The Proton Radius

Old Measurements and New Ideas

Guy Ron
Hebrew University of Jerusalem

GHP Meeting, Baltimore, MD
8 Apr., 2015

http://www.phys.huji.ac.il/~gron

Fundamental Interactions Group

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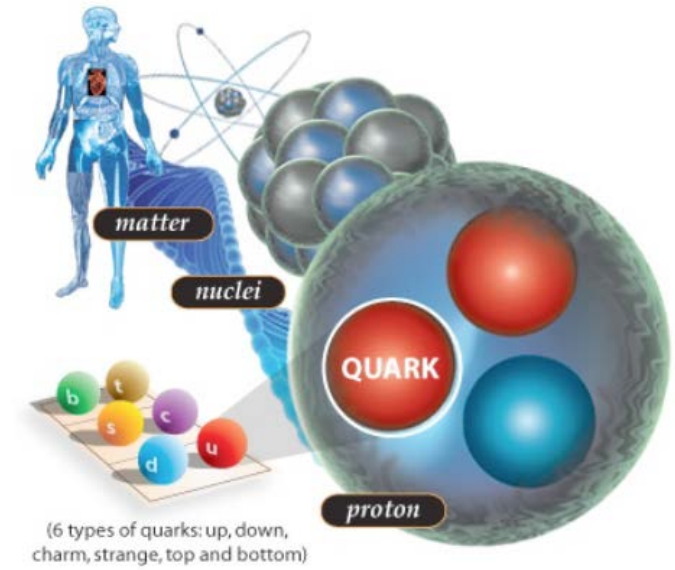
Outline



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

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

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

Mott - Spin-1/2

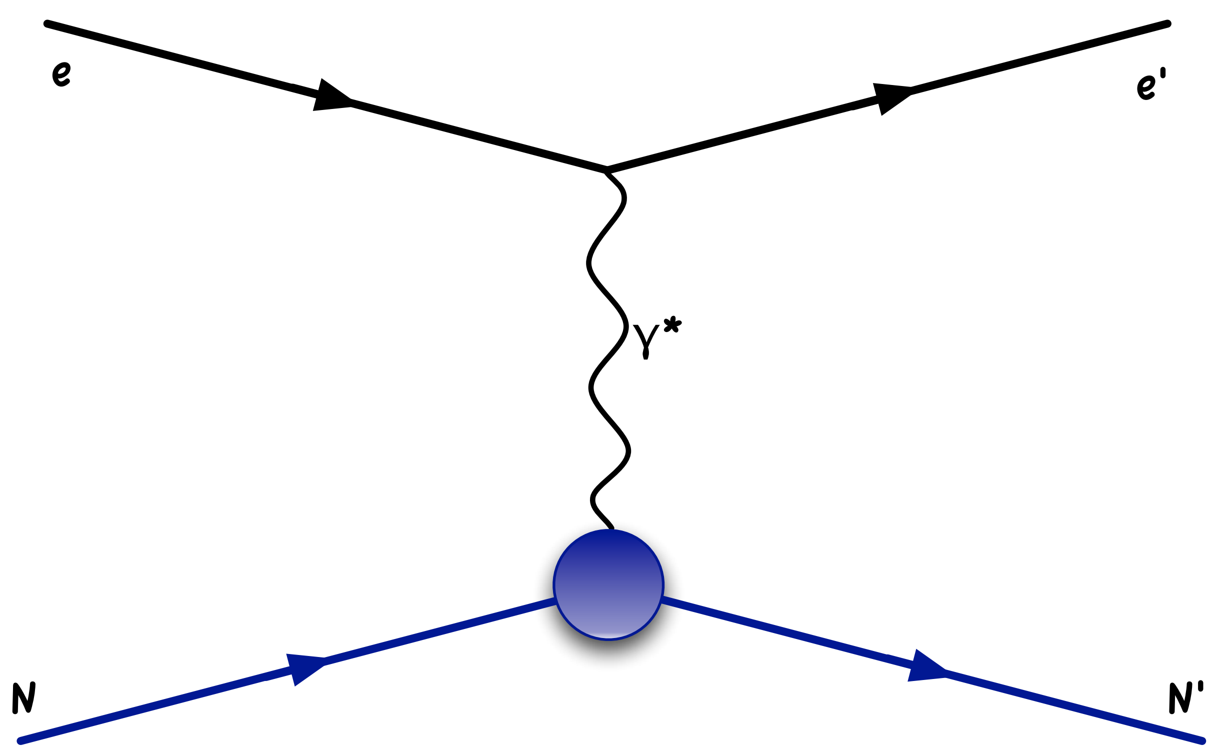
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

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

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

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



Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

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

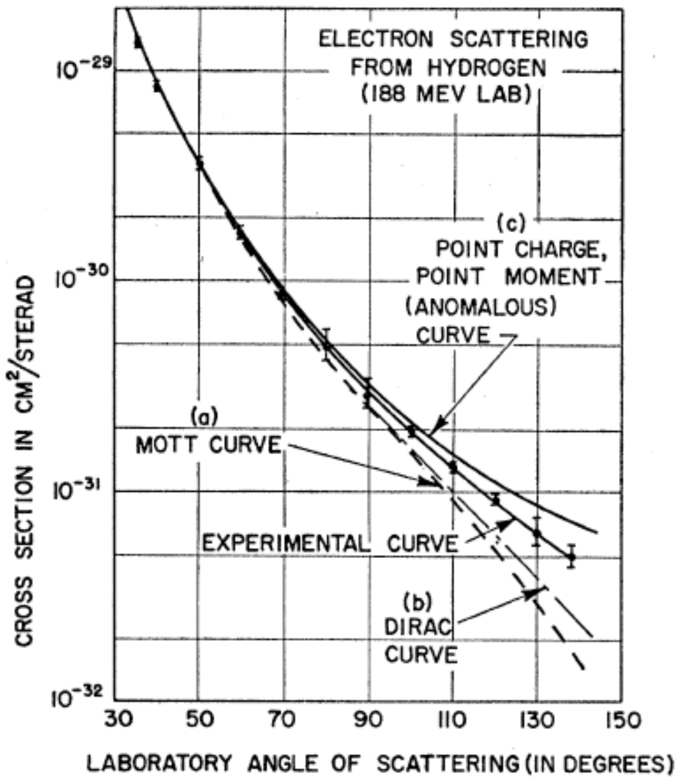
$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\left\langle r^2_{E,M}\right\rangle Q^2 + \frac{1}{120}\left\langle r^4_{E,M}\right\rangle Q^4 - \frac{1}{5040}\left\langle r^6_{E,M}\right\rangle Q^6 + \cdots$$

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

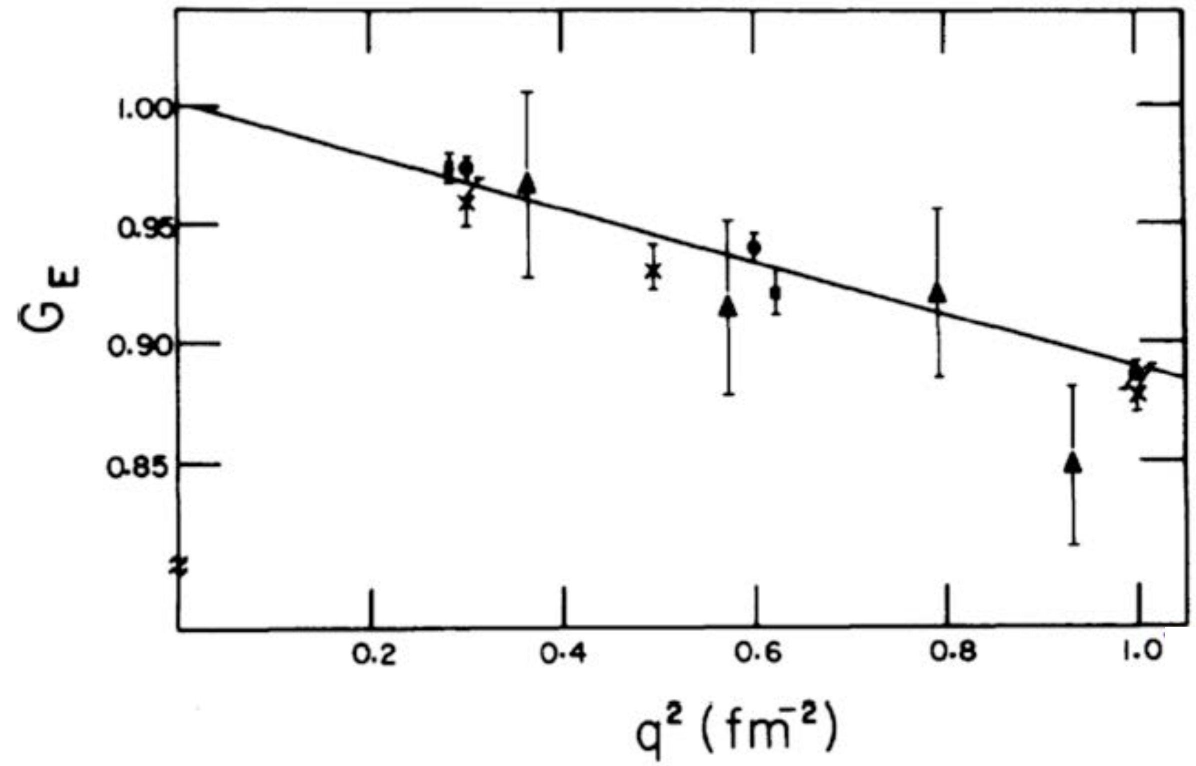
$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \left\langle r^2_{E,M}\right\rangle \equiv r^2_{E,M}$$

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

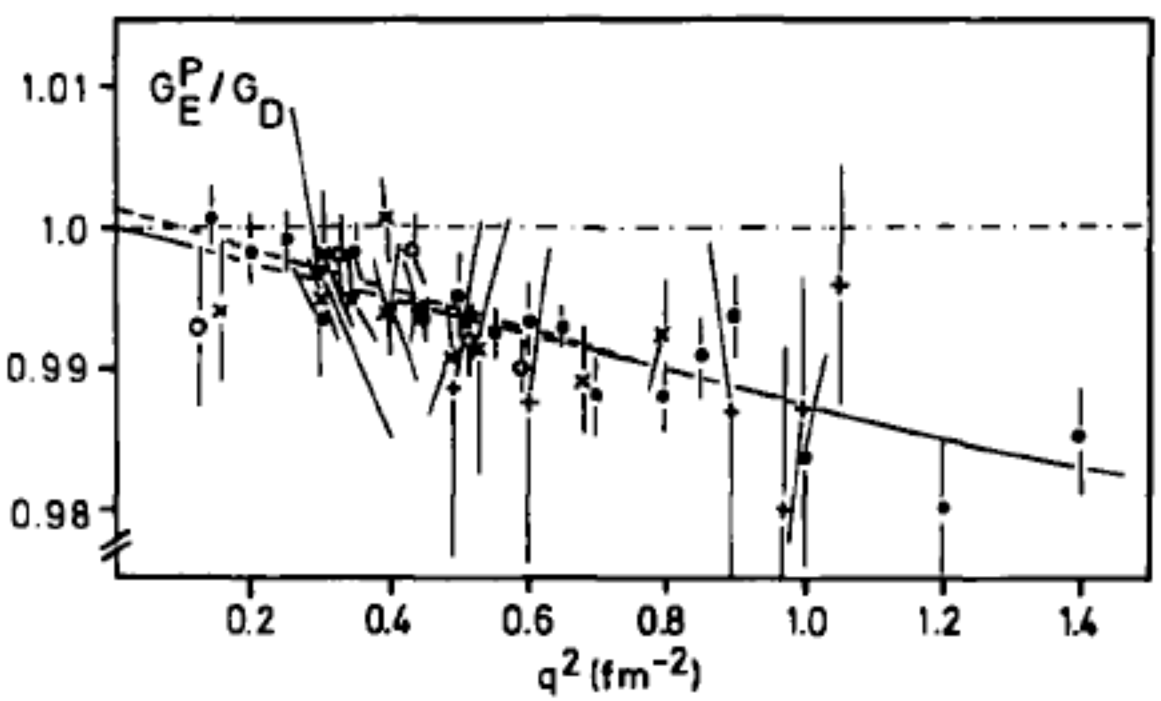
50s



70s

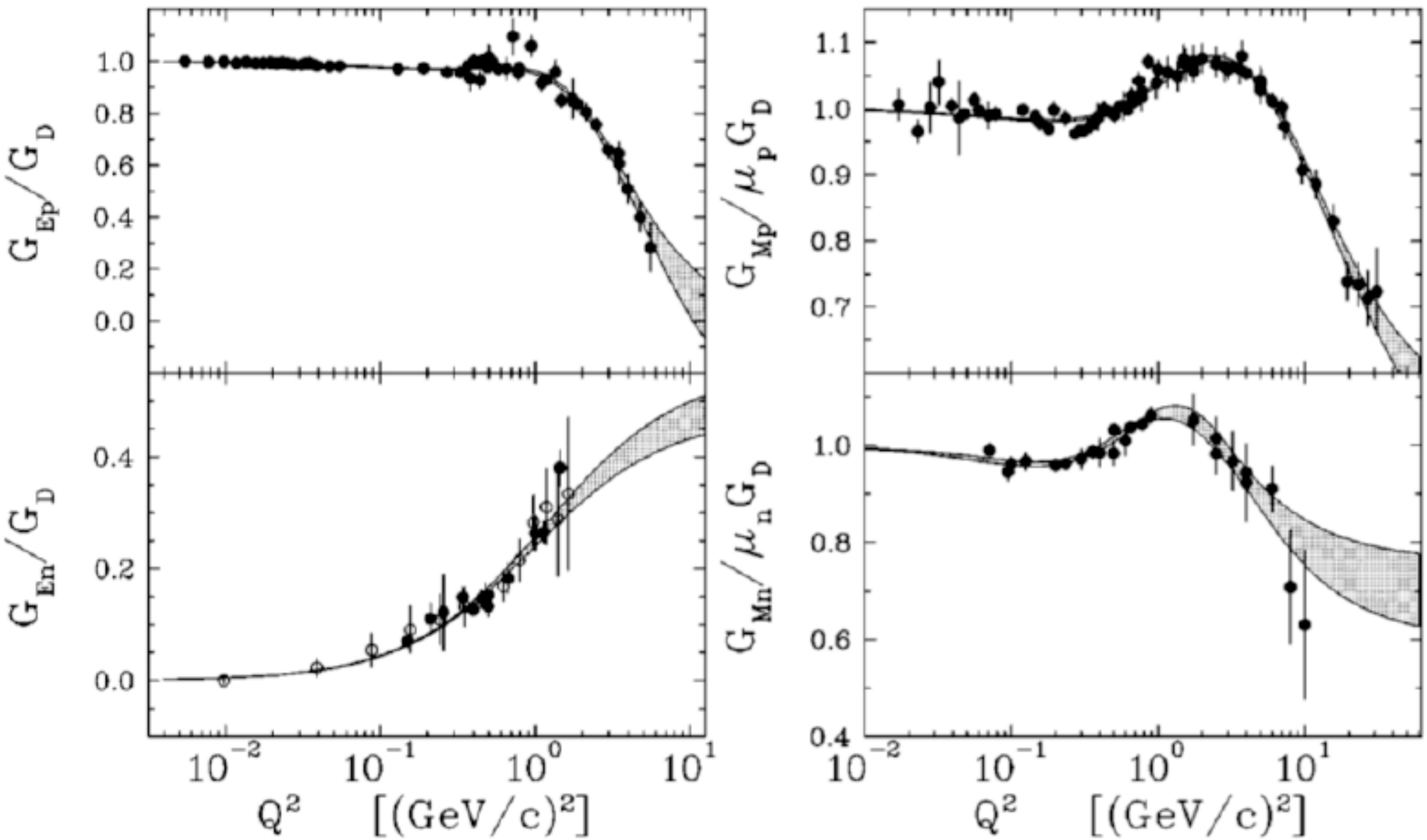


80s



Better measurements lead to...

A multitude of fits



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

Which in turn lead to...

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

A multitude of Radii

$$-6G'_E(0) = r_E^2$$

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

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

$$G^{E,M}_{\text{polynomial, n}}(Q^2) = 1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{poly+dipole}}(Q^2) = G_D(Q^2) + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{poly x dipole}}(Q^2) = G_D(Q^2) \times \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{inv. poly.}}(Q^2) = \frac{1}{1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}}$$

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)

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

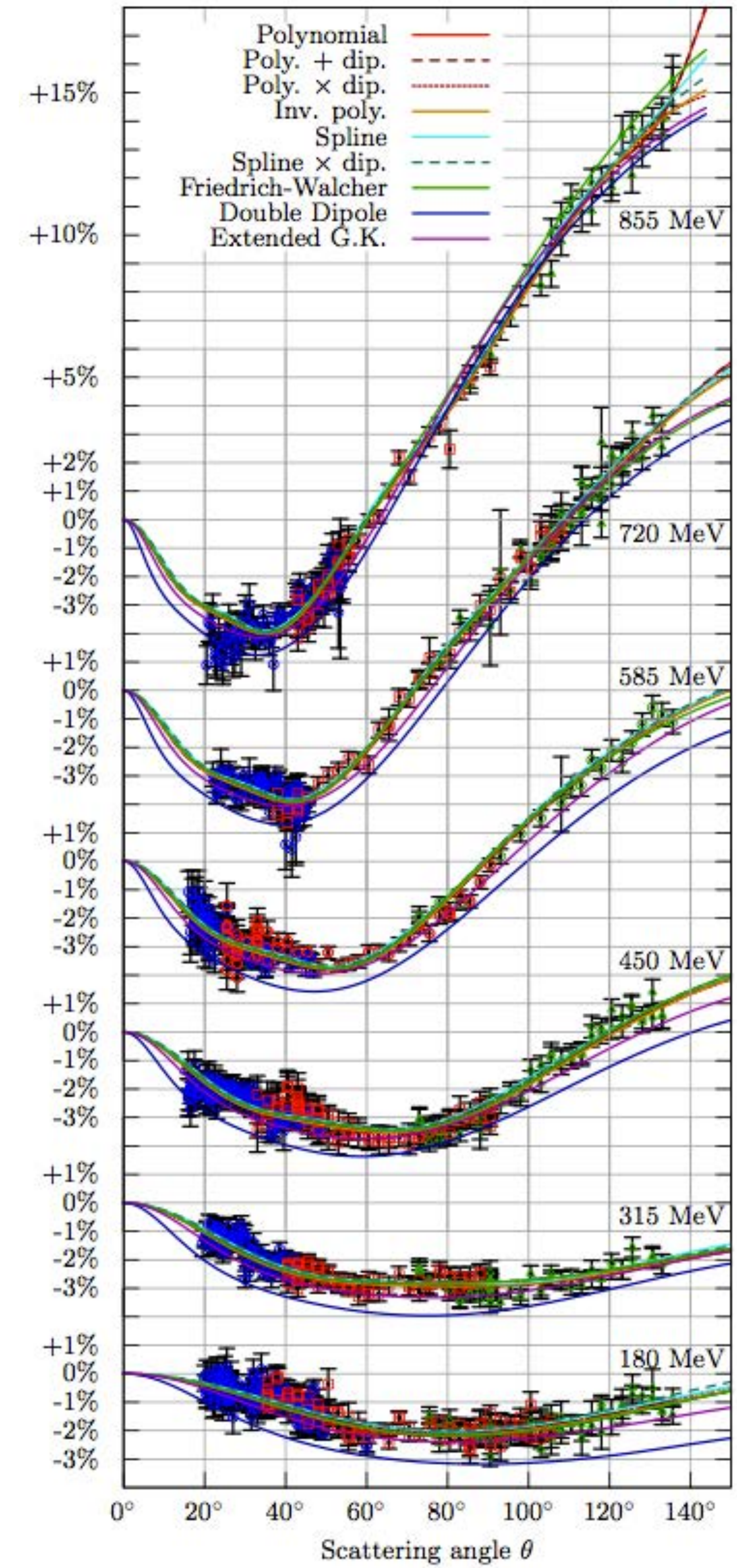
r_E = 0.863, r_M = 0.848 fm

Kelly PRC70, 068202 (2004)

New Mainz ep

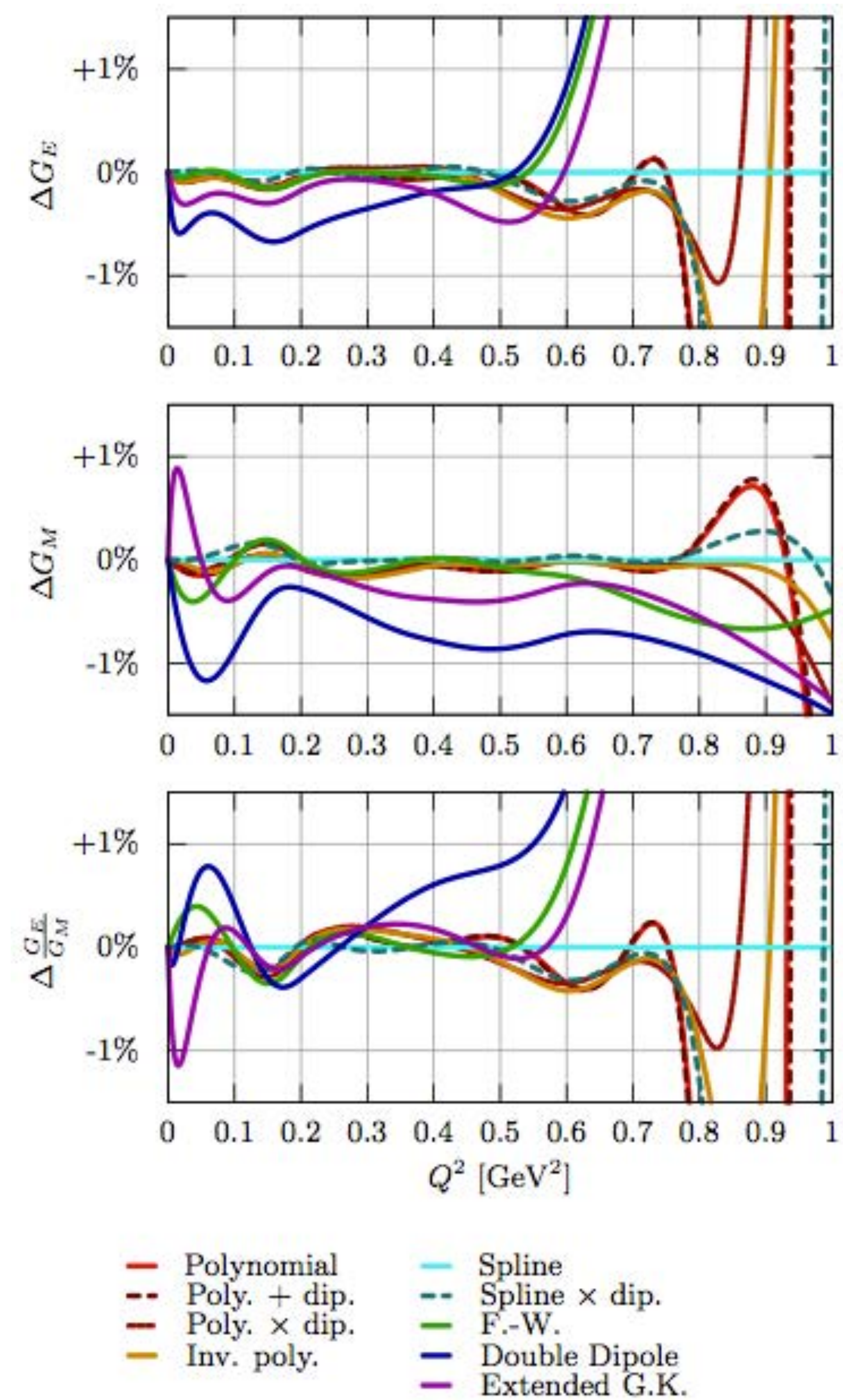
J. Bernauer et al PRL 105, 242001 (2010)

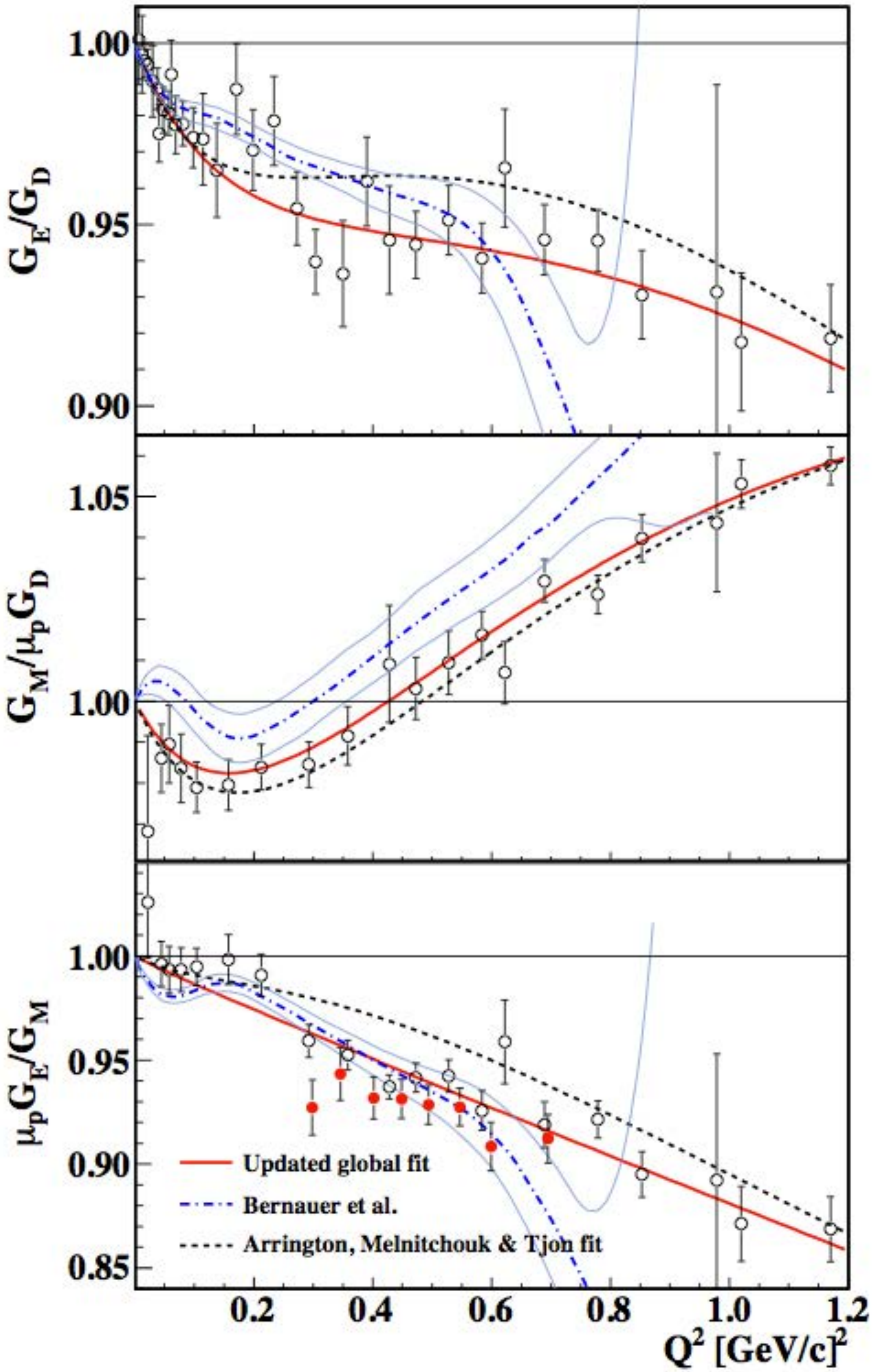
r_p = 0.879 ± 0.008 fm



Left: Cross sections relative to standard dipole

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



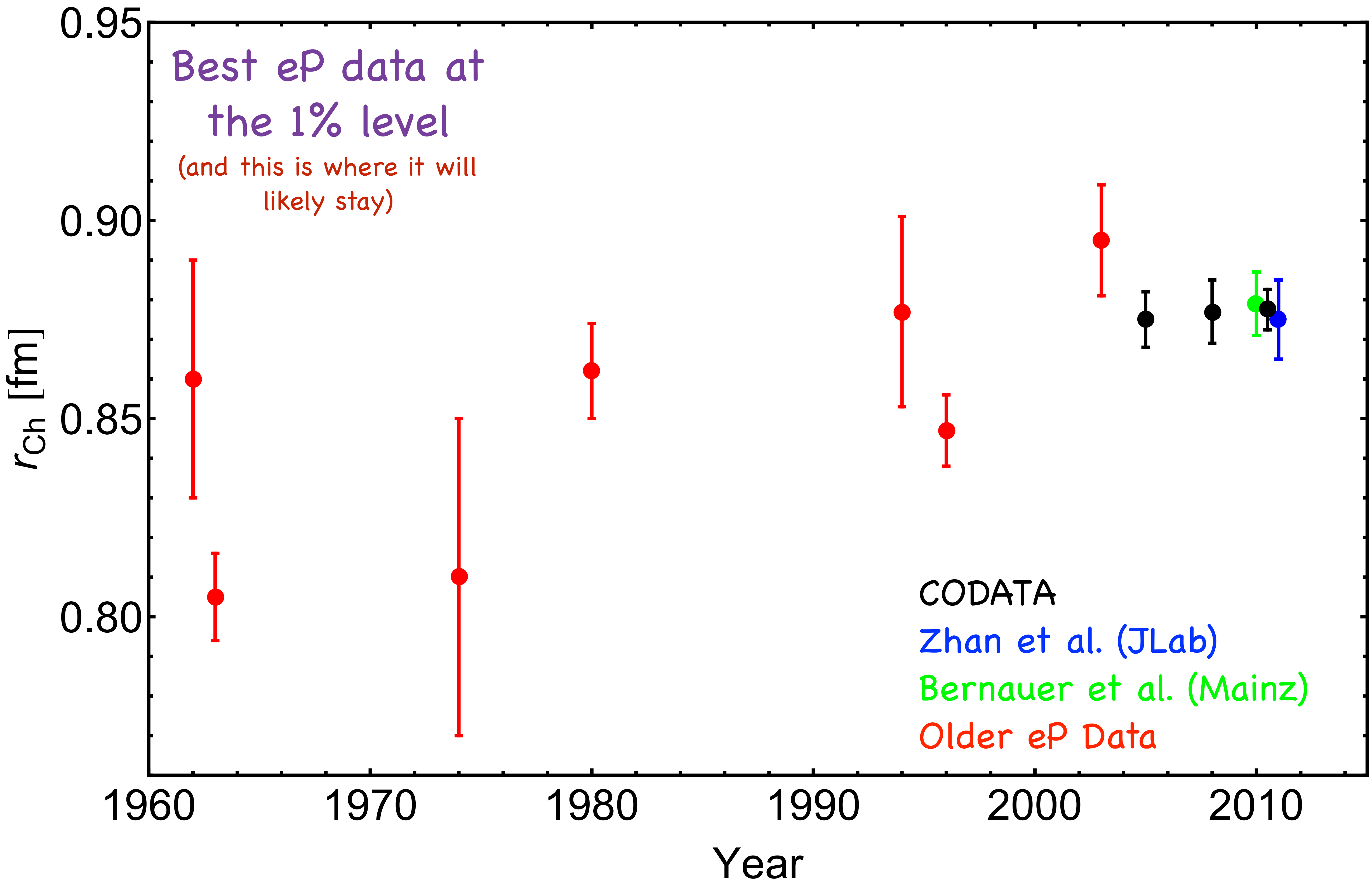


New JLab ep E08-007 Part I (GR,...)

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

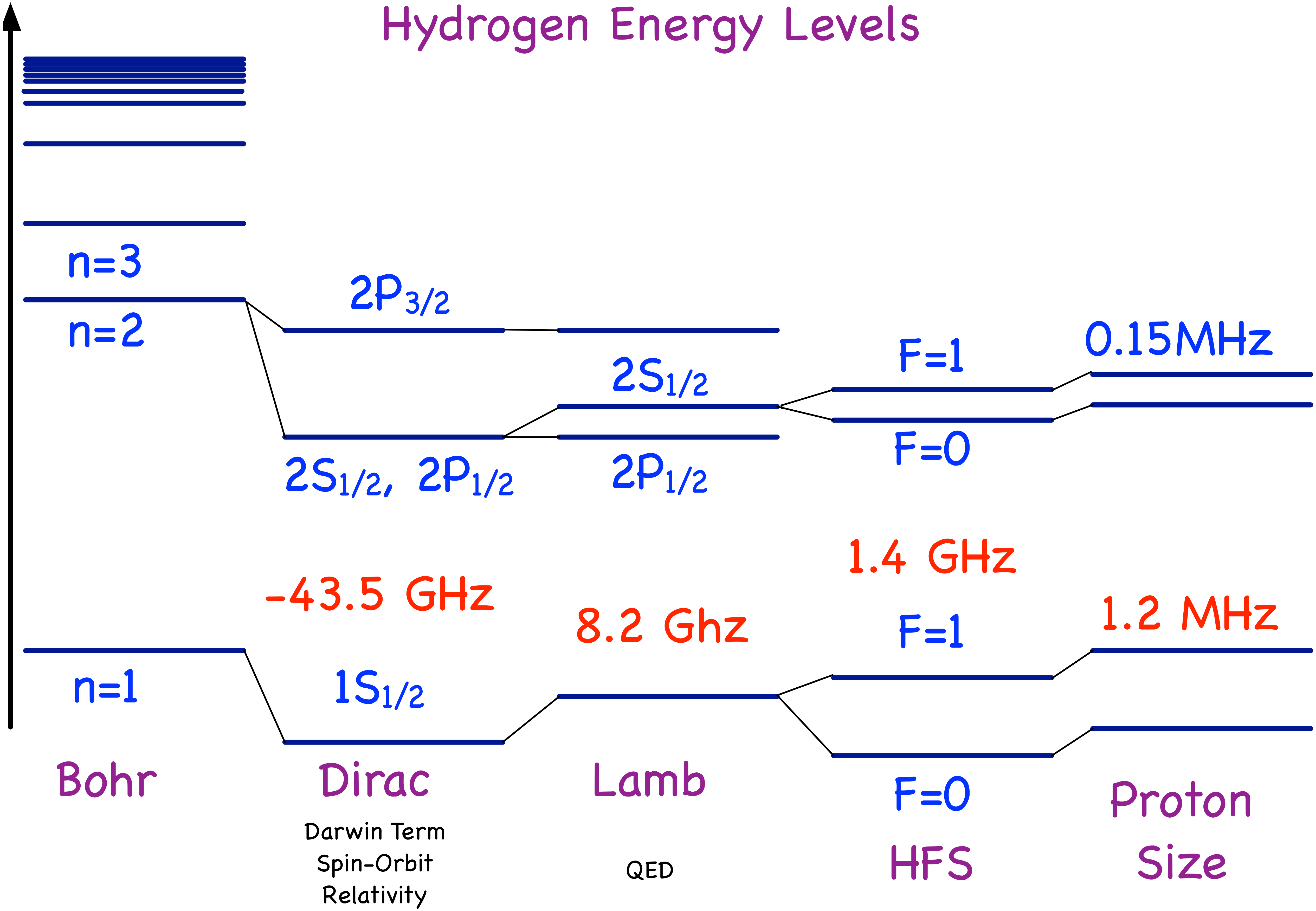
r_p = 0.875 ± 0.009 fm

Time evolution of the Radius from eP data



Spectroscopic Measurements

Components of a calculation
Hydrogen Energy Levels



H-Like Lamb Shift Nuclear Dependence

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

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

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

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

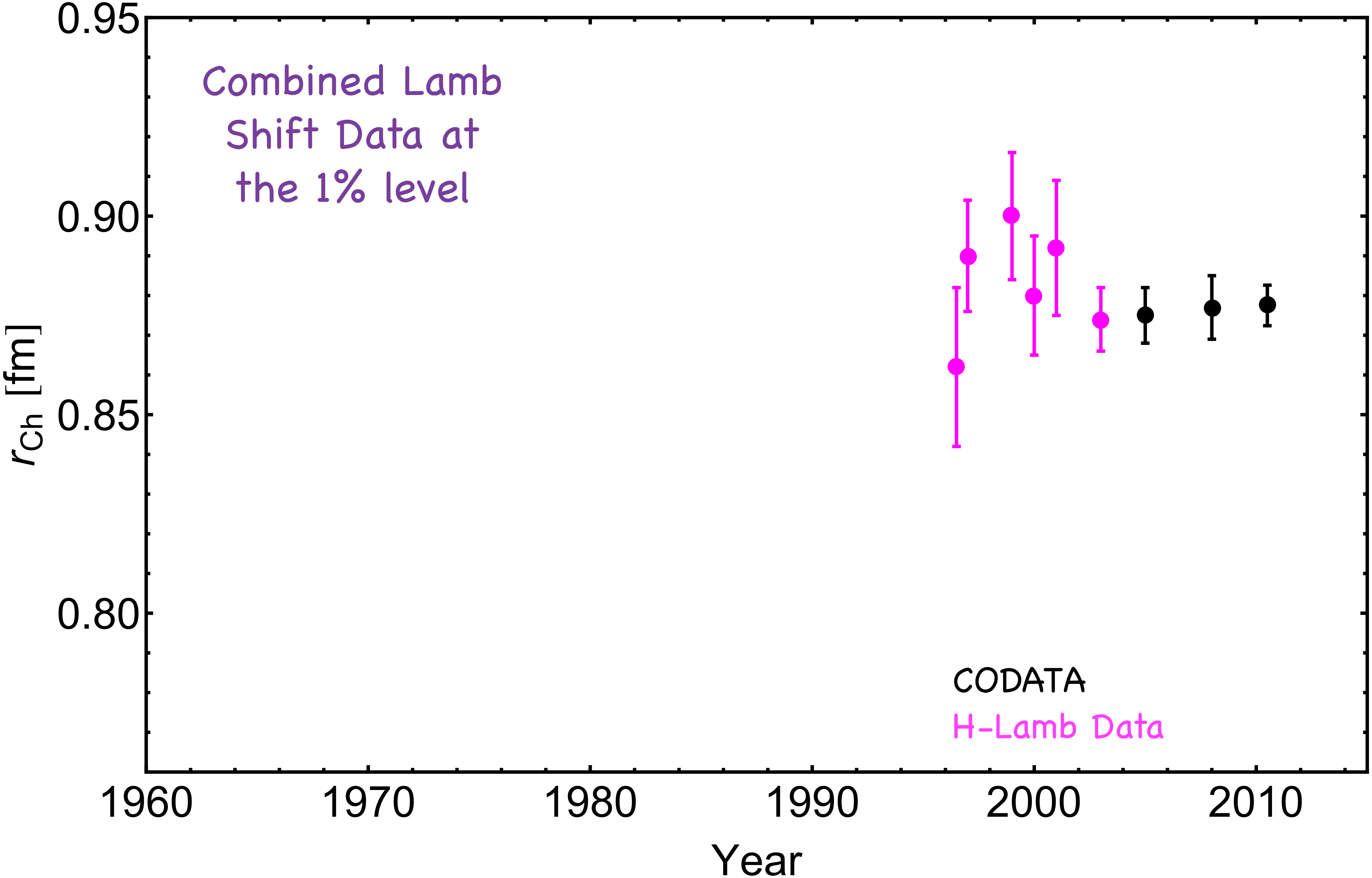
$\Delta E_{\mathrm{Lamb}}(1S) = 8172.582(40)$ MHz

$\Delta E_{\mathrm{Nucl}}(1S) = 1.269$ MHz for rp = 0.9 fm
$\Delta E_{\mathrm{Nucl}}(1S) = 1.003$ MHz for rp = 0.8 fm

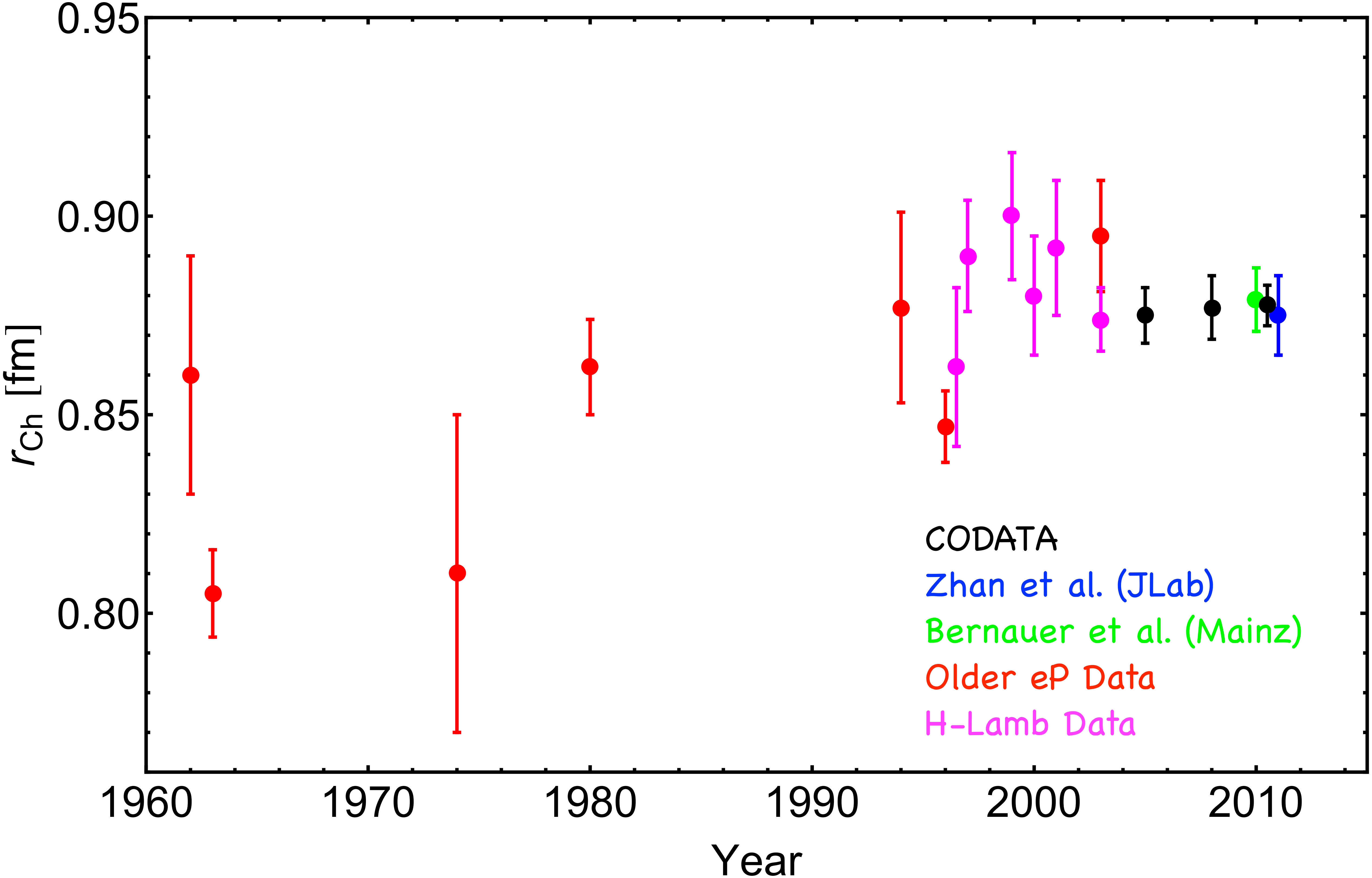
$\Delta E_{\mathrm{Lamb}}(2S) = 1057.8450(29)$ MHz

$\Delta E_{\mathrm{Nucl}}(2S) = 0.1586$ MHz for rp = 0.9 fm
$\Delta E_{\mathrm{Nucl}}(2S) = 0.1254$ MHz for rp = 0.8 fm

Time evolution of the Radius from H Lamb Shift



Time evolution of the Radius from H Lamb Shift + eP



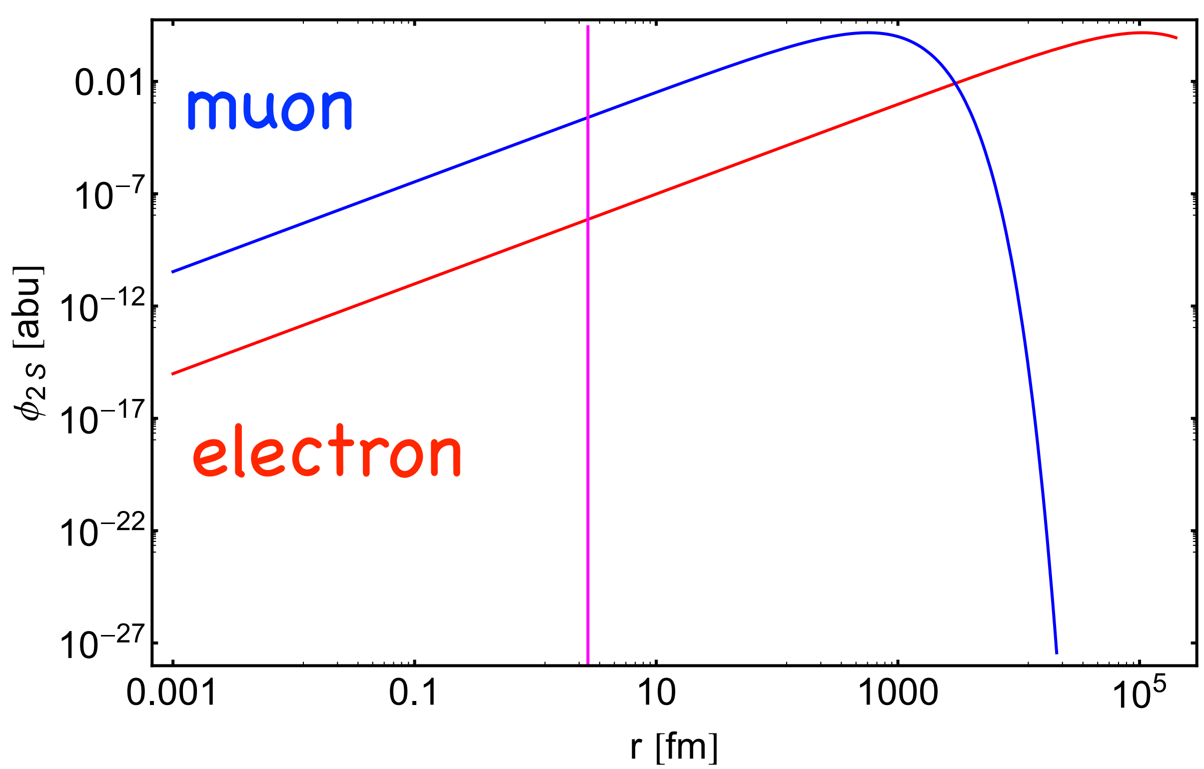
Why μH?

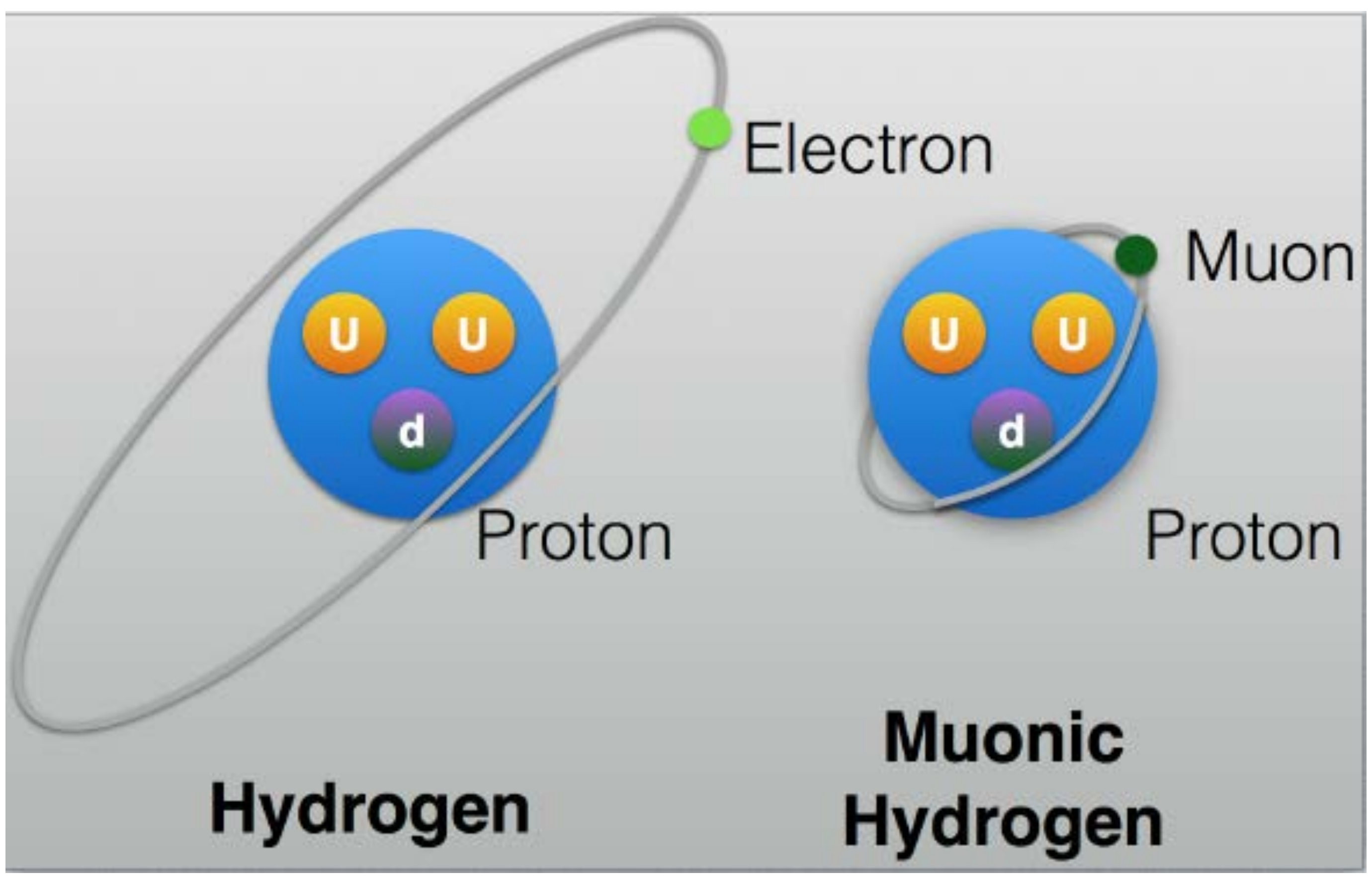
Probability for lepton to be inside the proton:
proton to atom volume ratio

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

Lepton mass to the **third** power!

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





Proton charge radius and muonic hydrogen

MPQ

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

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

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

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

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

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

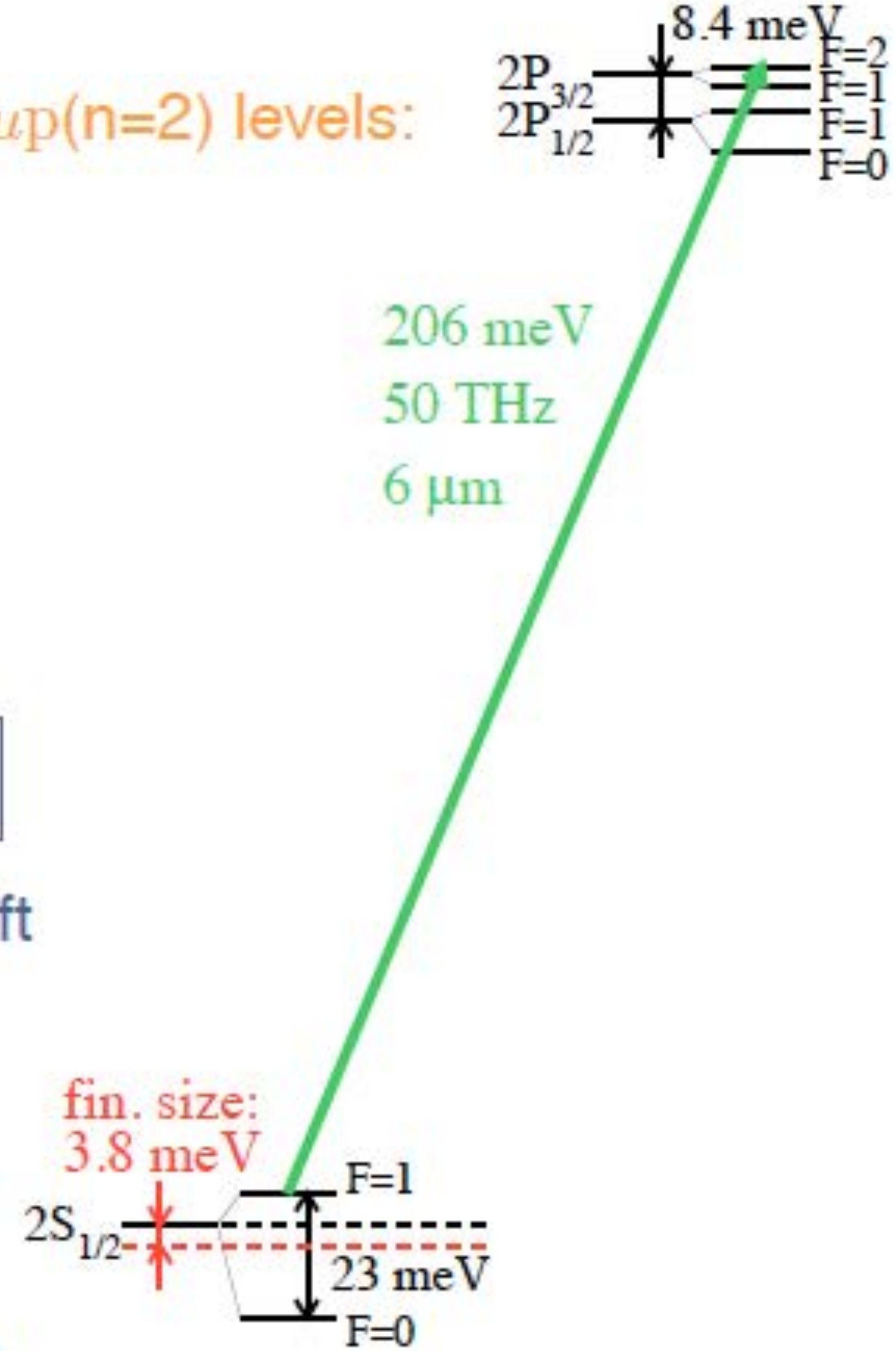
finite size contribution is 2% of the μp Lamb shift

measure ΔE(2S-2P) to 30 ppm = 1.5 GHz

$$\boxed{\Rightarrow r_{\rm p} \text{ to } 10^{-3}}$$

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

μp(n=2) levels:

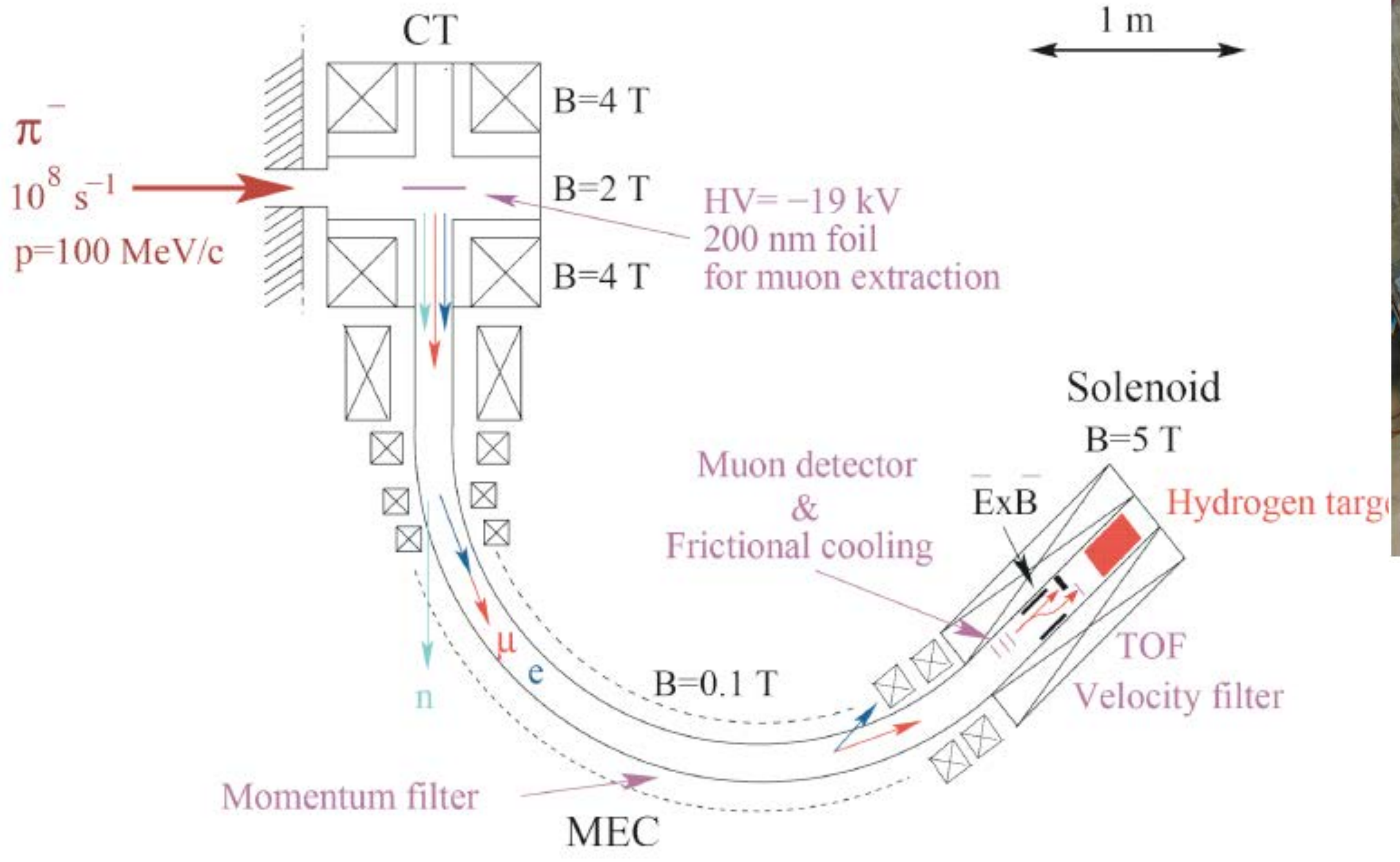


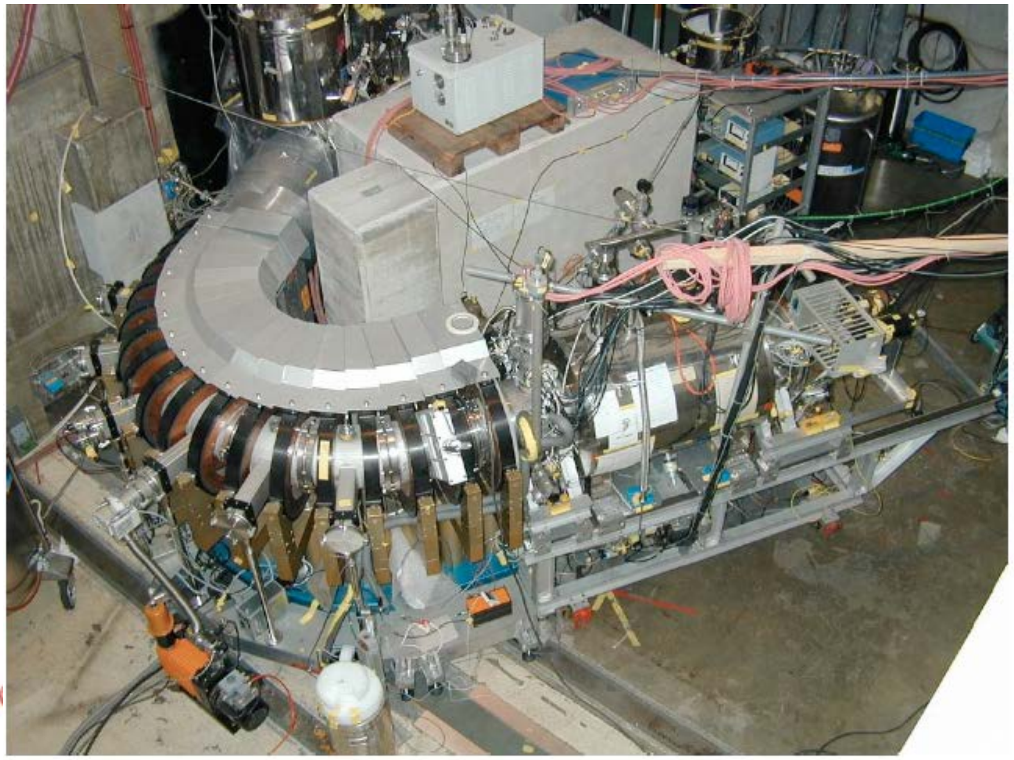
Courtesy of R. Pohl

μP Lamb Shift Measurement

μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)





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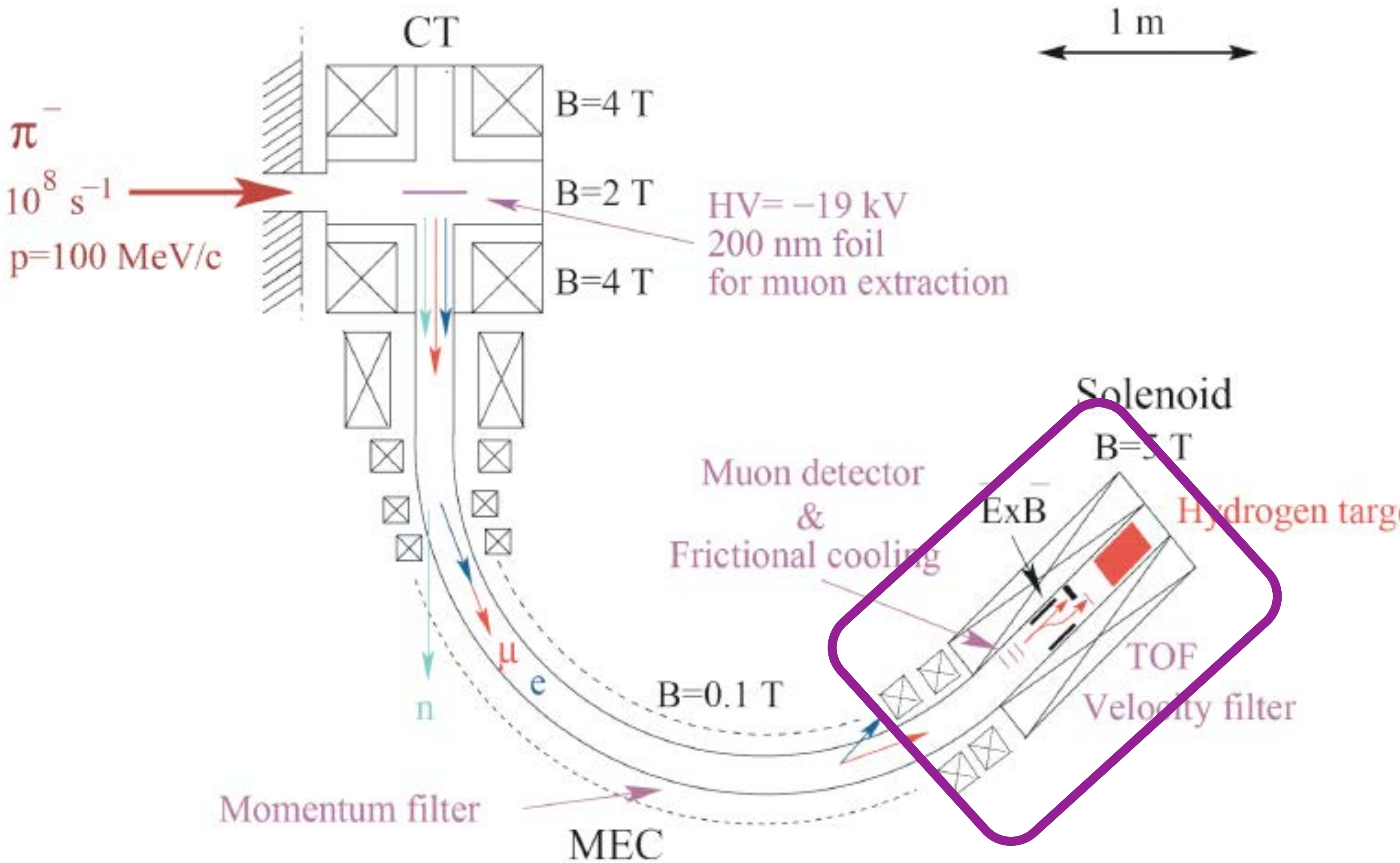

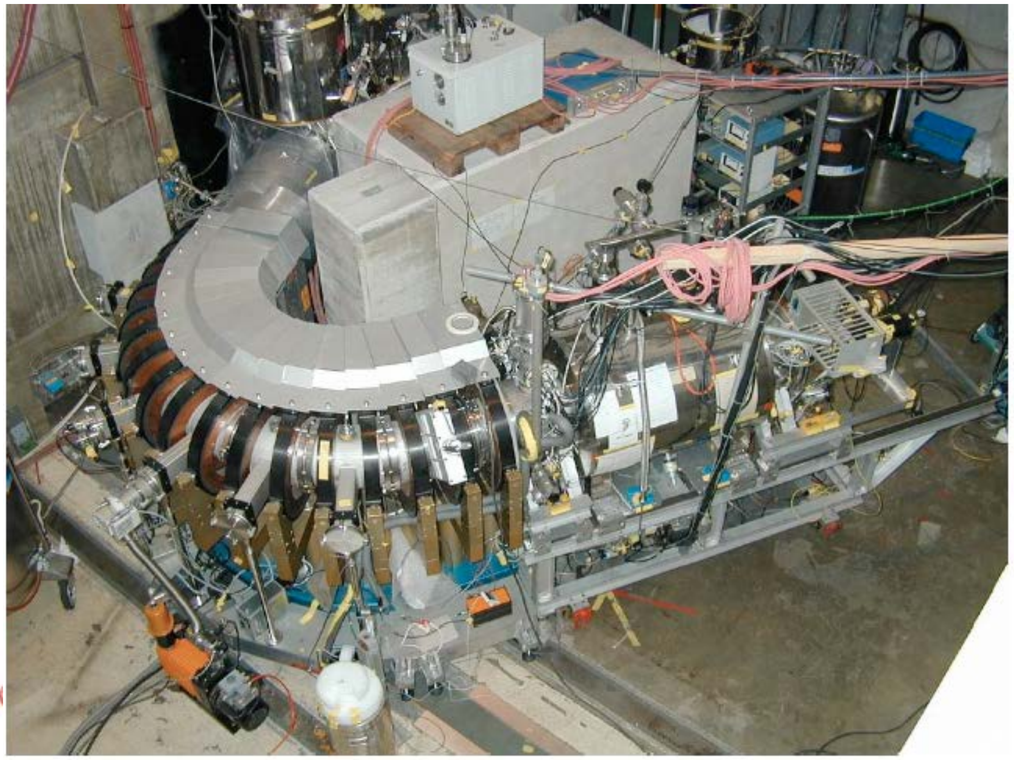

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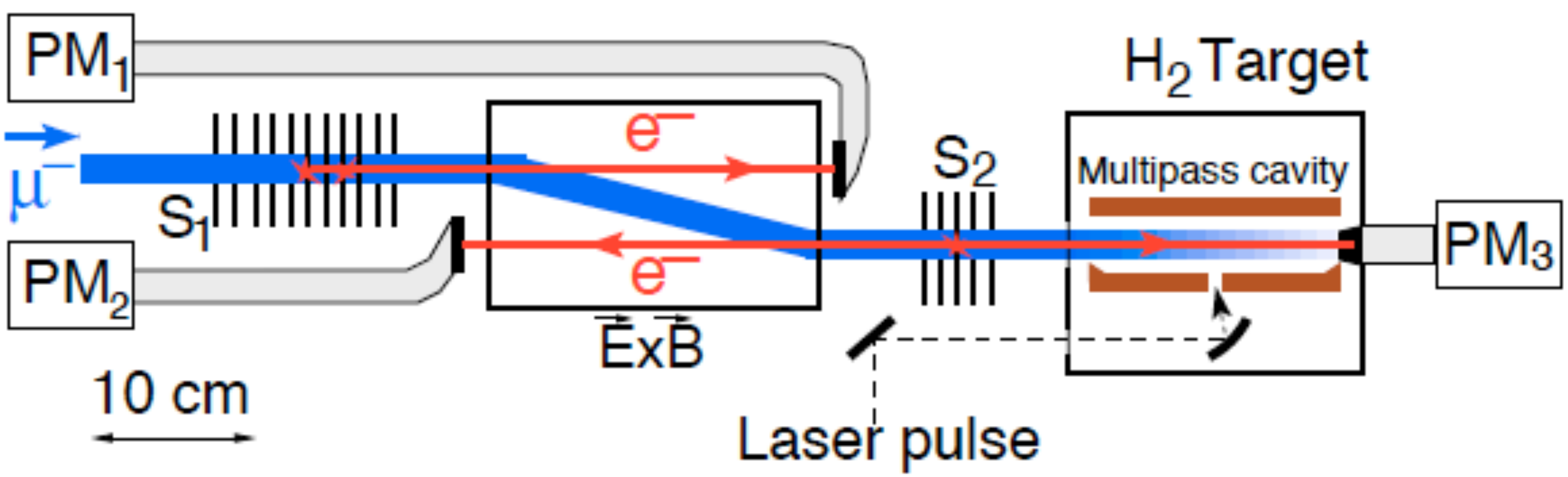
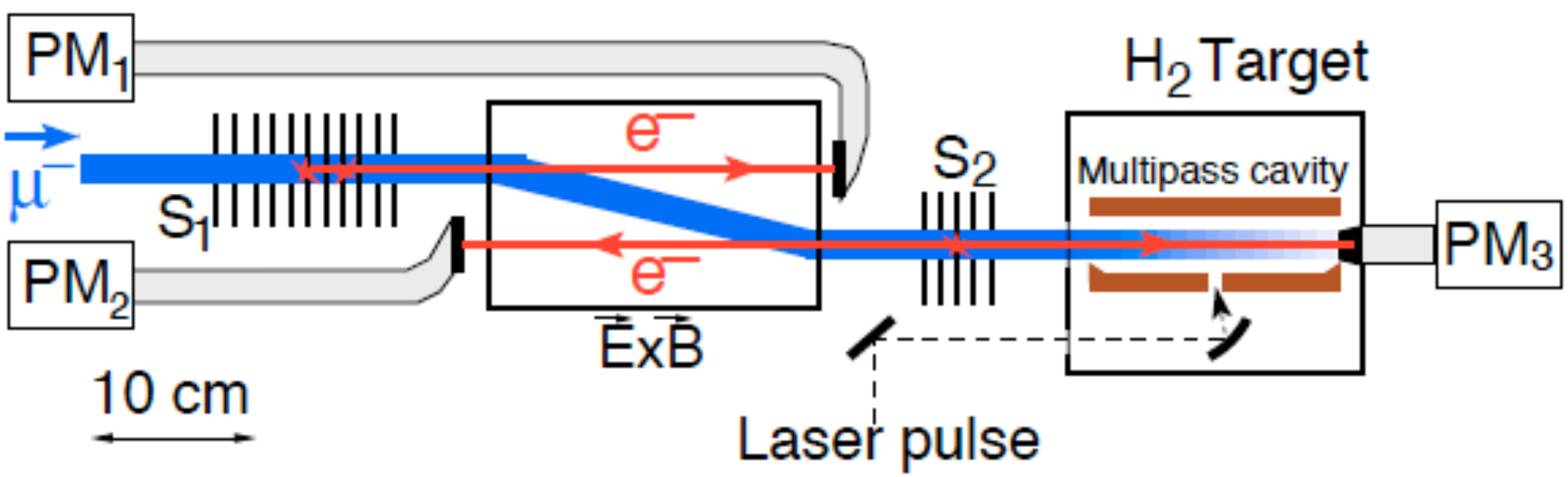


μP Lamb Shift Measurement

- 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



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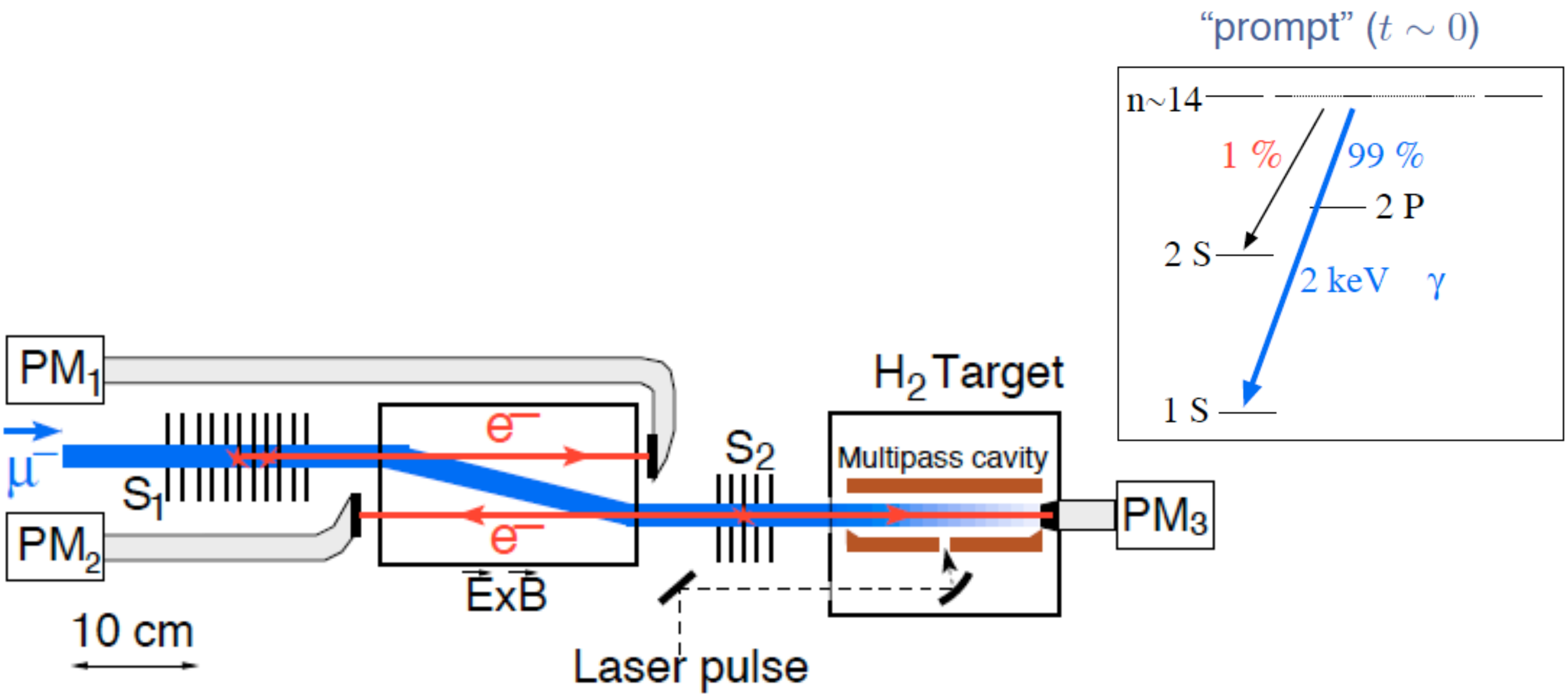
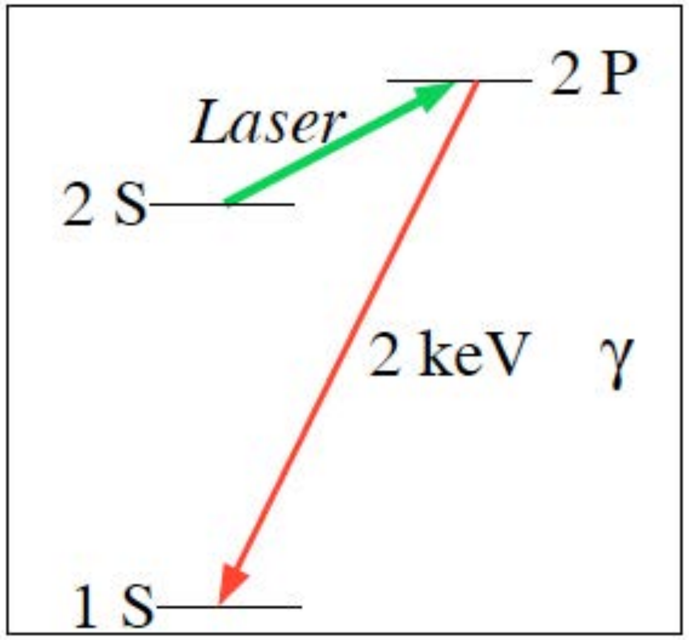
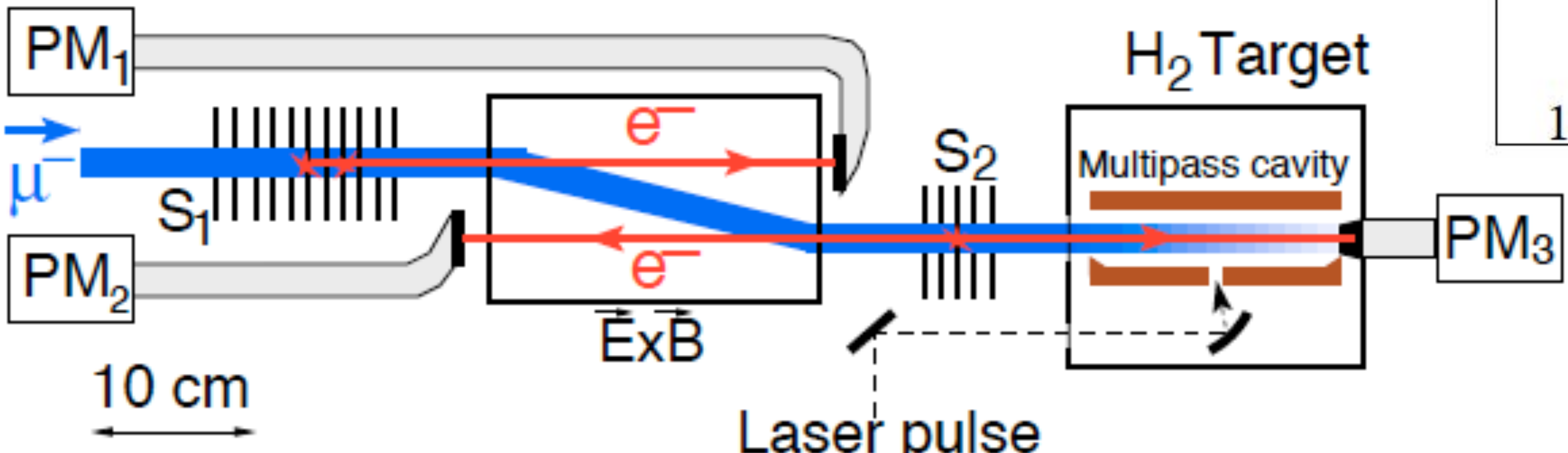
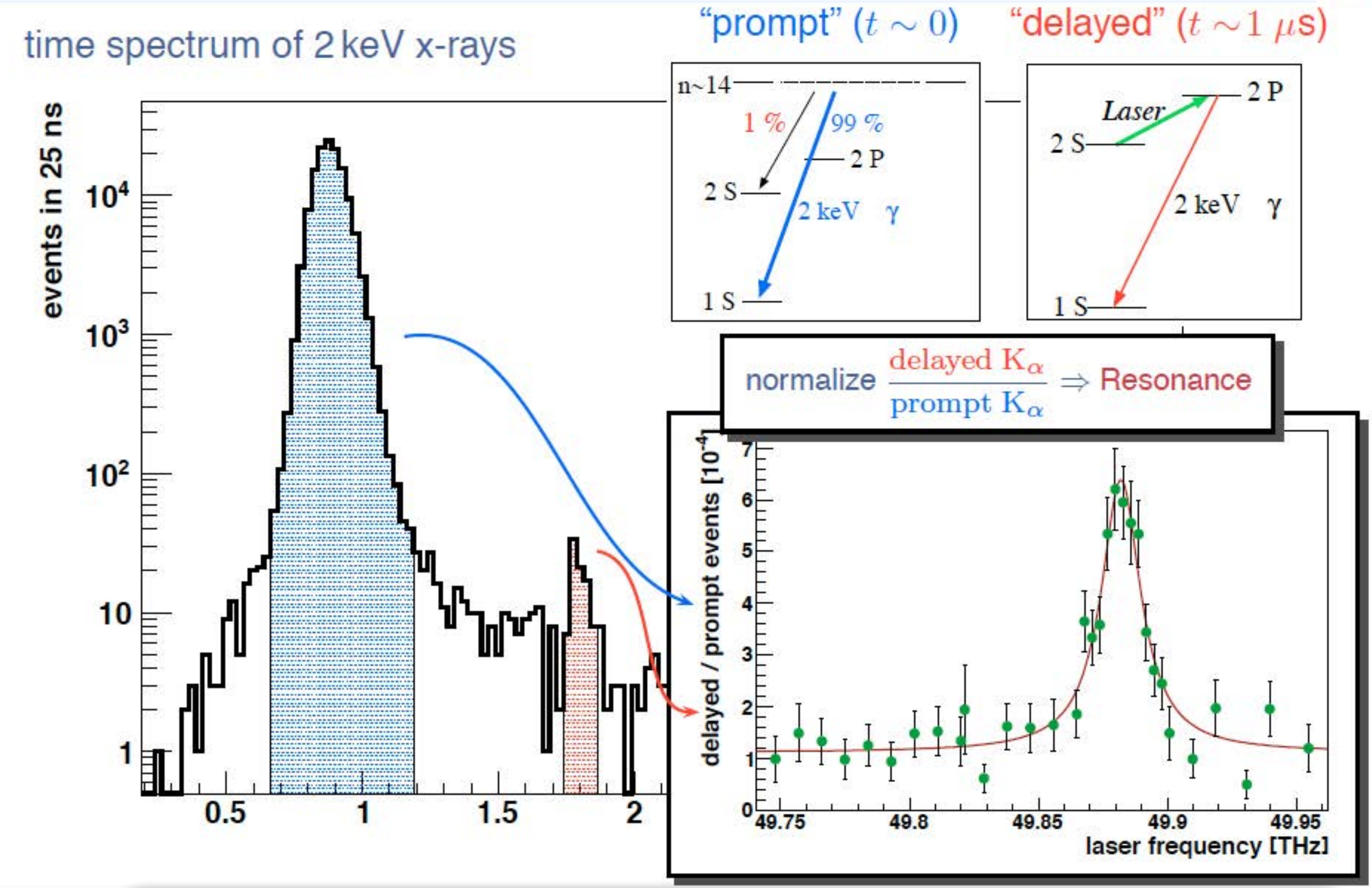


μP Lamb Shift Measurement

- 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
- 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.

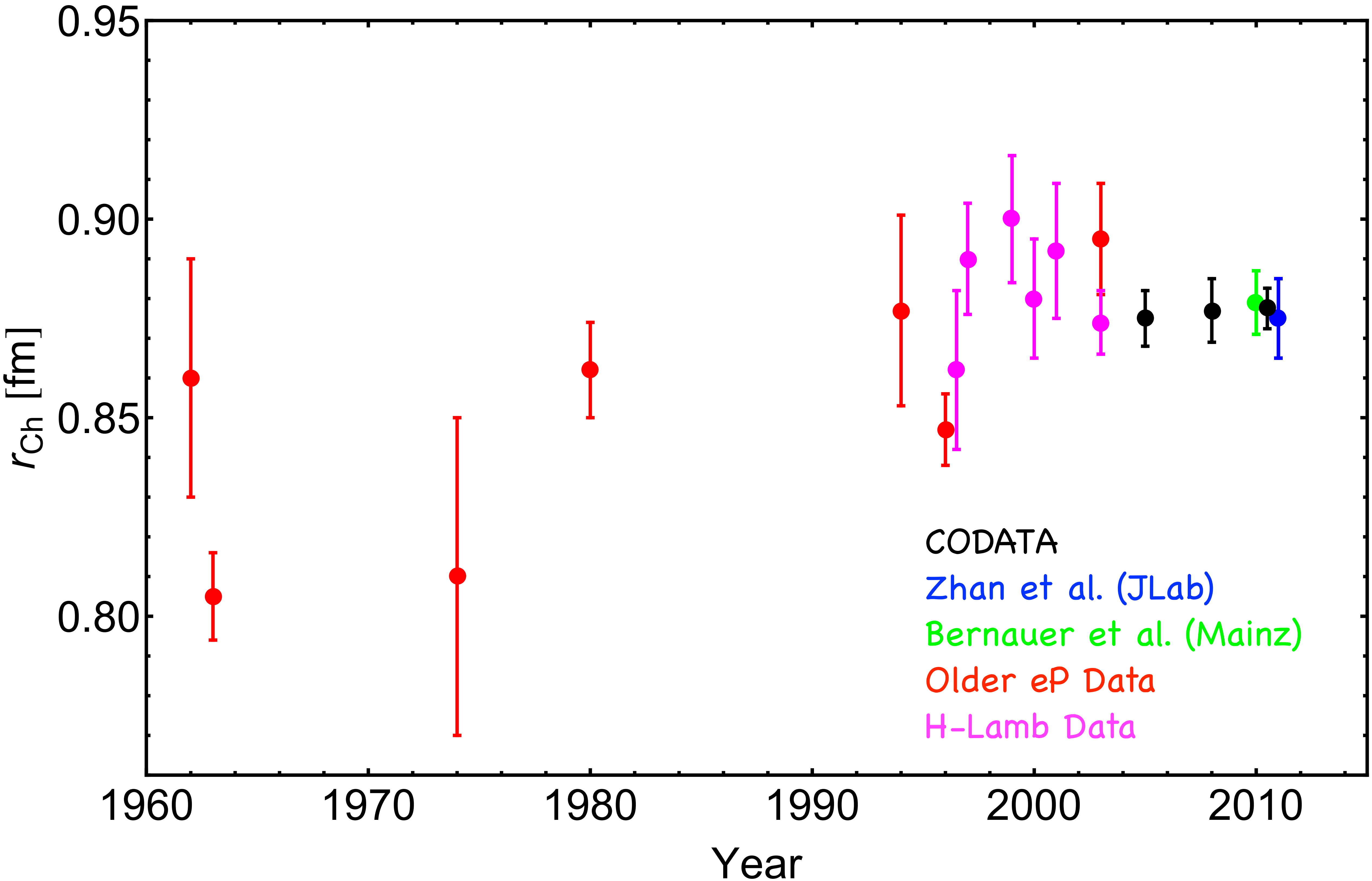




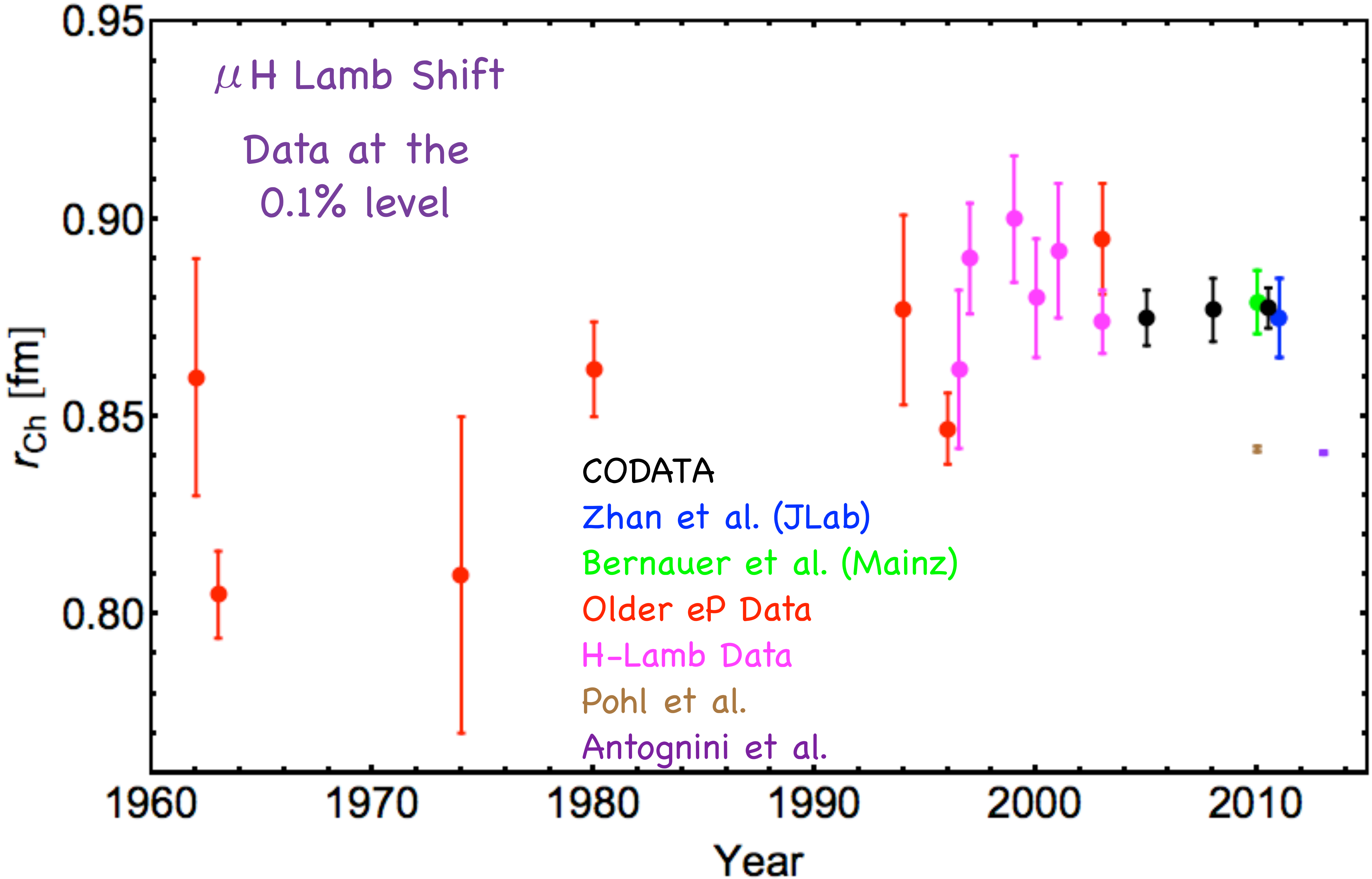


$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \; [\mathrm{meV}]$$

Time evolution of the Radius from H Lamb Shift + eP



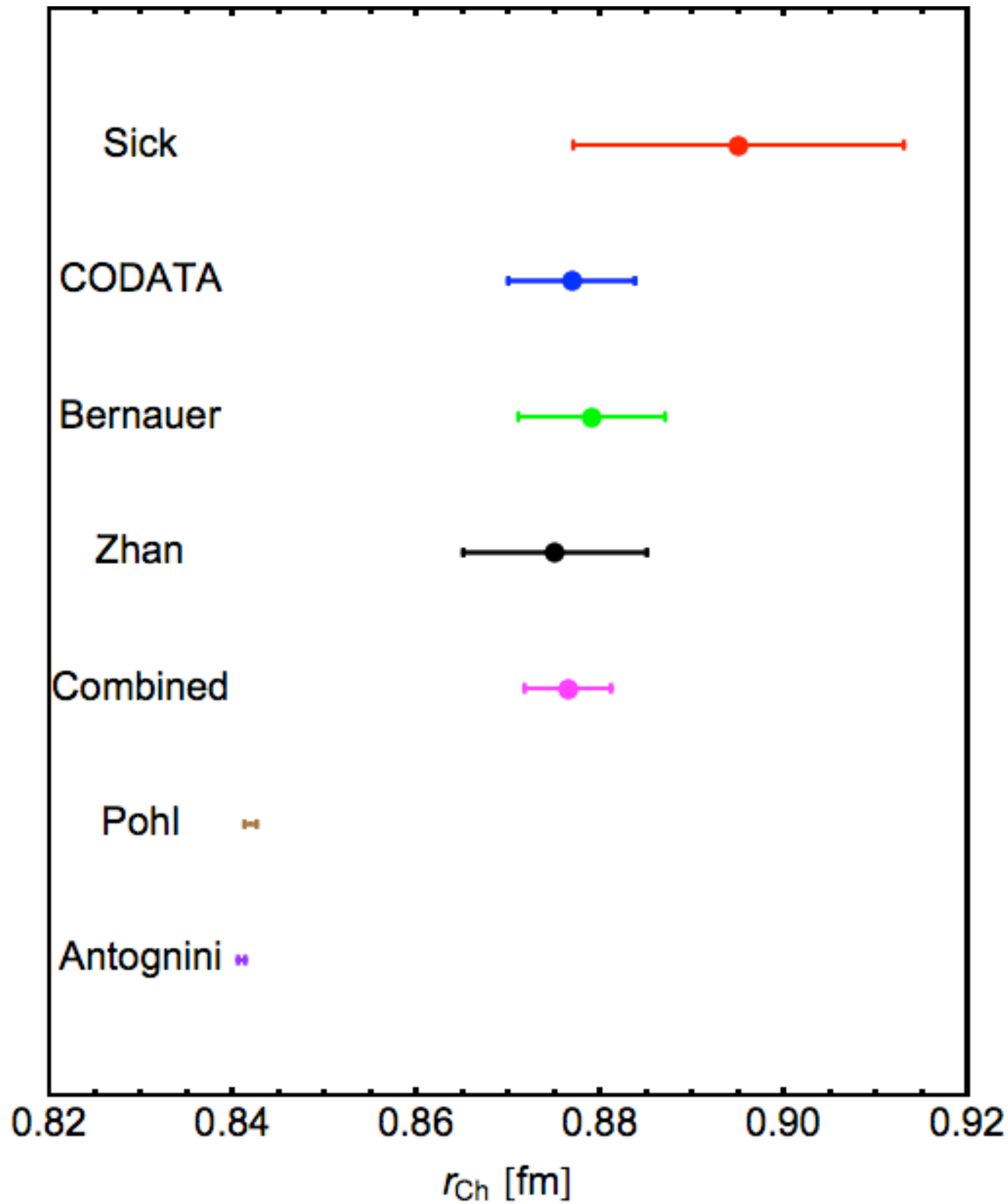
Time evolution of the Radius from H Lamb Shift + eP



Proton Radius Puzzle

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

#	Extraction	<r
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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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.

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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)

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

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07|13|13 ISSUE

CONTENTS

When the atom went

Proton's radius revised downward

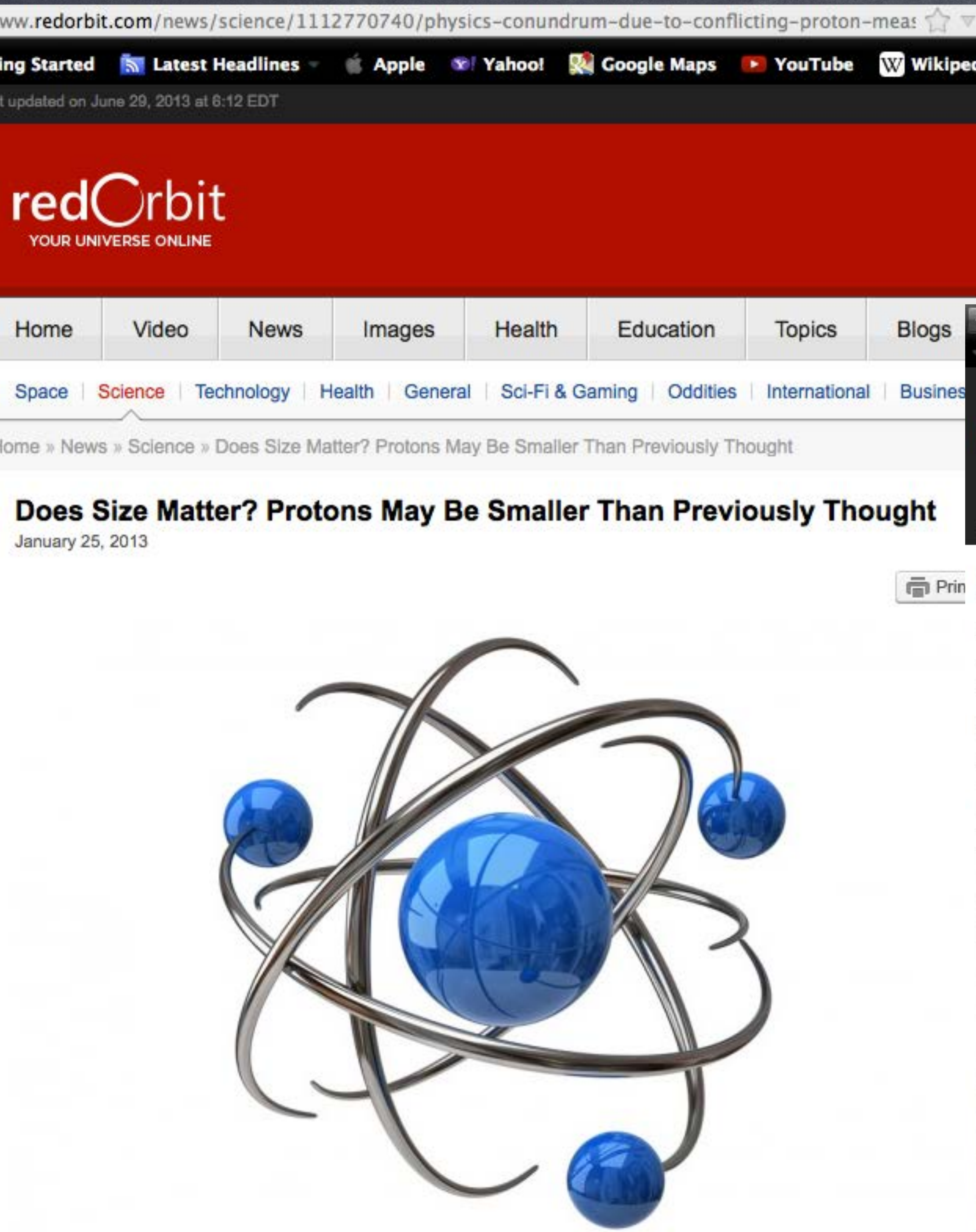
Surprise measurement may point to new physics

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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t updated on June 29, 2013 at 6:12 EDT

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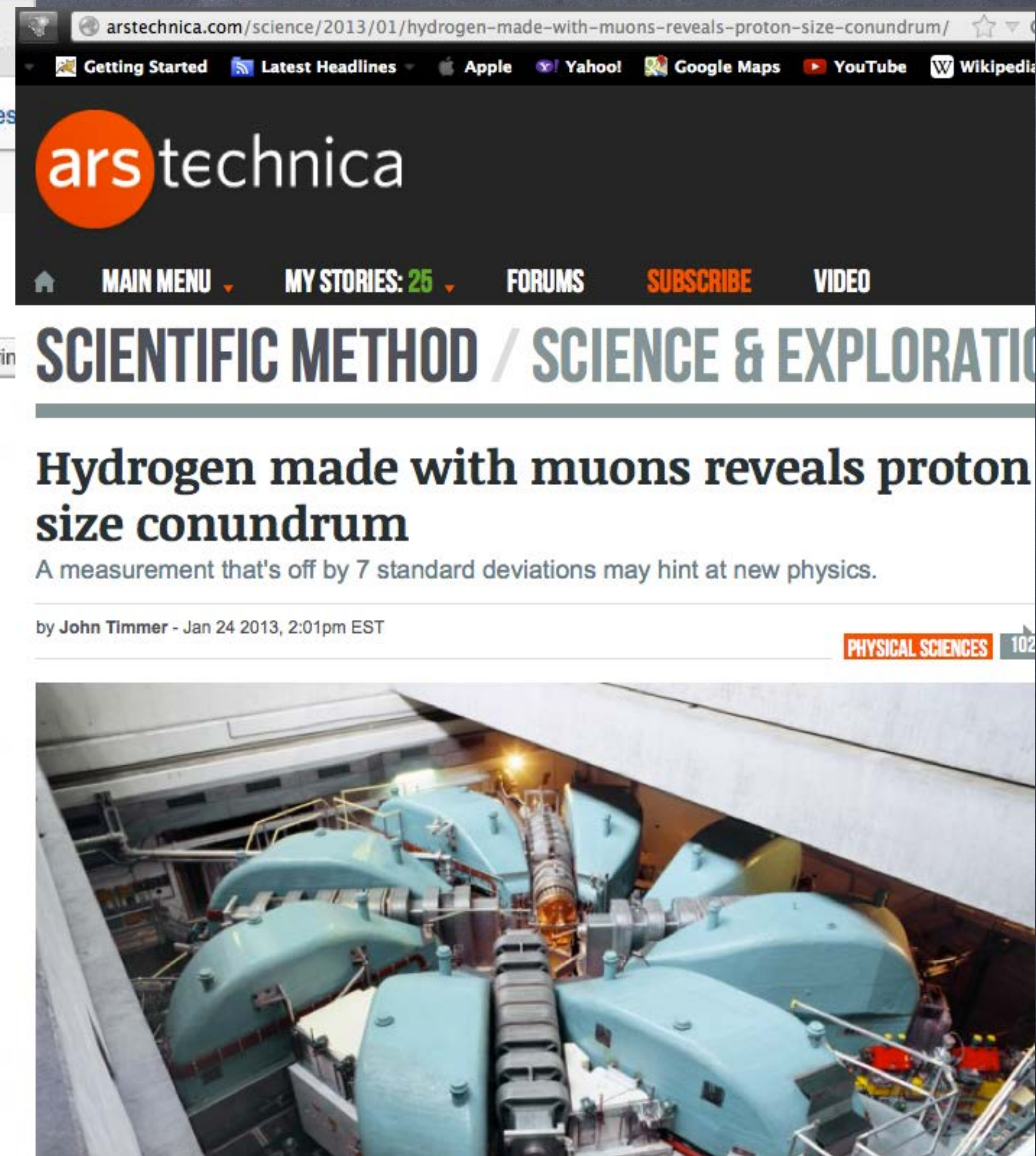
Does Size Matter? Protons May Be Smaller Than Previously Thought

January 25, 2013

Prin



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

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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

Physicists confirm surprisingly s

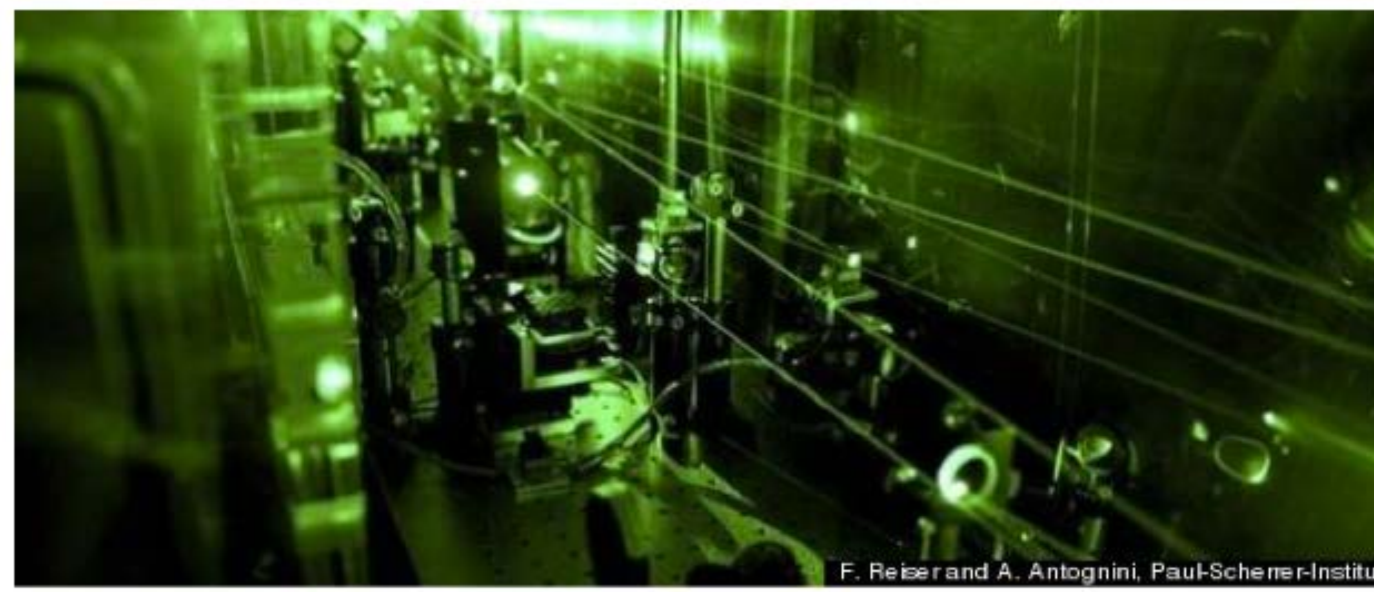
Jan 24, 2013

International team of physicists confirms surprisingly small proton
spectroscopy of exotic hydrogen. The initial results puzzled the w
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

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

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



F. Reiser and A. Antognini, Paul-Scherrer-Institut

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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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NATURE | NEWS

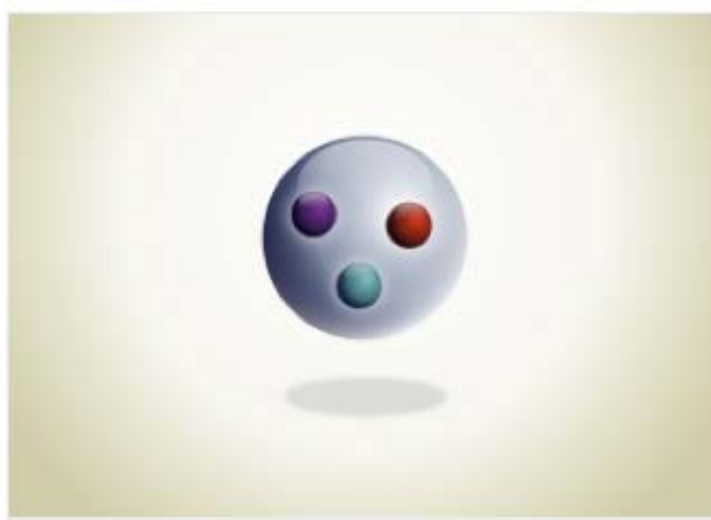
Shrunken proton baffles scientists

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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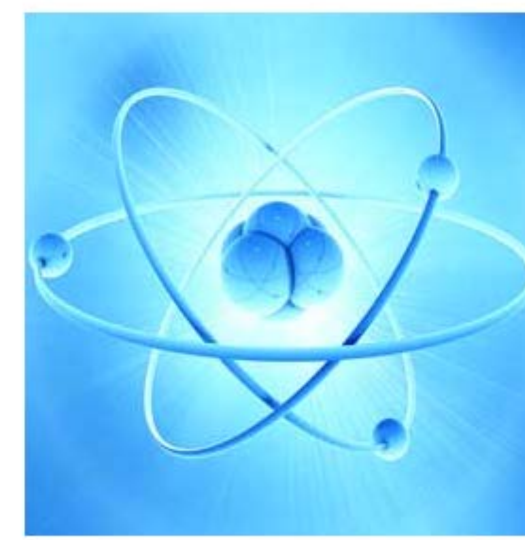
Shrunken Proton Baffles Scientists

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?

www.newscientist.com/article/mg21929262.100-particle-puzzle-honey-i-shrunk-the-proton.html

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Particle puzzle: Honey, I shrunk the proton

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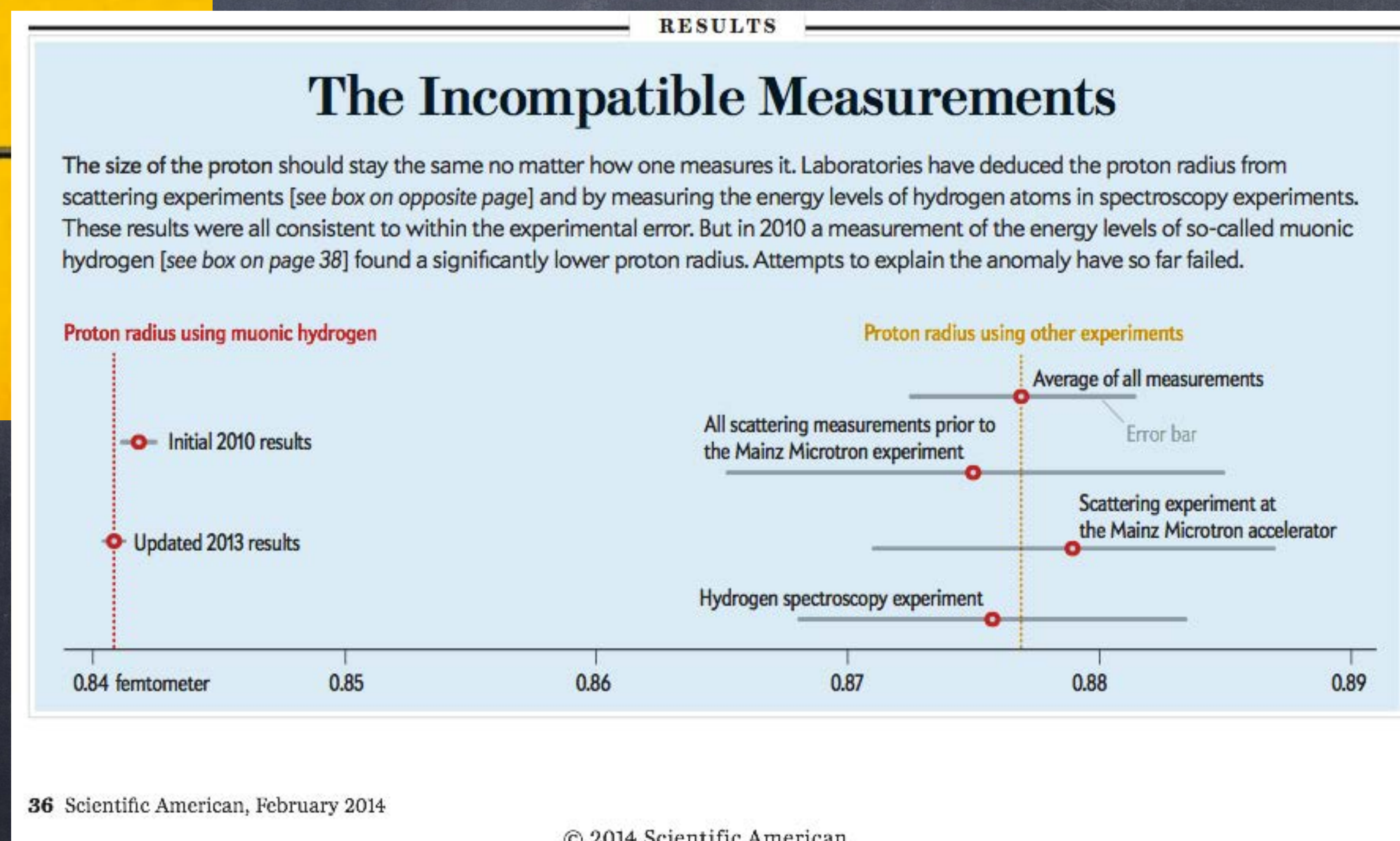
ONE quadrillionth of an inch. If you lost that off your waistline, you wouldn't expect a fuss. Then again, you are not a proton.

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.

36 Scientific American, February 2014

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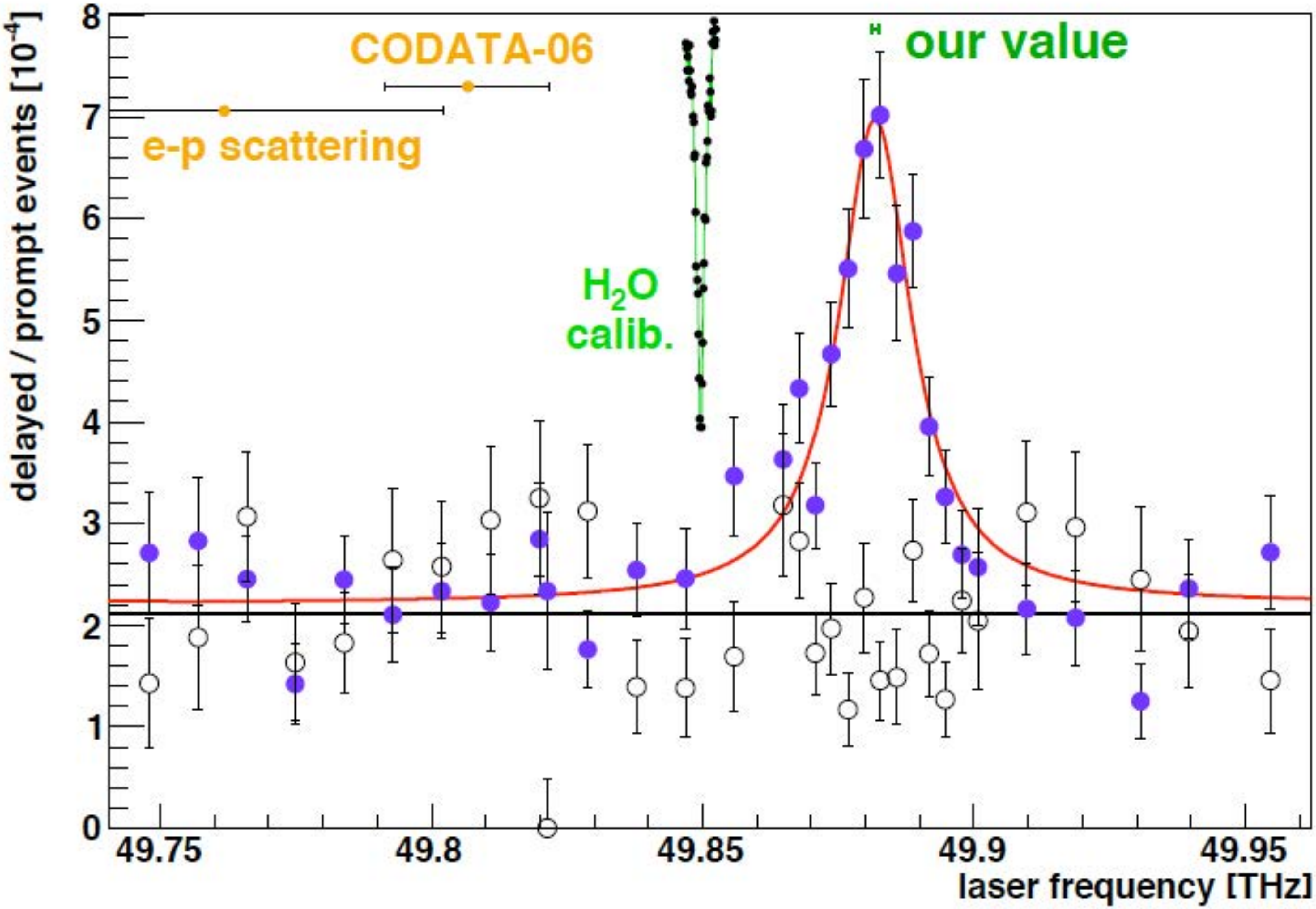
Nov 1, 2011 ... The recent discovery that the charge **radius** of **proton** deduced from quantum average of nuclear charge density from the muonic version of ...
vixra.org/abs/1111.0017 - Similar

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 even
20 references
in viXra.org

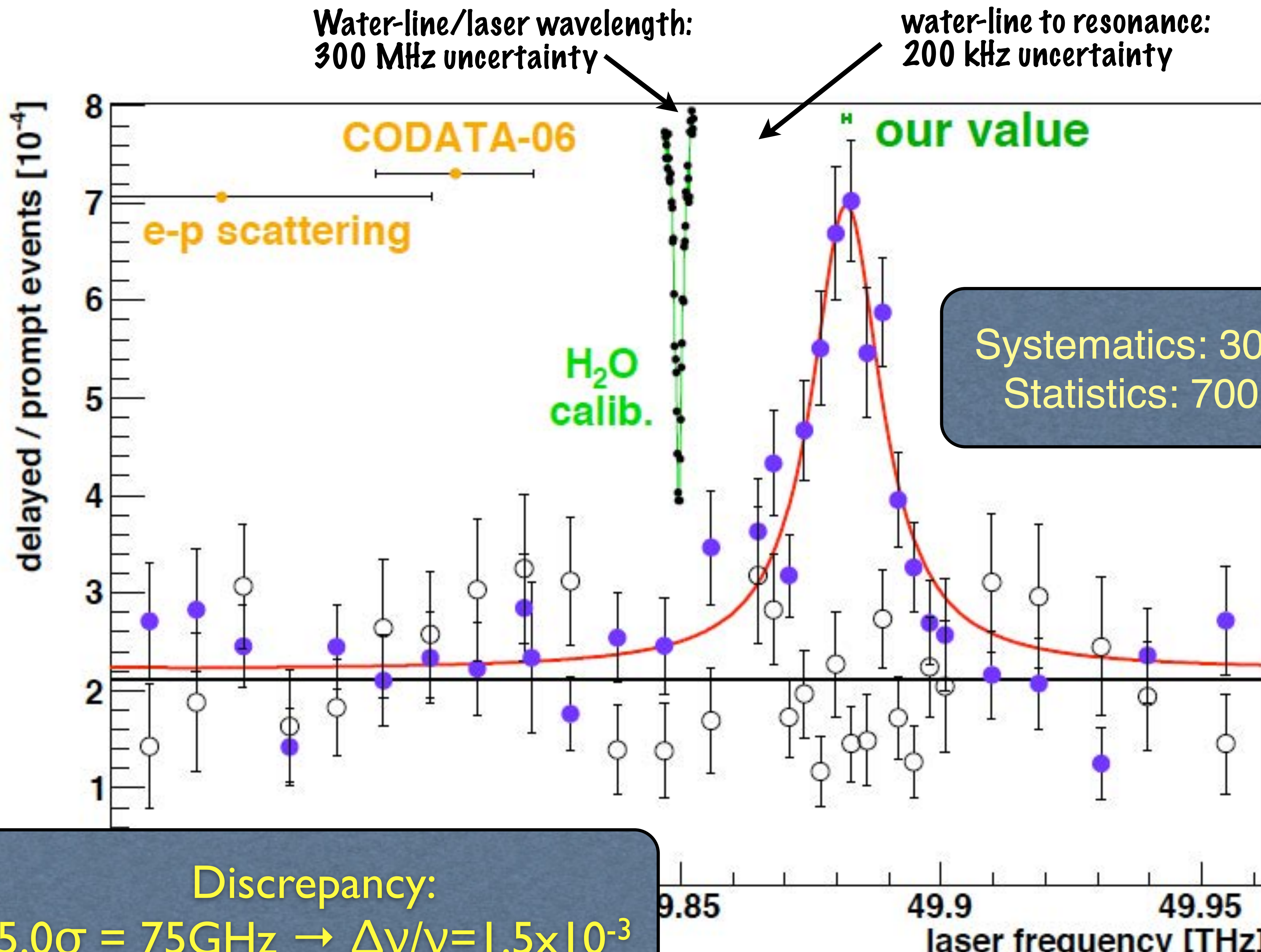
A look at possible experimental errors

Experimental Error?



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

Experimental Error?



Systematics: 300 MHz
Statistics: 700 MHz

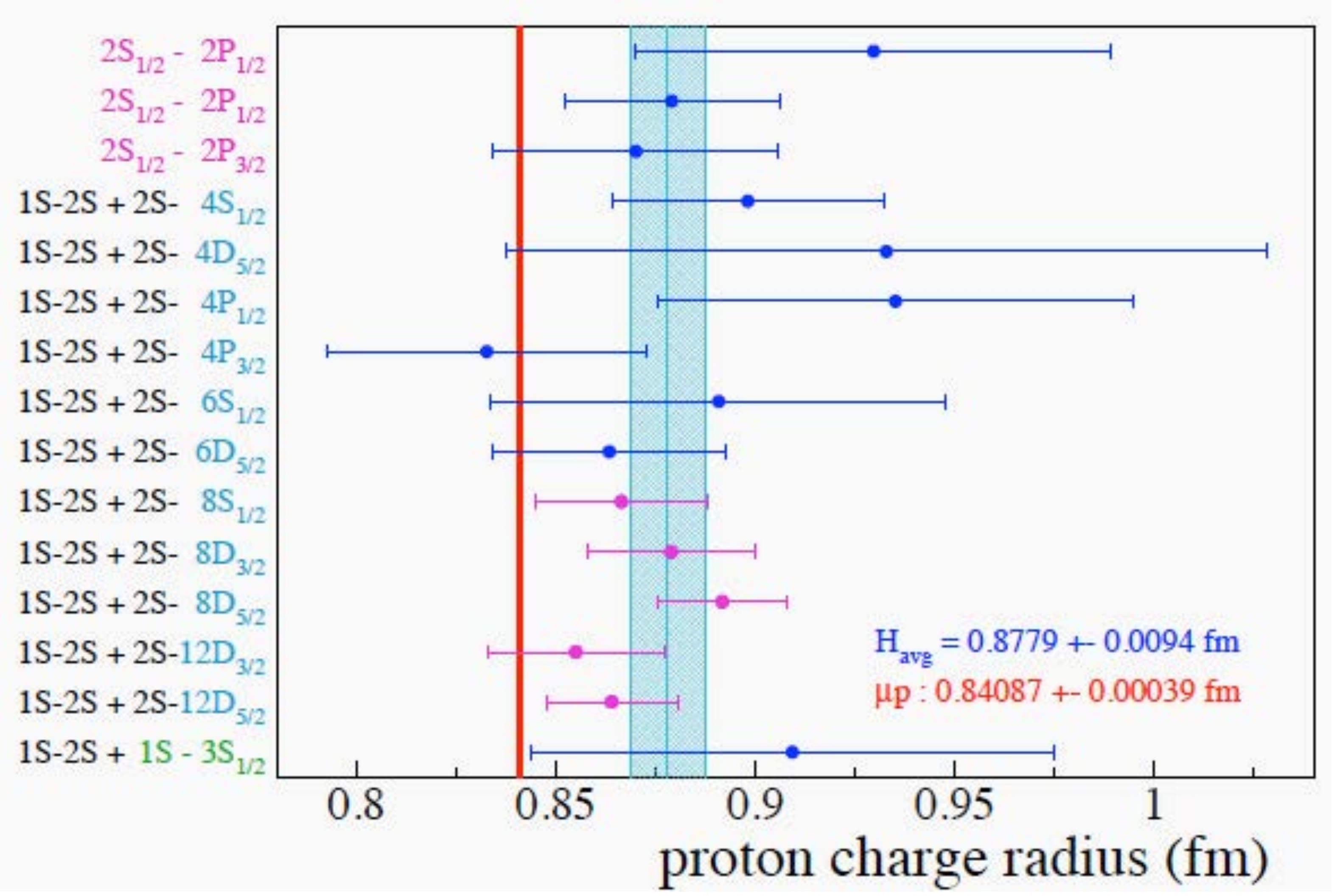
Discrepancy:
5.0σ = 75GHz → $\Delta\nu/\nu=1.5\times10^{-3}$

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.....



The Scattering Experiments

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

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

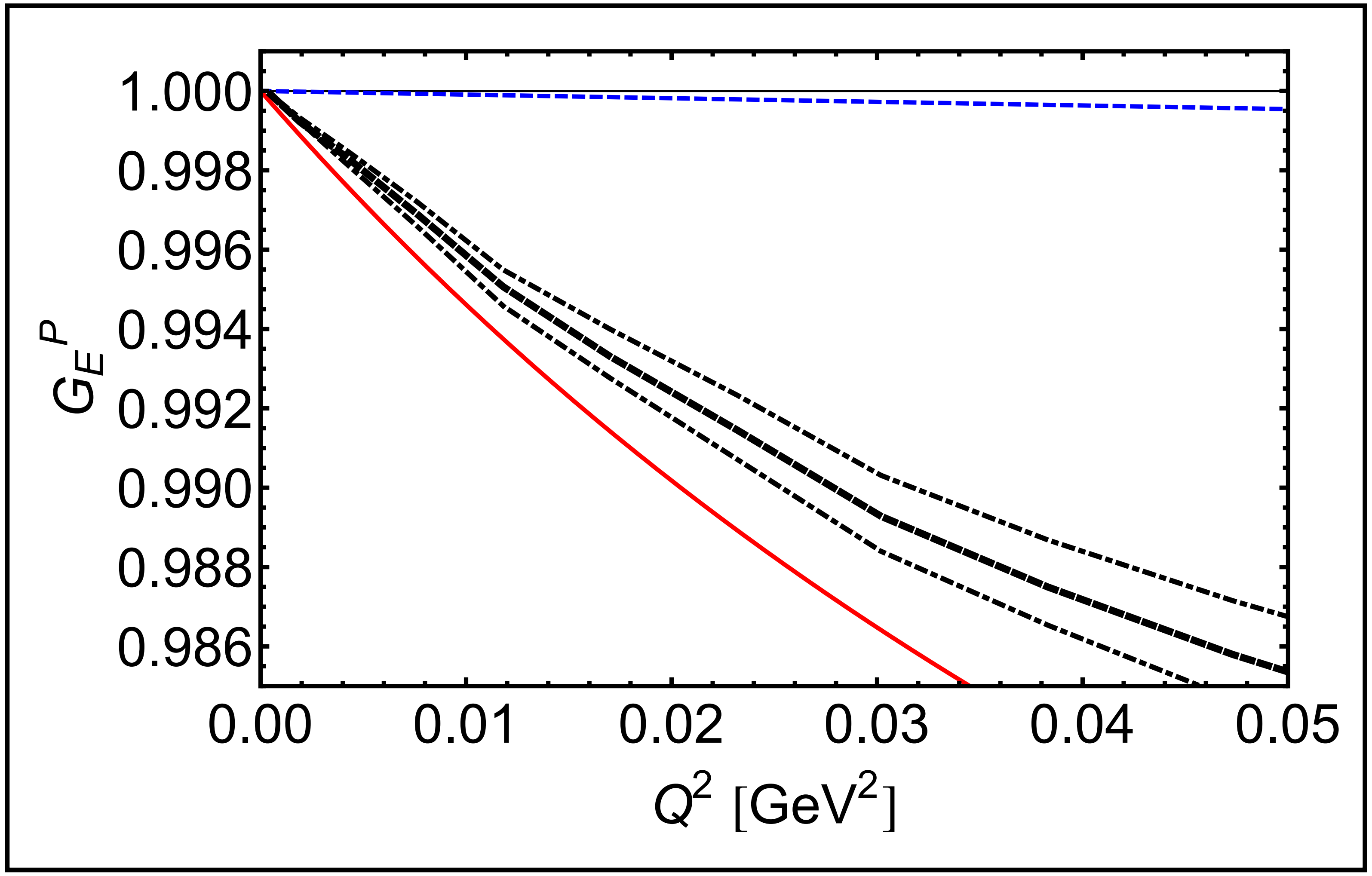
Until recently, all analyses ignored most of the following issues:

- 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.

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?

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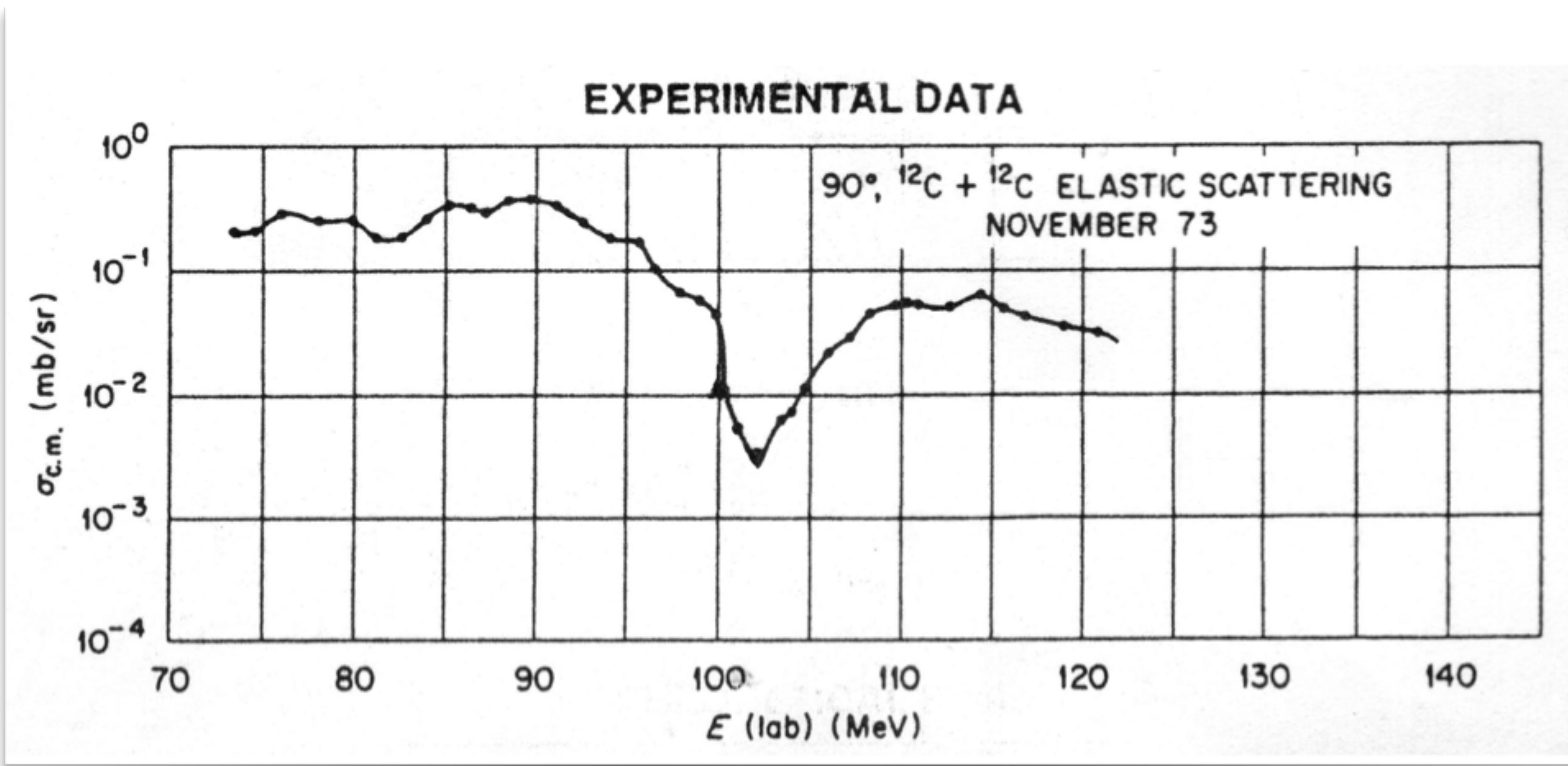

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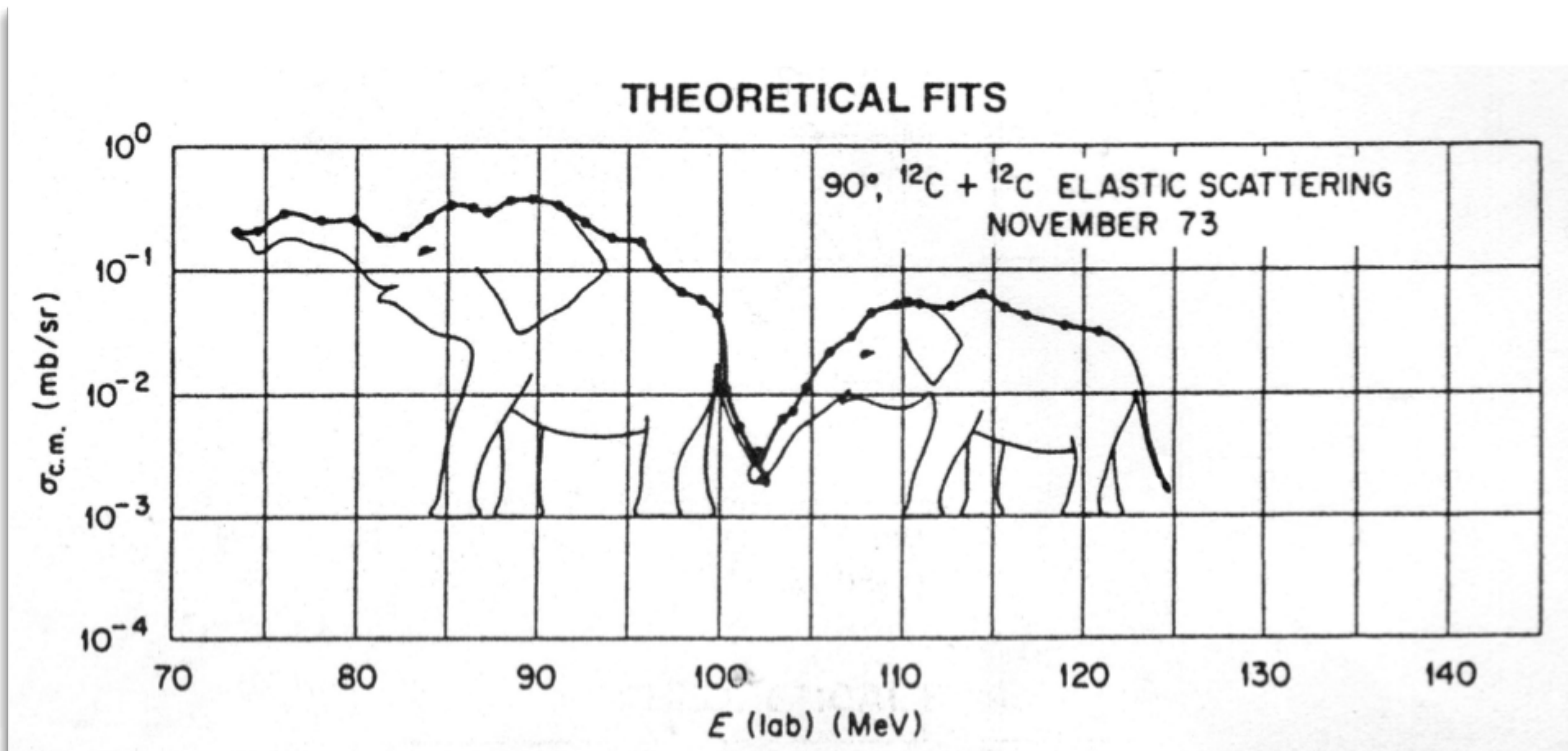

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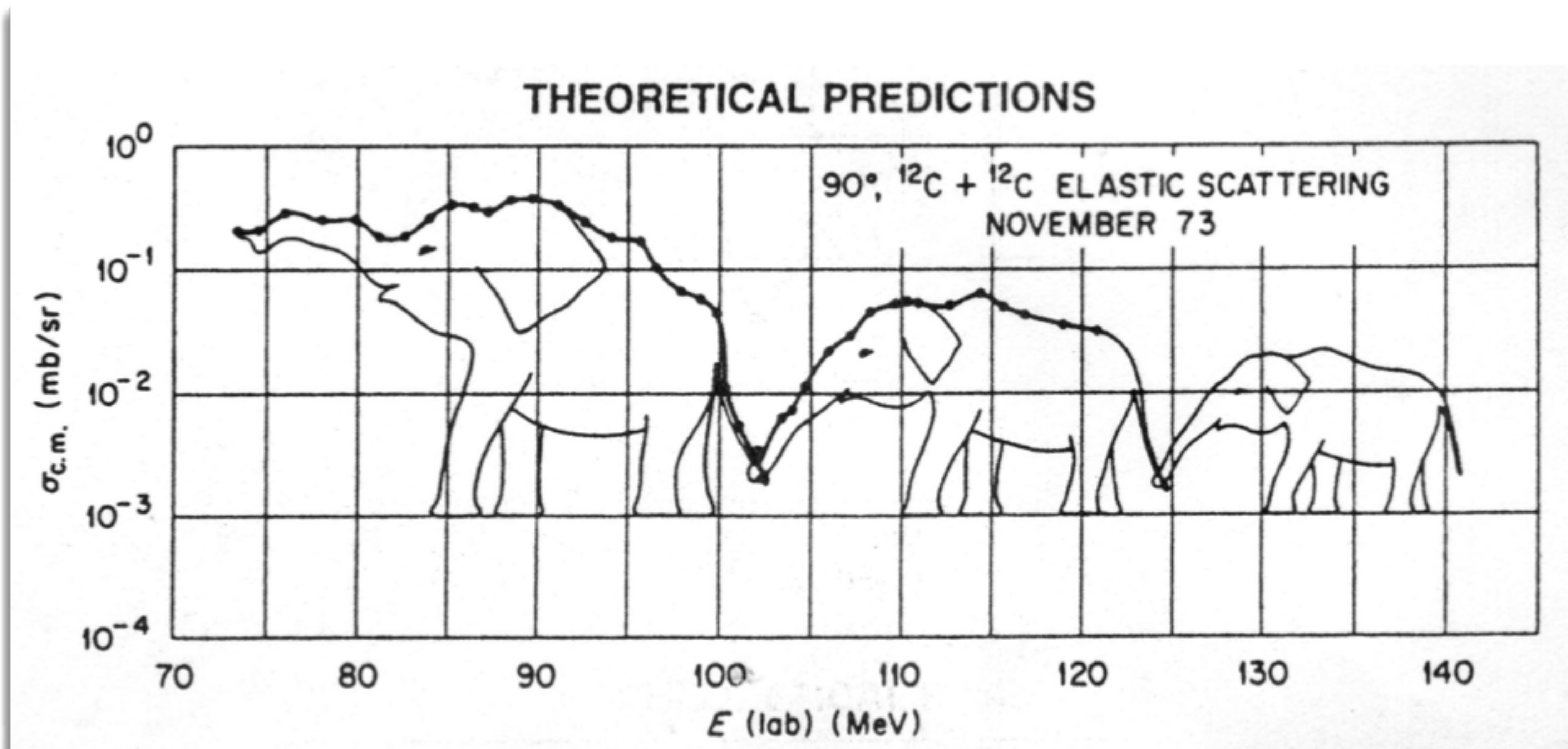
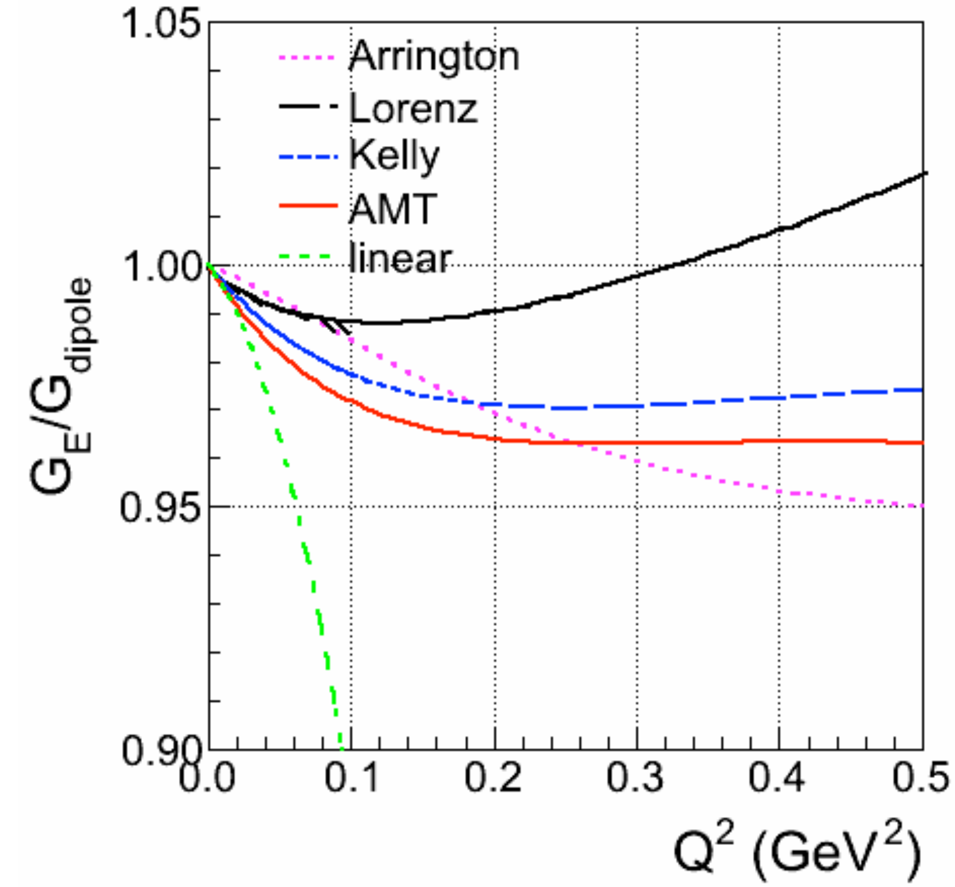
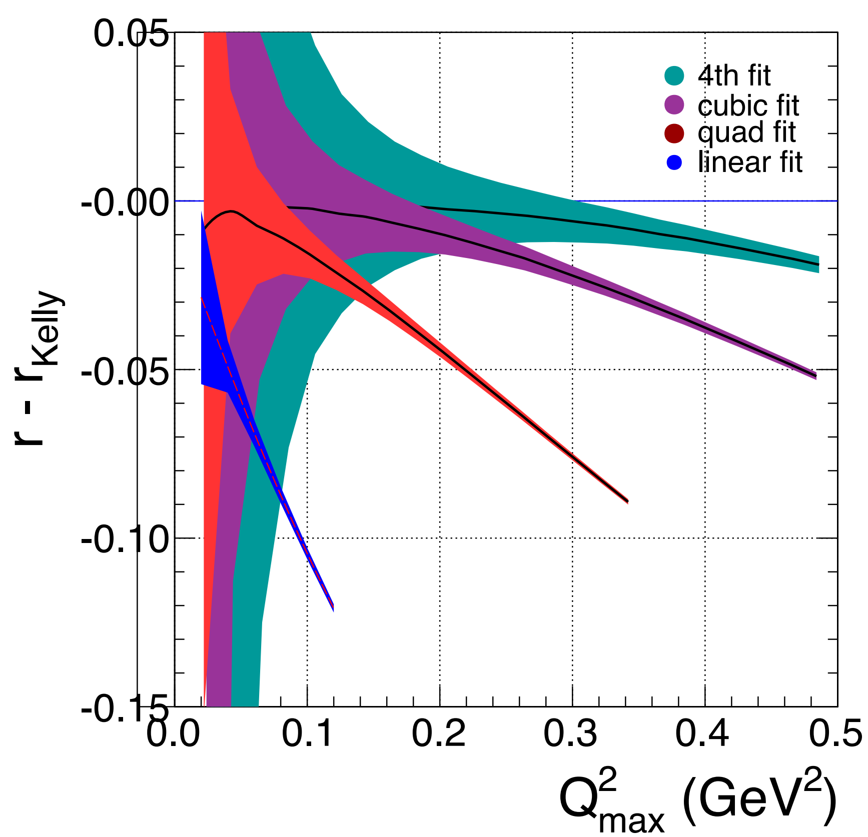


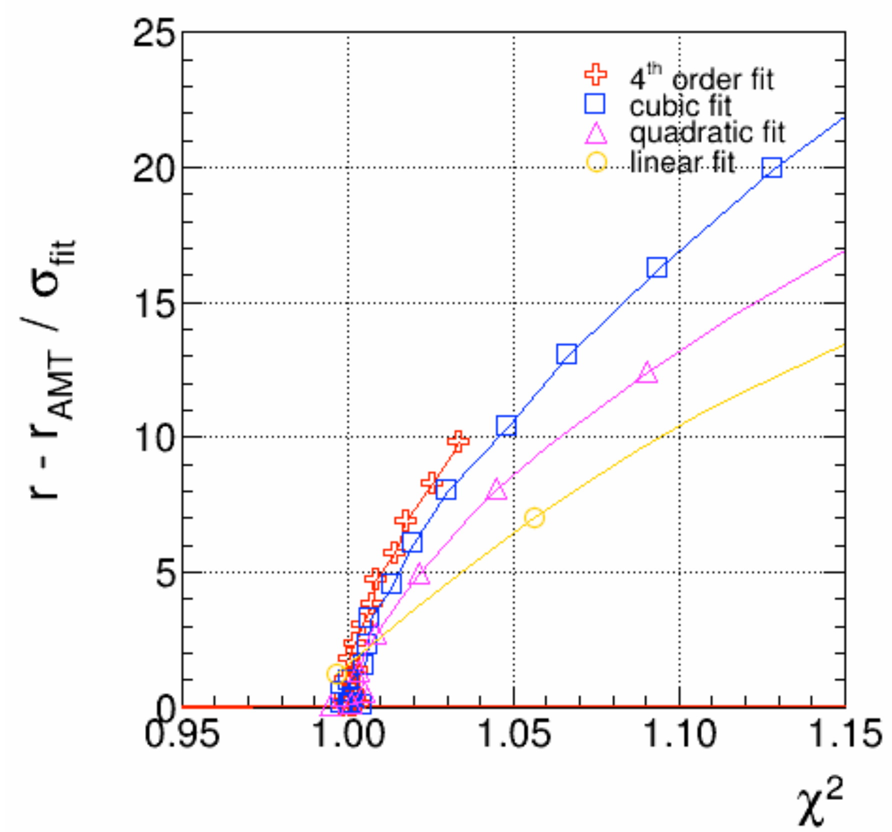
Truncation Errors

Gilman et al. studied truncation errors in Taylor series expansions by generating pseudodata from 4 world-data fits, and refitting the data, varying the order of the fit and max Q^2. The pseudodata were similar in density and uncertainties to the Mainz Bernauer data.

Low Q^2 fits are unreliable - and they always underestimate the radius!

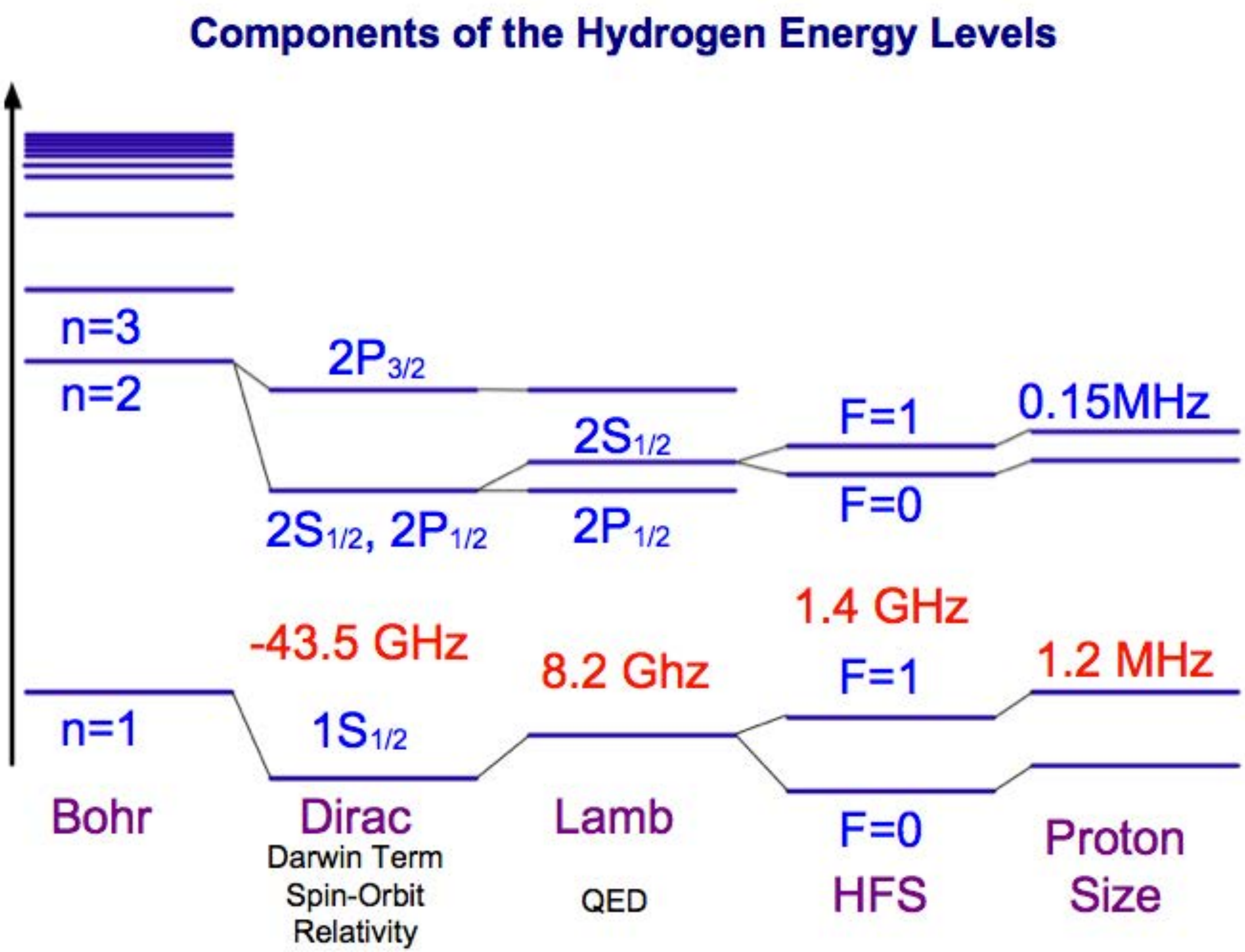






So it must be the theory....

Atomic Physics Gets Complicated...



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).

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

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

So it must be new physics....

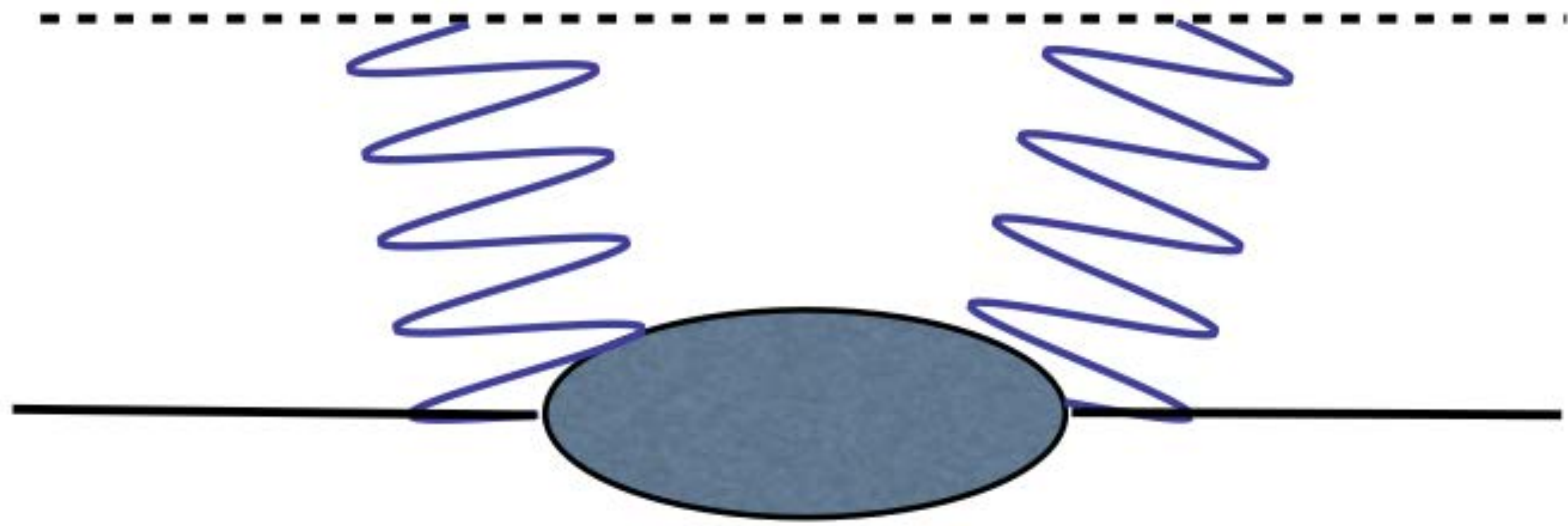
Possible Theory Explanations

- 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:

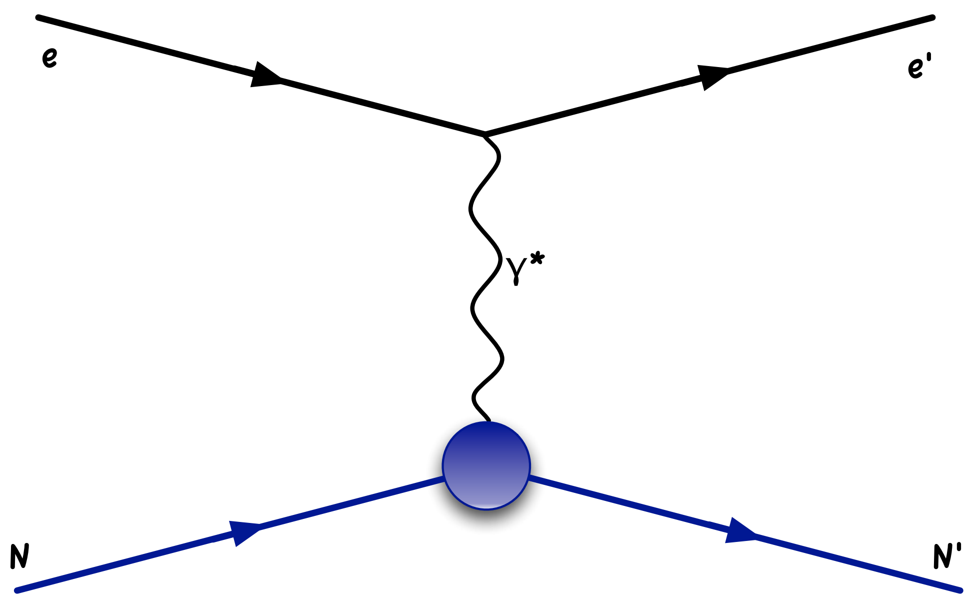
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

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



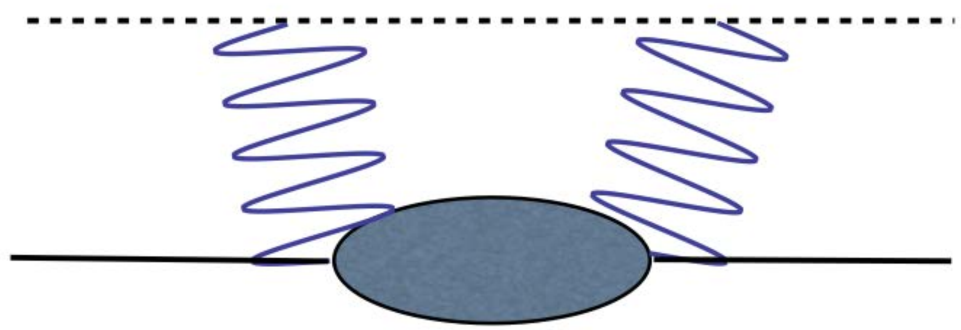
- Ideally (?), one new particle explains (dark photon?) Proton Radius Puzzle, μ g-2,

  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...

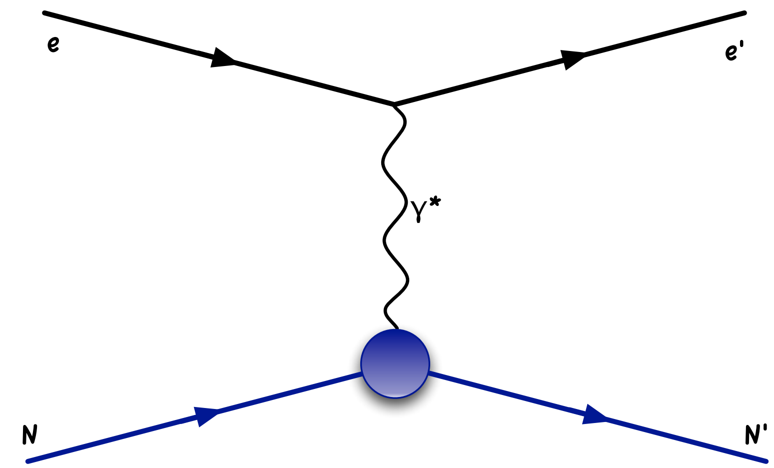
The (surviving) Theory Explanations

- 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

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 experiment planned for PSI (Already have preliminary results for ^4He).

- 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^+

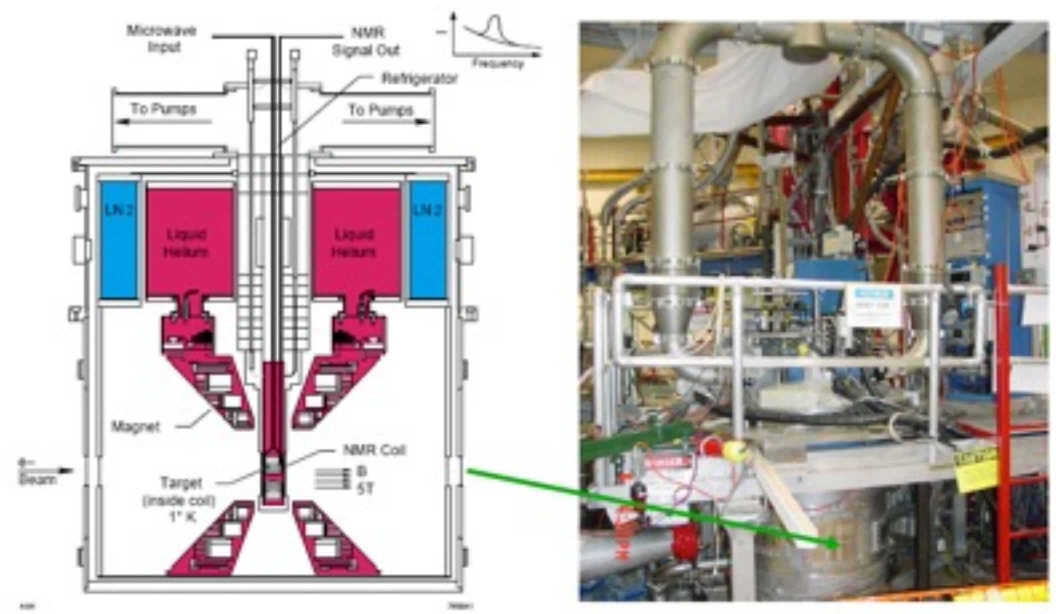
$$\Delta E(2P_{1/2} - 2S_{1/2})^{\mu^4He^+} = 1670.370(600) - 105.322 r_{He}^2 + 1.529 r_{He}^3 \ meV$$
$$= 403.893(145) - 25466 r_{He}^2 + 370 r_{He}^3 \ GHz$$

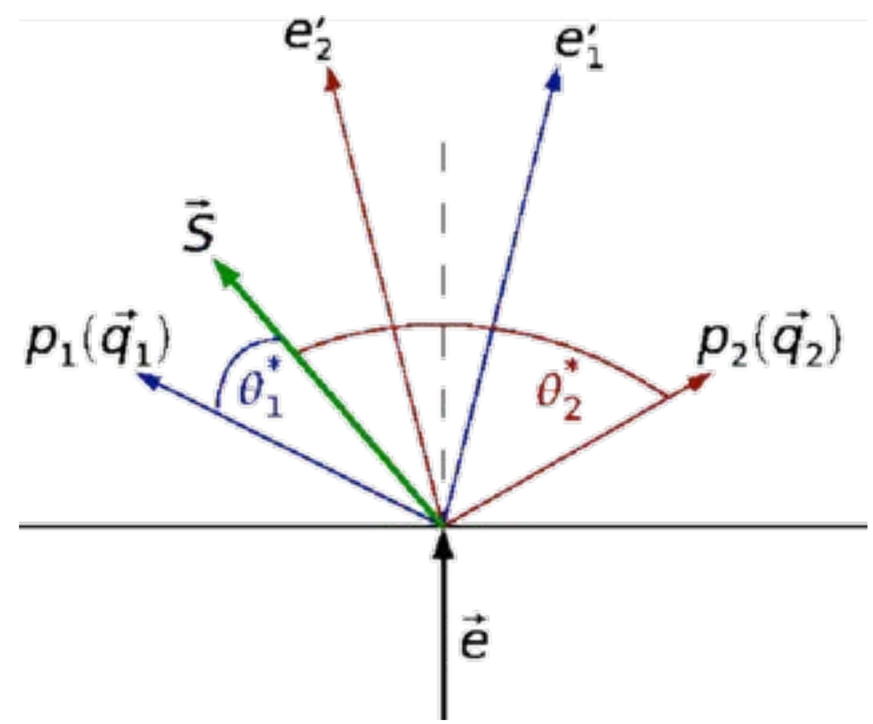
A. Antognini et al, Can. J. Phys. 89, 47 (2011)

Where to now?

E08007 - Part II

- High precision (< 1%) survey of the FF ratio at Q^2=0.01 - 0.16 GeV^2.
- Beam-target asymmetry measurement by electron scattering from polarized NH_3 target.
- Electrons detected in two matched spectrometers.
- Ratio of asymmetries cancels systematic errors → only one target setting to get FF ratio.
- Ran Feb-May 2012 - Moshe Friedman (HUJI) Thesis project.
- Expect final results in 2-3 months.

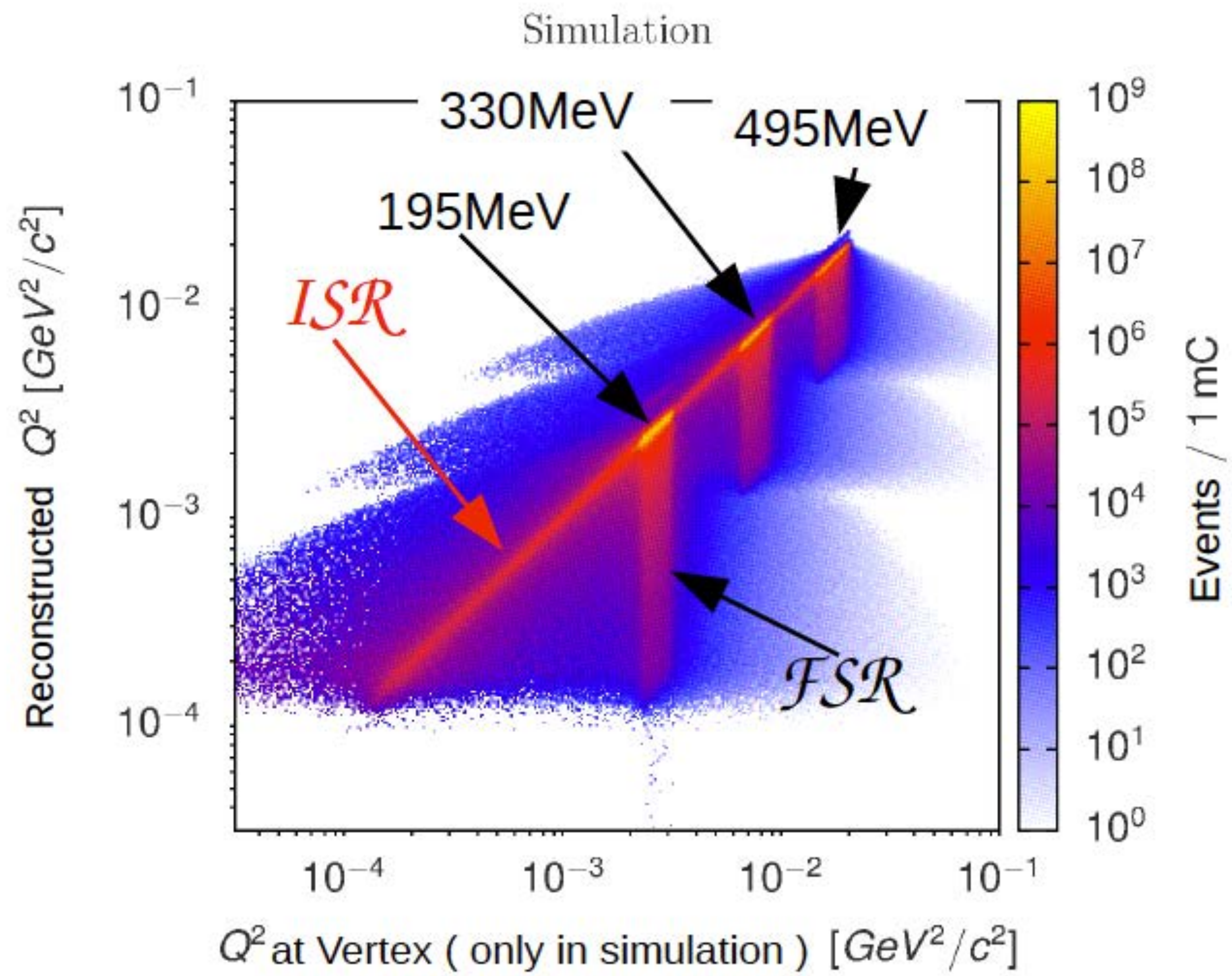


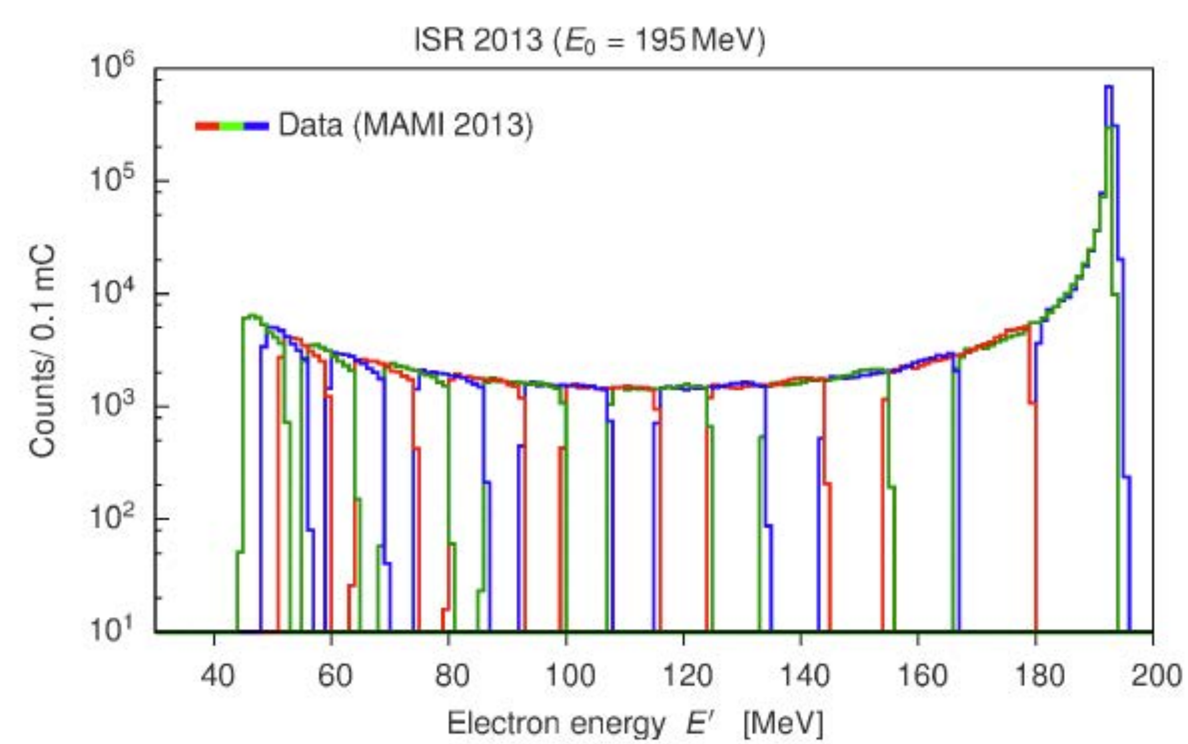


Where to now?

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?

Newest Idea
μP Scattering

- 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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Tel Aviv University
E Fuchey, Z-E Meziani, E Schulte
Temple University
N Liyanage
University of Virginia
C Perdrisat
College of William & Mary

MUSE - PSI R12-01.1 Technique

r	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)

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

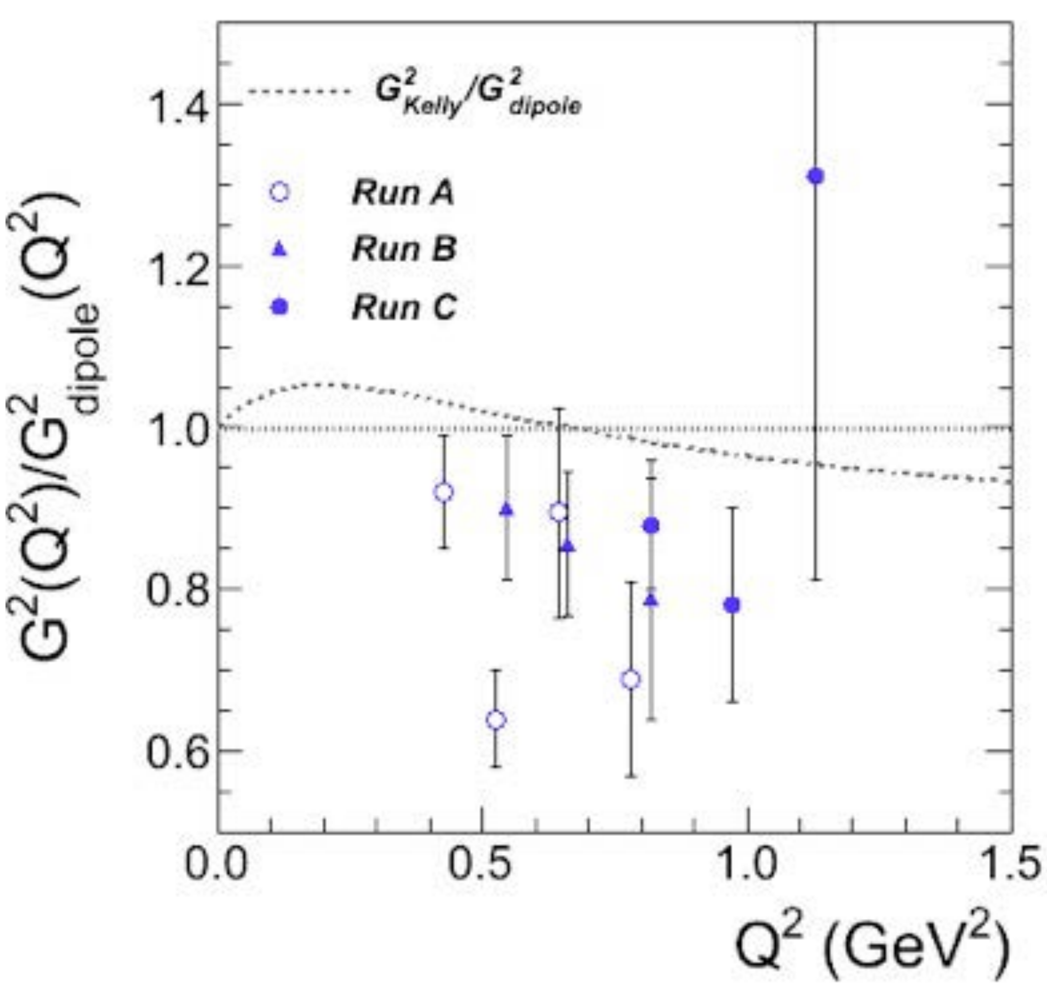
$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2} \frac{1-\eta}{\eta^2} \frac{1/d}{\left[1 + \frac{2Ed}{M}\sin^2\frac{\theta}{2} + \frac{E}{M}(1-d)\right]} \qquad d = \frac{\left[1 - \frac{m^2}{E^2}\right]^{1/2}}{\left[1 - \frac{m^2}{E'^2}\right]^{1/2}}$$

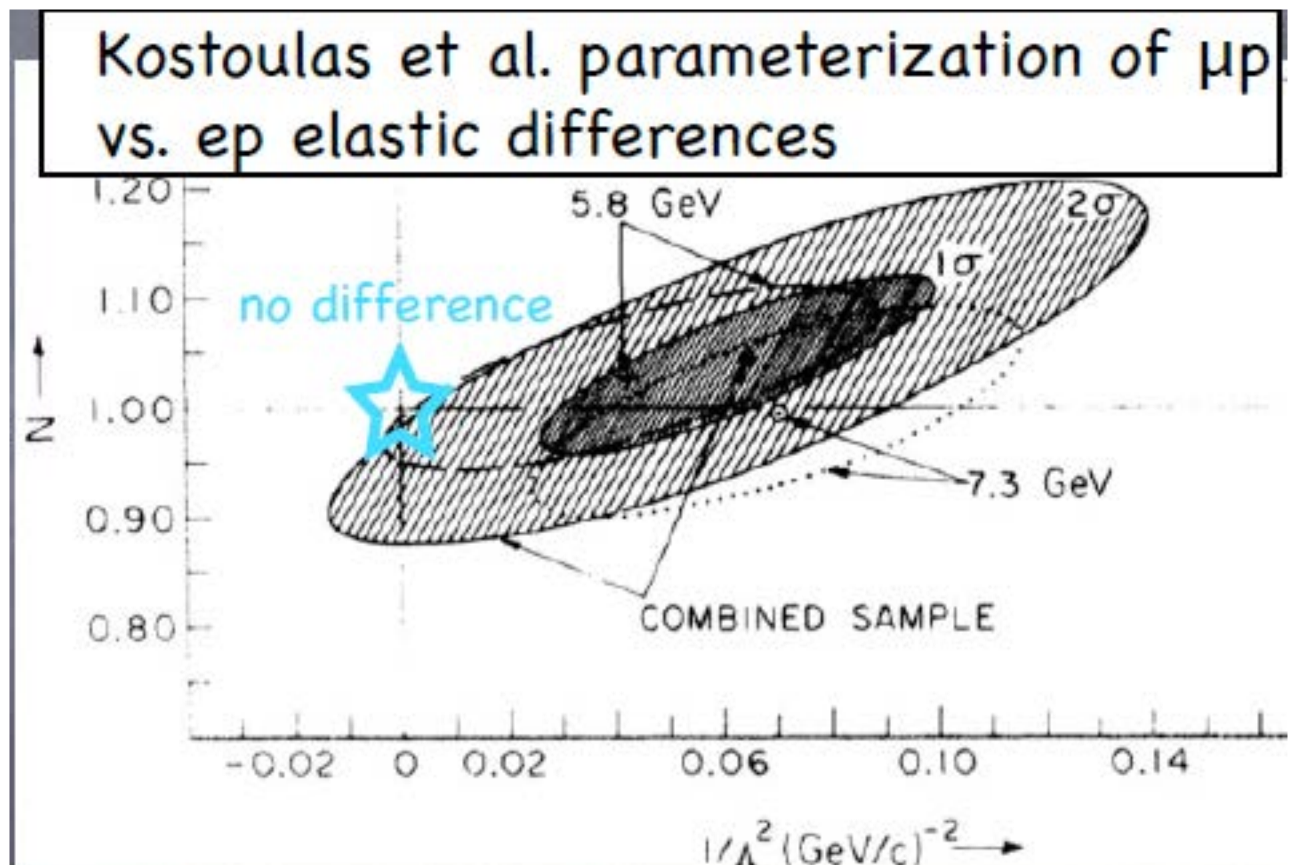
$$\eta = Q^2/4EE'$$

following Preedom & Tegen, PRC36, 2466 (1987)

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.





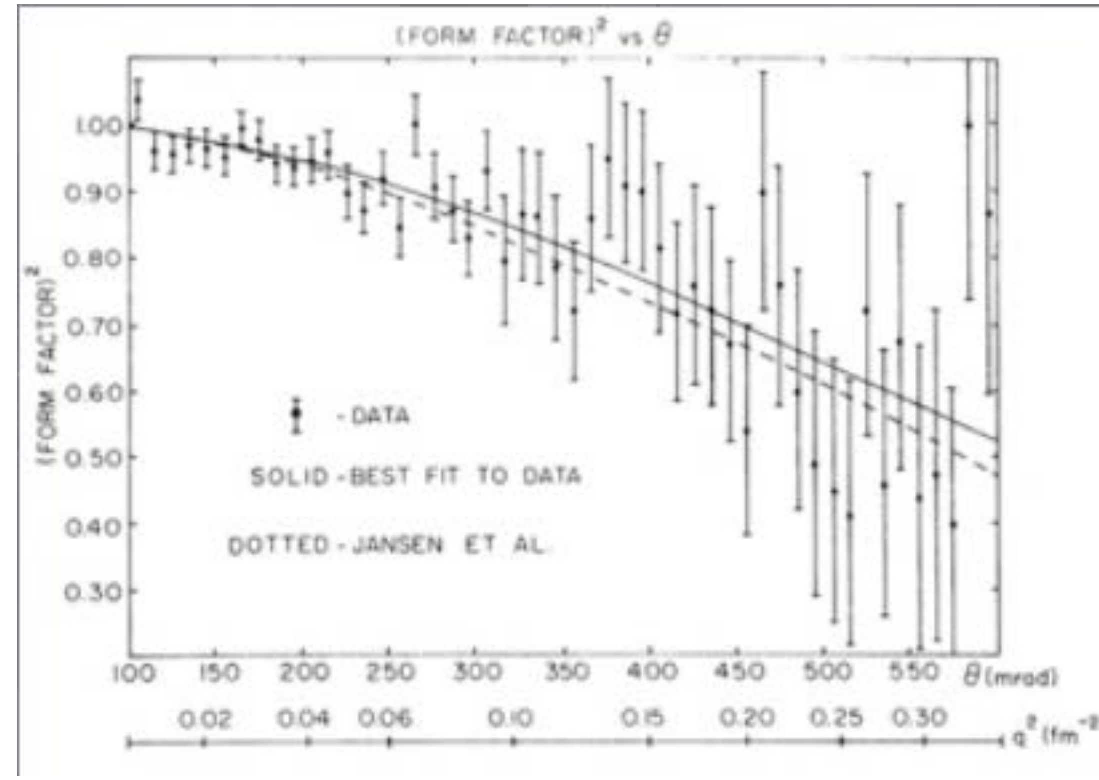
e-μ Universality

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.

MUSE is not your garden variety scattering experiment

Low beam flux

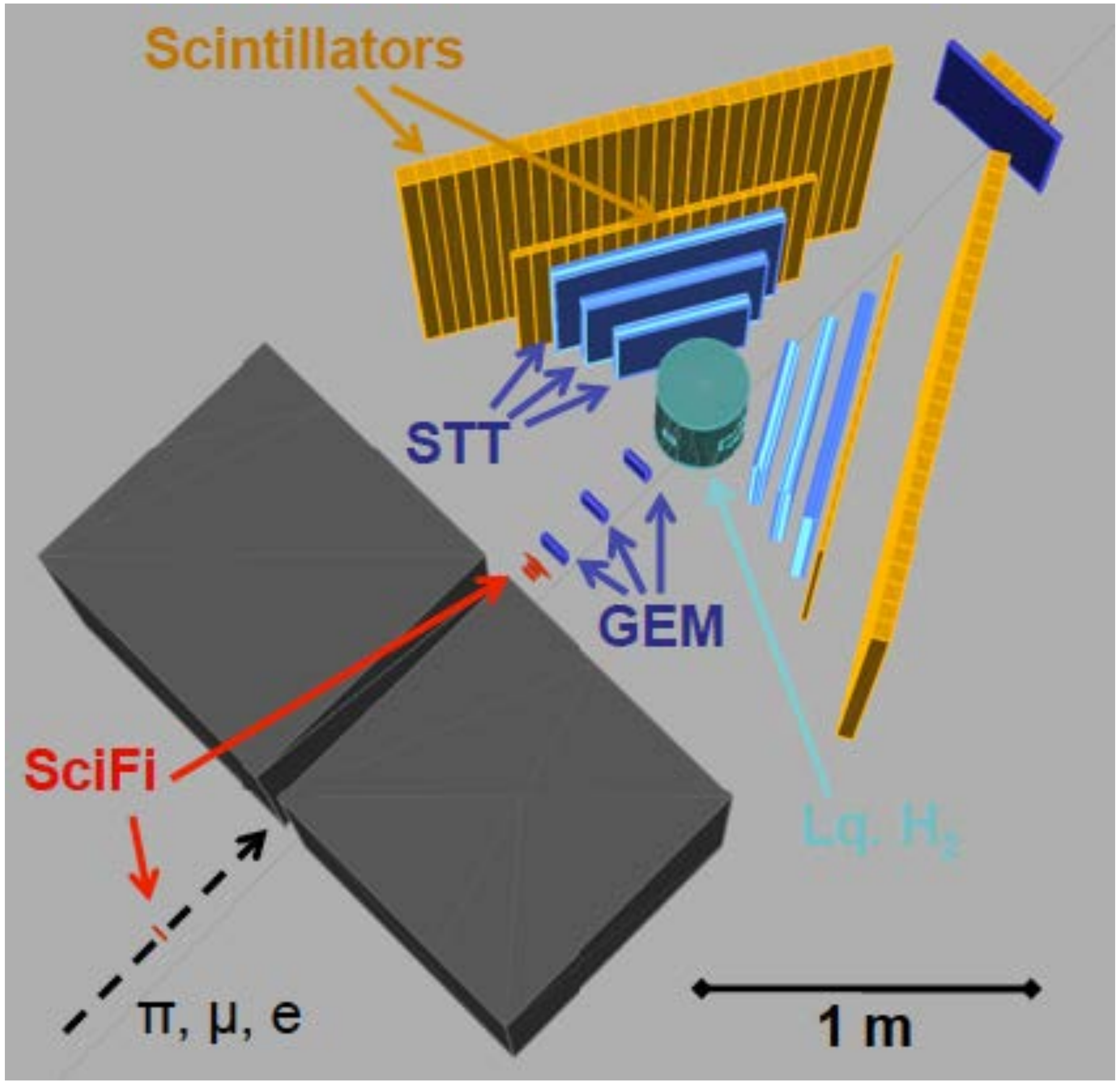
- Large angle, non-magnetic detectors.

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 $\pi^{\pm}$

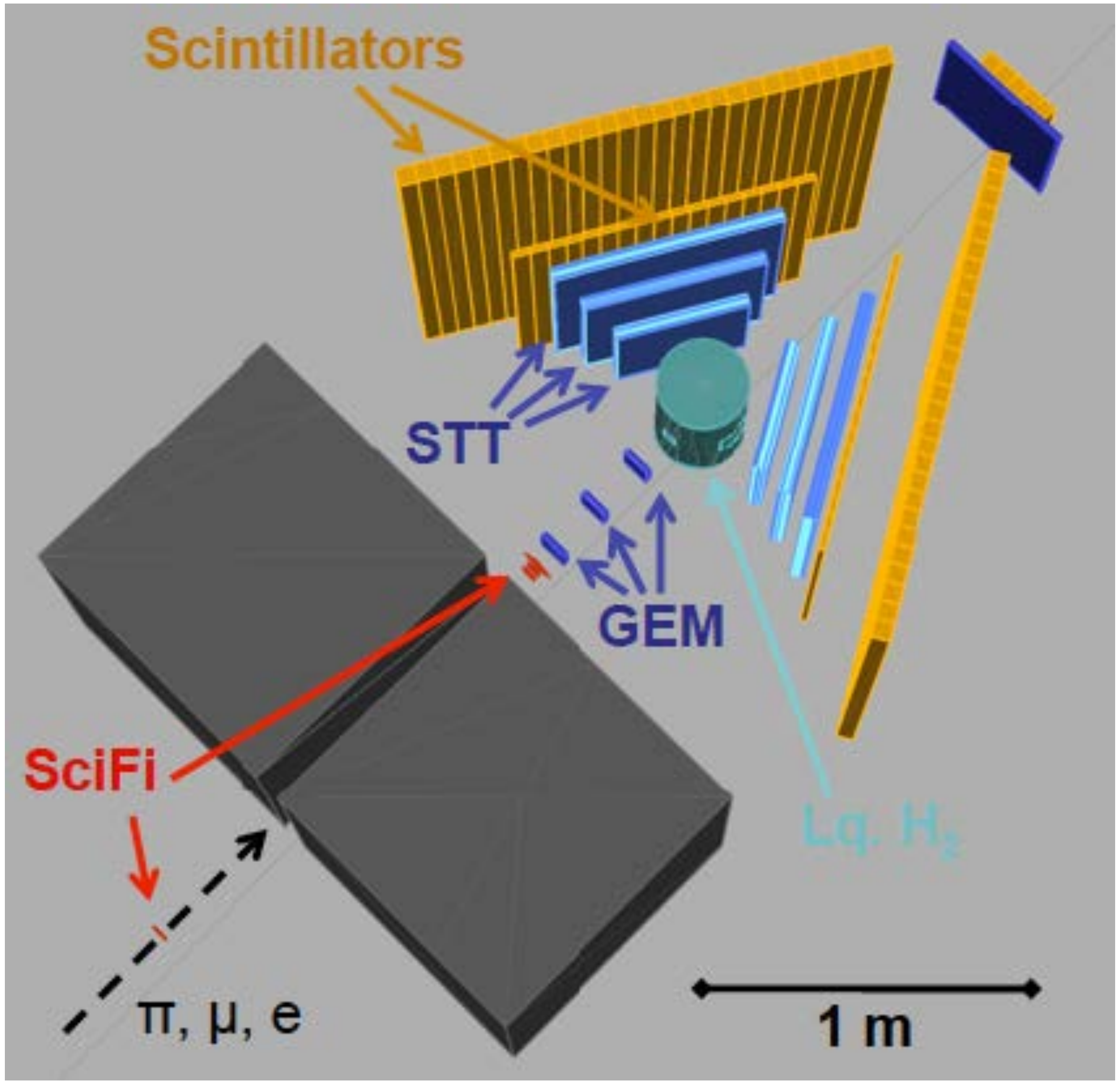
$\theta \approx 20^o - 100^o$

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

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

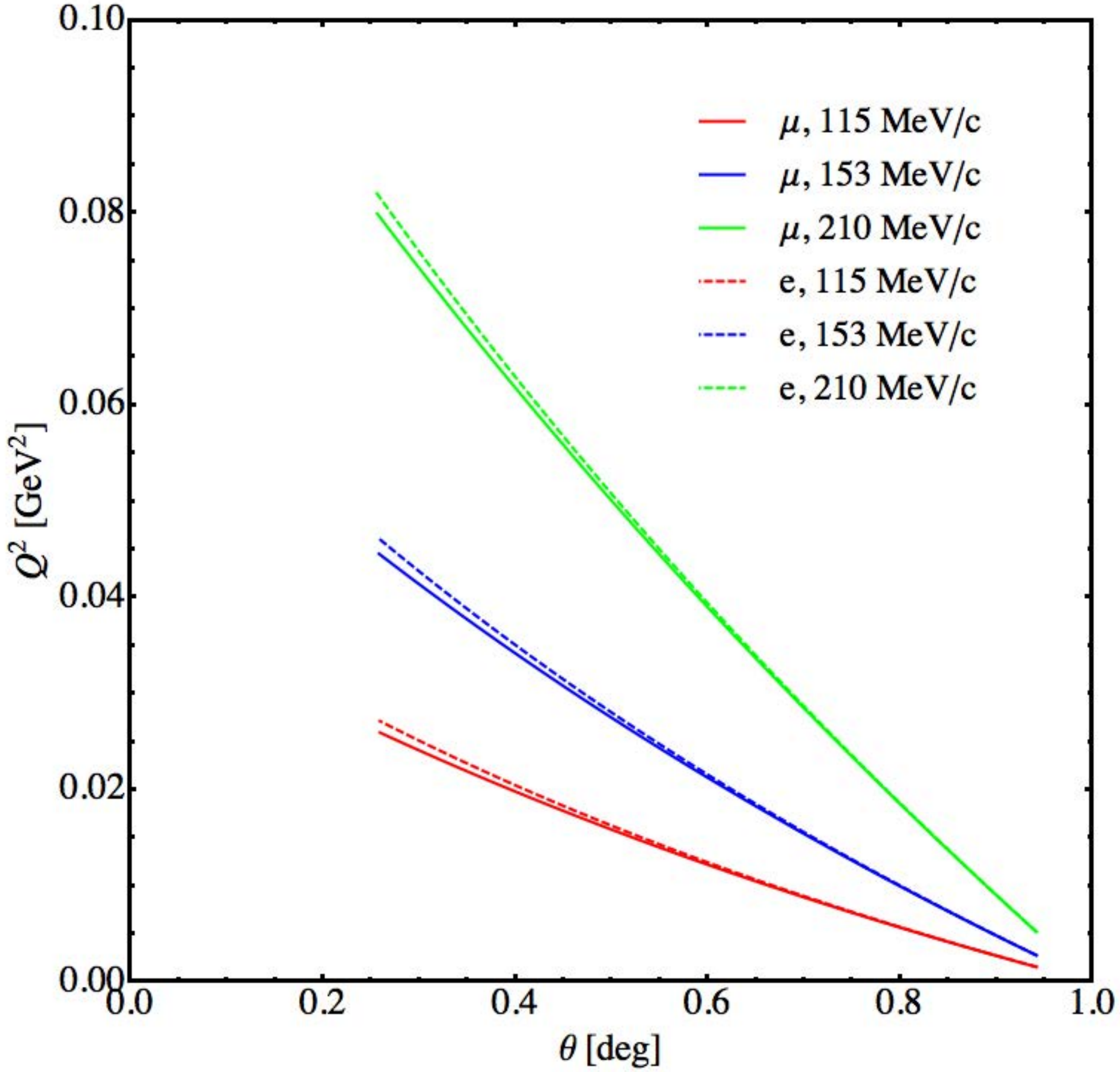
Beam monitored with SciFi, beam Cerenkov, GEMs

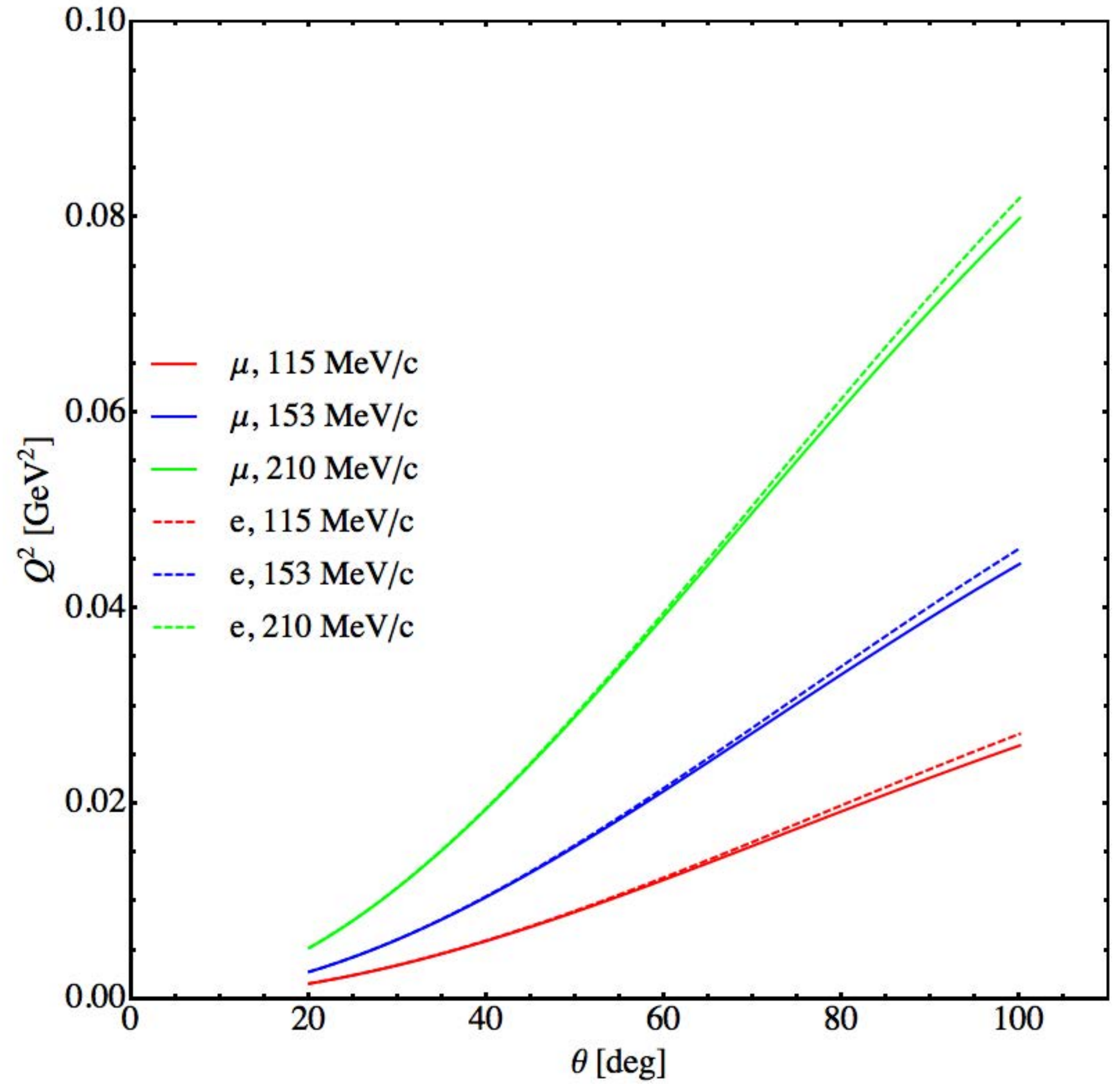
Scattered particles detected with straw chambers and scintillators



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, ...

Experiment Overview





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

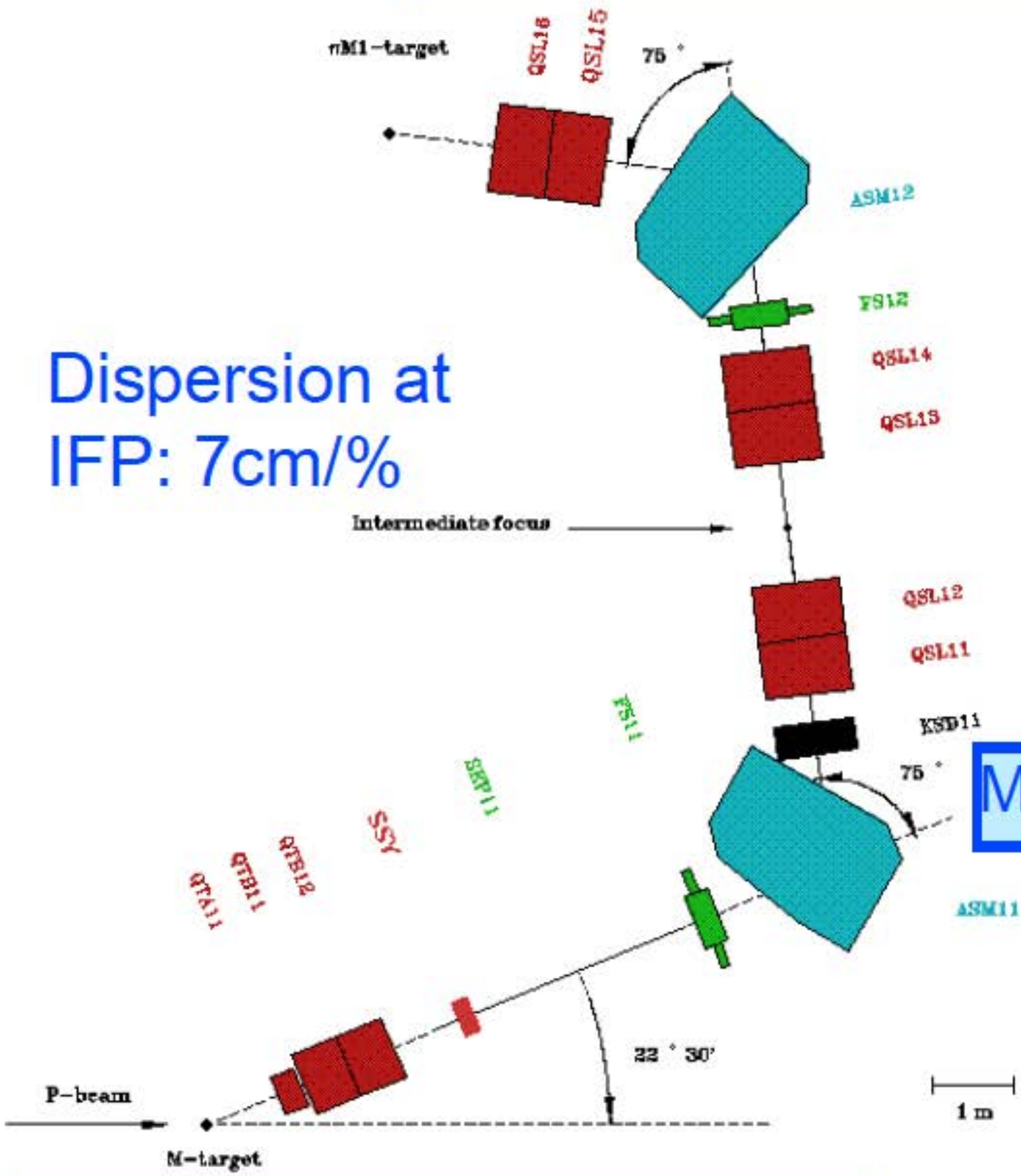
$Q^2 \approx 0.0015 - 0.08$ GeV^2

$\varepsilon \approx 0.256 - 0.94$

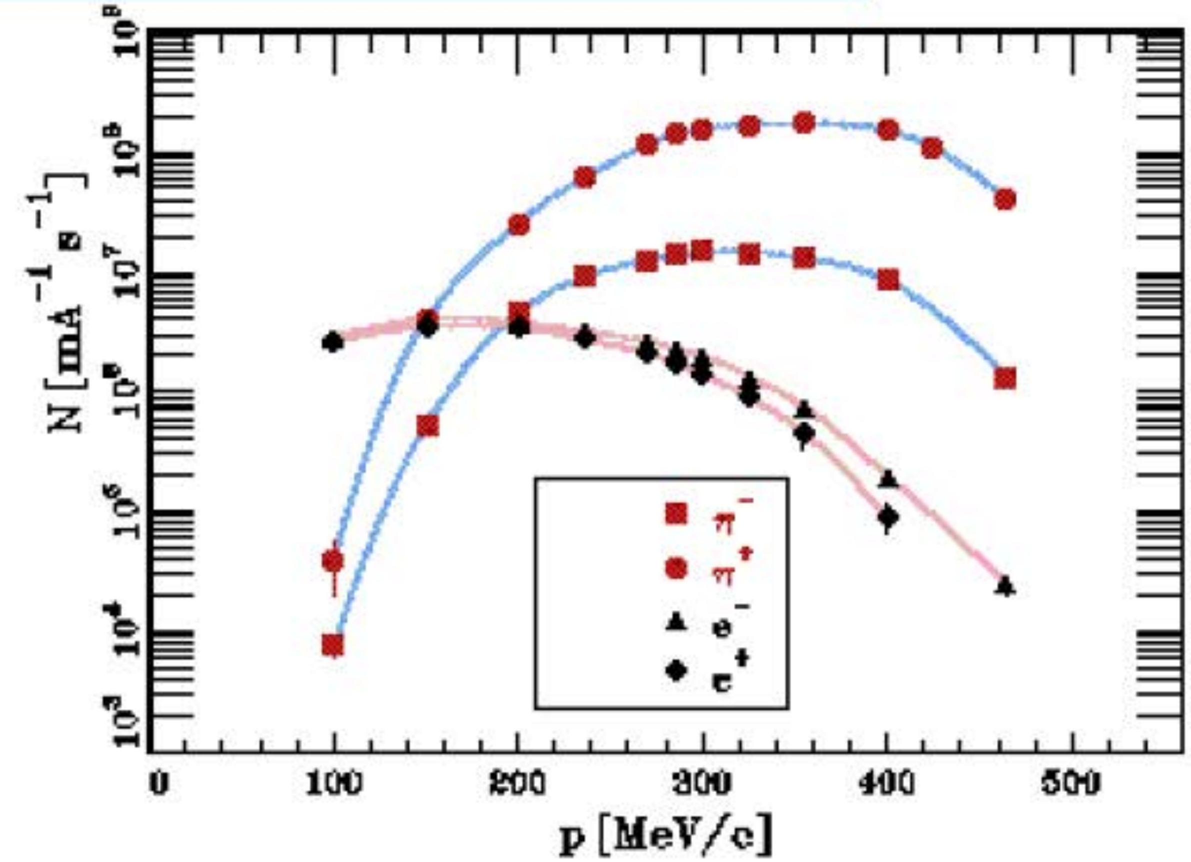
Essentially same coverage for all beam particles.

PSI πM1 Channel Characteristics

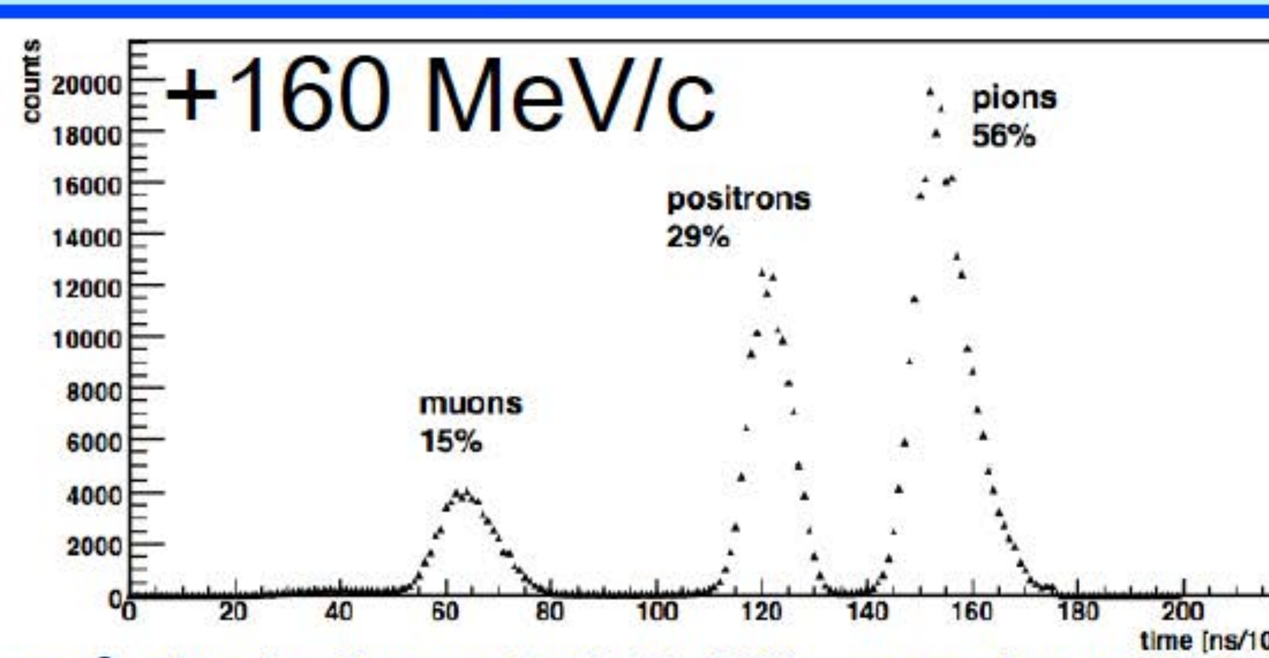
≈100 - 500 MeV/c mixed beam of μ's + e's + π's



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.

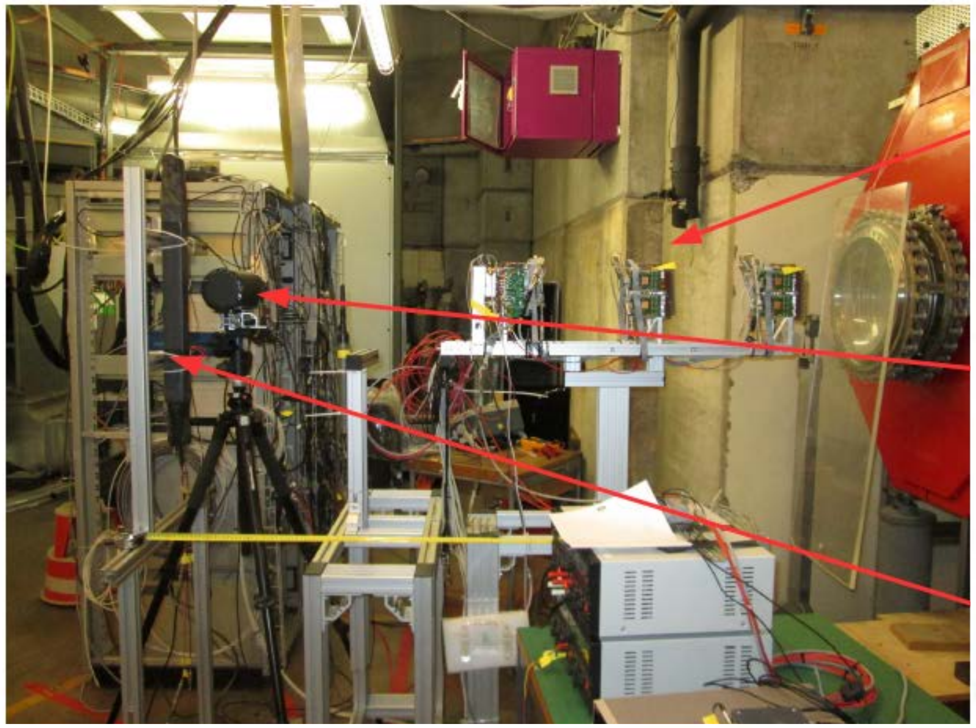
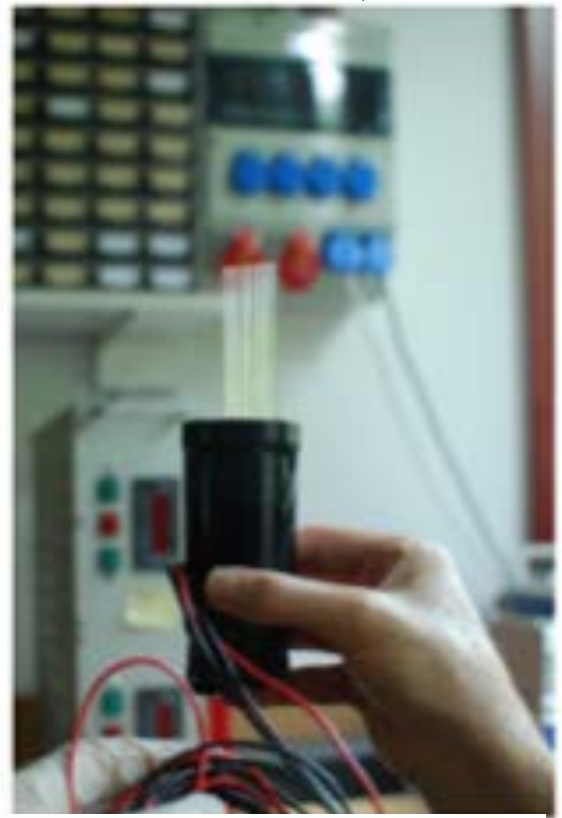
MUSE Test Runs

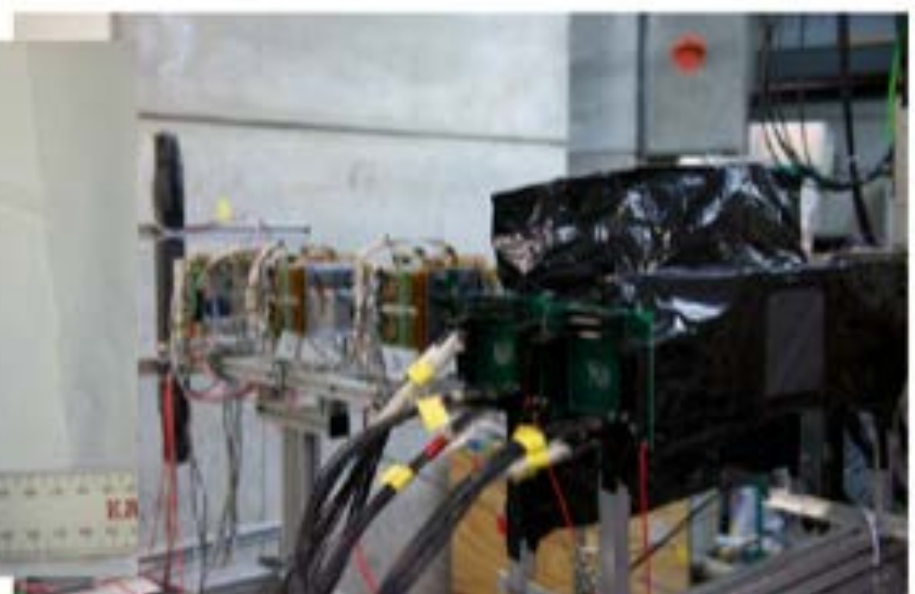
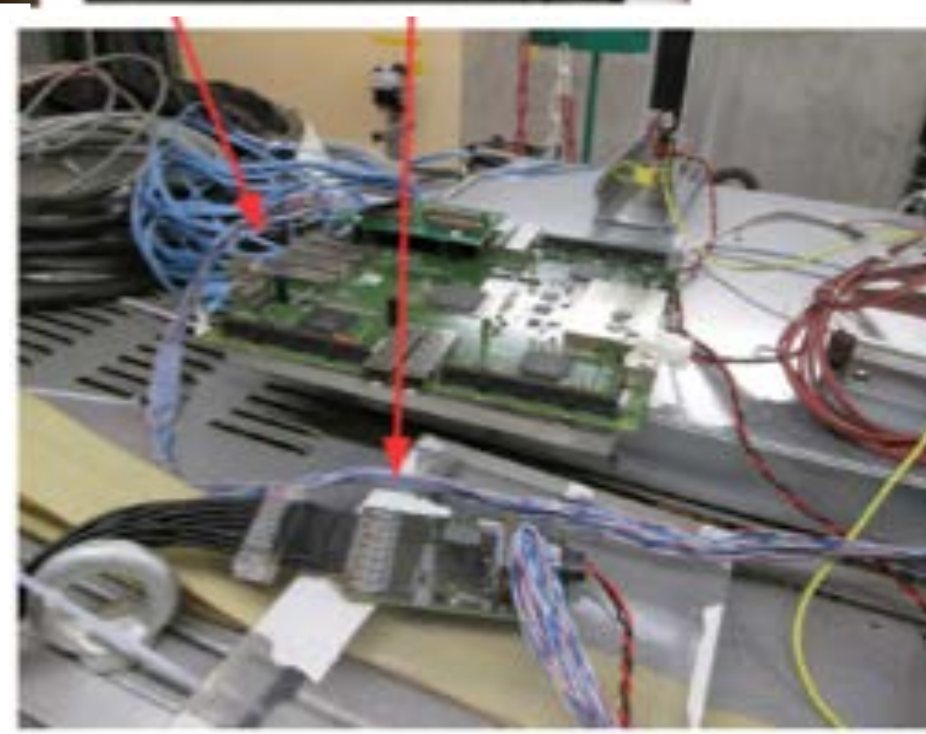
- 7 MUSE Test Runs
  - October 2012
  - May-June 2013
  - October 2013*
  - December 2013
  - June 2014
  - December 2014
  - February 2015*
- Representation from 12 institutions, 30 individuals (Faculty, Postdocs, Graduate Students, Undergraduate Students)

*tests with no beam

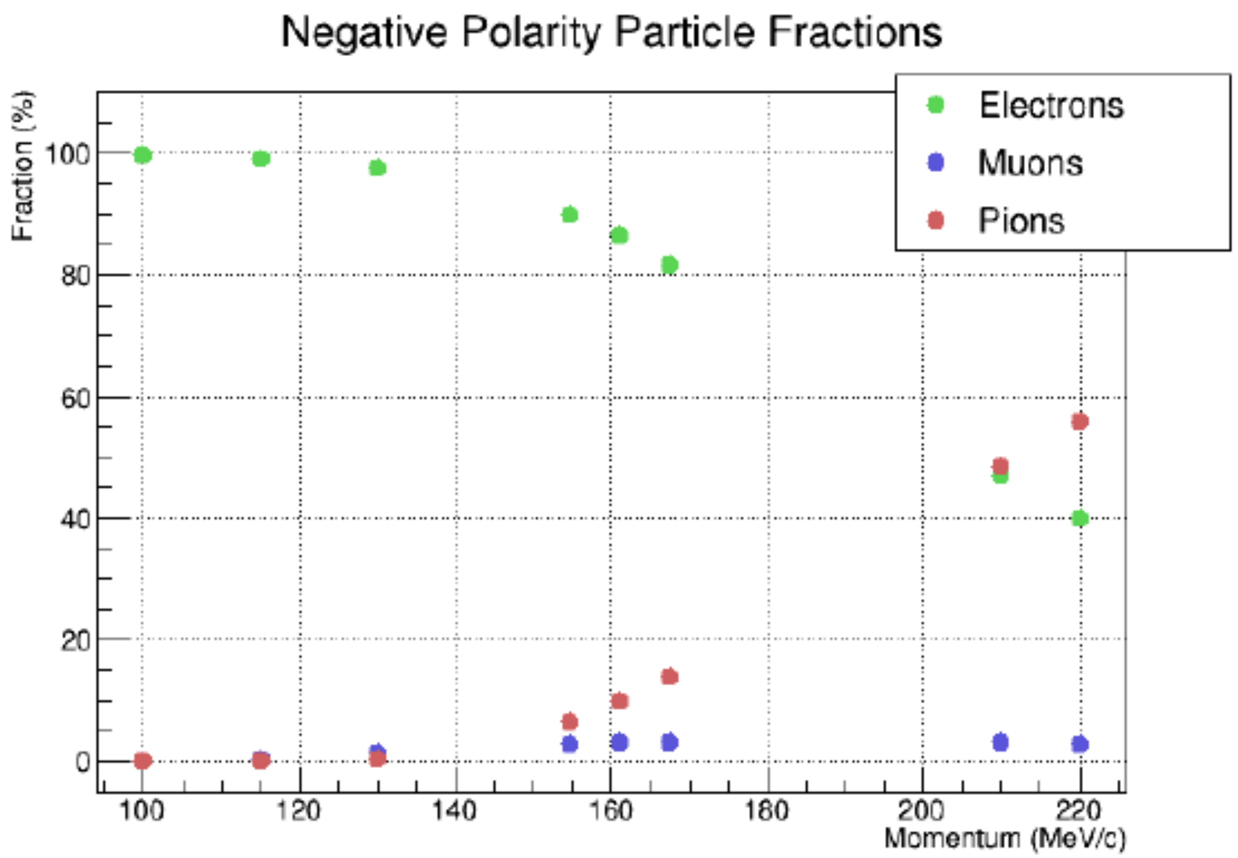
MUSE Test Runs

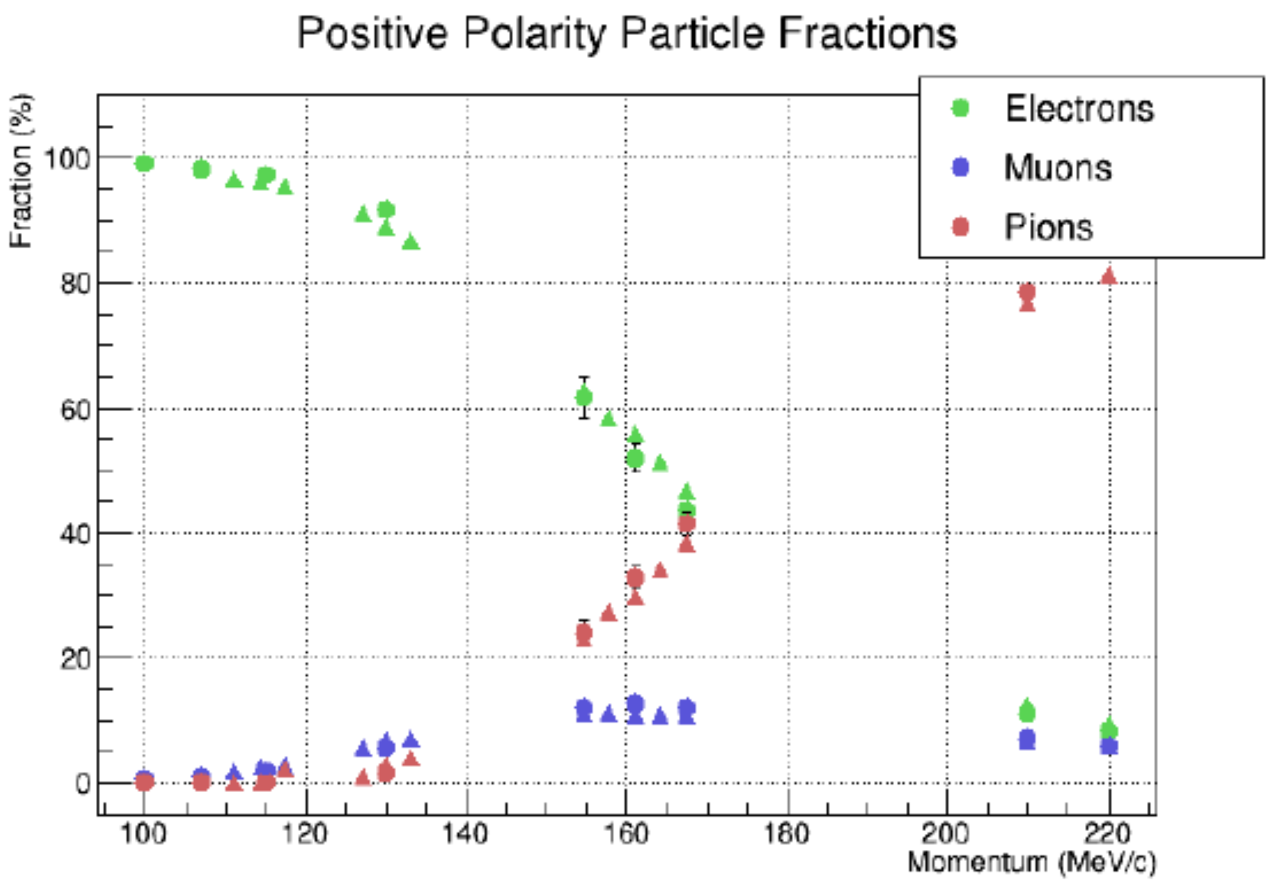
- Varies measurement-to-measurement, but includ

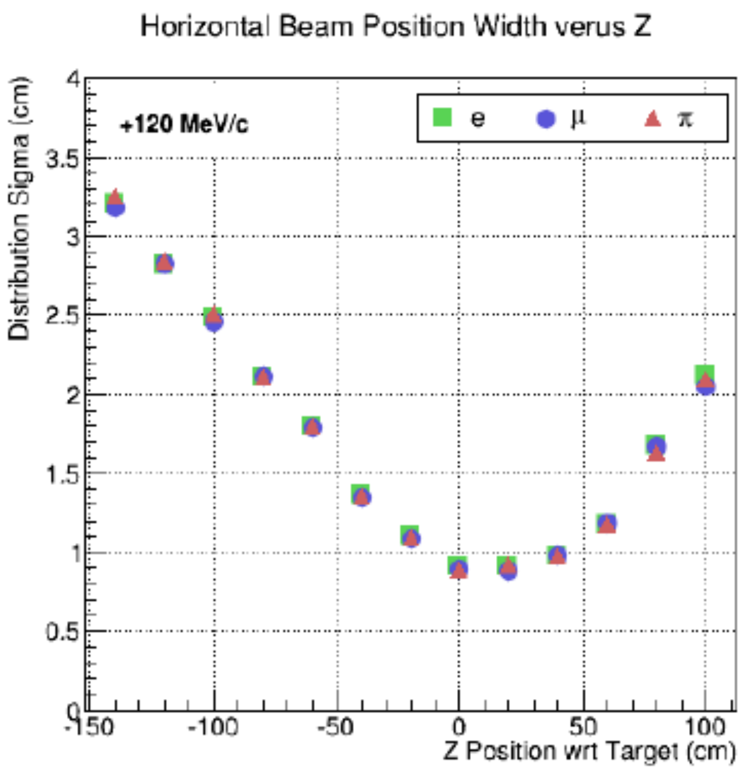




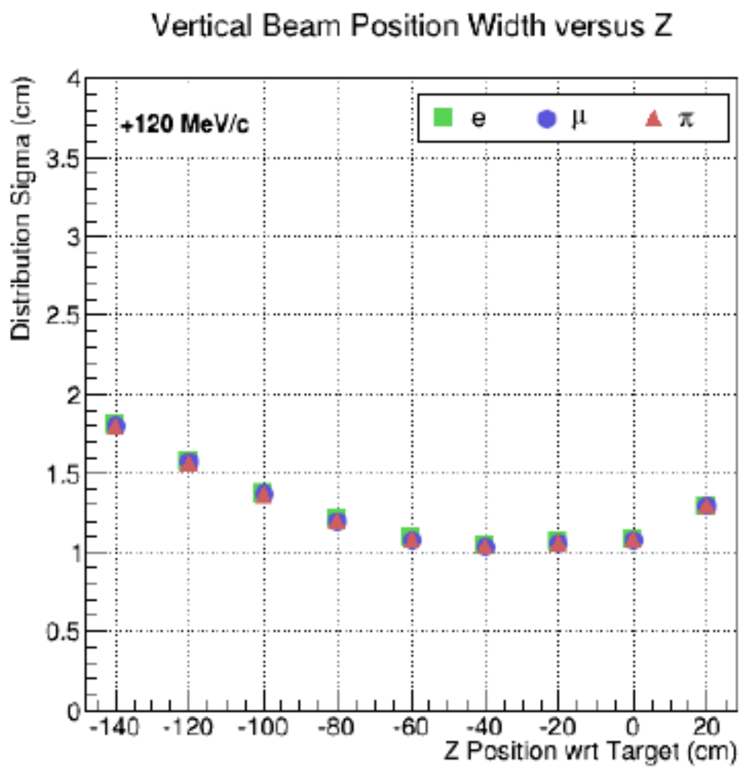
MUSE Test Runs

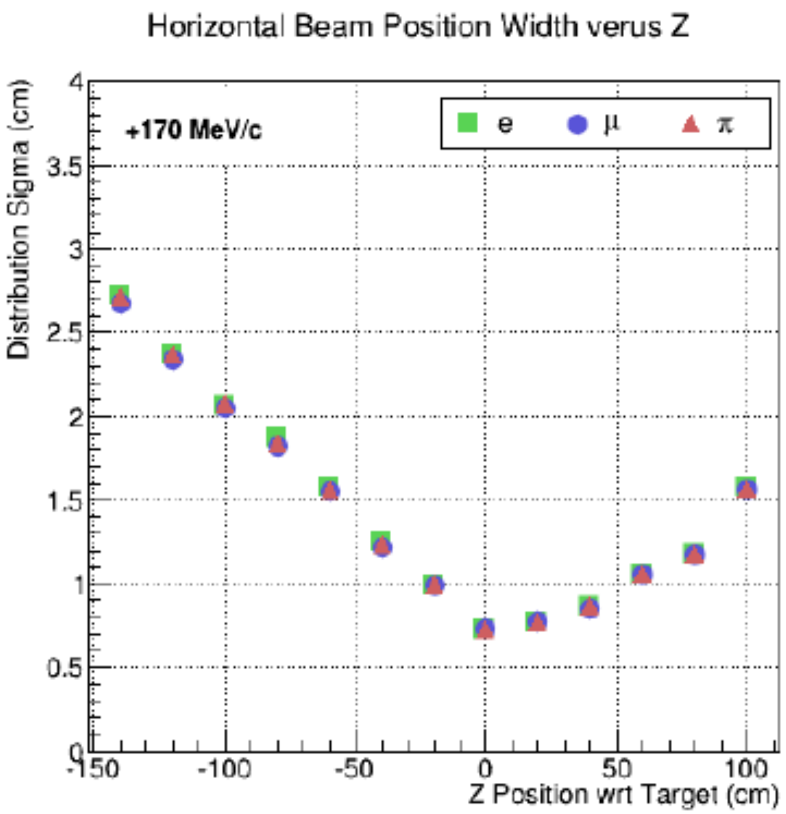


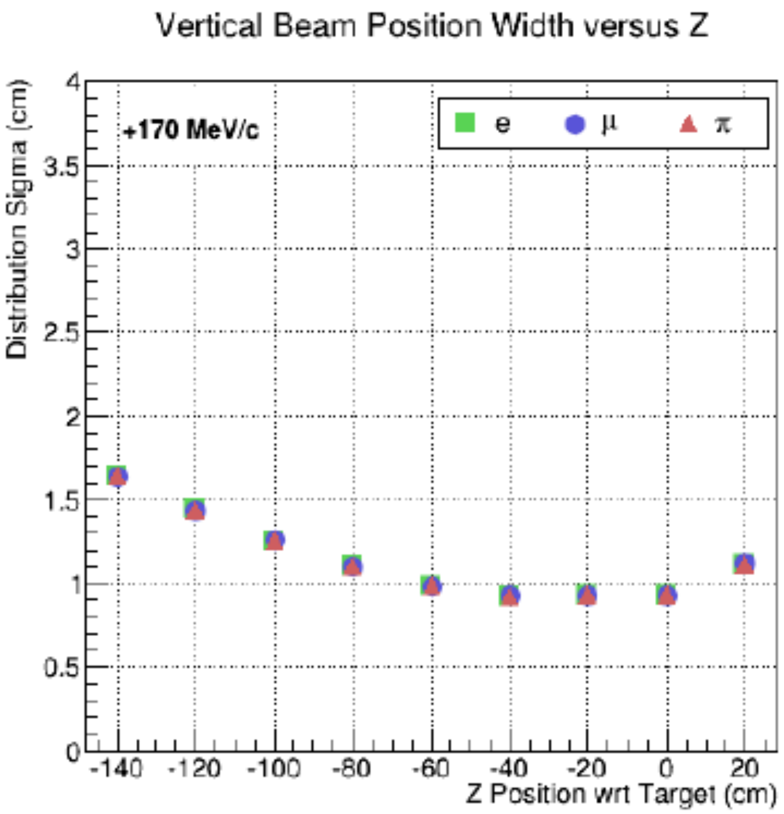


MUSE Test Runs

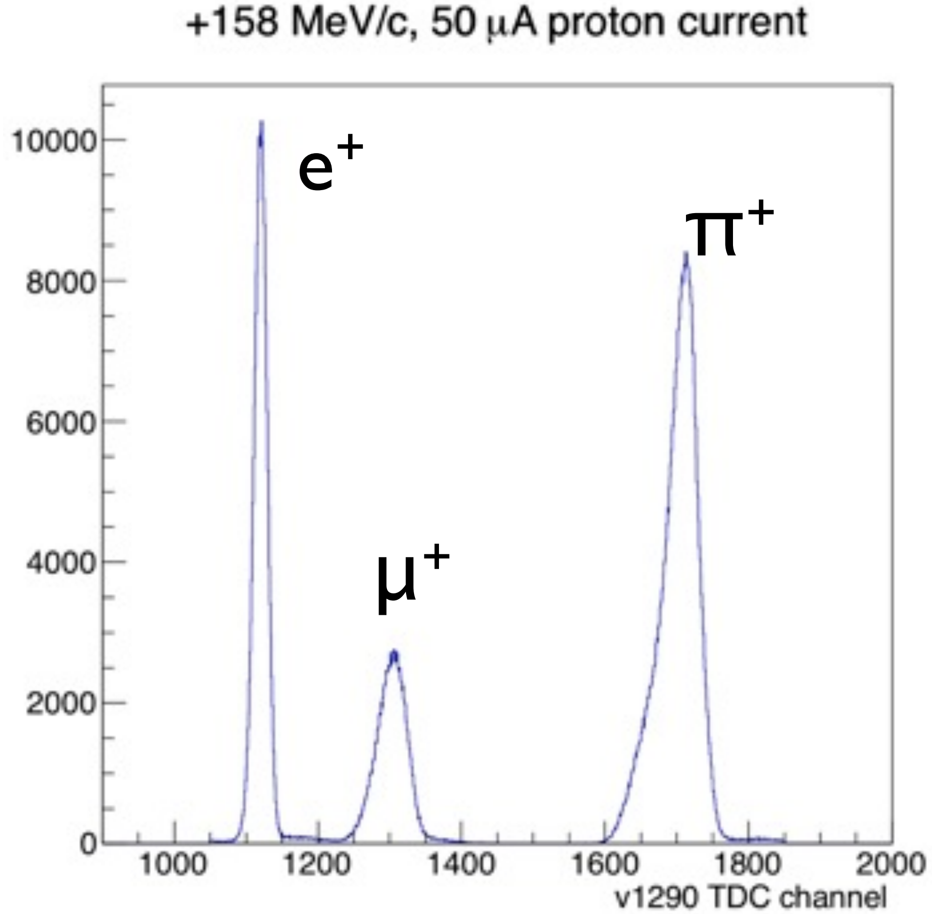


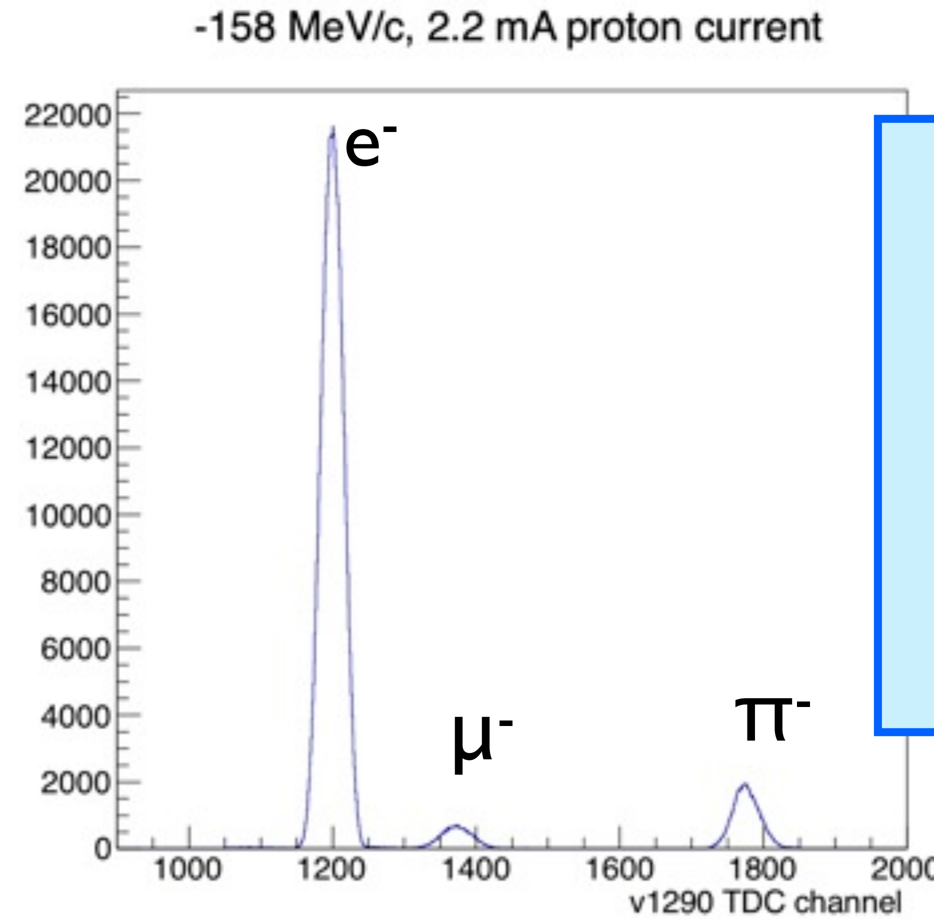






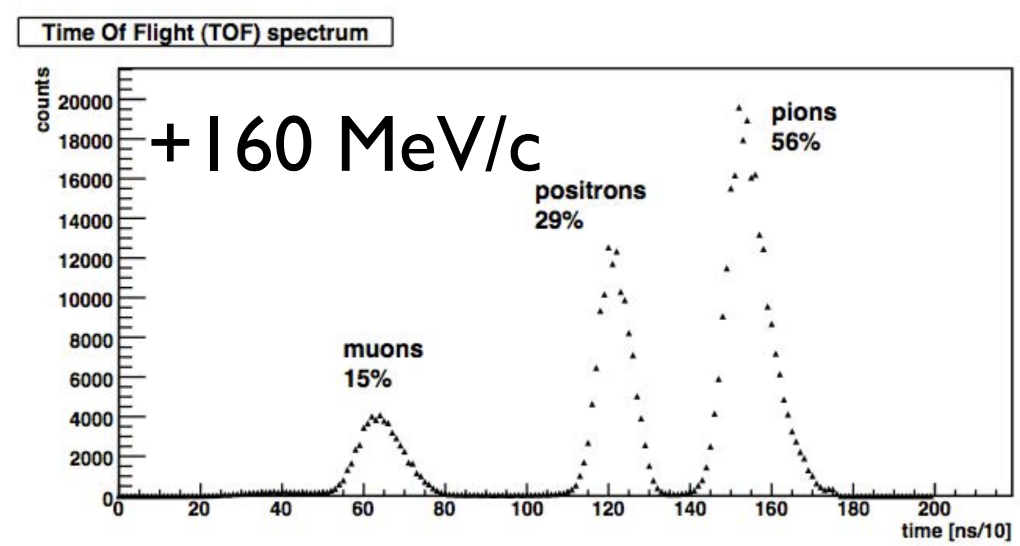
πM1 Channel - RF time in target region





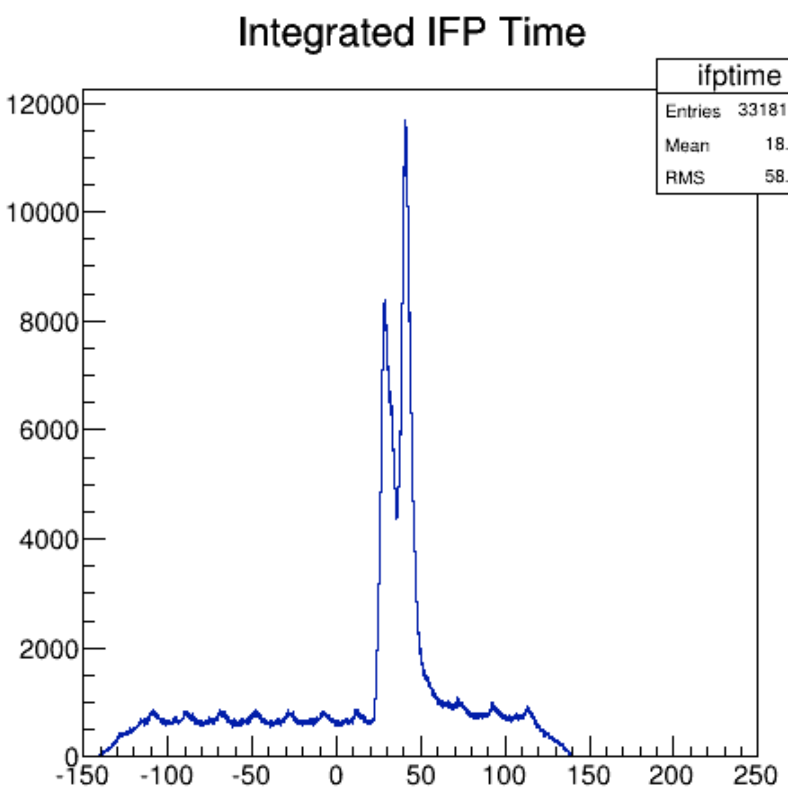
RF peaks broader with 2.2 mA protons, ≈350 ps (σ) for e's and 400 - 500 ps (σ) for μ's and π's

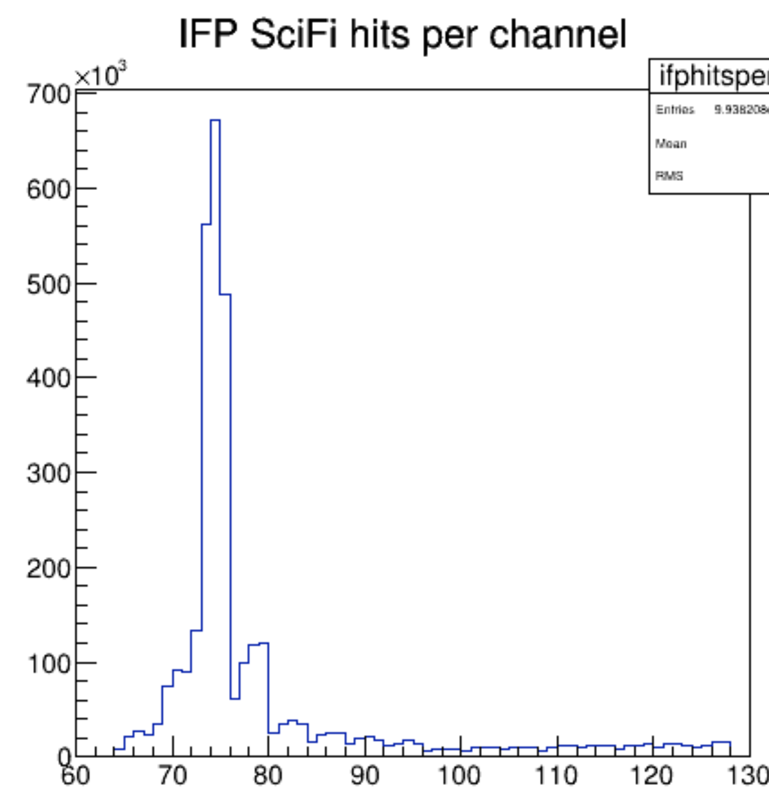
Obtained RF time spectra for several momenta from ≈110 to 225 MeV/c, and used these to determine relative particle fluxes

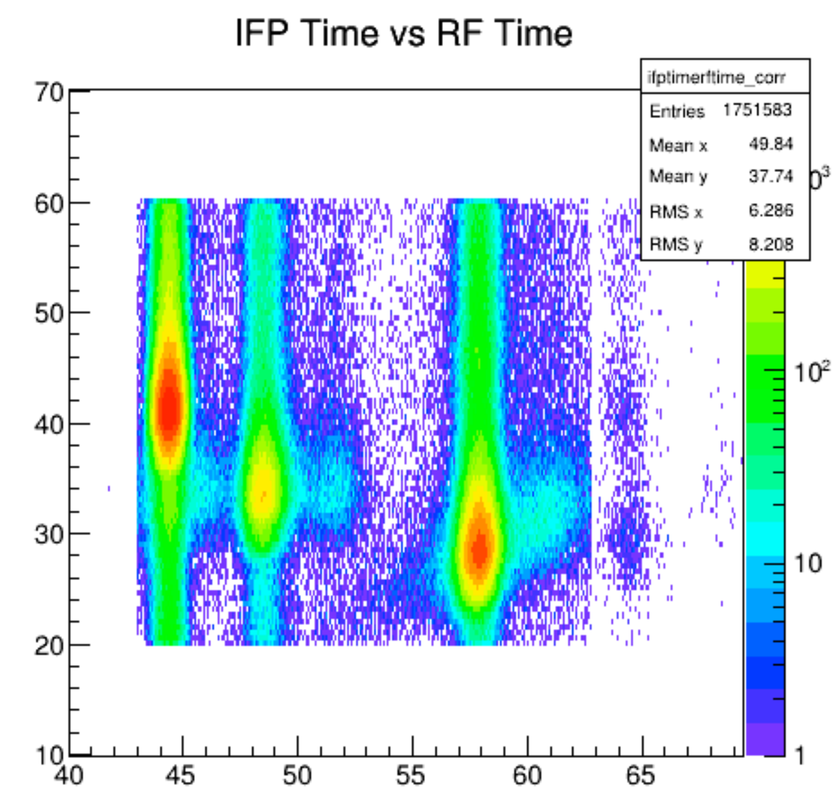


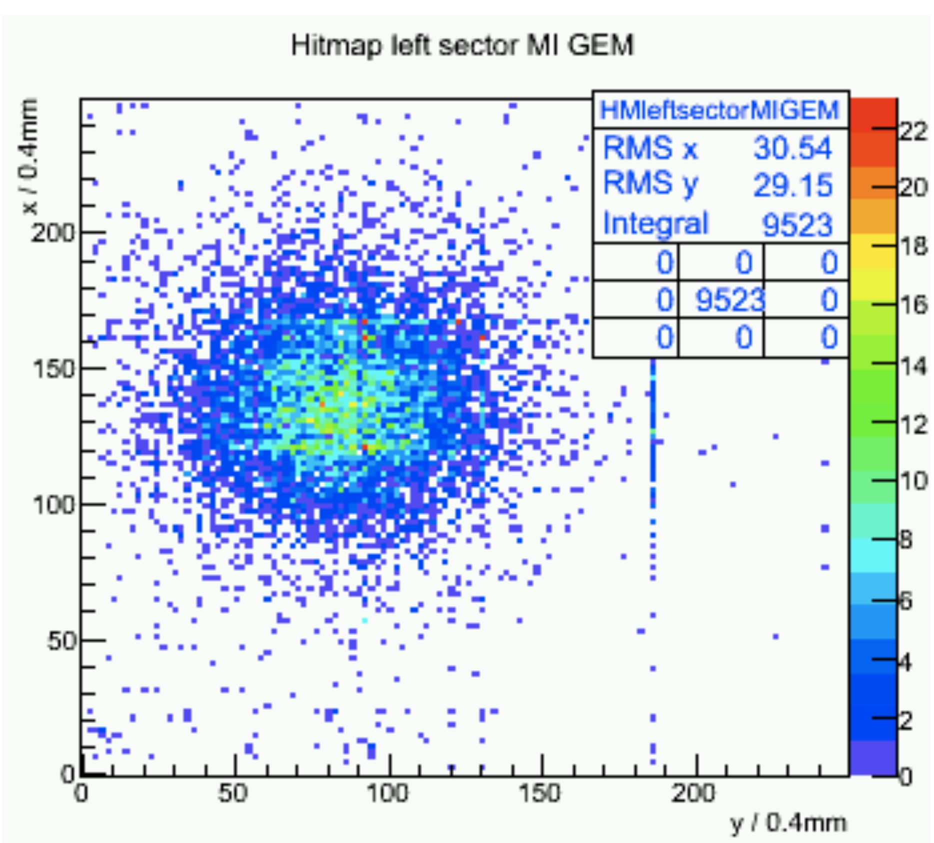
Old spectra, for comparison

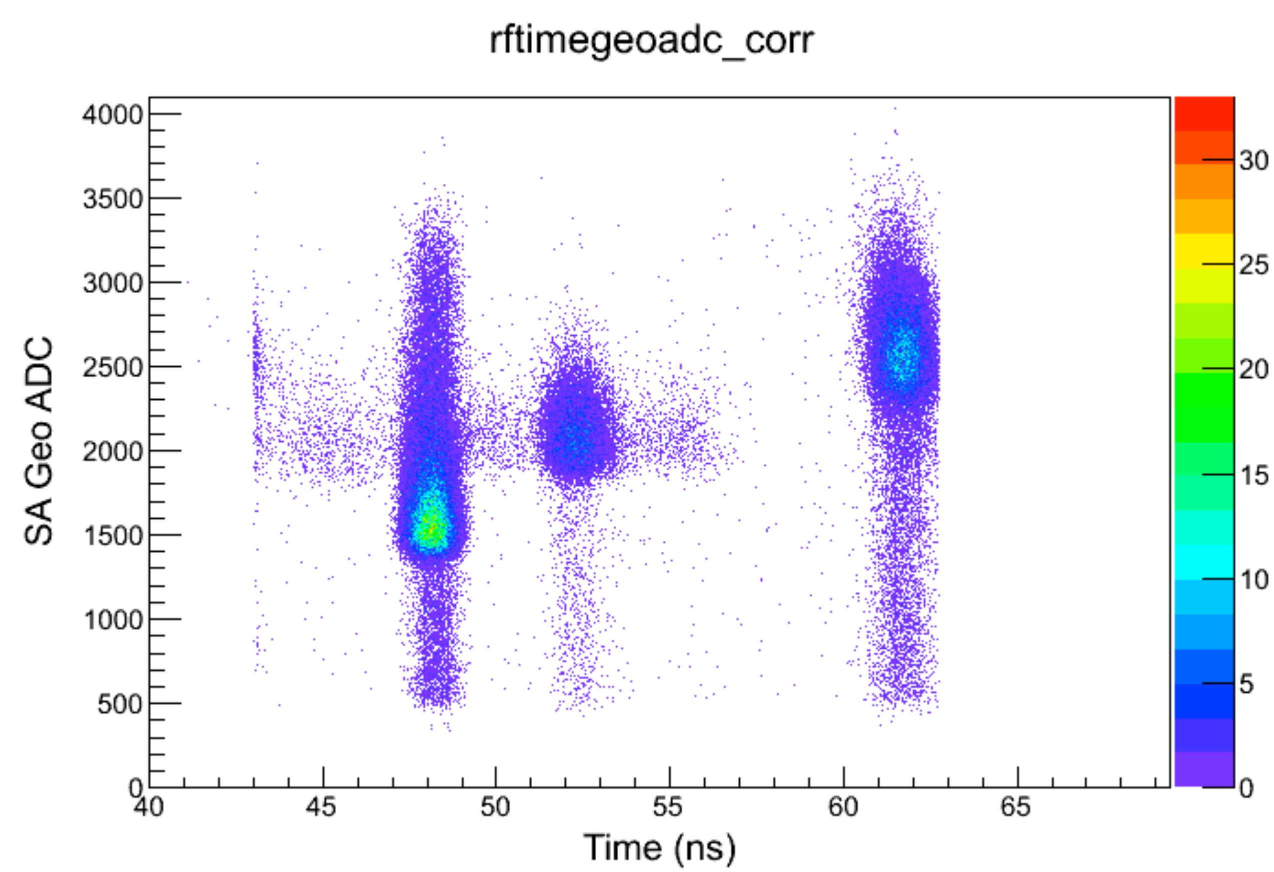
Summer 2013 Test Run







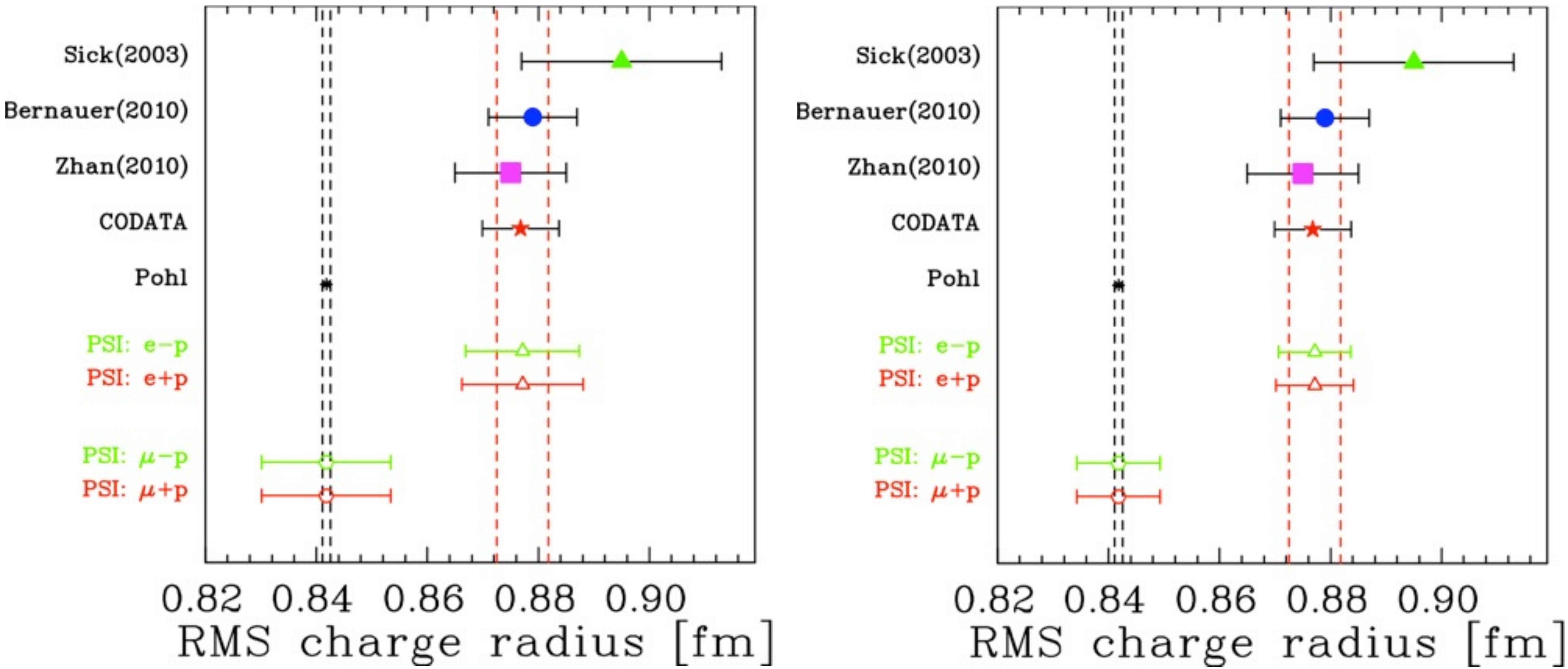




Next Few Years for MUSE

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 money)
June 2014	Test Run
Sep-Oct 2014	R&D Money
summer 2015	Proof of Concept Run
late 2015 ?	Full funding review
late 2016 ?	set up and have dress rehearsal
2017 - 2018 ?	2 6-month experiment production runs

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

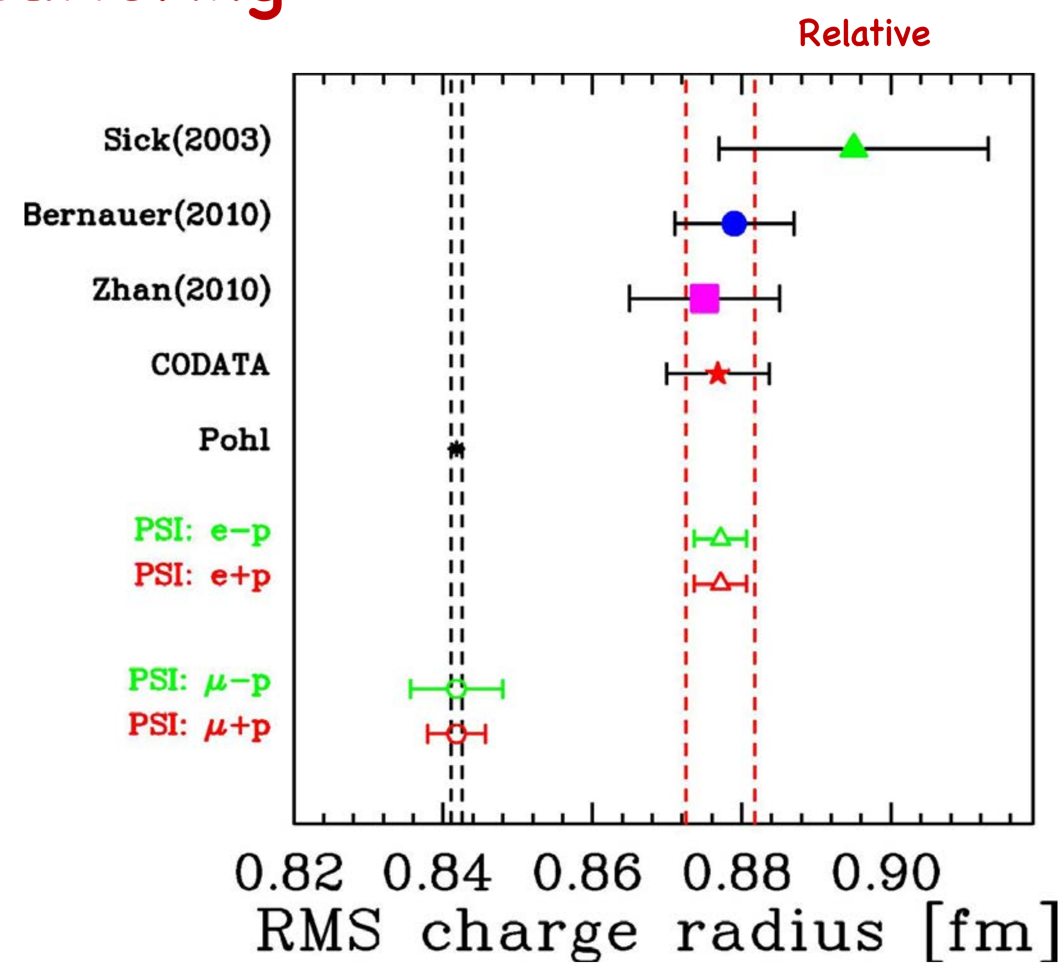
Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, m+/m-, and m/e comparisons

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)!



Other Possible Ideas

(w/o Elaborating)

- Very low Q^2 JLab experiment, near 0^0 using ``PRIMEX" setup: A. Gasparian, D. Dutta, H. Gao et al.
- 2 New eH measurements ongoing (York, Garching).

Approved/ Ongoing

- μ scattering on light nuclei - MUSE Extension?
- Very low Q^2 eP scattering on collider (with very forward angle detection) - MEIC/EIC.
- 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.

Summary

- Proton radii have been measured very accurately over the last 50 years.
- Major discrepancy has now arisen (between electron and muon results).
  - Ideas abound on how too fix this, either the muonic side, the electronic side, or by inventing fancy new physics.
  - But none currently seem to solve the puzzle completely.
  - But remember that we also have another puzzle with the muon in (almost) pure QED.
- Several new experiments, both approved and planned, may help shed (some) light on the issue.

The spectrum of hydrogen atom has proved to be the Rosetta stone of modern physics.

T.W. Hänsch, A. L. Schalow, G.W. Series