The Proton Radius Puzzle

Saturday Morning Physics

November 10, 2018

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Physics Department

University of Michigan

Radius (Size)

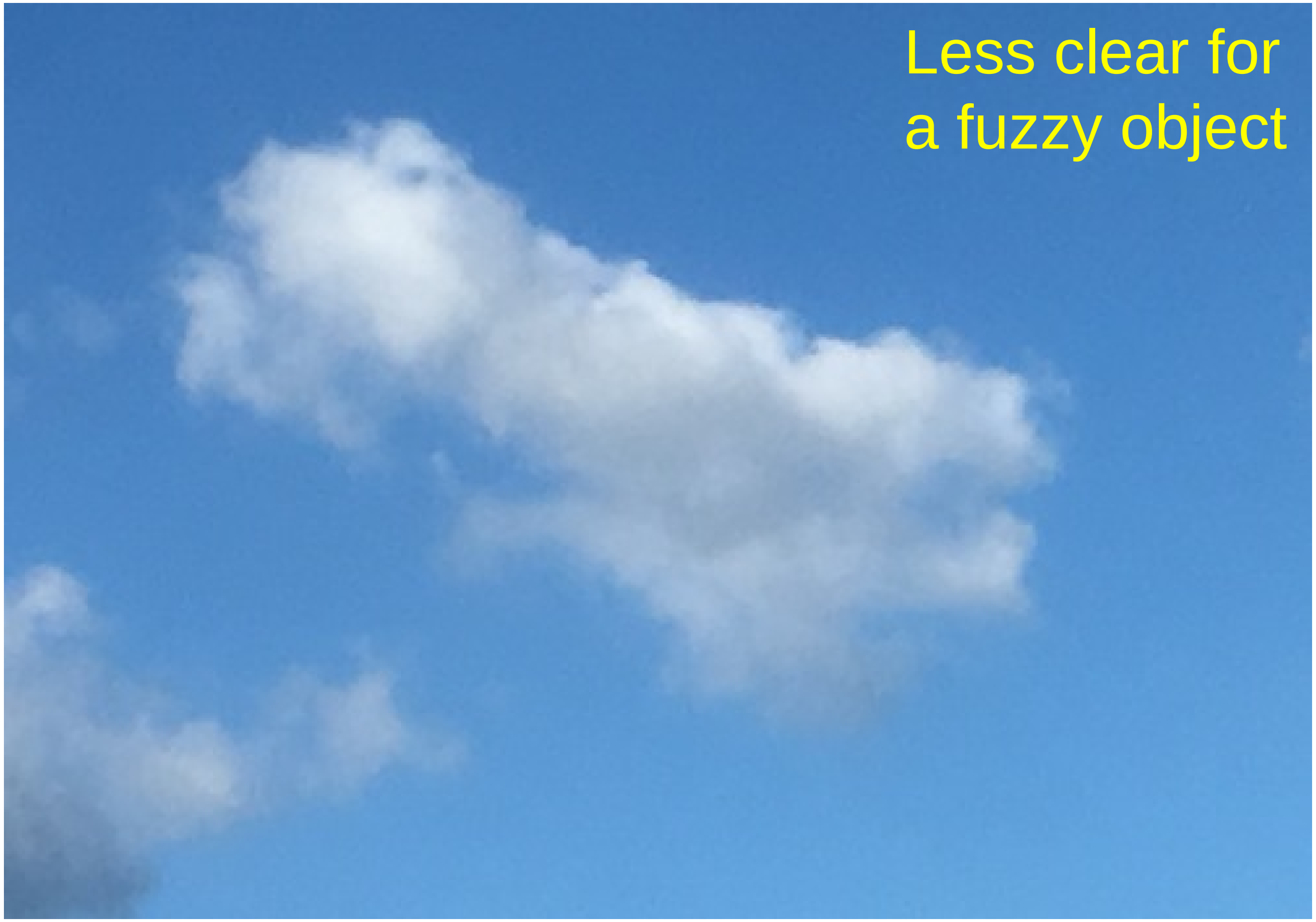
- What is a **radius** (or size) of an object?

Well-defined for a macroscopic, hard object (ie. steel ball)

Credit: Nature

Radius (Size)

- What is a radius (or **size**) of an object?



How do you measure size?

Object:

- macroscopic:
  hard sphere

Tool:

caliper

- small:

Let's measure the width of a hair!

Need a volunteer

How do you measure size?

Object:

- macroscopic:
  hard sphere

Tool:

caliper

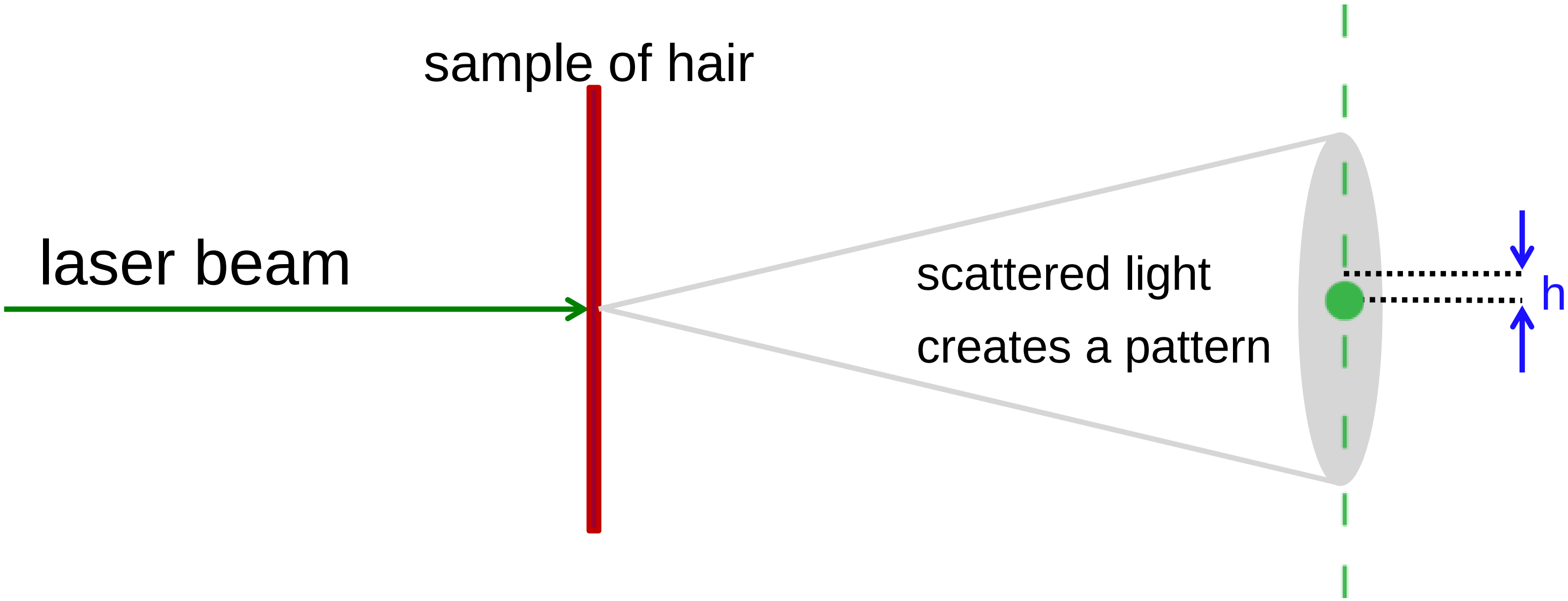
- small:

Let’s measure the width of a hair!

2

Need ~~a~~ volunteers

How do you measure width of hair?



laser wavelength: 532 nm

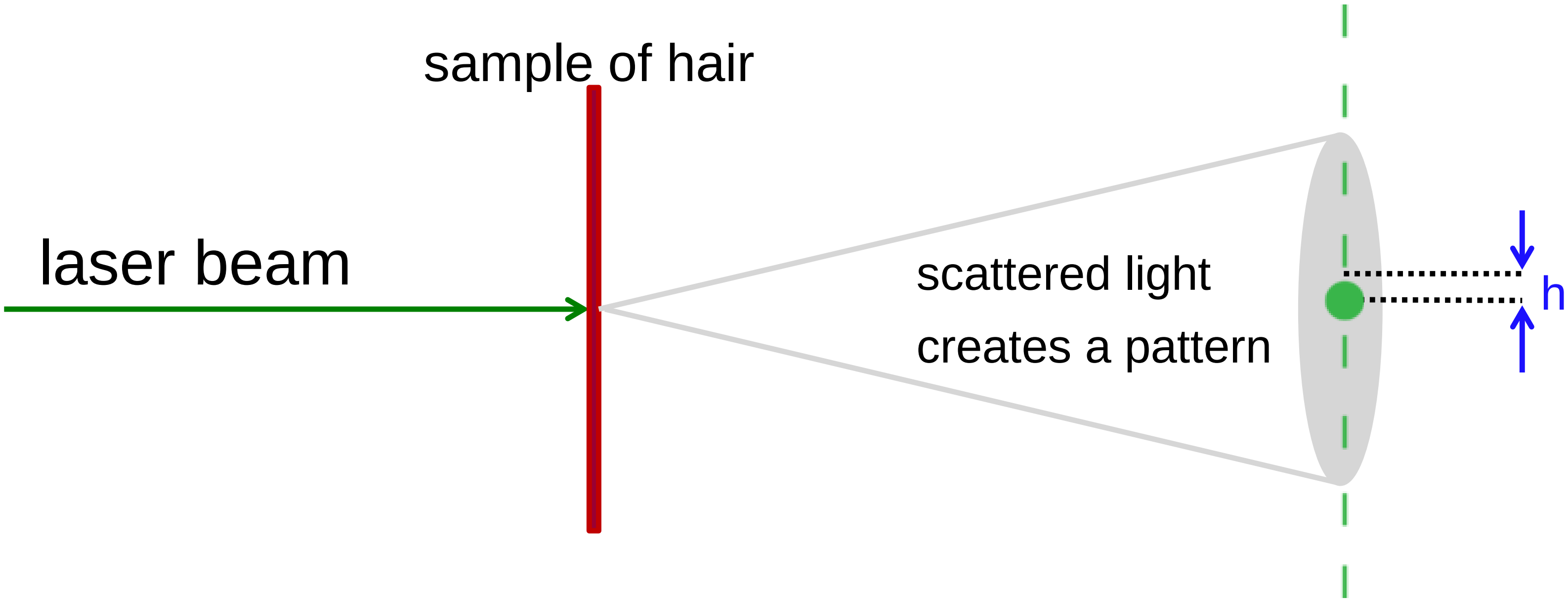
distance hair to wall: 128 in

D:diameter of hair

h: distance center of dot to 1st minimum
(ie. “dark” section)

$$D = \frac{0.000532 \text{ mm}}{\sin\left(\frac{h \text{ mm}}{3251 \text{ mm}}\right)}$$

How do you measure width of hair?



laser wavelength: 532 nm

distance hair to wall: 128 in

D:diameter of hair

h: distance center of dot to 1st minimum
(ie. “dark” section)

enter h (mm)	29
hair thickness (μm)	60

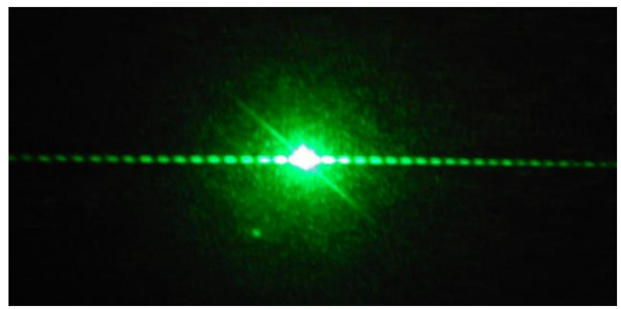
How do you measure size?

Object: | **Tool:**

- macroscopic:
  hard sphere (~5 cm)
  (~0.05 m)

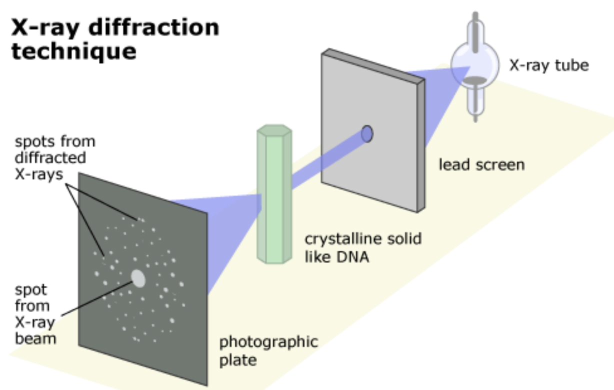
caliper

- small:
  hair (~60 μm)
  (~0.000,06 m)
  (~60 thousands of a meter)



laser

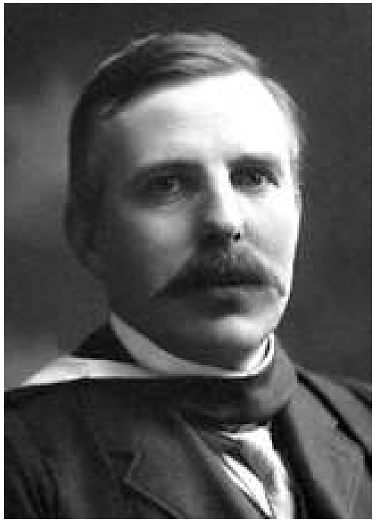
- tiny:
  atom (~1Å)
  (~0.000,000,000,1 m)
  (~a tenth of a billionth of a meter)



Credit: undsci.berkeley.edu

Brownian motion
X-ray diffraction

How do you measure something even smaller?



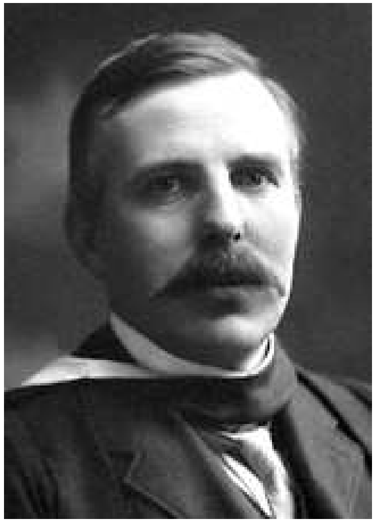
Ernest Rutherford (1871 - 1937)

half-life; α and β rays

1908: Nobel prize Chemistry:

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances“

How do you measure something even smaller?



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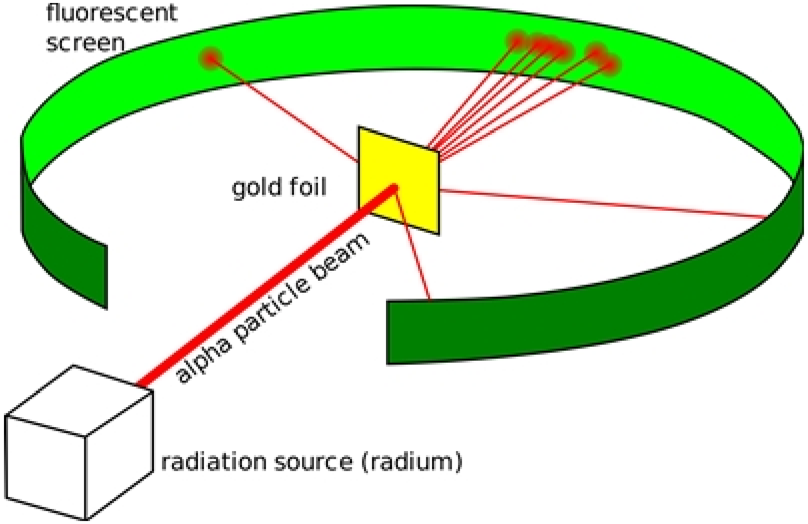
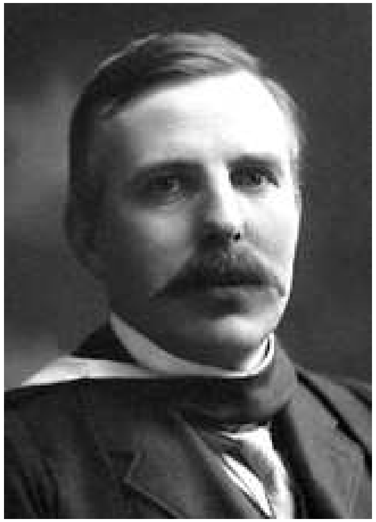
1911: Most α particles pass a thin gold foil undeflected



Source: Wikimedia Commons

How do you measure something even smaller?



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half-life; α and β rays

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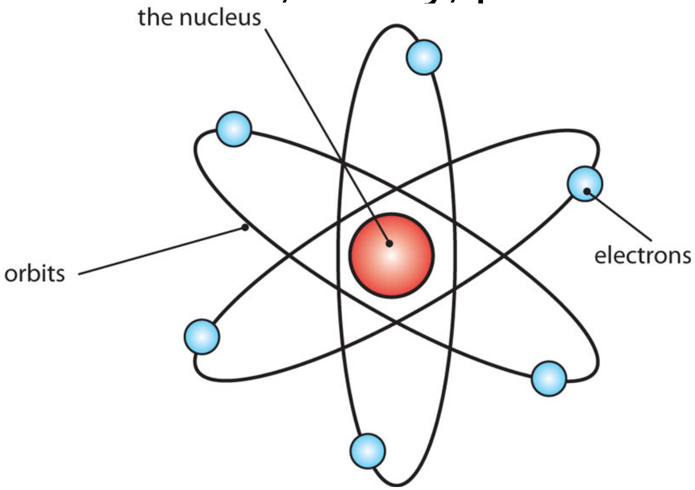
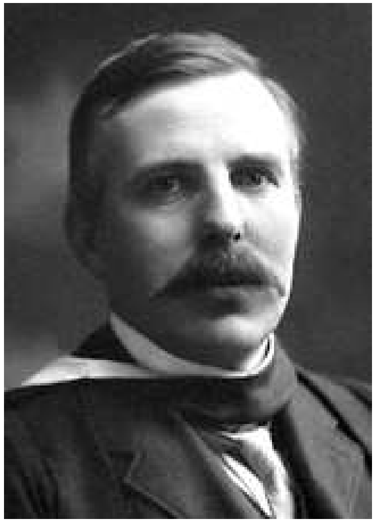
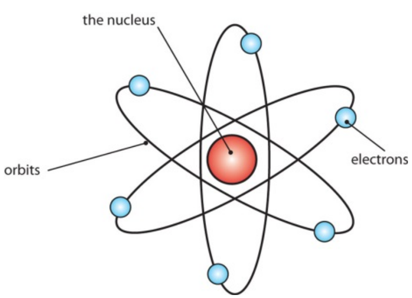
$\Rightarrow$ Atom = small, heavy, positive nucleus + electrons



Source: atomic.lindahall.org

How do you measure something even smaller?





Ernest Rutherford (1871 - 1937)

half-life: α and β rays

1908: Nobel prize Chemistry:

> "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances“

1911: Most α particles pass a thin gold foil undeflected

⇒ Atom = small, heavy, positive nucleus + electrons

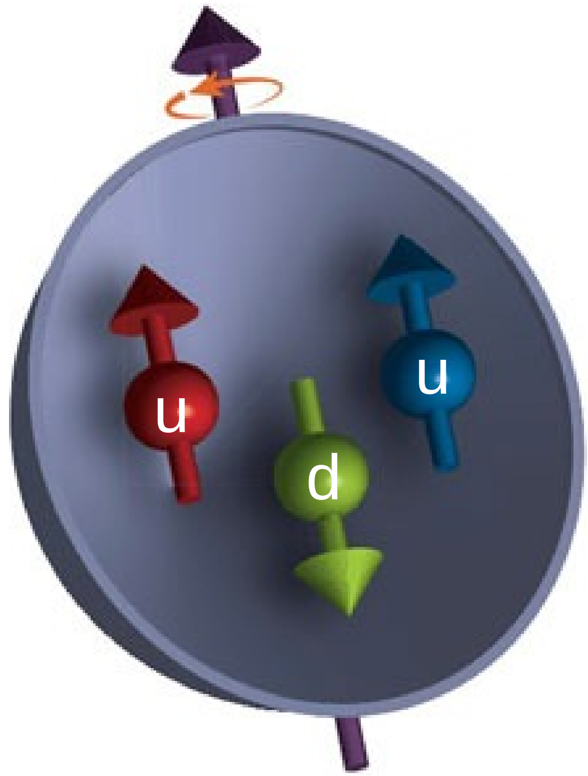
1917: Discovery of the proton

$$^{14}\mathrm{N} + \alpha \rightarrow {}^{17}\mathrm{O} + \mathrm{p}$$

~1928: electron accelerators replace α particles

The Proton

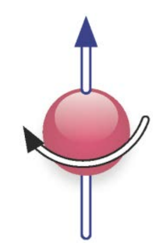
Quark Model
(1964)



size: (~1 fm)
(~0.000,000,000,000,001 m)
(~a millionth of a billionth of a meter)

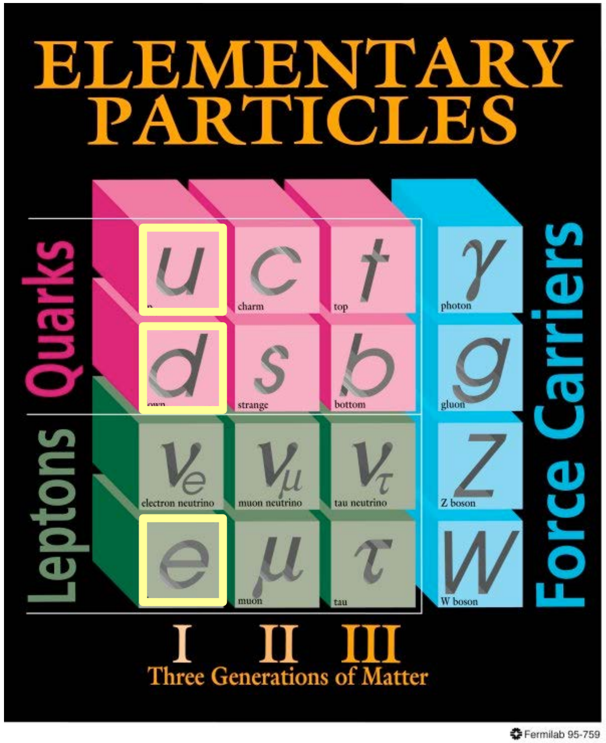
electric charge

$$+1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$$

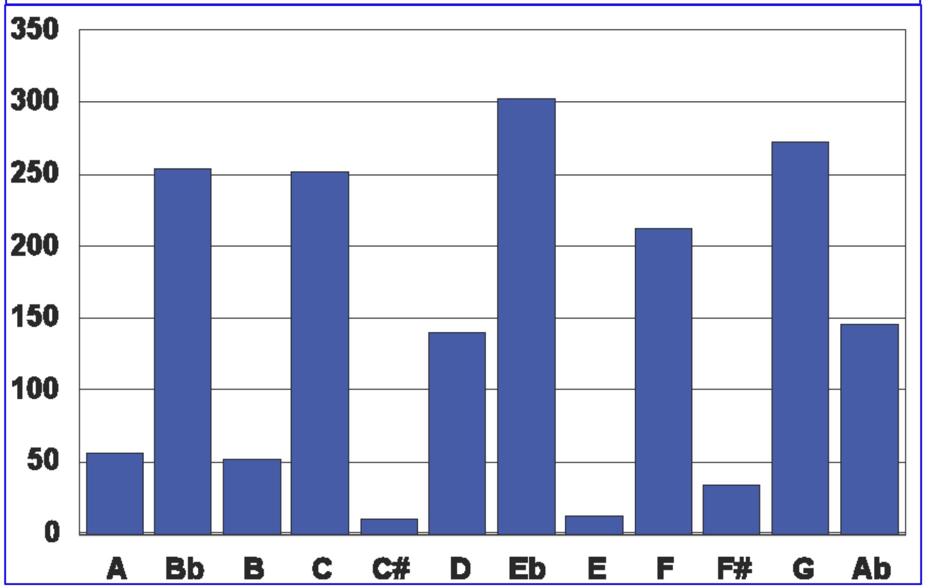


- proton is spin-1/2 particle
- proton is not pointlike
  (made of three constituents, called quarks)

Proton - more than just constituents



Histogram of notes used in Beethoven's 5th symphony



Both plots focus on constituents rather than interactions

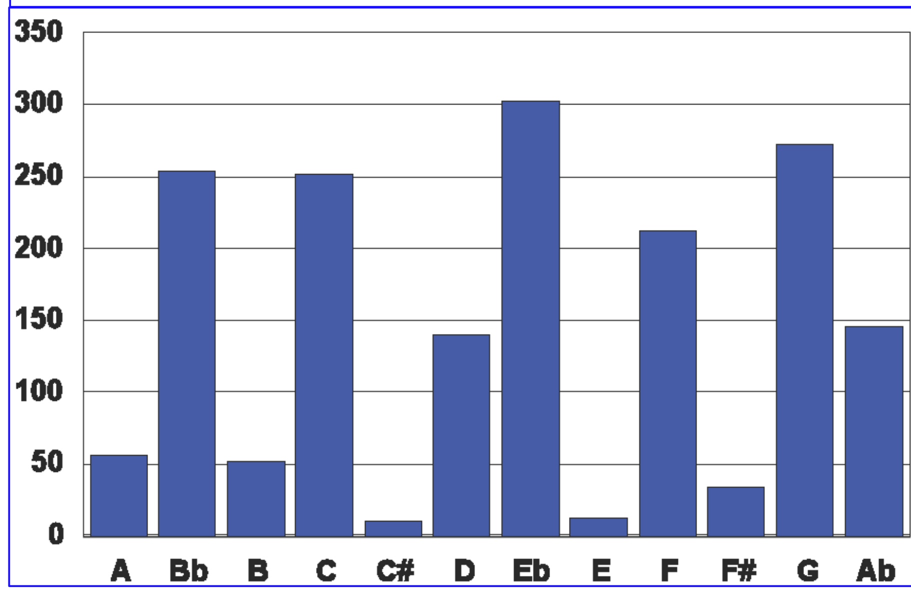
Interactions are important - they create the dynamics

Plot inspired by J. Arrington (ANL):

Proton - more than just constituents

- the 1st four notes (G, E, F, D)
- adding rhythmic variation
- with full dynamics

Histogram of notes used in Beethoven's 5th symphony



Interactions are important - they create the dynamics

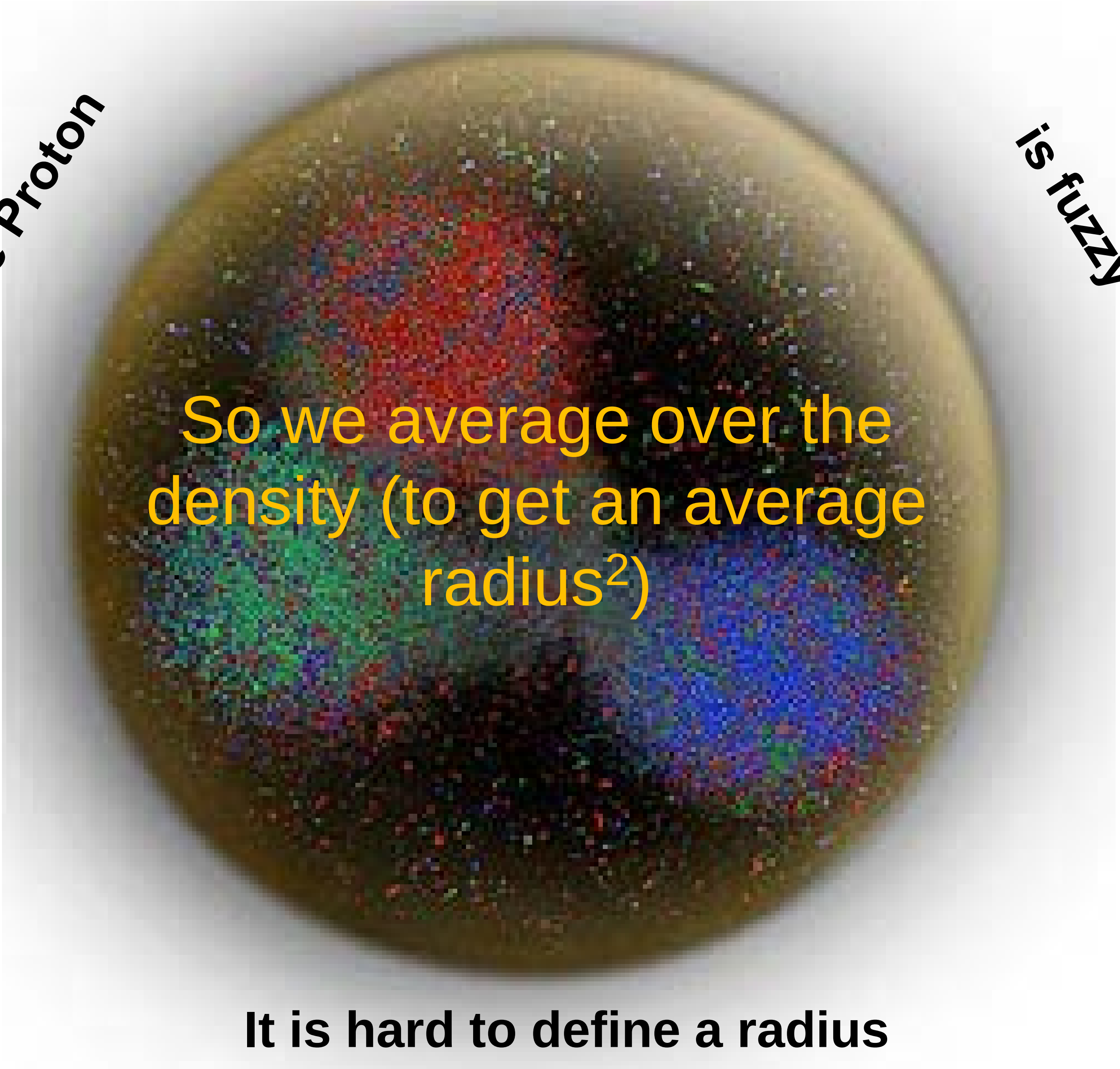
Plot inspired by J. Arrington (ANL):

The Proton

- quarks are held together by strong nuclear force, which arises when quarks exchange gluons
- complex internal structure generated by interactions between pointlike constituents (quarks/partons).
- Uncertainty Principle dictates: quarks must be in motion - at close to speed of light

→ proton is a strongly-coupled, relativistic, infinite-body system

The Proton is fuzzy

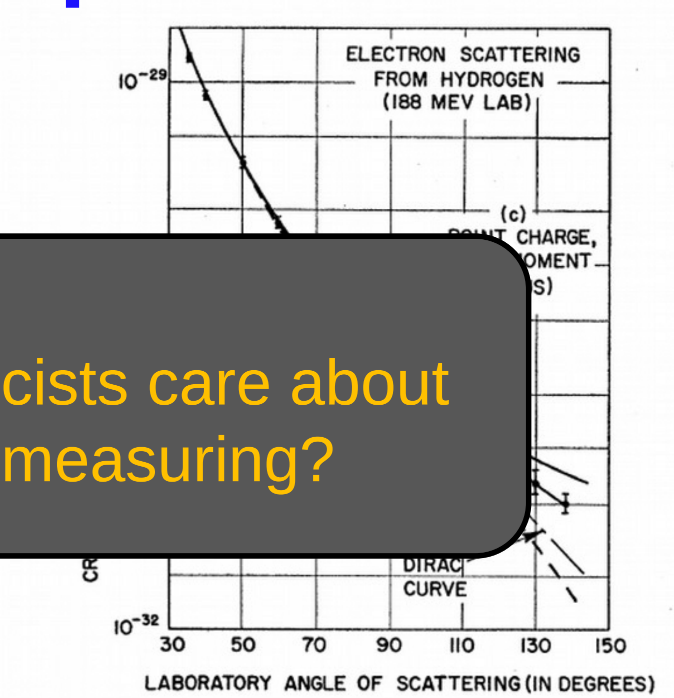


So we average over the density (to get an average radius^2)

It is hard to define a radius

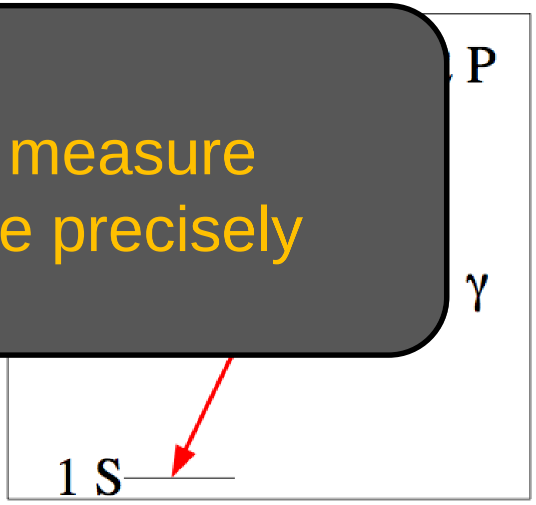
How do you measure proton size?

- Scattering experiments
  (Hofstadter @ Stanford: 1950s -
  ele



Question:
Why should hadronic physicists care about what atomic physicists are measuring?

- At
  (At
  ato



Answer:
Because sometimes they can measure things in Nuclear Physics more precisely than we can!

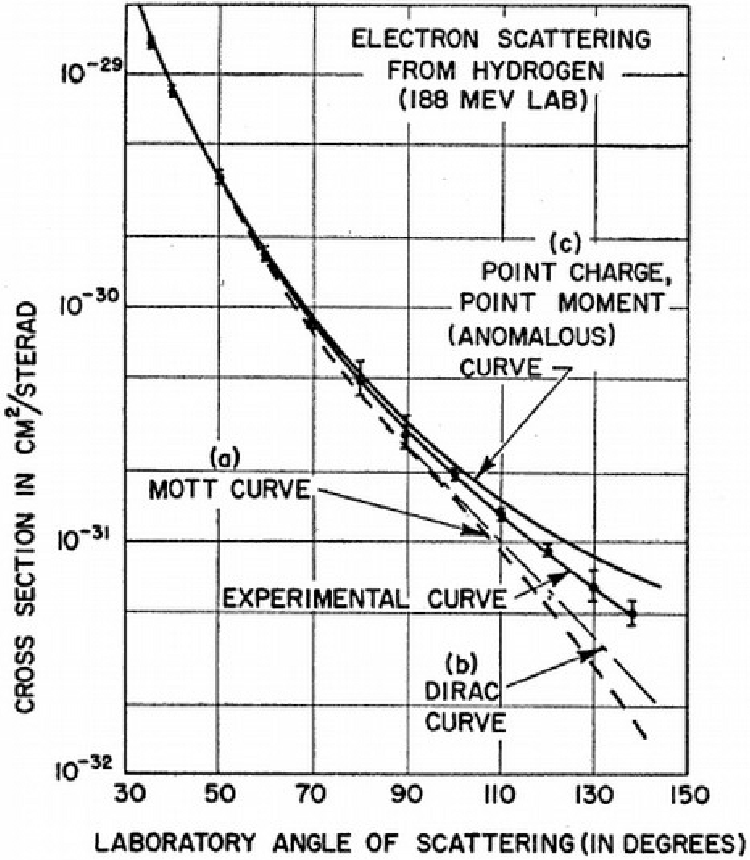
Electron scattering measurements 1950s

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**"

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



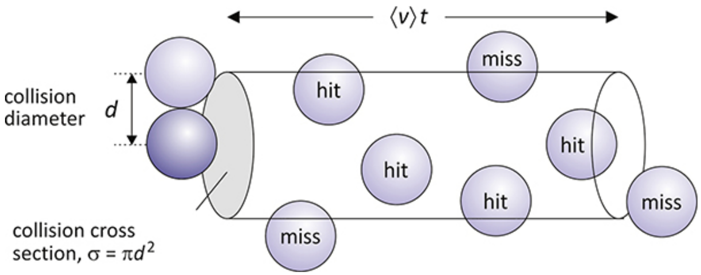
What is a Cross Section?

Cross Section

- the term cross section is used in physics to quantify the probability of a certain particle-particle interaction

- collision among gas particles: (interact only upon contact)

$$\sigma = \pi(2r)^2$$

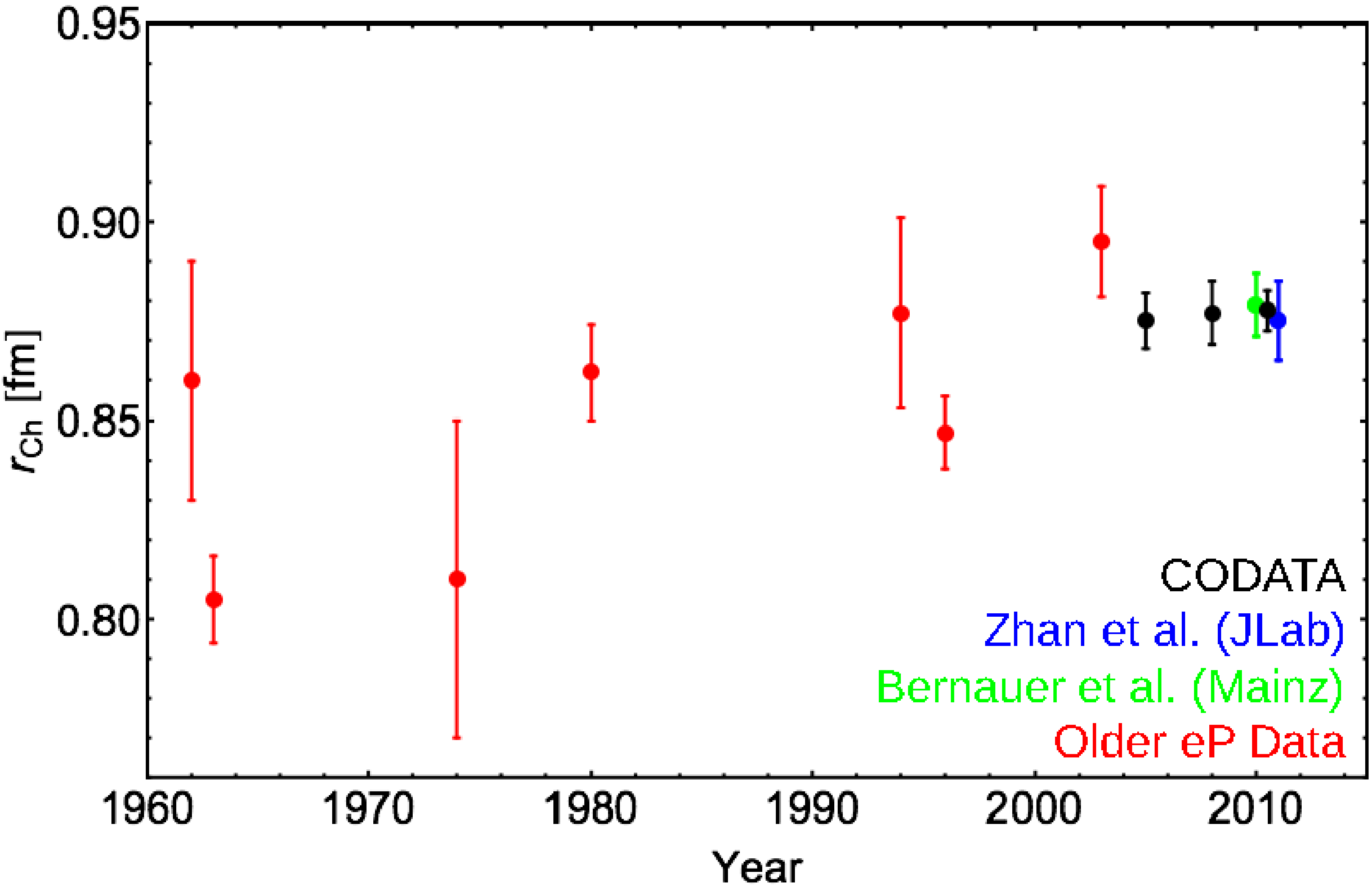


- if particles interact through some action-at-a-distance force (ie. electromagnetism or gravity):
  $\rightarrow$ scattering cross section is generally larger than their geometric size

Let's do a simple scattering experiment

Slide inspired by Wikipedia & IOPscience

Time evolution of Proton Radius from ep data

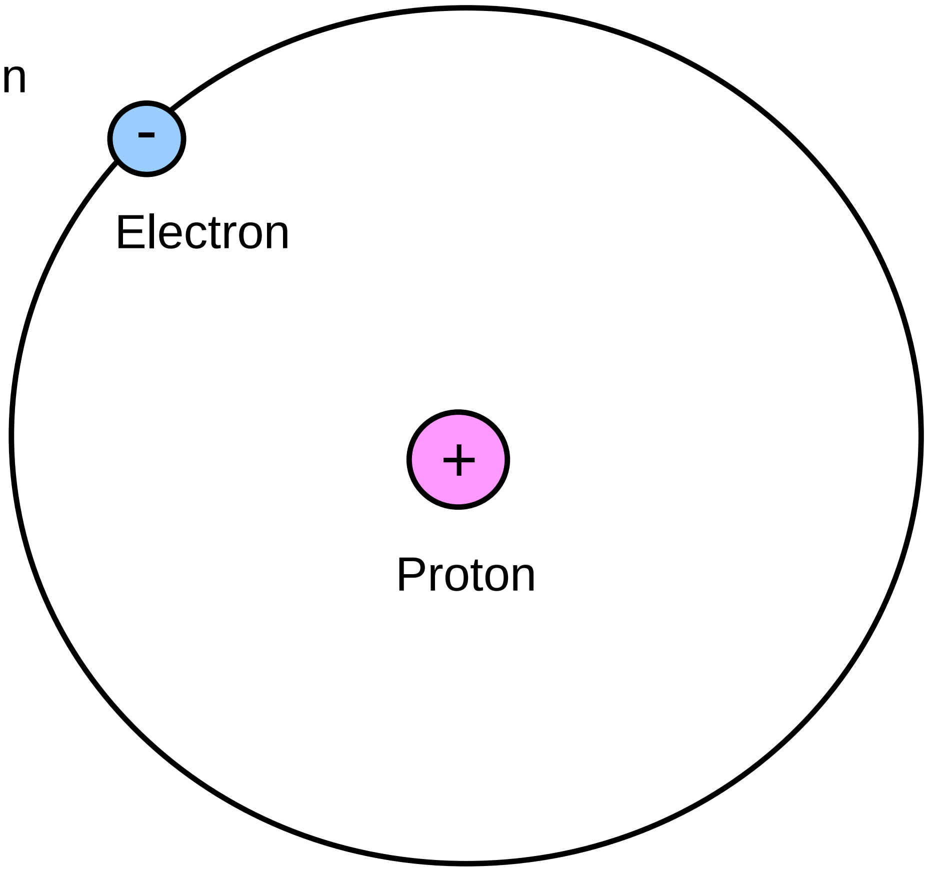


CODATA: Committee on Data for Science and Technology, the international group which publishes the recommended values for fundamental physical constants every four years.

Atomic Spectroscopy Measurements

Bohr Model of the atom

- Electrons orbit the nucleus
  "Planetary system"
- Hydrogen: 1 electron + 1 proton

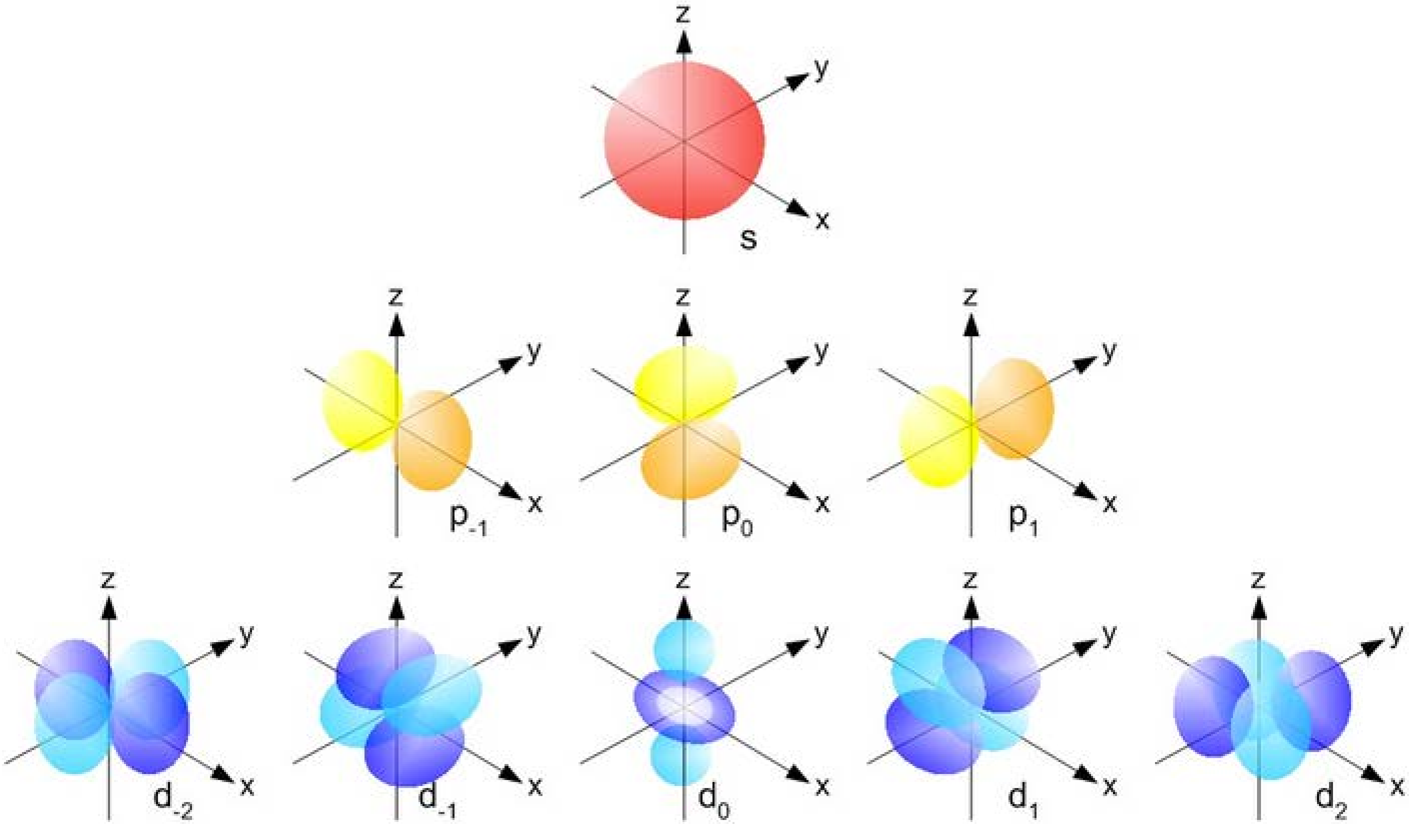


Bohr Model

… is simply inaccurate…

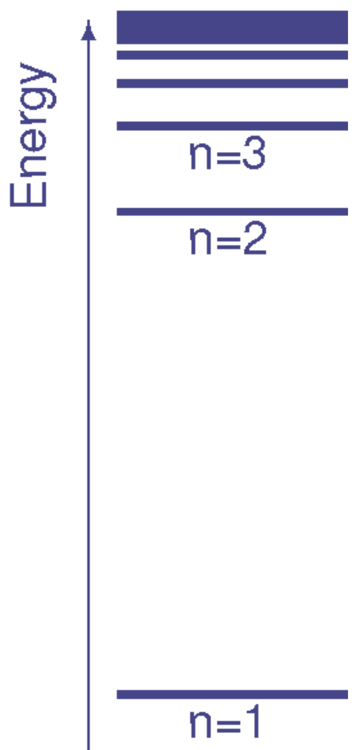
Bohr model → Quantum Mechanics

"planetary orbits" → "wave function"



Hydrogen Energy Levels

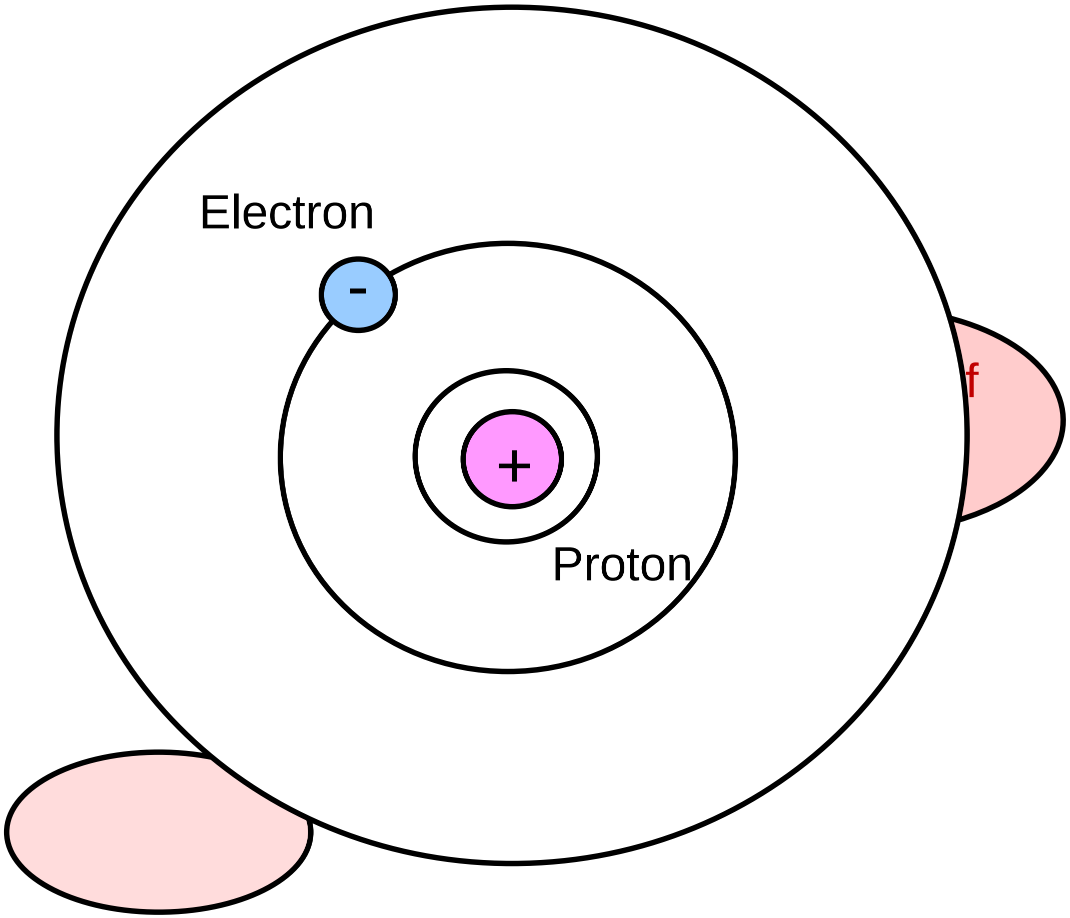
Components of a calculation



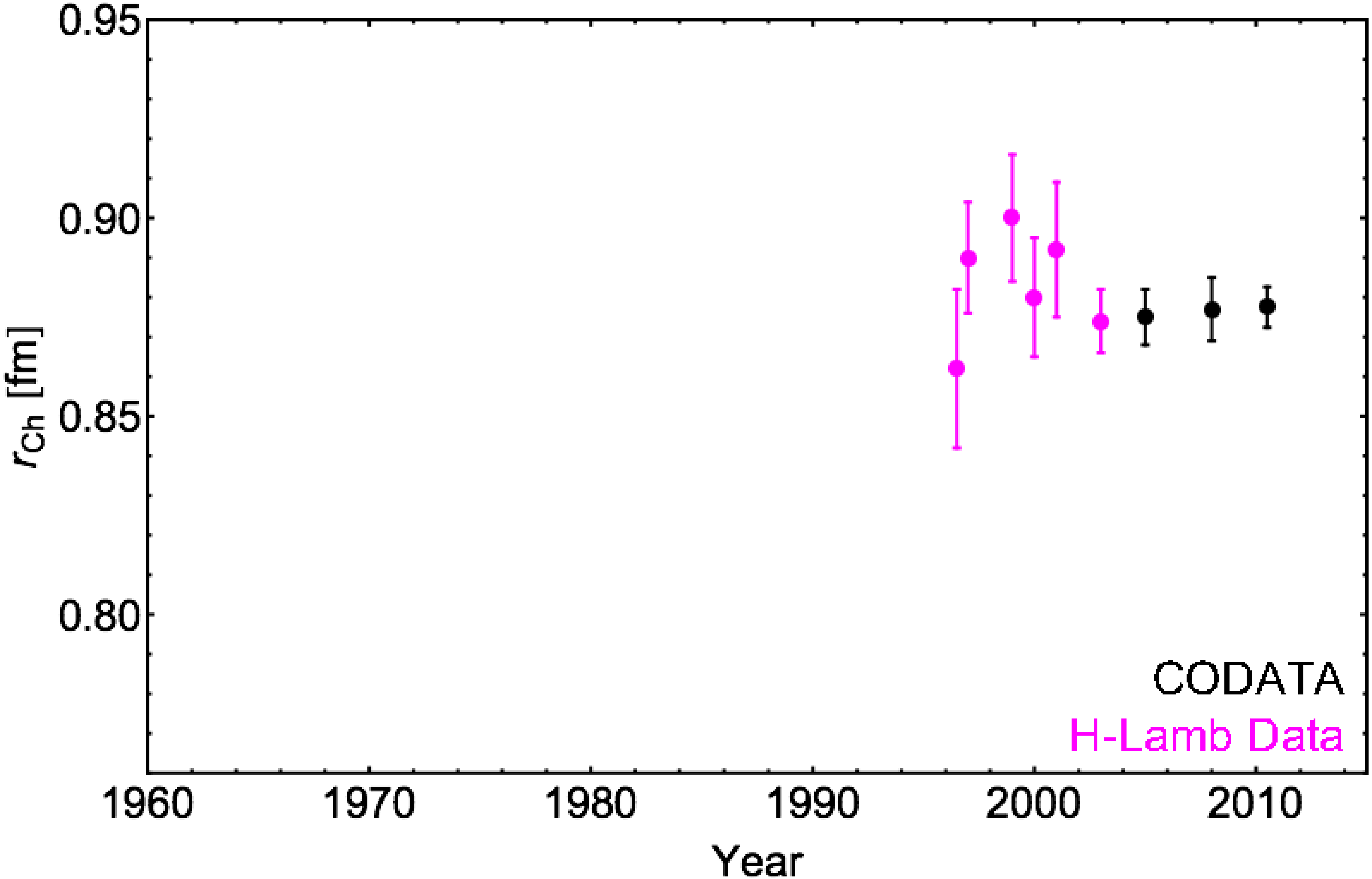
Bohr

$$E = R_\infty / n^2$$

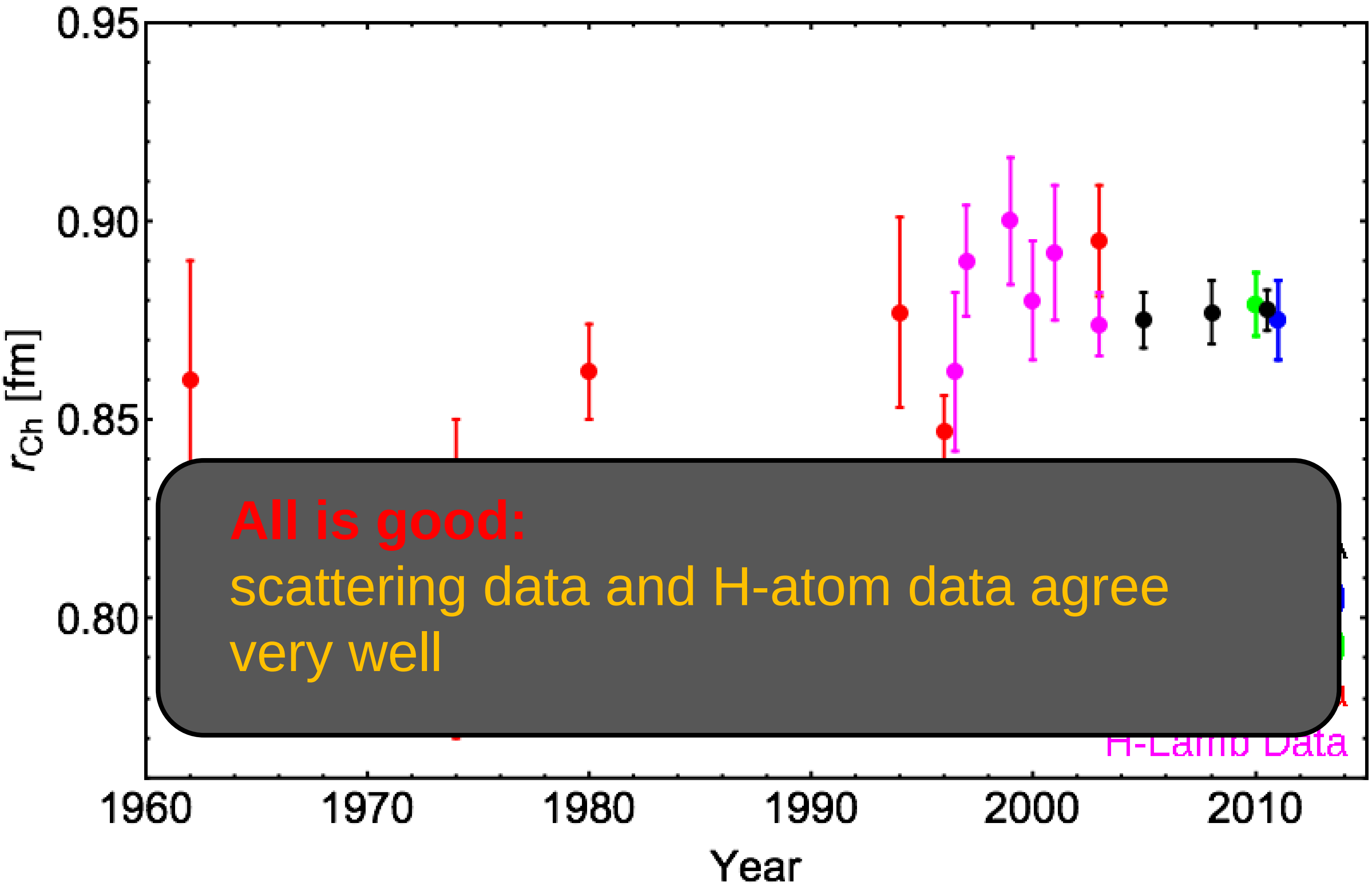
$$V \sim 1/r$$



The Proton Radius vs Time from Hydrogen Lamb Shift data



The Proton Radius from Hydrogen Lamb Shift and ep



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

proton rms charge radius measured with electrons:
0.8770 ± 0.0045 fm

But can we do better?

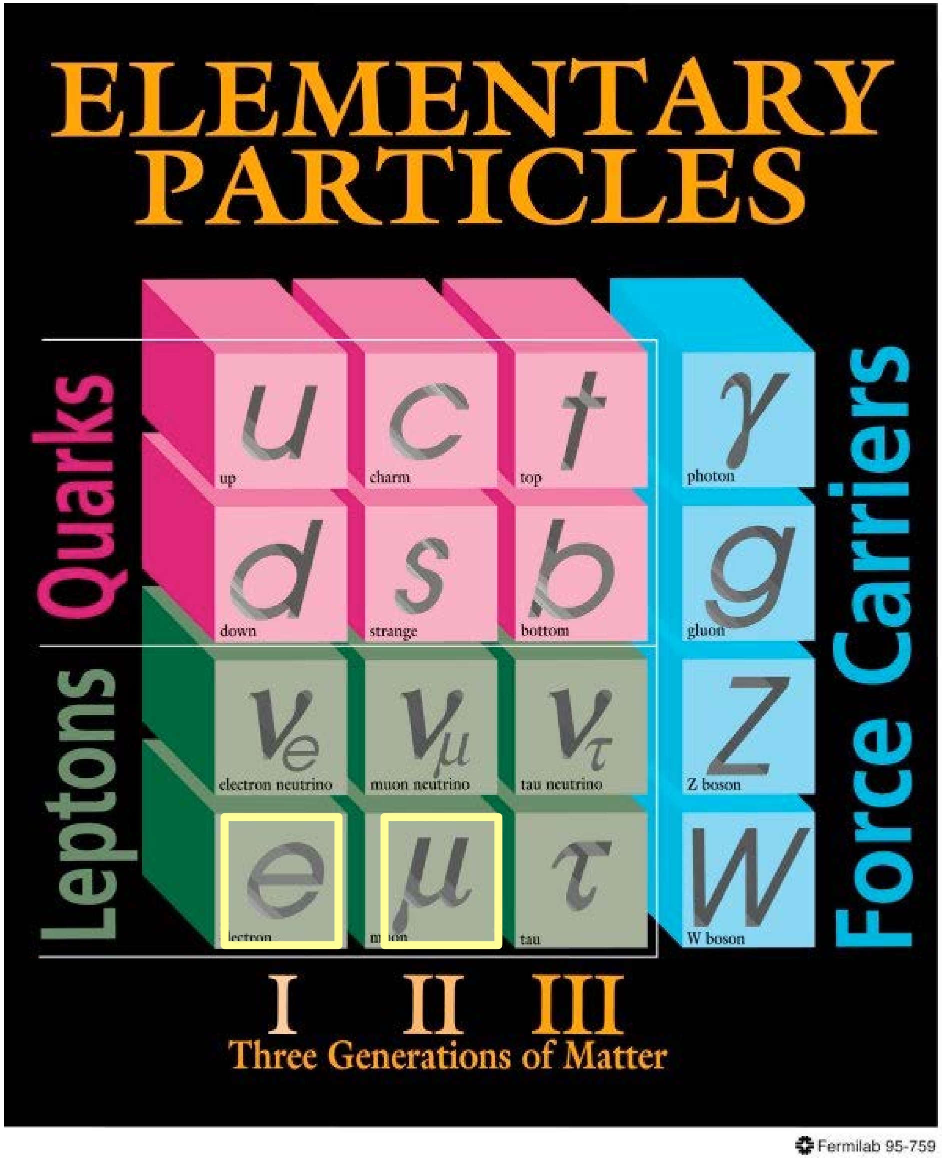
Probably "Yes"

Use Muonic Hydrogen

Why?

What is it?

Why use Muonic Hydrogen?



In the standard model the muon is just a heavier version (~207 times) of the electron

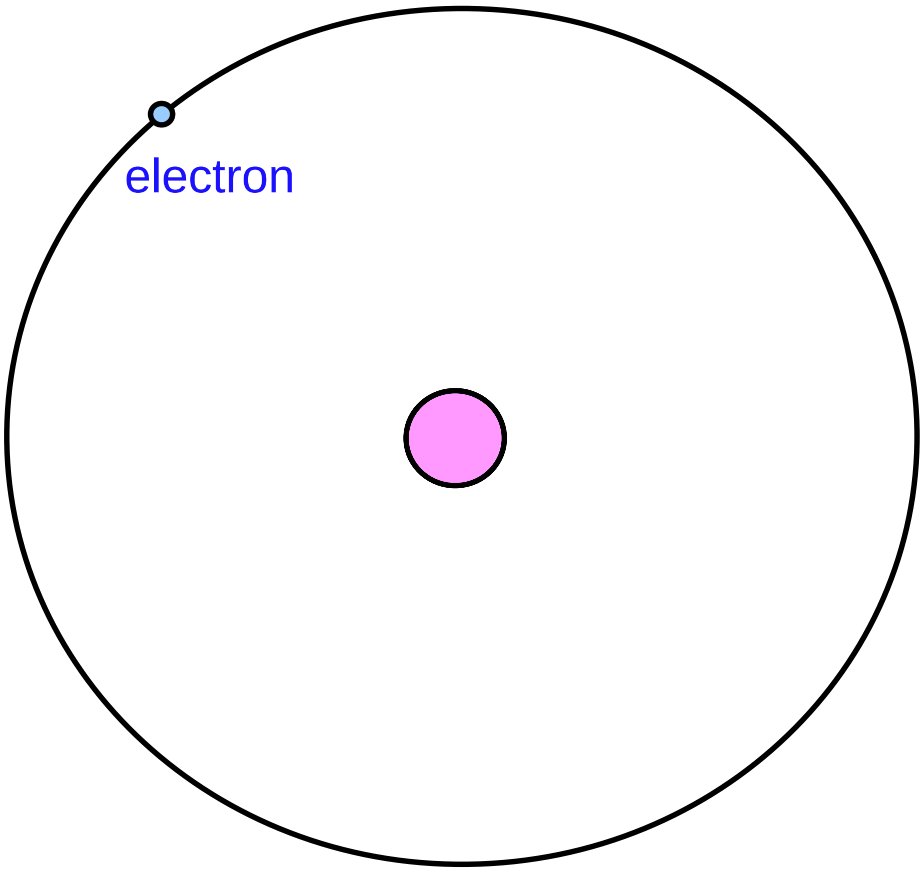
The muon decays into an electron (and some neutrinos) with a lifetime of ~2.2 μs

It has exactly the same interactions…

What is Muonic Hydrogen?

Regular hydrogen:

electron e^- + proton p



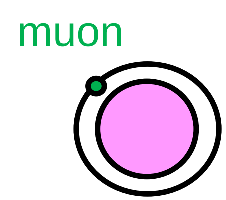
Muonic hydrogen:

muon μ^- + proton p

Muon mass $m_\mu = 207 \times m_e$

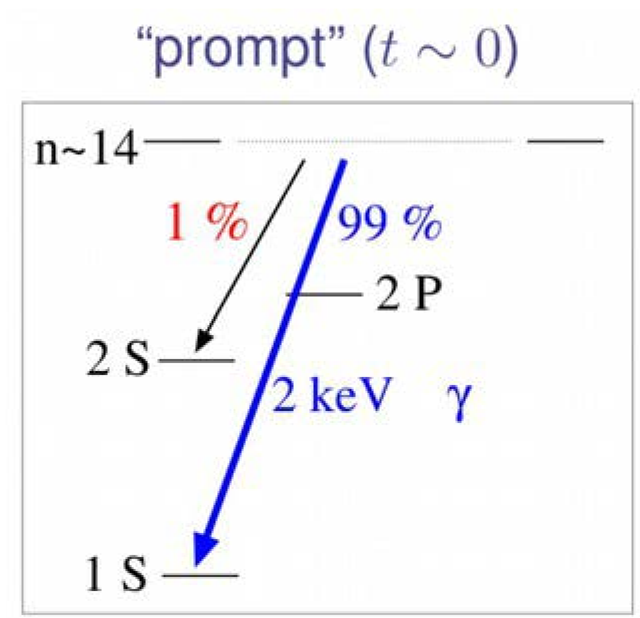
Bohr radius $r_\mu = 1/207 \times r_e$

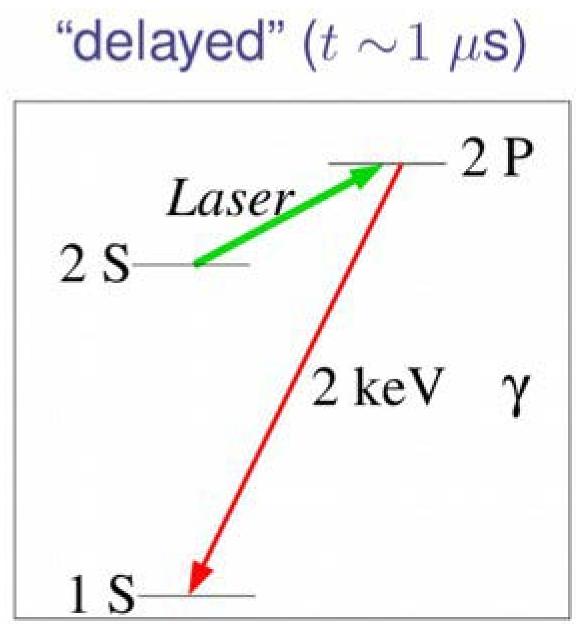
Probability for μ^- to be inside proton: $207^3 \approx 8$ *million*



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

How to Measure with μH ?

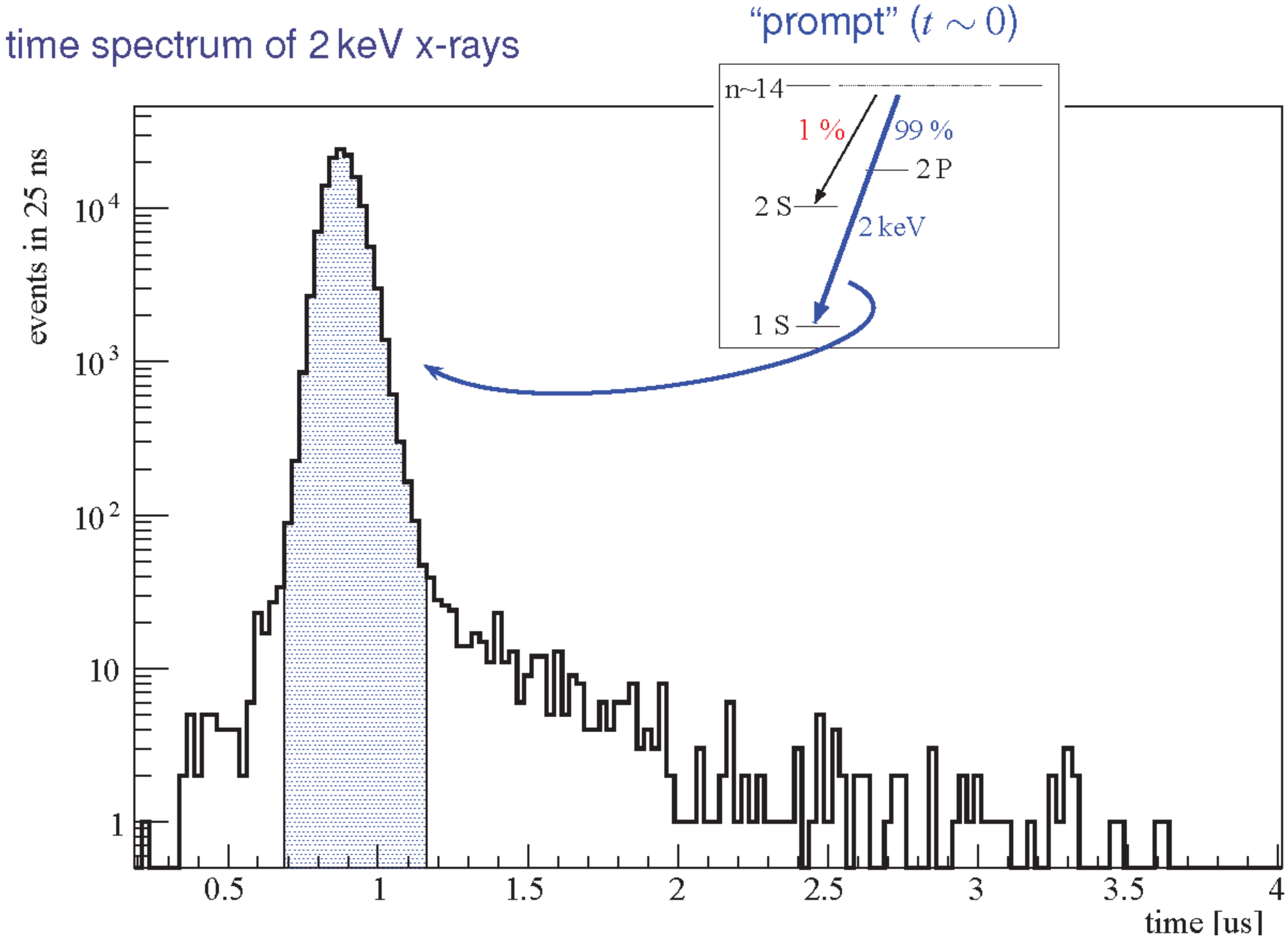




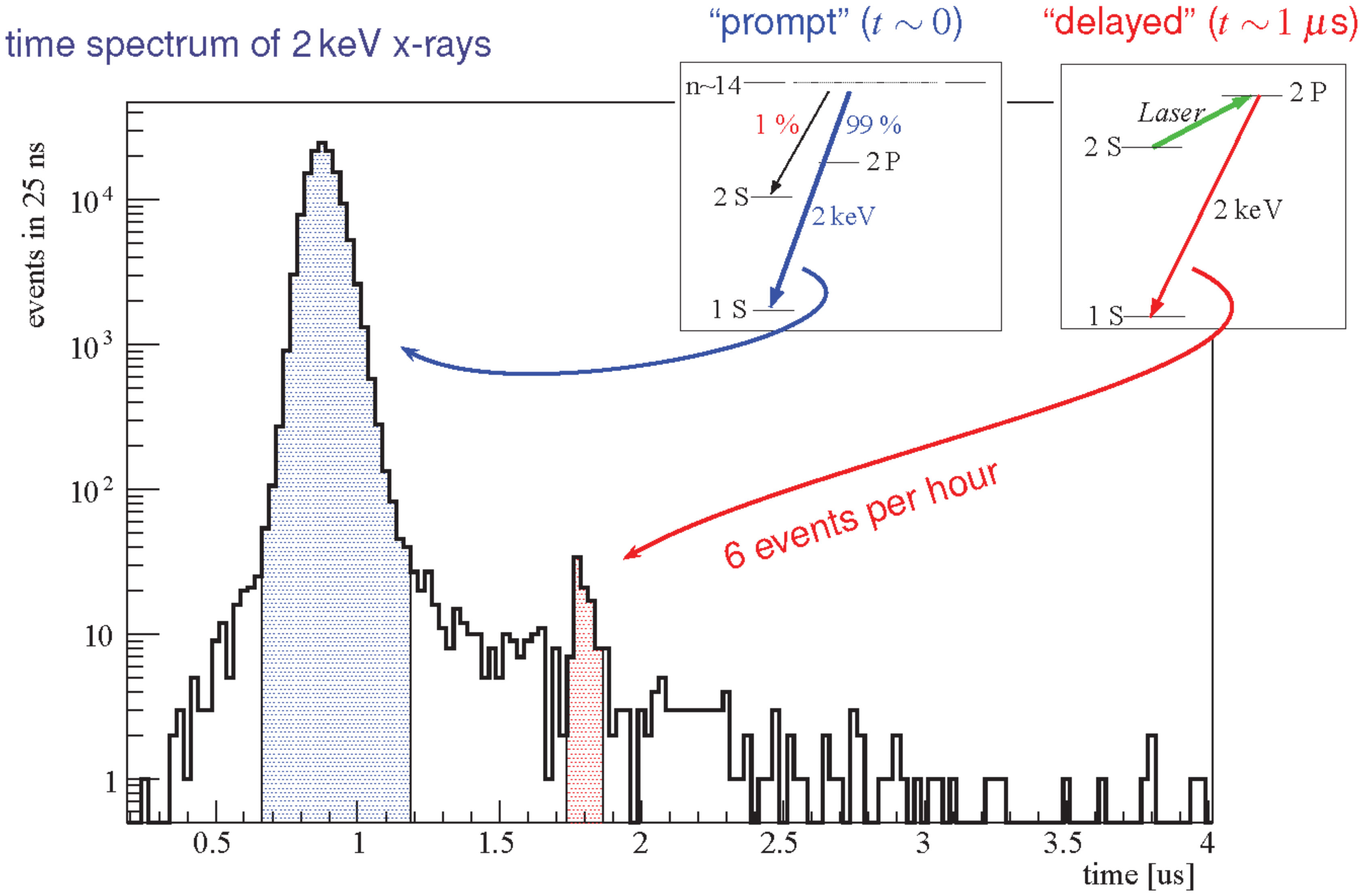
- beautifully simple, but technically challenging!
- form μH*(n~14) by shooting μ beam on 1 mbar H_2 target
  - 99% decay to 1S, giving out fast γ pulse
  - 1% decay to longer-lived 2S state
  - 2S state excited to 2P state by tuned laser & decay with release of delayed γ
- vary laser frequency to find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

Pictures: R. Pohl

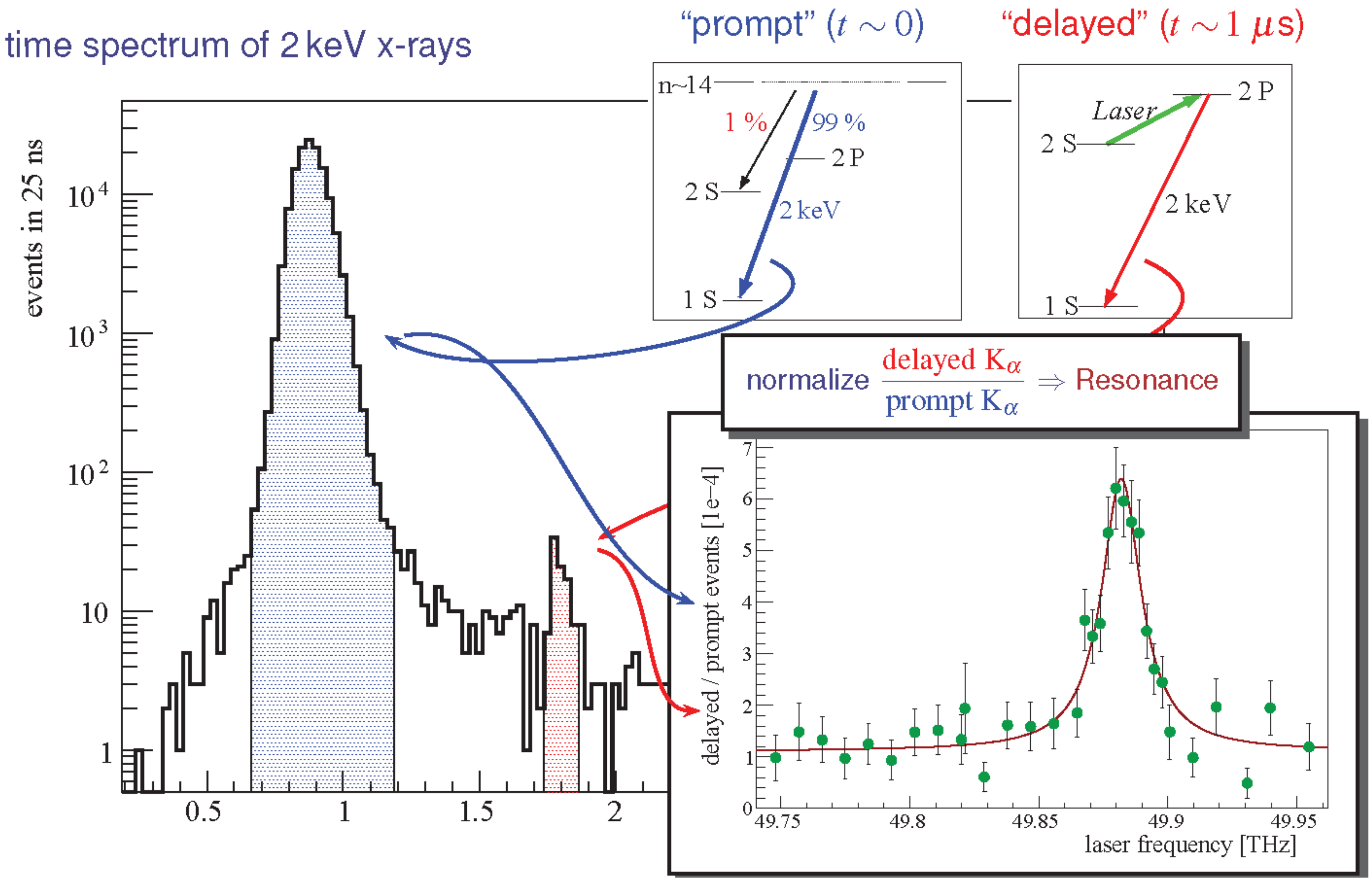
How to Measure with μH ?



How to Measure with μH ?



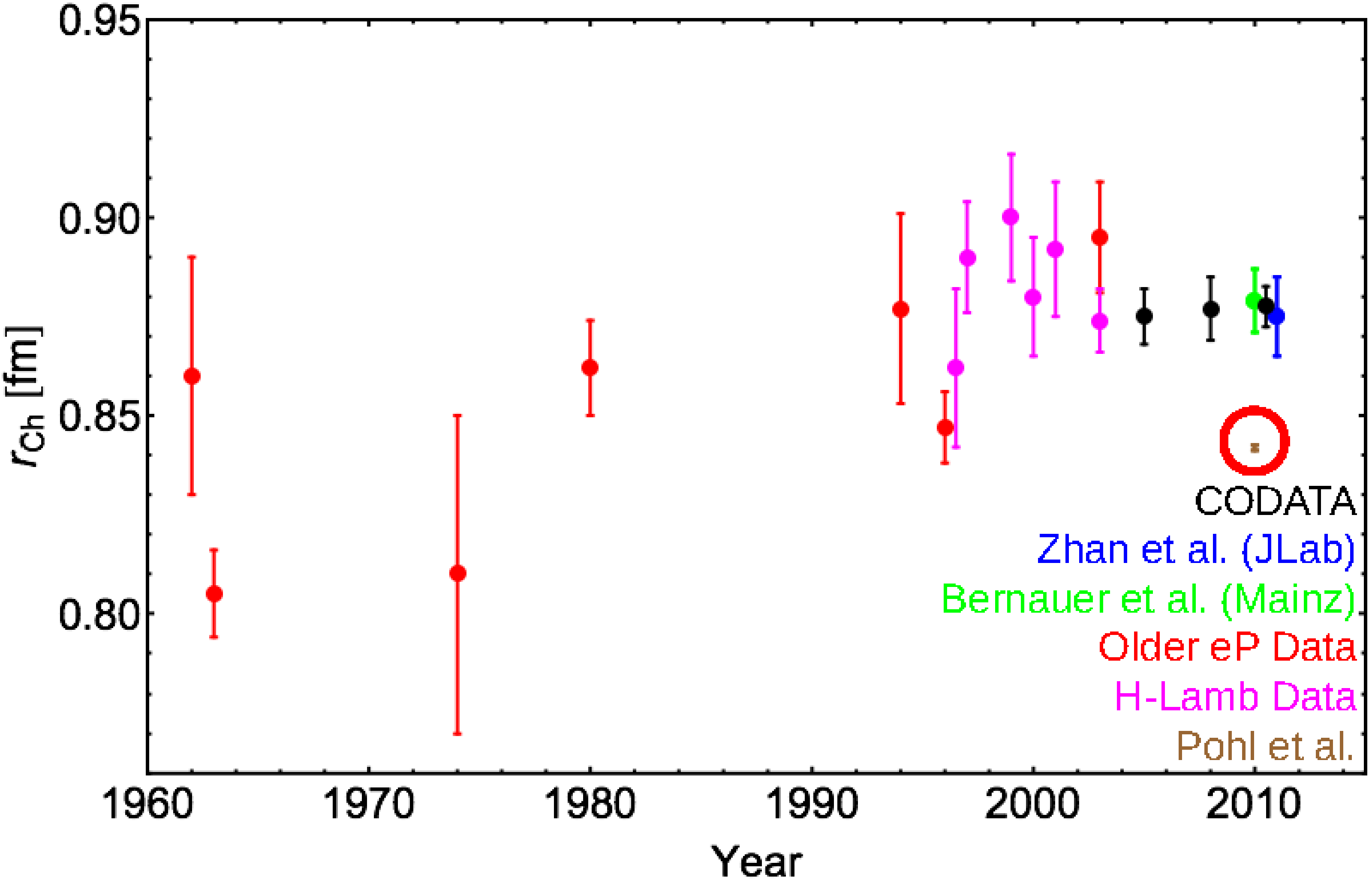
Proton Radius from μH



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

0.84184 ± 0.00067 fm

The Proton Radius from H & μH Lamb Shift and ep

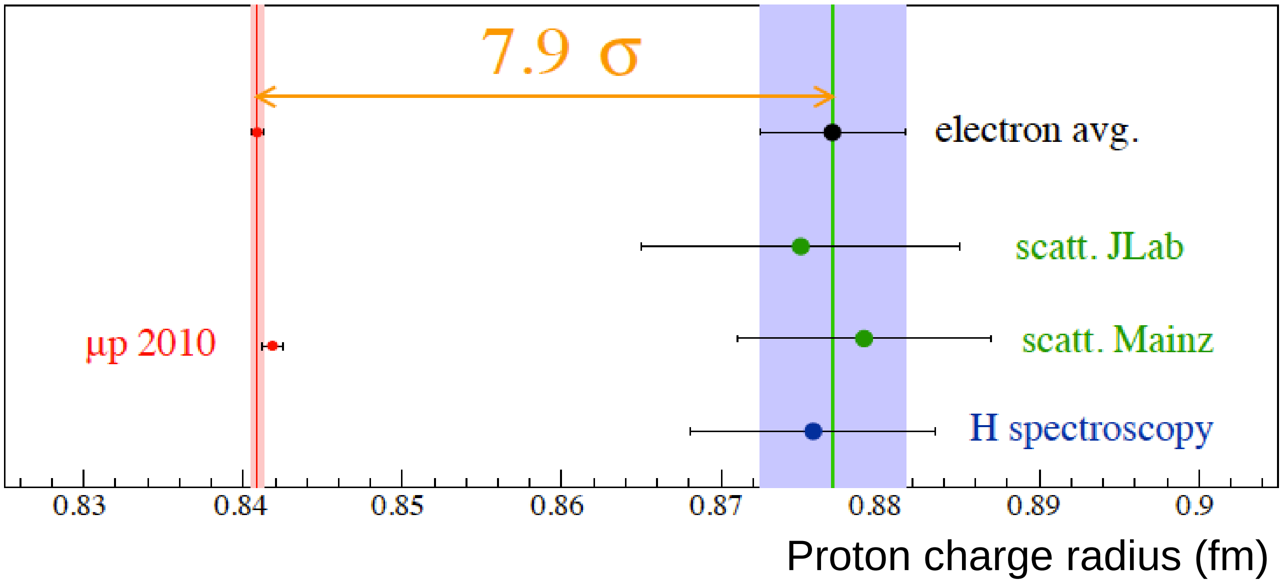


The Proton Radius Puzzle

Proton radius measured with

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

muonic hydrogen: **0.8409 ± 0.0004 fm**



Radius from Muonic Hydrogen 4% below previous best value

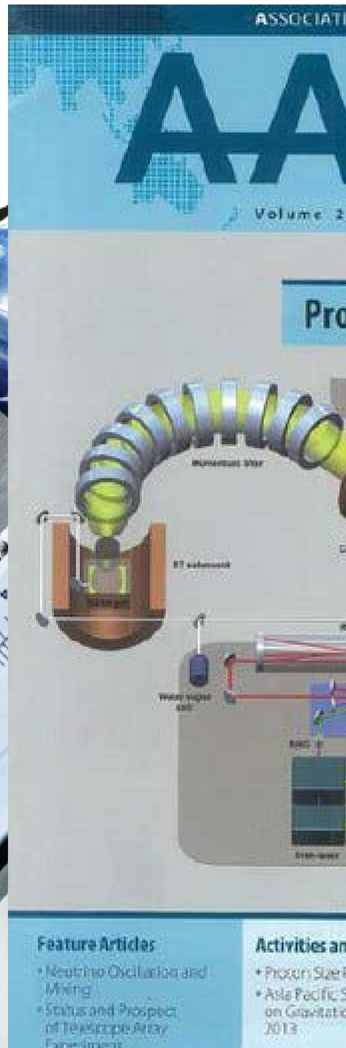
→ 11-12% smaller (volume), 11-12% denser than previously believed

This needed to be confirmed before it can be believed!!

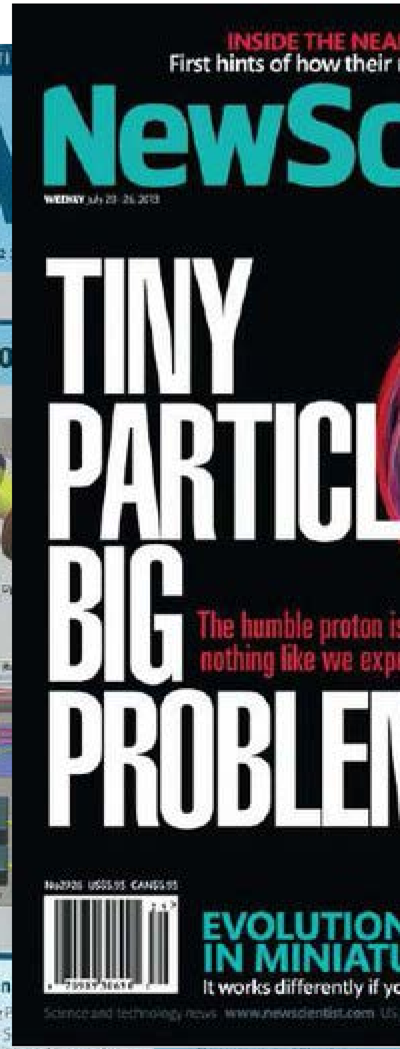
The Proton Radius Puzzle

July 2010

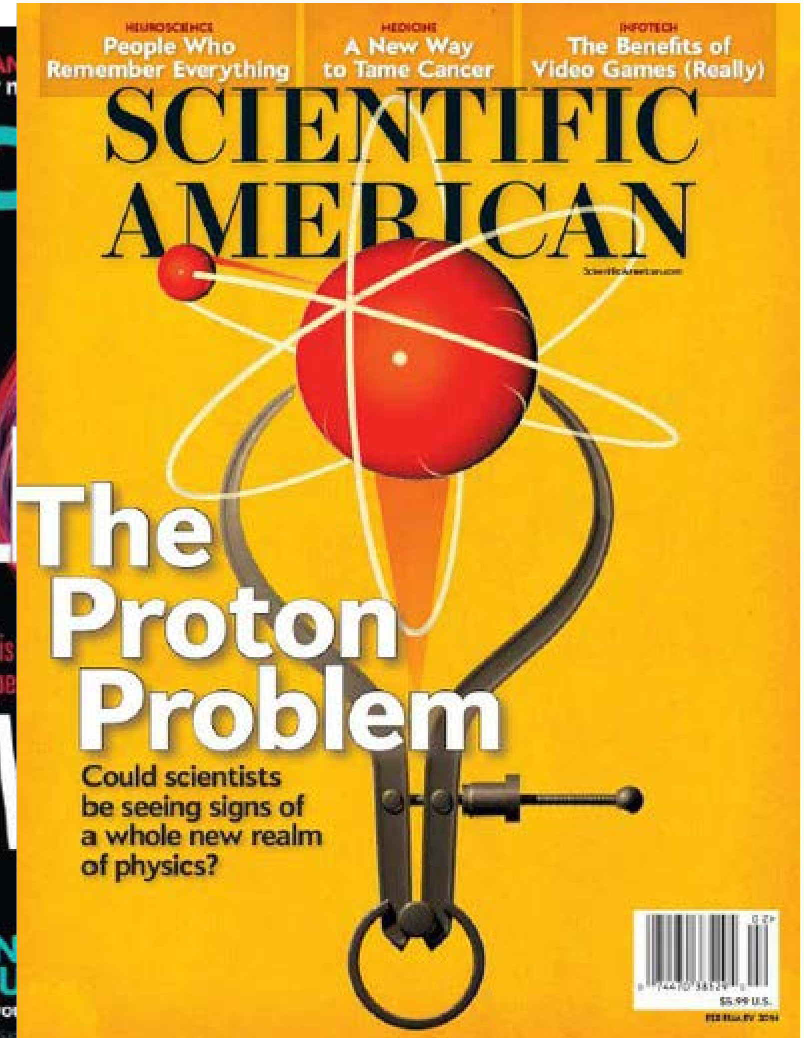
April 2013



July 2013

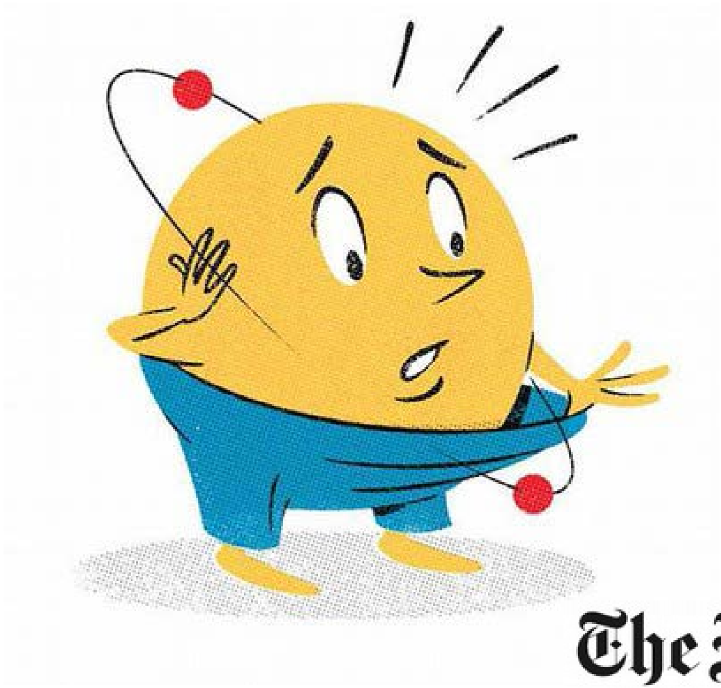


January 2014



The Proton Radius Puzzle

The Proton Radius Puzzle



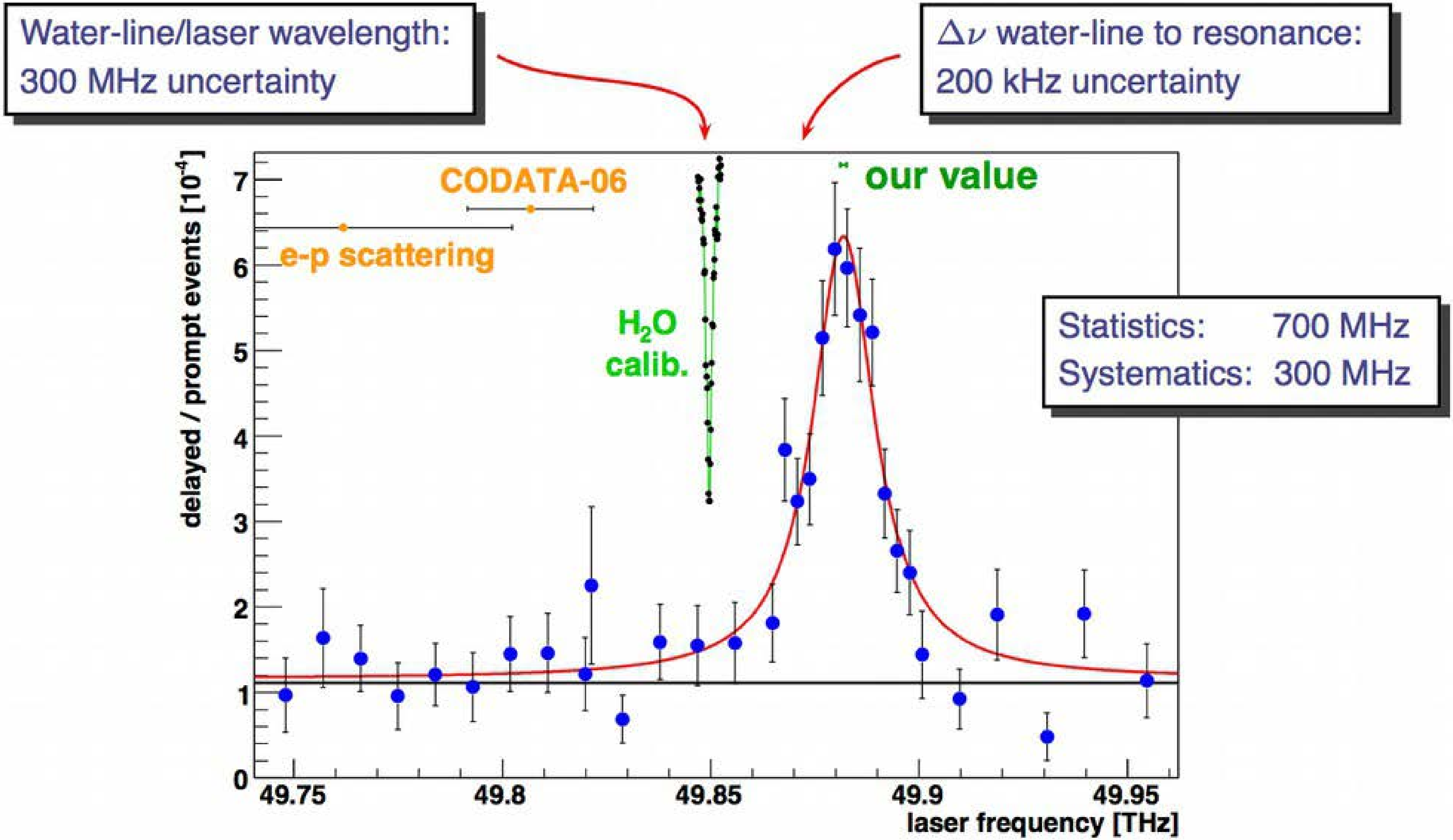
The New York Times

- The Proton Radius Puzzle 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)

?

How do we resolve the puzzle?

Experimental Error in μH Measurement ?



Experimental Error in Electron Measurements ?

Electron Scattering

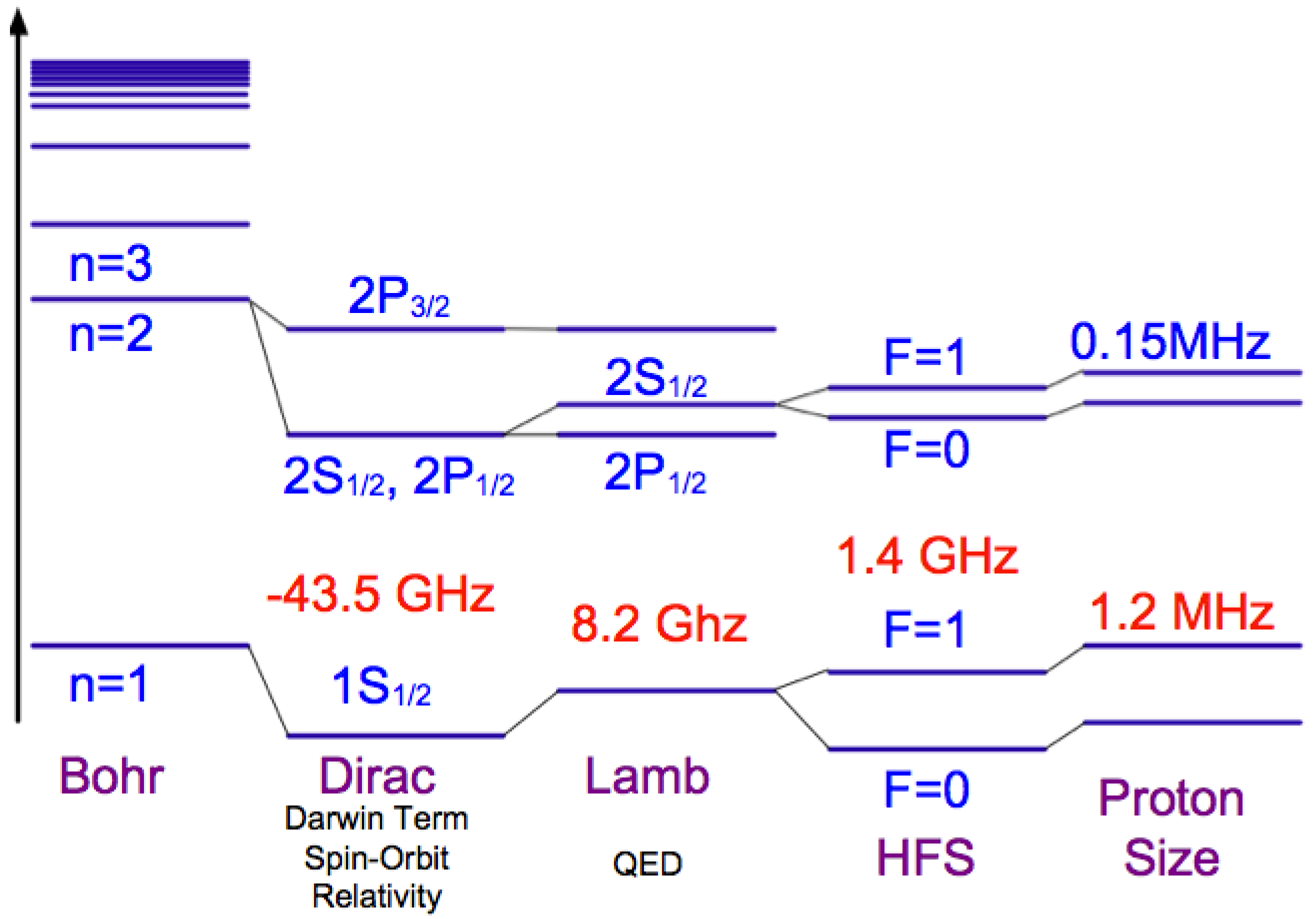
Essentially all (newer) electron scattering results are consistent within errors

Atomic Hydrogen Lamb Shift

Only an error of about 1,700 times the quoted experimental uncertainty could account for the observed discrepancy

Theory Error ?

Atomic Physics Gets Complicated...



The basic point: the hydrogen atom is not simple, and extracting a radius requires detailed calculations

Theory Error ?

#	Contribution	Ref.	Our selection Value	Unc.	Pachucki [31–33] Value	Unc.	Borie [34] 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

Checked,

Rechecked,

and Checked again

No Error Found

What's next ?

More and better theory calculations ?

→ But it seems like we've reached a dead end - nothing obvious has been discovered so far

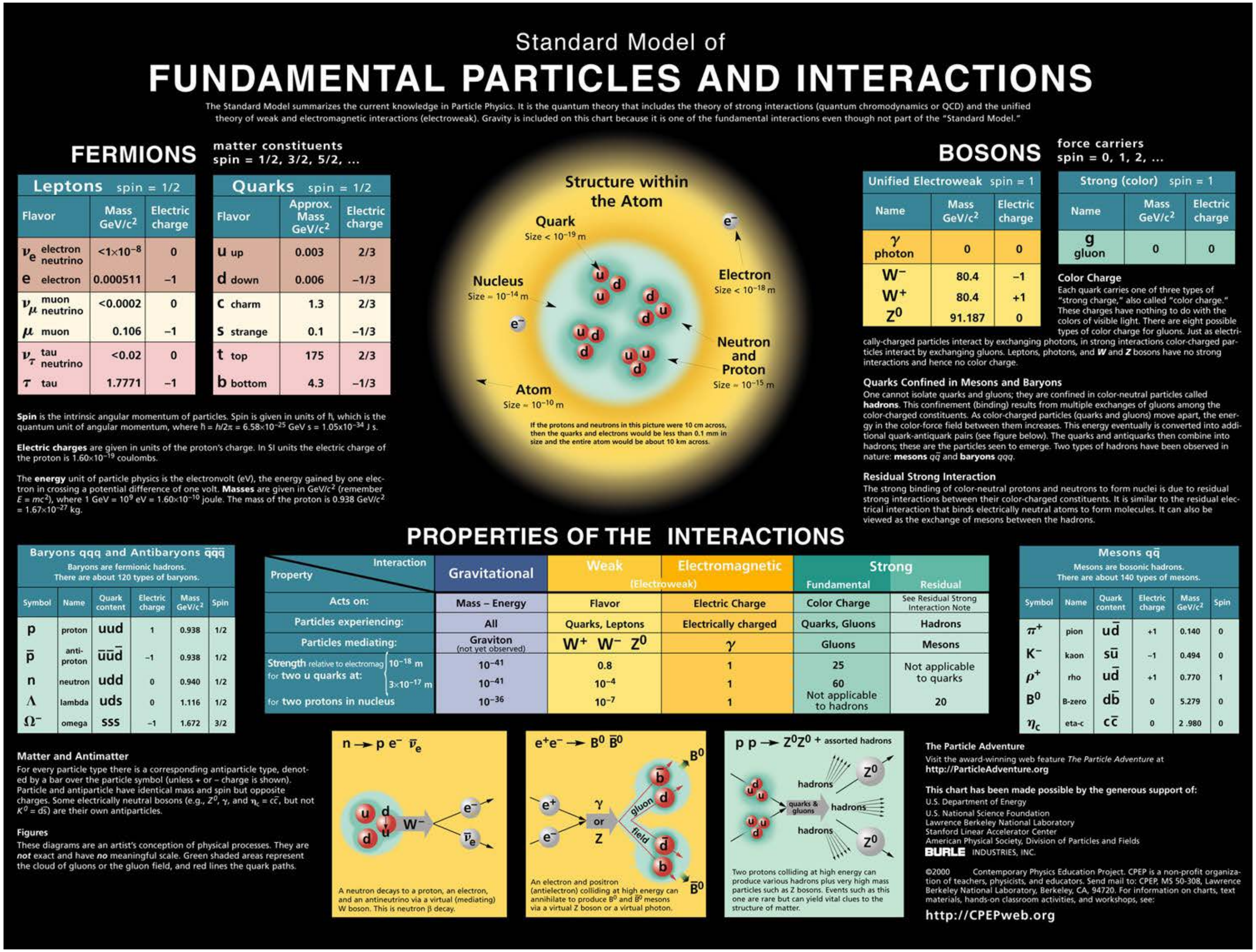
Another Look at Experimental Errors ?

→ Done over and over - again, nothing obvious so far and it's hard to think of something that would cause this

What about our Assumption?

Muons and electrons have exactly the same interaction

Potential solution: Beyond Standard Model (BSM) physics



Standard model: lepton universality, mass is only difference between μ & e

BSM: electrons measure electromagnetic radius, but muons experience extra effect from new particles

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

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

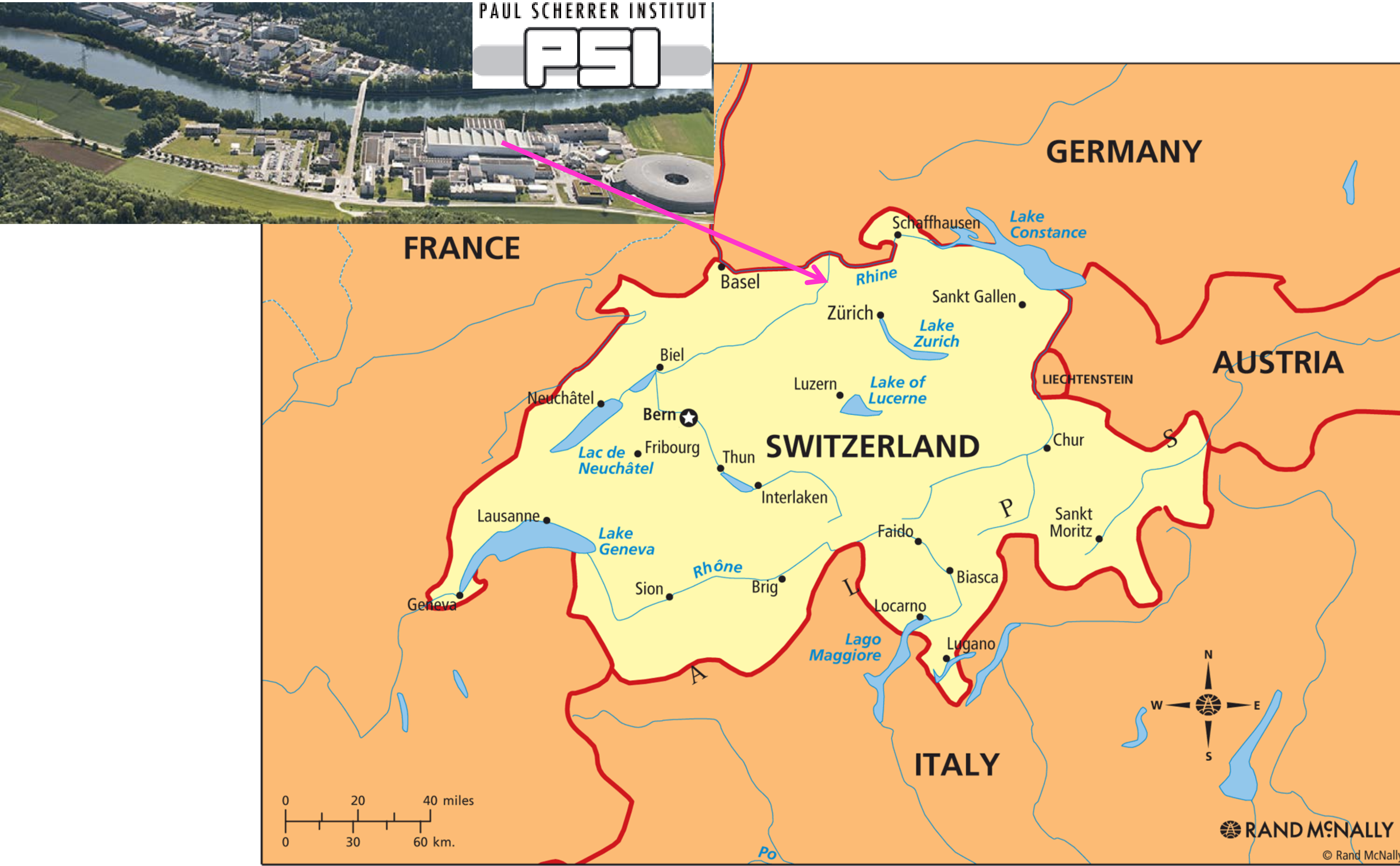
Muon scattering

???

Swiss Muons


GERMANY
FRANCE
AUSTRIA
LIECHTENSTEIN
SWITZERLAND
ITALY
Schaffhausen
Lake Constance
Basel
Rhine
Sankt Gallen
Zürich
Lake Zurich
Biel
Luzern
Lake of Lucerne
Neuchâtel
Bern
Chur
Lac de Neuchâtel
Fribourg
Thun
Interlaken
Sankt Moritz
Lausanne
Faido
Lake Geneva
Rhône
Biasca
Sion
Brig
Geneva
Locarno
Lago Maggiore
Lugano
Po
A L P S
N
W
E
S
0 20 40 miles
0 30 60 km.
RAND McNALLY
© Rand McNally

Swiss Muons


PAUL SCHERRER INSTITUT
PSI
GERMANY
FRANCE
AUSTRIA
SWITZERLAND
ITALY
LIECHTENSTEIN
Schaffhausen
Lake Constance
Basel
Rhine
Sankt Gallen
Zürich
Lake Zurich
Biel
Luzern
Lake of Lucerne
Neuchâtel
Bern
Lac de Neuchâtel
Fribourg
Thun
Chur
Interlaken
Lausanne
Lake Geneva
Faido
Sankt Moritz
Geneva
Sion
Rhône
Brig
Biasca
Locarno
Lago Maggiore
Lugano
Po
N
W
E
S
0 20 40 miles
0 30 60 km.
RAND McNALLY
© Rand McNally

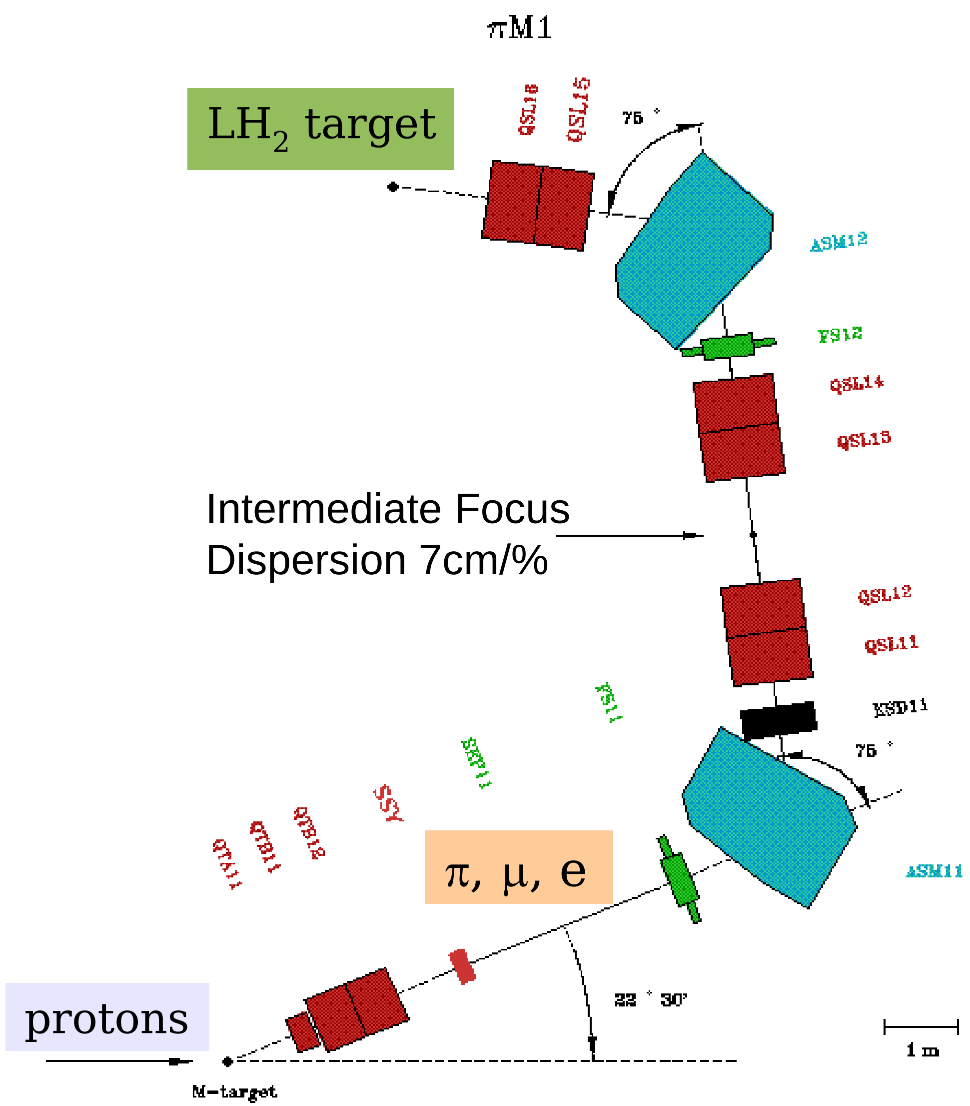
MUon Scattering Experiment (MUSE) at PSI

- Simultaneous measurement of $e^+/\ \mu^+$ $e^-/\ \mu^-$ 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 (if $\mu = e$)

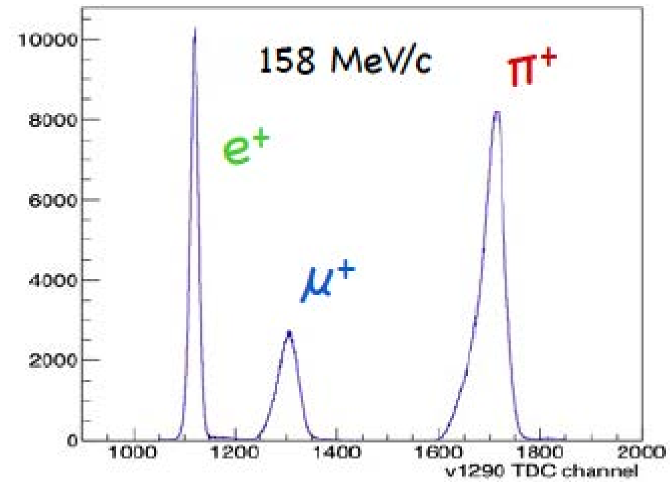
Paul Scherrer Institute πM1 Beam

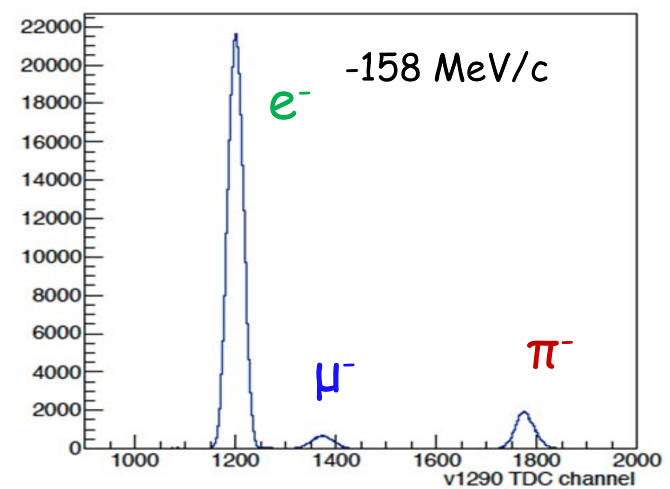
- 590 MeV proton beam, 2.2mA, 1.3MW beam, 50.6MHz RF frequency
- World's most powerful proton beam
- Converted to $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ in πM1 beamline

πM1 / MUSE beamline

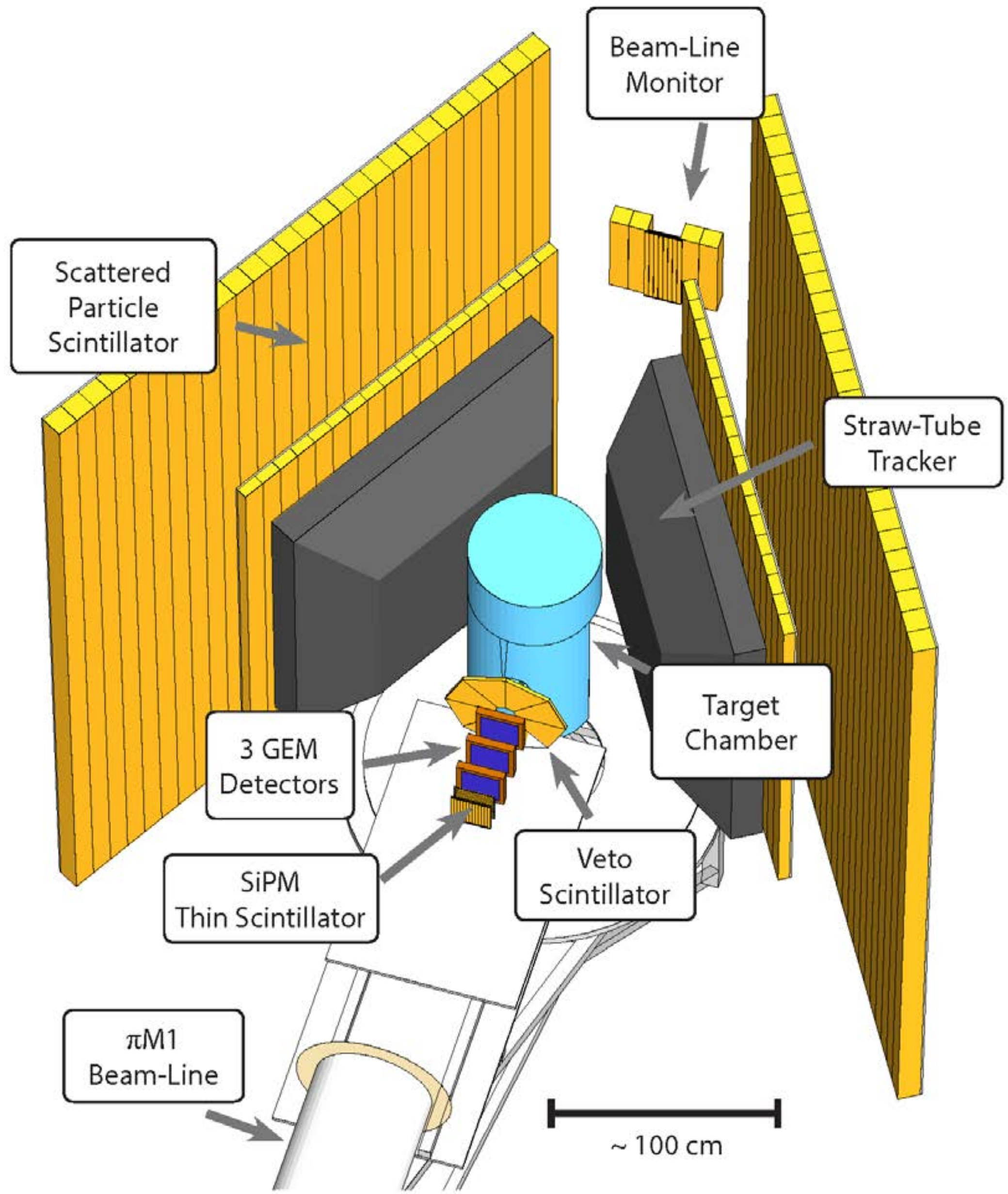


πM1: 100-500 MeV/c RF+TOF separated π, μ, e



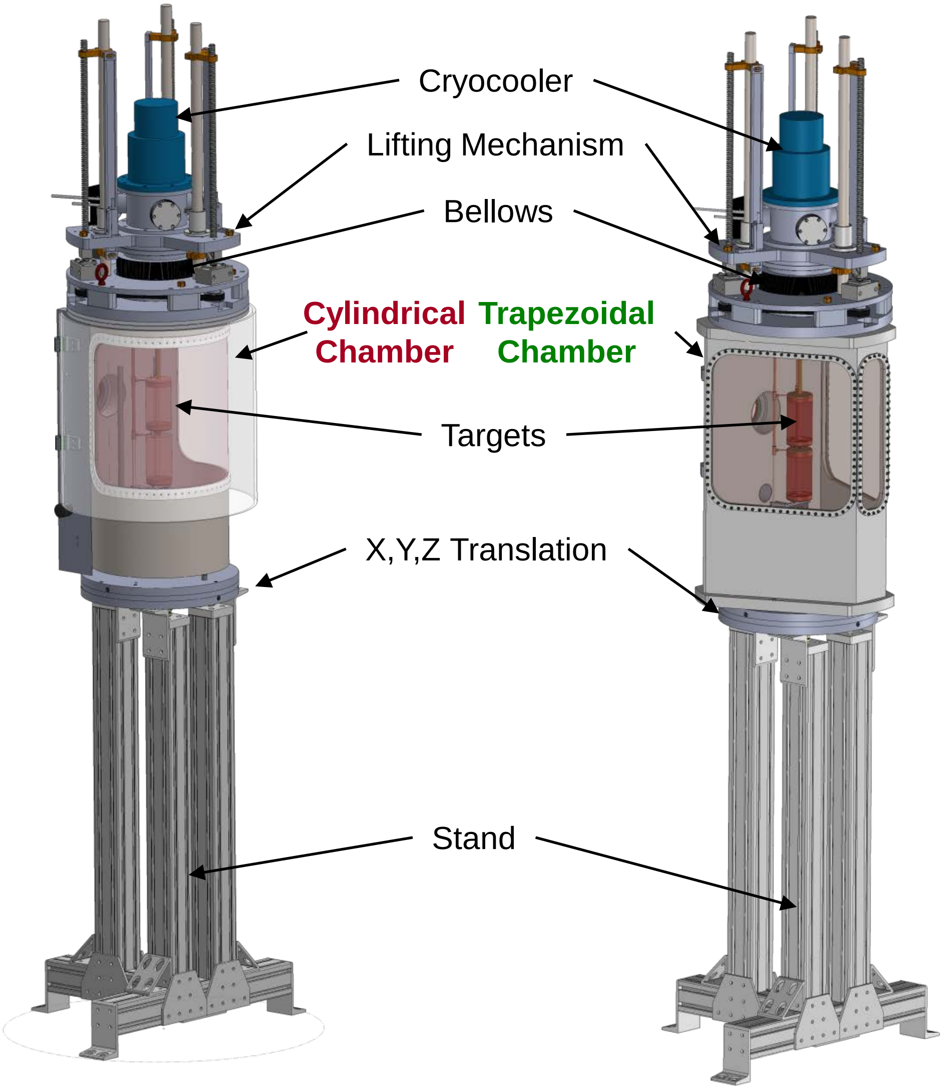


MUSE experiment layout



MUSE Target Design (U-M effort)

- Two chamber designs have been considered
  - Cylindrical chamber with a single wrap-around exit window
  - Trapezoidal chamber with three discrete exit windows
- Physicists prefer cylindrical chamber
- Engineers prefer trapezoidal chamber



Unsupported Windows form Pleats

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

Window Burst Shortly after Photo

Does not work

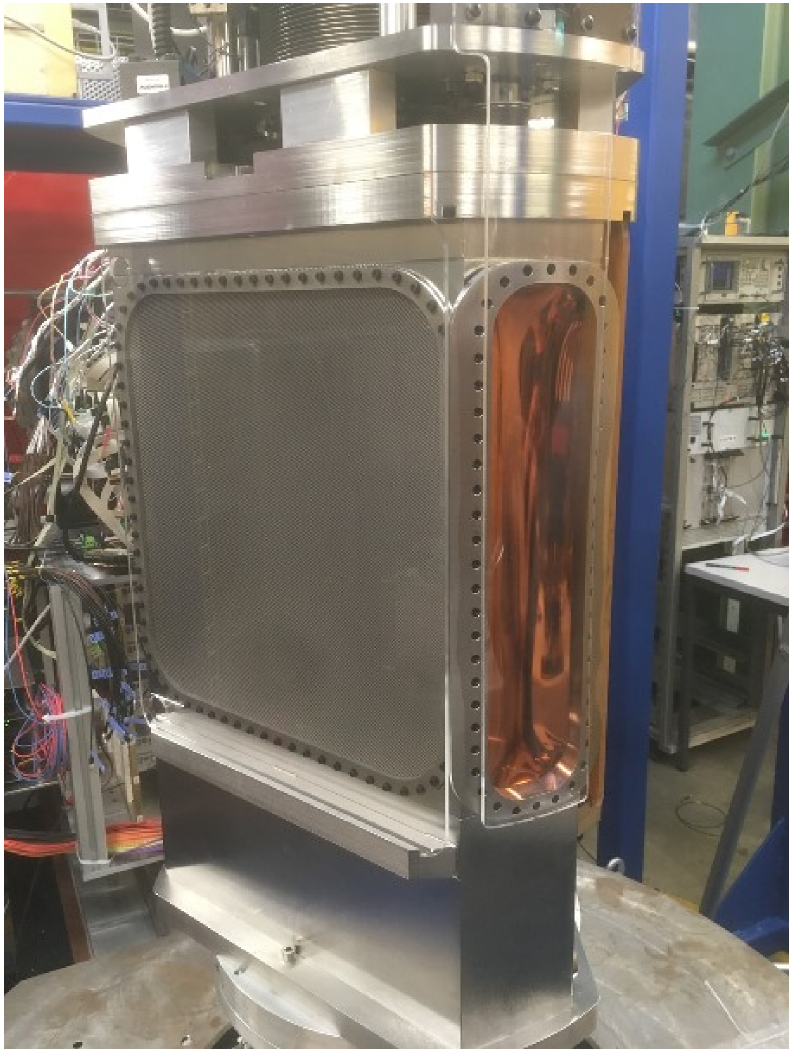
Flat Windows don't form Pleats

window deforms 68 mm at 1atm

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

Hydrogen Target

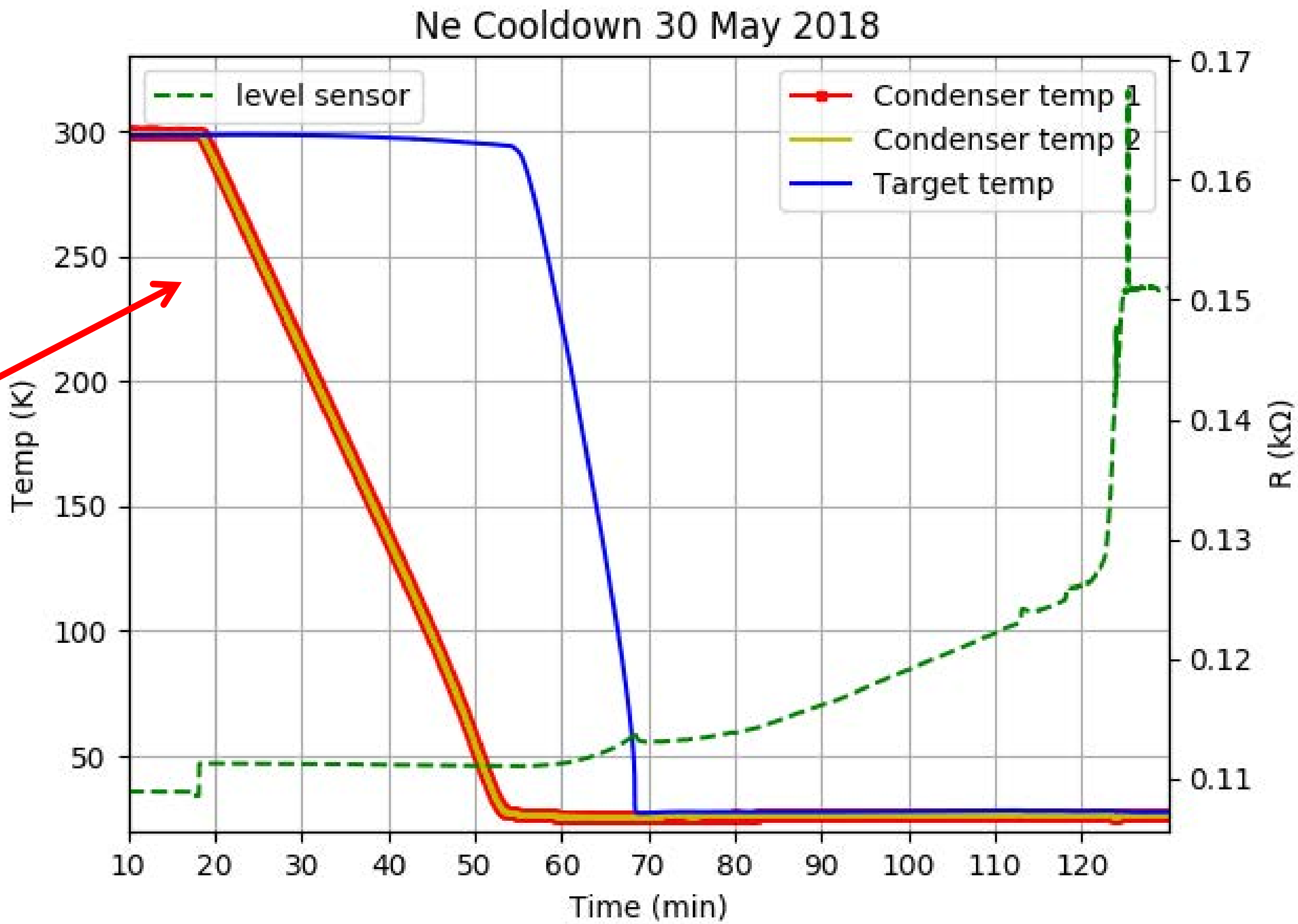
Target chamber



Target cells

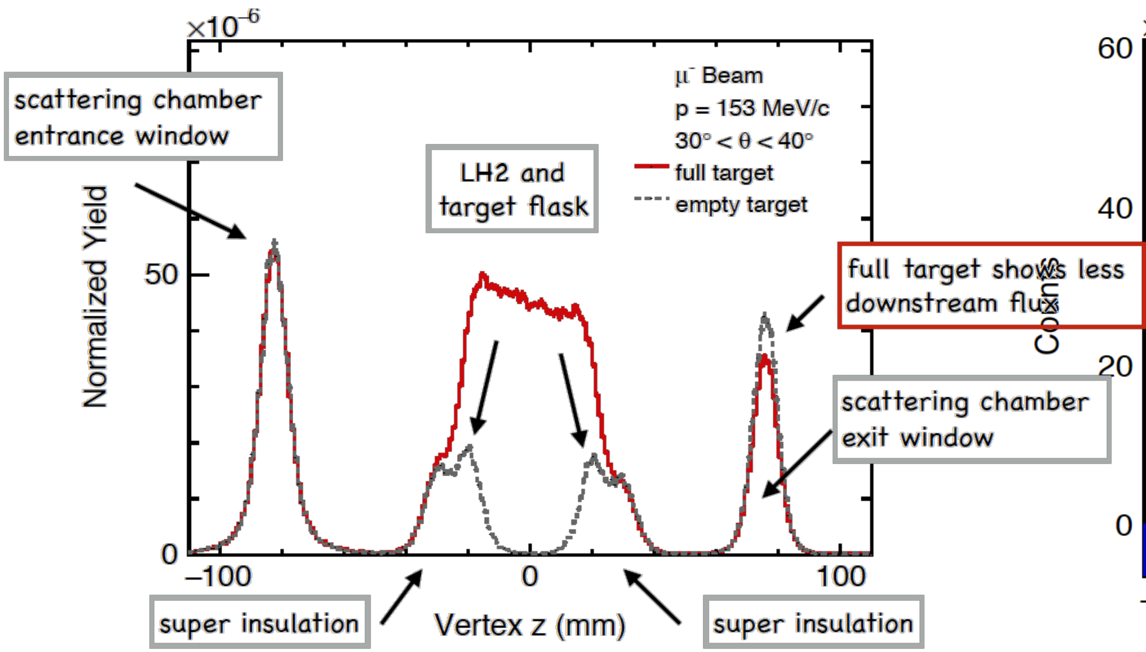
Target cell destruction tests

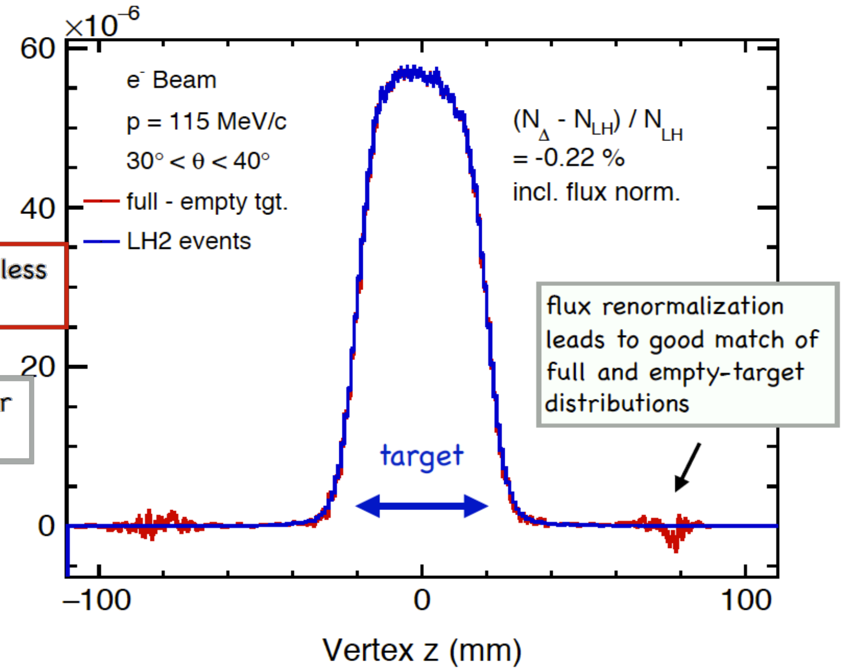
Hydrogen Target Cooldown

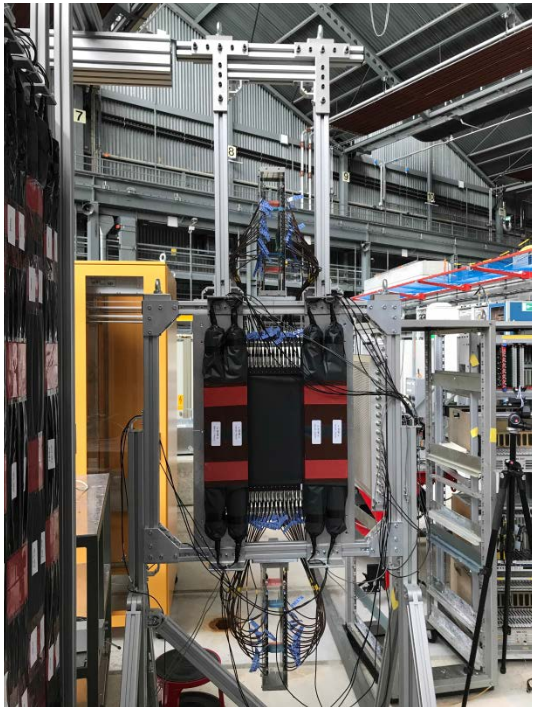


Target Simulations

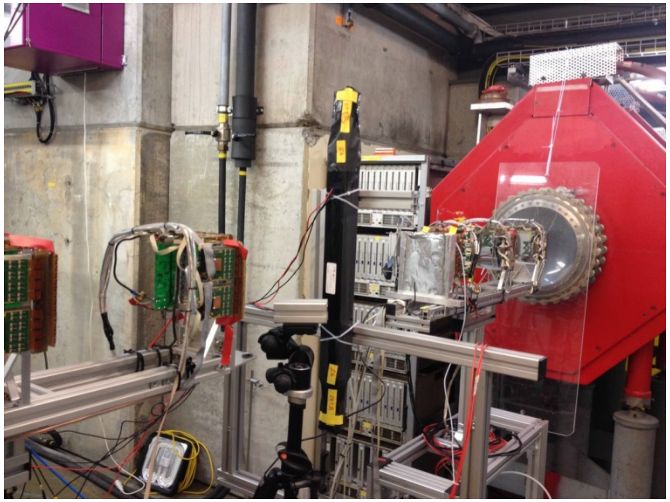
Background from target walls and windows can be cleanly eliminated or subtracted







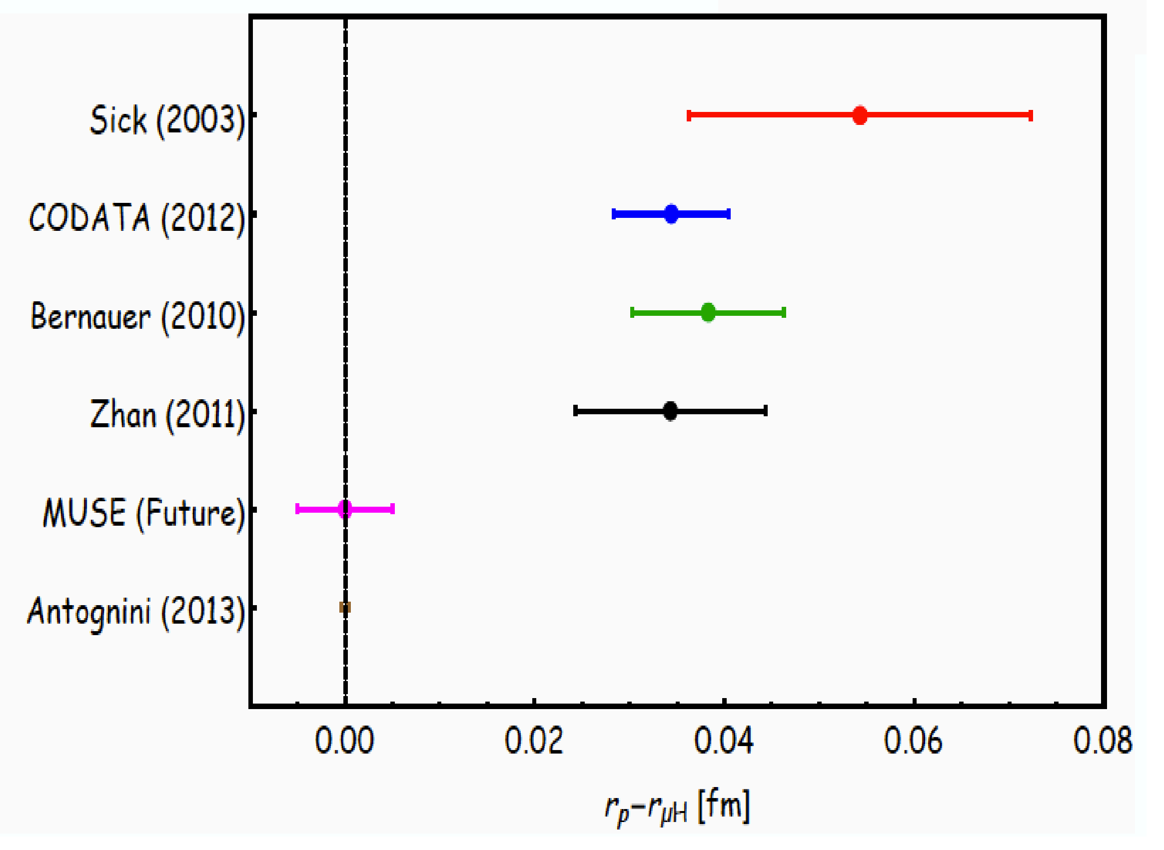
MUSE status



- 16 test runs (2012 – 2018) demonstrate simulation agreement & reliable performance
- Construction almost completed
  - Two six-month data-taking runs in 2019/20

Projected sensitivity for MUSE

- Extract radius from ep and μp scattering
- Error on radius difference ~0.009 fm
- MUSE will
  - verify the effect
  - compare cross sections
  - 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, **P. Roy**, T. Rostomyan, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, **N. Steinberg**, V. Sulkosky, A.S. Tadepalli, M. Taragin, L. Weinstein, and **N. Wuerfel**

*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*

~~Conclusions~~

Summary

- Proton radii have been measured very accurately over the last 50 years
- **Major** discrepancy has now arisen (between electron and muon results)
  - Some ideas for how to fix this: either the muonic side, the electronic side, or by inventing fancy new physics
  - But none currently seem to solve the puzzle completely
- Common thinking seems to be
  - **Theorists** - "it's an experimental problem, some systematic issue"
  - **Experimentalists** - "Theorists have forgotten some obscure correction"
    - "Problem with electron results"
  - **Fringe** - "Exciting new physics"

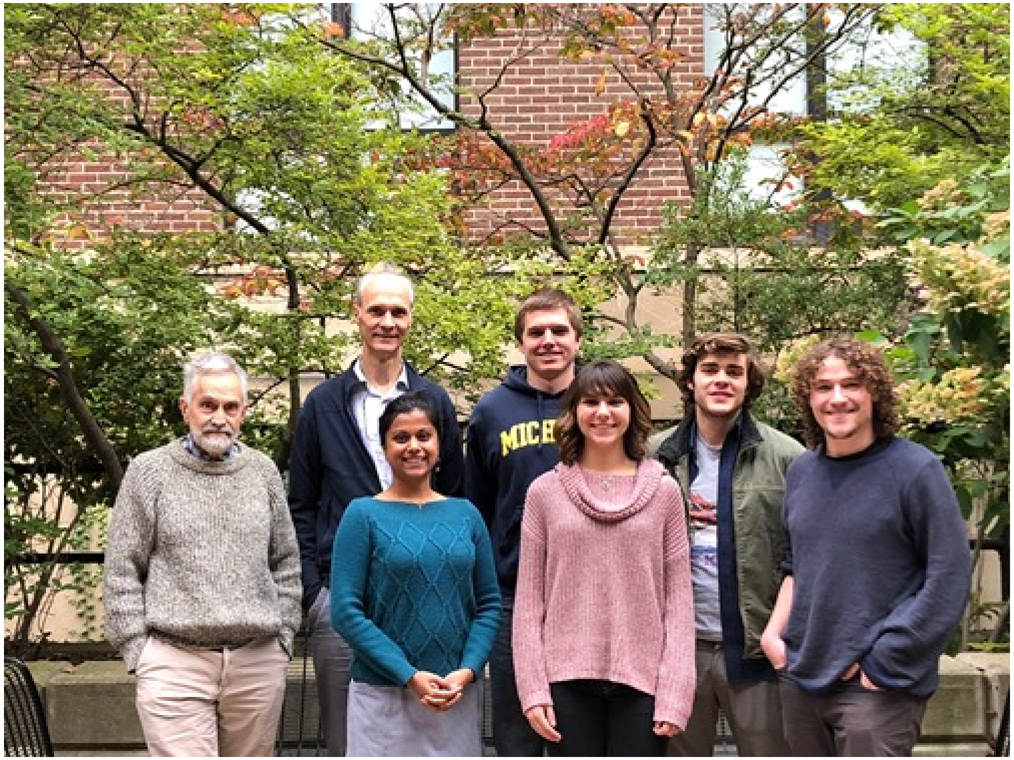
We are still (possibly more) puzzled!

- New experiments may help shed (some) light on the issue

Thanks to

Evie Downie, Guy Ron, Randolph Pohl for slide materials

and the Michigan group to do all the work



Backup slides

How do you measure size?

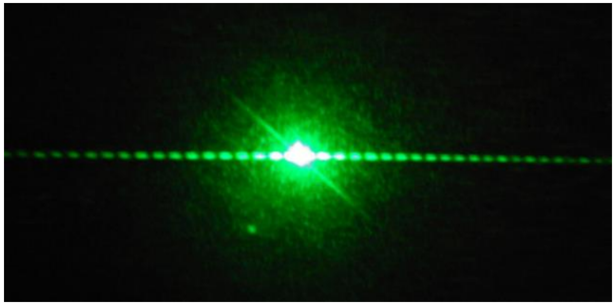
Object:

- macroscopic:
  hard sphere

Tool:

caliper

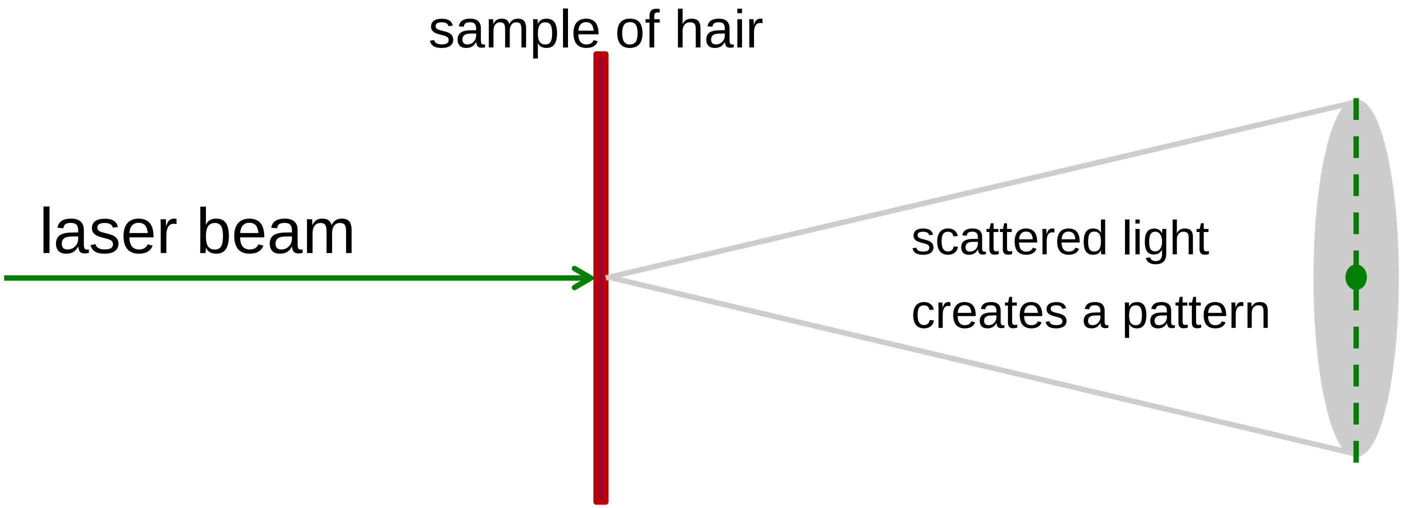
- small:
  hair



laser

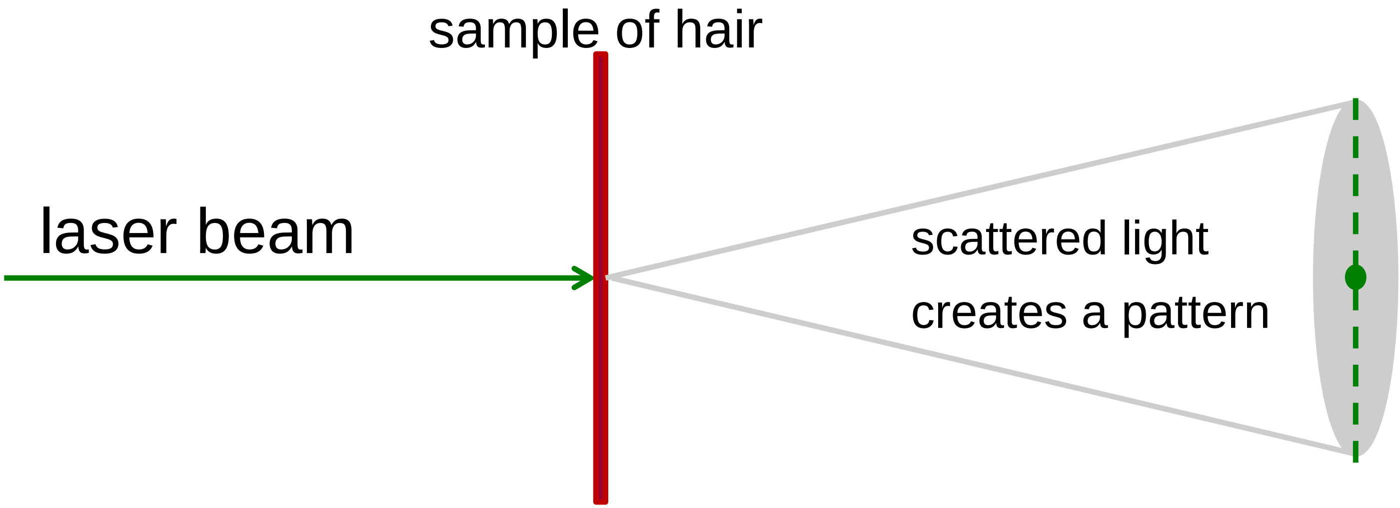
Let's measure the width of a hair!

How do you measure size of hair?



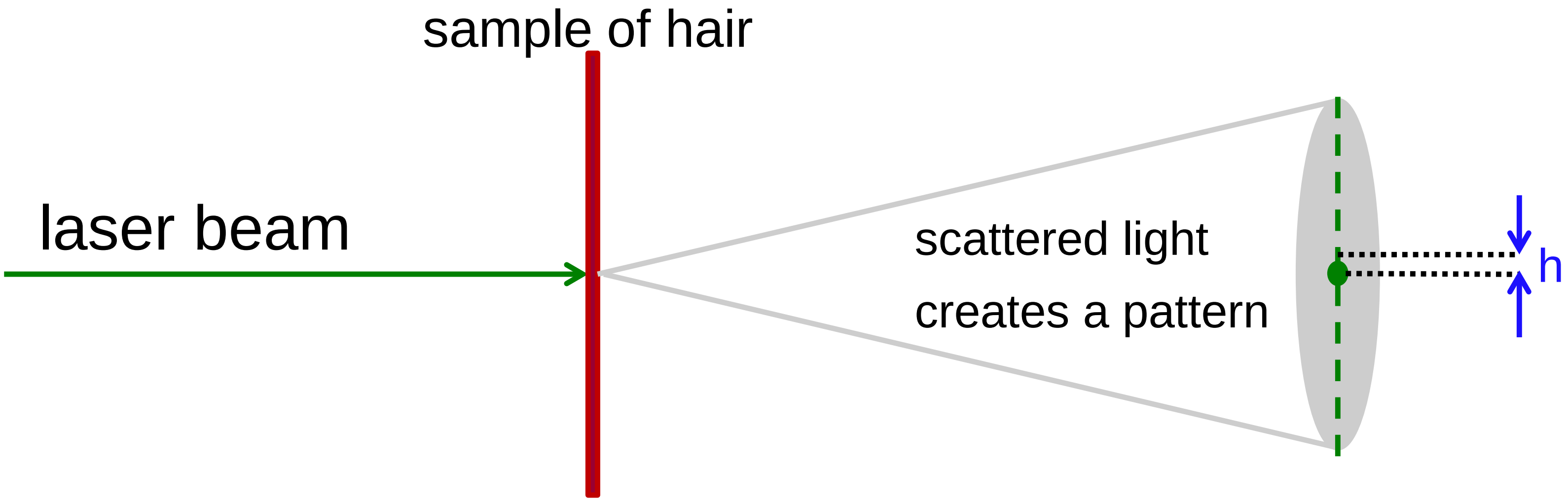
Need a volunteer

How do you measure size of hair?



Need ~~a~~ 2 volunteers

How do you measure size of hair?



laser wavelength: 532 nm

distance hair to wall: 128 in

D:diameter of hair

h: distance center of dot to 1st minimum
(ie. “dark” section)

$$D = \frac{0.000532\ \text{mm}}{\sin\left(\frac{h\ \text{mm}}{3251\ \text{mm}}\right)}$$

What is a differential Cross Section?

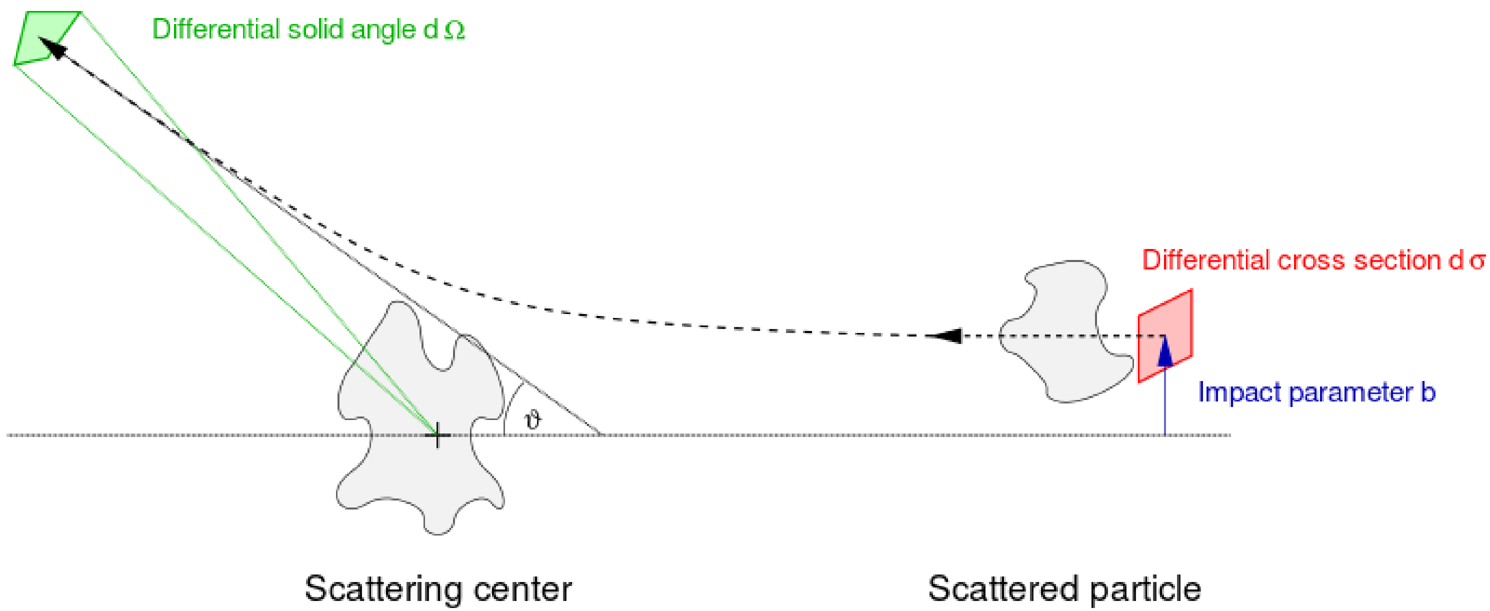
Differential Cross Section

- single particle is scattered off a single stationary target particle at an angle θ and φ
  (with $d\Omega = \sin\theta \, d\theta \, d\varphi$)

$$\sigma = \int \frac{d\sigma}{d\Omega} \, d\Omega$$

- differential cross section depends on impact parameter **b** and scattering angle **θ**

$$\frac{d\sigma}{d\Omega}$$



Slide inspired by Wikipedia

Extracting the radius from scattering data

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

Differential cross section — will be measured

Mott cross section — We know this

Form Factor — We extract this from the other two

Form factor $G(Q^2)$ is related to charge distribution $\rho(r)$ in proton

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

Extracting the radius from scattering data

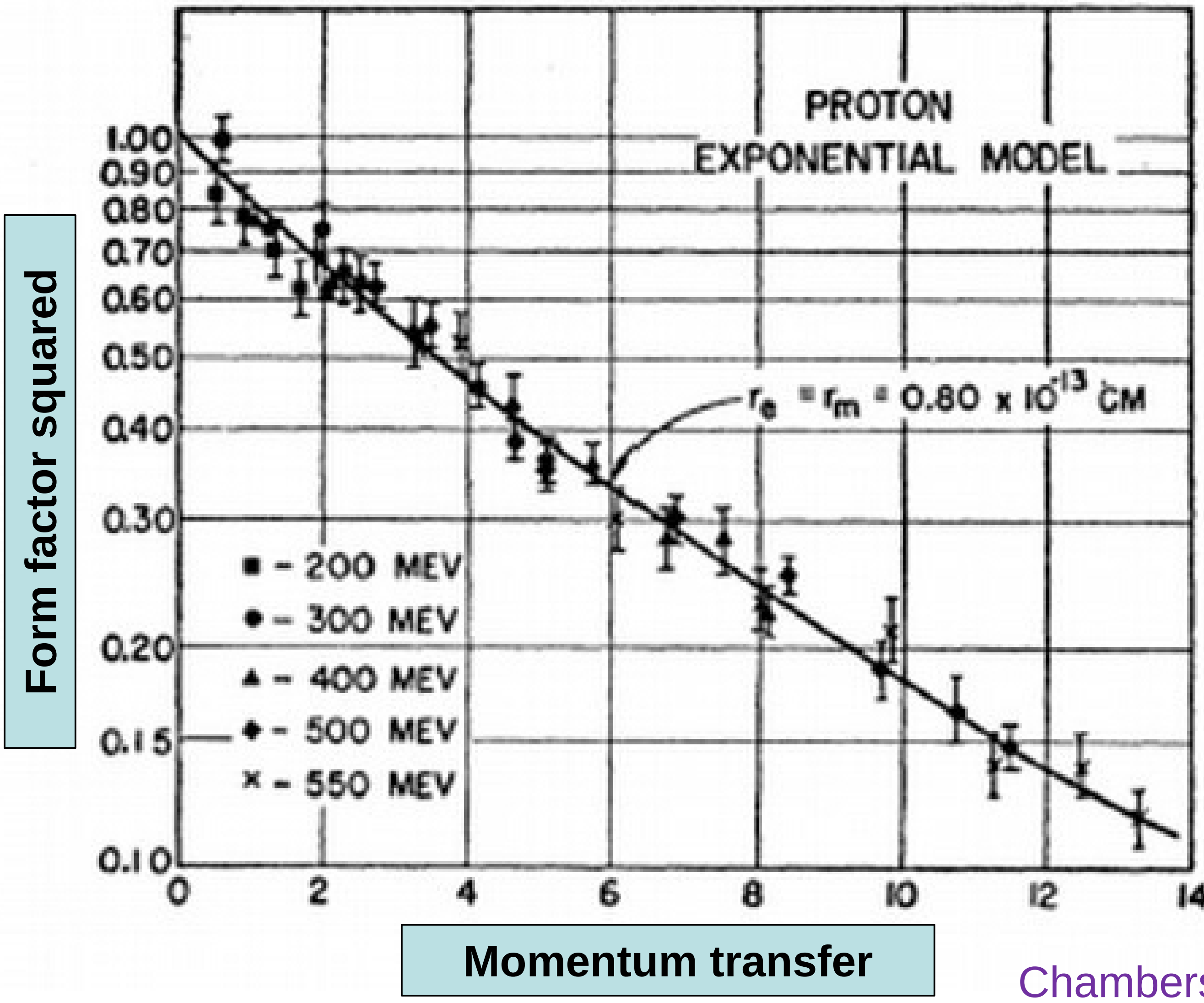
proton radius squared

Slope of the form factor as a function of momentum transfer

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

evaluated at momentum transfer =0

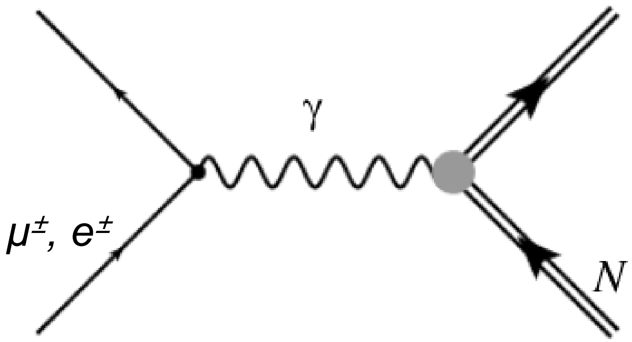
Extracting the radius from scattering data



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

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:

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

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

Expect identical result for ep and μp scattering

How do you measure size?

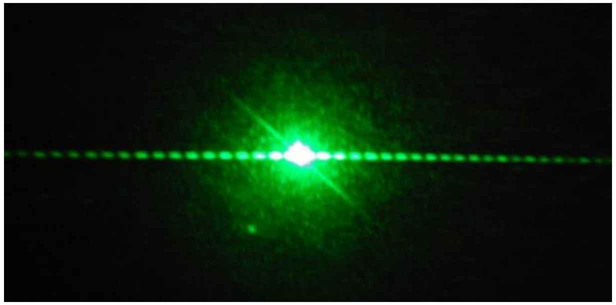
Object:

Tool:

- macroscopic:
  hard sphere

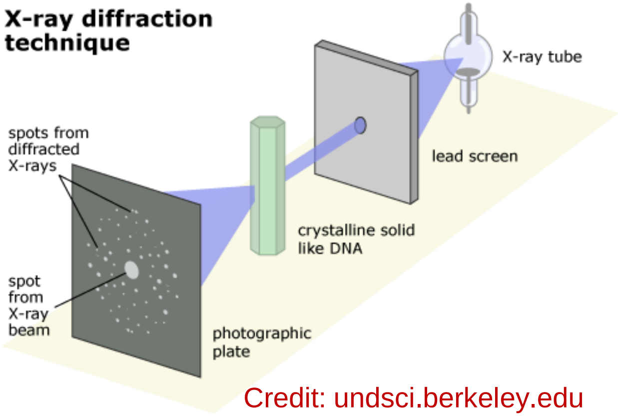
caliper

- small:
  hair



laser

- tiny:
  atom



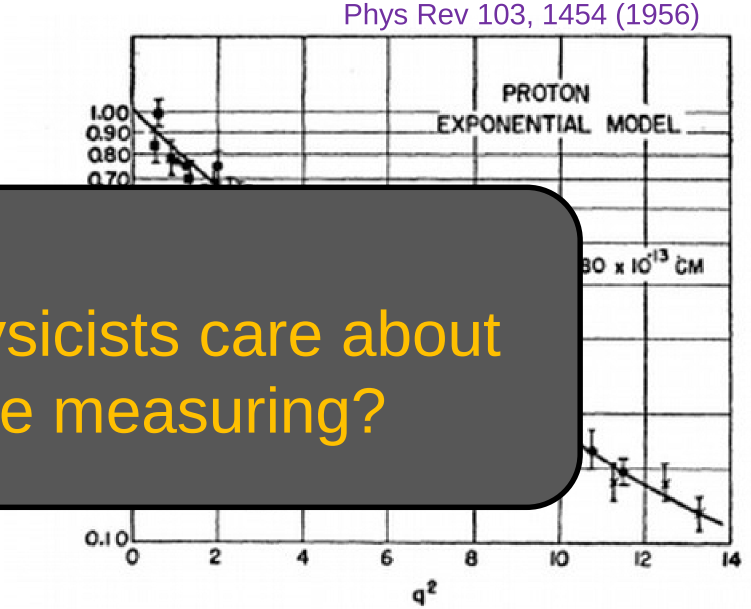
Credit: undsci.berkeley.edu

oil monolayer
X-ray diffraction

How do you measure proton size?

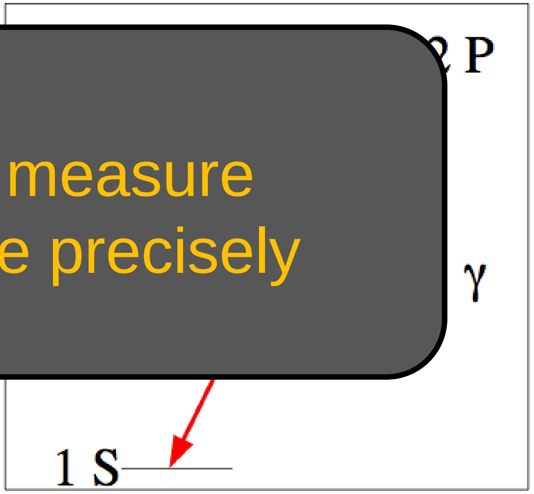
Chambers and Hofstadter,
Phys Rev 103, 1454 (1956)

- Scattering experiments
  (Hofstadter @ Stanford: 1950s -
  elec



Question:
Why should hadronic physicists care about what atomic physicists are measuring?

- At
  (At
  ato

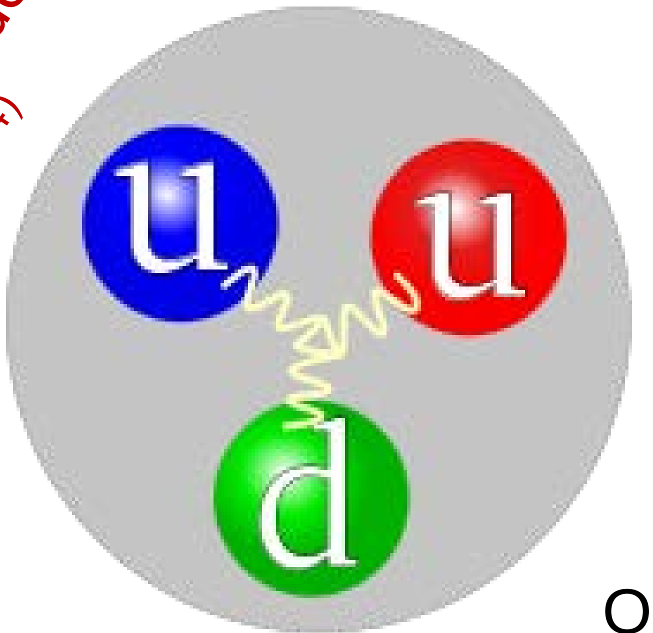


Answer:
Because sometimes they can measure things in Nuclear Physics more precisely than we can!

The Proton

Quark Model
(1964)

size: (~1 fm)
(~0.000,000,000,000,001 m)



Credit: wikipedia.org

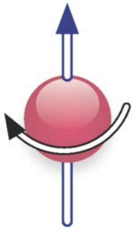
electric charge

$$+1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$$

Quarks are held together by strong nuclear force

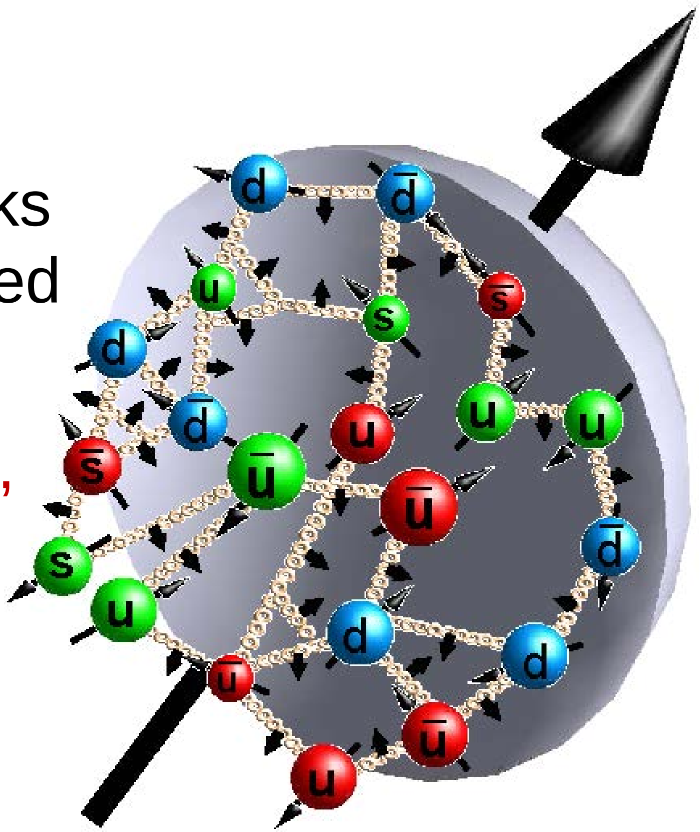
strong nuclear force
arises when quarks exchange gluons

The Proton Structure



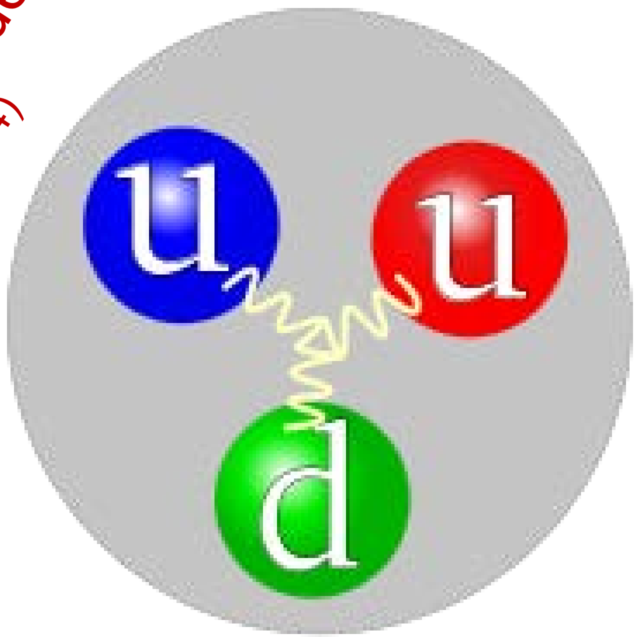
- proton is spin-1/2 particle
- proton is not pointlike
- complex internal structure generated by interactions between pointlike constituents (quarks/partons).
- Uncertainty Principle dictates: quarks must be in motion - at close to speed of light

→ proton is a strongly-coupled, relativistic, infinite-body system



The Proton

Quark Model (1964)

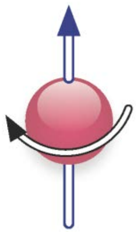


Credit: wikipedia.org

size: (~1 fm)
(~0.000,000,000,000,001 m)

electric charge

$$+1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$$



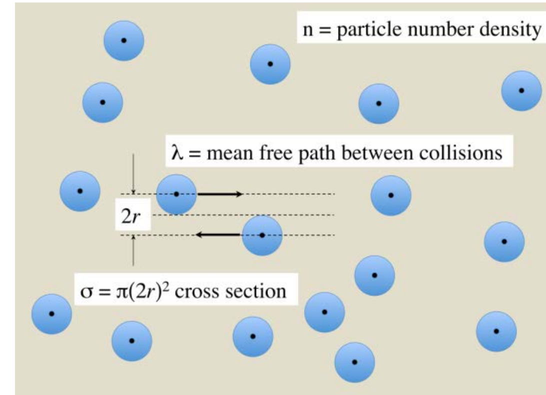
- proton is spin-1/2 particle
- proton is not pointlike
- complex internal structure generated by interactions between pointlike constituents (quarks/partons).

What is a (differential) Cross Section?

Cross Section

- collision among gas particles:
(interact only upon contact)

$$\sigma = \frac{1}{n\lambda} = \pi(2r)^2$$



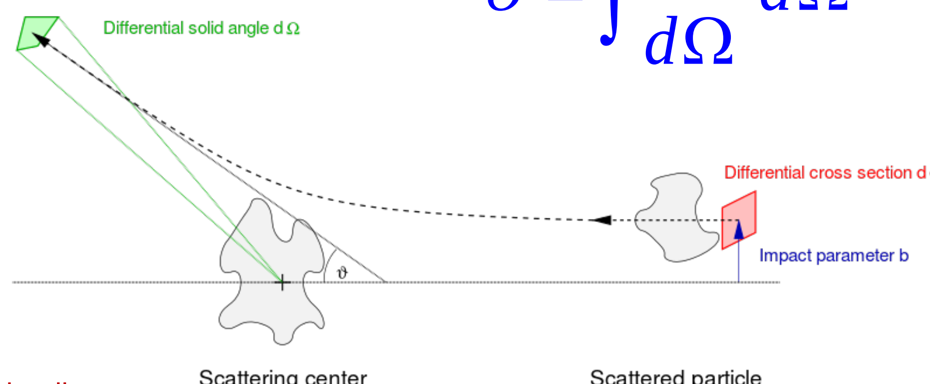
- if particles interact through some action-at-a-distance force (ie. electromagnetism or gravity):
→ scattering cross section is generally larger than their geometric size

Differential Cross Section

- single particle is scattered off a single stationary target particle at an angle θ and π (with $d\Omega = \sin\theta \, d\theta \, d\varphi$)

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$$

- differential cross section $\frac{d\sigma}{d\Omega}$ depends on impact parameter b and scattering angle θ

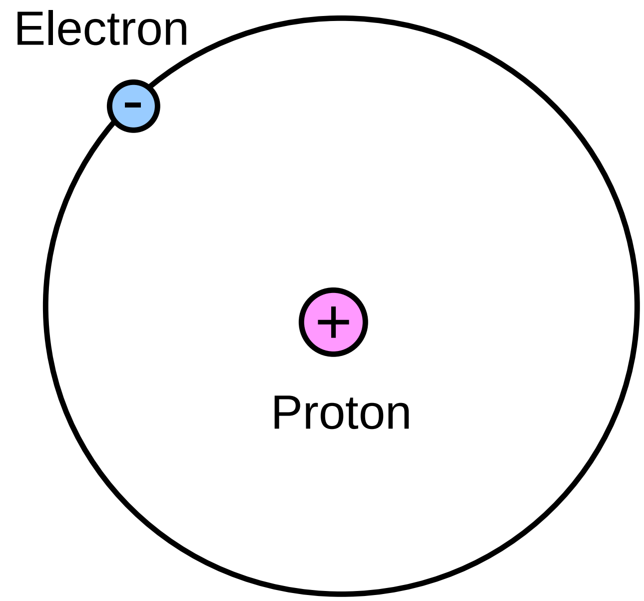


Slide inspired by Wikipedia

Atomic Spectroscopy Measurements

Bohr Model of the atom

- Electrons orbit the nucleus
  "Planetary system"
- Hydrogen: 1 electron + 1 proton



Bohr Model

The Proton Radius Puzzle

Proton radius from muonic hydrogen:

0.84184 ± 0.00067 fm

disagrees with atomic physics and electron scattering measurements:

0.8779 ± 0.0094 fm

Muonic Hydrogen radius 4% below previous best value

→ 11-12% smaller (volume), 11-12% denser than previously believed

This needs to be confirmed before it can be believed!!