Columbian College of Arts & Sciences

THE GEORGE WASHINGTON UNIVERSITY

The Proton Radius: Are We Still Puzzled?

E. J. Downie

on behalf of the

MUSE Collaboration

Award DE-SC0012485

Awards PHY-1309130,1314148,1614850

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Outline

- Why are we puzzled:
  - ➔ What is a radius? How do we measure it?
  - ➔ Electron scattering measurements
  - ➔ The source of all the trouble: muonic spectroscopy measurements
- Are we still puzzled?
  - ➔ Possible explanations
  - ➔ What are we doing now?
- Conclusions

Proton Radius Problem

R. Pohl et al., Nature 466, 09259 (2010)

Proton Radius Problem

Proton Radius Problem

Proton Radius Problem

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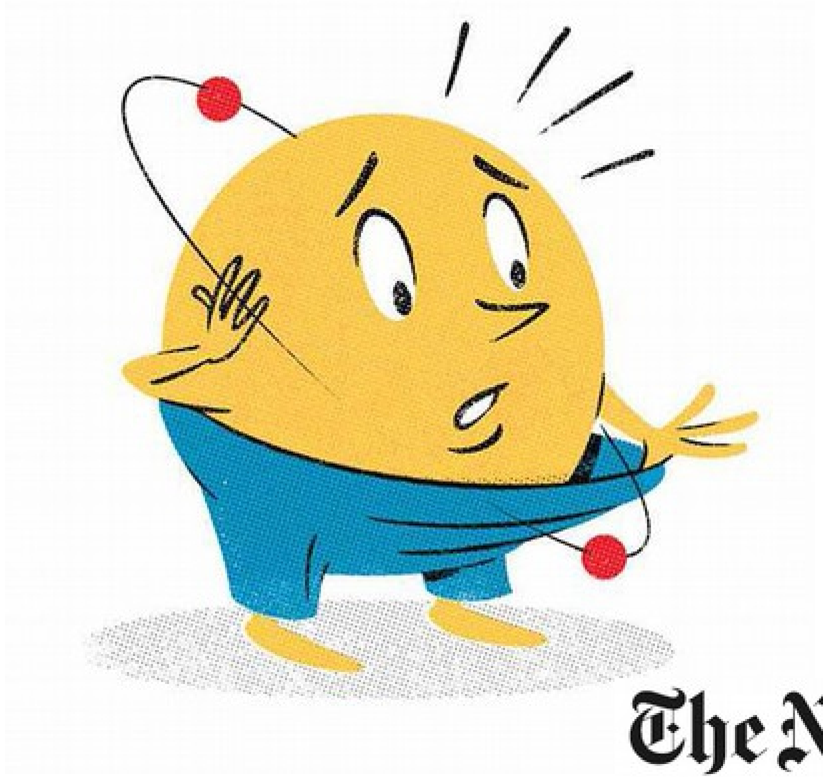
Proton Radius Problem



The New York Times

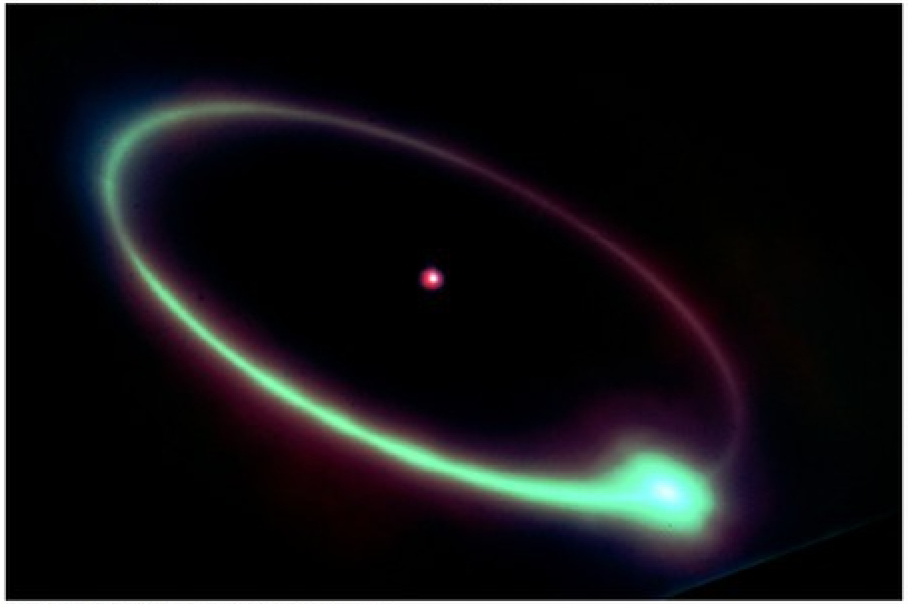
- The Proton Radius Puzzle (PRP) has garnered a lot of interest!
- Not just interesting:
  - ➔ Tests our theoretical understanding of proton
  - ➔ Radius of proton is dominant uncertainty in many QED processes
- What exactly is the puzzle?

Proton Radius Problem

NewScientist

DAILY NEWS 11 August 2016

How big is a proton? No one knows exactly, and that's a problem



The experiments used modified hydrogen atoms to get at the size of the proton

Fritz Goro/The LIFE Picture Collection/Getty Images

By Aviva Rutkin

It's a subatomic mystery with big implications. Six years after physicists announced a bafflingly too small measurement of the size of the proton, we're still not sure what's going on. With the release of new data today, the mystery has, if anything, got deeper.

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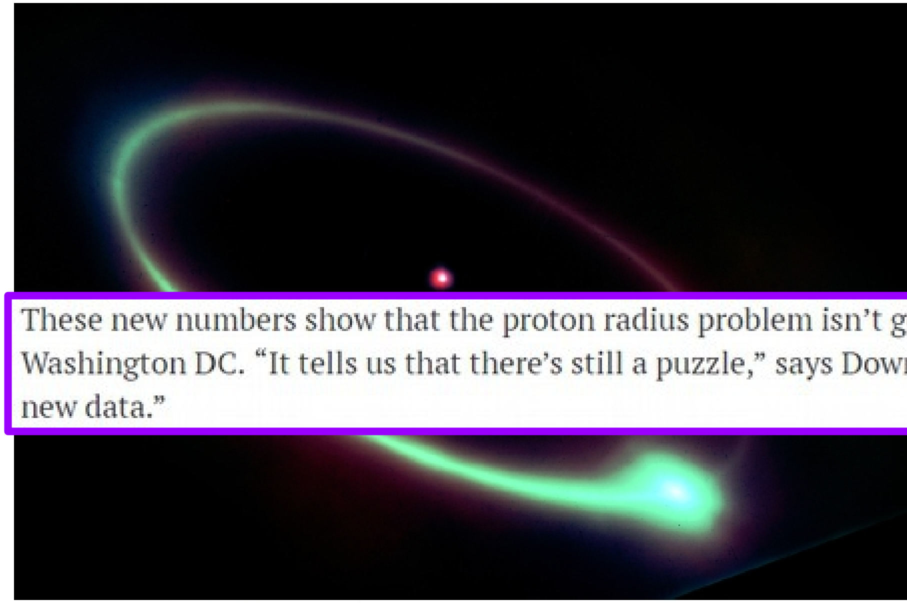

These new numbers show that the proton radius problem isn't going away, says Evangeline J. Downie at the George Washington University in Washington DC. "It tells us that there's still a puzzle," says Downie. "It's still very open, and the only thing that's going to allow us to solve it is new data."

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Proton Radius Problem

NewScientist

DAILY NEWS 11 A

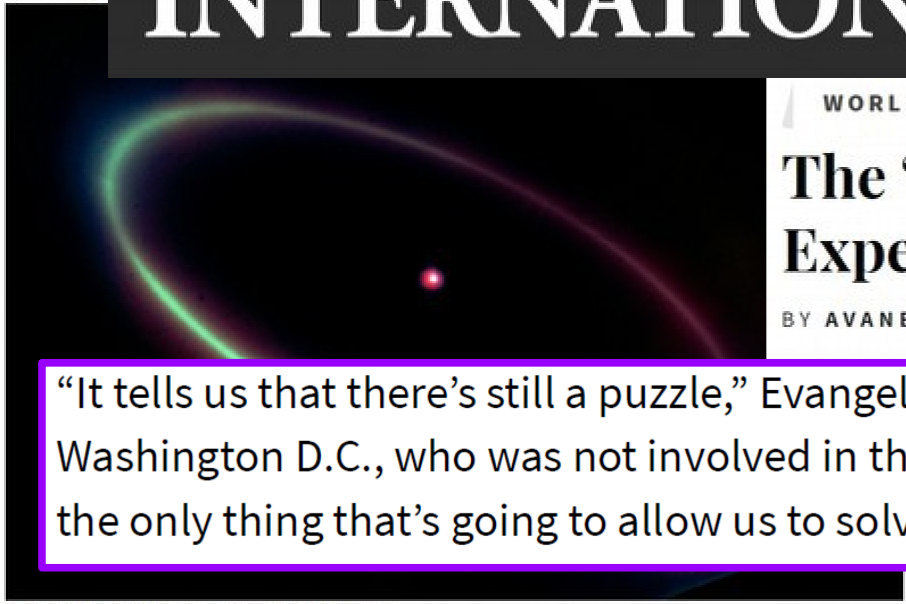
How big

INTERNATIONAL BUSINESS TIMES

WORLD

The 'Proton Radius Puzzle' Is Very Real, New Experiment Confirms

BY AVANEESH PANDEY ON 08/13/16 AT 4:19 AM



"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."

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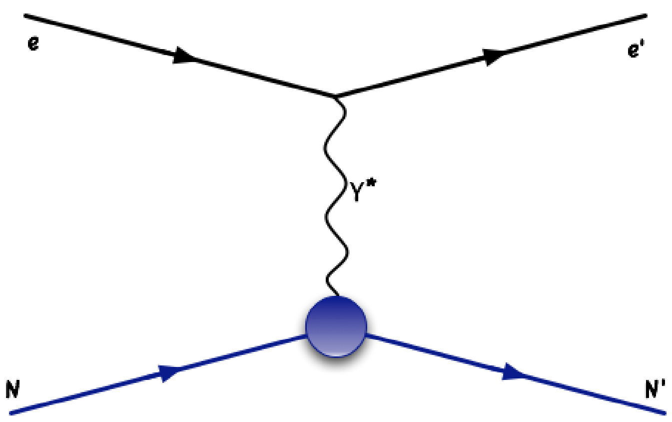
The Proton Radius

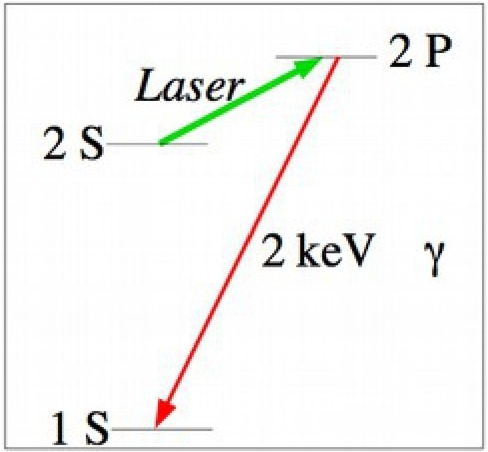
- What is a radius? How do we measure it?
- Classical physics: $r^2 = \int \rho(r) r^2 d^3r$
- Non-relativistic quantum mechanics: $r^2 = \int < \psi^*(r) | r^2 | \psi(r) > d^3r$
- Relativistic quantum mechanics: $r^2 = -6dG(Q^2)/dQ^2|_{Q^2=0}$

Electron Scattering



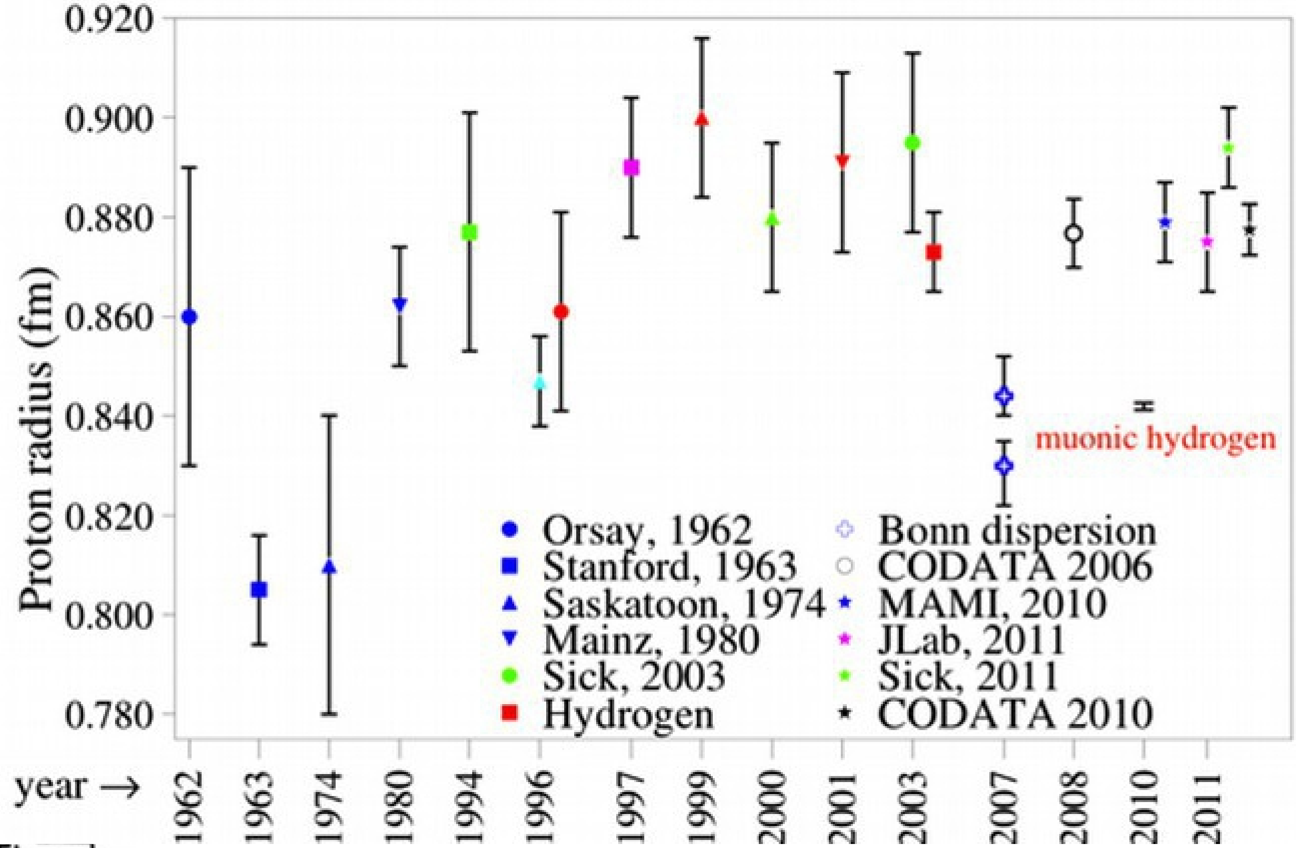
Fit form factor trend with q^2, to data, find slope as $q^2 \to 0$

Atomic Energy Levels



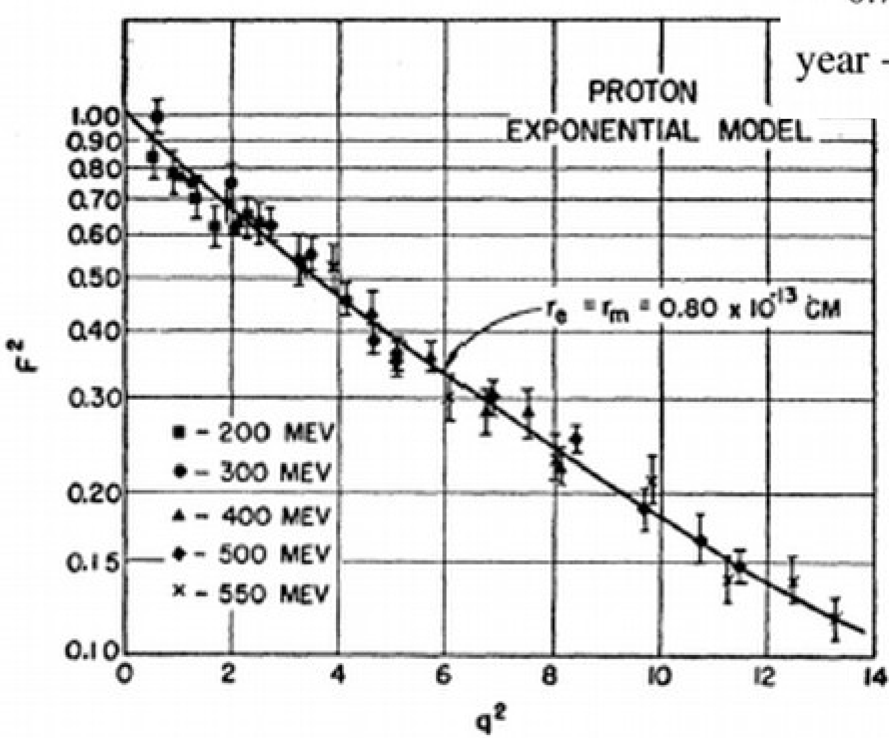
NRQM: finite size of proton perturbs energies of s states - $r_p <<<< r_{atomic}$, so effect proportional to $\psi^2_a(r=0)$.

The Proton Radius as a function of time



From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, AnnRevNPS, modified

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

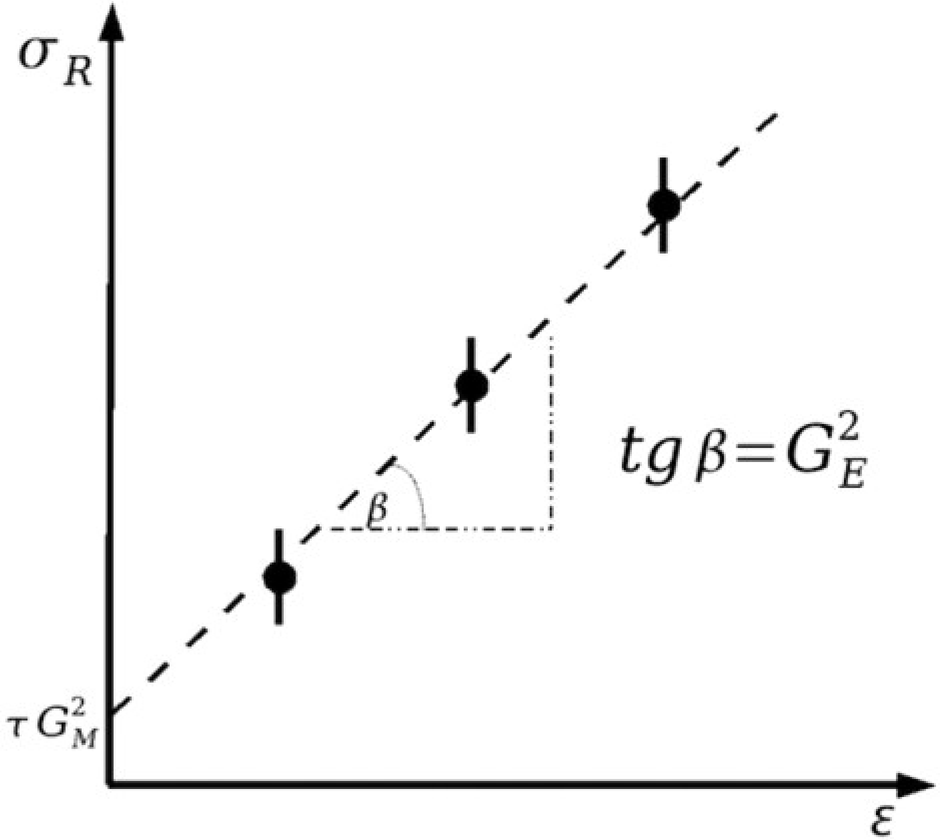


Electron Scattering Measurements

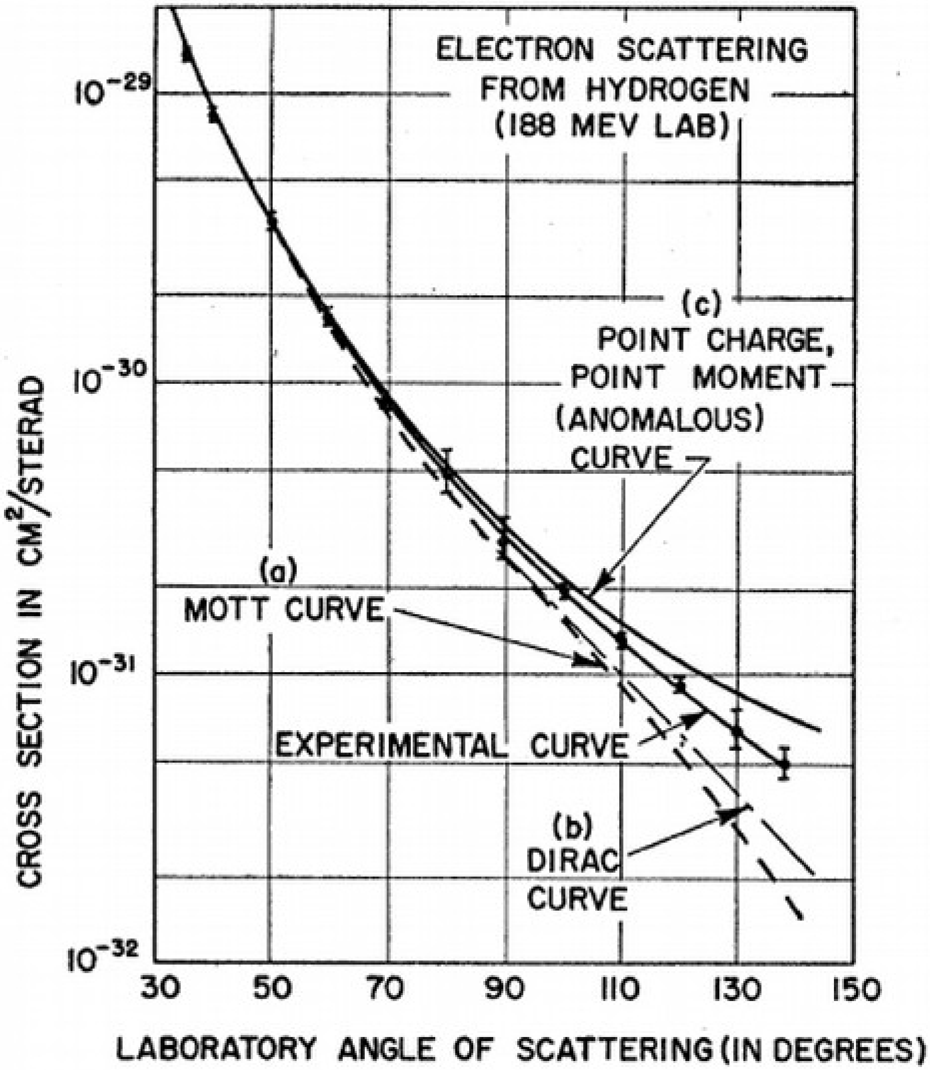
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right] \; ; \; \tau \equiv \frac{Q^2}{4M^2}$$

$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- 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.



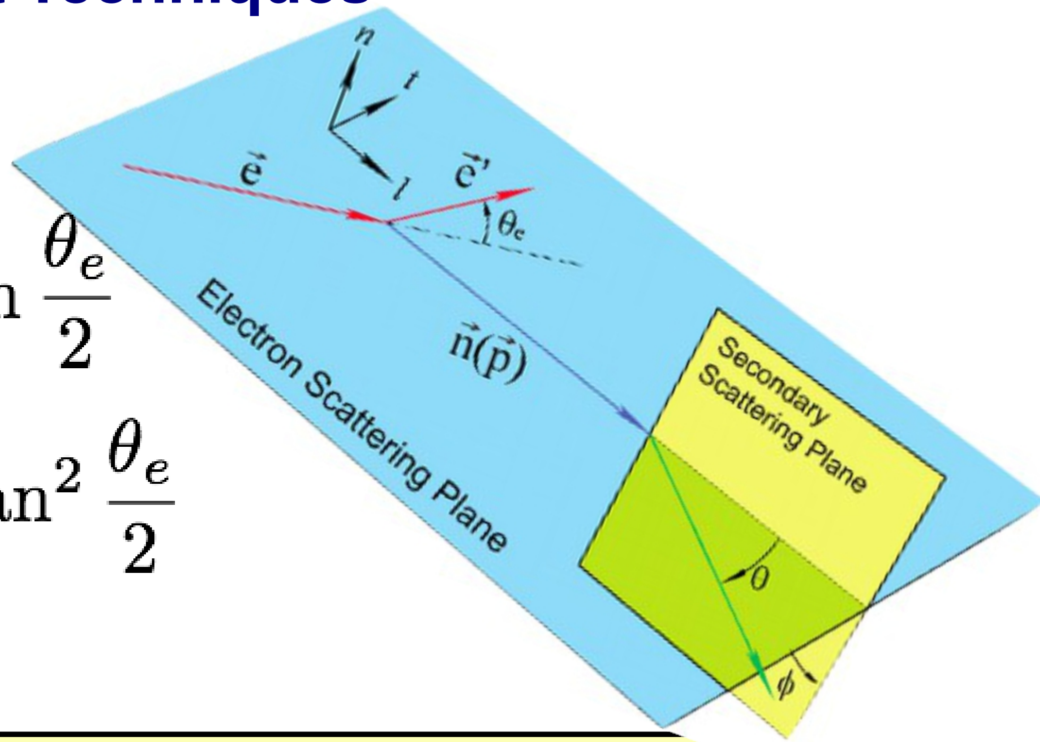
Electron Scattering Measurements 1950s



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

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

Measurement Techniques



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

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

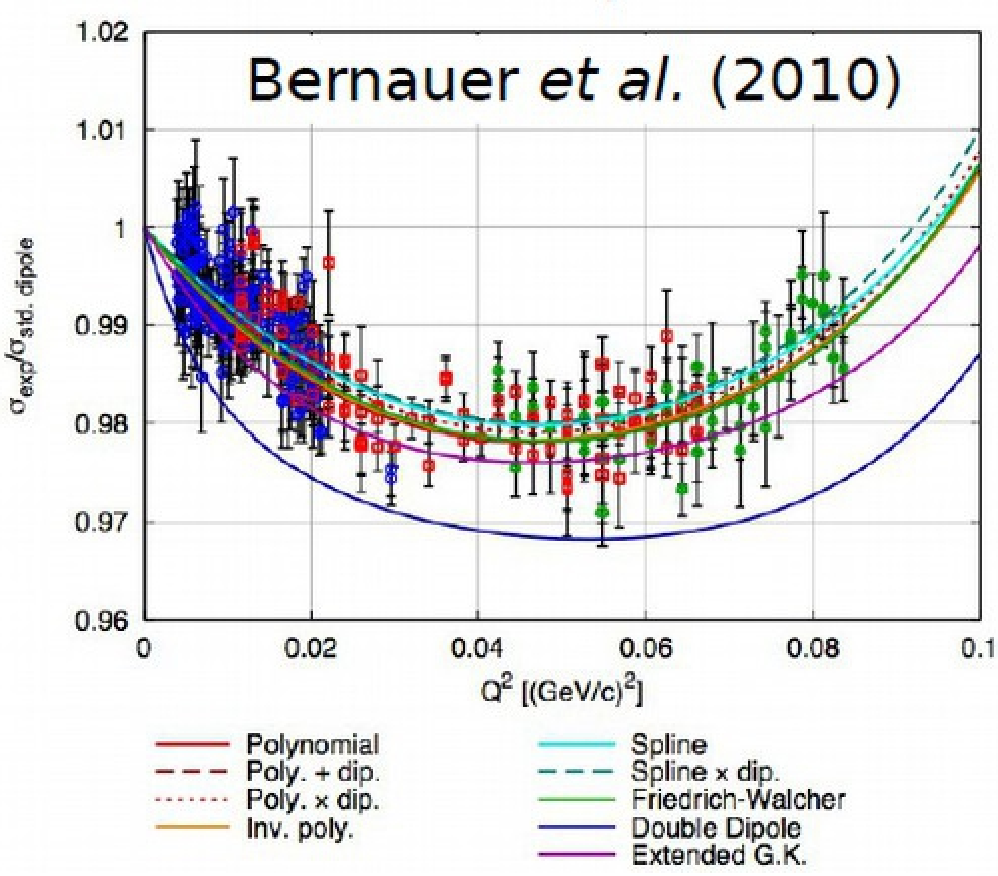
$$P_n = 0 \ (1\gamma)$$

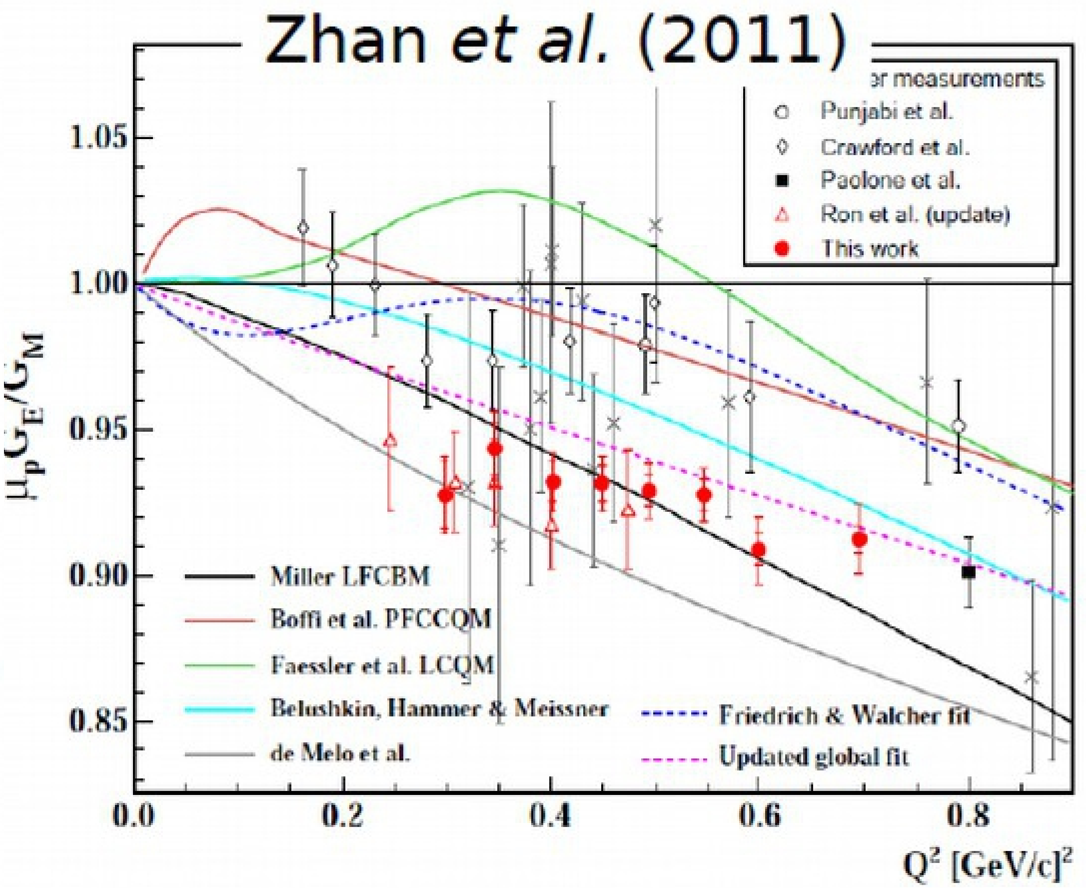
$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of “small” and “large” terms allow measurement at practically all values of Q^2.

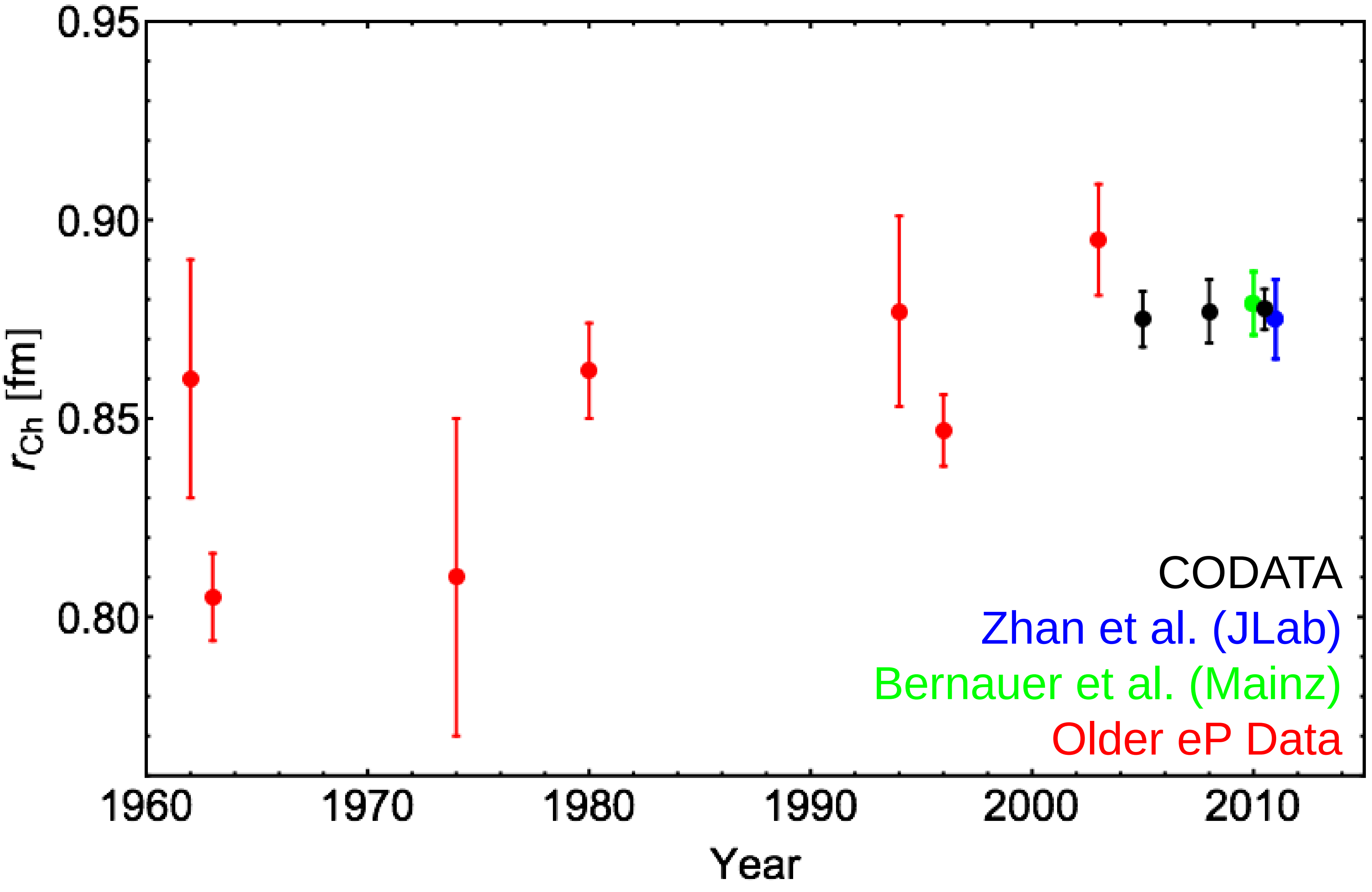
Electron Scattering Measurements

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

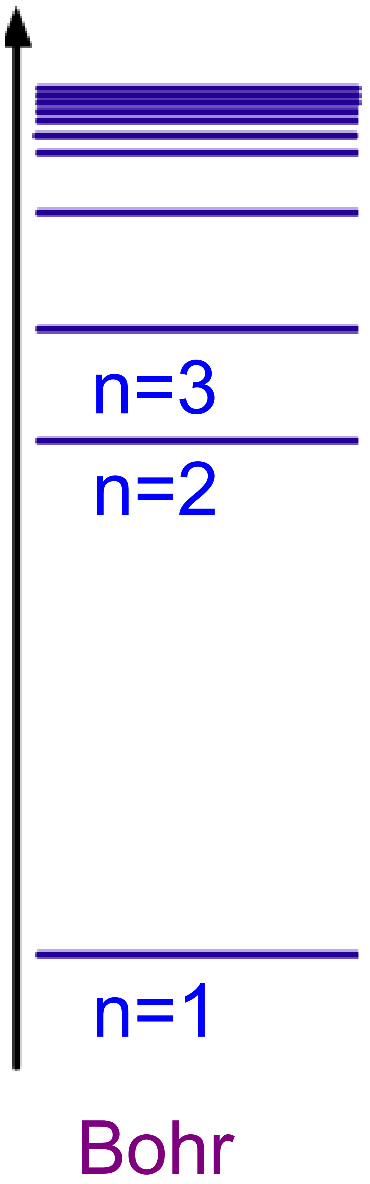




Time evolution of the radius from eP data



Components of the Hydrogen Energy Levels



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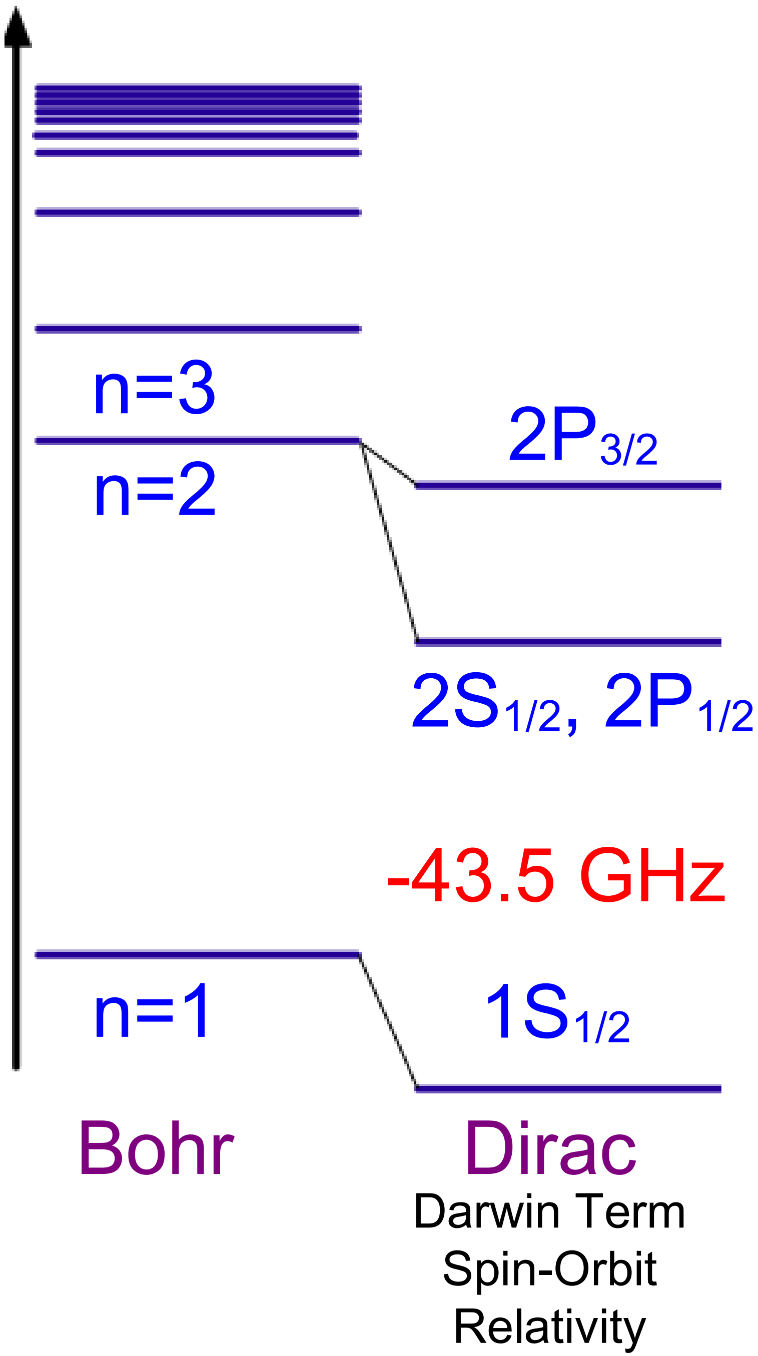

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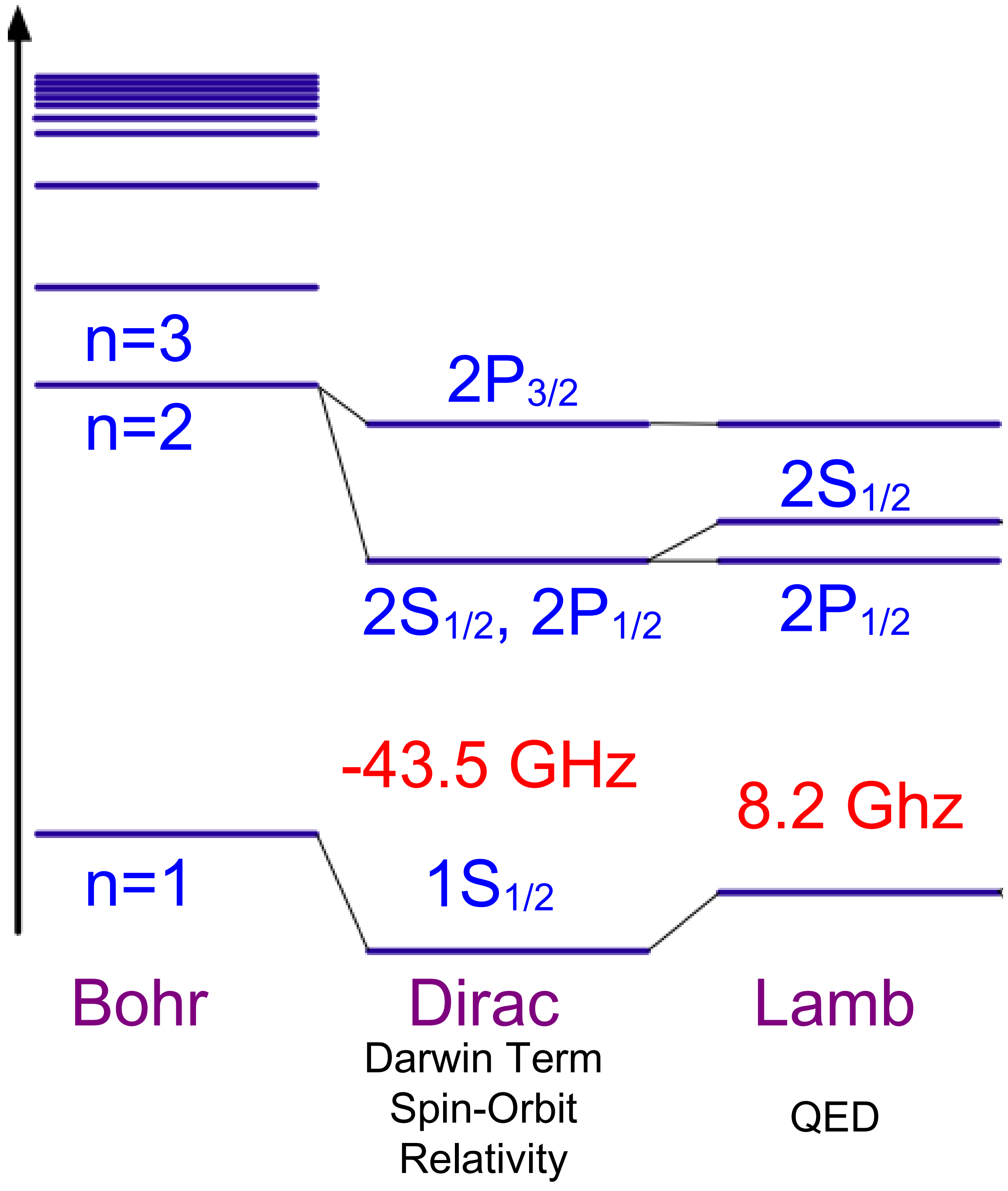

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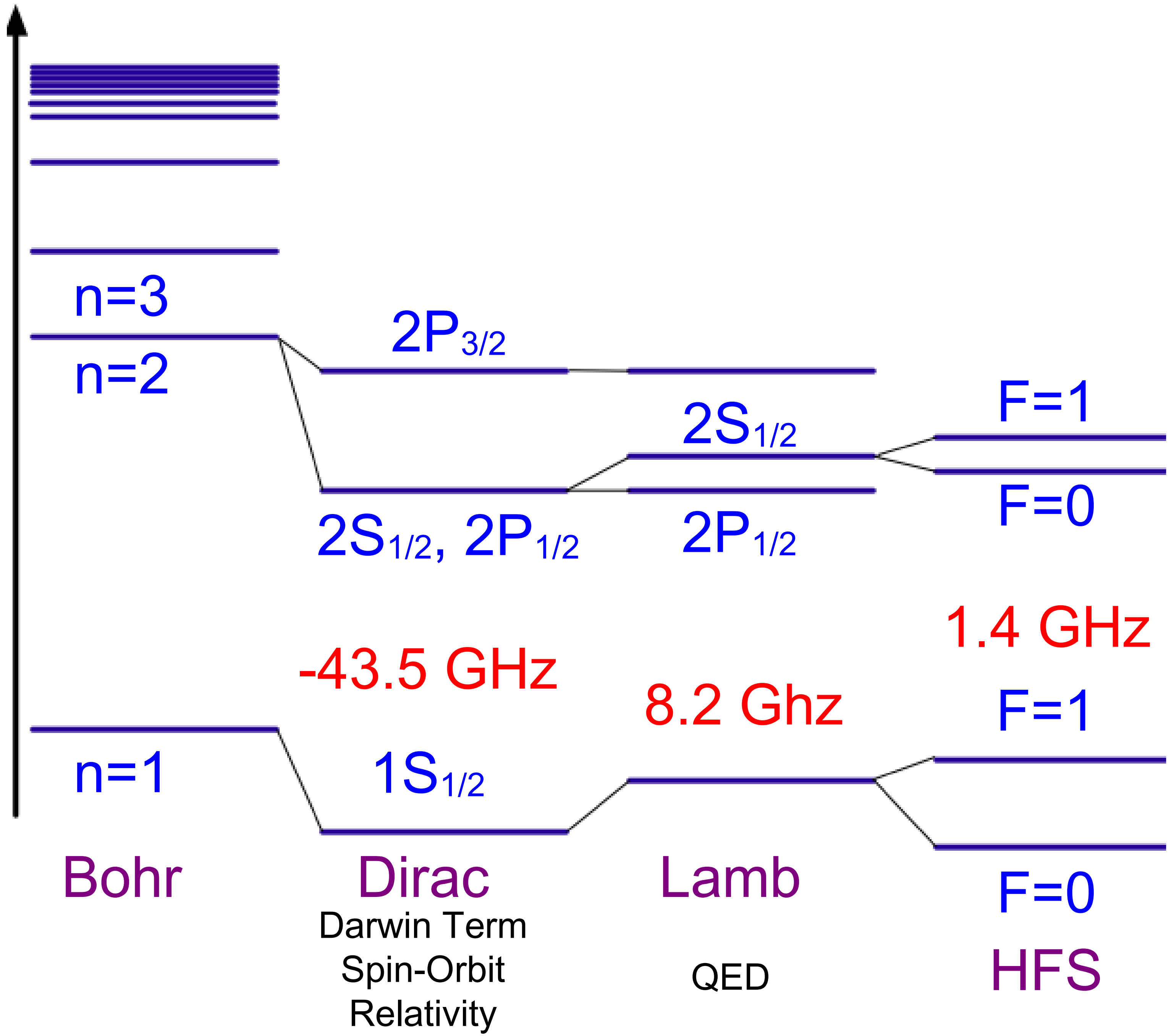

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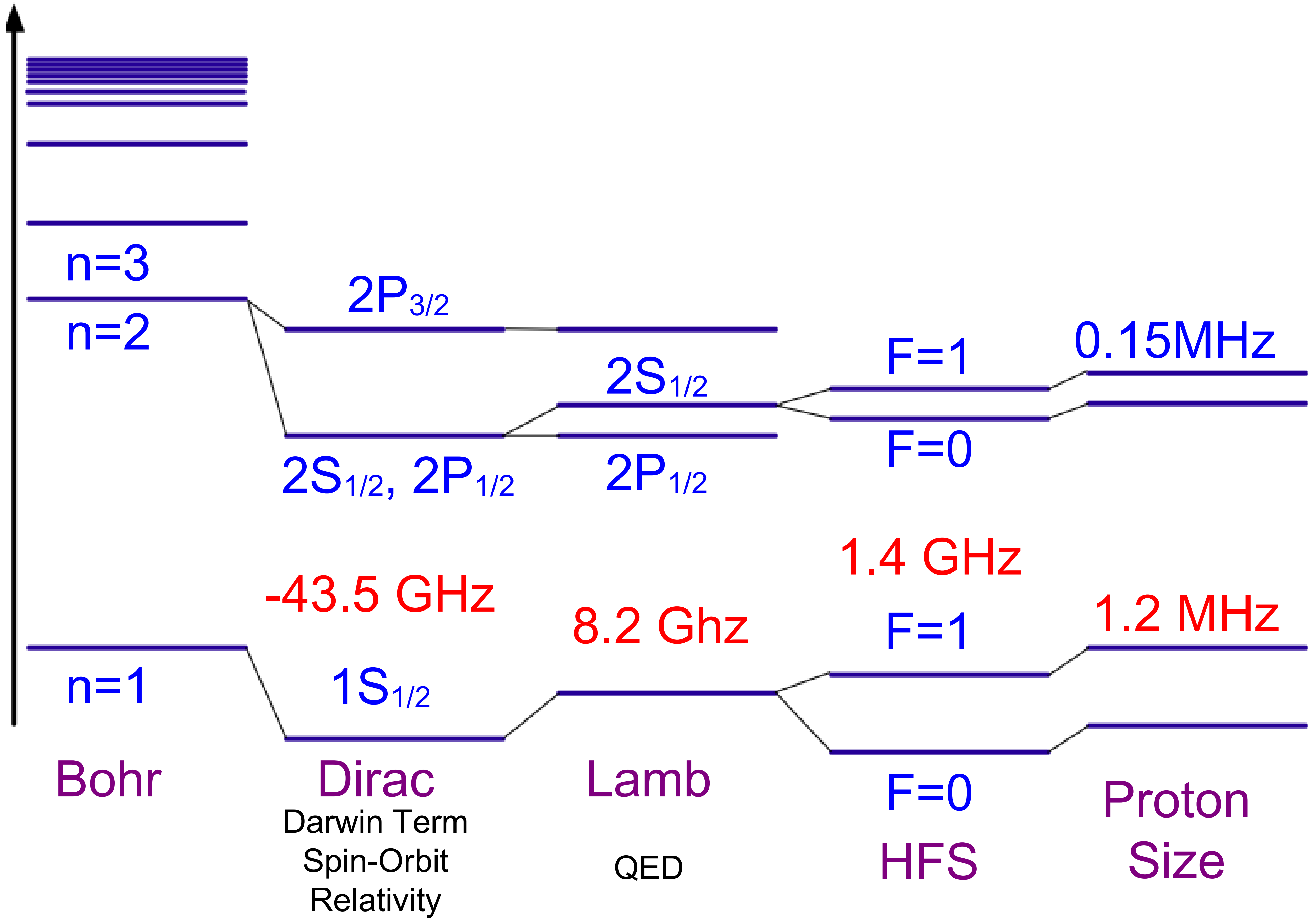

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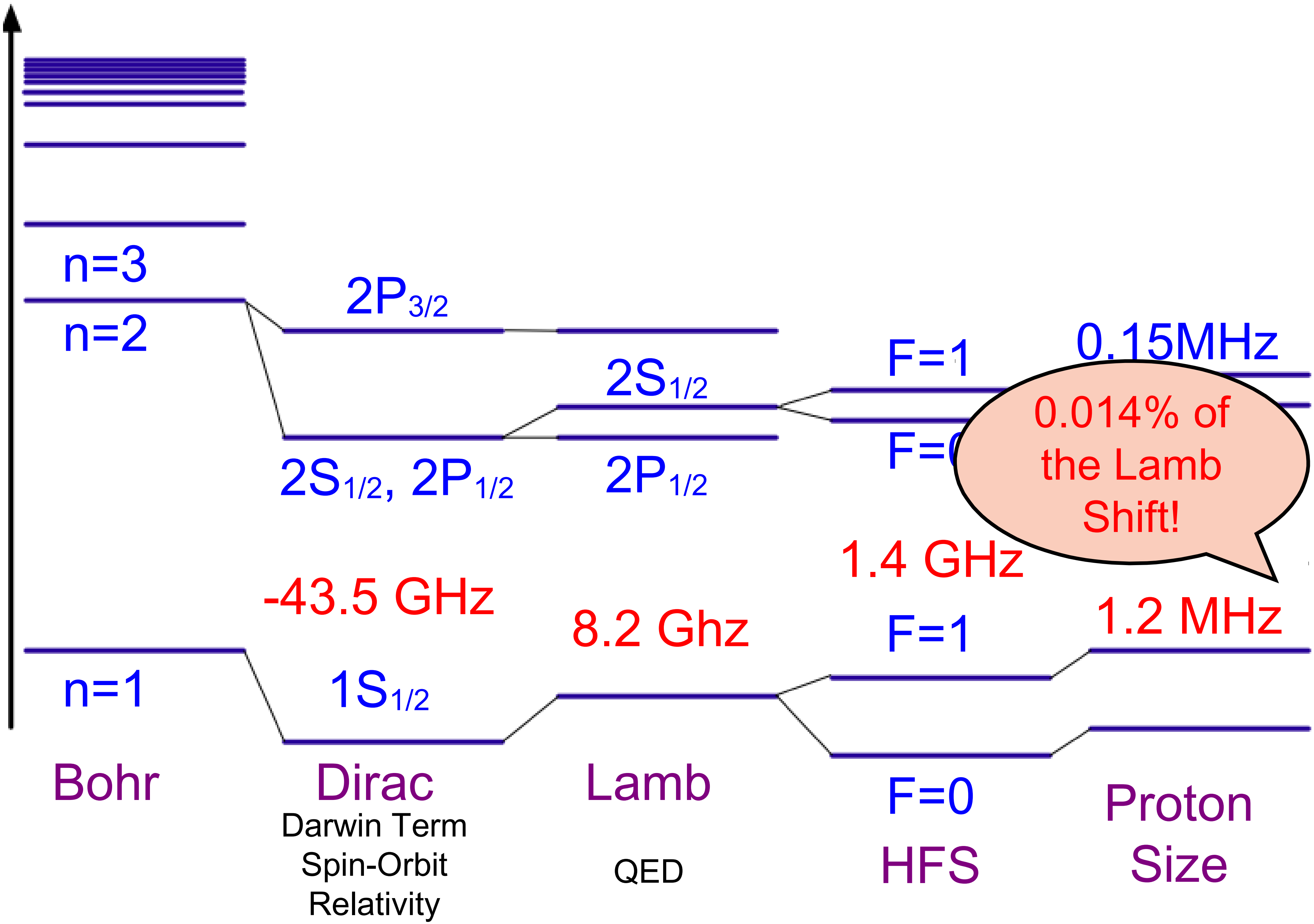
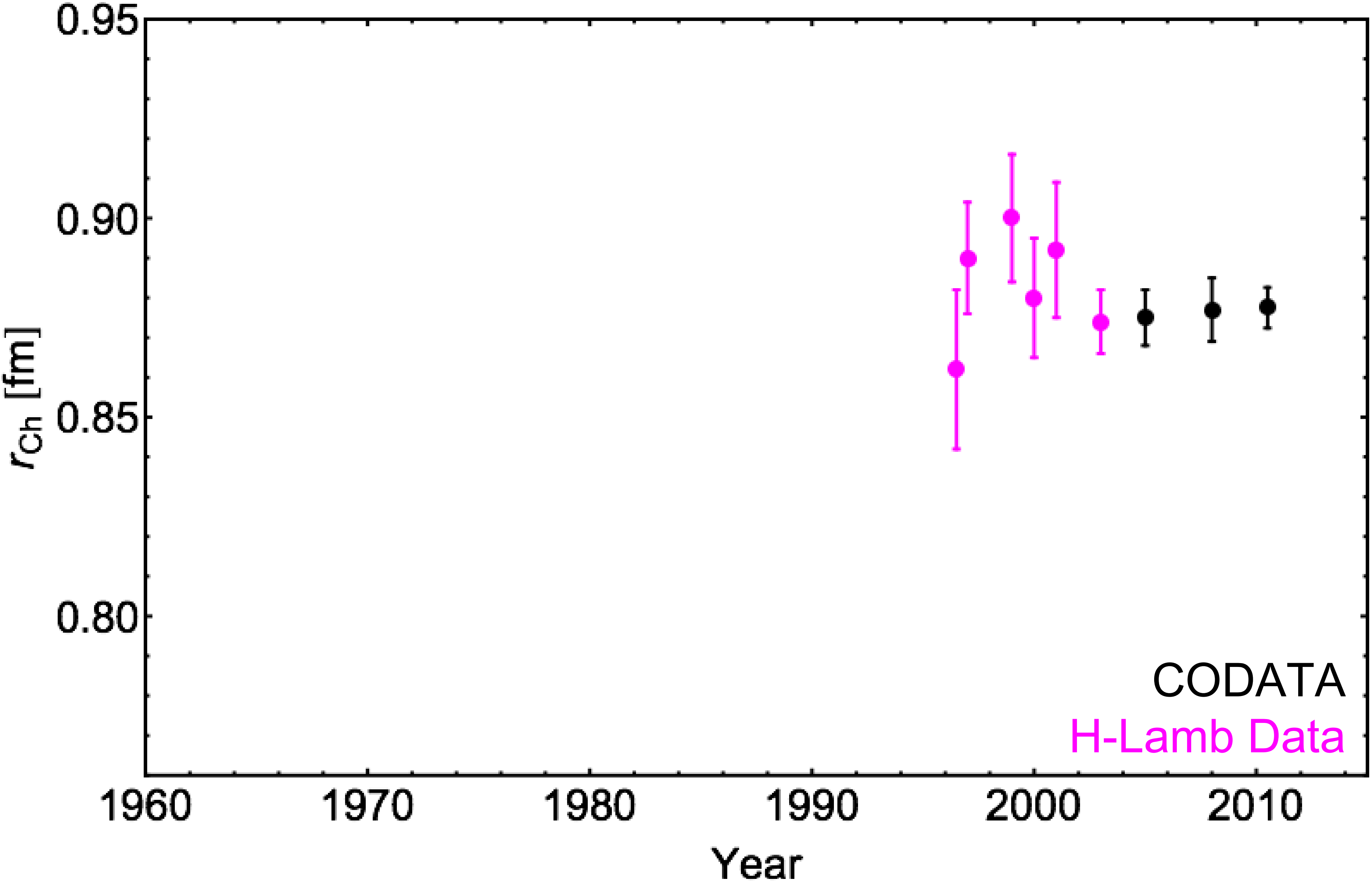
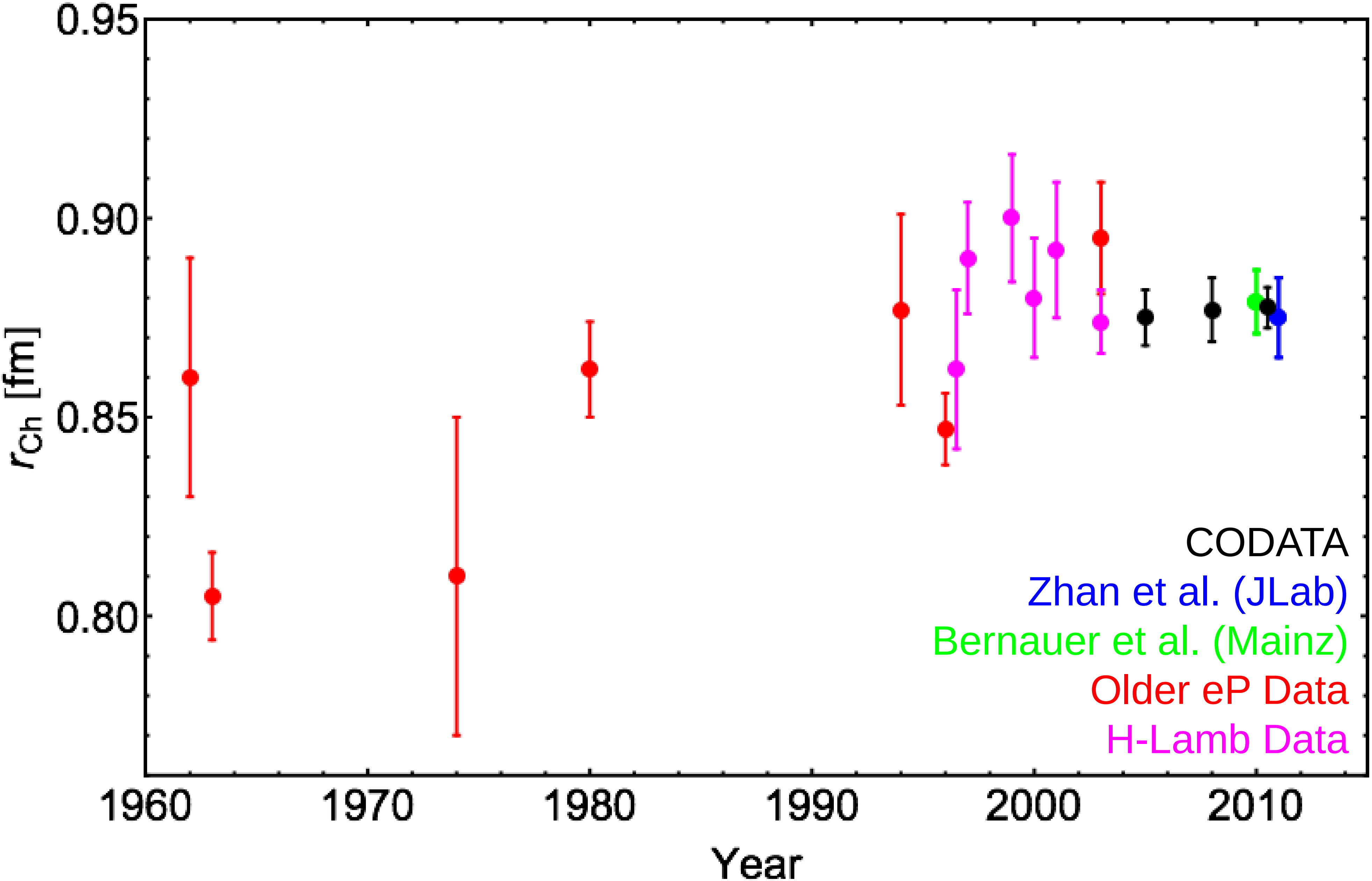


Time Evolution of the radius from Hydrogen Lamb Shift

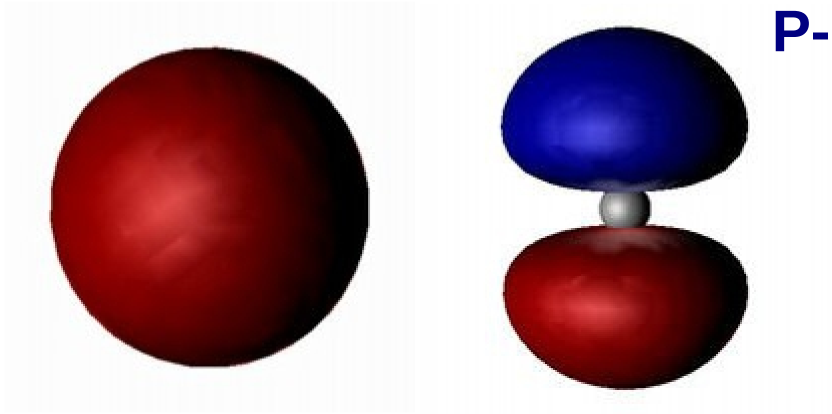


Time Evolution of the radius from Hydrogen Lamb Shift and eP



Why measure with μH?

S-Orbital



P-Orbital

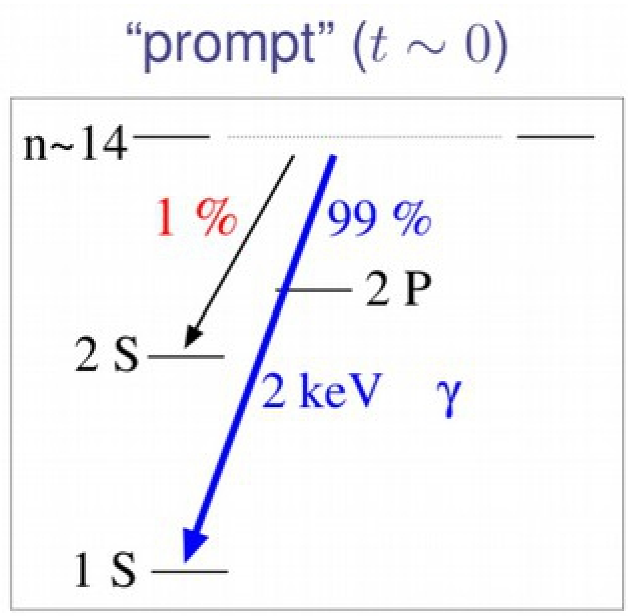
- While lepton is inside proton, attractive potential is lower
- Average potential reduced the longer lepton spends inside proton
- Strongly affects S orbitals, much less so P, so SP transitions change
- Probability for lepton to be inside proton = volume of P / volume of atom:

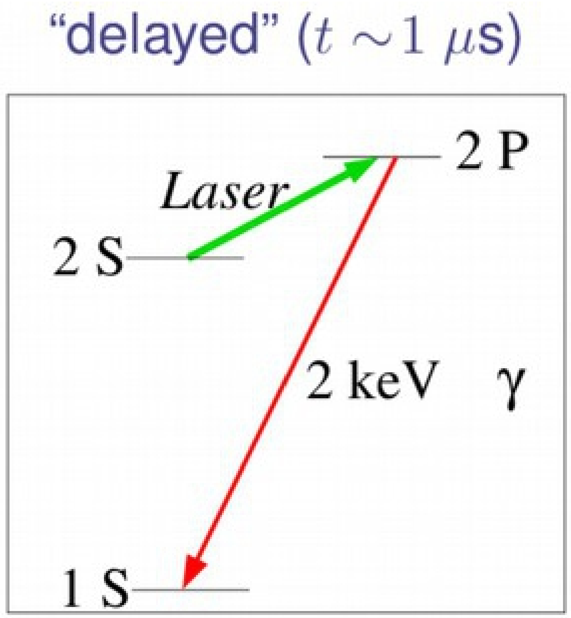
$$\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p \alpha)^3 m^3$$

- m_μ=~205m_e is μH is ~205^3 ~ **8 million times more sensitive to r_P**

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

Mechanics of measuring with μH



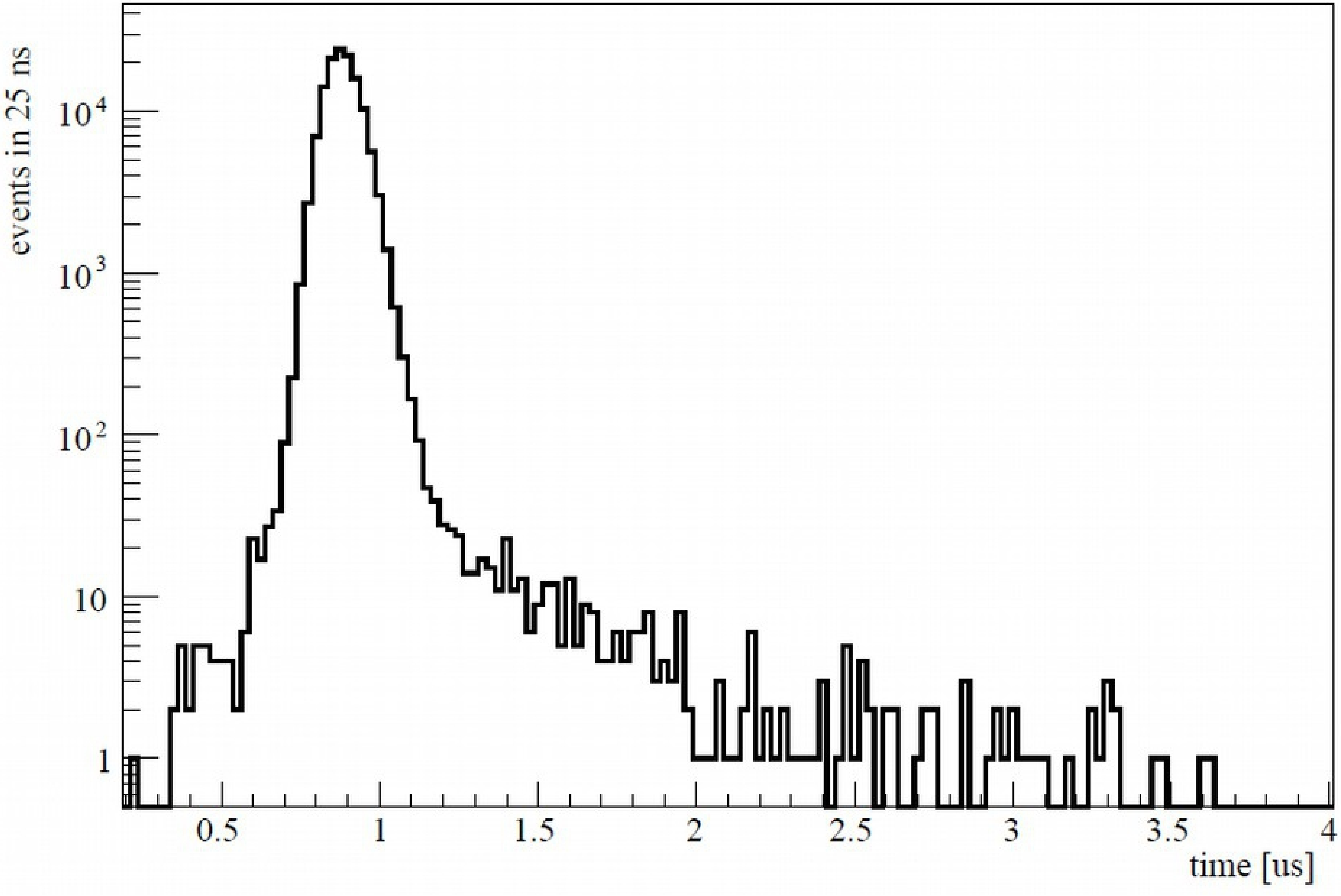


- Beautifully simple, but technically challenging!
- Form μH*(n~14) by firing muon beam on 1mbar H_2 target
- 99% decay to 1s, giving out fast γ pulse
- 1% decay to longer-lived 2s state
- Excited to 2P state by tuned laser & decay with release of delayed γ
- Vary laser frequency to find transition peak → 2P to 2S ΔE → r_p

Pictures: R. Pohl

Mechanics of measuring with μH

time spectrum of 2 keV x-rays (∼ 13 hours of data @ 1 laser wavelength)



Pictures: R. Pohl

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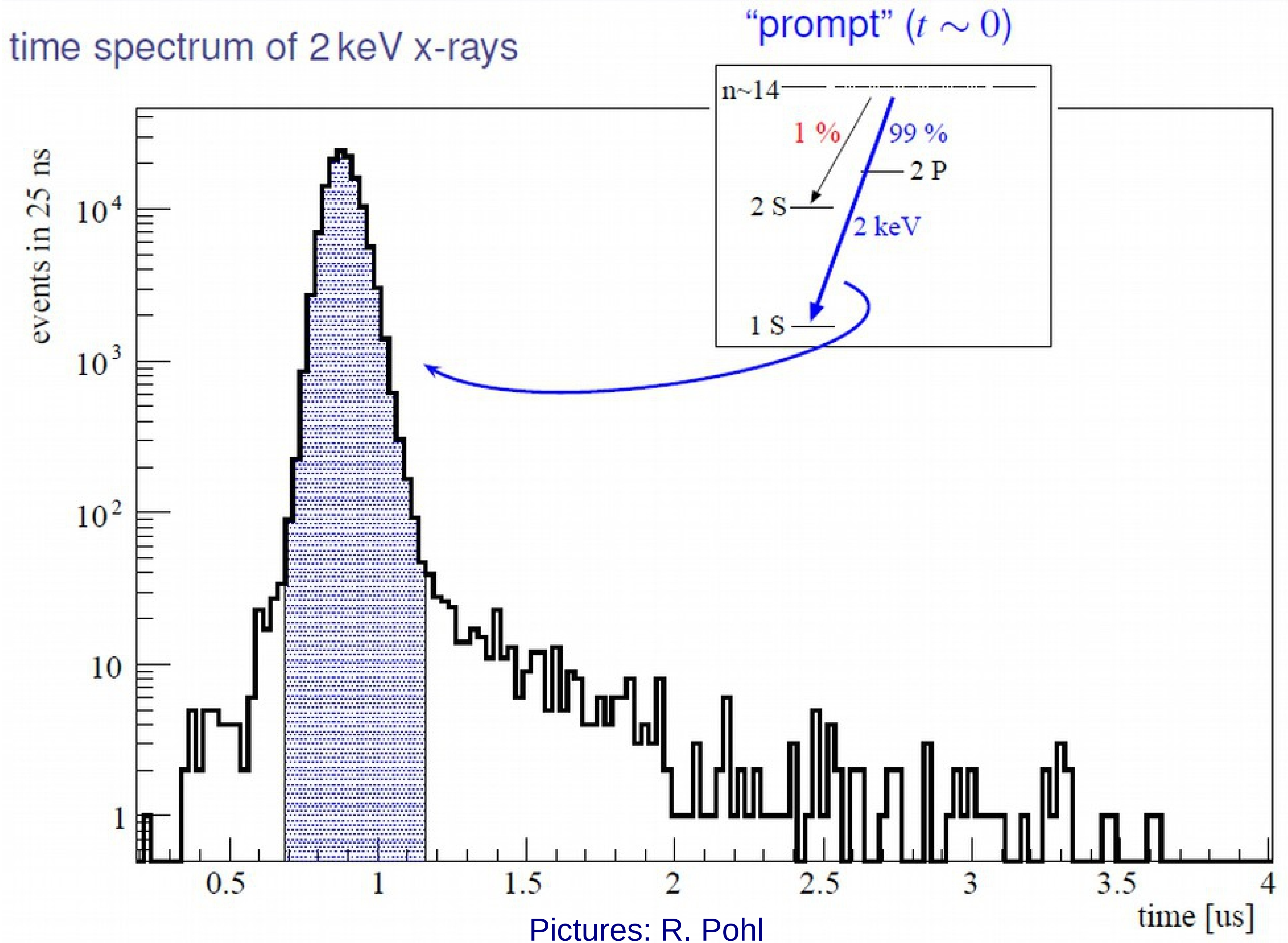

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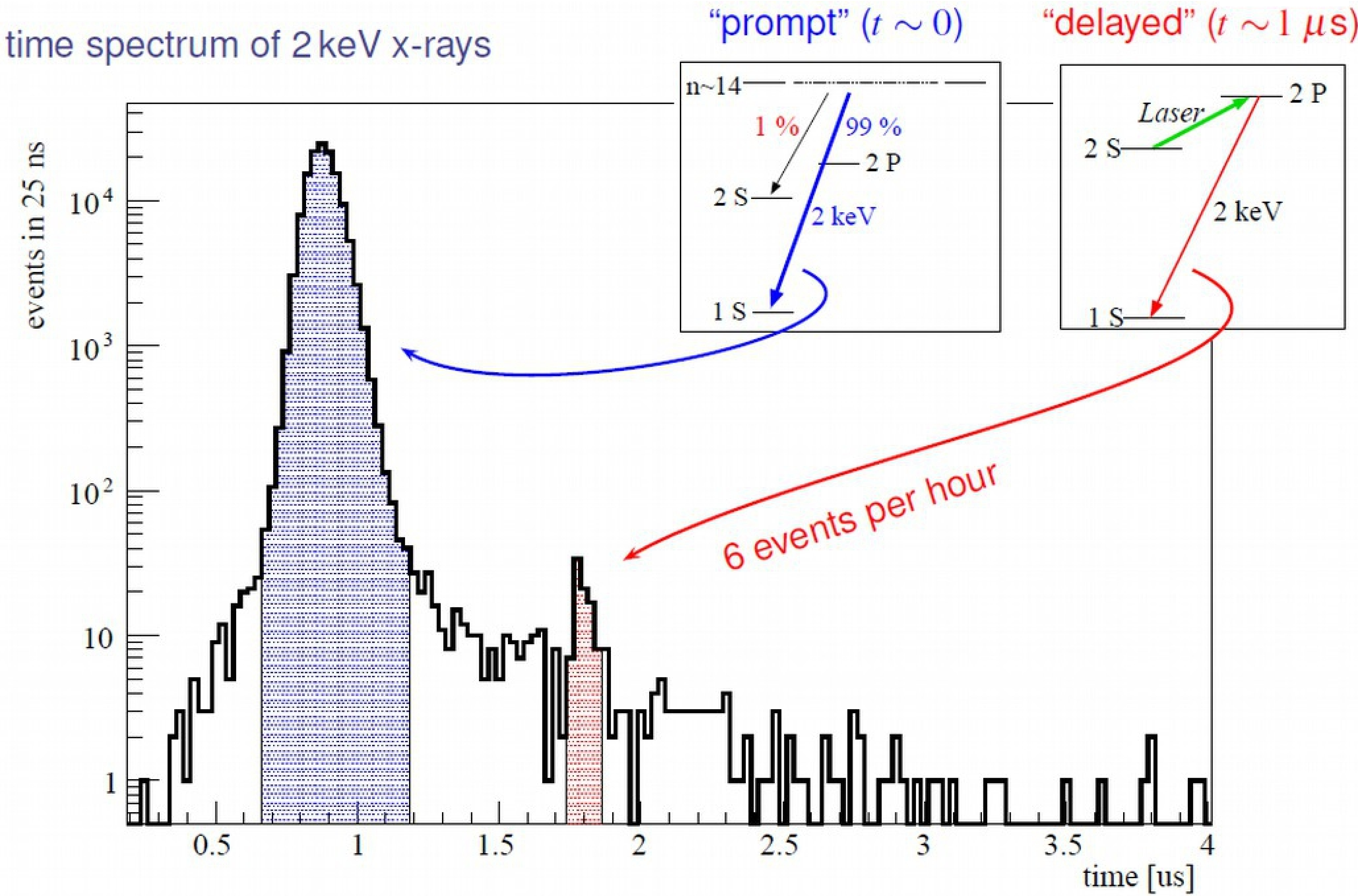

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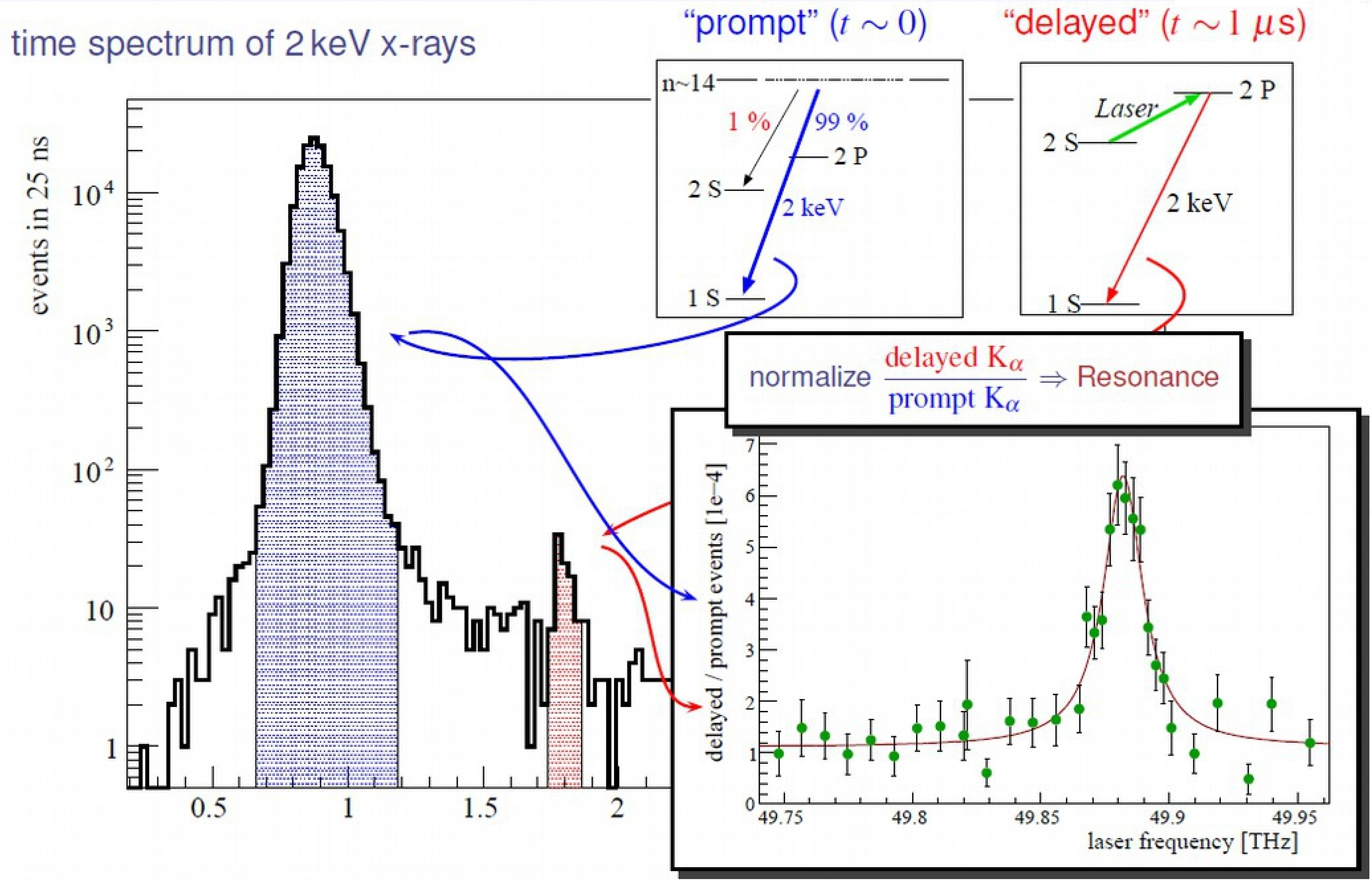

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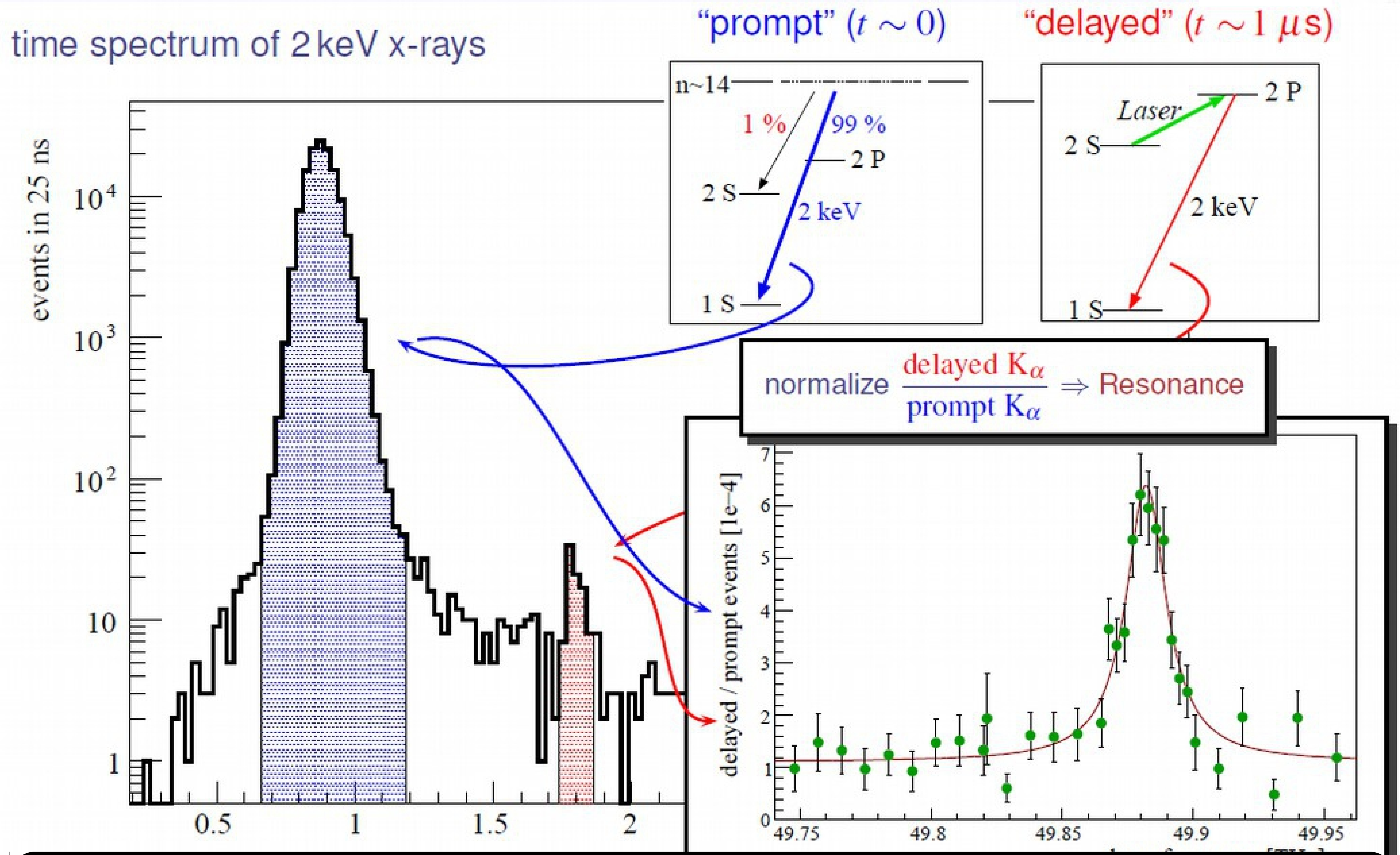
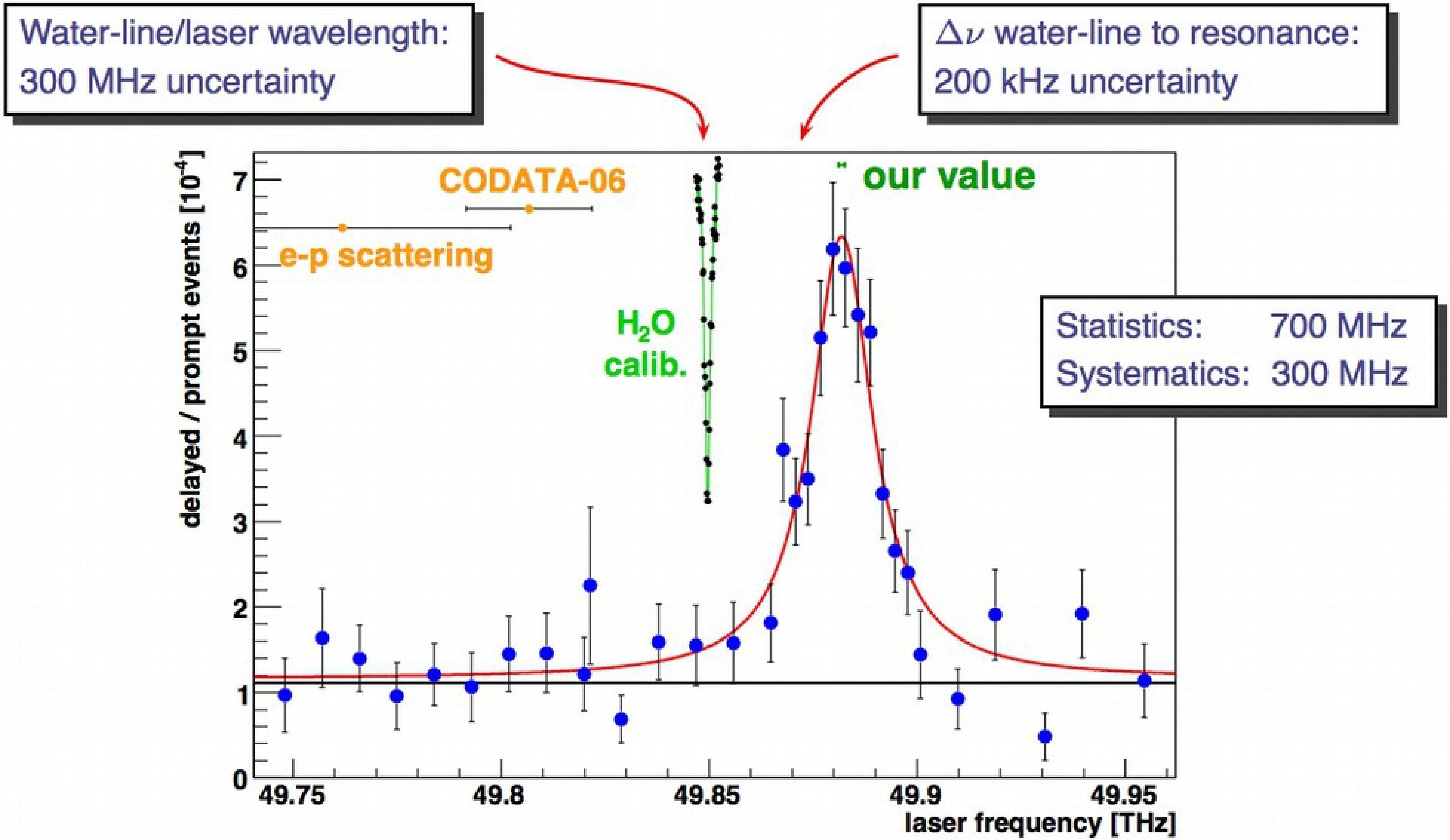


$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \ [\mathrm{meV}]$$

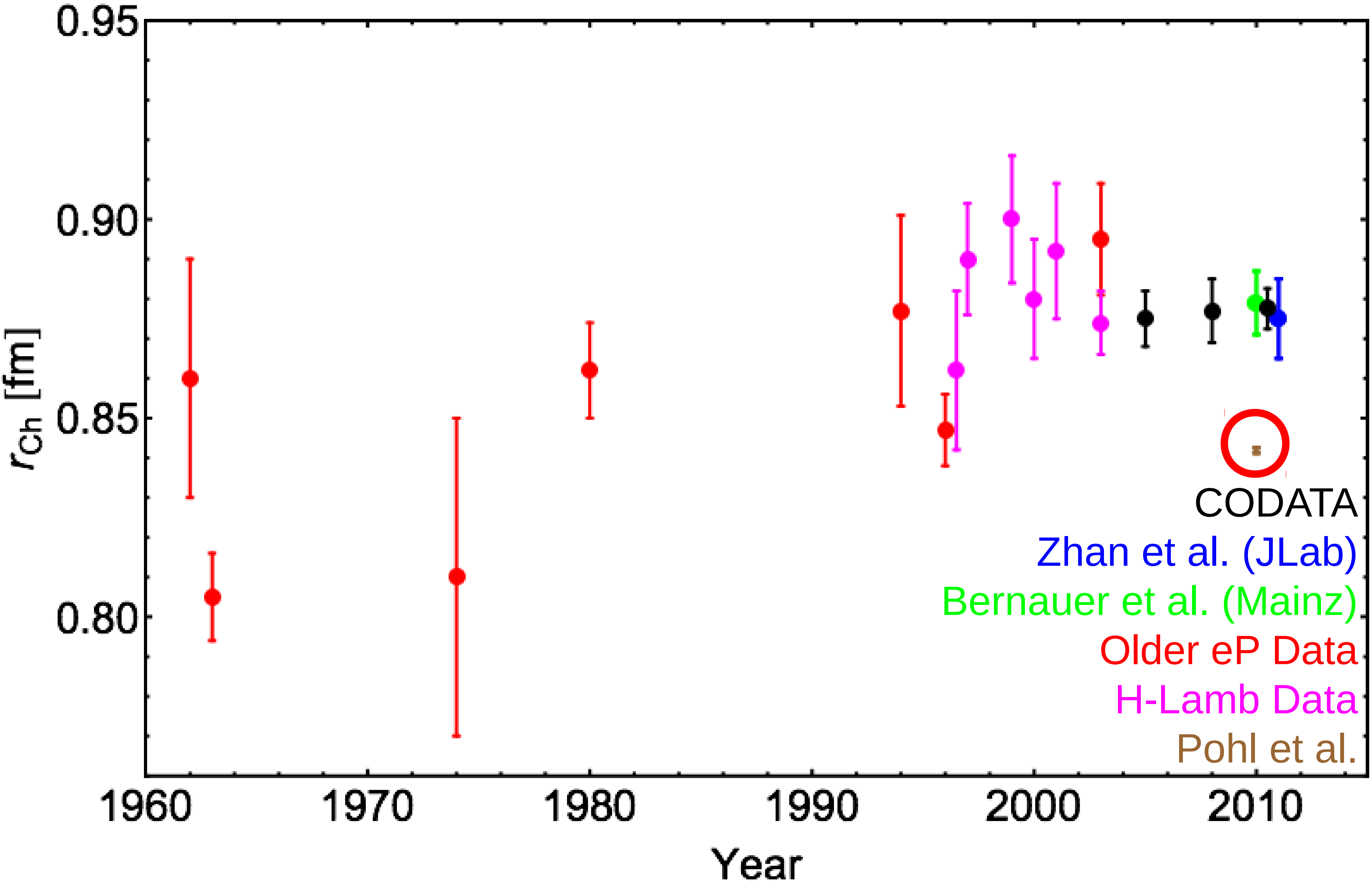
The Proton Radius from excitation spectrum



- Take ratio of delayed to prompt as a function of laser frequency:

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

Time evolution of the Lamb Shift Measurements & eP data



Curiouser & Curiouser...

- Aldo Antognini *et al*. Science **339**, 417 (2013)
- Further analysis of data taken in Pohl measurement
- Magnetic radius agrees with e^- scattering data
- Electric radius in agreement with Pohl 0.84087 ± 0.00039 fm
- 7.9σ from 2010 CODATA

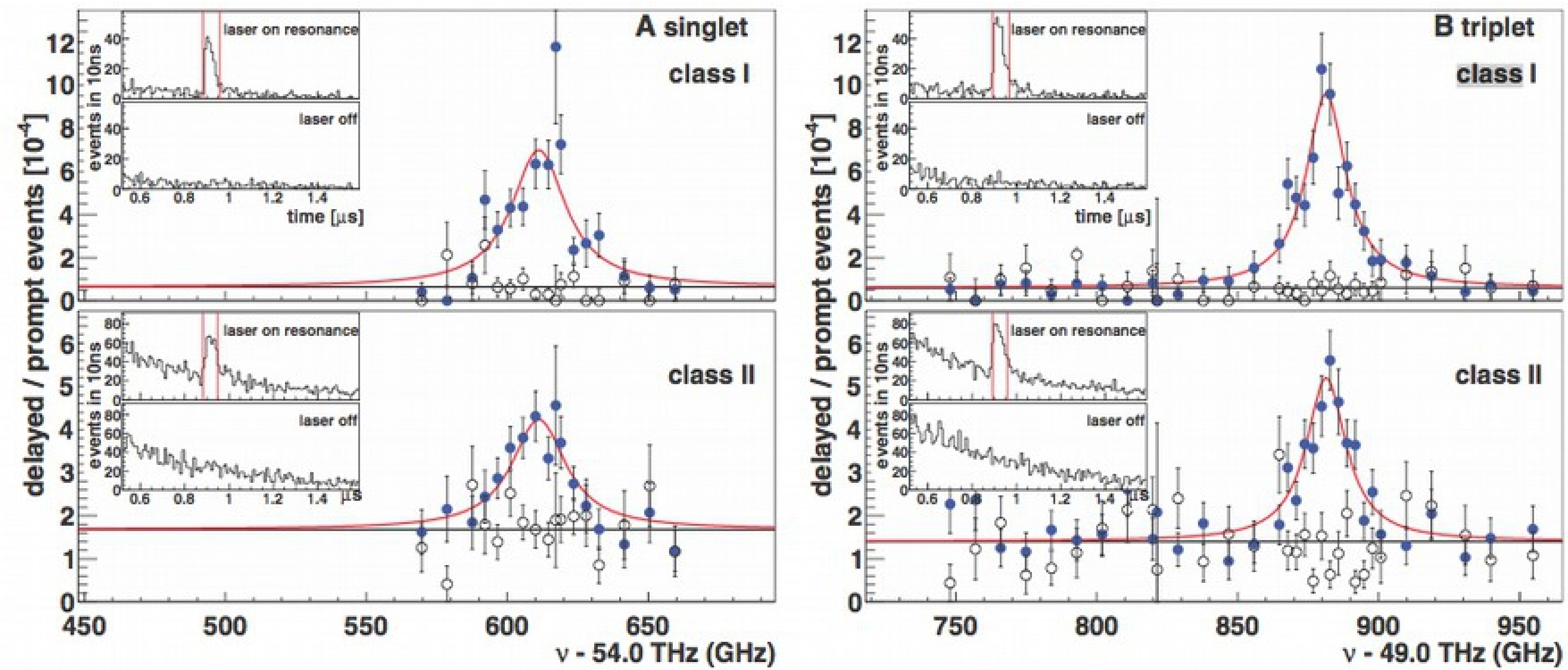


Fig. 3. Muonic hydrogen resonances (solid circles) for singlet ν_s (**A**) and triplet ν_t (**B**) transitions. Open circles show data recorded without laser pulses. Two resonance curves are given for each transition to account for two different classes, I and II, of muon decay electrons (*12*). Error bars indicate the standard error. (Insets) The time spectra of K_α x-rays. The vertical lines indicate the laser time window.

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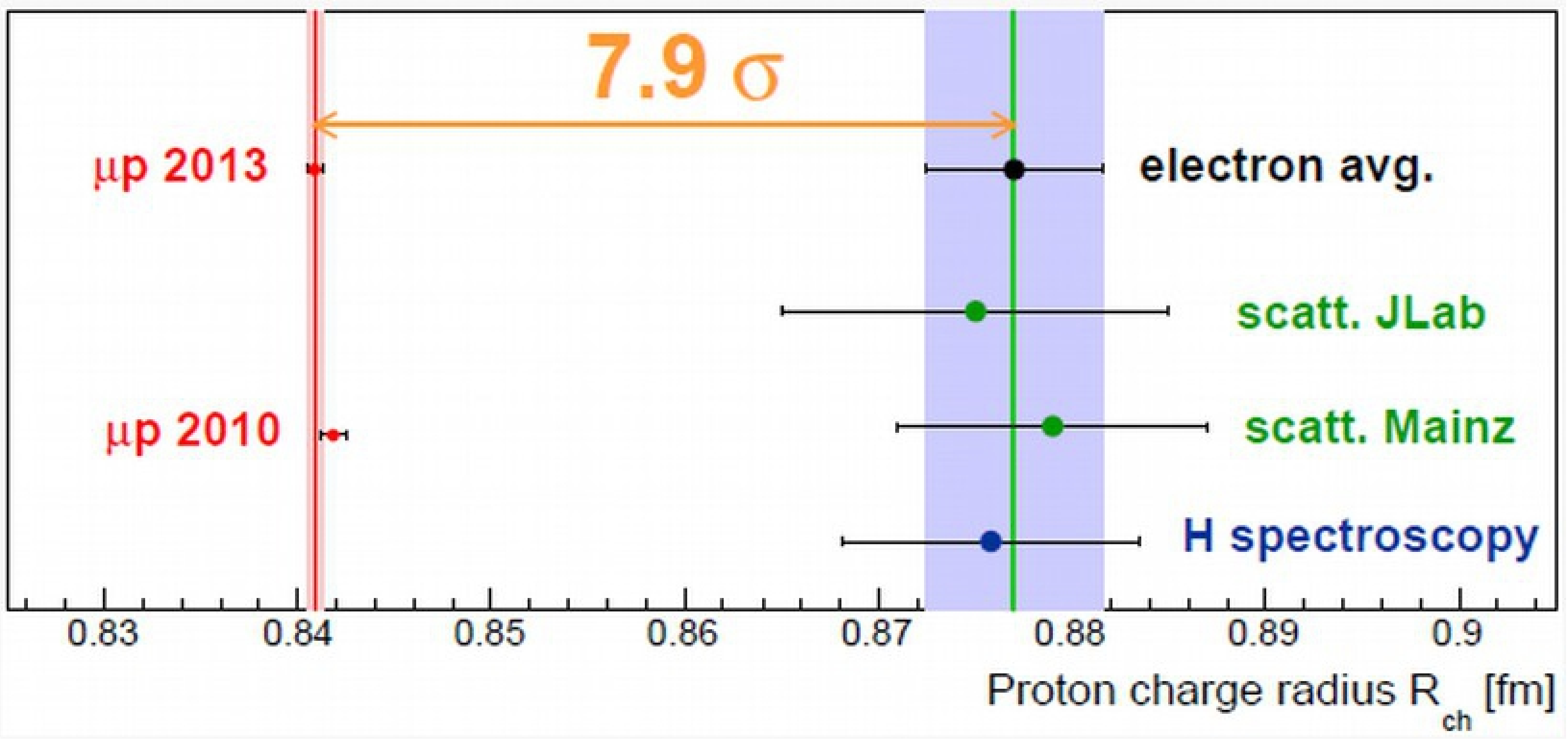
- Analysis gives:



Are we still puzzled?

Why do the muon and electron give different proton radii?

- Assuming the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?
- Novel Beyond Standard Model Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
- Novel Hadronic Physics: G. Miller: currently unconstrained correction in proton polarizibility affects μ, but not e (effect$\propto m_l^4$)
- Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, ...
- See Trento Workshops on PRP for more details:

  http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento (2012)

  http://www.ectstar.eu/node/1659 (2016)

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:
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing atomic hydrogen
  - Redoing electron scattering at lower Q^2
  - Muon scattering!

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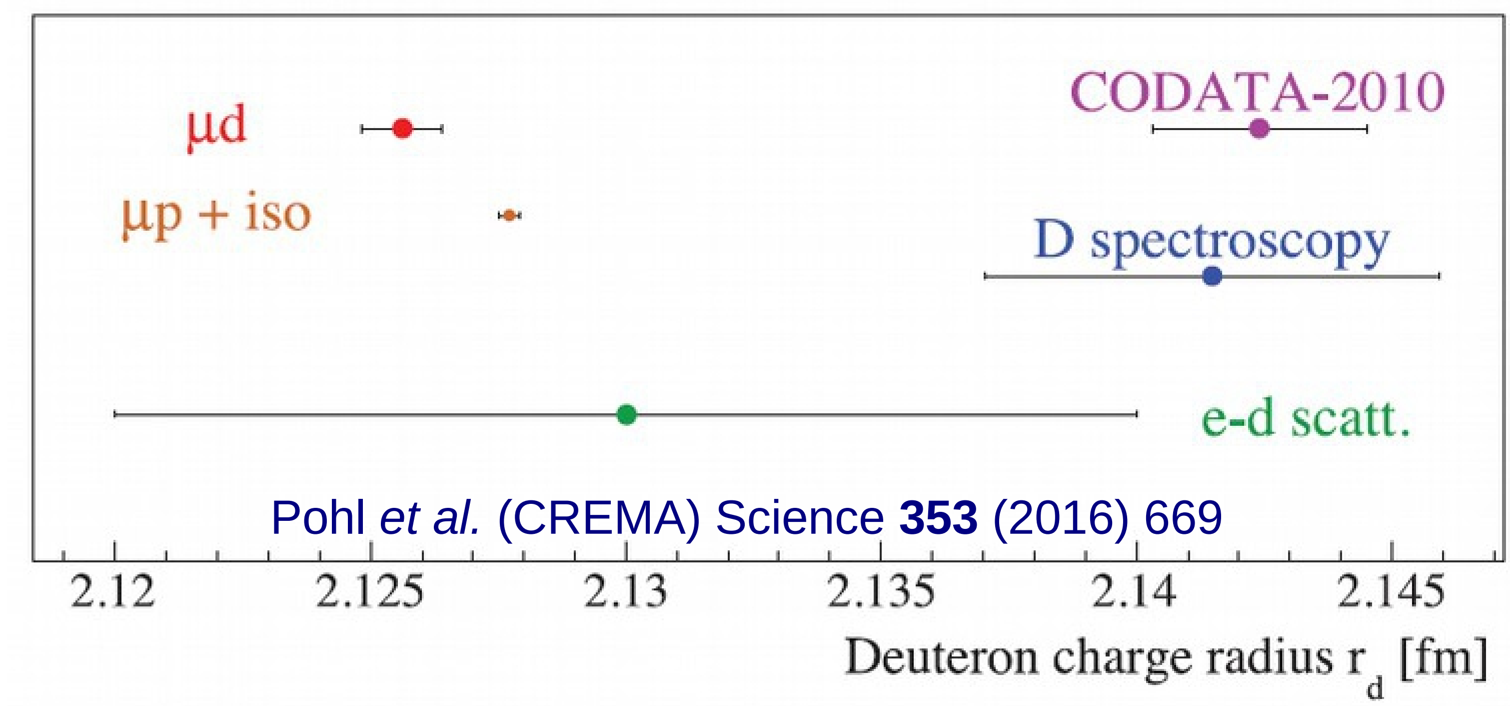
Light Muonic Atoms



- CREMA Collaboration moved on to heavier things
- Deuterium radius from μD agrees with μH (using isotope shift)
- Recent analysis gives 3.5σ difference between atomic and muonic D
  Pohl *et al.* arXiv:1607.03165v2 [atom-ph]
- Electron scattering on Deuterium too imprecise for comparison
- More to follow...

Light Muonic Atoms

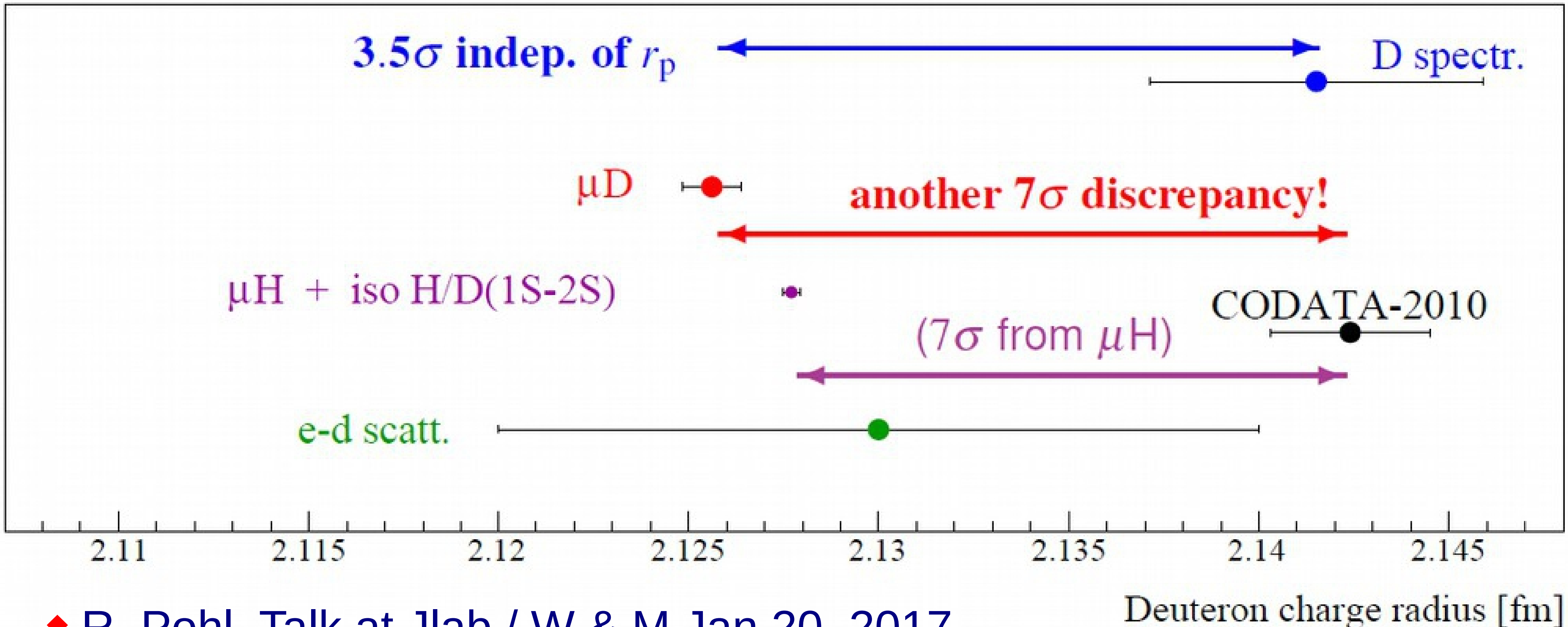
H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \mathrm{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010 $r_d = 2.14240(210)$ fm

r_p from μH gives $r_d = 2.12771(\ 22)$ fm $\leftarrow 7\sigma$ from r_p

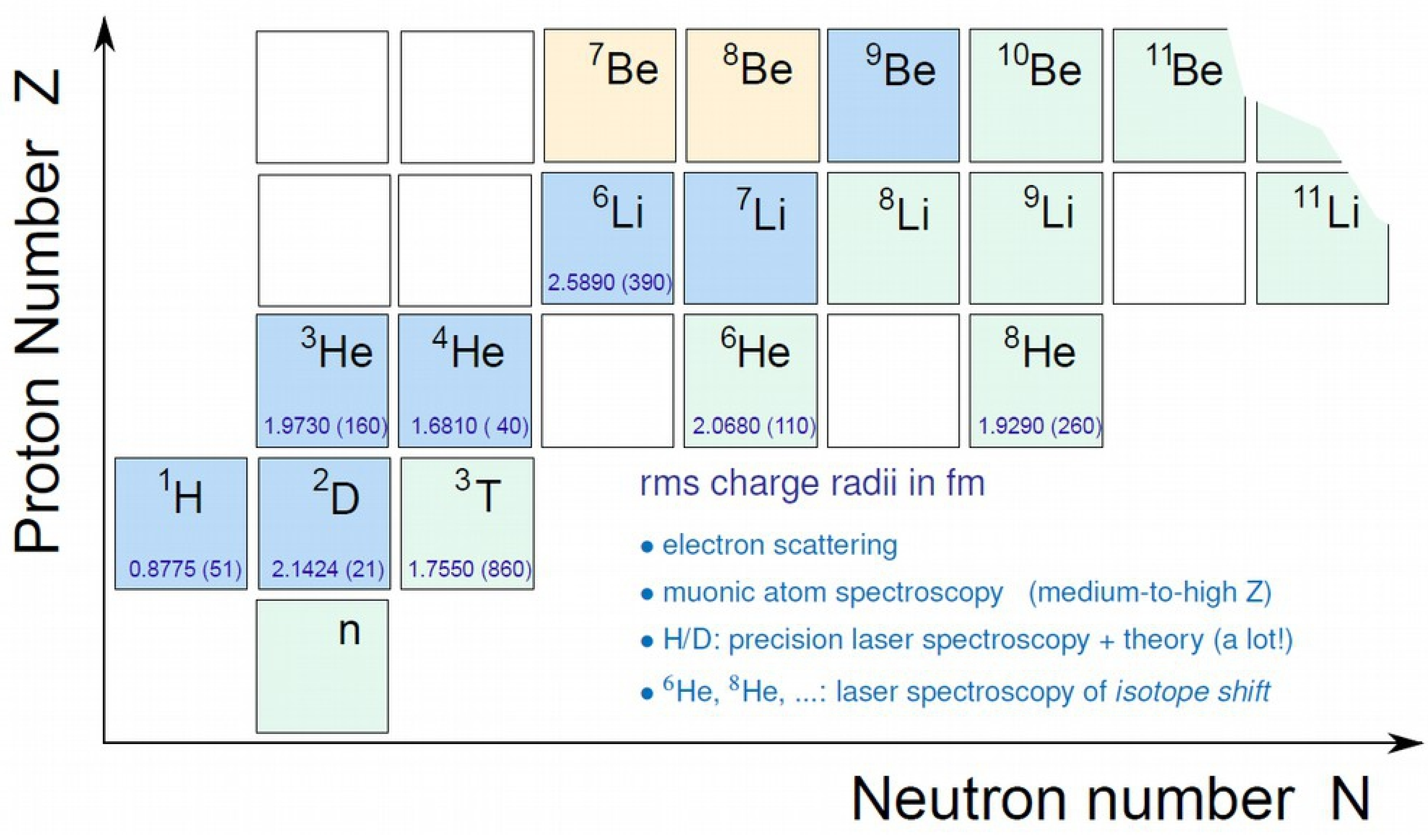
Muonic DEUTERIUM $r_d = 2.12562(\ 13)_{exp}(77)_{theo}$ fm RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450)$ fm $\leftarrow 3.5\sigma$ RP *et al.* arXiv 1607.03165



- R. Pohl, Talk at Jlab / W & M Jan 20, 2017

Light Muonic Atoms



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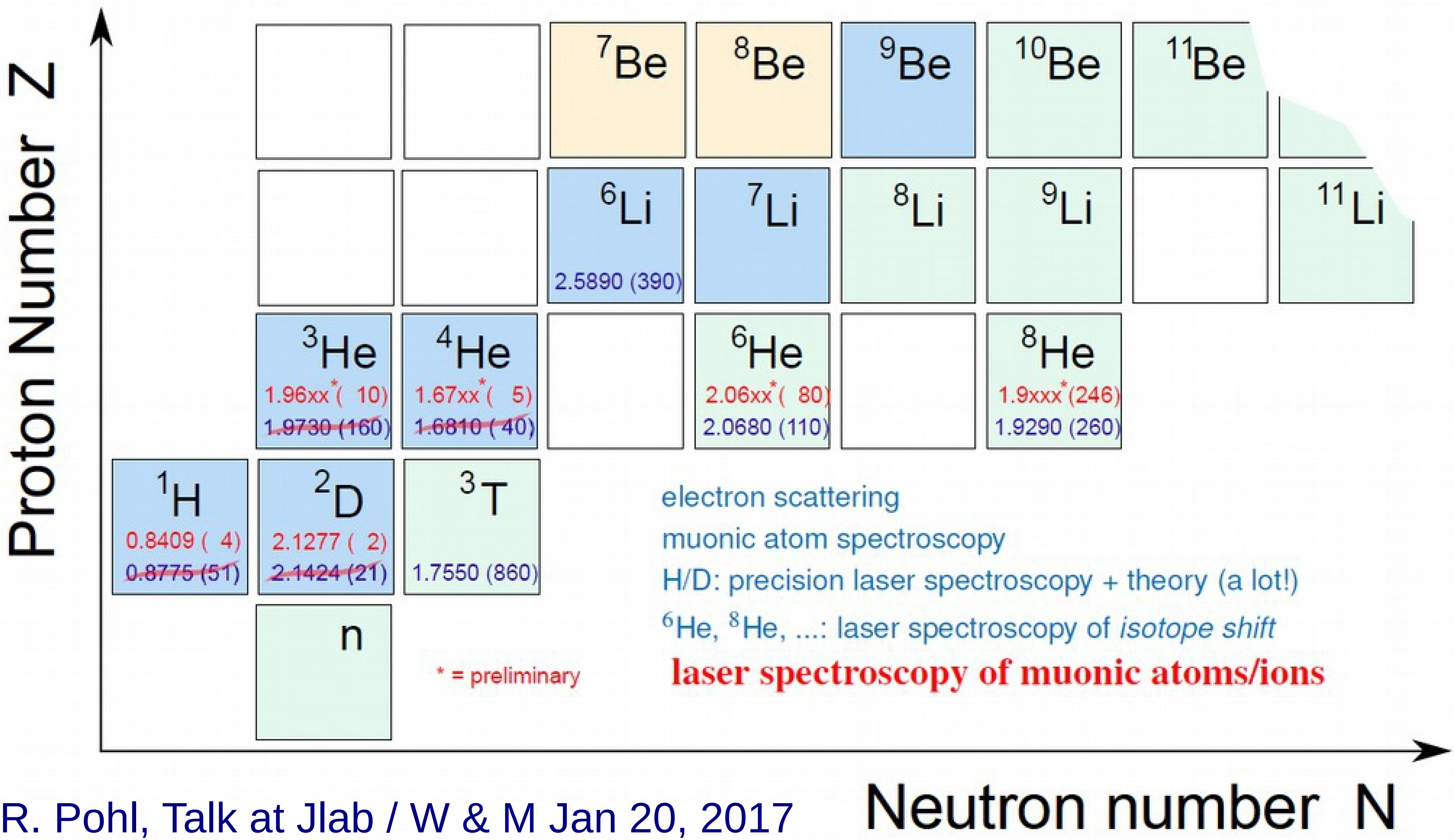

- R. Pohl, Talk at Jlab / W & M Jan 20, 2017
- Helium isotopes seem to agree (preliminary results)
- Puzzle seen in H & D (Z=1 radius puzzle?)

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  - ➔ **Redoing atomic hydrogen**
  - ➔ Redoing electron scattering at lower Q^2
  - ➔ Muon scattering!

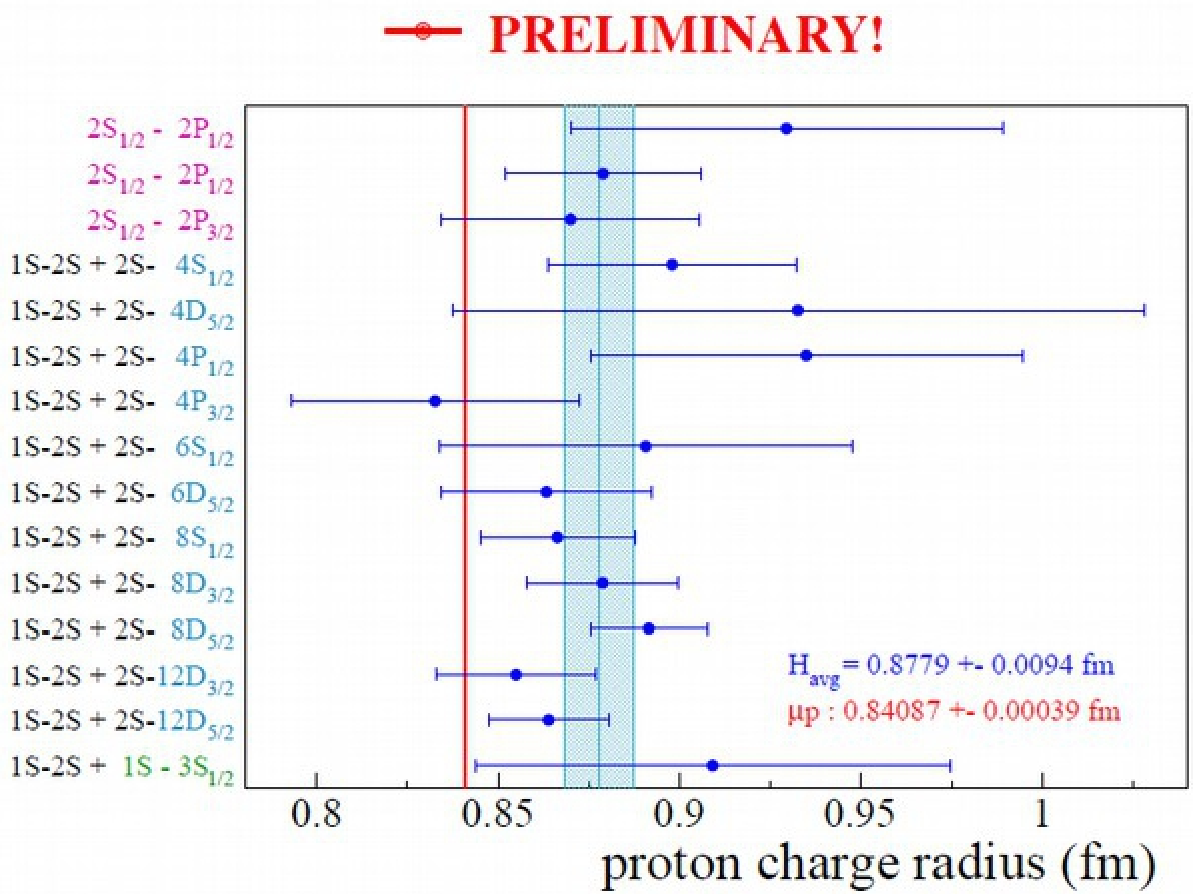
Redoing Atomic Hydrogren

New hydrogen 2S→4P at MPQ!

JG|U MPQ

Proton is small in regular hydrogen, too!

Proton radius puzzle is NOT "solved".
Our main systematics do NOT affect the previous measurements.



$2S \to 4P_{1/2}$ and $4P_{3/2}$

cold H(2S) beam
optically excited $(1S \to 2S)$

$\Delta\nu \sim 2\,\text{kHz} \quad \equiv \Gamma/10'000$!!!

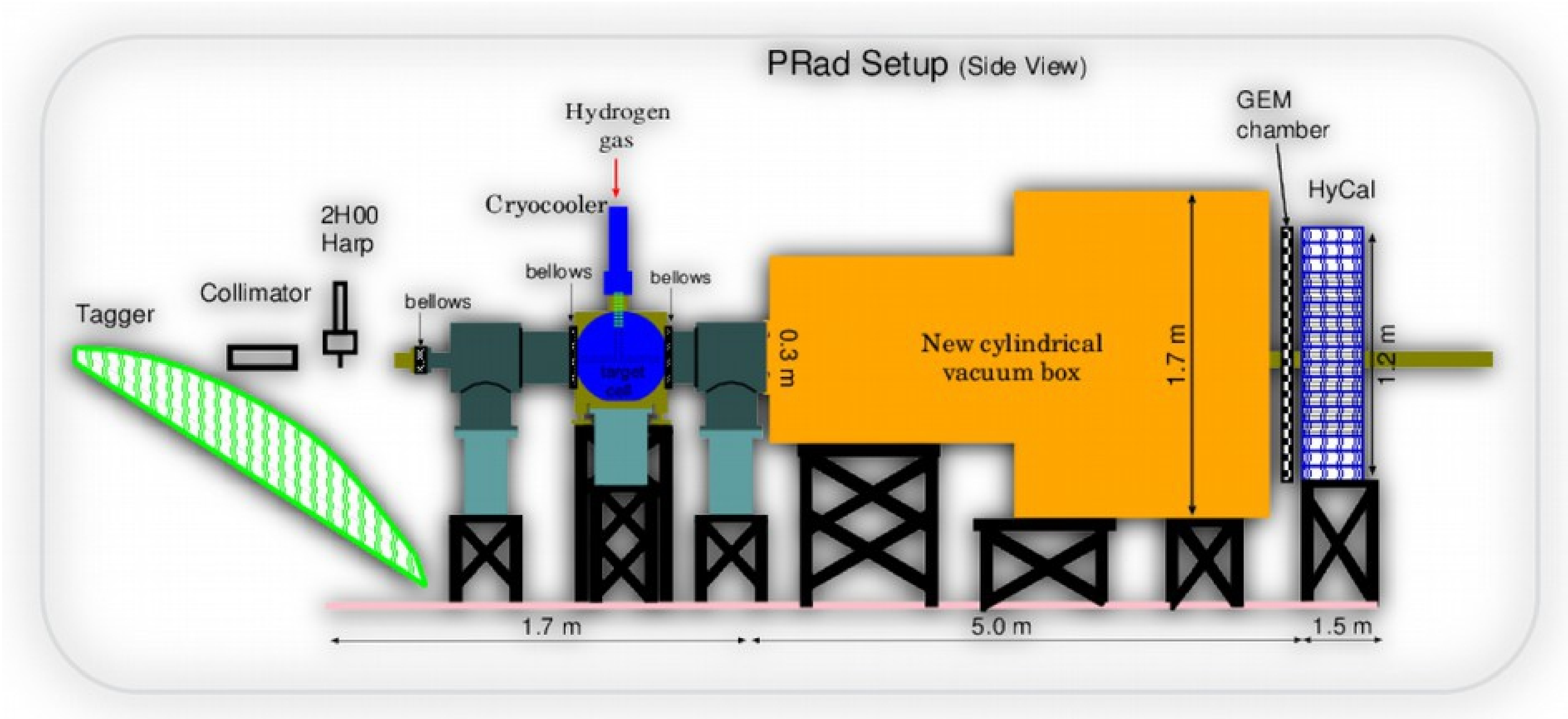
Beyer, Maisenbacher, Matveev, RP, Khabarova, Grinin, Lamour, Yost, Hänsch, Kolachevsky, Udem, submitted (2016)

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:
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing atomic hydrogen
  - **Redoing electron scattering at lower Q^2**

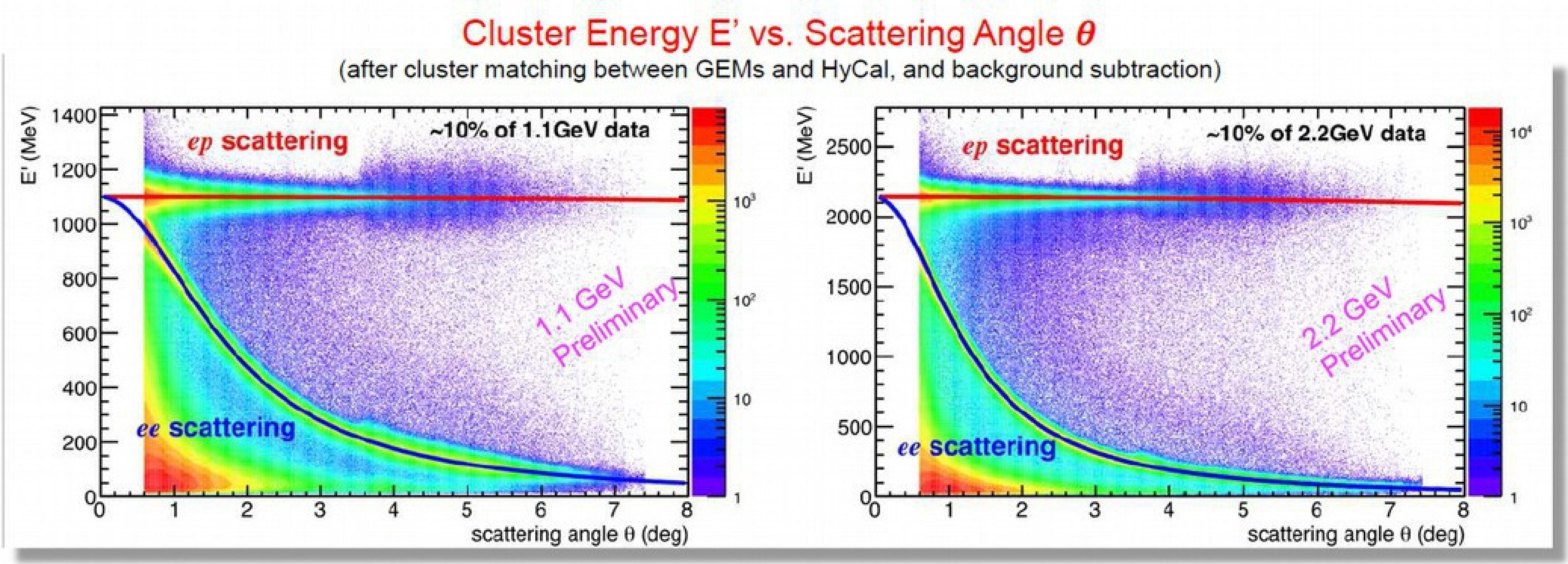
    NB: Many efforts, not an exhaustive list!!!!
  - Muon scattering!

Jlab: PRad



- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0 deg.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M
- Data taking: May & June 2016, 1.1 & .2.2 GeV beams, 1.3 billion H events

Jlab: PRad

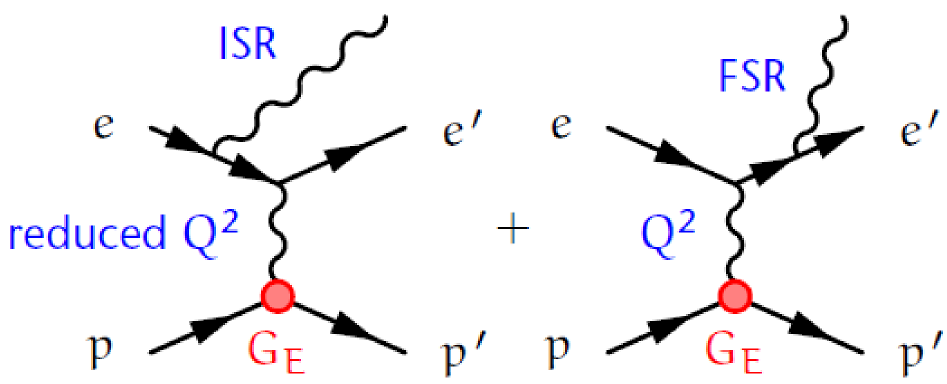


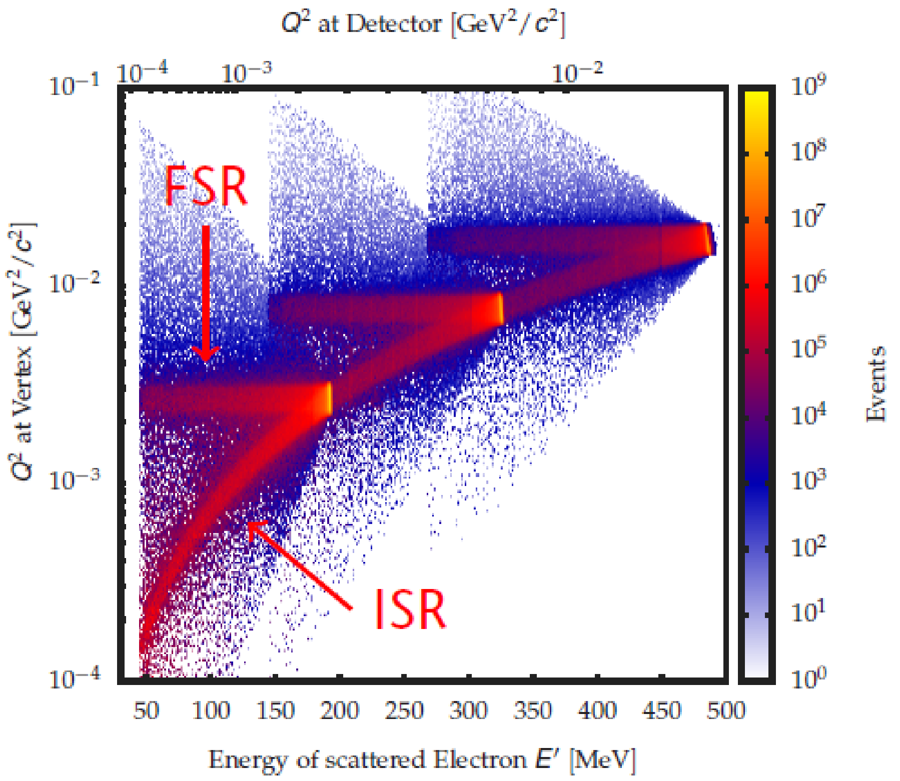
- Calibration complete: expected energy resolutions achieved
- Preliminary result for HyCal trigger efficiency of >99.5%
- Detector alignment completed, matching of GEMS & HyCal achieved
- GEM position resolution of 72μm and preliminary efficiency of ~92%
- Cross section analysis ongoing

Mainz: ISR

Exploit information in radiative tail

- Dominated by coherent sum of two Bethe-Heitler diagrams: ISR and FSR
- ISR: Electron energy reduced $\longrightarrow$ Lower Q^2 at given scattering angle
- Investigate G_E down to $Q^2 = 10^{-4}\,\mathrm{GeV}^2/c^2$
- ISR and FSR cannot be distinguished $\longrightarrow$ Sophisticated simulation needed





Mainz: ISR

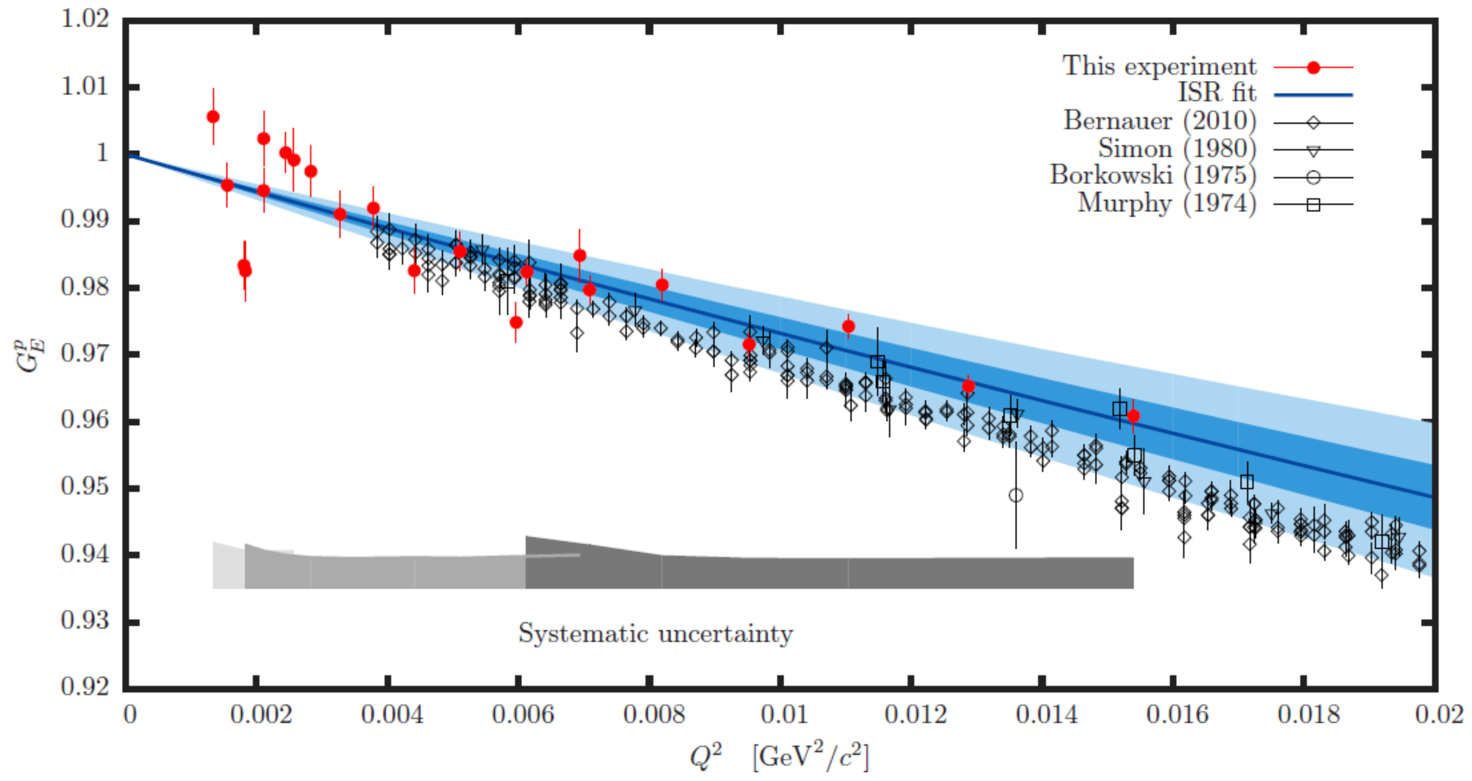
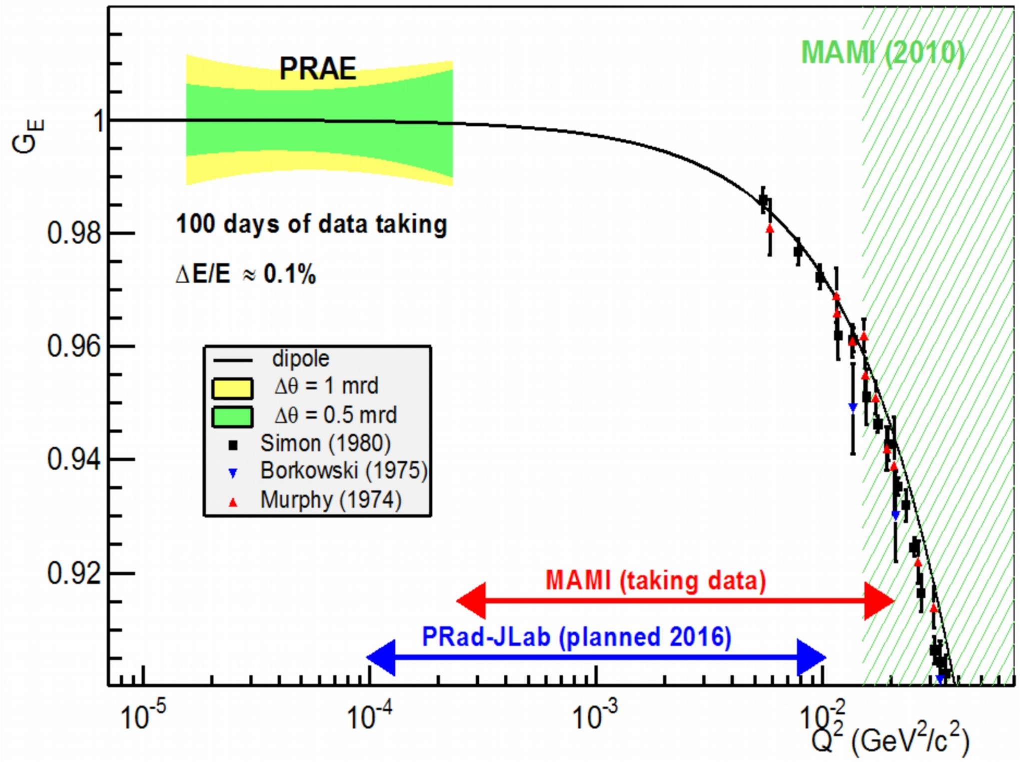


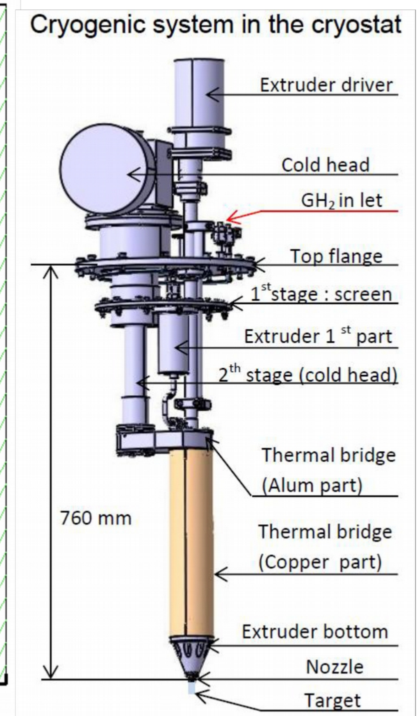
FIG. 3. (Color on-line) The proton electric form factor as a function of $Q^2(= Q^2_{\mathrm{Out}})$. Empty black points show previous data [19–22]. The results of this experiment are shown with full red circles. The error bars show statistical uncertainties. Gray structures at the bottom shows the systematic uncertainties for the three energy settings. The curve corresponds to a polynomial fit to the data defined by Eq. (2). The inner and the outer bands around the fit show its uncertainties, caused by the statistical and systematic uncertainties of the data, respectively.

- Experiment & analysis complete, paper submitted (arXiv:1612.06707)
- Result: $r_p=(0.810\pm0.035_{stat}\pm0.074_{syst}\pm0.003_{\Delta a\Delta b})$fm, not precise enough to differentiate
- New experiment with jet target (and MESA) planned

Platform for Research and Applications with Electrons: ProRad

J.-M. Gheller et al. AIP Conf. Proc. 1573 (2014) 58



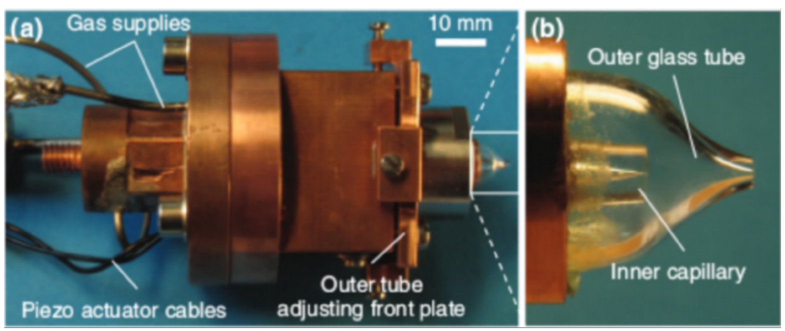


CHyMENE

Details from Eric Voutier LPSC, Grenoble (France).

Bi-national ANR proposal with Francfort University submitted.

Droplet Sream



- New accelerator to be built in France,
- Beginning measurement 2020
- Measurements in unexplored Q^2-range
  - → **1.5×10^{-5} – 3×10^{-4} $(GeV/c^2)^2$**
- Constrain Q^2-dependence of G_E and extrapolation to zero
- Non-magnetic spectrometer, frozen hydrogen wire / film target

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MUSE tests these

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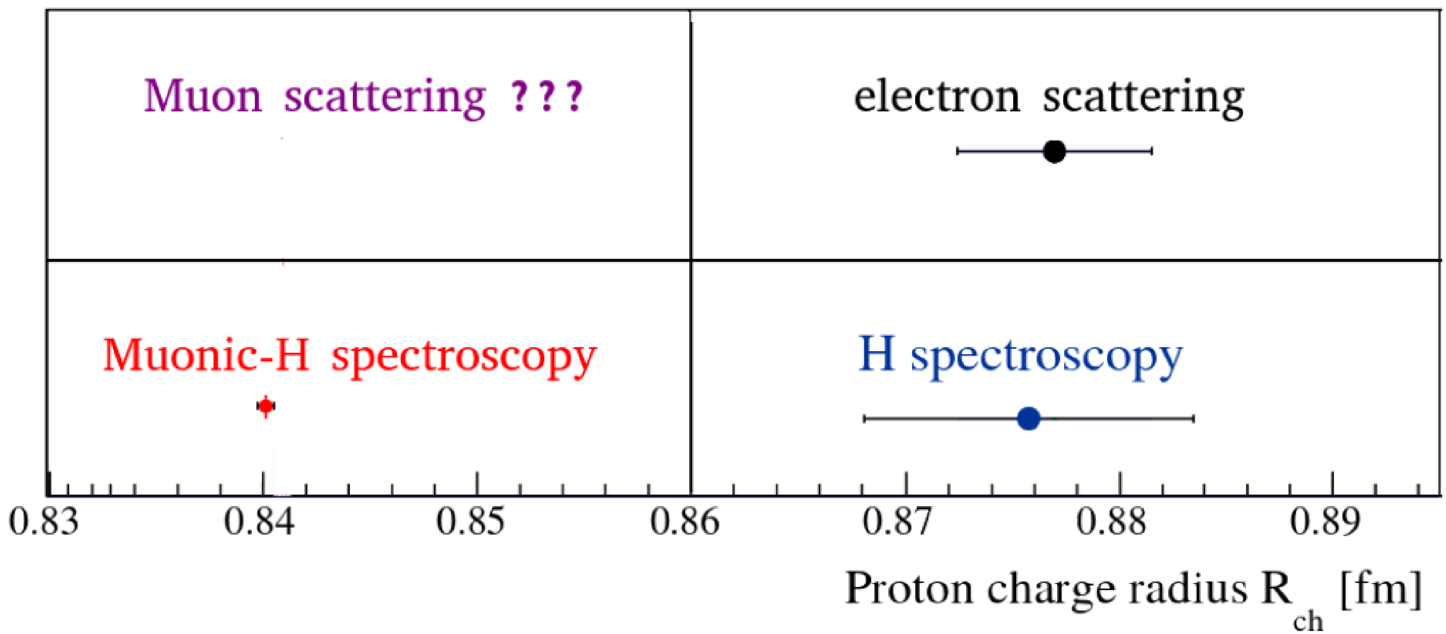
MUSE Experiment



- Simultaneous measurement of e^+/μ^+ e^-/μ^- at beam momenta of 115, 153, 210 MeV/c in πM1 channel at PSI allows:

  ➔ Determination of two photon effects

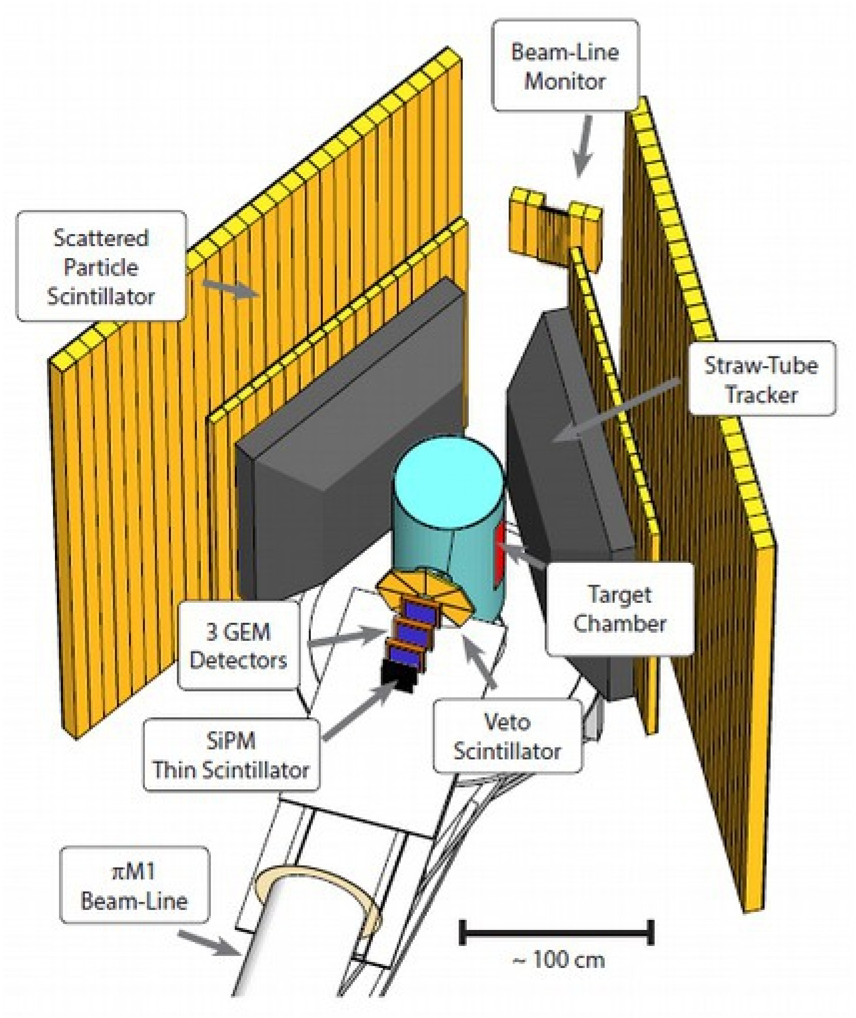
  ➔ Test of Lepton Universality

  ➔ Simultaneous determination of proton radius in both eP and μP scattering

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 $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ in piM1 beamline
- Separate out particle species by timing relative to beam RF
- Cut as many pions as possible, trigger on $e^{\pm}$, $\mu^{\pm}$

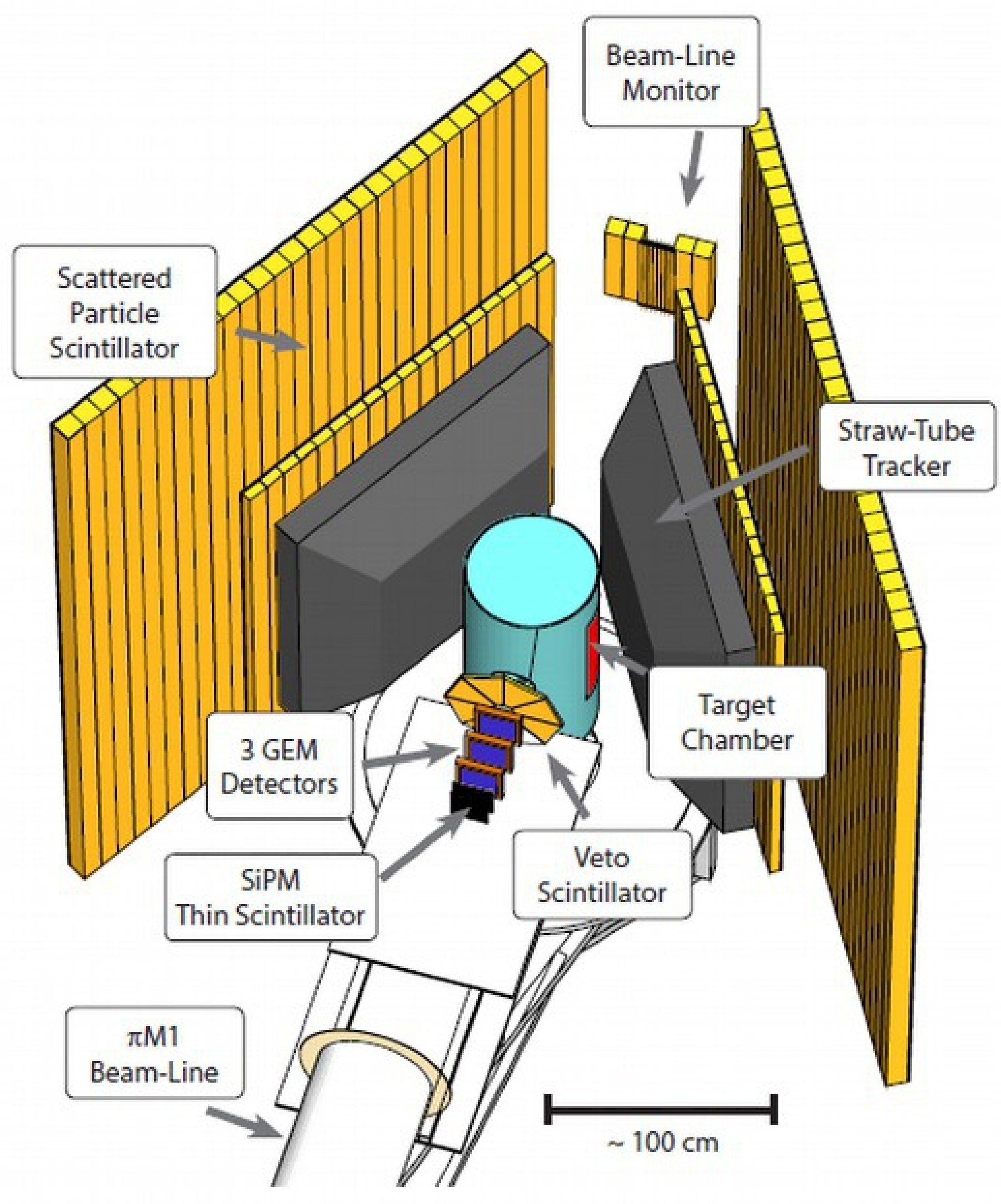
MUSE Experiment



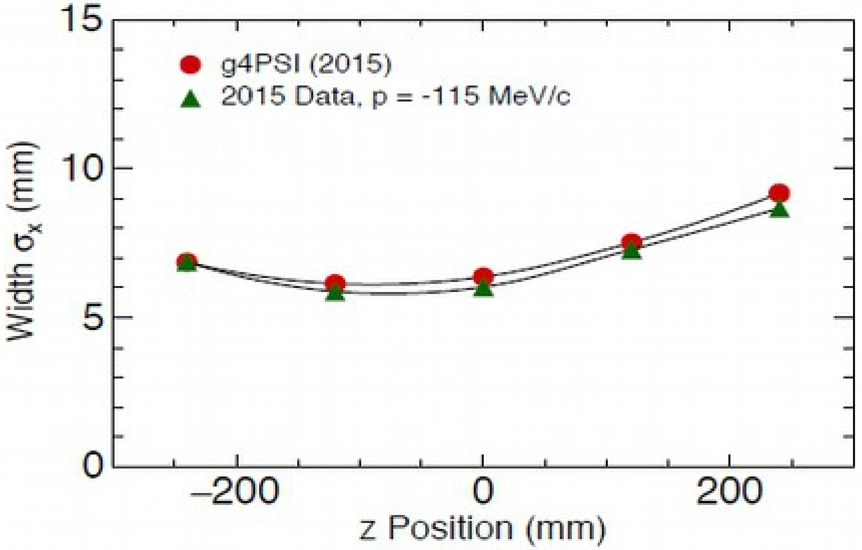
- Low beam flux. → Large angle, non-magnetic detectors.
- Secondary beam. → Tracking of beam particles to target.
- Mixed beam. → Identification of beam particle in trigger.

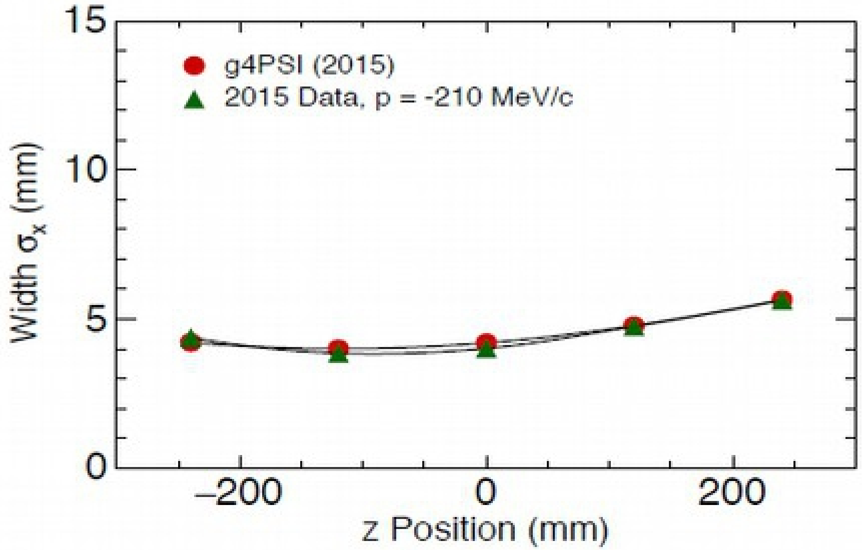
MUSE Experiment

- PSI πM1 channel
- P≈115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$
- FPGA trigger with beam PID (GWU / Rutgers)
- $\theta \approx 20^{o} – 100^{o}$
- $Q^2 \approx 0.002$ - 0.07 GeV^2
- About 3 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's
- Beam monitored with SiPM (Tel Aviv/Rutgers/PSI), GEMs (Hampton)
- Scattered particles detected with straw-tube trackers (HUJI/Temple) and scintillators (USC)
- Liquid H target (UMich)

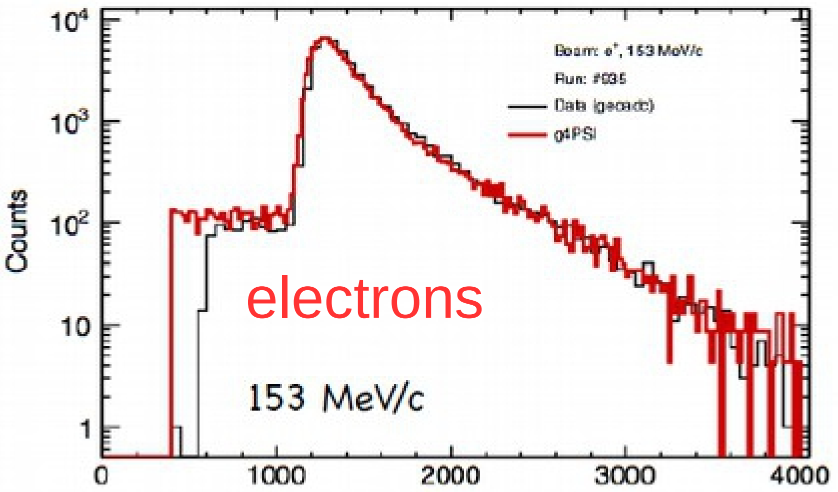


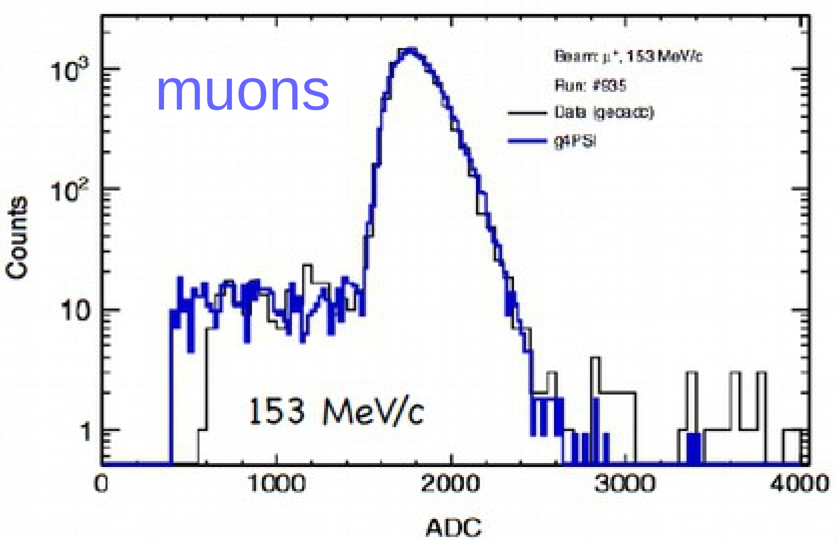
Test Beam Results





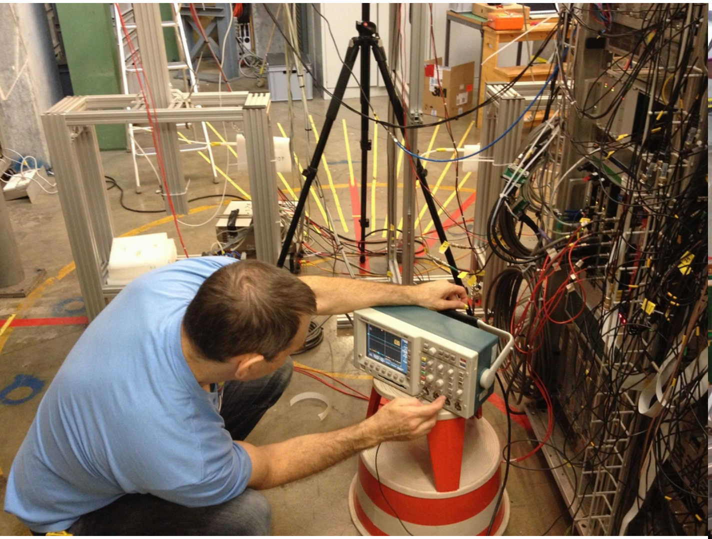
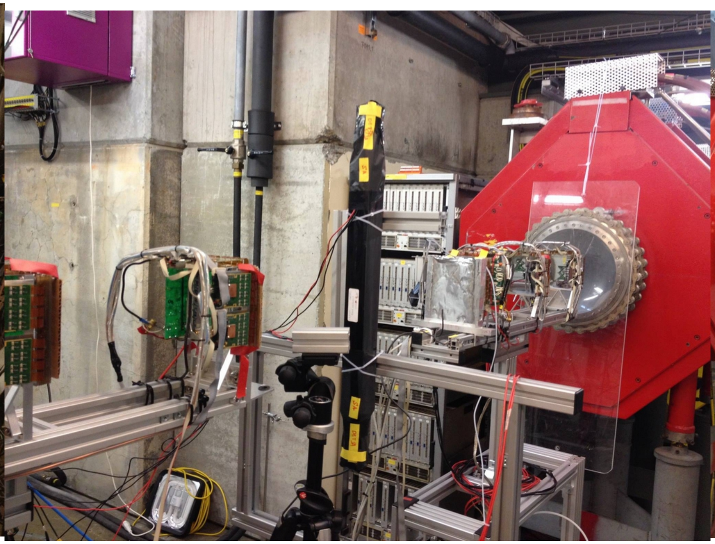
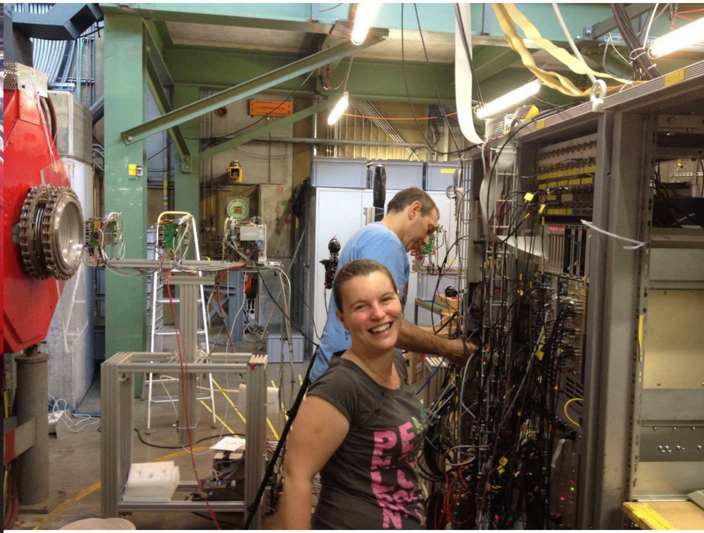
(2015) beam profile data agrees with simulation





(2013) pulse height data agrees with simulation

Where are we now?

- Many test beams 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
  - ➔Detector complete and two six-month data-taking runs in 2018/19

Anticipated MUSE Results

- Extract radius from ep and μp form factors
- Error on radius difference ~0.009fm
- MUSE will:

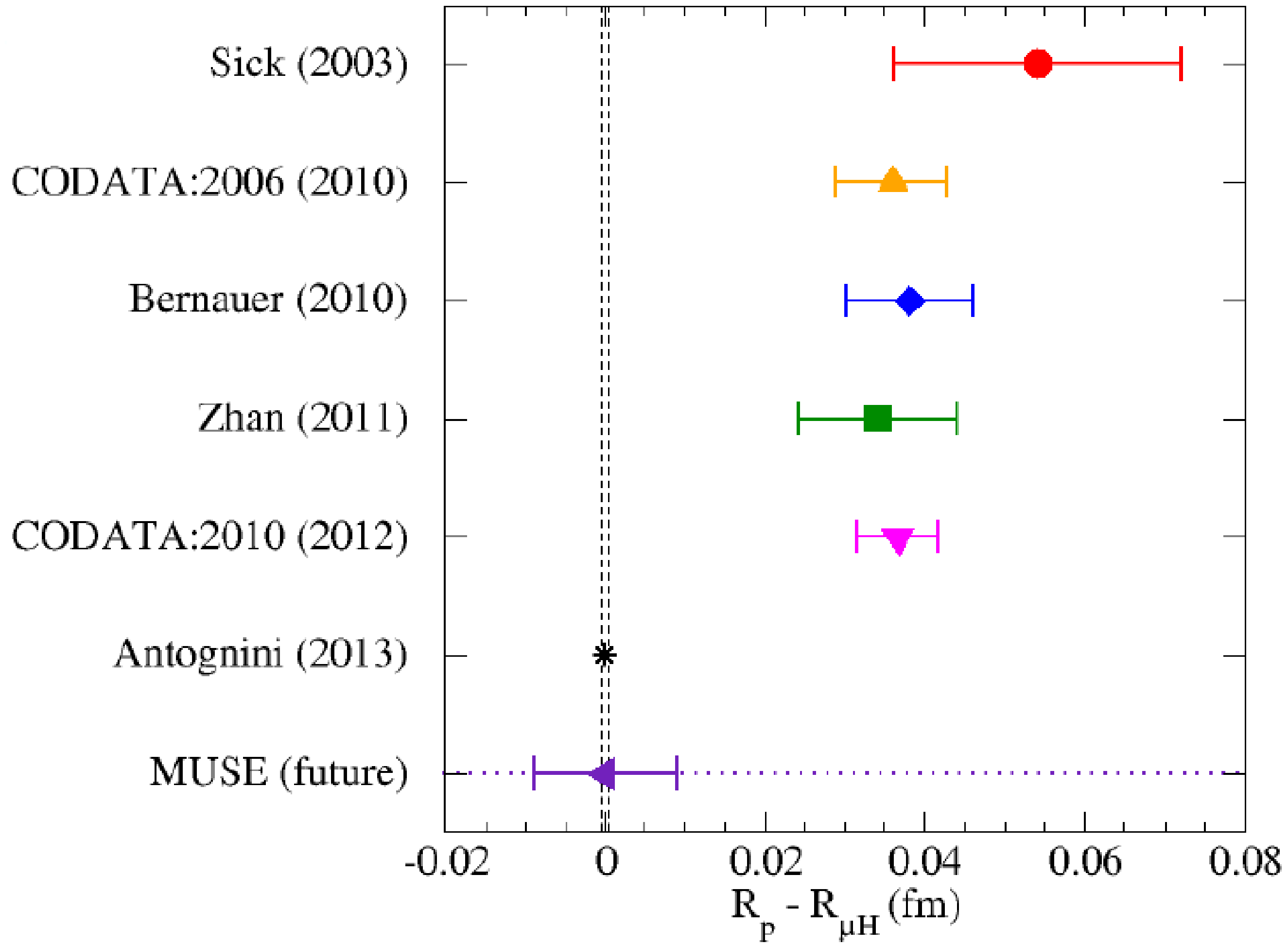
➔ Verify the effect

➔ Compare form factors

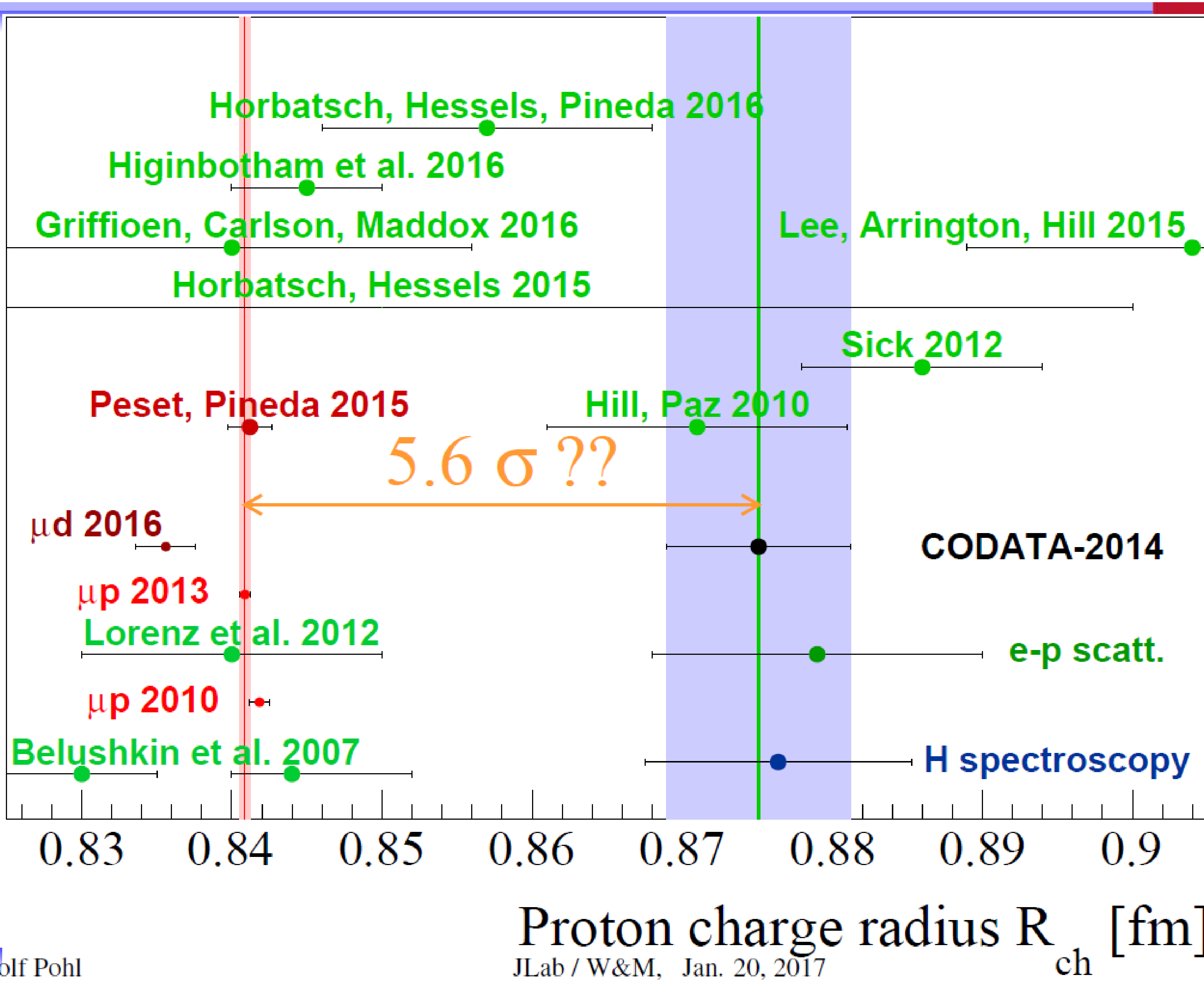
➔ Compare cross sections

➔ Test two photon effect

➔ Solve the PRP?



Theory / Extraction Update



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."

INTERNATIONAL BUSINESS TIMES

WORLD

The 'Proton Radius Puzzle' Is Very Real, New Experiment Confirms

BY AVANEESH PANDEY ON 08/13/16 AT 4:19 AM

- 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
- Conclusion: we are still (possibly more) puzzled!
- Several undefeated, but not conclusively proved explanations remain
- Still much work to be done, and many groups doing it!

Thank you for your attention!

Thank you to:

Ashot Gasparyan, Harald Merkel, Ulrich Mueller, Randof Pohl, Eric Voutier, Weizhi Xiong

The MUSE Collaboration