Status of the Proton Radius Puzzle

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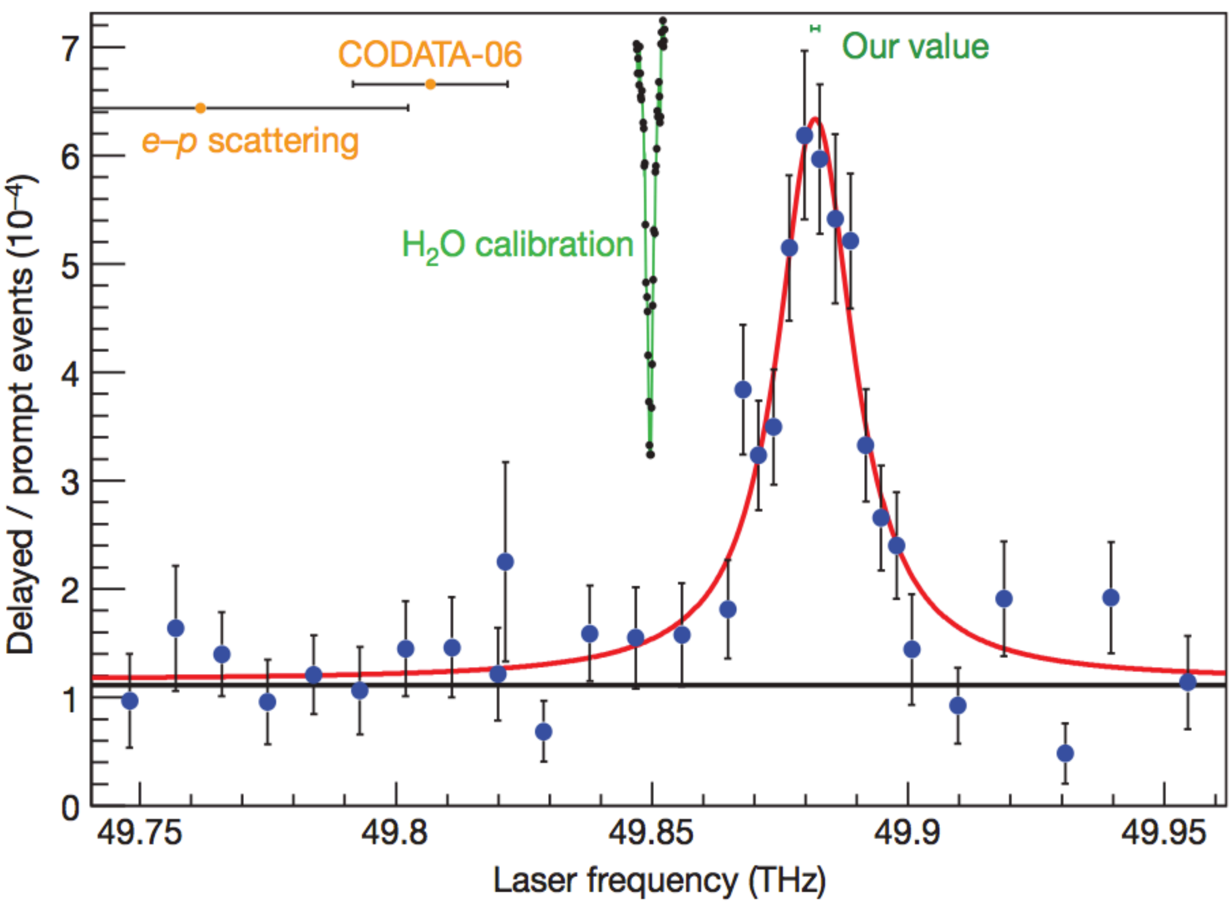
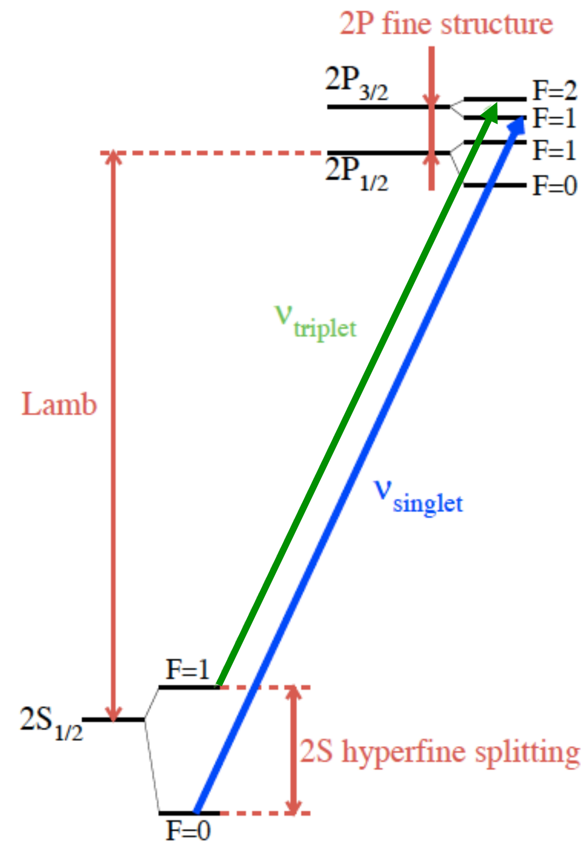
PSI muonic hydrogen measurements

- **2010: R. Pohl et al., Nature 466, 09259 (2010):** **2S➪2P Lamb shift**
  $\Delta E(\text{meV}) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ ➪ $r_p = 0.84184 \pm 0.00067$ fm

  Possible issues: atomic theory & proton structure

- **2013: A. Antognini et al., Science 339, 417 (2013):** **2S➪2P Lamb + 2S-HFS**
  $\Delta E_L(\text{meV}) = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20)_{TPE}$ ➪ $r_p = 0.84087 \pm 0.00039$ fm





The proton radius puzzle in the media

R. Pohl et al., Nature 466, 09259 (2010)

The proton radius puzzle in the media

July 2010

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The New York Times — **Space & Cosmos**

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ENVIRONMENT **SPACE & COSMOS**

For a Proton, a Little Off the Top (or Side) Could Be Big Trouble

By DENNIS OVERBYE
Published: July 12, 2010

For most of us, 4 percent off around the waist — a couple of belt notches — would be a great triumph.

Enlarge This Image

Chris Gash

Not so for the proton, the subatomic particle that anchors atoms and is the building block of all ordinary matter, of stars, planets and people. Physicists announced last week that a new experiment had shown that the proton is about 4 percent smaller than they thought.

Instead of celebration, however, the result has caused consternation. Such a big discrepancy, say the physicists, led by Randolf Pohl of the Max Planck Institute for Quantum Optics in Garching, Germany, could mean that the most accurate theory in the history of physics, quantum electrodynamics, which describes how light and matter interact, is in trouble.

"What you have is a result that actually shocked us," said Paul Rabinowitz, a chemist from Princeton University, who was a member of Dr. Pohl's team.

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January 2013

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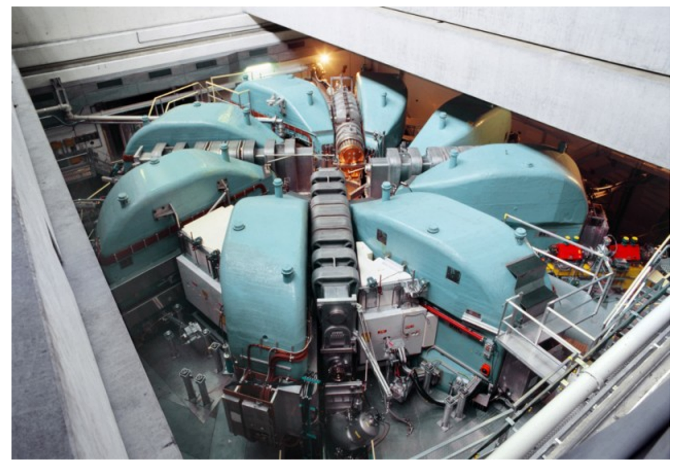
SCIENTIFIC METHOD / SCIENCE & EXPLORATION

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



The proton accelerator at the Paul Scherrer Institute, which was used to create the muons used in this experiment.
Paul Scherrer Institute

Proton Mass Mystery Could Mean New Physics

APR 15, 2013 08:35 PM ET // BY STEPHANIE PAPPAS, LIVESCIENCE

The proton radius puzzle in the media

April 2013

The proton radius puzzle in the media

July 2013

The proton radius puzzle in the media

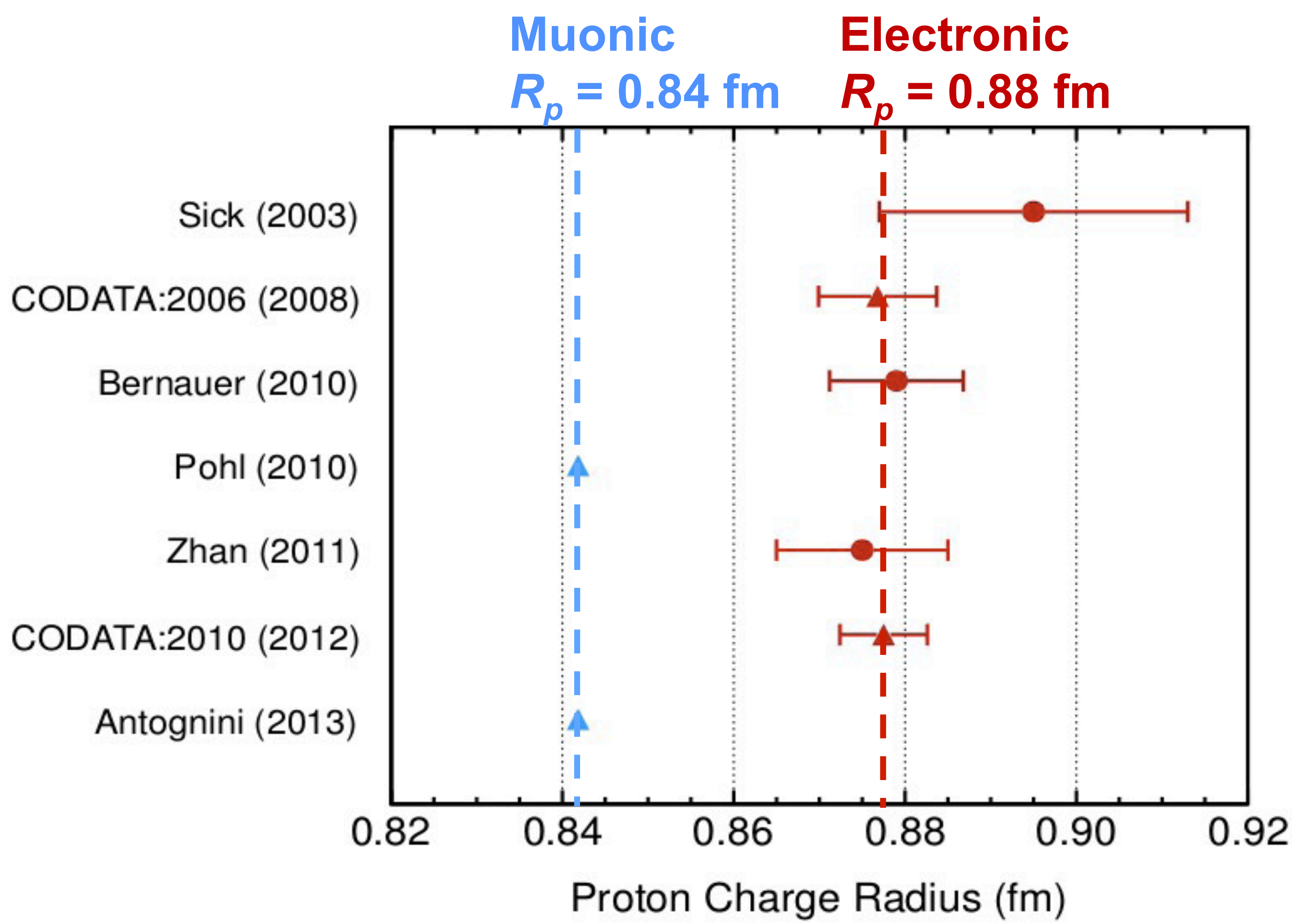
January 2014

The proton radius puzzle in the media

January 2014

The proton radius puzzle

- >7σ (4%) discrepancy between **muonic** and **electronic** measurements
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly New Physics



▲ Spectroscopy

● Scattering

R_p = 0.84184(67) fm

R_p = 0.875(10) fm

R_p = 0.8775(51) fm

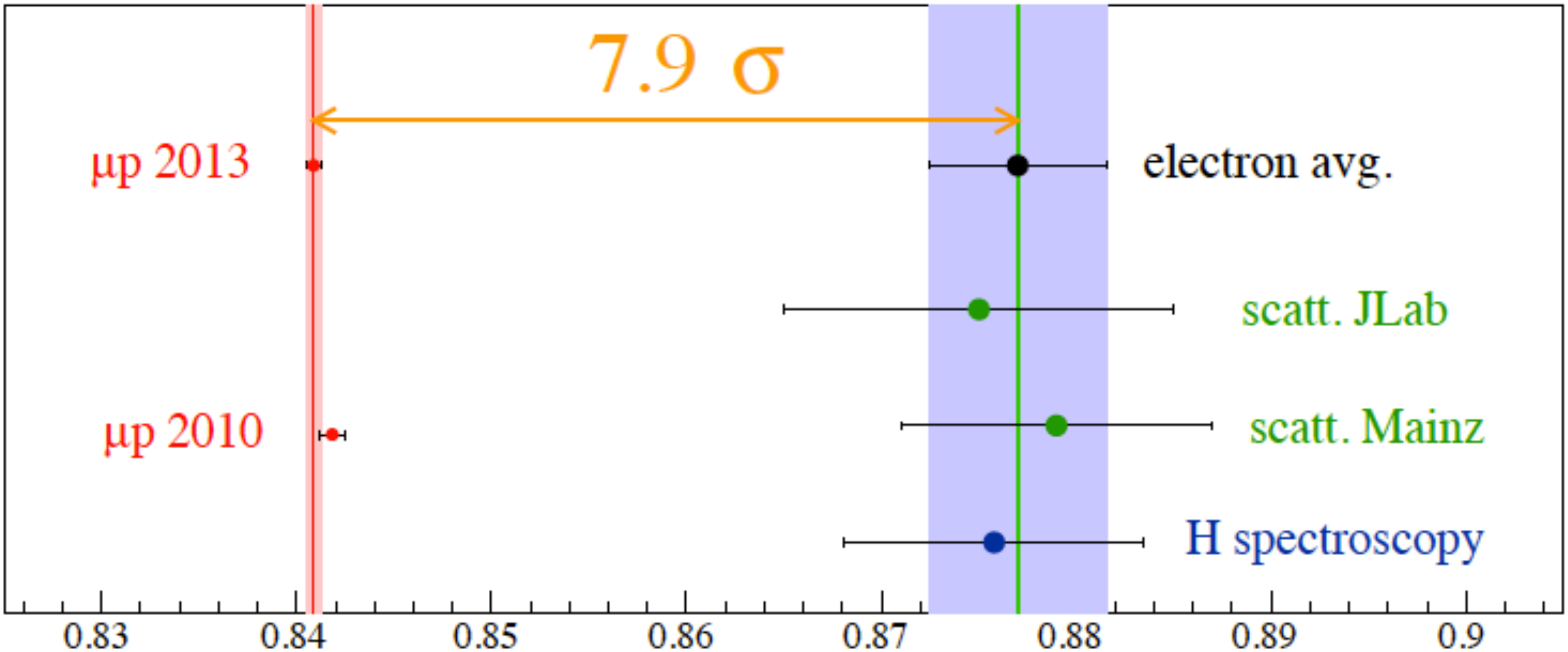
R_p = 0.84087(39) fm

The proton radius puzzle in 2013

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

muons: 0.8409 ± 0.0004 fm



Proton charge radius (fm)

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

A. Antognini et al., Science 339, 417 (2013)

Possible resolutions to the puzzle

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma
- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability (*effect* $\propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics e.g. from kaon decays

New measurements are on their way

- **Additional measurements needed / in preparation / done**
  - Spectroscopy with μD, μHe, and regular H; Rydberg constant
  - ep-, ed-scattering
    (PRad at Jlab, ISR-ep and ed elastic at MAMI; MESA)
  - $\mu^{\pm}$p- and $e^{\pm}$p-scattering in direct comparison at PSI (MUSE)
  - Searches for lepton universality violating light bosons
    (e.g. kaon decays such as TREK/E36 at J-PARC)

r_p (fm)	ep	μp
Spectroscopy	**0.8758 ± 0.077**	**0.84087 ± 0.00039**
Scattering	**0.8770 ± 0.060**	**???**

Need more precision for extraction from scattering
More insights from comparison of ep and μp scattering

Workshop series: Trento 2012+2016; Mainz 2014

ECT*

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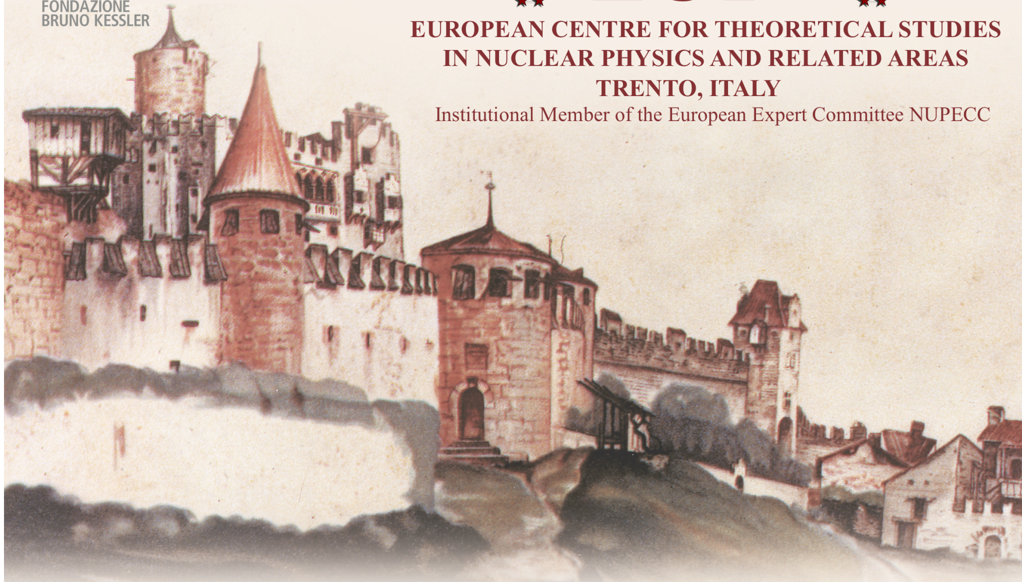

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

The proton radius puzzle

Trento, June 20 - 24, 2016

Main Topics

The proton radius puzzle and beyond: Structure of the lightest nuclei, Laser spectroscopy of light muonic atoms and ions
Precision spectroscopy of regular atoms, Electron scattering, Nuclear polarizability, two-photon exchange
Beyond-Standard-Model solutions of the proton radius puzzle

Speakers

Jan C. Bernauer, *(MIT, USA)*, Carl E. Carlson, *(William & Mary, USA)*, Kjeld S.E. Eikema, *(LaserLAB Amsterdam, The Netherlands)*, Eric A. Hessels, *(York University, Toronto, Canada)*, Michael Kohl, *(Hampton U. / Jefferson Lab, USA)*, Krzyztof Pachucki, *(University of Warsaw, Poland)*, Gil Paz, *(Wayne State University, USA)*.Ingo Sick, *(University of Basel, Switzerland)*, Vladimir A. Yerokhin, *(Center for Advances Studies, St. Petersburg, Russia)*

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Director of the ECT*: Professor Jochen Wambach (ECT*)

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.

For local organization please contact: Gianmaria Ziglio - ECT* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 - 38123 Villazzano (Trento) - Italy
Tel.:(+39-0461) 314721 Fax:(+39-0461) 314750, E-mail: **ect@ectstar.eu or visit http://www.ectstar.eu**

Trento workshop June 20-24, 2016

2nd ECT* Workshop on the Proton Radius Puzzle

June 19-25, 2016 Trento, Italy **Version 2**

Sunday, June 19, 20:00: Pizza Dinner

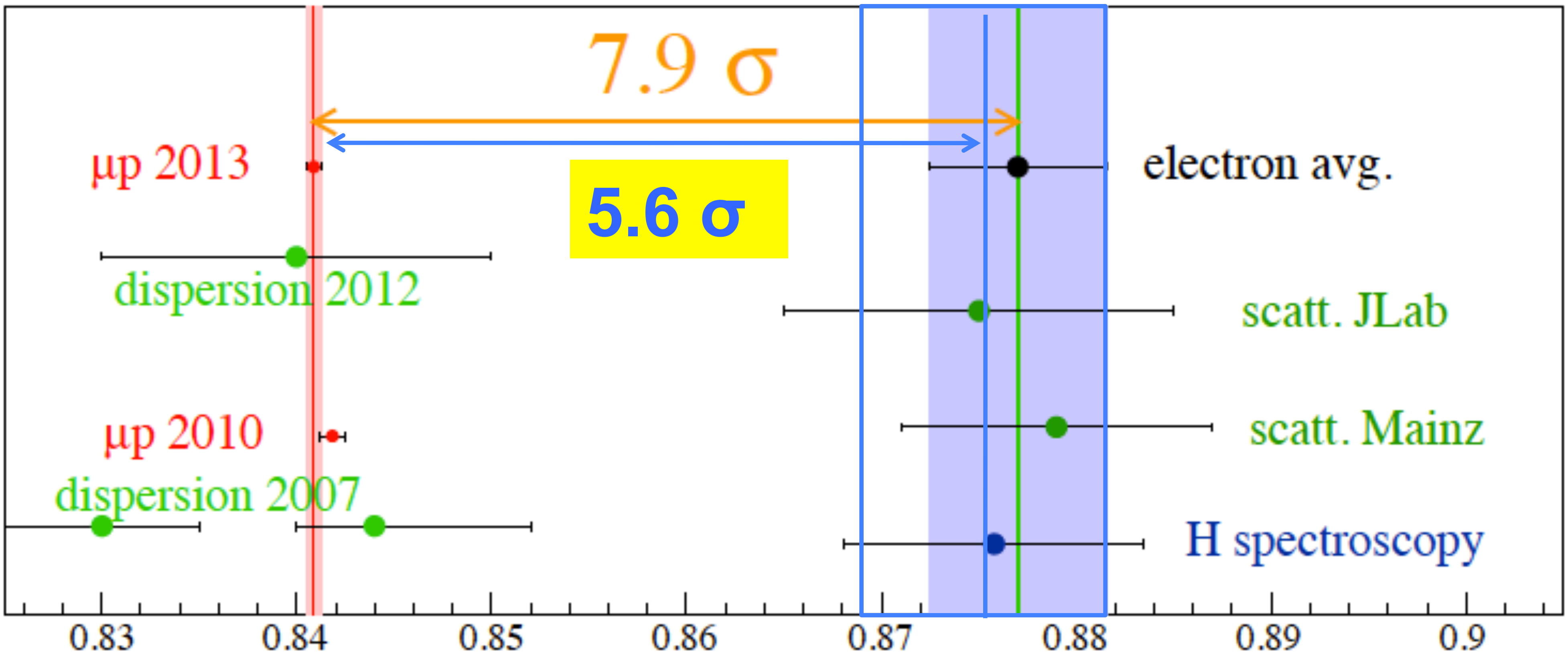
Time	Monday June 20	Tuesday June 21	Wednesday June 22	Thursday June 23	Friday June 24
9:00 – 10:30	**(9:30) Ron, Jerry, Randolf** (10) *Welcome* **Julian Krauth** (35+10) *Muonic deuterium*	**Gerald A. Miller** (35+10) *Electrophobic Scalar Boson and Muonic Puzzles* **John Ralston** (35+10) *The Muon Experimental Anomalies Are Explained by a New Interaction Proportional to Charge*	**Eric A. Hessels** (35+10) *Determining the Proton Charge Radius from Electron-Proton Scattering and from Hydrogen Spectroscopy* **Kjeld S.E. Eikema** (35+10) *Precision deepUV Ramsey-comb spectroscopy of H_2 and prospects for 1S-2S excitation of He-ions*	**Marc Diepold** (35+10) *News from muonic Helium: Theory status and results* **Chen Ji** (35+10) *Nuclear Structure Contributions to Lamb shift in Light Muonic Atoms*	**Toshimi Suda** (35+10) *e+p project at ultra-low Q^2 in Japan* **Ashot Gasparian** (35+10) *The PRad Experiment at Jefferson Lab*
10:30 – 11:00	*coffee break*				
11:00 – 12:30	**M. Mihovilovič** (35+10) *The Initial state radiation experiment at MAMI* **Ingo Sick** (35+10) *Proton rms-radius: recent determinations from (e,e)*	**Krzysztof Pachucki** (35+10) *Toward the absolute nuclear charge radius determination from the spectra of light atomic and molecular systems* **V.A. Yerokhin** (35+10) *Nuclear recoil effect in the Lamb shift of hydrogen and light hydrogen-like ions*	**Joan M. Dreiling** (35+10) *Progress Towards Generating Rydberg State, One-Electron Ions* **Lothar Maisenbacher** (35+10) *Precision spectroscopy of the 2S-4P transition in atomic hydrogen*	**Carl E. Carlson** (35+10) *Two-photon exchange corrections to the Lamb shift in muonic helium* **Antonio Pineda** (35+10) *The Lamb shift in muonic hydrogen and the proton radius from effective field theories*	**Randolf Pohl** (35+10) *CREMA++: Future experiments with muons, and more*
12:30 – 14:30	*lunch break*				
14:30 – 16:00	**Jan C. Bernauer** (35+10) *Why I believe that proton scattering gives a big radius* **Douglas Higinbotham** (35+10) *Statistical Modeling of Electron Scattering Data*	**Excursion** *Ferrari Spumante Cellars*	**Michael Kohl** (35+10) *TREK/E36 @ J-PARC: Investigating lepton universality with stopped kaon decays* **Andrea Vacchi** (35+10) *Muonic hydrogen ground state hyperfine splitting - towards the high precision measuremen*	**Gil Paz** (35+10) *Addressing the Proton Radius Puzzle Using QED-NRQED Effective Field Theory* **Franziska Hagelstein** (35+10) *Proton Structure in the Hyperfine Splitting of Muonic Hydrogen*	
16:00 – 16:30	*coffee break*				
16:30 – 18:00	**Evangeline Downie** (35+10) *MUSE Overview* **Discussions**		**Savely Karshenboim** (35+10) *t.b.a* **Discussions**	**Discussions**	

The proton radius puzzle in 2016

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm (CODATA2014)

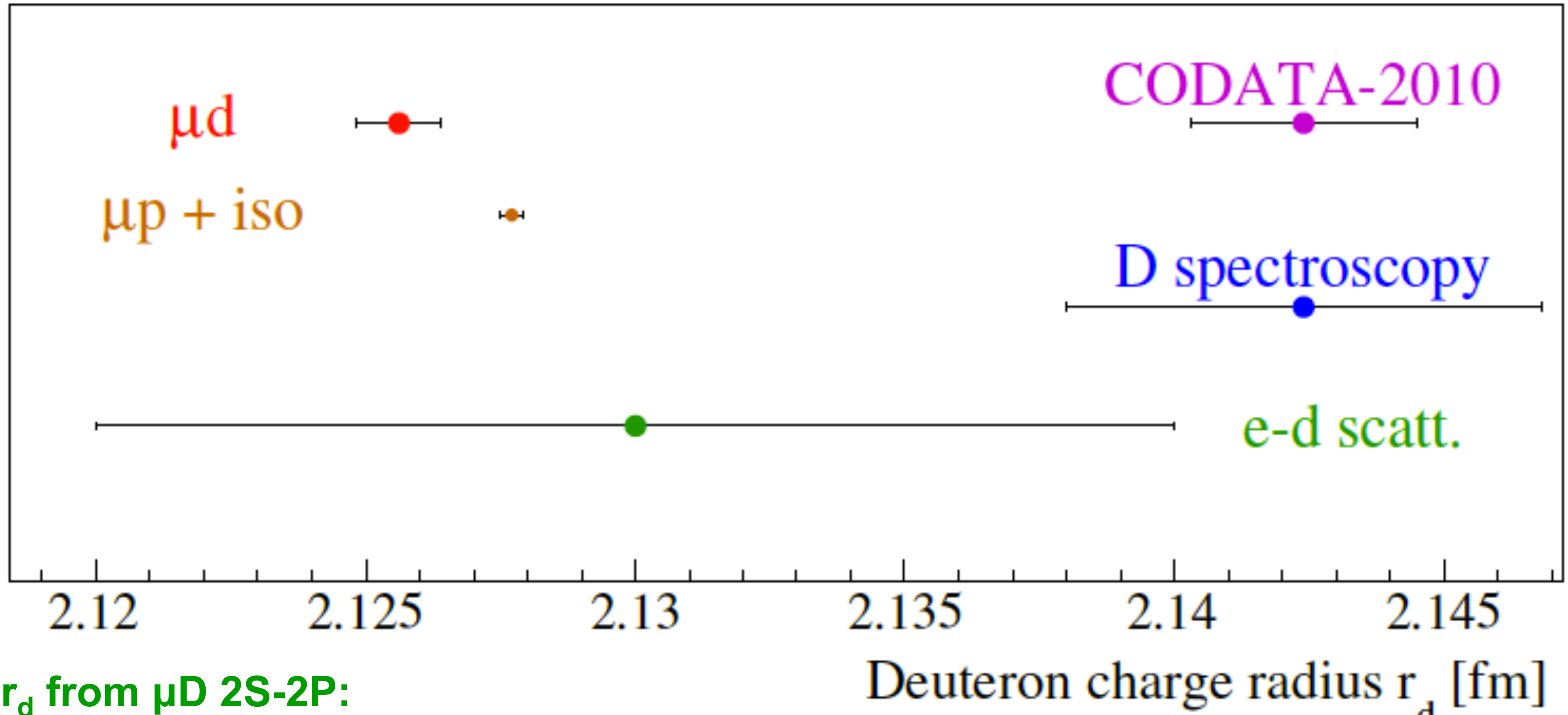
muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

Belushkin, Hammer, Meissner PRC 75, 035202 (2007)
Lorenz, Hammer, Meissner EPJ A 48, 151 (2012)

Muonic Deuterium

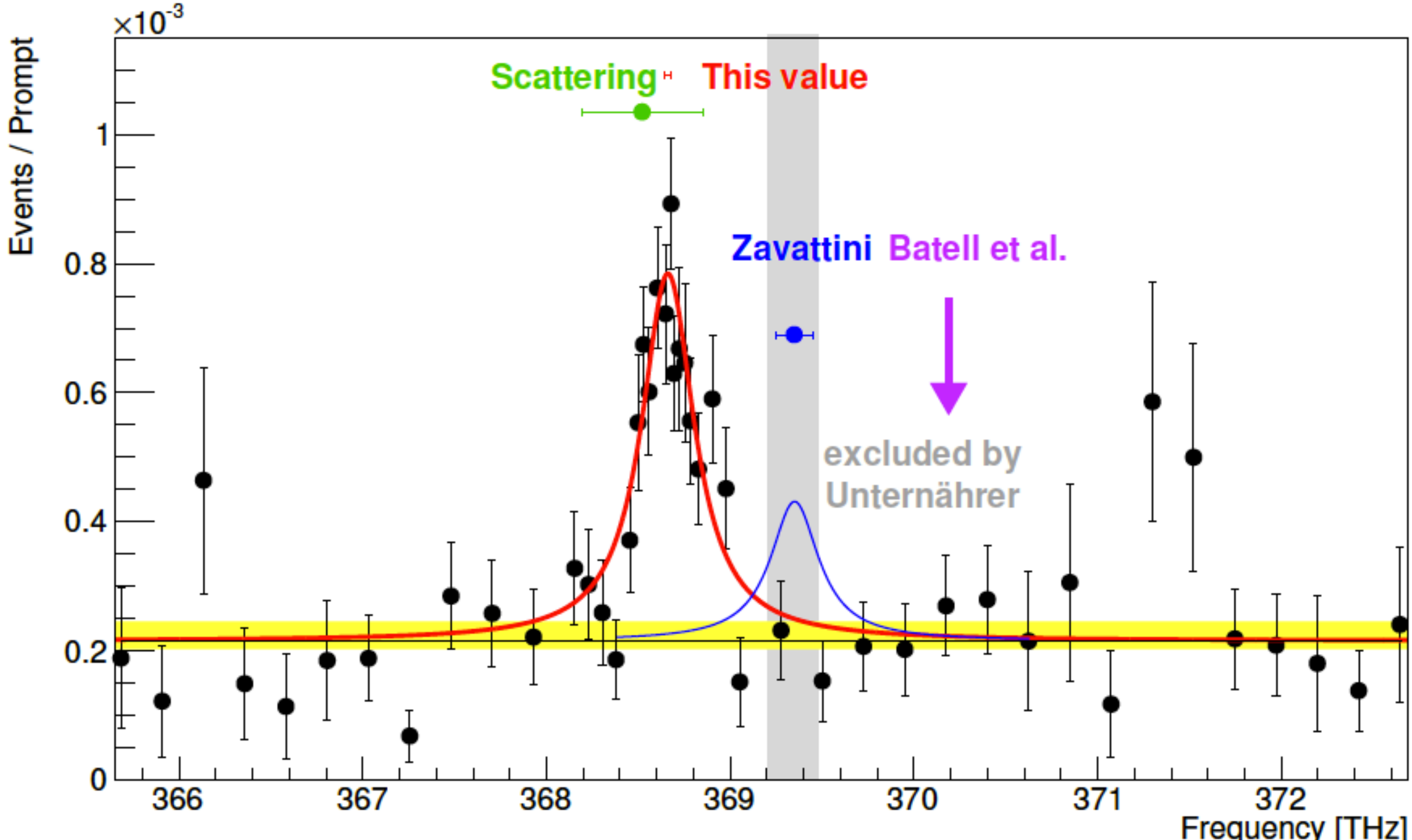


r_d from μD 2S-2P:
J. Krauth, PSAS2016
+ PRP2016 (Trento),
submitted

Theory: J. Krauth et al., Ann. of Phys. 366, 168 (2016)
arXiv:1506.01298v2 [physics.atom-ph]

There is a deuteron radius puzzle:
7.5 σ between r_d (μD) and CODATA-2010

Muonic Helium-4

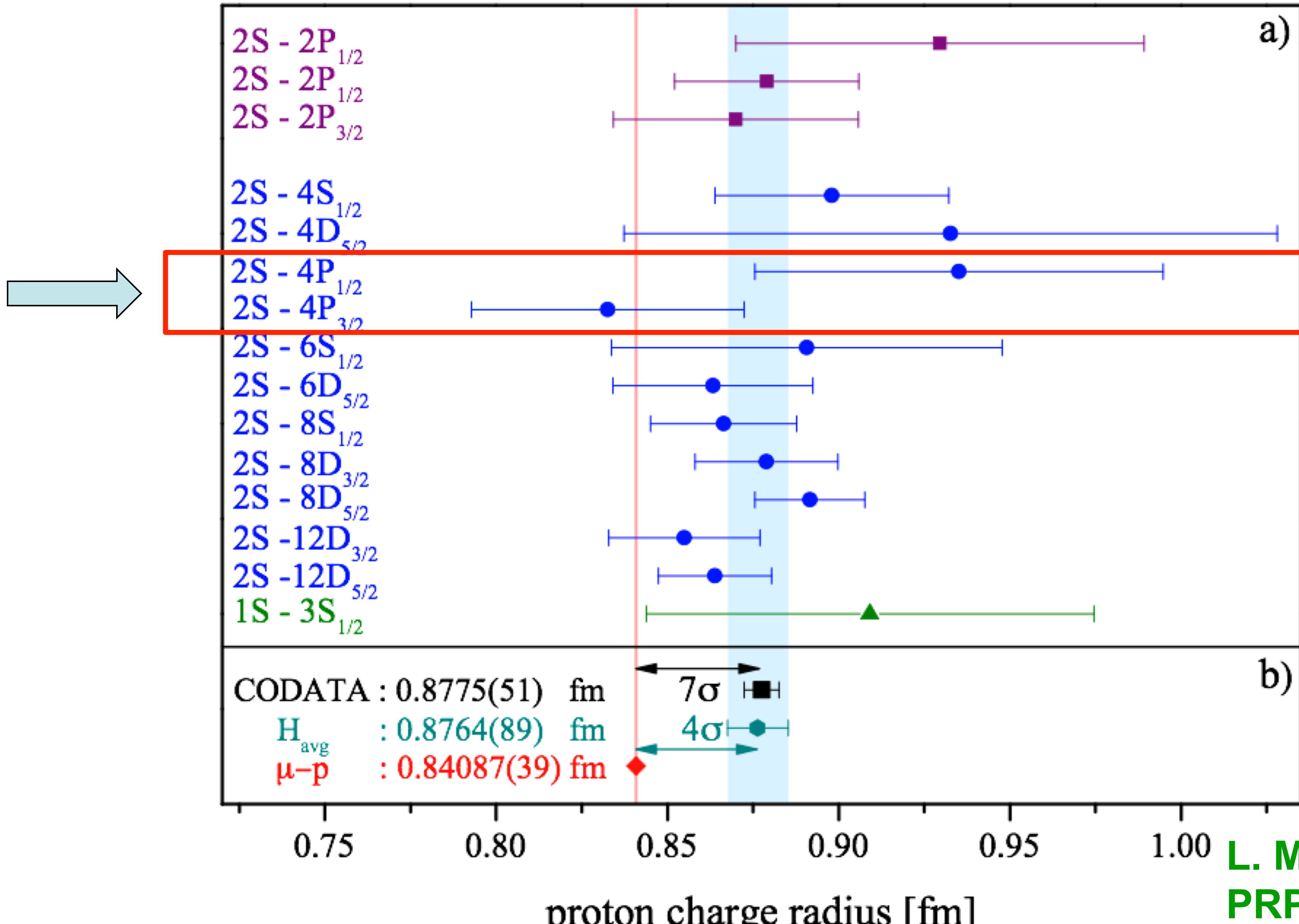


J. Krauth, PSAS2016(Jerusalem) + PRP2016 (Trento)

Muonic Helium-4 results constrain parameter space of new physics and (un)conventional hadronic physics

(Muonic Helium-3 theory (polarizability) still being developed)

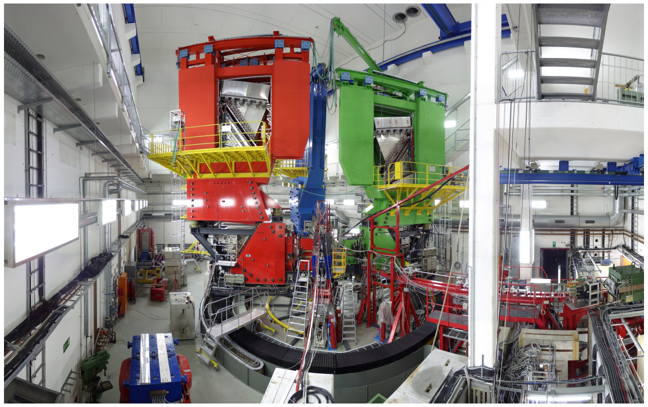
Atomic hydrogen spectroscopy (2016)



L. Maisenbacher, PRP2016 (Trento)

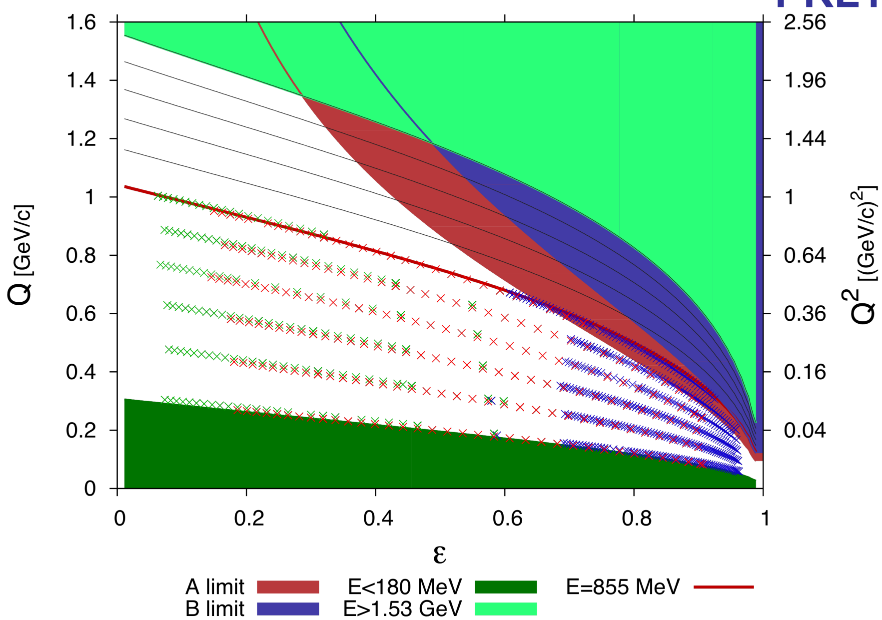
New, preliminary value consistent with muonic hydrogen but ~4σ below previous average → puzzle solved? NO!!

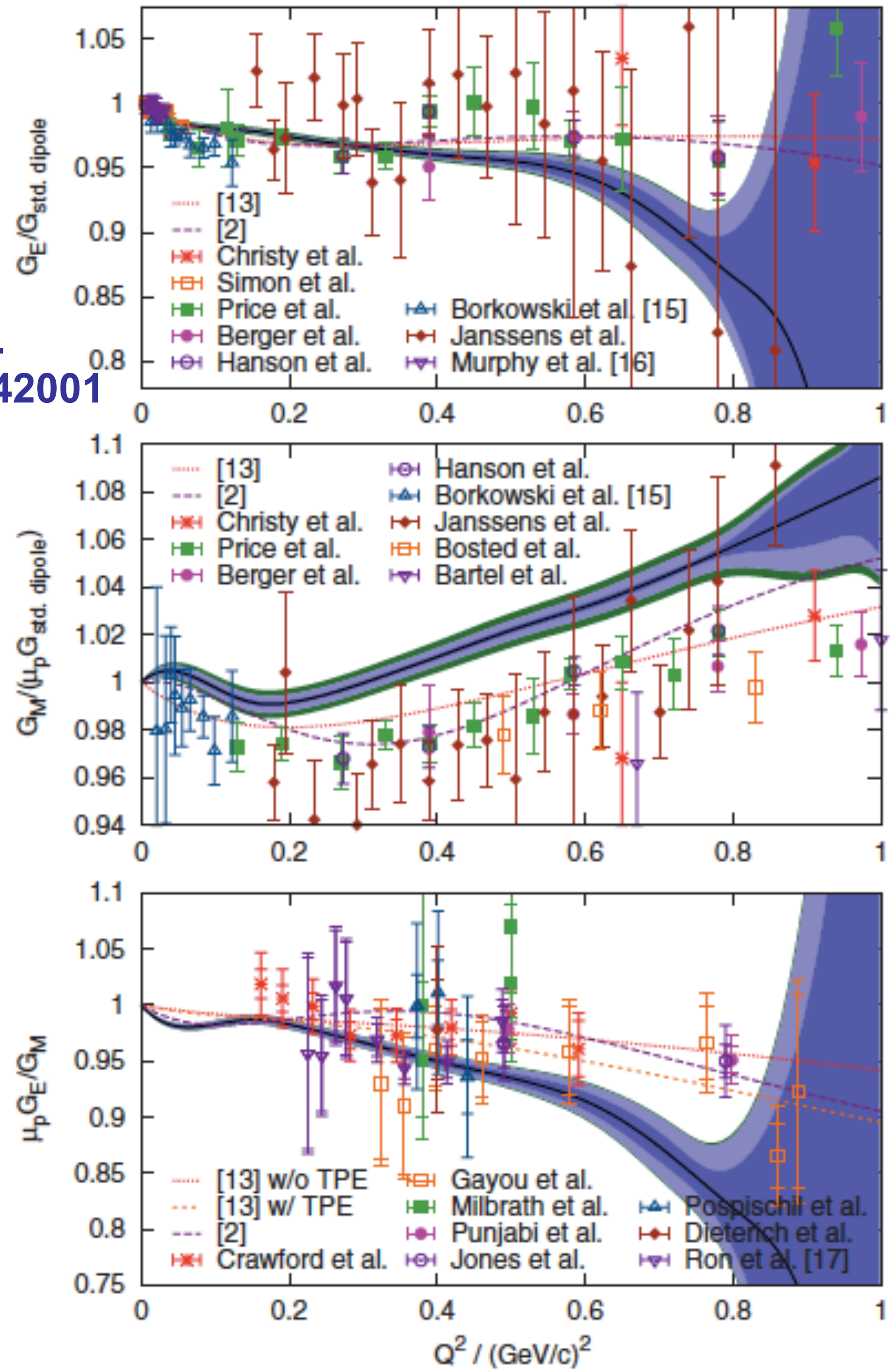
Mainz ep scattering at low Q^2



MAMI A1

J. Bernauer et al.
PRL105 (2010) 242001

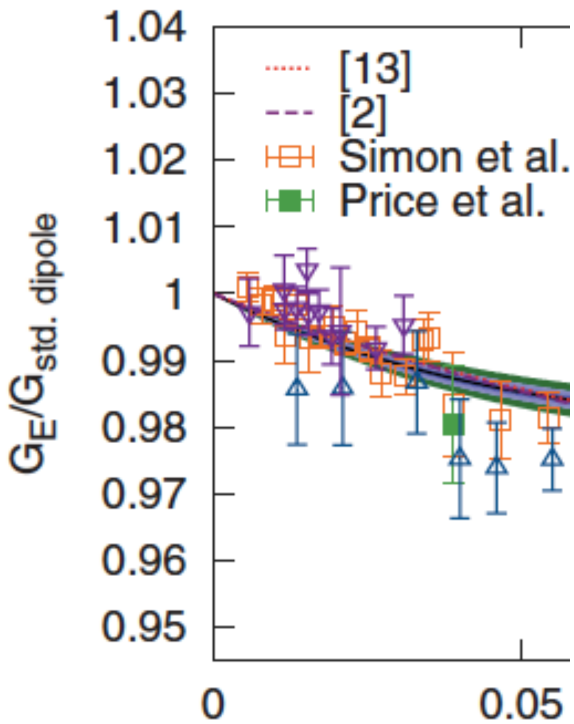


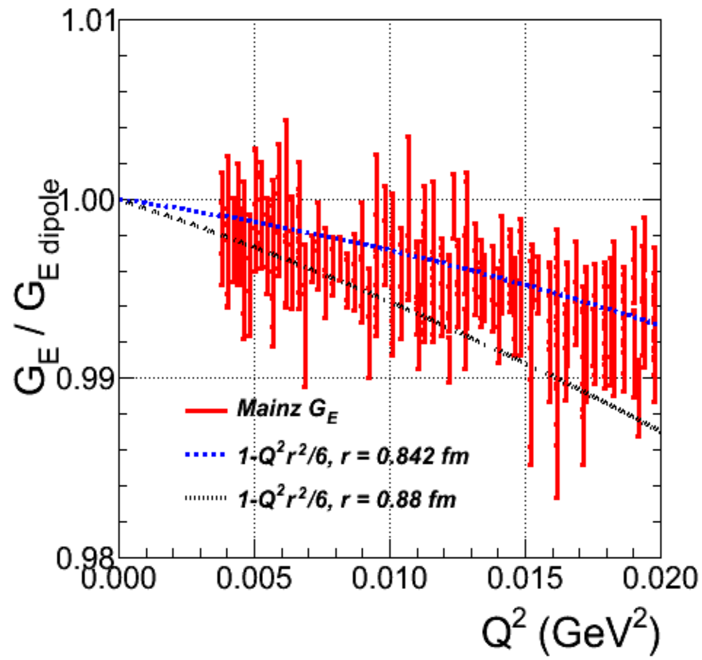


Rosenbluth separation at low Q^2
Precise charge and magnetic rms radii:

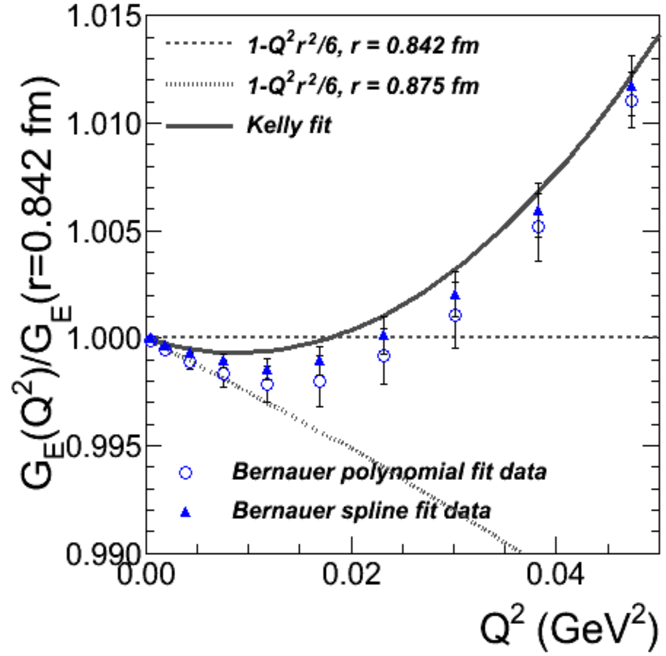
R_E = 0.879 ± 0.008 fm
R_M = 0.777± 0.017 fm

Proton radius from Mainz A1 data





$G_E(Q^2) = 1 - Q^2r^2/6 + \ldots$

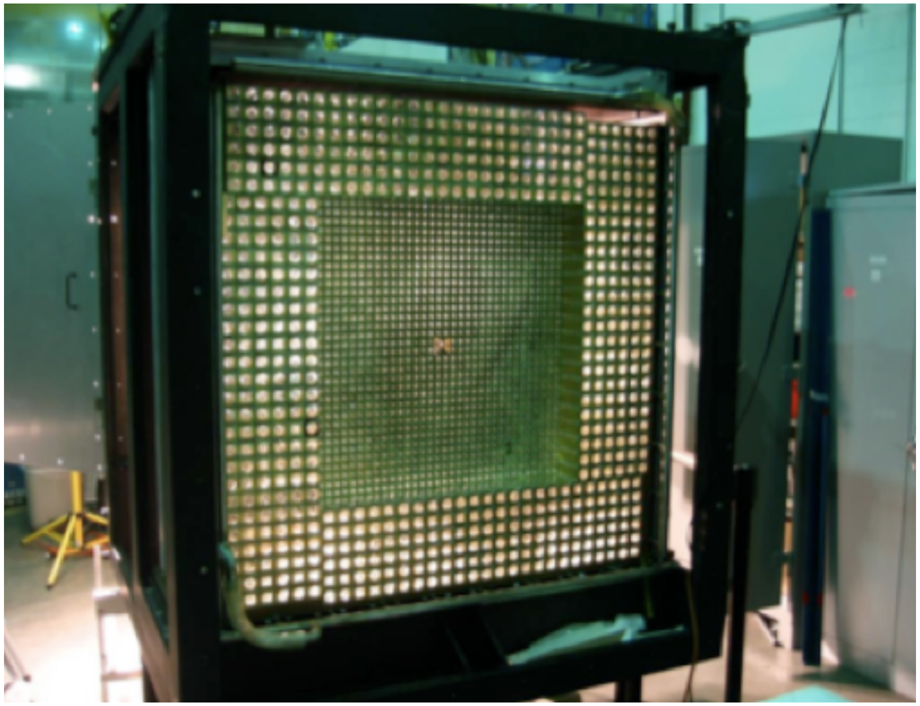


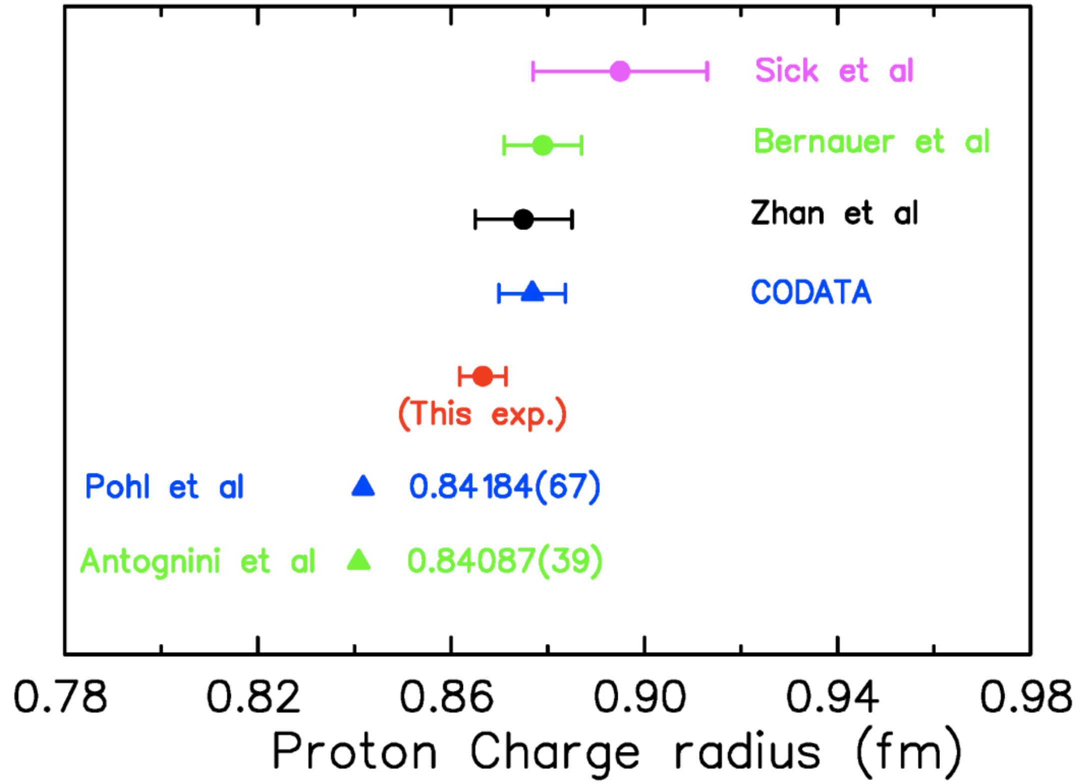
- Low Q^2 – J. Bernauer et al., PRL105 (2010) 242001; PRC90, 015206 (2014)
- Left: world + Mainz fit; Middle: Mainz raw data; Right rebinned G_E
- Large difference in slope between r = 0.84 and 0.88 fm
- Floating normalization, higher-order Q^2 terms present
- Controversies about radius extraction – dependence on fit model
- Need yet higher precision

Controversy about scattering results

- **Recently, radius extractions from same scattering data have been controversial**
- **Group 1: Bernauer, Distler, Sick: large radius ~0.88 fm**
  J.C. Bernauer and M. Distler, arXiv:1606.02159v1 [nucl-th]
  I. Sick, Progress in Particle and Nuclear Physics 67, 473 (2012)
  - Importance of corrections Q^4 and Q^6 even at low $Q^2 \sim 10^{-3}$ $(GeV/c)^2$ which affect cross section at the 15% level
  - Linear fits (like all polynomial or Taylor expansions) give biased result
  - Need large Q^2 range to determine higher order terms, these affect low-Q^2
- **Group 2: Griffioen, Carlson, Higinbotham: small radius ~0.84 fm**
  D.W. Higinbotham et al., Phys. Rev. C93, 055207 (2016), arXiv:1510.01293 [nucl-ex]
  K. Griffioen, C. Carlson, and S. Maddox, arXiv:1509.06676 [nucl-ex]
  - reduced Q^2 range and order of fit function
  - justifying significance with F-tests etc.
- **Horbatsch & Hessels: can produce any radius 0.84-0.88 fm depending on fit function and range. Get small radius even over full Q^2 range fit, however fit function is biased**
  M. Horbatsch and E. A. Hessels, Phys. Rev. C93, 015204 (2016), arXiv:1509.05644 [nucl-ex]
- **VMD fits are biased, too (small radius)**
  I.T. Lorenz, U.-G. Meißner, H.W. Hammer, and Y.B. Dong, Phys. Rev. D 91, 014023 (2015)
- **Perhaps most realistic is the z-expansion with realistic physics constraints for convergence (= large radius!)**
  R.J. Hill and G. Paz, Phys. Rev. D 82, 113005 (2010)
  G. Lee, J.R. Arrington, and R.J. Hill, Phys. Rev. D 92, 013013 (2015)

The PRad proton radius proposal (JLAB)

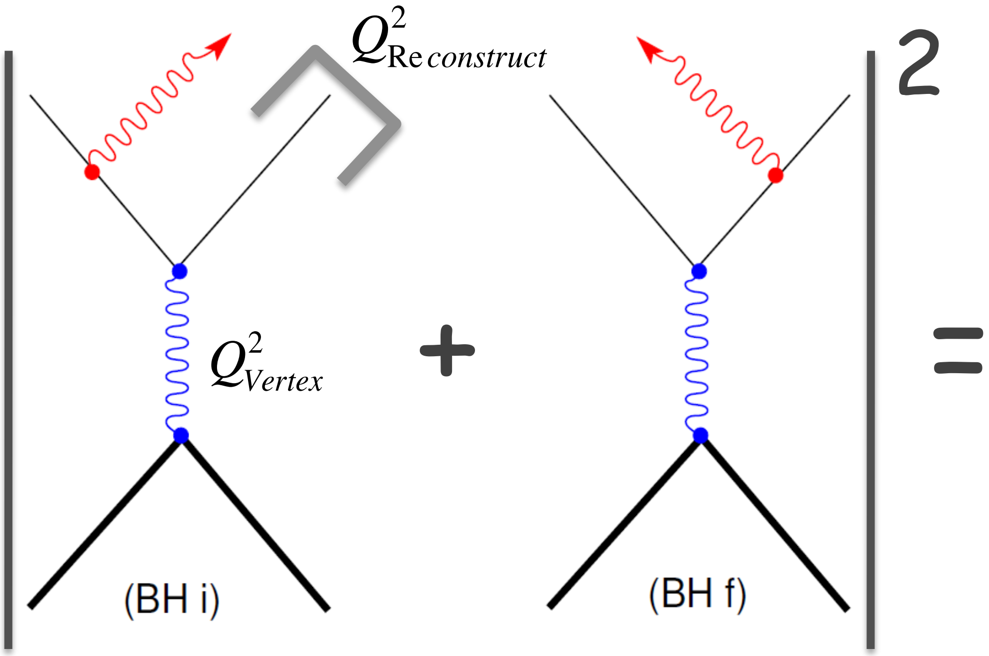


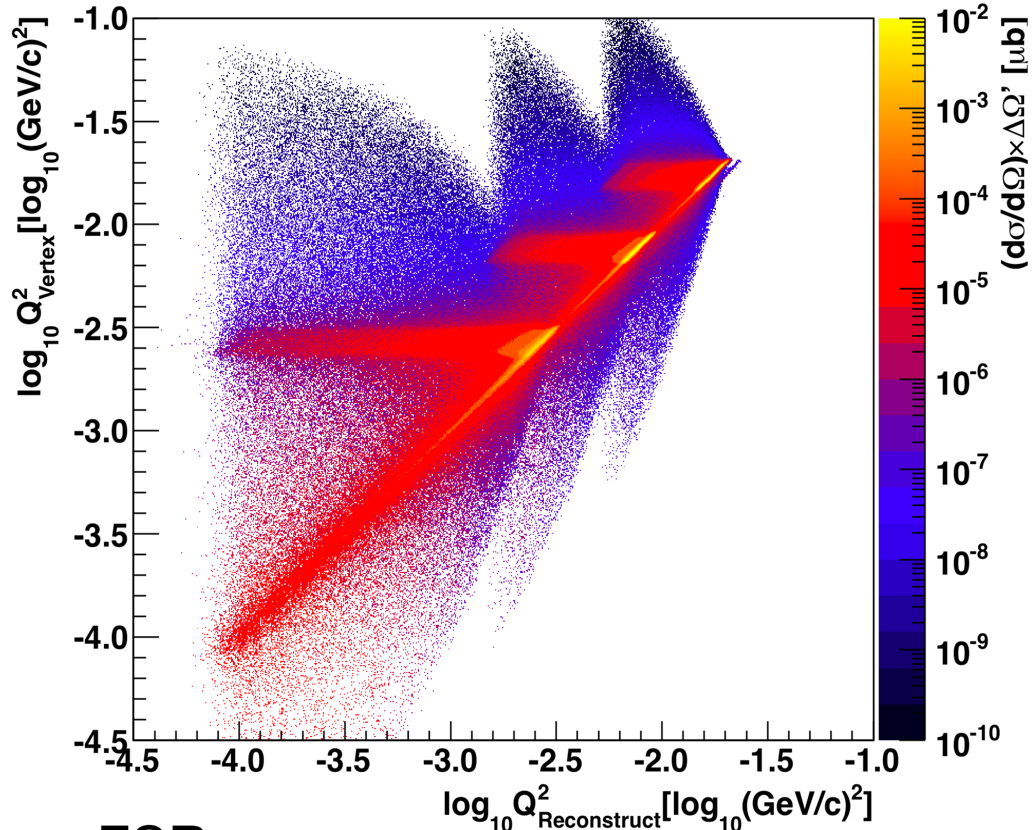


- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0°
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M
- Conditionally approved by PAC38 (Aug 2011): "Testing of this result is among the most timely and important measurements in physics."
- Approved by PAC39 (June 2012), graded "A"
- Running in Hall B in May-June 2016 (completed)

Initial state radiation (ISR) at MAMI

- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams





- In data ISR can not be distinguished from FSR
- **Combining data and simulation, ISR and form factor can be extracted**
- Q^2 (Reconstructed) > Q^2 (Vertex for ISR)
- Idea behind new MAMI experiment to extract $\mathbf{G_E^p}$ at **lowest $Q^2 \sim 10^{-4}$ (GeV/c)^2**
- Method tested at higher Q^2
- Data taken in 2014, under analysis, bgd. systematics limited, new ISR planned

A light boson and the proton radius puzzle

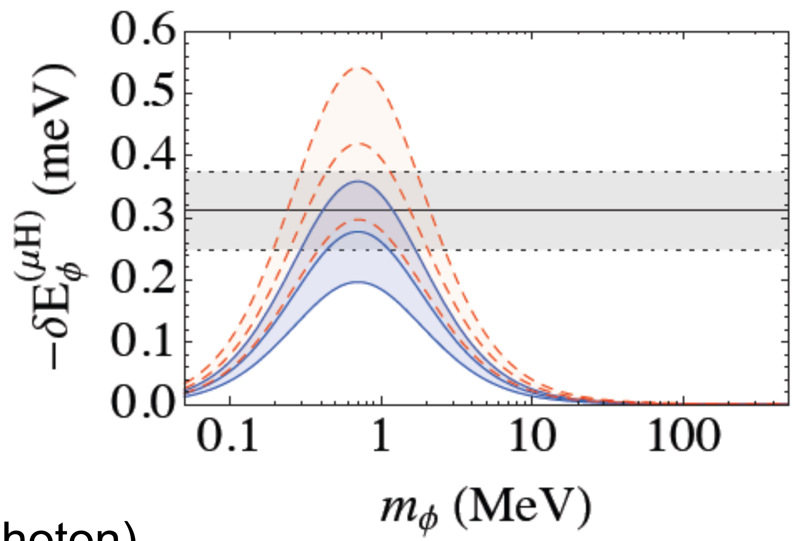
Jaeckel, Roy (arXiv:1008.3536)

- Hidden U(1) photon can decrease charge radius for muonic hydrogen, however even more so for regular hydrogen

Tucker-Smith, Yavin (arXiv:1011.4922)

can solve proton radius puzzle

- MeV particle coupling to p and μ (not e) consistent with g_μ-2



Batell, McKeen, Pospelov (arXiv:1103.0721):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_μ-2
- <100 MeV vector or scalar gauge boson V (poss. dark photon)
- resulting in large PV μp scattering

Carlson, Rislow (arXiv:1310.2786):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_μ-2
- Two fine-tuned scalar/pseudoscalar or vector/axial gauge bosons

Liu, McKeen, Miller (arXiv:1605. 04612):

can solve proton radius puzzle

- Electrophobic scalar boson consistent with g_μ-2

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):

- Light bosons constrained by K → μν decay

Search for a new particle in $K^+ \rightarrow \mu^+ \nu\, e^+ e^-$

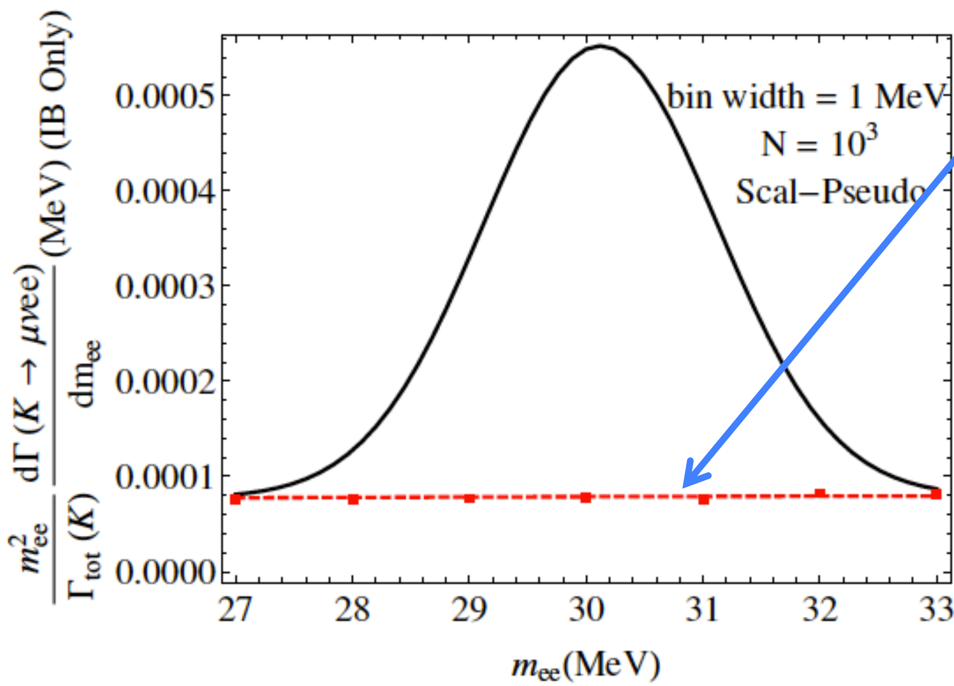
QED background: $K^+ \rightarrow \mu^+ \nu\, e^+ e^-$

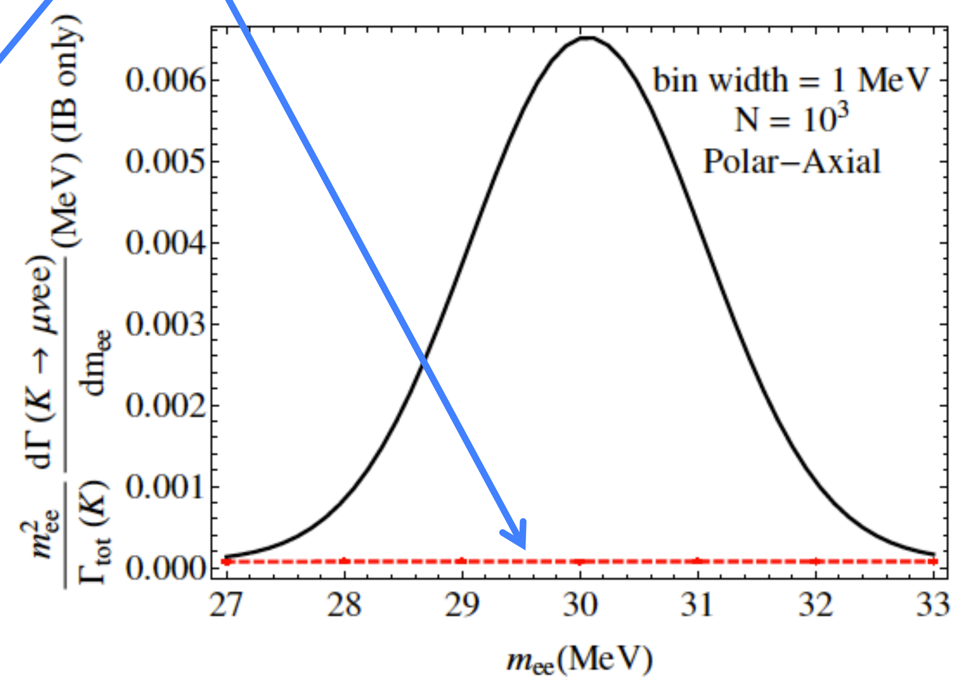
- $\Gamma(K^+ \rightarrow \mu^+ \nu\, ee) \sim 2.5 \times 10^{-5}$
- *10^{10} stopped K^+ in TREK/E36@J-PARC*
- *250k QED evts or ~1000 / MeV*

C. Carlson, B. Rislow, hep-ph/1310.2786
Phys. Rev. D89, 035003 (2014)
… explains g_μ–2 and R_p

Signal: $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+ e^-$

same QED background!





Carlson&Rislow model
(universality-violating, fine tuned); $\Gamma(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-6} - 10^{-5}$

HUGE signals predicted, J-PARC TREK/E36 stringent test

Motivation for μp scattering

Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84184 ± 0.00067
0.84087 ± 0.00039

Scattering

Electron scattering

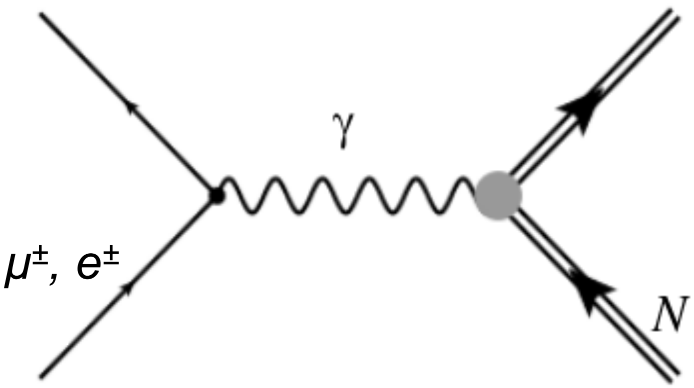
0.8770 ± 0.0060

Muon scattering

???

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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

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

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

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

Derivative in $Q^2 \to 0$ limit:

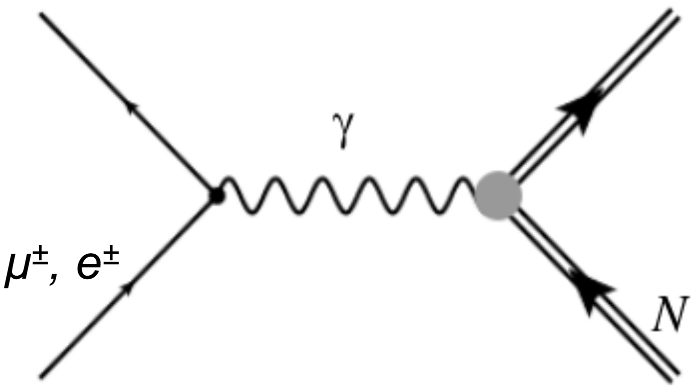
$$\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

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

Expect identical result for ep and μp scattering

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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

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

F_1, F_2 are the Dirac and Pauli form factors

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

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

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

following Preedom & Tegen, PRC36, 2466 (1987)

Expect identical result for ep and μp scattering

MUon Scattering Experiment (MUSE) at PSI

Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

- to **higher precision** than previously
- in the **low Q^2** region, similar to Mainz (Bernauer) and JLab (Zhan) for sensitivity to radius
- measure **both $\mu^{\pm}p$ and $e^{\pm}p$** for direct comparison and robust, convincing result
- depending on the results, 2nd generation experiments (lower Q^2, $\mu^{\pm}$n,D,He, higher Q^2, ...) might be desirable

MUon Scattering Experiment (MUSE) at PSI

Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

- Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H_2 target

→ Separation by time of flight

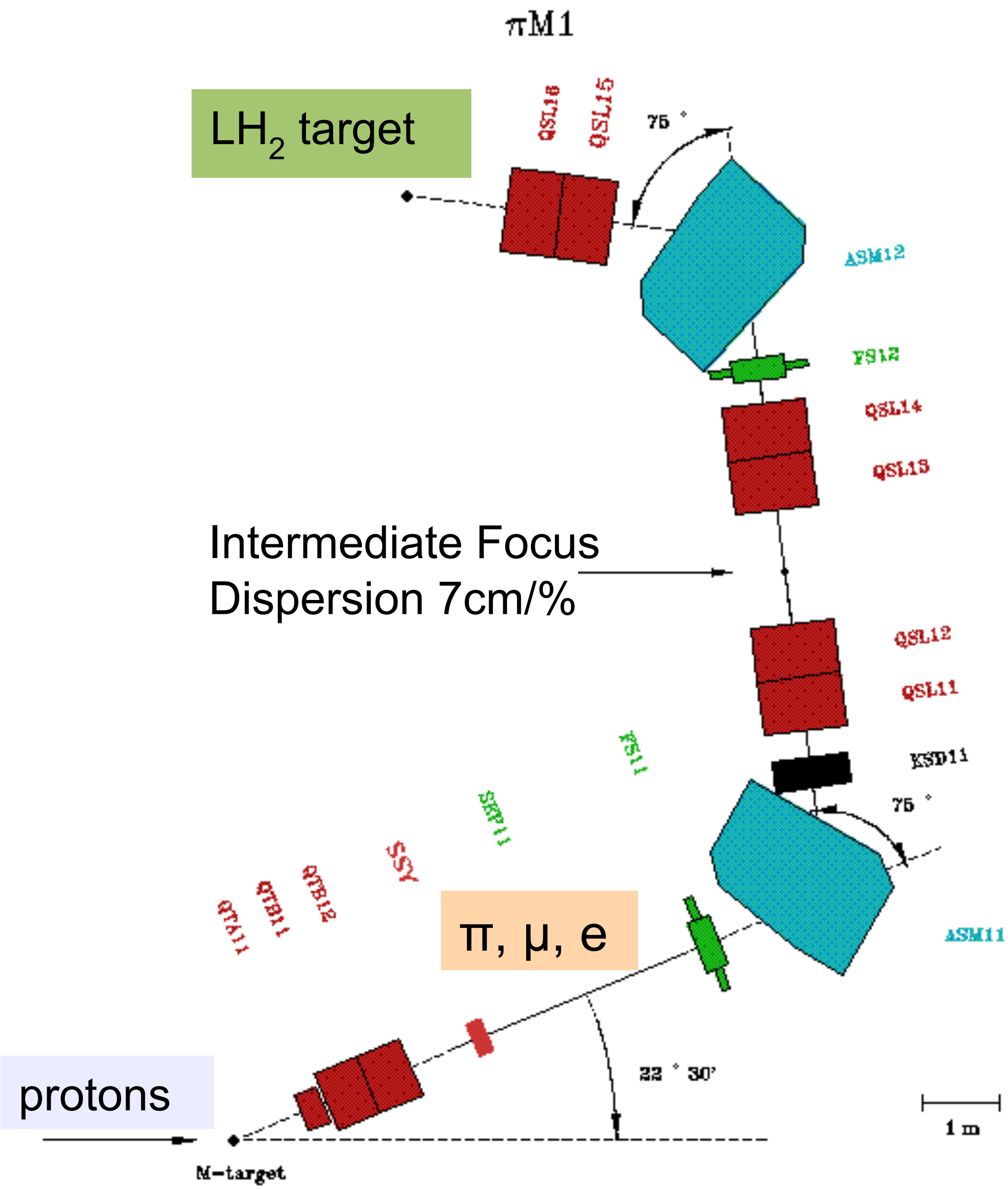
→ Measure absolute cross sections for ep and μp

→ If radii differ by 4%, then form factor slope by 8%, x-section slope by 16%

→ Measure e+/μ+, e-/μ- ratios to cancel certain systematics

- Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-
- Multiple beam momenta 115-210 MeV/c to separate G_E and G_M (Rosenbluth)

πM1 / MUSE beamline



- πM1: 100-500 MeV/c
  Momentum selective
  RF+TOF separated π, μ, e
- Limited beam flux (5 MHz)
  → Large angle, non-magnetic detectors to detect leptons
- Secondary beam
  → Tracking of beam particles to target
- Mixed beam
  → Identification of beam particle in trigger

MUSE experiment layout

- Beam particle tracking
- Liquid hydrogen target
- Scattered lepton detection

Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

p = 115, 153, 210 MeV/c

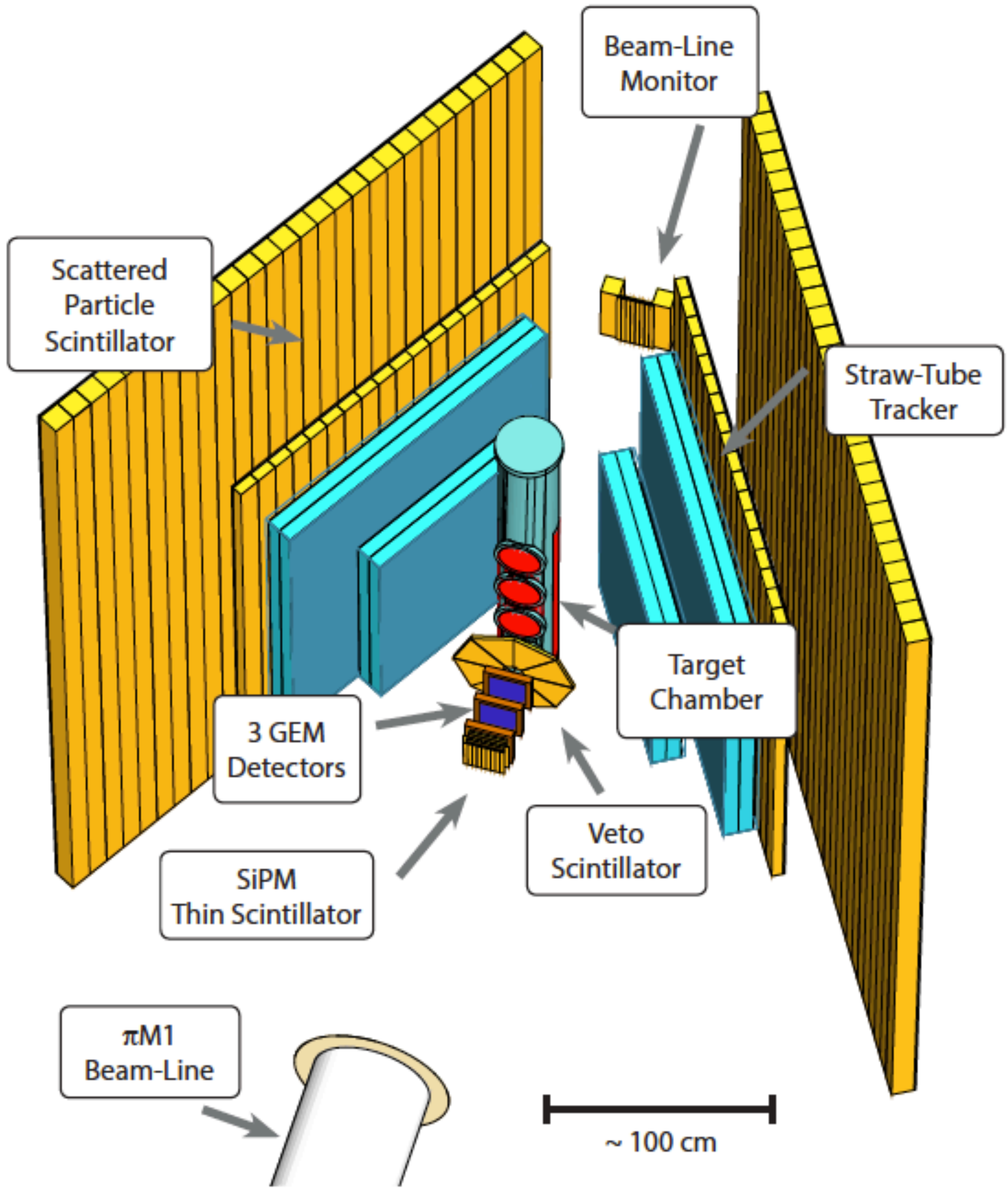
$\Theta = 20^{o}$ to 100^{o}

$Q^2 = 0.002 - 0.07\ (GeV/c)^2$

$\epsilon = 0.256 - 0.94$

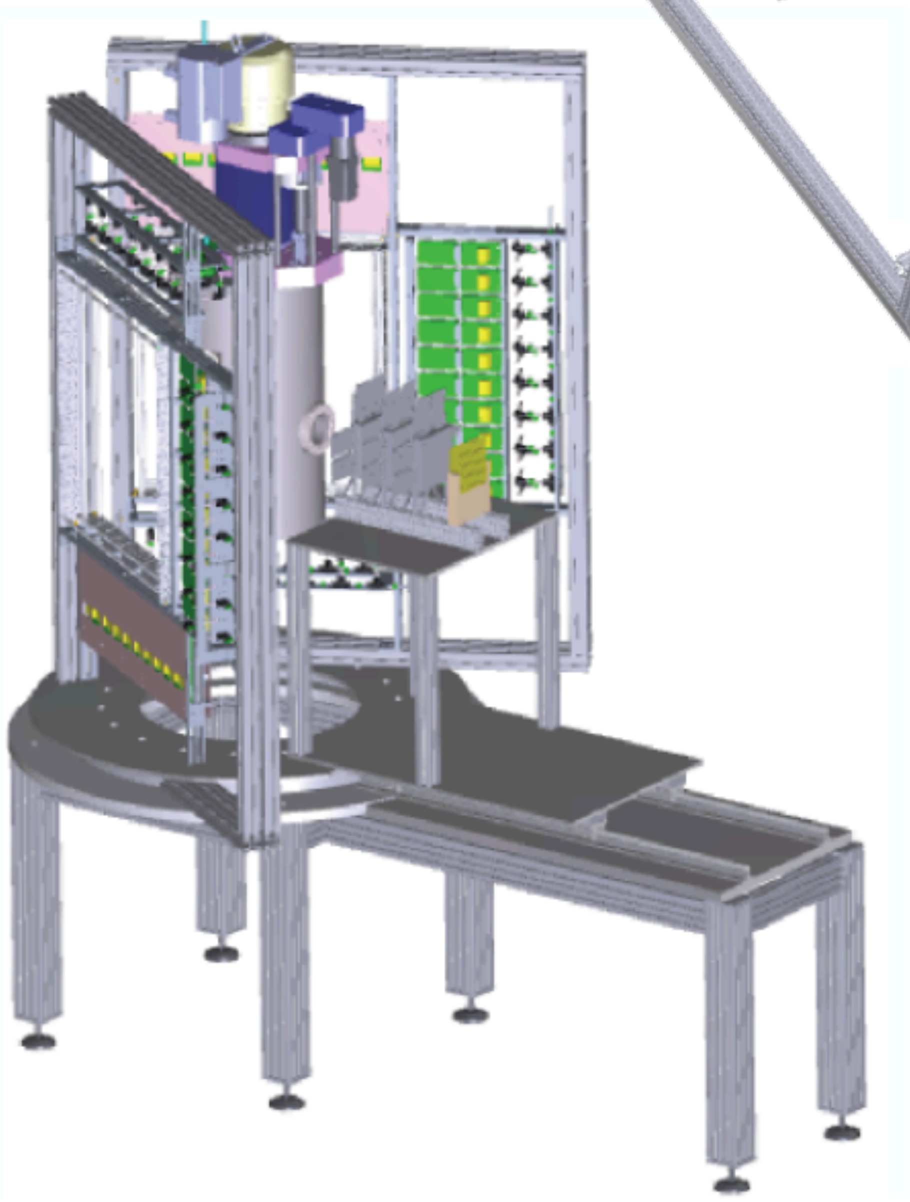
Challenges

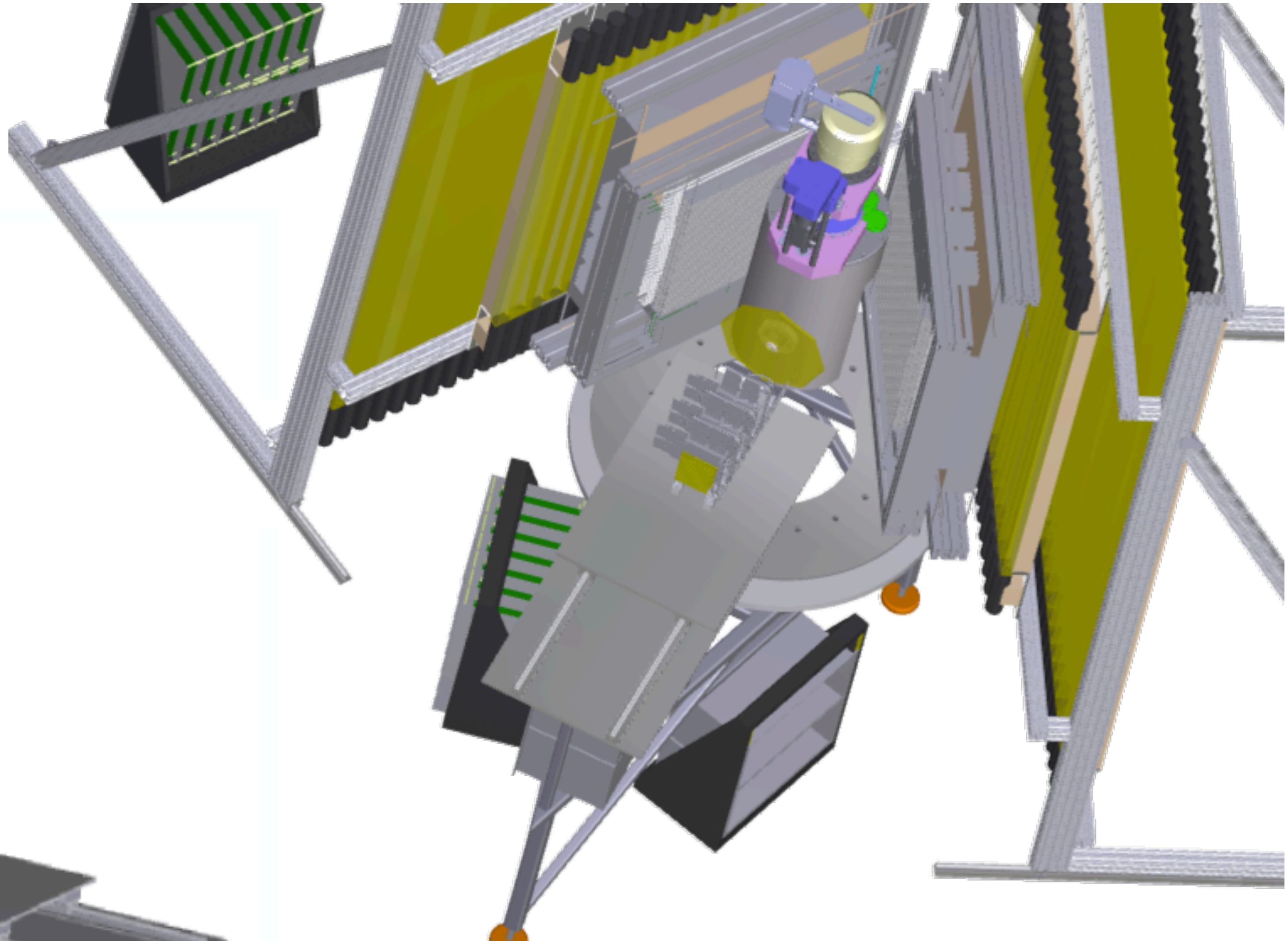
- Secondary beam with π background
- Non-magnetic spectrometer
- Background from Møller scattering and muon decay in flight



Mechanical assembly

T. O'Connor (ANL)





Rotating table
Retractable beam tracker
Dedicated alignment procedures

MUSE test beamtimes

12 MUSE Test Runs

to characterize piM1 beam

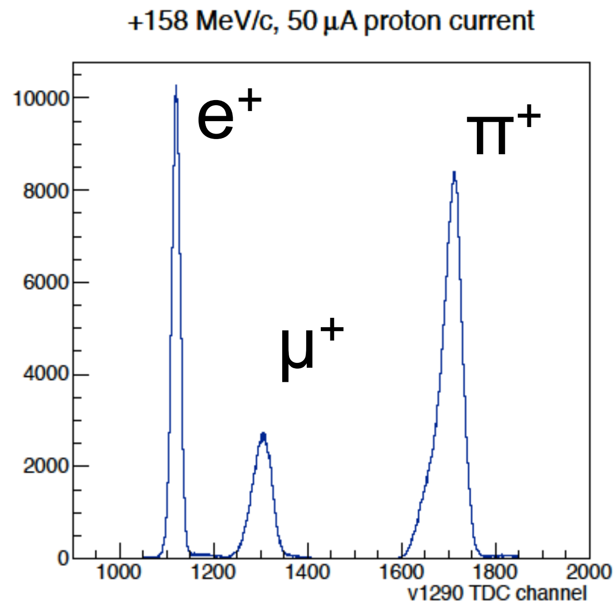
to test detector prototypes (scintillators, Cerenkov, straw tubes)

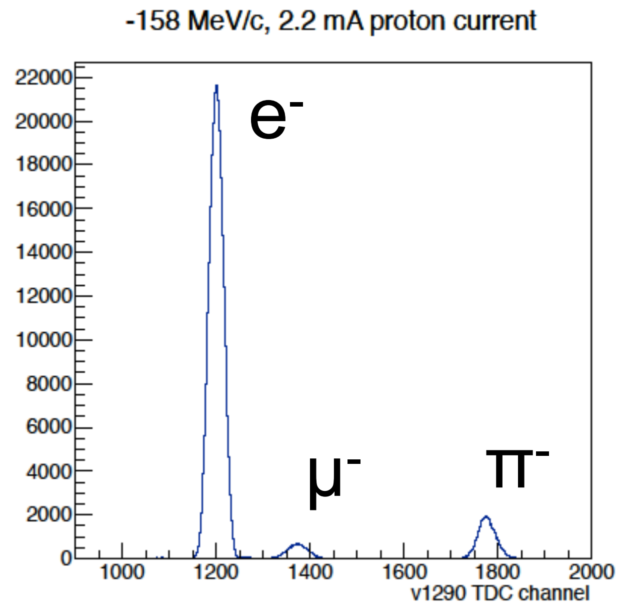
to study and optimize GEM performance

- Oct 2012
- May 2013
- July 2013
- Oct 2013 (Cosmics)
- Dec 2013
- June 2014
- Dec 2014
- Feb 2015 (Cosmics)
- June-July 2015
- Dec 2015
- May 2016
- June-July 2016

Representation from 13 institutions

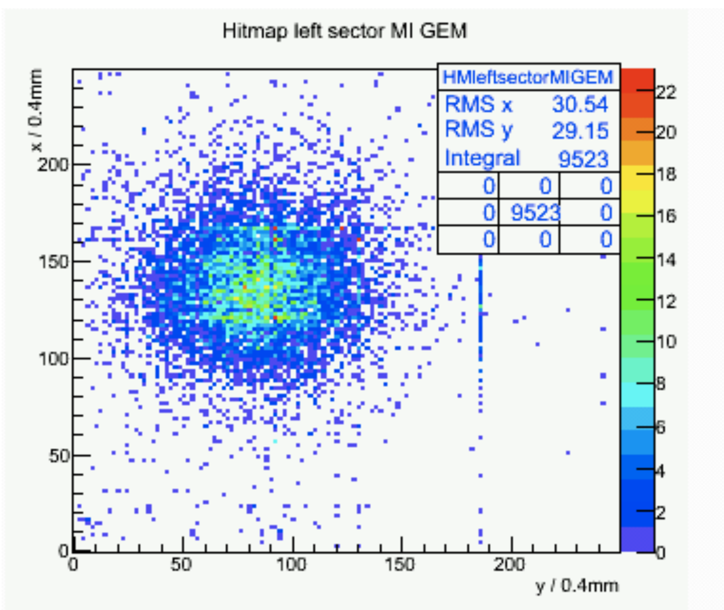
First beam tests

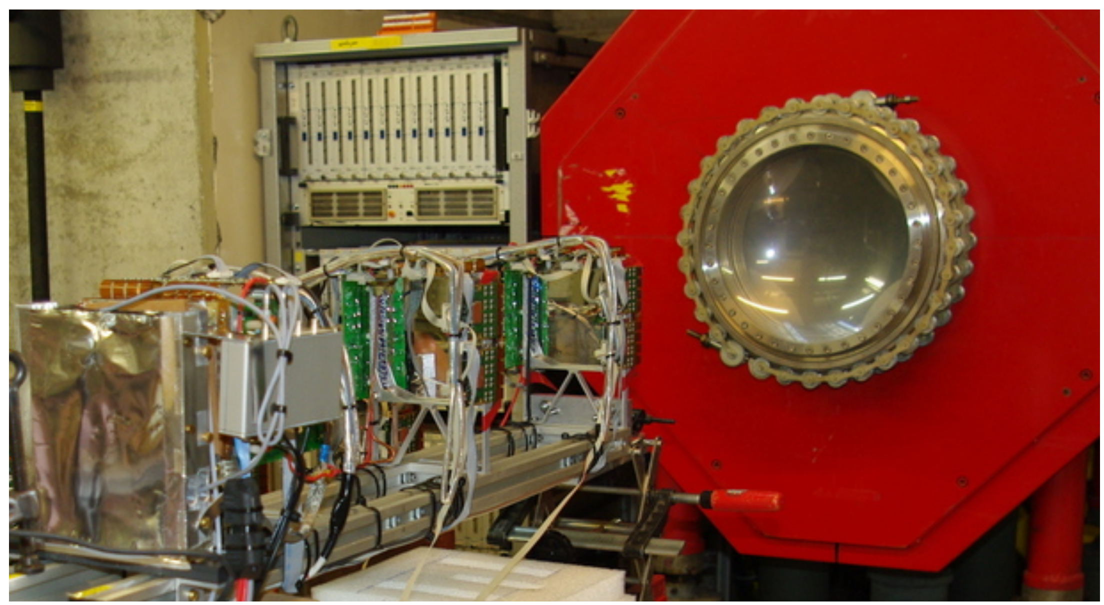




Time of flight relative to RF time (Fall 2012)

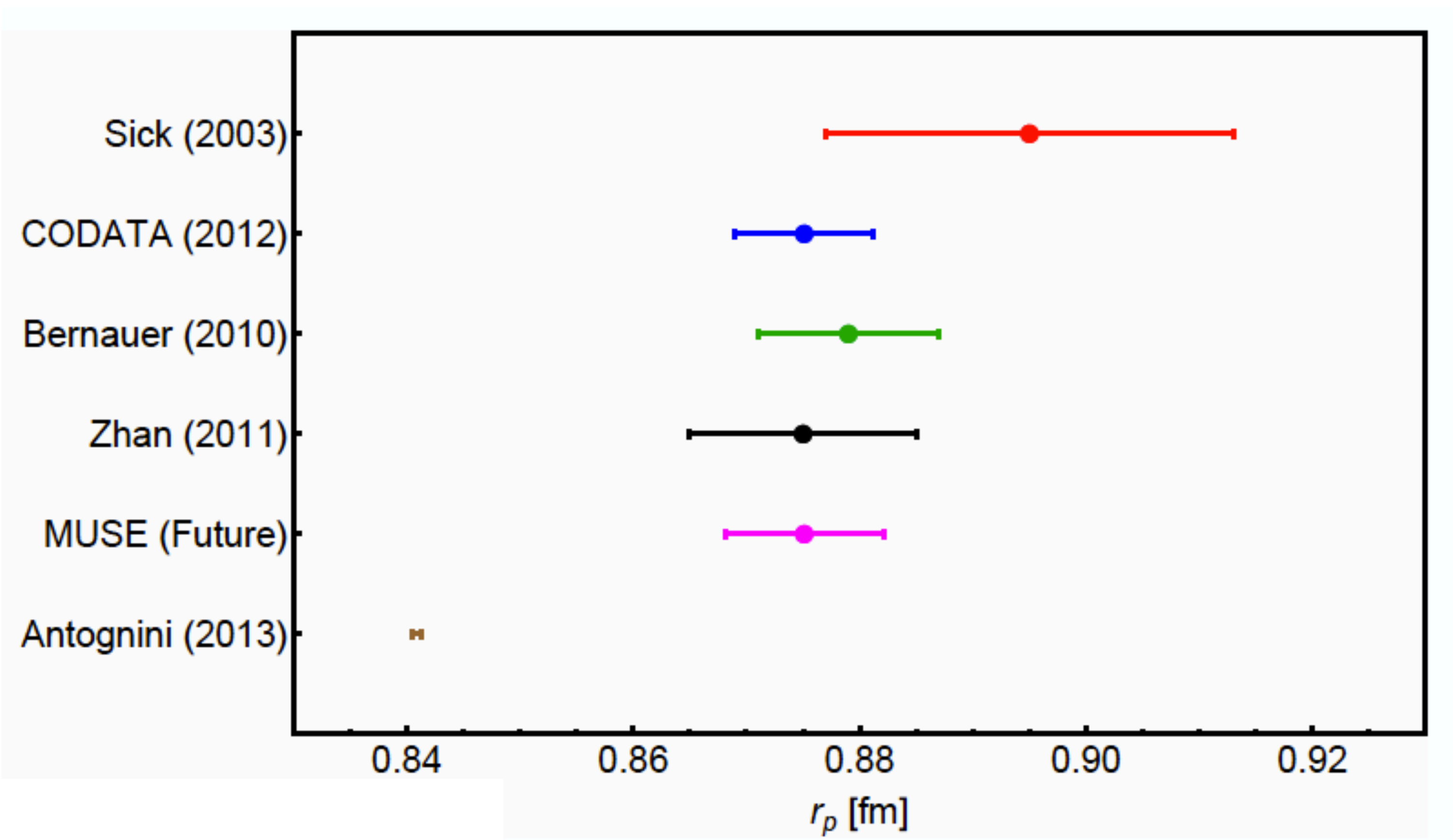
Beam spot with GEM – May 23, 2013





Projected sensitivity for MUSE

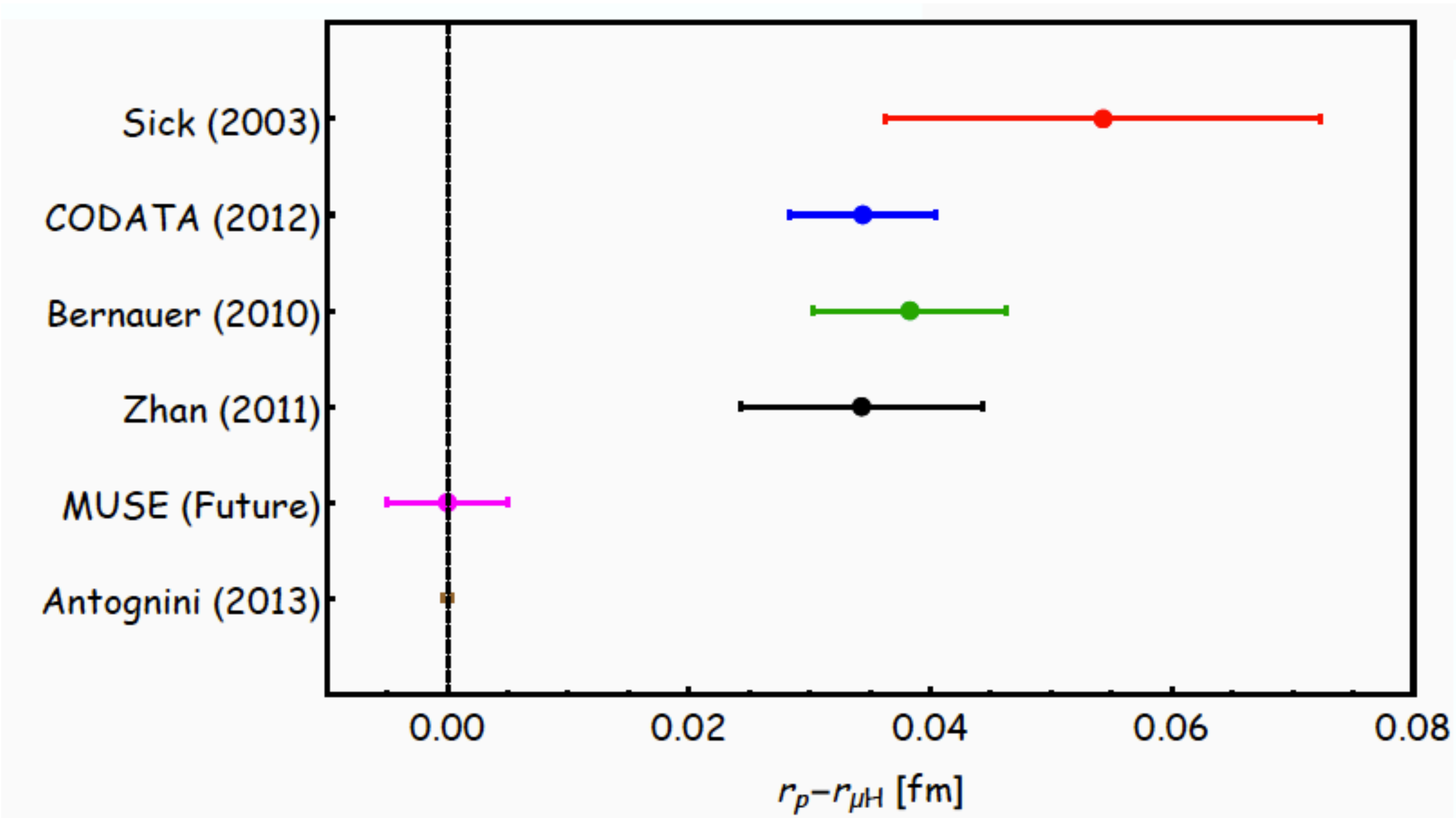
- Cross sections to <1% stat. for backward μ, <<1% for e and forward μ
  Absolute 2%, point-to-point relative uncertainties few x10^{-3}
- Individual radius extractions from $e^{\pm}$, $\mu^{\pm}$ each to 0.01 fm
- Compare $e^{\pm}$ xsecs and $\mu^{\pm}$ xsecs for TPE. Charge-average to eliminate TPE.
- From e/μ xsec ratios: extract e-μ radius difference with minimal truncation error to 0.0045 fm or ~8σ (1st-order fits)
- If no difference, extract radius to 0.007 fm (2nd-order fit)



Projected sensitivity for MUSE

- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
- R_e-R_μ = 0.034±0.006 fm (5.6σ), MUSE: δr = 0.0045 fm (7.6σ)

MUSE suited to verify 5.6σ effect (CODATA2014) with even higher significance



MUon Scattering Experiment – MUSE

55 MUSE collaborators from 24 institutions in 5 countries:

A. Afanasev, A. Akmal, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, N. Benmouna, J. Bernauer, A. Blomberg, E. Brash, W.J. Briscoe, E. Cline, D. Cohen, E.O. Cohen, K. Deiters, J. Diefenbach, B. Dongwi, E.J. Downie, L. El Fassi, S. Gilad, R. Gilman, K. Gnanvo, R. Gothe, D. Higinbotham, Y. Ilieva, L. Li, M. Jones, N. Kalantarians, M. Kohl, G. Kumbartzki, J. Lichtenstadt, W. Lin, A. Liyanage, N. Liyanage, Z.-E. Meziani, P. Monaghan, K.E. Mesick, P. Moran, J. Nazeer, C. Perdrisat, E. Piasetzsky, V. Punjabi, R. Ransome, D. Reggiani, P.E. Reimer, A. Richter, G. Ron, T. Rostomyan, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, V. Sulkosky, A.S. Tadepalli, M. Taragin, and L. Weinstein

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem,,Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Ieizmann Institute, Old Dominion University

MUon Scattering Experiment – MUSE

- **Proton Radius Puzzle – still unresolved ~6 years later**
- **MUSE Experiment at PSI**
  - Measure μp and ep scattering and compare μ+/e+ and μ-/e- directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Technical Challenges**
  - PID, timing, background rejection, momentum and flux determination
- **Timeline**
  - Initial proposal February 2012
  - Technical review July 2012
  - First beam tests in fall 2012
  - **PAC-approved in January 2013**
  - Further beam tests 2x yearly in summer and fall 2013–2016
  - Funding & construction 2016–2017
  - Production running 2018–2019 (2x 6 months)

Summary and outlook

- **Proton Radius Puzzle – still unresolved ~6 years later**
- **Substantial theoretical and experimental activity**
- **Numerous additional, high-quality experimental data expected in the next few years**
  PRad, ISR, MUSE, TREK/E36, muonic atoms, regular hydrogen

"Until the difference between the ep and μp values is understood, it does not make sense to average the values together. For the present, we give both values. It is up to workers in this field to solve this puzzle."

K.A. Olive et al. [Particle Data Group], Chin. Physics C 38, 090001 (2014)

R_P = 0.84087 ± 0.00026 ± 0.00029 fm [muonic hydrogen]

A. Antognini et al., Science 339, 417 (2013)

R_P = 0.8775 ± 0.0051 fm [CODATA2010]

P.J. Mohr, B.N. Taylor, and D.B. Newell, Rev. Mod. Phys. 84, 1527 (2012)

Backup