The Proton Radius

Current Measurements and New Ideas (but mostly MUSE....)

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11 Jan., 2018

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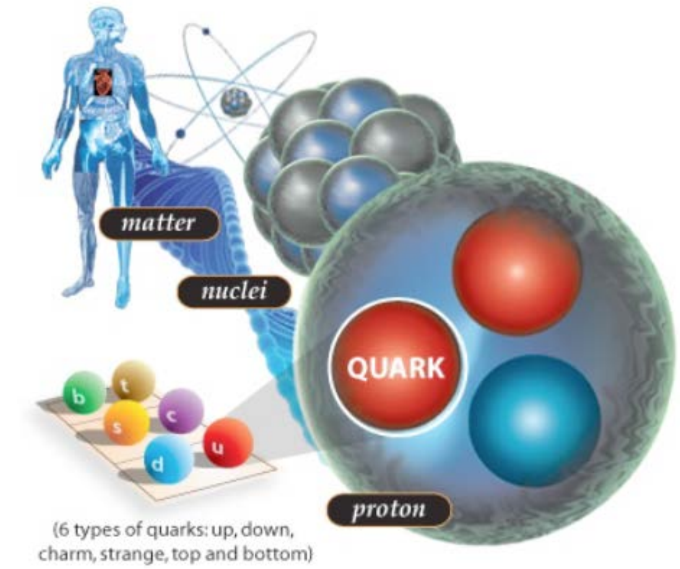
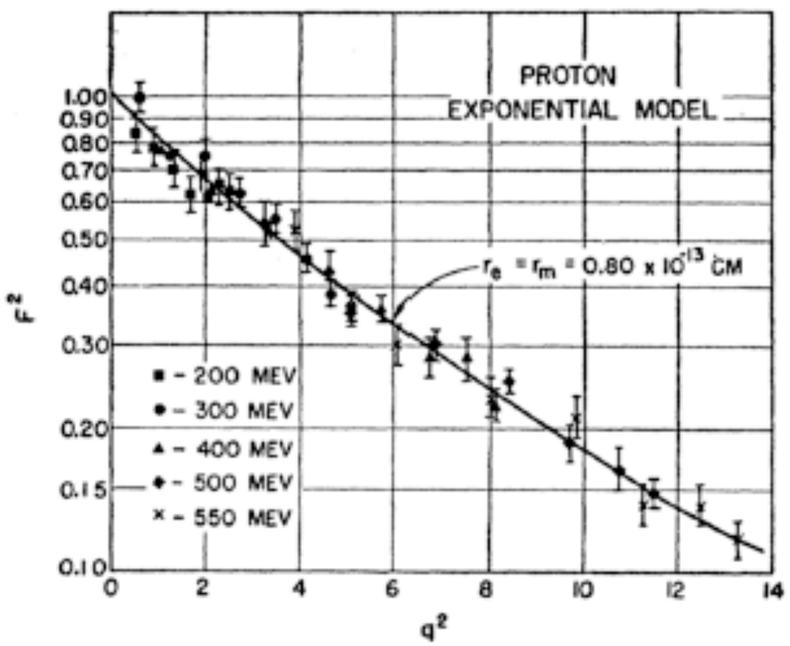
Outline



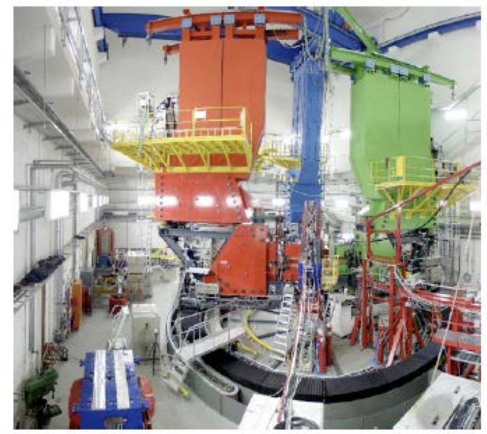
- How to measure the proton size.
- Evolution of measurements.
- Recent results and the "proton size crisis".
- (Some) attempts at resolutions.
- Looking forward.

How to measure the proton size

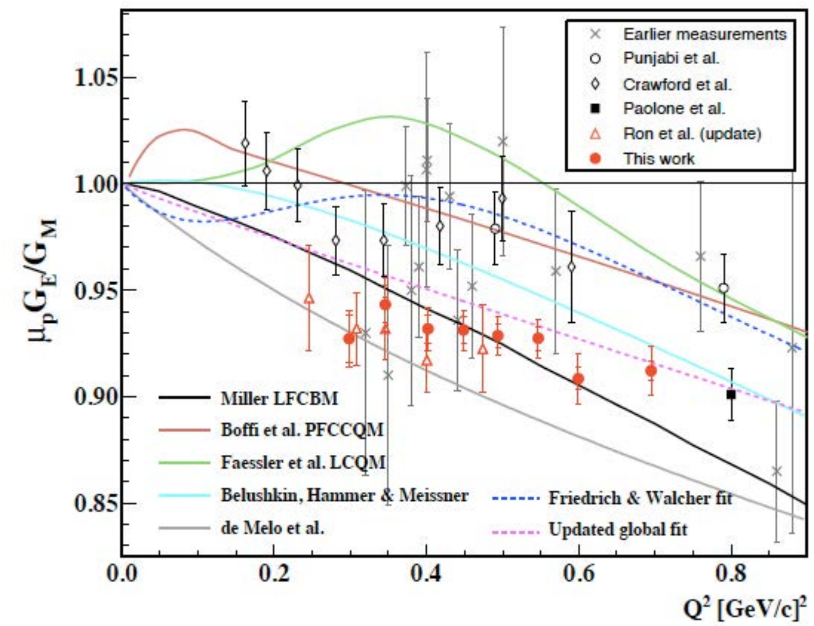


Chambers and Hofstadter, Phys Rev 103, 14 (1956)

Hofstadter @ Stanford: 1950s - electron scattering

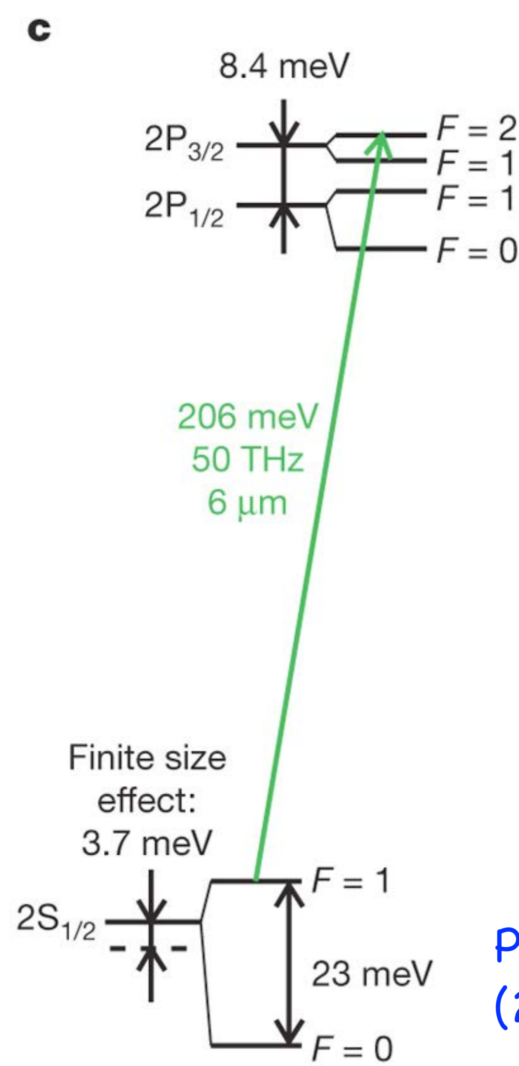


Bernauer et al., PRL105, 242001 (2010)



Zhan et al., PLB705, 59 (2011)
Ron et al., PRC84, 055204 (2011)

Hadronic physicists all over: 1960s-2010s - Form factors



Atomic physicists - precise atomic transitions in hydrogen

Pohl et al., Nature 466, 213 (2010)

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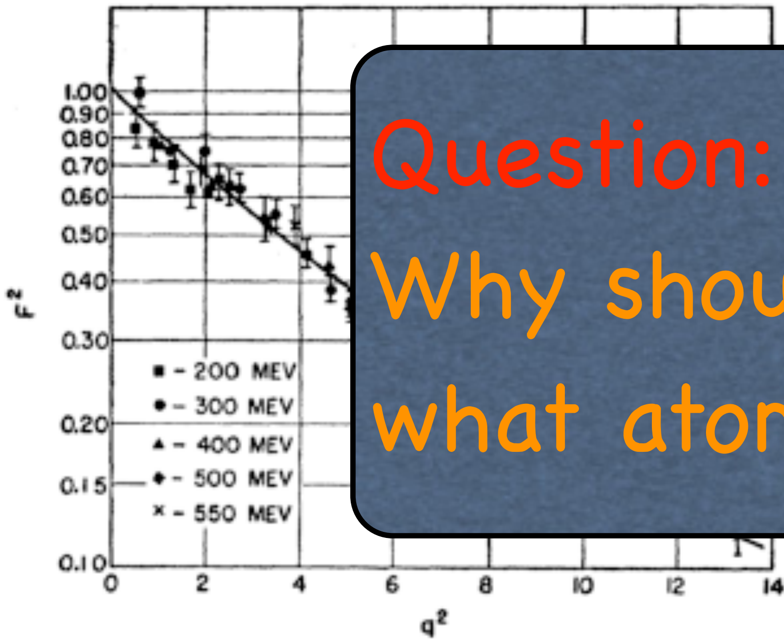
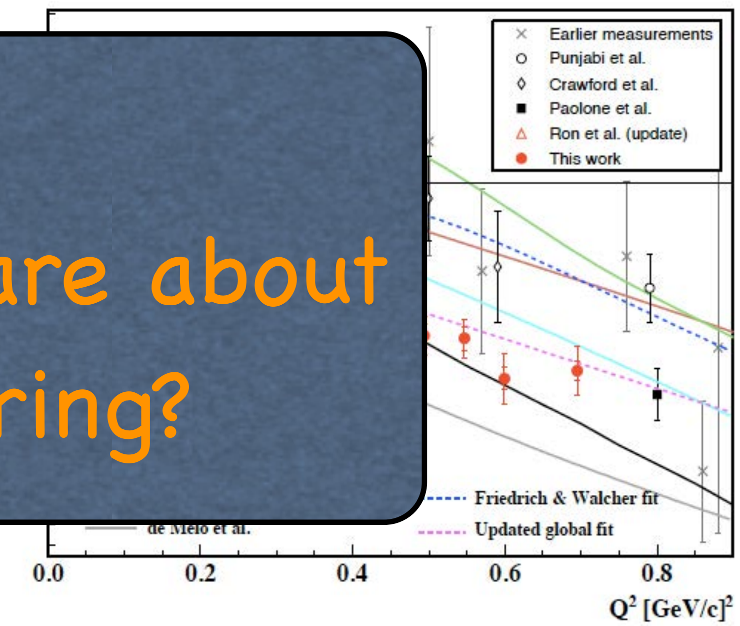
How to measure the proton size



242001 (2010)



Question:

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

Chambers a

Phys Rev 10

705, 59 (2011)

, 055204 (2011)

Answer:

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

Hofstadter

electron sc

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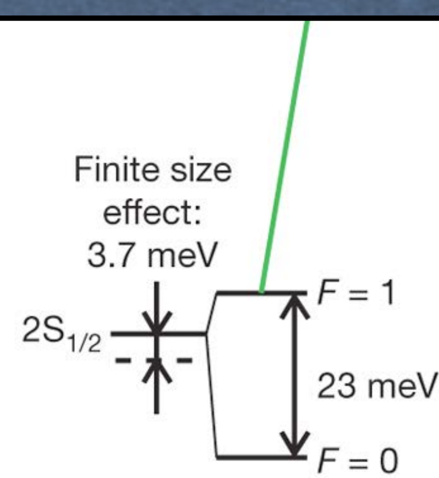
Atomic physicists – precise atomic transitions in hydrogen



Pohl et al., Nature 466, 213 (2010)

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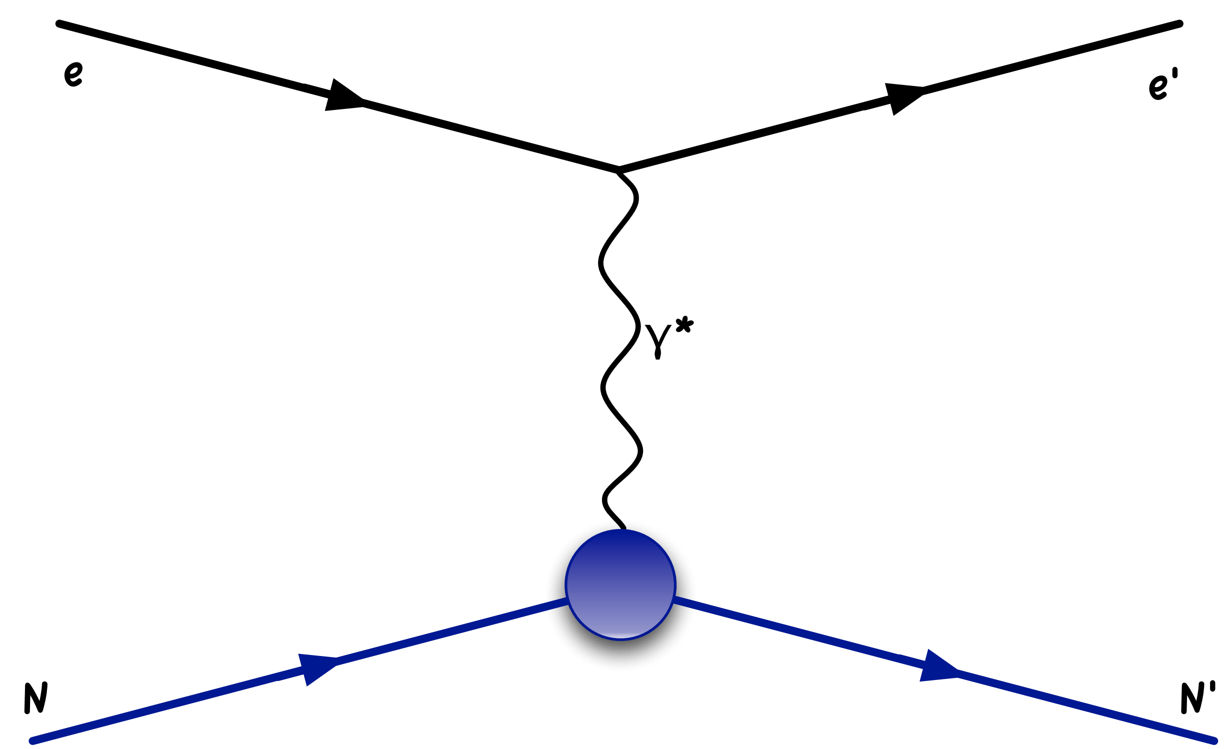
Scattering Measurements

Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

Rutherford - Point-Like

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$



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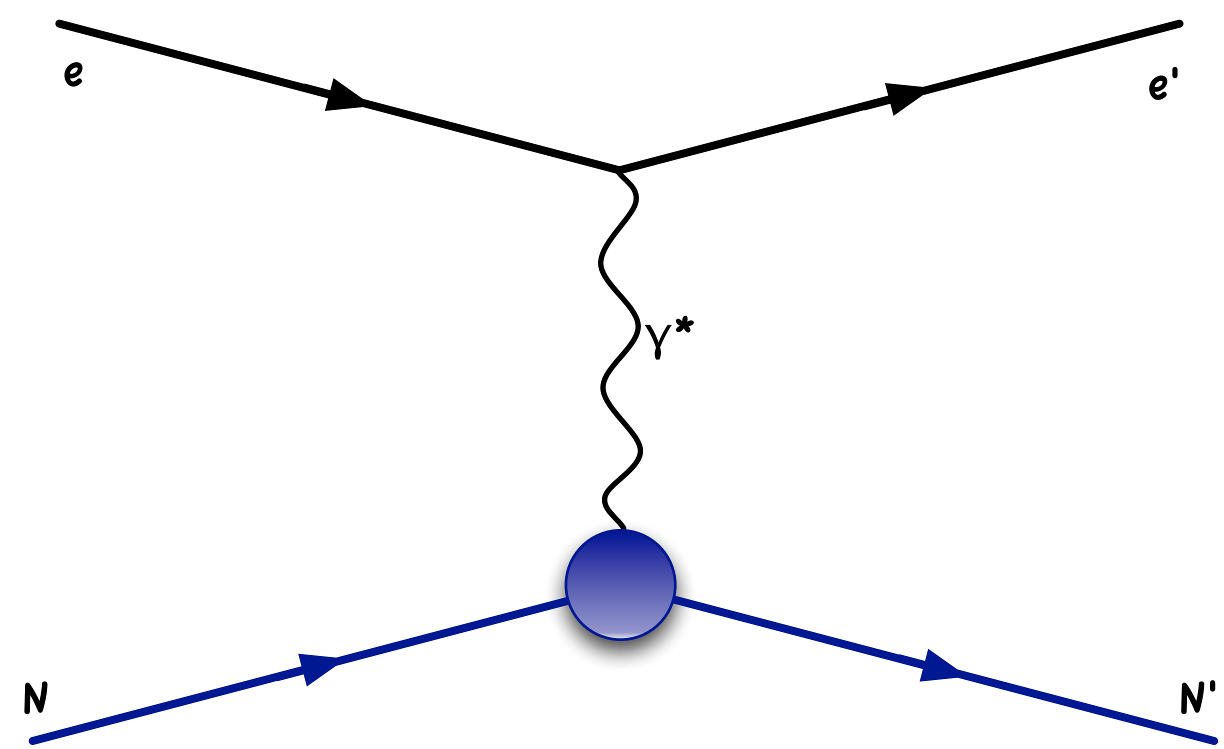
Rutherford - Point-Like

$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

Mott - Spin-1/2

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$



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Mott - Spin-1/2

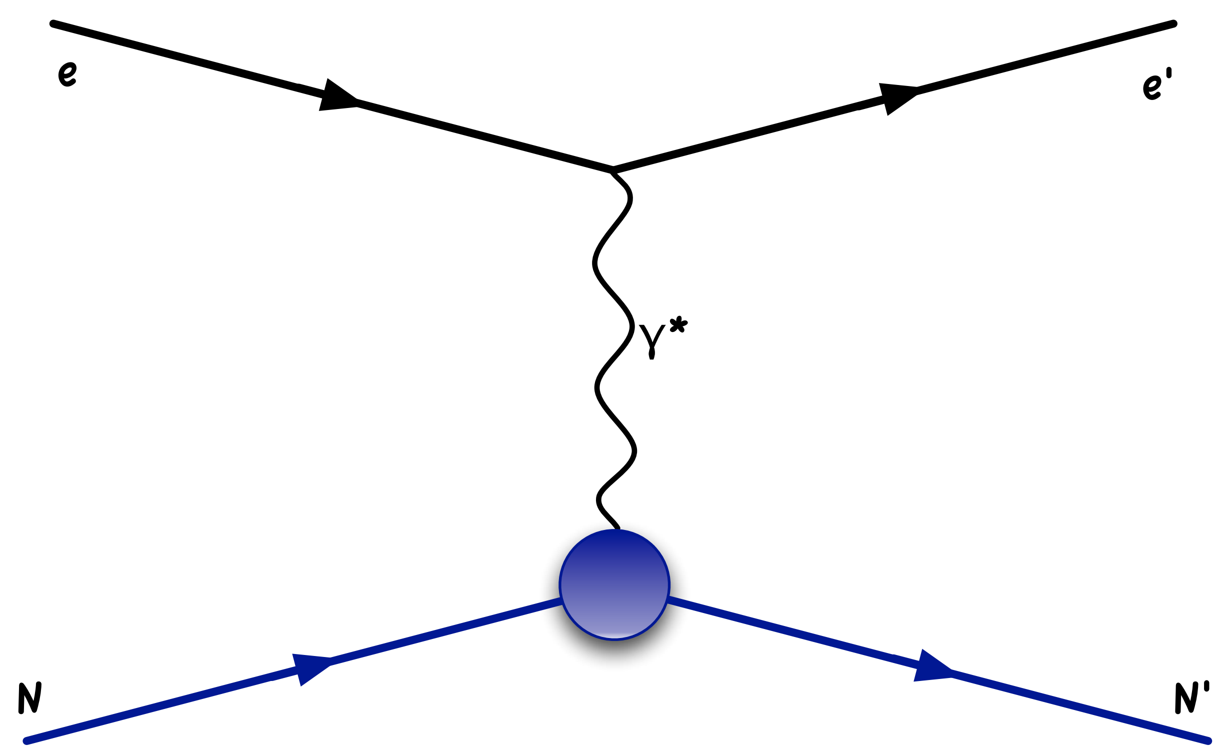
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

$$\tau = \frac{Q^2}{4M^2}, \ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$



Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

Everything we don't know goes here!

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

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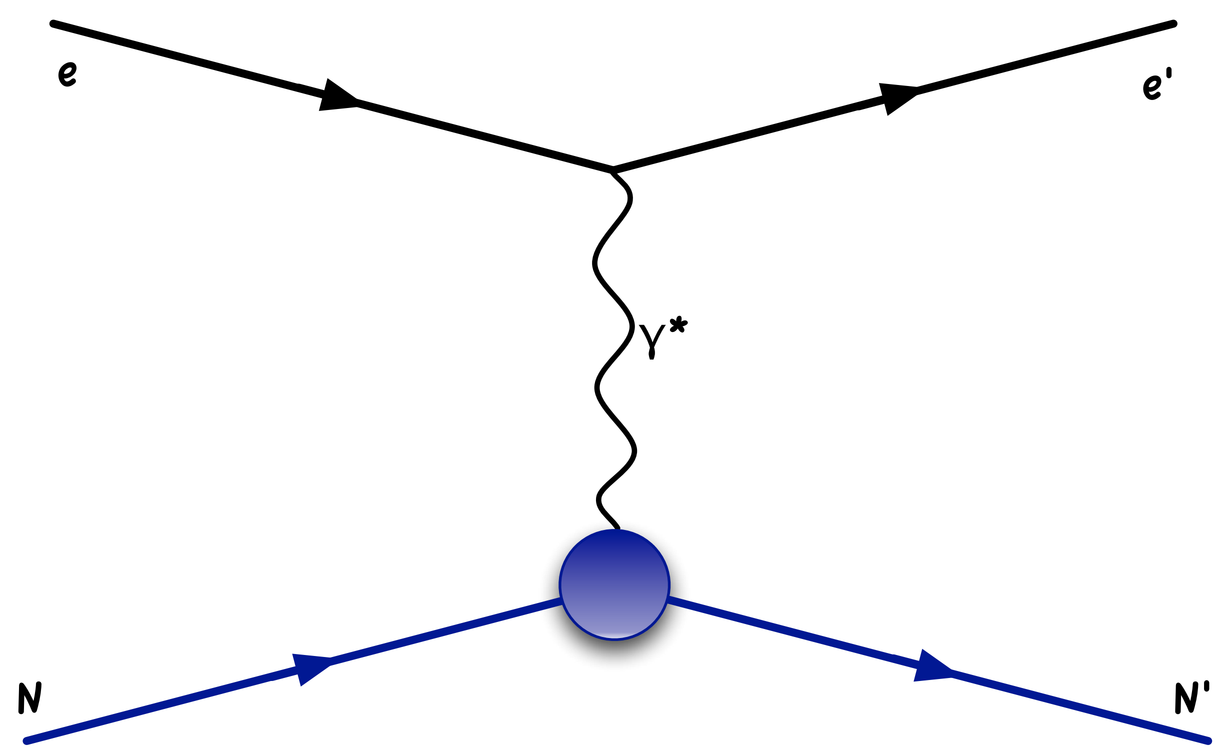


Form Factor Moments

$$\int e^{-i\vec{k}\cdot\vec{r}}\rho(\vec{r})d^3r \propto \int r^2\rho(r)j_0(kr)dr$$

3d Fourier Transform for isotropic density

$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\left\langle r^2_{E,M}\right\rangle Q^2 + \frac{1}{120}\left\langle r^4_{E,M}\right\rangle Q^4 - \frac{1}{5040}\left\langle r^6_{E,M}\right\rangle Q^6 + \cdots$$

Non-relativistic assumption (only) = k=Q; G is F.T. of density

$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \left\langle r^2_{E,M}\right\rangle \equiv r^2_{E,M}$$

Slope of $G_{E,M}$ at $Q^2=0$ defines the radii. This is what FF experiments quote.

Notes

- In NRQM, the FF is the 3d Fourier transform (FT) of the Breit frame spatial distribution, but the Breit frame is not the rest frame, and doing this confuses people who do not know better. The low Q^2 expansion remains.

Boost effects in relativistic theories destroy our ability to determine 3D rest frame spatial distributions. The FF is the 2d FT of the transverse spatial distribution.

The slope of the FF at $Q^2 = 0$ continues to be called the radius for reasons of history / simplicity / NRQM, but it is not the radius.

Nucleon magnetic FFs crudely follow the dipole formula, $G_D = (1+Q^2/0.71\ \mathrm{GeV}^2)^{-2}$, which a) has the expected high Q^2 pQCD behavior, and b) is amusingly the 3d FT of an exponential, but c) has no theoretical significance

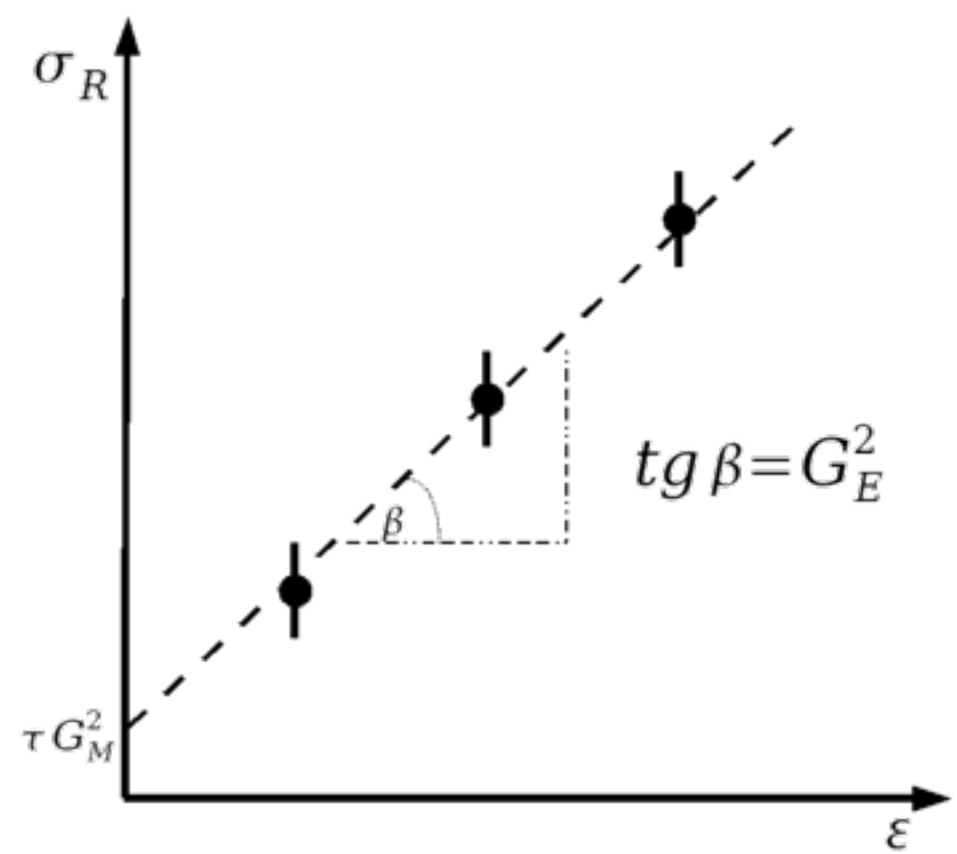
Measurement Techniques

Rosenbluth Separation

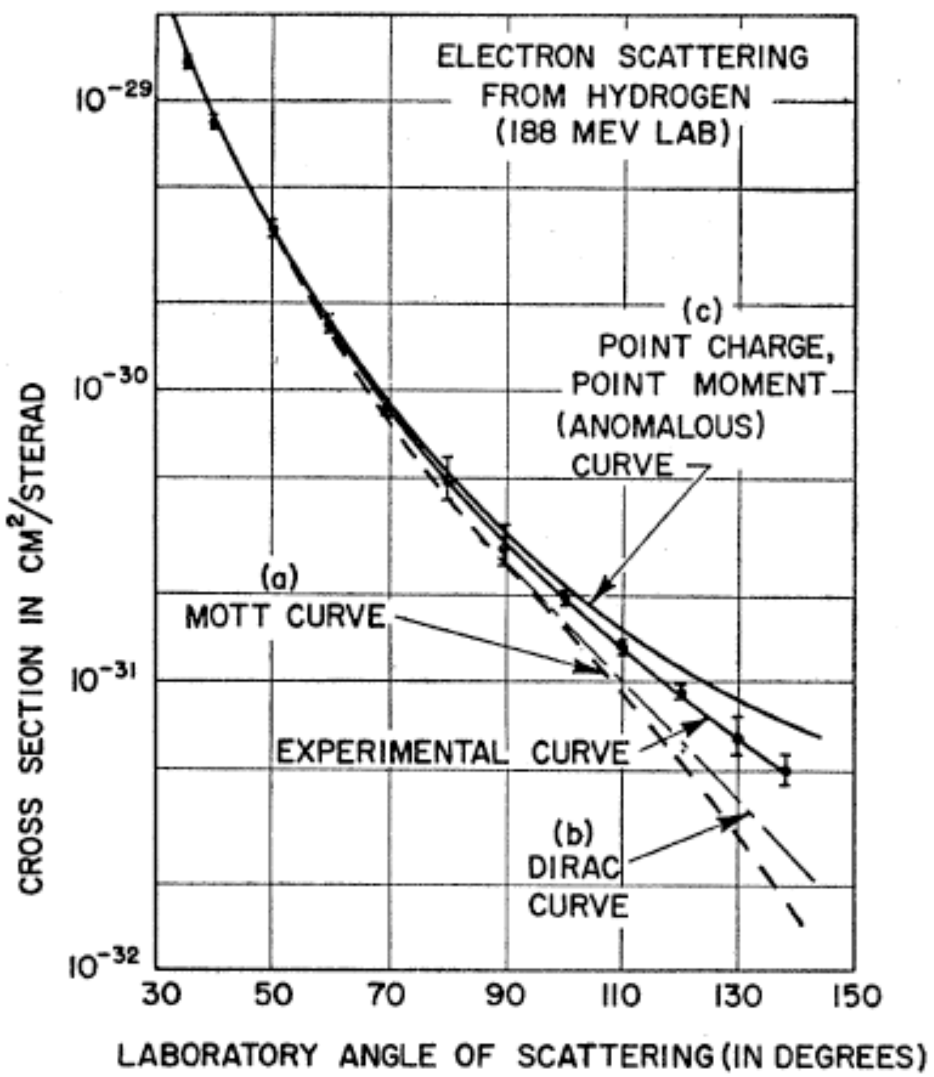
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right] \; ; \; \tau \equiv \frac{Q^2}{4M^2}$$

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

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed.
- Linear fit to get intercept and slope.



1950s



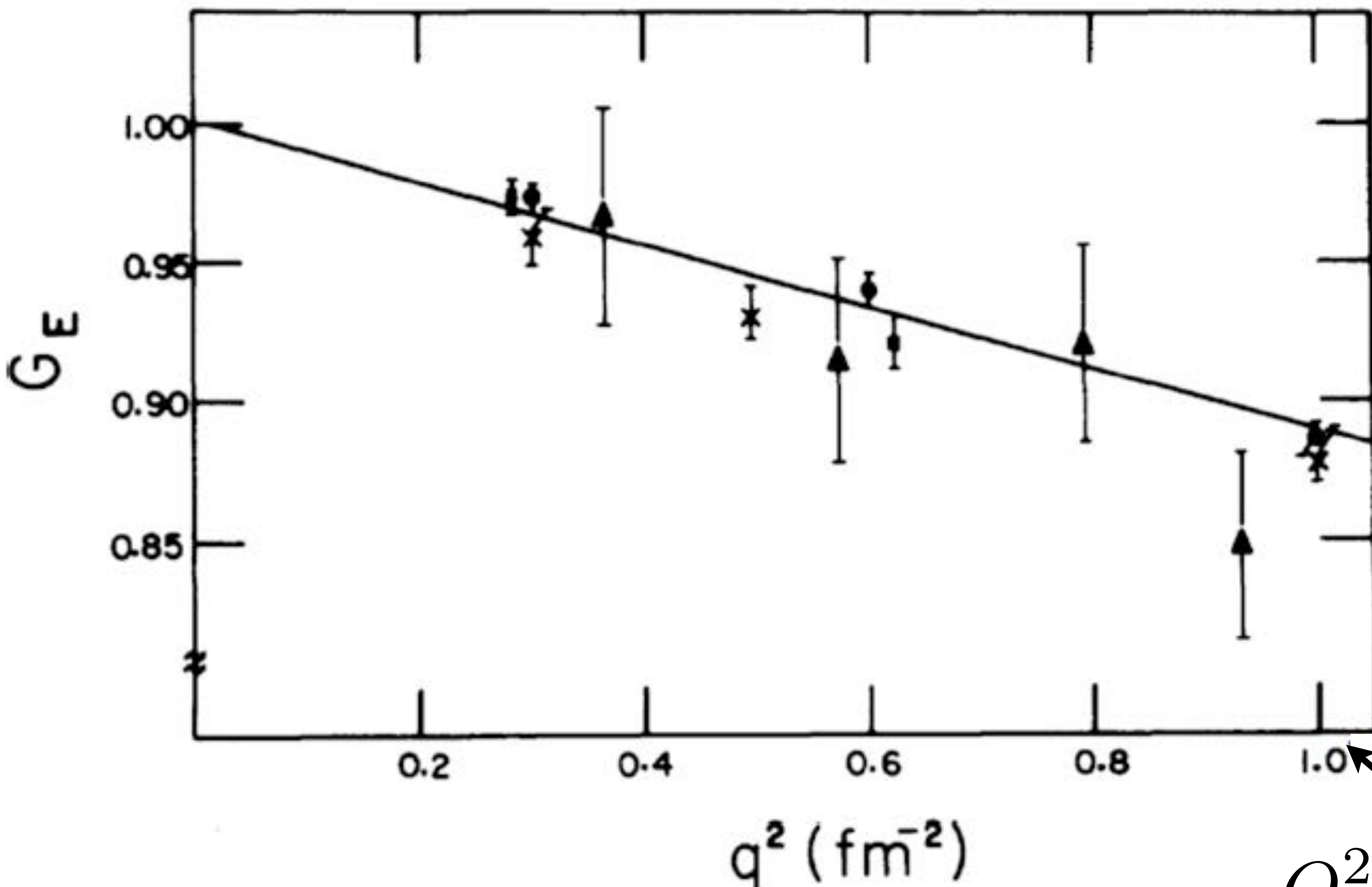
$$\langle r_E \rangle = 0.74(24)\ fm$$

Fit to RMS Radius
Stanford 1956

R. Hofstadter
Nobel Prize 1961

R.W. McAllister and R. Hofstadter, Phys. Rev. 102, 851 (1956)

Low Q^2 in 1974



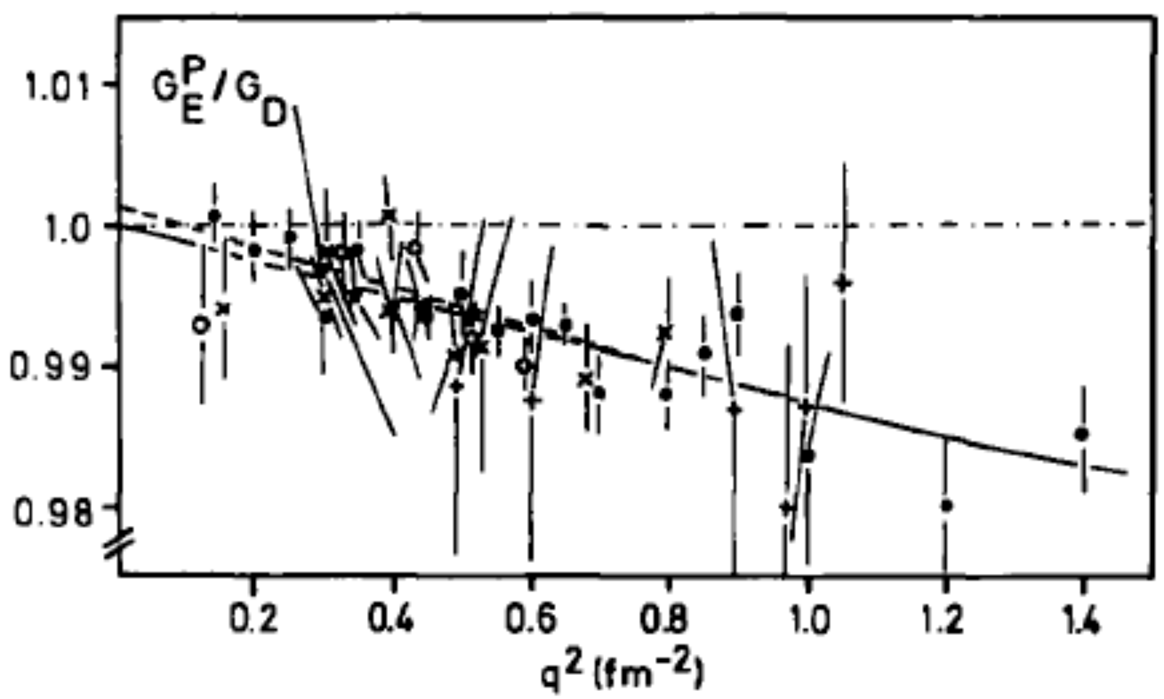
$\langle r_E \rangle = 0.810(40)\ fm$

$Q^2 = 0.0389\ GeV^2$

Fit to $G_E(Q^2) = a_0 + a_1 Q^2 + a_2 Q^4$
Saskatoon 1974

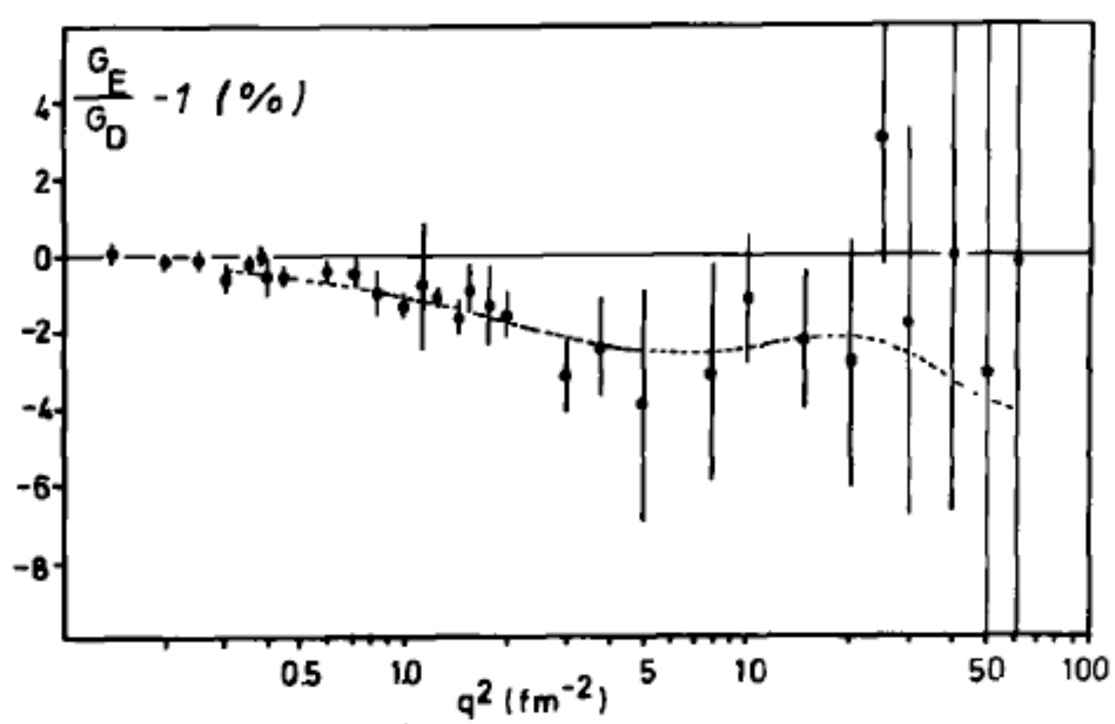
J. J. Murphy, Y. M. Shin, D. M. Skopik, Phys. Rev. C9, 2125 (1974)

Low Q² in the 80s



$$\boxed{\langle r_E \rangle = 0.862(12)\ fm}$$

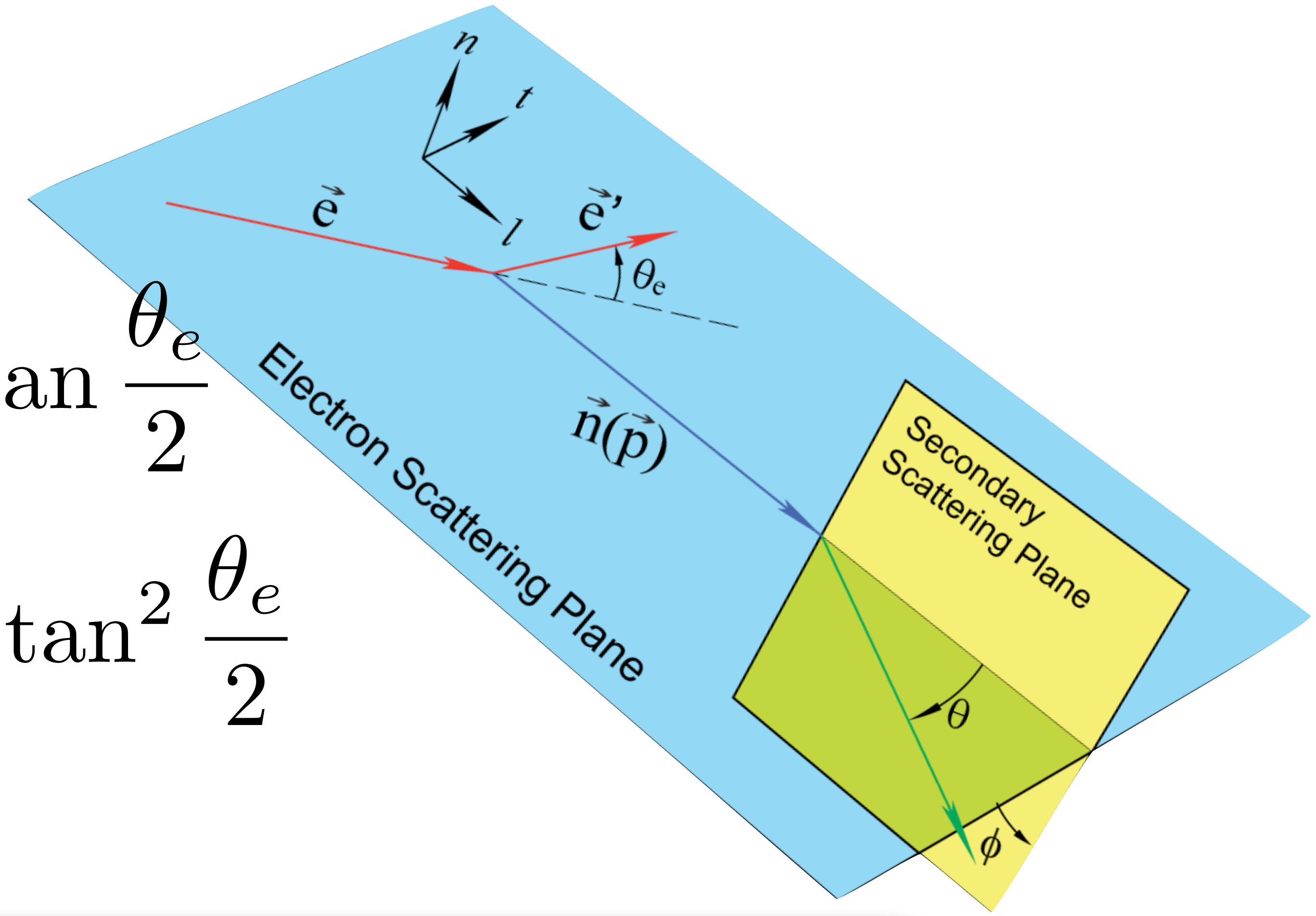
$$\begin{aligned} G_D &= (1 + Q^2/18.23\,\mathrm{fm}^{-2})^{-2} \\ &= (1 + Q^2/0.71\,\mathrm{GeV}^2)^{-2} \end{aligned}$$



From the dipole form get
r_E~0.81 fm

G. G. Simon, Ch. Smith, F. Borkowski, V. H. Walther, NPA333, 381 (1980)

Measurement Techniques



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

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

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

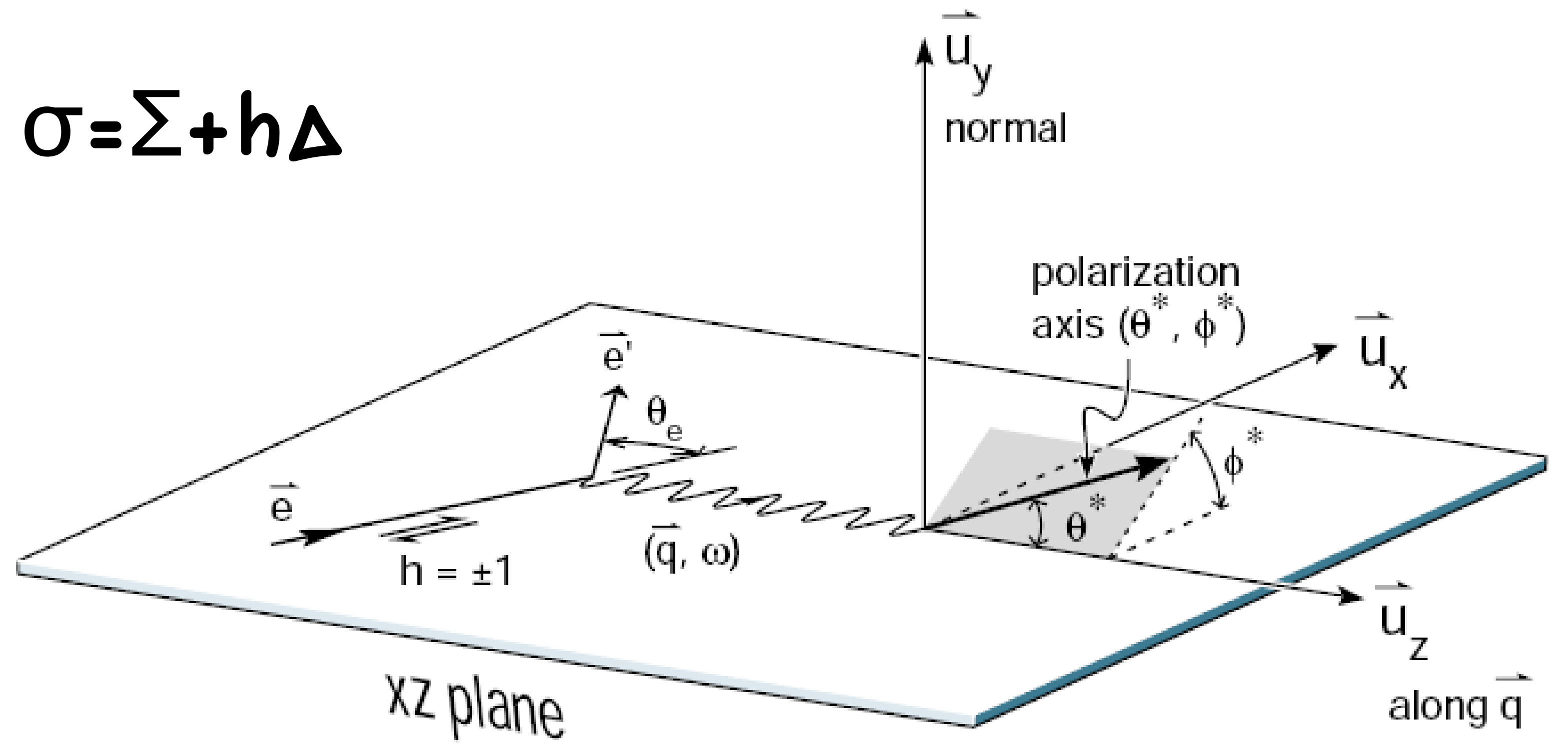
$$\boxed{\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}}$$

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

Measurement Techniques

Polarized Cross Section: σ=Σ+hΔ

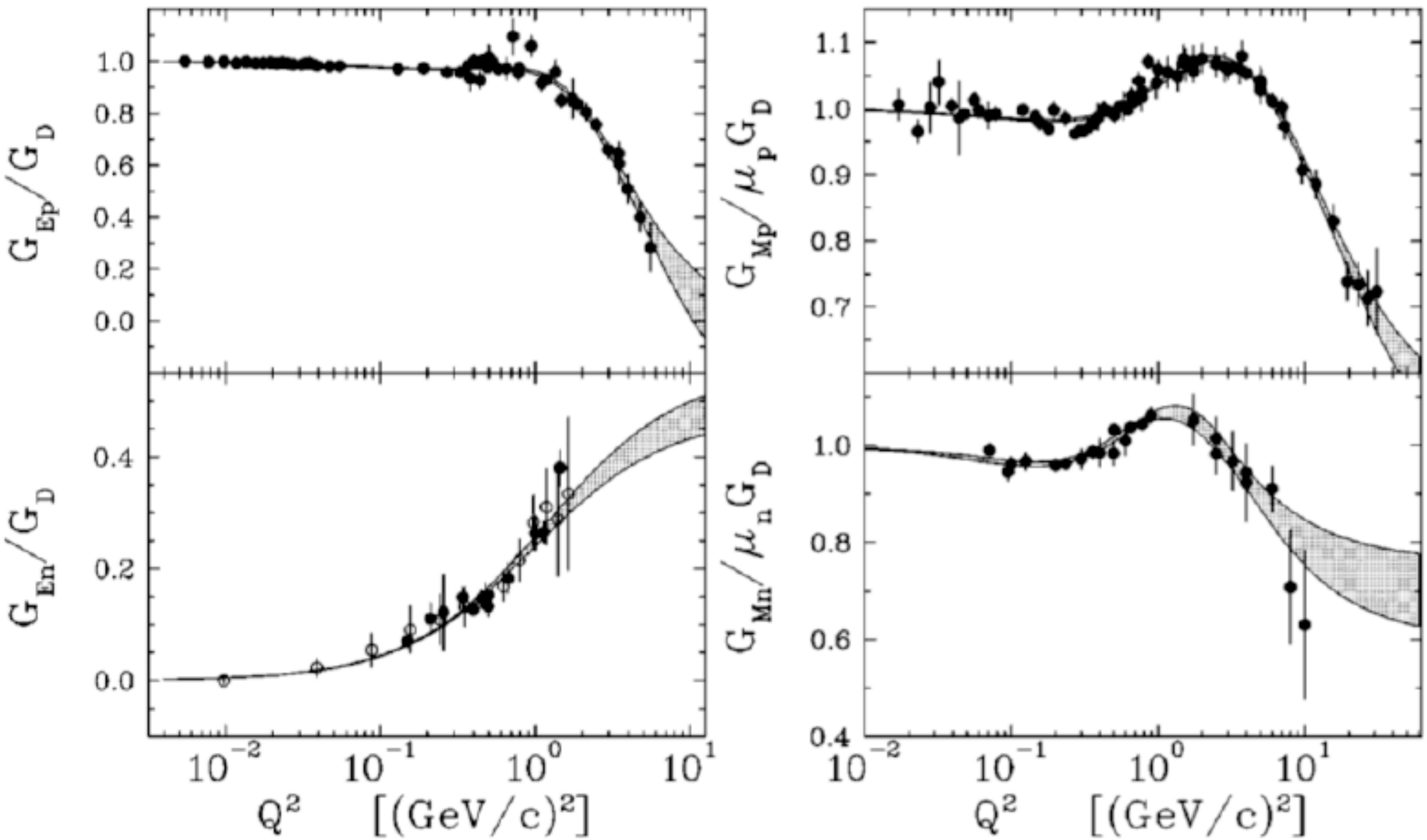
$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\, cos\theta^* G_M^2}^{A_T} + \overbrace{b\, sin\theta^*\ cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

Measure asymmetry at two different target settings, say θ*=0, 90.
Ratio of asymmetries gives ratio of form factors.
Functionally identical to recoil polarimetry measurements.

A multitude of fits



Better measurements, to higher Q^2 lead to a cornucopia of fits

J. J. Kelly, Phys. Rev. C70, 068202 (2004)

A multitude of Radii

$$\boxed{-6G'_E(0) = r_E^2}$$

$$G^{E,M}_{\text{dipole}}(Q^2) = \left(1 + \frac{Q^2}{a^{E,M}}\right)^{-2}$$

$$G^{E,M}_{\text{double dipole}}(Q^2) = a_0^{E,M}\left(1 + \frac{Q^2}{a_1^{E,M}}\right)^{-2} + \left(1 - a_0^{E,M}\right)\left(1 + \frac{Q^2}{a_2^{E,M}}\right)^{-2}$$

$$\left.\begin{aligned}
G^{E,M}_{\text{polynomial, n}}(Q^2) &= 1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i} \\
G^{E,M}_{\text{poly+dipole}}(Q^2) &= G_D(Q^2) + \sum_{i=1}^{n} a_i^{E,M} Q^{2i} \\
G^{E,M}_{\text{poly x dipole}}(Q^2) &= G_D(Q^2) \times \sum_{i=1}^{n} a_i^{E,M} Q^{2i} \\
G^{E,M}_{\text{inv. poly.}}(Q^2) &= \frac{1}{1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}}
\end{aligned}\right\}$$

r_E = 0.883 fm
r_M = 0.775 fm
Bernauer et al., PRL105, 242001 (2010)

$$G(Q^2) = \frac{1}{1 + \frac{Q^2 b_1}{1 + \frac{Q^2 b_2}{1 + \cdots}}}$$

r_E = 0.901, r_M = 0.868 fm Arrington&Sick, PRC76, 035201 (2007)
r_E = 0.875, r_M = 0.867 fm Zhan et al., PLB705, 59 (2011)

$$G(Q^2) \propto \frac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n+2} b_k \tau^k}$$

r_E = 0.863, r_M = 0.848 fm
Kelly PRC70, 068202 (2004)

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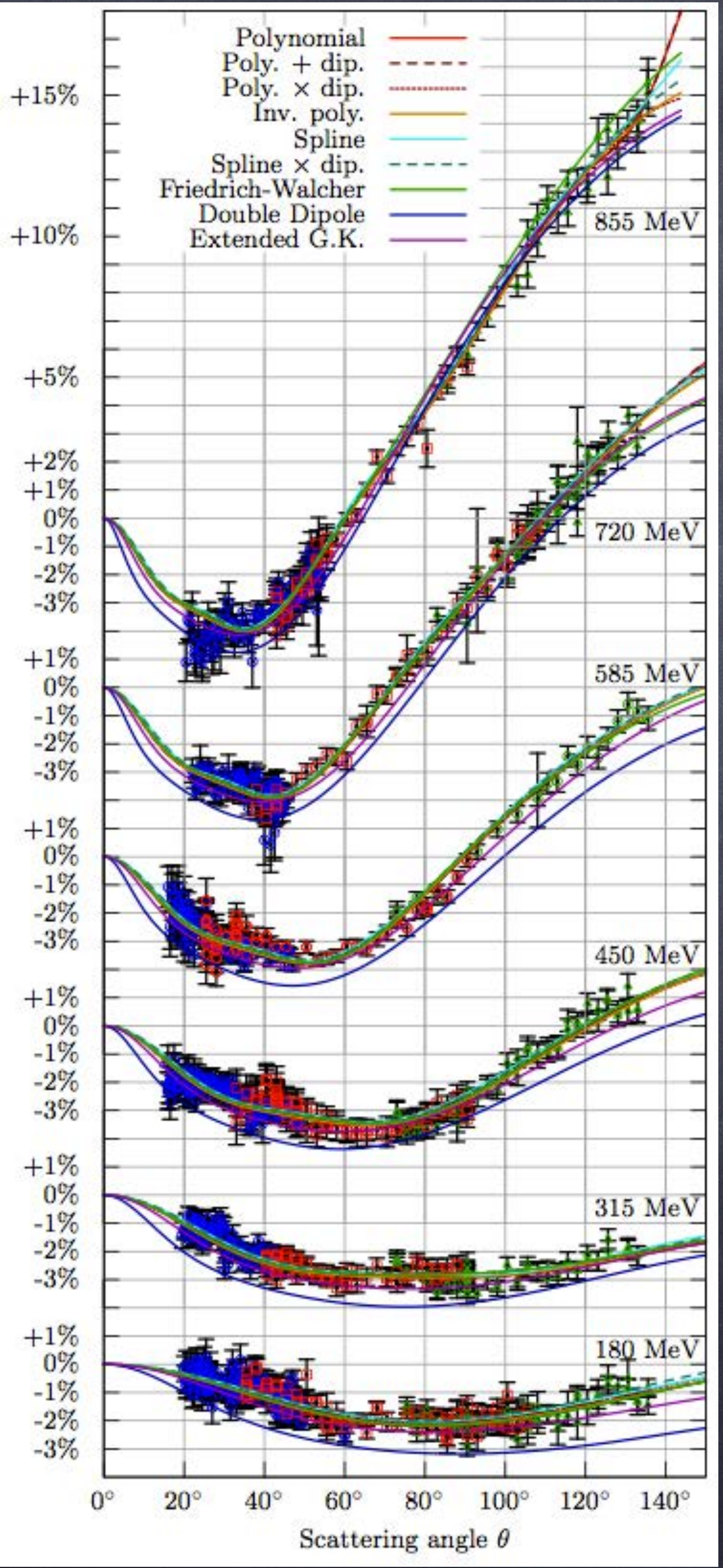
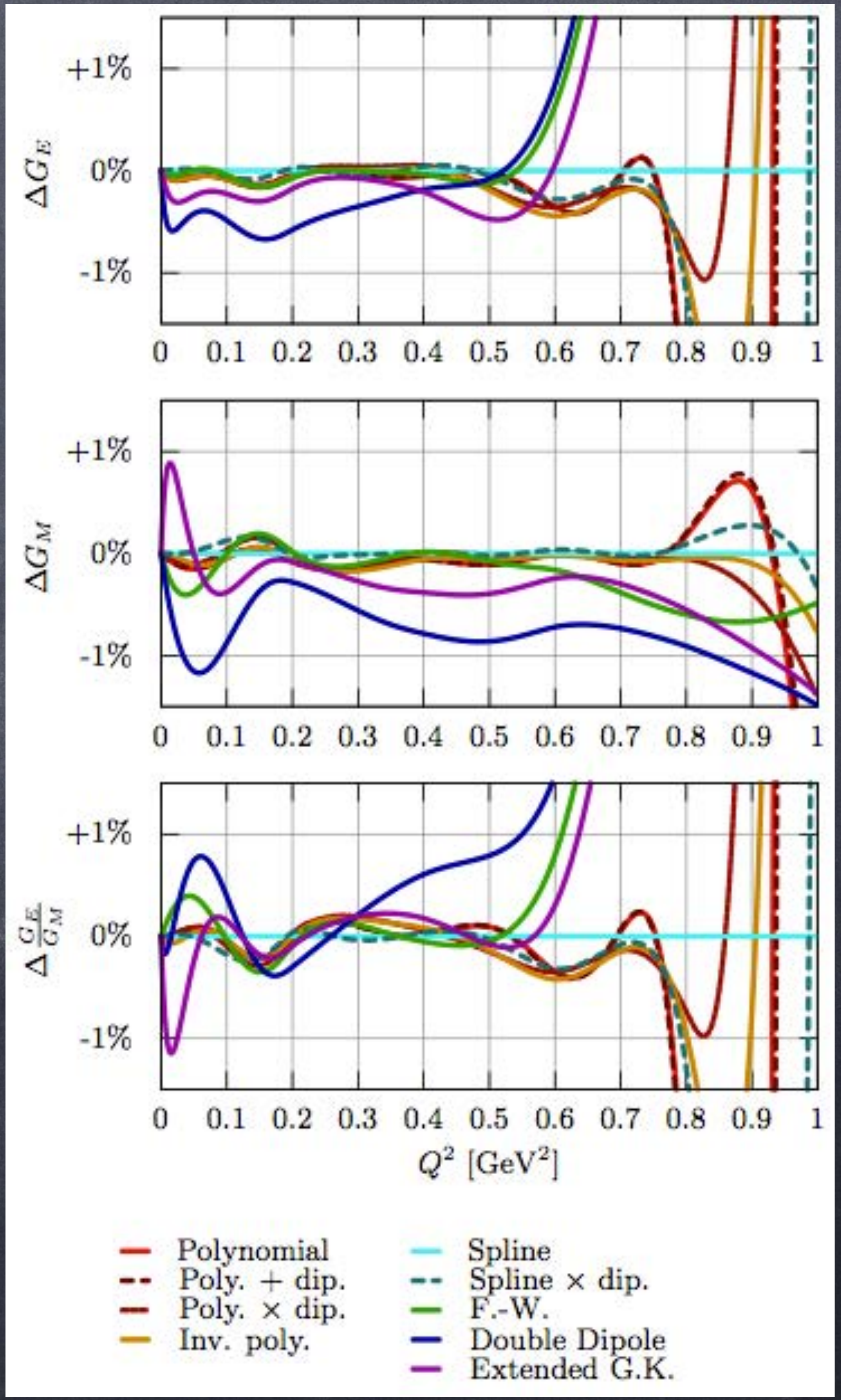


Mainz ep

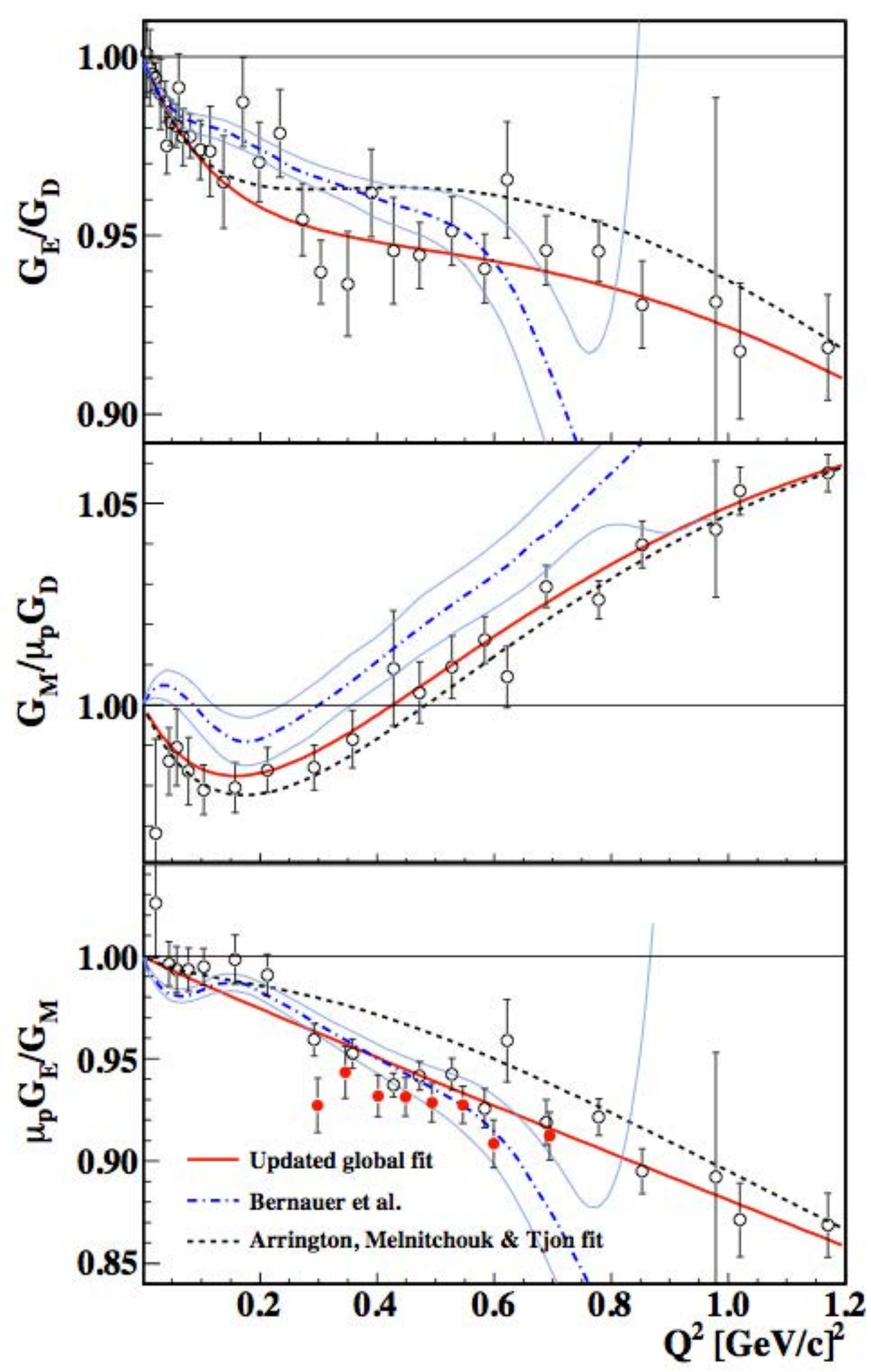
J. Bernauer et al PRL 105, 242001 (2010)

$r_p = 0.879 \pm 0.008$ fm



Left: Cross sections relative to standard dipole

Right: variation in fits to data - some fits have poor χ^2, so uncertainty is overestimated.

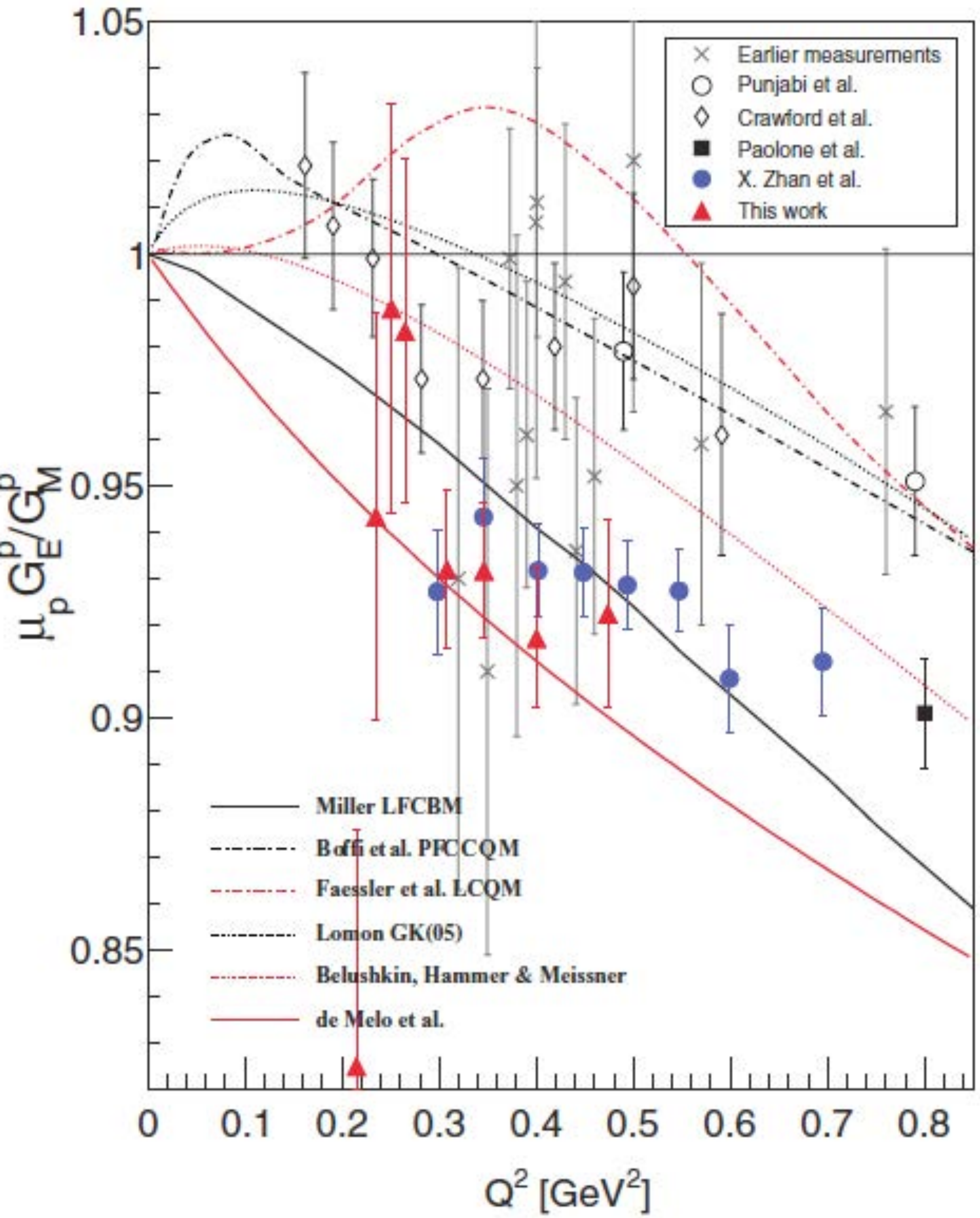


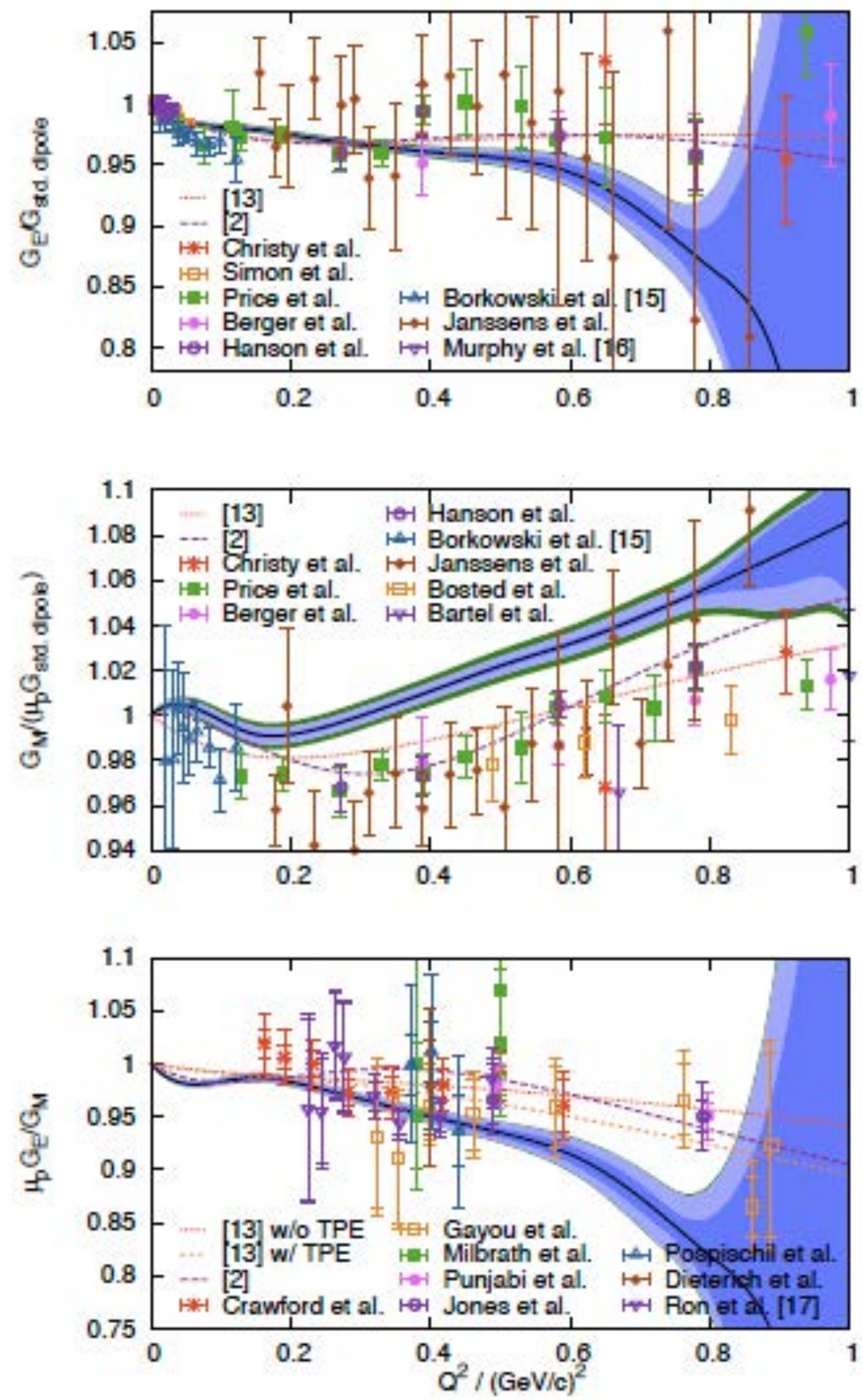
JLab ep E08-007 Part I (GR,…)

X. Zhan et al PLB 705, 59 (2011)

$r_p = 0.875 \pm 0.009$ fm

A flavor of the data

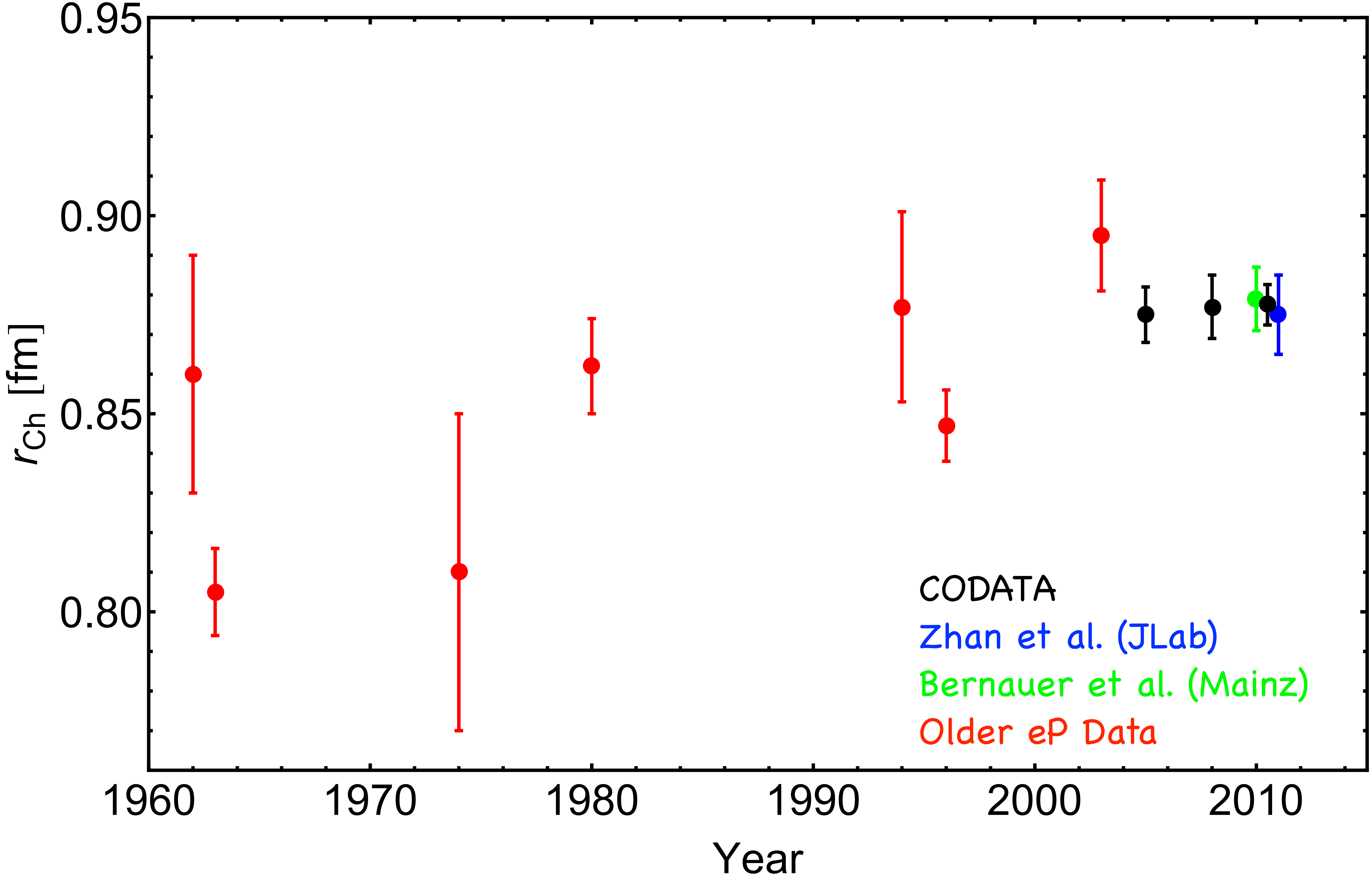




GR et al., PRC84, 055204(2011)

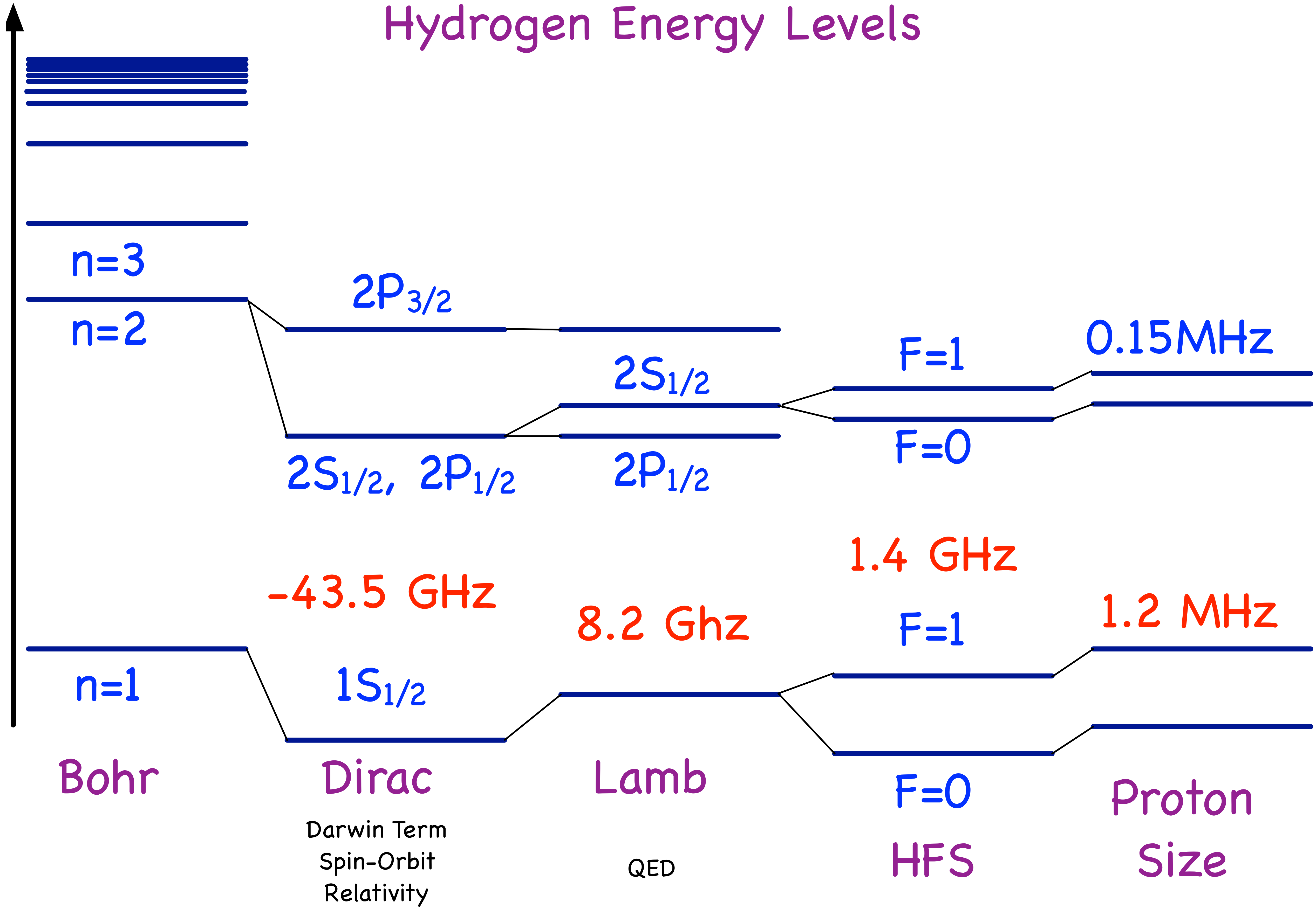
Bernauer et al, PRL105, 242001 (2010)

Time evolution of the Radius from eP data



Spectroscopic Measurements

Components of a calculation
Hydrogen Energy Levels



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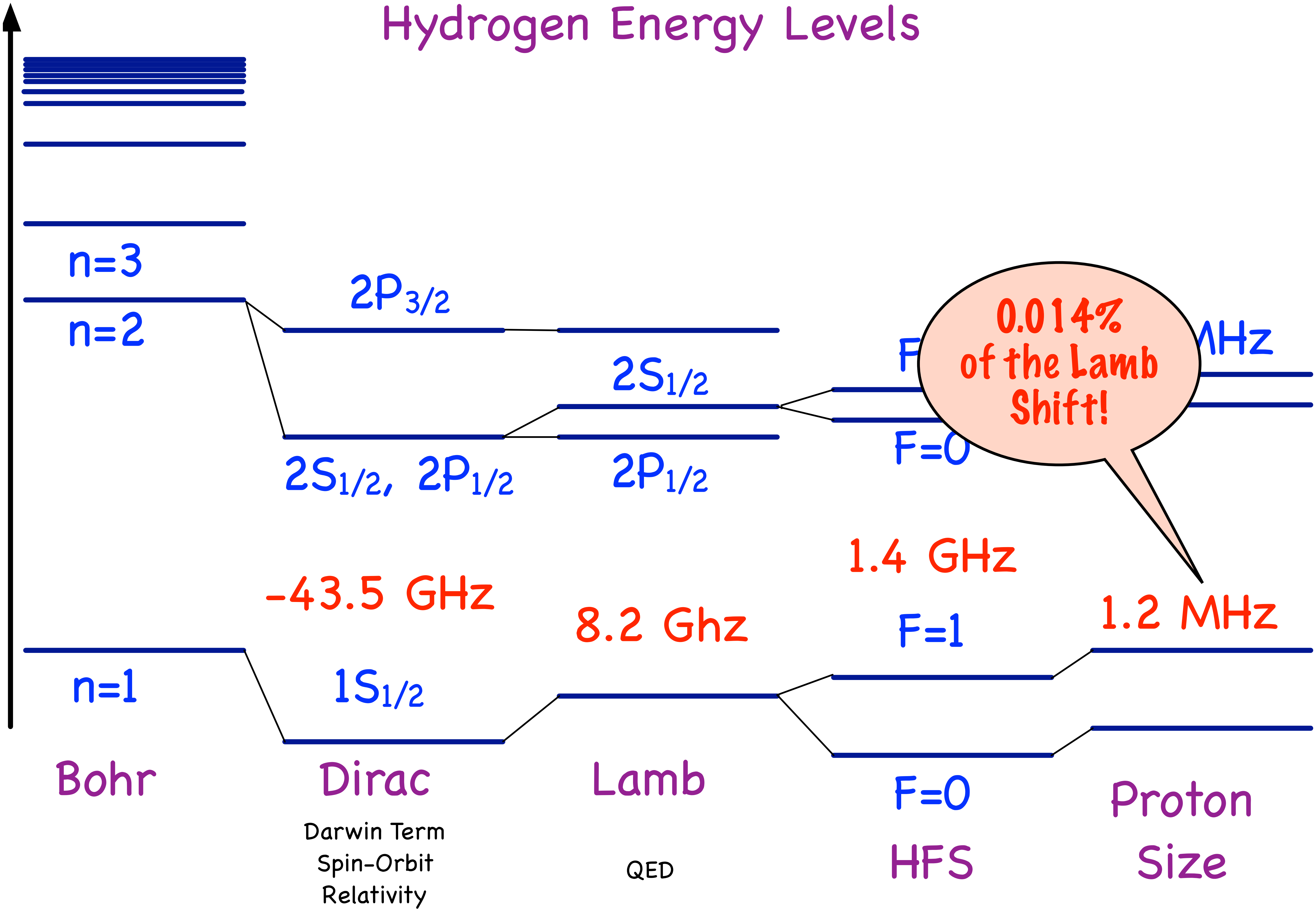

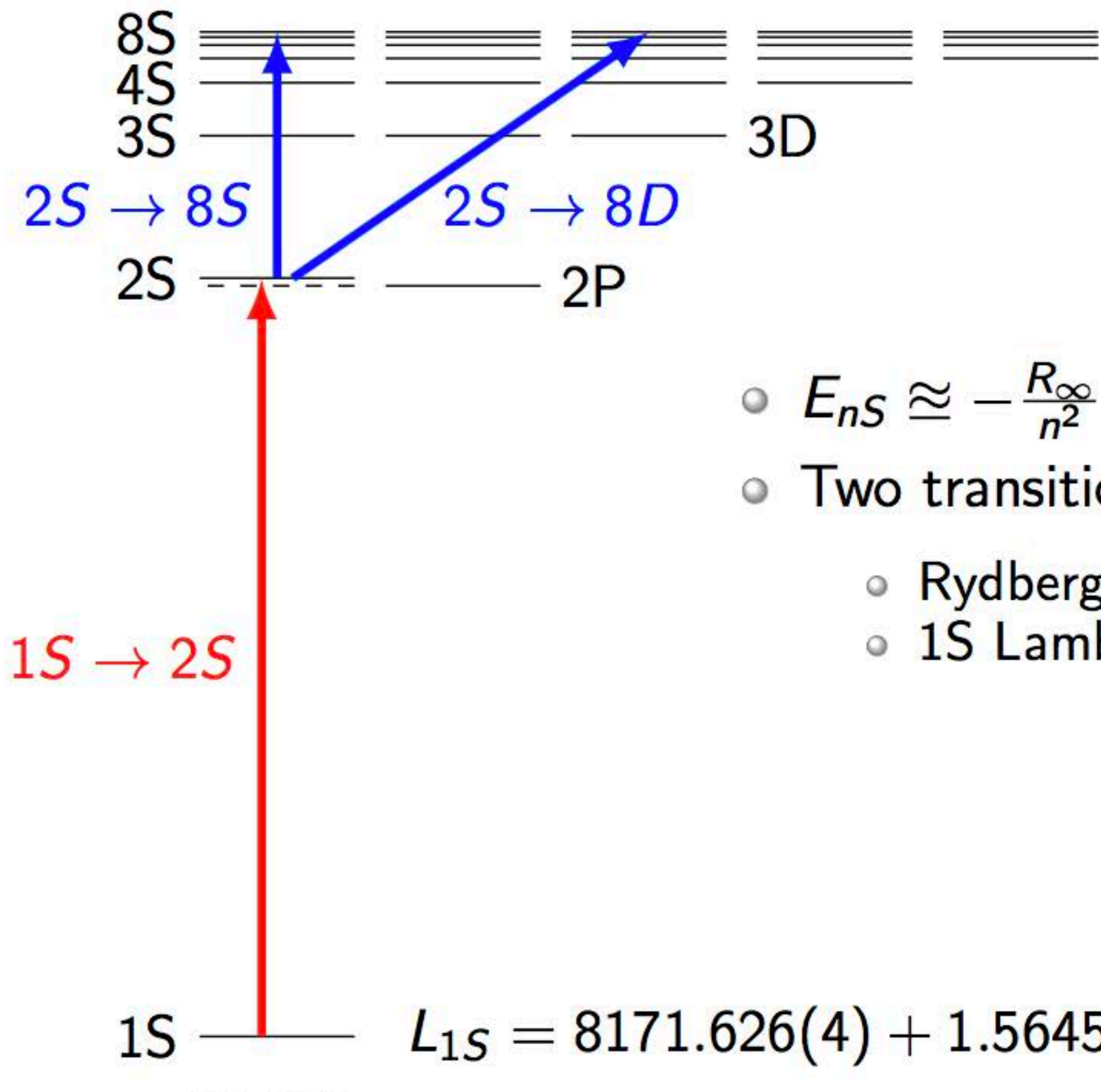

- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius

$L_{1S} = 8171.626(4) + 1.5645 \left\langle r_p^2 \right\rangle$ MHz

H-Like Lamb Shift Nuclear Dependence

$$\Delta E_{Nucl}(nl) = \frac{2}{3}\frac{(Z\alpha)^4}{n^3}(mR_N)^2\,\delta_{l0}\left(1+(Z\alpha)^2\ln\frac{1}{Z\alpha mR_N}\right)$$

$$\Delta E_{Nucl}(2p_{1/2})\frac{1}{16}(Z\alpha)^6 m\,(mR_N)^2$$

$$\Delta E_{Nucl}(2p_{3/2}) = 0$$

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

$\Delta E_{Lamb}(1S) = 8172.582(40)$ MHz

$\Delta E_{Nucl}(1S) = 1.269$ MHz for rp = 0.9 fm

$\Delta E_{Nucl}(1S) = 1.003$ MHz for rp = 0.8 fm

$\Delta E_{Lamb}(2S) = 1057.8450(29)$ MHz

$\Delta E_{Nucl}(2S) = 0.1586$ MHz for rp = 0.9 fm

$\Delta E_{Nucl}(2S) = 0.1254$ MHz for rp = 0.8 fm

ear Dependence

$$\ldots_0 \left(1 + (Z\alpha)^2 \ln \frac{1}{Z\alpha m R_N}\right)$$

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ear Dependence

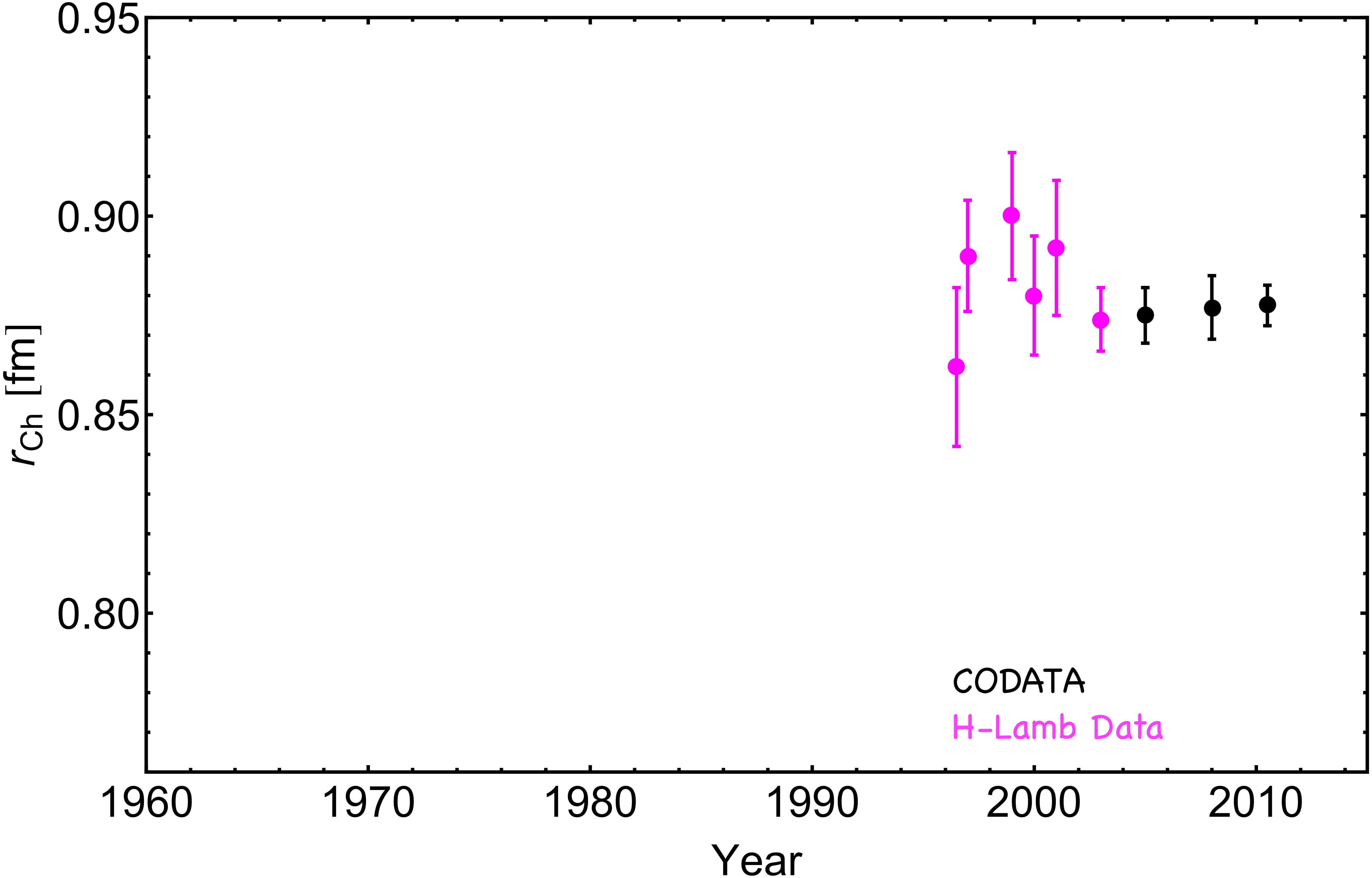
$$\left(1 + (Z\alpha)^2 \ln \frac{1}{Z\alpha m R_N}\right)$$

$$E_{1S}(r_p) =$$

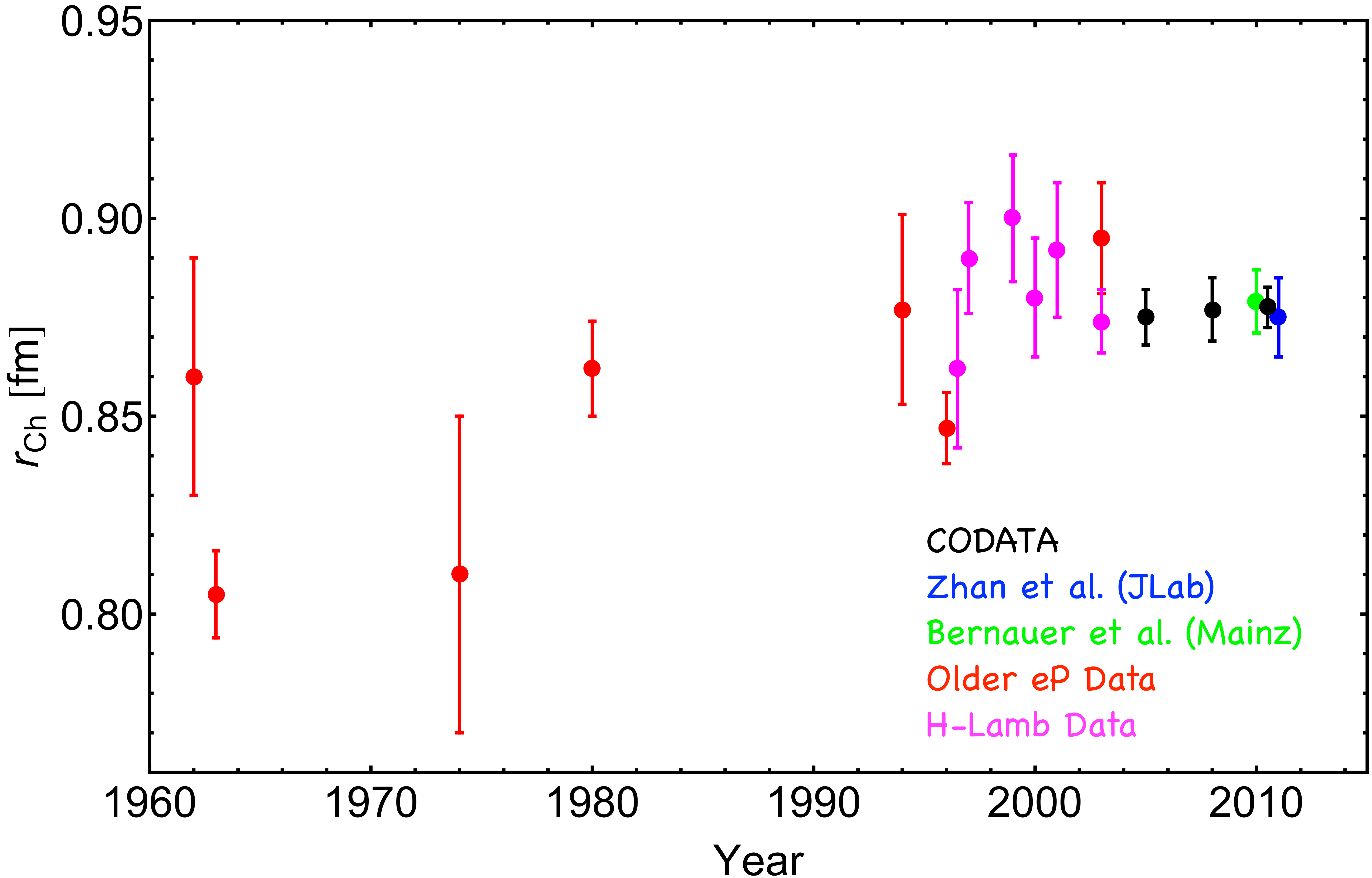
$\Delta E_{\mathrm{Lamb}}(1S) = 8172.582(40)$

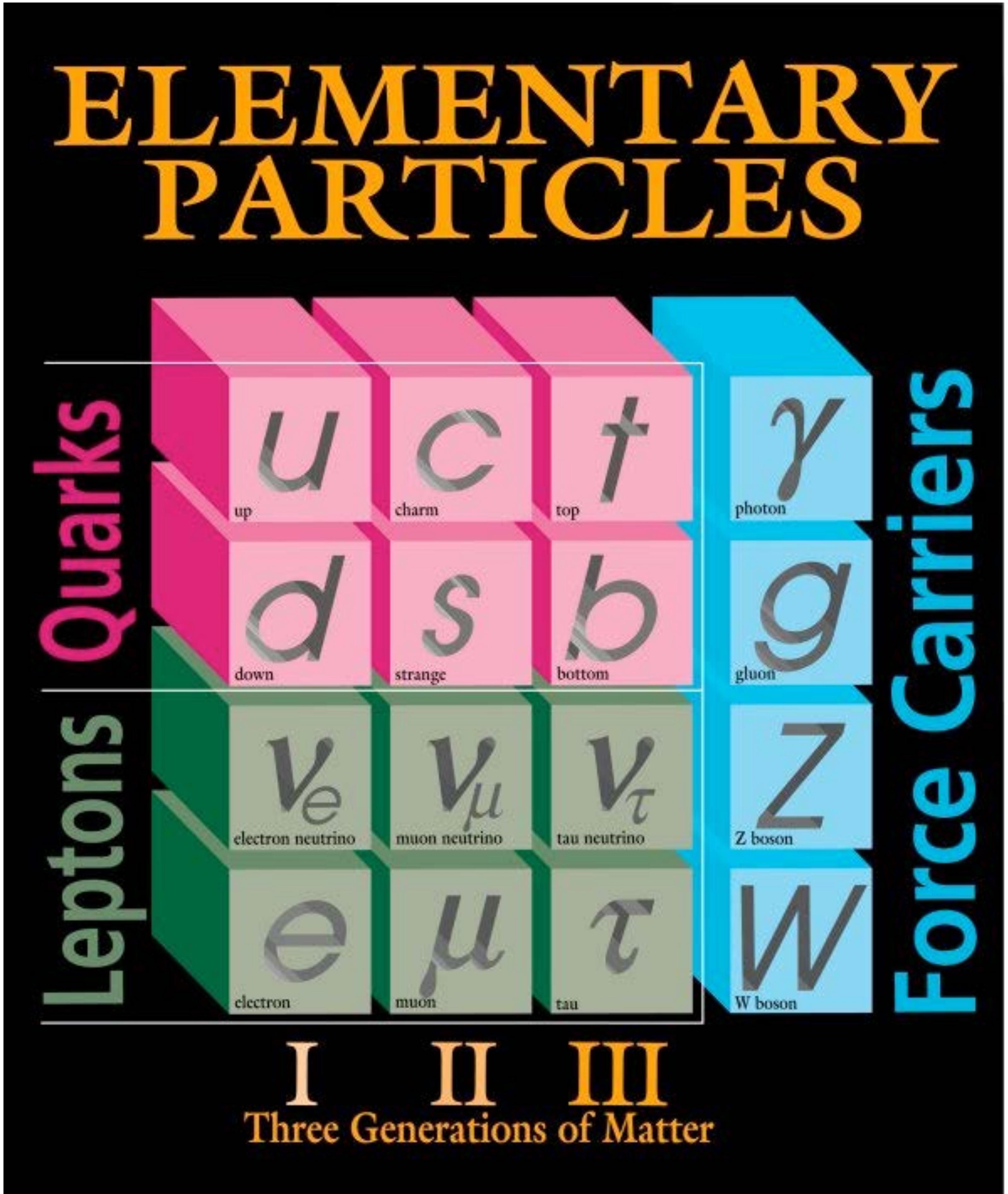
$\Delta E_{\mathrm{Lamb}}(2S) = 1057.8450(29)$

Time evolution of the Radius from H Lamb Shift

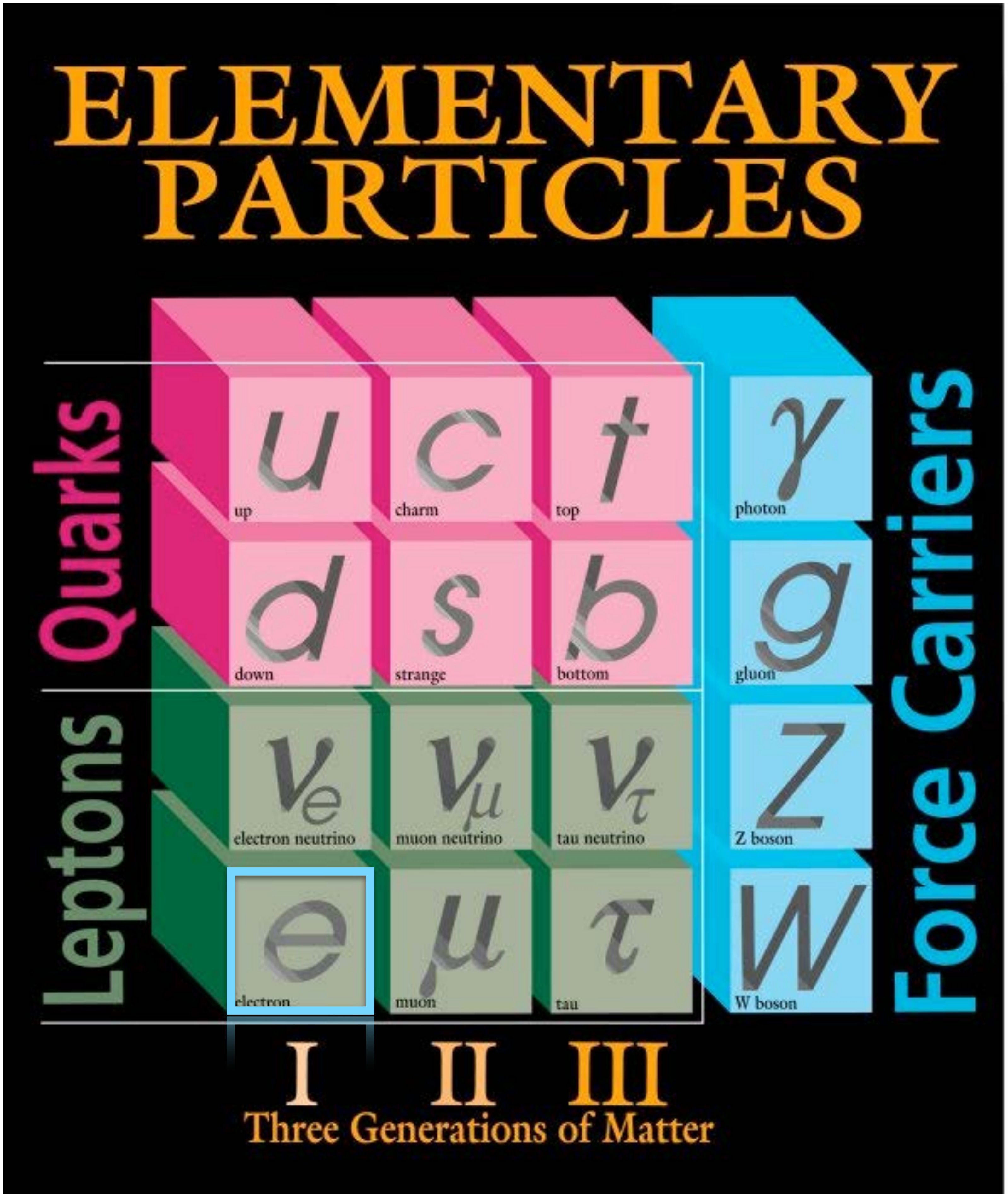


Time evolution of the Radius from H Lamb Shift + eP

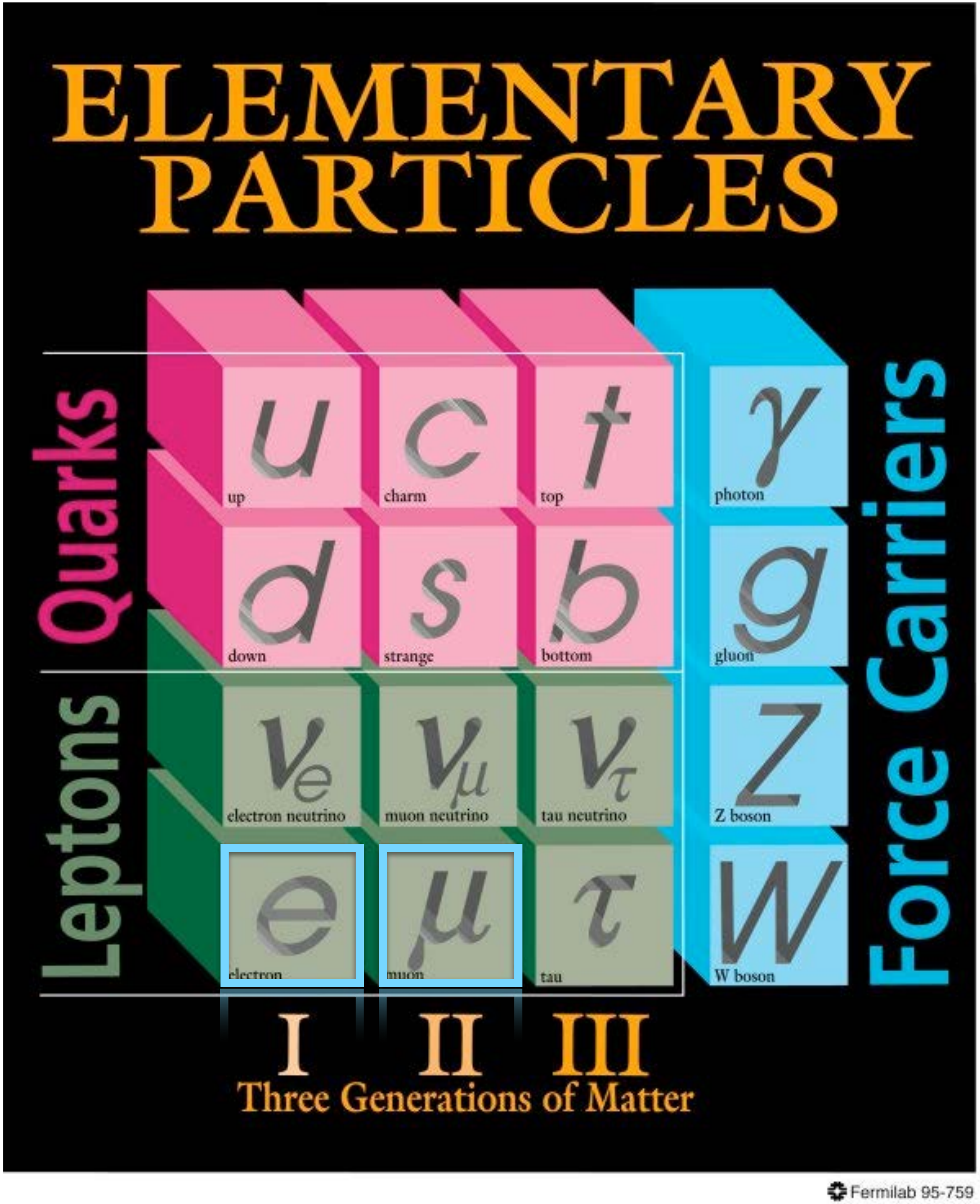




Fermilab 95-759



Fermilab 95-759



In the standard model the muon is just a heavier version (~200 times) of the electron. The muon decays into an electron (and some neutrinos) with a lifetime of ~2.2 uS.

It has exactly the same interactions…

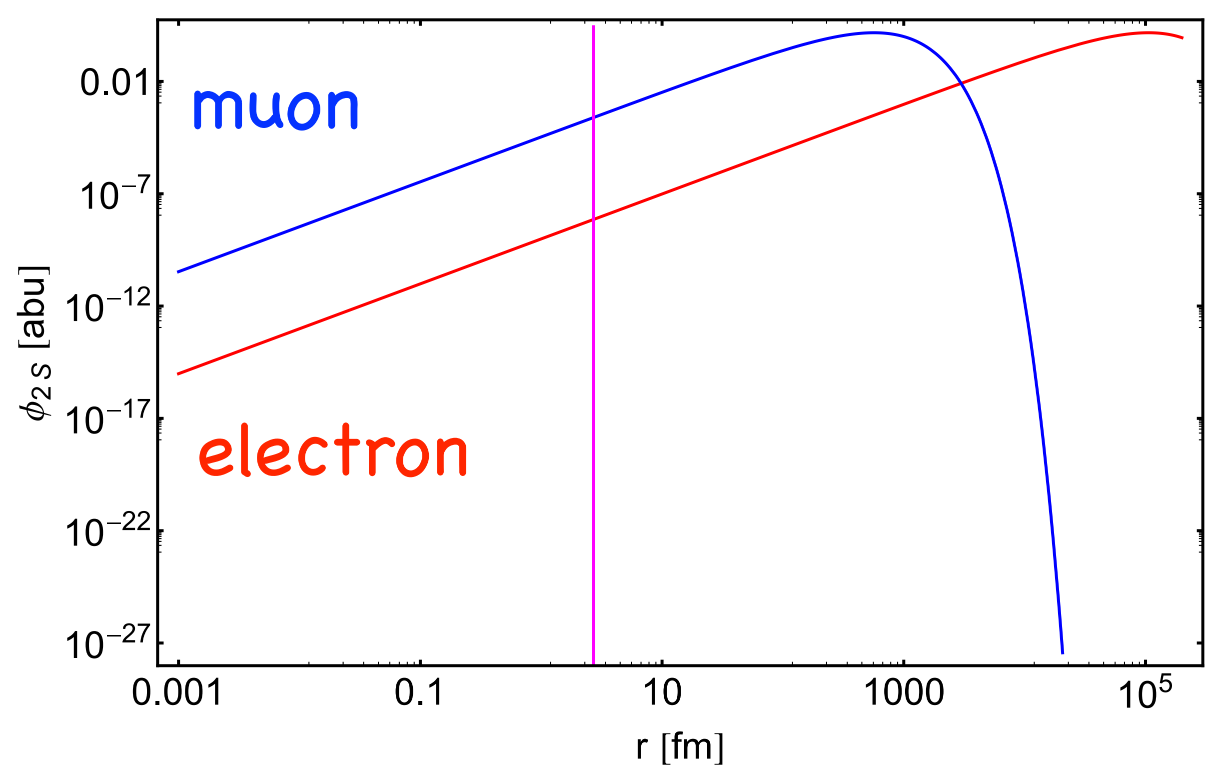
Why atomic physics to learn proton radius? Why μH?

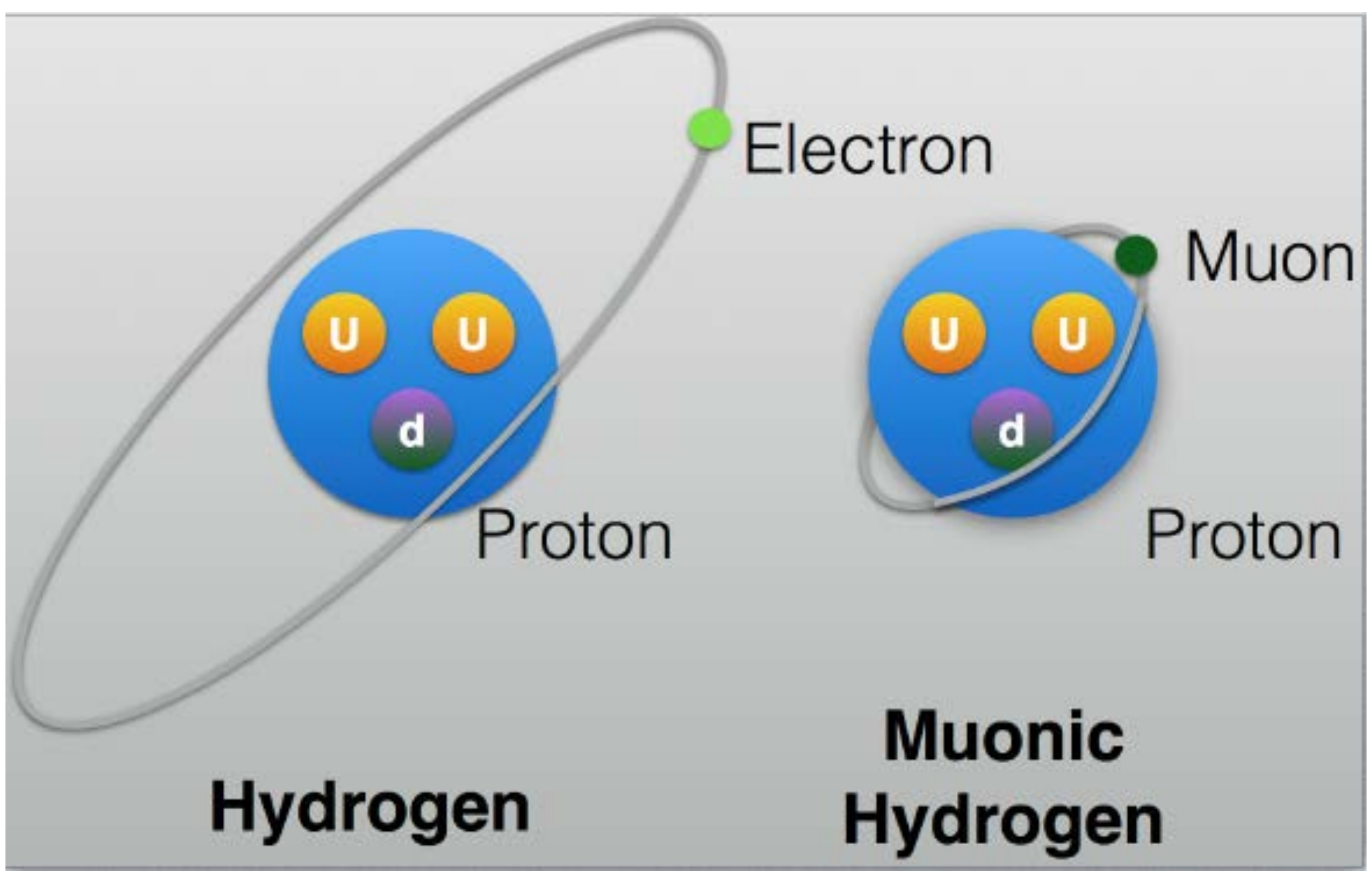
Probability for lepton to be inside the proton:
proton to atom volume ratio

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

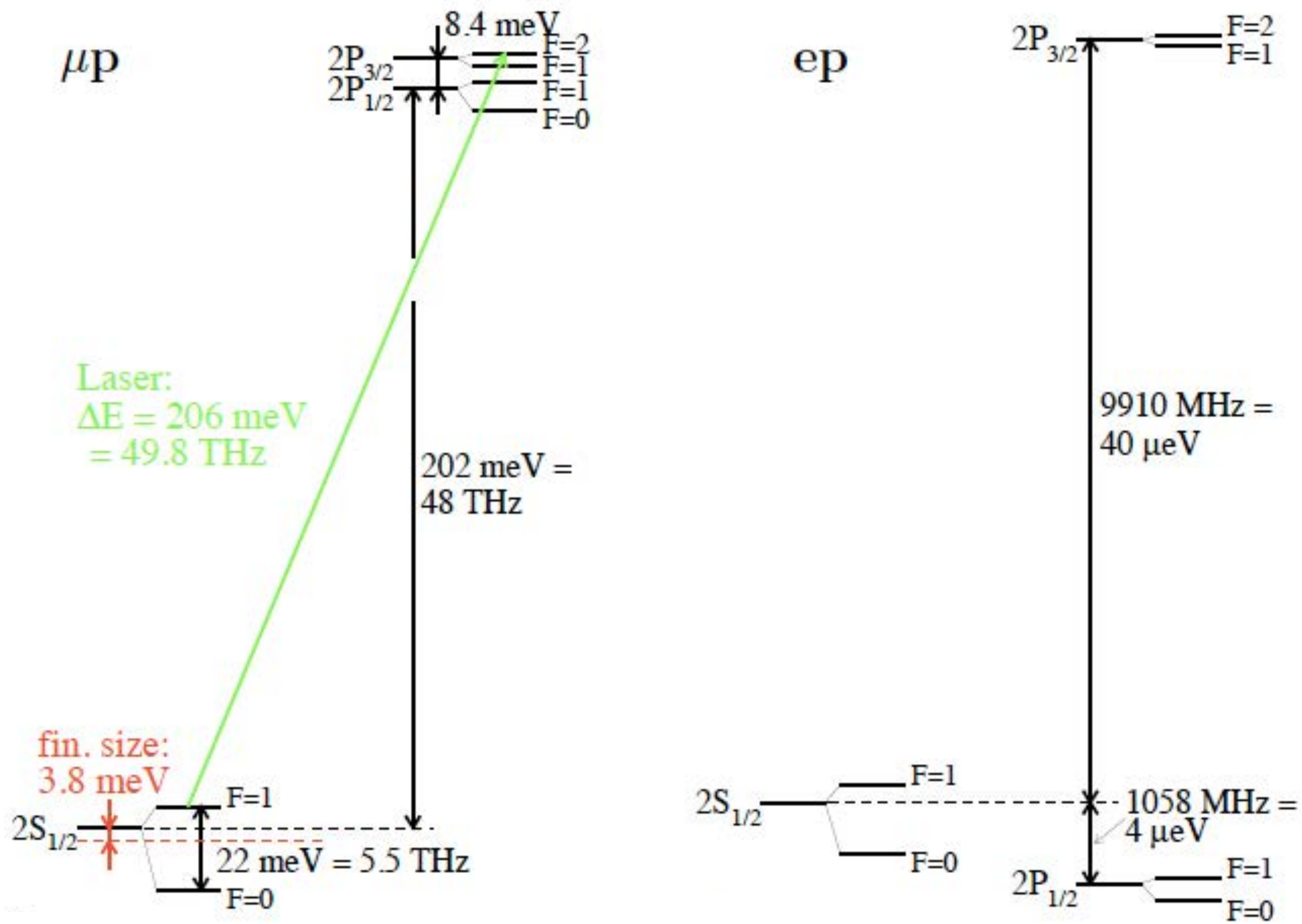
Lepton mass to the **third** power!

Muon to electron mass ratio ~205 → factor of about 8 million!



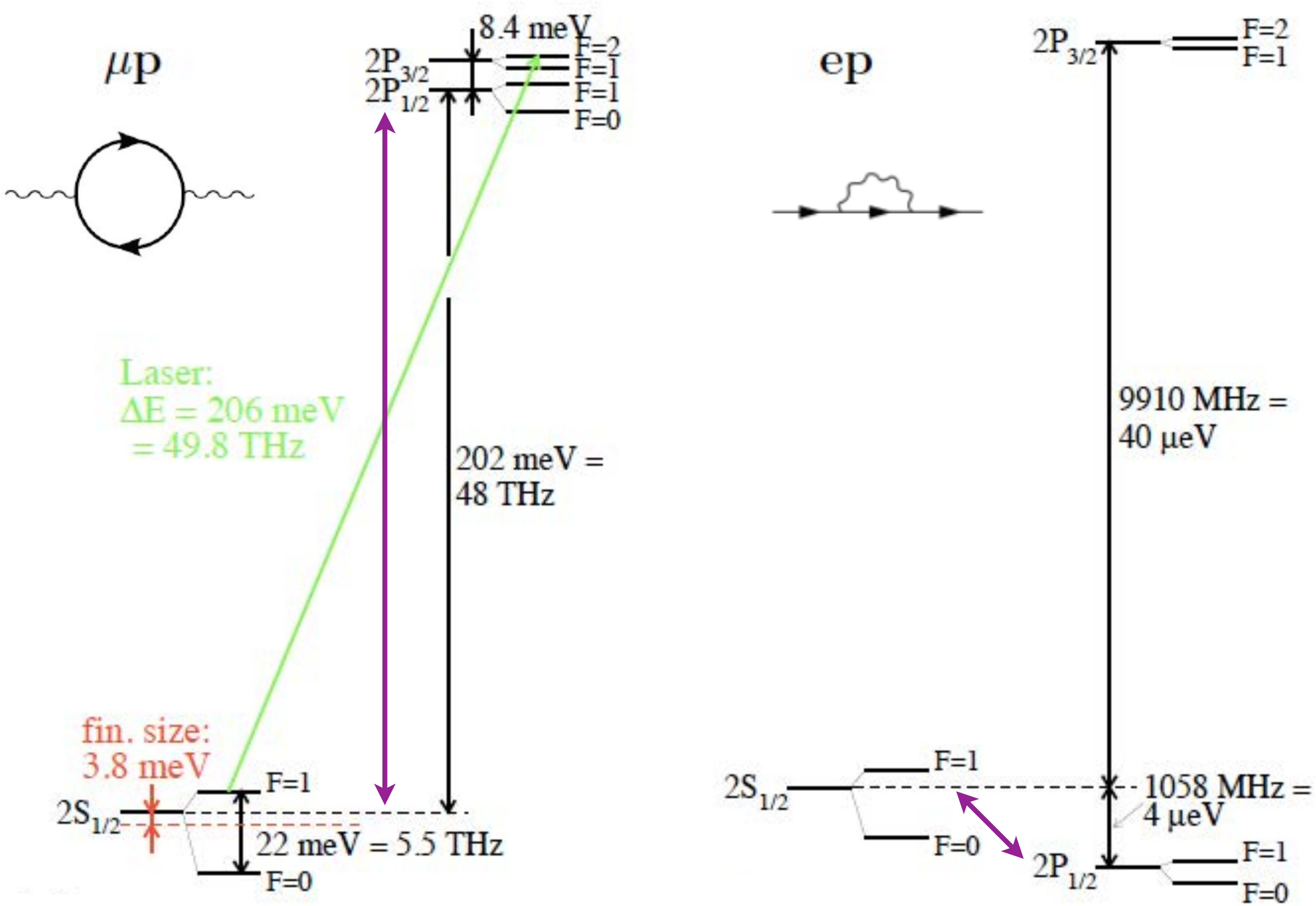


Lamb shift in eP and μP



T. Nebel, PhD Thesis

Lamb shift in eP and μP



T. Nebel, PhD Thesis

Proton charge radius and muonic hydrogen

MPQ

muonic hydrogen = $\mu^- p$ mass m_μ = 207 m_e

$\Rightarrow$ Bohr: $\langle r^{\text{orbit}} \rangle \sim \dfrac{\hbar}{Z\alpha\, m_r\, c} n^2$

$\Delta E_{\text{finite size}}(nl) \sim r_p^2 \, |\Psi(r=0)|^2$

$$\Rightarrow \boxed{\Delta E_{\text{finite size}}(nl) = \frac{2(Z\alpha)^4 c^4}{3\hbar^2 n^3} m_r^3 \, r_p^2 \, \delta_{l0}}$$

Lamb shift in μp: $\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1})$ =

$$\boxed{209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \ \text{[meV]}}$$

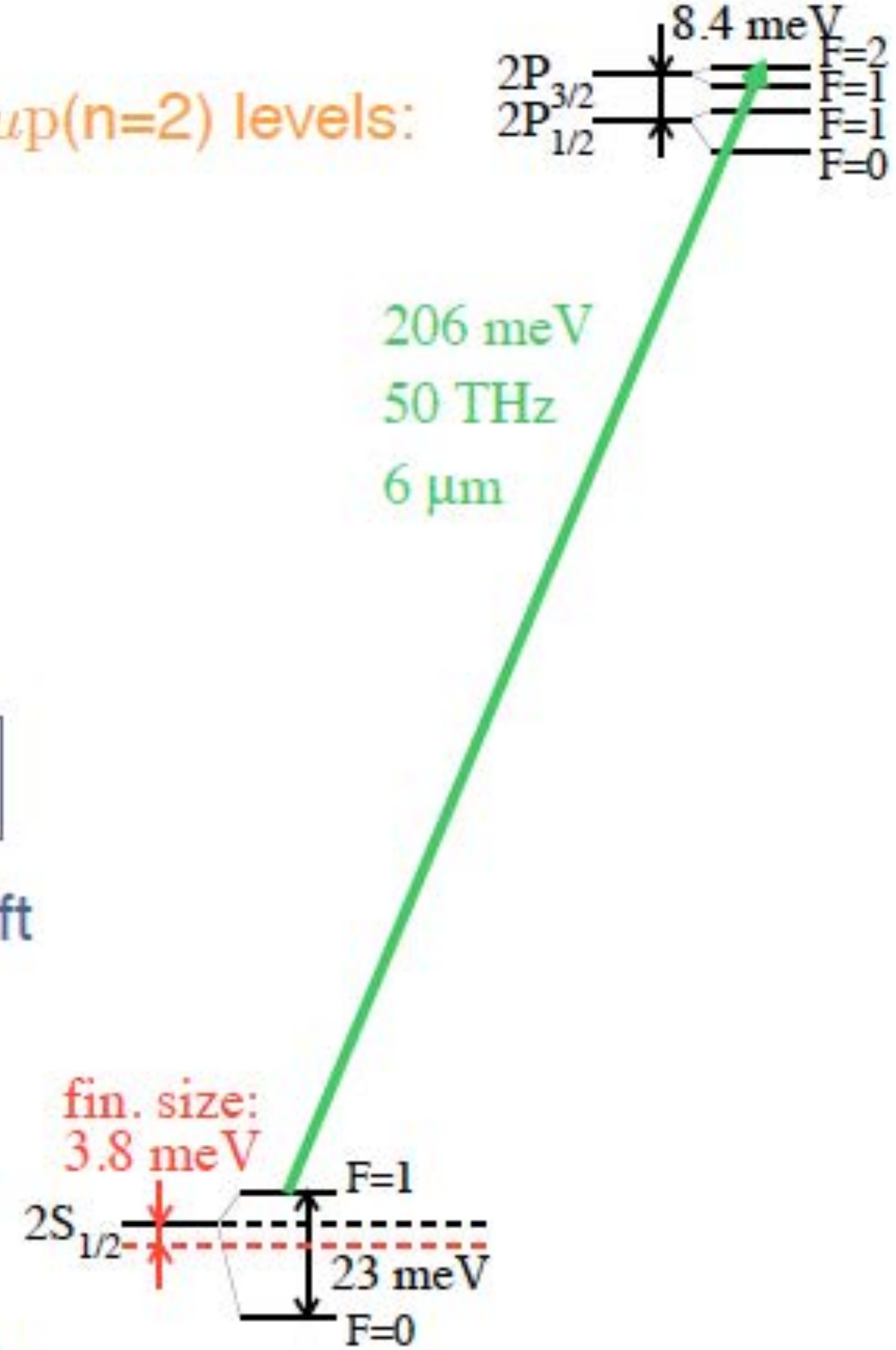
finite size contribution is 2% of the μp Lamb shift

measure ΔE(2S-2P) to 30 ppm = 1.5 GHz

$$\boxed{\Rightarrow r_p \text{ to } 10^{-3}}$$

$\Gamma_{2P} \; = \; 18.6$ GHz $\qquad (\Gamma_{\text{rad.}})$

μp(n=2) levels:

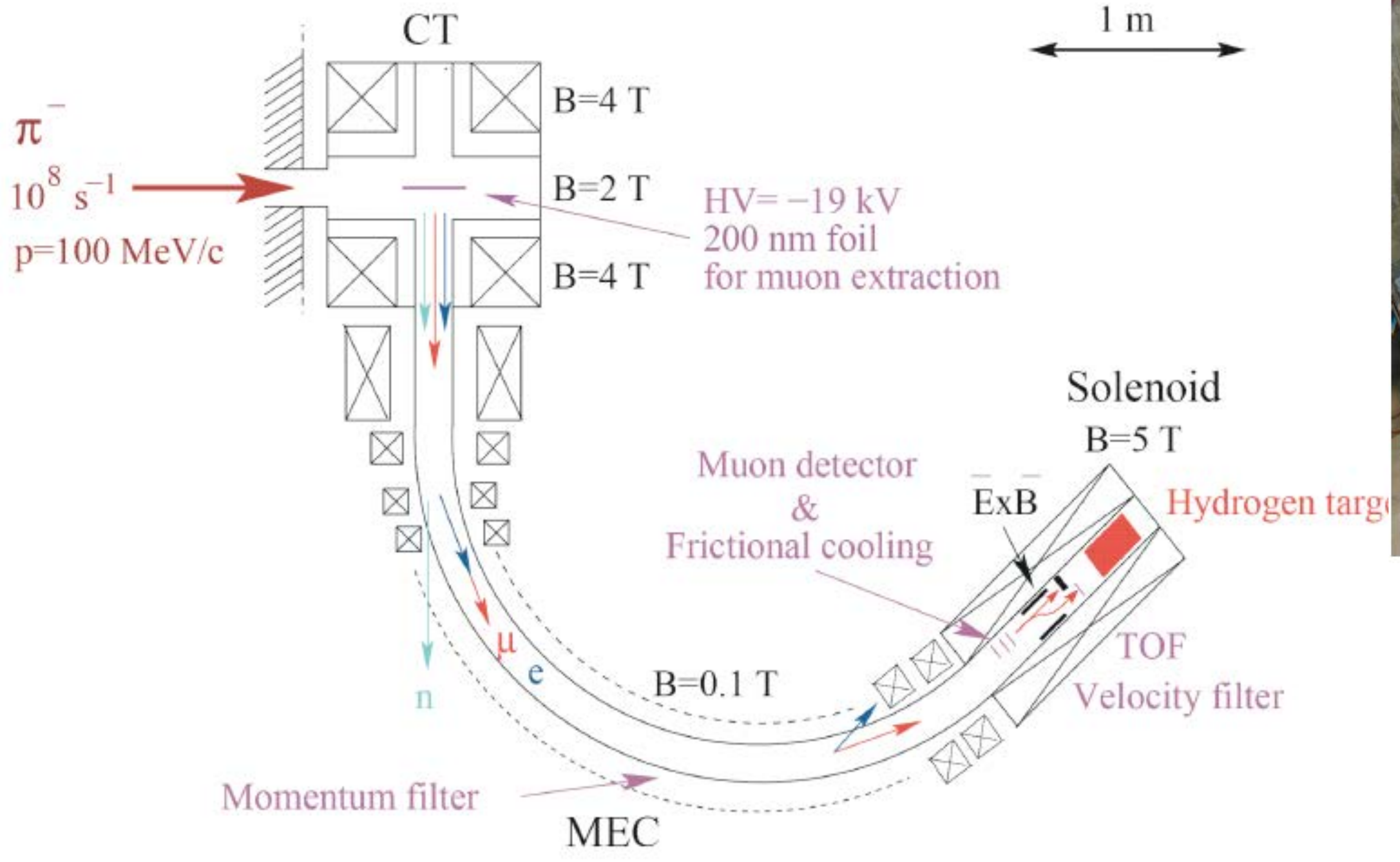


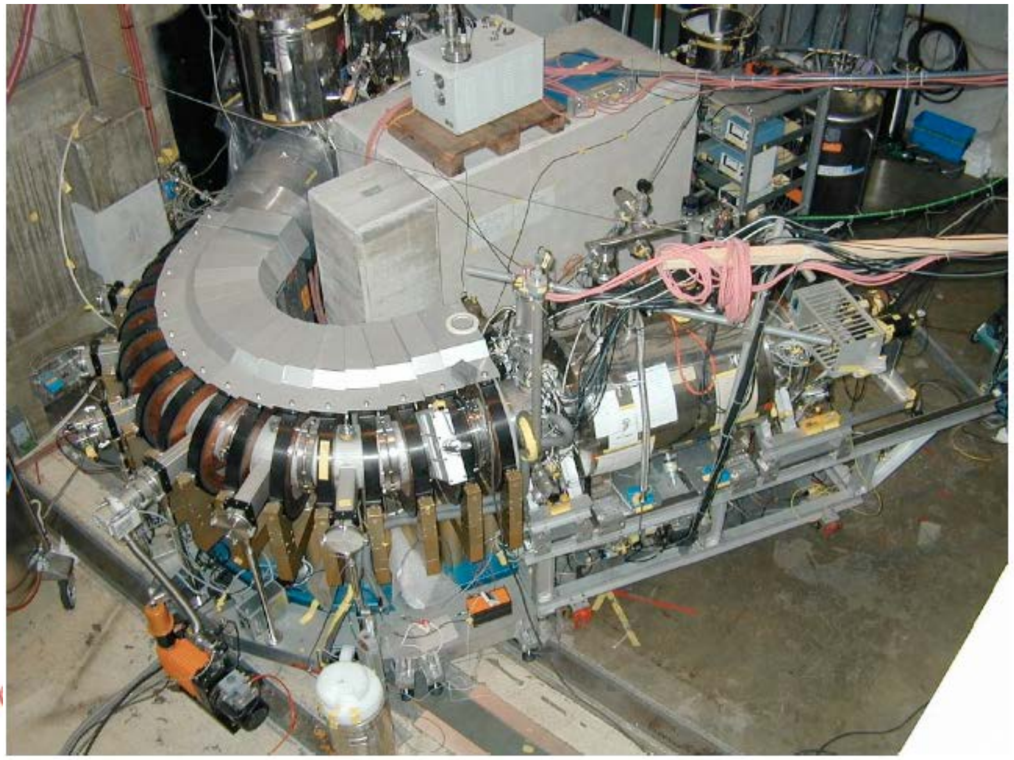
Courtesy of R. Pohl

μP Lamb Shift Measurement

μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)





μP Lamb Shift Measurement

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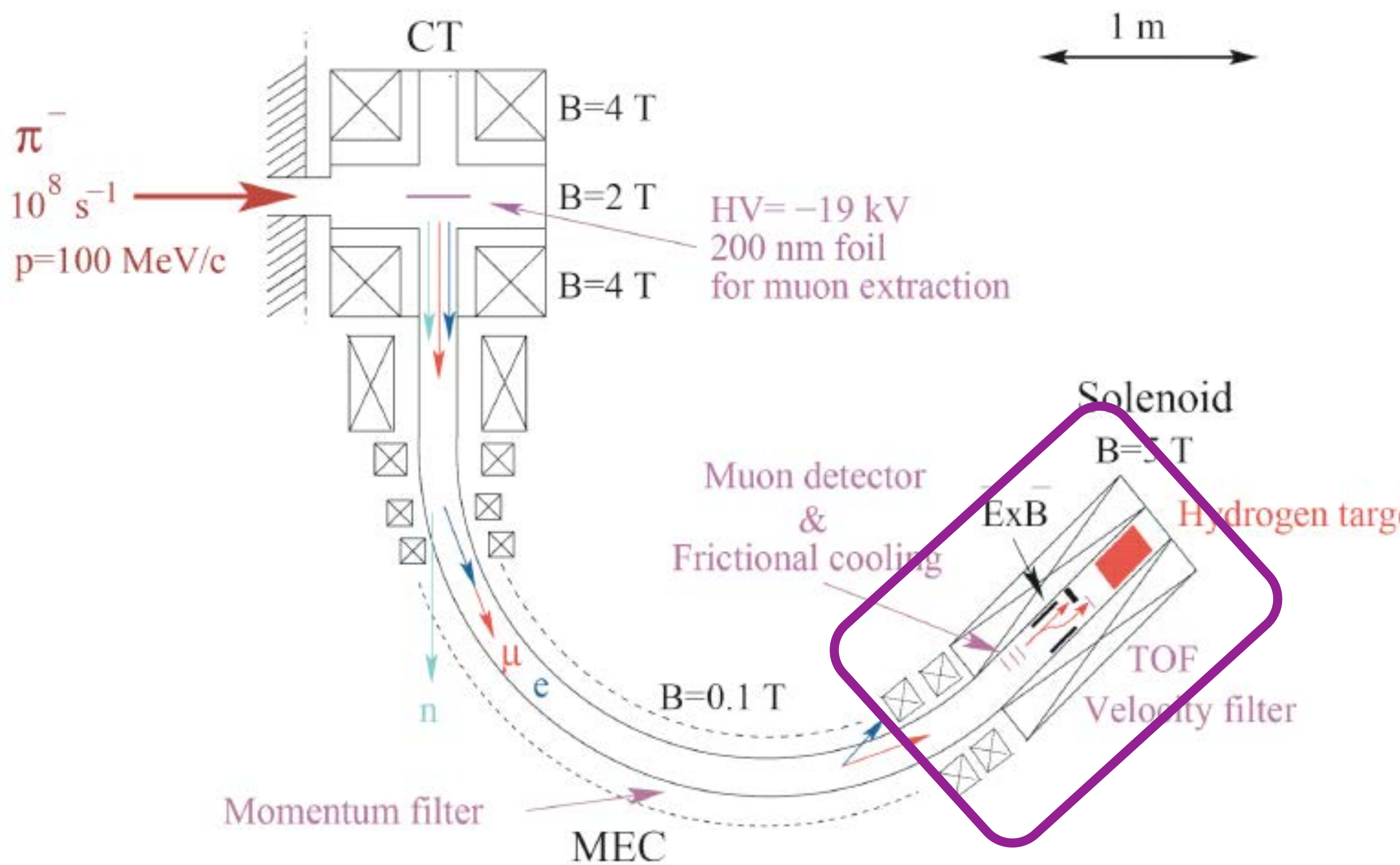
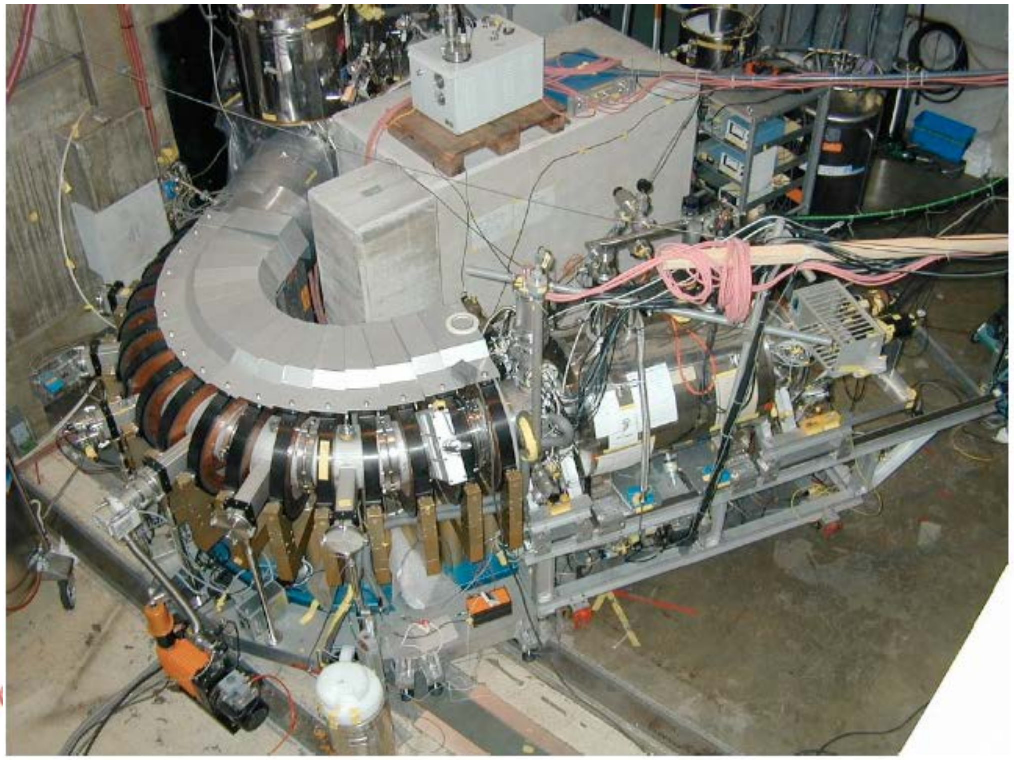
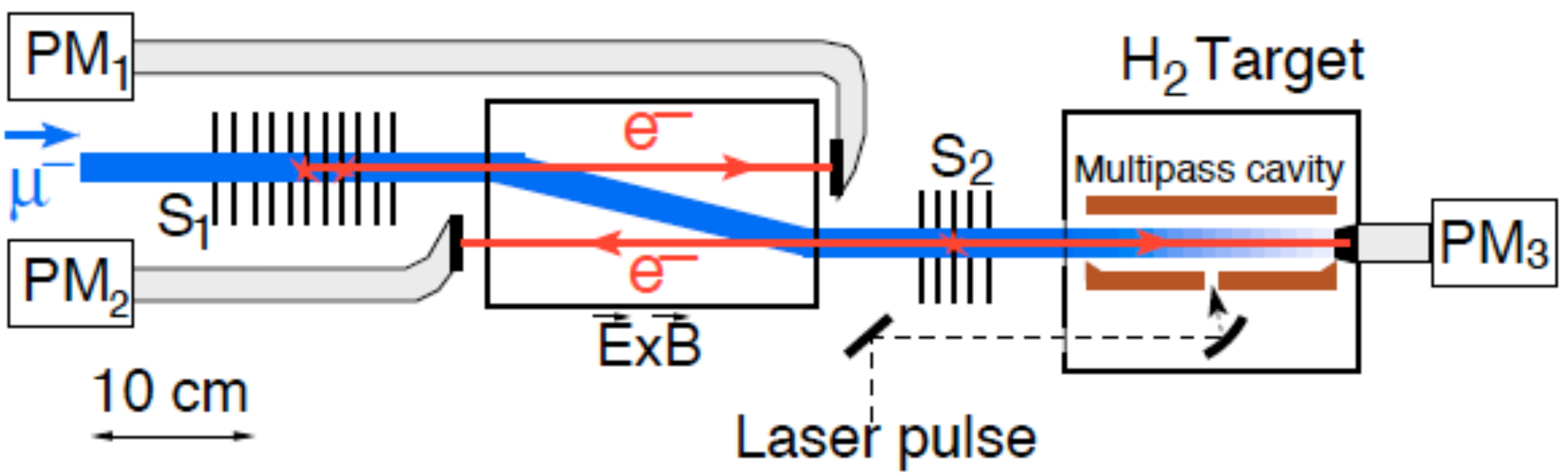




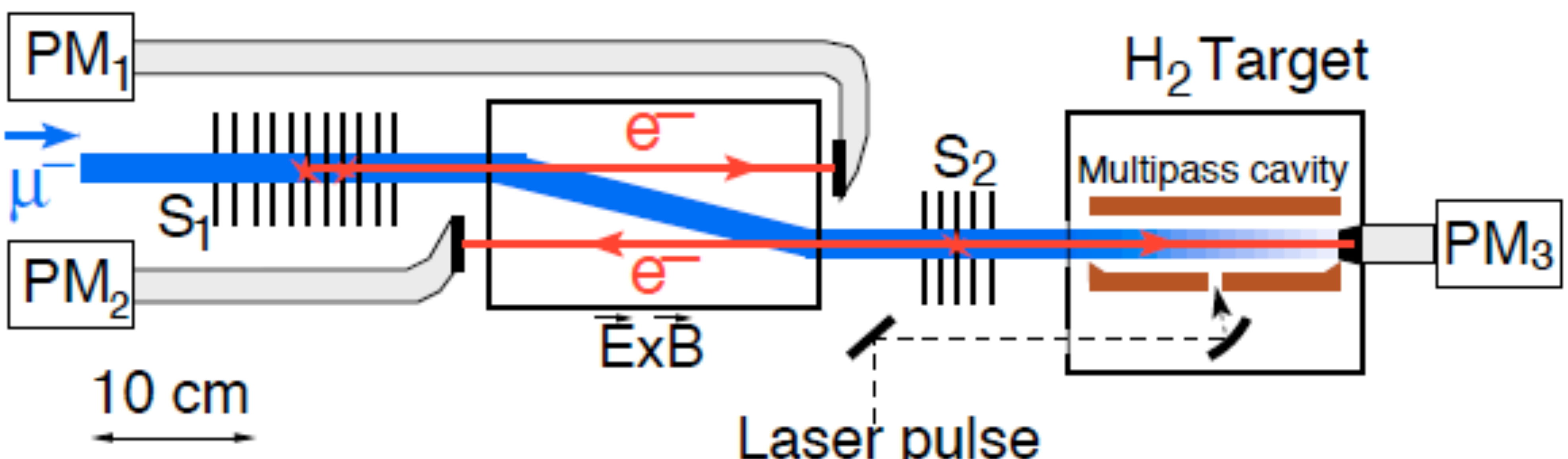
μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)



μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)
- μ's with 5 keV kinetic energy after carbon foils S1-2
- Arrival of the pulsed beam is timed by secondary electrons in PM1-3



μP Lamb Shift Measurement

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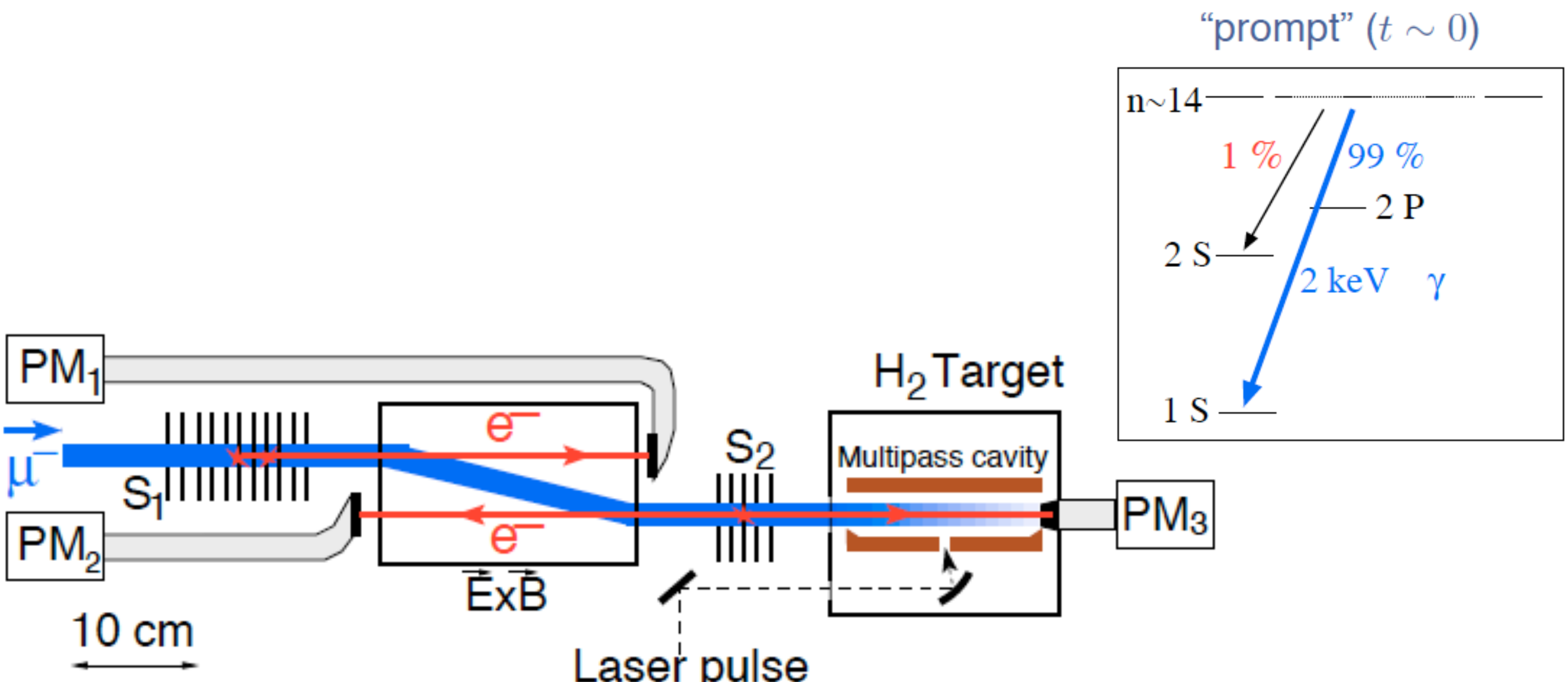

μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)
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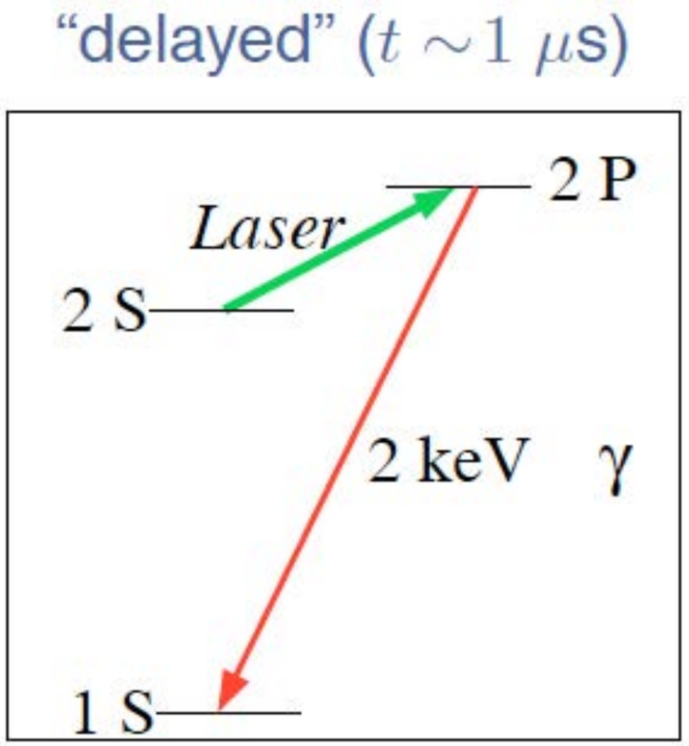
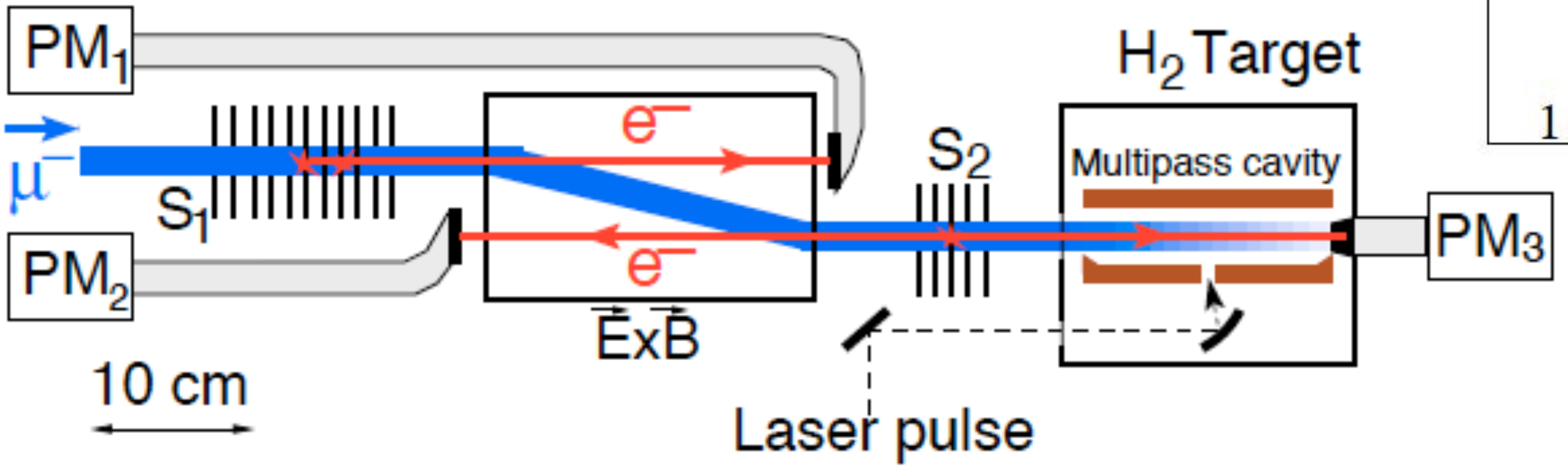
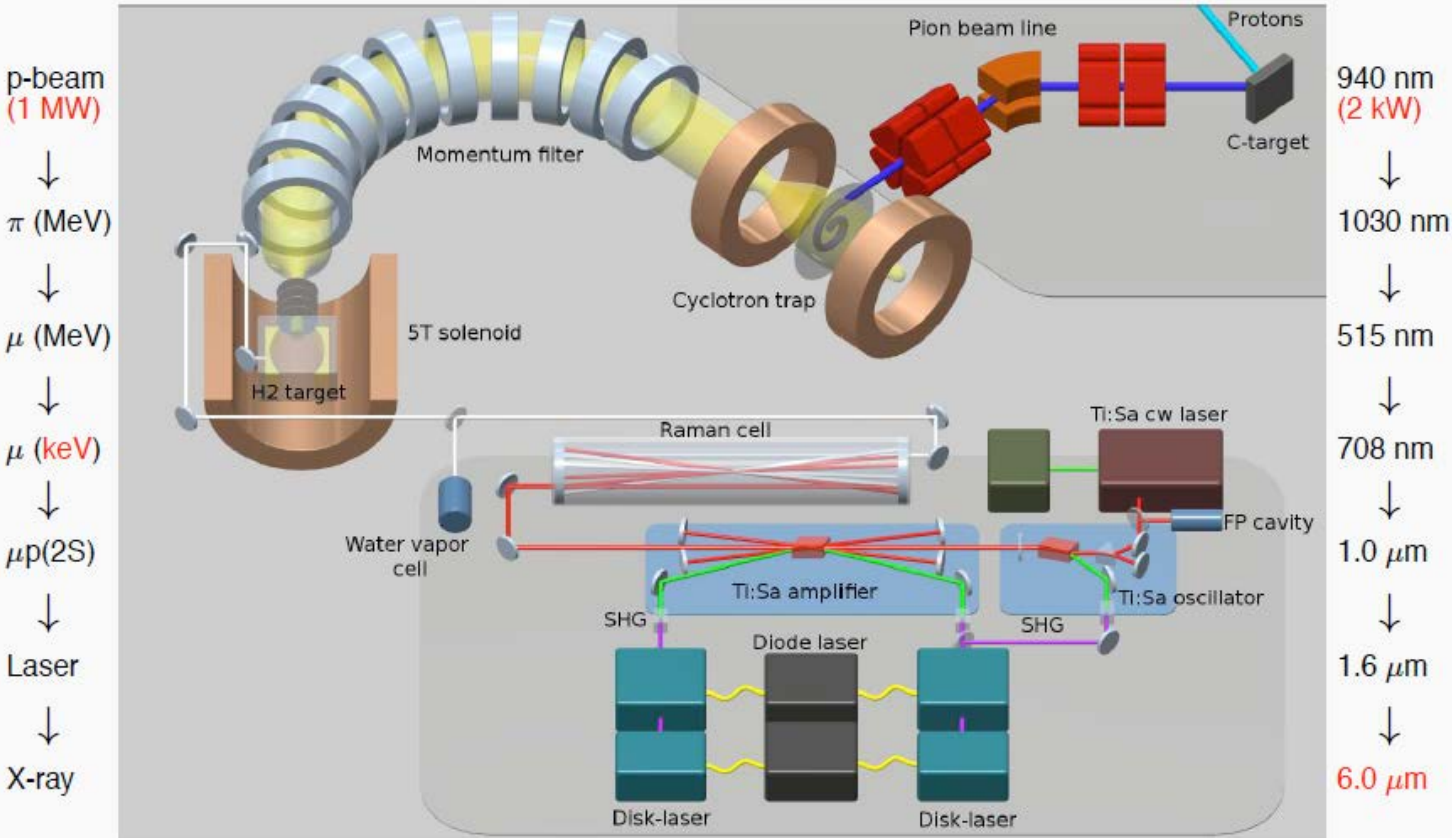
- Arrival of the pulsed beam is timed by secondary electrons in PM1-3
- μ's are absorbed in the H_2 target at high excitation followed by decay to the 2S metastable level (which has a 1 μs lifetime)
- A laser pulse timed by the PMs excites the $2S_{1/2}^{F=1}$ to $2P_{3/2}^{F=2}$ transition
- The 2 keV X-rays from 2P to 1S are detected.

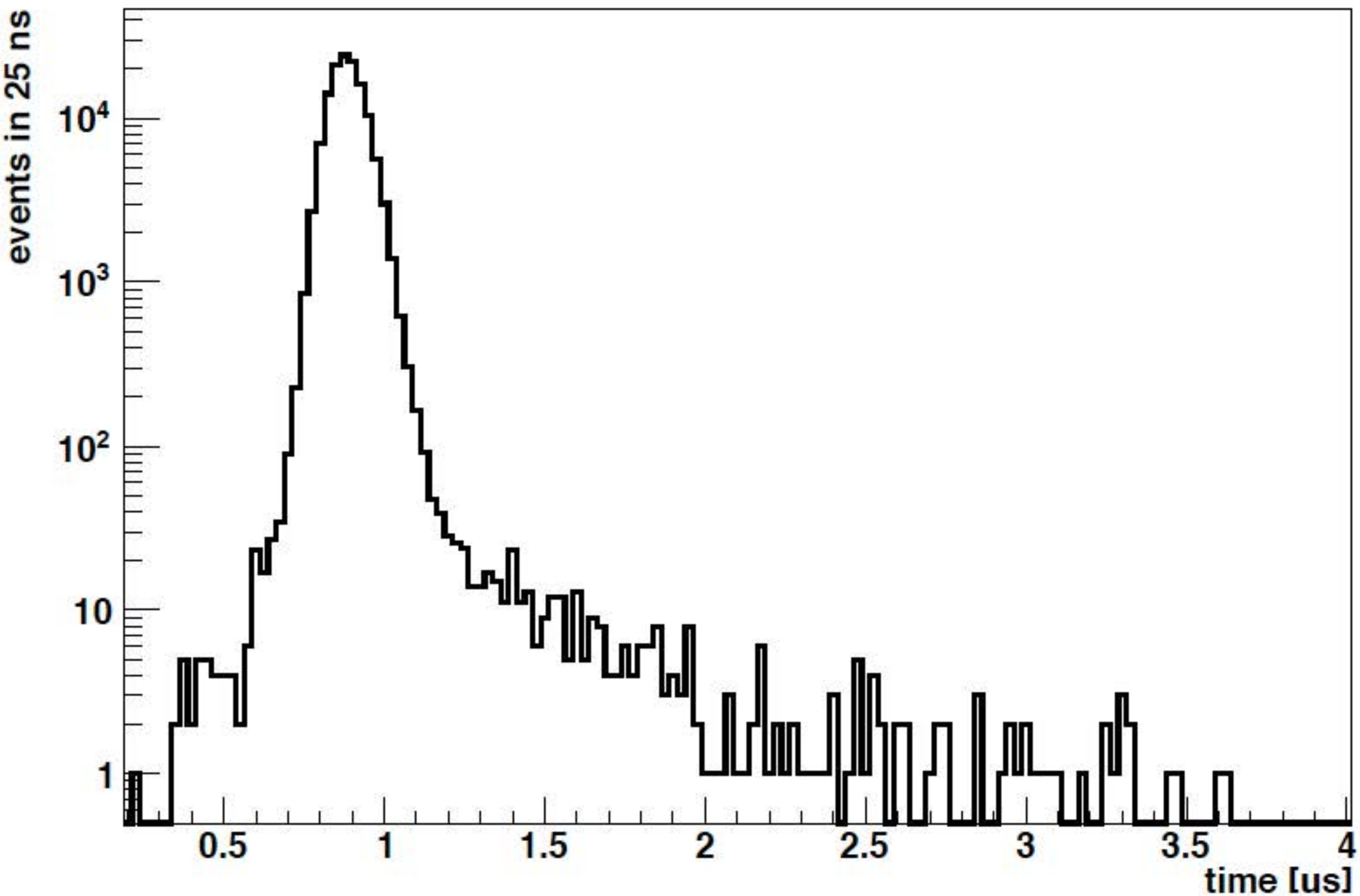






p-beam
(1 MW)
π (MeV)
μ (MeV)
μ (keV)
μp(2S)
Laser
X-ray
940 nm
(2 kW)
1030 nm
515 nm
708 nm
1.0 μm
1.6 μm
6.0 μm
Protons
Pion beam line
C-target
Momentum filter
Cyclotron trap
5T solenoid
H2 target
Raman cell
Ti:Sa cw laser
FP cavity
Water vapor cell
Ti:Sa amplifier
Ti:Sa oscillator
SHG
SHG
Diode laser
Disk-laser
Disk-laser

time spectrum of 2 keV x-rays   (~ 13 hours of data)



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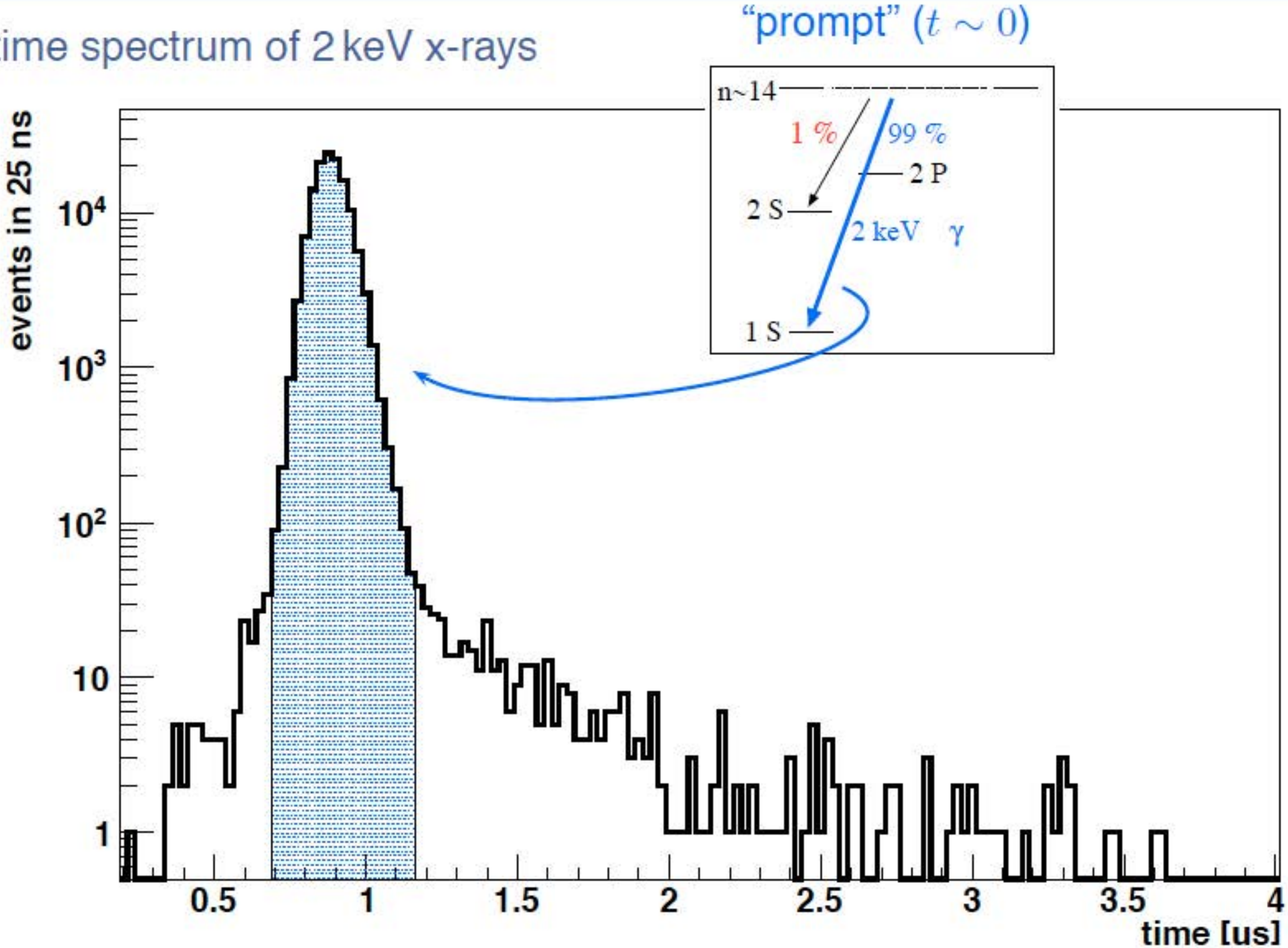
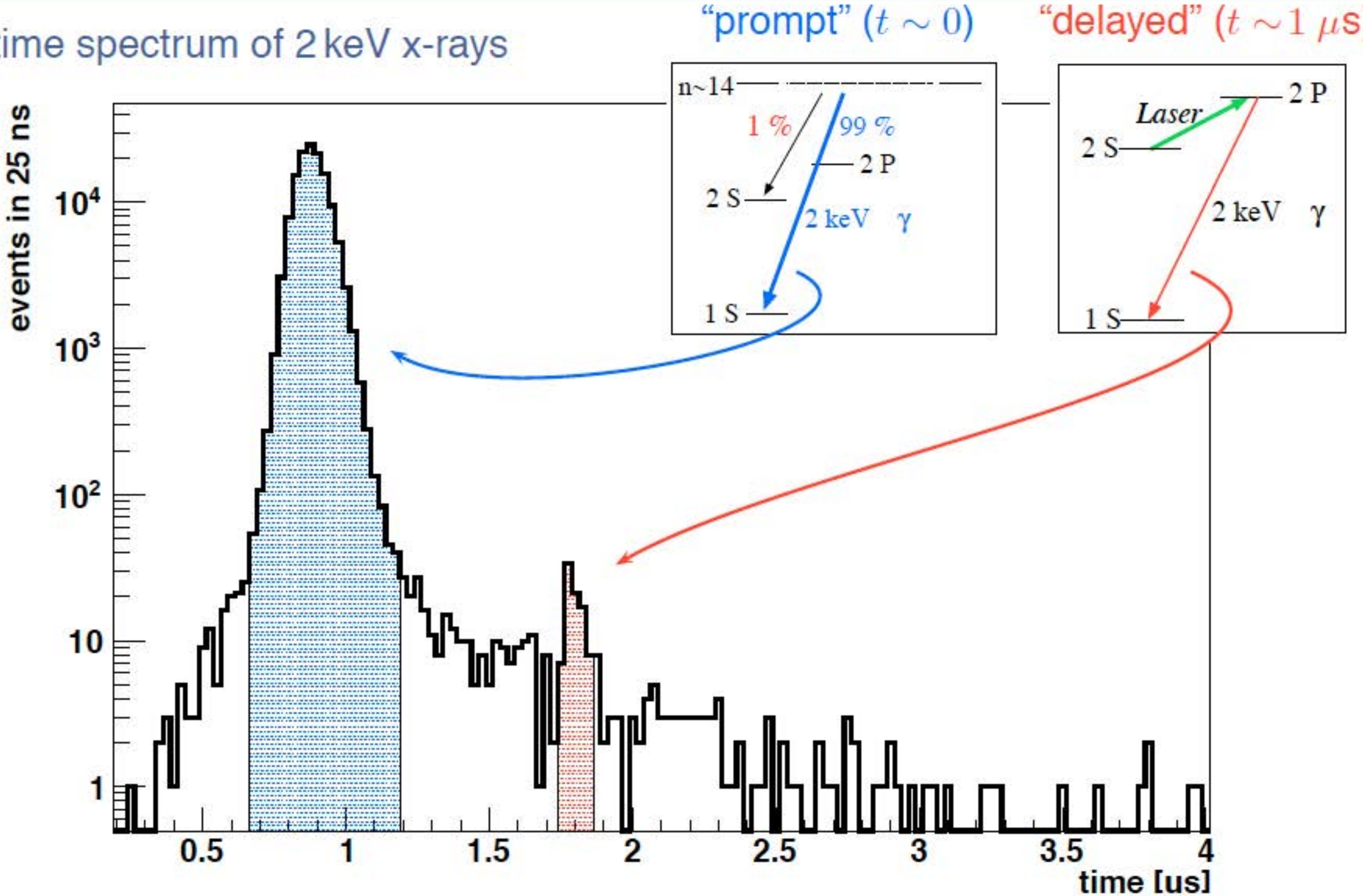
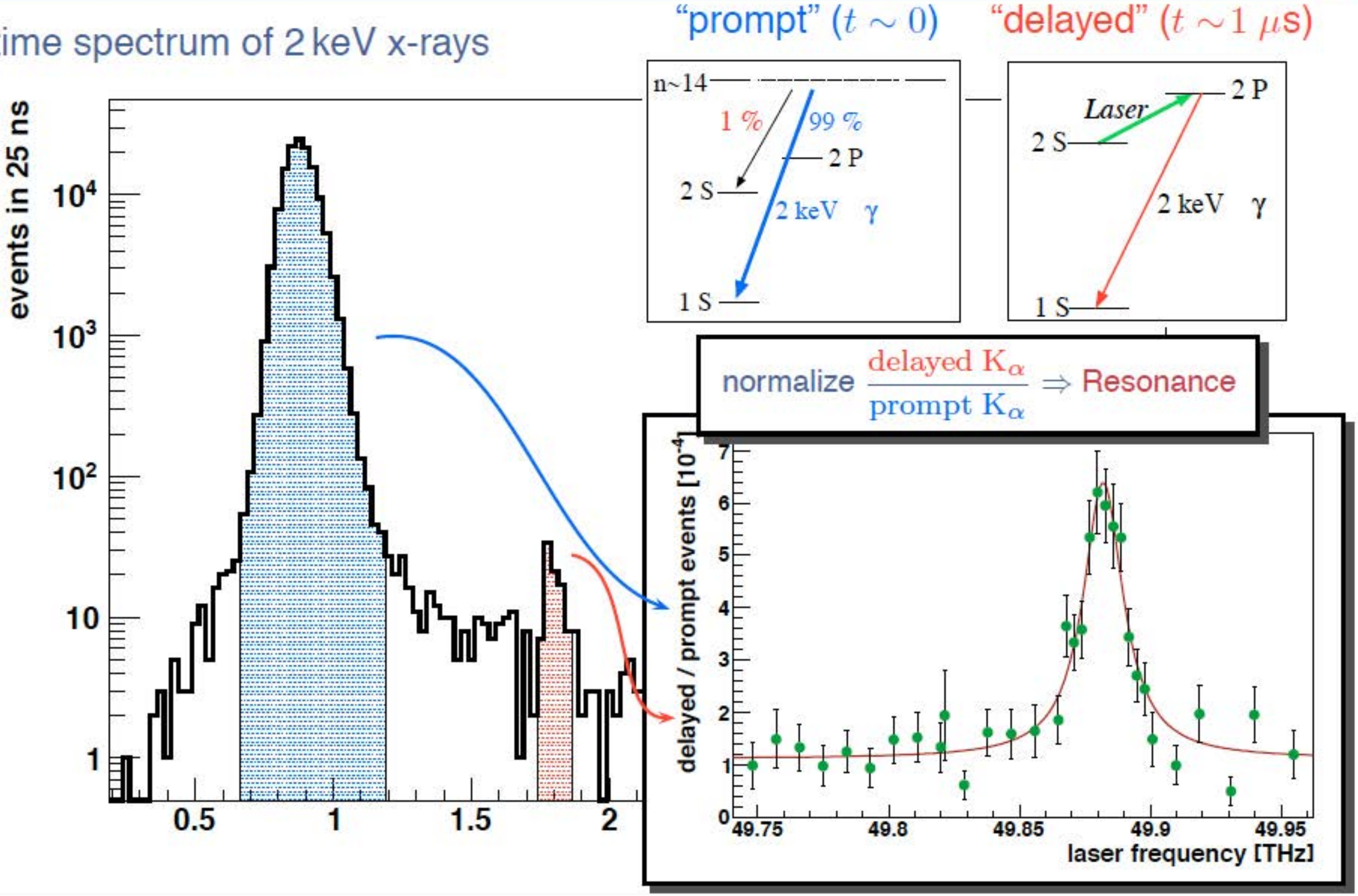
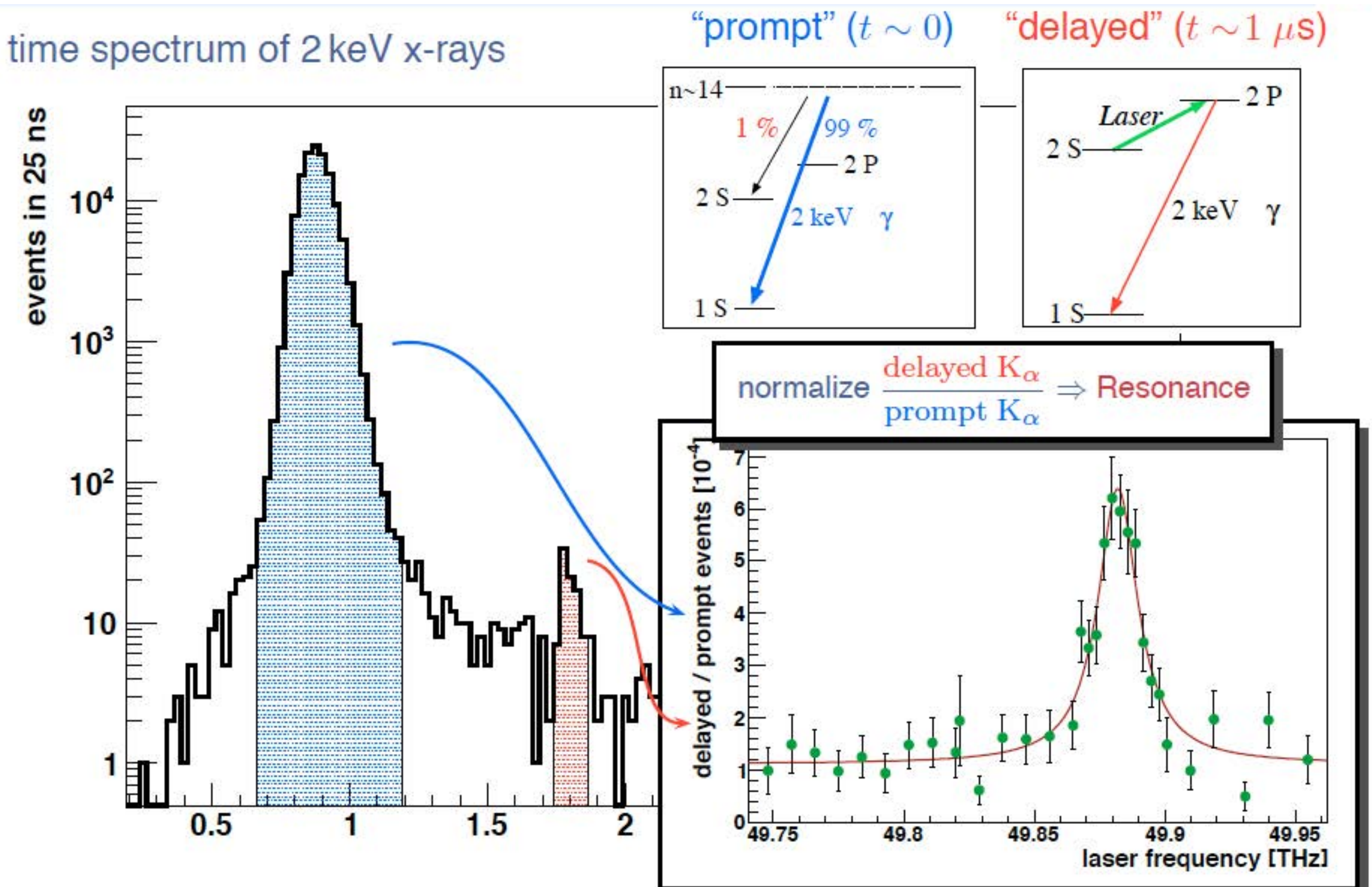


time spectrum of 2 keV x-rays



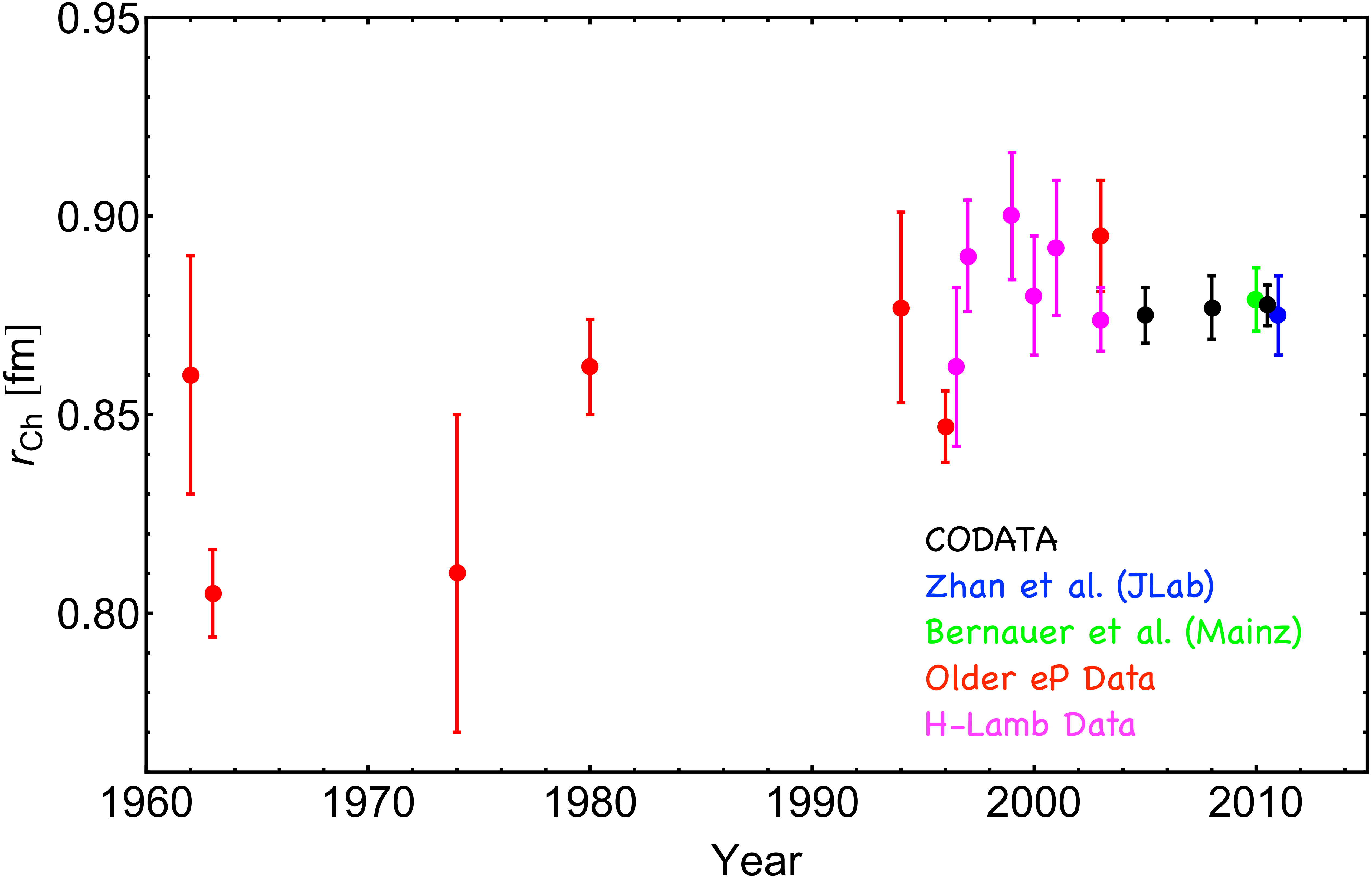
time spectrum of 2 keV x-rays



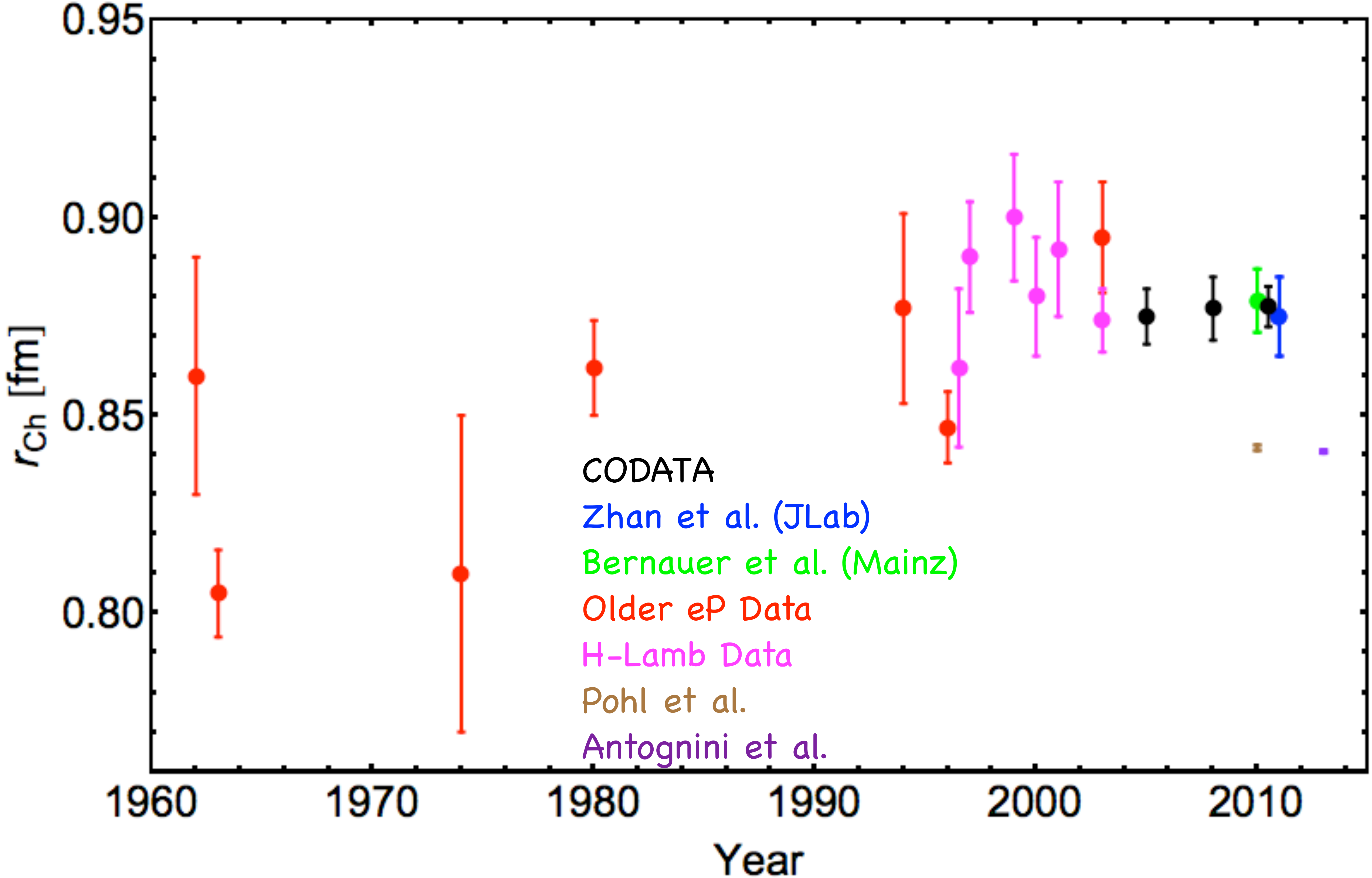


$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3\ [\mathrm{meV}]$$

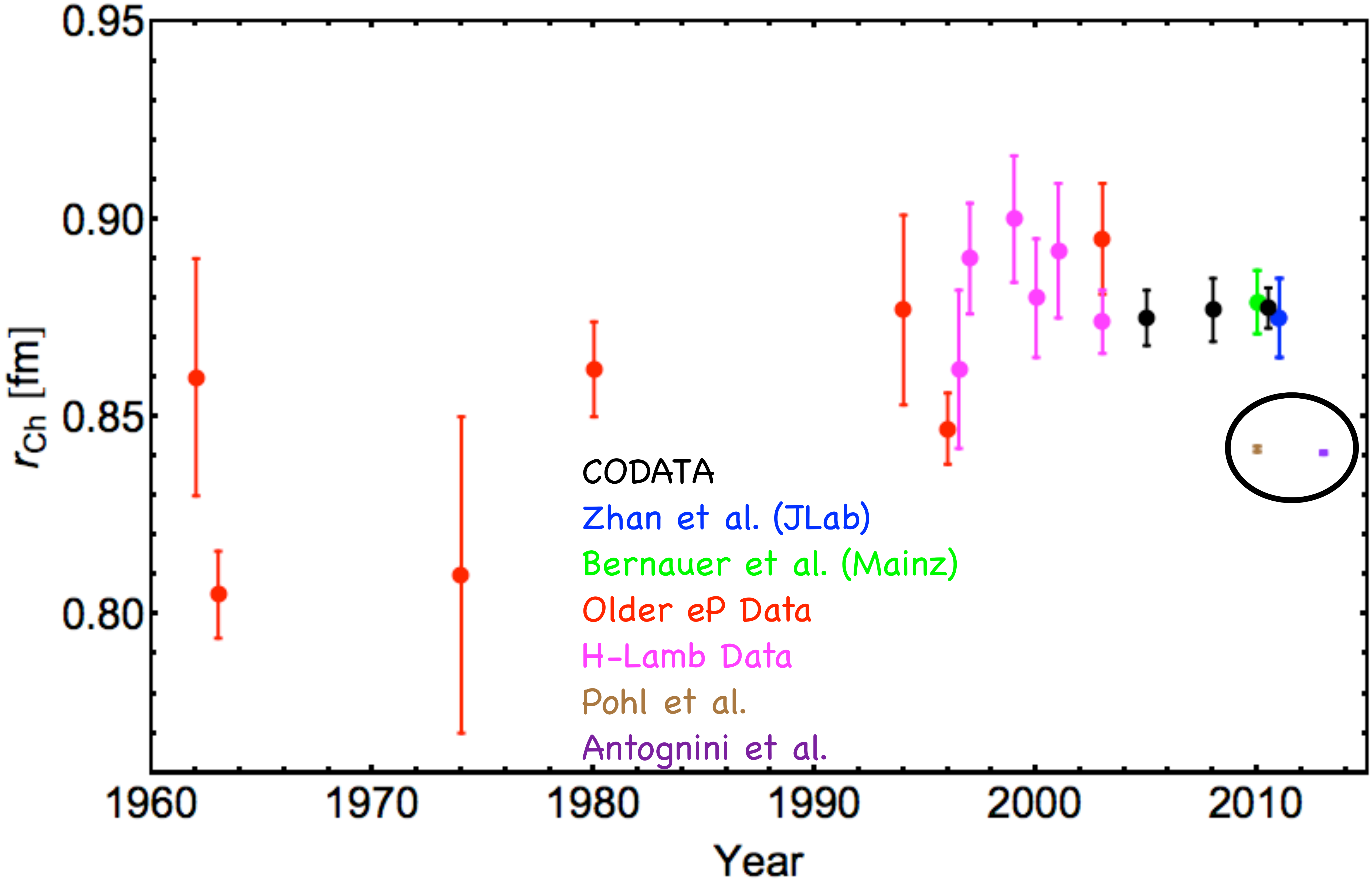
Time evolution of the Radius from H Lamb Shift + eP



Time evolution of the Radius from H Lamb Shift + eP



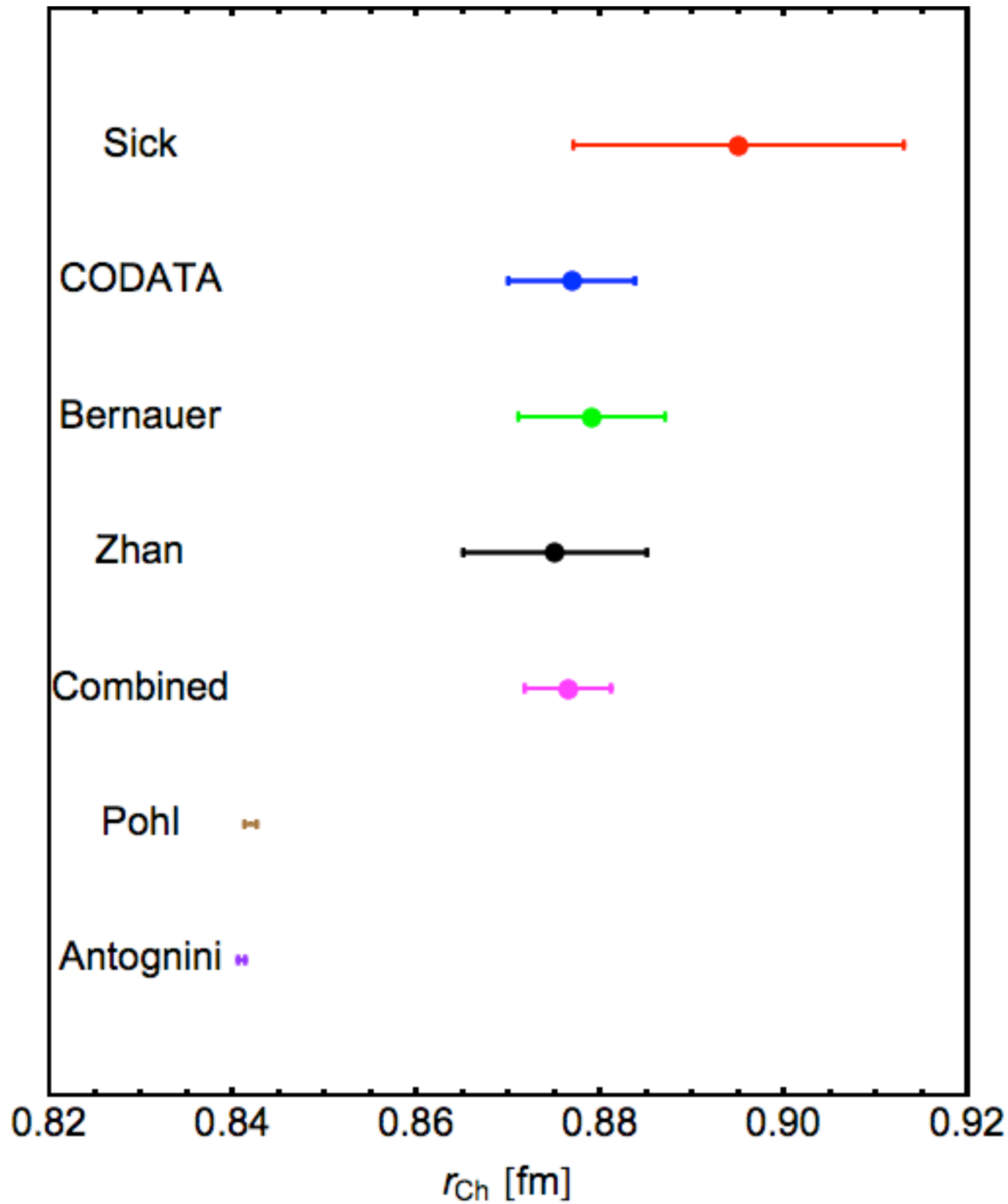
Time evolution of the Radius from H Lamb Shift + eP



Proton Radius Puzzle

Muonic hydrogen disagrees with atomic physics and electron scattering determinations of slope of FF at $Q^2 = 0$

#	Extraction	$\langle r_E \rangle^2$ [fm]
1	Sick	0.895 ± 0.018
2	CODATA	0.8768 ± 0.0069
3	Mainz	0.879 ± 0.008
4	This Work	0.875 ± 0.010
5	Combined 2-4	0.8764 ± 0.0047
6	Pohl	0.84184 ± 0.00067
7	Antognini	0.84087 ± 0.00039



Huh?

Muonic Hydrogen: Radius 4% below previous best value

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

Particle Data Group:

"Most measurements of the radius of the proton involve electron-proton interactions, and most of the more recent values agree with one another... However, a measurement using muonic hydrogen finds r_p = 0.84184(67) fm, which is eight times more precise and seven standard deviations (using the CODATA 10 error) from the electronic results... Until the difference between the **ep** and μ**p** values is understood, it does not make much sense to average all the values together. For the present, we stick with the less precise (and provisionally suspect) CODATA 2010 value. **It is up to workers in this field to solve this puzzle.**"

Directly related to the strength of QCD in the non perturbative region.

High Profile

The radius puzzle received a lot of publicity, as did its confirmation.

www.sciencedaily.com/releases/2013/01/130124140704.htm

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Science News

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Proton Size Puzzle: Surprisingly Small Proton Radius Confirmed With Laser Spectroscopy of Exotic Hydrogen

Jan. 24, 2013 — An international team of scientists confirms a surprisingly small proton radius with laser spectroscopy of exotic hydrogen.

Share This:

The initial results puzzled the world three years ago: the size of the proton (to be precise, its charge radius), measured in exotic hydrogen, in which the electron orbiting the nucleus is replaced by a negatively charged muon, yielded a value significantly smaller than the one from previous investigations of regular hydrogen or electron-proton-scattering. A new measurement by the same team confirms the value of the electric charge radius and makes it possible for the first time to determine the magnetic radius of the proton via laser spectroscopy of muonic hydrogen (*Science*, January 25, 2013). The experiments were carried out at the Paul Scherrer Institut (PSI) (Villigen, Switzerland) which is the only

Aldo Antognini and Franz Kottmann in PSI's large experimental hall. (Credit: Image courtesy of Paul Scherrer Institut)

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Shrinking proton puzzle persists in new measurement

› 19:00 24 January 2013 by Lisa Gros

A puzzle at the heart of the atom refuse
measurement yet of the proton's radius
smaller than the laws of physics demar
debated for two years.

The latest finding deepens the need for
explanation, to account for the inconsis
hole is deeper now," says Gerald Miller
Seattle, who was not involved in the ne

The saga of the proton radius began in
Pohl at the Max Planck Institute of Qua
determined the width of the fuzzy ball o
smaller than had been assumed.

Previous teams had inferred the proton
measure directly, by studying how elect
uses the simplest atom, hydrogen, whic
proton. A quirk of quantum mechanics s

www.sciencenews.org/view/generic/id/347775/description/Protons_radius_revised_downward

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07|13|13 ISSUE

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When the atom went

Home / News / February 23, 2013; Vol.183 #4

Proton's radius revised downward
Surprise measurement may point to new physics

By Andrew Grant
Web edition: January 24, 2013
Print edition: February 23, 2013; Vol.183 #4 (p. 8)

A+ A-

Only in physics can a few quintillionths of a meter be cause for uneasy
excitement. A new measurement finds that the proton is about 4 perce
smaller than previous experiments suggest. The study, published in the
25 issue of *Science*, has physicists cautiously optimistic that the discrep
between experiments will lead to the discovery of new particles or force

ww.redorbit.com/news/science/1112770740/physics-conundrum-due-to-conflicting-proton-meas

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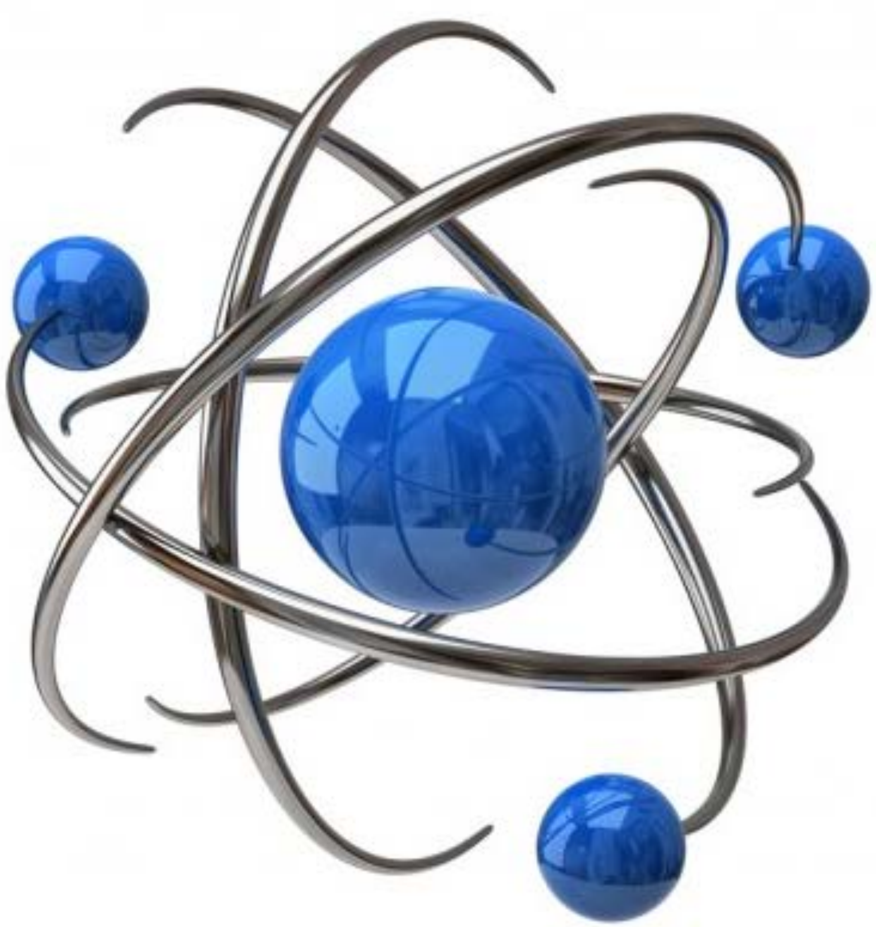
Does Size Matter? Protons May Be Smaller Than Previously Thought

January 25, 2013

Prin



arstechnica.com/science/2013/01/hydrogen-made-with-muons-reveals-proton-size-conundrum/

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SCIENTIFIC METHOD / SCIENCE & EXPLORATI

Hydrogen made with muons reveals proton size conundrum

A measurement that's off by 7 standard deviations may hint at new physics.

by John Timmer - Jan 24 2013, 2:01pm EST

PHYSICAL SCIENCES | 102

phys.org/news/2013-01-physicists-surprisingly-small-proton-radius.html

PHYS ORG

Physicists confirm surprisingly s

Jan 24, 2013

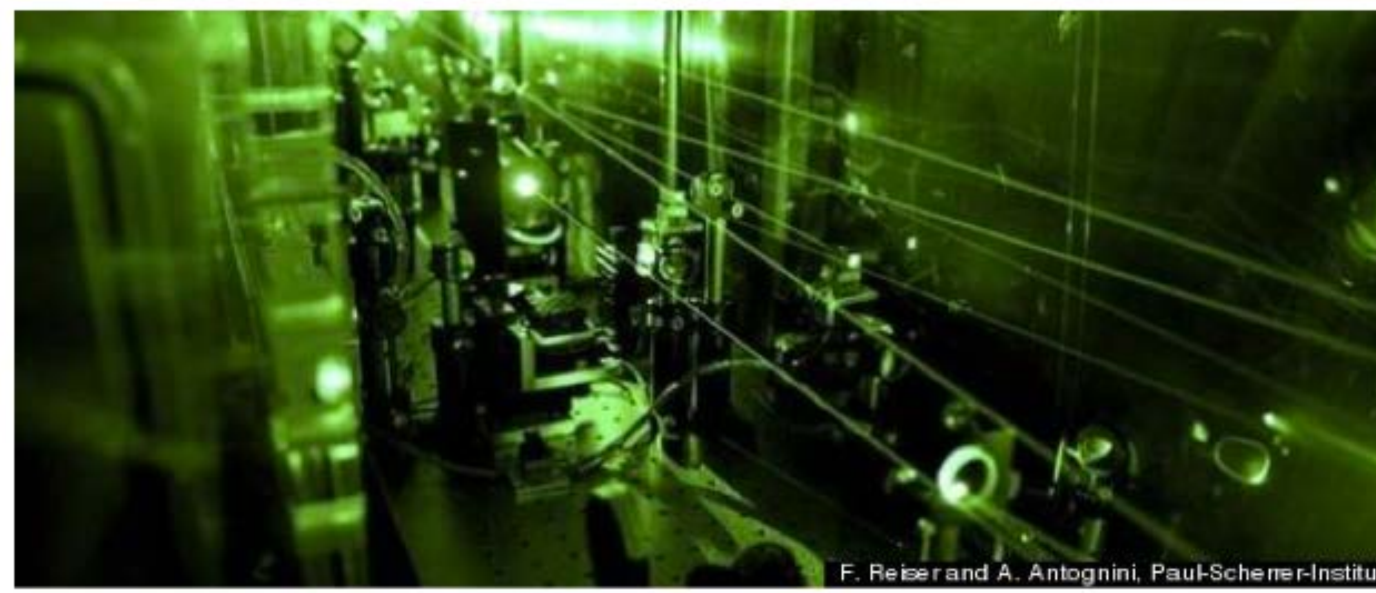
International team of physicists confirms surprisingly small proton
spectroscopy of exotic hydrogen. The initial results puzzled the wo
the size of the proton (to be precise, its charge radius), measured
which the electron orbiting the nucleus is replaced by a negatively
yielded a value significantly smaller than the one from previous in
hydrogen or electron-proton-scattering. A new measurement by th
the value of the electric charge radius and makes it possible for th
determine the magnetic radius of the proton via laser spectroscop

The experiments were carried out at the Paul Scherrer Institut (PS
Switzerland) which is the only research institute in the world provi
amount of muons. The international collaboration included the Ma
Quantum Optics (MPQ) in Garching near Munich, the Swiss Fede
Technology ETH Zurich, the University of Fribourg, the Institut für

www.huffingtonpost.com/2013/01/25/proton-radius-smaller-physicists-new-research_n_2549576.h

Proton Radius Is Smaller Than Physicists Had Thought, New Research Shows

Posted: 01/25/2013 8:20 am EST



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By: Jesse Emspak, LiveScience Contributor
Published: 01/24/2013 03:02 PM EST on LiveScience

How many protons can dance on the head of a pin? The answer is nowhere near as straightforward as one may think — and it might offer new insights into one of the most well-tested theories in physics.

www.nature.com/news/shrunken-proton-baffles-scientists-1.12289

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News & Comment > News > 2013 > June > Article

NATURE | NEWS

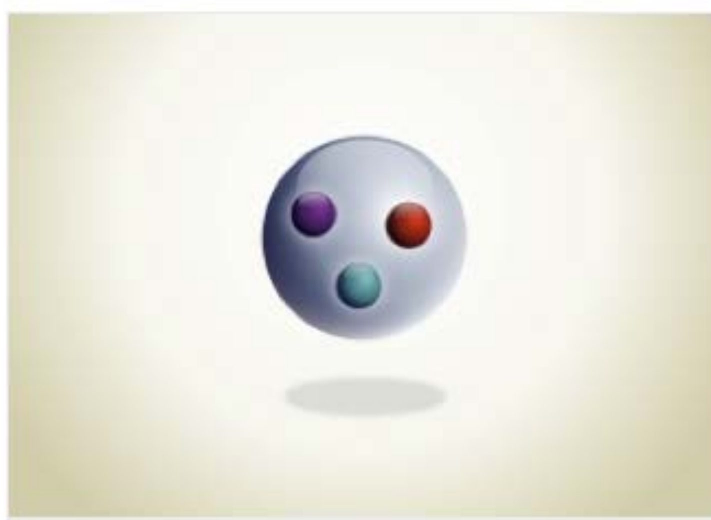
Shrunken proton baffles scientists

Researchers perplexed by conflicting measurements.

Geoff Brumfiel

24 January 2013

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.



The proton's three quarks are (mostly) confined within a region 0.87 femtometres in radius — or is it 0.84?

WESLEY FERNANDES

An experiment published today in *Science*[1] only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

www.scientificamerican.com/article.cfm?id=shrunken-proton-baffles-scientists

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More Science :: News :: January 24, 2013 :: 61 Comments :: Email :: Print

Shrunken Proton Baffles Scientists

Researchers are perplexed by conflicting measurements for one of the universe's most common particles

By Geoff Brumfiel and Nature magazine

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.

Pin it

The proton's three quarks are (mostly) confined within a region 0.87 femtometers wide — or is it 0.84?

Image: Flickr/Argonne National Laboratory

An experiment published today in *Science* only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

Prettiness of graphics inversely correlated with accuracy of physics?

This is a preview of the full article

Particle puzzle: Honey, I shrunk the proton

- 22 July 2013 by **Jon Cartwright**
- Magazine issue 2926. **Subscribe and save**
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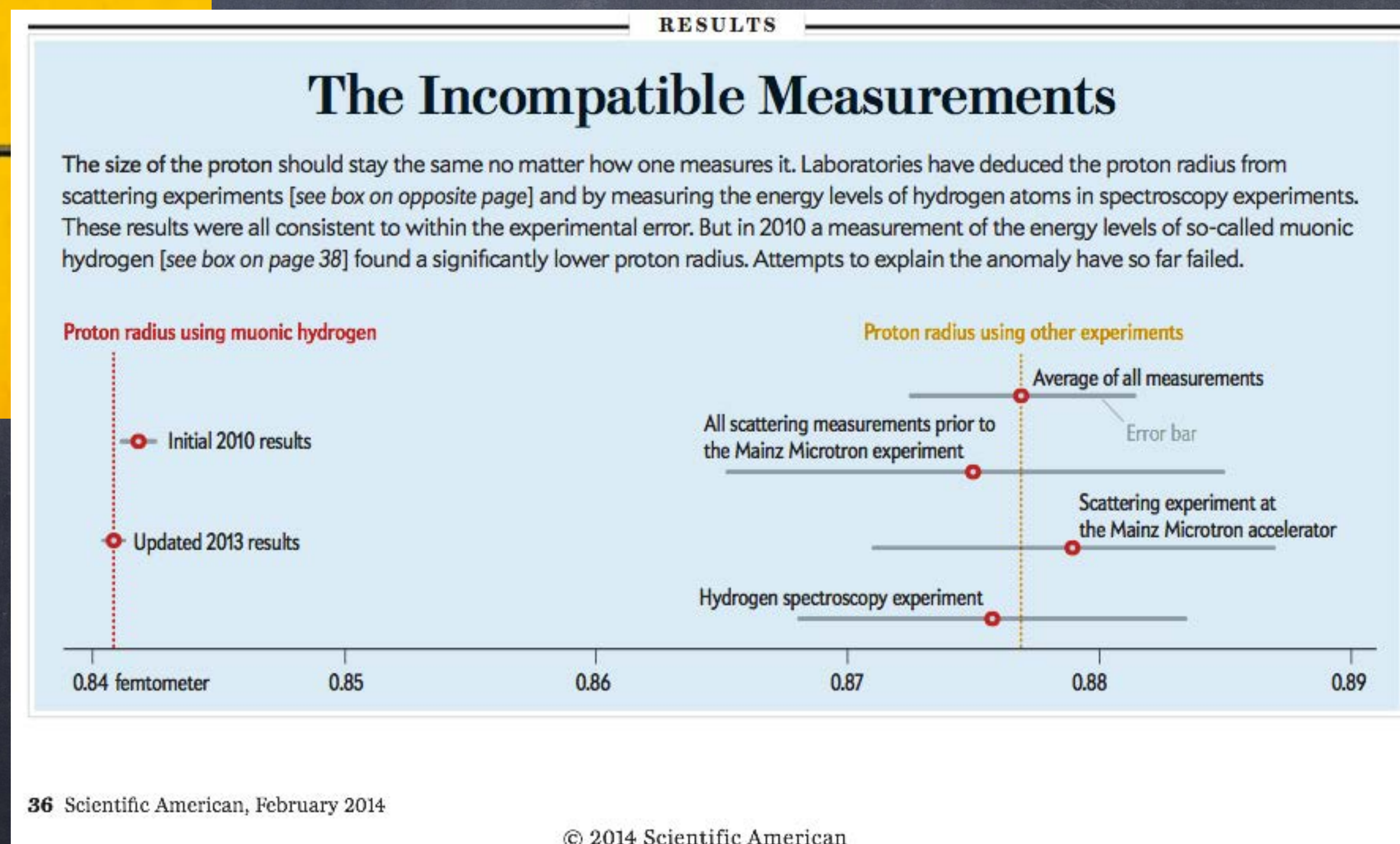
ONE quadrillionth of an inch. If you lost that off your waistline, you wouldn't expect a fuss. Then again, you are not a proton.

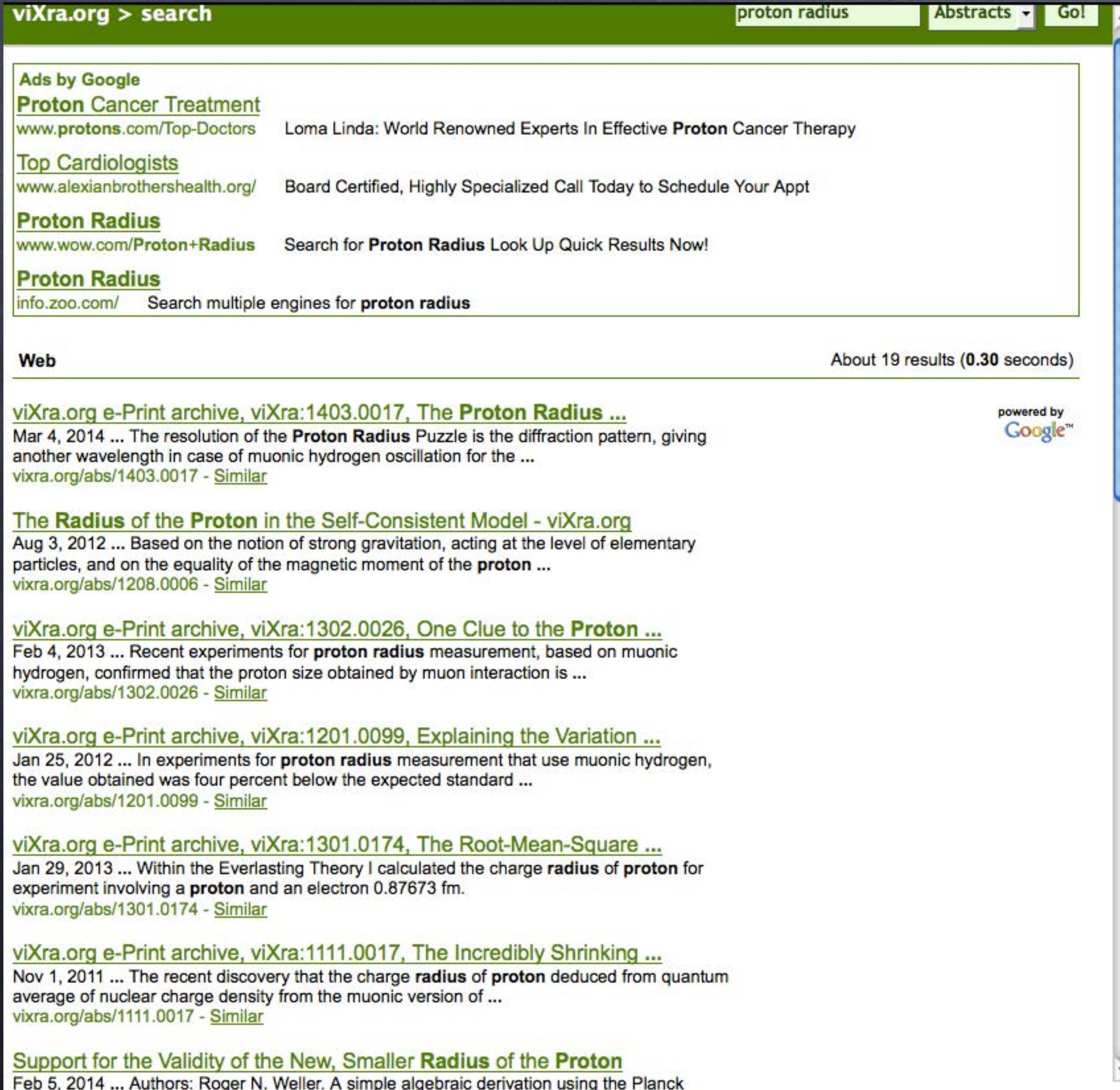
Until recently, it was unthinkable to question the size of the proton. Its radius is so well known that it appears on lists of nature's fundamental constants, alongside the speed of light and the charge of an electron. So when Randolf Pohl and his colleagues set out to make the most accurate measurement of the proton yet, they expected to just put a few more decimal places on the end of the official value. Instead this group of more than 30 researchers has shaken the world of atomic physics. Their new measurement wasn't just more accurate, it was decidedly lower. The proton had apparently been on a diet.

Most recently: Scientific American cover story, by R Pohl and J Bernauer


RESULTS

The Incompatible Measurements

The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.



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vixra.org/abs/1302.0026 - Similar

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Jan 25, 2012 ... In experiments for **proton radius** measurement that use muonic hydrogen, the value obtained was four percent below the expected standard ...
vixra.org/abs/1201.0099 - Similar

viXra.org e-Print archive, viXra:1301.0174, The Root-Mean-Square ...
Jan 29, 2013 ... Within the Everlasting Theory I calculated the charge **radius** of **proton** for experiment involving a **proton** and an electron 0.87673 fm.
vixra.org/abs/1301.0174 - Similar

viXra.org e-Print archive, viXra:1111.0017, The Incredibly Shrinking ...
Nov 1, 2011 ... The recent discovery that the charge **radius** of **proton** deduced from quantum average of nuclear charge density from the muonic version of ...
vixra.org/abs/1111.0017 - Similar

Support for the Validity of the New, Smaller **Radius** of the **Proton**
Feb 5, 2014 ... Authors: Roger N. Weller. A simple algebraic derivation using the Planck

And, apparently, more than 25 references in viXra.org

Which all look something like this....

The Proton Radius Puzzle and the Electro-Strong Interaction

Authors: [redacted]

The resolution of the Proton Radius Puzzle is the diffraction pattern, giving another wavelength in case of muonic hydrogen oscillation for the proton than it is in case of normal hydrogen because of the different mass rate. Taking into account the Planck Distribution Law of the electromagnetic oscillators, we can explain the electron/proton mass rate and the Weak and Strong Interactions. Lattice QCD gives the same results as the diffraction patterns of the electromagnetic oscillators, explaining the color confinement and the asymptotic freedom of the Strong Interactions.

Comments: 11 Pages.

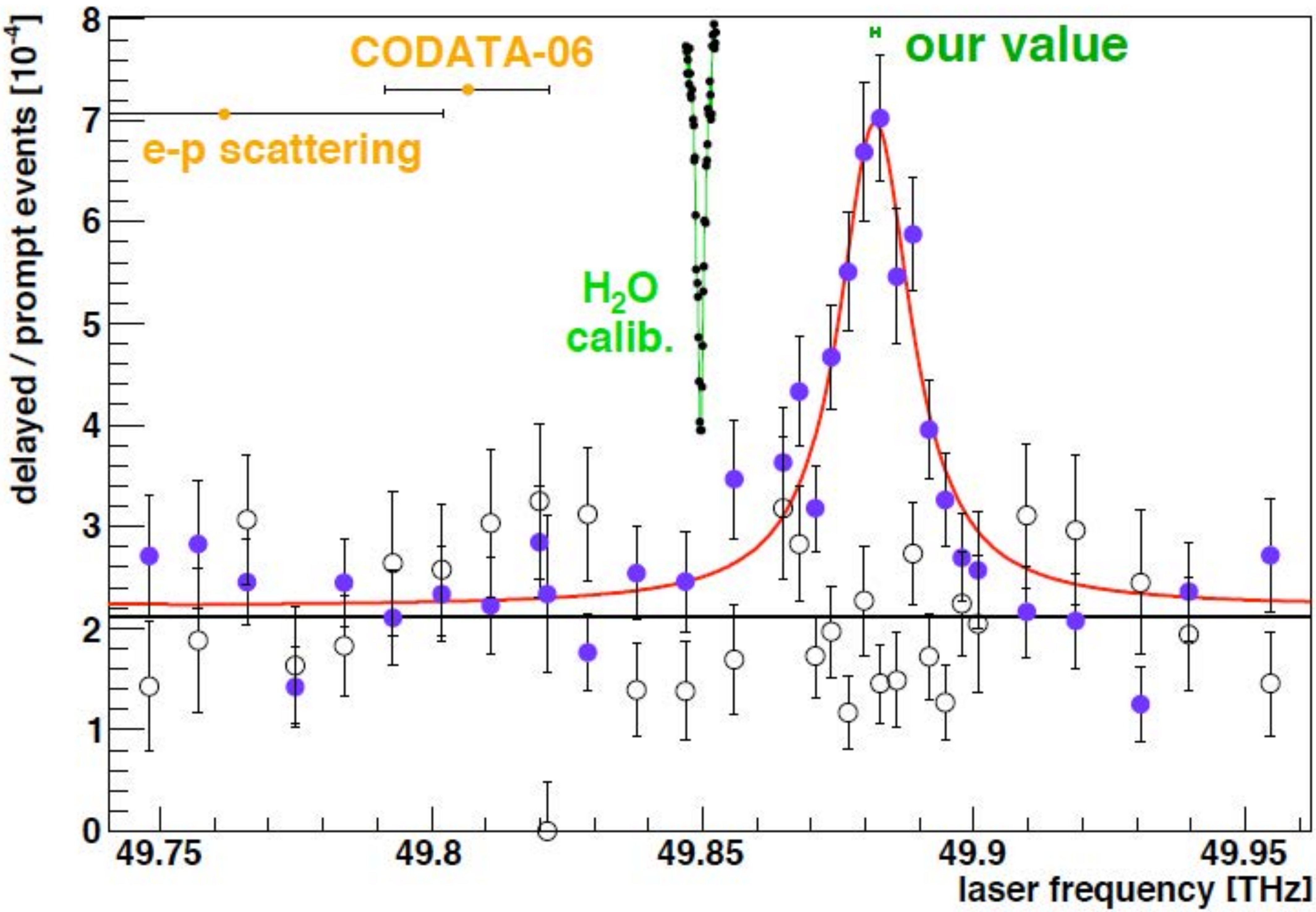
Download: PDF

The Radius of the Proton in the Self-Consistent Model

Authors: [redacted]

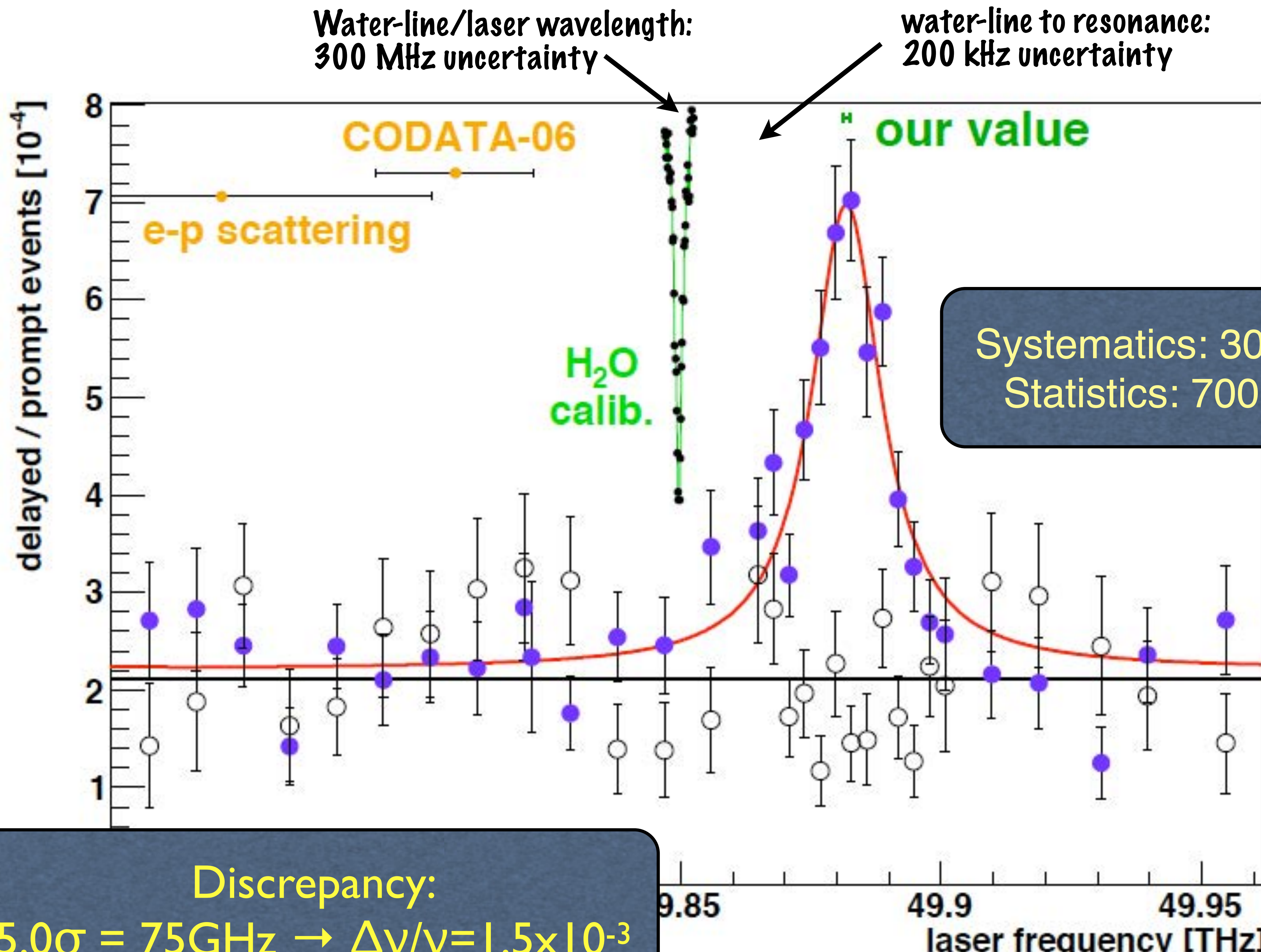
Based on the notion of strong gravitation, acting at the level of elementary particles, and on the equality of the magnetic moment of the proton and the limiting magnetic moment of the rotating non-uniformly charged ball, the radius of the proton is found, which conforms to the experimental data. At the same time the dependence is derived of distribution of the mass and charge density inside the proton. The ratio of the density in the center of the proton to the average density is found, which equals 1.57.

Experimental Error?



R. Pohl et al., Nature 466, 213 (2010).

Experimental Error?



Systematics: 300 MHz
Statistics: 700 MHz

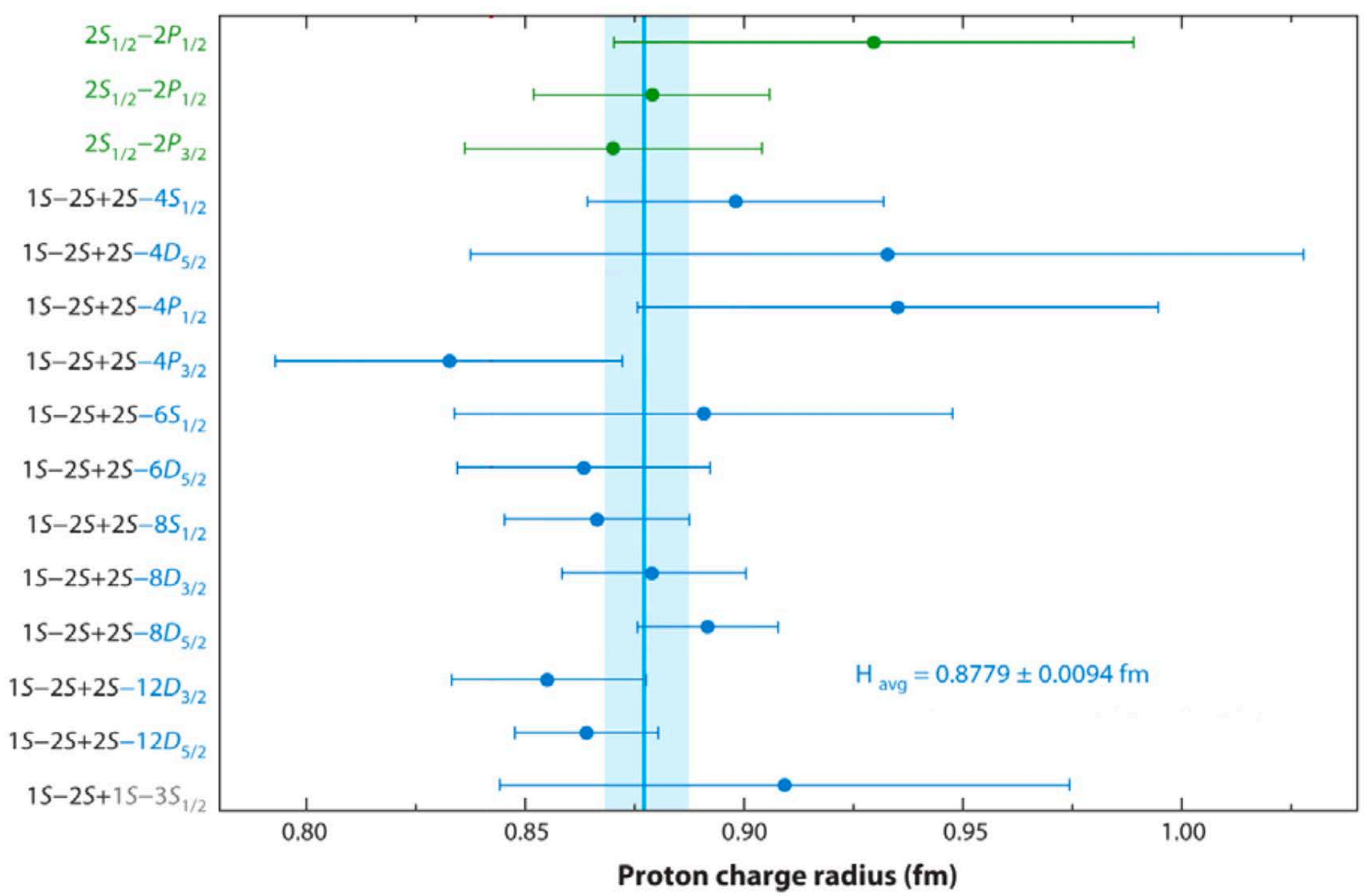
Discrepancy:
5.0σ = 75GHz → $\Delta\nu/\nu = 1.5\times10^{-3}$

R. Pohl et al., Nature 466, 213 (2010).

Experimental Error in the electron (Lamb shift) measurements?

The 1S-2S transition in H has been measured to 34 Hz, that is, 1.4×10^{-14} relative accuracy. Only an error of about 1,700 times the quoted experimental uncertainty could account for our observed discrepancy.

However.....



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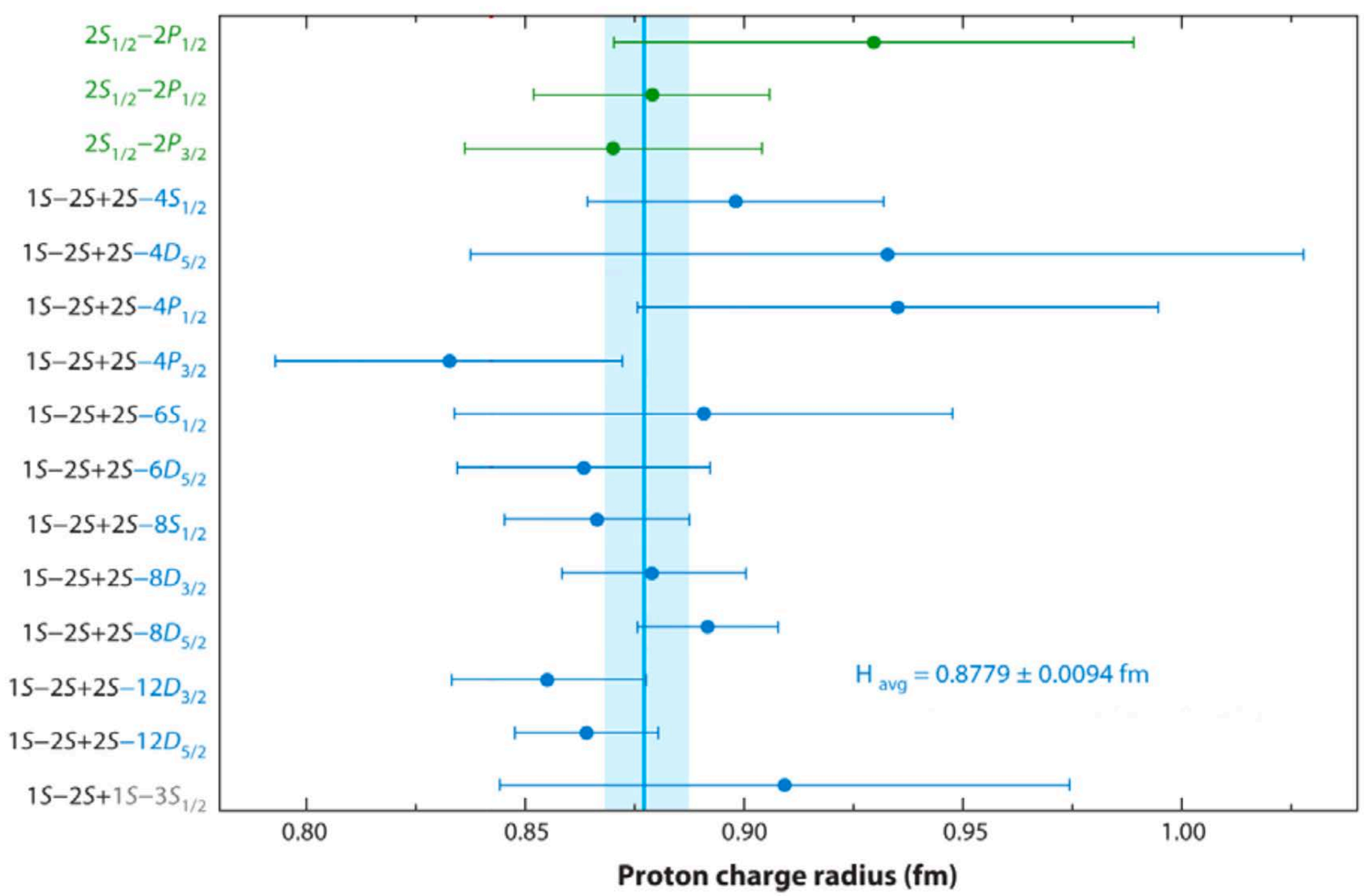


Important note:
This is NOT what CODATA uses to extract the radius!

The Scattering Experiments

The scattering knowledge is dominated by the recent Bernauer et al Mainz experiment, plus (our) JLab polarization data and older cross section experiments.

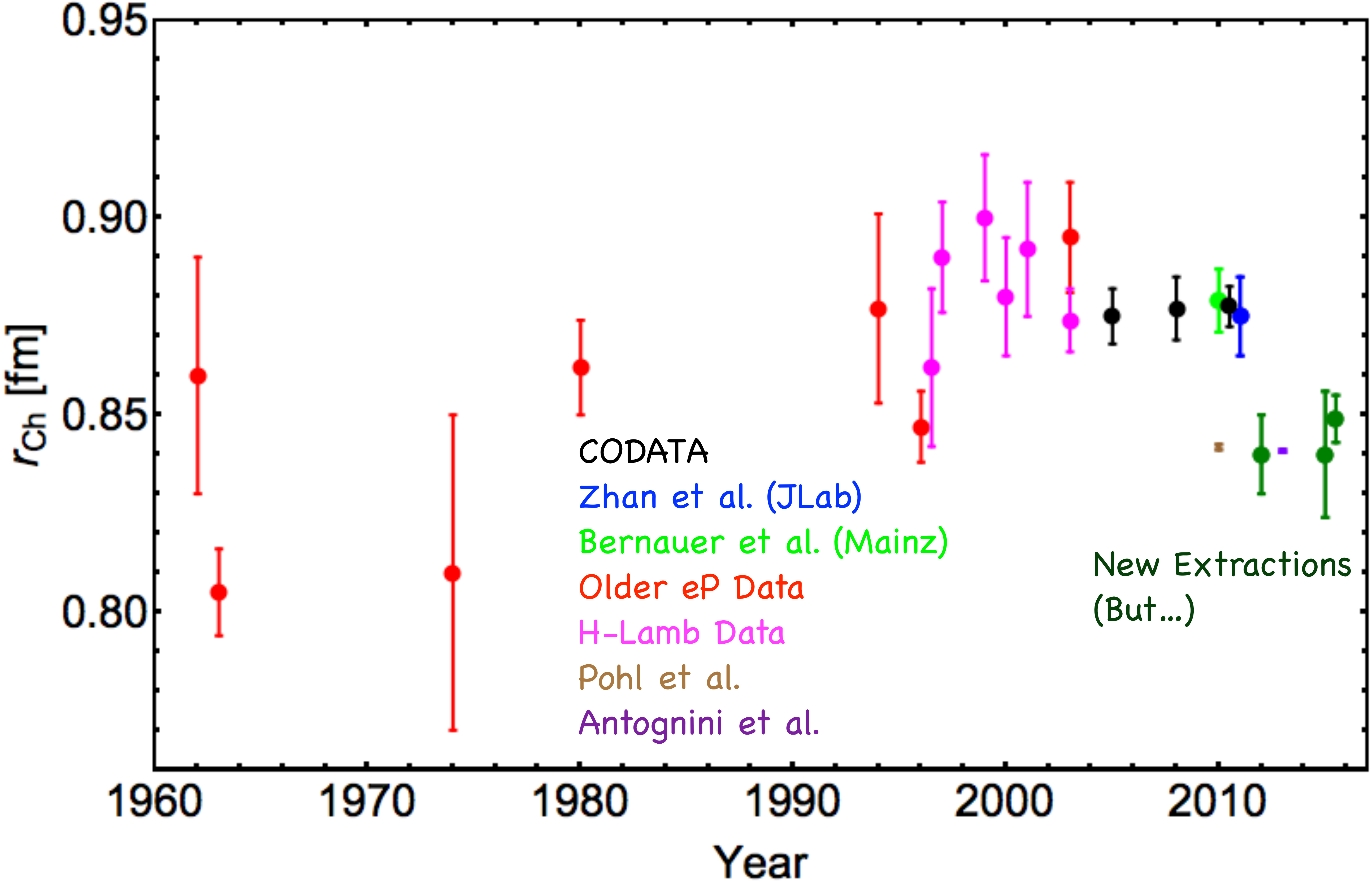
Extracting a radius from the scattering data has been a challenge.

Until recently, all analyses ignored most of the following issues:

- Coulomb corrections
- Two-photon exchange
- Truncation offsets
- World data fits vs radius fits
- Model dependence
- Treatment of systematic uncertainties
- Fits with unphysical poles
- Including time-like data to ``improve" radius

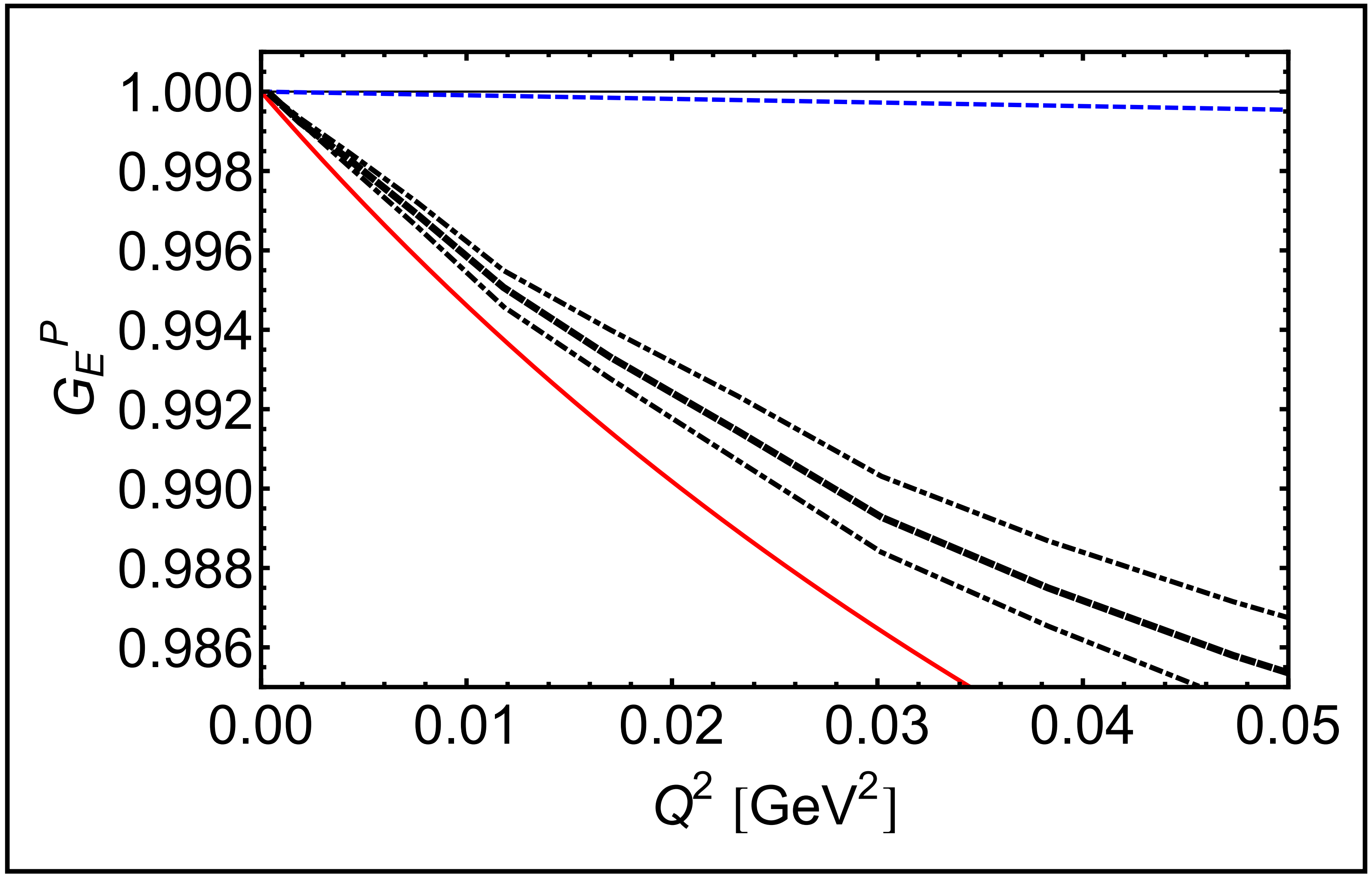
The good modern analyses tend to have fewer issues.

Time evolution of the Radius from H Lamb Shift + eP



Experimental Error in the electron scattering measurements?

Essentially all (newer) electron scattering results are consistent within errors, hard to see how one could conspire to change the charge radius without doing something very strange to the FFs.



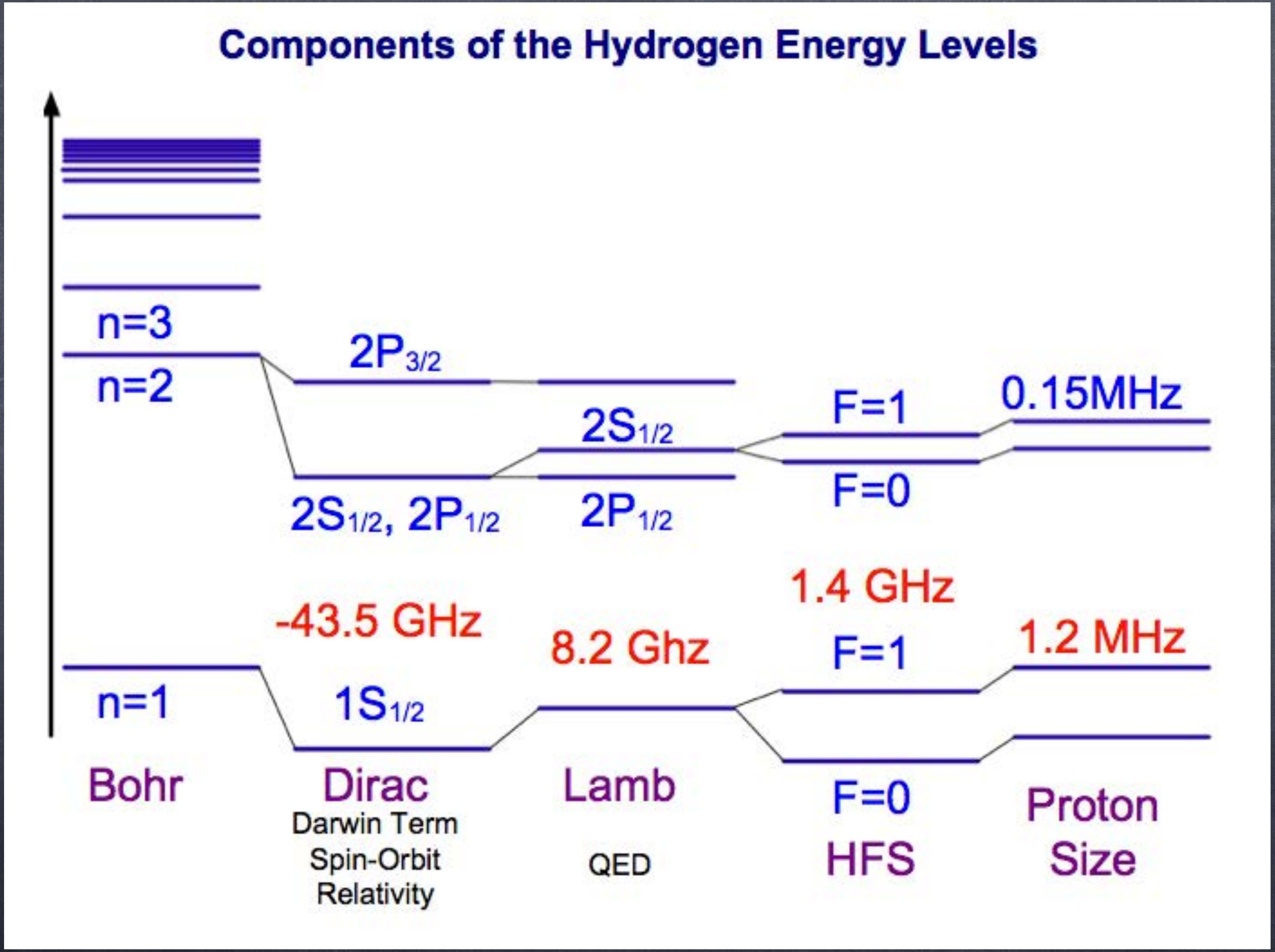
Experimental Error in the electron scattering measurements?

But a word of caution:
To get the slope at $Q^2=0$ we extrapolate over a rather large range. Are we doing something wrong?

Theory Error?

Theory Error?

Atomic Physics Gets Complicated...



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

The Atomic Physics

The atomic physics calculation is quite detailed and complicated, but basically all aspects of it have been computed by multiple independent groups.

The momentum-space Breit potential, for incorporating proton finite size effects. From Kelkar, Garcia Daza, and Nowakowski, NPB 864, 382 (2012).

$$
\begin{aligned}
\hat{U}(\mathbf{p}_X, \mathbf{p}_p, \mathbf{q}) = 4\pi e^2 \Bigg[& F_1^X F_1^p \Bigg(-\frac{1}{\mathbf{q}^2} + \frac{1}{8m_X^2 c^2} + \frac{1}{8m_p^2 c^2} + \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_p)}{4m_p^2 c^2 \mathbf{q}^2} \\
& - \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_X)}{4m_X^2 c^2 \mathbf{q}^2} + \frac{\mathbf{p}_X.\mathbf{p}_p}{m_X m_p c^2 \mathbf{q}^2} - \frac{(\mathbf{p}_X.\mathbf{q})(\mathbf{p}_p.\mathbf{q})}{m_X m_p c^2 \mathbf{q}^4} - \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_X)}{2m_X m_p c^2 \mathbf{q}^2} \\
& + \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_p)}{2m_X m_p c^2 \mathbf{q}^2} + \frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_X m_p c^2} - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_X m_p c^2 \mathbf{q}^2} \Bigg) \\
& + F_1^X F_2^p \Bigg(\frac{1}{4m_p^2 c^2} + \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_p)}{2m_p^2 c^2 \mathbf{q}^2} - \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_X)}{2m_X m_p c^2 \mathbf{q}^2} \\
& - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_X m_p c^2 \mathbf{q}^2} + \frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_X m_p c^2} \Bigg) \\
& + F_2^X F_1^p \Bigg(\frac{1}{4m_X^2 c^2} - \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_X)}{2m_X^2 c^2 \mathbf{q}^2} + \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_p)}{2m_X m_p c^2 \mathbf{q}^2} \\
& - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_X m_p c^2 \mathbf{q}^2} + \frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_X m_p c^2} \Bigg) \\
& + F_2^X F_2^p \Bigg(\frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_X m_p c^2} - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_X m_p c^2 \mathbf{q}^2} \Bigg) \Bigg],
\end{aligned}
$$

The Atomic Physics

The atomic physics calculation is quite detailed and complicated, but all aspects of it have been computed by multiple independent groups.

Contributions to 2s hyperfine structure, from Indelicato, arXiv 1210.5828

	#	Ref. [40]	Ref. [70]	This work
Fermi energy	1	22.8054	22.8054	
Dirac Energy (includes Breit corr.)	2			22.807995
Vacuum polarization corrections of orders α^5, α^6 in 2nd-order perturbation theory ϵ_{VP1}	3	0.0746	0.07443	
All-order VP contribution to HFS, with finite magnetisation distribution	4			0.07244
finite extent of magnetisation density correction to the above	5		−0.00114	
Proton structure corr. of order α^5	6	−0.1518	−0.17108	−0.17173
Proton structure corrections of order α^6	7	−0.0017		
Electron vacuum polarization contribution+ proton structure corrections of order α^6	8	−0.0026		
contribution of 1γ interaction of order α^6	9	0.0003	0.00037	0.00037
$\epsilon_{VP}2E_F$ (neglected in Ref. [40])	10		0.00056	0.00056
muon loop VP (part corresponding to ϵ_{VP2} neglected in Ref. [40])	11		0.00091	0.00091
Hadronic Vac. Pol.	12	0.0005	0.0006	0.0006
Vertex (order α^5)	13		−0.00311	−0.00311
Vertex (order α^6) (only part with powers of $\ln(\alpha)$ - see Ref. [103])	14		−0.00017	−0.00017
Breit	15	0.0026	0.00258	
Muon anomalous magnetic moment correction of order α^5, α^6	16	0.0266	0.02659	0.02659
Relativistic and radiative recoil corrections with proton anomalous magnetic moment of order α^6	17	0.0018		
One-loop electron vacuum polarization contribution of 1γ interaction of orders α^5, α^6 (ϵ_{VP2})	18	0.0482	0.04818	0.04818
finite extent of magnetisation density correction to the above	19		−0.00114	−0.00114
One-loop muon vacuum polarization contribution of 1γ interaction of order α^6	20	0.0004	0.00037	0.00037
Muon self energy+proton structure correction of order α^6	21	0.001		0.001
Vertex corrections+proton structure corrections of order α^6	22	−0.0018		−0.0018
"Jellyfish" diagram correction+ proton structure corrections of order α^6	23	0.0005		0.0005
Recoil correction Ref. [104]	24		0.02123	0.02123
Proton polarizability contribution of order α^5	25	0.0105		
Proton polarizability Ref. [104]	26		0.00801	0.00801
Weak interaction contribution	27	0.0003	0.00027	0.00027
Total		22.8148	22.8129	22.8111

Examples of Bad Theory Explanations

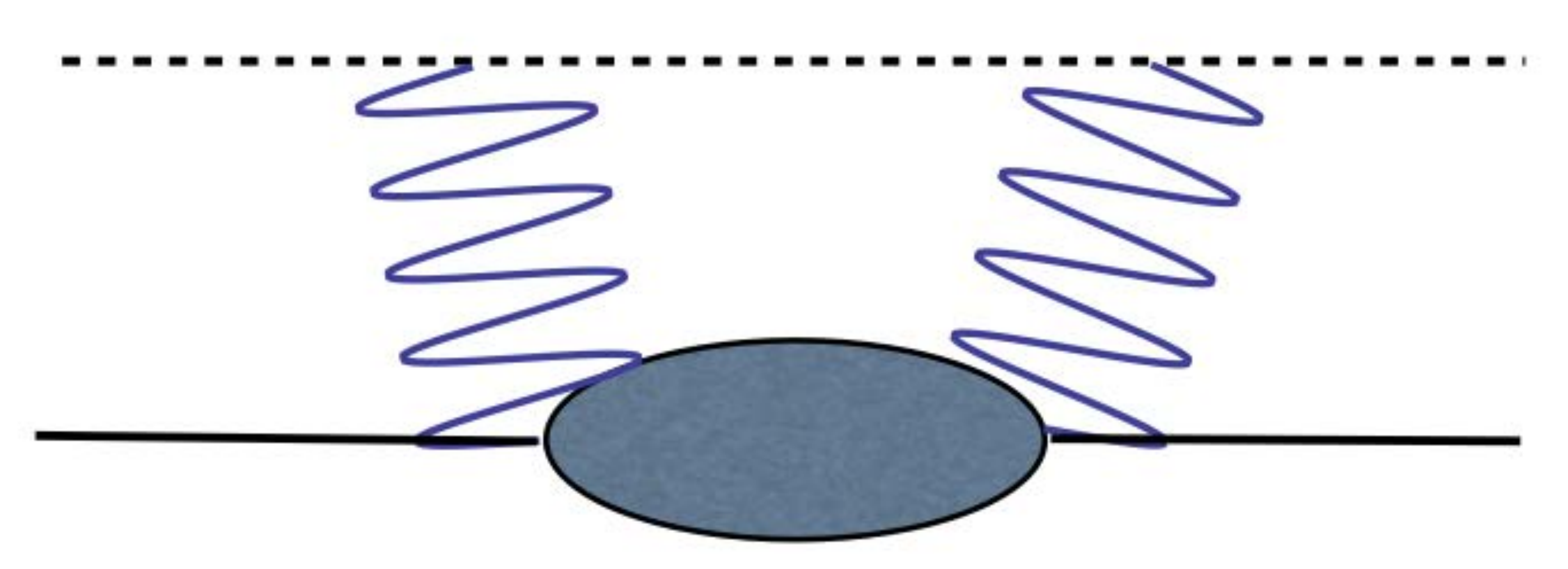
- De Rujula: large 3rd Zemach moment
- Thorns / lumps in form factor
- Quantum gravity!
- Non-commutative geometry
- Large extra dimensions!
- Mart & Sulaksono: oscillating protons
- Robson: rest frame form factor is not scattering form factor
- Giannini & Santopinto: frame dependence of charge radii

Possible Theory Explanations

- What are viable theoretical explanations of the Radius Puzzle?
  - Novel Beyond Standard Model Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
  - Novel Hadronic Physics: G. Miller: two-photon correction
  - No explanation with majority support in the community
  - See fall 2012 Trento Workshop on PRP for more details:

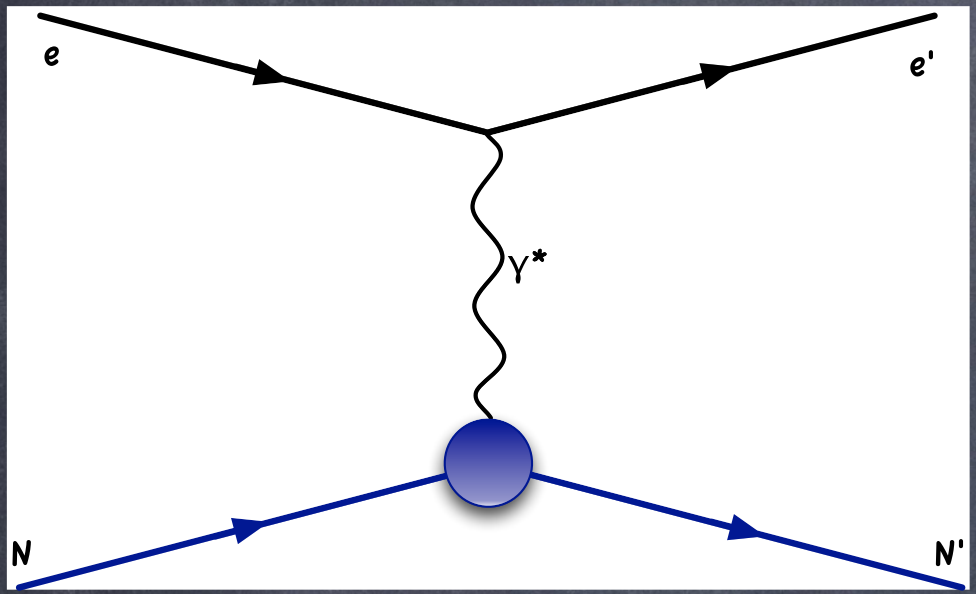
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

Theory Explanations: Novel Hadronic Physics



- There is a polarizibility correction that depends on m_l^4, affecting muons but not electrons
- Evaluation uses a model for the Q^2 dependence of the forward virtual Compton tensor for subtractions in dispersion relations
- Prediction: enhanced 2γ exchange in μ scattering: 2-4%
- Calculations using chiral perturbation theory for the low Q^2 behavior coupled to a pQCD inspired inspired Q^{-4} falloff suggest correction is far too small
- Infinite set of possible models allow constraints to be evaded.

Theory Explanations: Novel Beyond Standard Model Physics

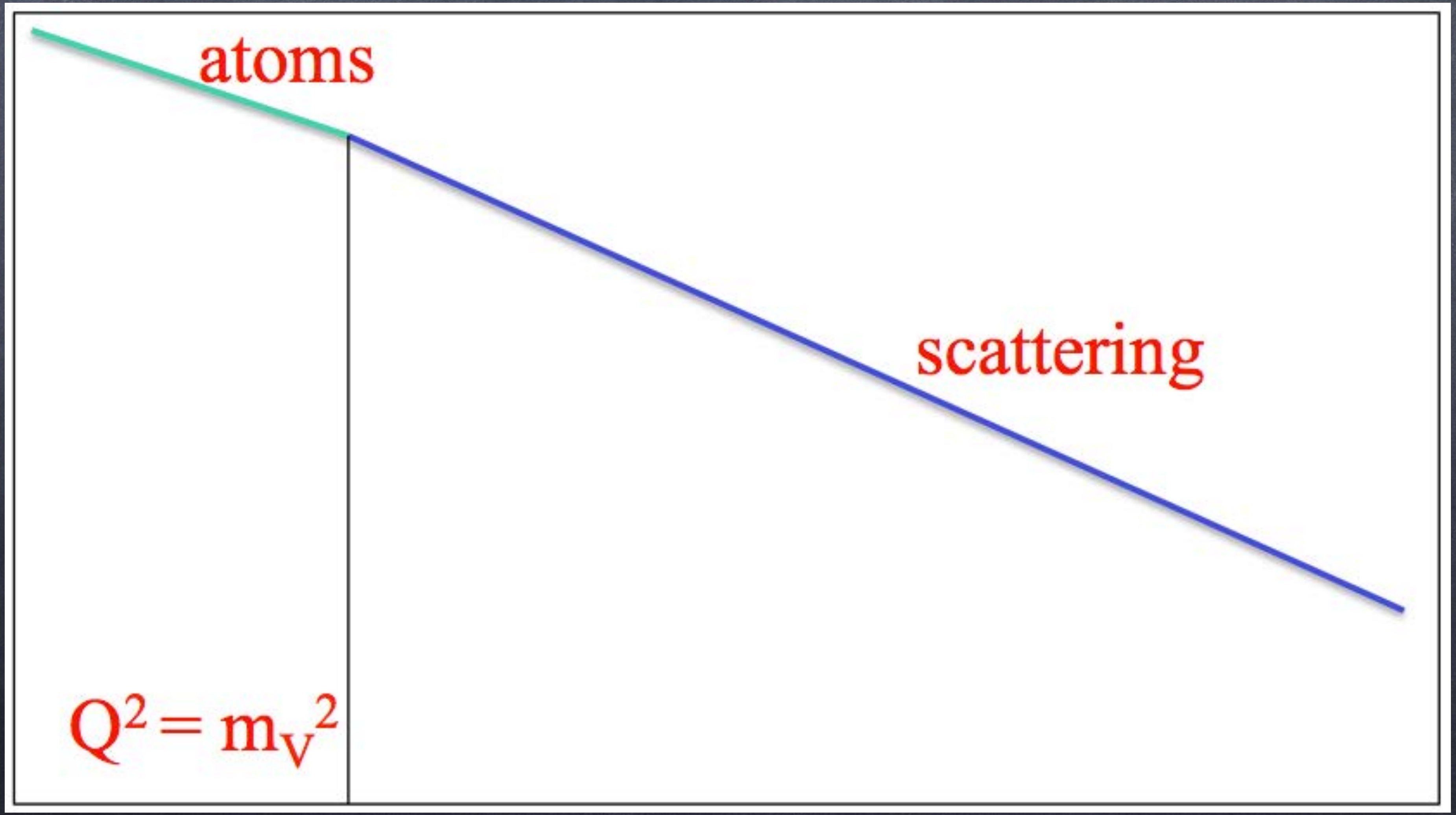


- Ideally (?), one new particle explains (dark photon?) Proton Radius Puzzle, μ g-2, cosmological positron excess / excess γ's from galactic center

- But many constraints from existing physics and the 3 issues may be unrelated
- Most constraints relaxed if you allow flavor dependent coupling.
- Examples follow...

Theory Explanations: Novel BSM Physics

- Pospelov: effect on form factors of new dark photon - would explain scattering vs. atom difference, but not hydrogen vs. muonic hydrogen



Newest idea - Ralston (2016)

A global fit to everything, permitting an alternative

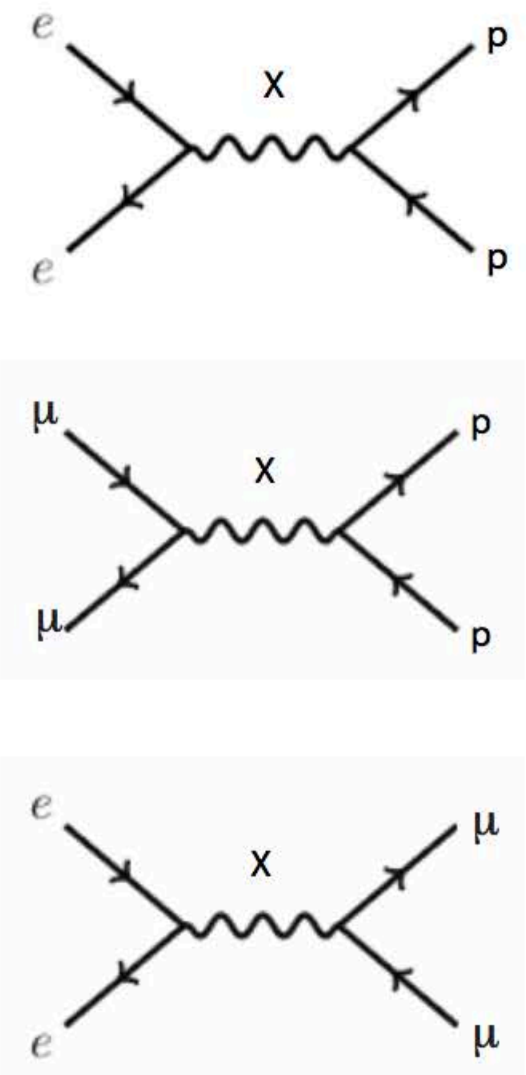
"no name theory" of particle X

$$g_e^2 = g_\mu^2 = g_p^2 = g^2$$

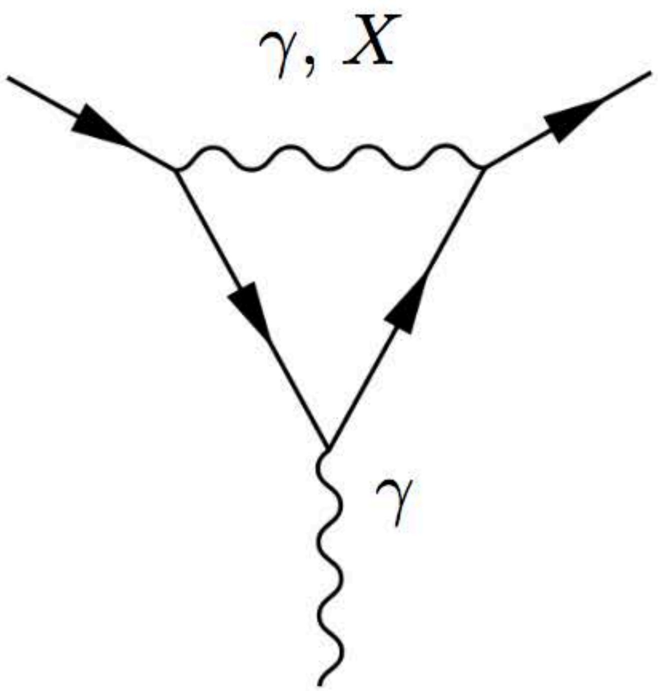
$$\alpha_X = \xi m_X^2 = g^2/4\pi$$

minimal
"bottom-up"
data driven

No other assumptions

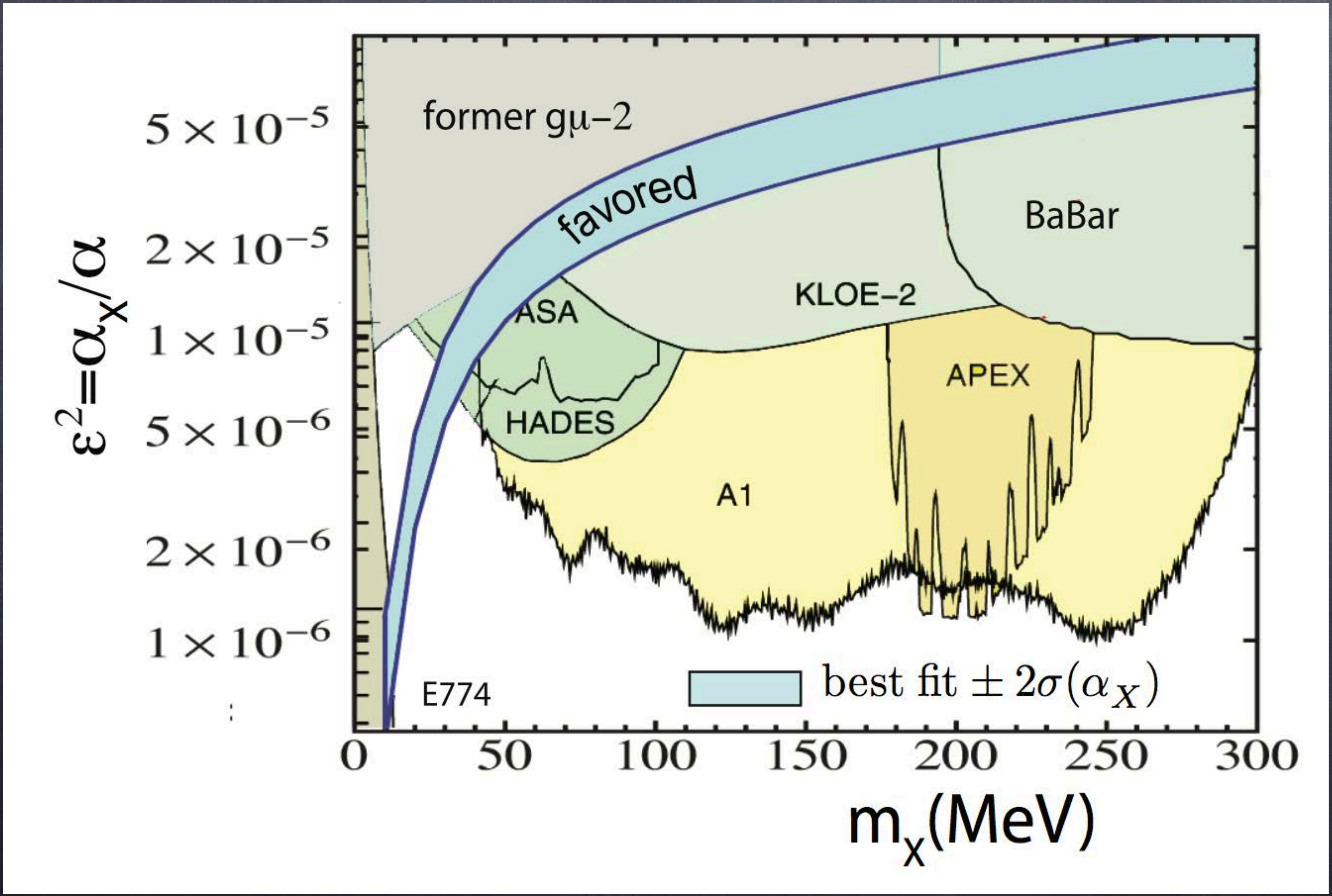


more general than dark photon



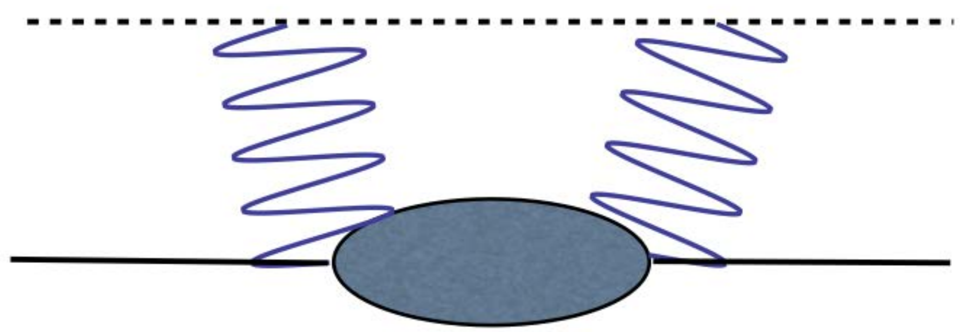
$$a_e^{theory} = 1.7147 \times 10^{-12} + 0.159155\alpha - 0.0332818\alpha^2 + 0.0380966\alpha^3$$
$$- 0.0196046\alpha^4 + 0.0299202\alpha^5 + 0.027706\,\xi m_X^2 f(m_X/m_\ell)$$

Newest idea - Ralston (2016)



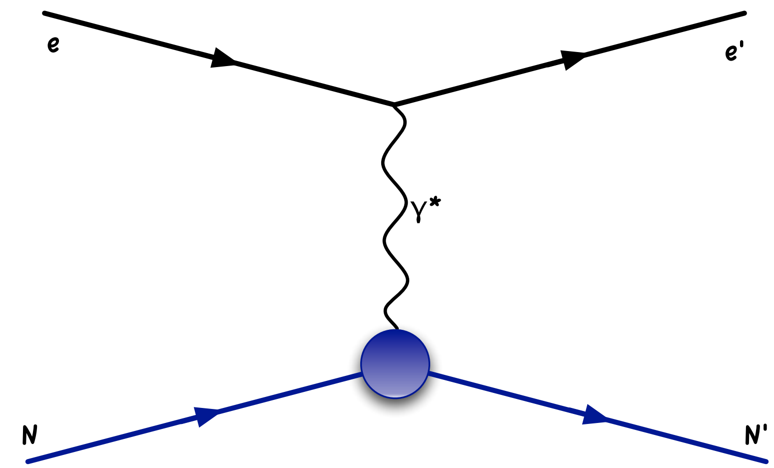
The (surviving) Theory Explanations

- Novel Hadronic Physics



- There is a polarizibility correction that depends on m_l^4, affecting muons but not electrons
- Part of the correction is not (strongly) constrained by data or theory; it might resolve puzzle

- Novel Beyond Standard Model Physics



- There could be unknown particles that couple μp but not ep, in addition to γ
- Evading impacts on known physics requires 2 new particles for cancellations

Status

- Up to 2010, we were all happy that atomic hydrogen and electron scattering gave the same proton radius.
- Now we are even happier that muonic hydrogen gives a different proton radius!
- Many possible explanations are ruled out, and the remaining explanations all seem unlikely
  - Experimental error: seems unlikely
  - BSM: not ruled out, but somewhat contrived models
  - Hadronic: not ruled out, but much bigger than most theorists find palatable.
- New data are needed

How do we Resolve the Radius Puzzle?

- Theorists keep checking theories
- Experiments check old results, test e / μ differences, new particles, scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation, enhanced 2γ exchange
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2 - Mainz ISR done and JLab Hall B in 2016
  - **Muon scattering!**
  - Rare K decays, etc etc

Where to now?

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 systematics.

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

Where to now?

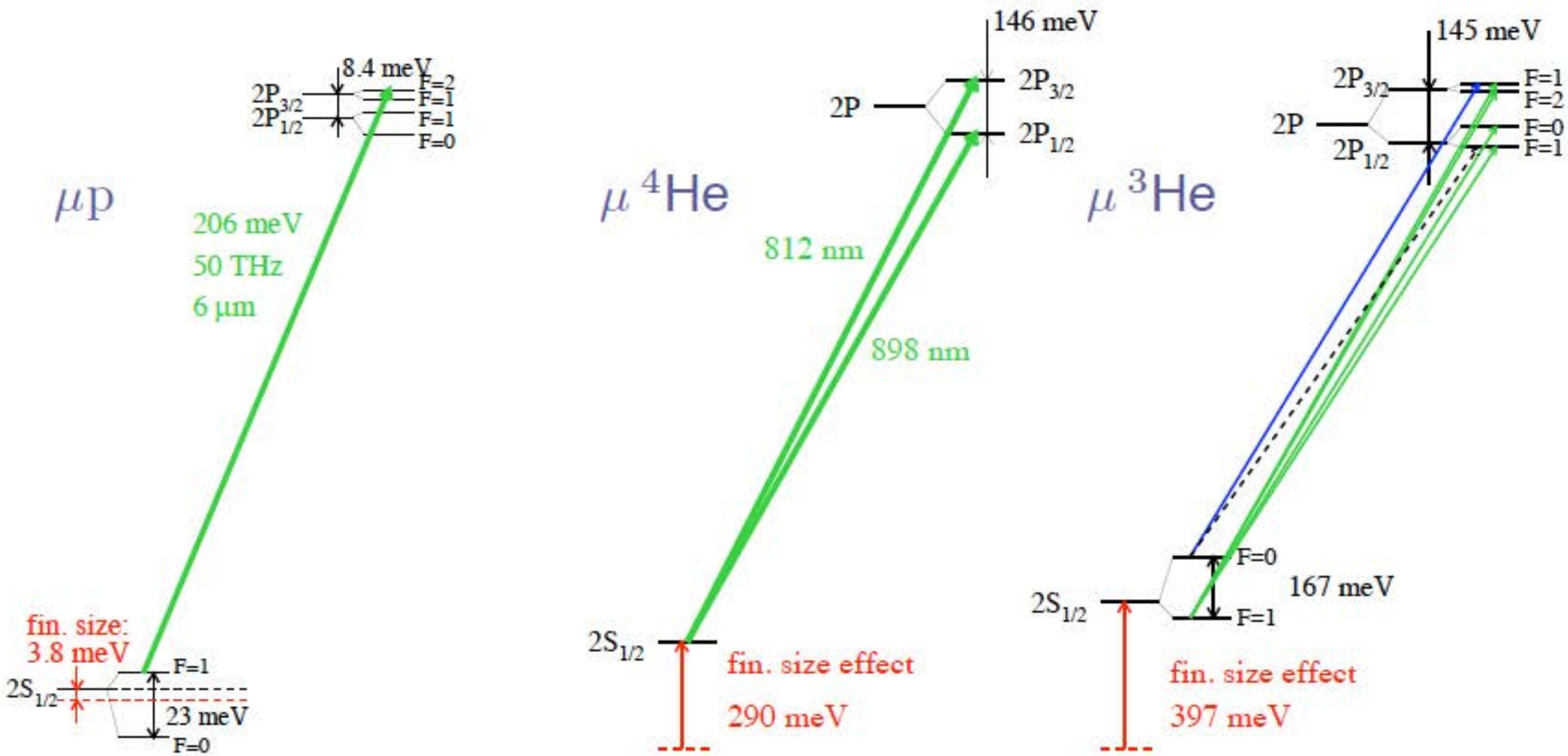
Lamb shift measurements on μ^3He^{+}, μ^4He^+ - New experiments @ PSI

- Helium radius known from electron scattering to better precision than proton radius.
- If effect comes from muonic sector it should scale with Z.
- No hyperfine corrections needed in μ^4He^+

$$\begin{aligned}\Delta E(2P_{1/2} - 2S_{1/2})^{\mu^4 He^+} &= 1670.370(600) - 105.322 r_{He}^2 + 1.529 r_{He}^3 \;\; meV \\ &= 403.893(145) - 25466 r_{He}^2 + 370 r_{He}^3 \;\; GHz\end{aligned}$$

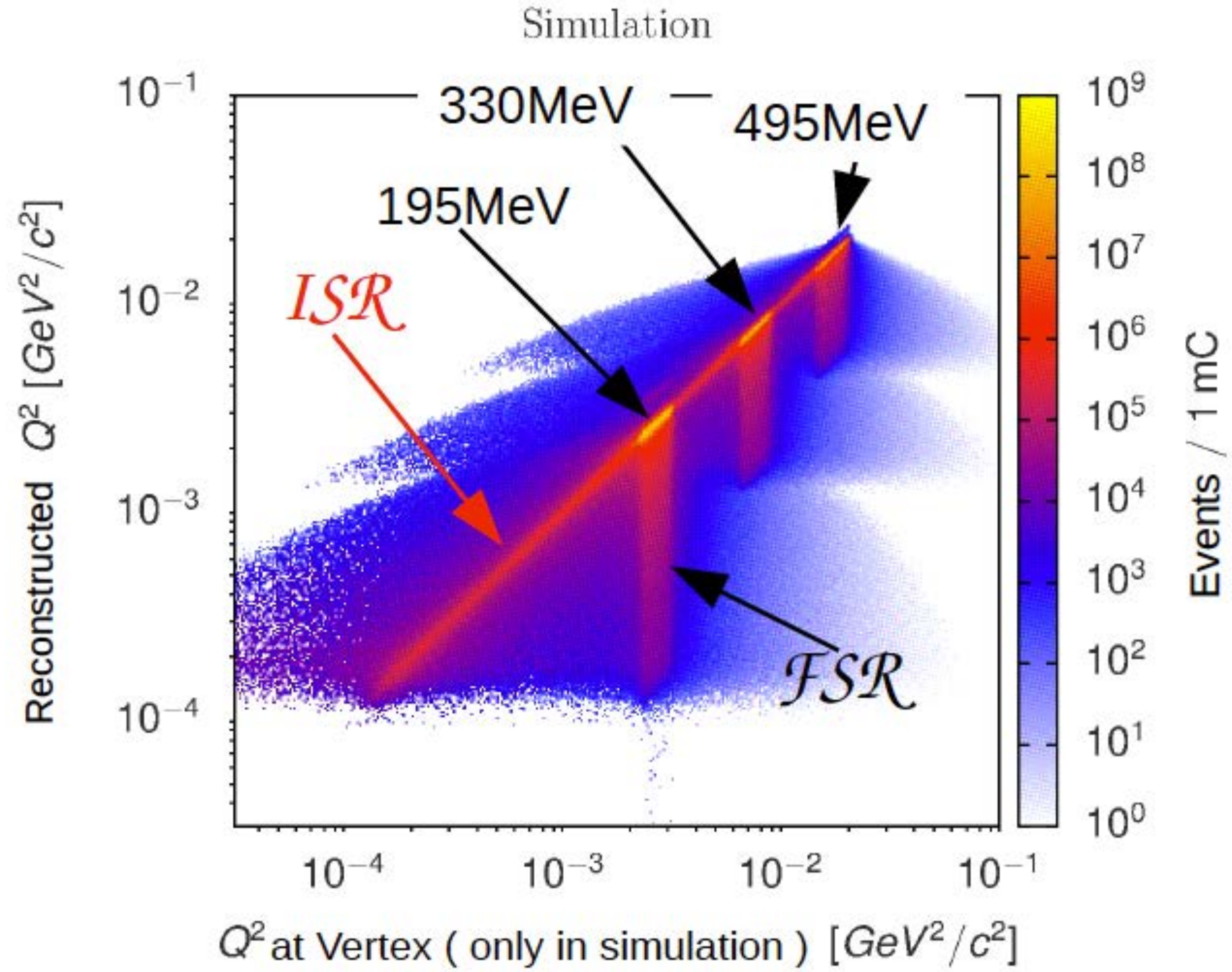
A. Antognini et al, Can. J. Phys. 89, 47 (2011)

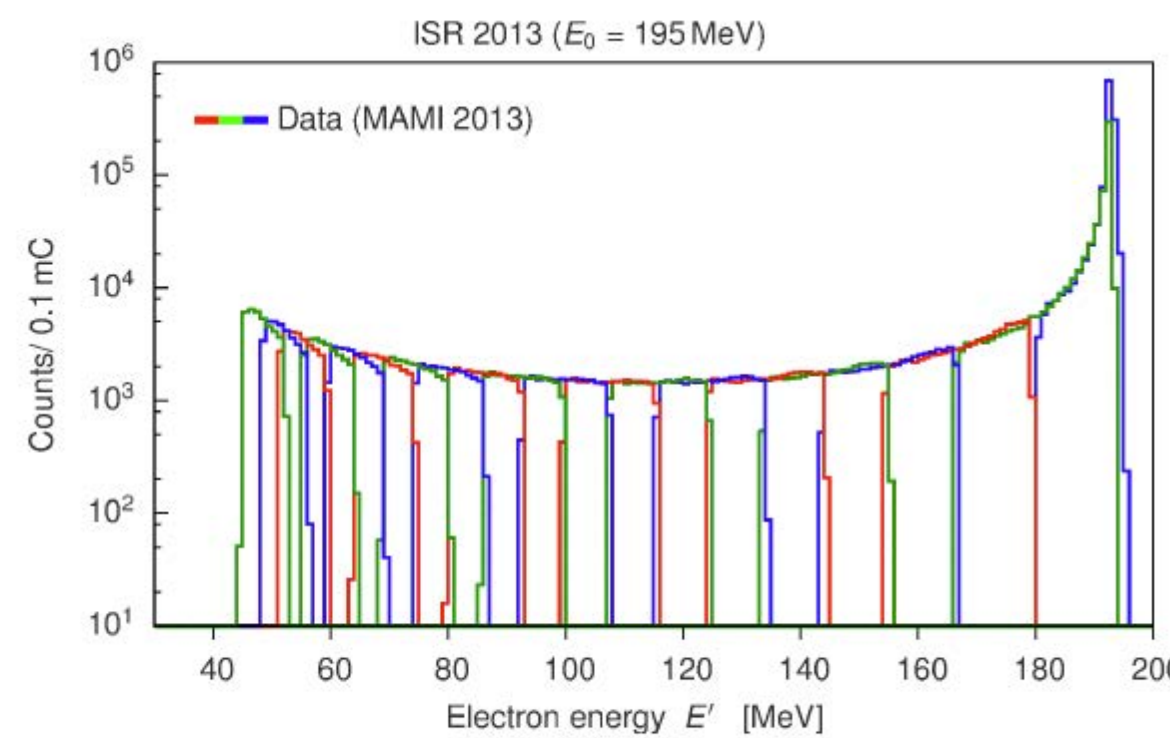
Where to now?

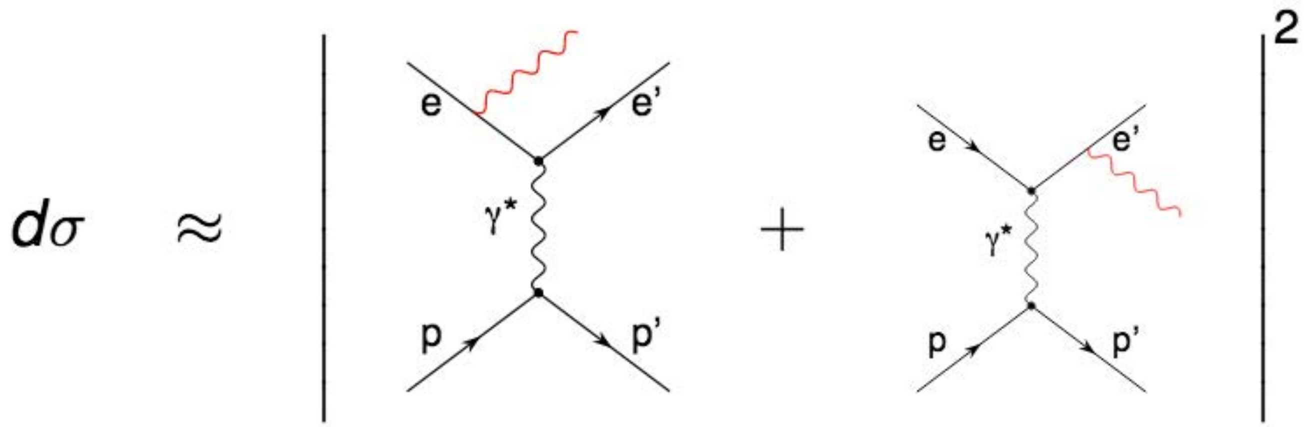

μp
8.4 meV
$2P_{3/2}$
$2P_{1/2}$
F=2
F=1
F=1
F=0
206 meV
50 THz
6 μm
fin. size:
3.8 meV
$2S_{1/2}$
F=1
23 meV
F=0
$\mu\,^4$He
146 meV
2P
$2P_{3/2}$
$2P_{1/2}$
812 nm
898 nm
$2S_{1/2}$
fin. size effect
290 meV
$\mu\,^3$He
145 meV
$2P_{3/2}$
2P
$2P_{1/2}$
F=1
F=2
F=0
F=1
F=0
167 meV
$2S_{1/2}$
F=1
fin. size effect
397 meV

Where to now? Mainz ISR Experiment

- Use initial state radiation to get effective low Q^2 at vertex.
- Q^2 downto 10^{-4} GeV^2.
- Requires highly accurate radiative models.
- Aiming for 1% cross sections.
- Already took data.



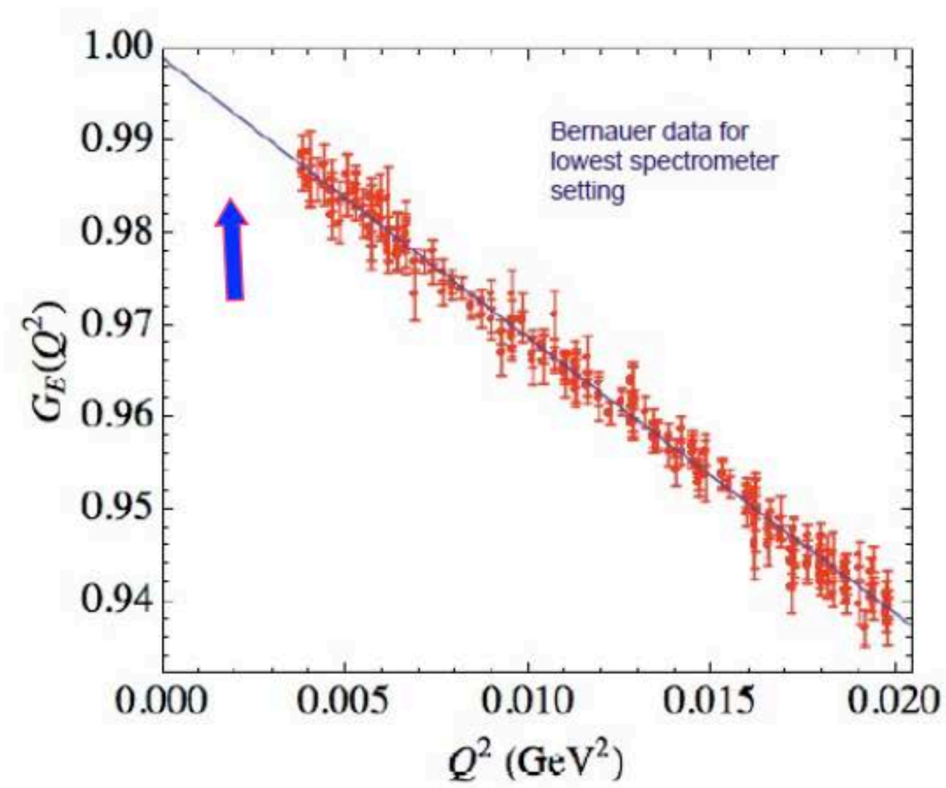




Where to now? JLab PRad

The PRad Experimental Approach

- Experimental goals:
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - reach to sub-percent precision in cross section
  - large Q^2 range in one experimental setting
- Suggested solutions:
  - ✓ use high resolution high acceptance calorimeter:
    - reach smaller scattering angles: ($\Theta = 0.7^0 - 7.0^0$)
      ($Q^2 = 1\text{x}10^{-4} \div 6\text{x}10^{-2}$) GeV/c^2
      large Q^2 range in one experimental setting!
      essentially, model independent r_p extraction
  - ✓ Simultaneous detection of *ee* → *ee* Moller scattering
    - (best known control of systematics)
  - ✓ Use high density windowless H_2 gas flow target:
    - beam background fully under control
    - minimize experimental background



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision in r_p extraction
- Approved by JLab PAC39 (June, 2012) with high "A" scientific rating

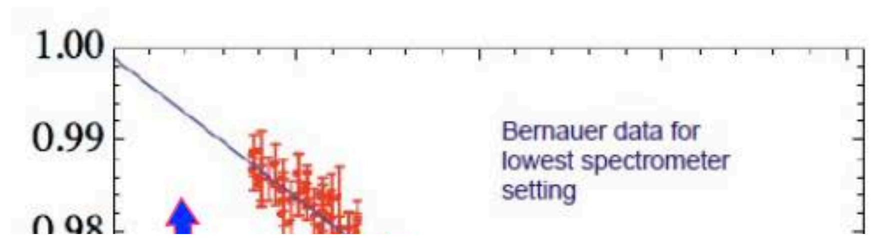
A. Gasparian Hadron-2016

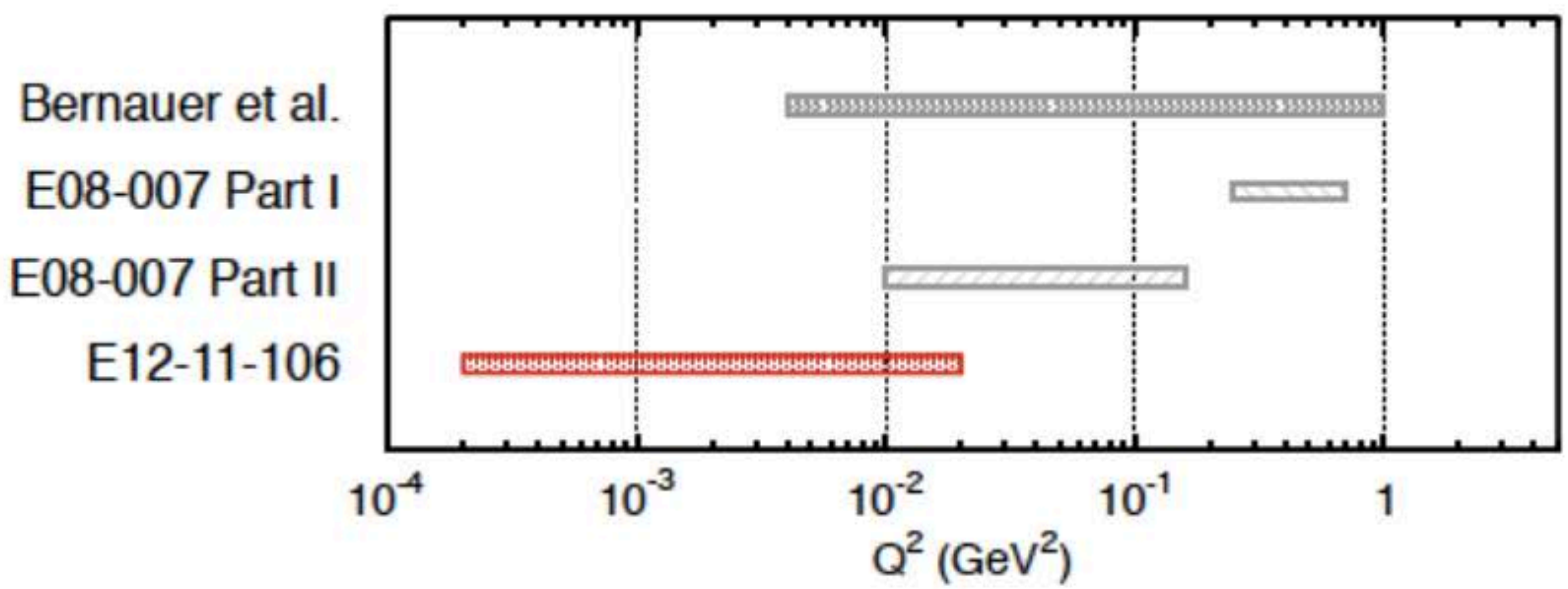
Where to now?

JLab PRad

The PRad Experimental Approach

- Experimental goals:
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - reach to sub-percent precision in cross section
  - large Q^2 range in one experimental setting

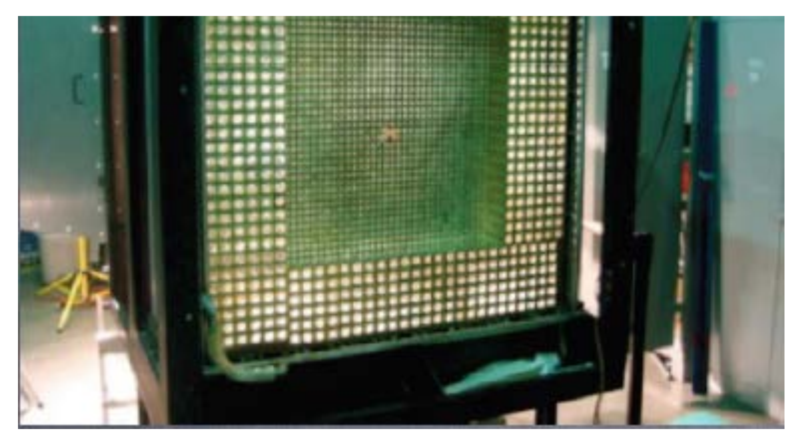




Jefferson Lab Experiment E12-11-106, A. Gasparian, H. Gao, and D. Dutta spokespeople.

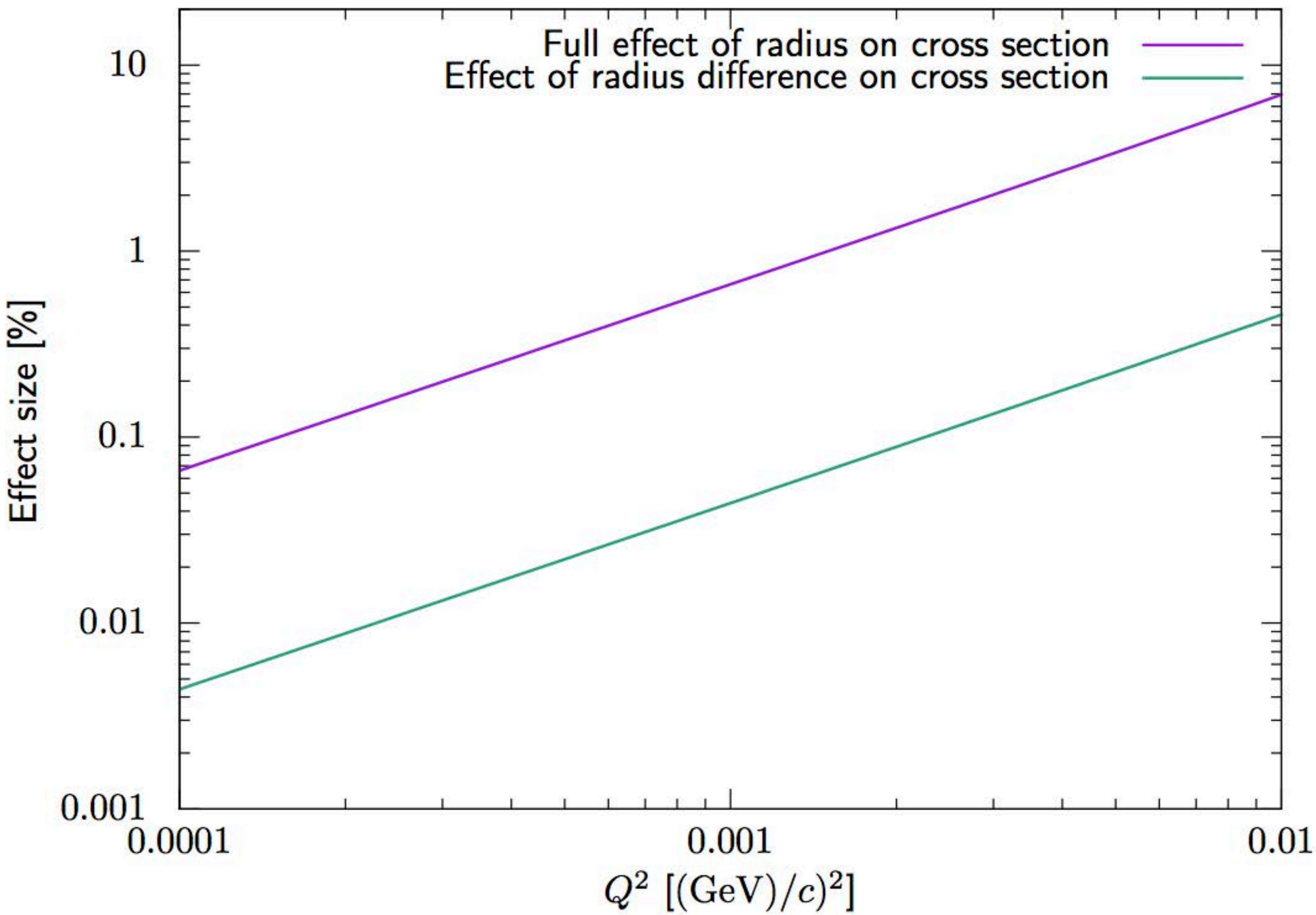
Very low Q^2 range: 2×10^{-4} to 2×10^{-2} GeV^2 → Model independent r_p extraction

- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision in r_p extraction
- Approved by JLab PAC39 (June, 2012) with high "A" scientific rating



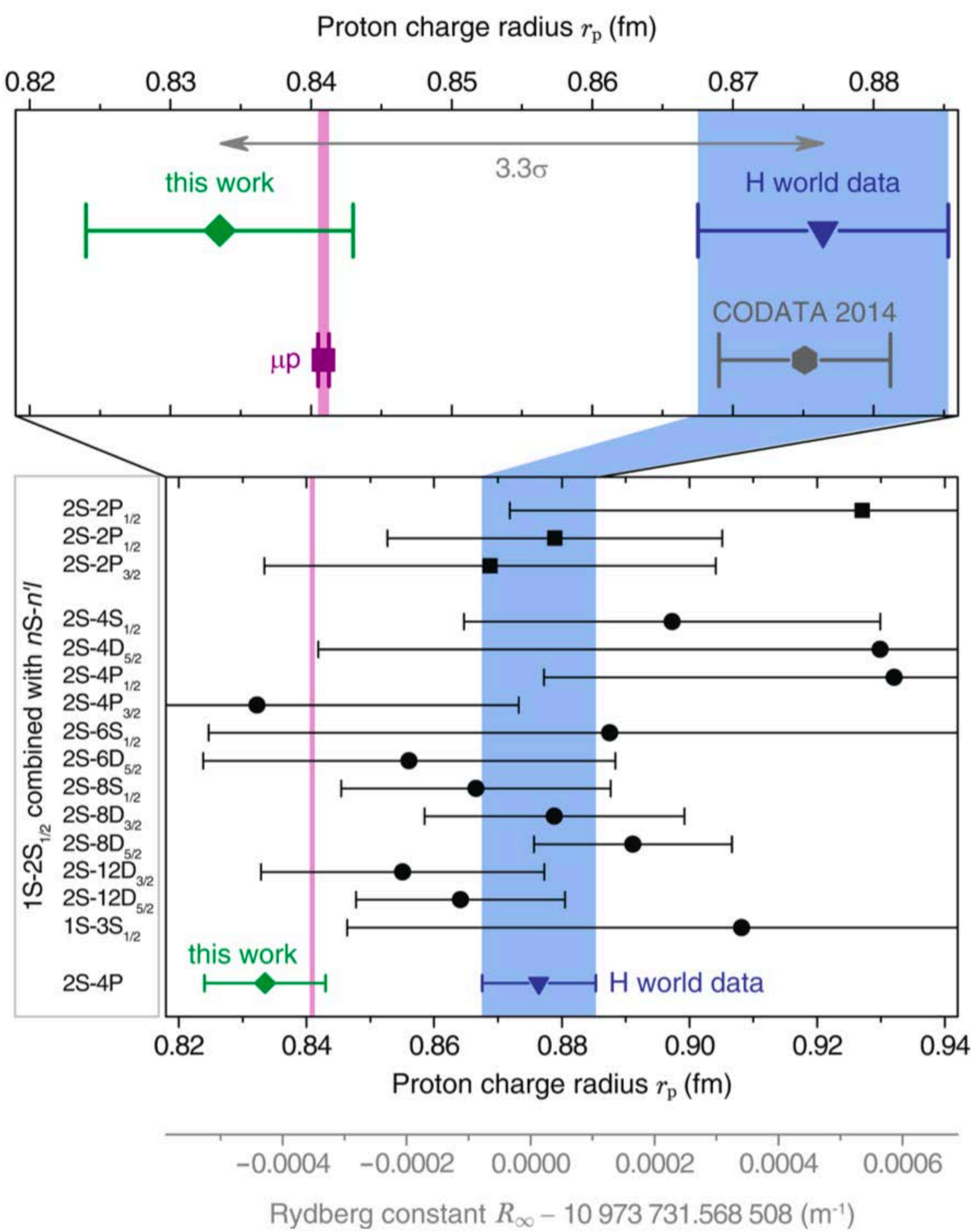
Unfortunately

Low Q² Measurements in eP scattering have been pushed about as far as they can go



The plot thickens

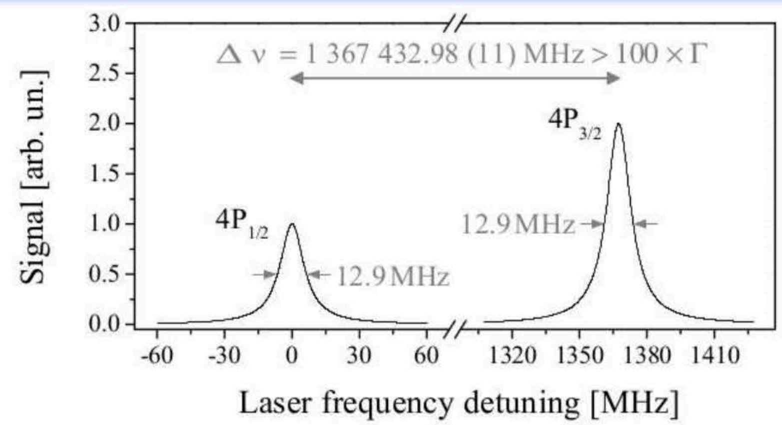
New eH 2s-4P measurement (Beyer et al.)

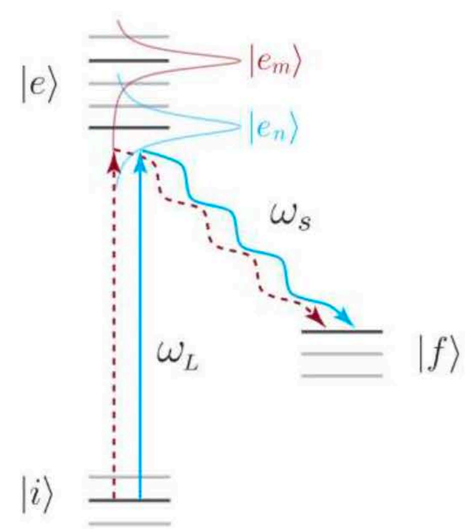


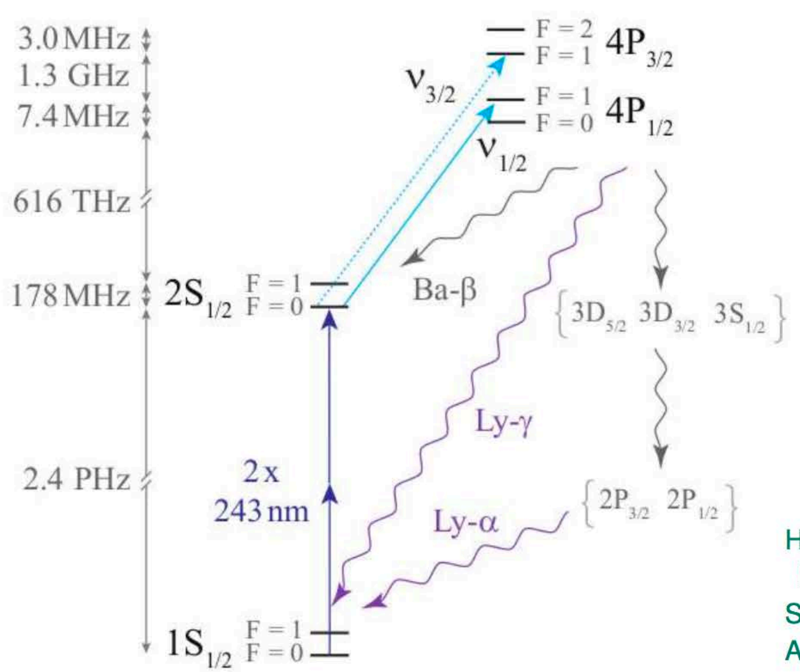
New eH measurement consistent with muonic hydrogen and inconsistent with all previous hydrogen spectroscopy measurements.

A word about Quantum Interference

Line shape distortions due to quantum interference of neighboring atomic resonances lead to a break-down of the simple approximation of natural atomic line shapes by Lorentz functions. They result in apparent geometry-dependent shifts of the observed line centers if not properly taken into account when fitting the experimental data. In the 2s-4p measurement the effect can be several times larger than the proton radius puzzle!





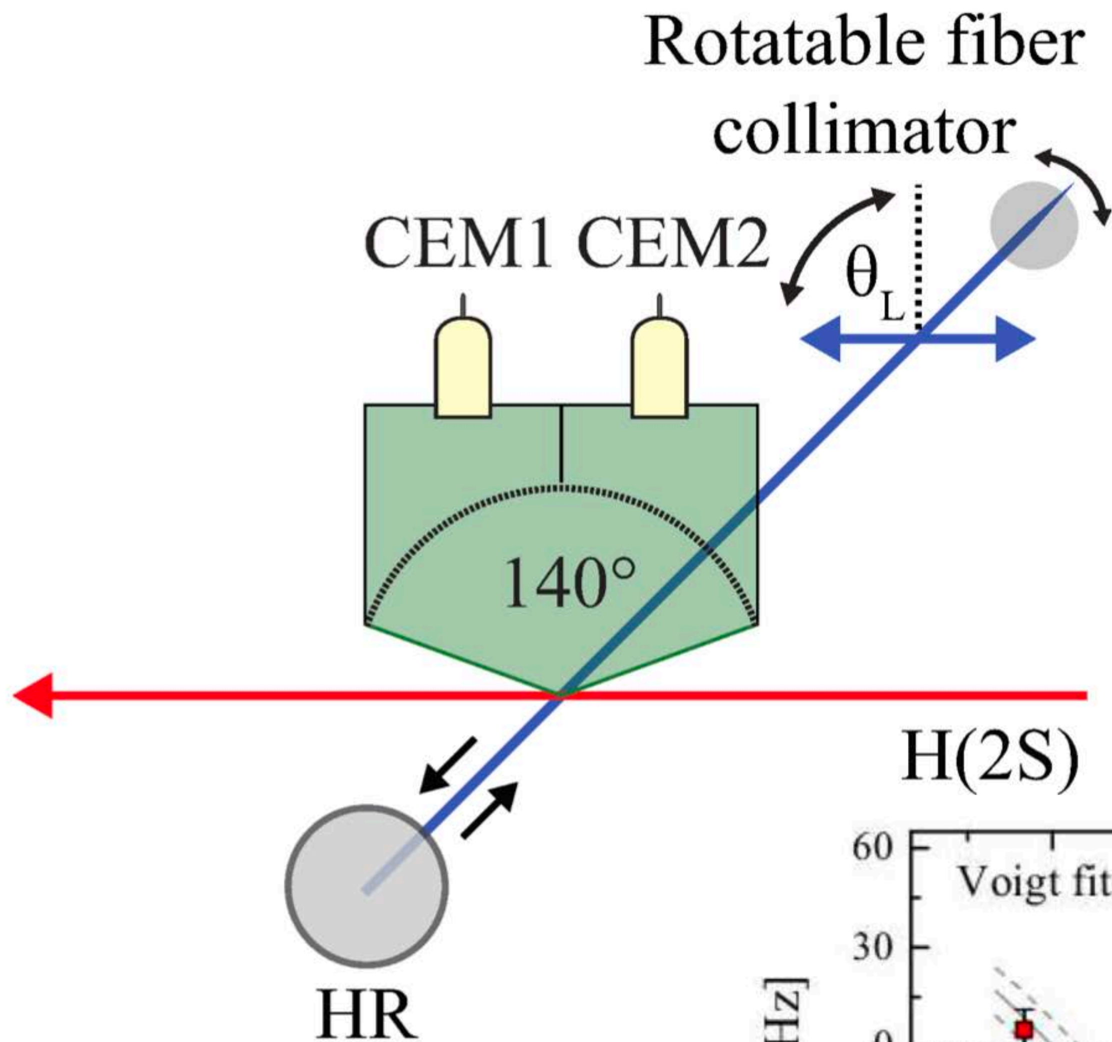


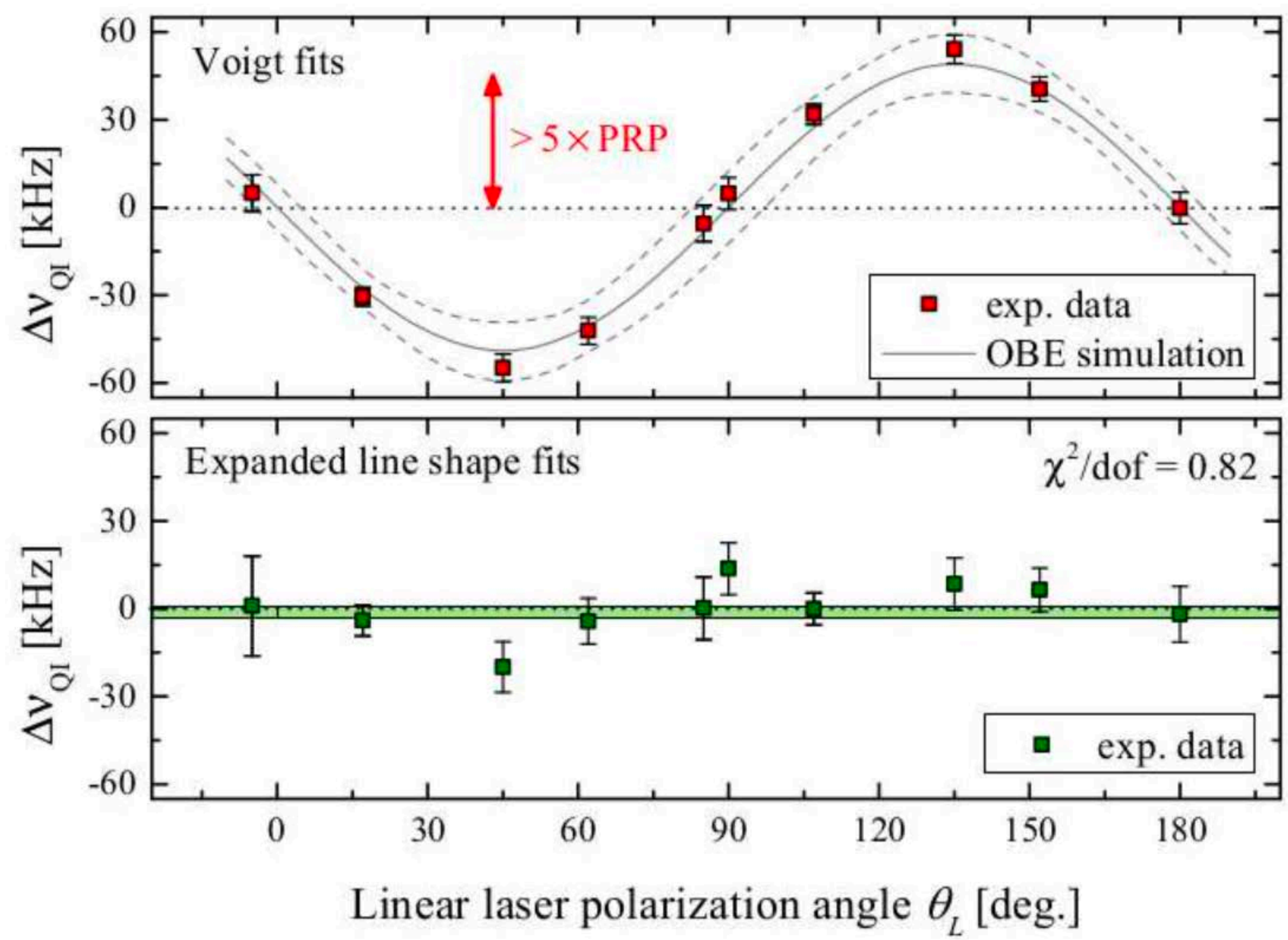
$$P(\omega) \propto \left| \frac{(\vec{d}_1 \cdot \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \cdot \vec{E}_0)\vec{d}_2 e^{i\Delta\phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

= Lorentzian(1) + Lorentzian(2) + cross-term (QI)

Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

Slide courtesy R. Pohl.

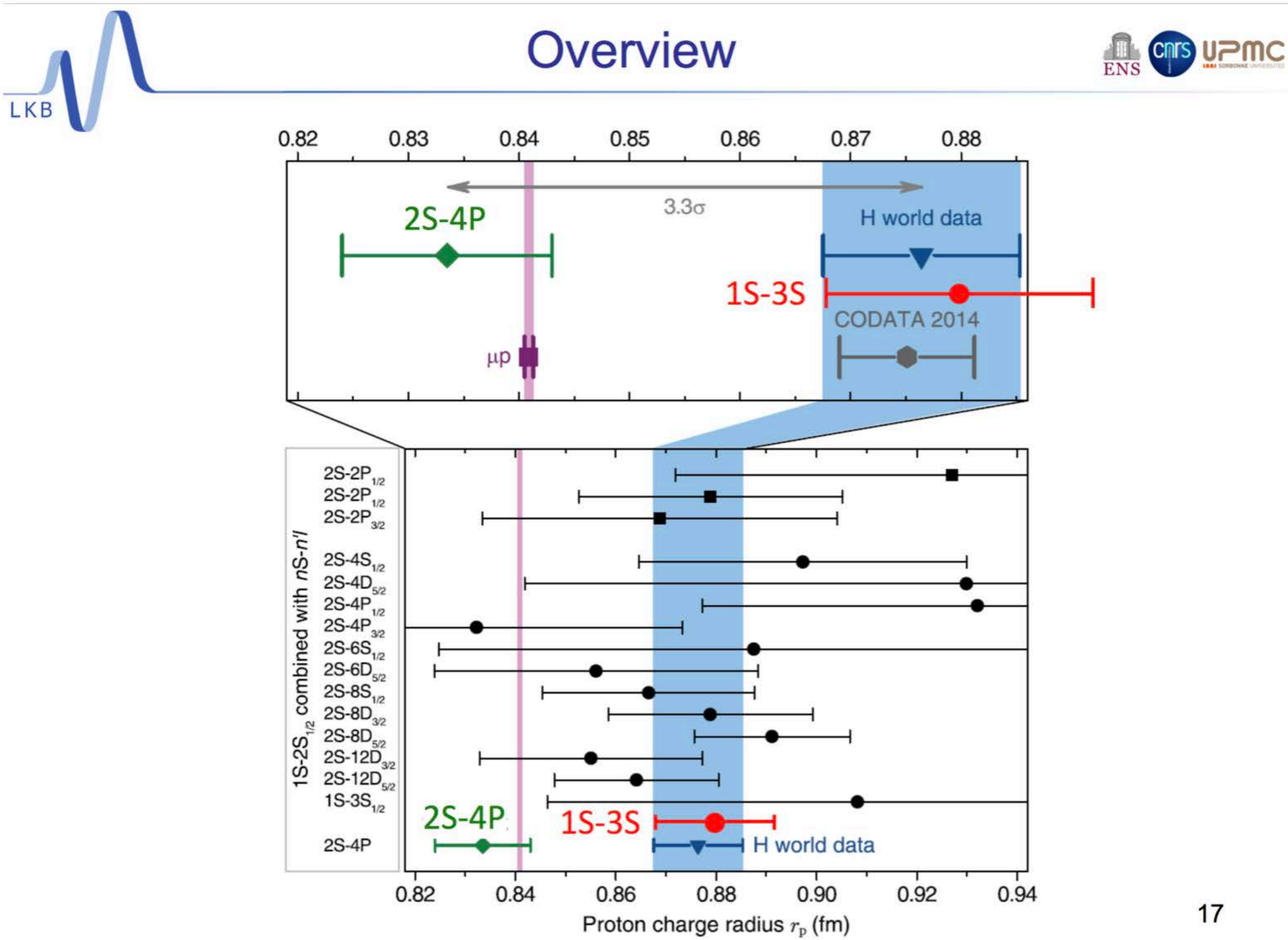


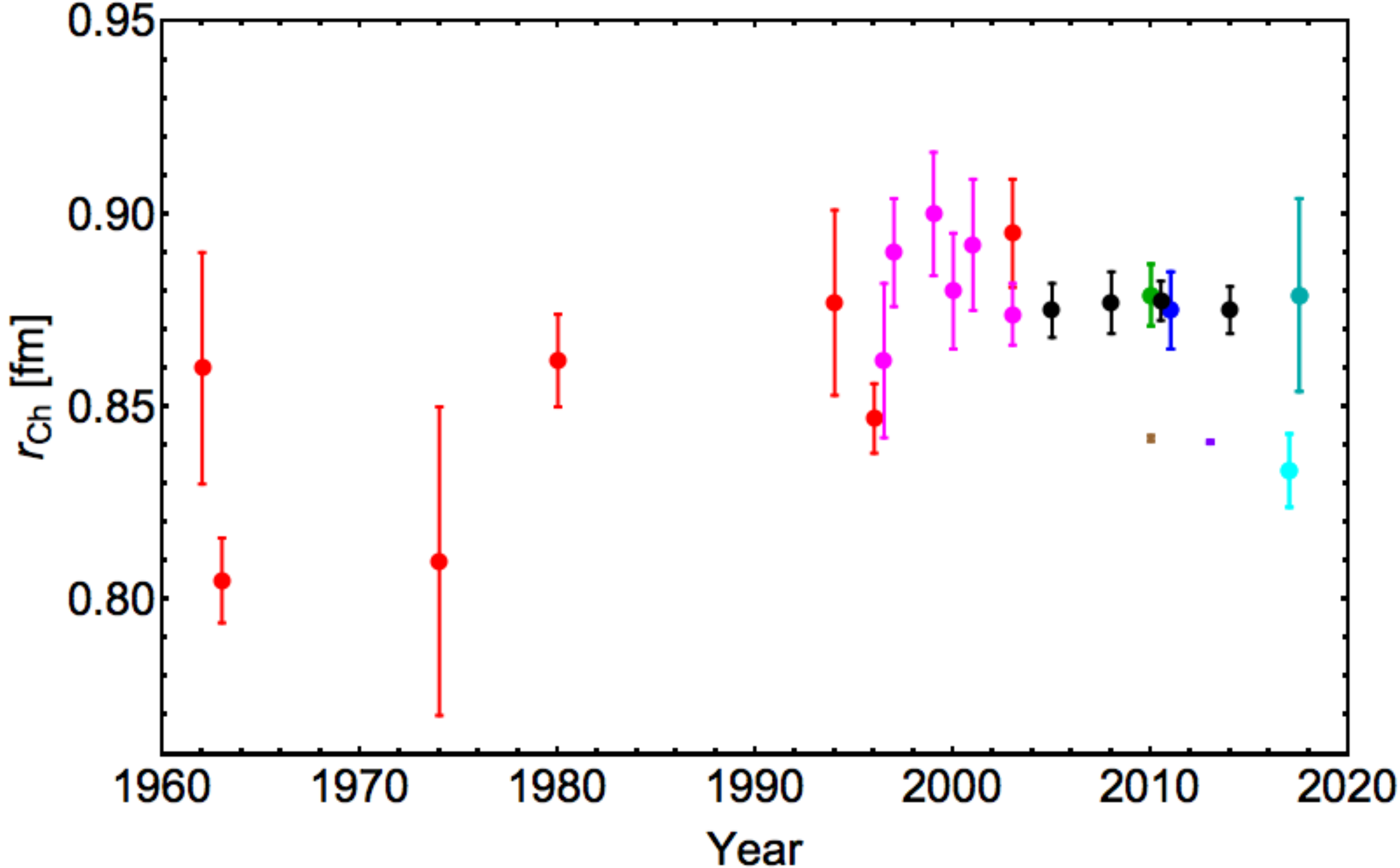


Beyer, RP *et al.*, submitted (2016)

And thickens again

New 1S-3S measurement (Fluerbaey)





0.95
0.90
0.85
0.80
r_{Ch} [fm]
1960
1970
1980
1990
2000
2010
2020
Year

- World's most powerful separated mu/e/pi beam.
- Why μp scattering?
- It should be relatively easy to determine if the μp and ep scattering are consistent or different, and, if different, if the difference is from novel physics or 2γ mechanisms:
  - If the μp and ep radii really differ by 4%, then the form factor slopes differ by 8% and cross section slopes differ by 16% - this should be relatively easy to measure.
  - 2γ affects e^+ and e^-, or μ^+ and μ^-, with opposite sign - the cross section difference is twice the 2γ correction, the average is the cross section without a 2γ effect. It is hard to get e^+ at electron machines, but relatively easy to get μ^+ and μ^- at PSI.

MUSE Collaboration

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Temple University
N Liyanage
University of Virginia
C Perdrisat
College of William & Mary

MUSE - PSI R12-01.1 Technique

r_p (fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

$d\sigma/d\Omega(Q^2)$ = counts / ($\Delta\Omega$ N_{beam} $N_{target/area}$ x corrections x efficiencies)

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + \left(2\tau - \frac{m^2}{M^2}\right) G_M^2(Q^2)\frac{\eta}{1-\eta}\right]$$

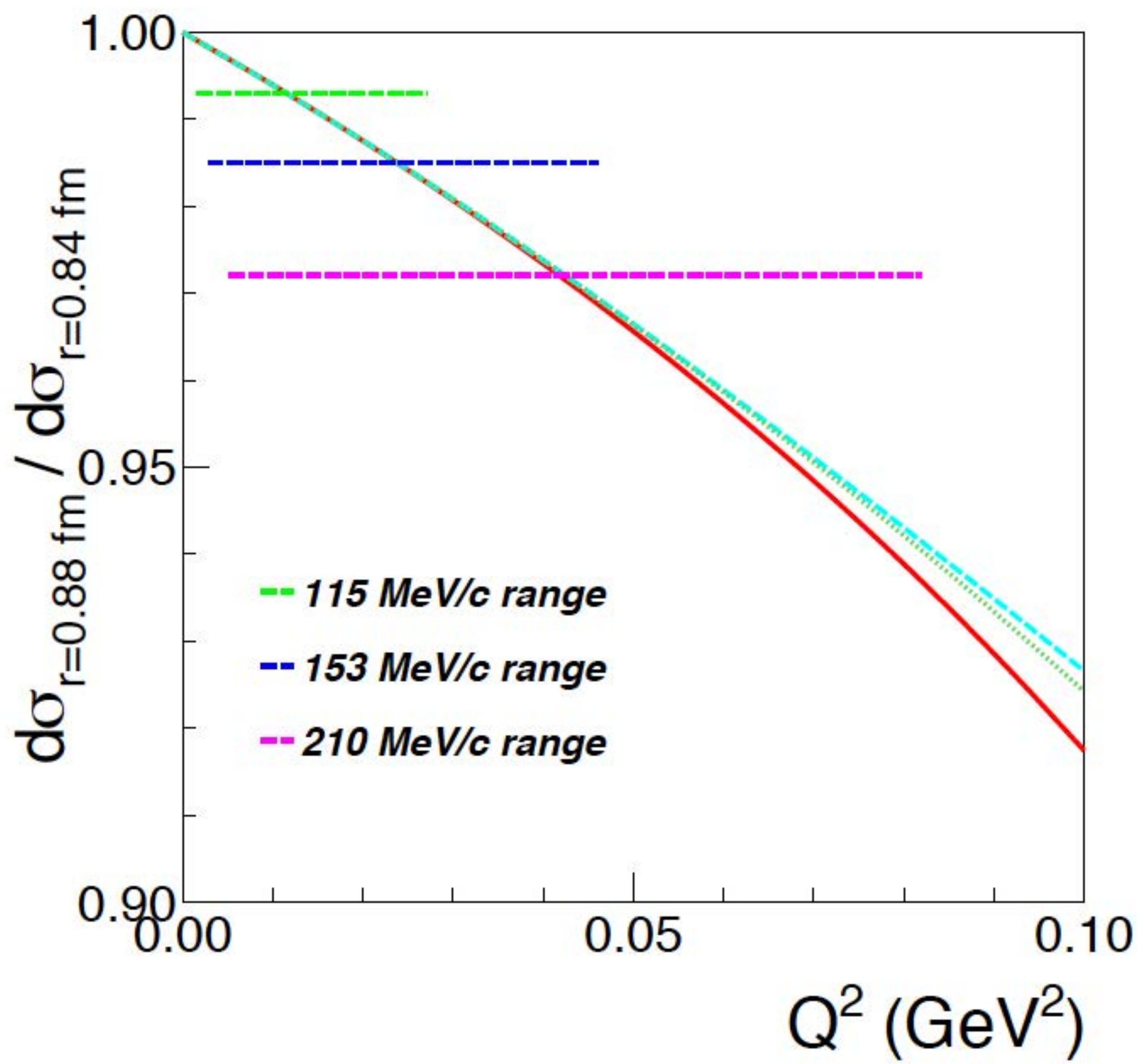
$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2}\frac{1-\eta}{\eta^2}\frac{1/d}{\left[1+\frac{2Ed}{M}\sin^2\frac{\theta}{2}+\frac{E}{M}(1-d)\right]} \qquad d = \frac{\left[1-\frac{m^2}{E^2}\right]^{1/2}}{\left[1-\frac{m^2}{E'^2}\right]^{1/2}}$$

$$\eta = Q^2/4EE'$$

following Preedom & Tegen, PRC36, 2466 (1987)

The effect of the radius on the cross section

Plot shows ratio of cross section assuming a charge radius of 0.88fm to that assuming a radius of 0.84fm.
MUSE kinematics are indicated.

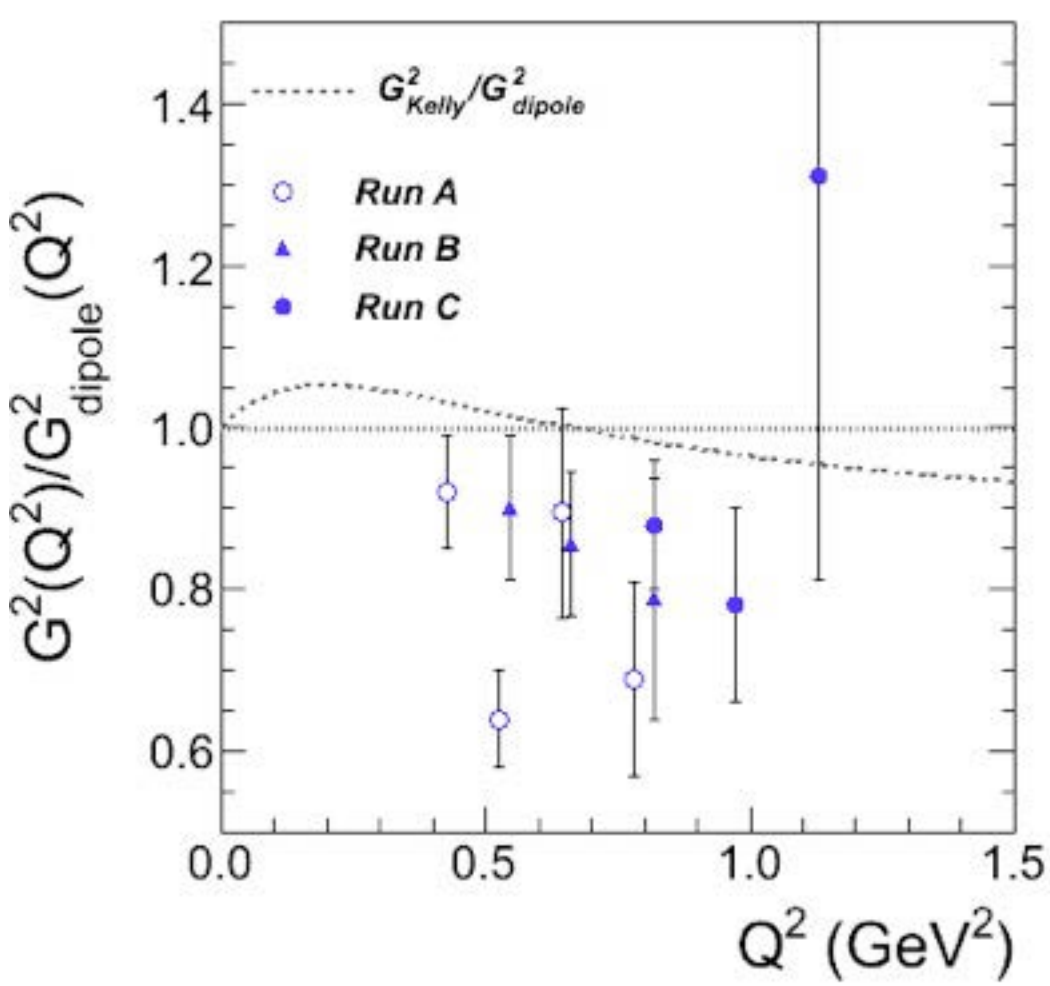


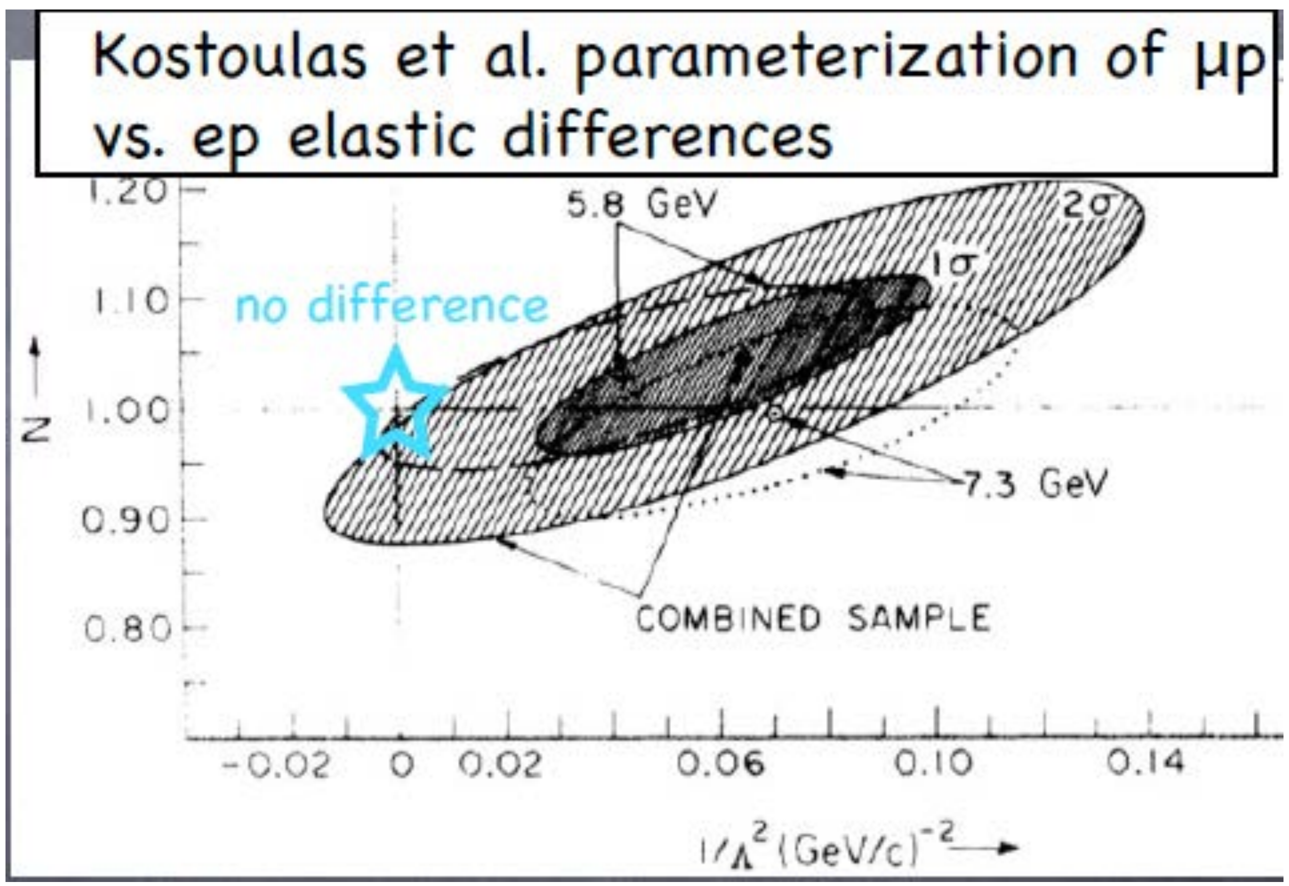
MUSE - PSI R12-01.1 Technique

r_p (fm)	ep	μp
atom	Several new efforts	Heavier light nuclei
scattering	Mainz ISR JLab PRAD LEDEX@JLab	**MUSE**

e-μ Universality

In the 1970s / 1980s, there were several experiments that tested whether the ep and μp interactions are equal. They found no convincing differences, once the μp data are renormalized up about 10%. In light of the proton ``radius'' puzzle, the experiments are not as good as one would like.

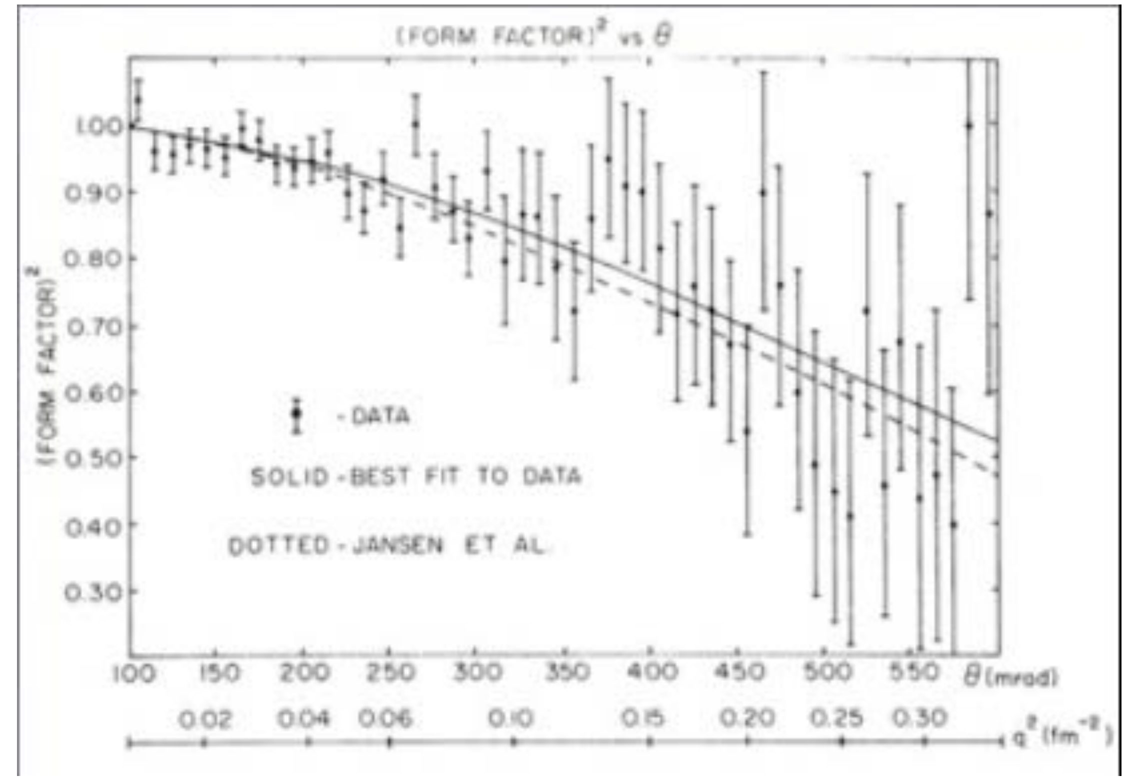




e-μ Universality

The 12C radius was determined with ep scattering and μC atoms.

The results agree:
Cardman et al. eC: 2.472 ± 0.015 fm
Offermann et al. eC: 2.478 ± 0.009 fm
Schaller et al. μC X rays: 2.4715 ± 0.016 fm
Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm
Sanford et al. μC elastic: 2.32 ± 0.13 fm



Perhaps carbon is right, e's and μ's are the same.
Perhaps hydrogen is right, e's and μ's are different.
Perhaps both are right - opposite effects for proton and neutron cancel with carbon.
But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice.

How do we Resolve the Radius Puzzle

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - BSM: scattering modified for Q^2 up to m^2_{BSM} , enhanced parity violation
  - Hadronic: enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - Muon scattering on nuclei.
  - **Muon scattering!**

How do we Resolve the Radius Puzzle

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  - Redoing electron scattering at lower Q^2
  - Muon scattering on nuclei.
  - **Muon scattering!**

MUSE tests these

Possible next Gen.

Other planned Experiments

MUSE is not your garden variety scattering experiment

Low beam flux

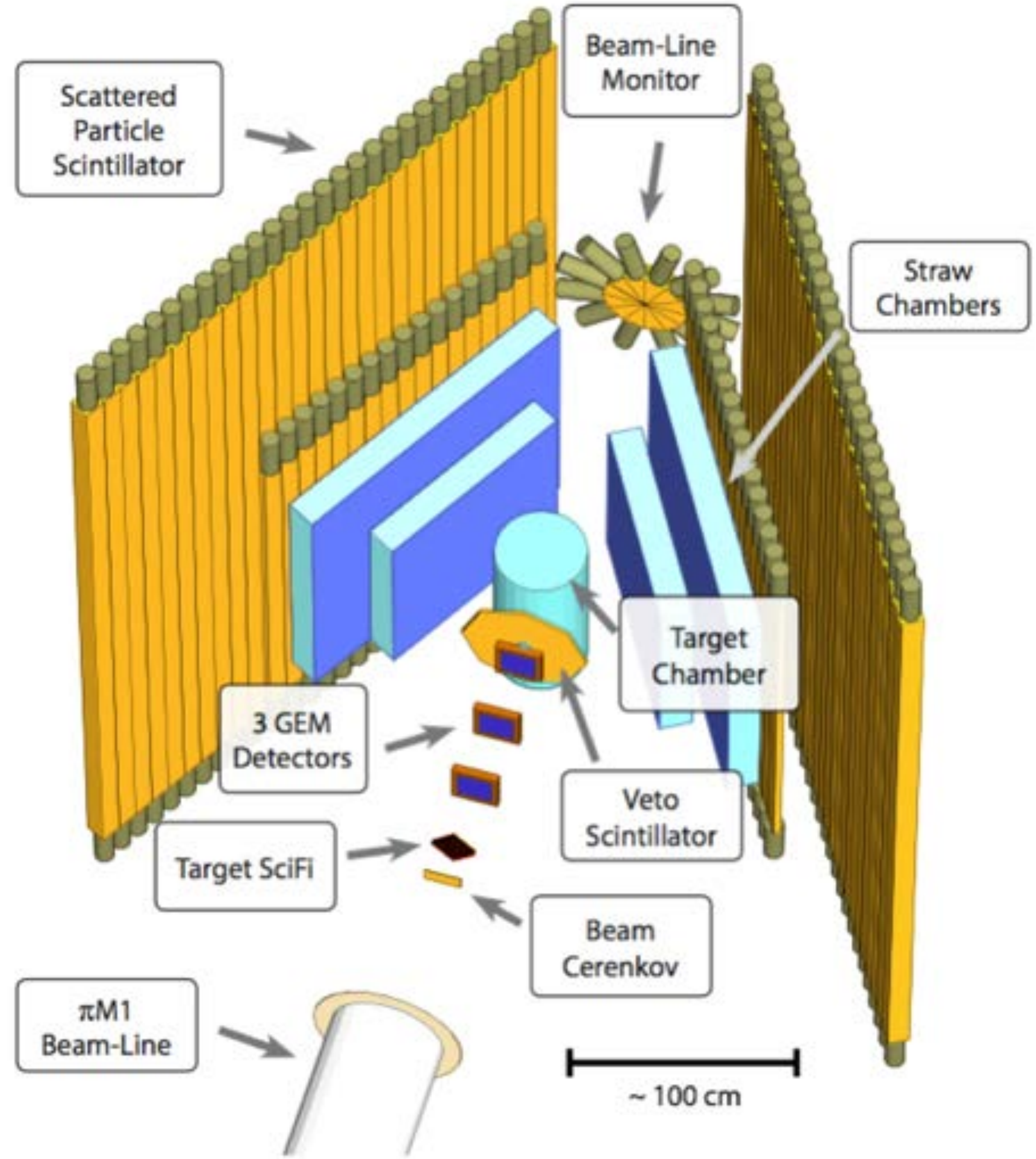
- Large angle, non-magnetic detectors.

Secondary beam (large emittance)

- Tracking of beam particles to target.

Mixed beam

- Identification of beam particle in trigger.



Experiment Overview

PSI πM1 channel

≈115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$

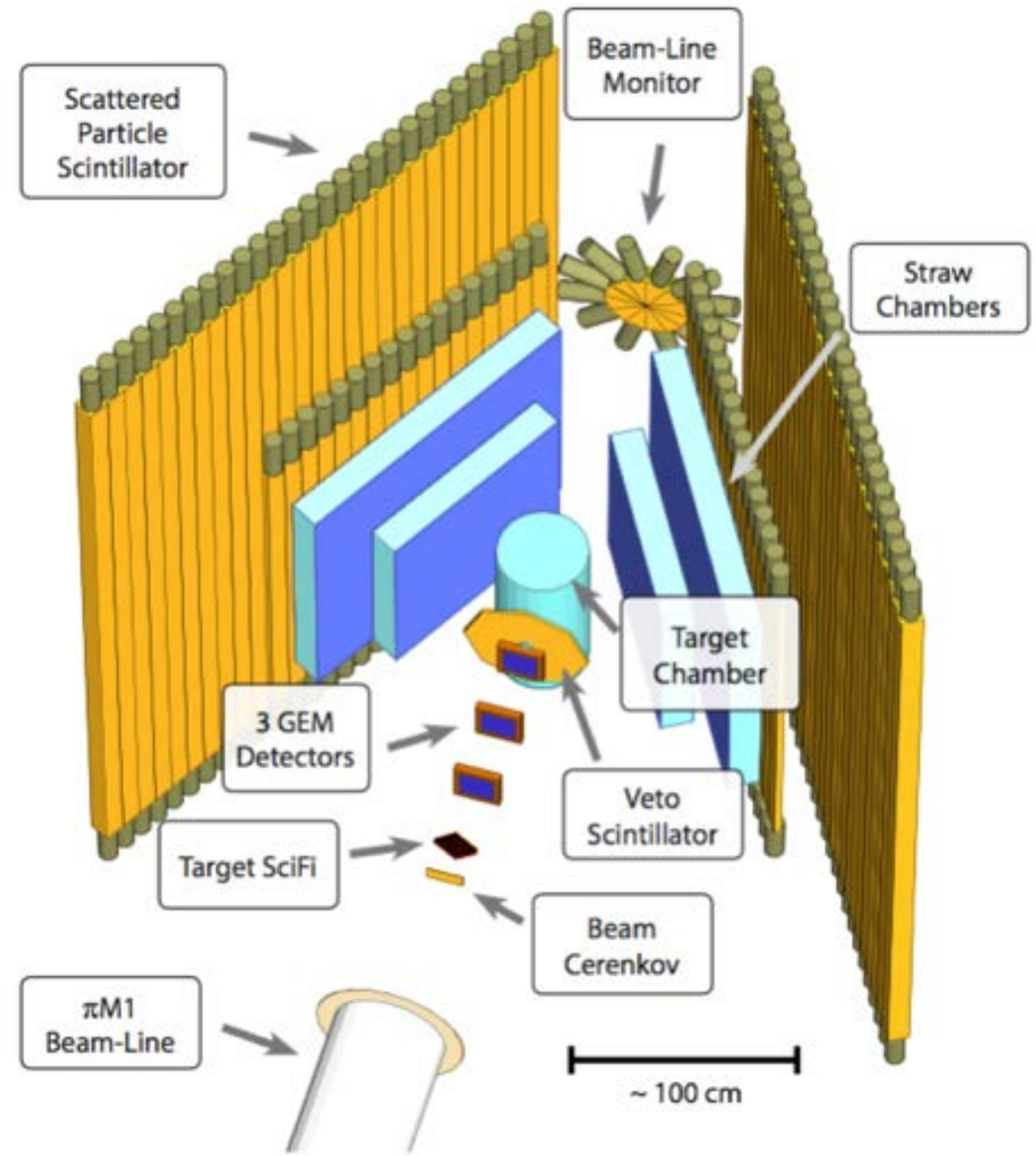
$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.002 - 0.07$ GeV^2

About 5 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's

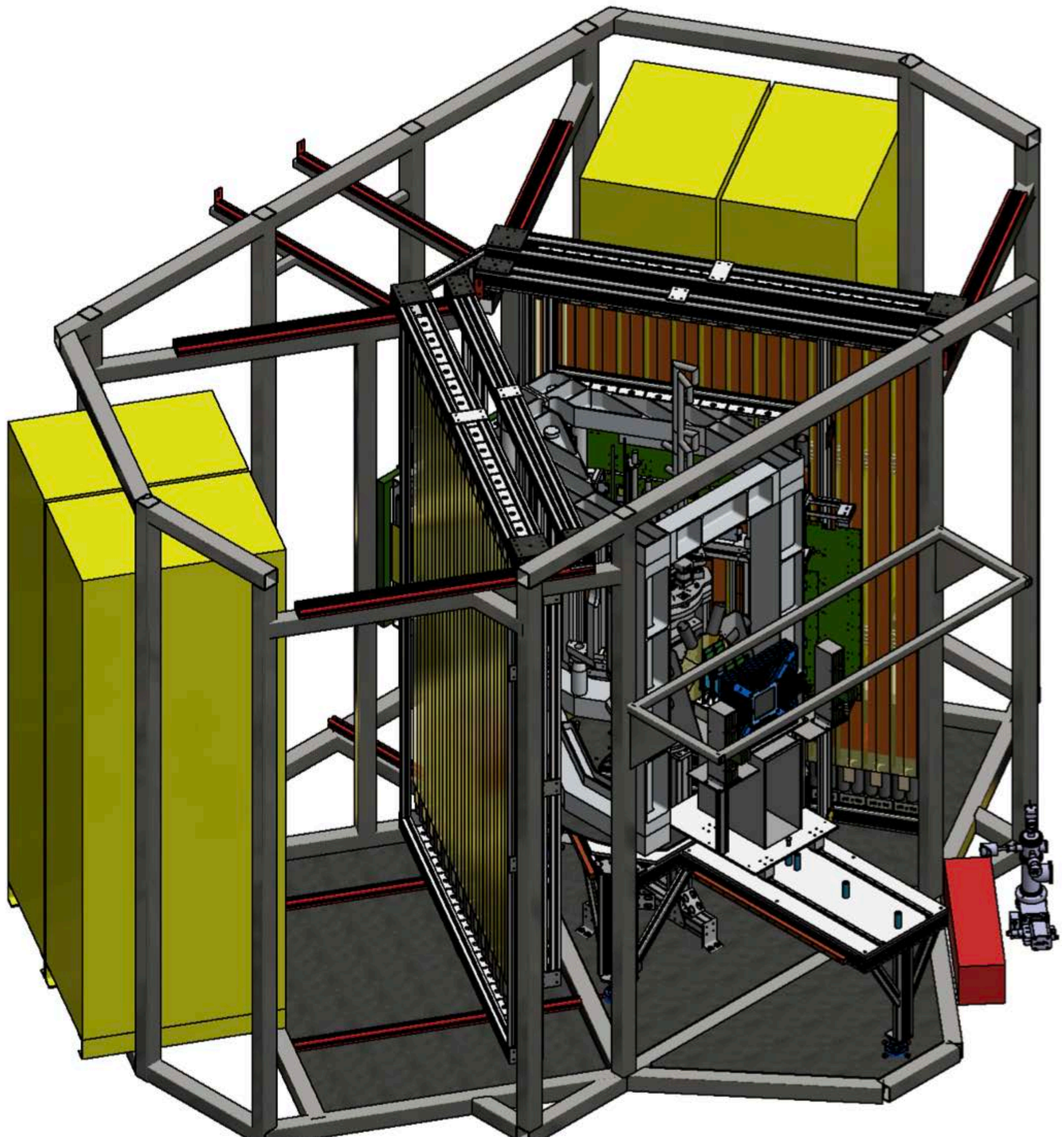
Beam monitored with SciFi, beam Cerenkov, GEMs

Scattered particles detected with straw chambers and scintillators



Not run like a normal cross section experiment - 7-8 orders of magnitude lower luminosity.
But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, …

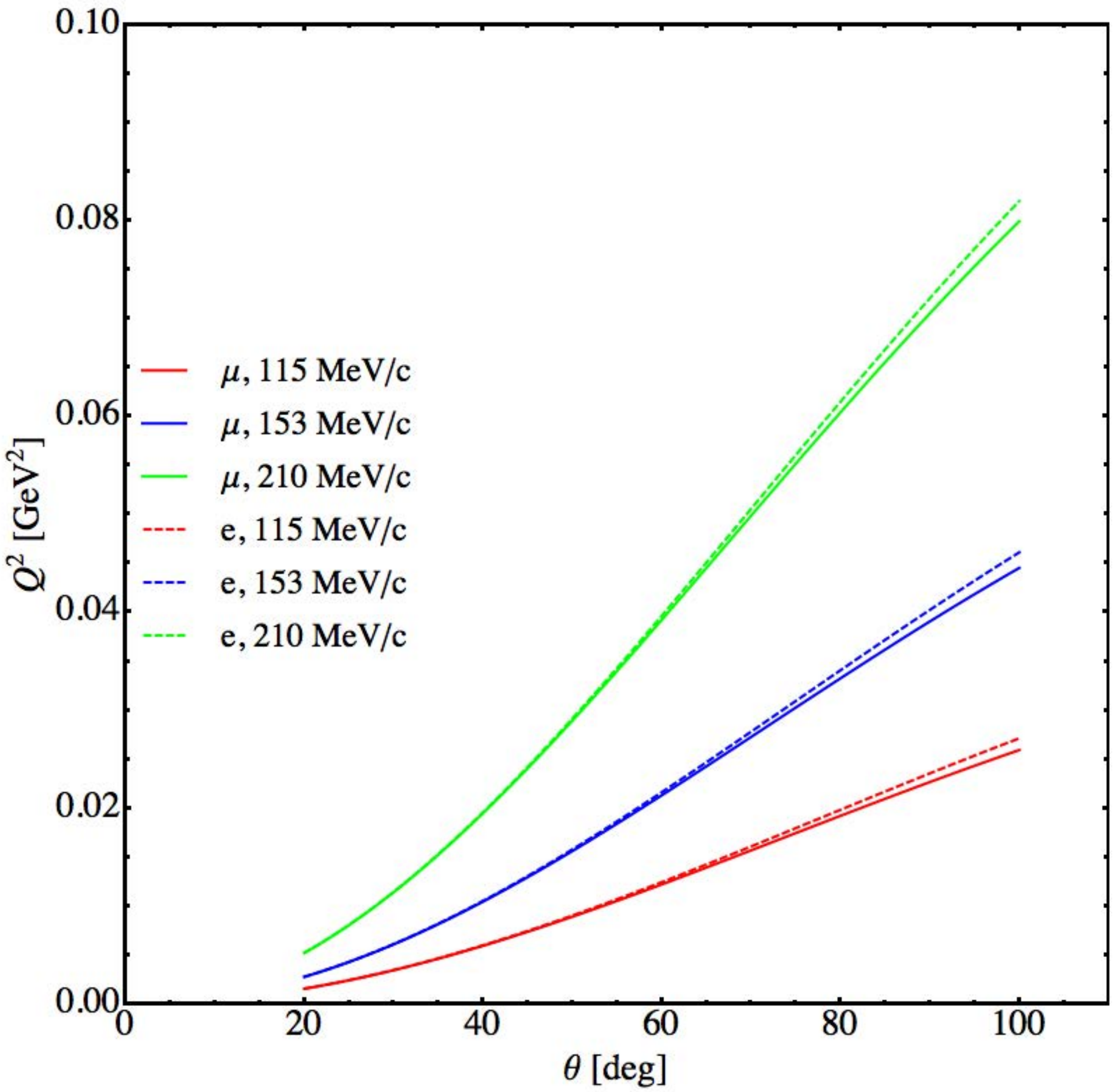
"Final Design"

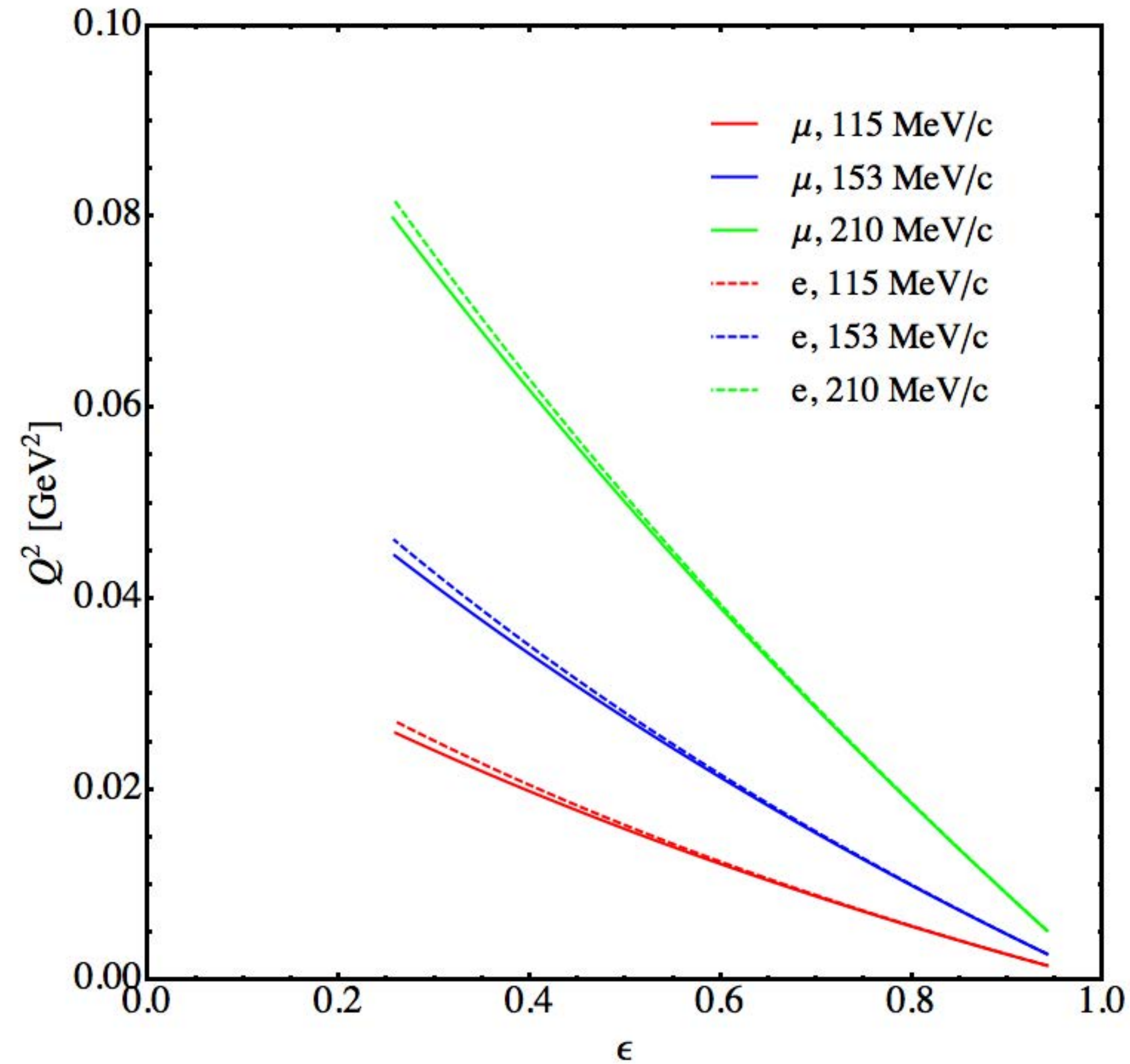


Component	Weight (lbs)	Weight (kg)
Frame	4200	1680
Table	716	325
Target	508	231
STT	550	250
Large SPS (2 @ 842lb each)	1684	766
Small SPS (2 @ 262lb each)	524	238
Beam Monitor	100	40
Electronics Racks (4 @ 500kg each)	4400	2000
Cables & Misc. (250kg per side)	1100	500
TOTAL	**13782**	**6030**

Experiment on movable (craneable) platform to allow for other uses of the experimental area.

Experiment Overview





$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.0015 - 0.08$ GeV^2

$\varepsilon \approx 0.256 - 0.94$

Allows Rosenbluth separation for some values of Q^2.

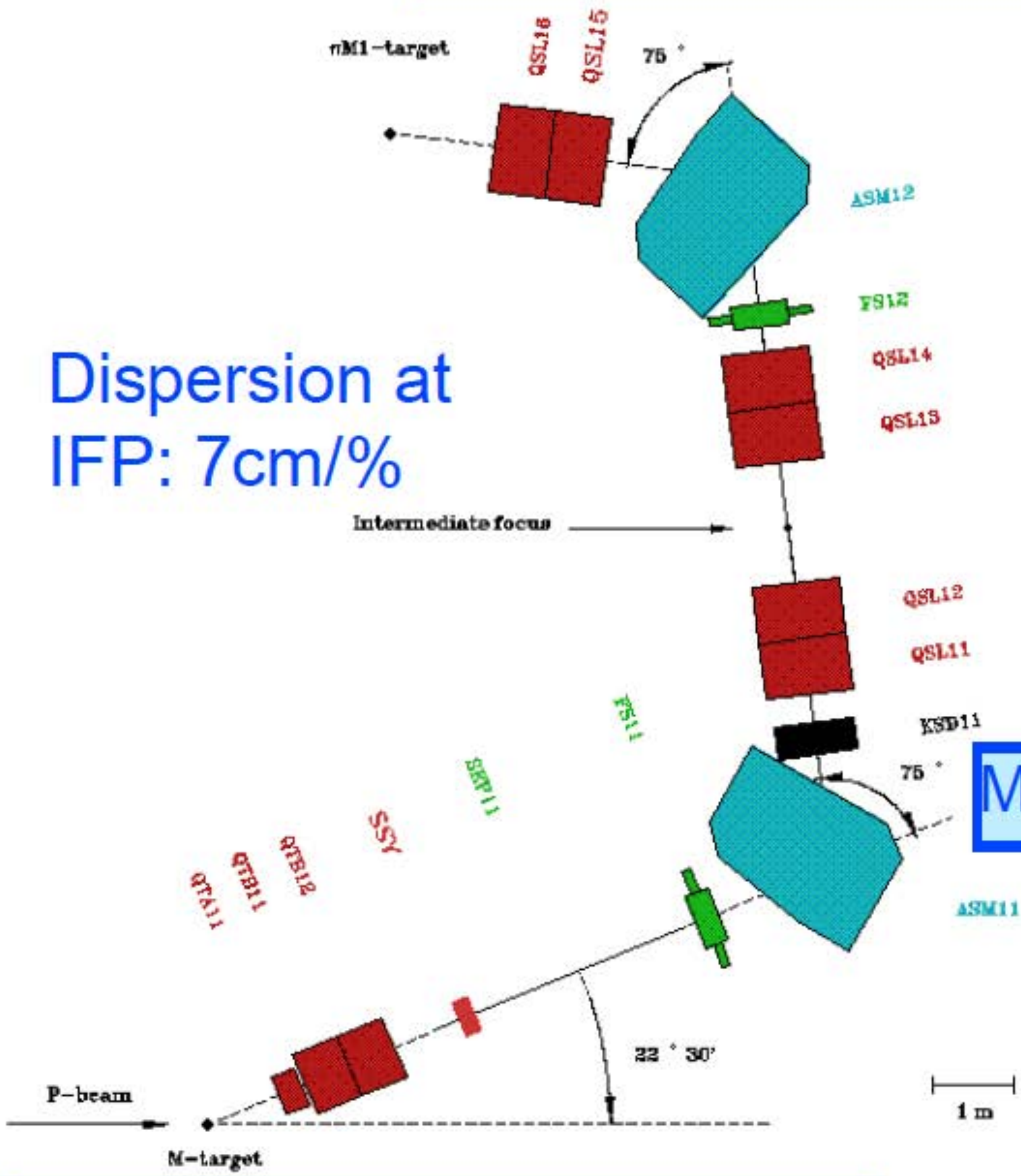
Important for controlling G_M

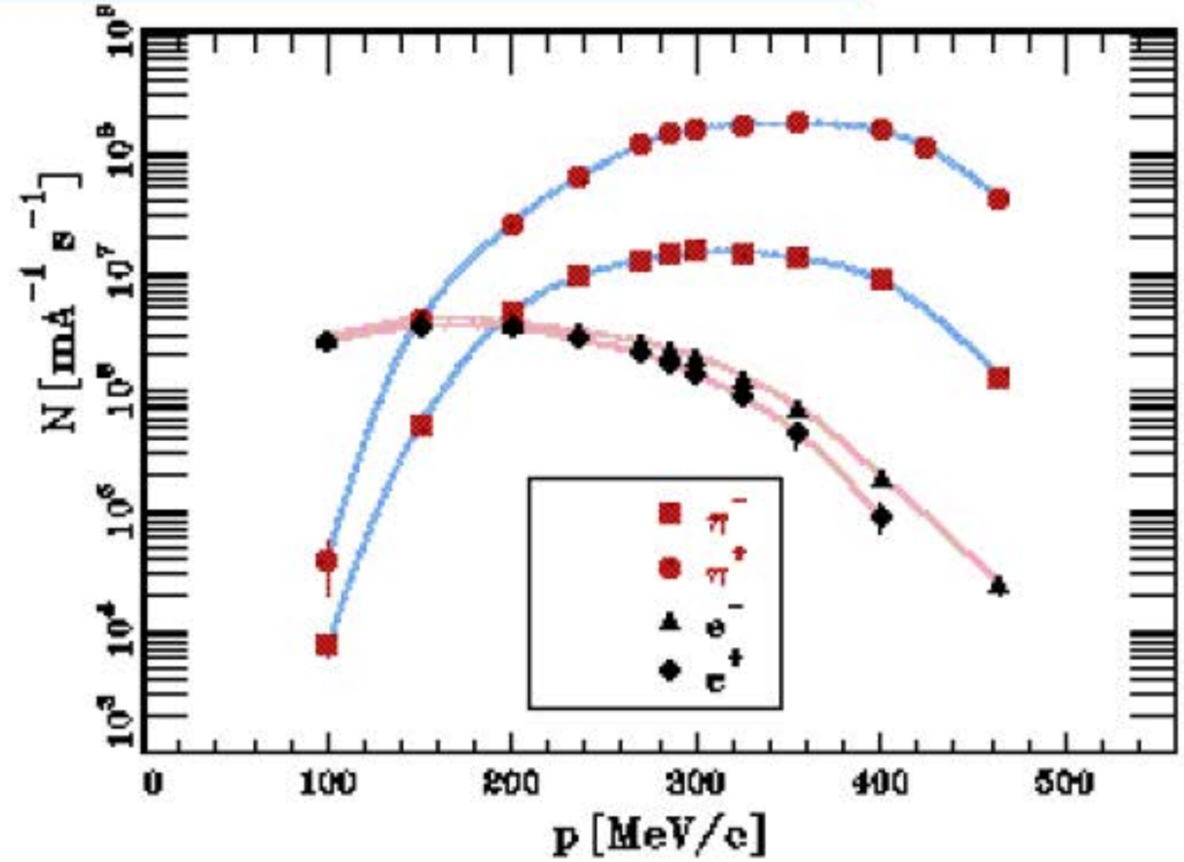
Essentially same coverage for all beam particles.

PSI πM1 Channel Characteristics

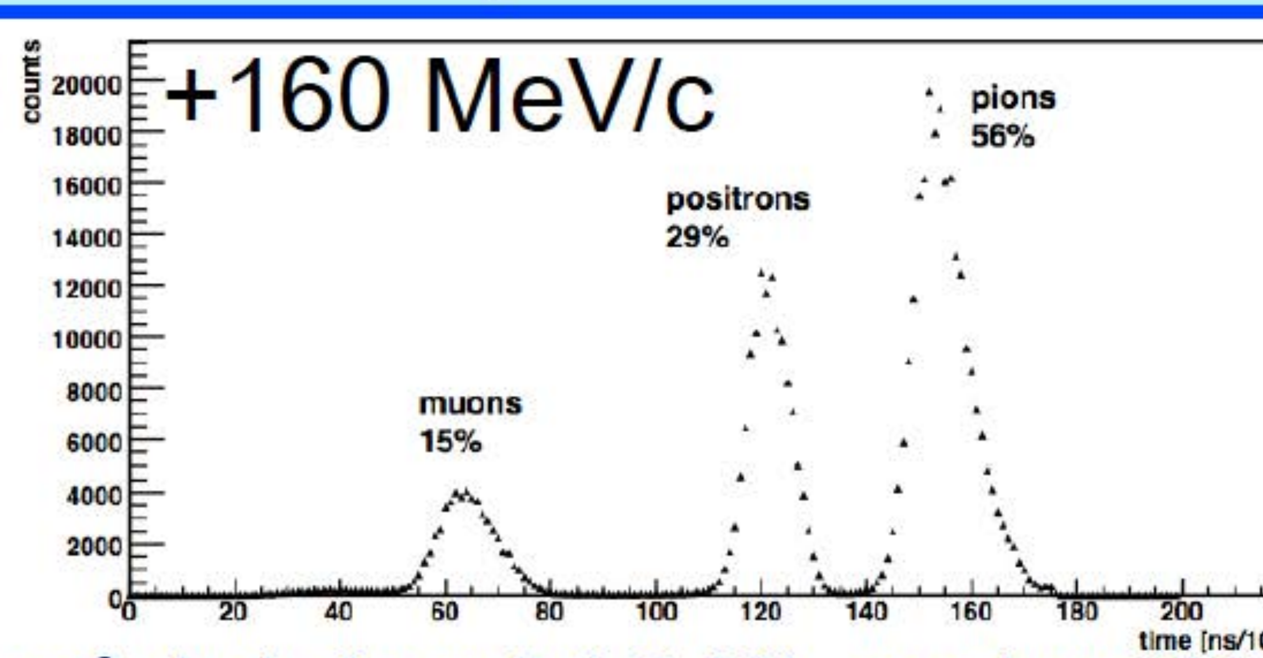
≈100 - 500 MeV/c mixed beam of μ's + e's + π's

Dispersion at IFP: 7cm/%





Momentum acceptance: 3% resolution: 0.1%



Beam spot (nominal): 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'

Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, Δp/p from 0.1-3.0%, used previously.

MUSE Design Choices

- Minimal R&D.
- Use existing designs as much as possible.
- Reuse equipment whenever possible.
- Maximal cost reduction.
- Modular construction (can run dress rehearsal with fewer components).

Performance Requirements

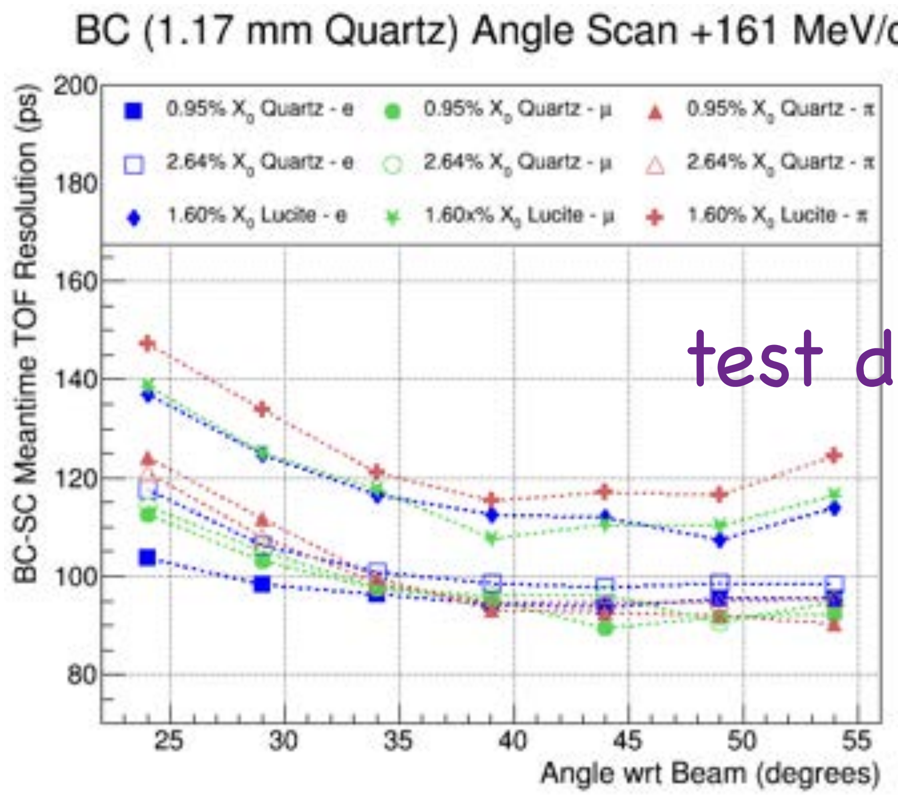
- Angle reconstruction to few mr (limited by multiple scattering).
- Reduce multiple scattering as much as possible.
- Mostly timing used for PID - O(50ps) time resolution.
- 99% or better online π rejection.

MUSE Test Runs

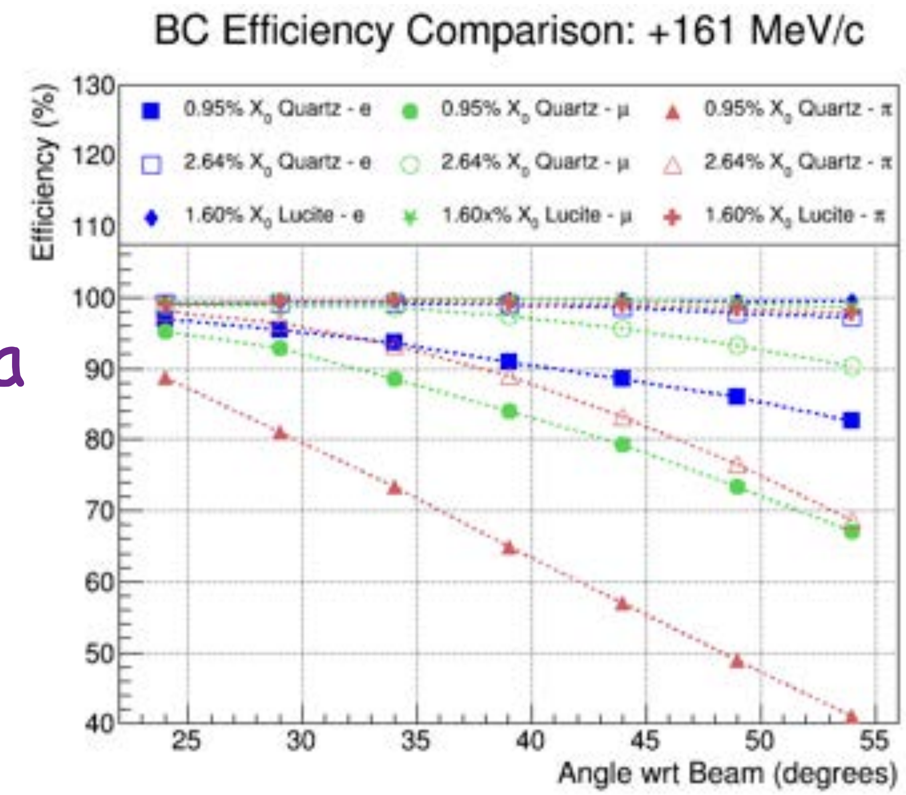
- 10 MUSE Test Runs
  - Oct 2012
  - May-June 2013
  - Oct 2013 (Cosmics)
  - Dec 2013
  - June 2014
  - Dec 2014
  - Feb 2015 (Cosmics)
  - June-July 2015
  - Fall 2016
  - June - Dec 2017
  - Representation from 13 institutions.

Beam Cerenkov (RU)

Used with RF signal for beam PID and triggering, and with scintillators (+tracks) for muon decay rejection



test data

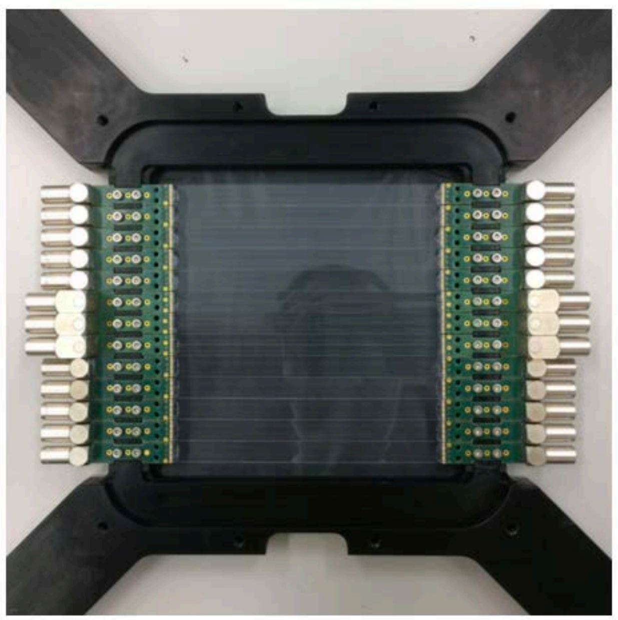


Dec 14 + June 15 test configuration - mount will be different for experiment

Copying Albrow et al Fermilab design with quartz radiator mounted on Photek PMT240 MCP, Ortec 9327 readout.
Studying various radiators.
System (BC-scintillator) resolutions of 80 - 120 ps (σ) obtained.

SiPM (Rutgers + TAU)

Used with Beam RF signal for PID and triggering and with SPS for muon decay rejection. Helps deal with multiplicity in GEMs. Timing to better than 100ps achieved.



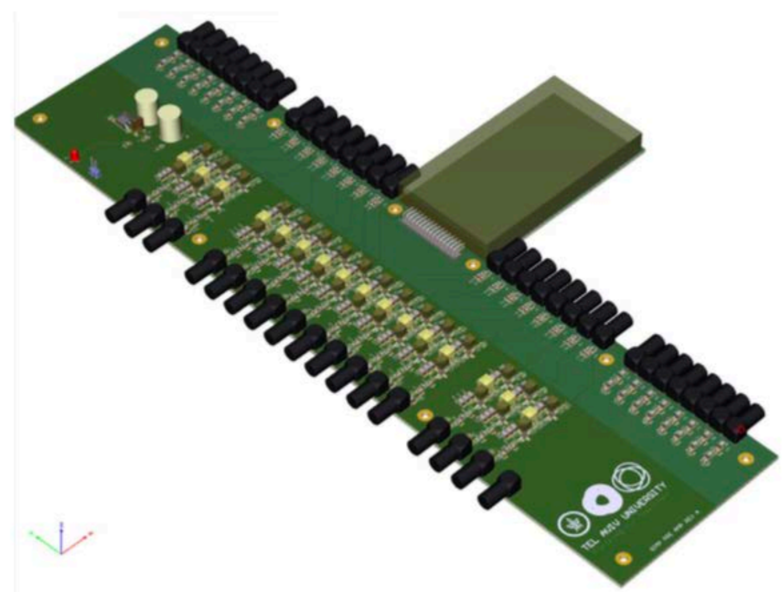
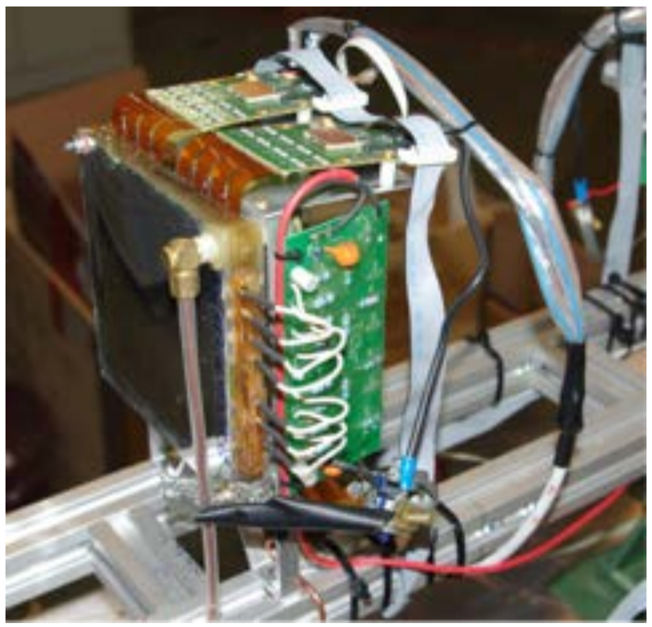


TABLE VI. Beam hodoscope detector requirements

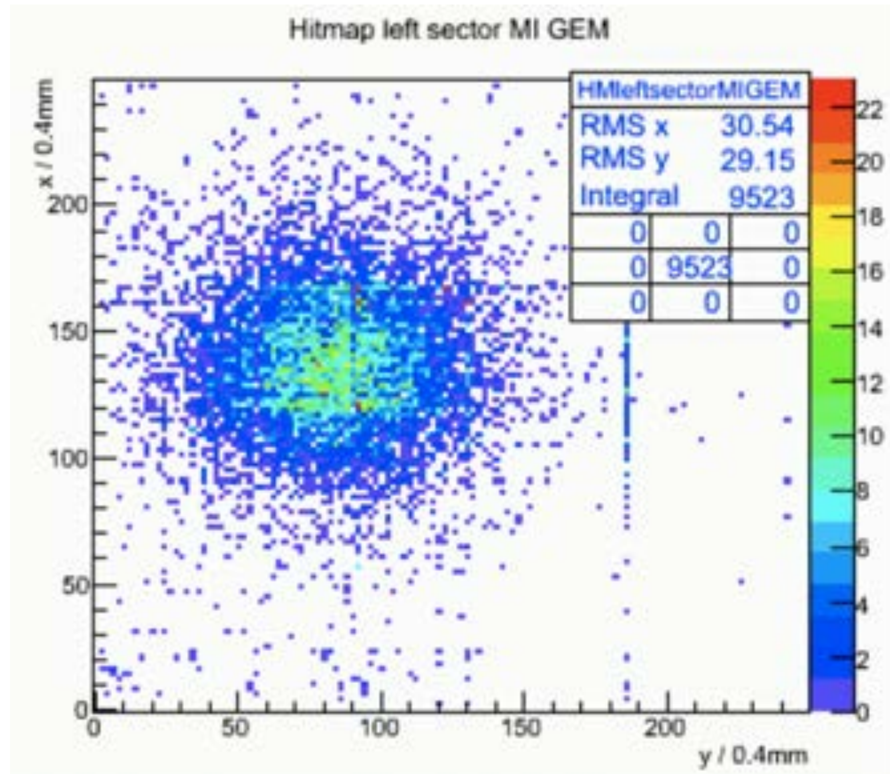
Parameter	Performance Requirement	Achieved
Time Resolution	<100 ps / plane	✓ 80 ps
Efficiency	99%	✓ 99.8%
Positioning	≈1 mm, ≈1 mr	not attempted; easy – calibrated by data
Rate Capability	3.3 MHz / plane	✓ >10 MHz / plane

GEMs (HU)

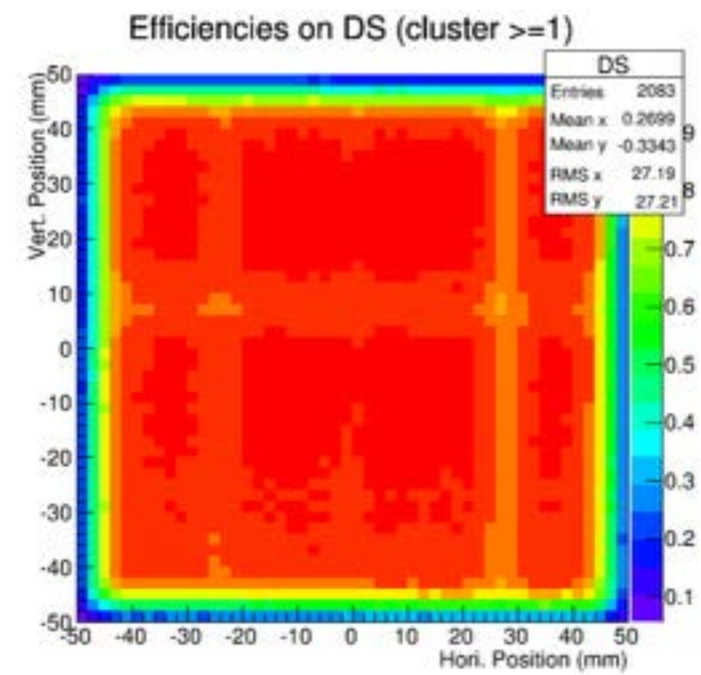
Used to track beam particles into the target



Existing GEM in MUSE test



Beam distribution measured by GEM

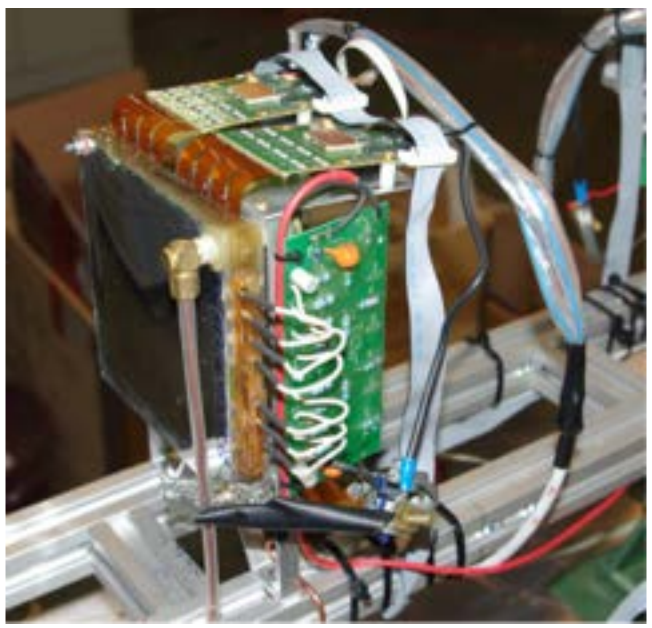


Measured efficiency map of a GEM

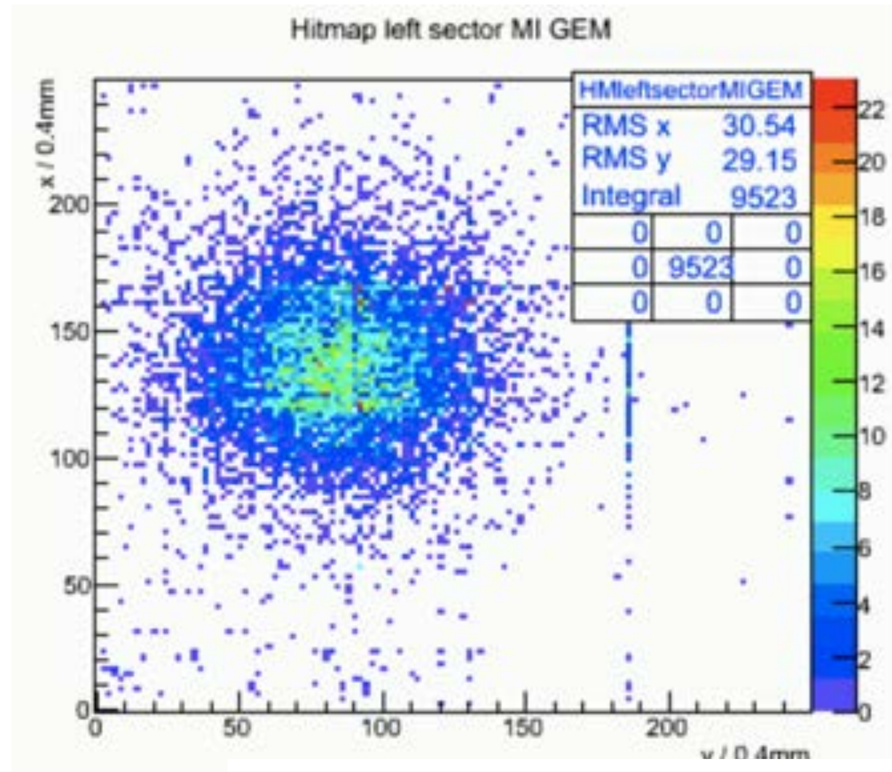
Using pre-existing OLYMPUS GEMs.
Upgrading DAQ rate capability.
(About 1 ms readout at OLYMPUS.)

GEMs (HU)

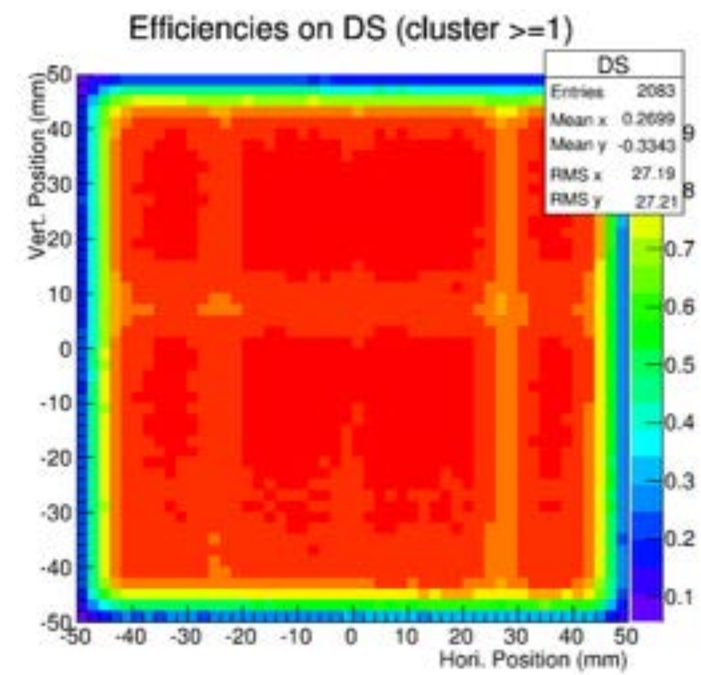
Used to track beam particles into the target



Existing GEM in MUSE test



Be
me



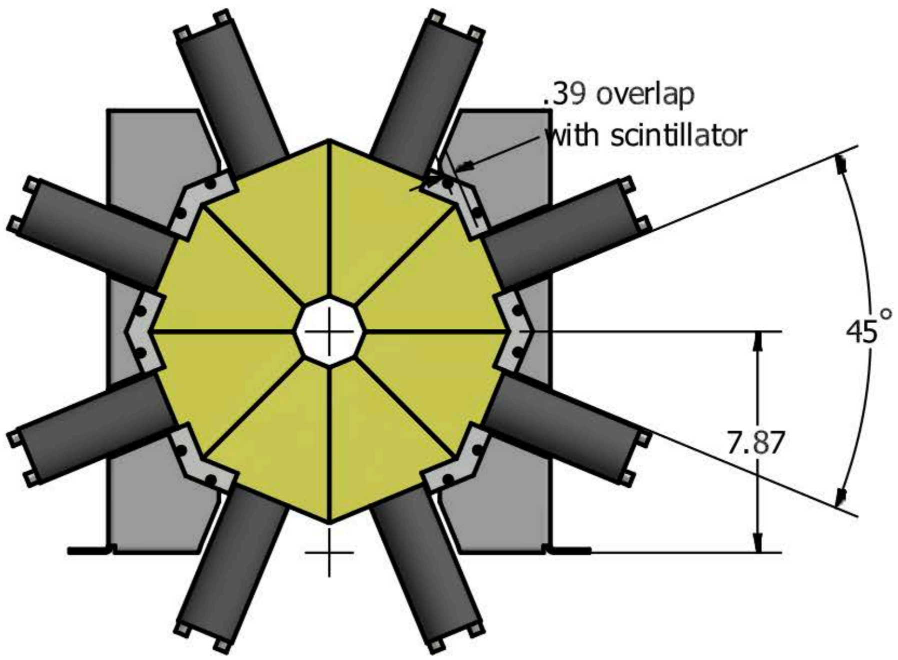
Using pre-existing OLYMPU
Upgrading DAQ rate capab
(About 1 ms readout at OL

TABLE VII. GEM detector requirements

Parameter	Performance Requirement	Achieved
Resolution	100 μm / element	✓ 70 μm
Efficiency	98%	✓ 98%
Positioning	≈0.1 mm, ≈0.2 mr	not attempted; easy
Rate Capability	3.3 MHz / plane	✓ 5 MHz
Readout Speed	2 kHz / 20% deadtime	1 kHz / 100% deadtime

Veto detector (USC)

Reduce trigger rate by vetoing scattering or beam particle decay events upstream of the target.



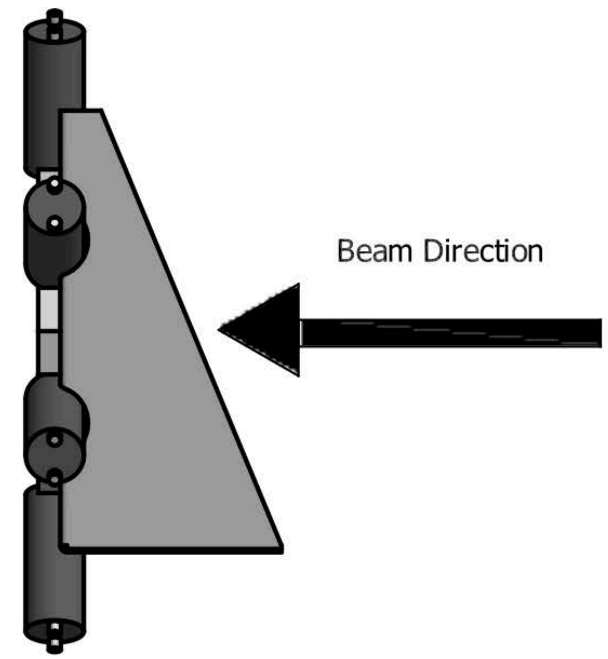


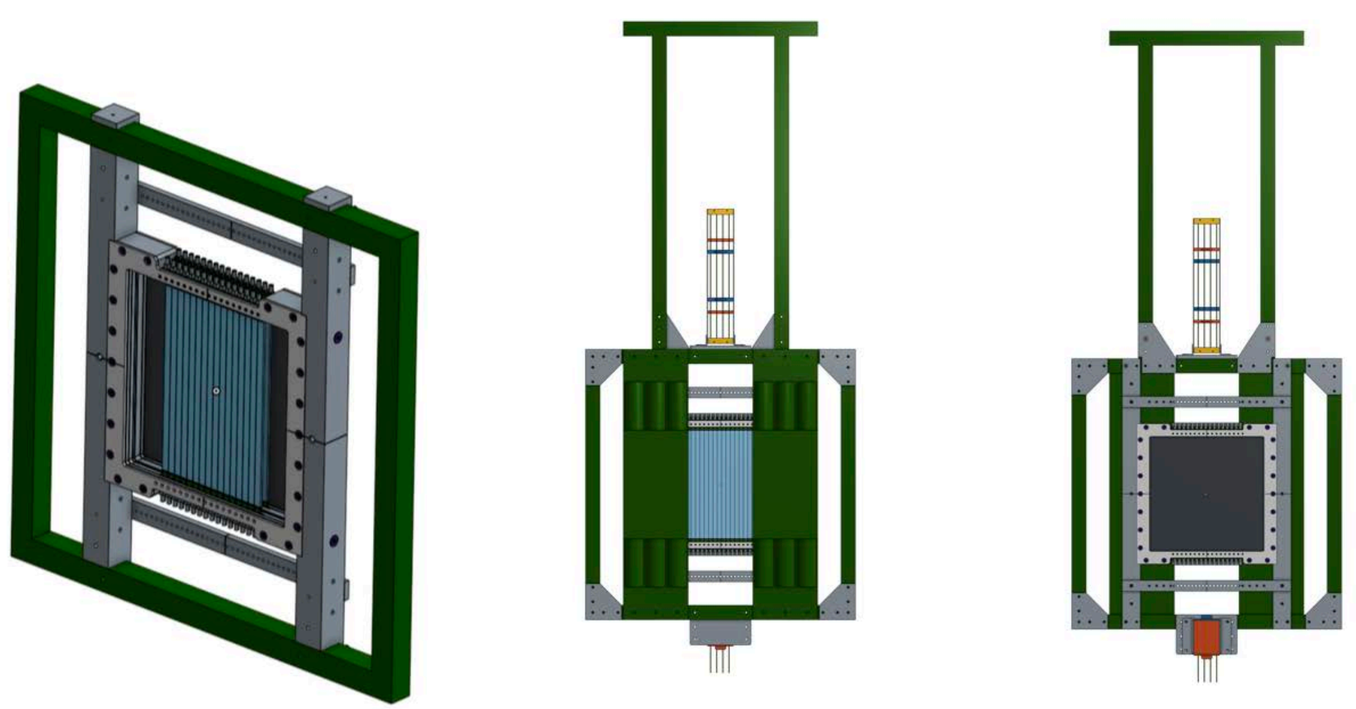
TABLE VIII. Beam veto detector requirements

Parameter	Performance Requirement	Achieved
Time Resolution	1 ns / plane	not attempted; easy
Efficiency	99%	not attempted; easy
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	1 MHz / plane	not attempted; easy

Beam monitor (Rutgers)

provides a high-precision particle time measurement and a flux determination of beam particles downstream of the target. For scattered particle events, it provides a determination of the time and particle type of randomly coincident unscattered particles, to monitor beam stability.

For Moller / Bhabha scattering events that generate triggers, the beam monitor detects the forward-going, high-momentum electron / positron.



Target (UMich + Creare)

The MUSE experiment requires a liquid hydrogen target of very stable density, and sufficient cooling power to minimize uncertainty in target length. The target will also be used for tracking tests and background subtraction measurements, which require multiple targets in addition to the full liquid hydrogen cell.

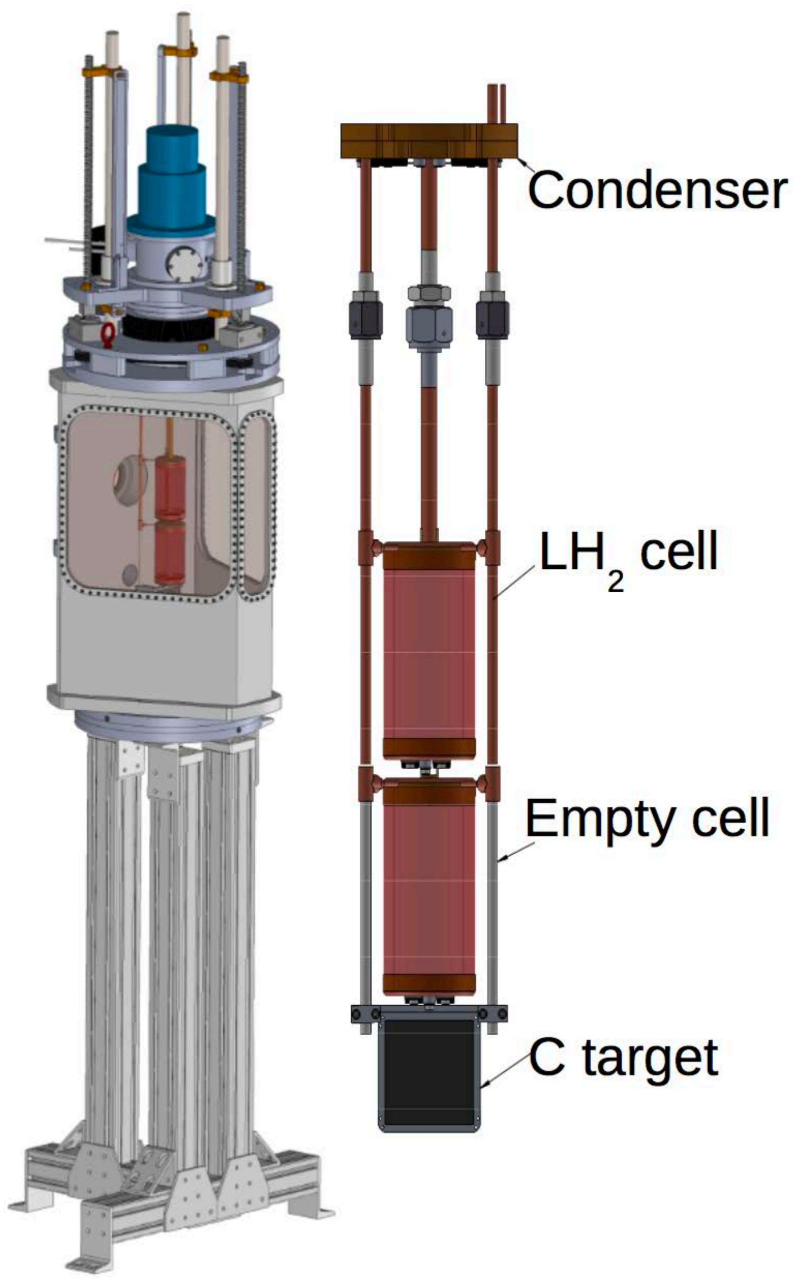


TABLE IX. Target system requirements.

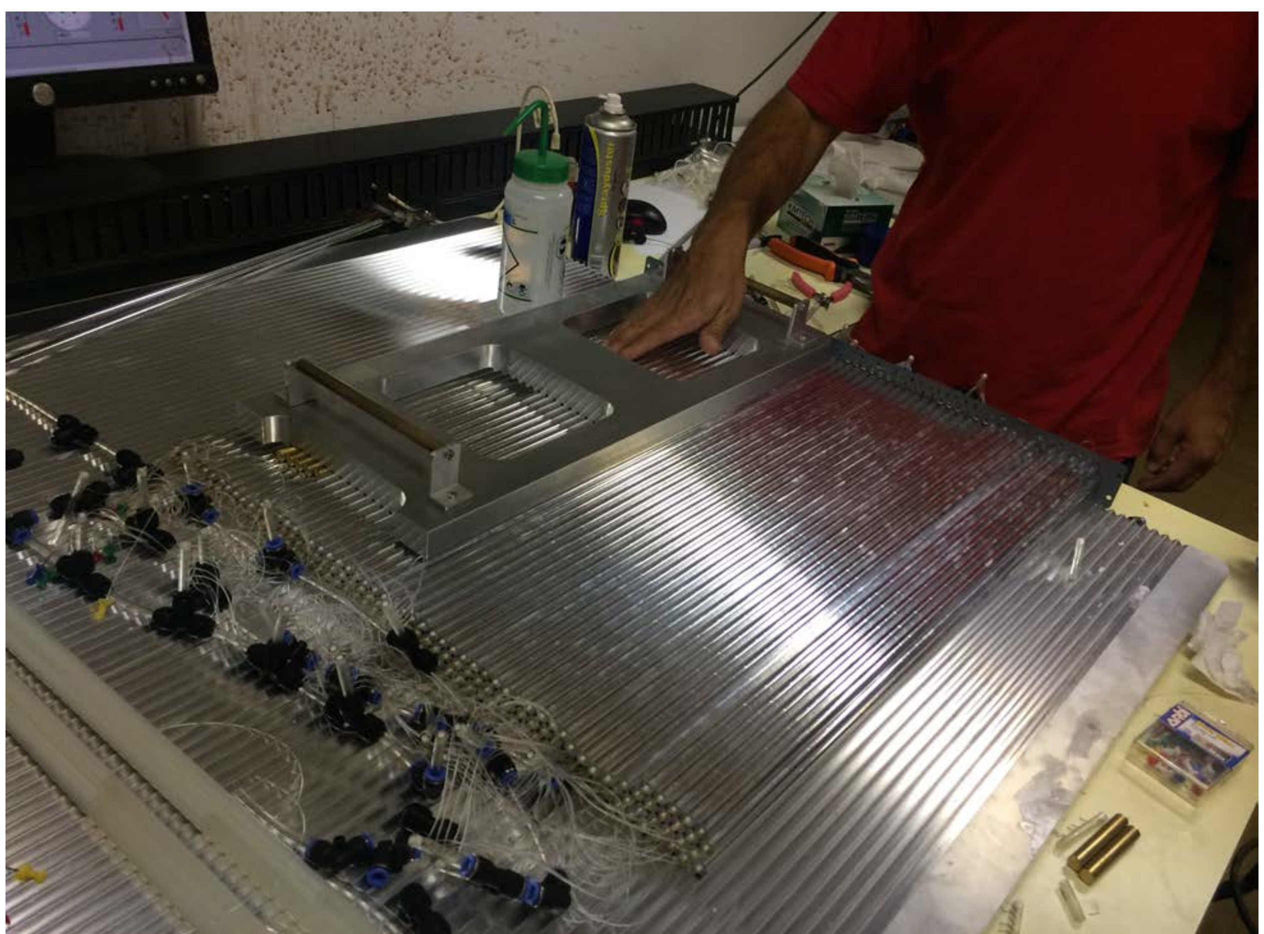
Parameter	Performance Requirement	Achieved?
Liquid hydrogen	maintain liquid hydrogen-filled cell at T≈19 k and P≥1 atm	not attempted; moderate
Cool down time	< 3 days	not attempted; moderate
Beam entrance window	>6 cm	not attempted; easy
Exit window(s) (One continuous or two symmetric on beam left and beam right)	$20^\circ < \theta < 100^\circ$; $\phi = 0^\circ \pm 45^\circ$ at $\theta = 60^\circ$ beam up-down and beam left-right symmetry	prototyping underway; challenging

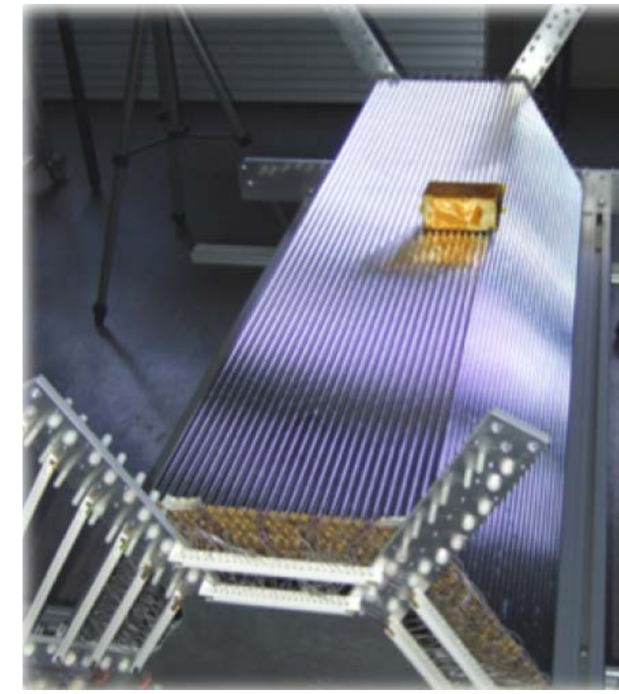
Straw Tube Tracker (HUJI + Temple)

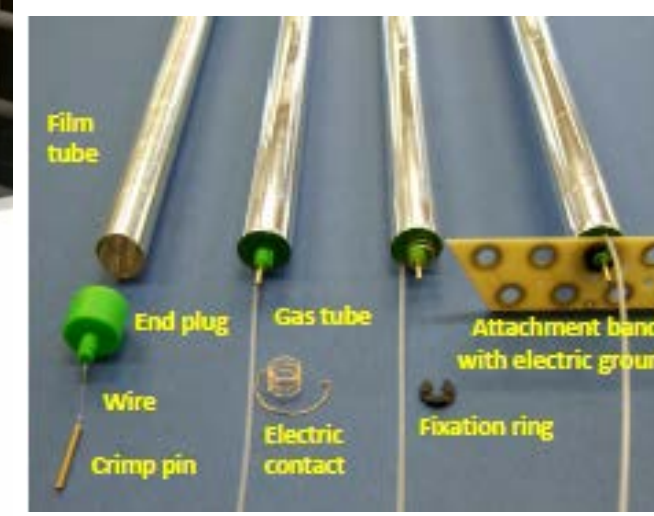
- Resolution on the order of ~1 mr for scattered particles
- Sustain rates of ~a few kHz/cm.
- Very low material budget.
- Design based on PANDA Straw Tube Tracker.
- Low materials straws over pressured (2 bar absolute) for rigidity.
- 5X/5Y planes per chamber.
- Readout using standard TRB3/PADIWA.

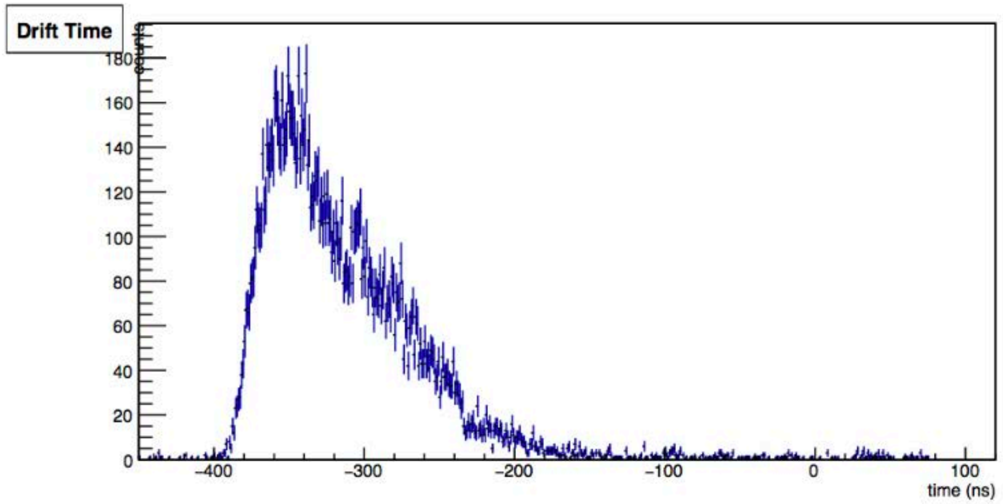
- Close packed straws, w/ minimal gaps.
- ~30 um thick straws -> low material budget.
- 90/10 Ar/CO_2

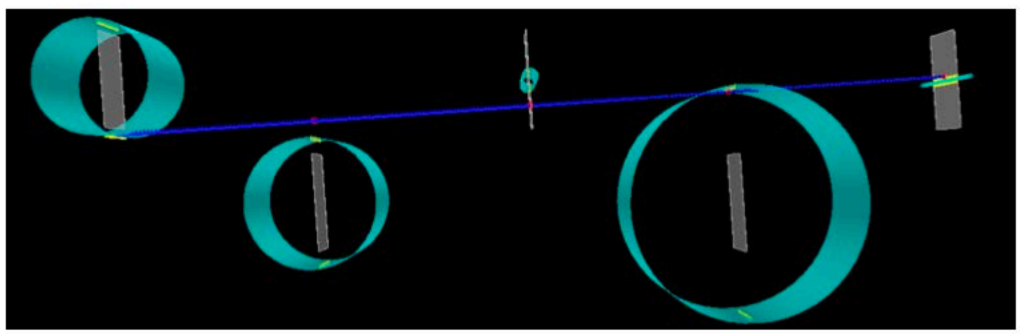
Element	Material	X[mm]	X_0 [cm]	X/X_0
Film Tube	Mylar, 27 μm	0.085	28.7	3.0×10^{-4}
Coating	Al, $2\times0.03\,\mu m$	2×10^{-4}	8.9	2.2×10^{-6}
Gas	$Ar/CO_2(10\,\%)$	7.85	6131	1.3×10^{-4}
Wire	W/Re, 20 μm	3×10^{-5}	0.35	8.6×10^{-6}
			$\sum_{straw}$	4.4×10^{-4}

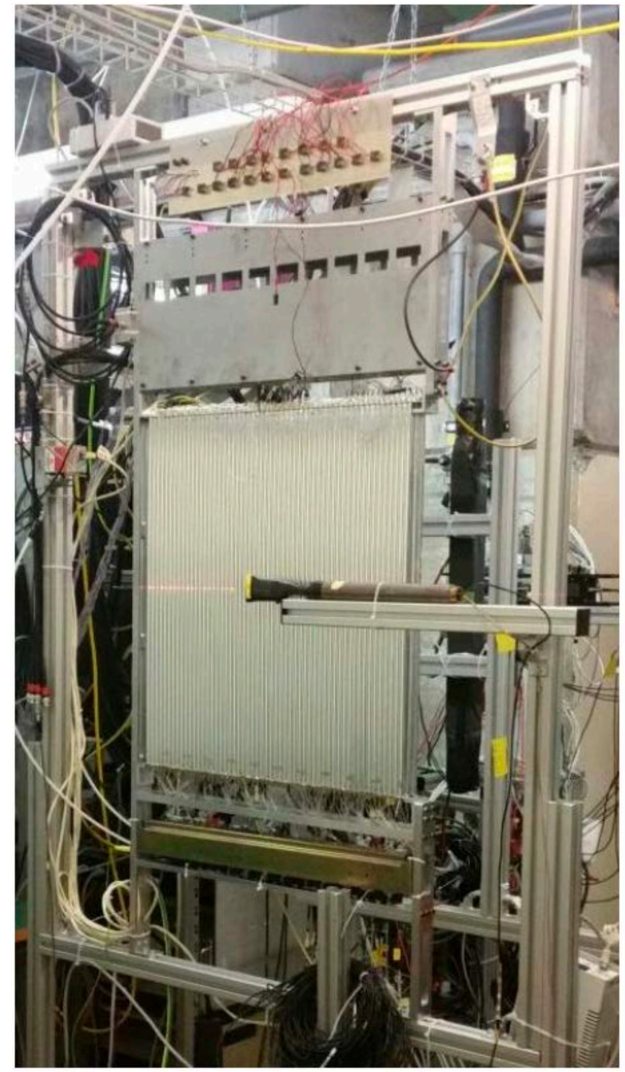


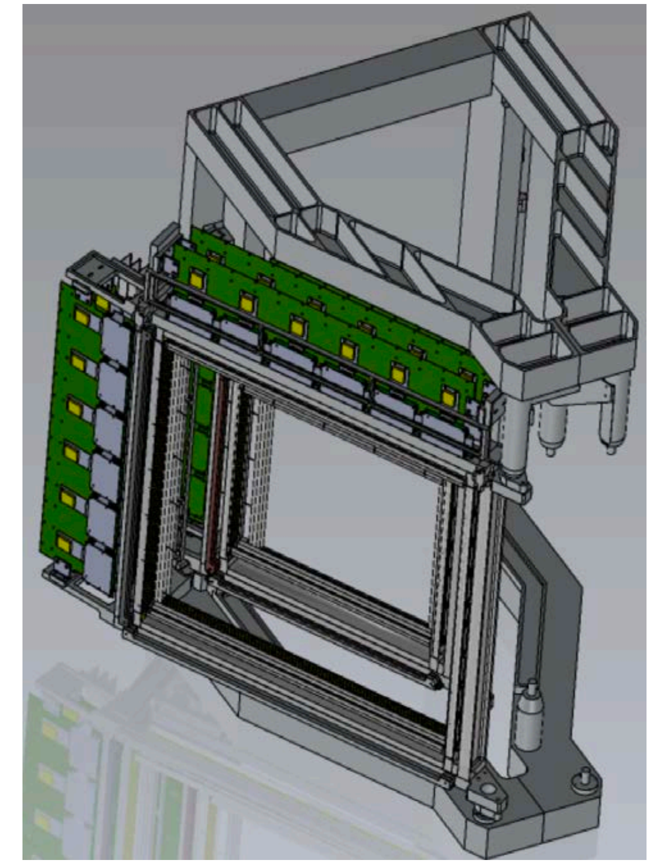












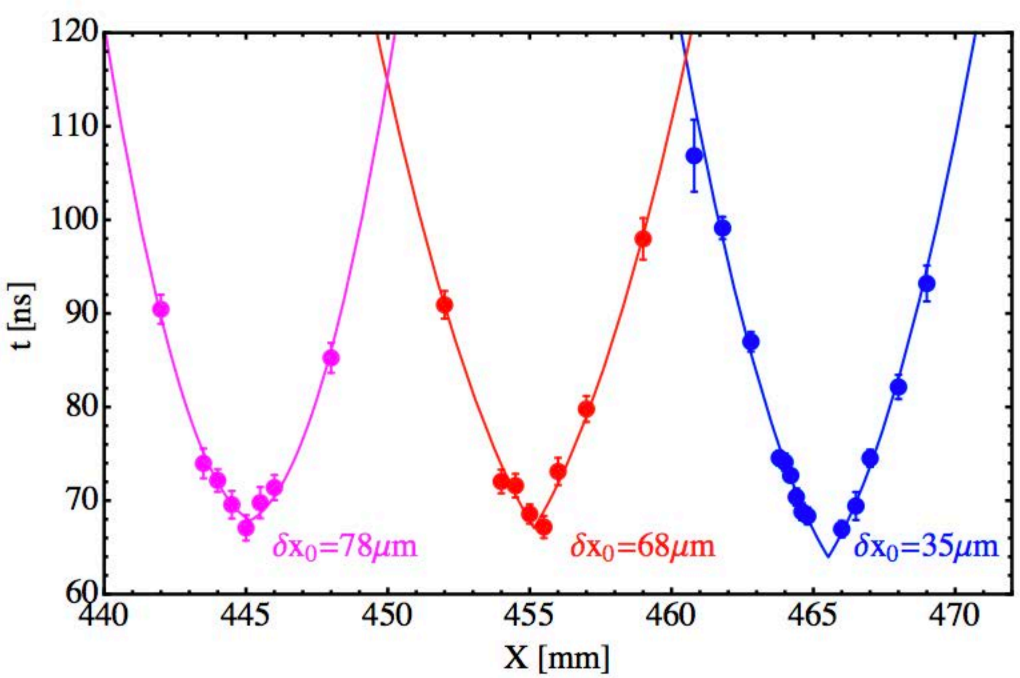
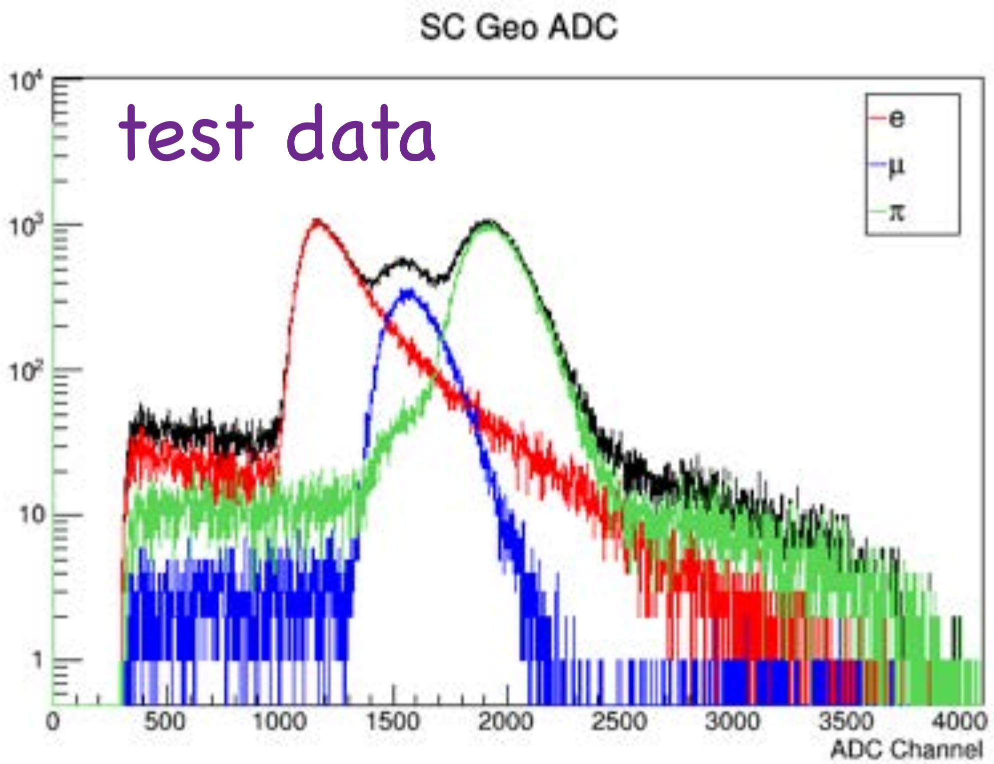


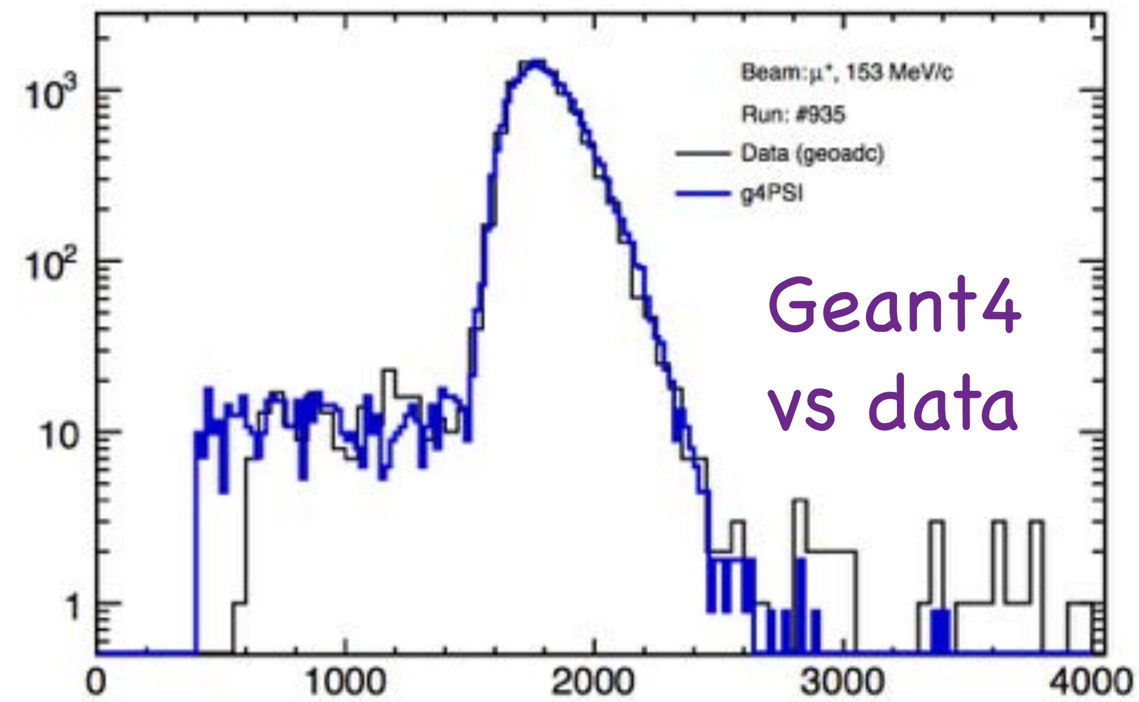
TABLE X. Straw Tube Tracker requirements

Parameter	Performance Requirement	Achieved
Position Resolution	150 μm	✓ <120 μm
Efficiency	99.8% tracking	≈ 99% in prototype; moderate
Positioning	≈0.1 mm, 0.2 mr in θ	not attempted; moderate
Positioning	≈0.5 mr pitch, yaw, roll	not attempted; moderate
Positioning	50 μm wire spacing	✓ 35μm achieved in dress rehearsal
Rate Capability	0.5 MHz	not attempted; easy

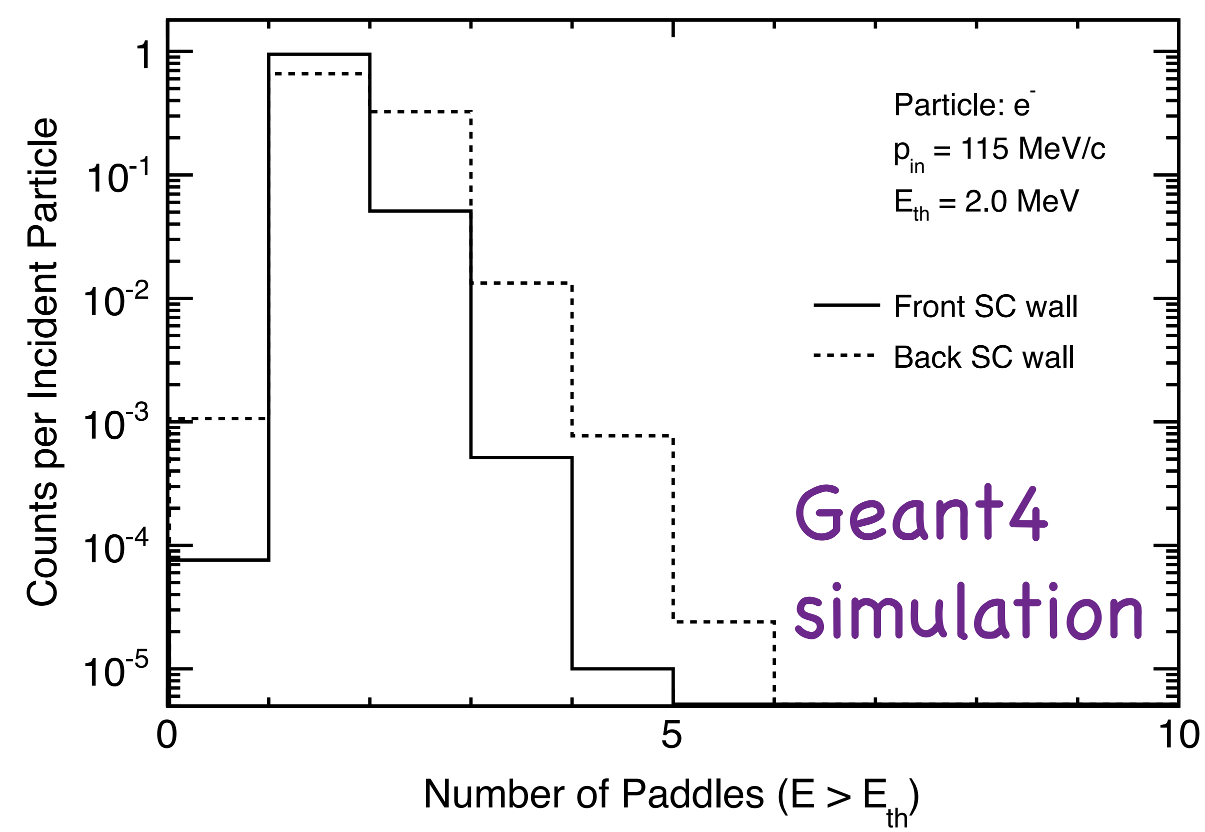
Scintillators (SC)

Used to detect scattered particles, time then, trigger with them





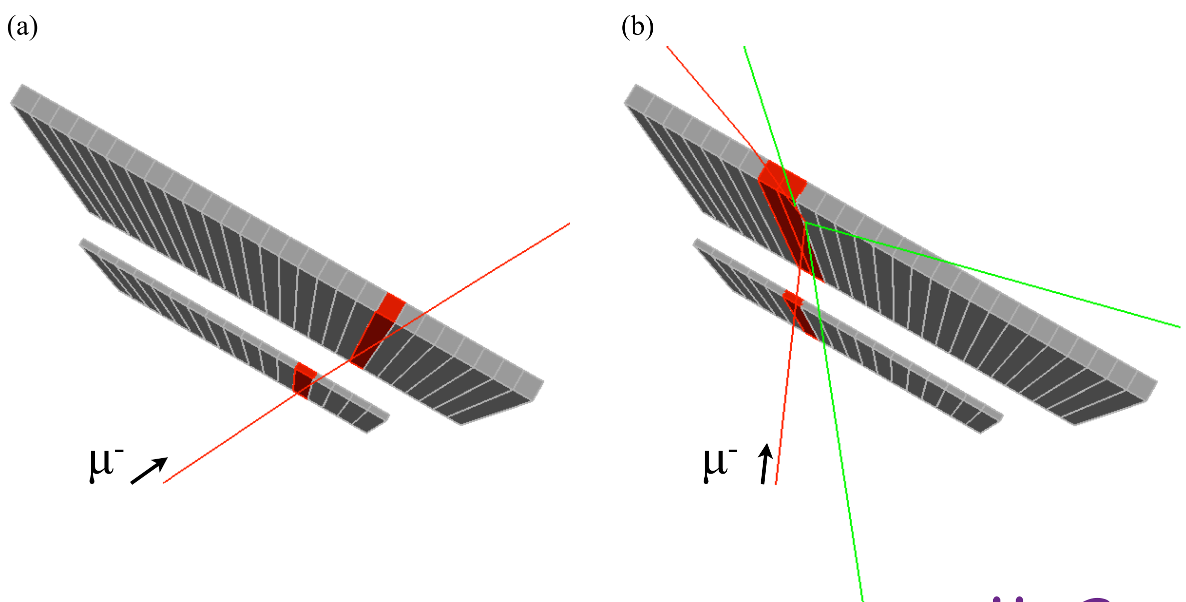
Particles lose several MeV on average in thick scintillator paddles. Low energy tail from particles that hit, but quickly scatter out of a paddle - which generally give large energy in neighboring paddle.

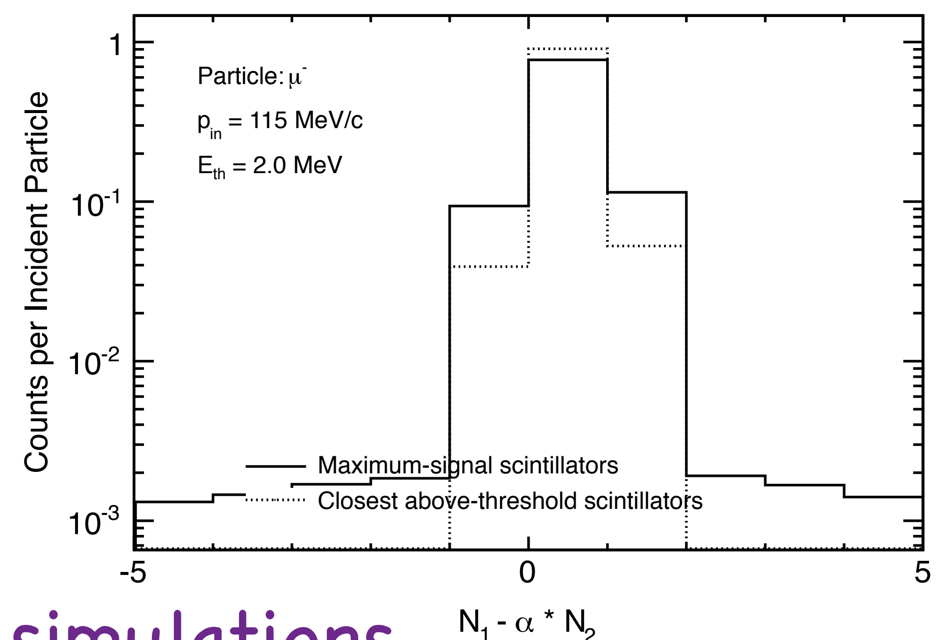


Scintillators (SC)

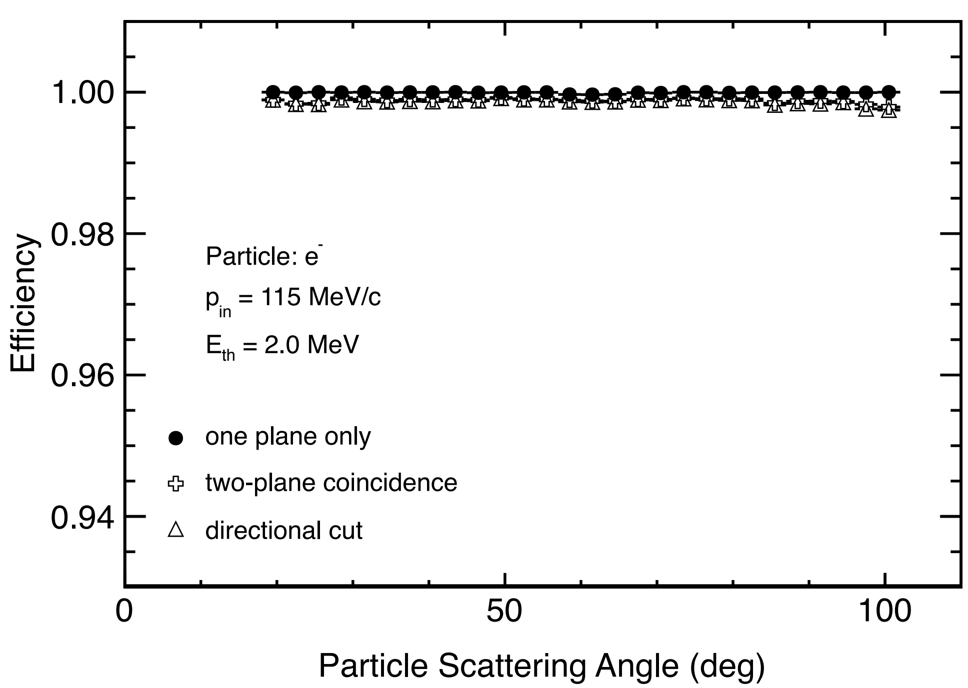
Individual paddles highly efficient

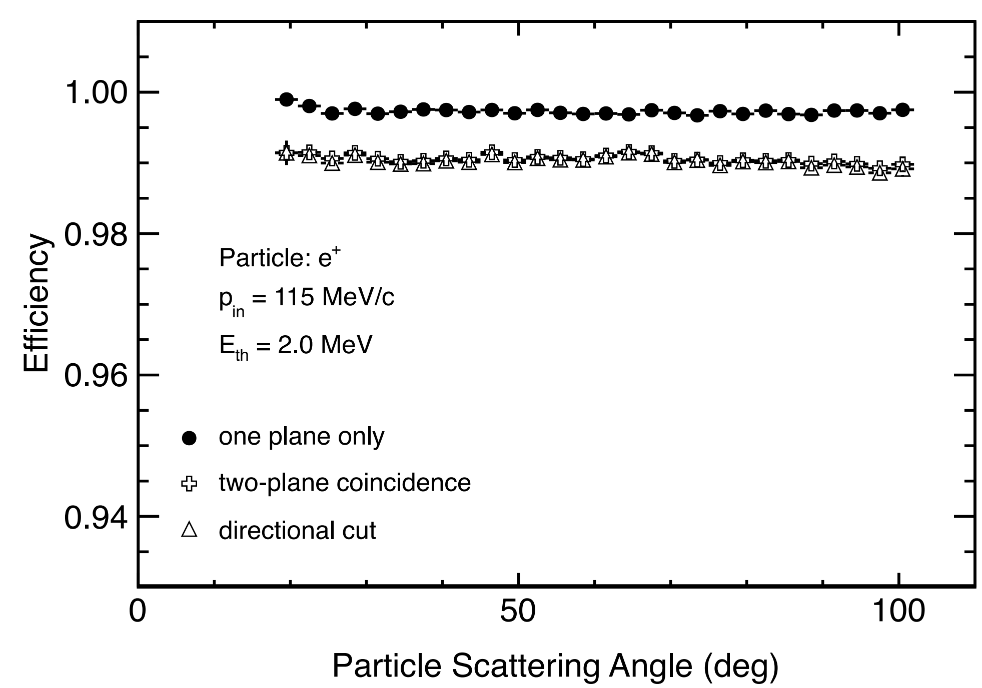
Two issues - two plane triggering, and e^+ annihilation





all Geant4 simulations





Efficiencies have been generated for all particles and beam momenta.

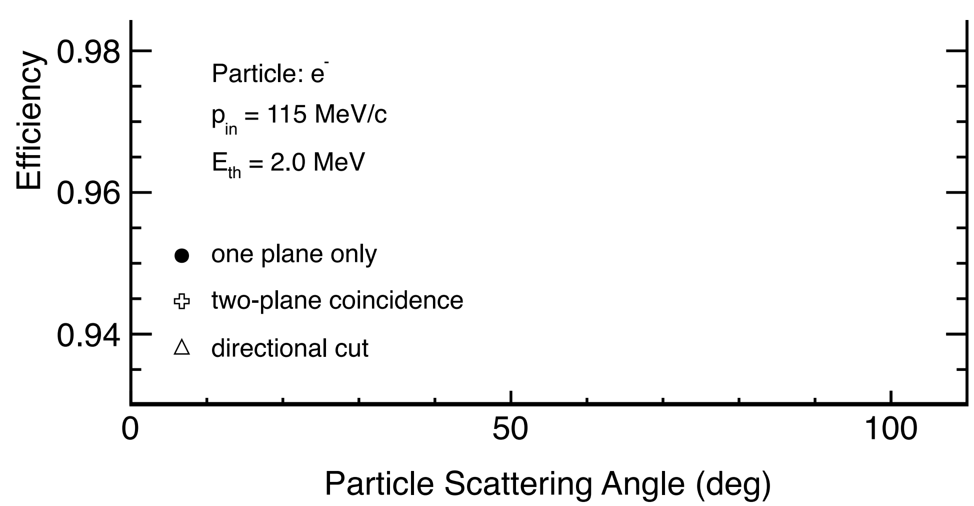
Scintillators (SC)

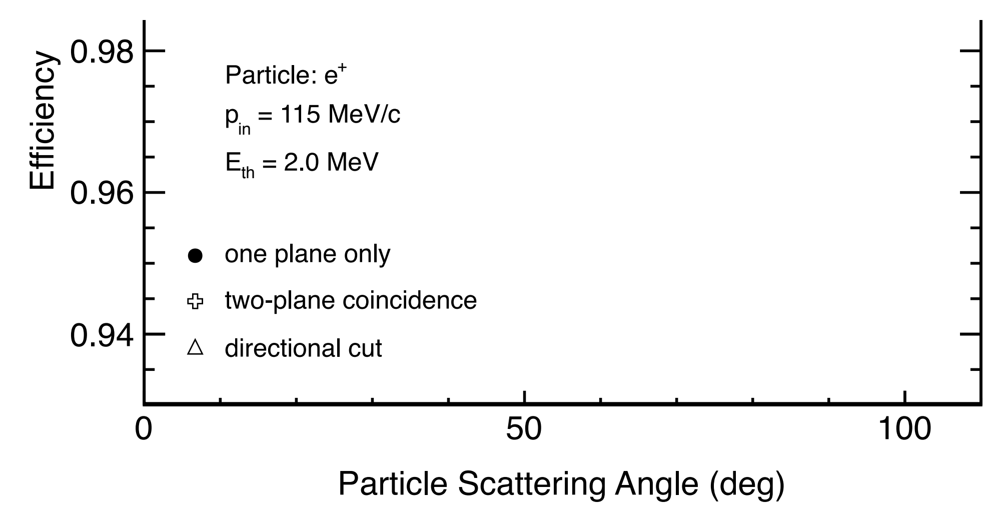
Individual paddles highly efficient

Two issues - two plane triggering, and e^+ annihilation

TABLE XII. Scattered-particle scintillation-detector requirements

Parameter	Performance Requirement	Achieved
Time Resolution	≈60 ps / plane	✓ 55 ps
Efficiency	99%, ≪ 1% paddle to paddle uncertainty	✓ 99%, paddle to paddle not attempted, moderate
Positioning	≈1 mm, ≈1 mr	not attempted; easy
Rate Capability	0.5 MHz / paddle	✓ 1 MHz

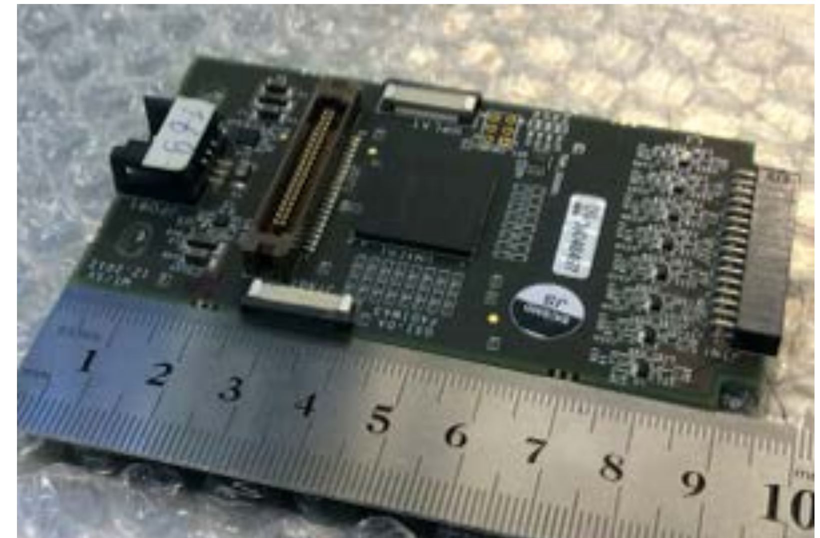




Efficiencies have been generated for all particles and beam momenta.

Electronics (GW)

TRB3 for TDCs:
- around 10 ps resolution
- custom GSI board
- 192 channels/board
- AD with PADIWA level disc



VME QDCs for charge
- Improve level disc timing to CFD level
- MESYTEC - individual channel gates

TRBs include 32-bit scalers

Trigger implemented on TRB FPGAs

DAQ (GWU)

Get fast event data from detectors as well as slow control information.

Discriminators: PASTTREC (STT CFAs+Level discriminators), PADIWA (Level Discriminators), MESYTEC CFDs.

TDCs: TRB3 (GSI Design) - Nominal 10ps resolution, 192 channels/board, gigabit ethernet readout.

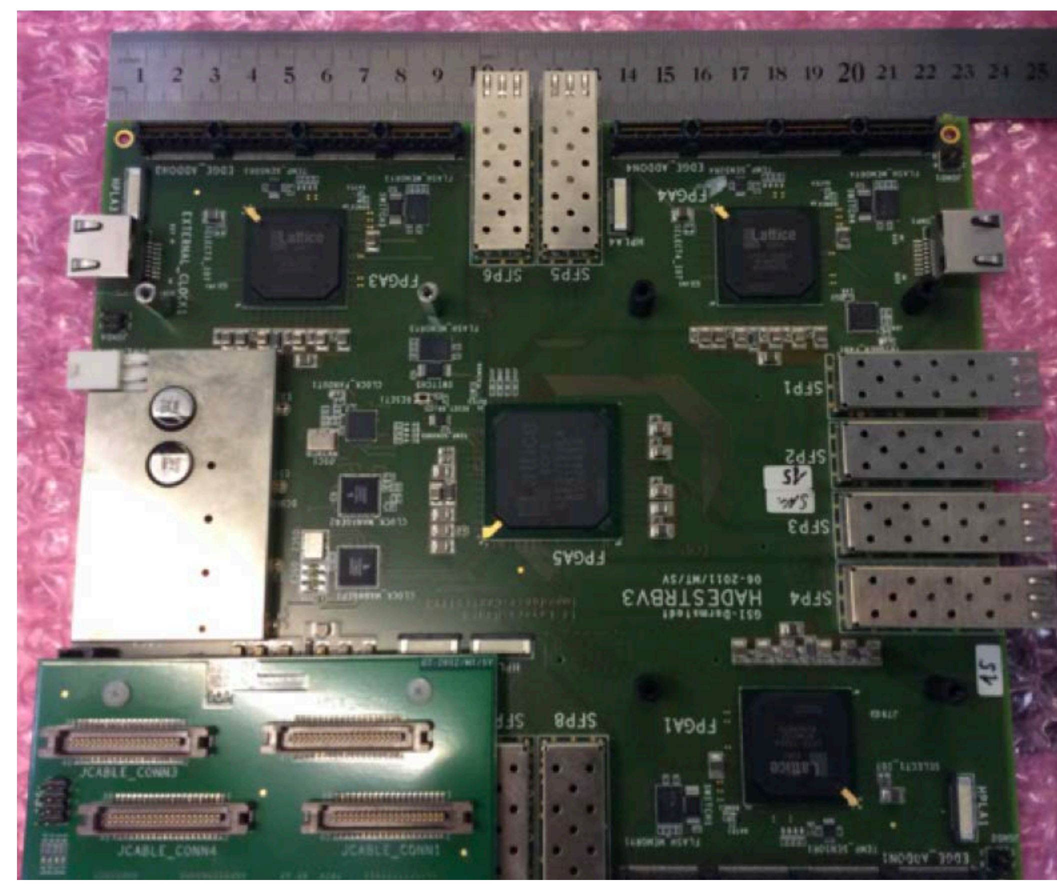
QDCs: MESYTEC MQDC (for SPS).

VME: For QDCs, GEM readout, Trigger distribution.

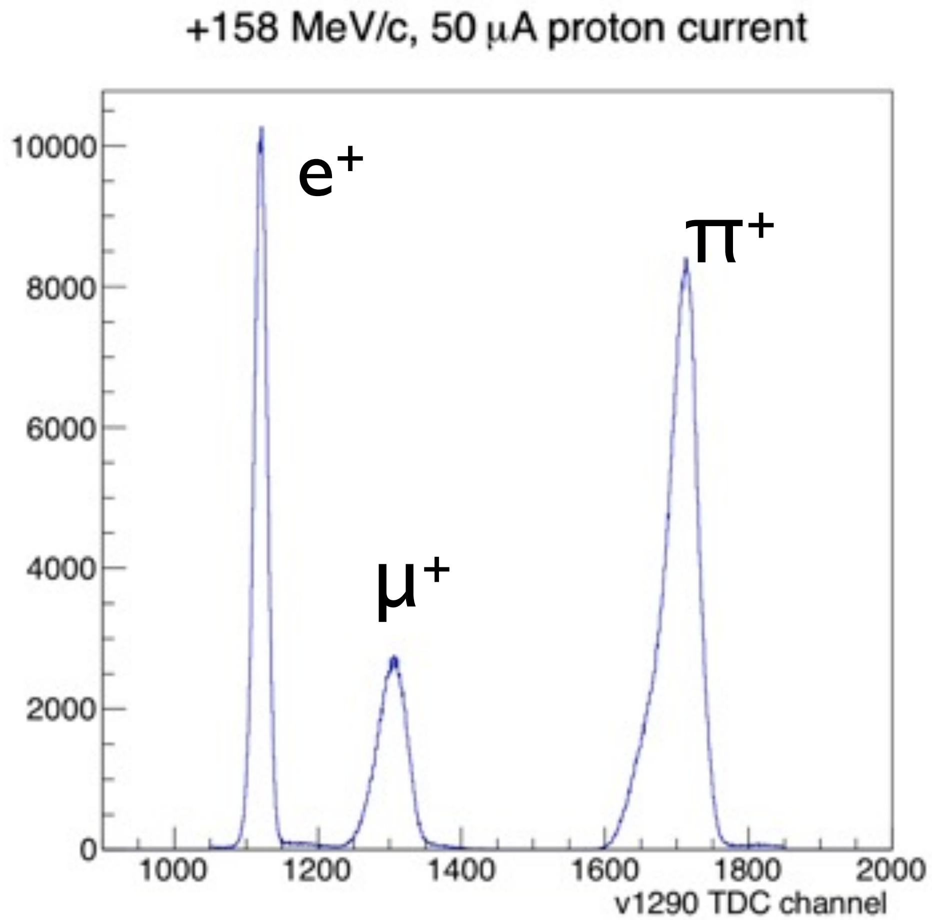
Custom LVDS splitter for logic trigger and QDC gating.

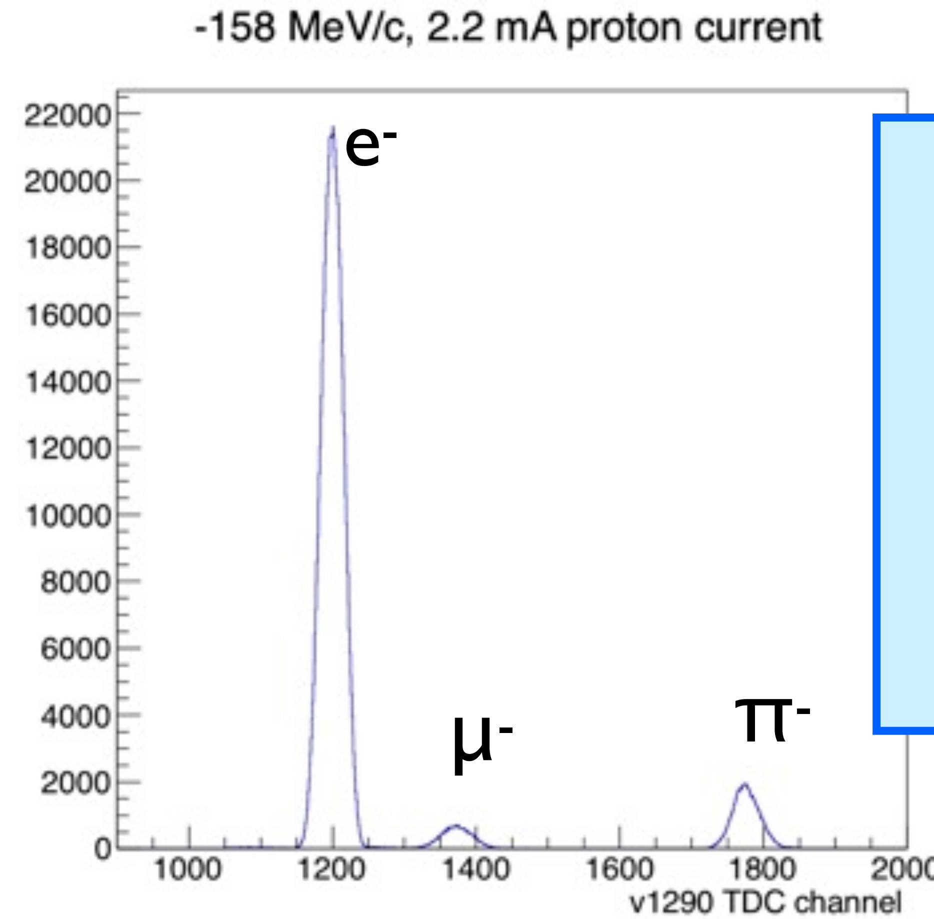
Based on MIDAS DAQ system.

All DAQ components (except PASTTREC) on order.



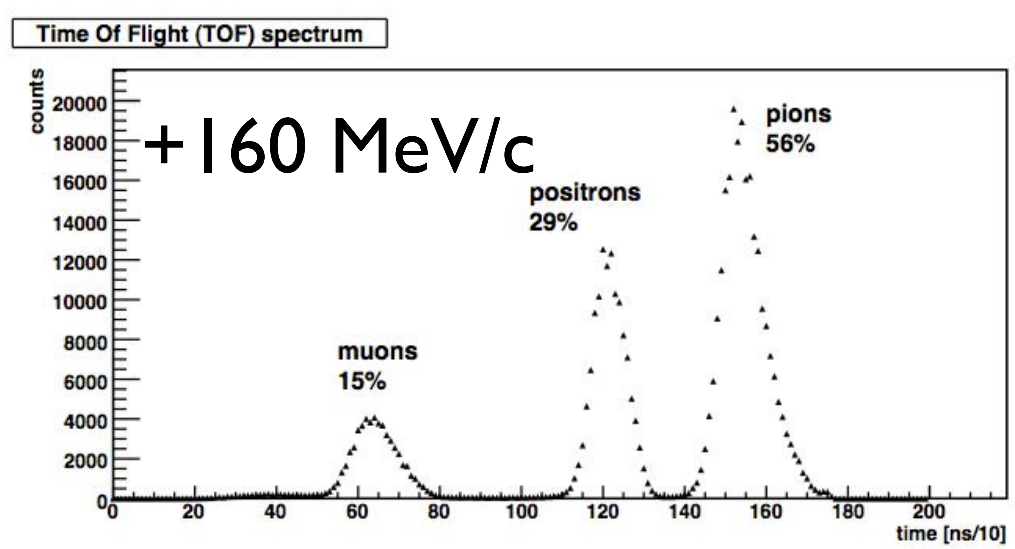
πM1 Channel - RF time in target region





RF peaks broader with 2.2 mA protons, ≈350 ps (σ) for e's and 400 - 500 ps (σ) for μ's and π's

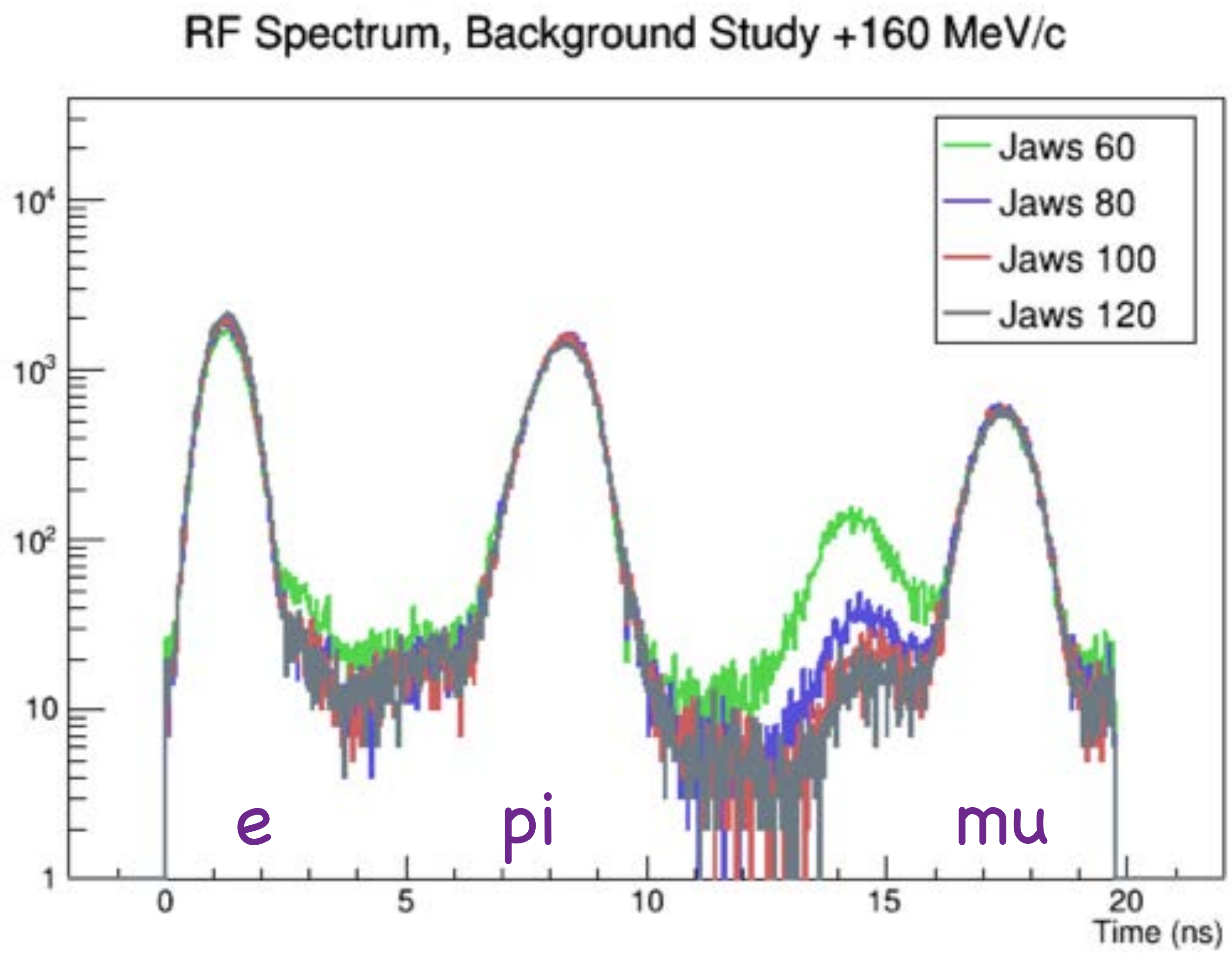
Obtained RF time spectra for several momenta from ≈110 to 225 MeV/c, and used these to determine relative particle fluxes



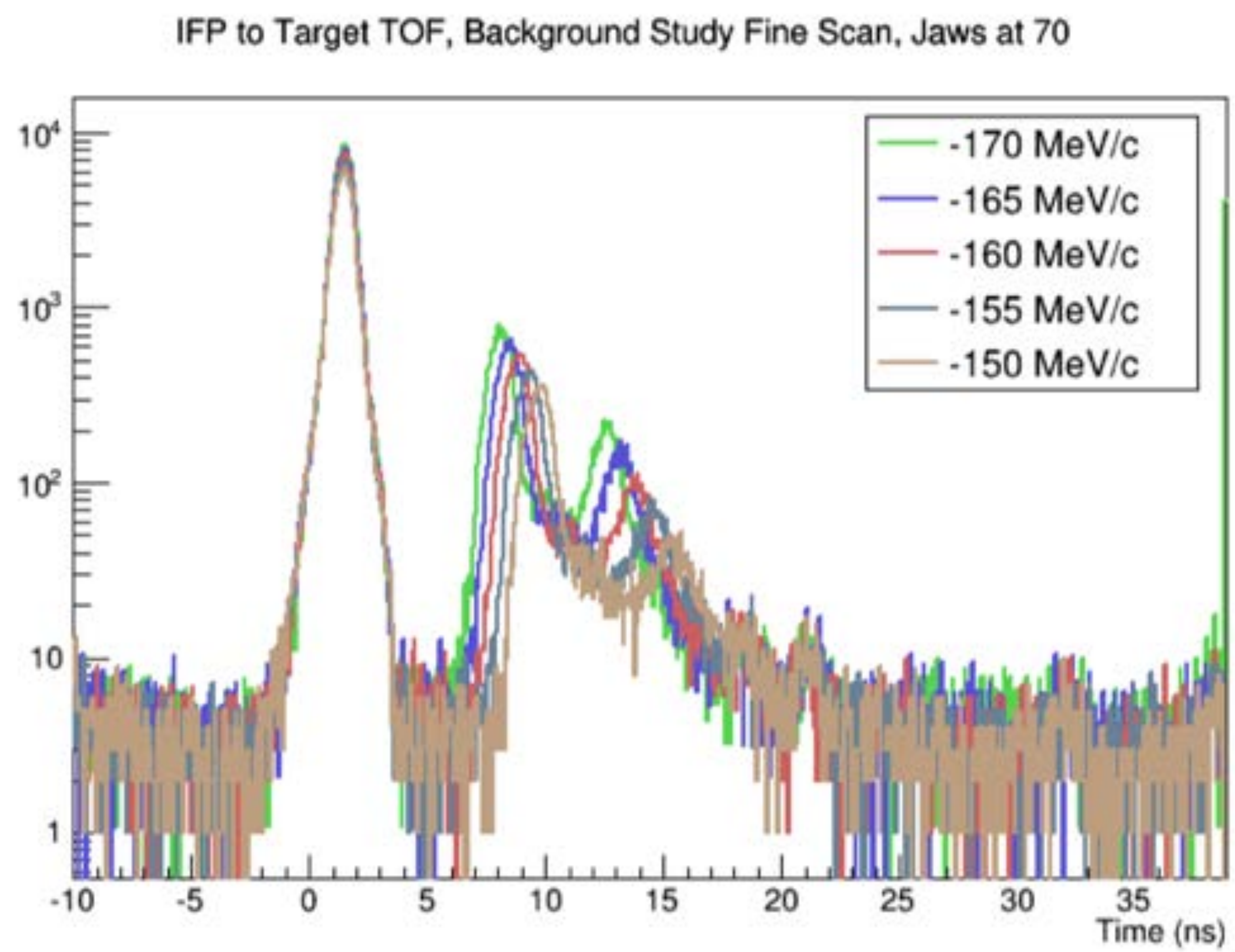
Old spectra, for comparison

Trigger

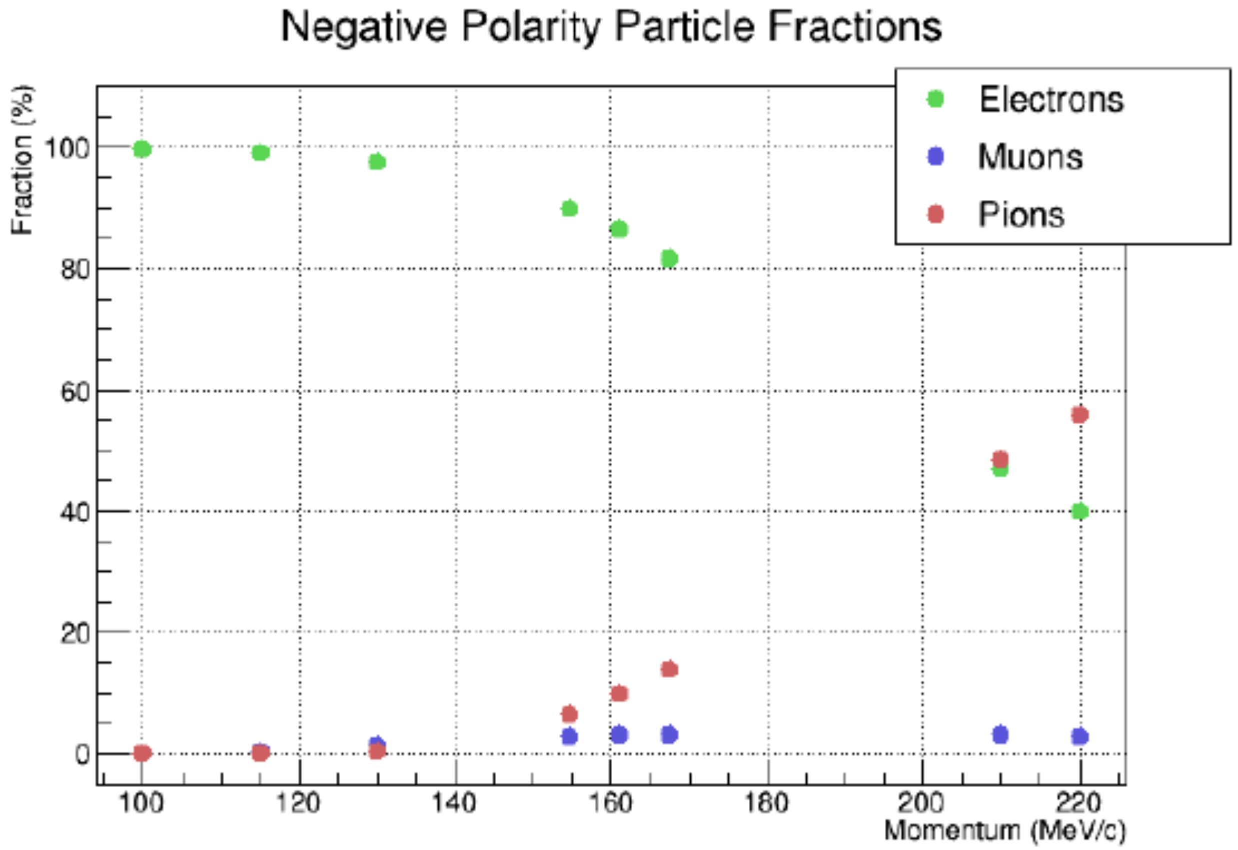
- e or mu beam particle + scattered particle + no veto hits
- Each implemented on TRB3 peripheral FPGAs
- Central FPGA needs to correlate information, include multiple trigger types with pre-scaling, latch, and output trigger and trigger-no-latch

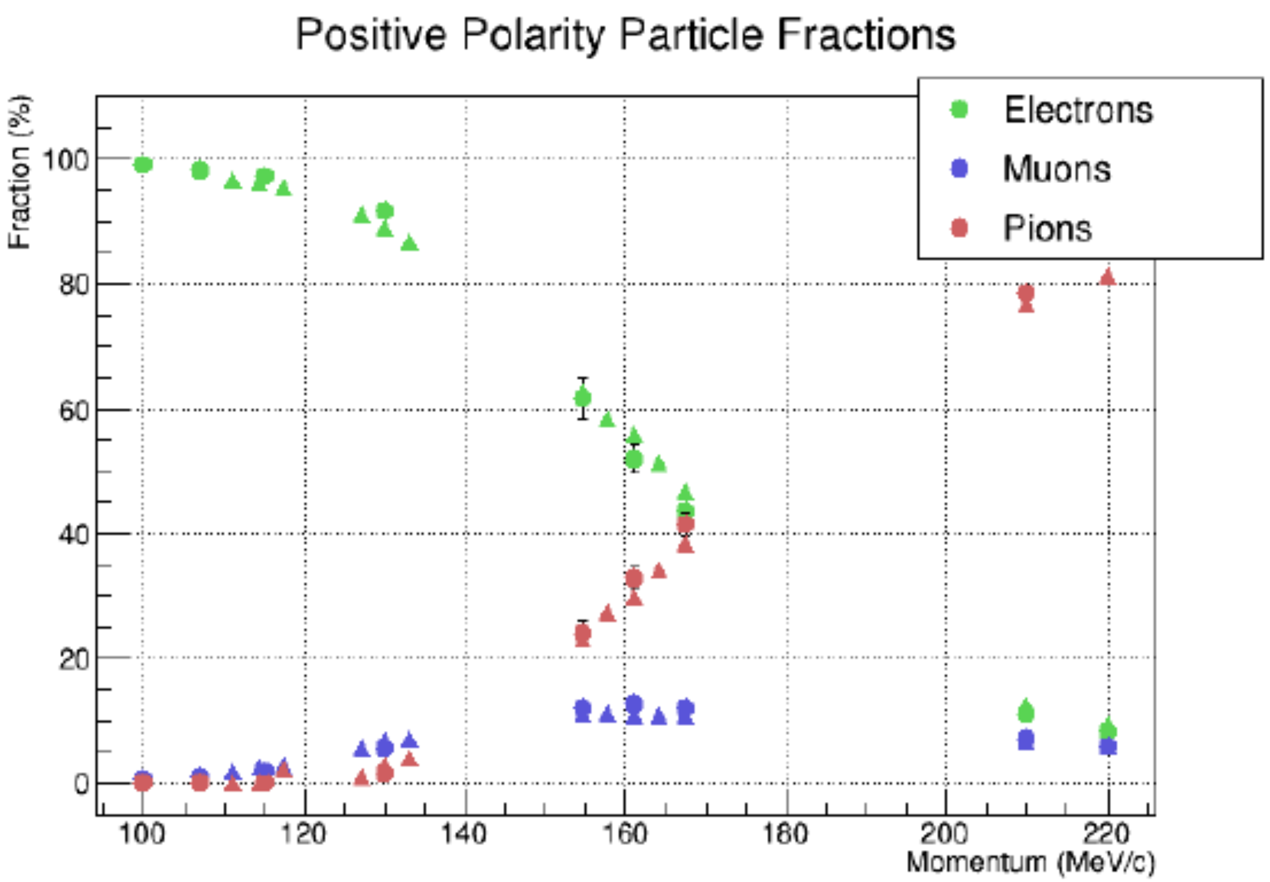


test data

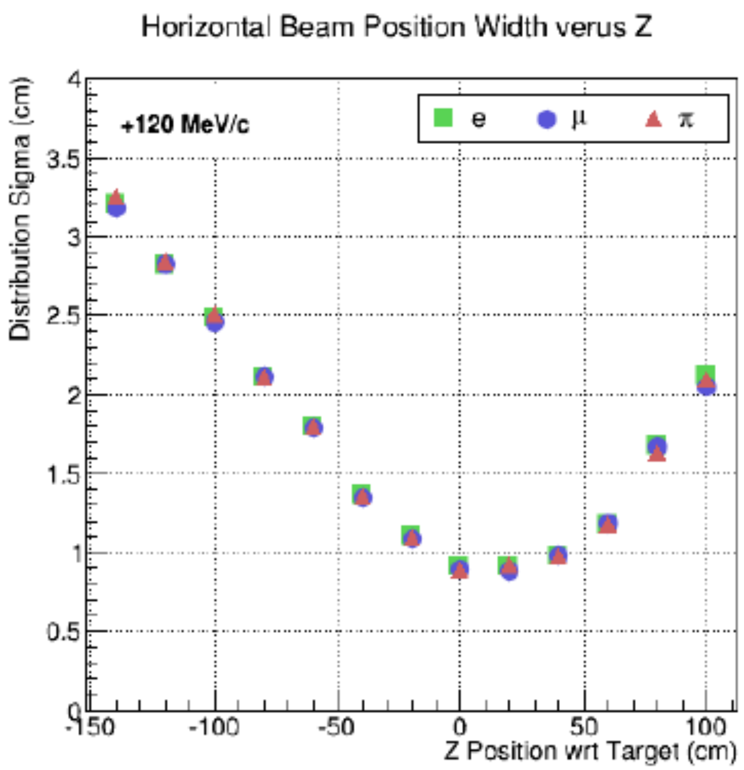


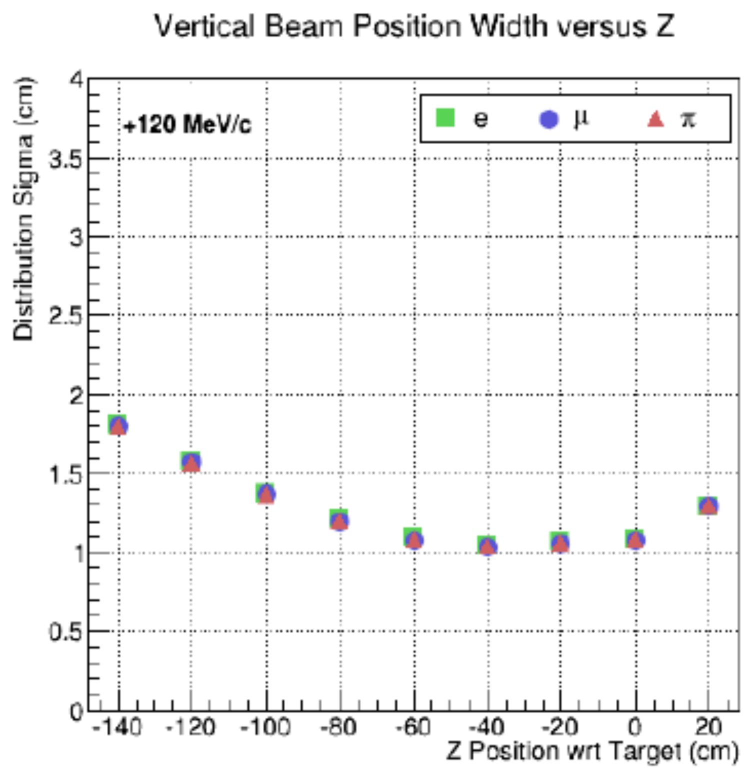
MUSE Test Runs

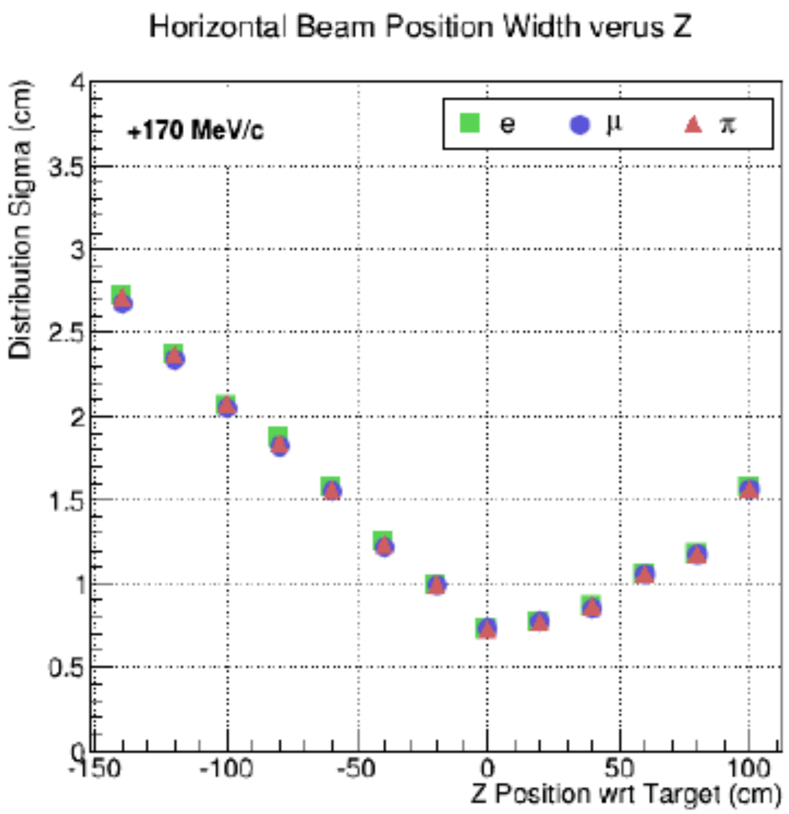


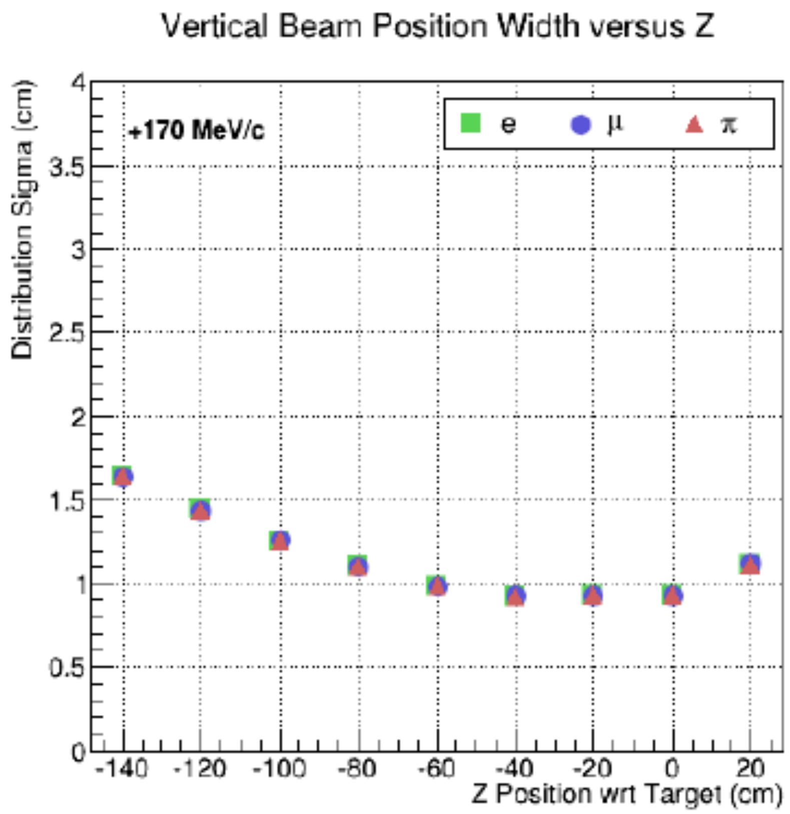


MUSE Test Runs









Experiment Status

PSI:
Approved, but must pass technical review every year to be awarded significant beam time.

NSF:
Funded prototyping and construction.
Application for operations submitted.

BSF:
Funded Israeli manpower for prototyping and construction.
Application for operations submitted.

Note: Ultimately need around 6M for experiment - equipment + people + travel

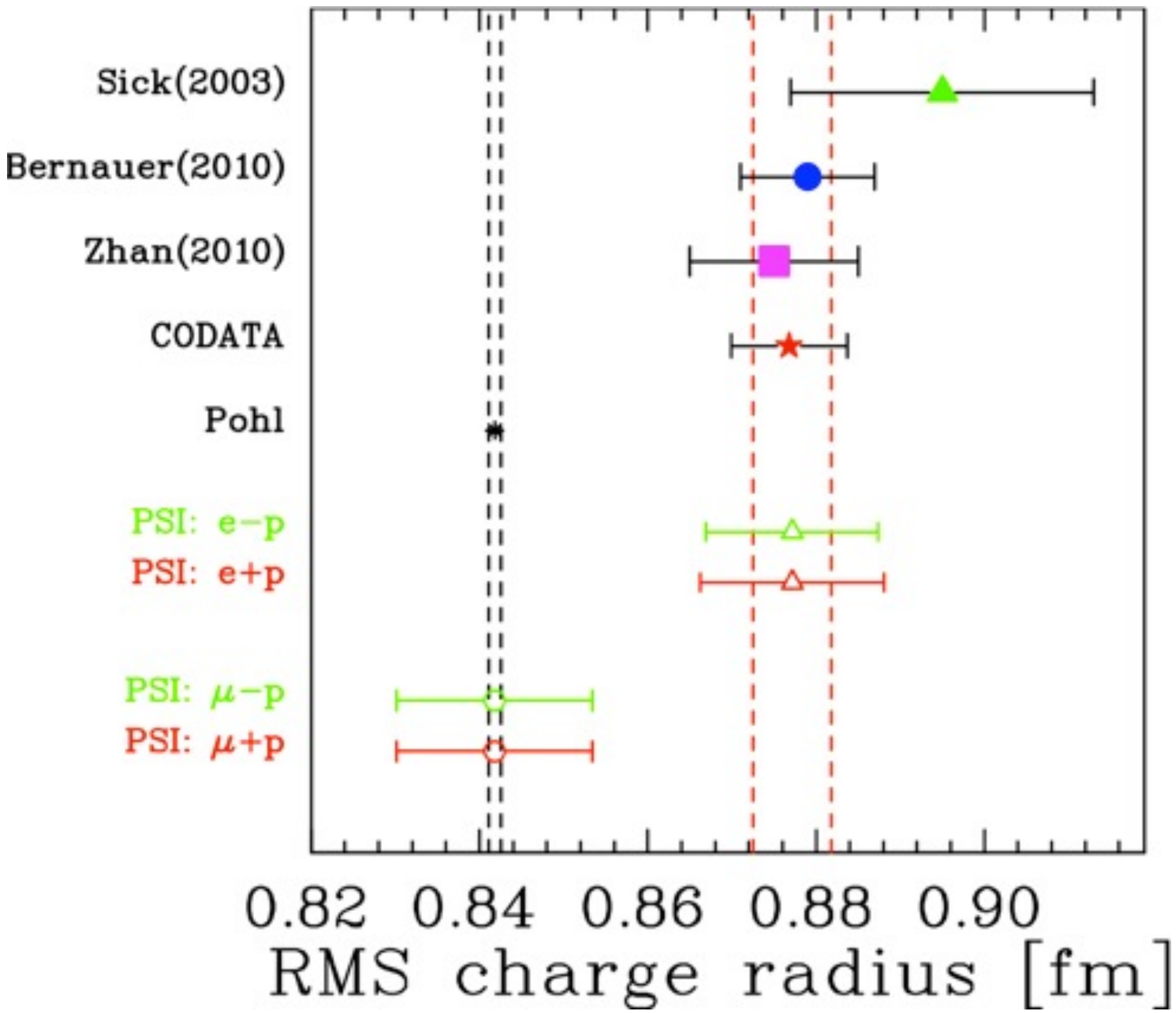
Next Few Years for MUSE (Optimistic)

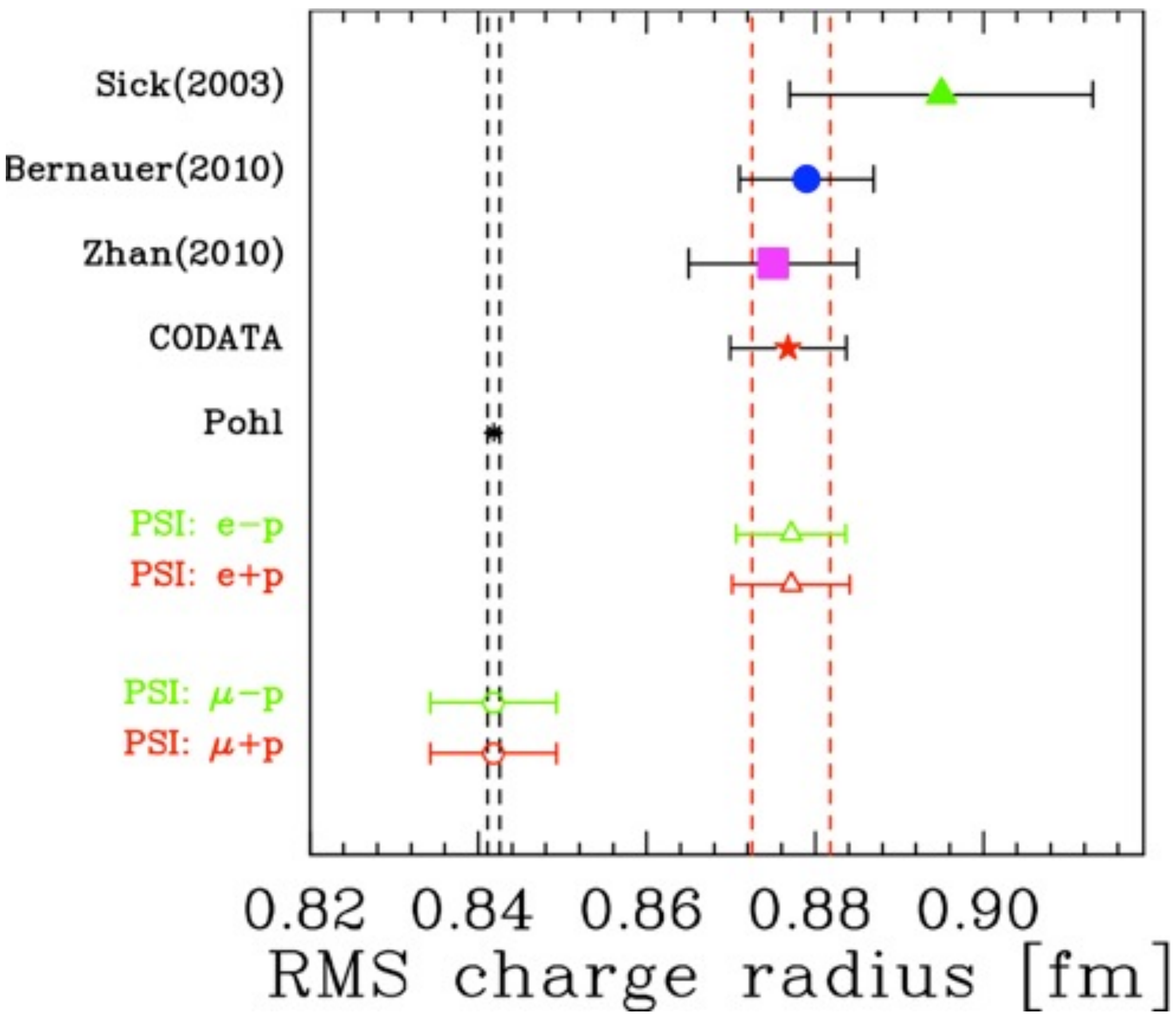
Feb 2012	First PAC presentation
July 2012	PAC/PSI Technical Review
fall 2012	1st test run in πM1 beamline
Jan 2013	PAC approval
summer 2013	2nd test run in πM1 beamline
fall 2013	funding requests
Mar 2014	Funding review @ NSF (allocated design
June 2014	Test Run
Sep-Oct 2014	R&D Money
summer 2015	Proof of Concept Test Run (+R&D funds)
late 2015	New NSF Proposal
Dec 2015	Test Run
Mid 2017	set up and have dress rehearsal
2018 - 2019	2 6-month experiment production runs

New Equipment Summary

Detector	Who	Technology
Beam SciFi	Tel Aviv	conventional
GEMs	Hampton	detector exists
Sapphire Cerenkov	Rutgers	prototyped (Albrow et al), prototying by us
FPGAs	Rutgers / Cracow	conventional
Target	George Washington	conventional - low power
Straw Tube Tracker	Hebrew	copy existing system
scintillators	South Carolina	copy existing system
DAQ	George Washington	conventional, except TRB3 prototyped by Darmstadt
Calorimeter	????	Not in proposal but we would really like this

Physics





Radius extraction from J Arrington.

Left: independent absolute extraction.

Right: extraction with only relative uncertainties.

The Real Bottom Line

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

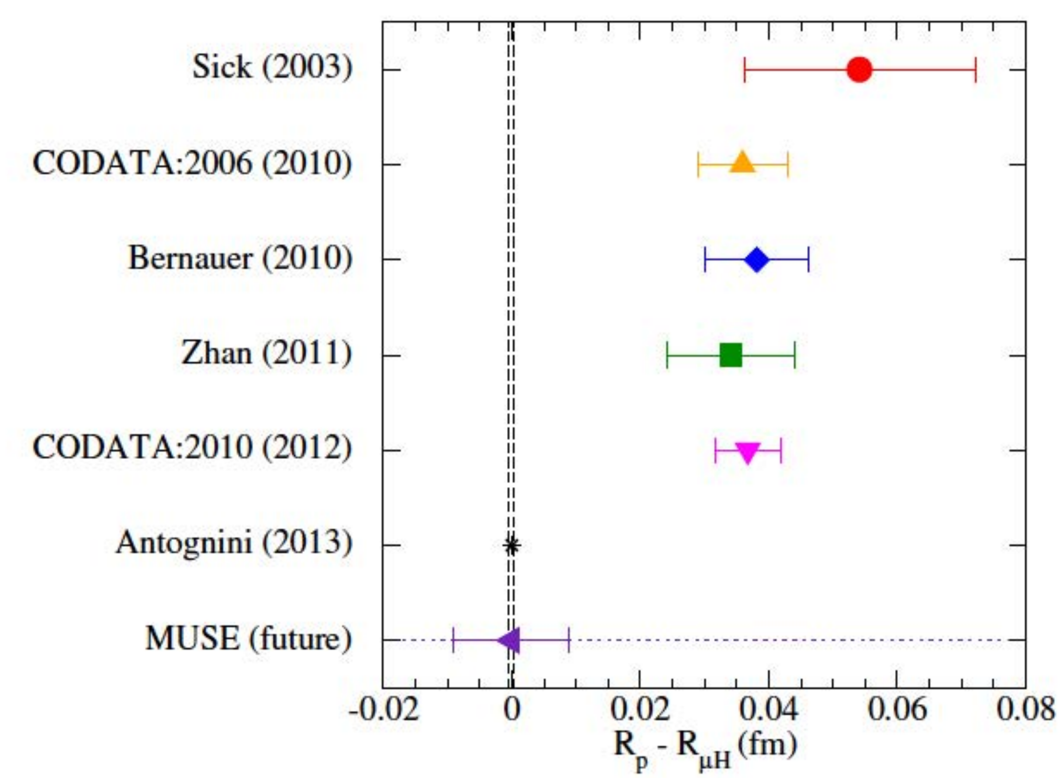
Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, m+/m-, and m/e comparisons

Precise tests of TPE in e-p and m-p or other differences for electron, muon scattering

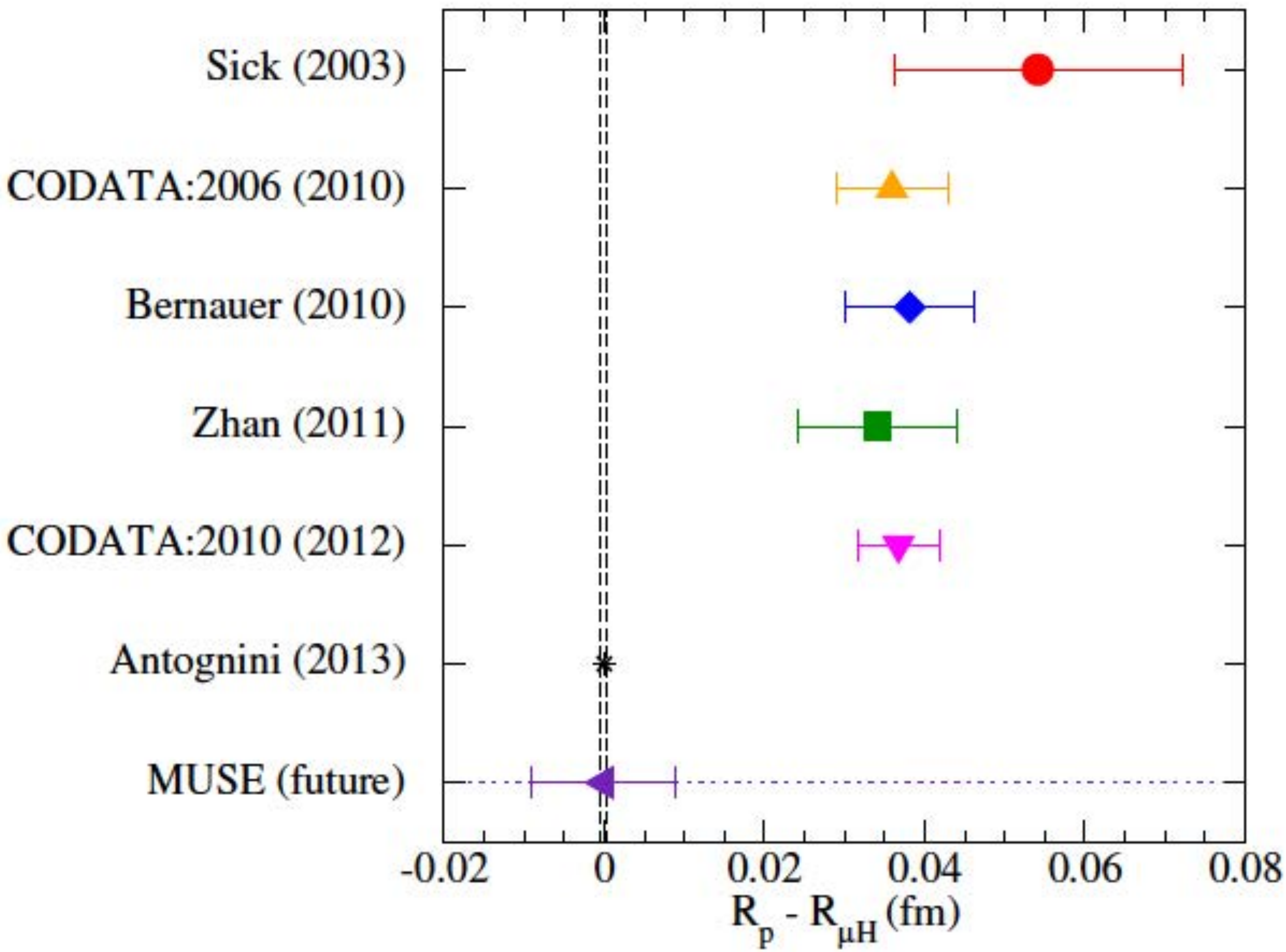
Comparing e/mu gets rid of most of the systematic uncertainties as well as the truncation error.

Projected uncertainty on the difference of radii measured with e/mu is 0.0045.

Test radii difference to the level of 7.7σ (the same level as the current discrepancy)!



The Real Real Botton Line



The Case for MUSE

	Spectroscopy	eP Scattering	MUSE

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	Spectroscopy	eP Scattering	MUSE
State	bound	unbound	unbound

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Q^2 range	limited	large	large

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Sensitivity to 2γ	none	very partial	complete

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Control of systematics in e/μ comparison	none	none	near complete

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Even though new hydrogen results agree with μH we still have a problem.

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Other Possible Ideas

(w/o Elaborating)

- Very low Q^2 JLab experiment, near 0^o using ``PRIMEX'' setup: A. Gasparian, D. Dutta, H. Gao et al. - Already took data, results soon.
- High energy proton beam (FNAL? J-PARC?) on atomic electrons, akin to low Q^2 pion form factor measurements - difficult - only goes to 0.01 GeV^2.
- Very low Q^2 eP scattering on collider (with very forward angle detection) - MEIC/EIC.
- New low Q^2 measurement at MAMI/A1 using Initial State Radiation.
- Accurate Lamb shift measurement on metastable C^{5+}.
- μ scattering on light nuclei - MUSE Extension?
- At least 2 New eH measurements ongoing

Conclusions

~~Conclusions~~

Summary

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  - But none currently seem to solve the puzzle completely.
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    - Experimentalists – "Theorists have forgotten some obscure correction"
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- Rydberg!!!!