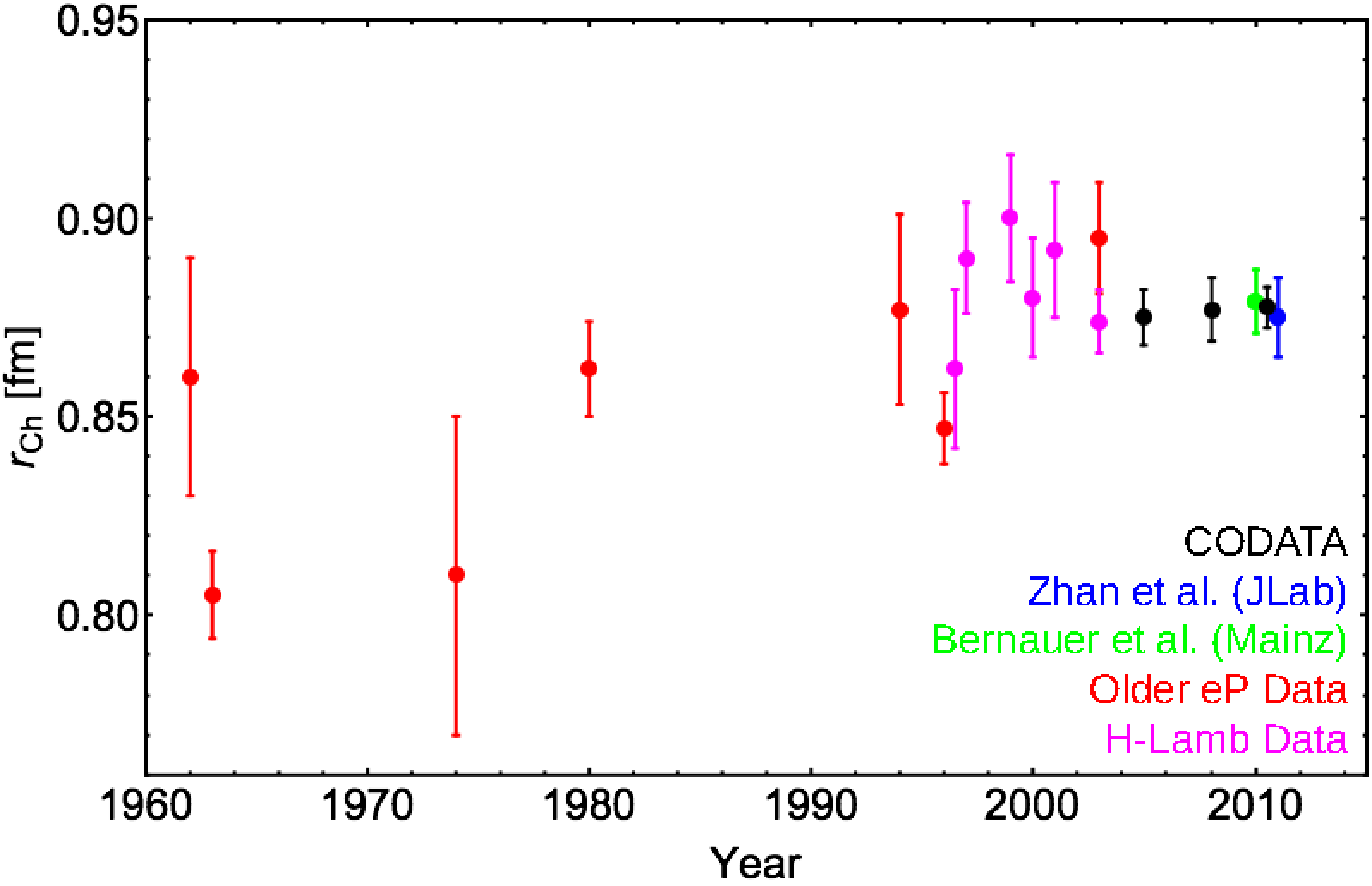
Hydrogen Atom Spectroscopy



The Proton Radius vs Time from H Lamb Shift data



The Proton Radius from H Lamb Shift and ep

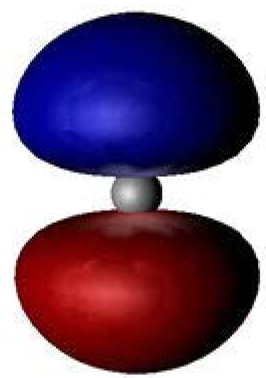


proton rms charge radius measured with electrons:
0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

Why Measure with μH ?

S-Orbital

max. at r=0



P-Orbital

zero at r=0

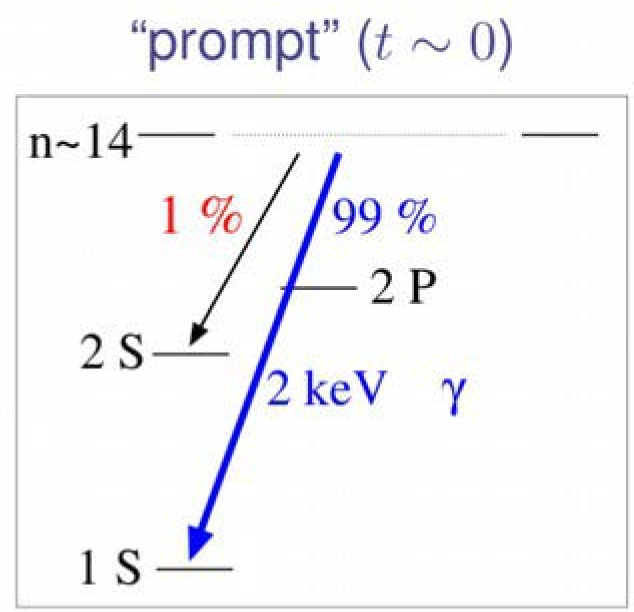
- While lepton is inside proton, attractive potential is lower
- Average potential reduced the longer lepton spends inside proton
- Strongly affects S orbitals, much less so P, so S-P transitions change
- Probability for lepton to be inside proton = volume of p / volume of atom:

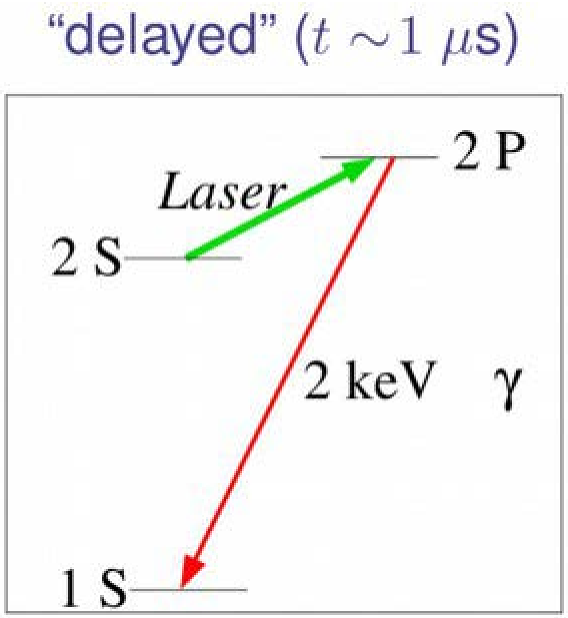
$$\cong \left(\frac{r_p}{a_{\mathbf{B}}}\right)^3 = \left(r_p\alpha\right)^3 m^3$$

- $m_\mu = 205\ m_e$: so μH is 205^3 ≈ **8 million times more sensitive to r_P**

Orbitals: http://chemistry.umeche.maine.edu/CHY251/Quantum.html

How to Measure with μH ?

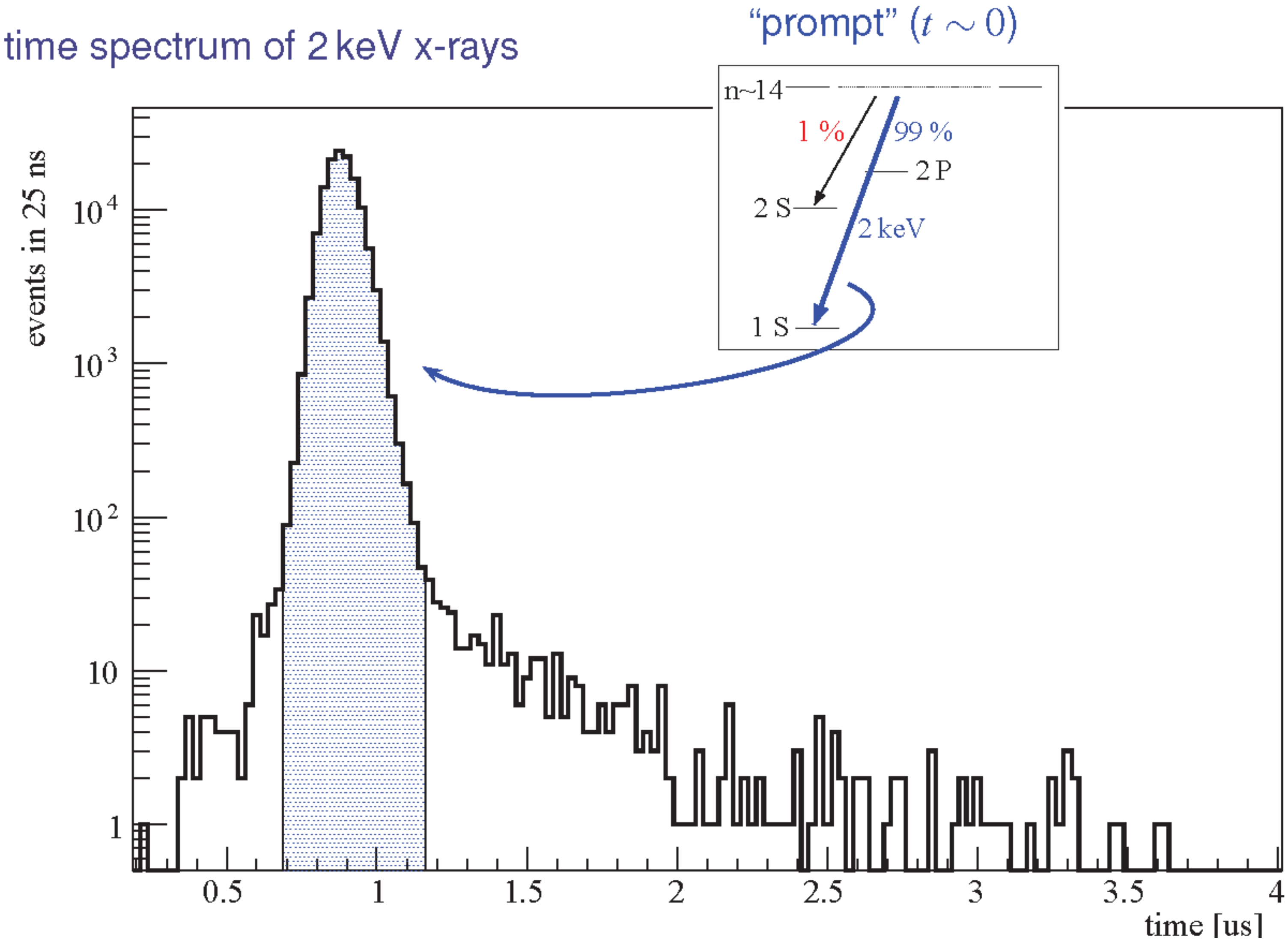




- beautifully simple, but technically challenging!
- form μH*(n~14) by shooting μ beam on 1 mbar H_2 target
  - 99% decay to 1S, giving out fast γ pulse
  - 1% decay to longer-lived 2S state
  - S2 state excited to 2P state by tuned laser & decay with release of delayed γ
- vary laser frequency to find transition peak → ΔE (2S to 2P) → r_p

Pictures: R. Pohl

How to Measure with μH ?



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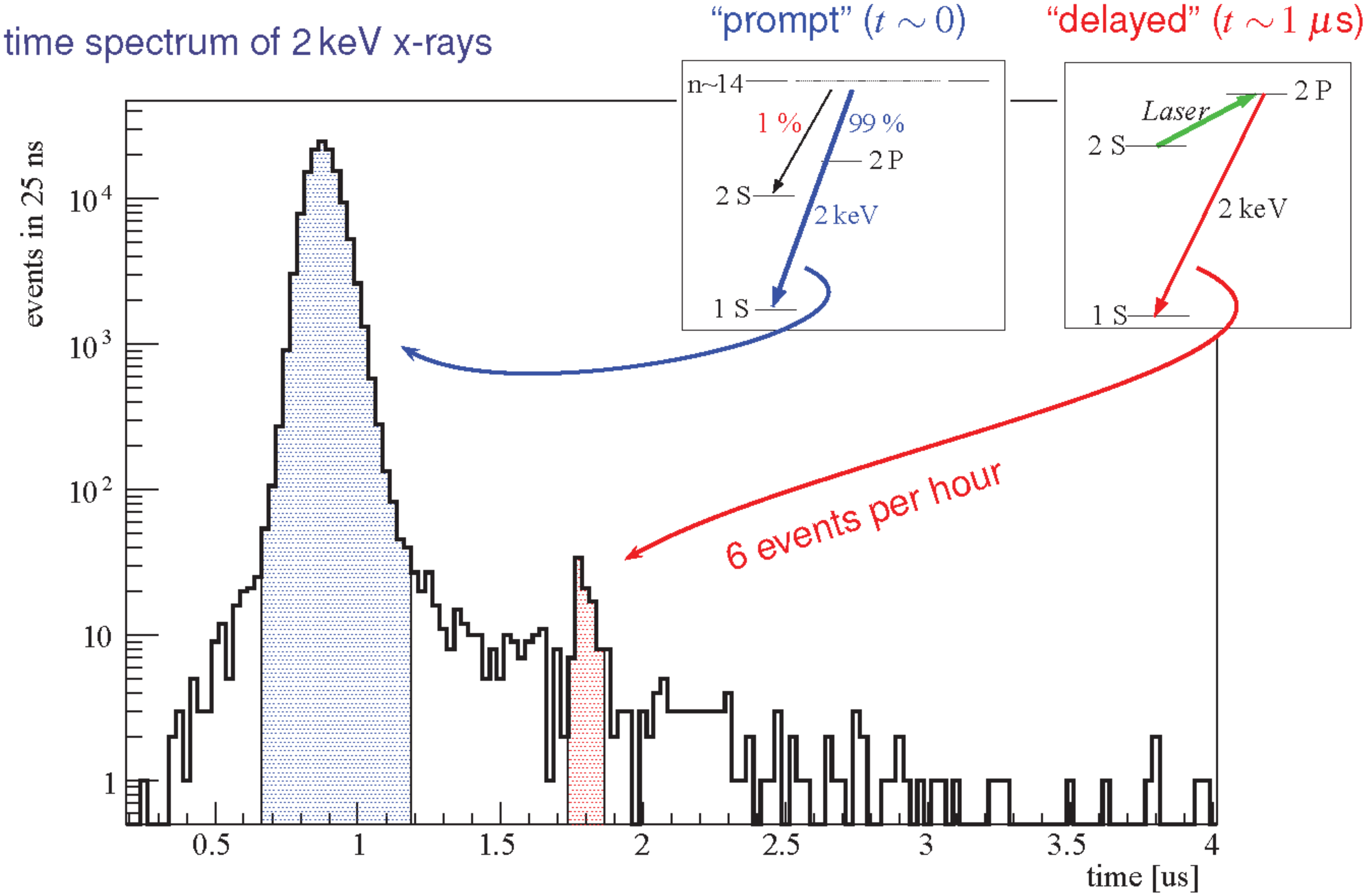
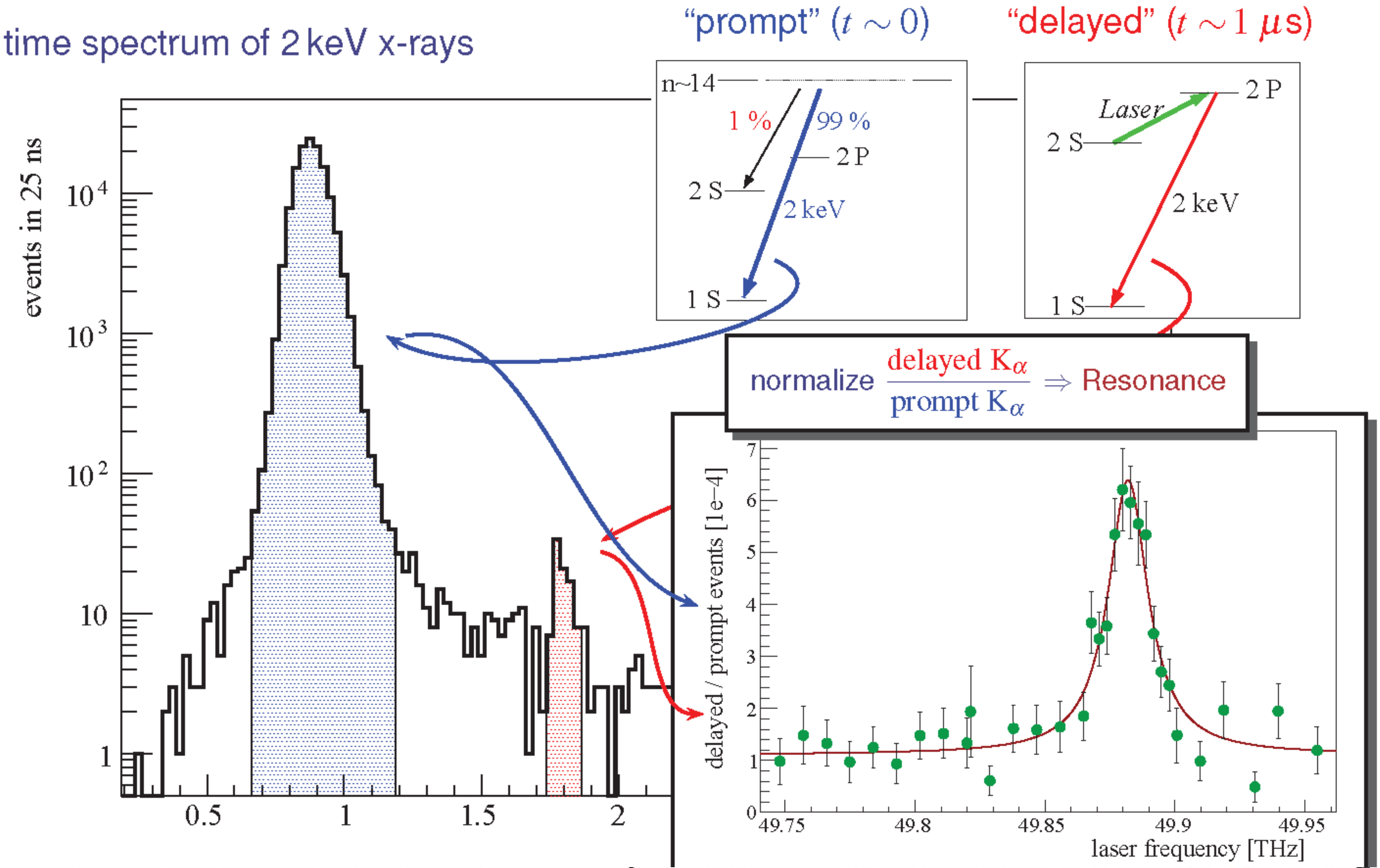


How to Measure with μH ?



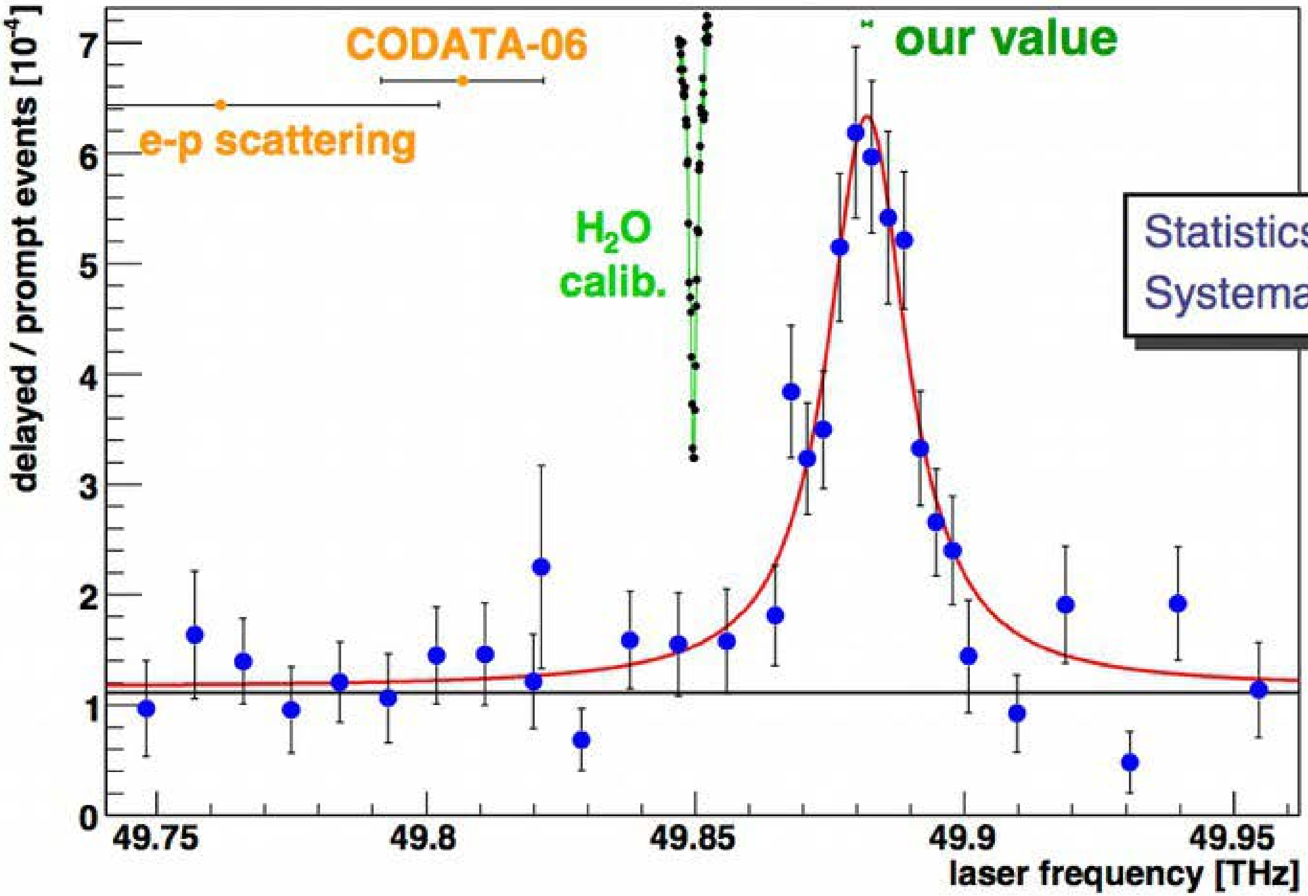
normalize $\dfrac{\text{delayed } \mathrm{K}_\alpha}{\text{prompt } \mathrm{K}_\alpha} \Rightarrow$ Resonance

$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ [meV]}$$

Proton Radius from μH (CREMA)

Water-line/laser wavelength:
300 MHz uncertainty

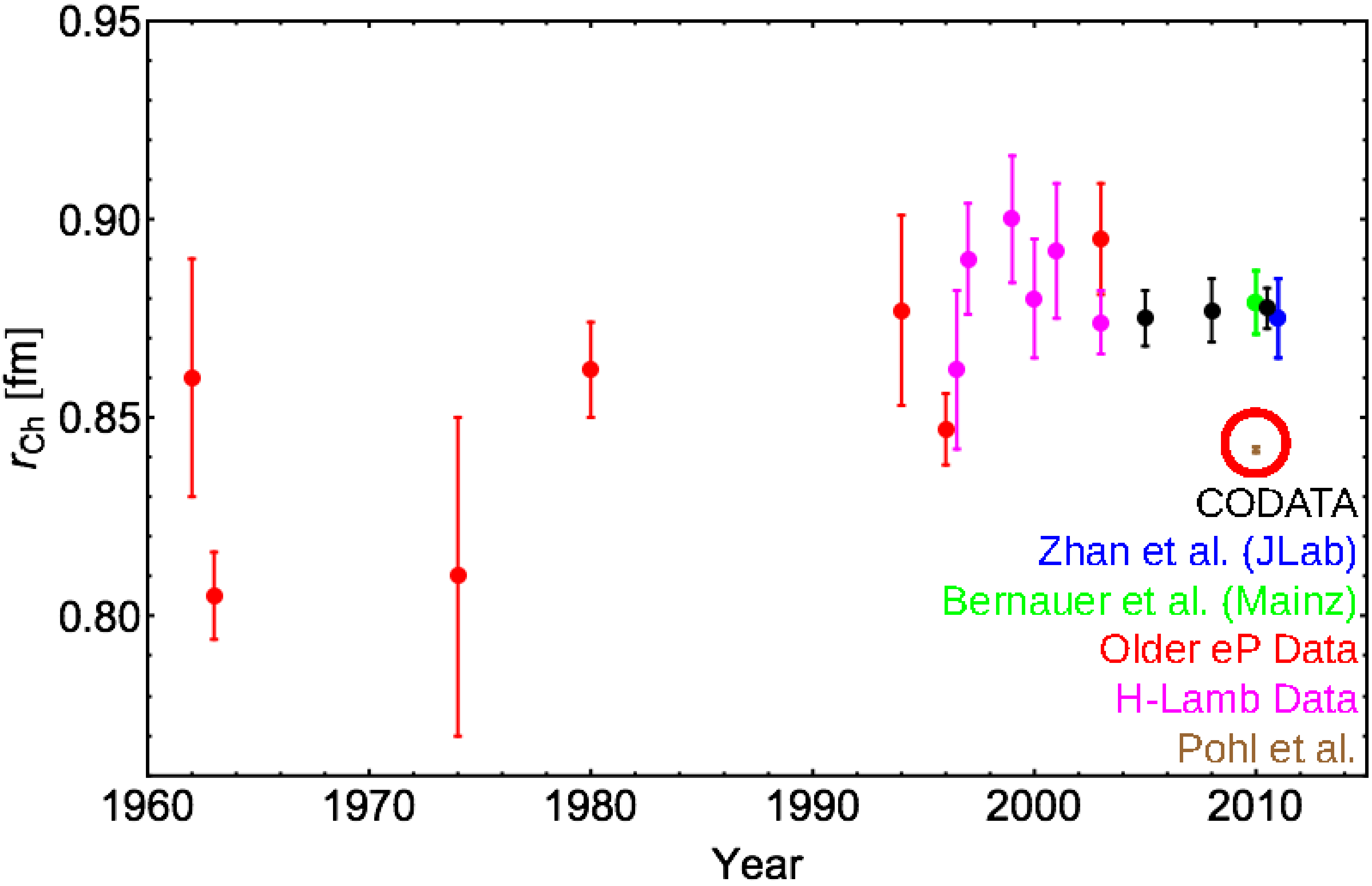
Δν water-line to resonance:
200 kHz uncertainty



Statistics: 700 MHz
Systematics: 300 MHz

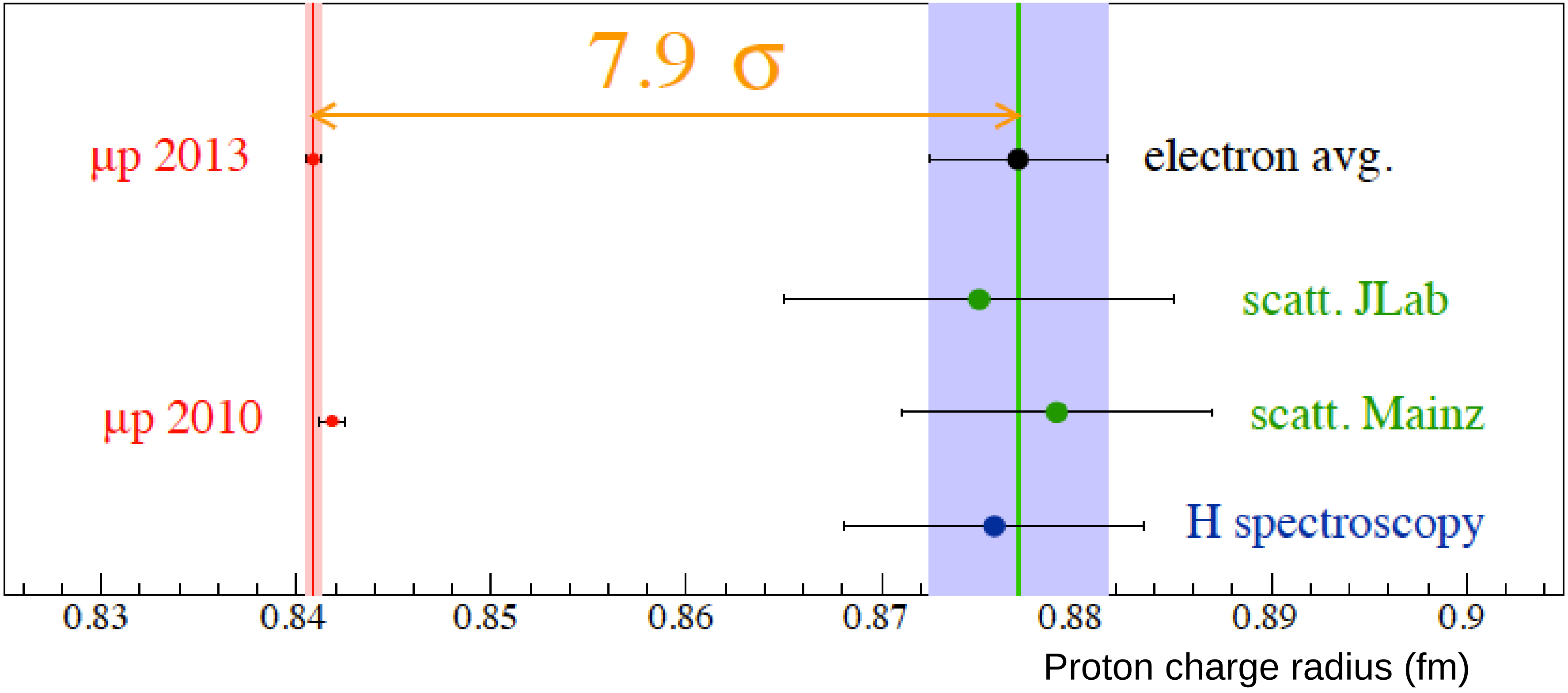
R. Pohl et al., Nature 466, 213 (2010):
0.84184 ± 0.00067 fm: 5σ off 2006 CODATA

The Proton Radius from H & μH Lamb Shift and ep



Puzzling & more Puzzling

- A. Antognini et al., Science **339**, 417 (2013)
- independent analysis of data of Pohl’s 2010 data
  - magnetic radius agrees with e^- scattering data
  - electric radius in agreement with Pohl: **0.84087 ± 0.00039 fm**
  - 7.9σ from 2010 CODATA



Why do the muon and electron give different proton radii?

- Are there problems with the experimental results?
  - The ep (scattering) results are wrong
    - fit procedures not good enough, Q^2 not low enough
  - The ep (spectroscopy) results are wrong
    - Rydberg constant could be off by 5 sigma
  - The μp (spectroscopy) result is wrong
- Assuming the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?
- Beyond Standard Model Physics
  - Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius → Lepton universality violation
- Proton structure issues
  - G. Miller: currently unconstrained correction proton polarizability affects μ, but not e (effect $\propto m_l^4$)
  - Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
- Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, ...

How do we Resolve the Radius Puzzle?

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - → BSM: scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - → Hadronic: enhanced 2γ exchange effects

- Experiments include
  - → redoing atomic hydrogen
  - → light muonic atoms for radius comparison in heavier systems
  - → redoing electron scattering at lower Q^2
  - → Muon scattering!

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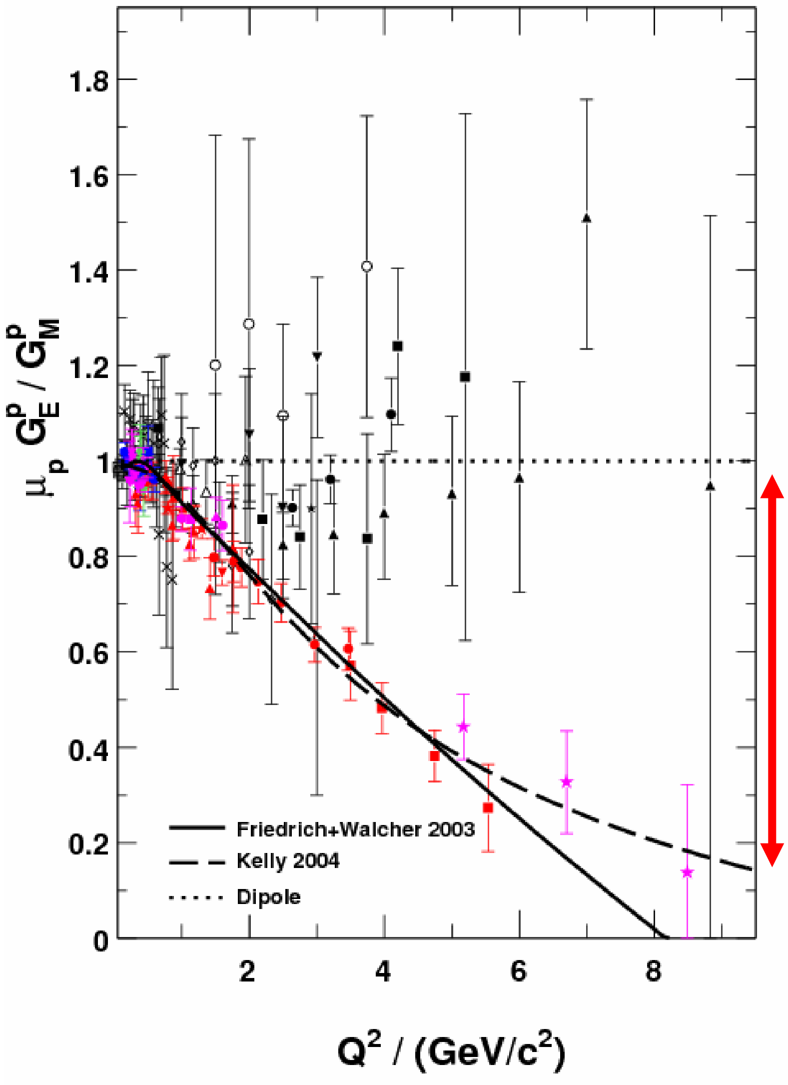
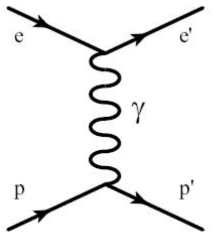
Proton Form Factor Ratio

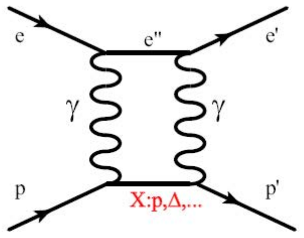


Dramatic discrepancy!

- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Two-photon exchange (TPE) considered best candidate
  - most prominent at high Q^2 and backward scattering angles, where cross section is suppressed



stand rad cor independent



TPE contributions to rad cor not independent

of hadronic structure

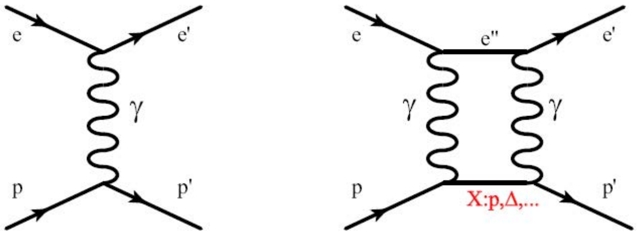
Two-photon exchange: exp. evidence

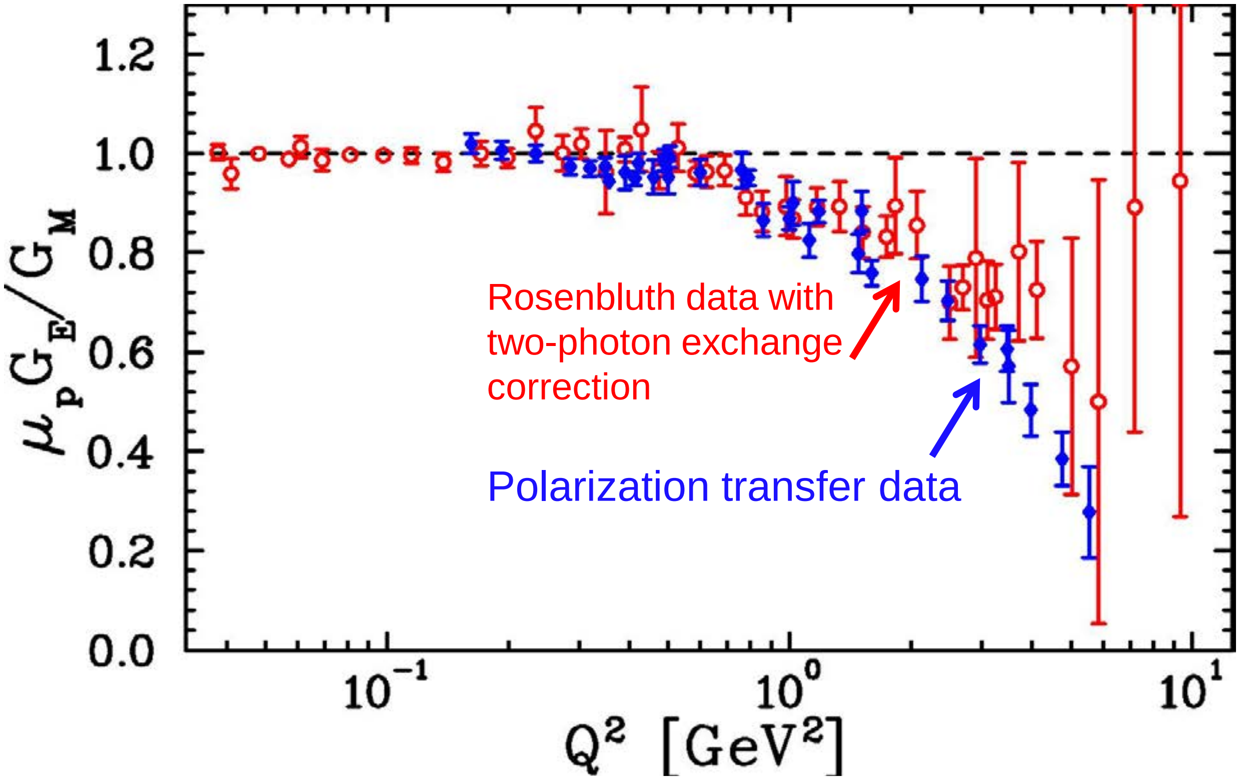
- TPE can explain form factor discrepancy

  J. Arrington et al, PRC76, 035205 (2007)

- TPE different for e^+ and e^- ?

- Are they the same for e and μ ?





Rosenbluth data with two-photon exchange correction

Polarization transfer data

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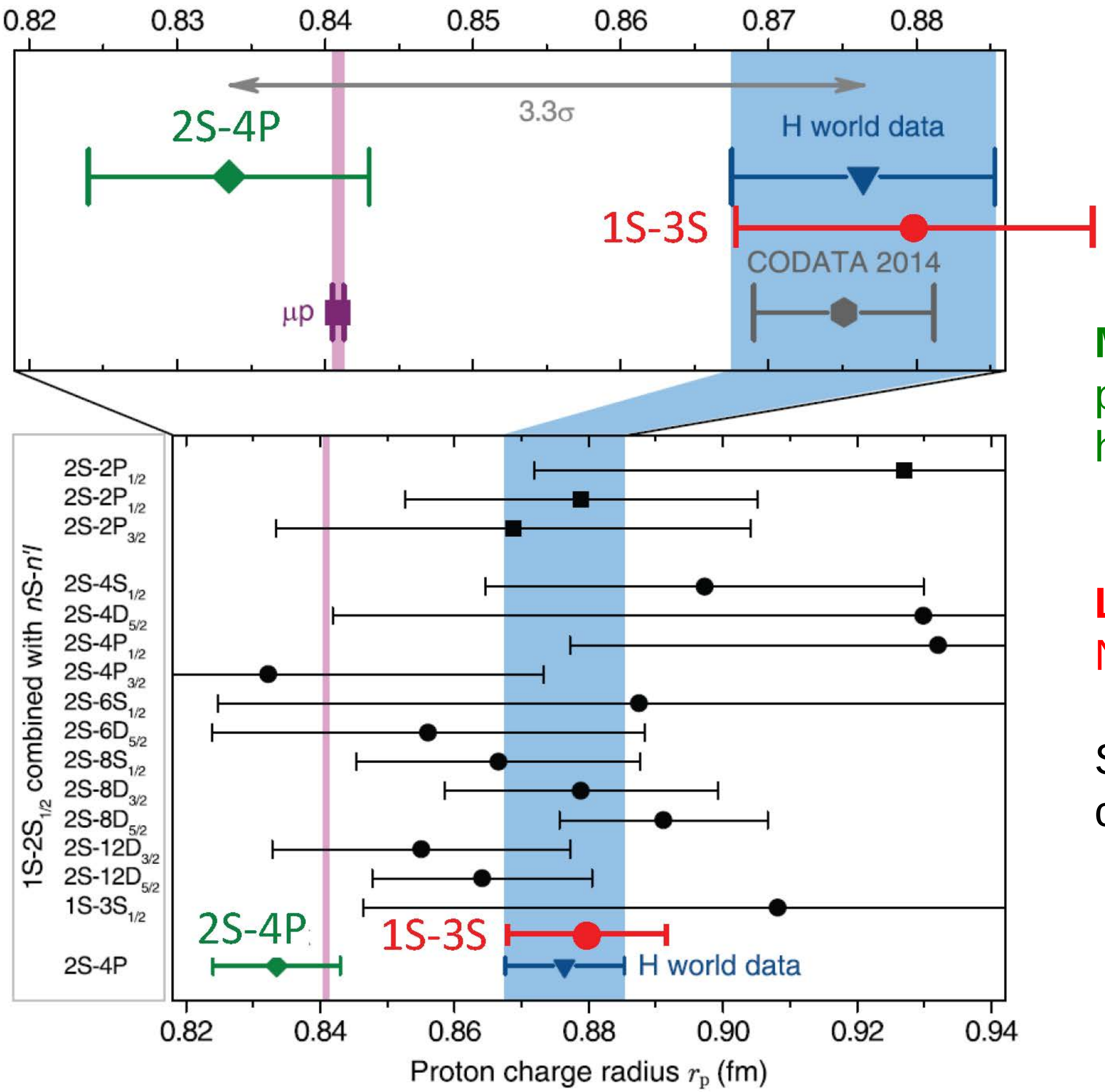
Redoing Atomic Hydrogen



MPQ (Garching): NEW proton is small in regular hydrogen, too!

LKB (Paris): Prelim. No, it's not!

Systematics need to be carefully determined

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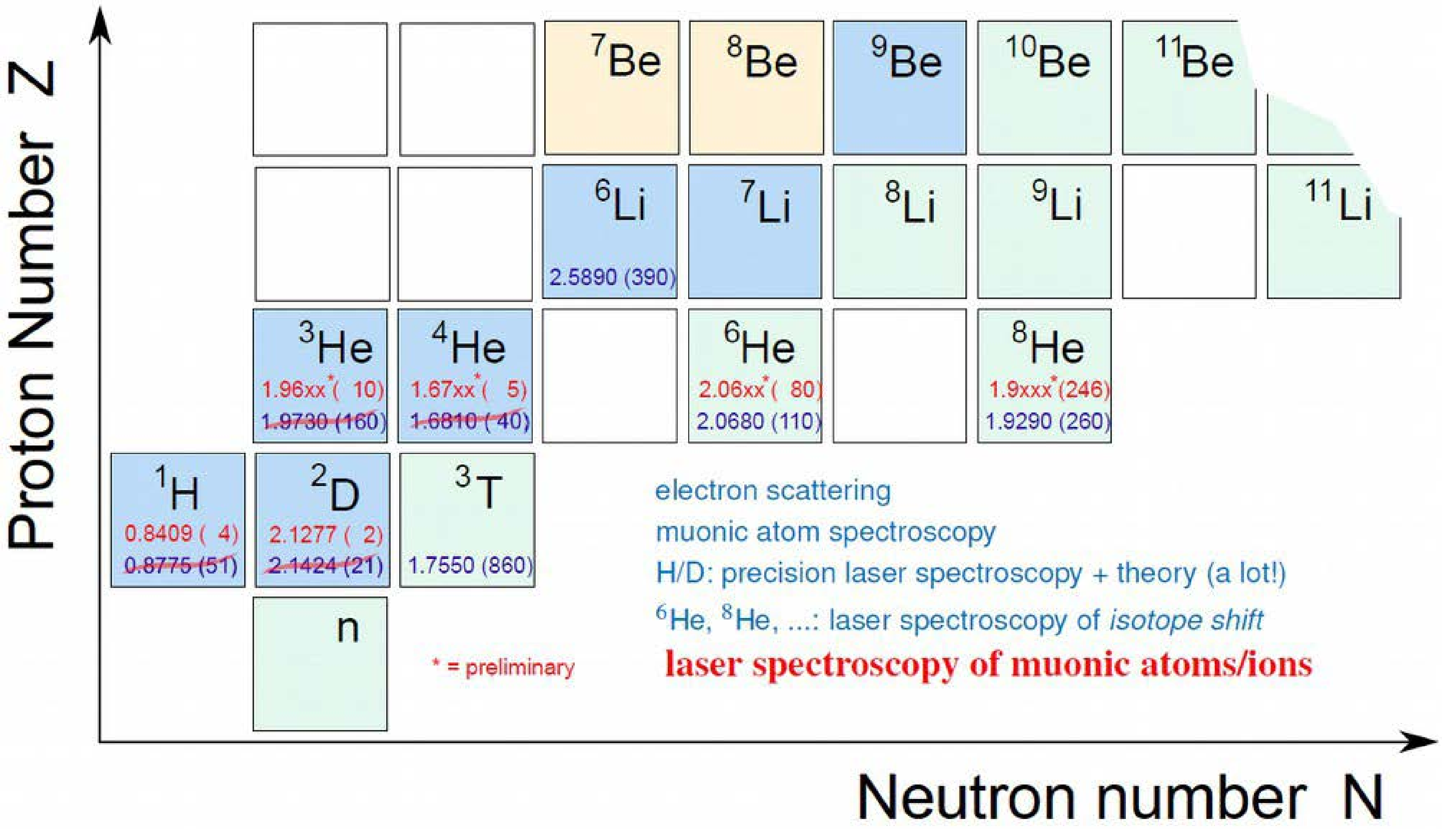
Light Muonic Atoms



- CREMA Collaboration moved on to heavier atoms!
- Deuterium radius from μD agrees with μH
  - deuteron charge radius: r_d again 7σ away from CODATA
- Helium isotopes seem to agree (preliminary results)
- Puzzle seen in H & D (Z=1 radius puzzle?)

Pictures: R. Pohl

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  → Hadronic: enhanced 2γ exchange effects γ

- Experiments include

  → redoing atomic hydrogen

  → light muonic atoms for radius comparison in heavier systems

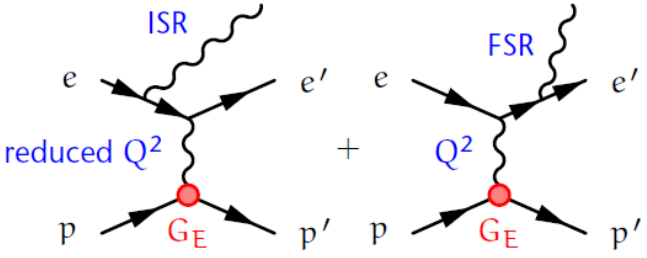
  → **redoing electron scattering at lower Q^2**

  NB: Many efforts, not an exhaustive list!!!!

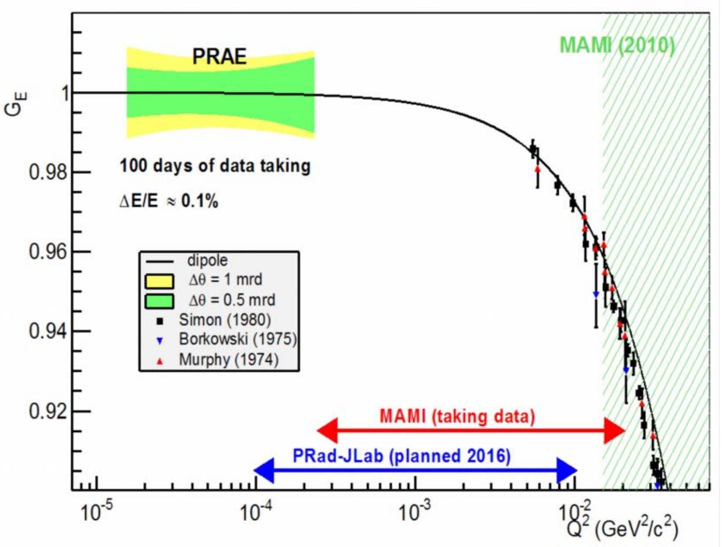
  → Muon scattering!

Redoing electron scattering at lower Q^2

- Jlab: PRad
  - low intensity beam in Hall B @ JLab into windowless gas target (1.3 billion H events)
  - Awaiting results
- Mainz: ISR
  - exploit information in radiative tail
  - dominated by coherent sum of ISR and FSR
  - investigate G_E down to $Q^2 = 10^{-4}$ GeV^2/c^2
  - results not precise enough → upgrades underway



- LPSC, Grenoble: ProRad
  - New accelerator to be built in France
  - constrain Q^2-dependence of G_E and extrapolation to zero
  - non-magnetic spectrometer, frozen hydrogen wire / film target



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  - → **Muon scattering!**

Motivation for μp scattering

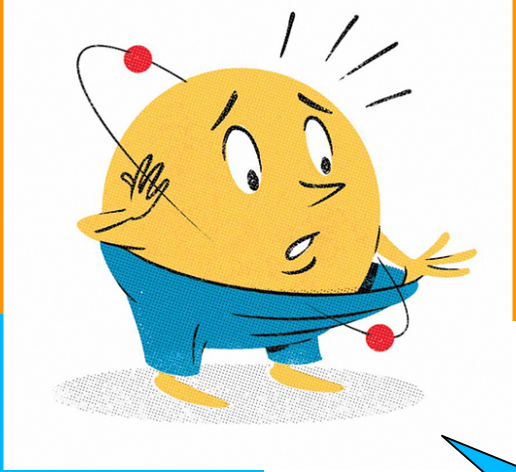
Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84087 ± 0.00039



Electron scattering

0.8770 ± 0.0060

Scattering

Muon scattering

???

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  - → BSM: scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - → Hadronic: enhanced 2γ exchange effects

MUSE will test

- Experiments include
  - → redoing atomic hydrogen
  - → light muonic atoms for radius comparison in heavier systems
  - → redoing electron scattering at lower Q^2
  - → **Muon scattering!**

Done

MμSE

MUon Scattering Experiment (MUSE) at PSI

Paul Scherrer Institute
Villigen, Switzerland

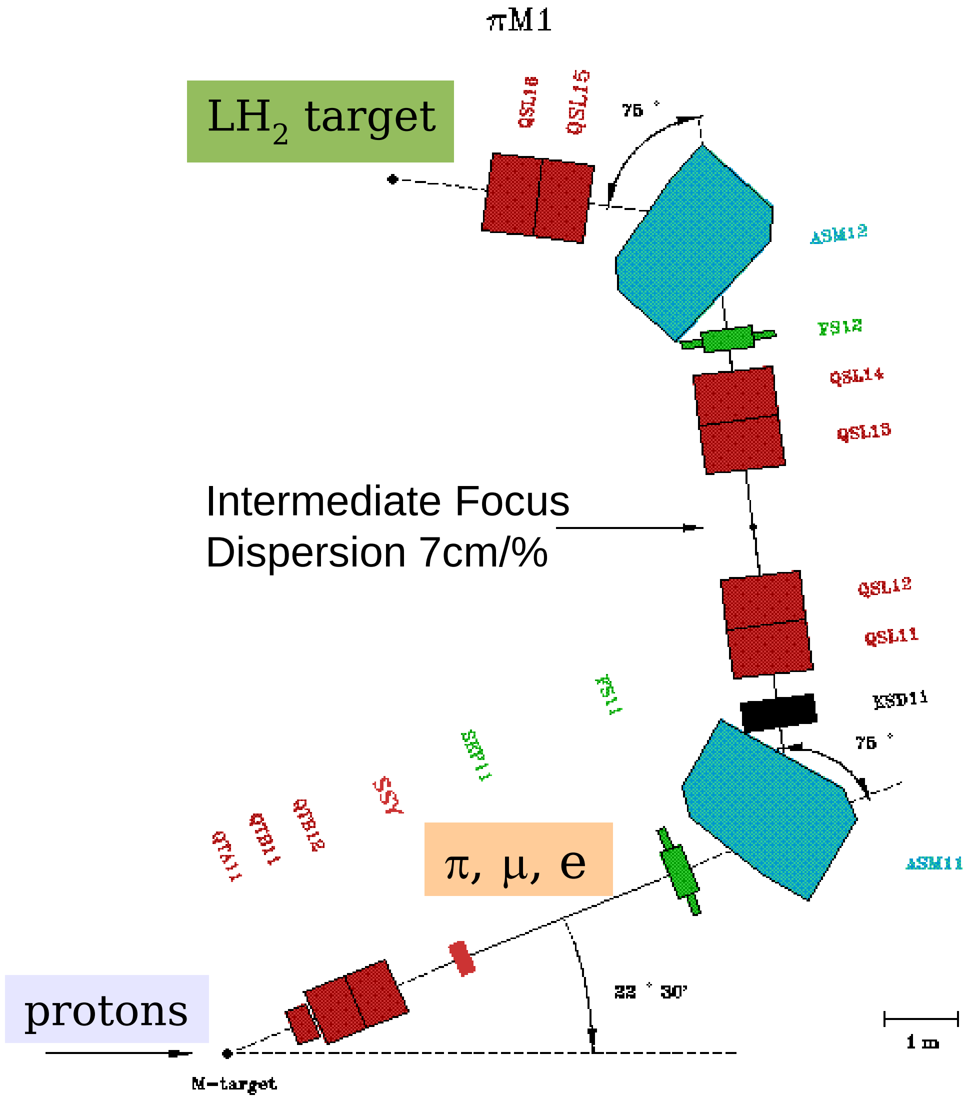
- Simultaneous measurement of e^+/ μ^+ e^-/ μ^- at beam momenta of 115, 153, 210 MeV/c in πM1 channel at PSI allows:
  - → Simultaneous determination of proton radius in both ep and μp scattering
  - → Test of Lepton Universality
  - → Determination of two photon effects
  - → Separation of G_E and G_M (Rosenbluth)

Paul Scherrer Institute πM1 Beam

- 590 MeV proton beam, 2.2mA, 1.3MW beam, 50.6MHz RF frequency
- World's most powerful proton beam
- Converted to $e^{\pm}$, $\mu^{\pm}$, $p^{\pm}$ in πM1 beamline
- Separate out particle species by timing relative to beam RF
- Cut as many pions as possible, trigger on $e^{\pm}$, $\mu^{\pm}$

πM1 / MUSE beamline

- πM1: 100-500 MeV/c RF+TOF separated π, μ, e

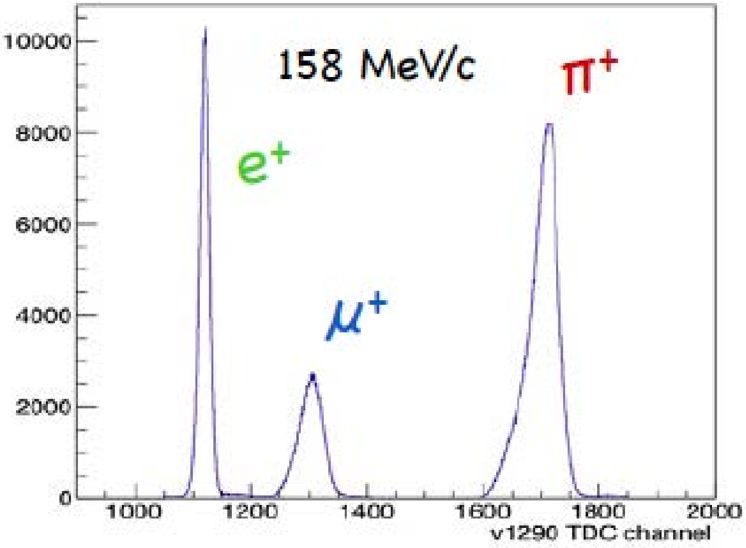


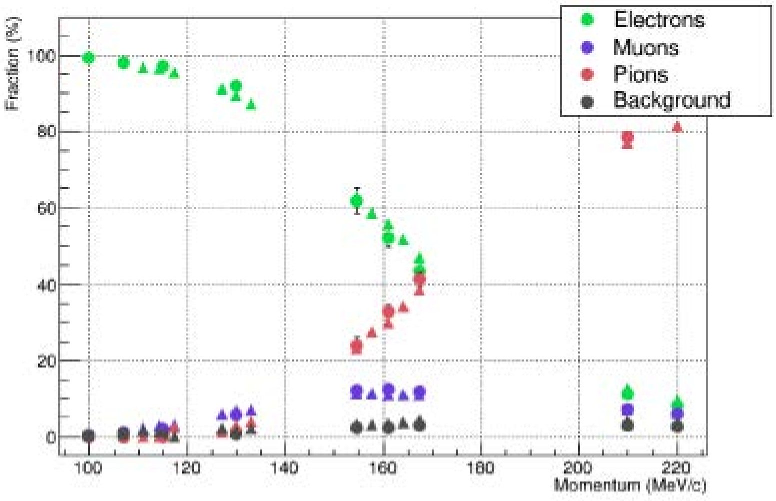
LH_2 target

Intermediate Focus
Dispersion 7cm/%

π, μ, e

protons





MUSE experiment layout

- Beam particle tracking
- Liquid hydrogen target
- Scattered lepton detection

Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

$p \approx 115, 153, 210$ MeV/c

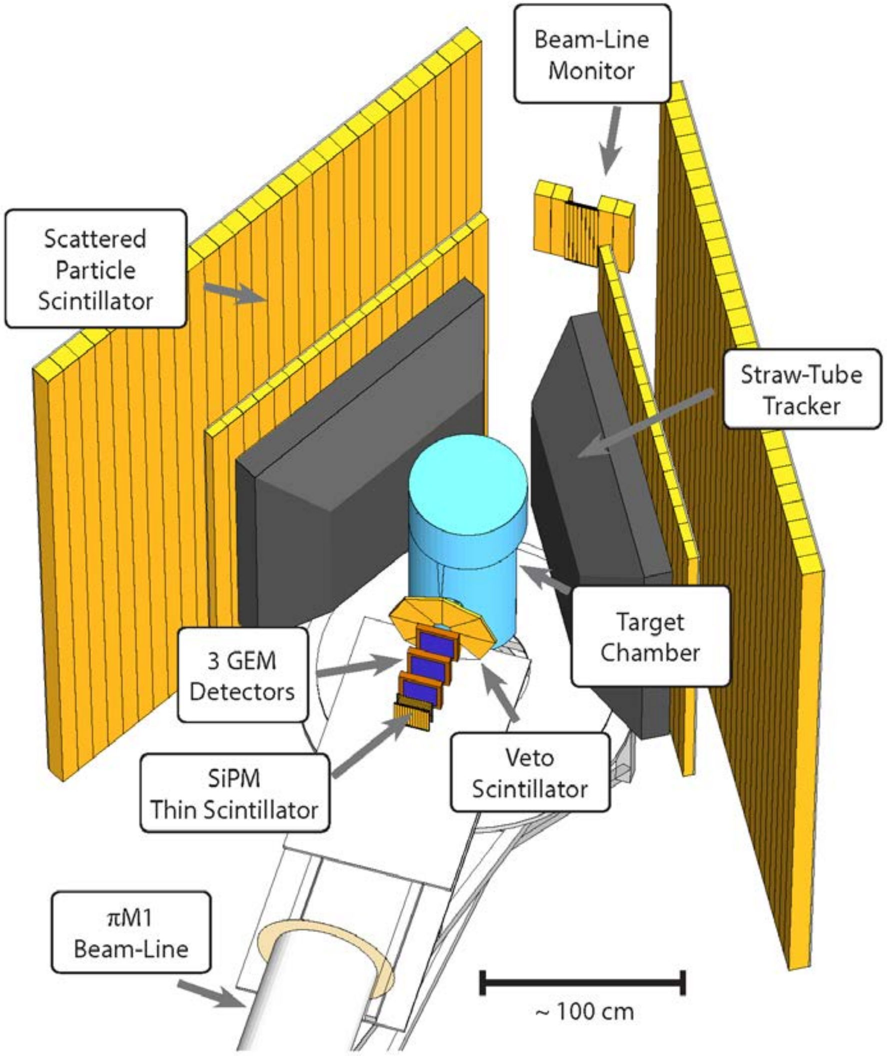
$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.002 - 0.07 \, (\mathrm{GeV/c})^2$

$\epsilon \approx 0.256 - 0.94$

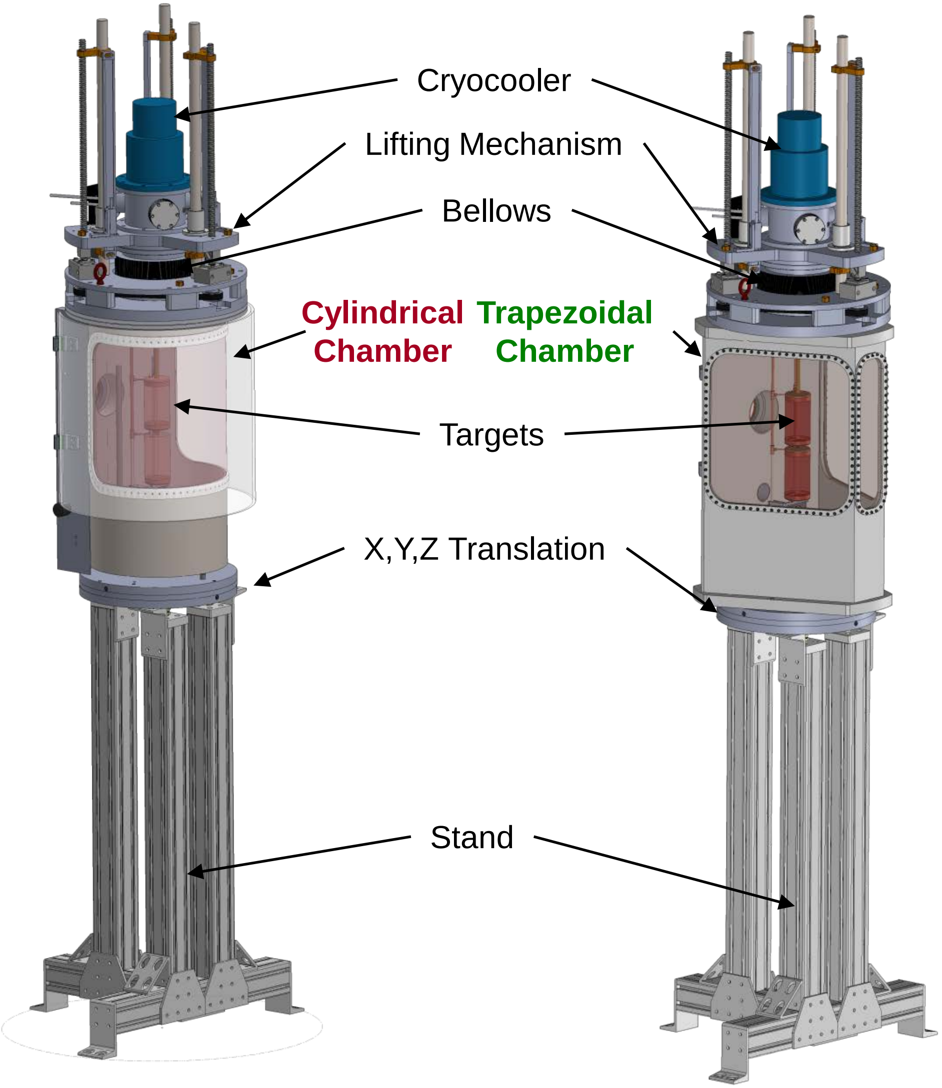
Challenges

- Secondary beam with π background
- Non-magnetic spectrometer
- Background from Møller scattering and muon decay in flight



MUSE Target Design

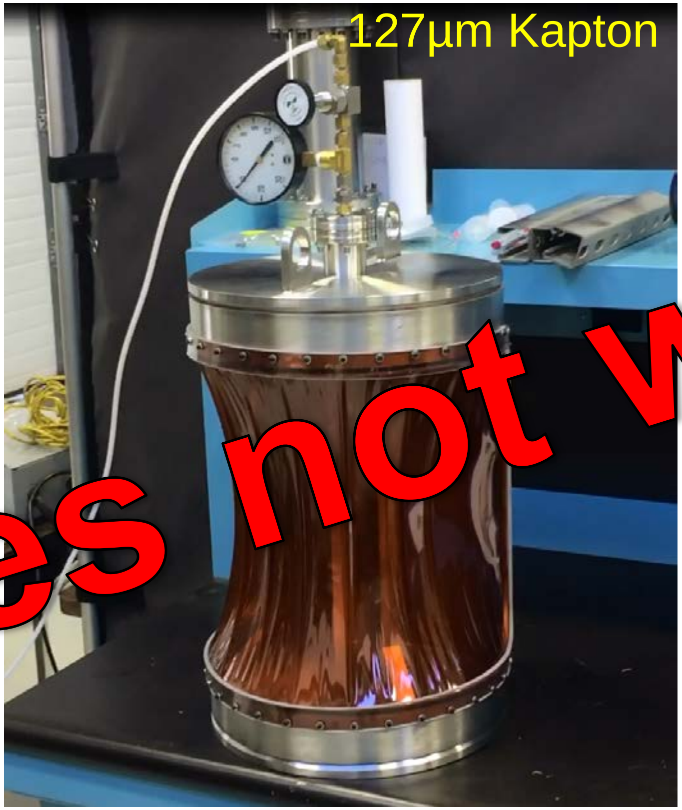
- Two chamber designs have been considered
  - Cylindrical chamber with a single wrap-around exit window
  - Trapezoidal chamber with three discrete exit windows
- Both designs use similar stands, target assemblies, and lifting lid assemblies
- Physicists prefer cylindrical chamber
- Engineers prefer trapezoidal chamber



Unsupported Windows form Pleats

- 127µm Kapton window deflecting inward about 2.5” (6.35cm) at about 0.5atm
- C785 sailcloth (258µm Kapton equivalent) at 1atm still forms pleats

Does not work



Window Burst Shortly after Photo

Flat Windows don’t form Pleats

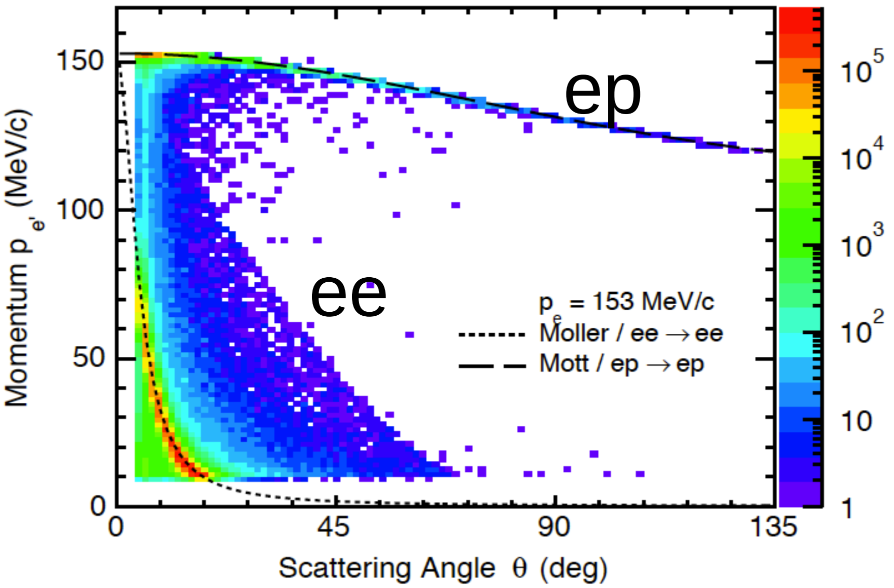
window deforms 68mm at 1atm

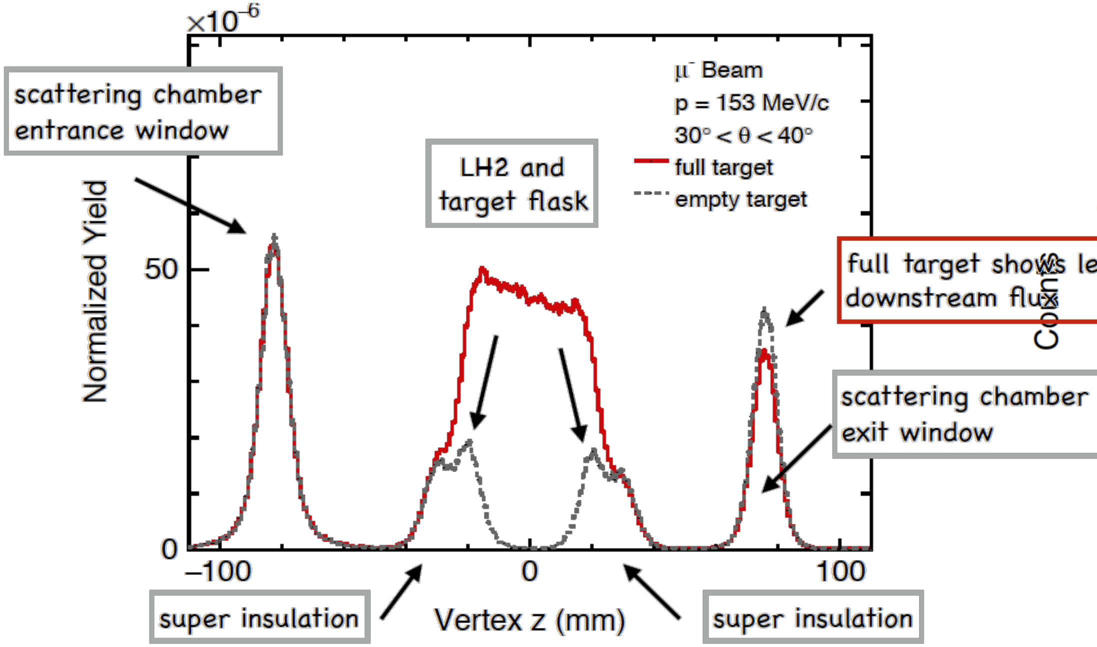
Mylar laminated on aramid fabric
window deforms 27mm at 1atm

Target Simulations

- Particle vertex and scattering-angle reconstruction meet MUSE requirements

- Background from target walls and windows can be cleanly eliminated or subtracted





scattering chamber entrance window

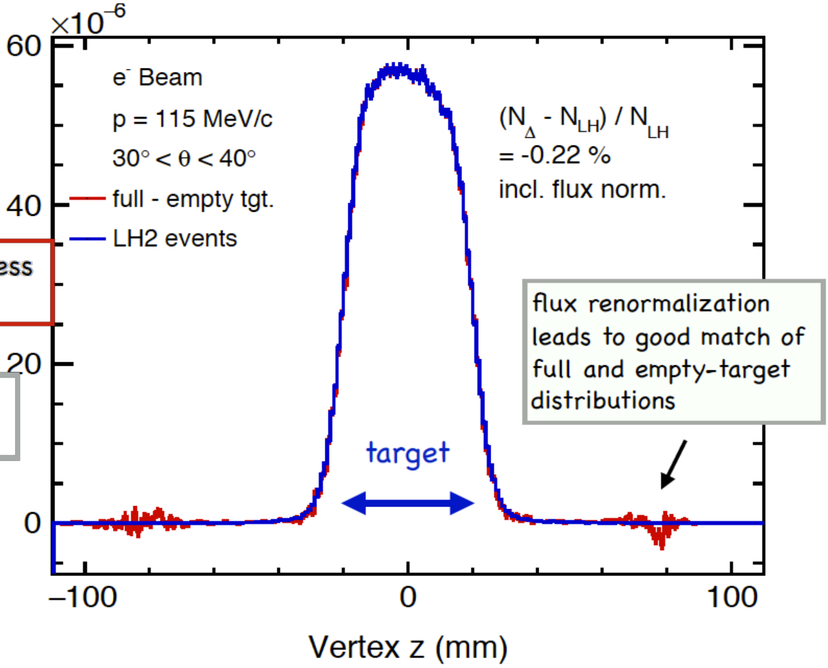
LH2 and target flask

full target shows less downstream flux

scattering chamber exit window

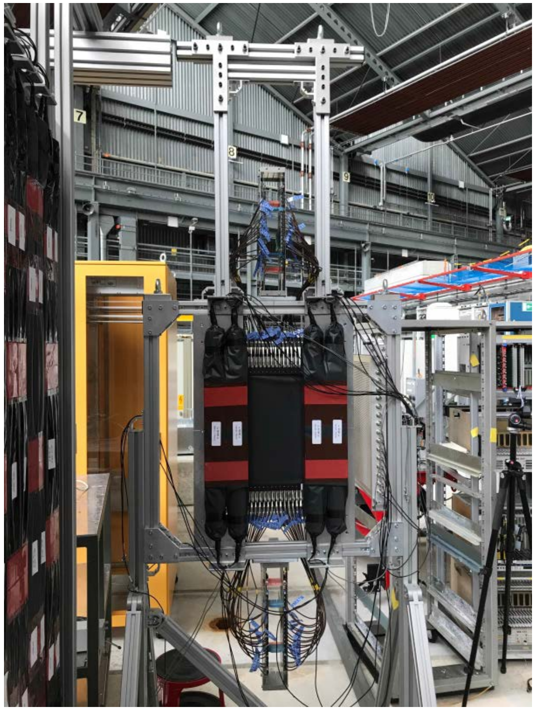
super insulation

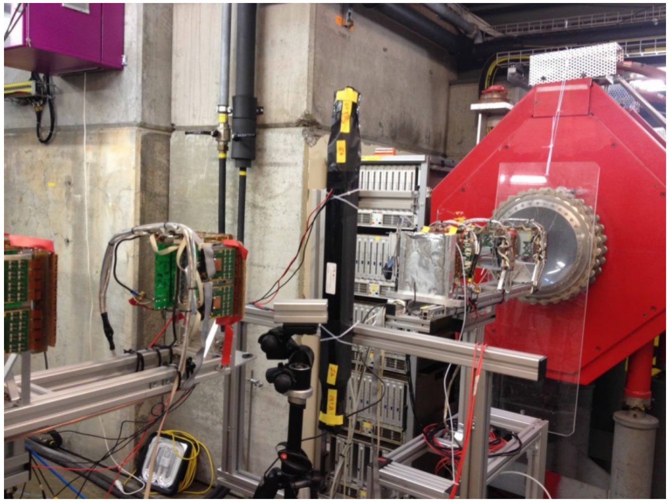
super insulation



flux renormalization leads to good match of full and empty-target distributions

MUSE status

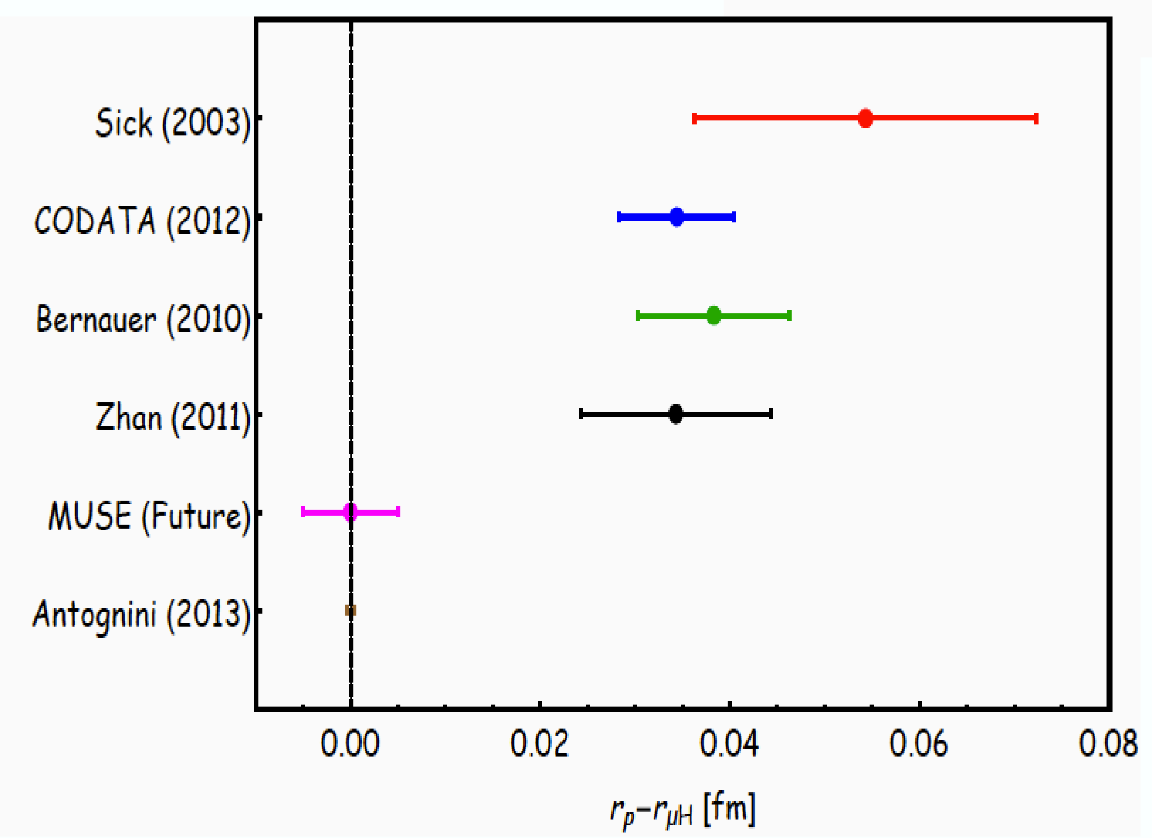




- 15 test runs (2012 – 2017) demonstrate simulation agreement & reliable performance
- Physics approved by PSI
- Construction fully funded by NSF in mid-September 2016
  - “Dress Rehearsal” run 2017: all beamline detectors, complete side of detector
  - Two commissioning runs in 2018: target complete, detector almost complete
  - Two six-month data-taking runs in 2019/20

Projected sensitivity for MUSE

- Extract radius from ep and μp form factors
- Error on radius difference ~0.009 fm
- MUSE will
  - verify the effect
  - compare form factors
  - compare cross sections
  - test two photon effect
  - solve the PRP?



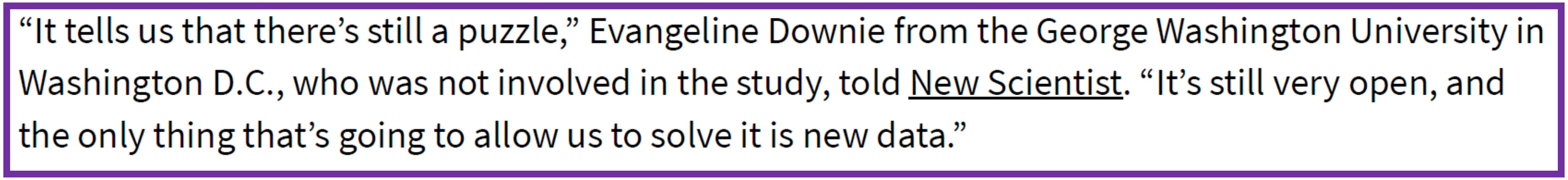
MUon Scattering Experiment (MUSE) at PSI

58 MUSE collaborators from 25 institutions in 5 countries:

A. Afanasev, A. Akmal, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, N. Benmouna, J. Bernauer, A. Blomberg, E. Brash, W.J. Briscoe, E. Cline, D. Cohen, E.O. Cohen, K. Deiters, J. Diefenbach, B. Dongwi, E.J. Downie, L. El Fassi, S. Gilad, R. Gilman, K. Gnanvo, R. Gothe, D. Higinbotham, Y. Ilieva, L. Li, M. Jones, N. Kalantarians, M. Kohl, G. Kumbartzki, J. Lichtenstadt, W. Lin, A. Liyanage, N. Liyanage, W. Lorenzon, Z.-E. Meziani, P. Monaghan, K.E. Mesick, P. Moran, J. Nazeer, C. Perdrisat, E. Piasetzsky, V. Punjabi, R. Ransome, R. Raymond, D. Reggiani, P.E. Reimer, A. Richter, G. Ron, T. Rostomyan, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, N. Steinberg, V. Sulkosky, A.S. Tadepalli, M. Taragin, and L. Weinstein

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem,,Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Ieizmann Institute, Old Dominion University

Conclusion



> "It tells us that there's still a puzzle," Evangeline Downie from the George Washington University in Washington D.C., who was not involved in the study, told New Scientist. "It's still very open, and the only thing that's going to allow us to solve it is new data."

- Spectroscopy
  - CODATA 2014 5.6σ from μH
  - μH disagrees with (almost) all atomic H
  - μD disagrees with atomic D (3.5σ disagreement)
  - ^{X}He results seem to agree (preliminary)
- Elastic scattering
  - Depending on extraction agrees with / disagrees strongly with μH
  - More low Q^2 measurements in preparation / analysis / underway
  - MUSE under construction to give first precise muon scattering results
- We are still (possibly more) puzzled!

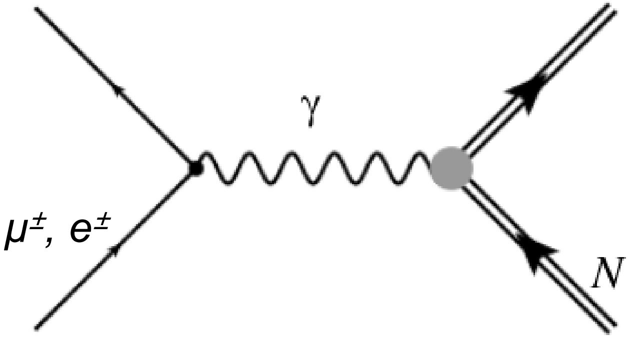
Outlook

- The proton radius puzzle is a high-profile issue
  - → Explanation unclear
  - → PSI MUSE tests interesting possibilities: Are μp and ep interactions different? If so, does it arise from 2γ exchange effects ($\mu^+ \neq \mu^-$) or BSM physics ($\mu^+ \approx \mu^- \neq e^-$)?
- Within 2-3 years we should start to see the muon scattering results, and possibly start to resolve the puzzle, perhaps seeing new physics!

Backup slides

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\overline{u}_e\gamma^\mu u_e$$

$$J_N^\mu = \overline{\psi}_N \left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N} \right] \psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivative in $Q^2 \to 0$ limit:

$$\boxed{\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2\to 0}}$$

$$\langle r_M^2 \rangle = -6 \frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\to 0}$$

Expect identical result for ep and μp scattering