

# The Proton Radius Puzzle



*Saturday Morning Physics*

*November 10, 2018*

**Wolfgang Lorenzon**

**Physics Department**

# Radius (Size)

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



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

# 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



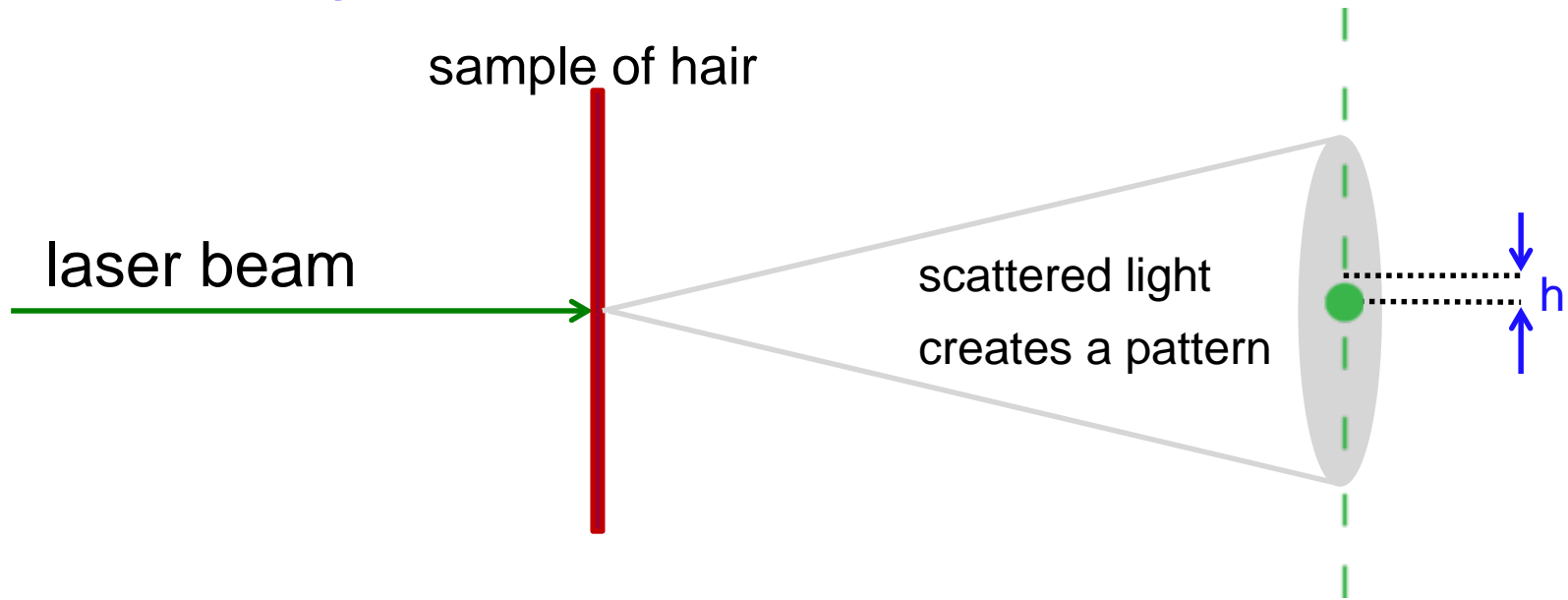
Tool:  
caliper

- small:

**Let's measure the width of a hair!**

**2**  
**Need a volunteers**

# How do you measure width of hair?



laser wavelength: 532 nm

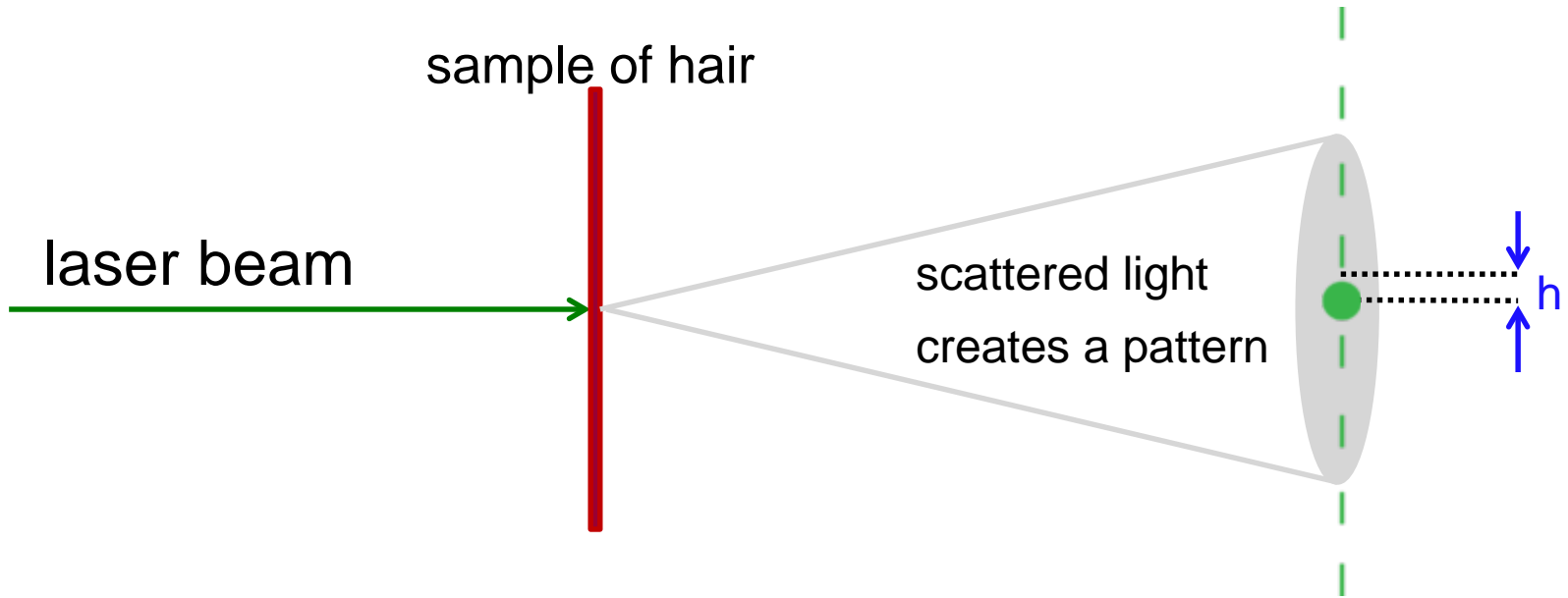
distance hair to wall: 128 in

D:diameter of hair

h: distance center of dot to 1<sup>st</sup> 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 1<sup>st</sup> minimum  
(ie. "dark" section)

		enter $h$ (mm)		<b>29</b>	
		hair thickness ( $\mu\text{m}$ )		<b>60</b>	

# How do you measure size?

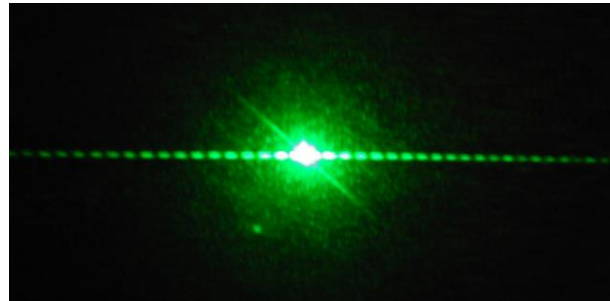
## Object:

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



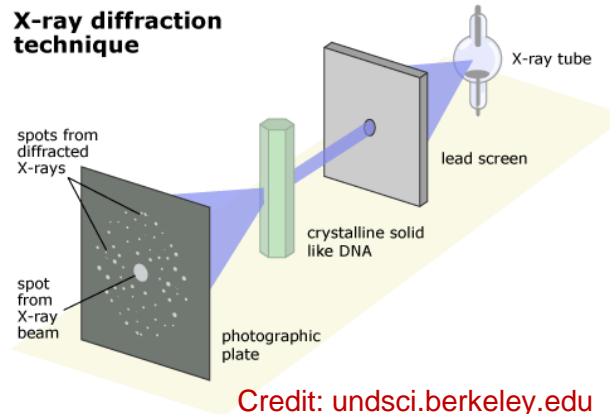
Tool:  
caliper

- small:  
hair (~60  $\mu\text{m}$ )  
(~0.000,06 m)  
(~60 thousands of a meter)



laser

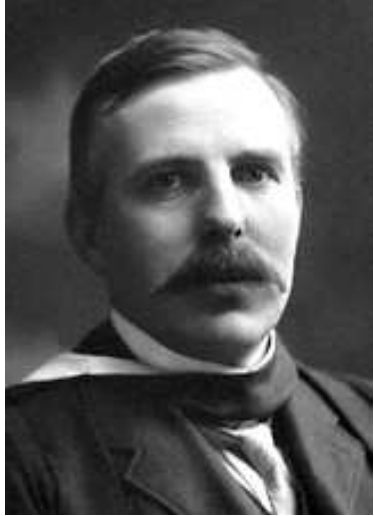
- tiny:  
atom (~1 $\text{\AA}$ )  
(~0.000,000,000,1 m)  
(~a tenth of a billionth  
of a meter)



Brownian motion  
X-ray diffraction



# How do you measure something even smaller?



Ernest Rutherford (1871 - 1937)

half-life;  $\alpha$  and  $\beta$  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?



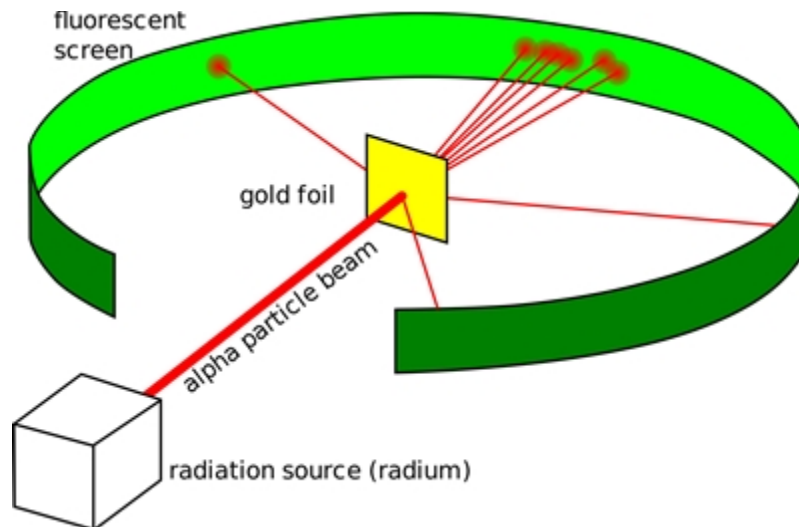
Ernest Rutherford (1871 - 1937)

half-life;  $\alpha$  and  $\beta$  rays

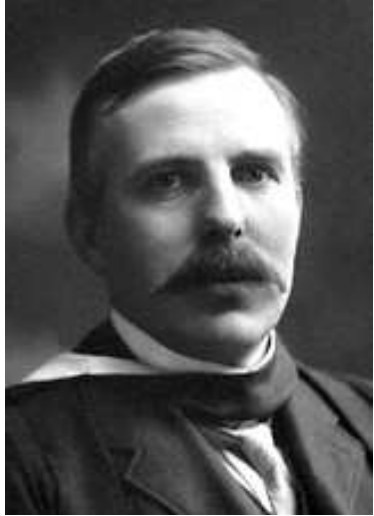
1908: Nobel prize Chemistry:

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1911: Most  $\alpha$  particles pass a thin gold foil undeflected



# How do you measure something even smaller?



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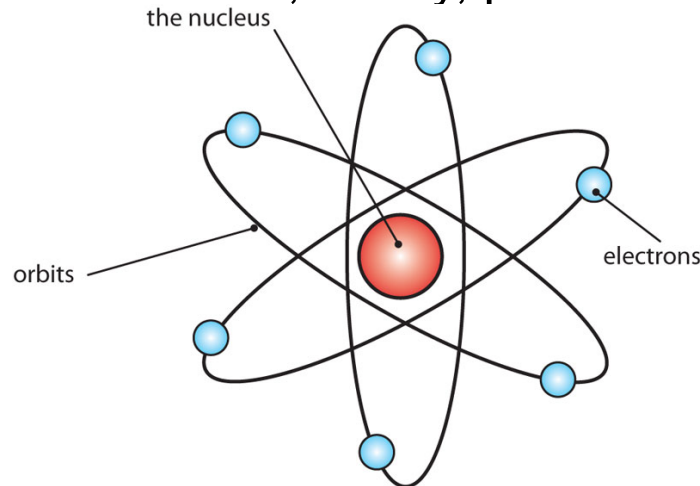
half-life;  $\alpha$  and  $\beta$  rays

1908: Nobel prize Chemistry:

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

1911: Most  $\alpha$  particles pass a thin gold foil undeflected

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



Source: [atomic.lindahall.org](http://atomic.lindahall.org)

# How do you measure something even smaller?



**Ernest Rutherford (1871 - 1937)**

half-life:  $\alpha$  and  $\beta$  rays

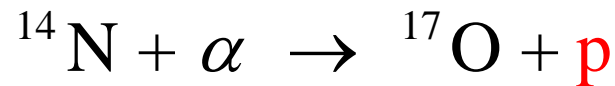
1908: Nobel prize Chemistry:

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

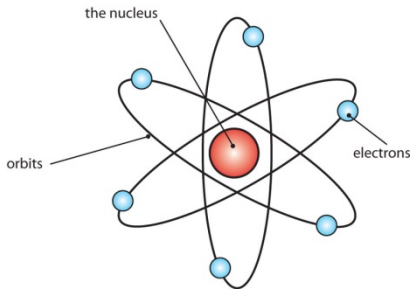
1911: Most  $\alpha$  particles pass a thin gold foil undeflected

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

**1917: Discovery of the proton**

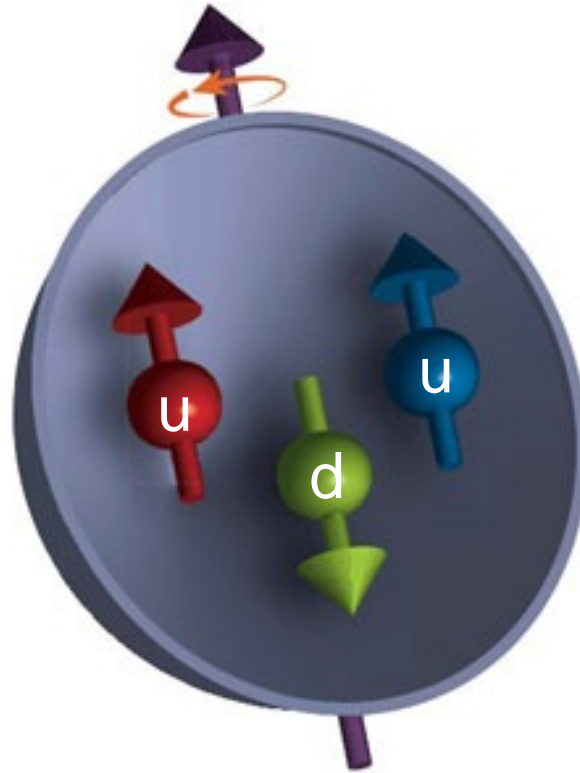


~1928: electron accelerators replace  $\alpha$  particles



# The Proton

Quark Model  
(1964)

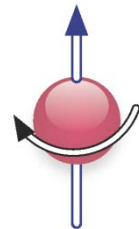


size: (~1 fm)  
(~0.000,000,000,000,001 m)  
(~a millionth of a billionth of a meter)

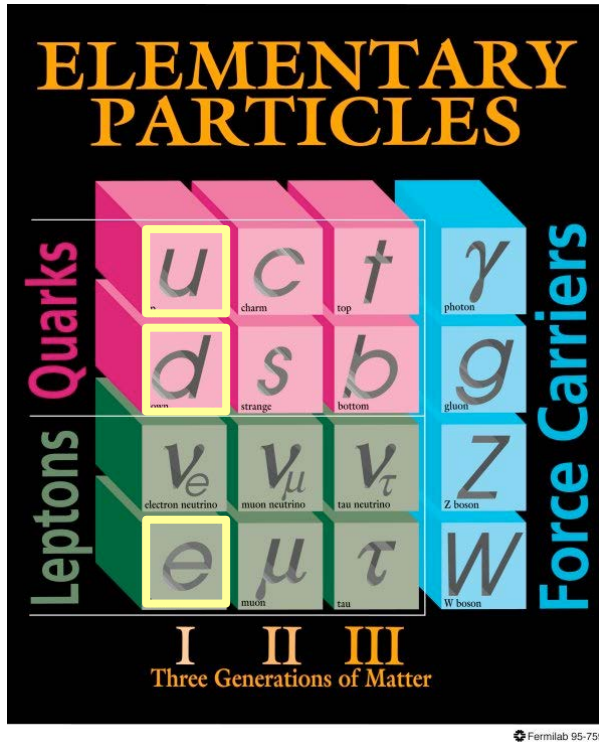
electric charge

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

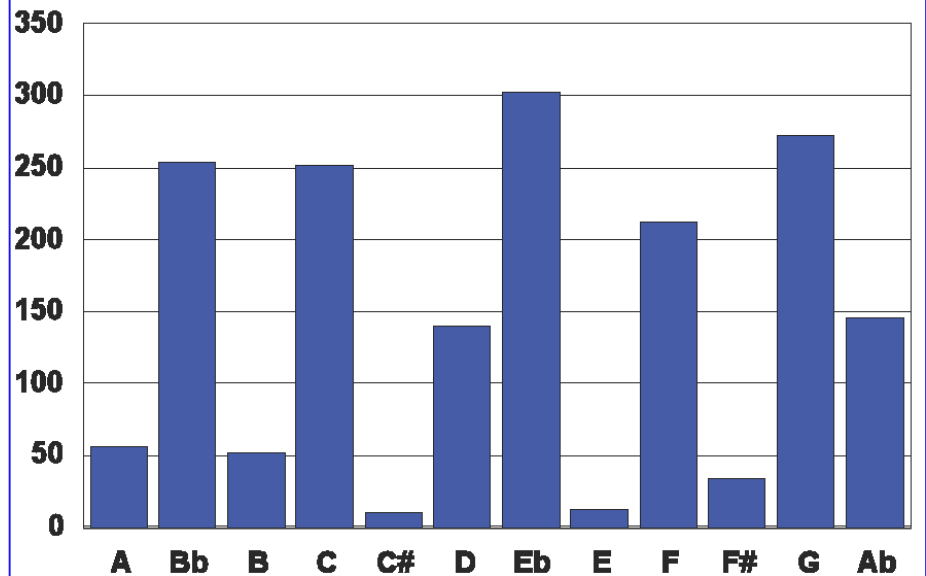
- proton is spin-1/2 particle
- proton is **not pointlike**  
(made of three constituents, called **quarks**)



# Proton - more than just constituents



Histogram of notes used in Beethoven's 5<sup>th</sup> symphony

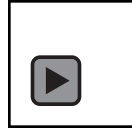


**Both plots focus on constituents rather than interactions**

**Interactions are important - they create the dynamics**

# Proton - more than just constituents

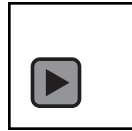
- the 1<sup>st</sup> four notes (G, E, F, D)



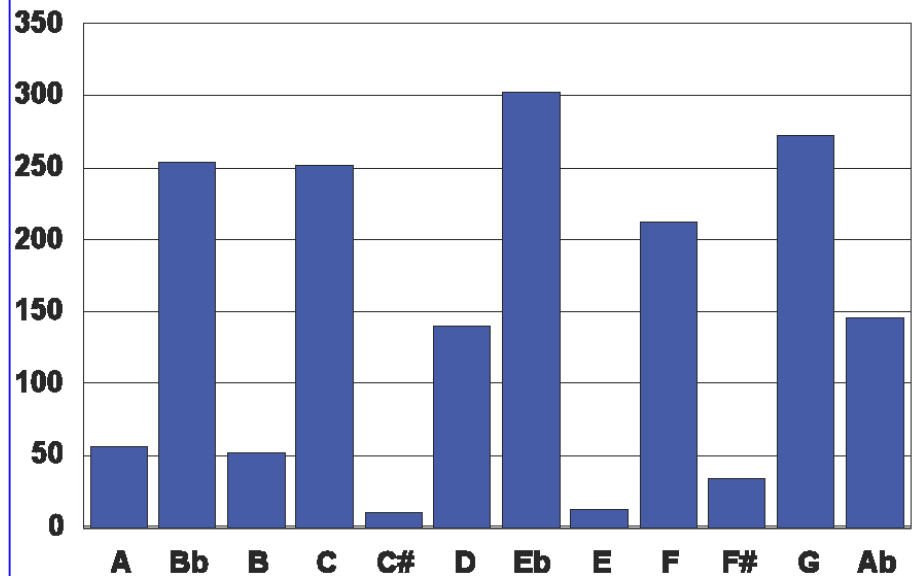
- adding rhythmic variation



- with full dynamics



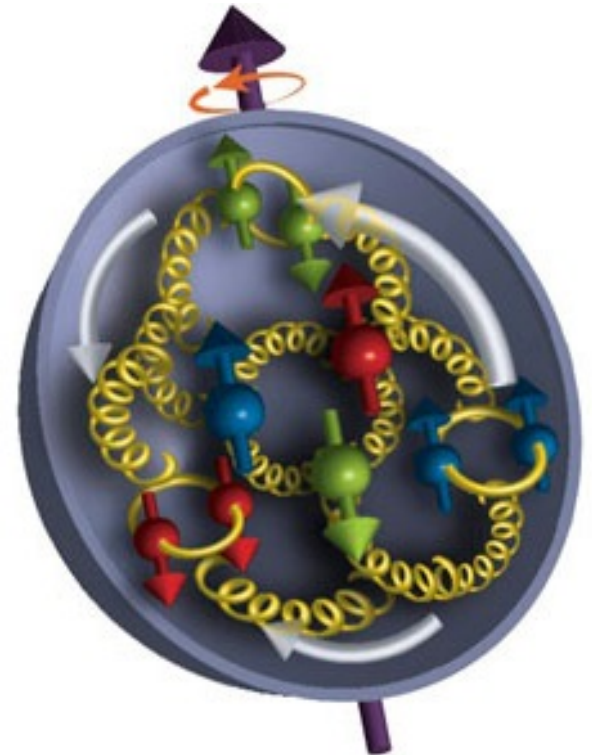
Histogram of notes used in Beethoven's 5<sup>th</sup> symphony



**Interactions are important - they create the dynamics**

# 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**

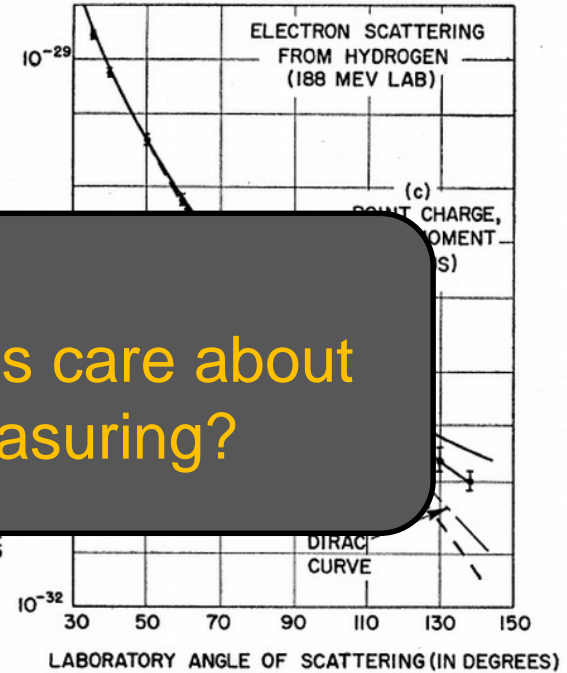
**So we average over the  
density (to get an average  
radius<sup>2</sup>)**

**It is hard to define a radius**

# How do you measure proton size?

- **Scattering experiments**

(Hofstadter @ Stanford: 1950s -  
electron scattering)



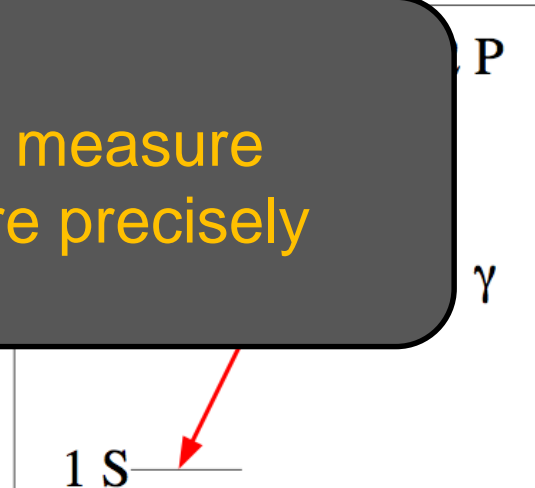
**Question:**

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

- **Atomic Physics**  
(Atomic Physics)

**Answer:**

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



# Electron scattering measurements 1950s

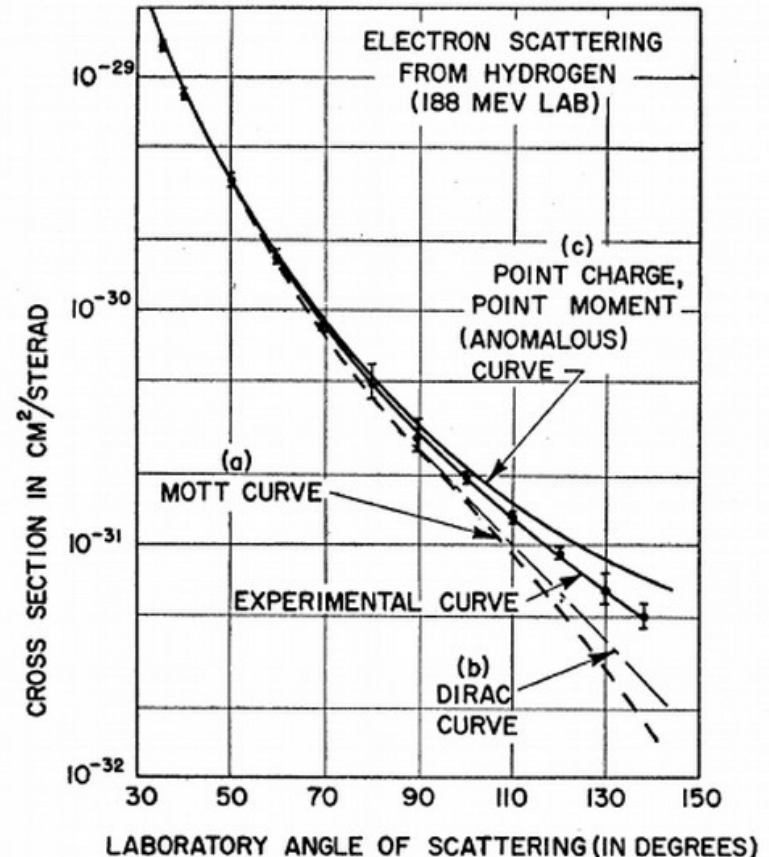


Robert Hofstadter (1915 - 1990)

1961: Nobel prize Physics:

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

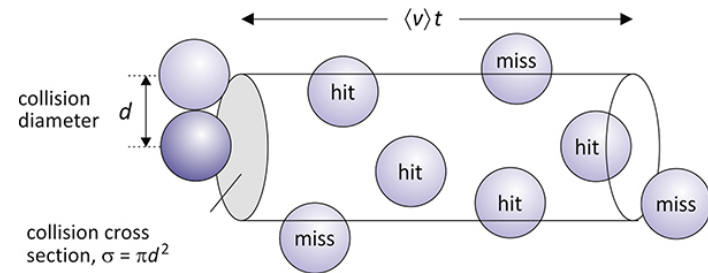
$$r_E : 0.74(\pm 0.24) \text{ fm}$$



# What is a Cross Section?

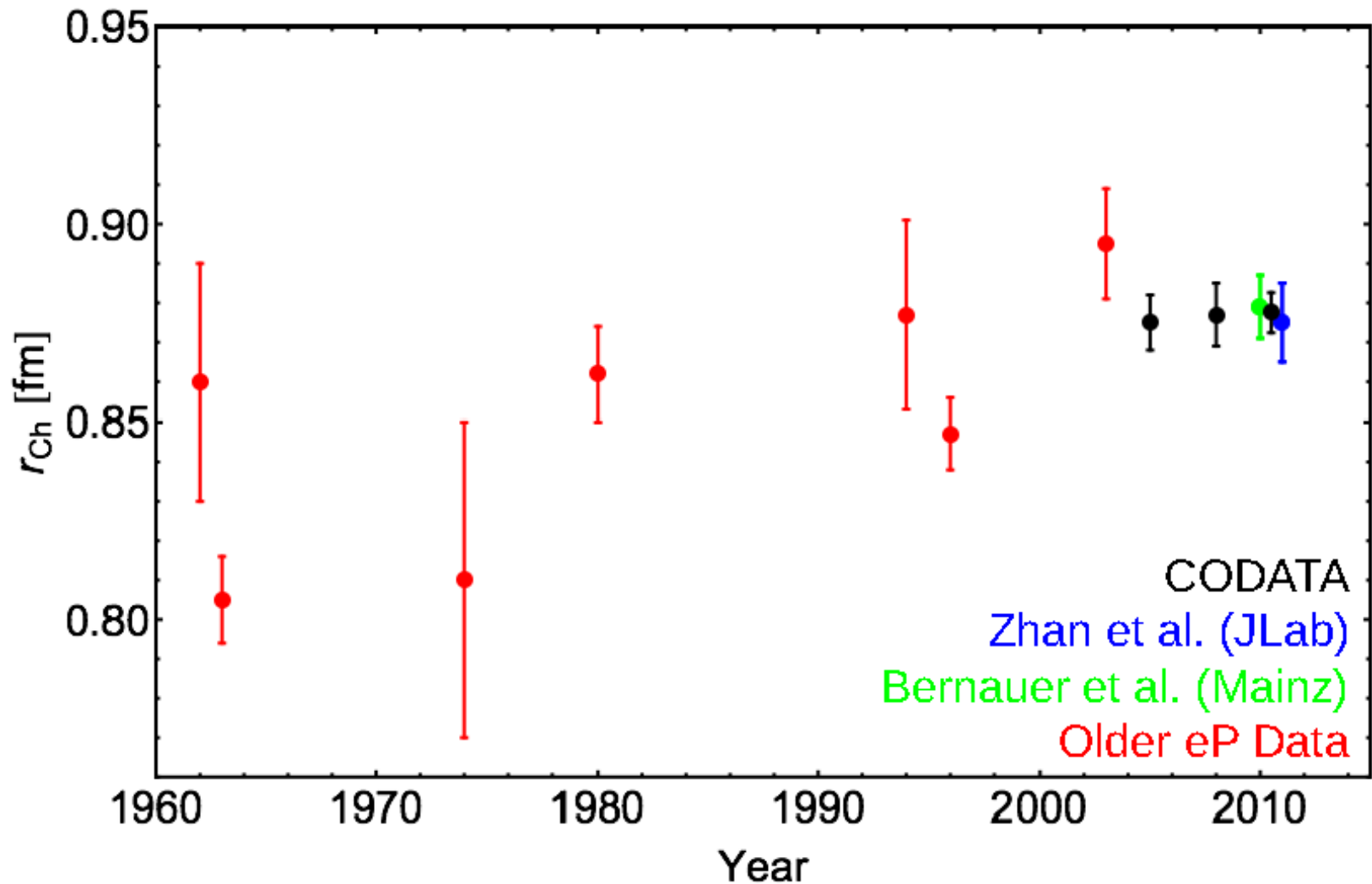
## Cross Section

- 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):  
→ scattering cross section is generally larger than their geometric size



**Let's do a simple scattering experiment**

# Time evolution of Proton Radius from ep data

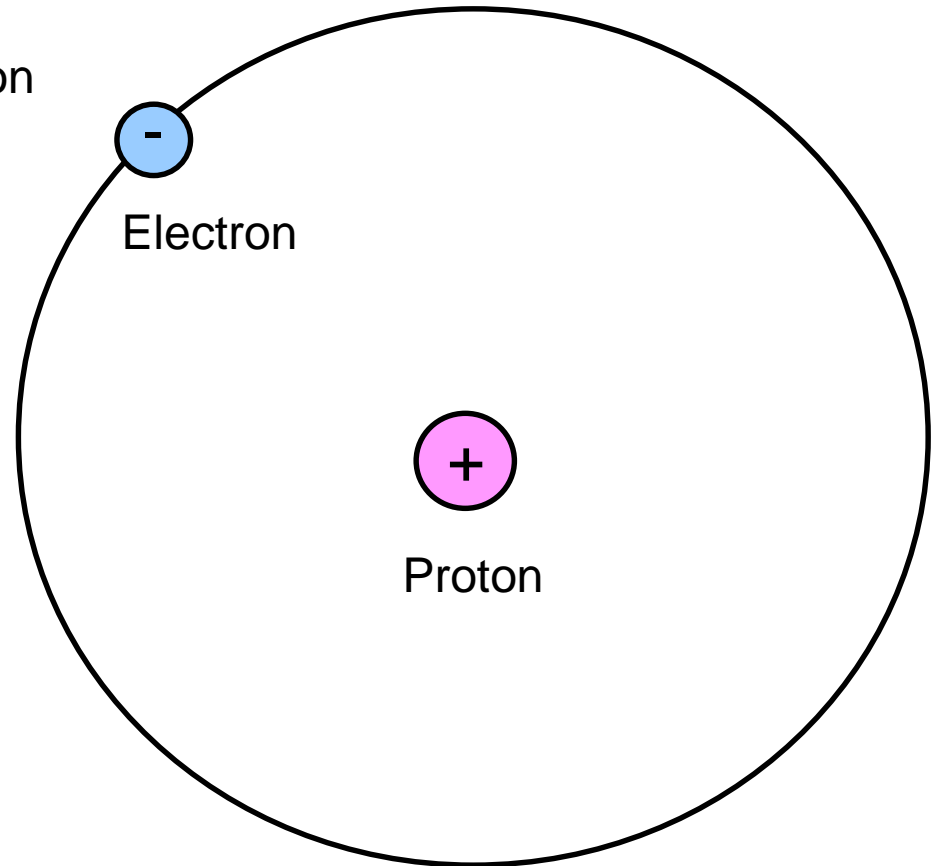


**CODATA:** Committee on Data for Science and Technology, the international group which publishes the recommended values for fundamental physical constants every four years.

# Atomic Spectroscopy Measurements

## Bohr Model of the atom

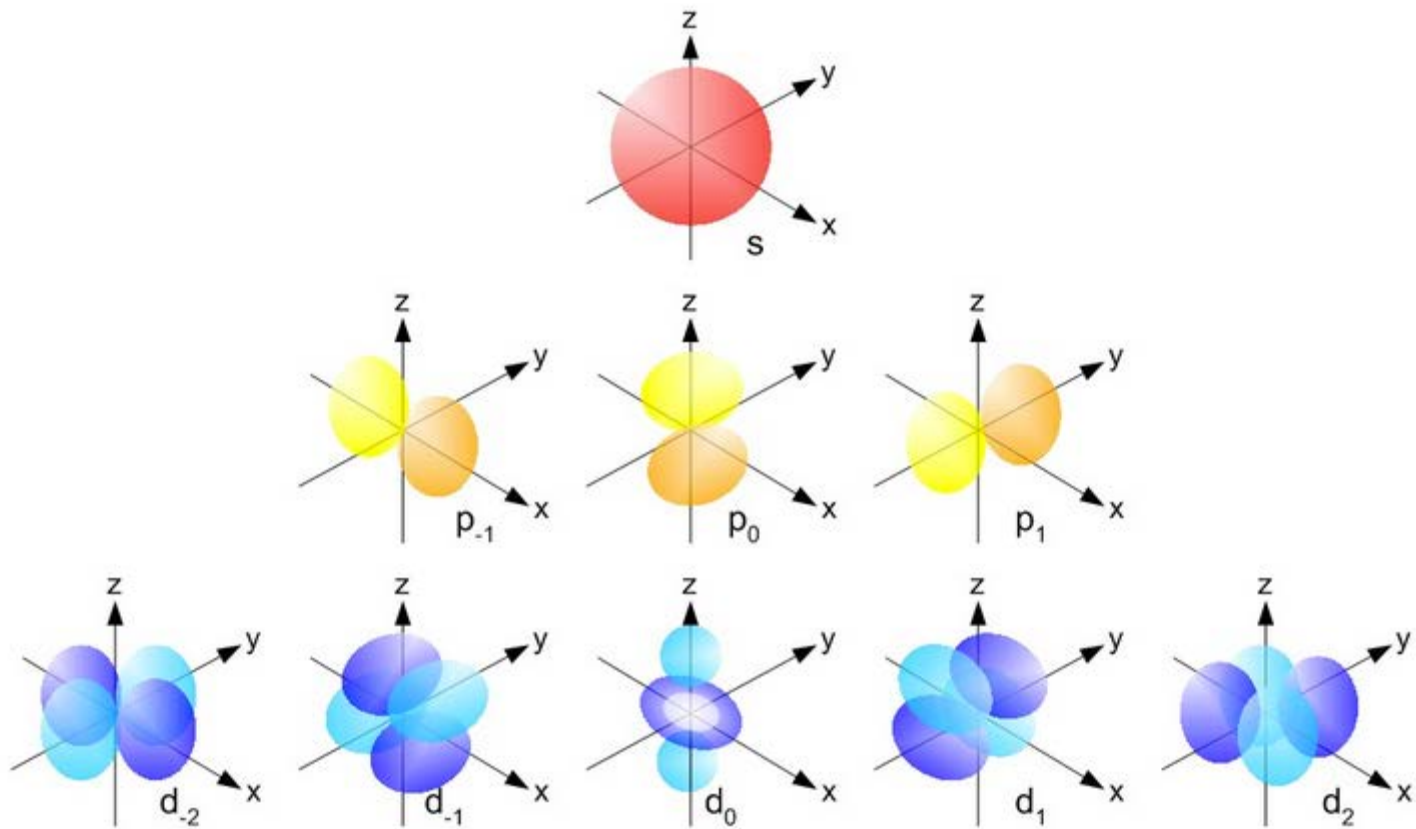
- Electrons orbit the nucleus  
“Planetary system”
- Hydrogen: 1 electron + 1 proton



**Bohr Model**

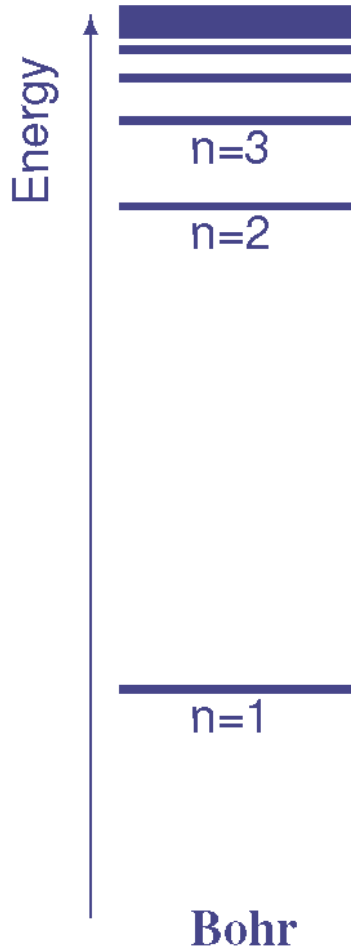
# ... is simply inaccurate...

Bohr model → Quantum Mechanics  
“planetary orbits” → “wave function”

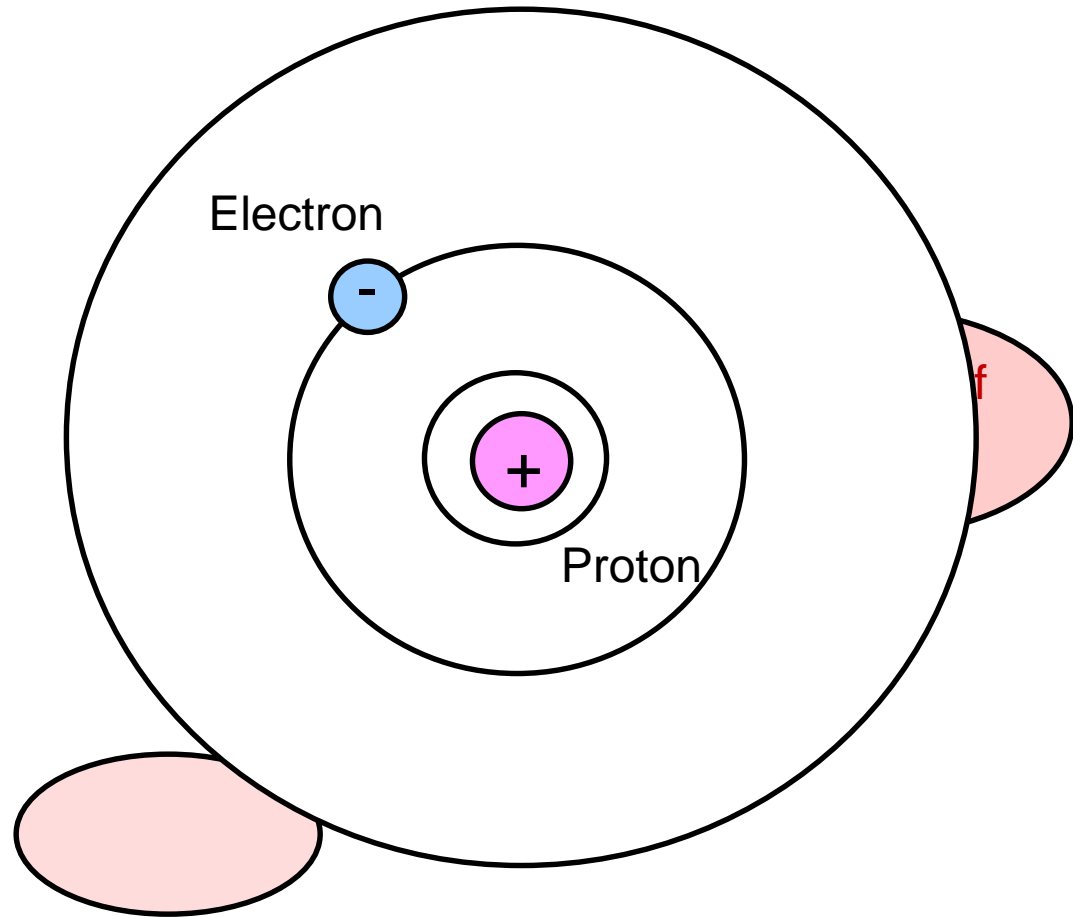


# Hydrogen Energy Levels

Components of a calculation

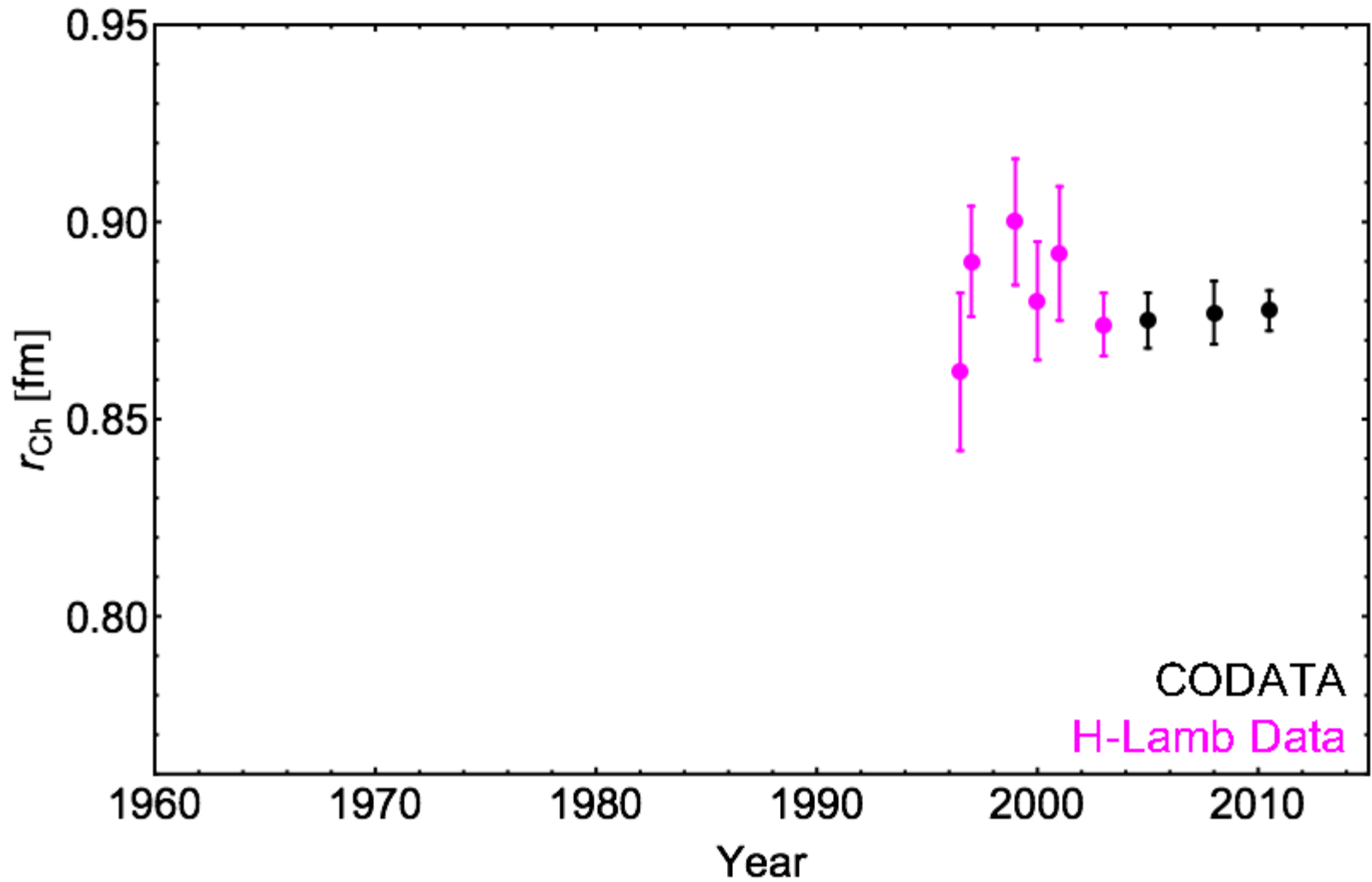


$$E = R_{\infty}/n^2$$
$$V \sim 1/r$$

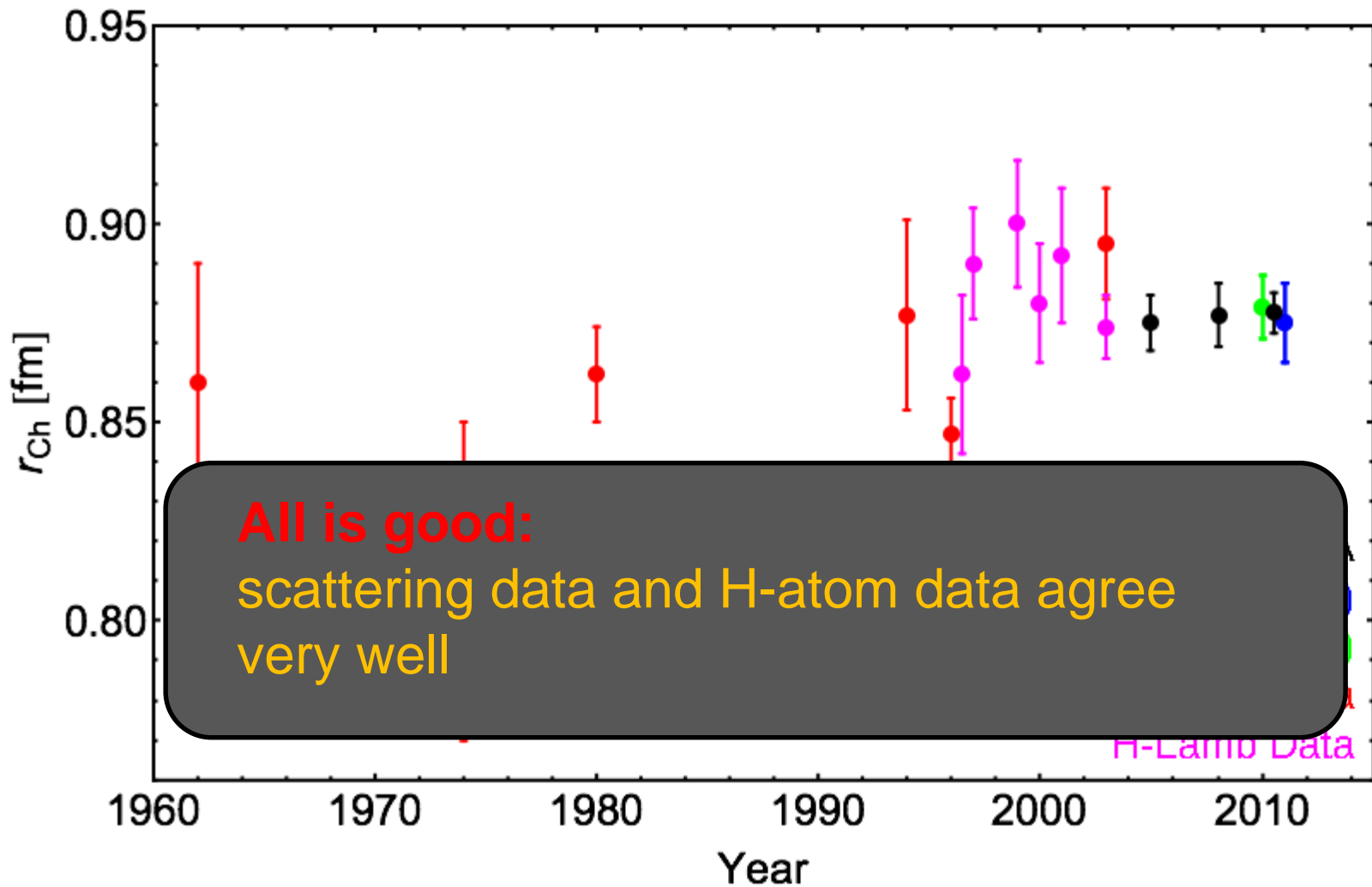




# The Proton Radius vs Time from Hydrogen Lamb Shift data



# The Proton Radius from Hydrogen Lamb Shift and $e\bar{p}$



proton rms charge radius measured with electrons:  
 **$0.8770 \pm 0.0045$  fm**

**But can we do better?**

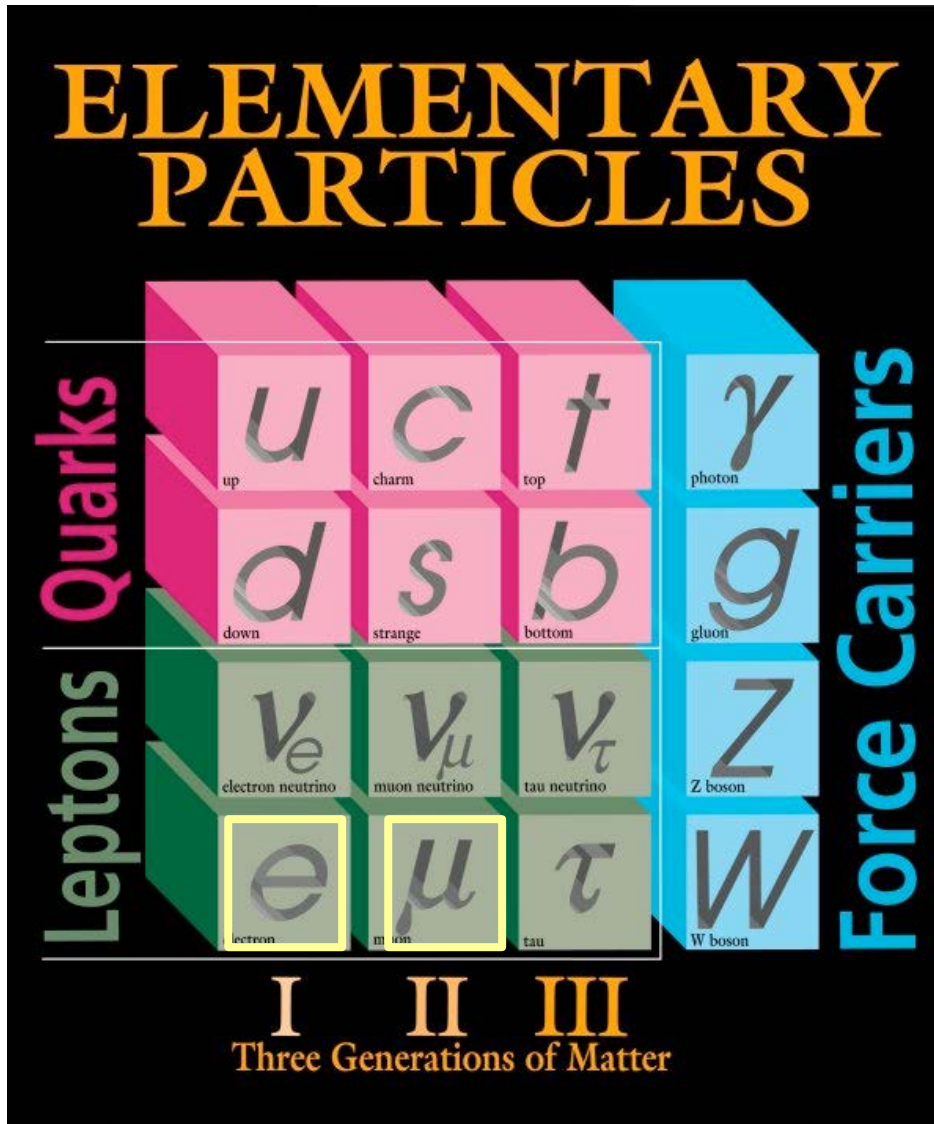
**Probably “Yes”**

**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

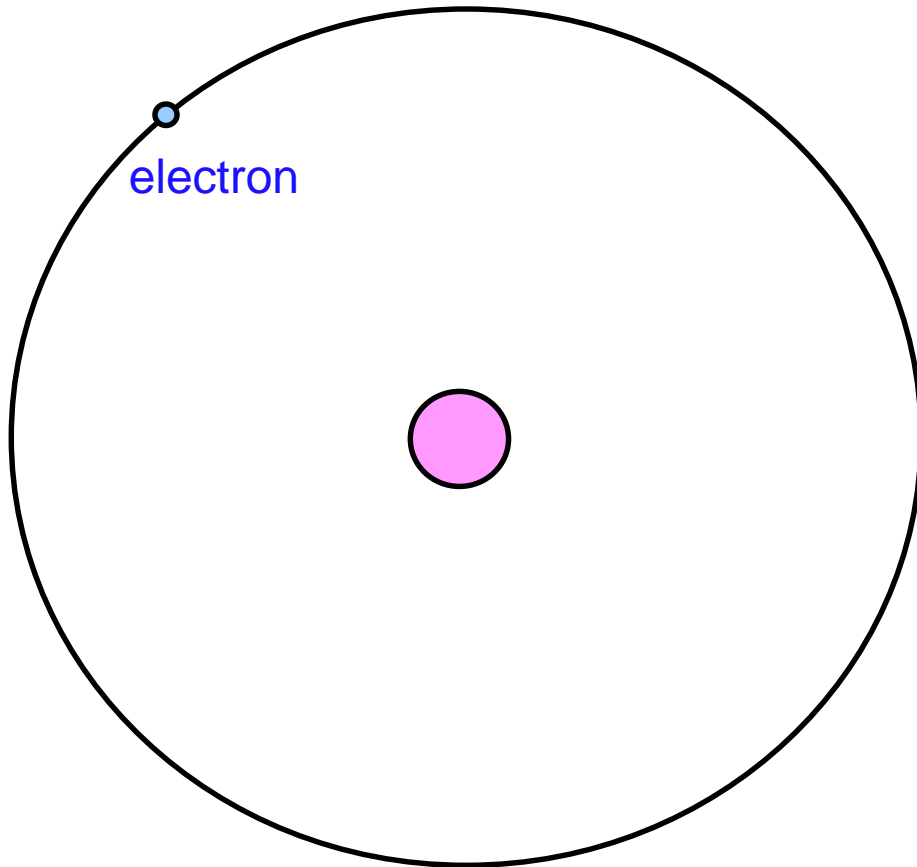
The muon decays into an electron (and some neutrinos) with a lifetime of  $\sim 2.2 \mu\text{s}$

**It has exactly the same interactions...**

# What is Muonic Hydrogen?

Regular hydrogen:

electron  $e^-$  + proton  $p$



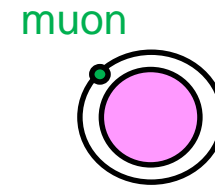
Muonic hydrogen:

muon  $\mu^-$  + proton  $p$

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

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

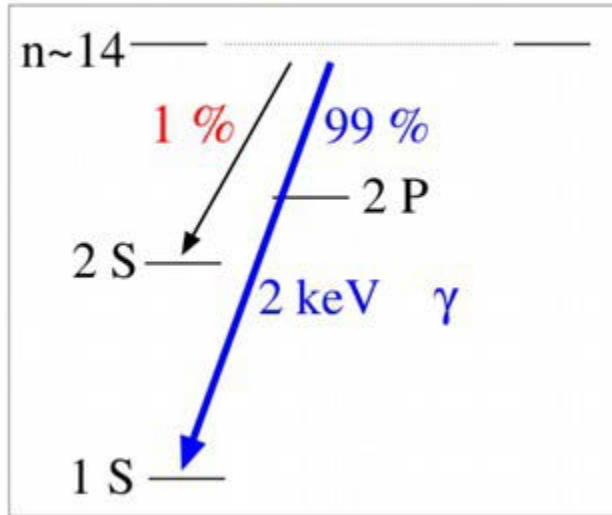
Probability for  $\mu^-$  to be inside proton:  $207^3 \approx 8 \text{ million}$



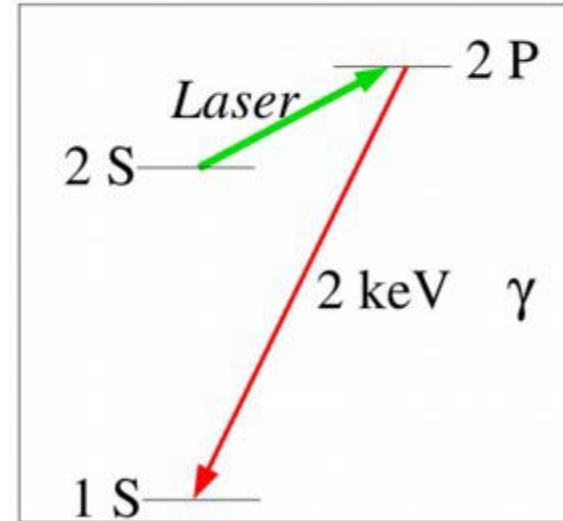
muon is **much** more sensitive to proton radius

# How to Measure with $\mu\text{H}$ ?

“prompt” ( $t \sim 0$ )



“delayed” ( $t \sim 1\ \mu\text{s}$ )



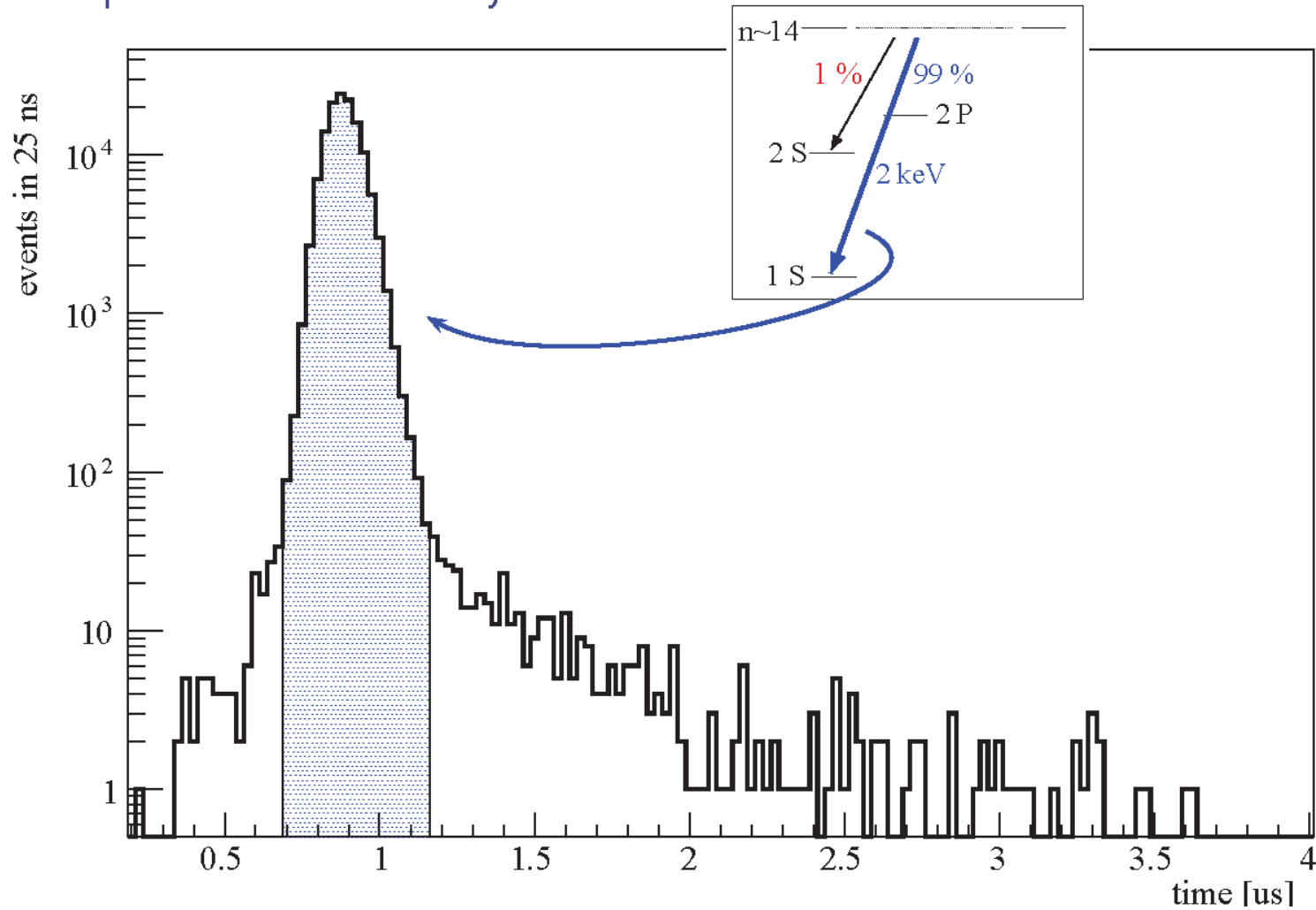
- beautifully simple, but technically challenging!
- form  $\mu\text{H}^*(n \sim 14)$  by shooting  $\mu$  beam on 1 mbar  $\text{H}_2$  target
  - 99% decay to  $1\text{S}$ , giving out fast  $\gamma$  pulse
  - 1% decay to longer-lived  $2\text{S}$  state
  - $2\text{S}$  state excited to  $2\text{P}$  state by tuned laser & decay with release of delayed  $\gamma$
- vary laser frequency to find transition peak  $\rightarrow \Delta E$  ( $2\text{S}$  to  $2\text{P}$ )  $\rightarrow r_p$

Pictures: R. Pohl

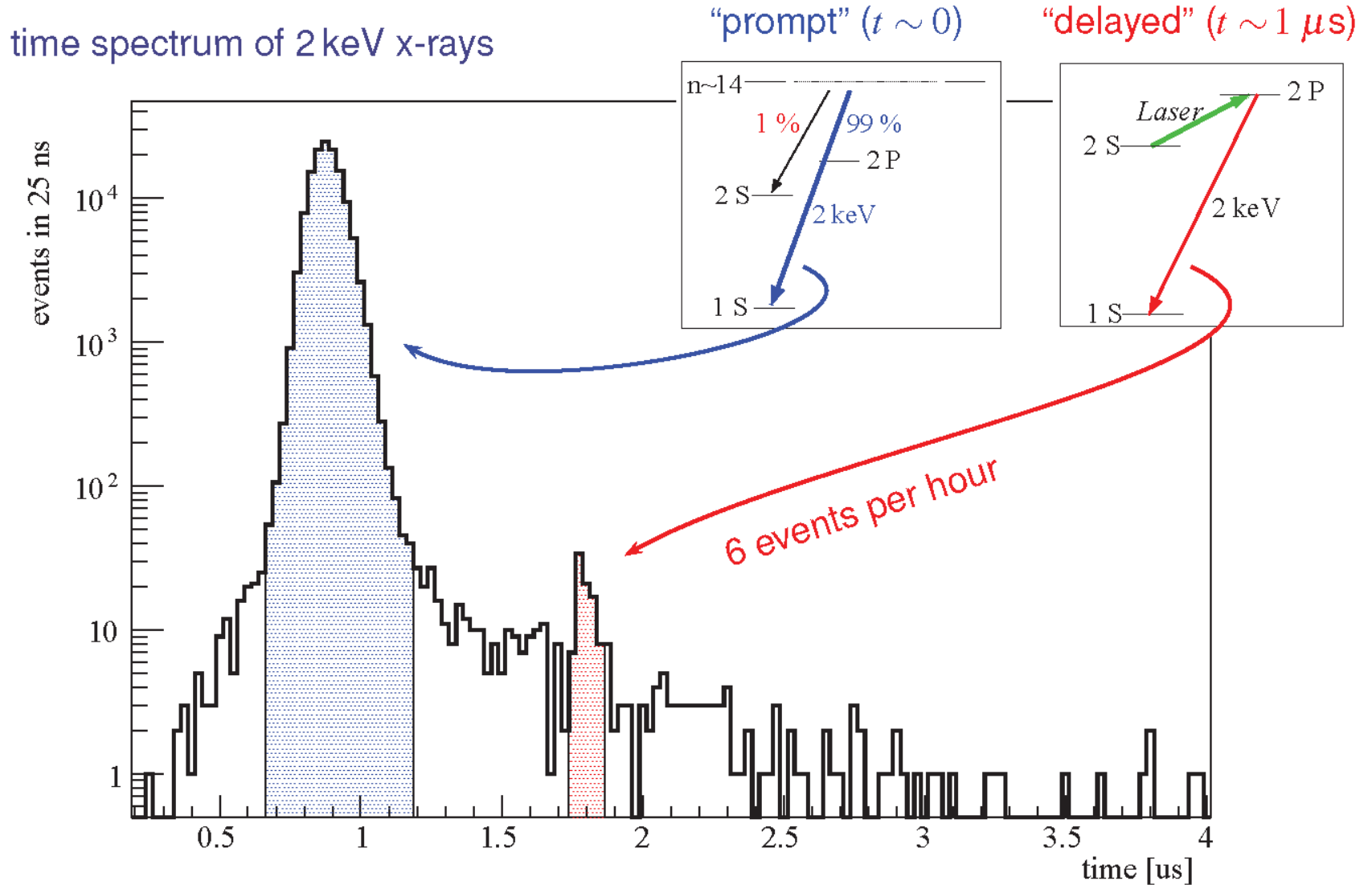
# How to Measure with $\mu\text{H}$ ?

time spectrum of 2 keV x-rays

"prompt" ( $t \sim 0$ )

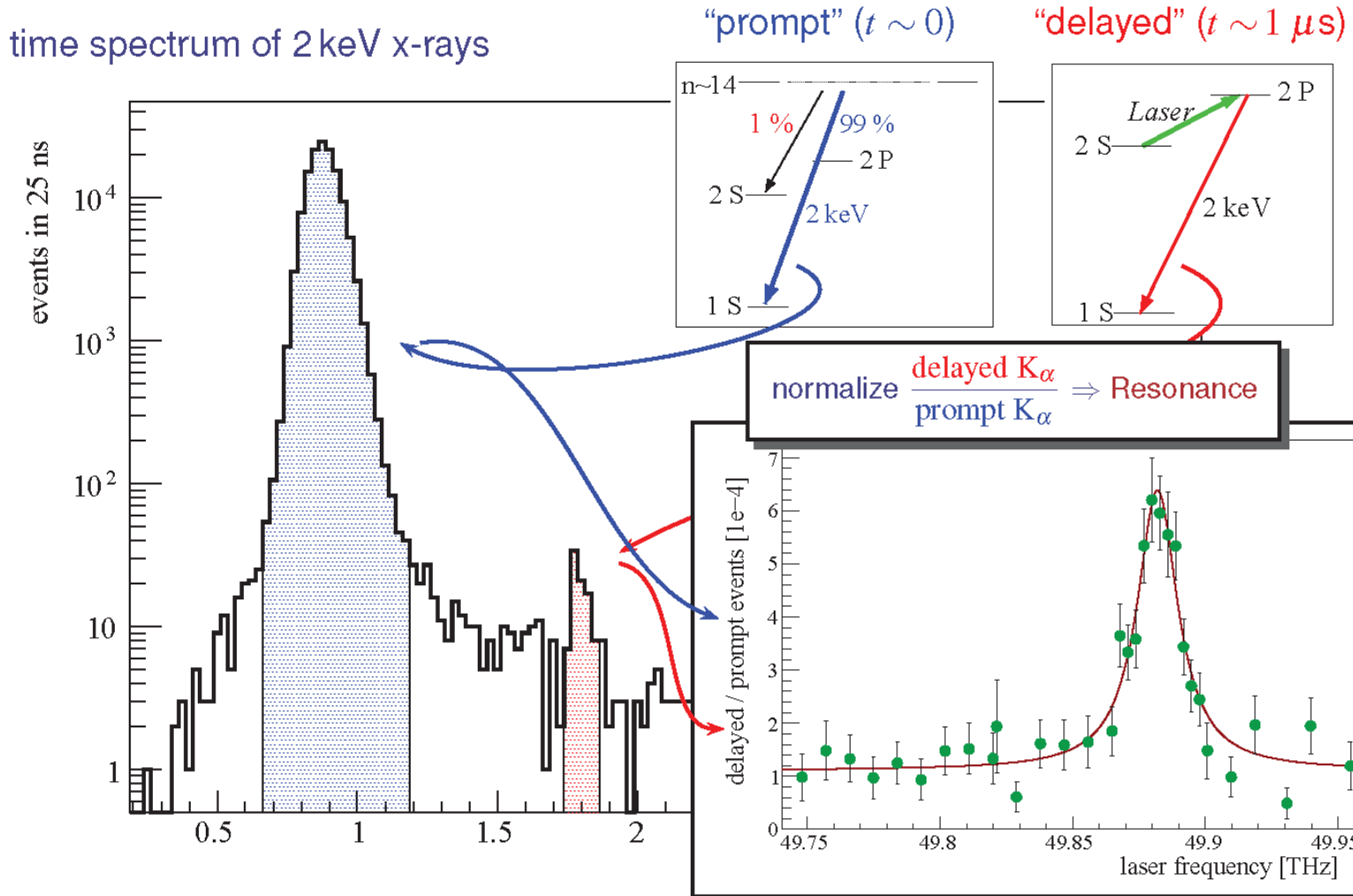


# How to Measure with $\mu\text{H}$ ?





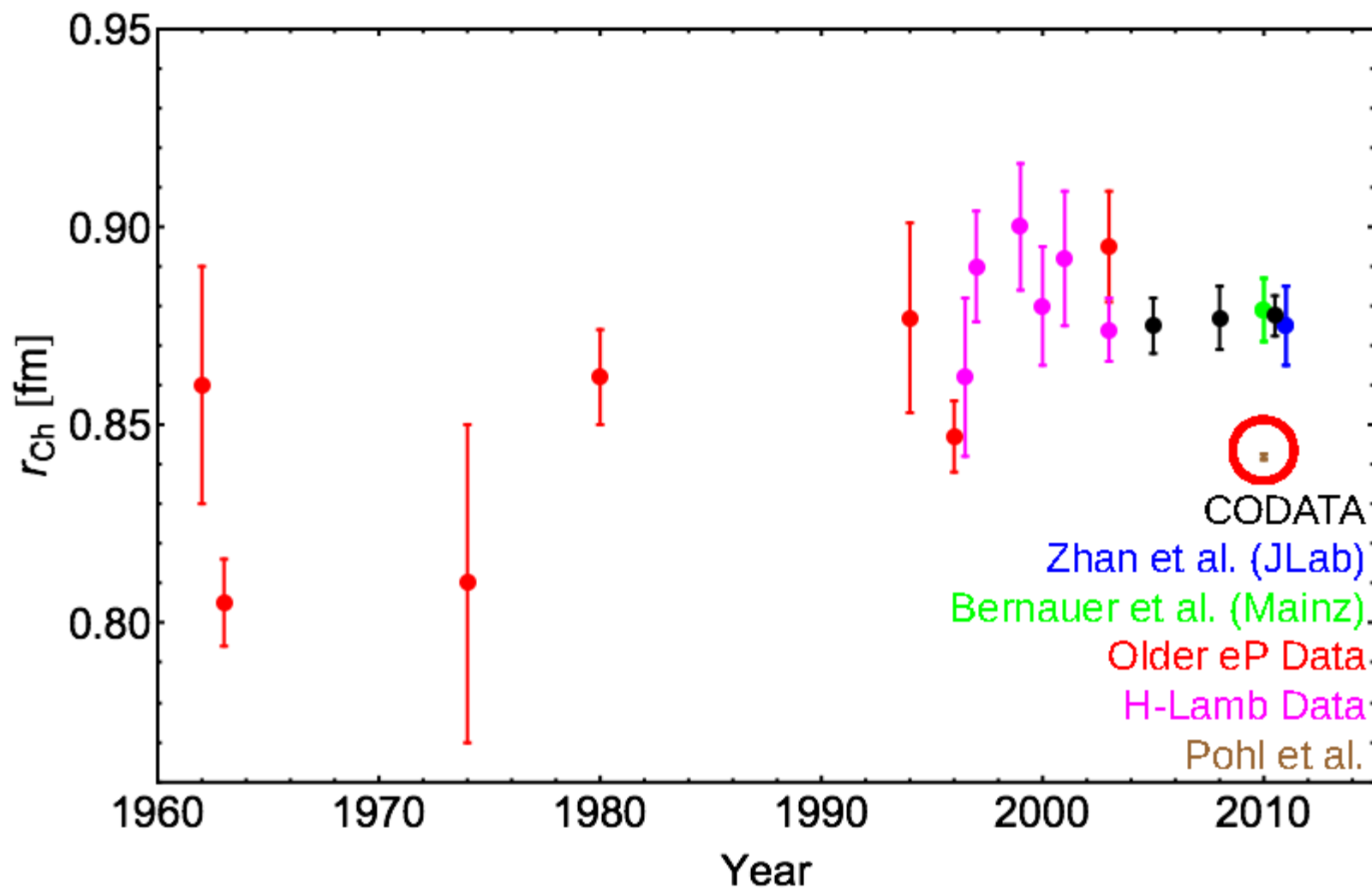
# Proton Radius from $\mu\text{H}$



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

$$0.84184 \pm 0.00067 \text{ fm}$$

# The Proton Radius from H & $\mu$ H Lamb Shift and ep



# The Proton Radius Puzzle

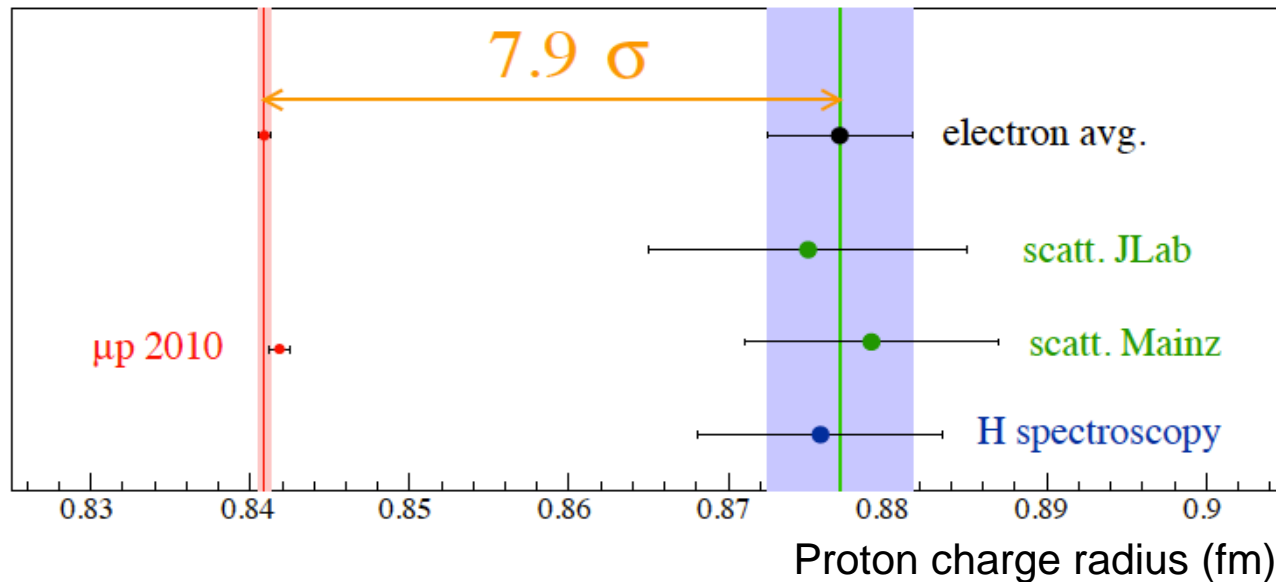
Proton radius measured with

atomic physics and electron scattering:

$0.8751 \pm 0.0061$  fm

muonic hydrogen:

$0.8409 \pm 0.0004$  fm



Radius from Muonic Hydrogen 4% below previous best value

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

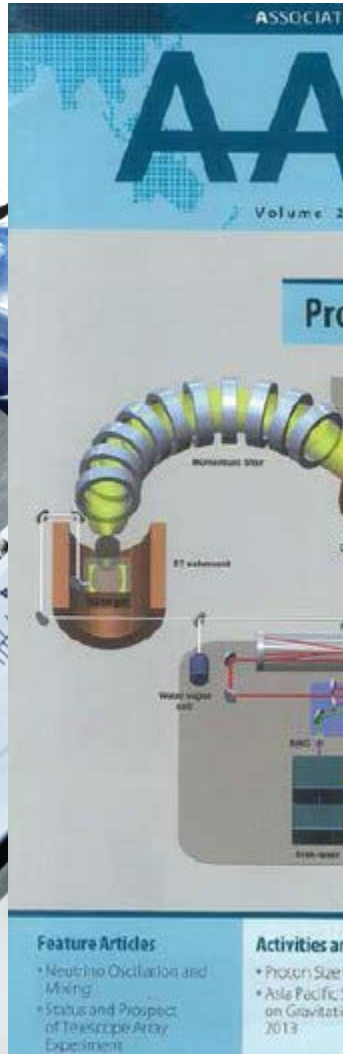
**This needed to be confirmed before it can be believed!!**

# The Proton Radius Puzzle

July 2010



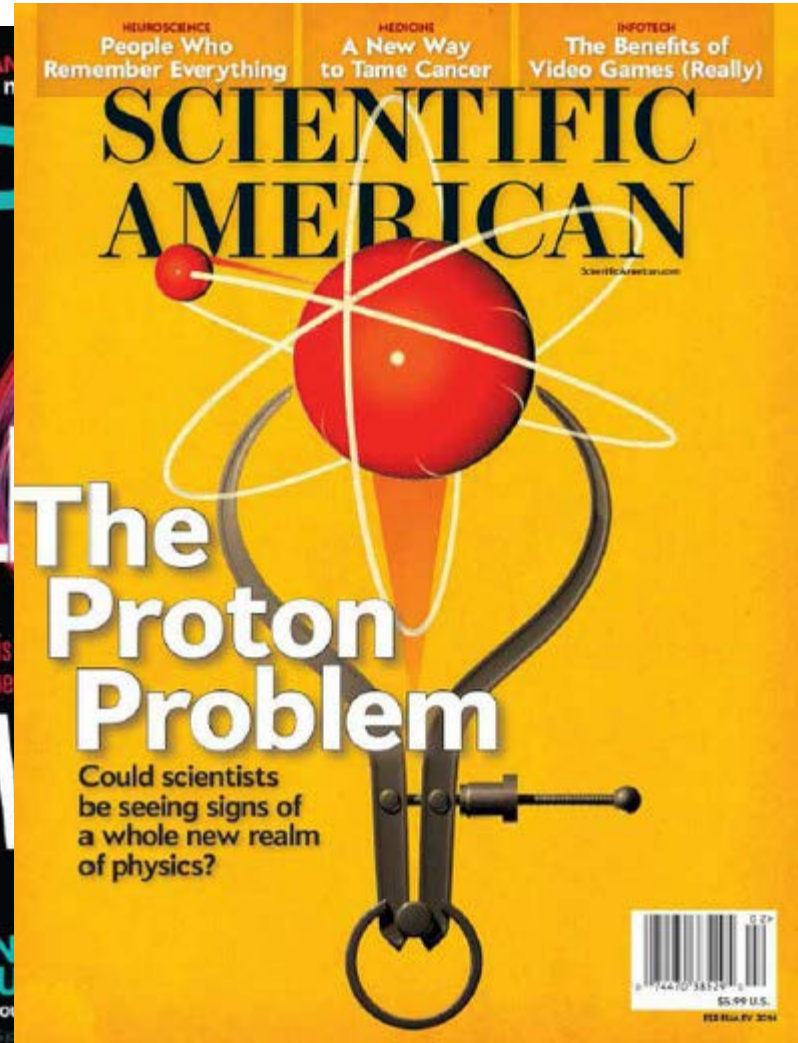
April 2013



July 2013



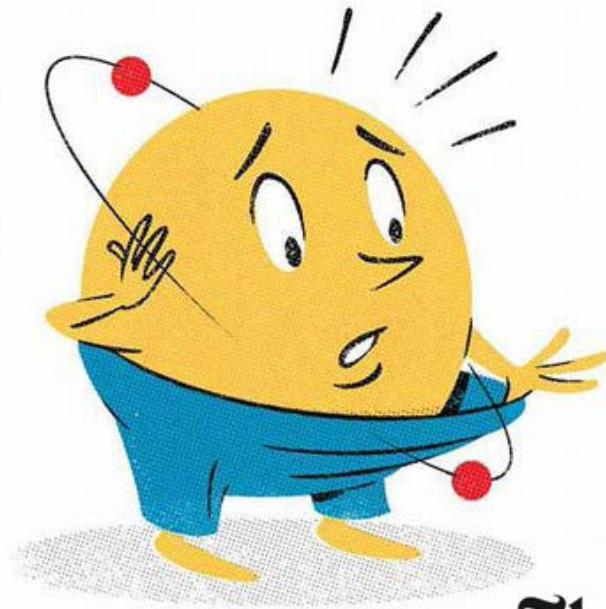
January 2014



# The Proton Radius Puzzle

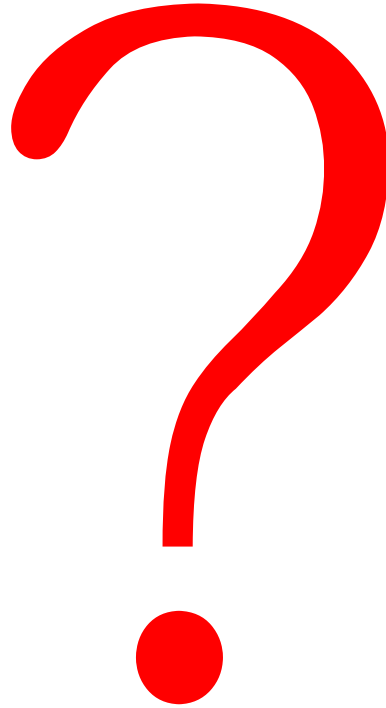


# The Proton Radius Puzzle



**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)

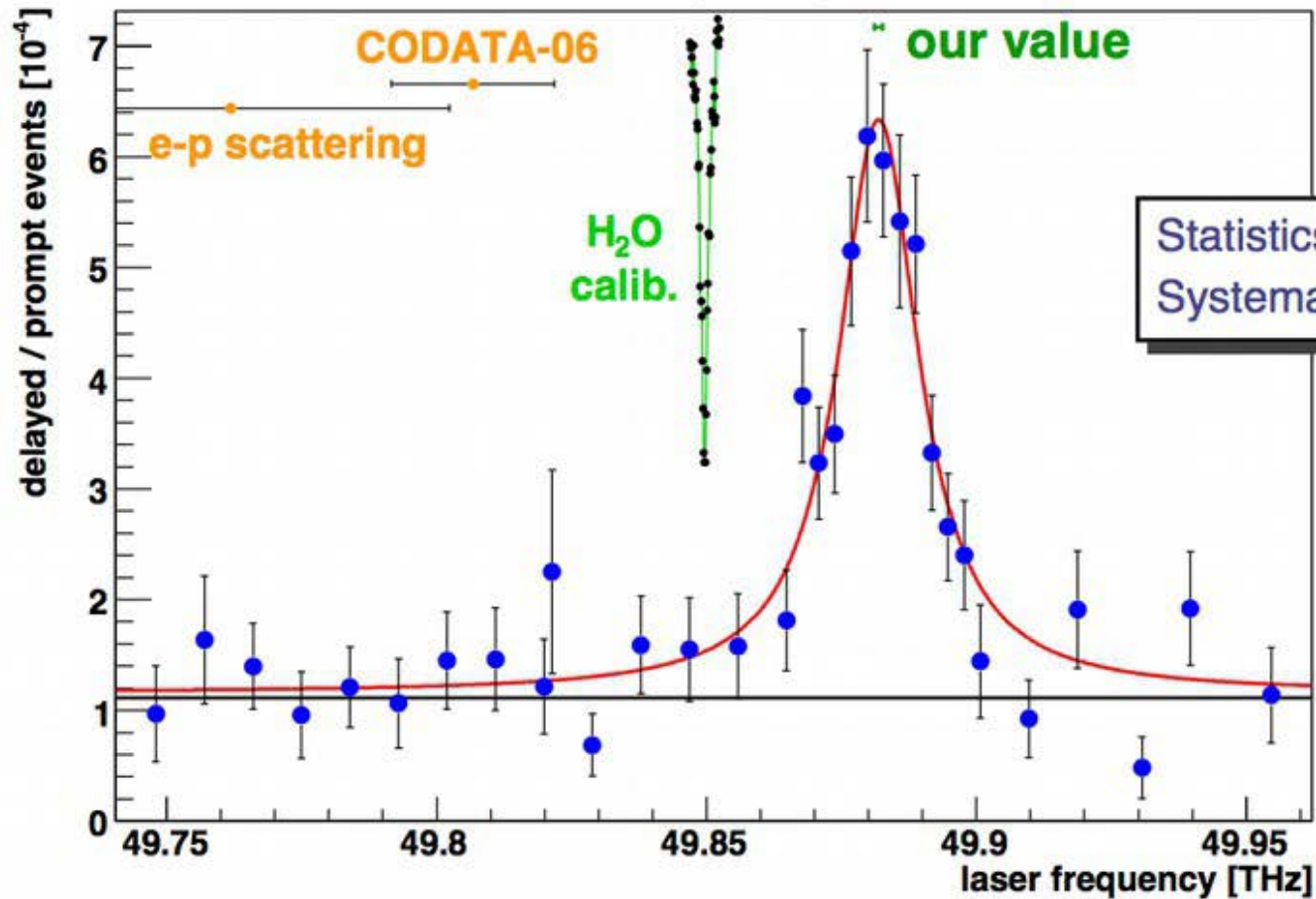


**How do we resolve the puzzle?**

# Experimental Error in $\mu\text{H}$ Measurement ?

Water-line/laser wavelength:  
300 MHz uncertainty

$\Delta\nu$  water-line to resonance:  
200 kHz uncertainty



Statistics: 700 MHz  
Systematics: 300 MHz



# Experimental Error in Electron Measurements ?

## Electron Scattering

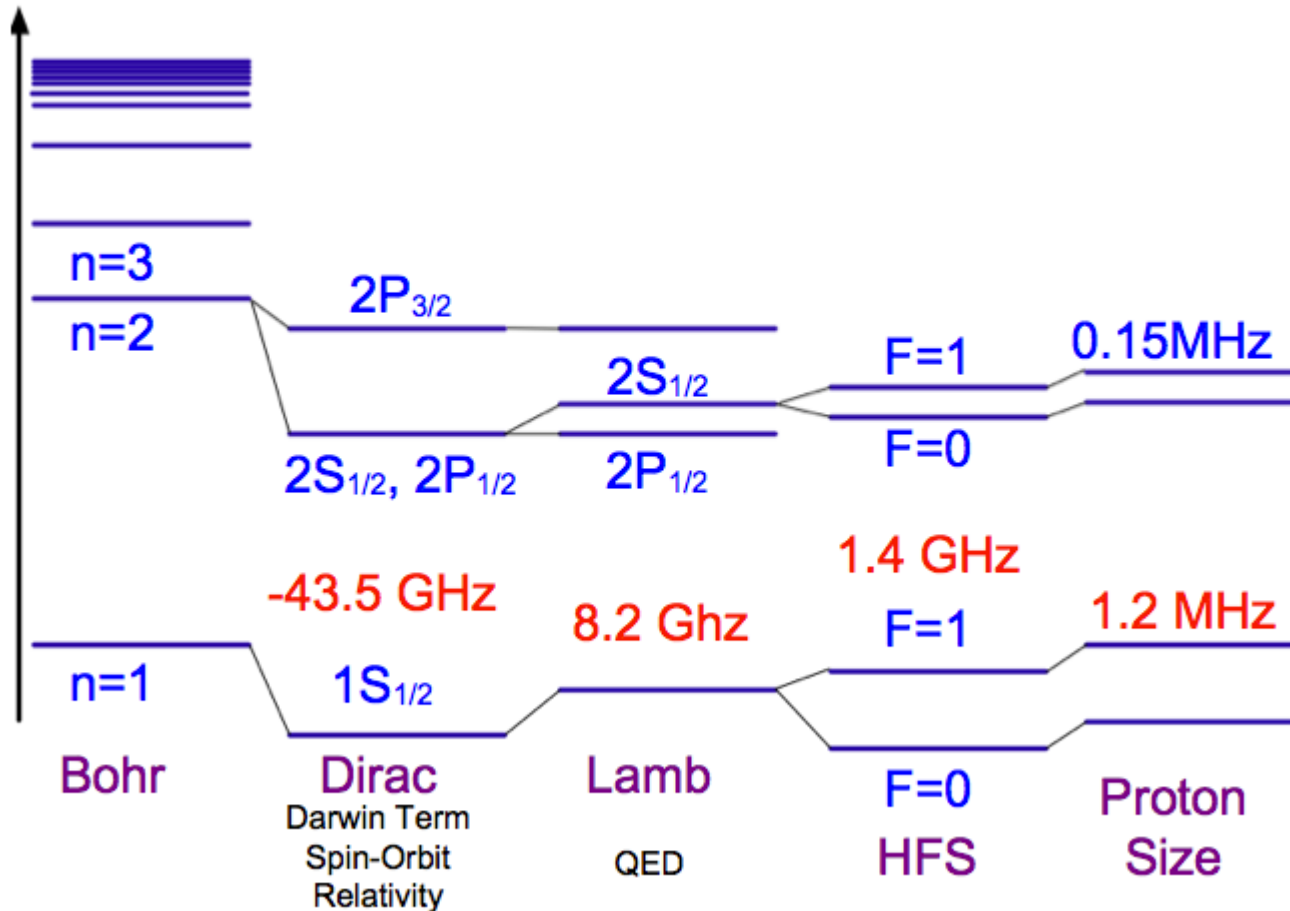
Essentially all (newer) electron scattering results are consistent within errors

## 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		Pachucki [31–33]		Borie [34]	
			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 $\alpha(Z\alpha)^5 \frac{m_r}{M} m_r$	[19, 32, 34, 39]	-0.04497		-0.045		-0.04497	
23	Recoil of order $\alpha^6$	[32]	0.00030		0.0003			
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m_r}{M} m_r$	[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 of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

### FERMIONS

**Leptons** spin = 1/2

Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0
$e^-$ electron	0.000511	-1
$\nu_\mu$ muon neutrino	$<0.0002$	0
$\mu^-$ muon	0.106	-1
$\nu_\tau$ tau neutrino	$<0.02$	0
$\tau^-$ tau	1.7771	-1

**Quarks** spin = 1/2

Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
<b>u</b> up	0.003	2/3
<b>d</b> down	0.006	-1/3
<b>c</b> charm	1.3	2/3
<b>s</b> strange	0.1	-1/3
<b>t</b> top	175	2/3
<b>b</b> bottom	4.3	-1/3

### BOSONS

**Unified Electroweak** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.4	-1
$W^+$	80.4	+1
$Z^0$	91.187	0

**Strong (color)** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

**Color Charge**  
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-35}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ), where 1 GeV =  $10^9$  eV =  $1.60 \times 10^{-10}$  joule. The mass of the proton is 0.938 GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.

**Quarks Confined in Mesons and Baryons**  
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

**Residual Strong Interaction**  
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

### PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
		Mass - Energy	Flavor	Electric Charge	Fundamental	Residual
<b>Acts on:</b>		Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
<b>Particles experiencing:</b>		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
<b>Particles mediating:</b>		Graviton (not yet observed)	$W^+ W^- Z^0$	$\gamma$	Gluons	Mesons
<b>Strength relative to electromag for two u quarks at:</b>		$10^{-41}$	0.8	1	25	Not applicable to quarks
	$10^{-18}$ m	$10^{-41}$	$10^{-4}$	1	60	
	$3 \times 10^{-17}$ m	$10^{-36}$	$10^{-7}$	1	Not applicable to hadrons	20
	for two protons in nucleus					

#### Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$p$	proton	$uud$	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
$n$	neutron	$udd$	0	0.940	1/2
$\Lambda$	lambda	$uds$	0	1.116	1/2
$\Omega^-$	omega	$sss$	-1	1.672	3/2

#### Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	$u\bar{d}$	+1	0.140	0
$K^-$	kaon	$s\bar{u}$	-1	0.494	0
$\rho^+$	rho	$u\bar{d}$	+1	0.770	1
$B^0$	B-zero	$d\bar{b}$	0	5.279	0
$\eta_c$	eta-c	$c\bar{c}$	0	2.980	0

#### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless - or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ , but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

**Figures**  
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating)  $W$  boson. This is neutron  $\beta$  decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce  $B^0$  and  $\bar{B}^0$  mesons via a virtual  $Z$  boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as  $Z$  bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

#### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:  
 U.S. Department of Energy  
 U.S. National Science Foundation  
 Lawrence Berkeley National Laboratory  
 Stanford Linear Accelerator Center  
 American Physical Society, Division of Particles and Fields  
**BURLE INDUSTRIES, INC.**

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**Standard model:** lepton universality, mass is only difference between  $\mu$  &  $e$   
**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  $\mu$  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 $\mu p$ scattering

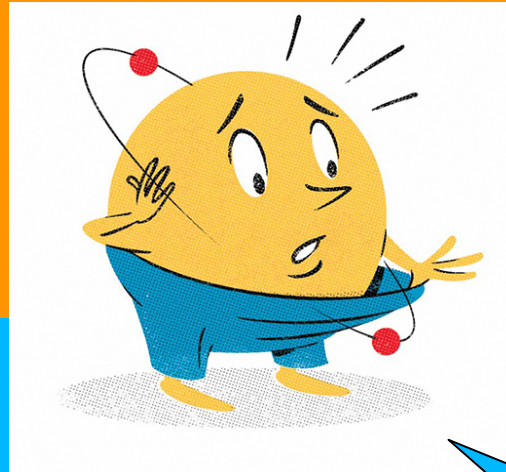
Electronic hydrogen

$0.8758 \pm 0.0077$

Spectroscopy

Muonic hydrogen

$0.84087 \pm 0.00039$



Electron scattering

$0.8770 \pm 0.0060$

Scattering

Muon scattering

???



# Swiss Muons



# Swiss Muons



# MUon Scattering Experiment (MUSE) at PSI



Paul Scherrer Institute  
Villigen, Switzerland

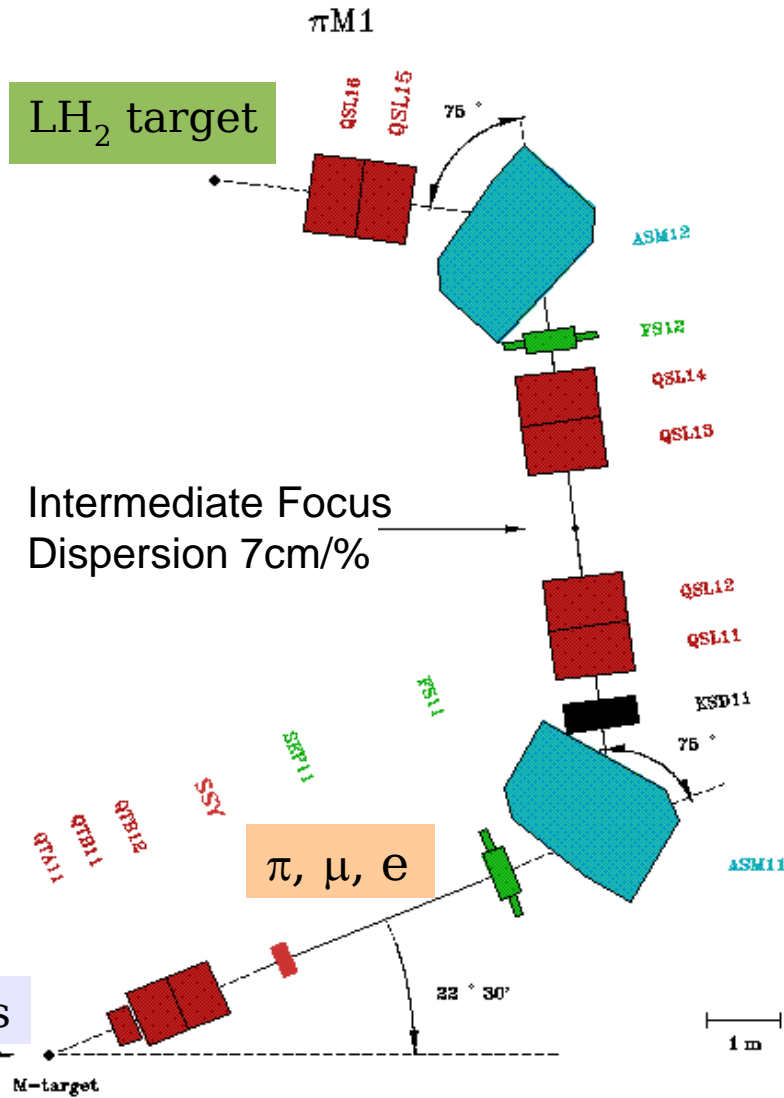
- Simultaneous measurement of  $e^+/\mu^+ e^-/\mu^-$  at beam momenta of 115, 153, 210 MeV/c in  $\pi M1$  channel at PSI allows:
  - Simultaneous determination of proton radius in both  $ep$  and  $\mu p$  scattering
  - Test of Lepton Universality ( if  $\mu = e$  )

# Paul Scherrer Institute $\pi$ M1 Beam

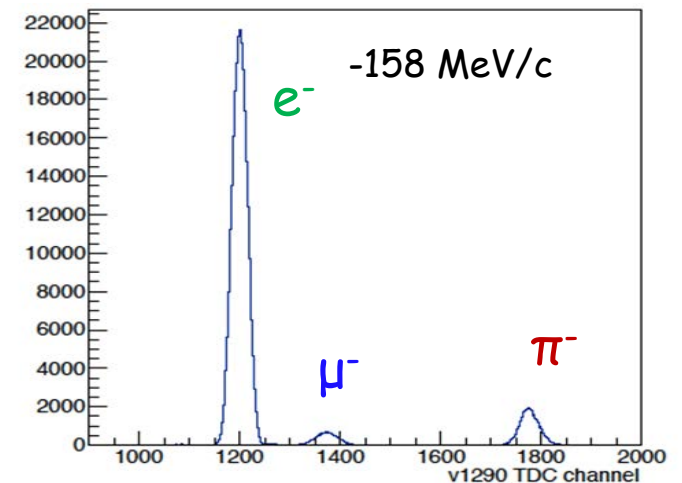
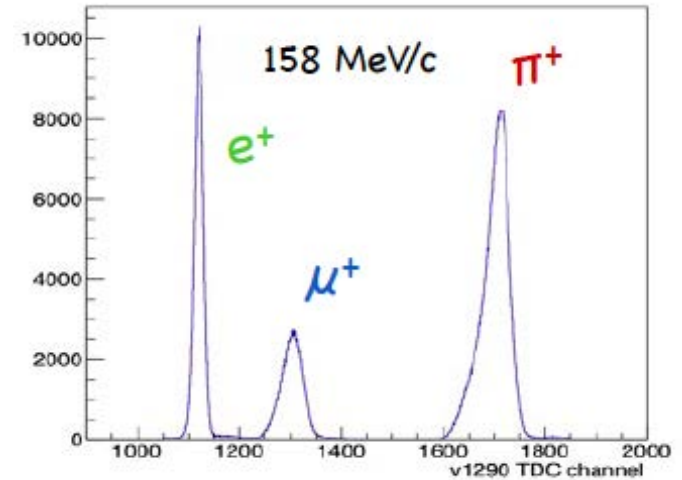


- 590 MeV proton beam, 2.2mA, 1.3MW beam, 50.6MHz RF frequency
- World's most powerful proton beam
- Converted to  $e^{\pm}$ ,  $\mu^{\pm}$ ,  $\pi^{\pm}$  in  $\pi$ M1 beamline

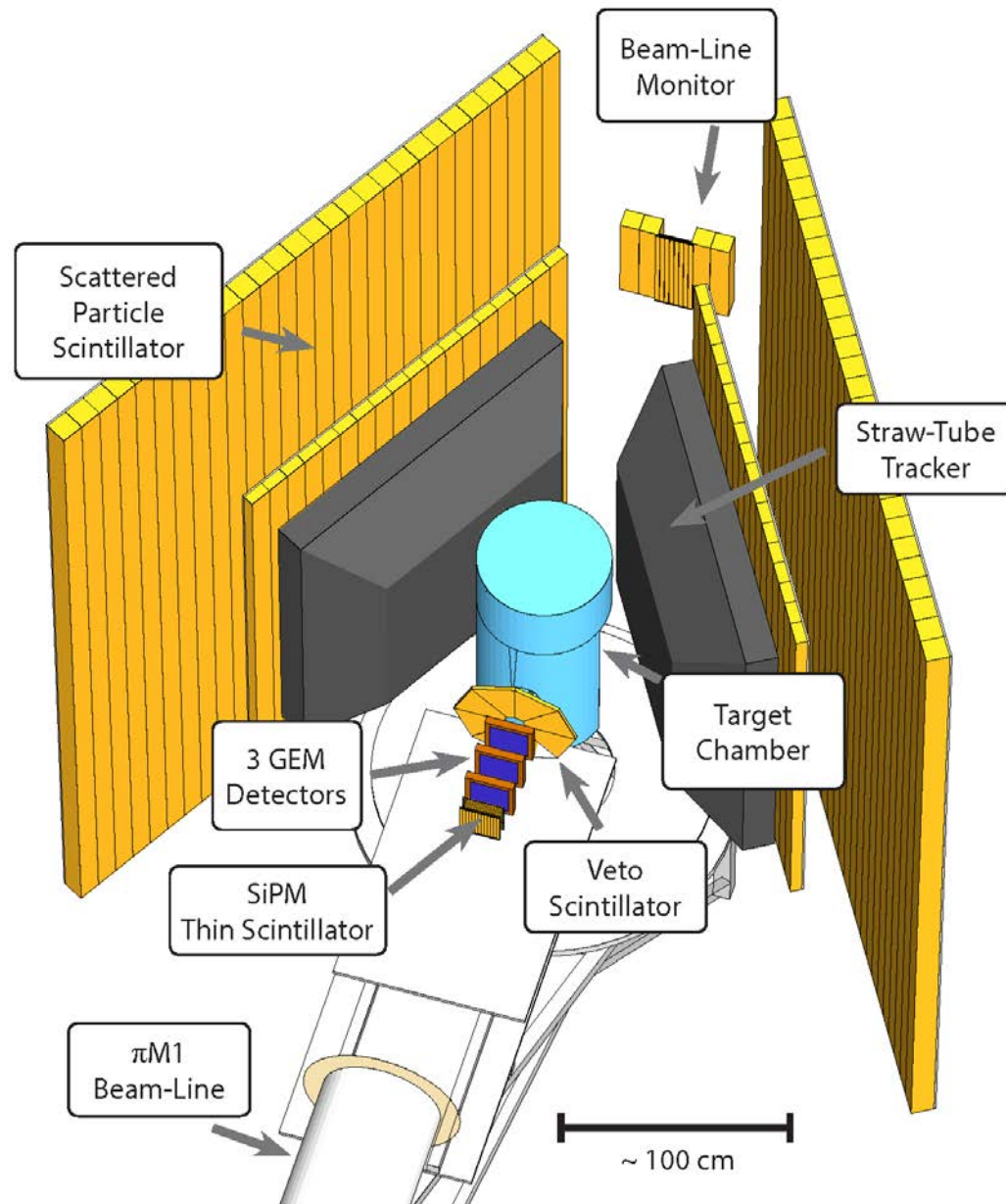
# $\pi$ M1 / MUSE beamline



$\pi$ M1: 100-500 MeV/c RF+TOF separated  $\pi, \mu, e$

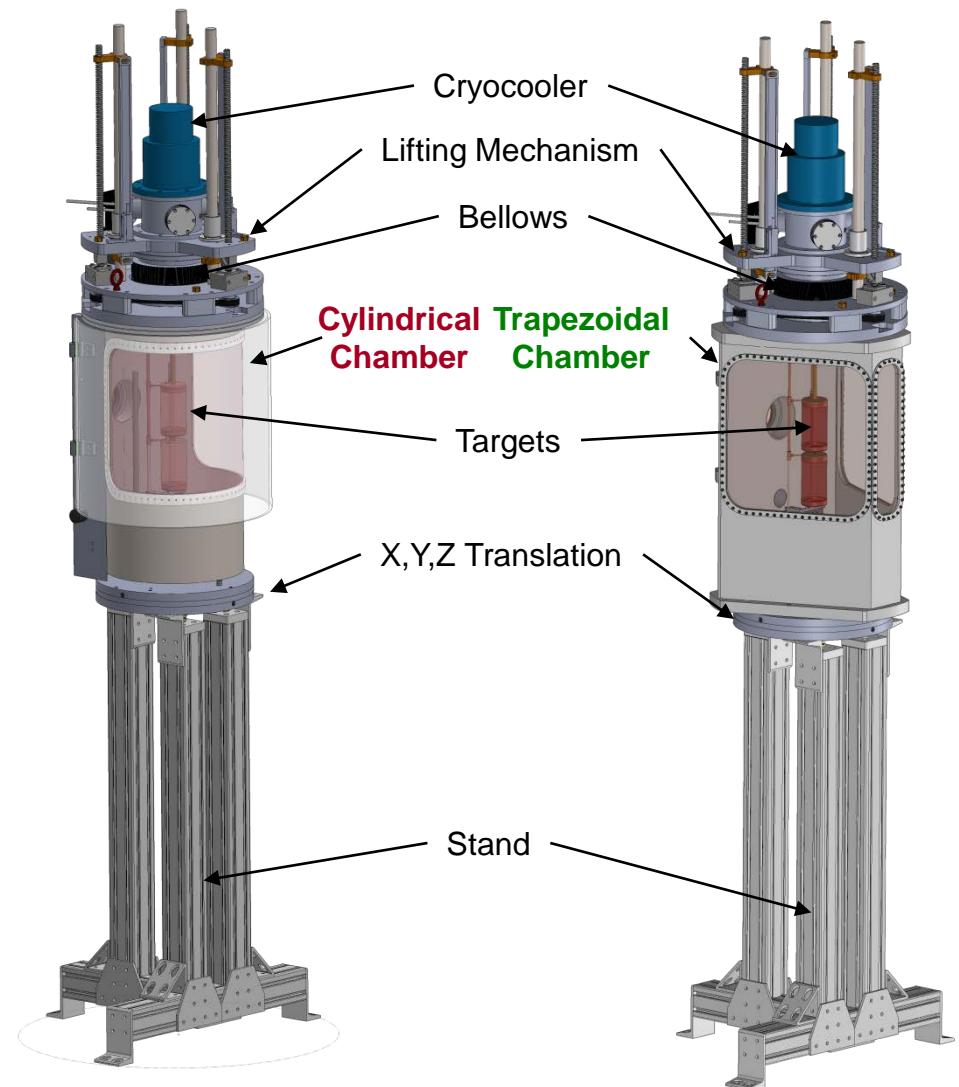


# MUSE experiment layout



# 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

- 127 $\mu$ m Kapton window deflecting inward about 2.5" (6.35 cm) at about 0.5 atm
- C785 sailcloth (258  $\mu$ m Kapton equivalent) at 1 atm still forms pleats



**Does not work**

Window Burst Shortly after Photo



# Flat Windows don't form Pleats



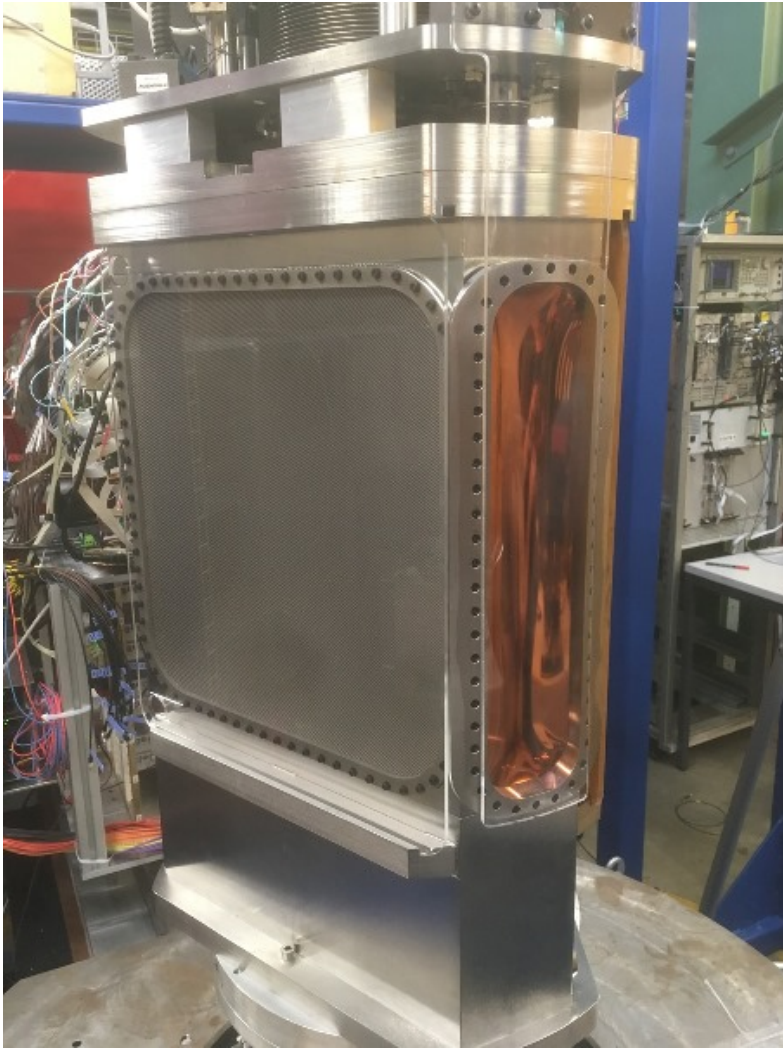
window deforms 68 mm at 1atm



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

# Hydrogen Target

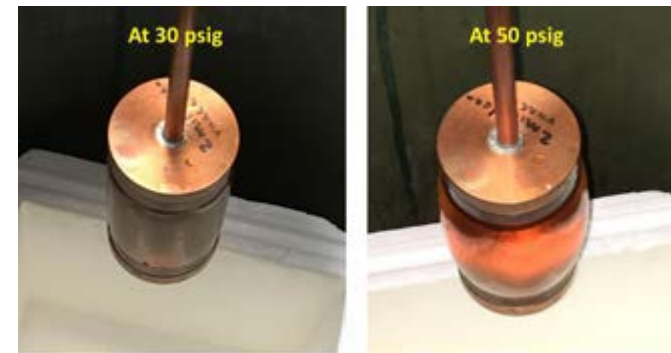
Target chamber



Target cells

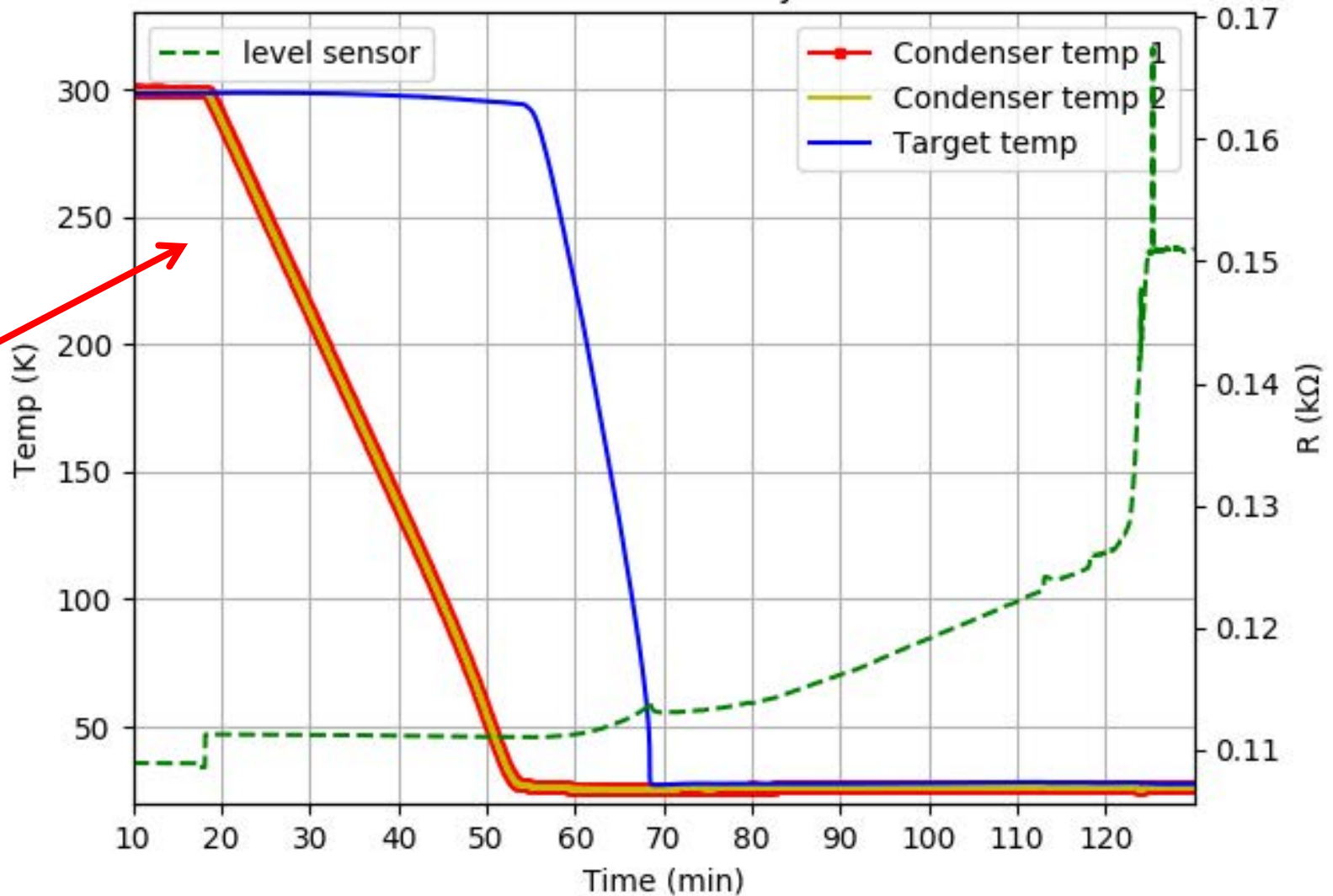


Target cell destruction tests



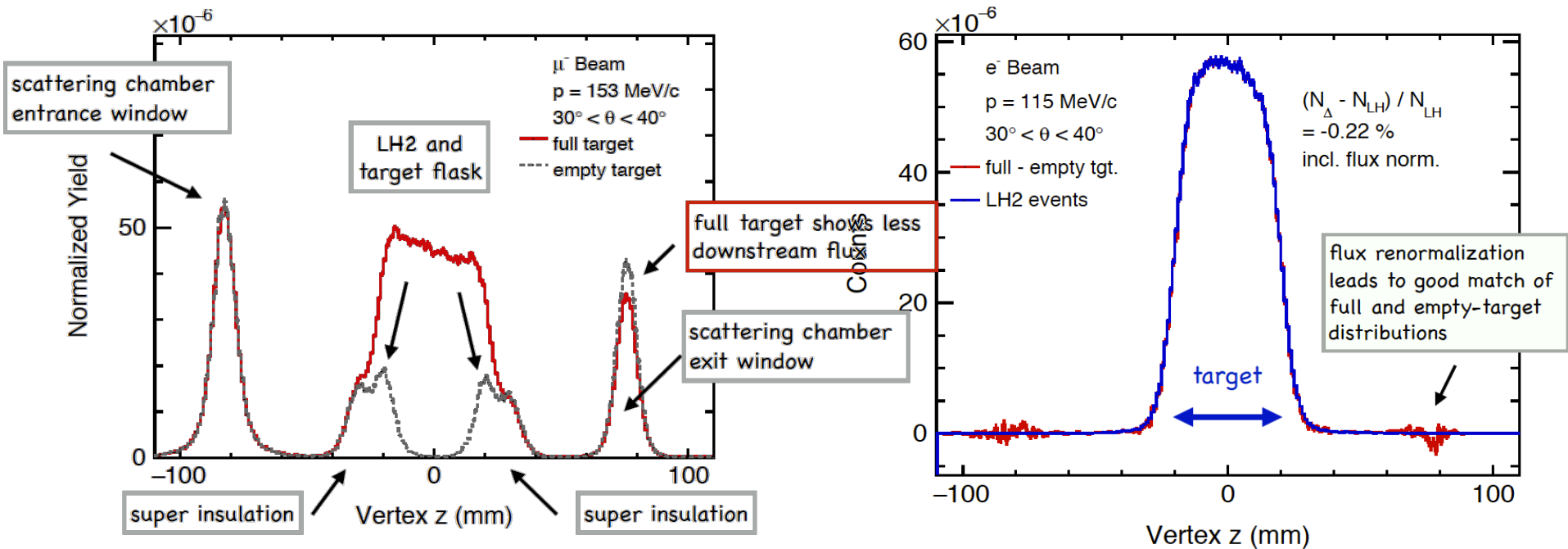
# Hydrogen Target Cooldown

Ne Cooldown 30 May 2018

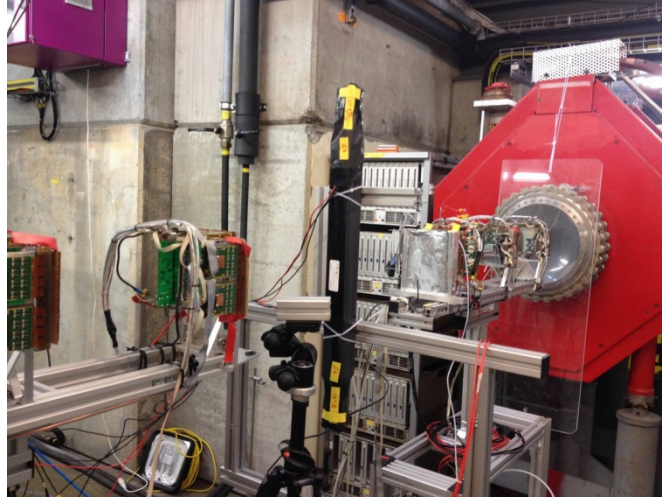
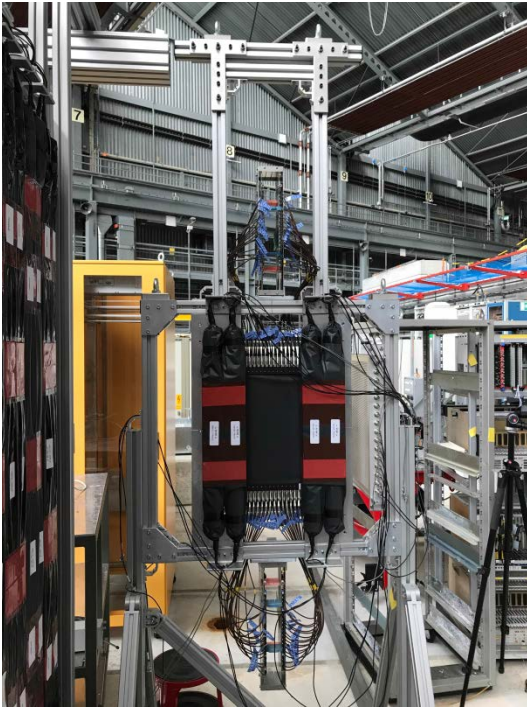


# Target Simulations

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



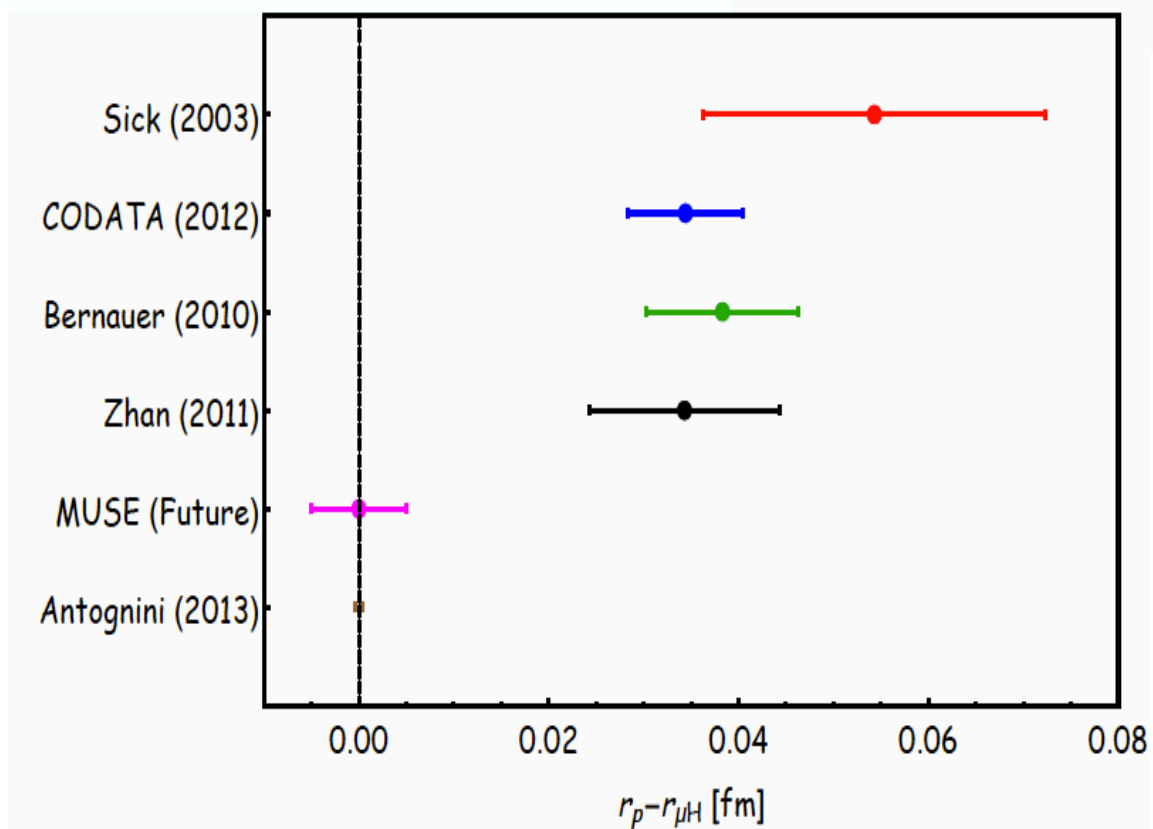
# MUSE status



- 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  $\mu p$  scattering
- Error on radius difference  $\sim 0.009$  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?

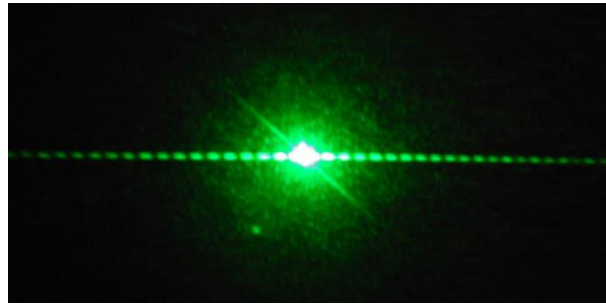
## Object:

- macroscopic:  
hard sphere



Tool:  
caliper

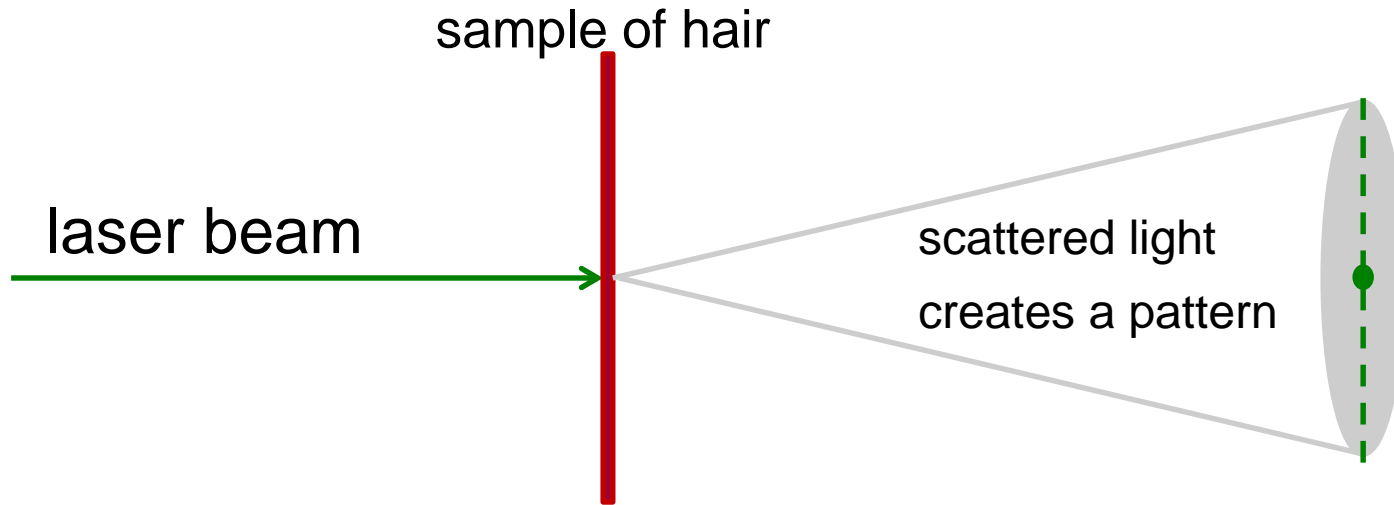
- small:  
hair



laser

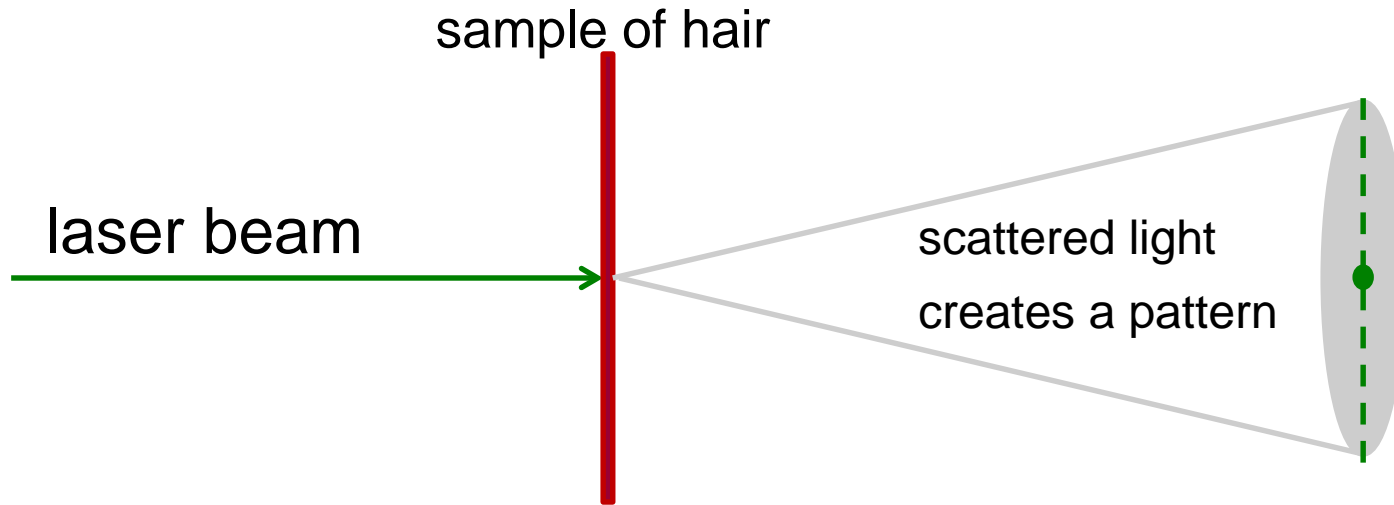
**Let's measure the width of a hair!**

# How do you measure size of hair?



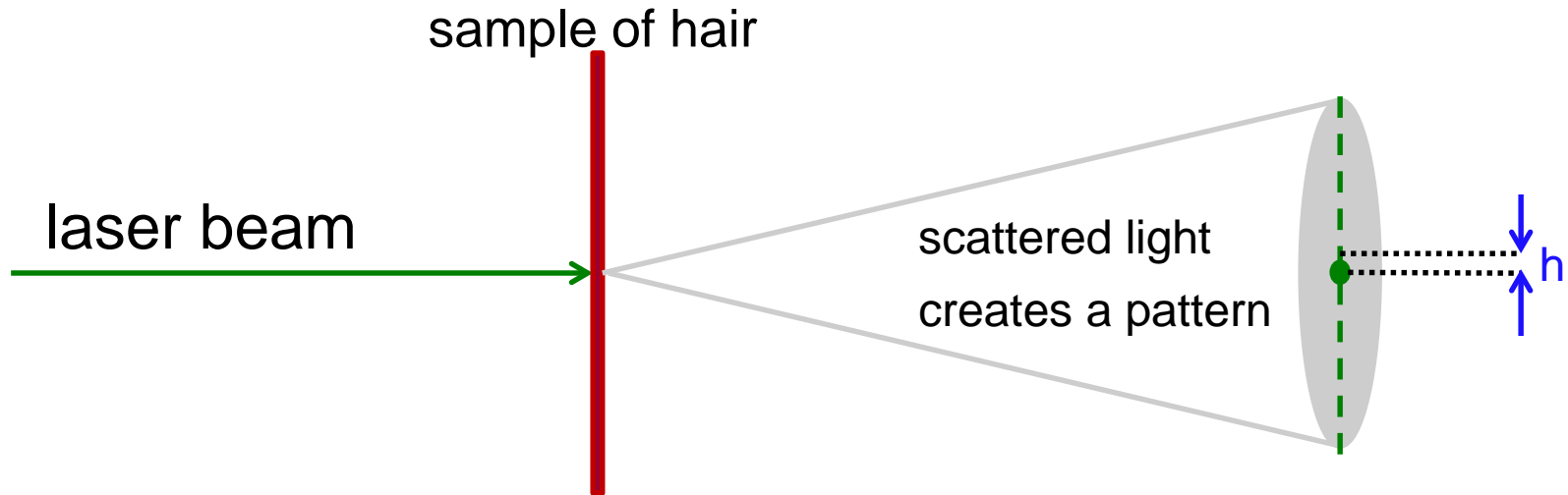
**Need a volunteer**

# How do you measure size of hair?



**2**  
**Need a 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 1<sup>st</sup> minimum  
(ie. "dark" section)

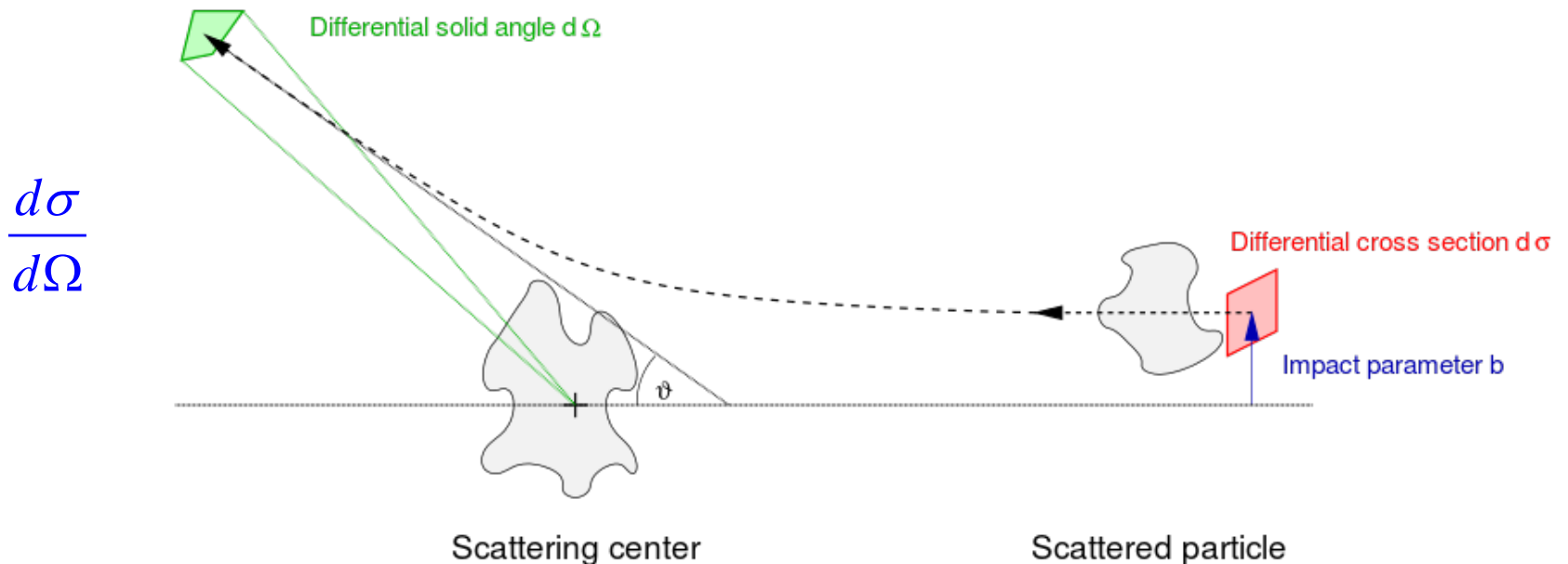
$$D = \frac{0.000532 \text{ mm}}{\sin\left(\frac{h \text{ mm}}{3251 \text{ mm}}\right)}$$

# What is a differential Cross Section?

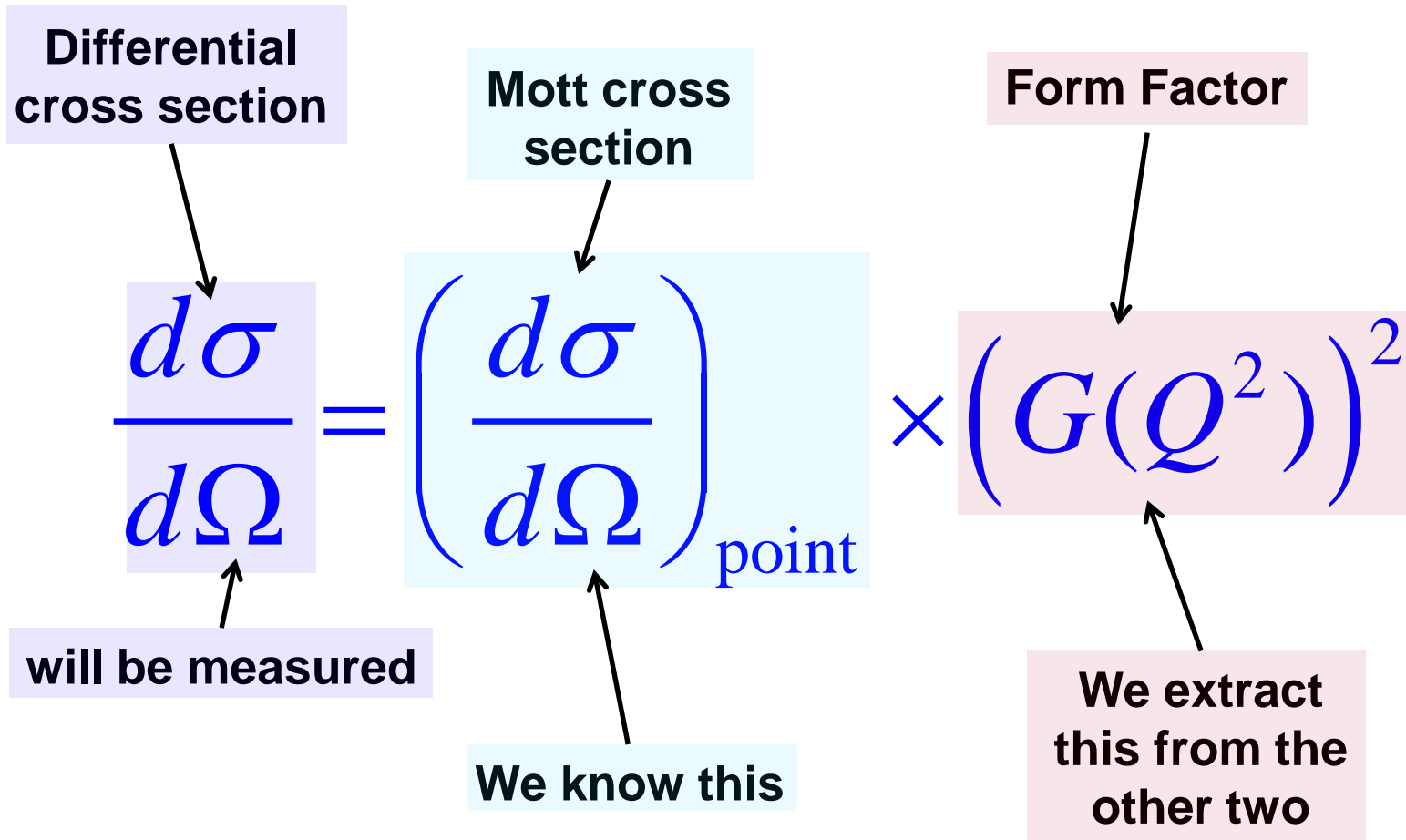
## Differential Cross Section

- single particle is scattered off a single stationary target particle at an angle  $\theta$  and  $\varphi$  (with  $d\Omega = \sin \theta d\theta d\varphi$ )
- differential cross section depends on impact parameter  $b$  and scattering angle  $\theta$

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



# Extracting the radius from scattering data



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

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



# Extracting the radius from scattering data

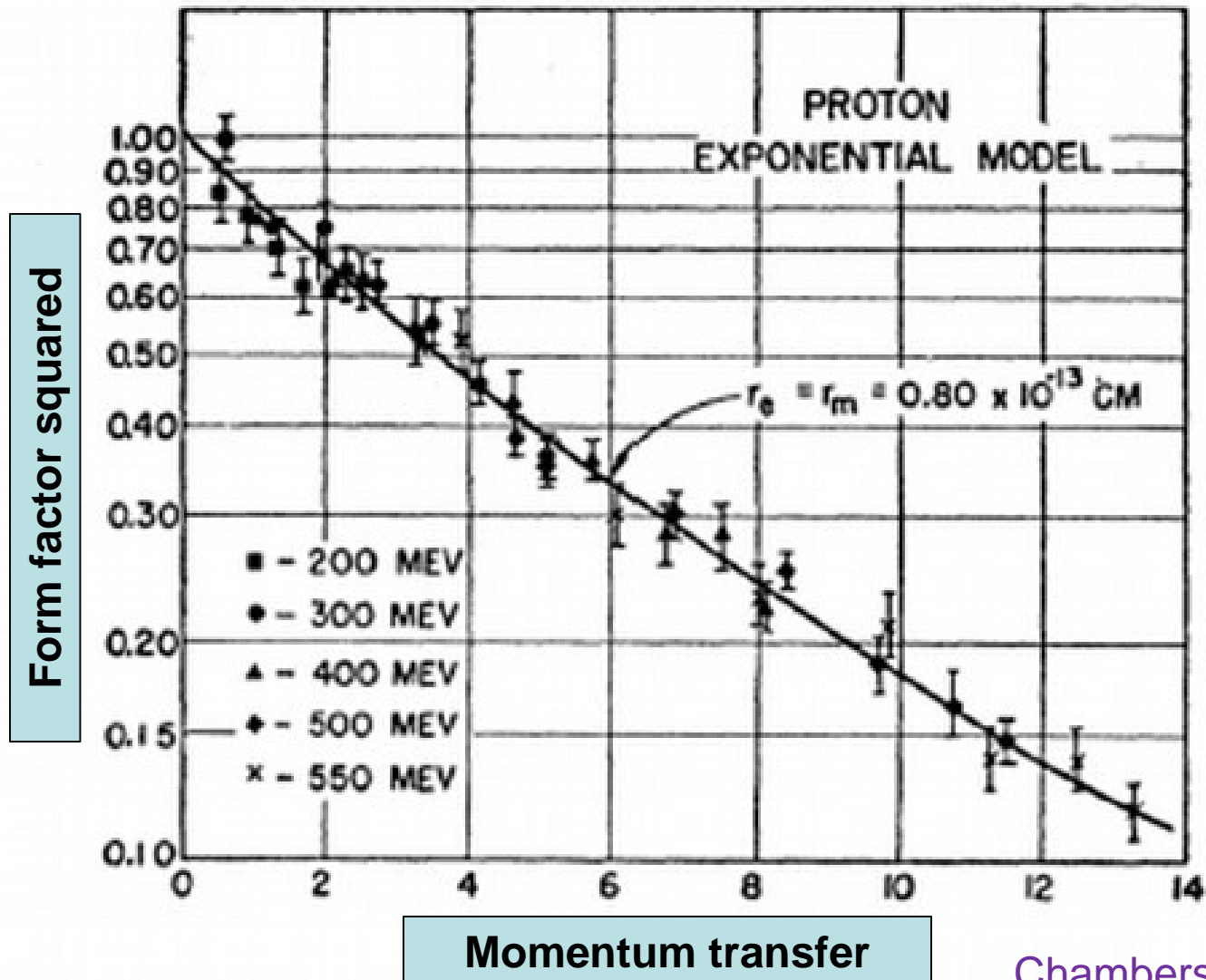
proton radius squared

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

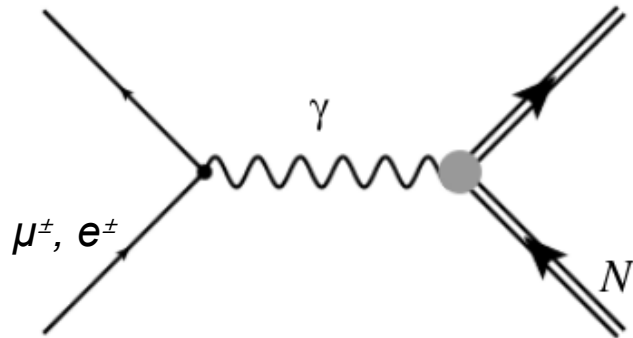
# Extracting the radius from scattering data



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

# Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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

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

$F_1, F_2$  are the Dirac and Pauli form factors

**Sachs form factors:**

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

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

**Derivative in  $Q^2 \rightarrow 0$  limit:**

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

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

**Expect identical result for ep and  $\mu p$  scattering**

# How do you measure size?

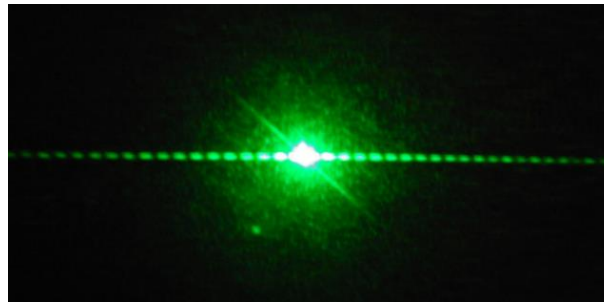
## Object:

- macroscopic:  
hard sphere



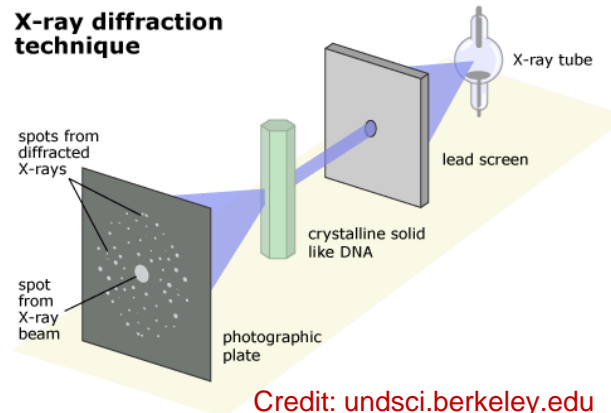
Tool:  
caliper

- small:  
hair



laser

- tiny:  
atom



oil monolayer  
X-ray diffraction

# How do you measure proton size?

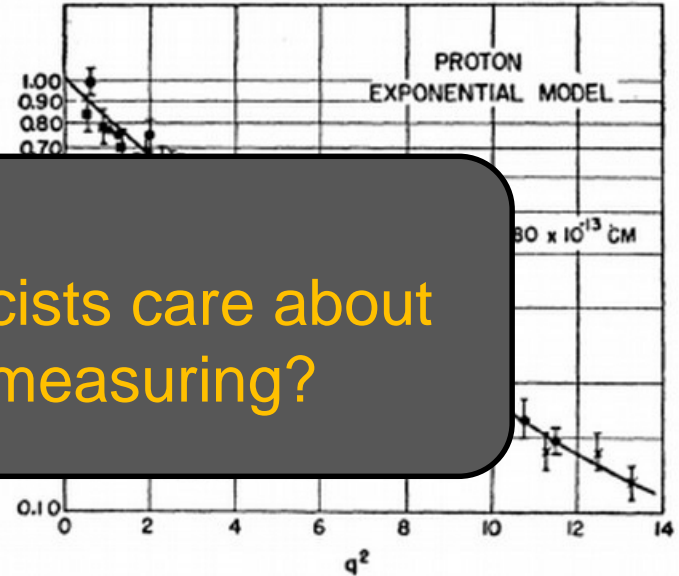
Chambers and Hofstadter,  
Phys Rev 103, 1454 (1956)

- **Scattering experiments**

(Hofstadter @ Stanford: 1950s -  
electron scattering)

**Question:**

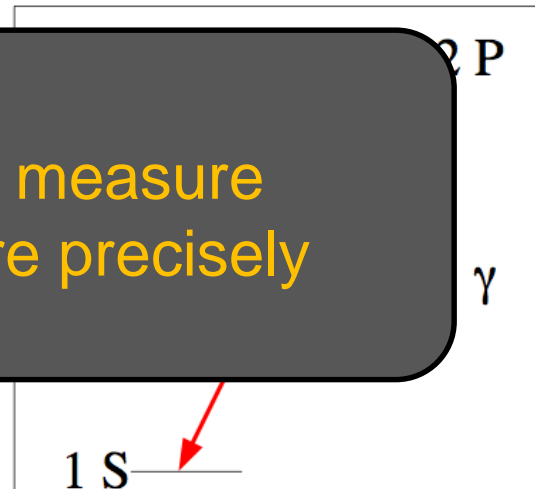
Why should hadronic physicists care about what atomic physicists are measuring?



- **Atomic**  
(Atomic  
atomic)

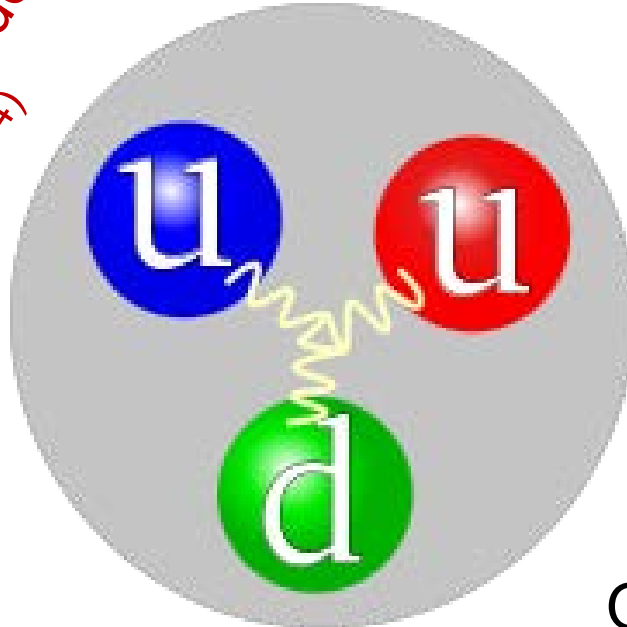
**Answer:**

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)

electric charge

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

Credit: wikipedia.org

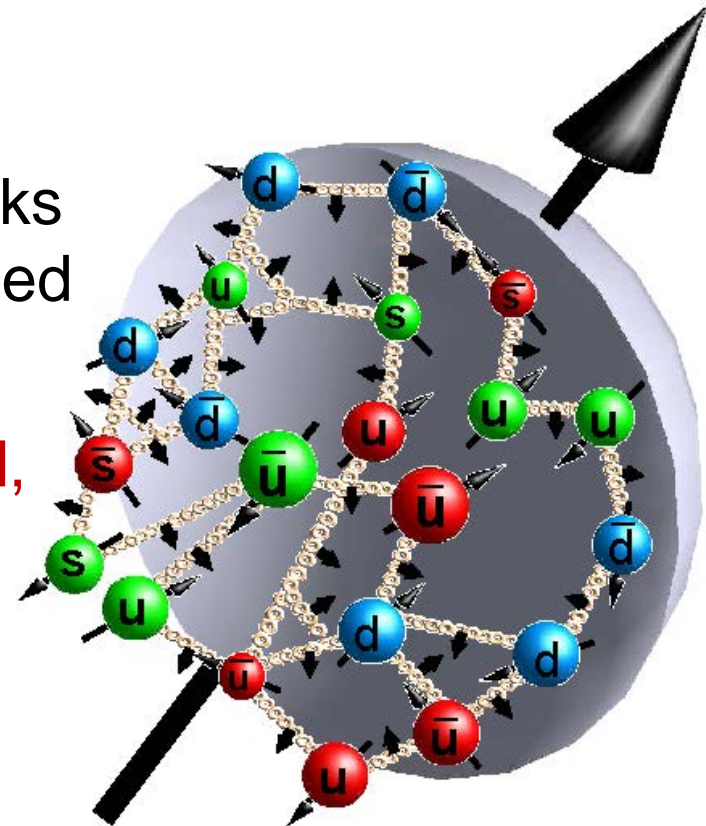
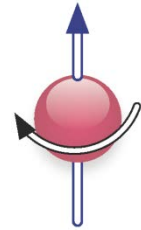
Quarks are held together  
by **strong nuclear force**

**strong nuclear force**  
arises when quarks exchange gluons

# The Proton Structure

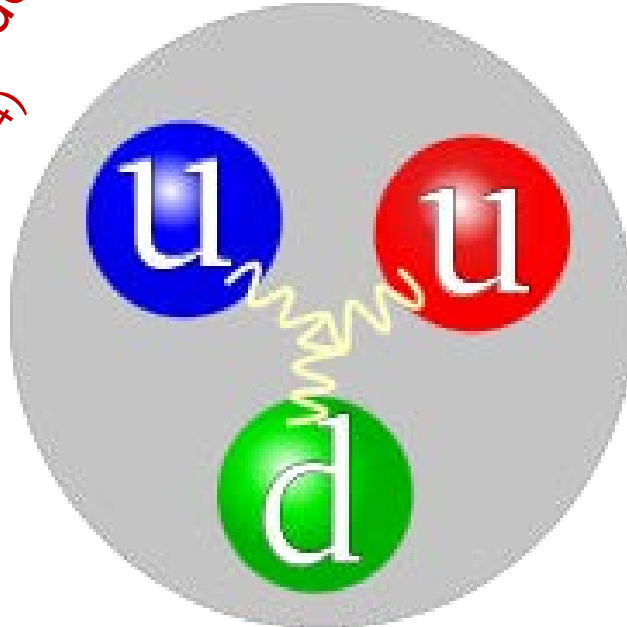
- proton is spin-1/2 particle
- proton is **not pointlike**
- complex internal structure generated by interactions between pointlike constituents (quarks/partons).
- Uncertainty Principle dictates: quarks must be in motion - at close to speed of light

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



# The Proton

Quark Model  
(1964)



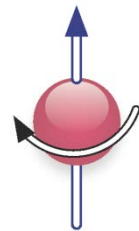
Credit: wikipedia.org

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).

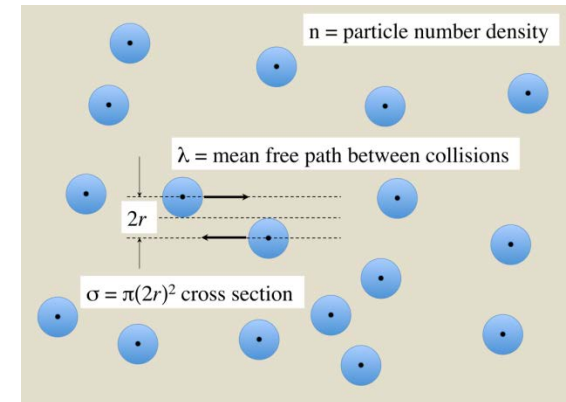




# What is a (differential) Cross Section?

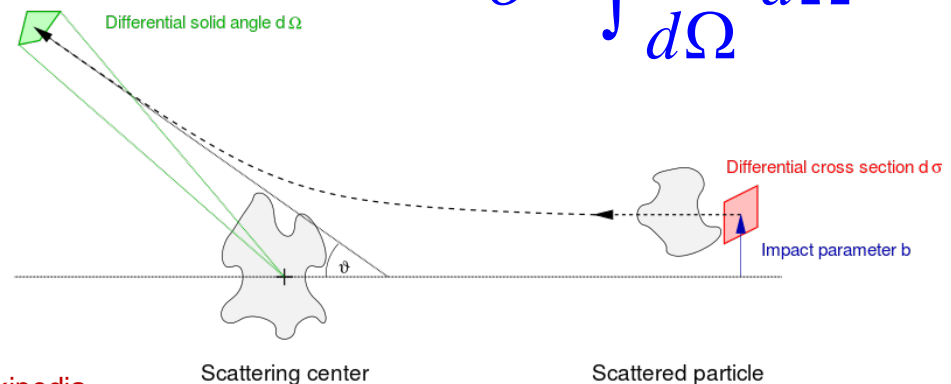
## Cross Section

- 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  $\theta$  and  $\pi$  (with  $d\Omega = \sin \theta d\theta d\phi$ )
- differential cross section  $\frac{d\sigma}{d\Omega}$  depends on impact parameter  $b$  and scattering angle  $\theta$

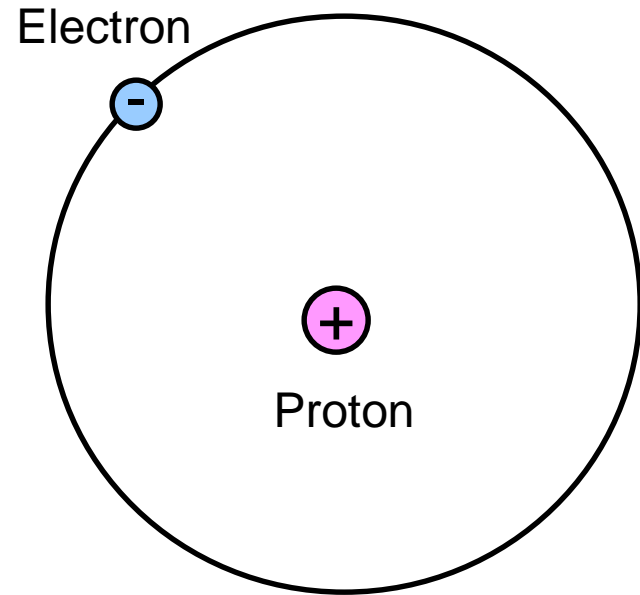


$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$$

# 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:

$$0.84184 \pm 0.00067 \text{ fm}$$

**disagrees** with atomic physics and electron scattering measurements:

$$0.8779 \pm 0.0094 \text{ fm}$$

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!!**