

# Low Energy Physics

CHIPP winter school of particle physics 2025 – Gstaad

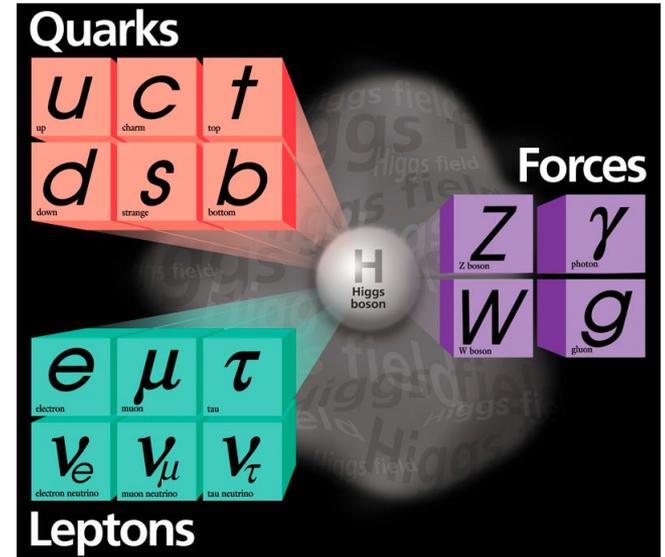
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(23-Jan-2025)

# The Standard Model

- The Standard Model is remarkably powerful and successful
  - e-m, weak and strong interactions
  - not gravity
- established in 1970s, demonstrated large predictive power
  - W and Z bosons (1983)
  - top quark (1995)
  - $\tau$  neutrino (2000)
  - Higgs boson (2012)
  - various properties of weak neutral currents
- The most successful theory?

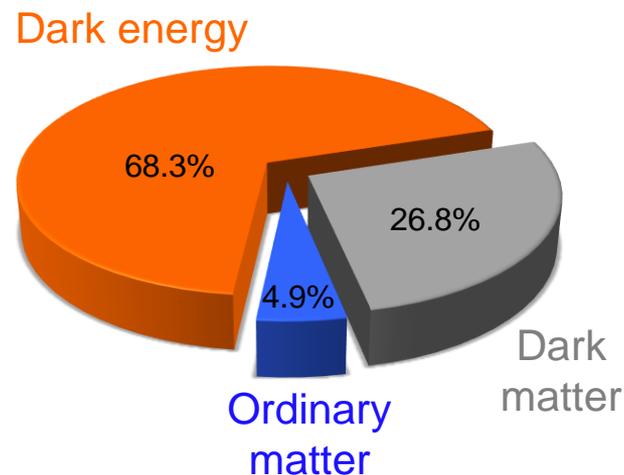


Credit: Fermilab

# The Standard Model - Challenges

- Standard Model is not complete

- Dark Matter?
- Dark Energy?
- baryon to anti-baryon asymmetry?
- neutrino masses, oscillations?
- CP violation?
- origin of families?
- gravity?
- ....



- might need BSM physics to address these puzzles!

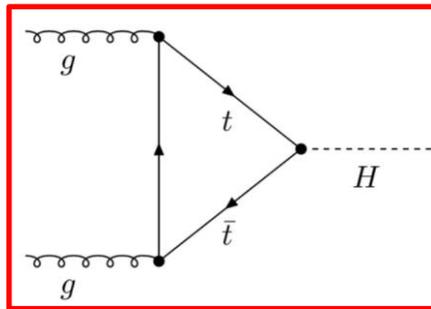
- where is the 'new' physics?
- what's its mass and coupling?
- energy or intensity frontier?

} theory lecture!

# Search for BSM Physics

high energy  
frontier

direct production of new particle

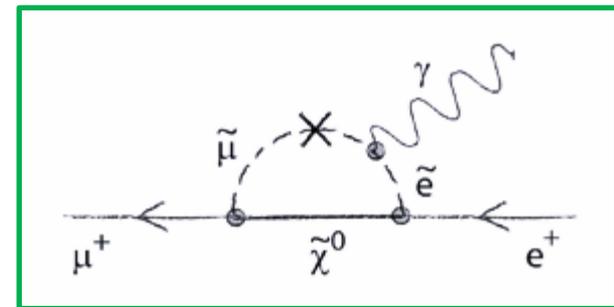


$$g + g \rightarrow H$$

- limited by collider energy ( $\sim$ TeV)

high intensity /  
precision frontier

indirect search for “footprint” of  
virtual particle

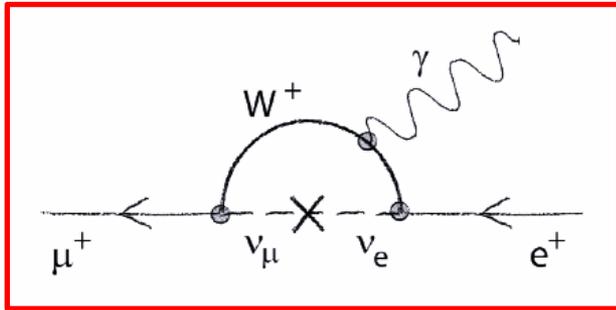


$$\mu^+ \rightarrow e^+ + \gamma$$

- rare or SM-forbidden decays
- precision measurements of SM-allowed processes

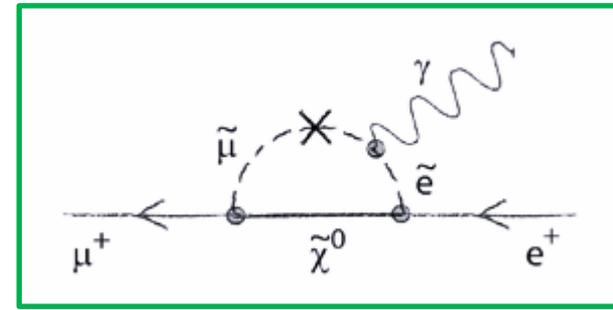
# Ex: Muon Decay in SM vs SUSY

SM: LFV loop



$$\mu^+ \rightarrow e^+ + \gamma$$

SUSY loop



$$\mu^+ \rightarrow e^+ + \gamma$$

branching ratios:

$$\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$$

not measurable

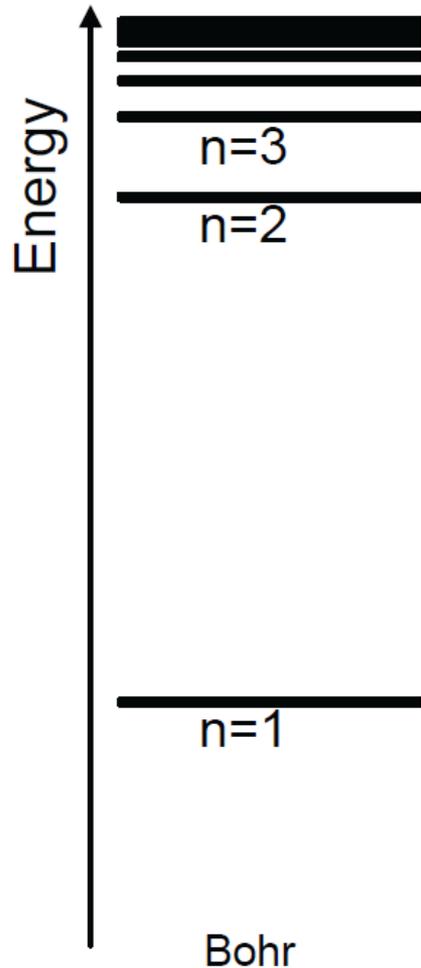
$$10^{-14} \dots 10^{-11} ?$$

if BR is  $10^{-11} \rightarrow 10^{13} \mu^+$  needed

sensitivity to new particles is limited by the rarity of the process

→ excellent when SM process is (highly) suppressed!

# Hydrogen atom as precision probe



solve Schrödinger equation:

$$\left[ \frac{\hbar^2 \nabla^2}{2m_e} + V(r) \right] \Psi = E\Psi$$

• in the Coulomb potential:

$$V(r) = -\frac{1}{4\pi\epsilon_0} \frac{Ze^2}{r}$$

• (non-rel.) correction: need to take into account finite mass of proton by reduced mass:

$$m_r = \frac{m_p m_e}{m_p + m_e} (\cong m_e)$$

• principle eigenenergies are:

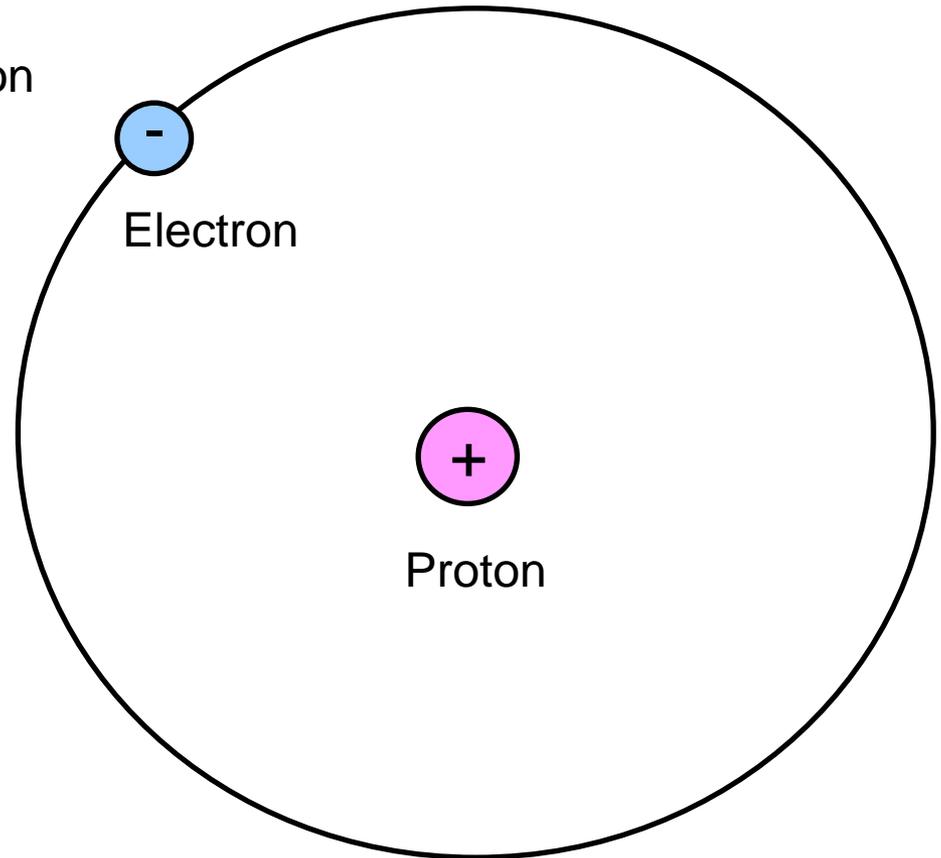
$$E_n = -\frac{(Z\alpha)^2 m_r c^2}{2n^2} = -\frac{m_r}{m_e} \frac{R_\infty}{n^2}$$

$$\left( R_\infty = \frac{\alpha^2 m_e c}{2h} ; \alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \right)$$

# Bohr Hydrogen Atom

## Bohr Model of the atom (1913)

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



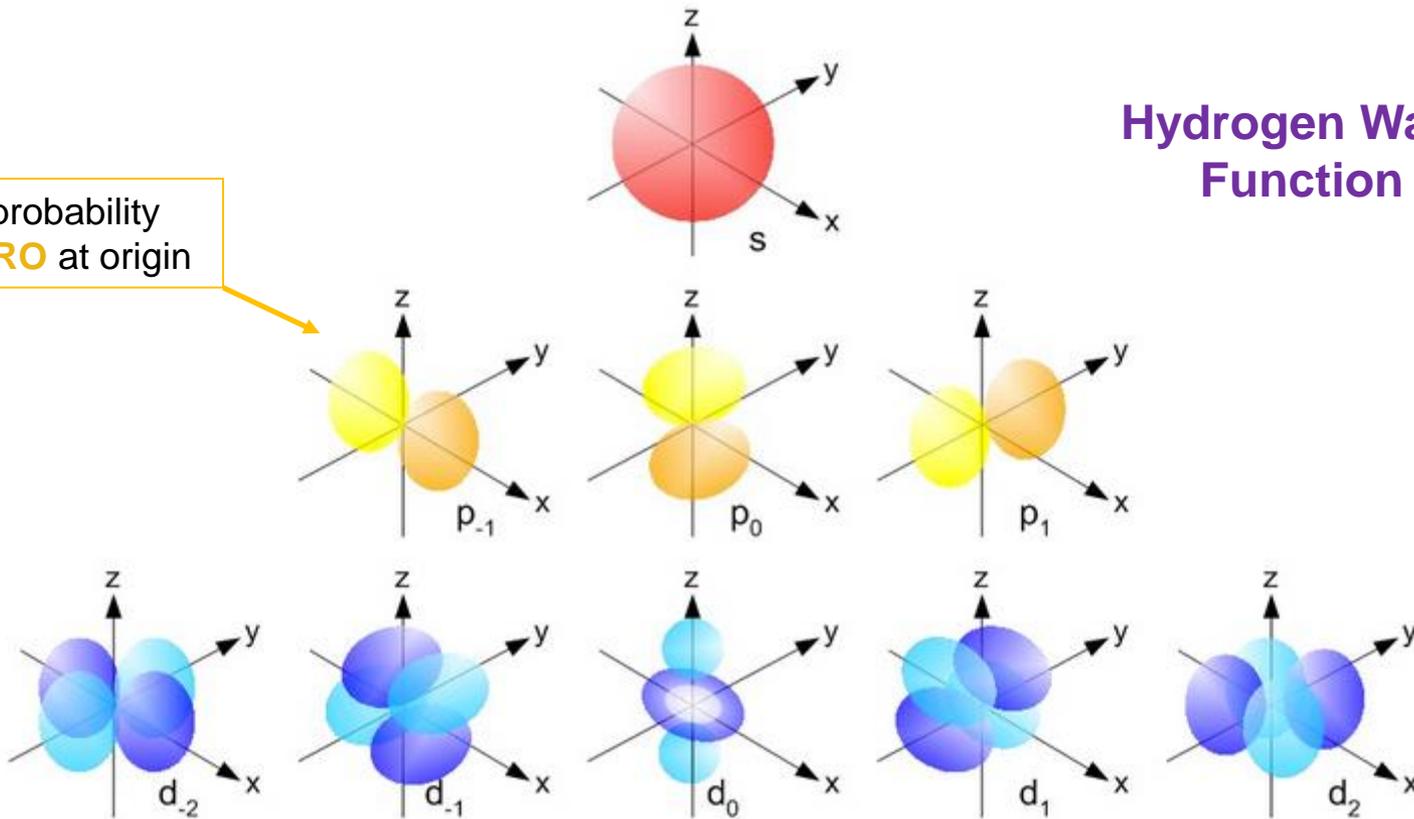
**Bohr Model**

# ... is simply inaccurate...

Bohr model → Quantum Mechanics

“planetary orbits” → “wave function”

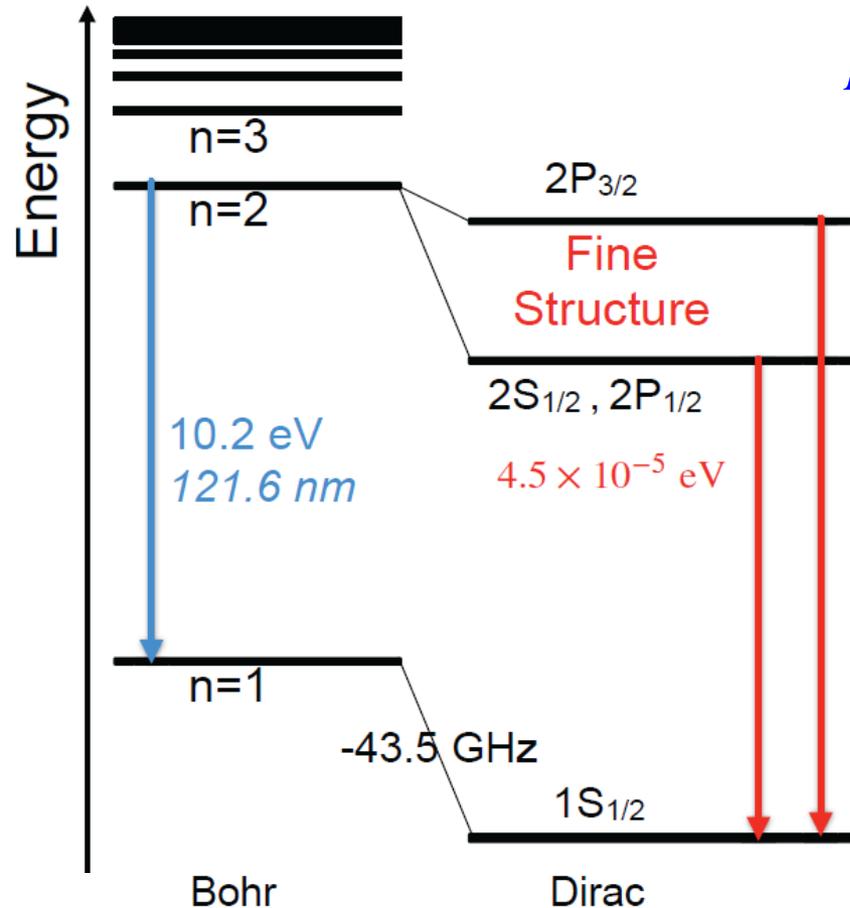
p-states: probability density: **ZERO** at origin



# Relativistic Correction

Dirac introduces correction for relativistic treatment of electron KE and spin-orbit interaction:

$$E_{nj} = m_e c^2 \left[ 1 - \frac{Z^2 \alpha^2}{2n^2} - \frac{(Z^2 \alpha^2)^2}{2n^4} \left( \frac{n}{j + \frac{1}{2}} - \frac{3}{4} \right) + \dots \right]$$



- relativistic effect leads to **fine structure** of H atom:
  - $2P_{3/2}$  and  $2P_{1/2}$  split
  - $2S_{1/2}$  and  $2P_{1/2}$  are same
- rule:
  - levels split with same  $n$  but different  $j$  ( $=l+s$ : OAM + spin)
- remember:  $E(\text{eV}) \cdot \lambda(\text{nm}) = 1240 \text{ eV nm}$ 
  - $4.5 \times 10^{-5} \text{ eV}$  splitting ( $\rightarrow \Delta\lambda = ?$ )

# Spin-Orbit Interaction

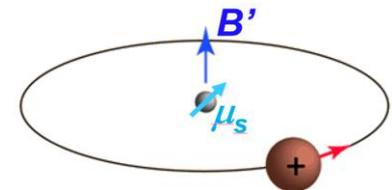
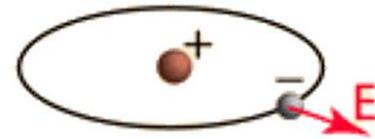
- Dirac equation unifies [quantum mechanics](#) and [special relativity](#) ([APS article](#))
- In QM, the spin-orbit interaction is a relativistic interaction of a particle's spin with its motion inside a potential
- **for H atom:** In lab frame,  $e^-$  sees the electric (Coulomb) field  $\mathbf{E}$  from nucleus
- In the  $e^-$  rest frame, electron sees an apparent magnetic field  $\mathbf{B}'$  caused by the relative motion of the nucleus
  - $e^-$  moving with (high) velocity  $\mathbf{v}$  in the Coulomb field  $\mathbf{E}$  of the proton induces a magnetic field  $\mathbf{B}'$  in its rest frame:

$$\mathbf{B}' = -\frac{\mathbf{v} \times \mathbf{E}}{c^2}$$

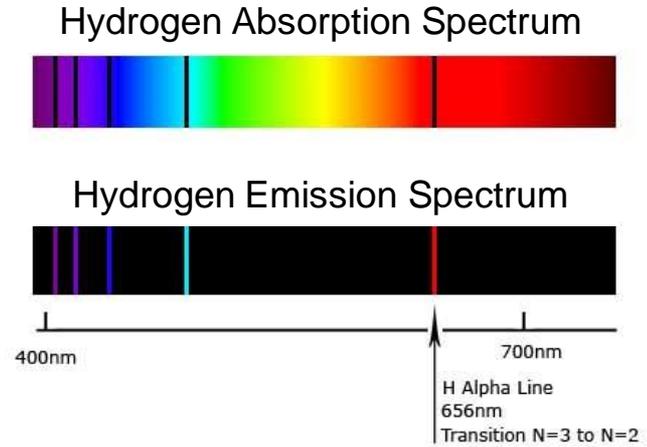
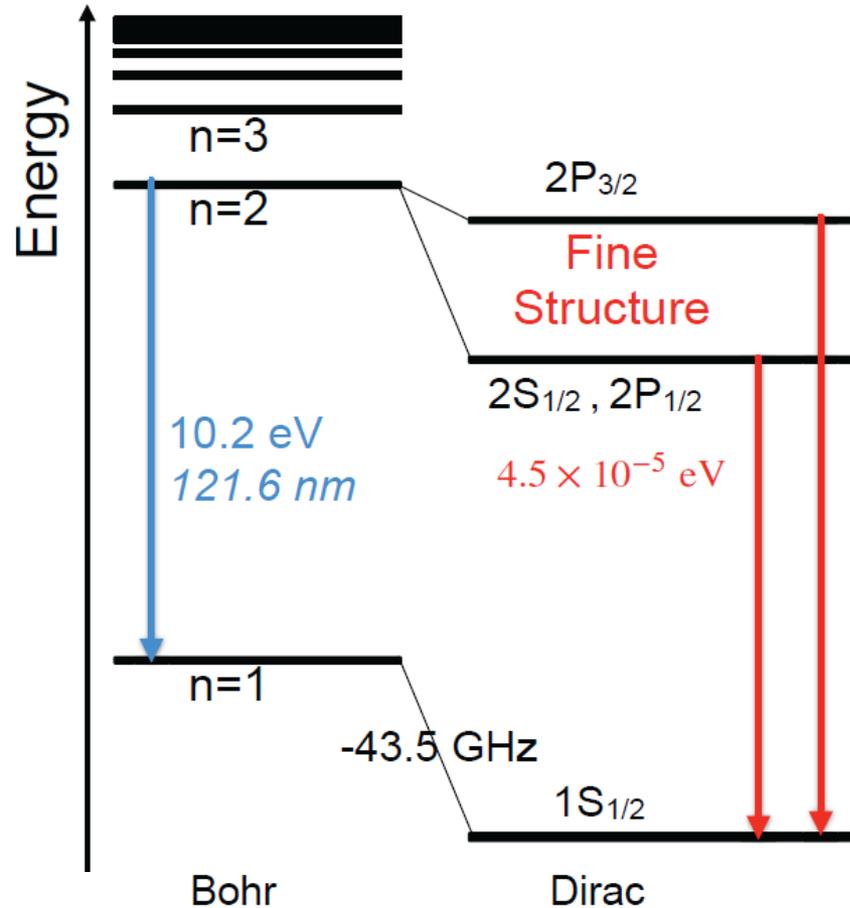
- the  $e^-$  magnetic moment  $\mu_s$ , associated with its intrinsic spin due to QM, interacts with this  $\mathbf{B}'$  field:

$$E' = -\boldsymbol{\mu}_s \cdot \mathbf{B}'$$

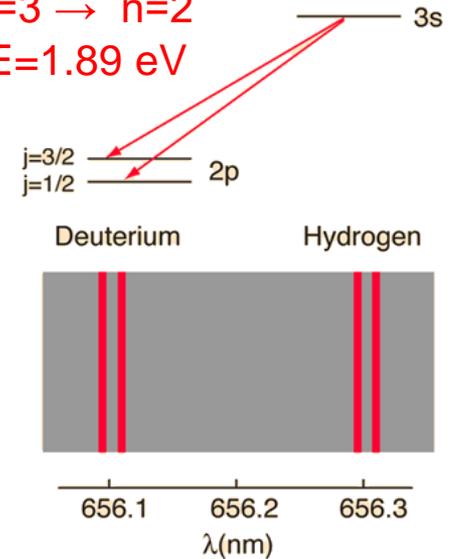
- Note:  $\mu_s$  is parallel to  $e^-$  spin angular momentum  $\mathbf{S}$ , and  $\mathbf{B}$  is parallel to  $e^-$  orbital angular momentum  $\mathbf{L}$ : **spin-orbit interaction**, which leads to splitting of spectral lines



# Splitting of Balmer lines

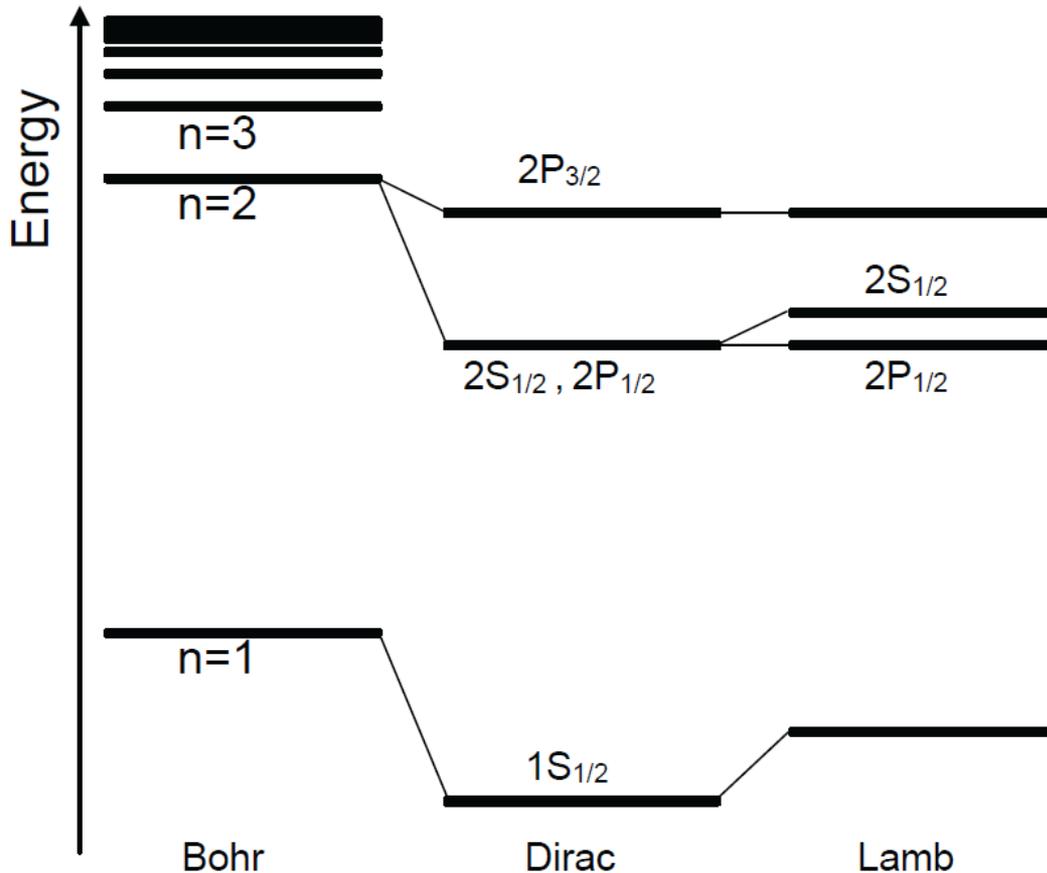


Balmer  $\alpha$  line:  $n=3 \rightarrow n=2$   
 $\Delta E = 1.89 \text{ eV}$



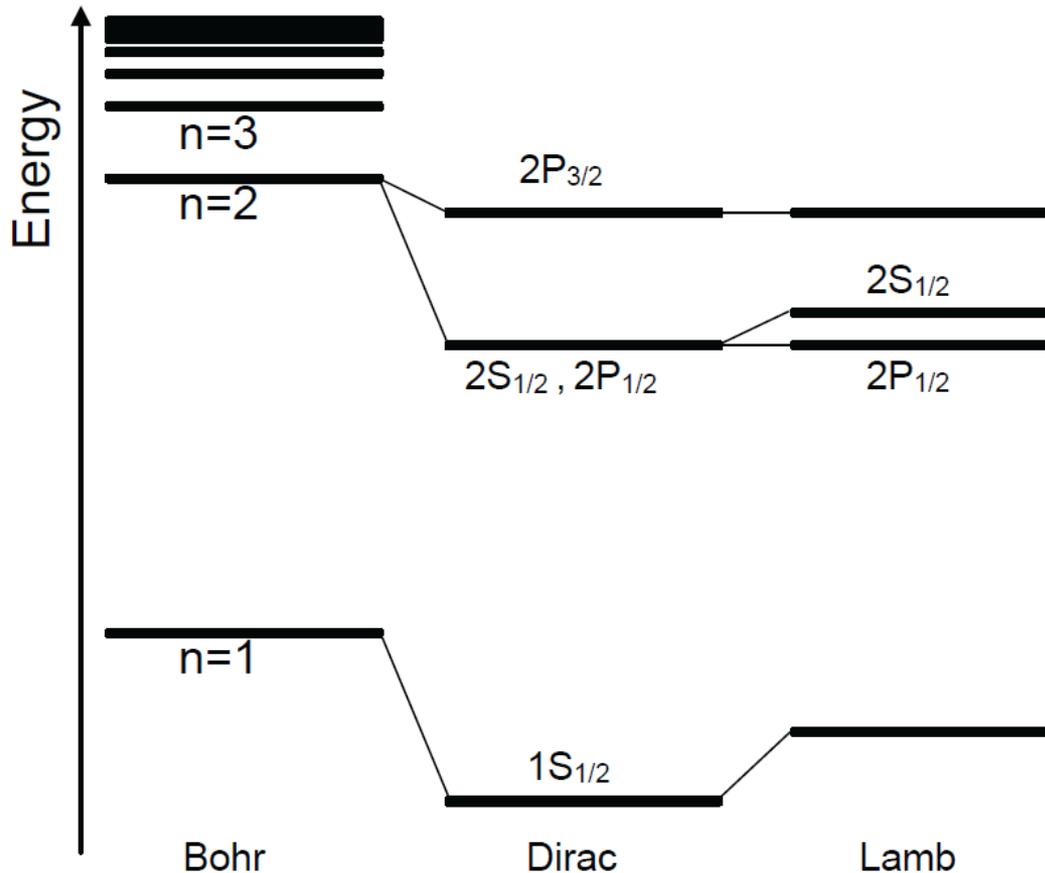
(splitting is 0.016 nm, but increases for heavy nuclei)

# Lamb's Experiment

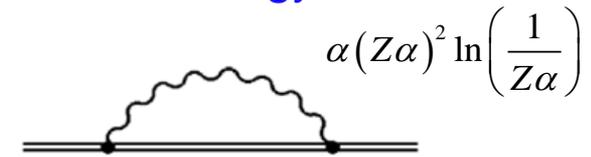


- Lamb uses resonant spectroscopy  
→ finds disagreement with Dirac prediction
  - $2S_{1/2}$  and  $2P_{1/2}$  in H **split**  
 $4.5 \times 10^{-6} eV$
  - $\Delta E(2P_{3/2} - 2S_{1/2})$  not as predicted
- Dirac theory not sufficient:
  - “BSM” physics needed
  - leads to development of QED

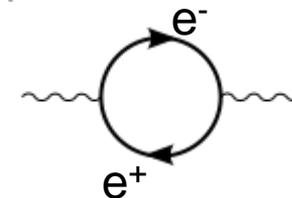
# Lamb's Experiment: start of QED



- leading QED effect of Lamb shift in H atom is self energy

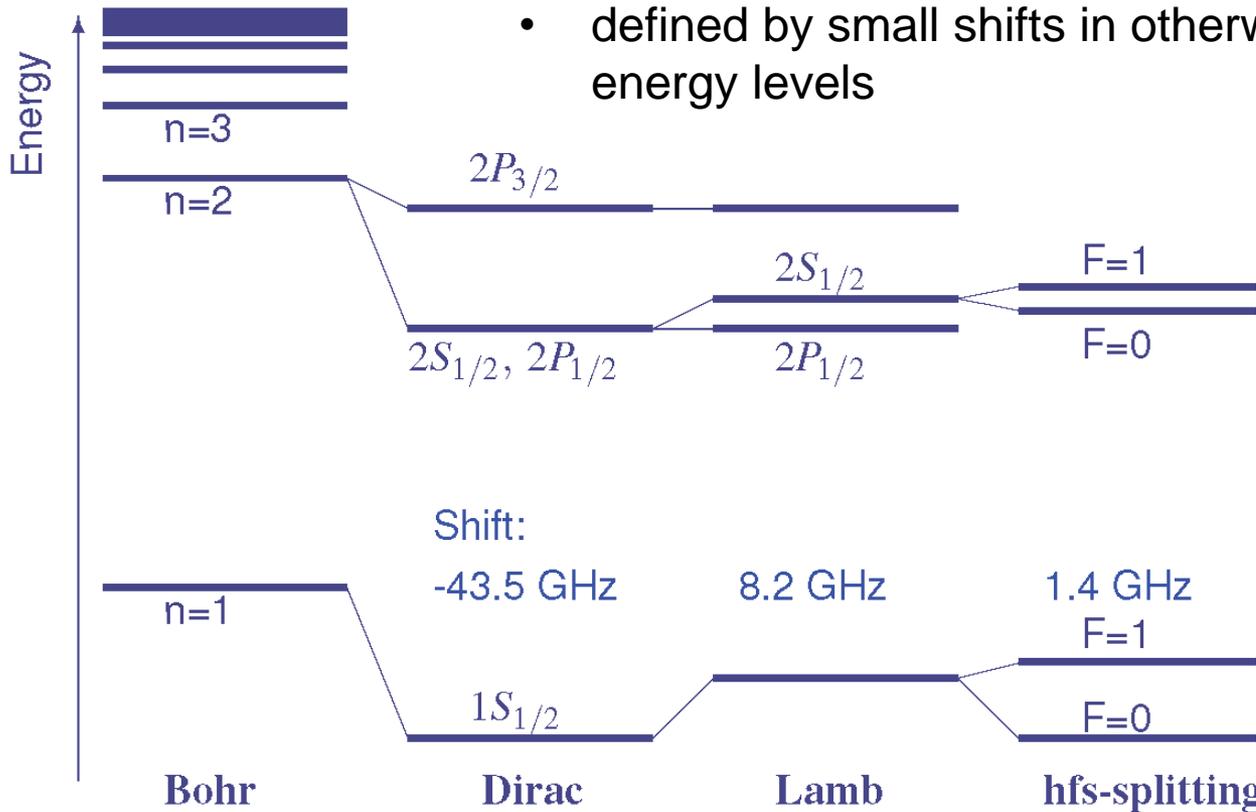


- virtual  $\gamma$  can be emitted and re-absorbed by bound  $e^-$
- perturbs  $e^-$  orbit  $\rightarrow$  shifts energy levels
- rule:
  - levels split with same  $j$  but different  $l$
- sub-leading effect (in H) due to vacuum polarization



# Hyperfine Splitting

- next correction: account for **proton spin**
- hfs-splitting originates from the interaction of the magnetic moments of the electron and proton due to their spin
- defined by small shifts in otherwise degenerate electronic energy levels



$F=I+J$  is total angular momentum,  $I$  is nuclear spin,  $J$  total  $e^-$  angular momentum

$$5.9 \times 10^{-6} \text{ eV}$$

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

$$V \sim 1/r$$

$e^-$  spin  
relativity

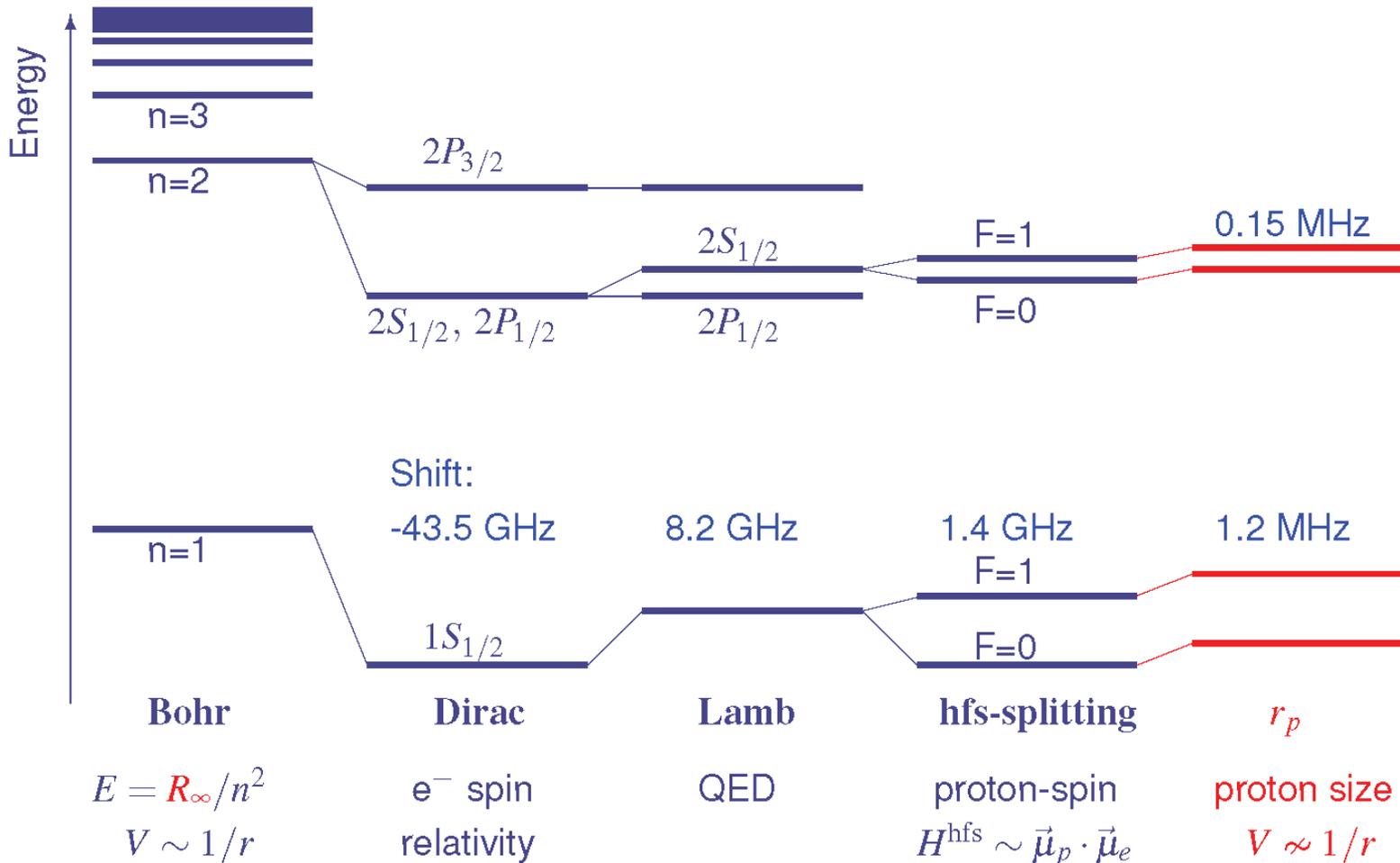
QED

proton-spin

$$H^{\text{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$$

# Hydrogen Energy Levels

- including nuclear effects: finite size of the proton
- can be turned around **find the size of the proton**



# How do you measure size?

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



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

Credit: Nature

# How do you measure size?

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



# How do you measure size?

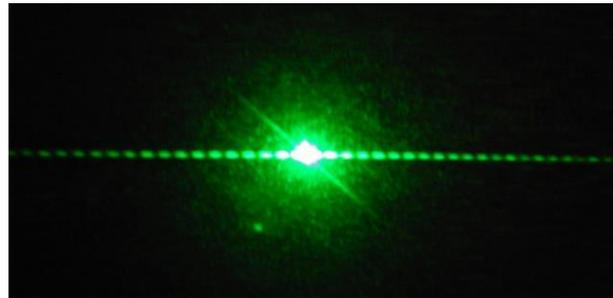
## Object:

- macroscopic:  
hard sphere (~5 cm)



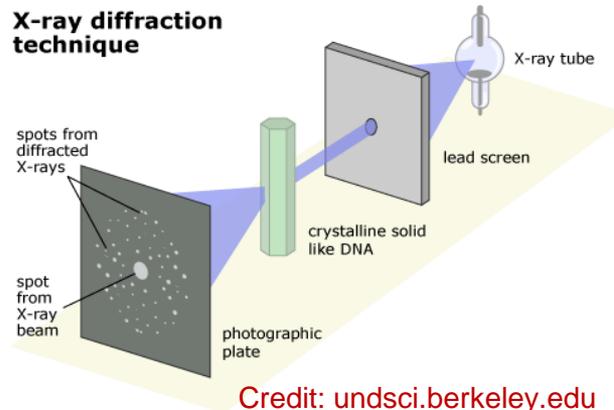
Tool:  
caliper

- small:  
hair (~60  $\mu\text{m}$ )



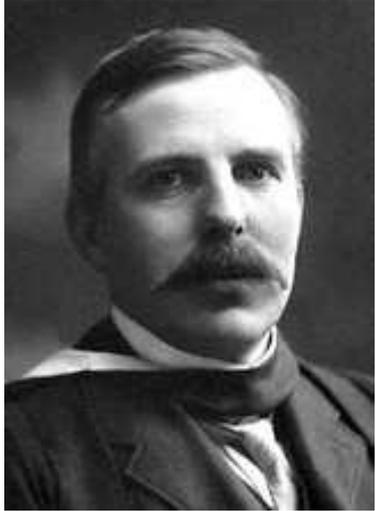
laser

- tiny:  
atom (~1 $\text{\AA}$ )



oil monolayer  
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?



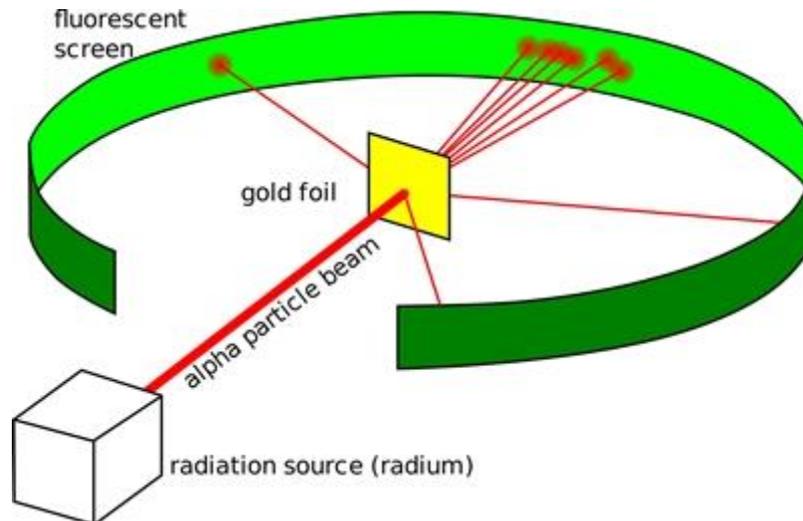
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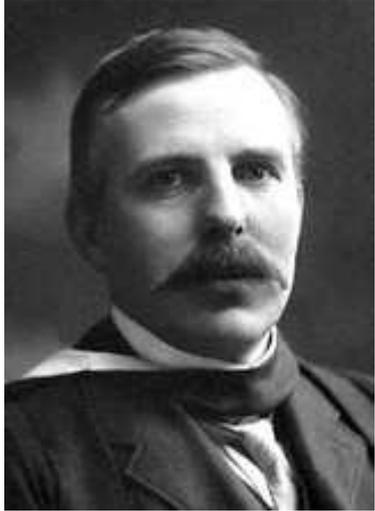
"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

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



Source: [Wikimedia Commons](#)

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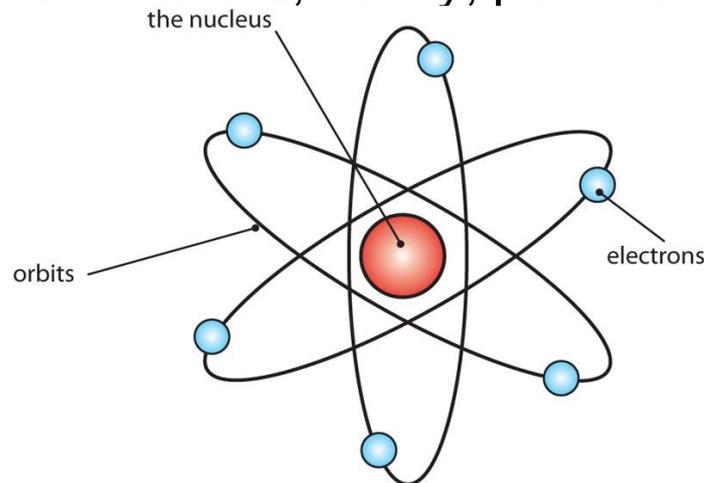
half-life;  $\alpha$  and  $\beta$  rays

1908: Nobel prize Chemistry:

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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)

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**Ernest Rutherford (1871 - 1937)**

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

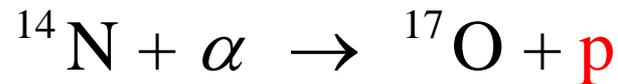
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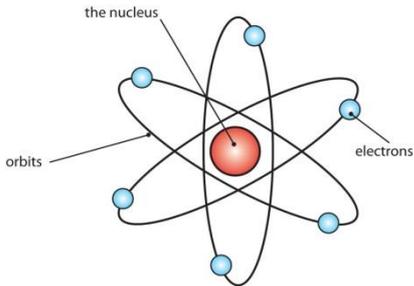
1911: Most  $\alpha$  particles pass a thin gold foil undeflected

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

**1917: Discovery of the proton**

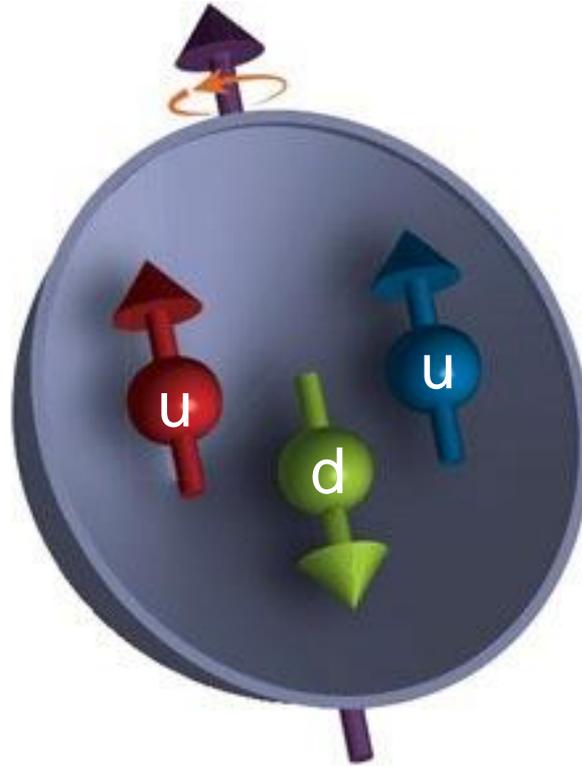


~1928: electron accelerators replace  $\alpha$  particles



# The Proton

Quark Model  
(1964)

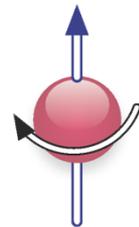


size: (~1 fm)

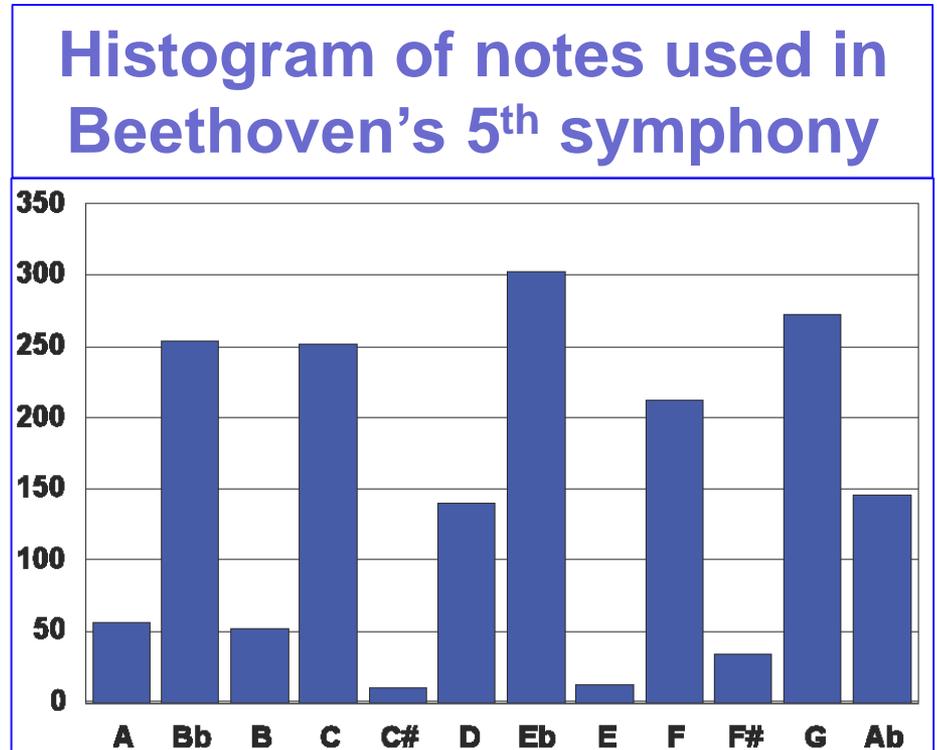
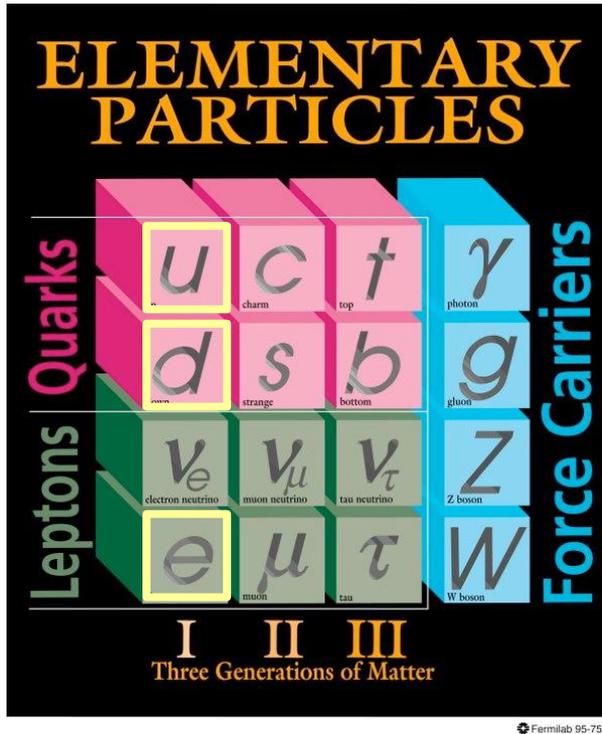
electric charge

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

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



# Proton - more than just constituents



sum=1670

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

# Proton - more than just constituents

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



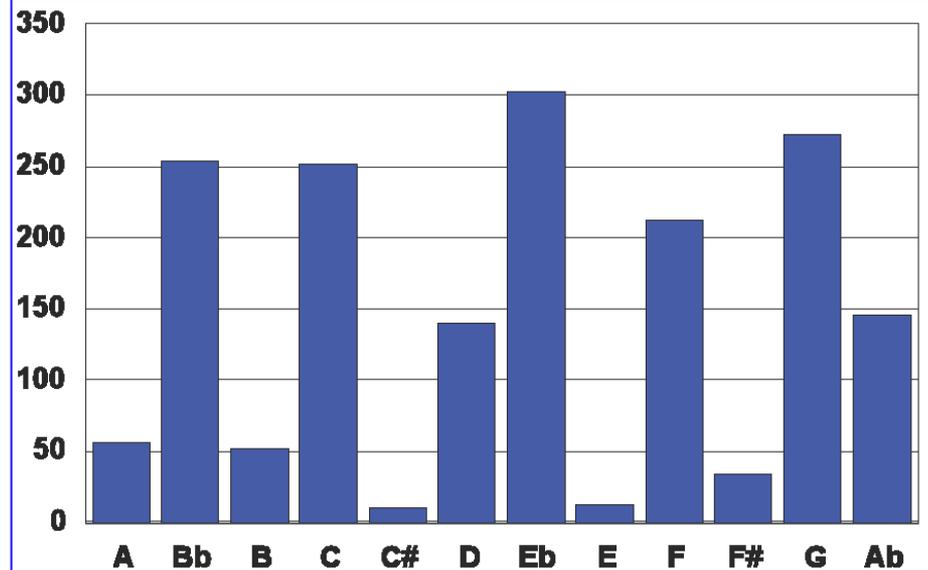
- adding rhythmic variation



- 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 radius?

- Scattering experiments**

(Hofstadter @ Stanford: 1950s - electron scattering)

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

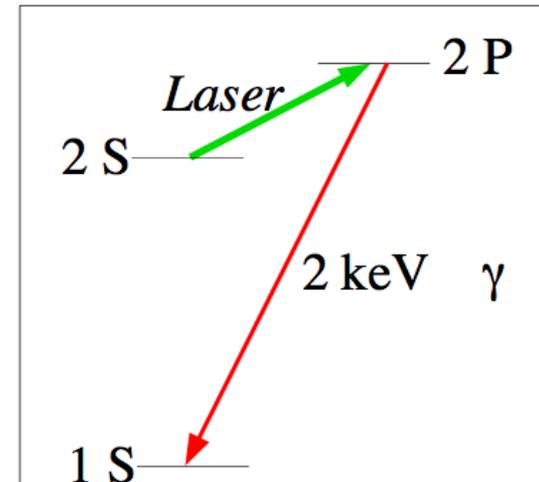
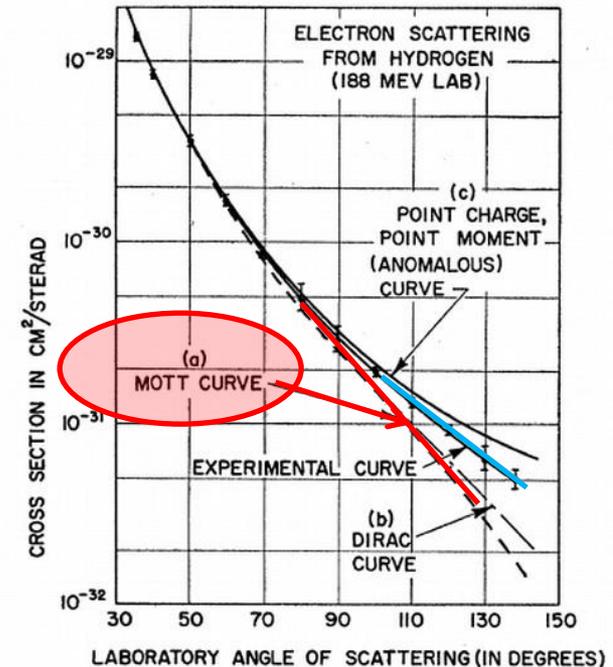
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG(Q^2)}{dQ^2} \Big|_{Q^2=0}$$

- Atomic Energy Levels**

(extract from hydrogen spectroscopy)

$$\Delta E_1 = \frac{2\pi\alpha}{3} |\phi^2(0)| \langle r_E^2 \rangle \quad (\text{Schwinger 1952})$$

- $\phi(0)$ :  $e^-$  wave-fct at origin in coord. space
- correction to **Lamb Shift**: finite size of proton changes hydrogen energy level (only affects s states significantly, not p states!)

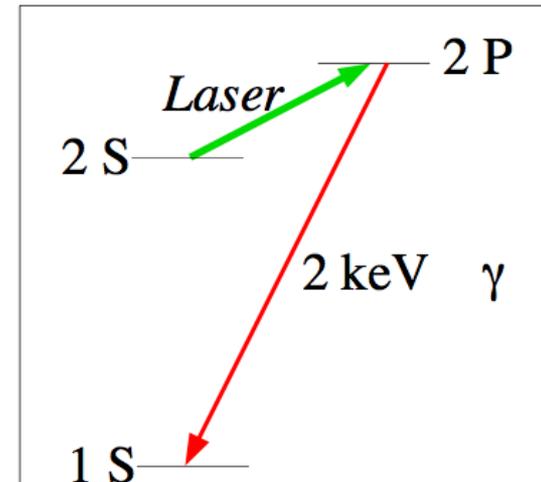
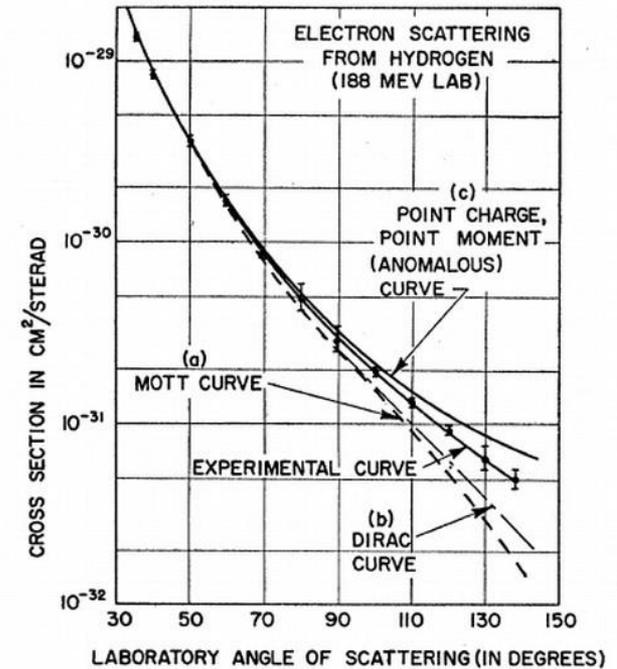


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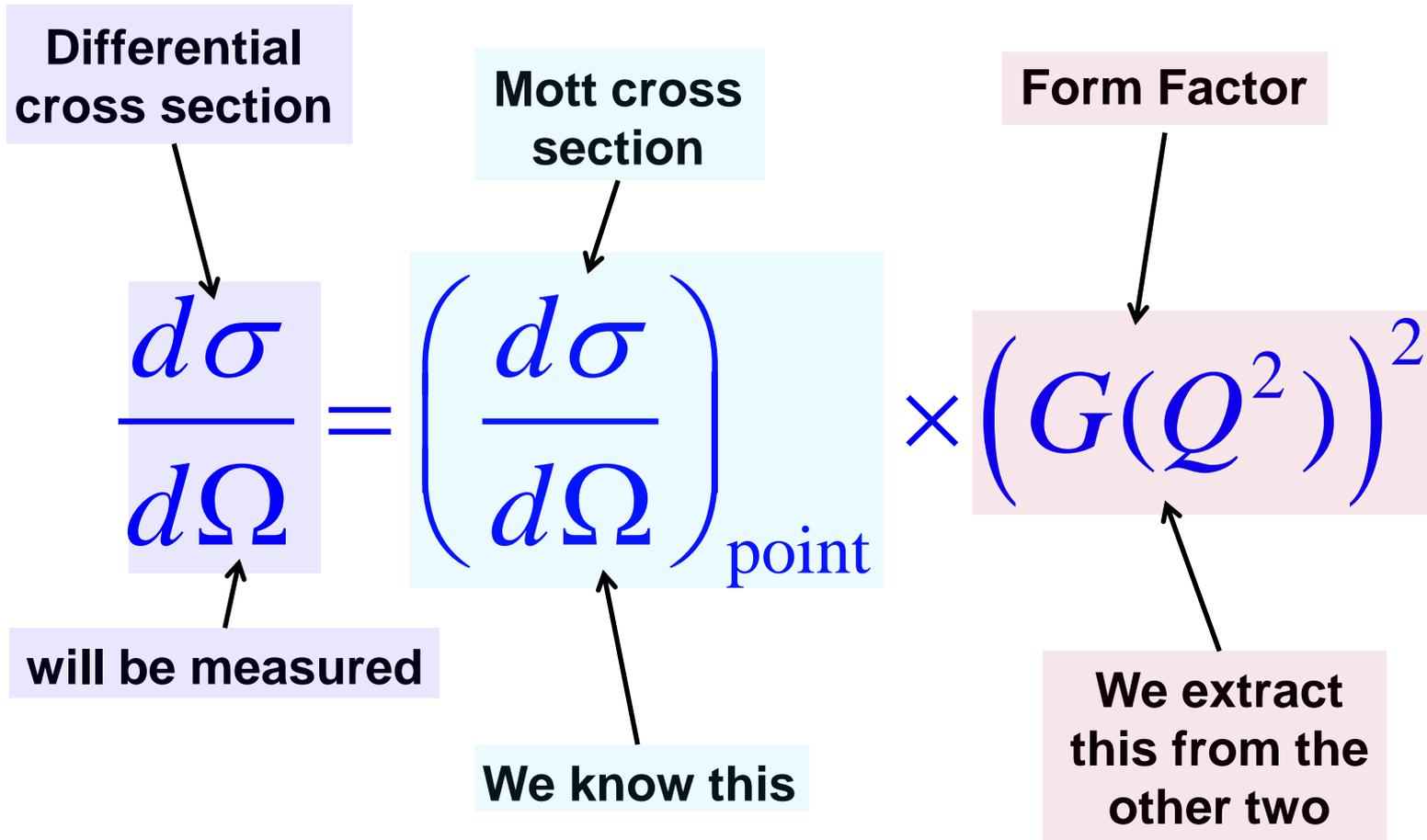
- **Scattering experiments**  
(Hofstadter @ Stanford: 1950s –  
extract from **electron scattering**)

↑  
equivalent  
↓

- **Atomic Energy Levels**  
(extract from **hydrogen spectroscopy**)



# 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

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

evaluated at momentum transfer =0

The diagram illustrates the extraction of the proton radius squared from scattering data. It features the equation  $r_E^2 = -6 \left. \frac{dG(Q^2)}{dQ^2} \right|_{Q^2=0}$ . Callouts explain that  $r_E^2$  is the proton radius squared, the fraction is the slope of the form factor as a function of momentum transfer, and the evaluation is at  $Q^2=0$ .

# Electron Scattering Measurements

- Cross section for ep scattering (Born approximation)

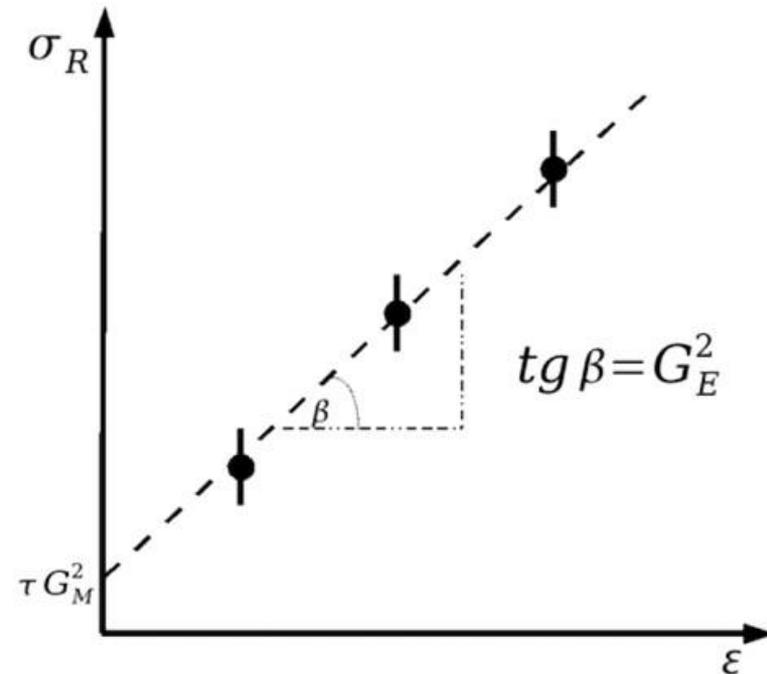
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega} \Big|_{Mott} \frac{1}{\varepsilon(1+\tau)} \overbrace{\left[ \tau G_M^2 + \varepsilon G_E^2 \right]}^{\sigma_R}; \quad \text{with } \tau = \frac{Q^2}{4M^2} ; \quad \varepsilon = \left[ 1 + 2(1+\tau) \tan^2 \frac{\theta}{2} \right]^{-1}$$

$G_E^2(0) = 1$ ;  $G_M^2(0) = \mu_p$ 
current density
charge distr.

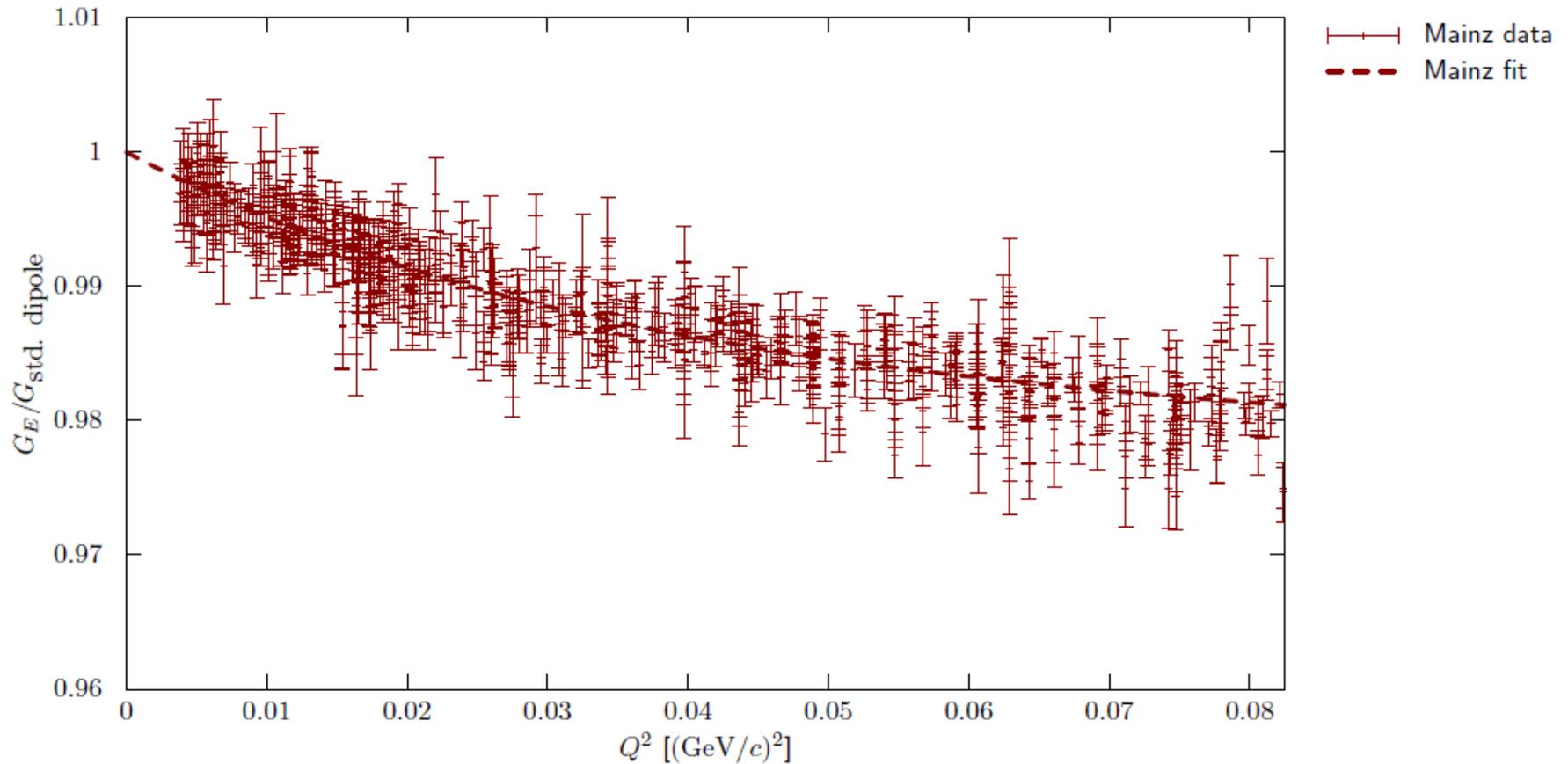
$$Q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

Mott cross section is scattering of an unpolarized spin-1/2 electron from a point-like spin-0 target

- Classical **Rosenbluth separation**
  - measure the reduced cross section at several values of  $\varepsilon$  (angle/beam energy combination) while keeping  $Q^2$  fixed
  - linear fit to get intercept and slope
- Note:  $G_M$  is suppressed at low  $Q^2$   
 $\rightarrow G_E$  dominates cross section at low  $Q^2$
- Alternatively:** direct fits of  $G_M(Q^2)$  and  $G_E(Q^2)$  to experimental cross section data



# Extracting the proton radius



A sample  $G_E(Q^2)$  behavior

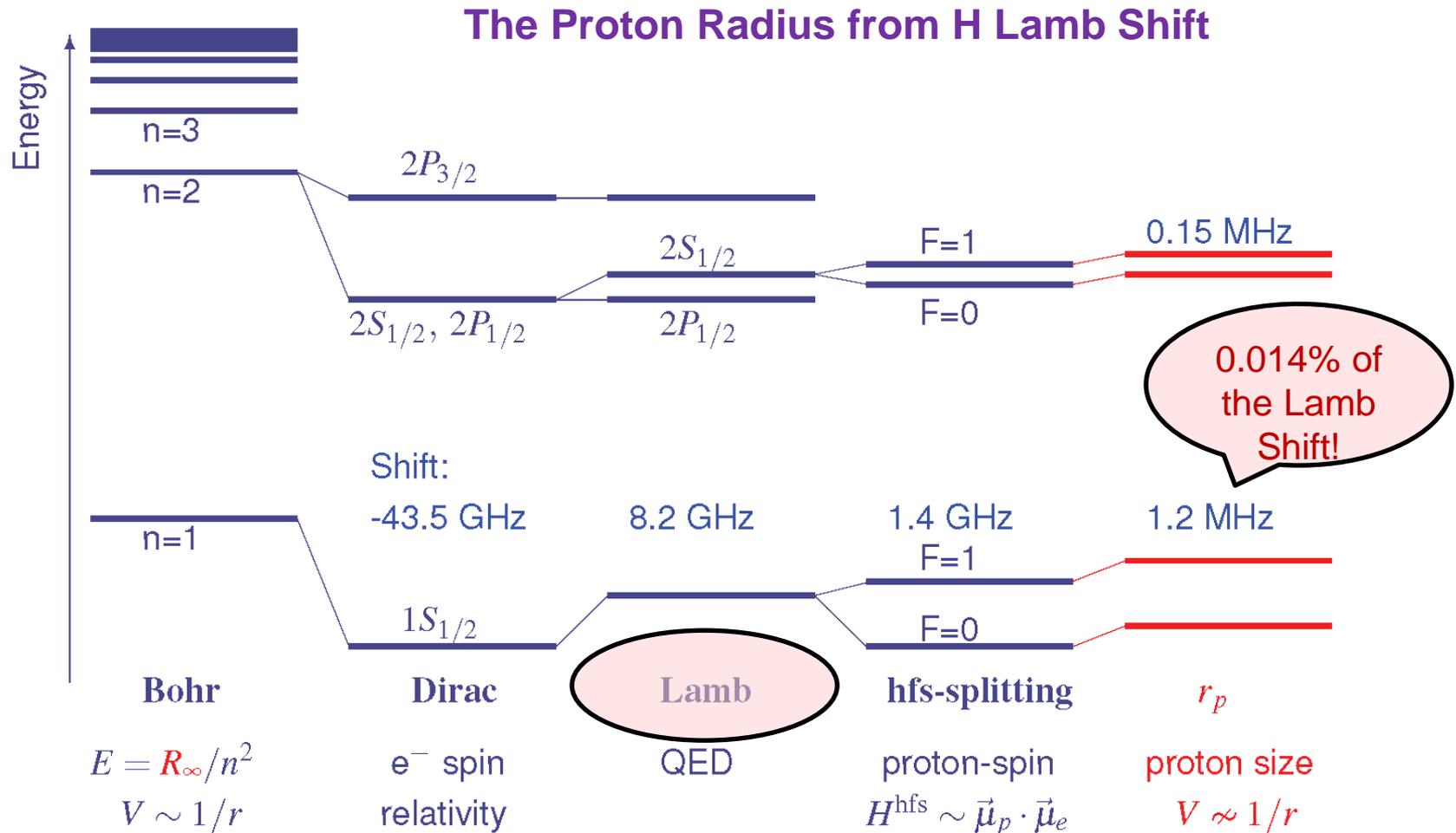
# Standard Dipole Form Factor

- describes spatial distribution of charge or magnetization within a particle
- serves as an approximation to model the way internal structure of a particle influences its interaction with e-m fields
- Standard **Dipole Approximation** (functional form):

$$G(Q^2) = \frac{1}{(1 + Q^2 / \Lambda^2)^2}$$

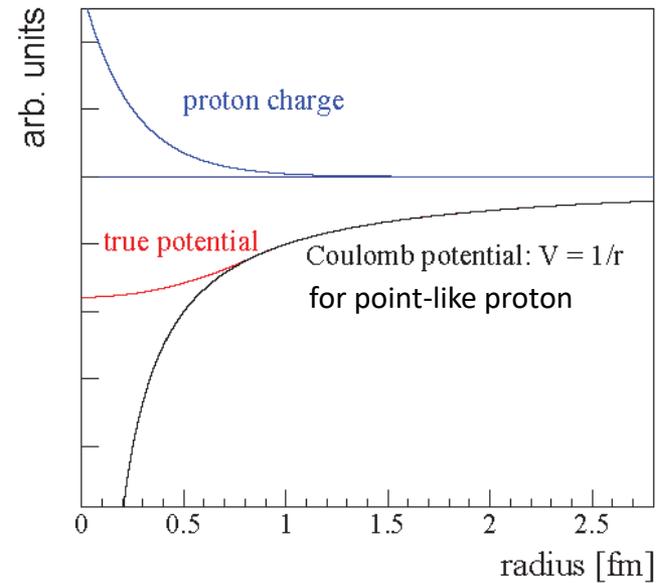
- $Q^2$ : squared four-momentum transfer in interaction, related to spatial resolution of probe
  - $\Lambda^2$ : cutoff parameter related to the size of the particle
  - “dipole”: form resembles potential of a dipole field in certain limits
  - $G(Q^2)$  dependence implies a rapid fall-off of form factor at high  $Q^2$ , consistent with finite size of particle
- simplifies theoretical calculations and provides a reasonable first-order approximation of the experimental data

# Hydrogen Spectroscopy Measurements



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

# Finite-size shift of atomic energy levels



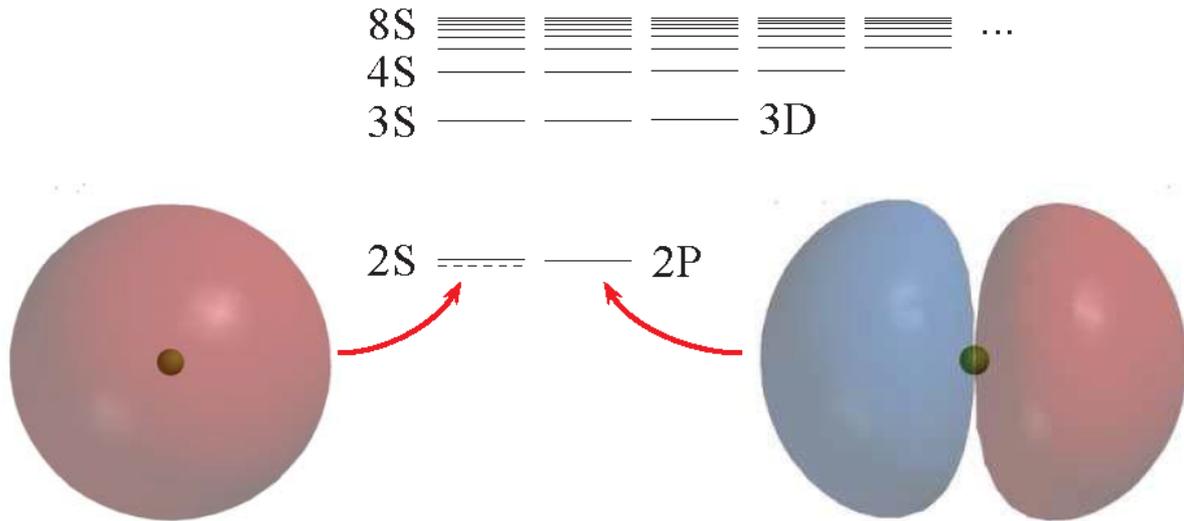
S states: max. at  $r=0$

Electron sometimes **inside** the proton.

**S states are shifted.**

Shift is proportional to the

**size of the proton**



P states: zero at  $r=0$

Electron is **not** inside the proton.



Orbital pictures from Wikipedia

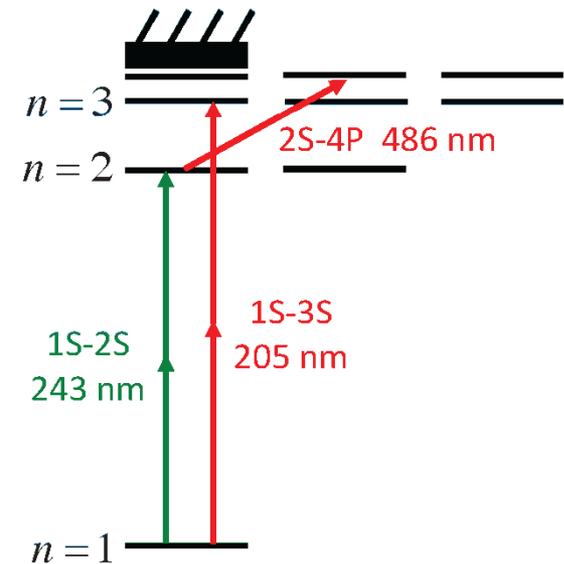
Pictures: R. Pohl

# Hydrogen Atom Spectroscopy

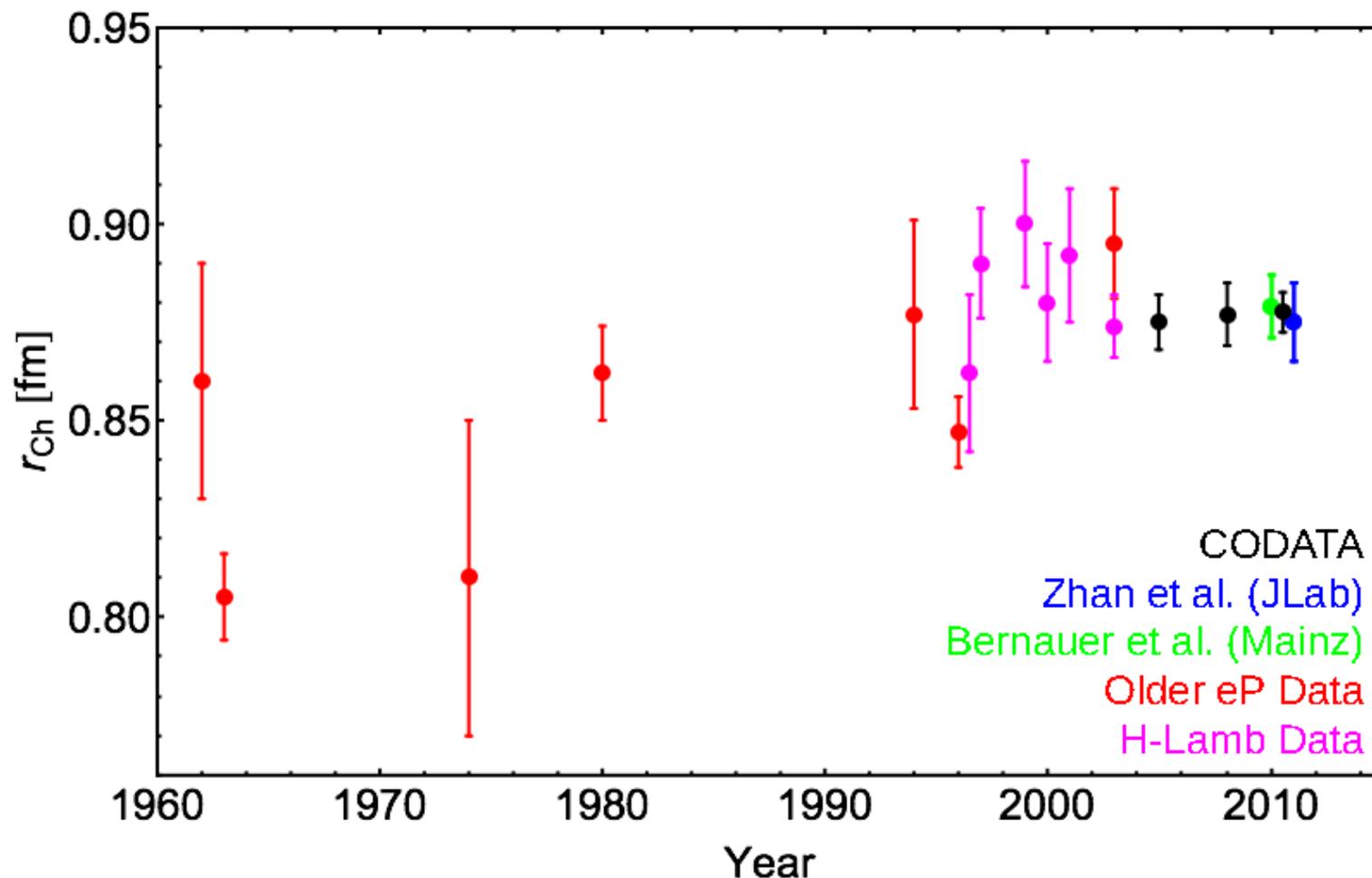
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

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

- 2 measurements required to determine  $R_\infty$  and  $r_p$ 
    - A **single** narrow transition: 1S-2S ( $\Delta\nu = 1.3$  Hz) measured with high accuracy.
    - Other transitions: natural width  $\sim$  MHz.
- Each measurement, combined with 1S-2S, yields a **correlated pair**  $(R_\infty, r_p)$ .



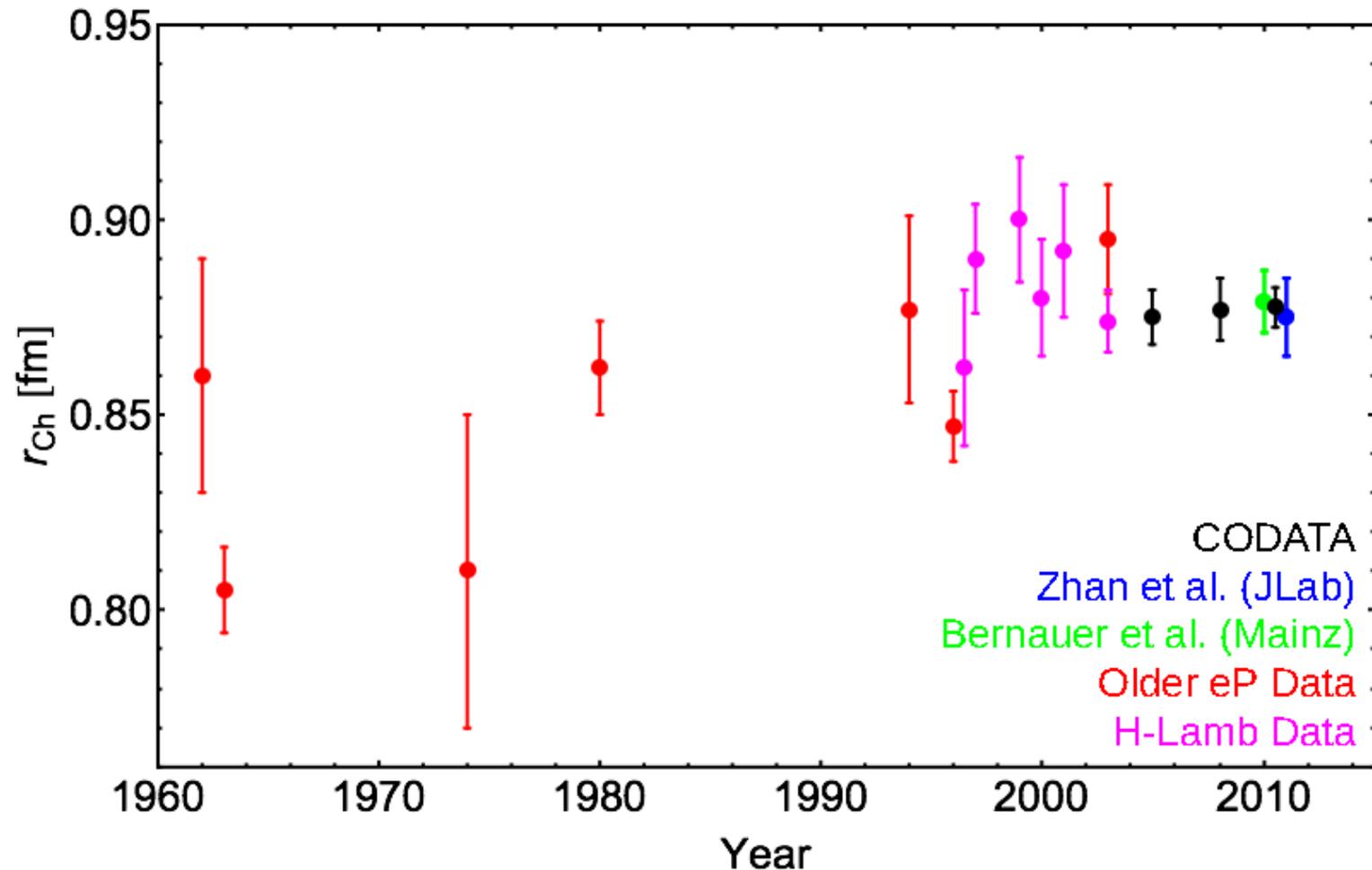
# The Proton Radius from H Lamb Shift and ep



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

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

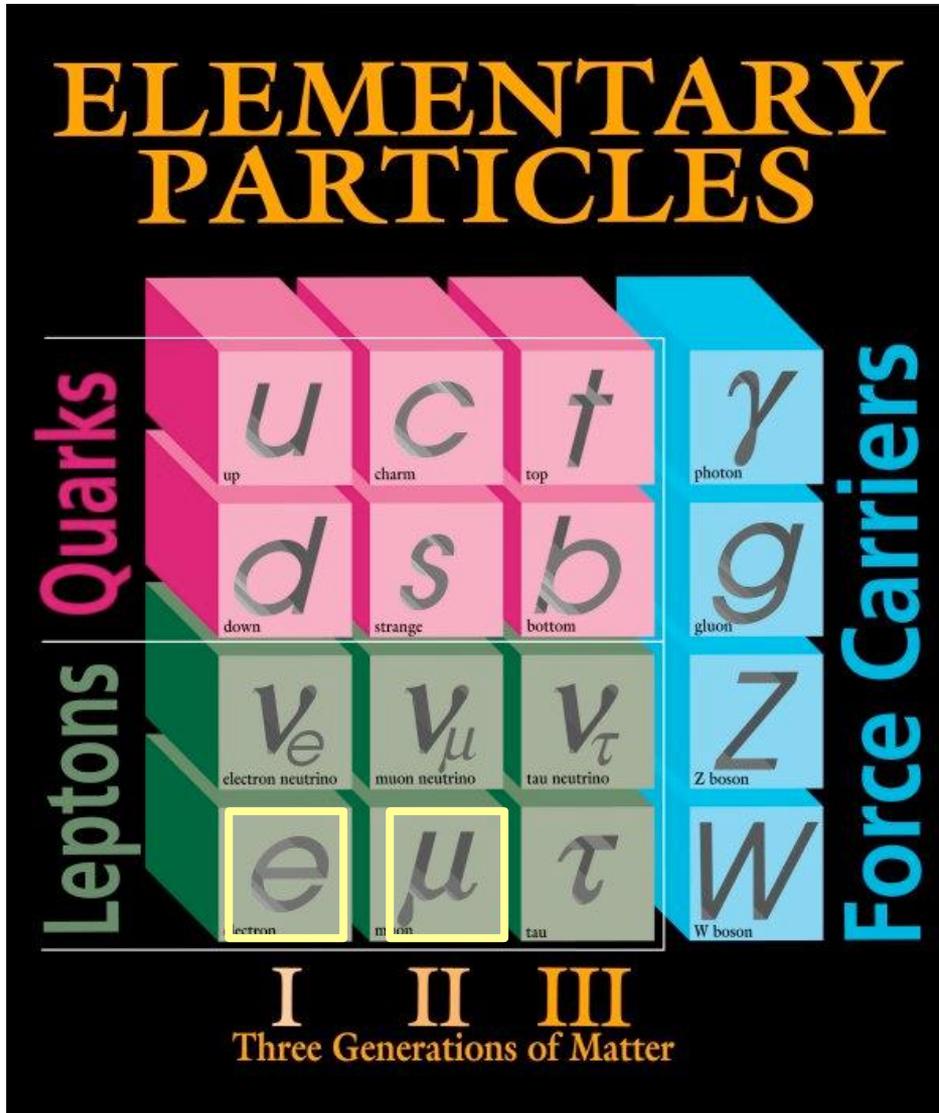
# The Proton Radius from H Lamb Shift and $e\text{p}$



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

**But can we do better?** use Muonic Hydrogen

# Why use Muonic Hydrogen?



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

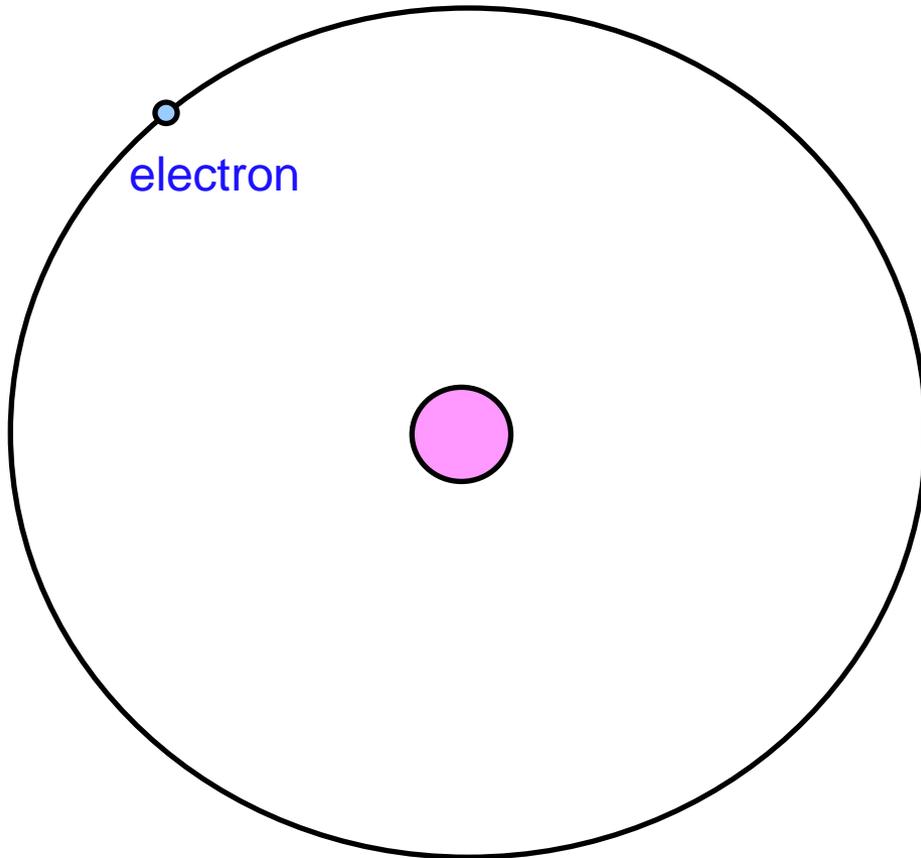
The muon decays into an electron (and some neutrinos) with a lifetime of  $\sim 2.2 \mu\text{s}$

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

# Why Measure with $\mu\text{H}$ ?

Regular hydrogen:

electron  $e^-$  + proton  $p$



Muonic hydrogen:

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

muon mass  $m_\mu = 207 m_e$

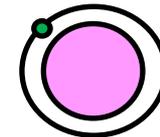
Bohr radius  $a_{B,\mu} = 1/207 a_{B,e}$

Probability for  $\mu^-$  to be inside proton:

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

$\rightarrow 207^3 \approx 8 \text{ million}$

muon

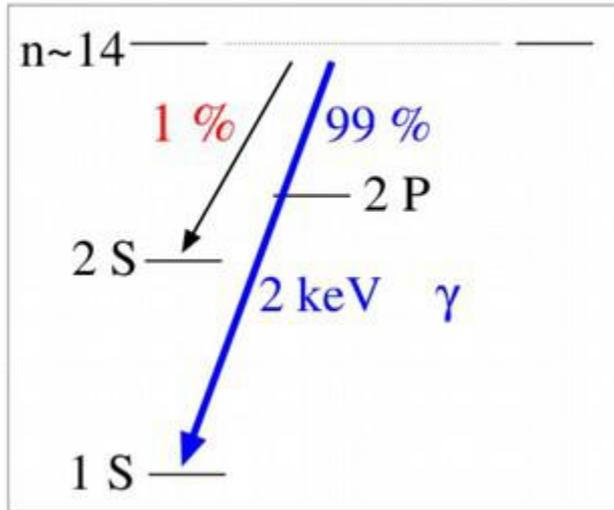


muon is **much** more sensitive to proton radius

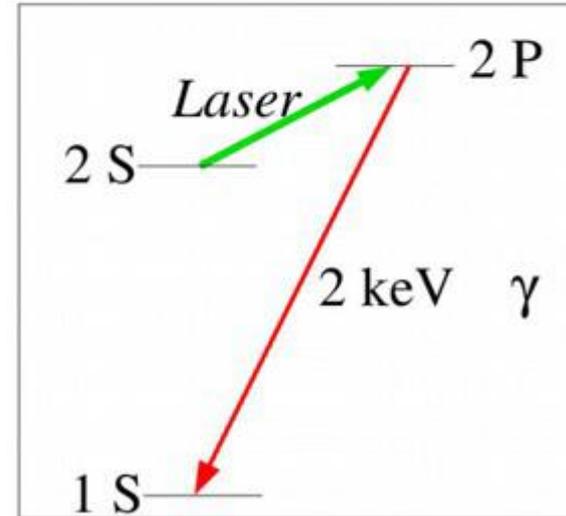
figure not to scale ( $r_{\text{atom}} / r_p \sim 50,000$  (250) for  $e$  ( $\mu$ ))

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

“prompt” ( $t \sim 0$ )



“delayed” ( $t \sim 1\ \mu\text{s}$ )

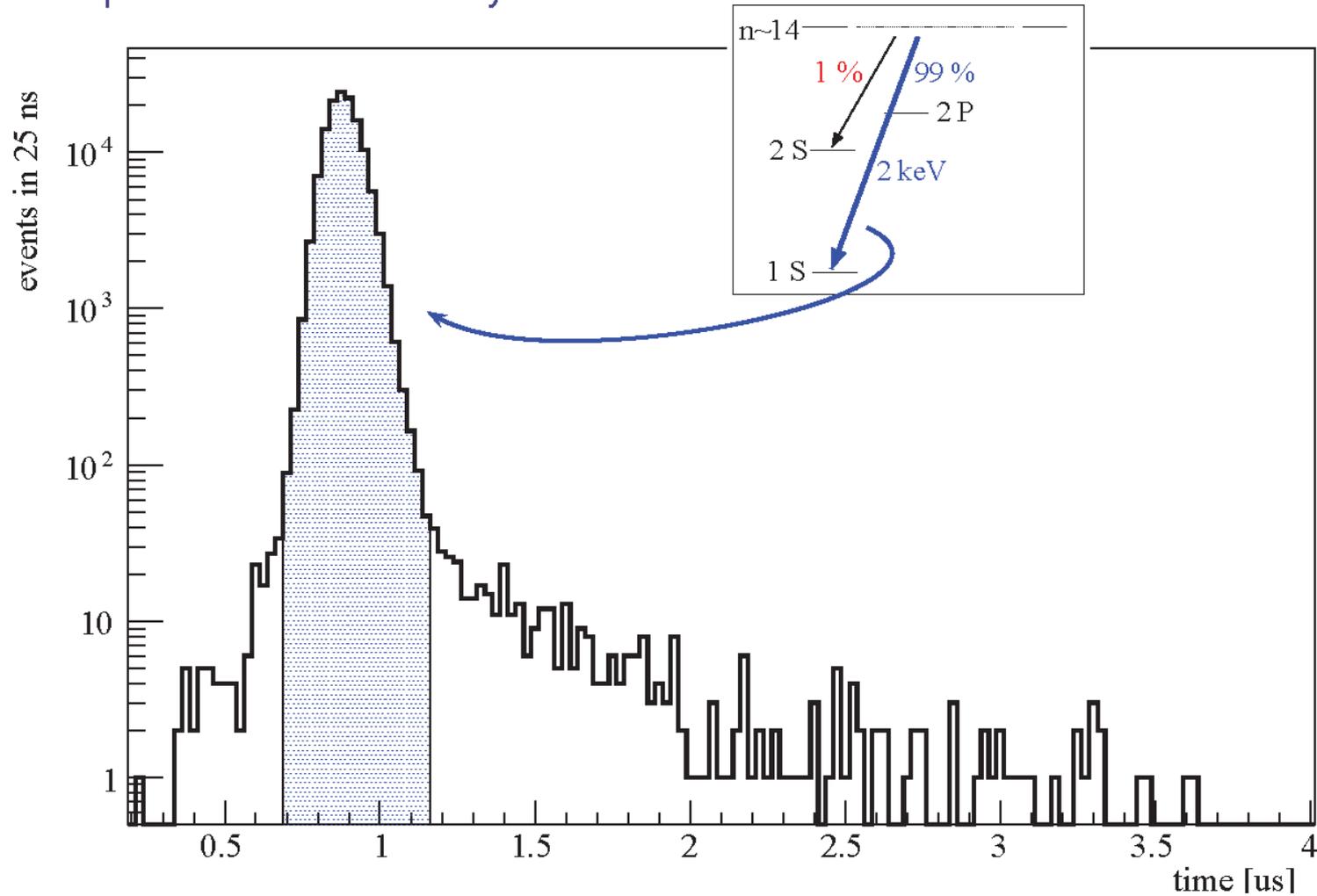


- beautifully simple, but technically challenging!
- form  $\mu\text{H}^*(n \sim 14)$  by shooting  $\mu$  beam on 1 mbar  $\text{H}_2$  target
  - 99% decay to  $1\text{S}$ , giving out fast  $\gamma$  pulse
  - 1% decay to longer-lived  $2\text{S}$  state
  - $2\text{S}$  state excited to  $2\text{P}$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

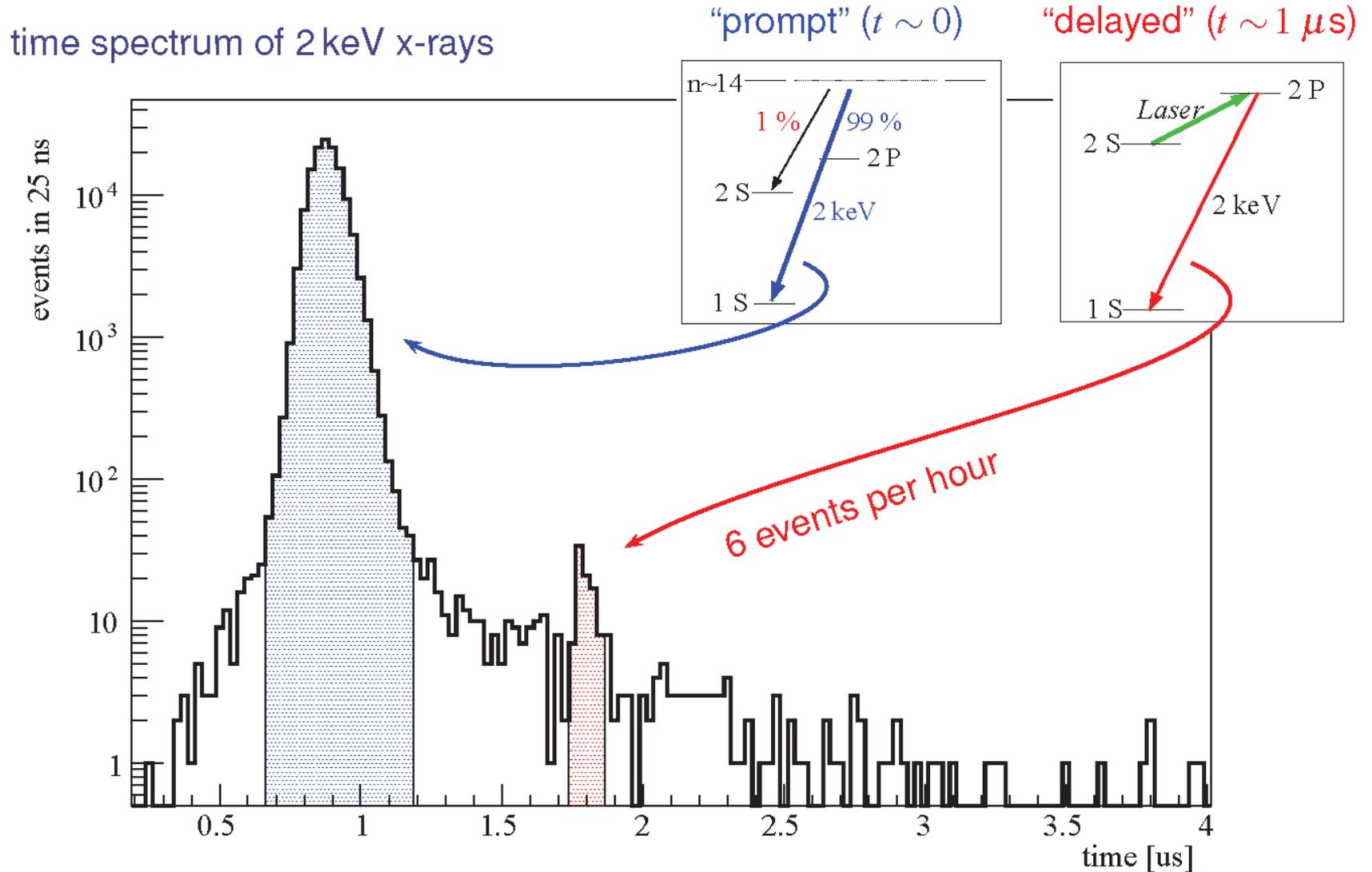
# How to Measure with $\mu\text{H}$ ?

time spectrum of 2 keV x-rays

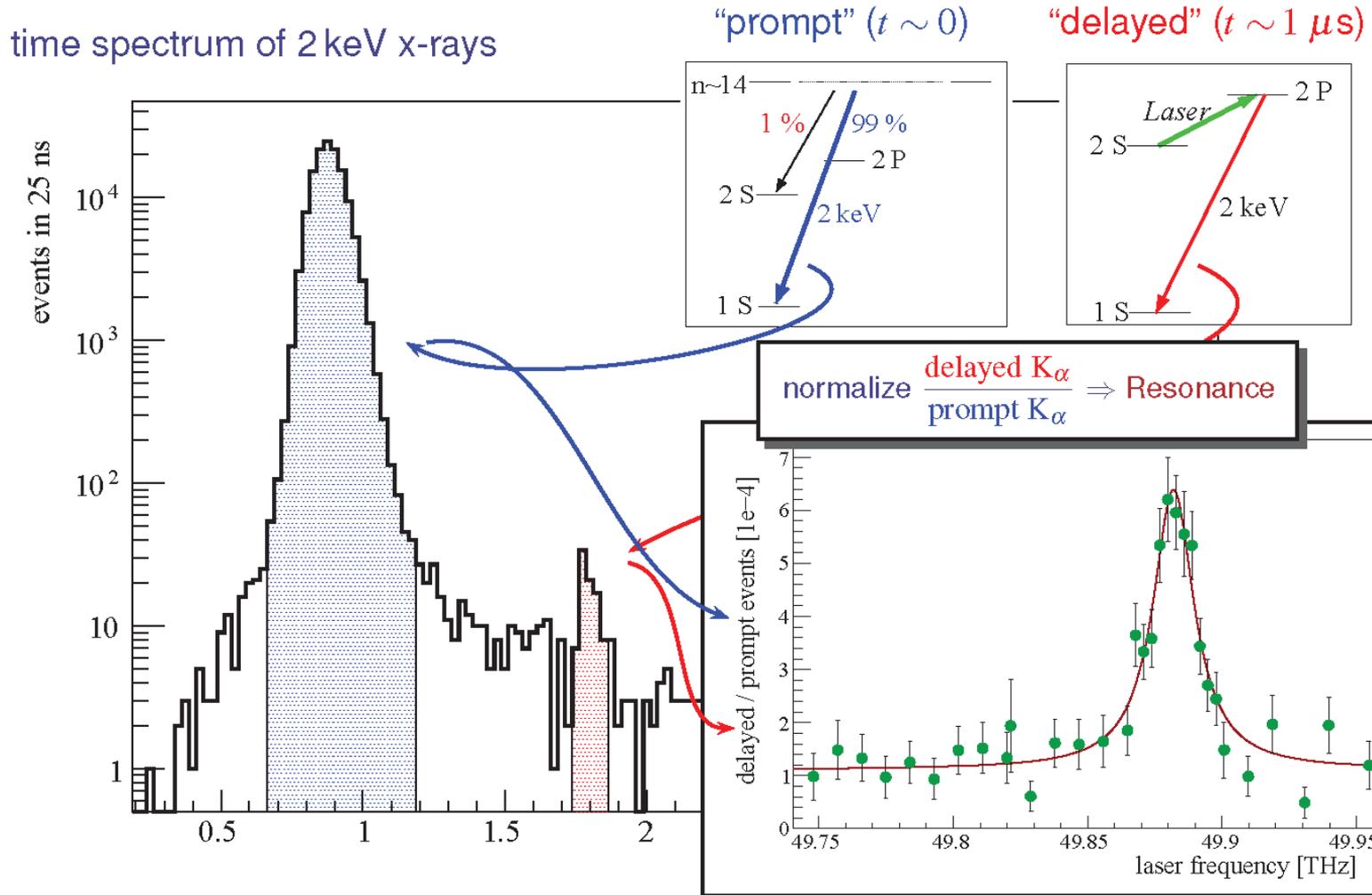
"prompt" ( $t \sim 0$ )



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



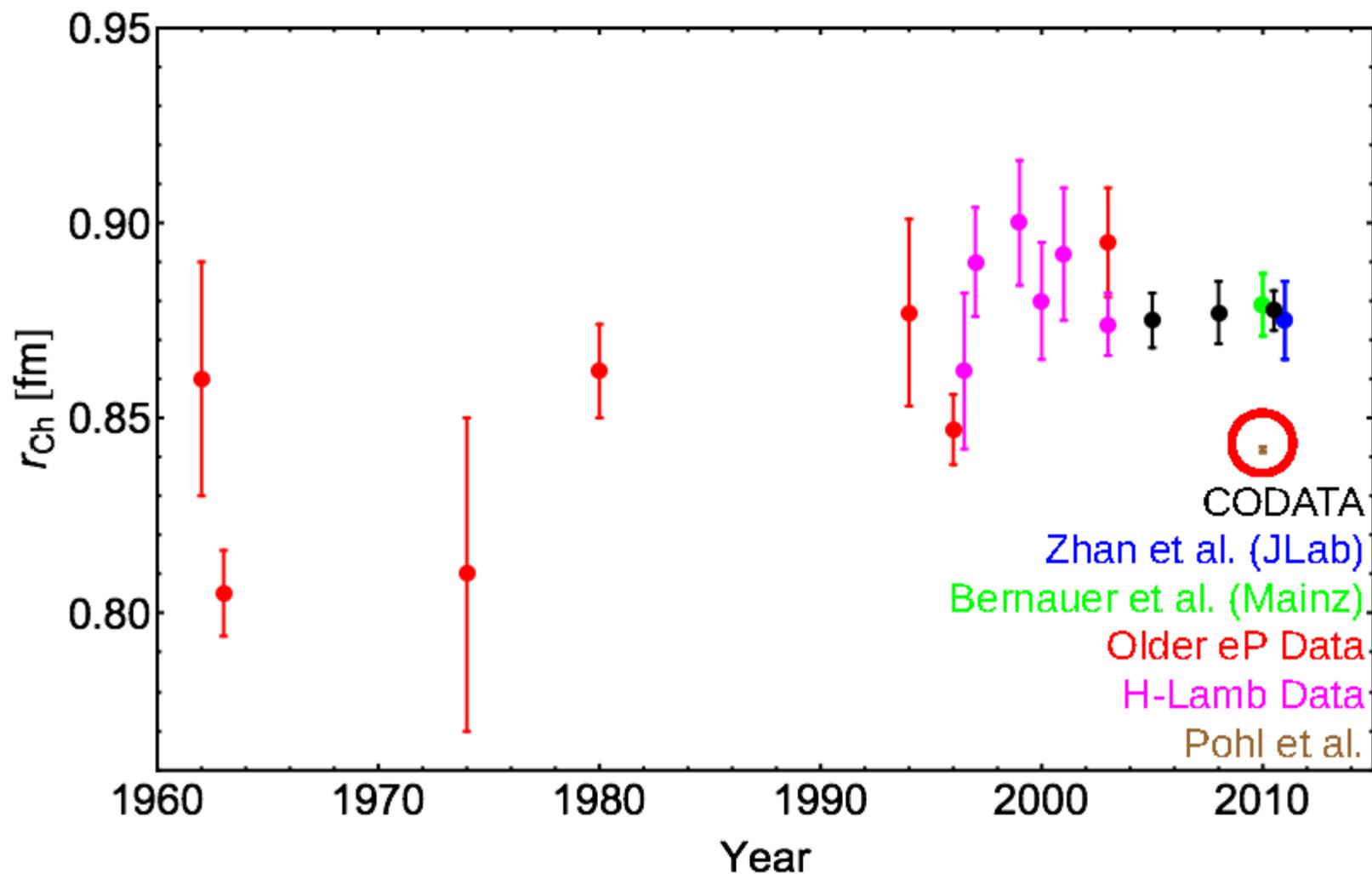
# Proton Radius from $\mu\text{H}$



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

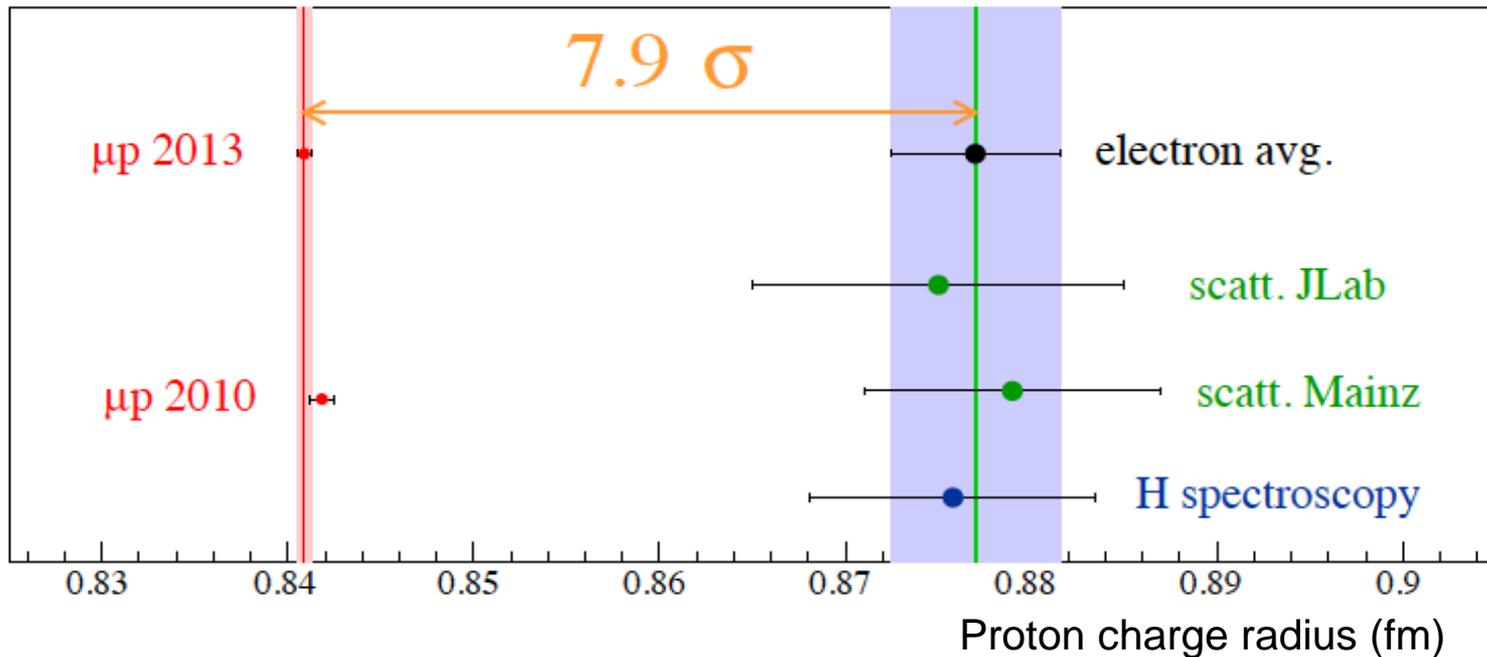


# The Original Proton Radius Puzzle (2013)

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

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

# Why do the muon and electron give different proton radii?

- **Experimental error in  $\mu p$  measurement ?**
  - seems unlikely
- **Experimental error in ep measurements ?**
  - both scattering and H-spectroscopy are wrong?
  - Rydberg constant off by  $5\sigma$ ?
  - fit procedures not good enough?
  - $Q^2$  not low enough, or structures in the form factors?

- **Theory Error?**

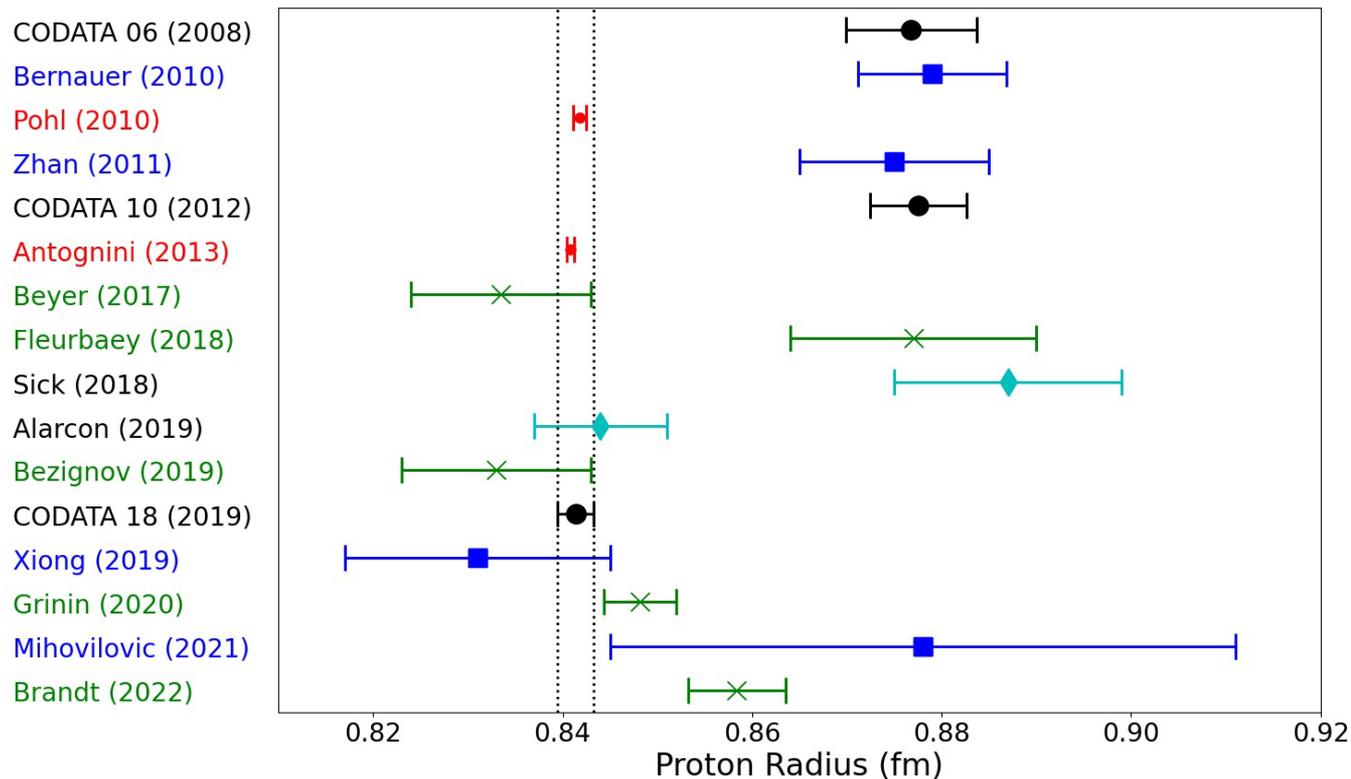
#	Contribution	Ref.	Our selection		Pachucki [31–33]		Borie [34]	
			Value	Unc.	Value	Unc.	Value	Unc.
1	NR One loop electron VP	[31,32]			205.0074			
2	Relativistic correction (corrected)	[31–34]			0.0169			
3	Relativistic one loop VP	[34]	205.0282				205.0282	
4	NR two-loop electron VP	[14,34]	1.5081		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 $\alpha(Z\alpha)^4 m_p$	[44–46]	0.01077	0.00038	0.0113	0.0003	0.011	0.002
15	Hadronic polarization $\alpha(Z\alpha)^5 m_p$	[45,46]	0.000047					
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_p$	[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 $\alpha^5(Z\alpha)^6 m_p$	[19,32]	-0.66770		-0.6677		-0.66788	
21	Muon Lamb shift 4th order	[34]	-0.00169				-0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m_p}{M} m_p$	[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 $\alpha(Z\alpha)^5 \frac{m_p}{M} m_p$	[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 $\alpha(Z\alpha)^5 m_p$	[46]	0.00019					
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_p$	[46]	-0.00001					
	Sum		206.0573	0.0045	206.0432	0.0023	206.05856	0.0046

# Why do the muon and electron give different proton radii?

- **Experimental error in  $\mu p$  measurement ?**
  - seems unlikely
- **Experimental error in  $ep$  measurements ?**
  - both scattering and H-spectroscopy are wrong?
  - Rydberg constant off by  $5\sigma$  ?
  - fit procedures not good enough?
  - $Q^2$  not low enough, or structures in the form factors?
- **Theory Error?**
  - checked, rechecked, and checked again
  - .... is framework wrong?
- **Everybody is correct ? New Physics !**
  - **BSM Physics**
    - violation of lepton universality, light massive gauge bosons(s)
  - **Novel Hadronic Physics**
    - proton polarizability affects  $\mu$ , but not  $e$  (effect  $\propto m_l^4$ )
    - two-photon exchange corrections (effects important at high  $Q^2$ )

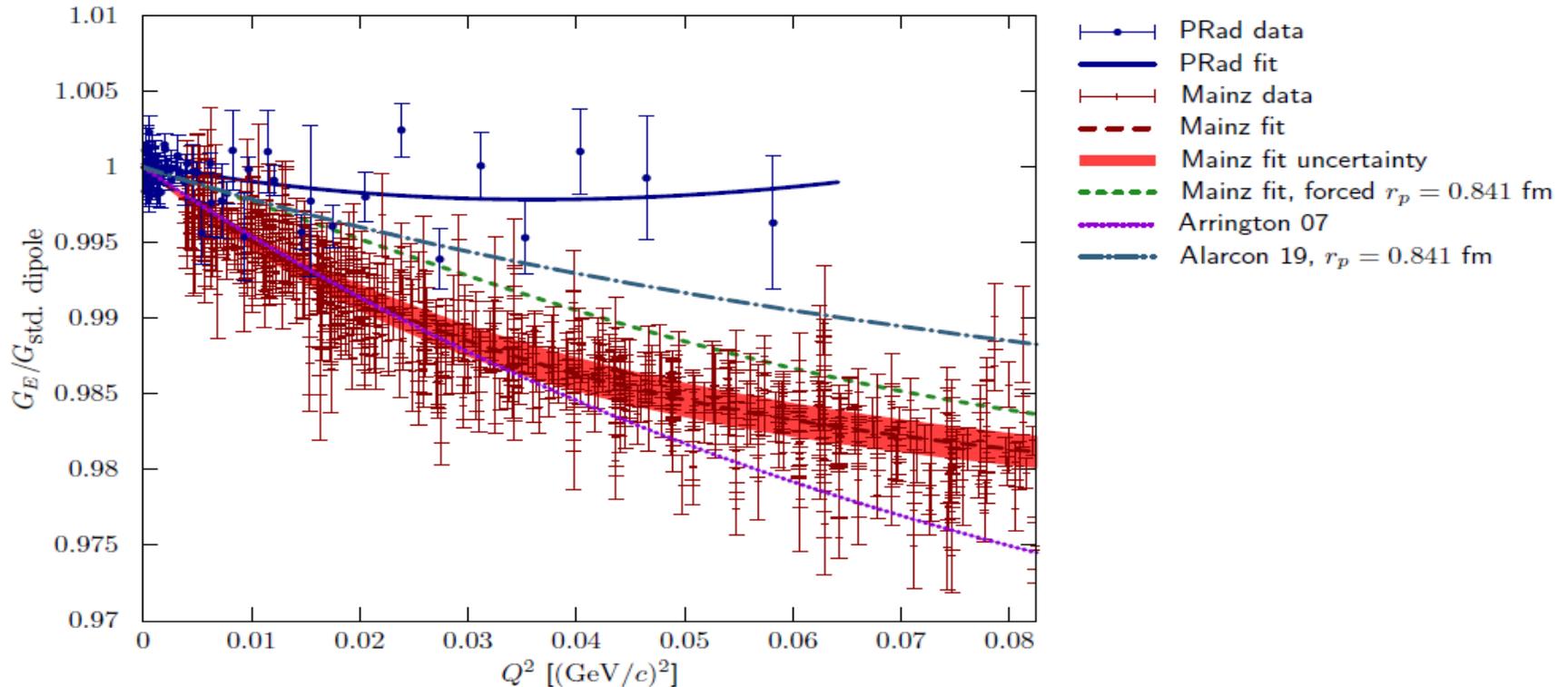
**Need More Data**

# The Puzzle Deepens: 2023 Status



black = CODATA  
blue = ep scattering  
red =  $\mu$ -H spectroscopy  
green = atomic-H spectroscopy  
light blue = re-fitting of ep scattering

# A closer look at Low- $Q^2$ Form Factor Measurements



- cross sections and form factors of PRad are different - why?
  - accuracy of radiative corrections?
  - which result is to be preferred, and why?
  - “higher”  $Q^2$  data seems to affect the slopes at  $Q^2 \rightarrow 0$
- need independent checks
  - redoing electron scattering at lower  $Q^2$ ?

# The Quest for New Data

## ■ Experiments include

- redoing atomic hydrogen
  - conflicting results: more careful systematics?
- light muonic atoms for radius comparison in heavier systems
  - puzzle seen in H & D, but not in He: (Z=1 radius puzzle?)
- redoing electron scattering at lower  $Q^2$ 
  - many efforts (backup slide)
  - PRad (windowless H<sub>2</sub> gas flow target → removes major bkgds)  
is consistent with  $\mu p$  results!
  - PRad-II starting 2025
- **Muon (elastic) scattering!**
  - never been done with high precision!
  - **MUSE** (first muon proton scattering experiment: 2023-2025)
  - plans at AMBER (100 GeV SPS muon beam at CERN: 2025)

# Motivation for $\mu p$ scattering

Electronic hydrogen

$0.8758 \pm 0.0077$

Spectroscopy

Muonic hydrogen

$0.84087 \pm 0.00039$



Electron scattering

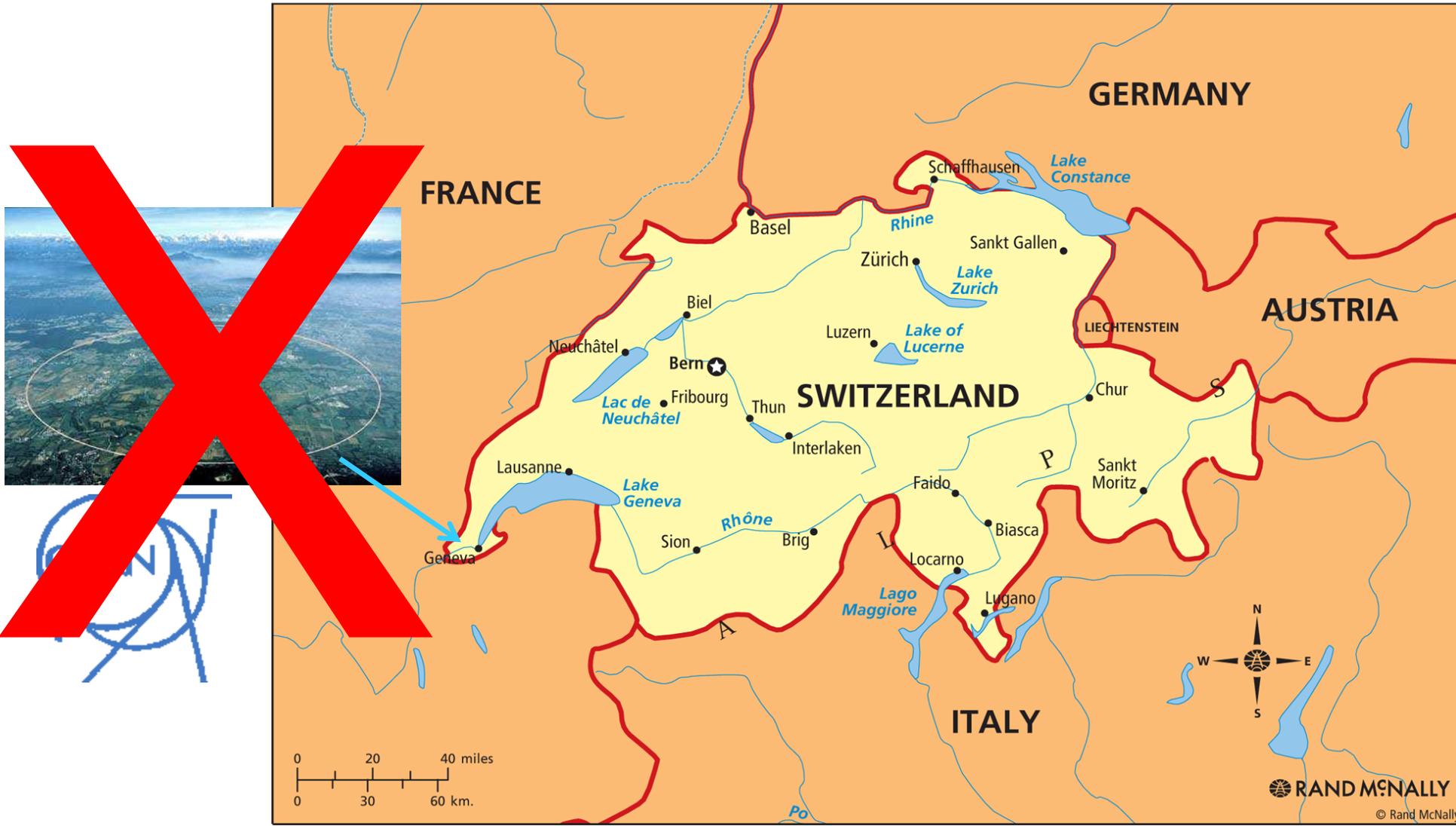
$0.8770 \pm 0.0060$

Scattering

Muon scattering

???

# Swiss Muons



# Swiss Muons

Paul Scherrer Institut  
Villigen, Switzerland



# MUon Scattering Experiment (MUSE) at PSI

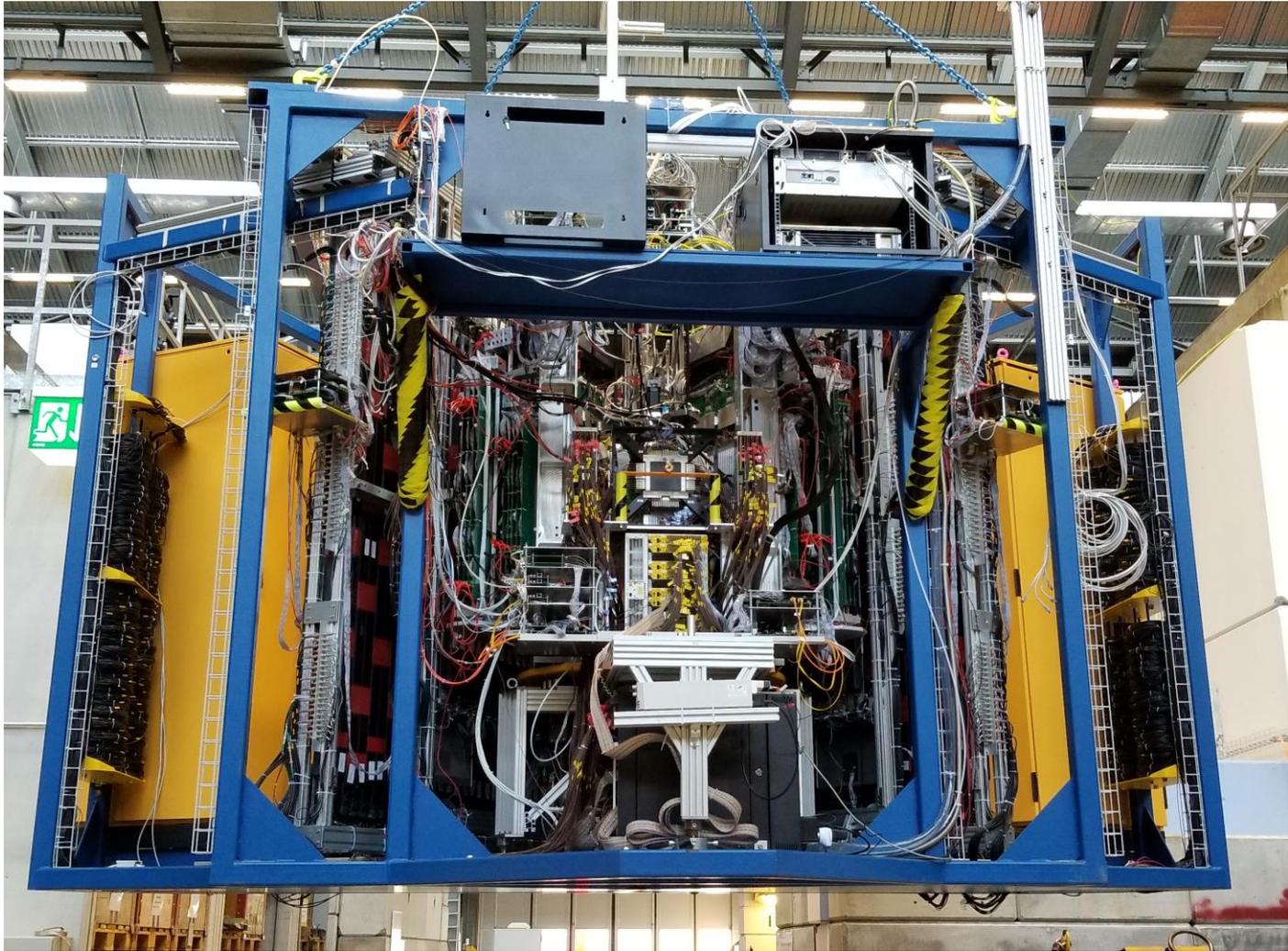


Direct comparison of  $\mu p$  &  $ep$  scattering!

- beam of  $e^+/\pi^+/\mu^+$  or  $e^-/\pi^-/\mu^-$  on  $\text{LH}_2$  target
  - separate particles by TOF, charge by magnets
- charge reversal: test two photon effects
- absolute cross sections for  $ep$  and  $\mu p$ 
  - use ratio to cancel (many) systematics
- momenta: 115, 160, 210 MeV/c and scattering angles:  $20^\circ - 100^\circ$ 
  - $Q^2 = 0.0016 - 0.08 \text{ GeV}^2$



# MUSE: an unusual Scattering Experiment

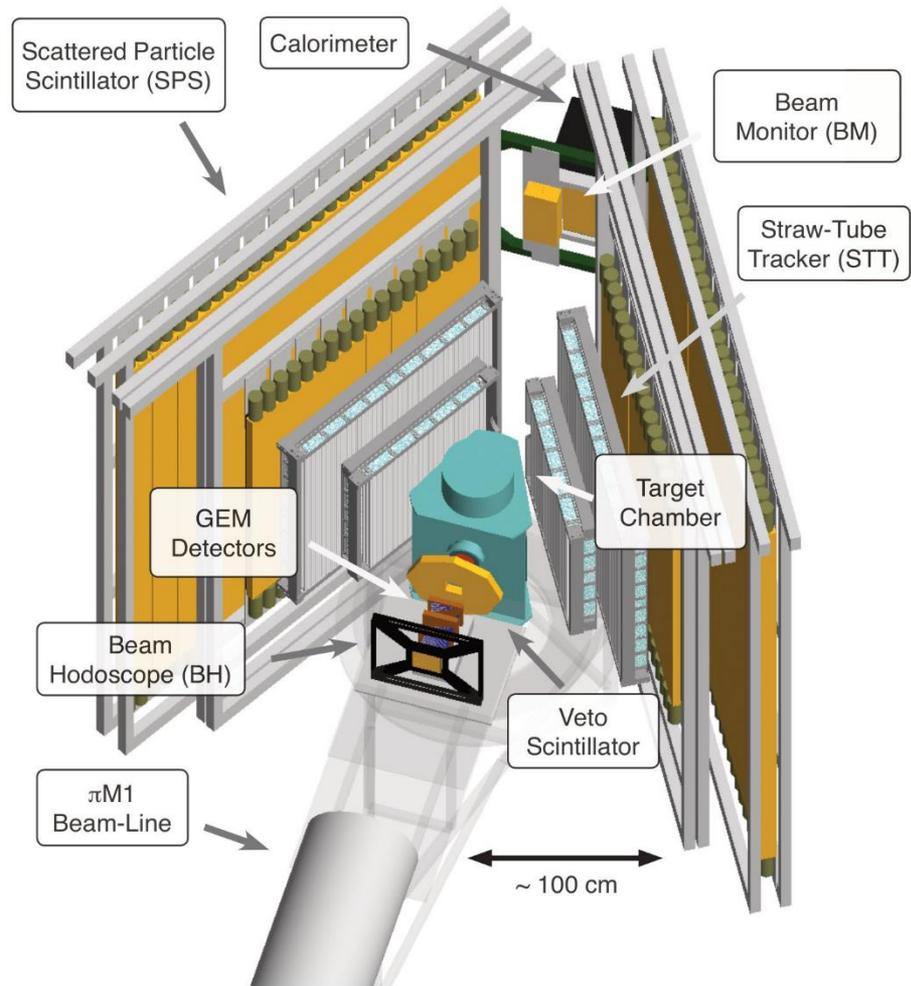


MUSE sits on a platform that can be craned in and out of  $\pi$ M1

# MUSE: an unusual Scattering Experiment

## A closer look

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

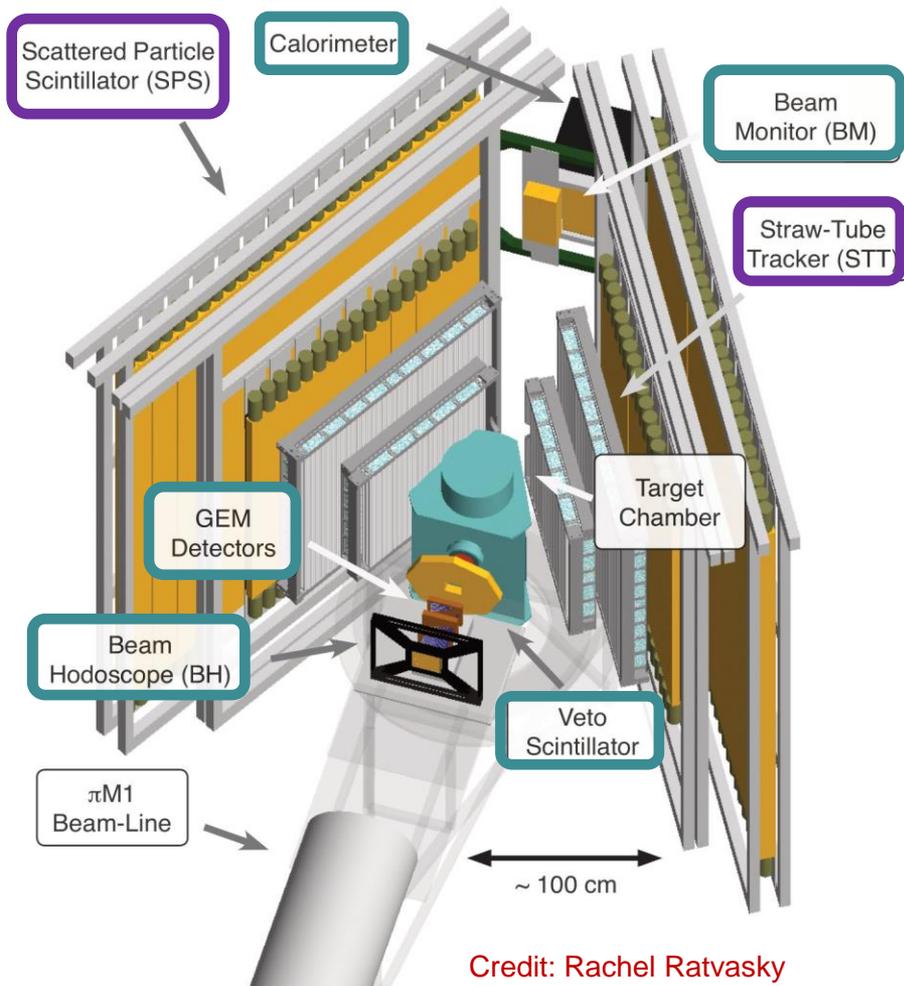


# MUSE experiment layout

## Detectors

**Beamline detectors** measure & monitor incoming & unscattered particles

**Scattering detectors** measure scattered particles



# MUSE experiment layout

## Beamline detectors

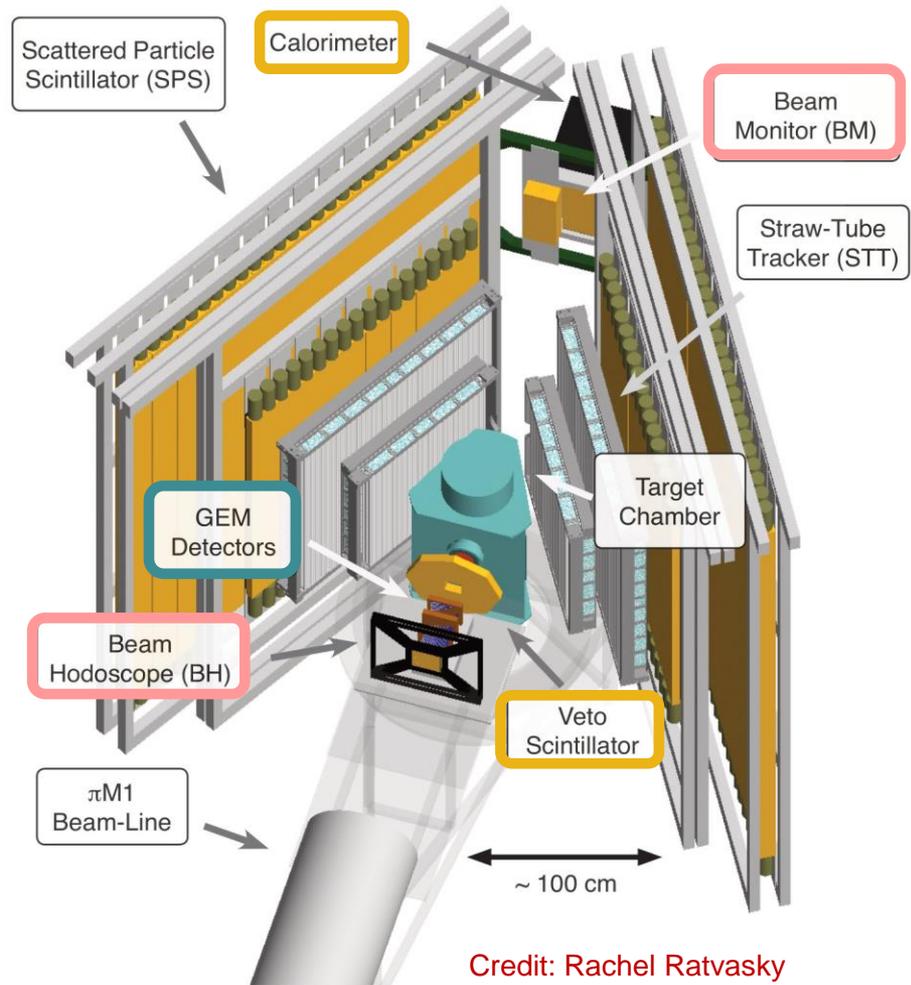
**Beam hodoscope** scintillator detector which measures particle timing & identity

**GEM detectors** four Gas Electron Multipliers which track incoming beam particles

**Beam veto** annular scintillator detector which rejects in-flight scatters & in-flight decays upstream of target chamber

**Beam monitor** scintillator detector which measures beam flux & position, particle identity & time-of-flight

**Calorimeter** scintillator detector which measures unscattered particles (radiative corrections)

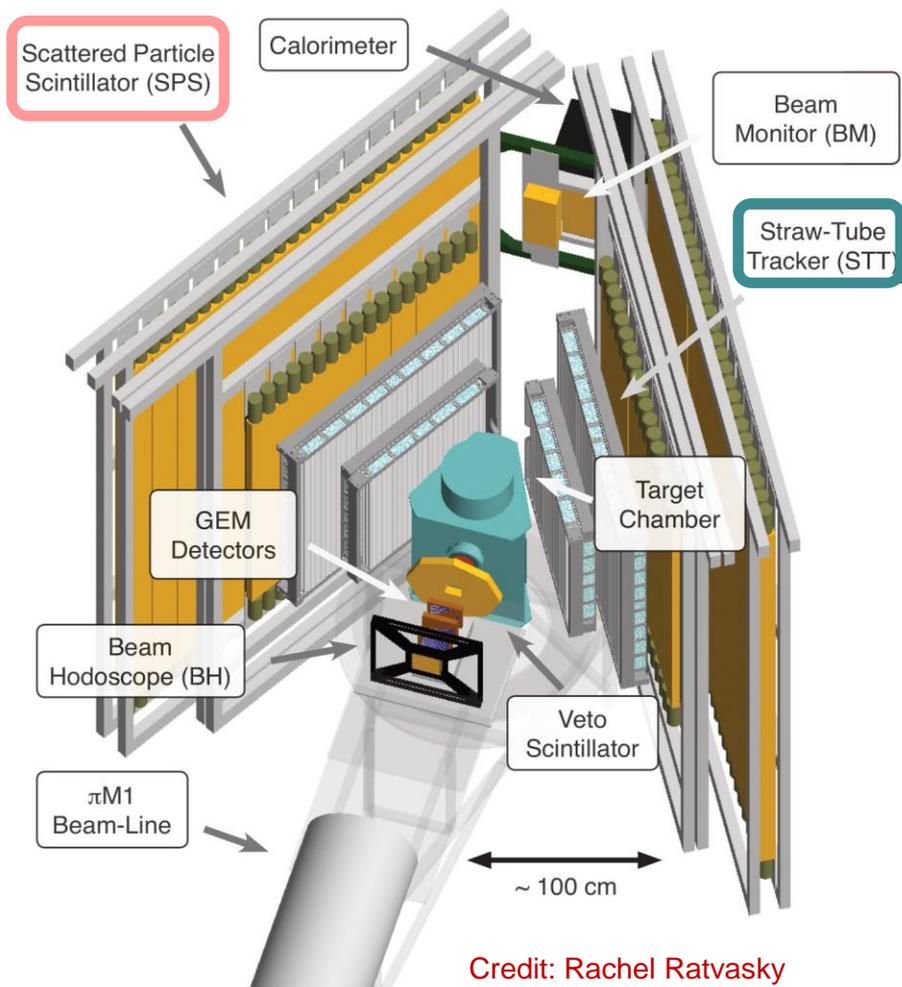


# MUSE experiment layout

## Scattering detectors

**Straw-Tube Tracker (STT)** wire-centered  $e$ -drift-chamber detector which tracks scattered particles

**Scattered Particle Scintillator (SPS)** scintillator detector which measures scattered-particle timing & identity

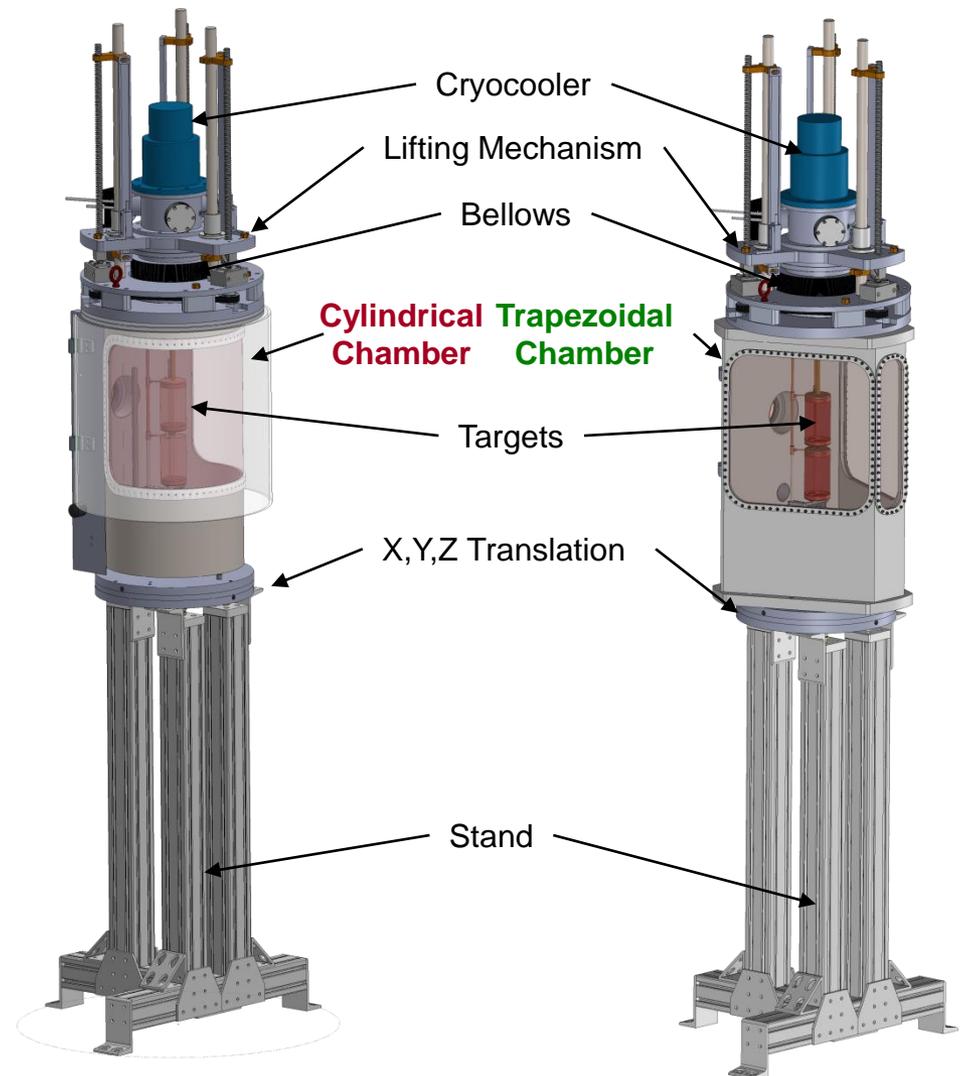


# Example of an Experimental Challenge

## MUSE Target Design:

Recall angular acceptance:  
 $20^\circ - 100^\circ$

- 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

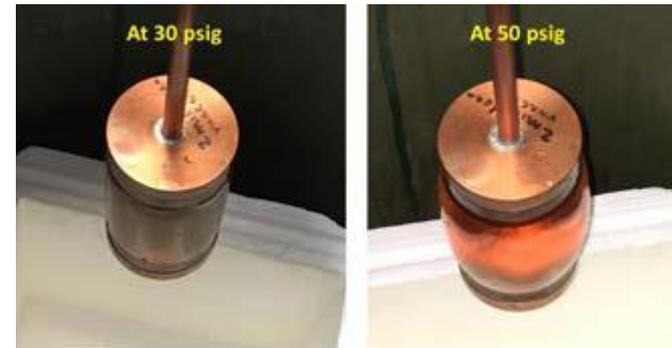
Target chamber



Target cells

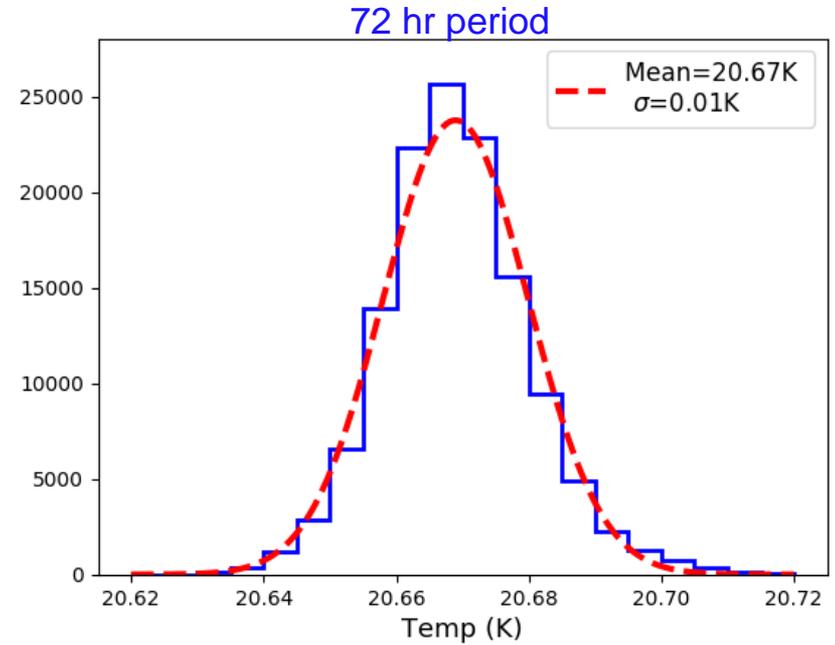
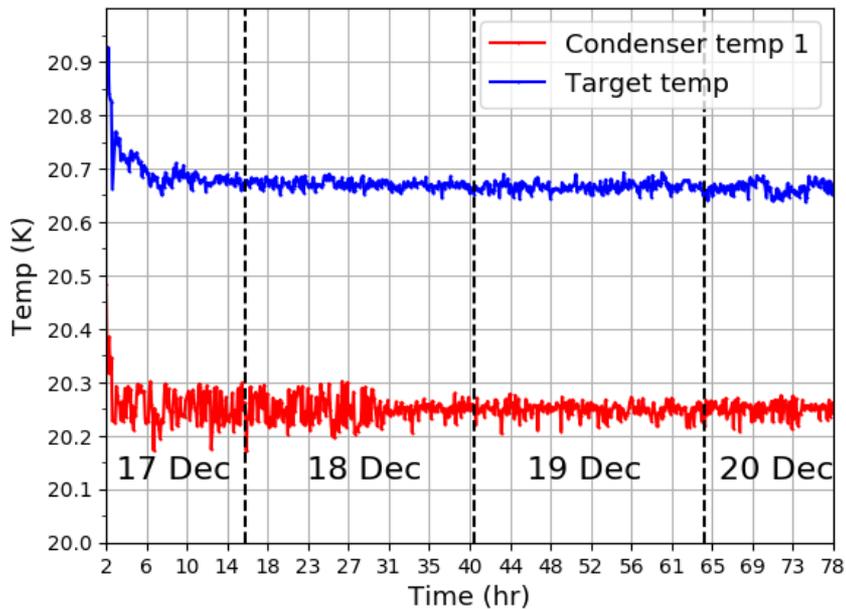


Target cell destruction tests



# Target Performance at 1<sup>st</sup> cooldown

Dec 2018



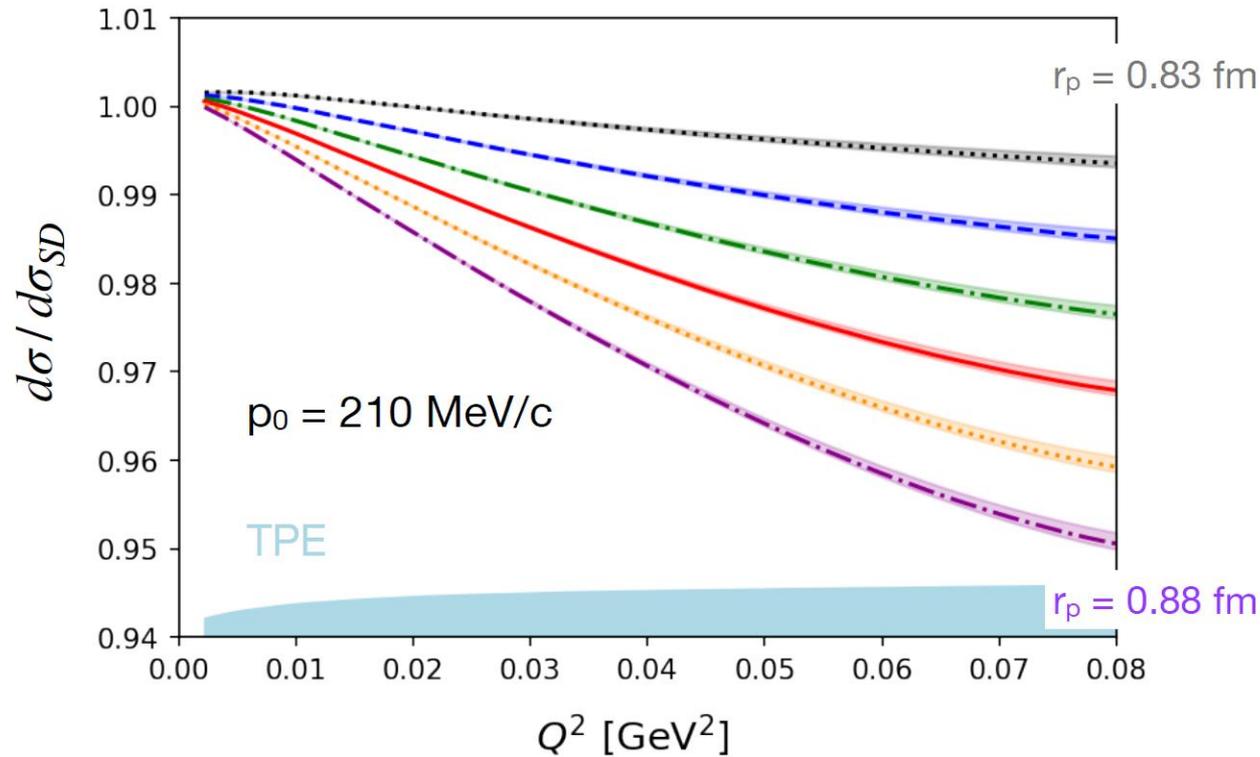
- Target Temperature:  $20.67 \pm 0.01$  K
  - corresponds to a pressure of  $\sim 1.1$  bar
- Target density:  $0.070$  g/cm<sup>3</sup> (stable to 0.02%)
- Heat load from beam:  $\sim 7$   $\mu$ W
  - cannot see when beam is on or off target cell

# MUSE Physics Coverage

- First high precision measurement of elastic  $\mu p$  scattering
  - at level necessary to inform proton radius puzzle (PRP)
- First simultaneous measurement of elastic  $\mu p$  and  $ep$  scattering
  - to reassess proton radius and remaining discrepancies
  - to perform high precision test of two photon effects (TPE) at low  $Q^2$
  - to test lepton universality
  - to test radiative corrections
- Low energy  $\pi p$  scattering important for  $\chi$ PT
- Search for  $\sigma(\pi^+ p)/\sigma(\pi^- p)$  resonances

# p radius extraction from muon scattering

$$\mu p \rightarrow \mu p$$



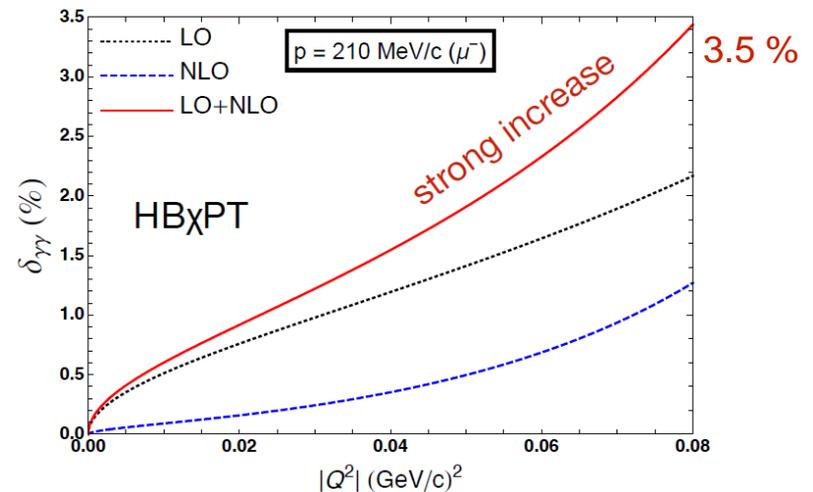
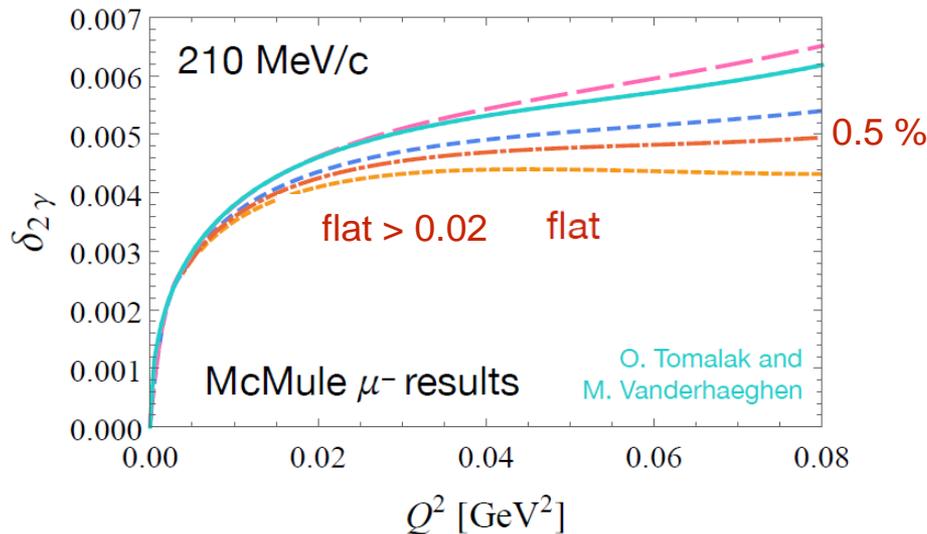
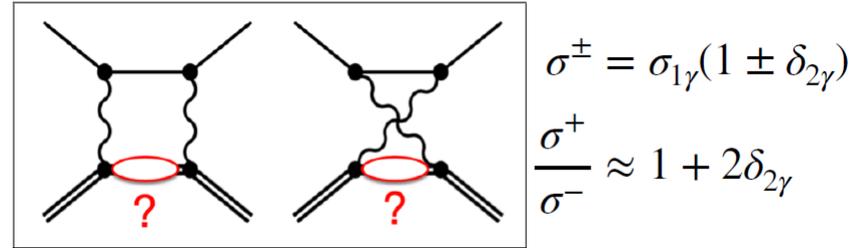
- 0.01 fm radius change  $\rightarrow$  0.9% cross sec. change at highest  $Q^2$
- good control of syst. uncertainties required to achieve goal of experiment
  - largest MUSE syst uncertainty: **radiative corrections** for  $ep \rightarrow ep$

Dispersively improved chiral effective field theory:

F. Gil-Domínguez, J.M. Alarcón and C. Weiss, Phys. Rev. D 108, no.7, 074026 (2023)

# MUSE two-photon exchange

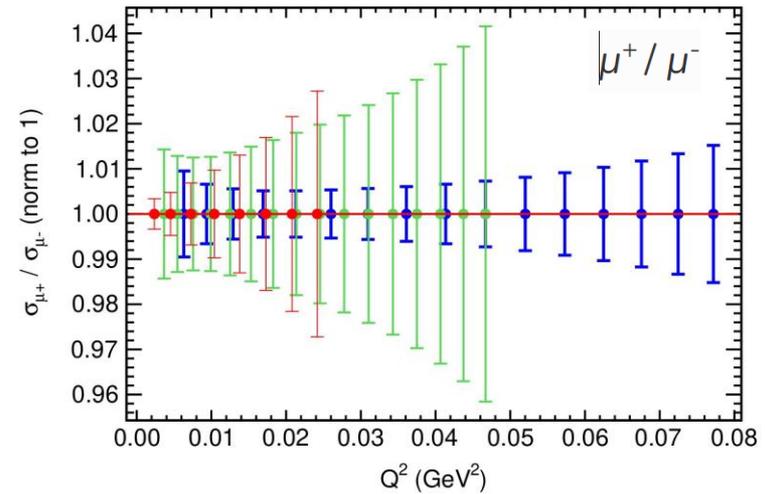
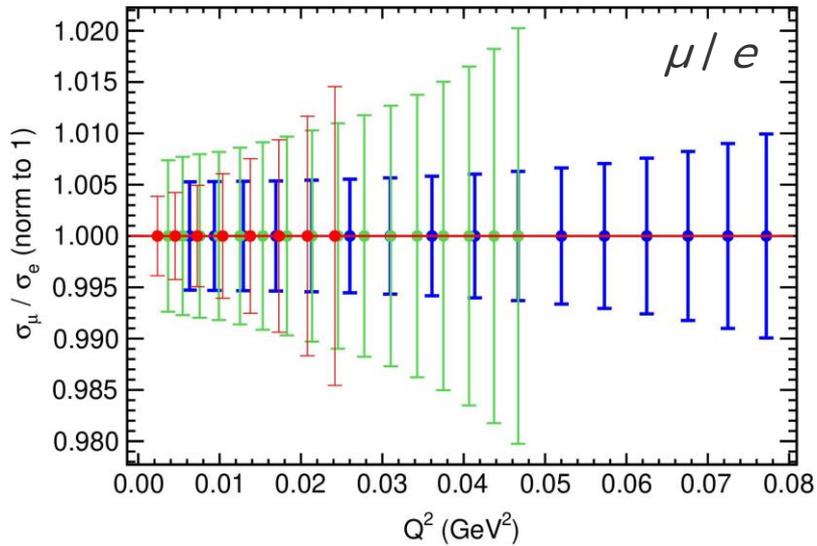
- High precision test of TPE for electron and muons at low  $Q^2$
- TPE largest theor. uncertainty in low-energy proton structure
- expect sign change for  $e^+/\mu^+$  and  $e^-/\mu^-$
- projected syst. uncertainty: 0.1% in  $\delta_{2\gamma}$



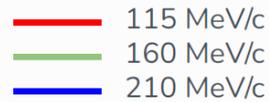
O. Tomalak, Few-Body Systems, 59, 87 (2018)  
 T. Engel, et al., Eur. Phys. J. A 59, 253 (2023) - McMule

P. Choudhary, et al., Eur. Phys. J. A 60, 69 (2024) - HB $\chi$ PT

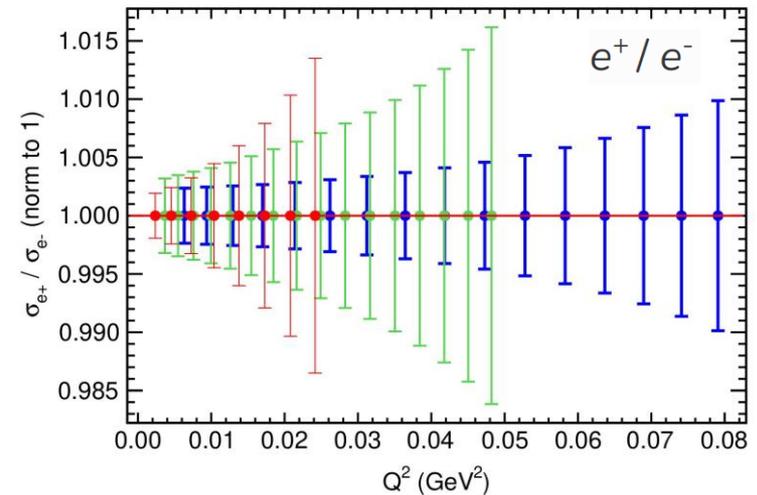
# MUSE projected cross section ratios



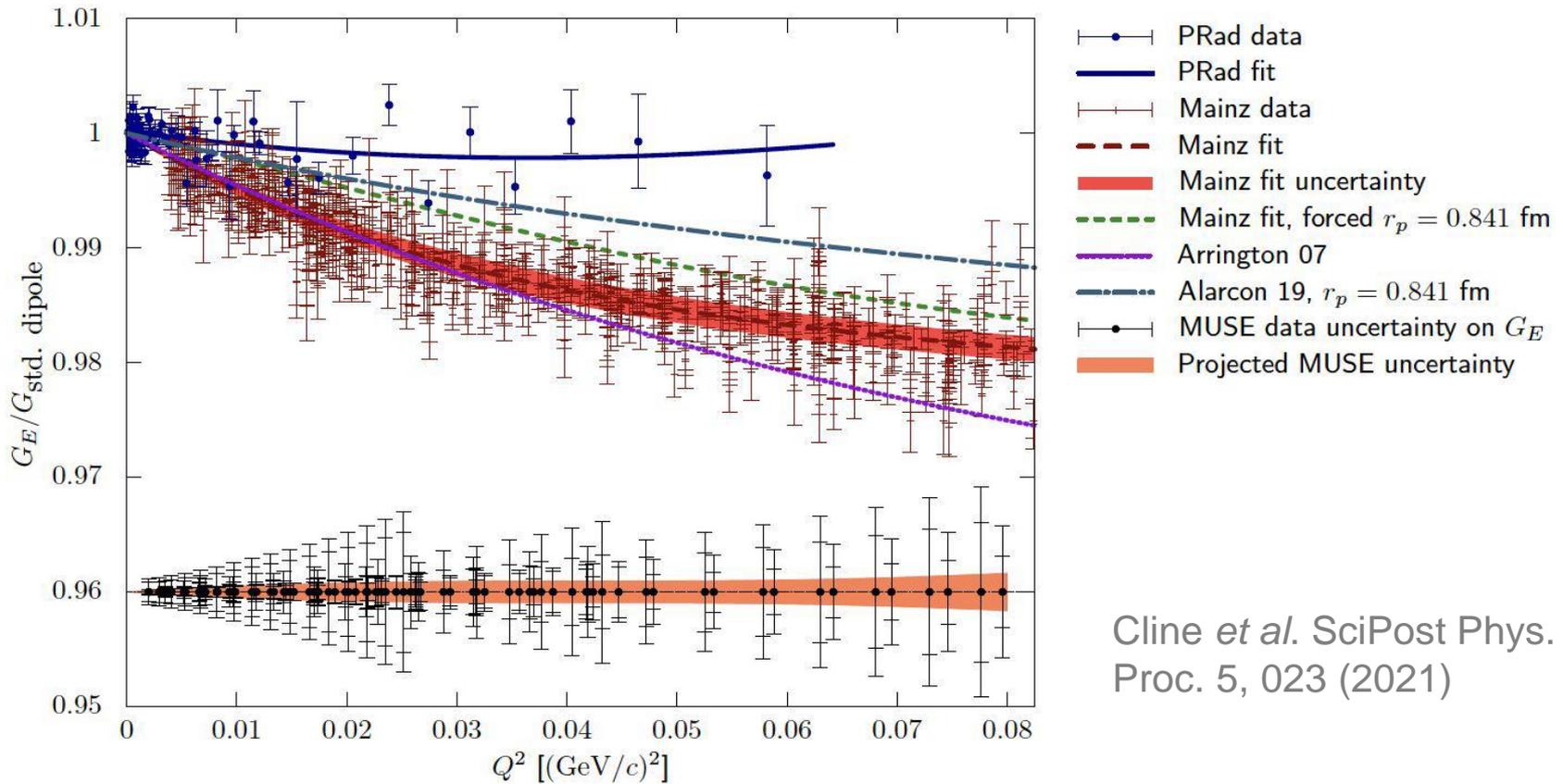
KEY



- stat. uncertainties shown
- final syst. uncertainties <0.5%



# MUSE projected form factor $G_E$



Cline *et al.* SciPost Phys.  
Proc. 5, 023 (2021)

- MUSE anticipated form factor uncertainty
  - arbitrarily placed at 0.96

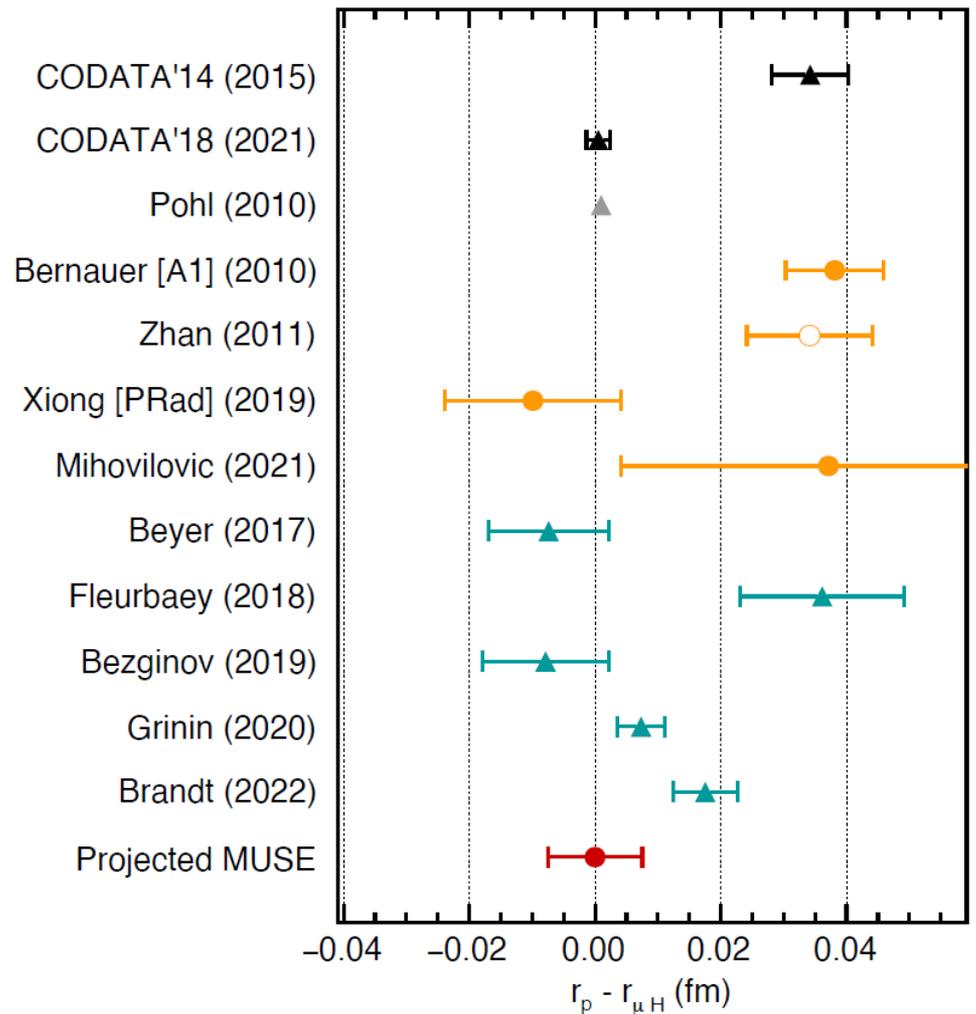
# Projected sensitivity for MUSE

- **absolute radius** extraction  
uncertainty similar to current experiments

$$\sigma(r_e), \sigma(r_\mu) \approx 0.007 \text{ fm}$$

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

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



inconsistent **electron-scattering** data  
inconsistent **hydrogen-spectroscopy** data

# MUSE Current Status and Plans

- MUSE proposed in 2012 (approved in 2013)
- started production data taking for 12 beam months over 2 years in 2023
  - $2.7 \times 10^9$  events (2023)
  - $4.8 \times 10^9$  events (2024)
- MUSE aims for ~12 billion events, with a 60/40 split between LH<sub>2</sub>/empty cell scattering events
- Aim to finish in 2025
- MUSE uniquely suited to address the proton radius puzzle and much more

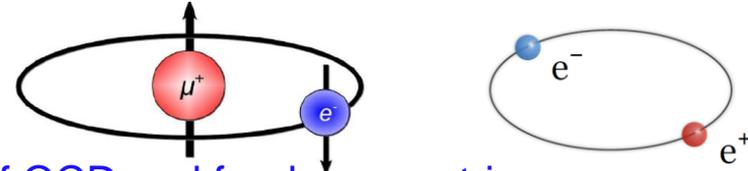
# Proton Radius Puzzle Conclusions

- We are **still** (possibly more) **puzzled!**
- **Proton radius puzzle**
  - discrepancy between muonic and electronic measurements has blurred
  - but inconsistent **electron-scattering** data and inconsistent **hydrogen-spectroscopy** data remains a serious problem
  - need new data with better control
- **Expect new results in the coming years**
- **MUSE (w/ electron & muon scattering)**
  - give first precise muon scattering results
  - will test existing values of radius
  - will test two photon exchange & radiative corrections
  - lepton universality

# Other Topics we did not discuss

- Exotic atoms

- Muonium (test fund. const:  $R_\infty$ ,  $\alpha$ ,  $m_\mu$ ) + test of QCD and fund. symmetries
- Positronium (pure onium: test of QED)
- Antihydrogen



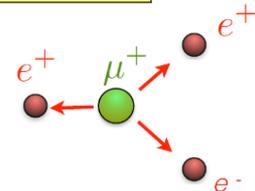
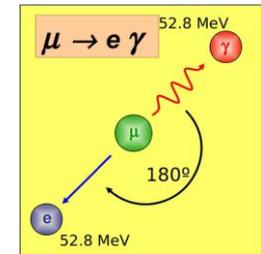
- Forbidden Decays

- MEG  $\mu^+ \rightarrow e^+ + \gamma$  (cLFV)
- Mu3e  $\mu^+ \rightarrow e^+ + e^- + e^+$
- Mu2e  $\mu^- N \rightarrow e^- N$

PSI

PSI

Fermilab, J-PARC



- Electric Dipole Moments

- n2EDM (sensitive probe for CP-violation)
- nEDM also at Munich, Gatchina, TRIUMF, LANL, SNS, J-PARC
- muEDM

PSI (UCN source)

PSI

- Others

- Muon g-2 (connection to dark photons?)
- Electron g-2 (most precisely measured quantity in EPP agrees with SM to  $1/10^{12}$ )
- ....

**Thank you**

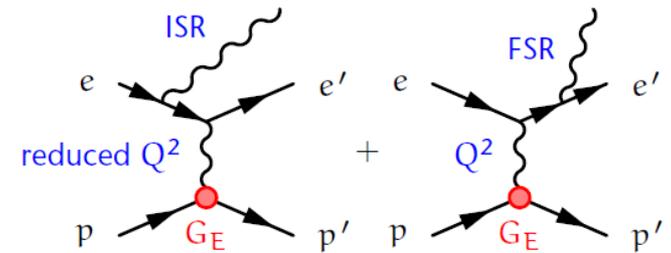
**Backup slides**

# Redoing electron scattering at lower $Q^2$

- Jlab: PRad (PRad-II approved)
  - low intensity beam in Hall B @ JLab into windowless gas target (1.3 billion H events)
  - $G_E$  slope favors smaller radius
  - PRad-II: planned total uncertainties 0.054%, reach  $Q^2 = 10^{-5} \text{ GeV}^2/c^2$

- Mainz: ISR

- exploit information in radiative tail
- dominated by coherent sum of ISR and FSR
- investigate  $G_E$  down to  $Q^2 = 10^{-4} \text{ GeV}^2/c^2$
- results not precise enough → upgrades underway



- LPSC, Grenoble: ProRad

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

