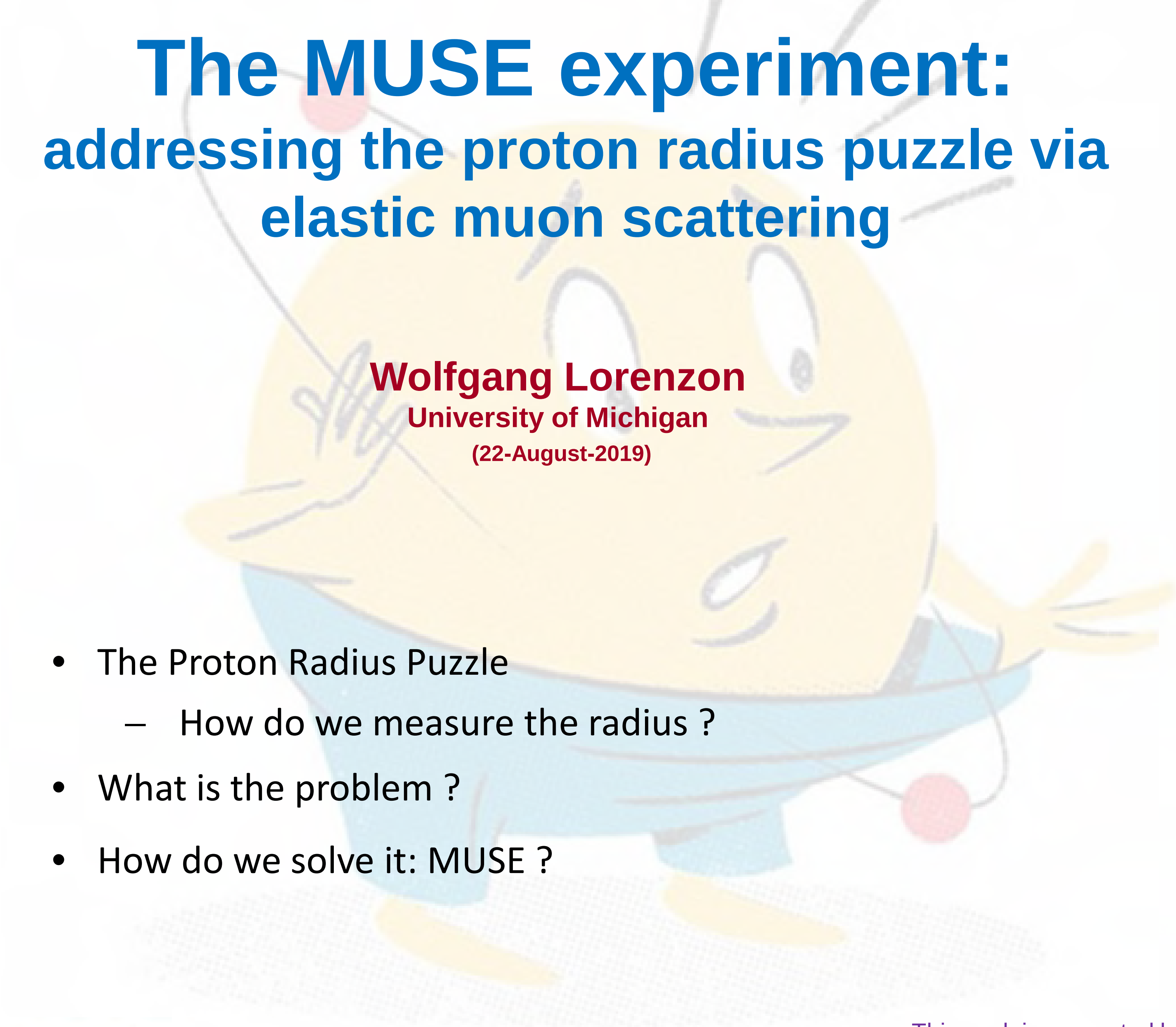


The MUSE experiment:
addressing the proton radius puzzle via elastic muon scattering

Wolfgang Lorenzon
University of Michigan

(22-August-2019)

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

This work is supported by NSF

The Proton Radius Puzzle

July 2010

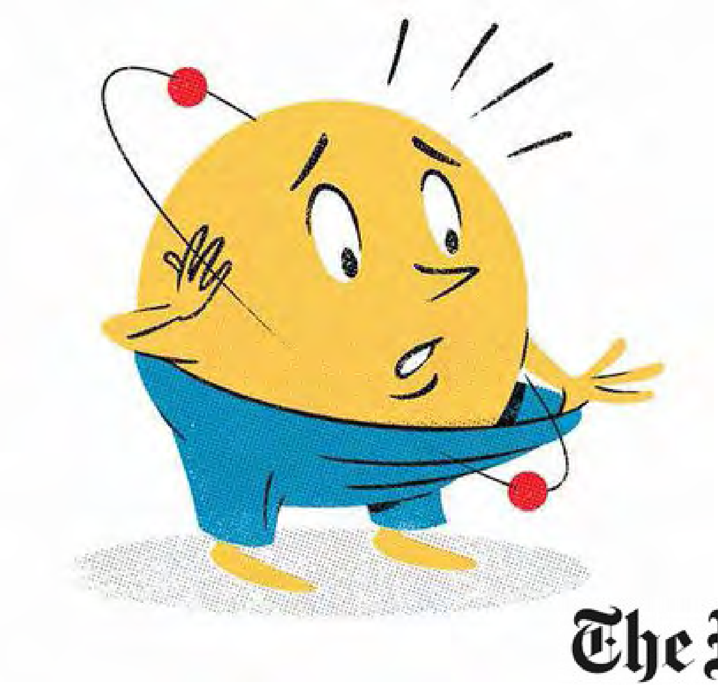
April 2013

July 2013

January 2014

The Proton Radius Puzzle

The Proton Radius Puzzle



The New York Times

- The Proton Radius Puzzle (PRP) has garnered a lot of interest!
- Not just interesting:
  - Tests our theoretical understanding of proton
  - Directly related to the strength of the Strong Interaction (QCD)
- What exactly is the puzzle ?

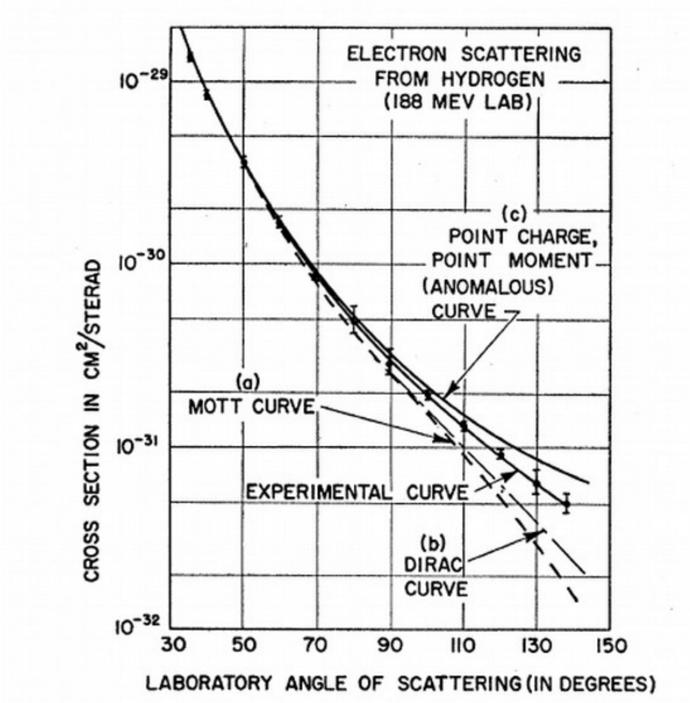
How do you measure proton radius?

- Scattering experiments

  (Hofstadter @ Stanford: 1950s - electron scattering)

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

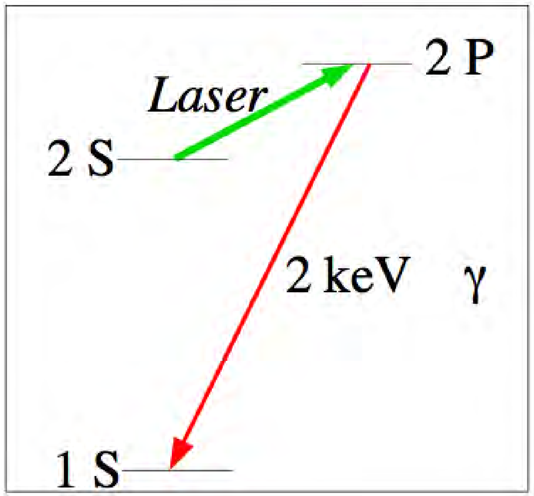
$$\left\langle r_E^2 \right\rangle = -6 \left.\frac{dG(Q^2)}{dQ^2}\right|_{Q^2=0}$$



- Atomic Energy Levels

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

  - Lamb Shift: Finite size of proton changes hydrogen energy levels
  - Extract from hydrogen spectroscopy



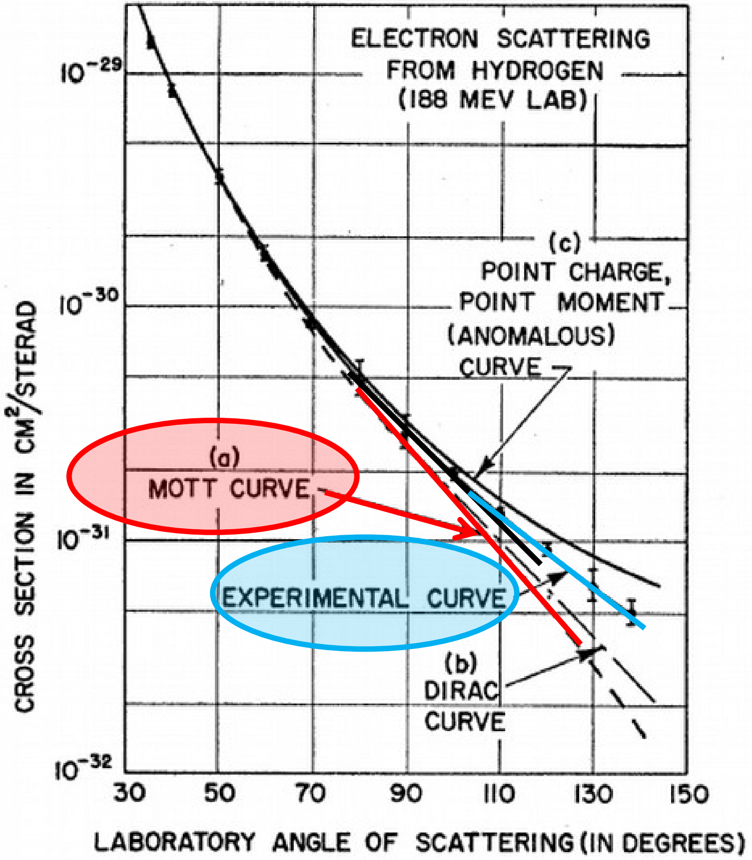
Electron Scattering Measurements (1950s)

Robert Hofstadter (1915 - 1990)

1961: Nobel prize Physics:

> "for his pioneering studies of **electron scattering** in atomic nuclei and for his consequent discoveries concerning the **structure of nucleons**"

$$r_E : 0.74(\pm 0.24)\ fm$$



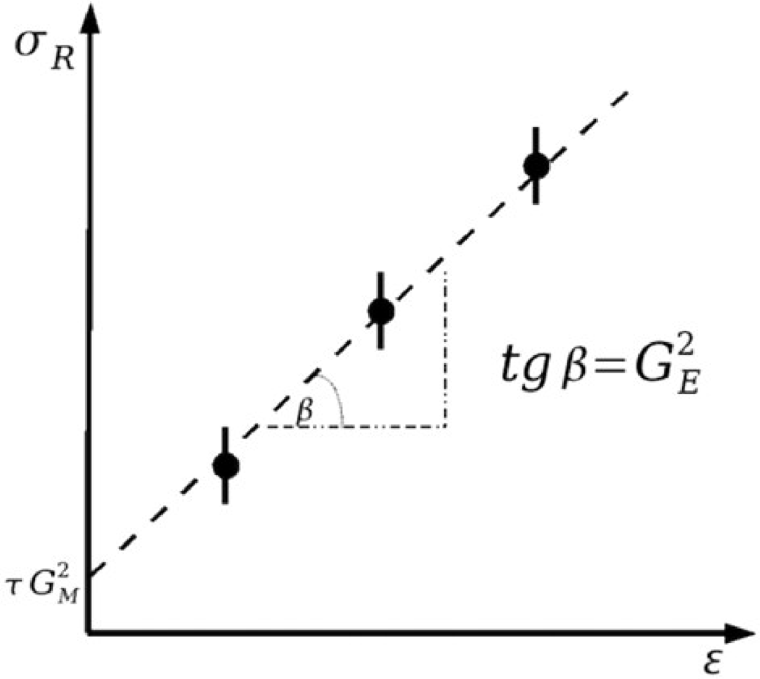
Electron Scattering Measurements

- Cross section for ep scattering (Born approximation)

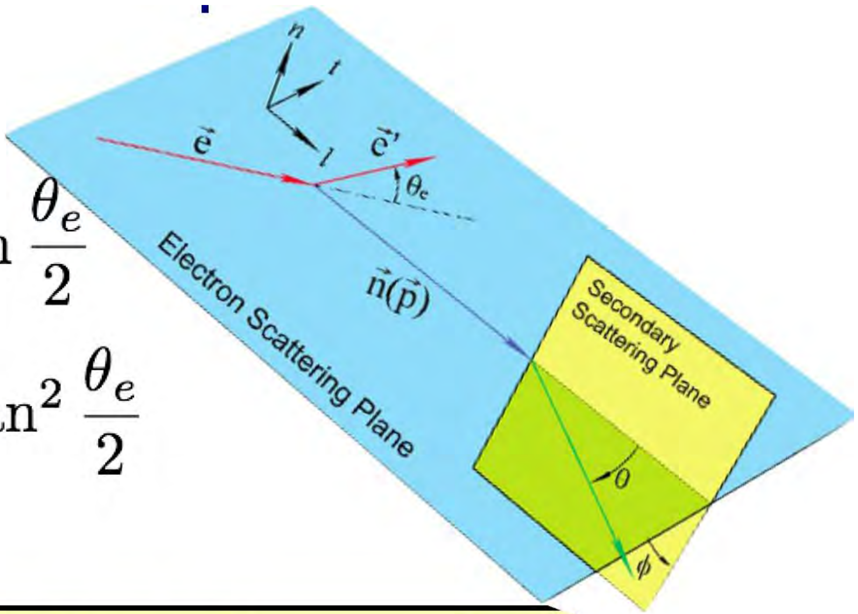
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{Mott} \frac{1}{\varepsilon(1+\tau)} \overbrace{\left[\underbrace{\tau {\color{blue}G_M^2}}_{\text{current density}} + \underbrace{\varepsilon {\color{red}G_E^2}}_{\text{charge distr.}}\right]}^{\sigma_R}; \quad \text{with } \tau = \frac{Q^2}{4M^2}\ ; \ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

$${\color{red}G_E^2(0) = 1}; \quad {\color{blue}G_M^2(0) = \mu_p}$$

- 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
- Note: G_M is suppressed at low Q^2 → G_E dominates cross section at low Q^2
- Alternatively: direct fits of $G_M(Q^2)$ and $G_E(Q^2)$ to experimental cross section data



Electron Scattering Measurements w/ polarization



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

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

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

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

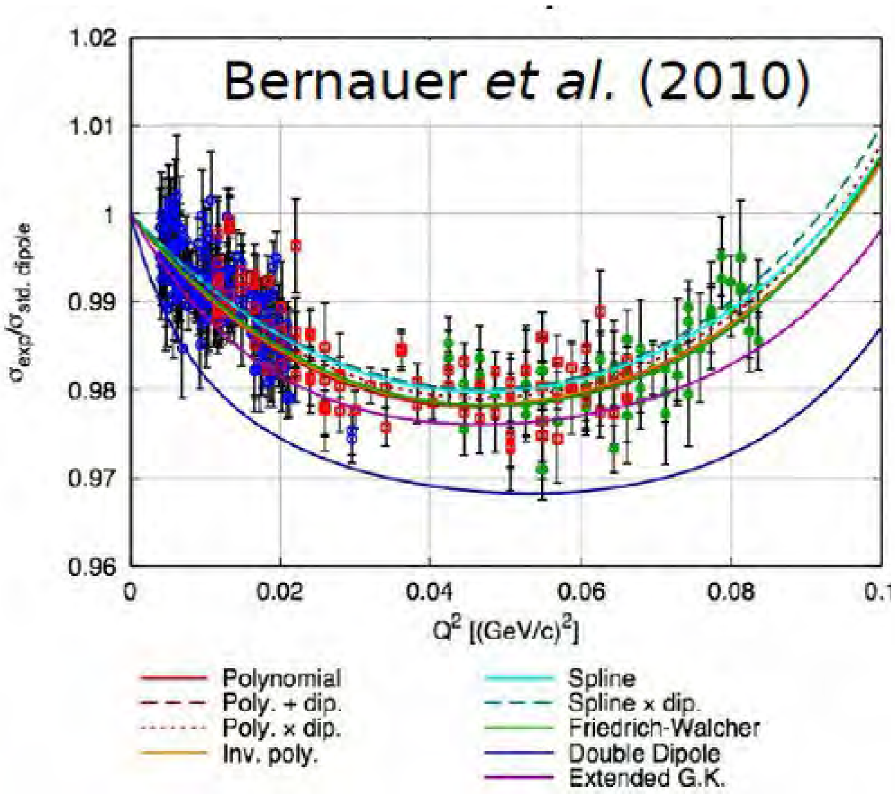
- Double polarization in elastic e-p scattering
  - measure recoil polarization or with (vector) polarized target

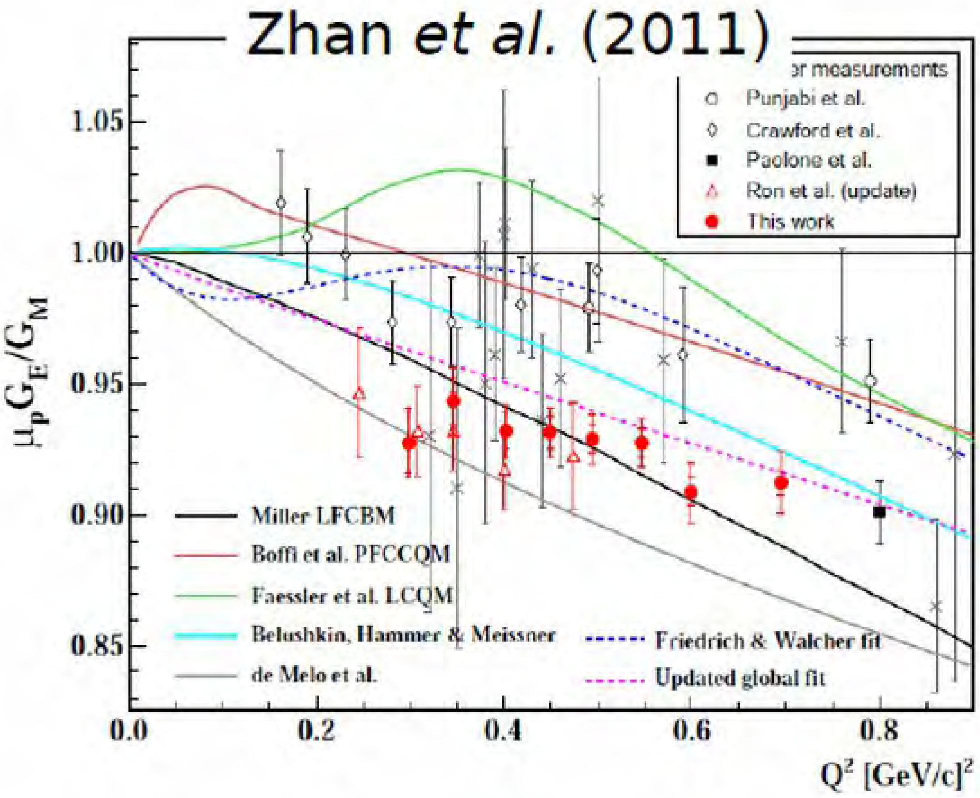
$^{1}\mathrm{H}(\vec{e},e'\vec{p})$, $^{1}\vec{\mathrm{H}}(\vec{e},e'p)$

- A single measurement gives ratio of form factors

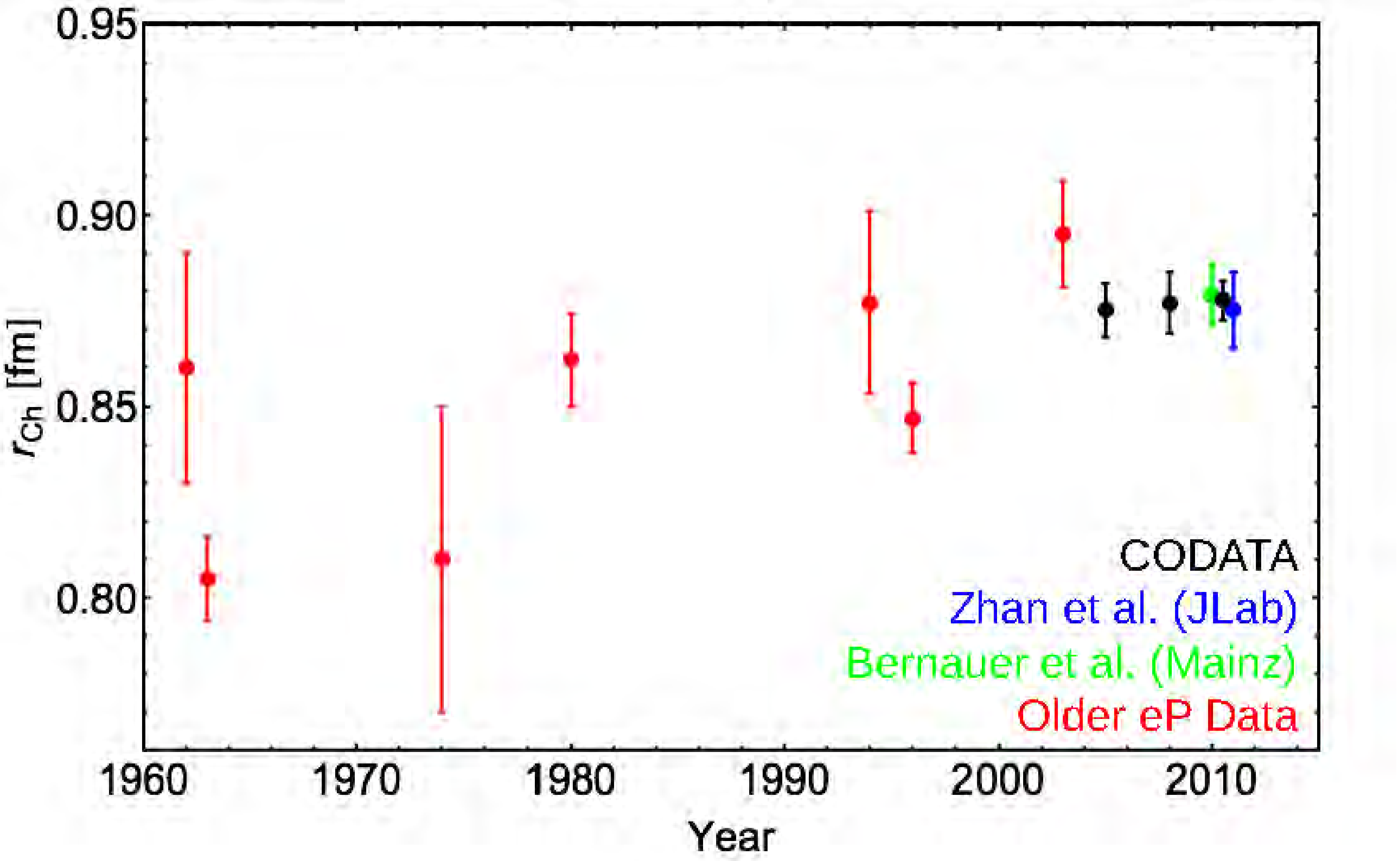
Electron Scattering Measurements (2010s)

- 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: Polarization measurements to get G_E/G_M, available over a large Q^2 range
  - fit(Jlab + world – Bernauer) gives radius compatible with Bernauer





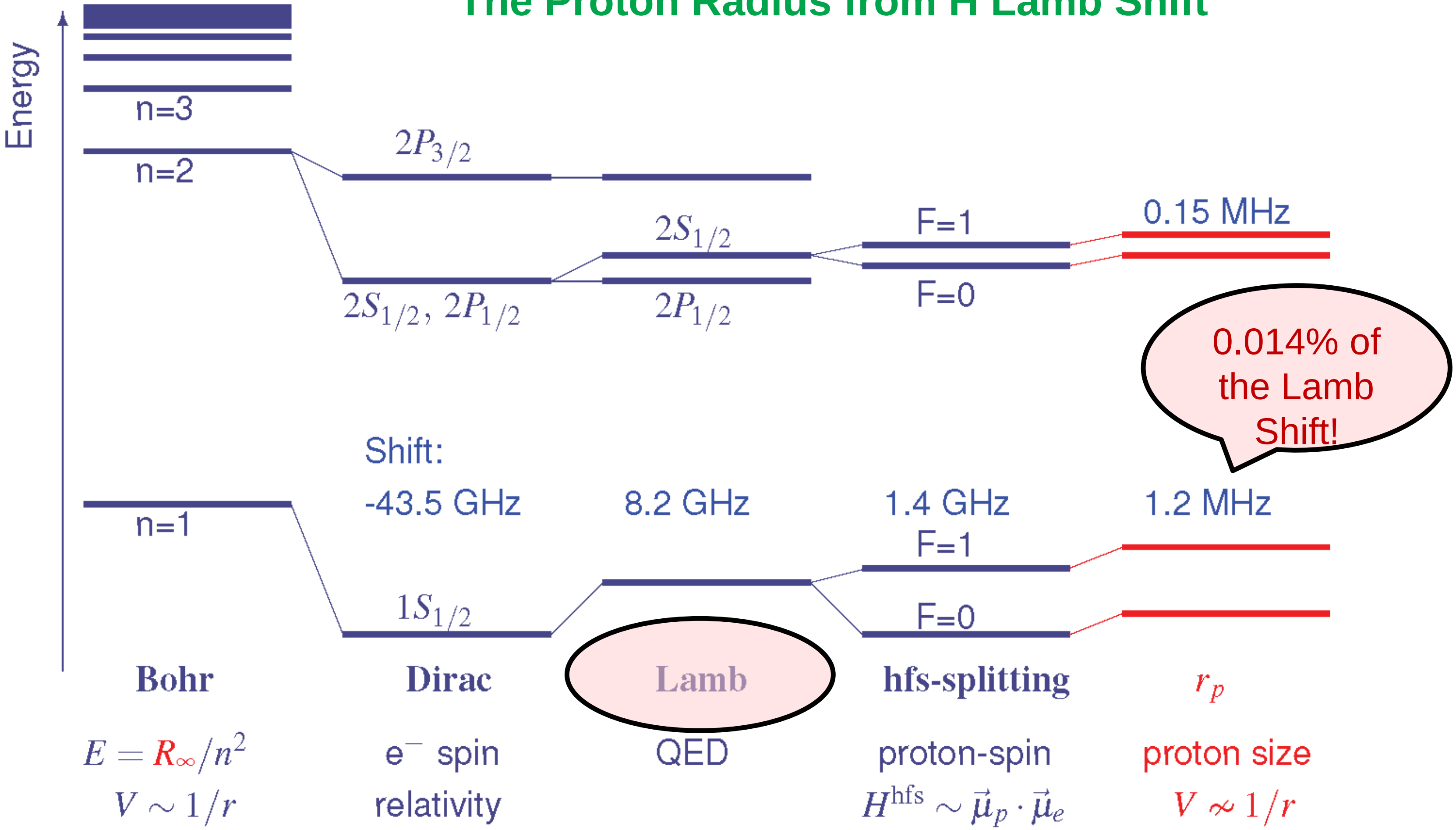
The Proton Radius vs Time from ep data



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

Hydrogen Spectroscopy Measurements

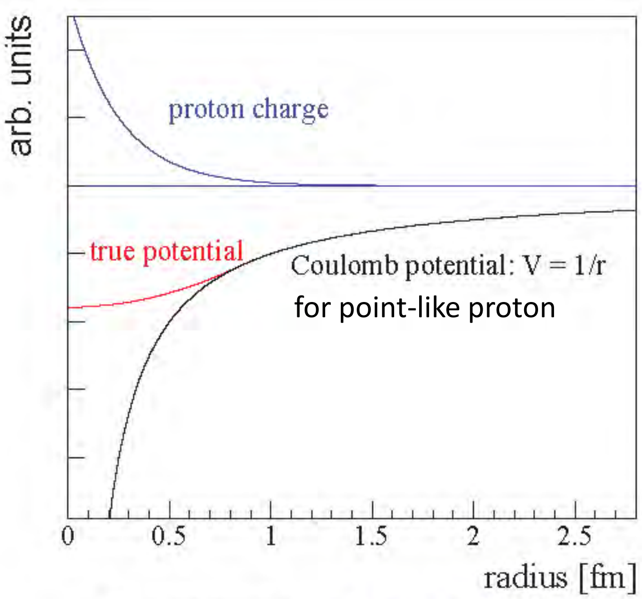
The Proton Radius from H Lamb Shift

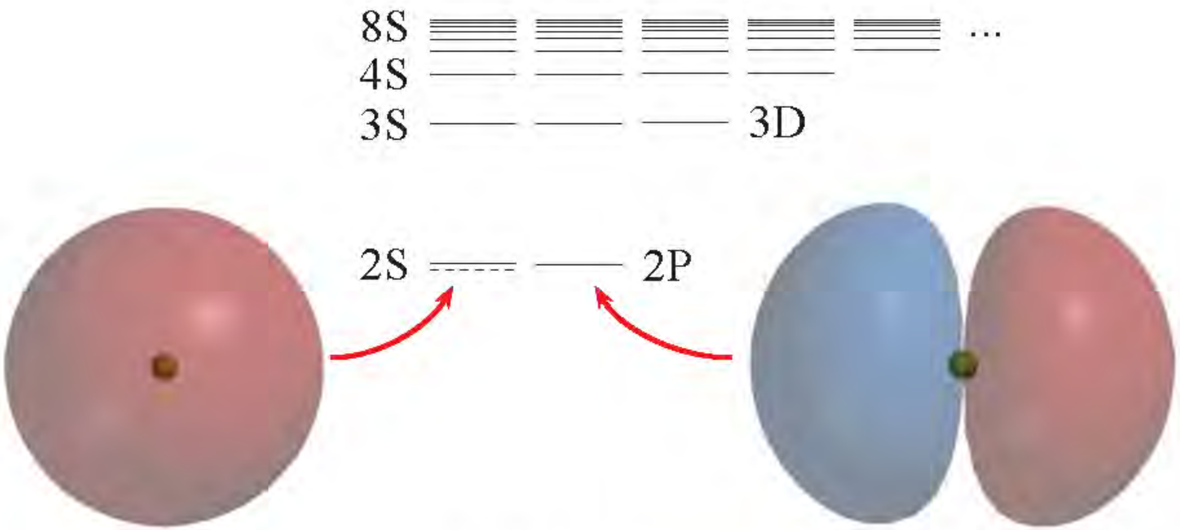


0.014% of the Lamb Shift!

comparing measurements with QED calculations that include corrections for finite size of proton provide indirect but very precise value for $\langle r_E^2 \rangle$

Finite-size shift of atomic energy levels





S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

size of the proton

P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

Pictures: R. Pohl

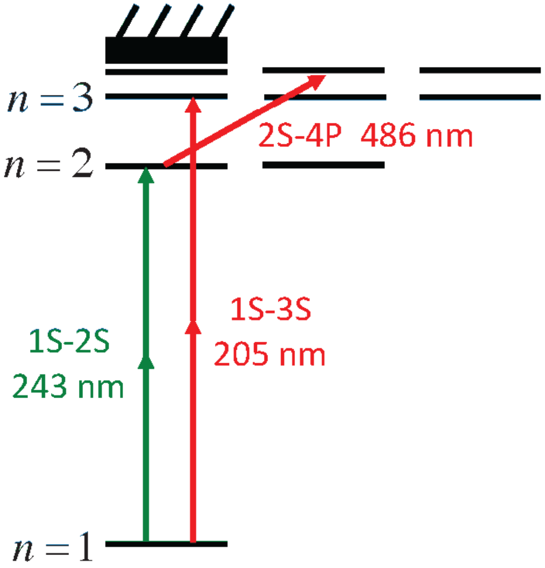
Hydrogen Atom Spectroscopy

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

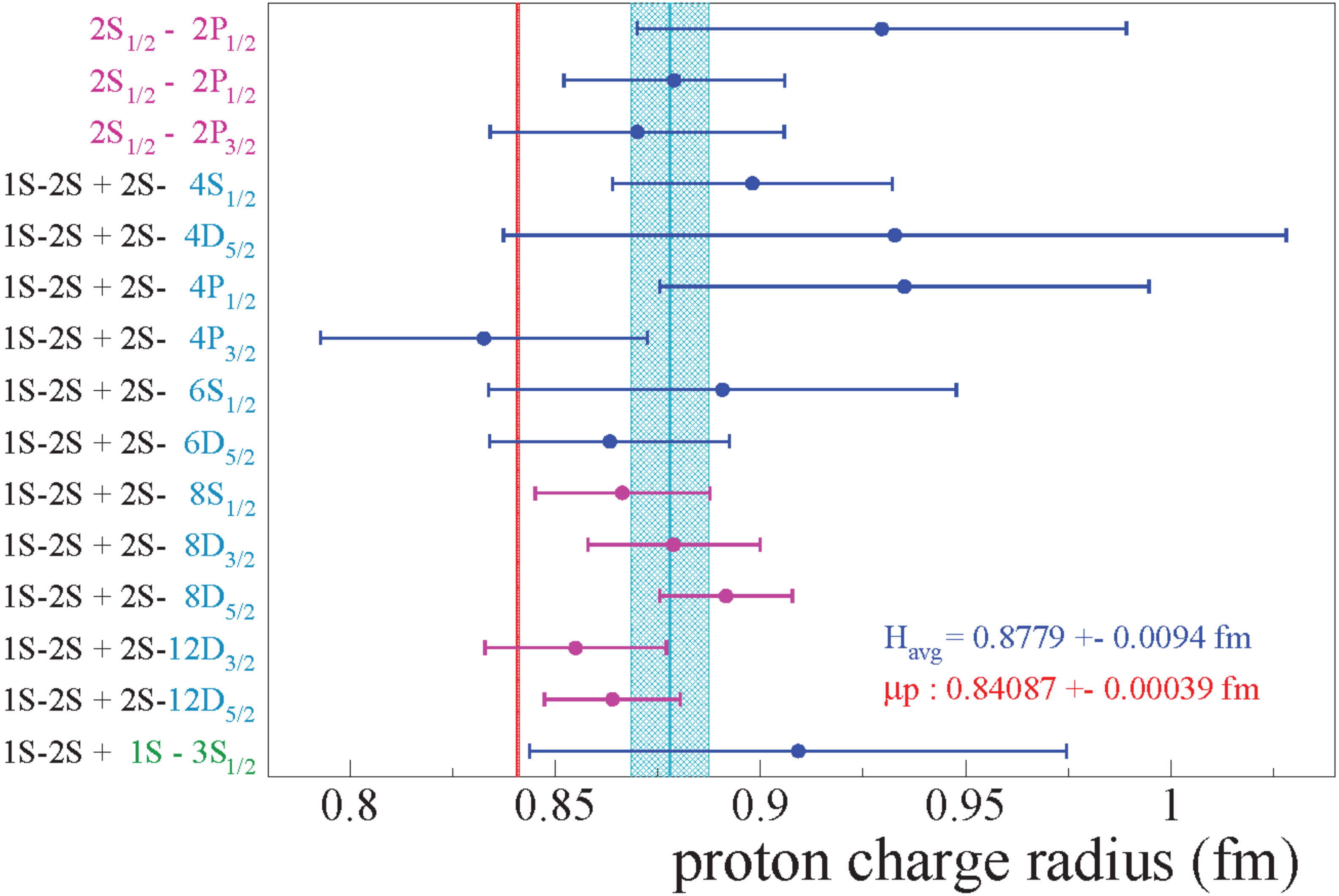
$$\text{Lamb shift}: \quad L_{1S}(r_\mathrm{p}) = 8171.636(4) + 1.5645 \langle r_\mathrm{p}^2 \rangle \ \mathrm{MHz}$$

- 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).

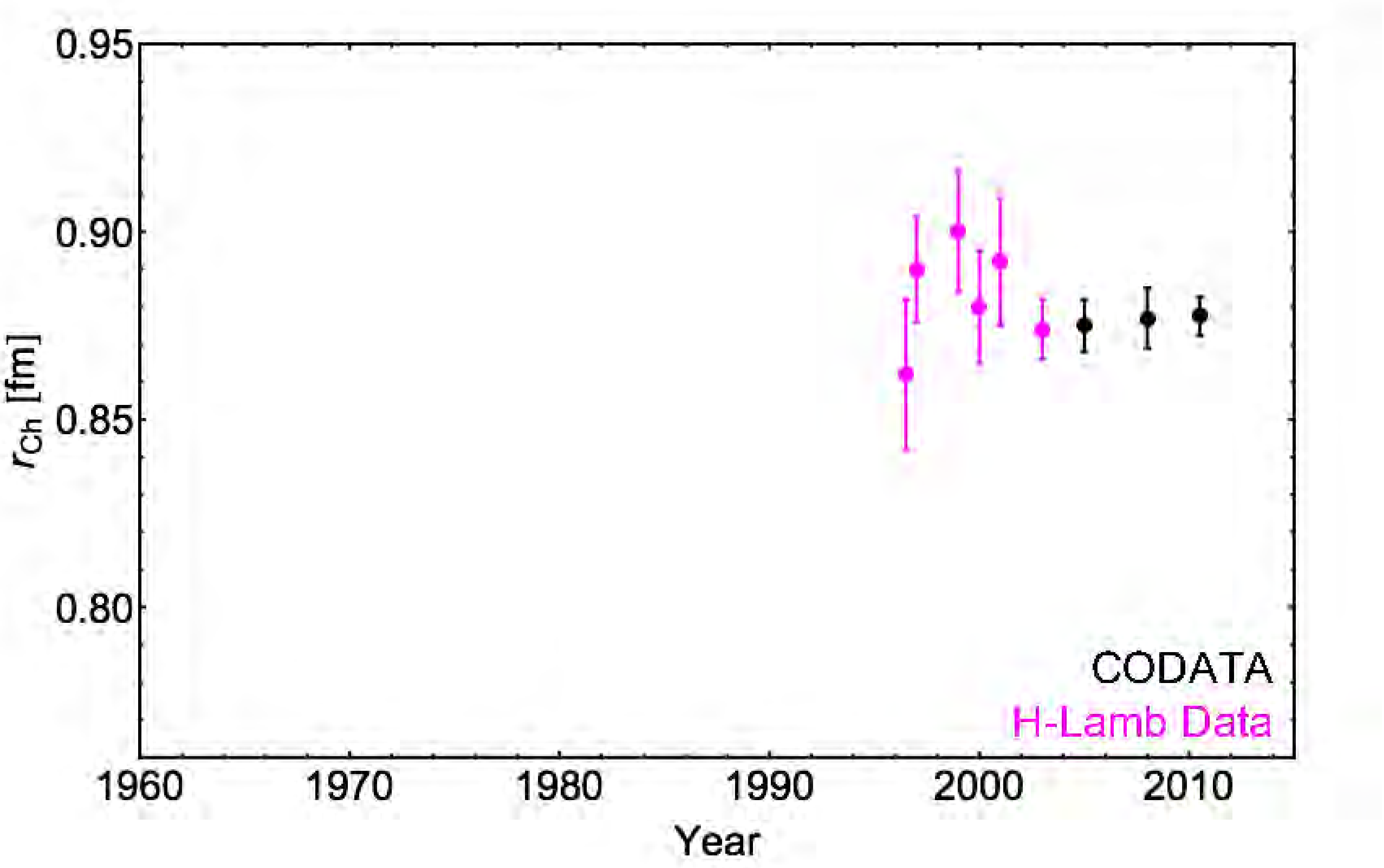


Hydrogen Atom Spectroscopy

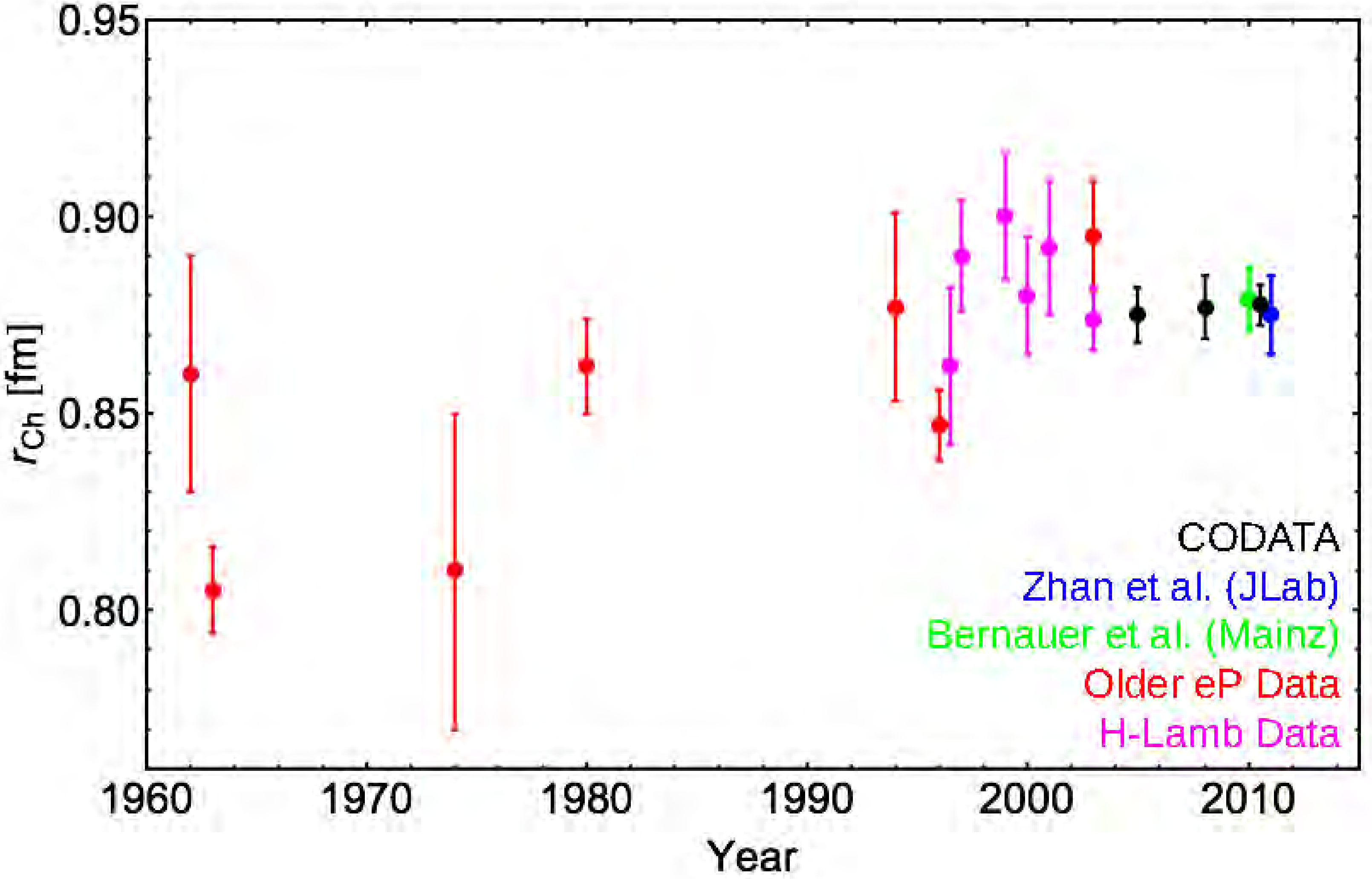


μH and eH difference is only significant when results are averaged

The Proton Radius vs Time from H Lamb Shift data

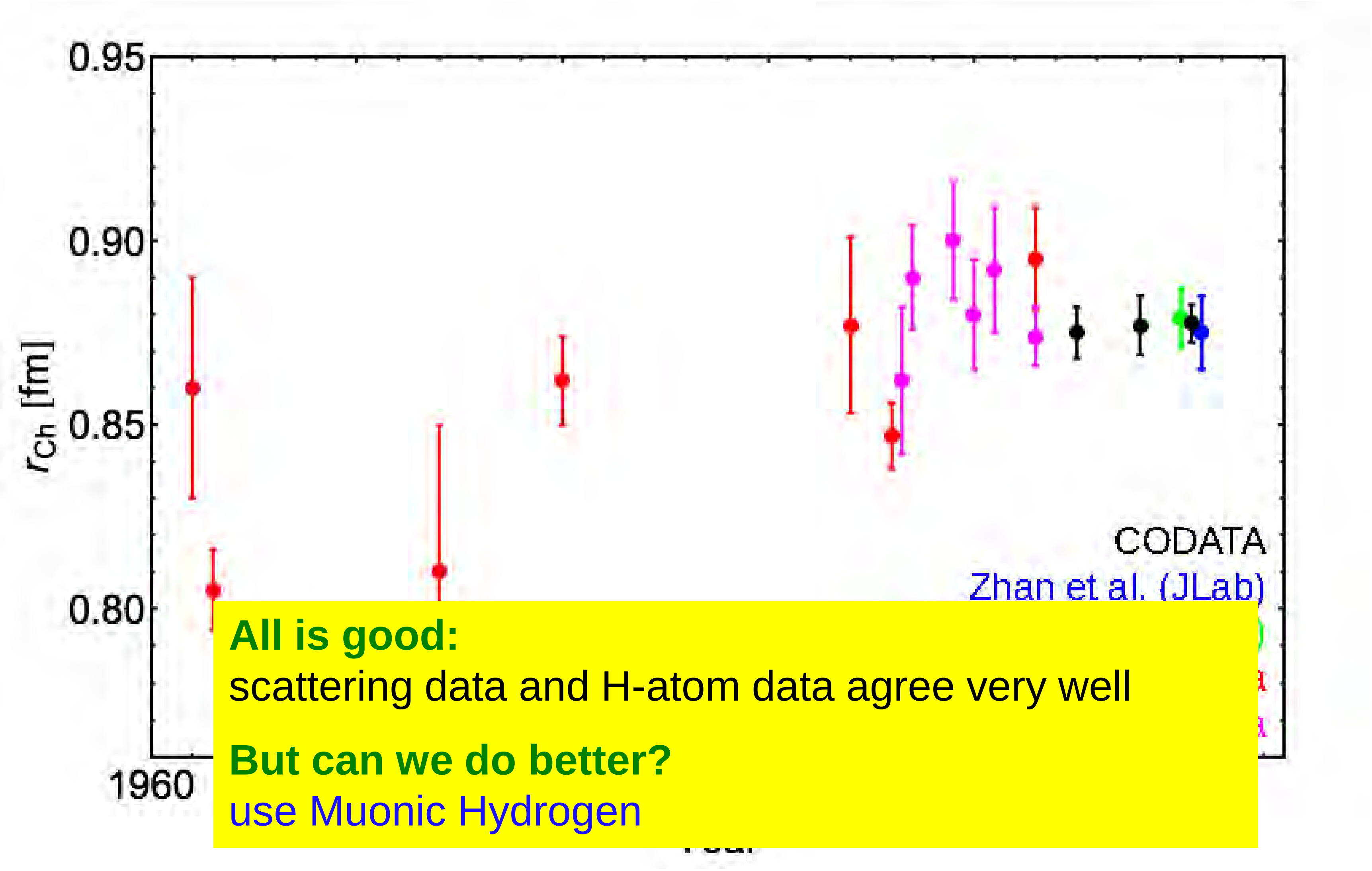


The Proton Radius from H Lamb Shift and ep



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

The Proton Radius from H Lamb Shift and ep



All is good:
scattering data and H-atom data agree very well

But can we do better?
use Muonic Hydrogen

Why Measure with μH ?

Regular hydrogen:

electron e^- + proton p

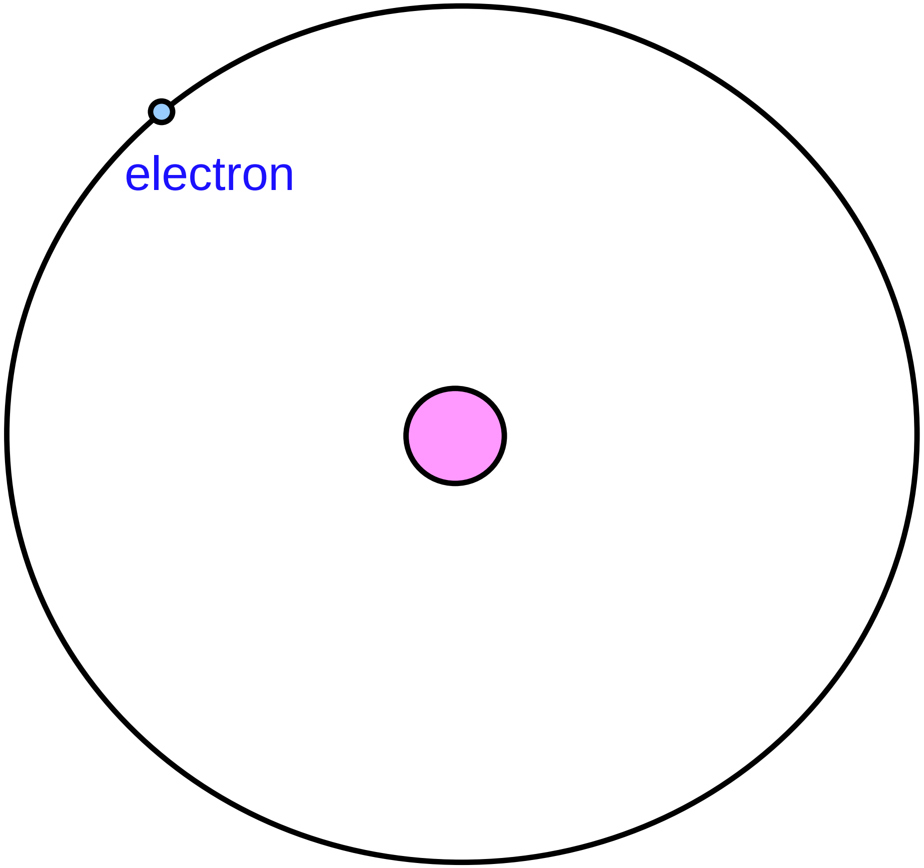


figure not to scale

Muonic hydrogen:

muon μ^- + proton p

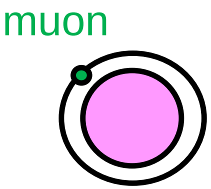
muon mass $m_\mu = 207\ m_e$

Bohr radius $a_{B,\mu} = 1/207\ a_{B,e}$

Probability for μ^- to be inside proton:

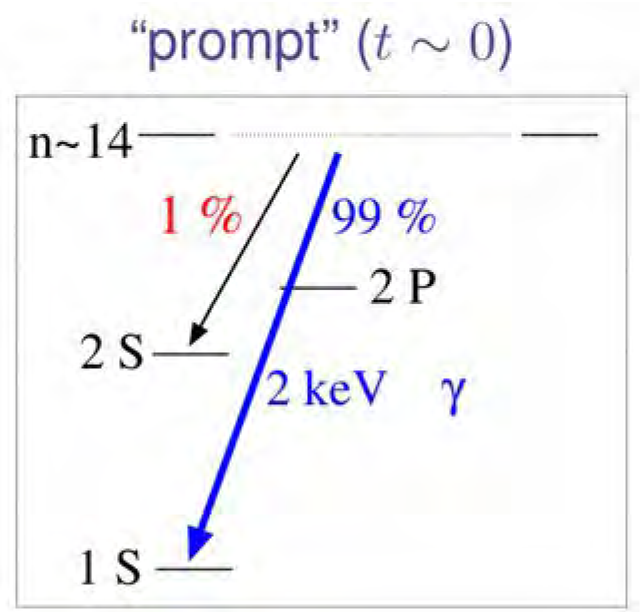
$$\cong \left(\frac{r_p}{a_B}\right)^3 = \left(r_p \alpha\right)^3 m^3$$

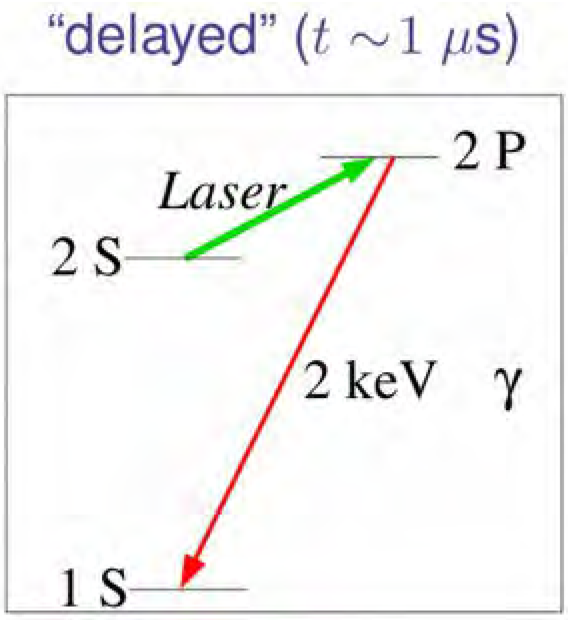
$\rightarrow 207^3 \approx 8$ million



muon is **much** more sensitive to proton radius

How to Measure with μH ?





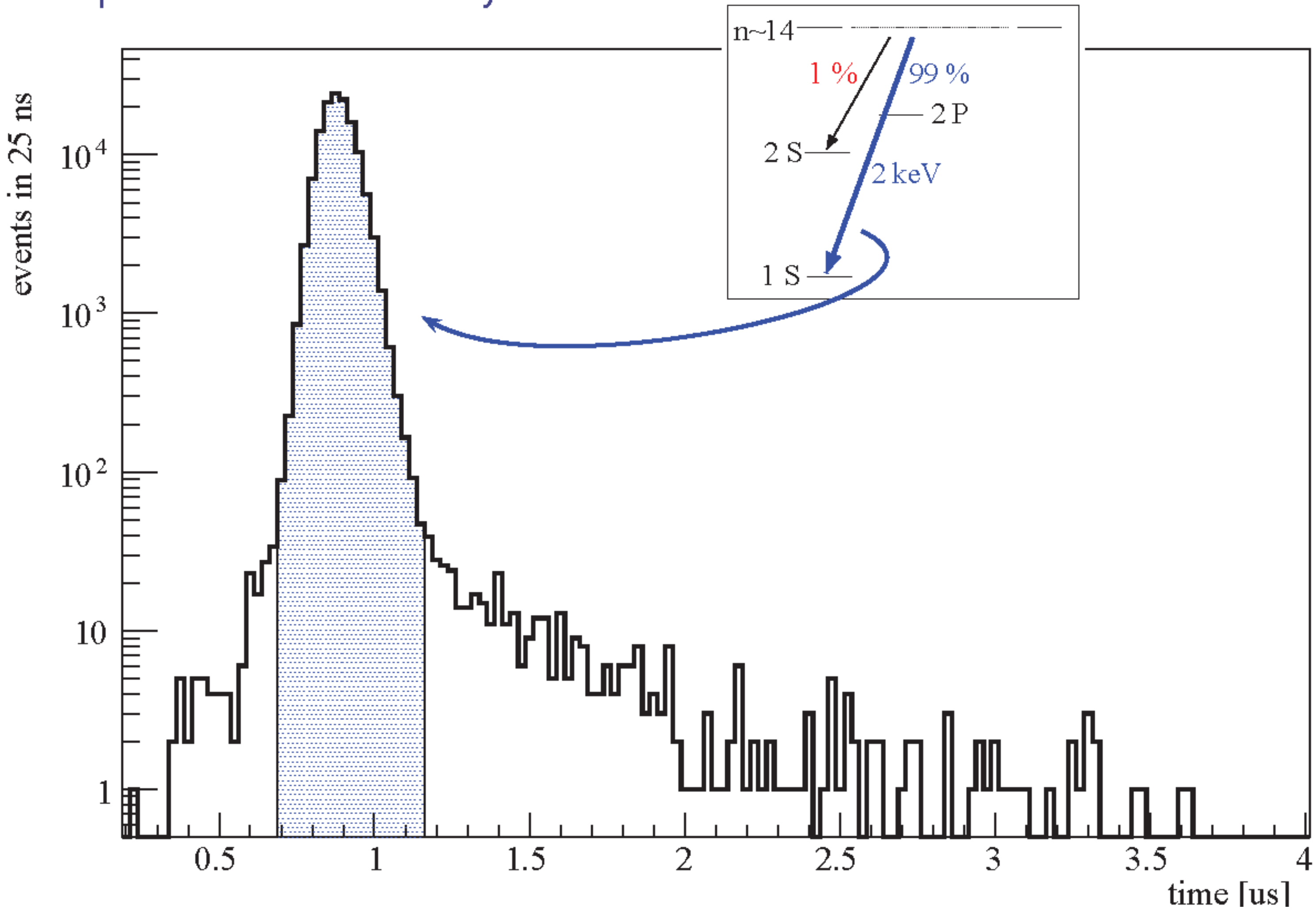
- beautifully simple, but technically challenging!
- form μH*(n~14) by shooting μ beam on 1 mbar H_2 target
  - 99% decay to 1S, giving out fast γ pulse
  - 1% decay to longer-lived 2S state
  - S2 state excited to 2P state by tuned laser & decay with release of delayed γ
- vary laser frequency to find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

Pictures: R. Pohl

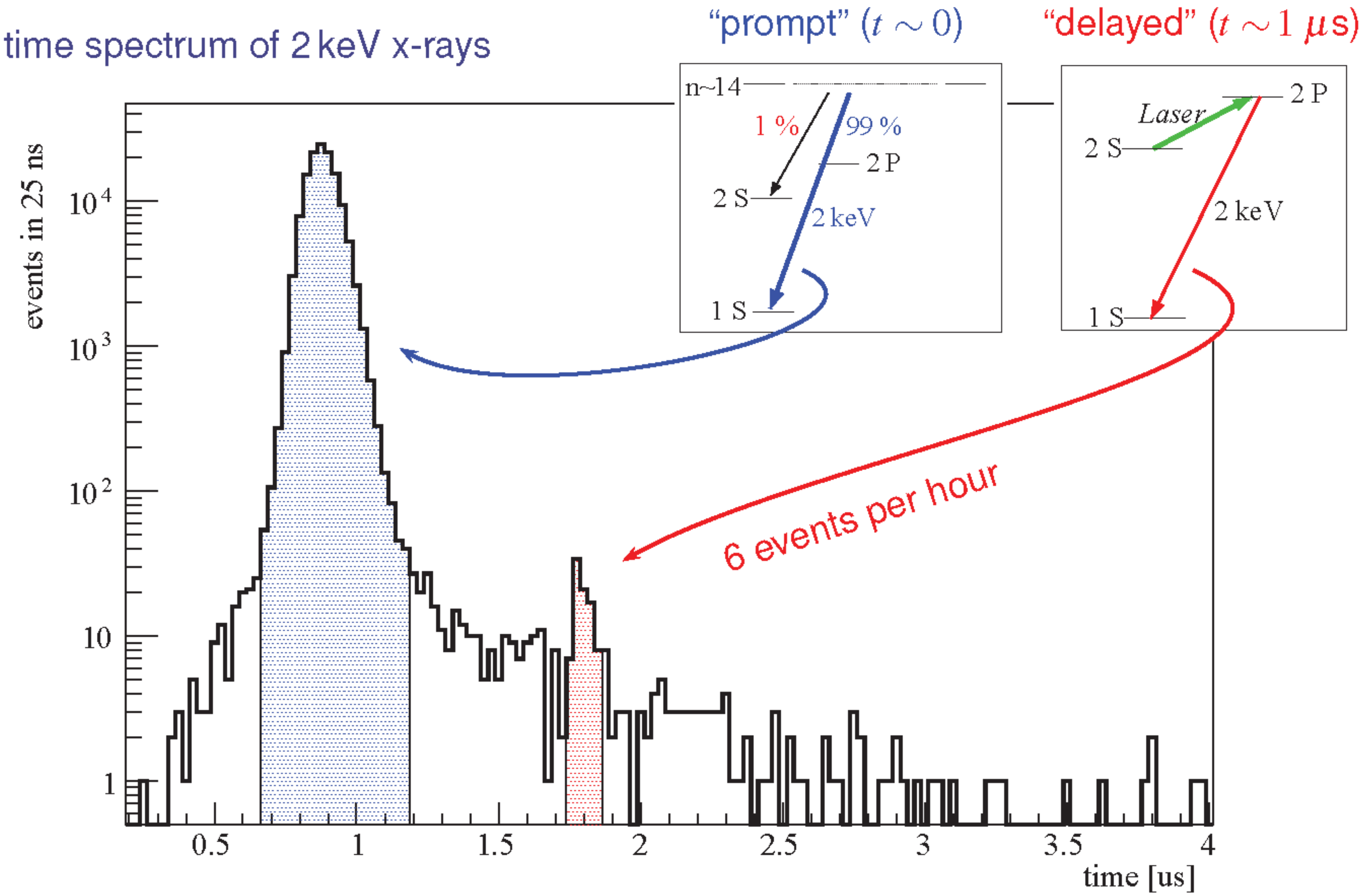
How to Measure with μH ?

time spectrum of 2 keV x-rays

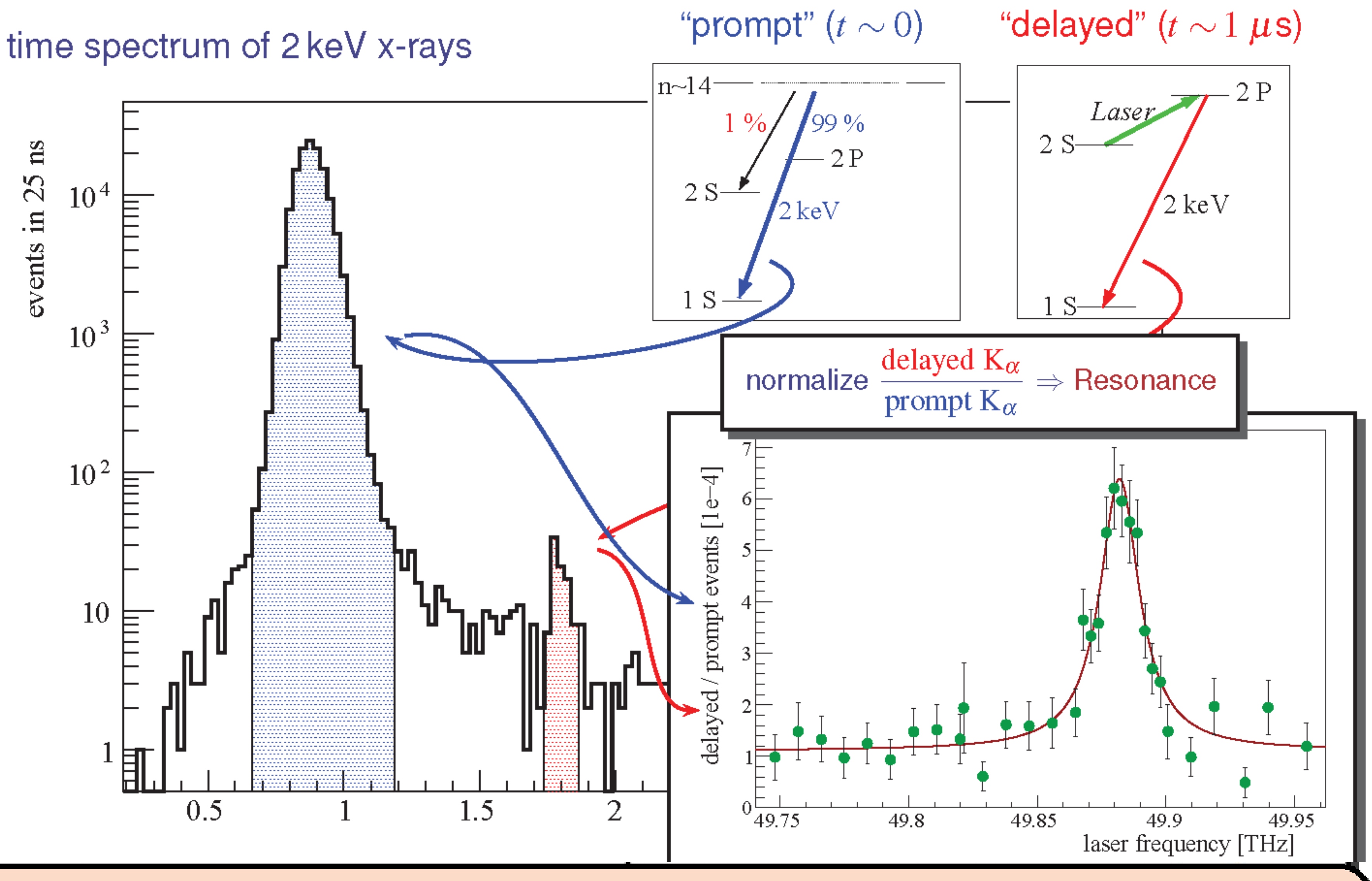
“prompt” ($t \sim 0$)



How to Measure with μH ?



How to Measure with μH ?



time spectrum of 2 keV x-rays

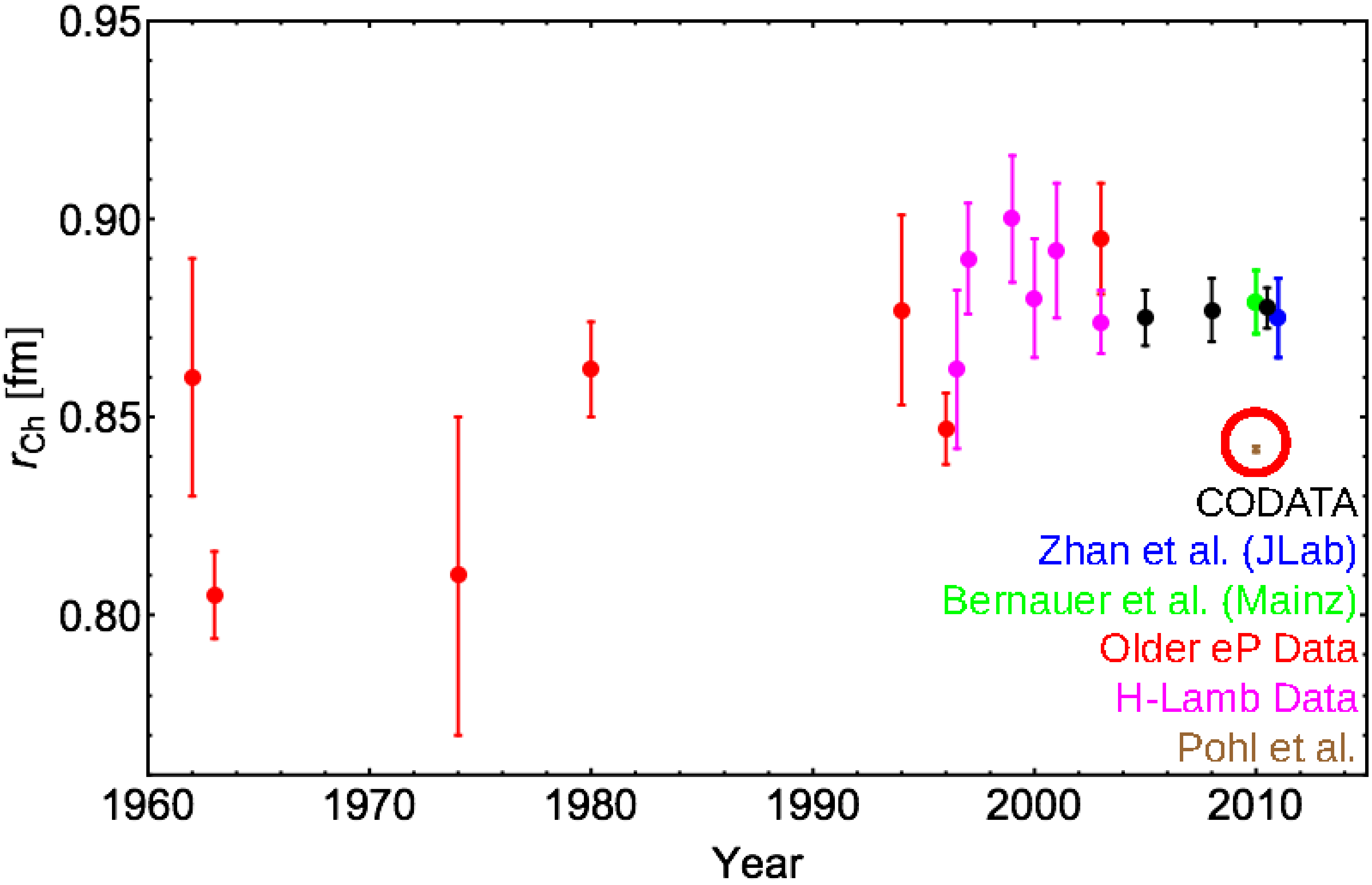
“prompt” ($t \sim 0$)

“delayed” ($t \sim 1\ \mu$s)

normalize $\frac{\text{delayed } K_\alpha}{\text{prompt } K_\alpha}$ ⇒ Resonance

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

The Proton Radius from H & μH Lamb Shift and ep

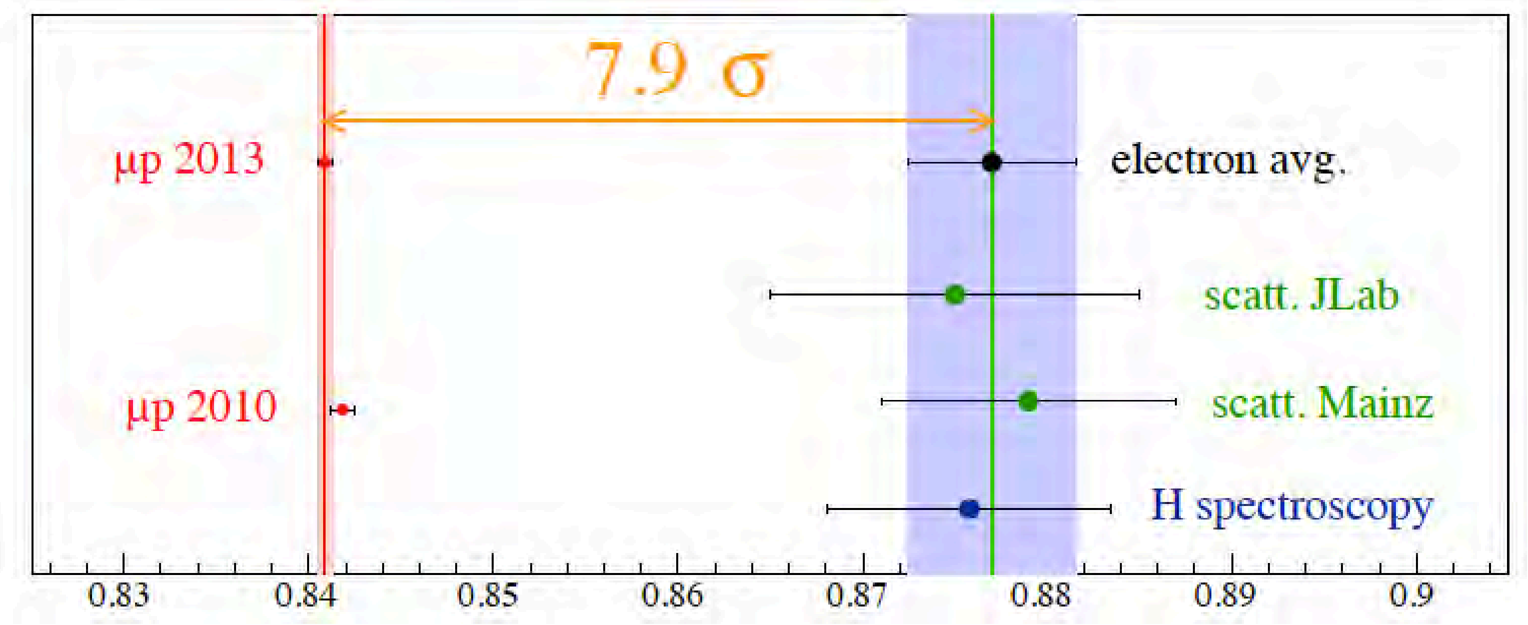


The Proton Radius Puzzle

Proton radius measured with

atomic physics and electron scattering: **0.8751 ± 0.0061 fm**

muonic hydrogen: **0.8409 ± 0.0004 fm**



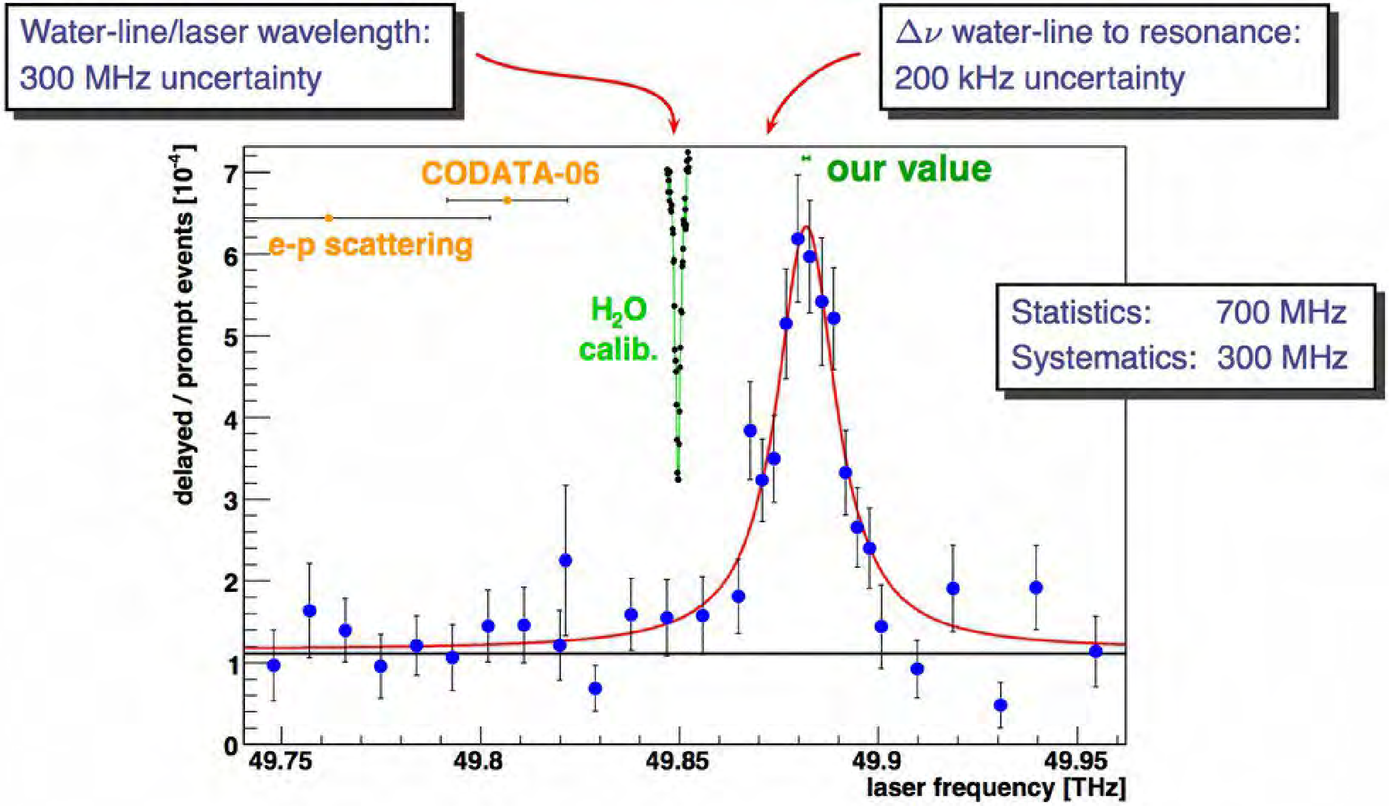
Proton charge radius (fm)

Radius from Muonic Hydrogen 4% below previous best value

→ 12% smaller (volume), 12% denser than previously believed

Why do the muon and electron give different proton radii?

- Experimental error in μp measurement ?



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

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

Why do the muon and electron give different proton radii?

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  - seems unlikely
- Experimental error in ep measurements ?
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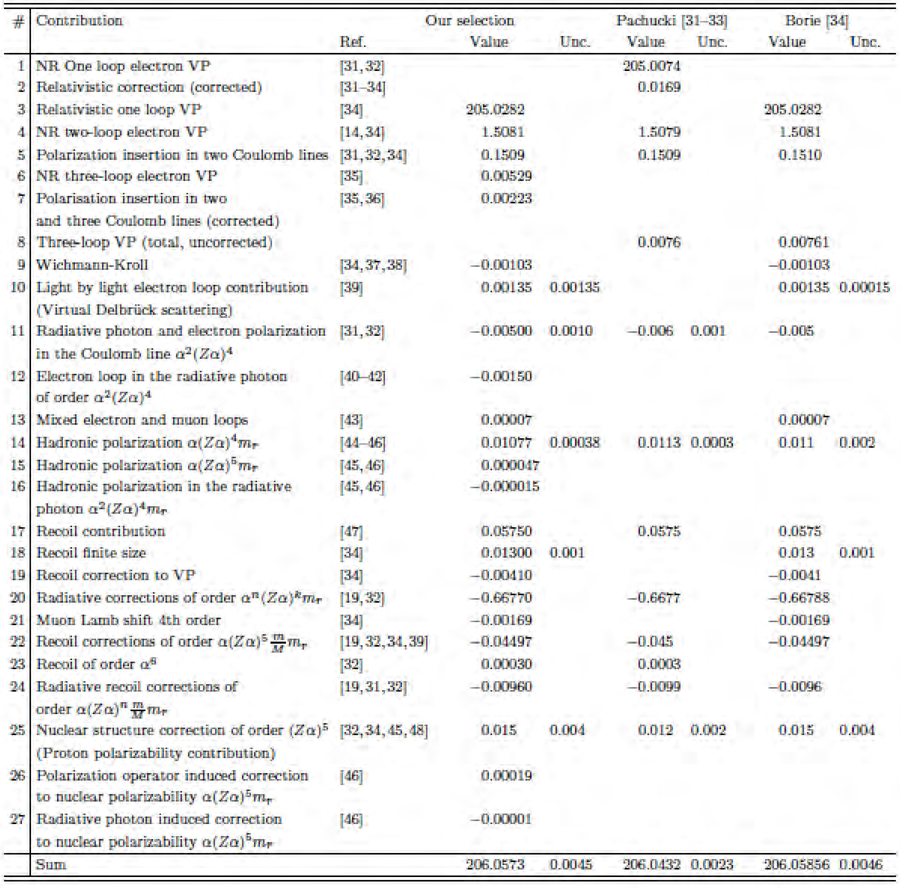
- Theory Error?



#	Contribution		Our selection		Pachucki [31–33]		Borie [34]	
		Ref.	Value	Unc.	Value	Unc.	Value	Unc.
1	NR One loop electron VP	[31, 32]			205.0074			
2	Relativistic correction (corrected)	[31–34]			0.0169			
3	Relativistic one loop VP	[34]	205.0282				205.0282	
4	NR two-loop electron VP	[14, 34]	1.5081		1.5079		1.5081	
5	Polarization insertion in two Coulomb lines	[31, 32, 34]	0.1509		0.1509		0.1510	
6	NR three-loop electron VP	[35]	0.00529					
7	Polarisation insertion in two and three Coulomb lines (corrected)	[35, 36]	0.00223					
8	Three-loop VP (total, uncorrected)				0.0076		0.00761	
9	Wichmann-Kroll	[34, 37, 38]	−0.00103				−0.00103	
10	Light by light electron loop contribution (Virtual Delbrück scattering)	[39]	0.00135	0.00135			0.00135	0.00015
11	Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	[31, 32]	−0.00500	0.0010	−0.006	0.001	−0.005	
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	[40–42]	−0.00150					
13	Mixed electron and muon loops	[43]	0.00007				0.00007	
14	Hadronic polarization $\alpha(Z\alpha)^4 m_r$	[44–46]	0.01077	0.00038	0.0113	0.0003	0.011	0.002
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	[45, 46]	0.000047					
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	[45, 46]	−0.000015					
17	Recoil contribution	[47]	0.05750		0.0575		0.0575	
18	Recoil finite size	[34]	0.01300	0.001			0.013	0.001
19	Recoil correction to VP	[34]	−0.00410				−0.0041	
20	Radiative corrections of order $\alpha^n(Z\alpha)^k m_r$	[19, 32]	−0.66770		−0.6677		−0.66788	
21	Muon Lamb shift 4th order	[34]	−0.00169				−0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m}{M} m_r$	[19, 32, 34, 39]	−0.04497		−0.045		−0.04497	
23	Recoil of order α^6	[32]	0.00030		0.0003			
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m_r$	[19, 31, 32]	−0.00960		−0.0099		−0.0096	
25	Nuclear structure correction of order $(Z\alpha)^5$ (Proton polarizability contribution)	[32, 34, 45, 48]	0.015	0.004	0.012	0.002	0.015	0.004
26	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[46]	0.00019					
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[46]	−0.00001					
	Sum		206.0573	0.0045	206.0432	0.0023	206.05856	0.0046

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- Experimental error in μp measurement ?
  - seems unlikely
- Experimental error in ep measurements ?
  - both scattering and H-spectroscopy are wrong?
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- Theory Error?
  - checked, rechecked, and checked again
  - …. is framework wrong?

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  - …. is framework wrong?
- Everybody is correct ? New Physics !
  - BSM Physics
    - violation of lepton universality
  - Novel Hadronic Physics
    - proton polarizability affects μ, but not e (effect $\propto m_l^4$)
    - two-photon exchange corrections (effects important at high Q^2)

Need More Data

The Quest for New Data

- New data needed to test that the e and μ are really different, and the implications of novel hadronic physics
  - → 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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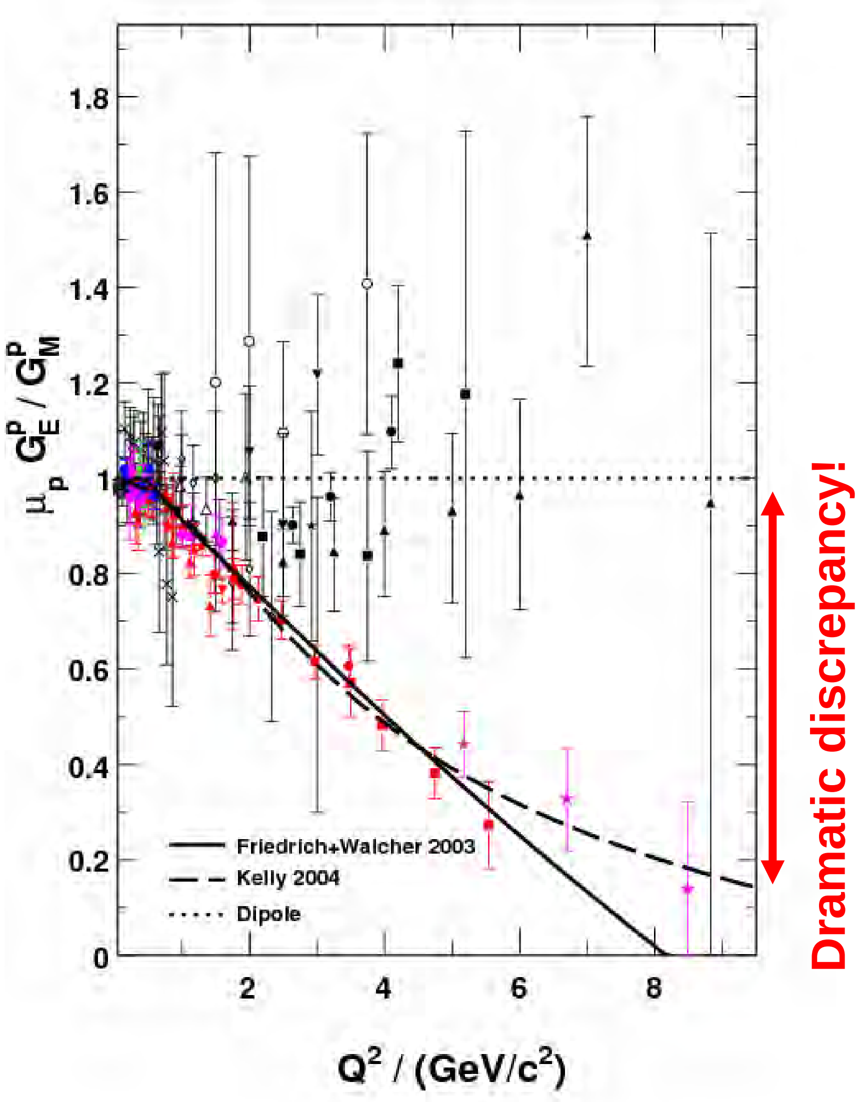
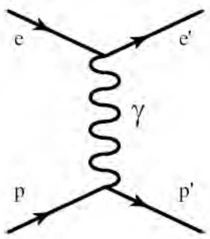
Proton Form Factor Ratio

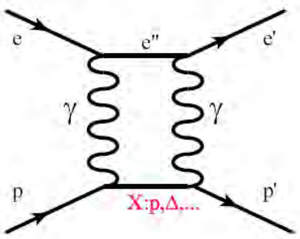


Dramatic discrepancy!

- 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

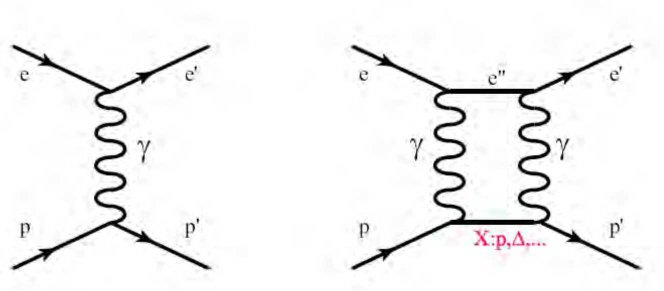


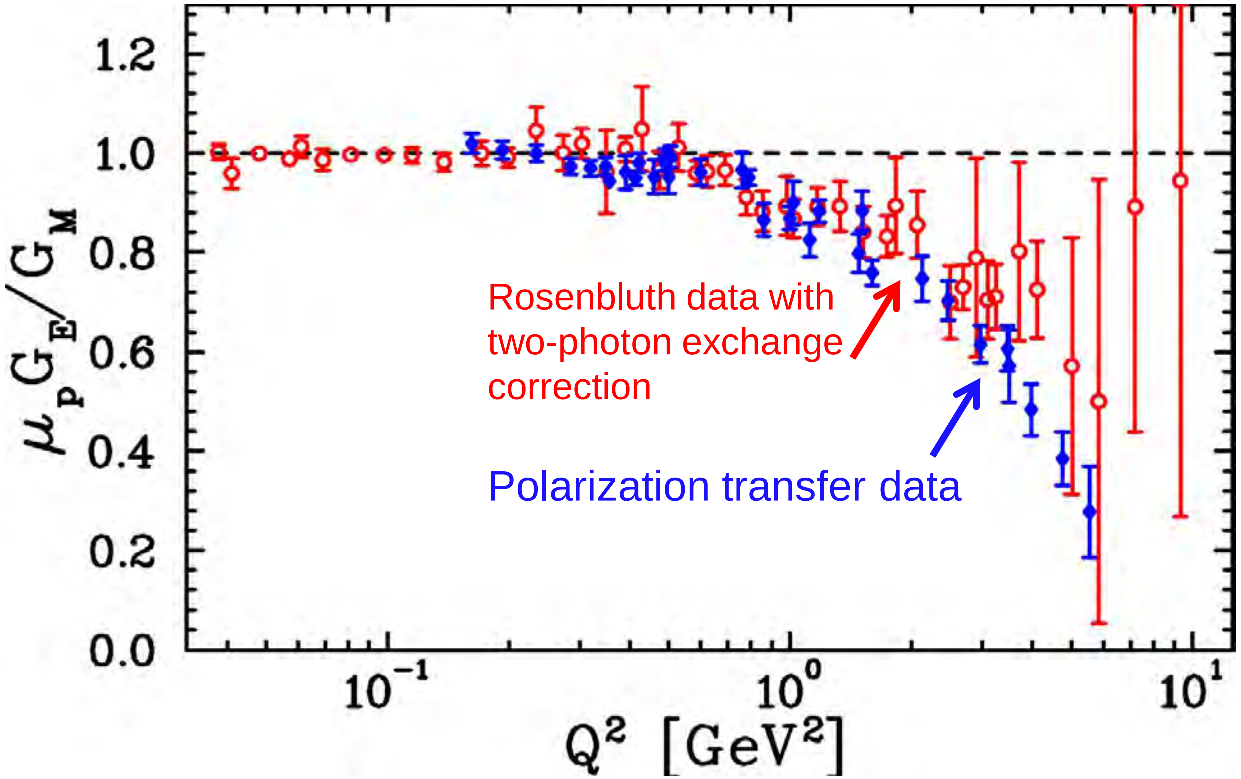
TPE contributions to rad cor not independent

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

The Quest for New Data

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  - → Hadronic: enhanced 2γ exchange effects

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  - → **redoing atomic hydrogen**
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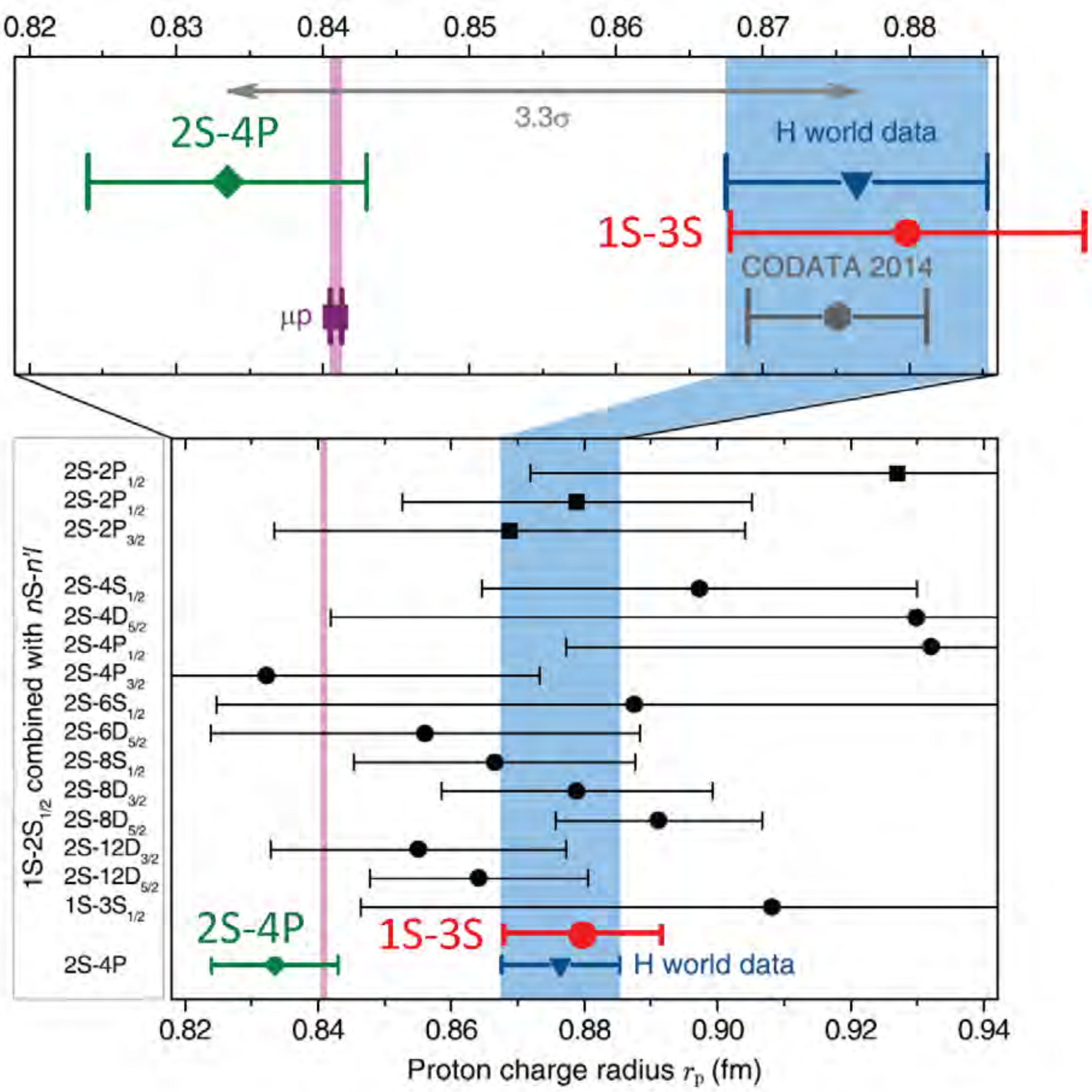
  - → Muon scattering!

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

The Quest for New Data

- New data needed to test that the e and μ are really different, and the implications of novel hadronic physics
  - → Hadronic: enhanced 2γ exchange effects
- Experiments include
  - → redoing atomic hydrogen
  - → **light muonic atoms for radius comparison in heavier systems**
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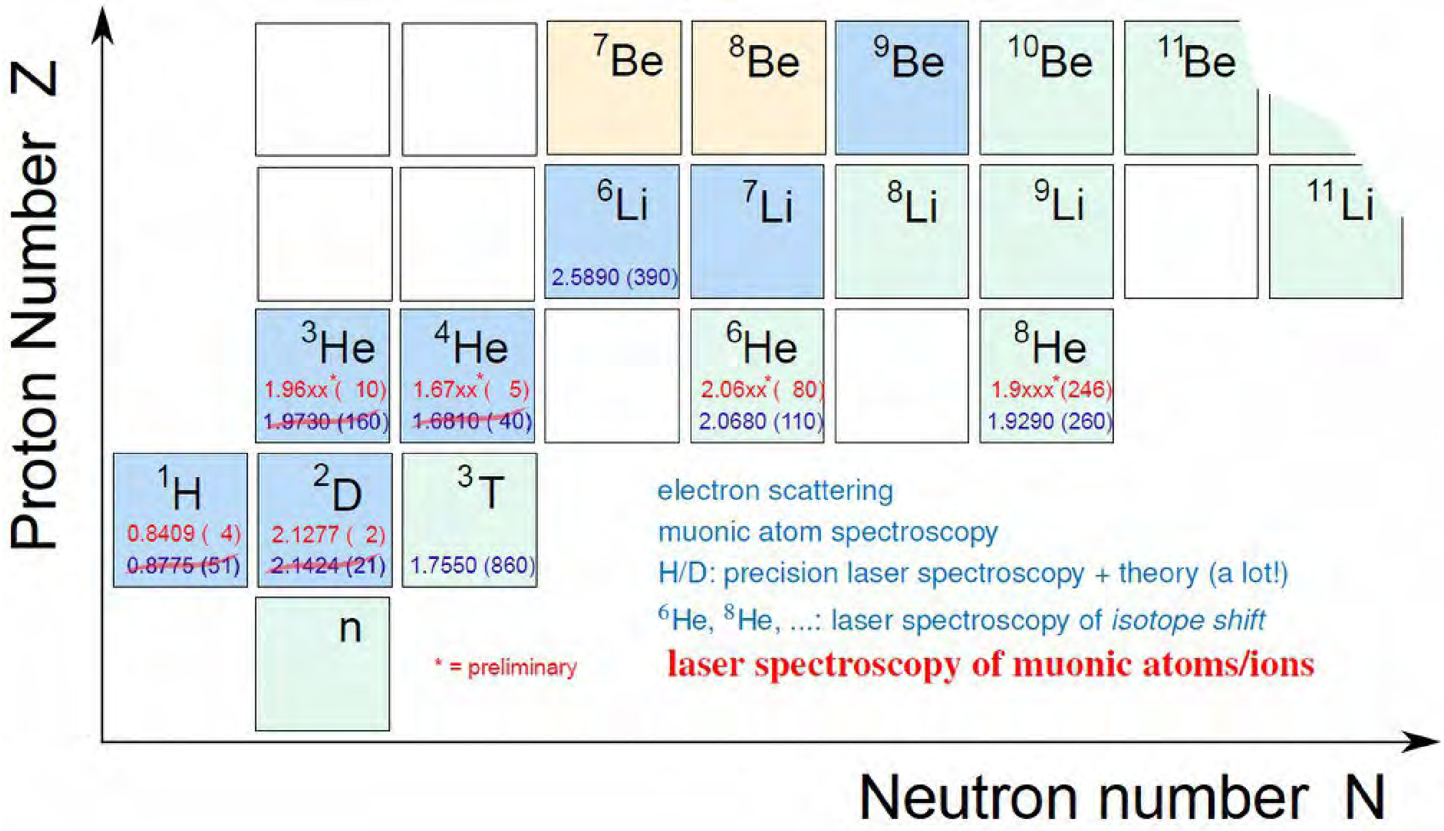
  - → Muon scattering!

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

The Quest for New Data

- New data needed to test that the e and μ are really different, and the implications of novel hadronic physics
  - → 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**

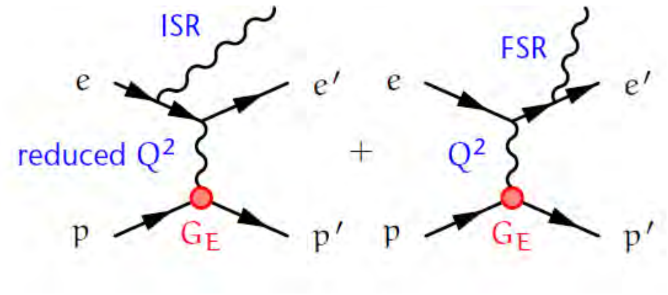
NB: Many efforts, not an exhaustive list!!!!

  - → Muon scattering!

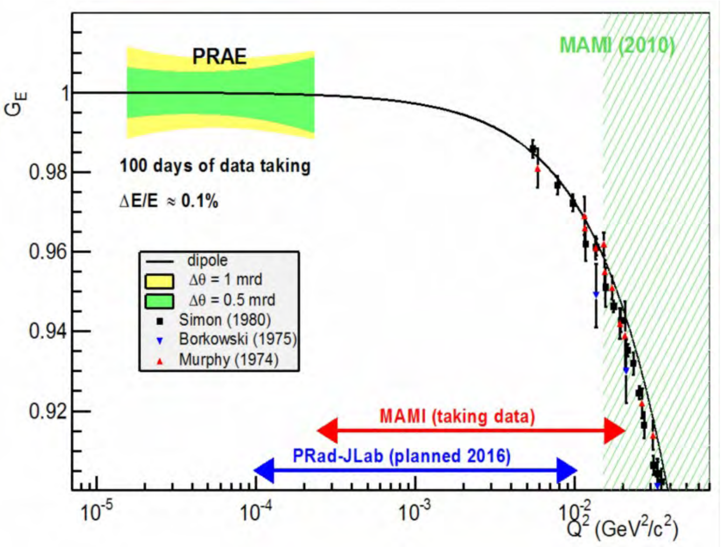
Redoing electron scattering at lower Q^2

- Jlab: PRad
  - low intensity beam in Hall B @ JLab into windowless gas target (1.3 billion H events)
  - Preliminary G_E slope favors smaller radius, consistent with μp 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



The Quest for New Data

- Experiments include
  - → redoing atomic hydrogen
    - conflicting results: more careful systematics?
  - → light muonic atoms for radius comparison in heavier systems
    - puzzle seen in H & D, but not in He: (Z=1 radius puzzle?)
  - → redoing electron scattering at lower Q^2
    - many efforts
    - PRad (windowless H_2 gas flow target → removes major bkgds) is consistent with μp results!
  - → **Muon scattering!**
    - **MUSE** (2019-2021)
    - plans at COMPASS (100 GeV SPS muon beam: 2021-2023)

μp Scattering – The missing Piece

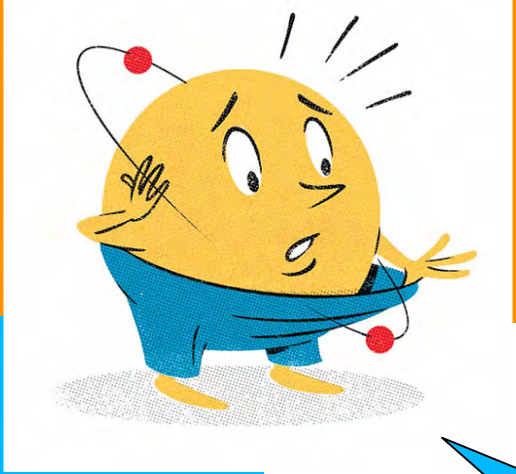
Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84087 ± 0.00039



Electron scattering

0.8770 ± 0.0060

Scattering

Muon scattering

???

MUon Scattering Experiment (MUSE) at PSI

Paul Scherrer Institute
Villigen, Switzerland

Direct comparison of μp and ep scattering!

→ beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on LH_2 target
  - separate particles by TOF, charge by magnets

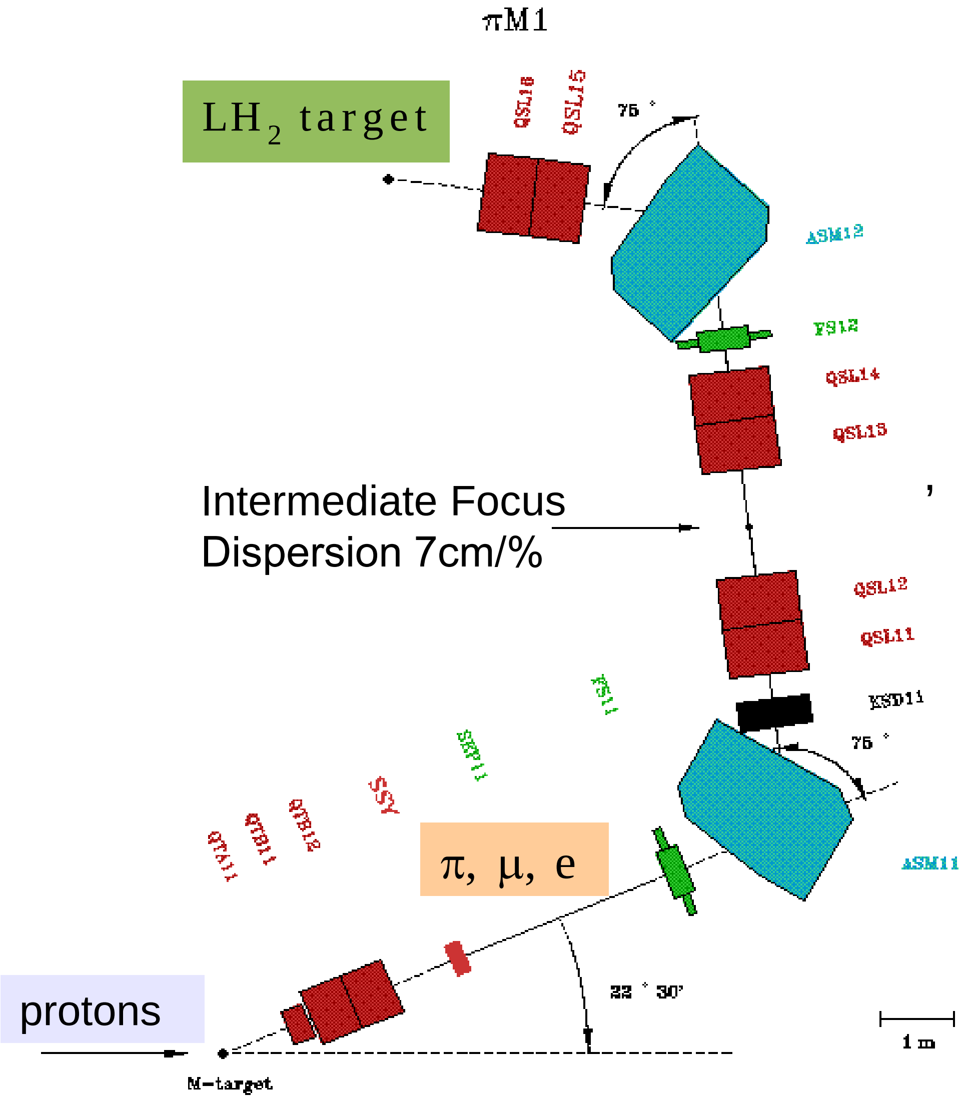
→ charge reversal: test two photon effects

→ absolute cross sections for ep and μp
  - use ratio to cancel systematics

→ momenta: 115 – 210 MeV/c; $Q^2 = 0.002 – 0.07\ \mathrm{GeV}^2$

→ extract G_E and G_M from fits to experimental cross section data

πM1 / MUSE beamline



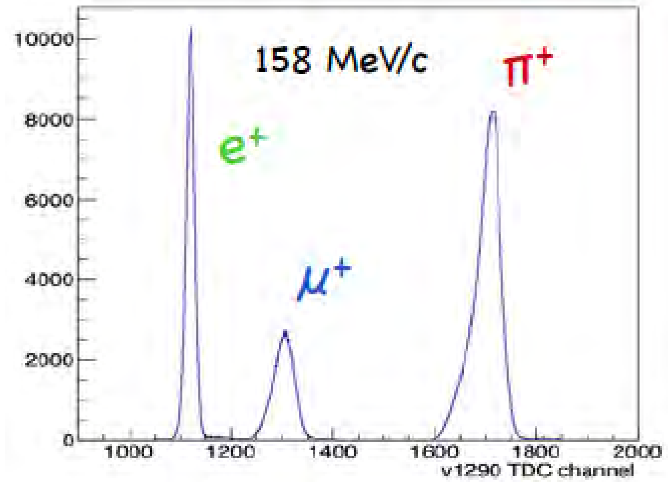
LH$_2$ target

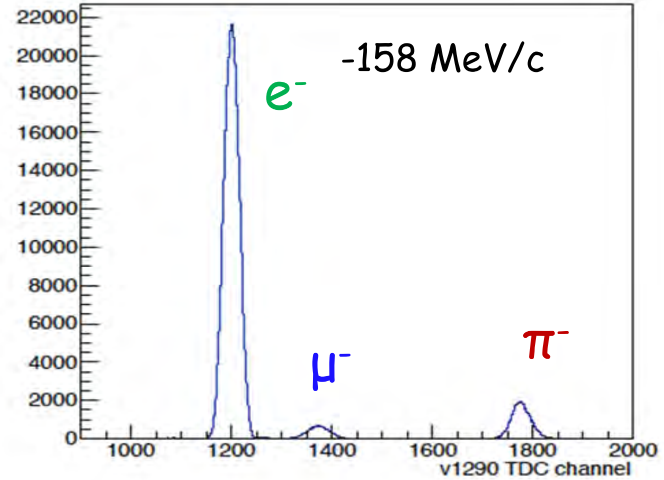
Intermediate Focus
Dispersion 7cm/%

π, μ, e

protons

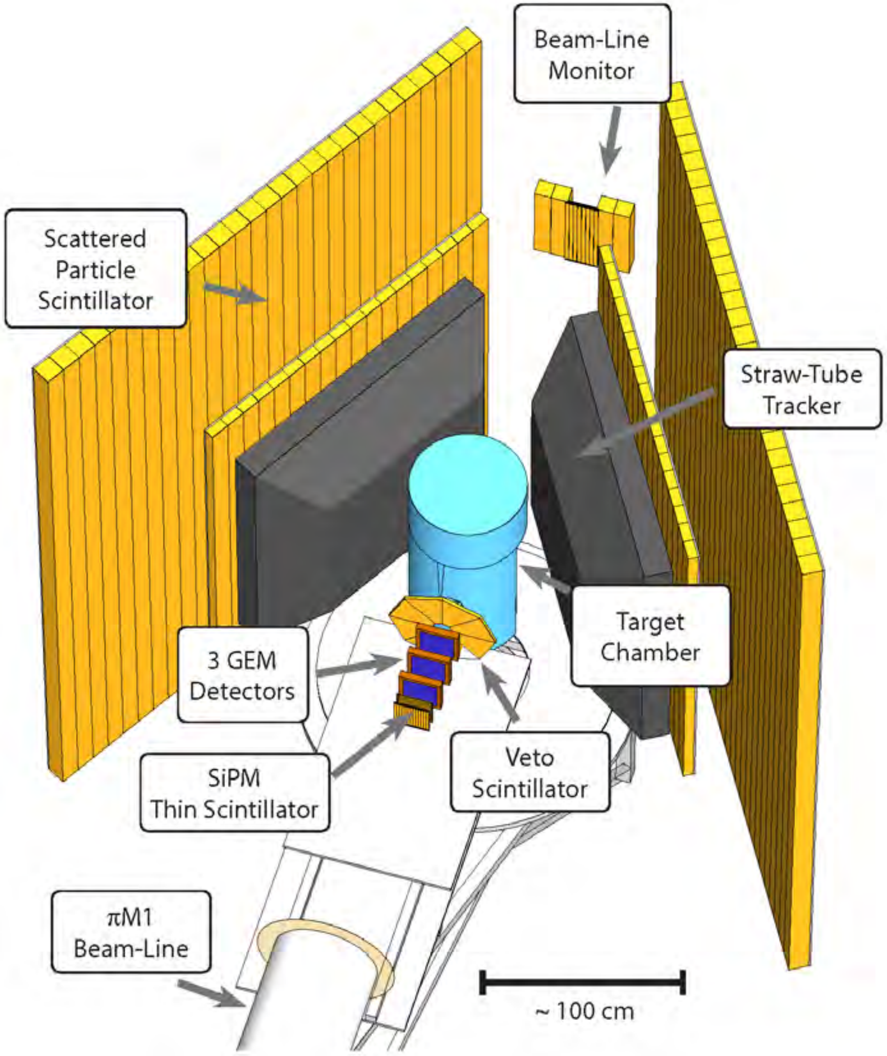
πM1: 100-500 MeV/c RF+TOF
separated π, μ, e





MUSE: an unusual Scattering Experiment

- Secondary beam → identify and track beam particles
- Low beam flux (3 MHz) → large acceptance, non-magnetic spectrometer
- Mixed beam → PID in trigger

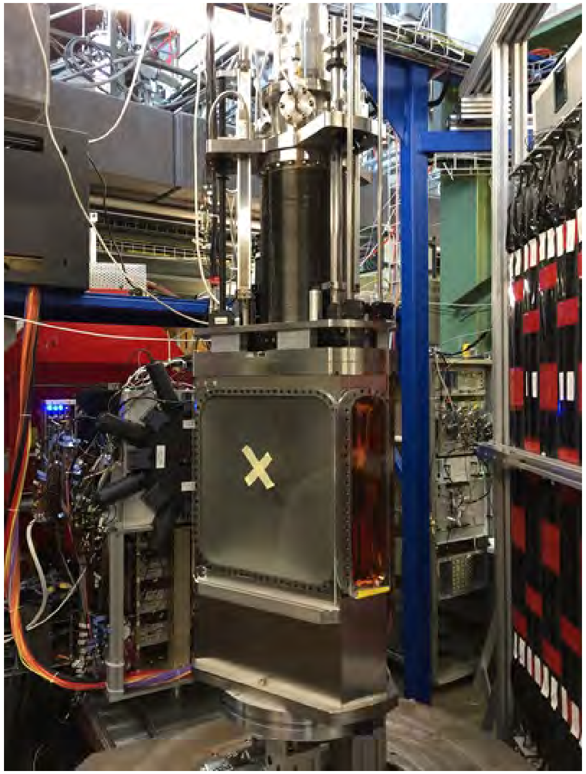


LH_2 Target (U-M)

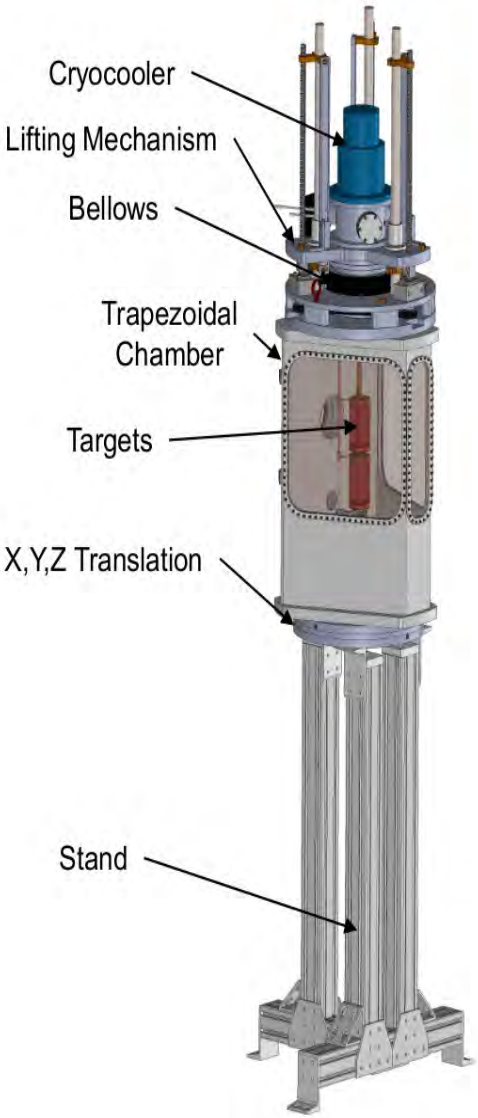
Liquid hydrogen target

→ 280 ml Kapton cylinder
→ full and empty targets

Target chamber in PiM1

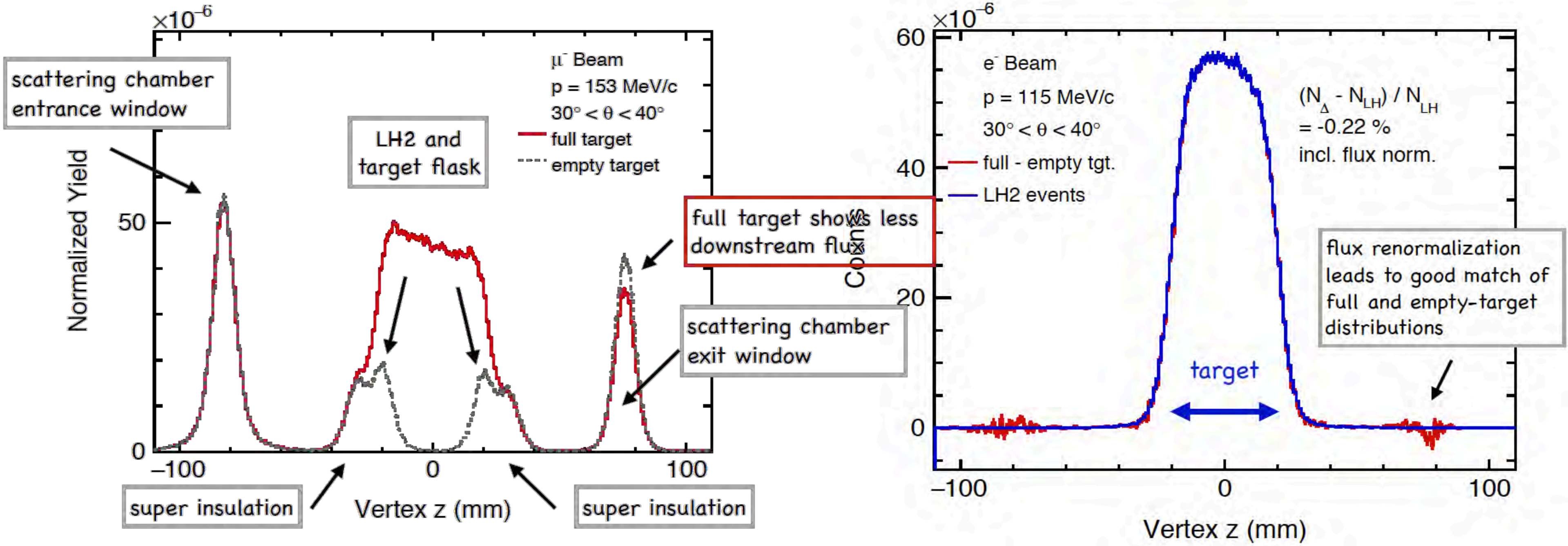


Target system

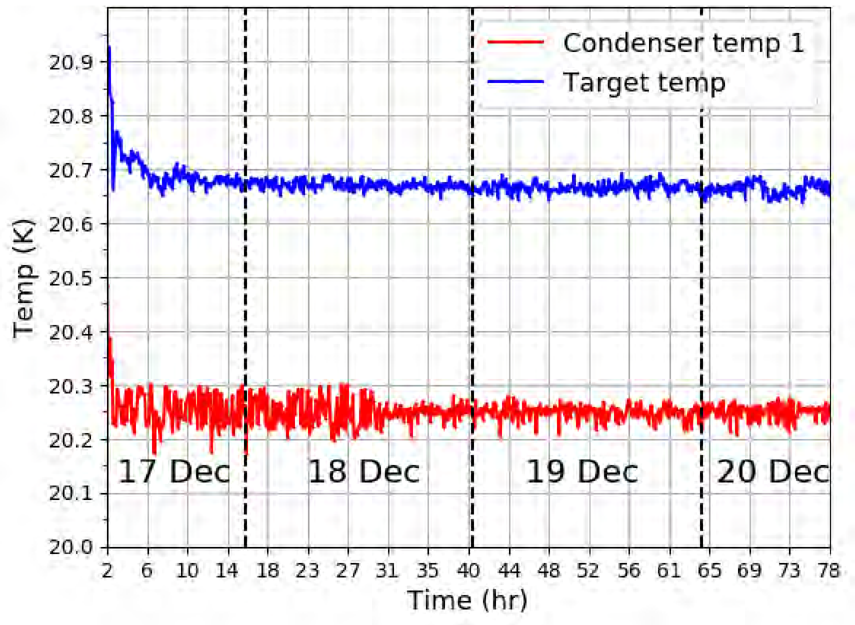


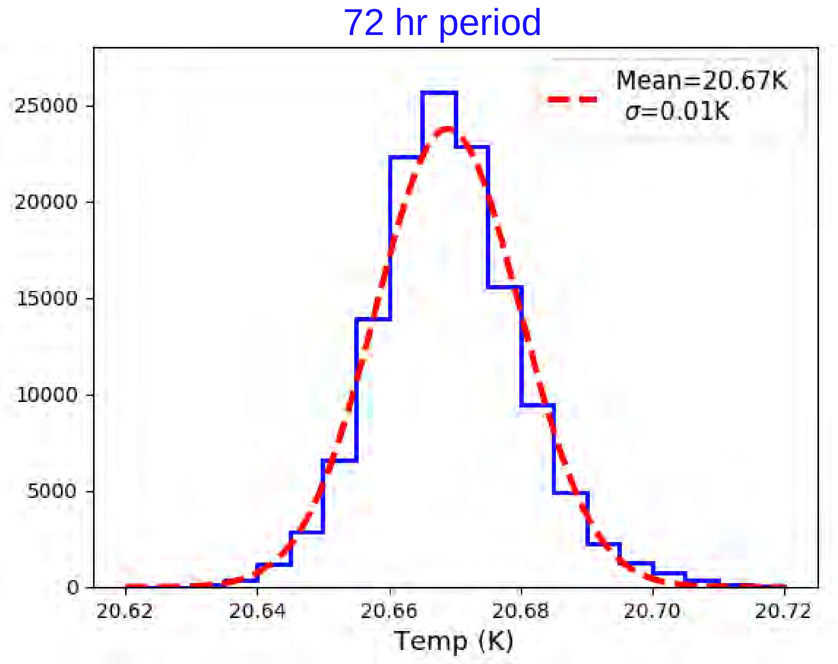
Target Simulations

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



Target Performance





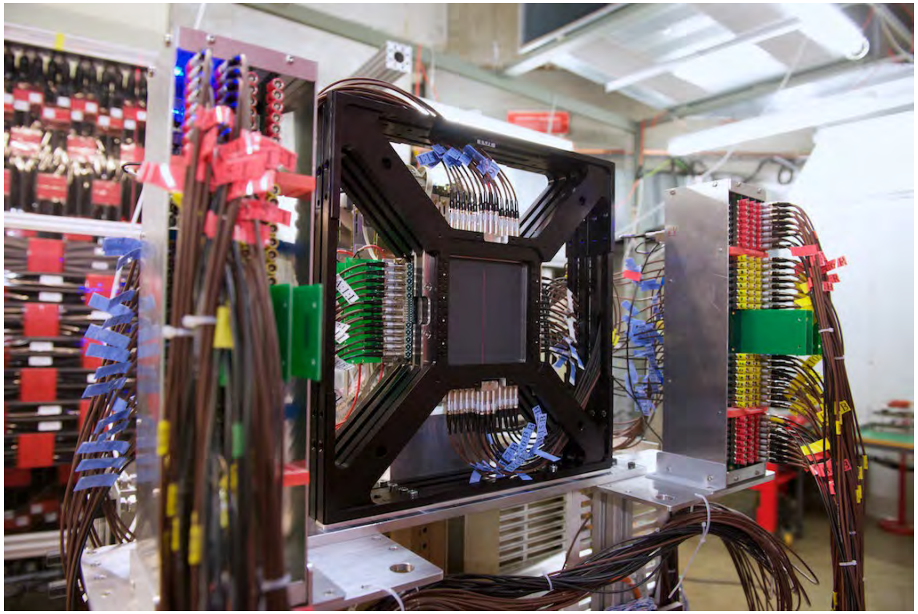
- Target Temperature: 20.67 ± 0.01 K
  - corresponds to a pressure of ~1.1 bar
- Target density: 0.070 g/cm^3 (stable to 0.02%)
  - once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached

Detector Components

MUSE detectors for TOF measurements

Beam hodoscope

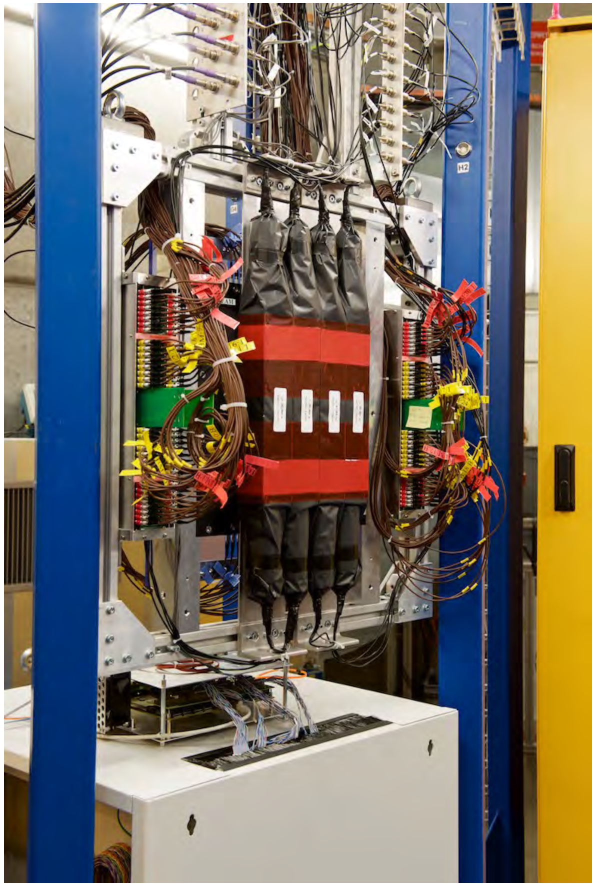
(TAU, Rutgers)



time resolution 70ps at 99.8% efficiency!

Beam Monitor

(TAU, Rutgers, USC)

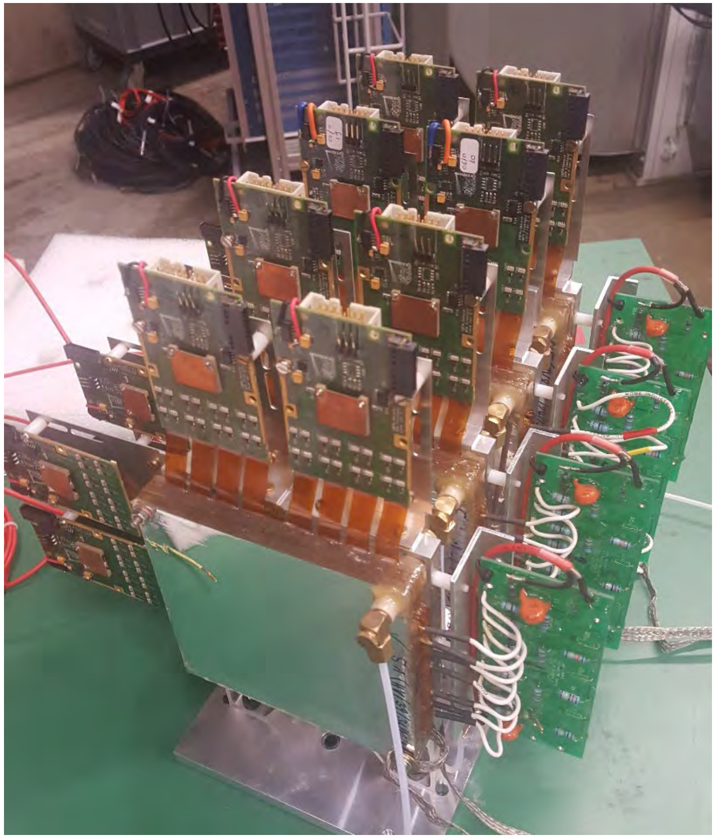


Determination of particle flux downstream of target, Moller/Bhabha veto, ToF

Detector Components

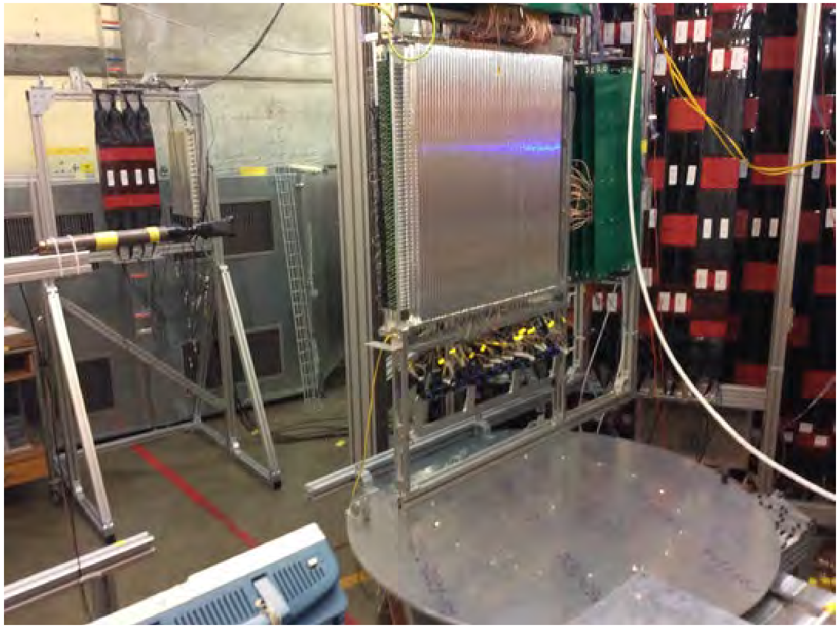
MUSE tracking detectors

GEM telescope
(HU)



measure location and timing
of each incoming particle

Strawtube tracker
(HUJI)



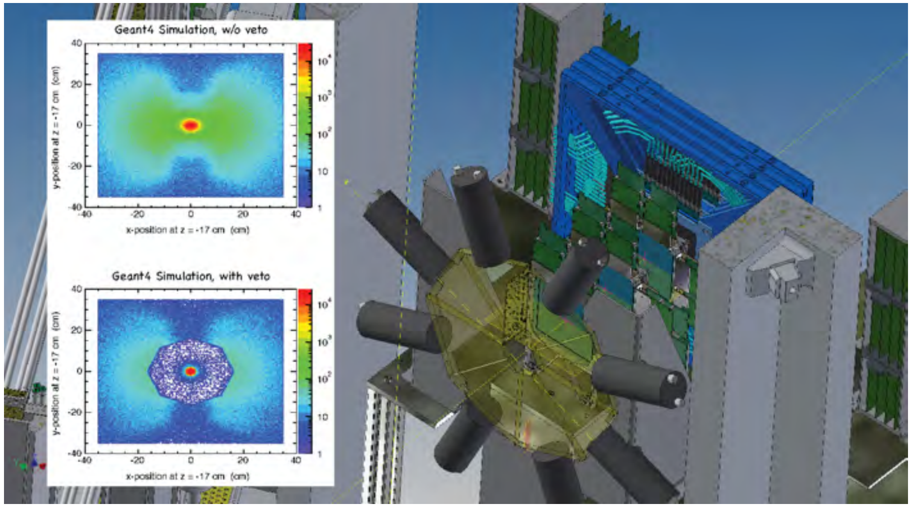
better track position resolution
(<120μm) than design requirement!

Detector Components

MUSE PID detectors

Beam veto detector

(USC)



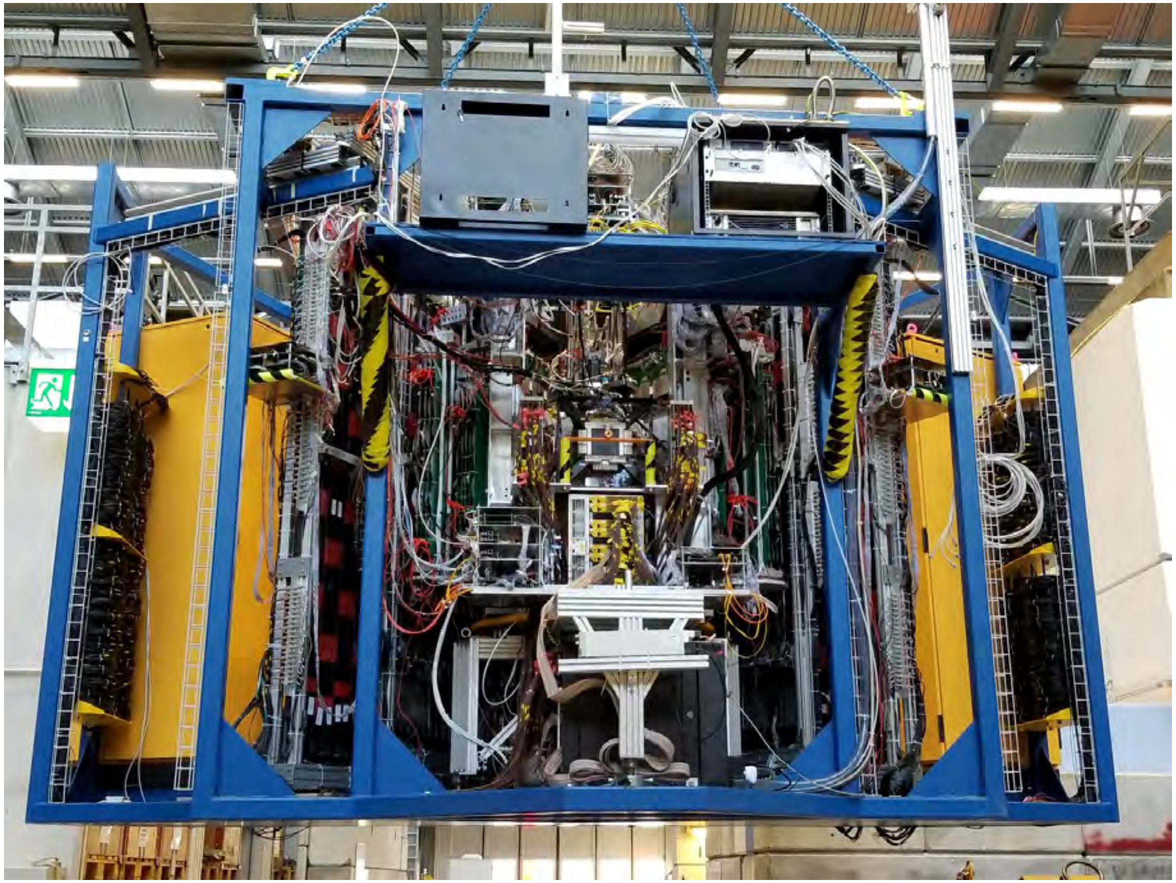
significantly reduces trigger rate from background events

Scintillator wall

(USC)

better time resolution (50ps) than design requirement!

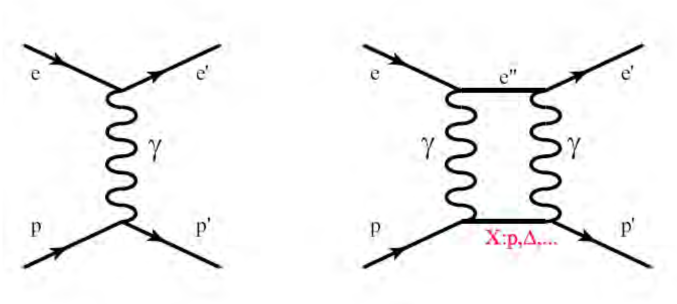
Current status



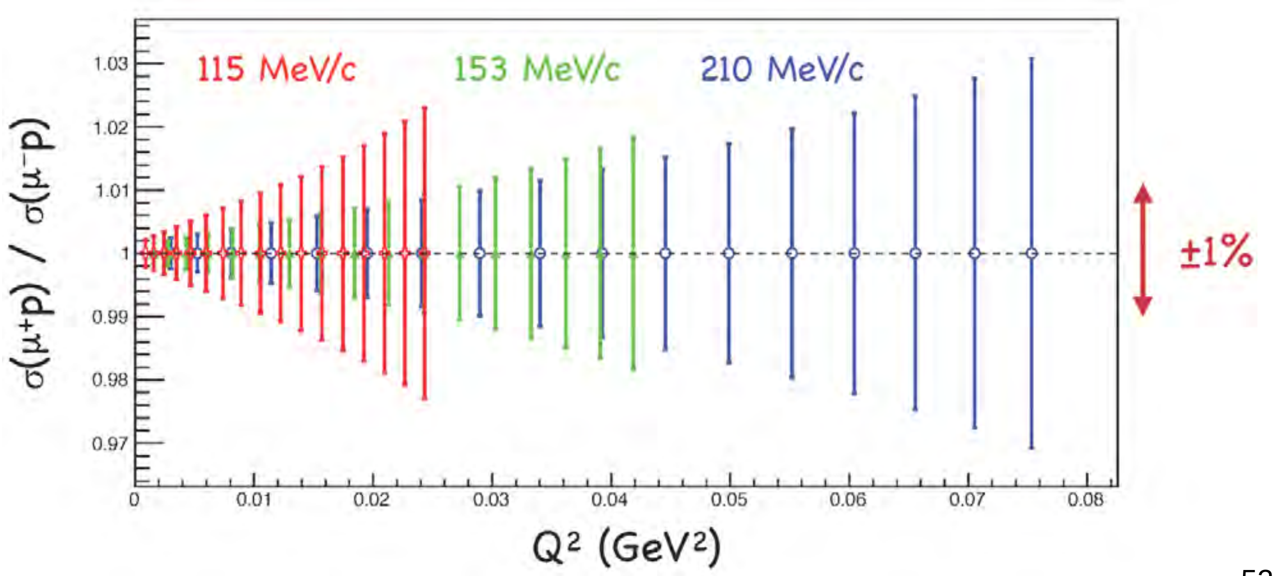
- 18 test runs (2012 – 2019) (beam studies, detector development, and commissioning) demonstrate simulation agreement & reliable performance
- Construction completed
  - commissioning almost complete
  - 12 months total data-taking in 2019 - 2021

Two-photon exchange at low Q^2

- High precision test of TPE for electron and muons at low Q^2
- TPE largest theor. uncertainty in low-energy proton structure
- expect sign change for e^+ and e^-

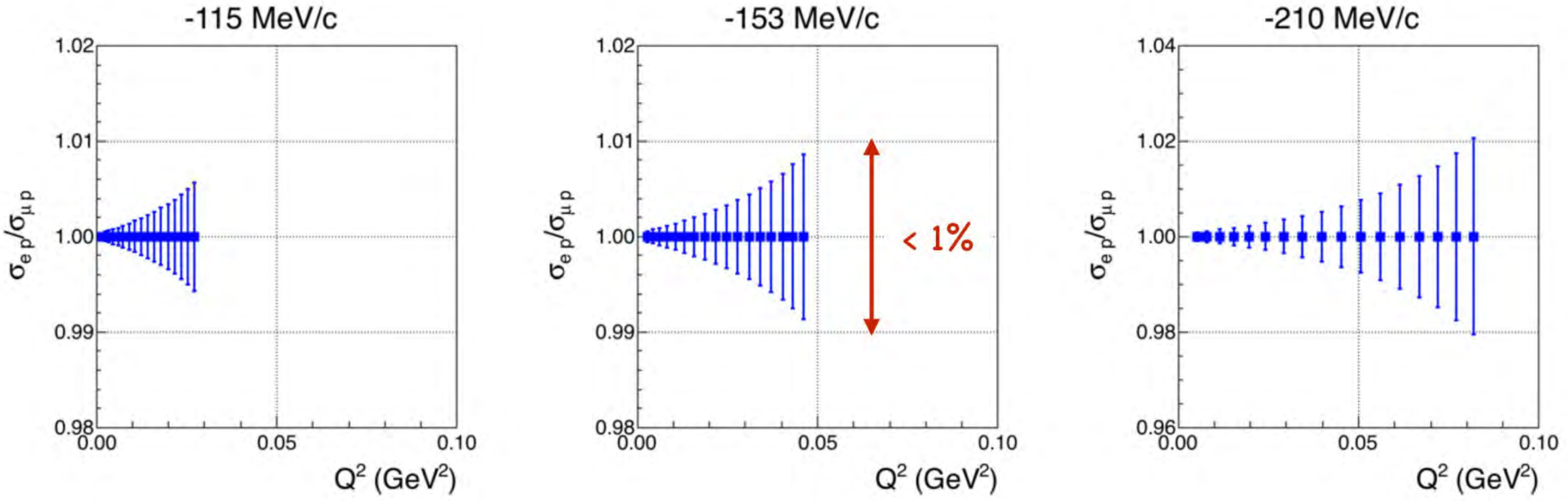


- projected relative uncertainty in μ^+p to μ^-p elastic cross sections
- systematics: 0.2%



Comparison of ep to μp cross sections

- projected relative statistical uncertainties in the ratio of ep to μp elastic **cross sections** (mass difference removed in ratio)
- systematics: 0.5%



- relative statistical uncertainties in the **form factors** are half as large

Projected sensitivity for MUSE

- absolute radius extraction uncertainty similar to current experiments

  $\sigma(r_e), \sigma(r_\mu) \approx 0.009$ fm

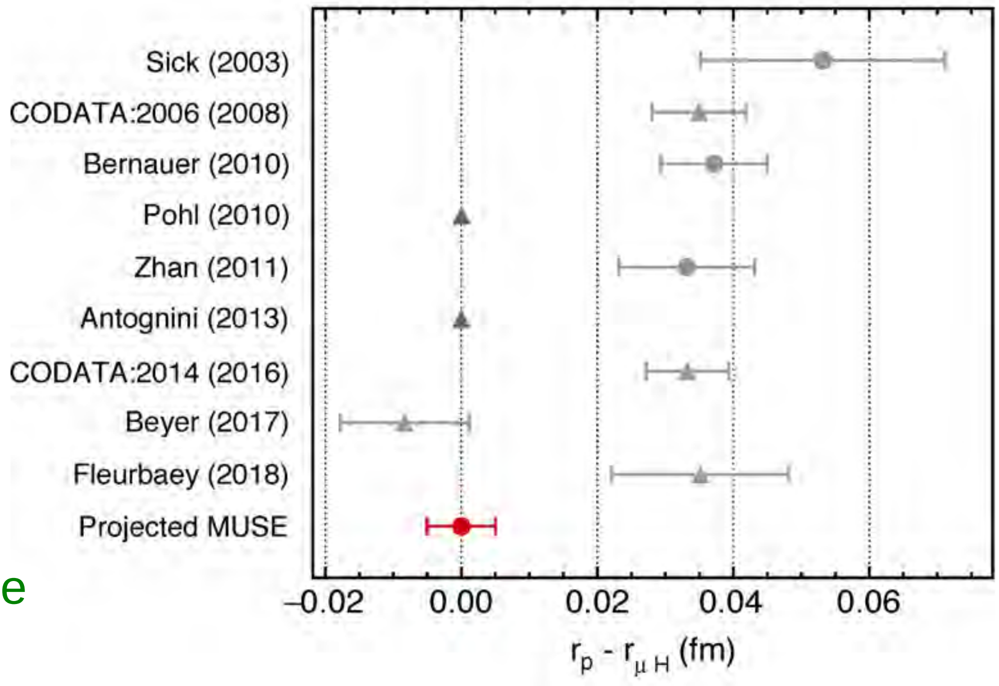
- radius difference: common uncertainties cancel
  - comparison of μ to e, or μ^+ to μ^- insensitive to many syst. errors

  $\sigma(r_e - r_\mu) \approx 0.005$ fm

  → almost factor two more sensitive than absolute radius extraction

  → almost factor ten better than current discrepancy

current discrepancy: $r_e - r_\mu \approx 0.034$ fm



Summary

- We are still (possibly more) puzzled!
- Proton radius puzzle
  - discrepancy between muonic and electronic measurements remains a serious problem
  - Need new data
- Expect new results in the coming years
- MUSE (w/ electron & muon scattering)
  - give first precise muon scattering results
  - will test existing values of radius
  - will test two photon exchange / proton polarizability
  - lepton universality

Thank you