Form Factors with Electrons and Positrons

Part 6: The proton charge radius puzzle

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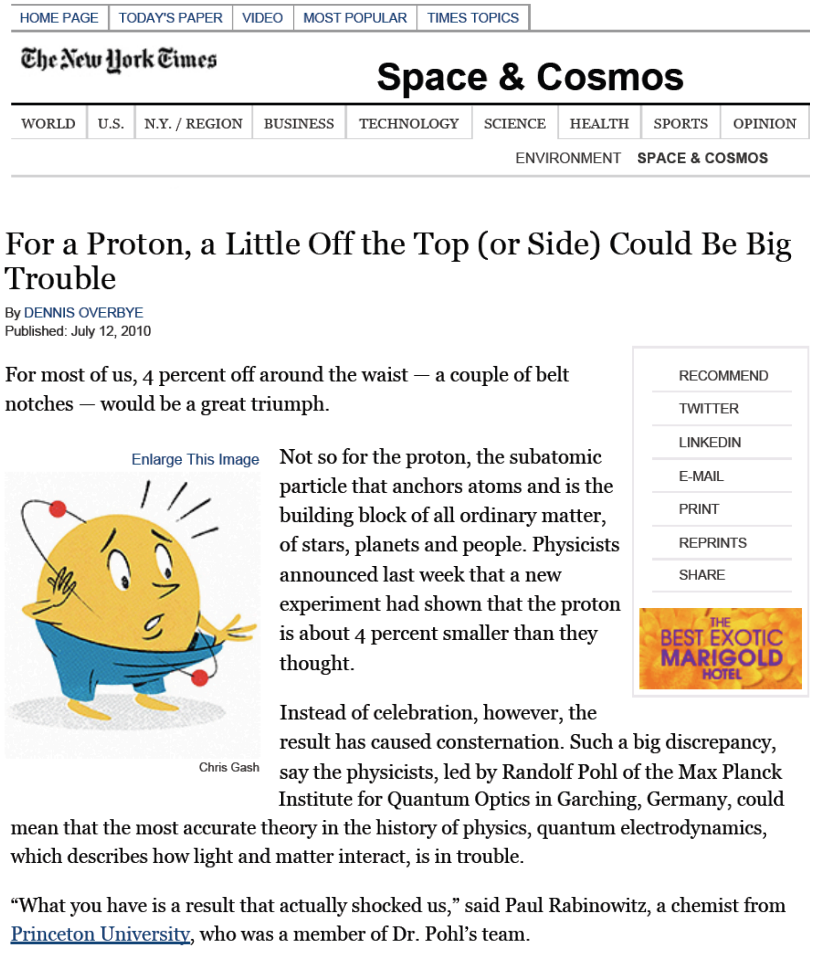
The proton radius puzzle

- 7σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Special feature at many recent conferences



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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.

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THE BEST EXOTIC MARIGOLD HOTEL

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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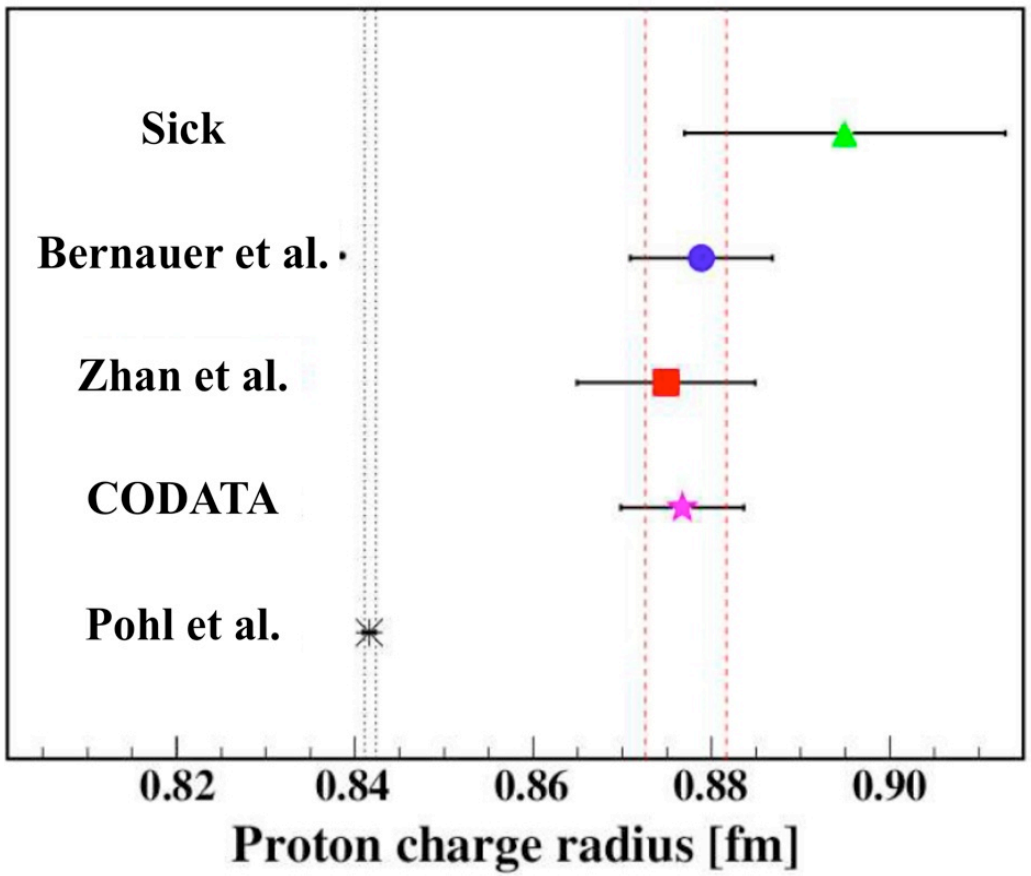

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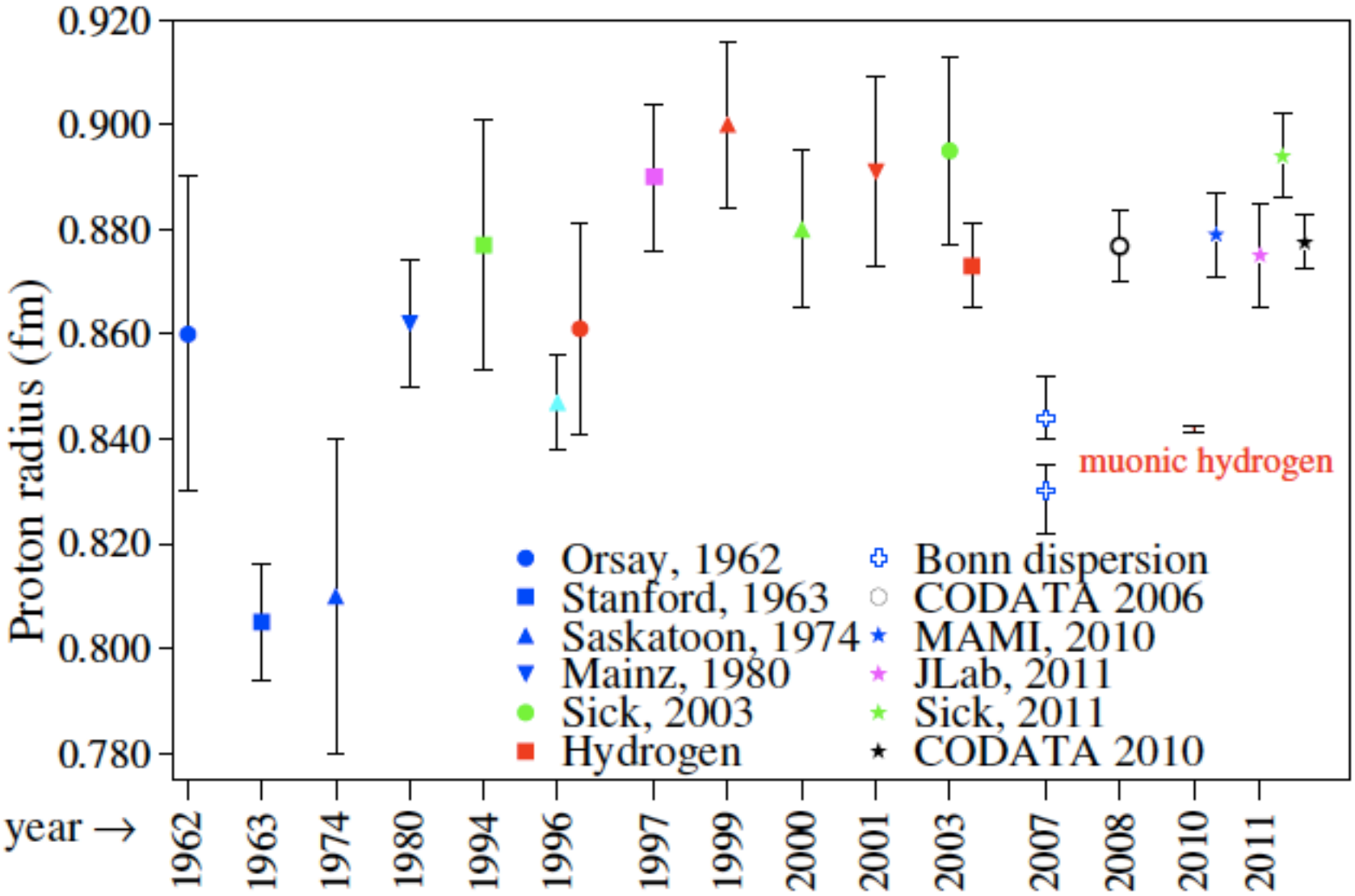
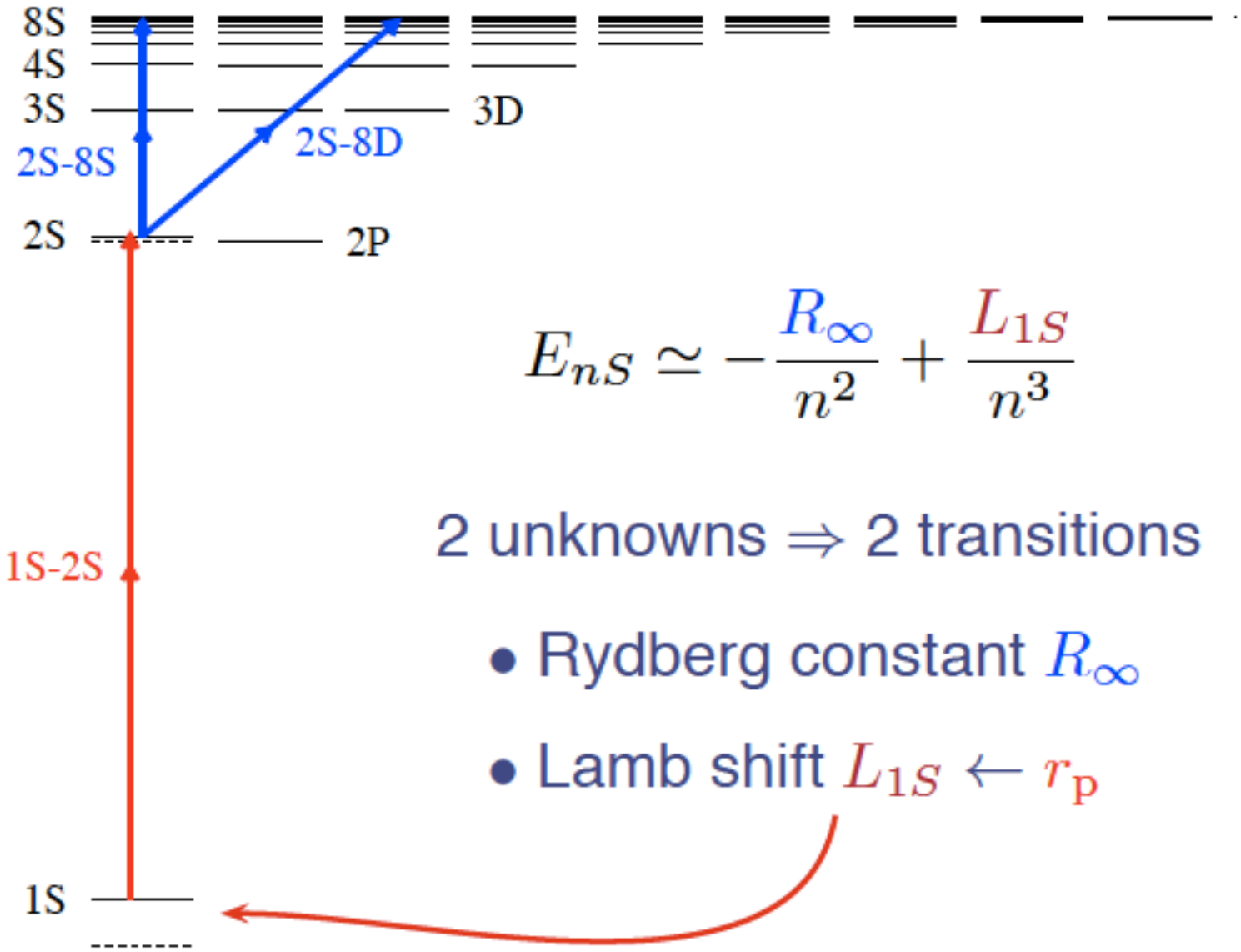
Proton radius evolution



Hydrogen spectroscopy (Lamb shift)

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



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

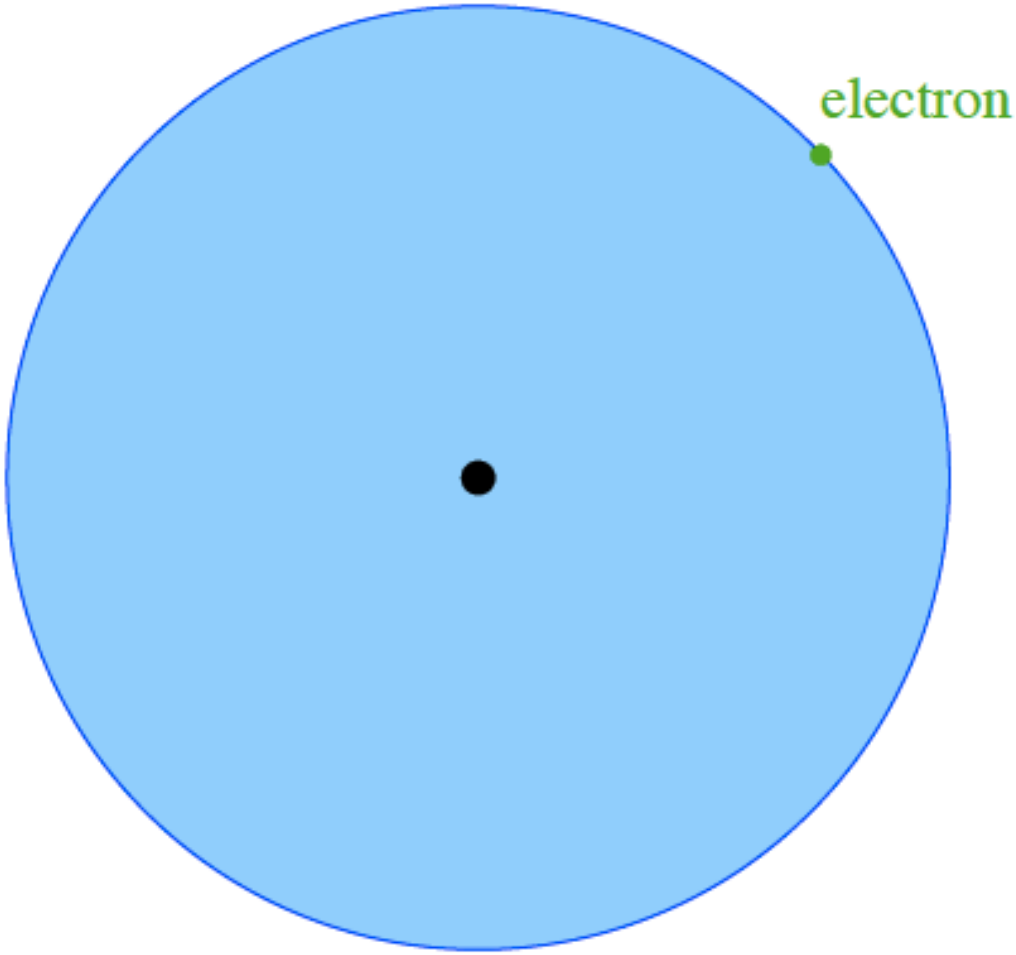
2 unknowns $\Rightarrow$ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$

Muonic hydrogen

Regular hydrogen:

electron e^- + proton p



Muonic hydrogen:

muon μ^- + proton p

muon mass $m_\mu \approx 200 \times m_e$

Bohr radius $r_\mu \approx 1/200 \times r_e$

μ inside the proton: $200^3 \approx 10^7$

muon **much** is more sensitive to r_{p}

Muonic hydrogen spectroscopy (Lamb shift)

muonic hydrogen = μ^- p mass $m_\mu = 207\, m_e$

Bohr radius $\sim$ 1/m

Finite size effects $\sim m^3 \approx 200^3 \approx 10^7$!!

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

$$206.0668(25) - 5.2275(10)\, r_{\rm p}^2 \quad \text{[meV]}$$

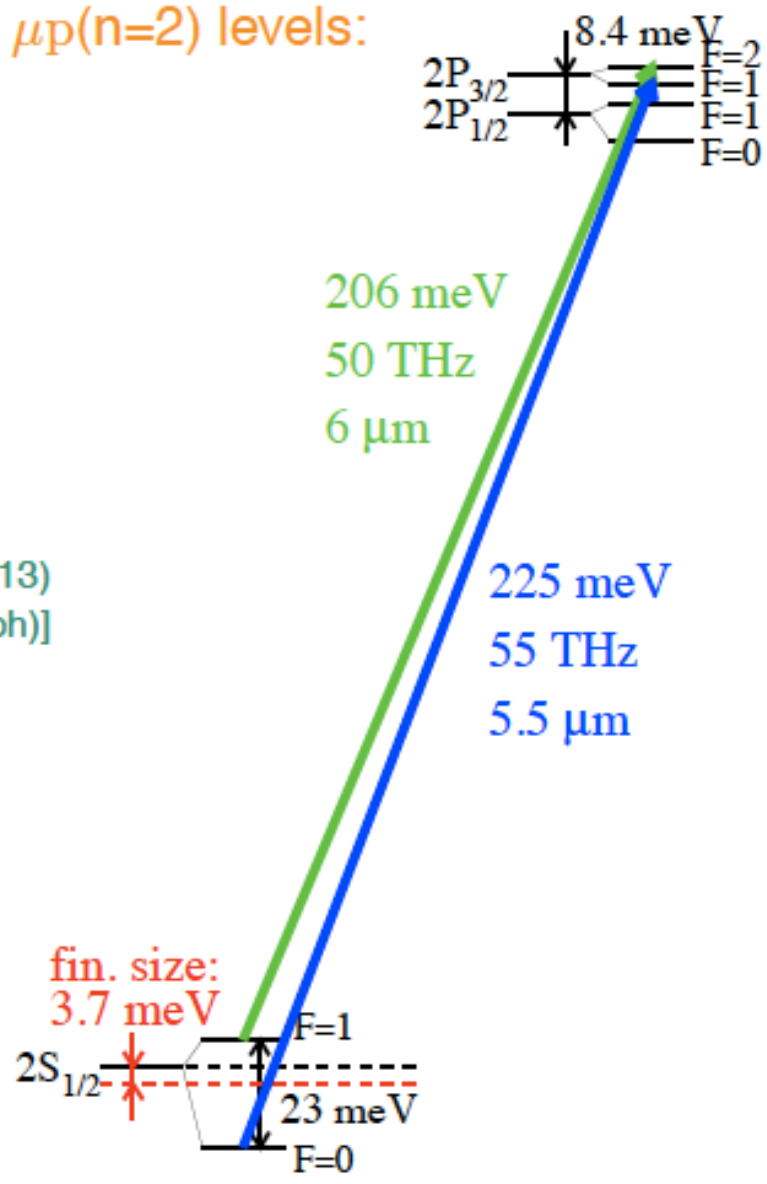
A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013)
[arXiv :1208.2637 (atom-ph)]

Finite size contribution is 2% of the μp Lamb shift

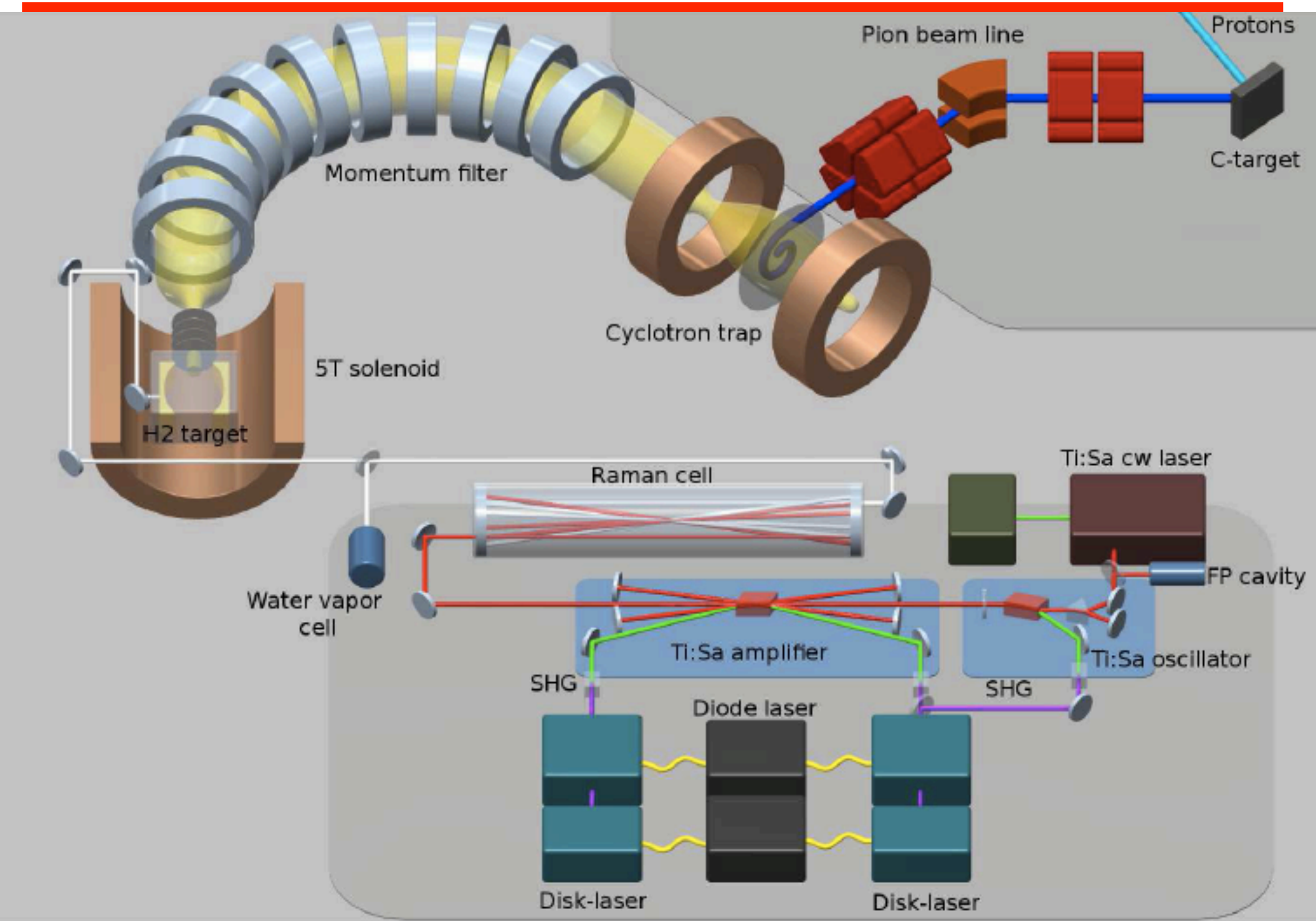
That's **huge!**

Laser spectroscopy to 10^{-5} gives $r_{\rm p}$ to 10^{-3}

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



PSI muonic hydrogen measurements



PSI muonic hydrogen measurements

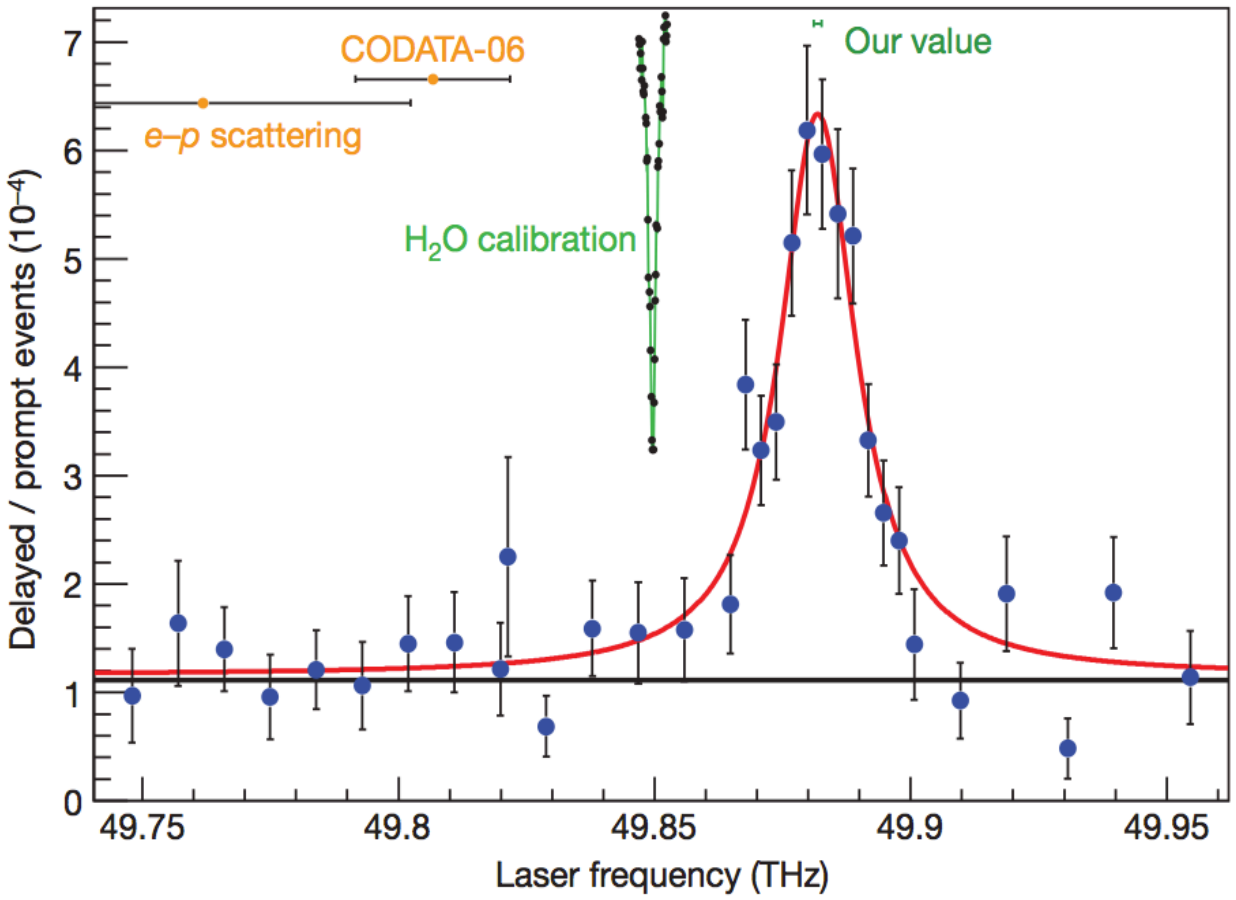
- **R. Pohl et al., Nature 466, 09259 (2010):** 2S⇨2P Lamb shift

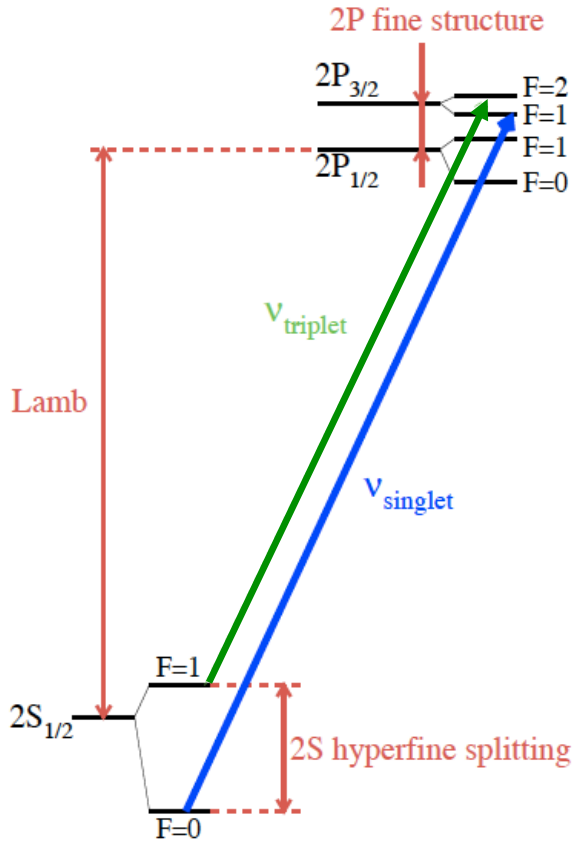
  $\Delta E(meV) = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3 \Rightarrow r_p = 0.842 \pm 0.001$ fm

  Possible issues: atomic theory & proton structure

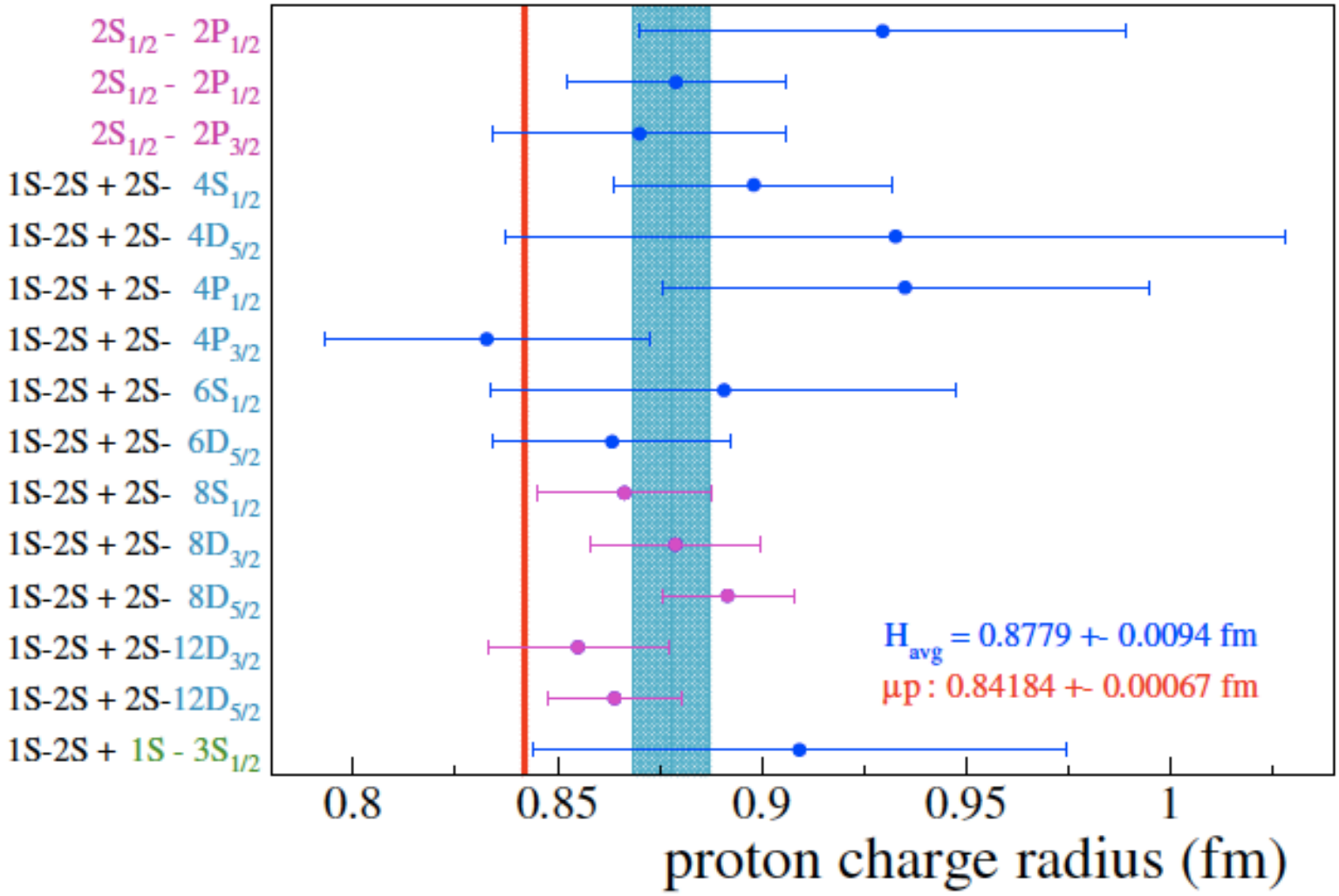
- **UPDATE: A. Antognini et al., Science 339, 417 (2013):** 2S⇨2P Lamb + 2S-HFS

  $\Delta E_L(meV) = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20)_{TPE} \Rightarrow r_p = 0.84087 \pm 0.00039$ fm





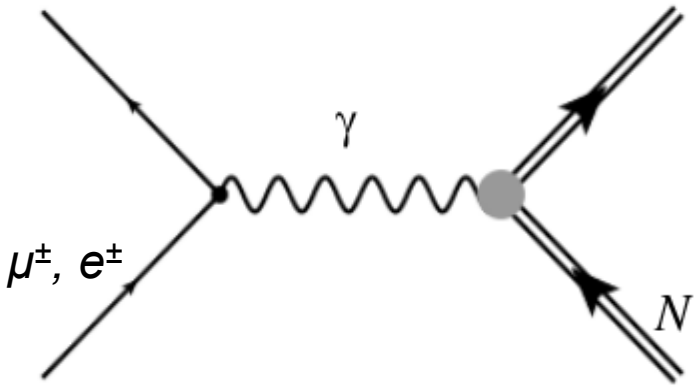
Lamb shift muonic vs electronic hydrogen



r_p (fm)	μp	ep
Spectroscopy	0.84087 ± 0.00039	0.875800 ± 0.07700

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:

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

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

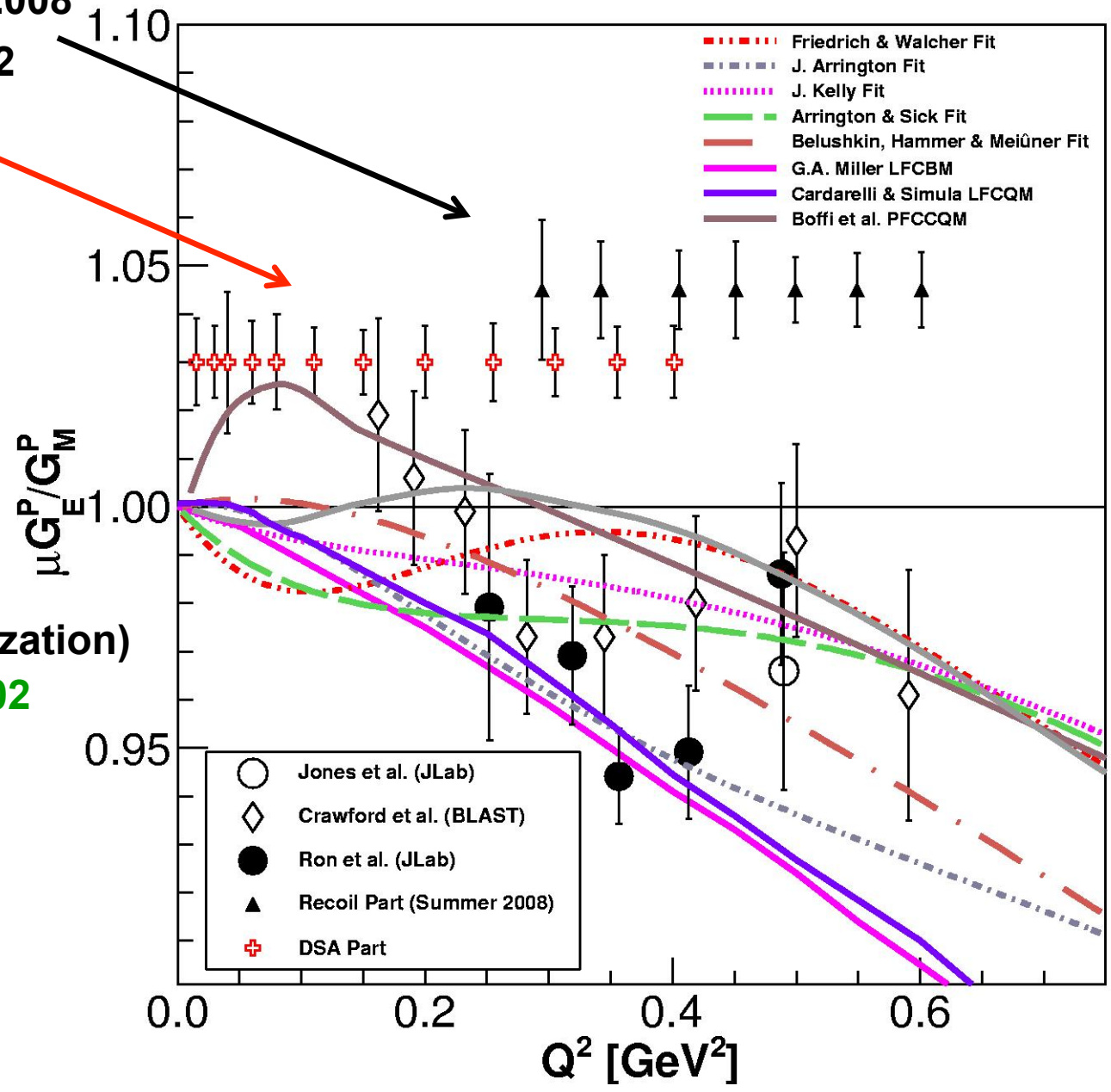
New proton measurements at low Q^2

Hall A PR07-004, PR08-007 (PAC31/33)

- **Recoil polarization, completed 2008**
- **Polarized target, completed 2012**

◇ **BLAST (polarized target)**
C. Crawford et al.,
PRL98 (2006) 052301

● **LEDEX PR05-004 (recoil polarization)**
G. Ron et al., PRL99 (2007) 202002



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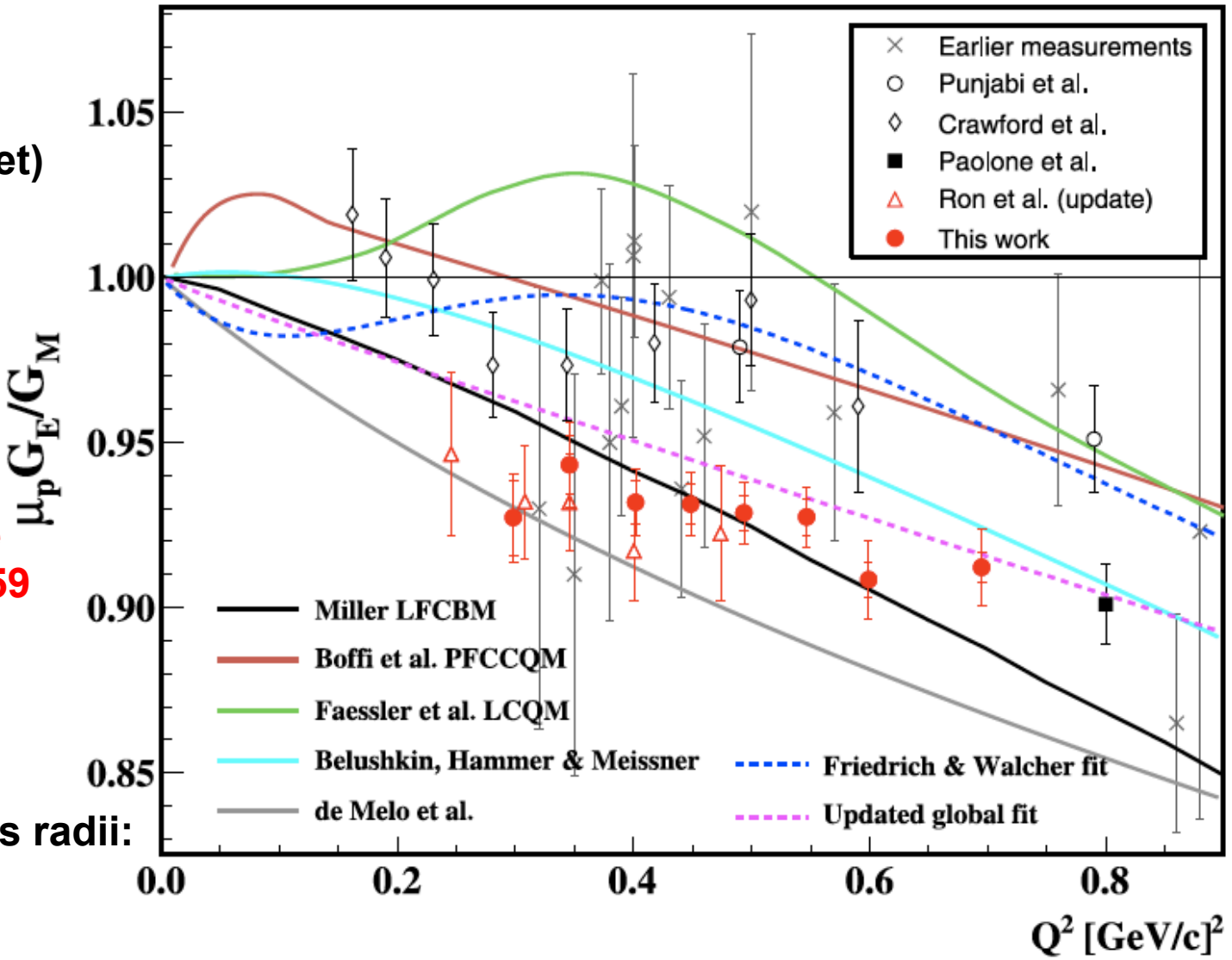
C. Crawford et al.,
PRL98 (2007) 052301

X. Zhan,
E08-007 + LEDEX update
Phys. Lett. B 705 (2011) 59

2-sigma difference lower than BLAST

Charge and magnetic rms radii:
$R_E = 0.875 \pm 0.010$ fm
$R_M = 0.867 \pm 0.020$ fm



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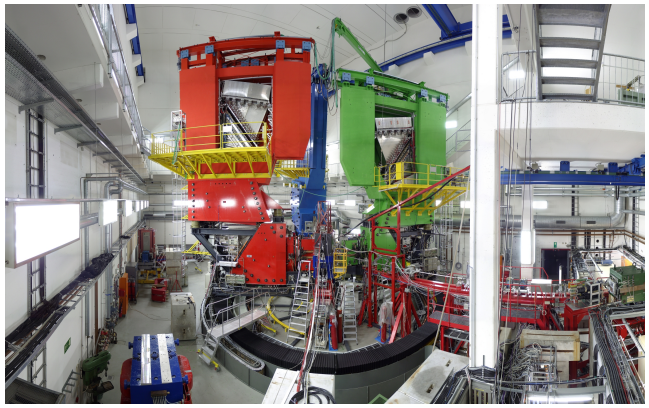
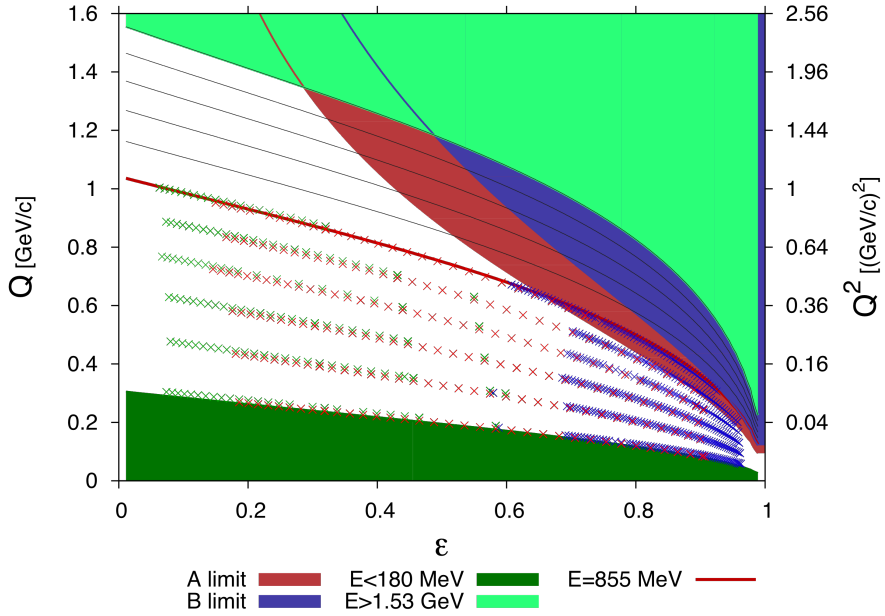
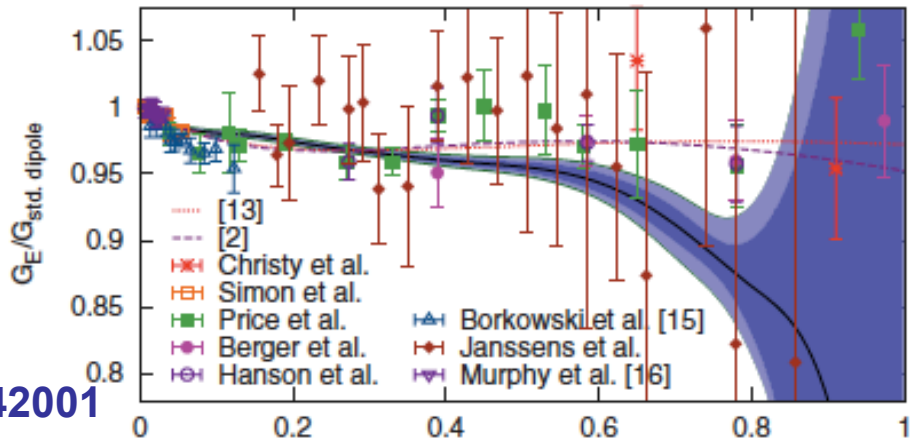
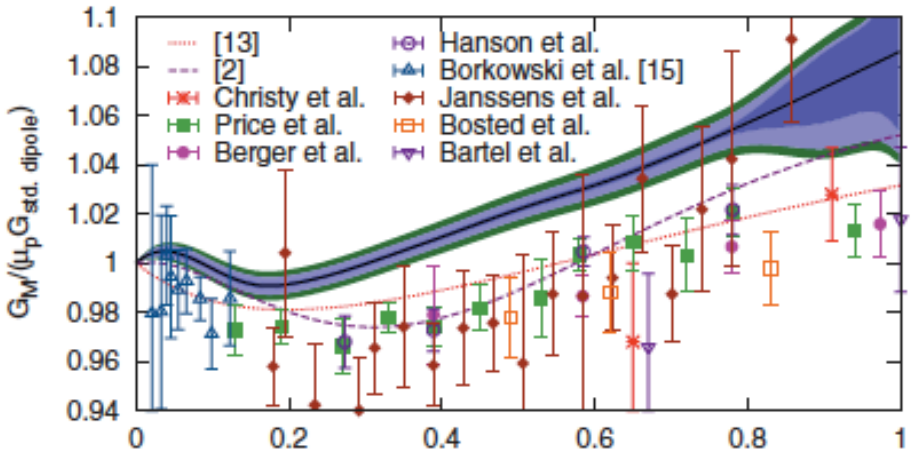


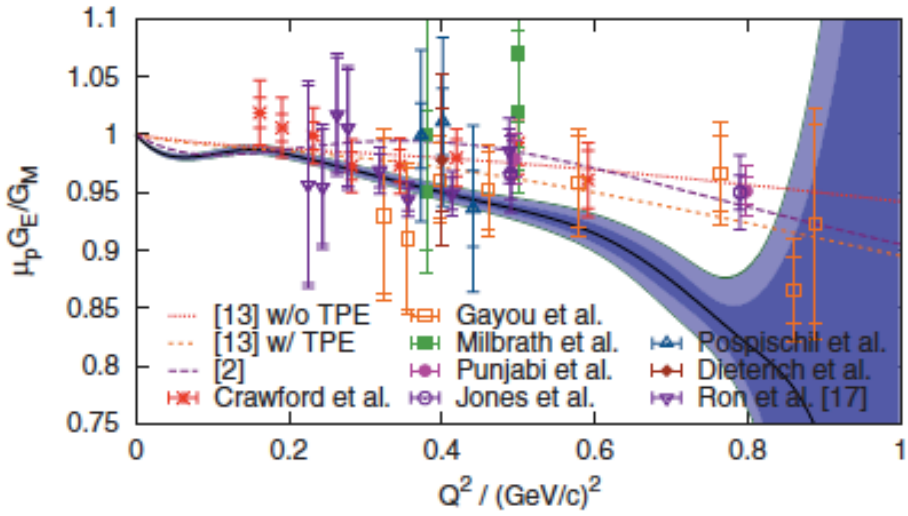
MAMI A1

J. Bernauer et al.
PRL105 (2010) 242001









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

$R_E = 0.879 \pm 0.008$ fm

$R_M = 0.777 \pm 0.017$ fm

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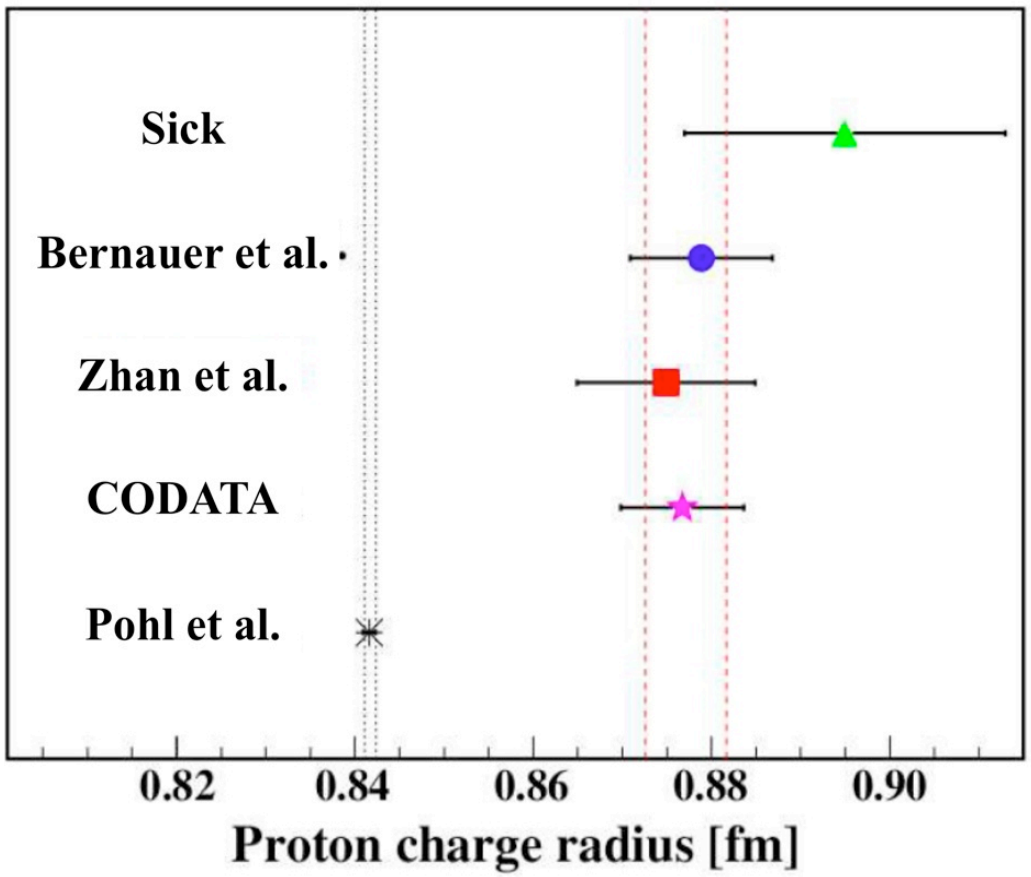

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Possible resolutions to the puzzle

- **The μp result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from Lamb shift measurement

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors

- **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
  Existing constraints on new physics

New measurements are on their way

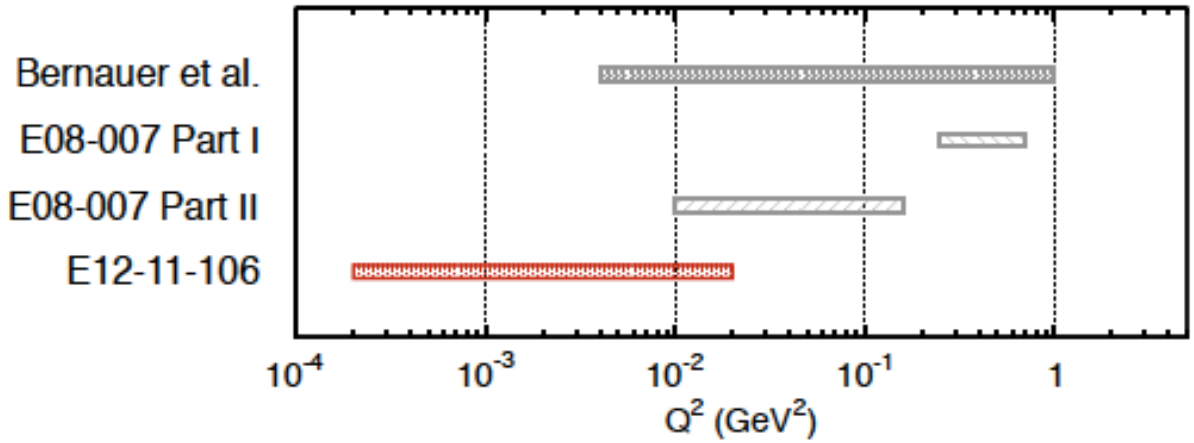
- **Additional measurements needed / in preparation**
  - Spectroscopy with μD, μHe, and regular H; Rydberg constant
  - ep-, ed-scattering at Jlab and MAMI
  - μp- and ep-scattering in direct comparison at PSI (MUSE), and for both lepton charges

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

More insights from comparison of ep and μp scattering

The PRad proton radius proposal (JLAB)

E12-11-106: Very-low Q^2 elastic ep-scattering



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

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N(e^-e^- \to e^-e^-)} \cdot \frac{\epsilon^{e^-e^-}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{e^-e^-}_{\det}}{\epsilon^{ep}_{\det}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

Møller scattering – well known QED process

Simultaneous detection of two processes

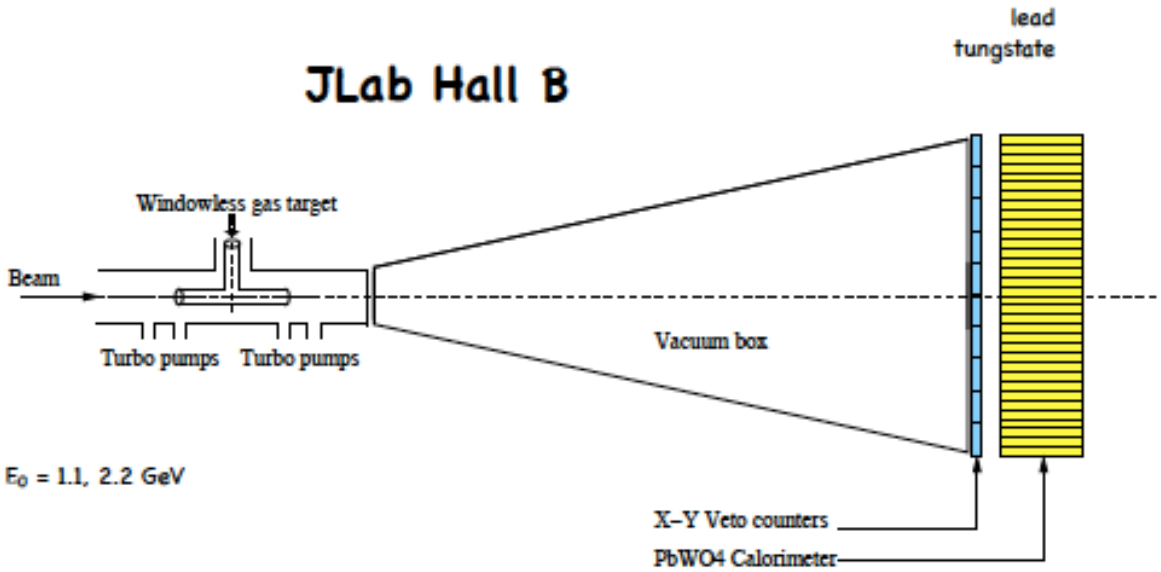
- ep → ep
- ee → ee (Møller scattering)

→ N_e and N_{tgt} cancel

The PRad proton radius proposal (JLAB)

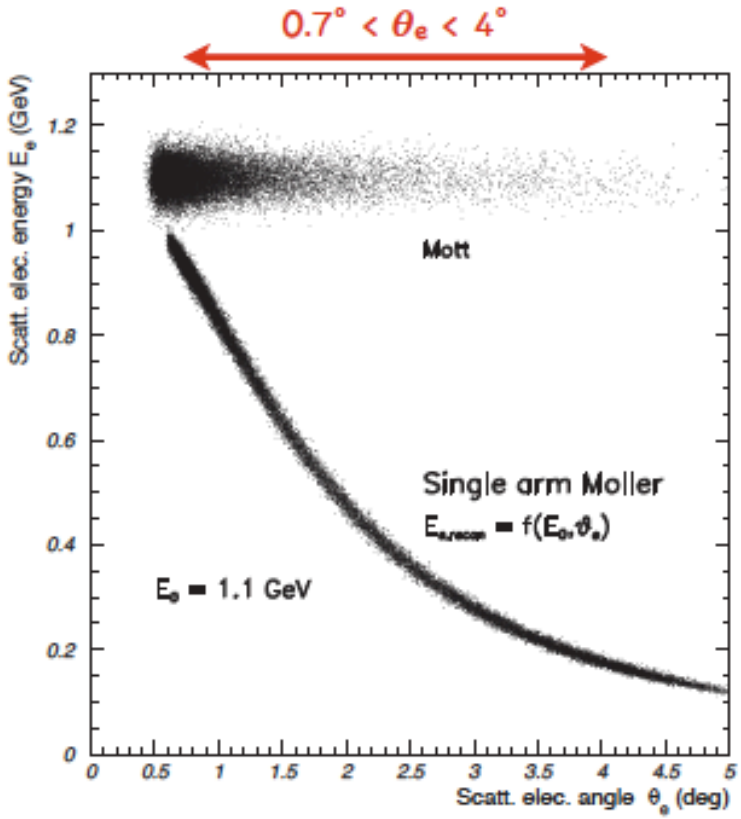
E12-11-106: Experimental method

(1) minimize experimental background:
high density windowless H_2 gas flow target



(2) Non-magnetic-spectrometer method:
high resolution, high acceptance crystal calorimeter

(3) Effective separation of Møller events from the ep elastic scattered events for angles $\theta_e > 0.7°$.



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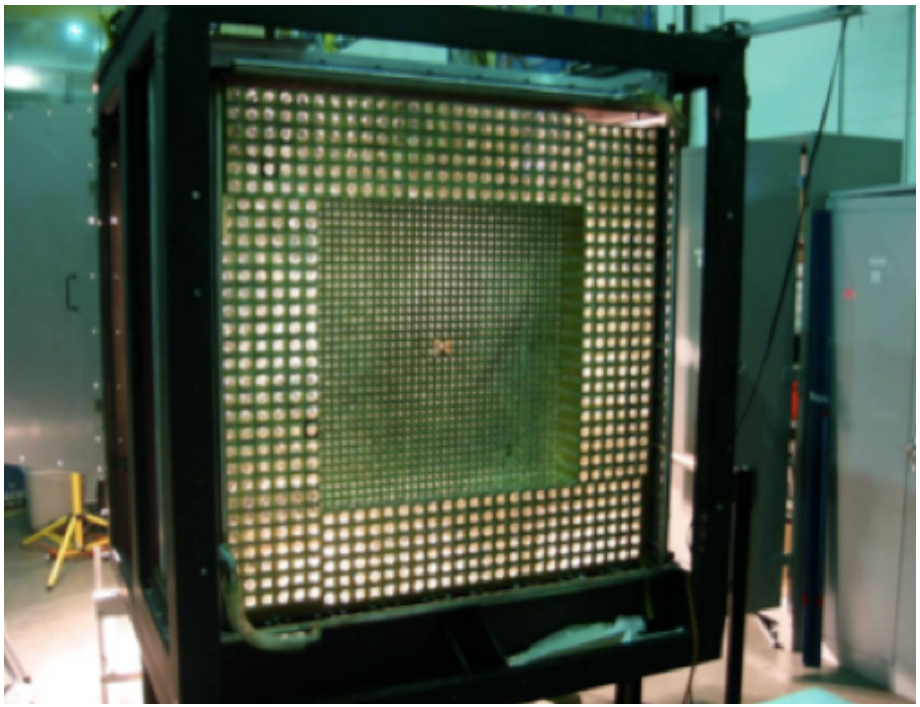
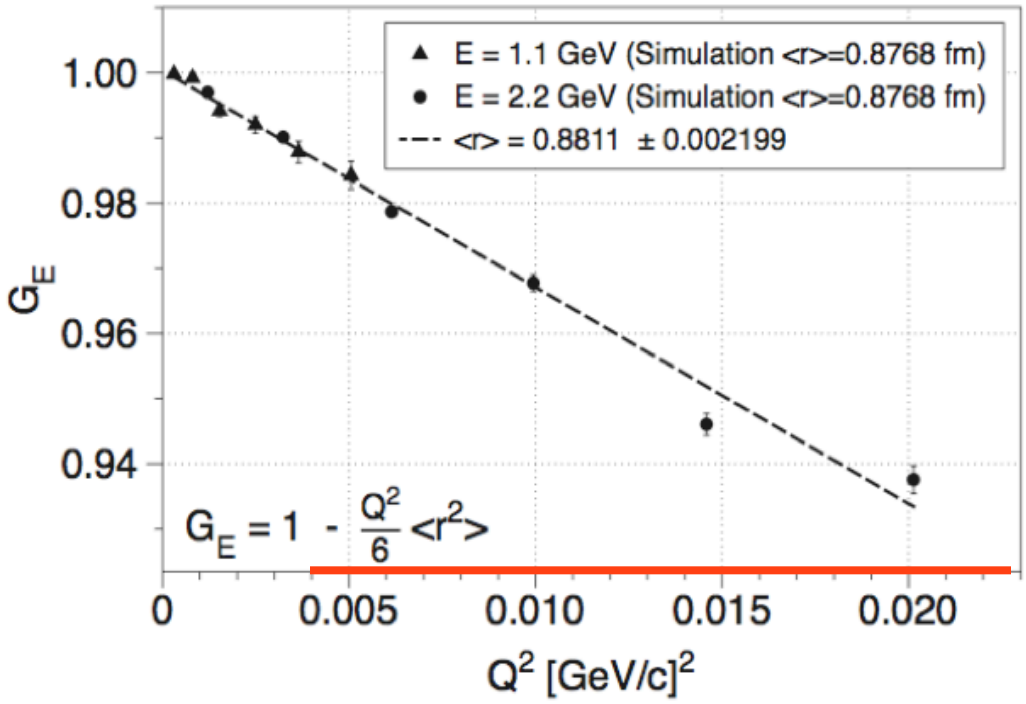




- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0^o.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements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

Motivation for μp scattering

Electronic hydrogen

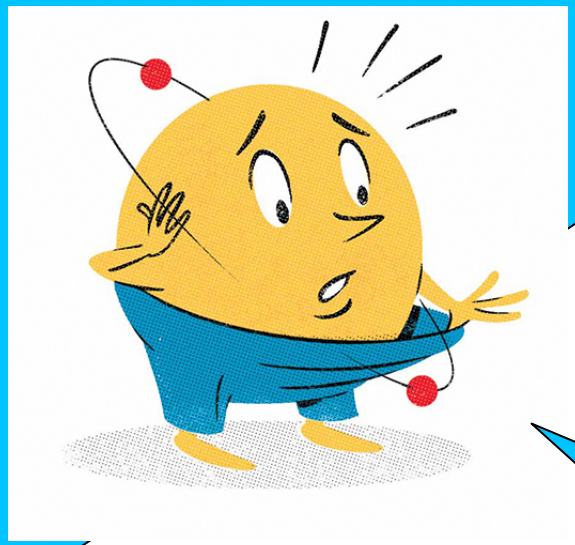
0.877±0.007

Lamb shift

Muonic hydrogen

0.842±0.001

0.84087±0.00039



Electron scattering

0.875±0.006

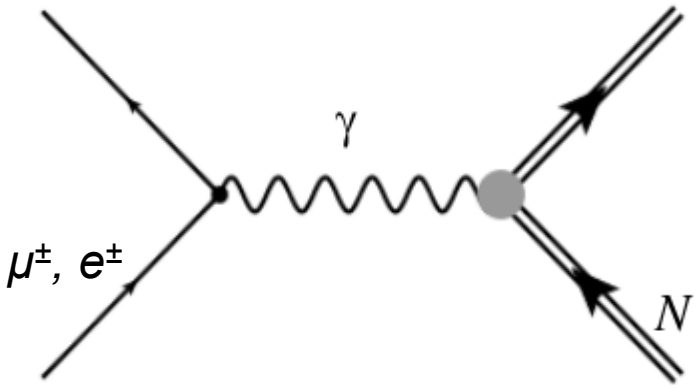
Elastic scattering

Muon scattering

???

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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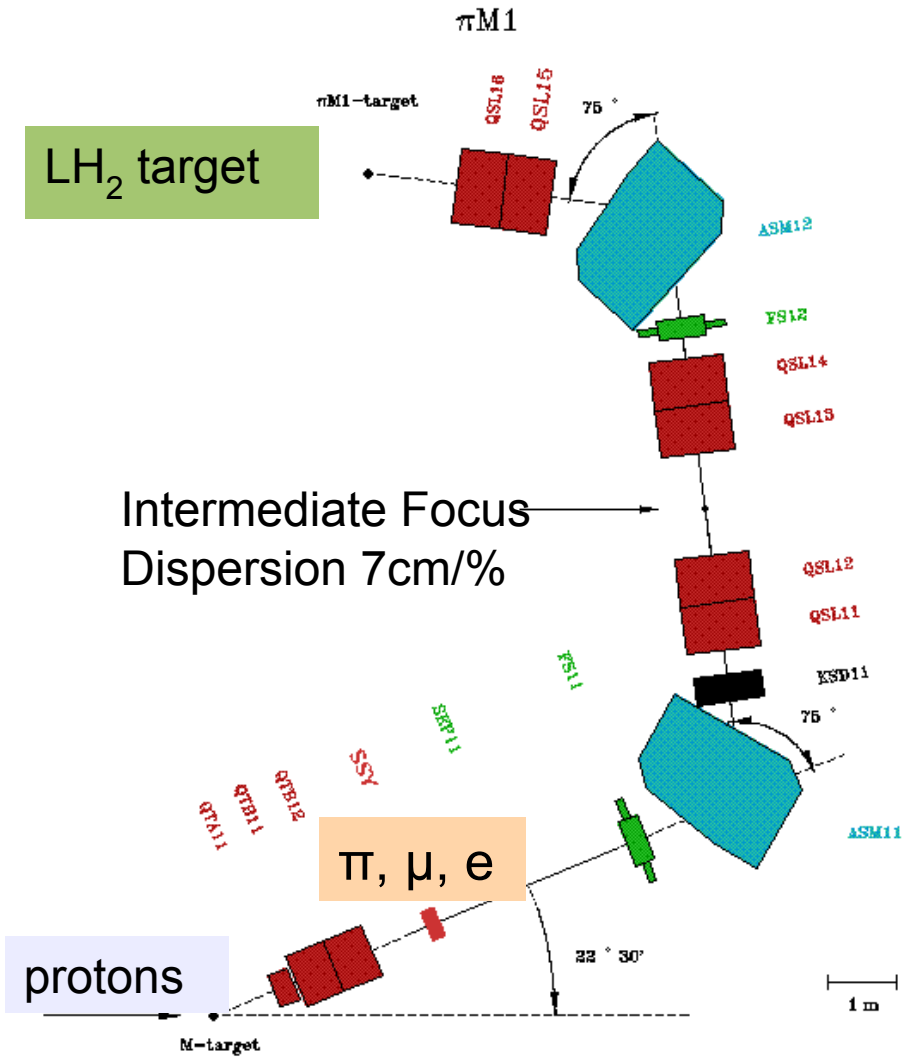
Expect identical form factors and radii for ep and μp scattering

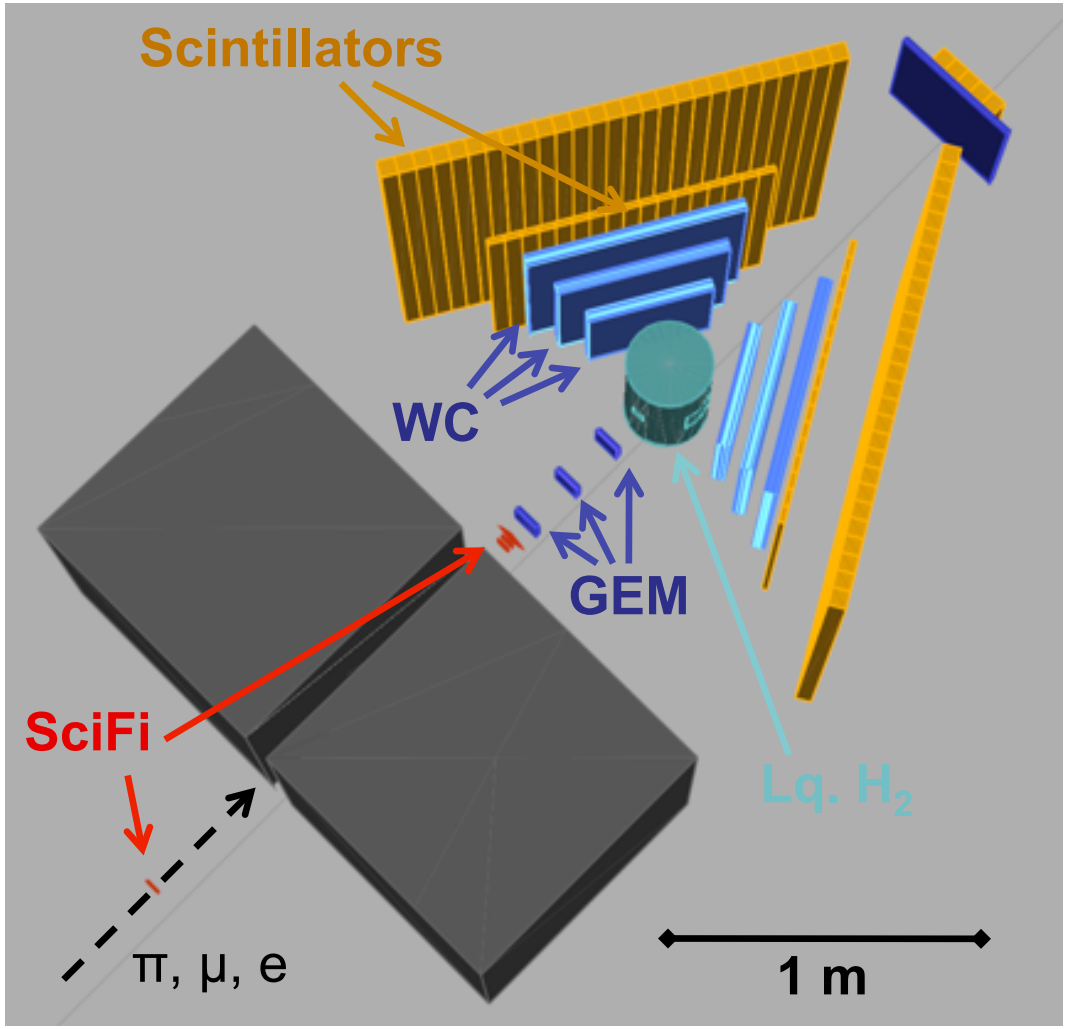
Proposal for muon scattering at PSI

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**
  - → **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)**

MUSE beamline and experiment layout

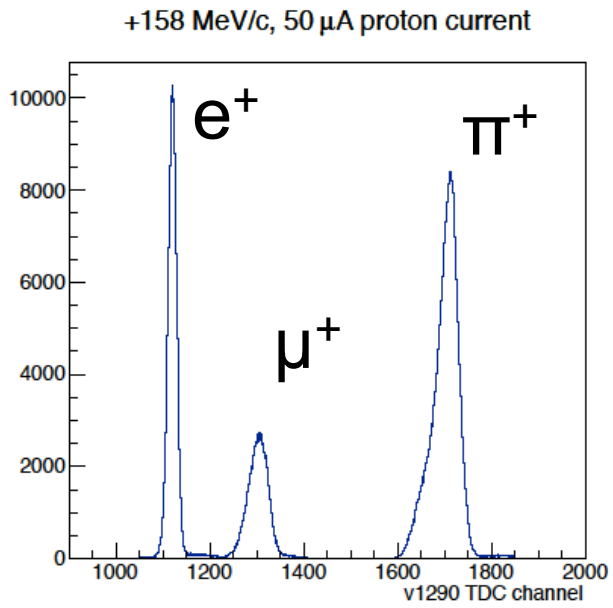


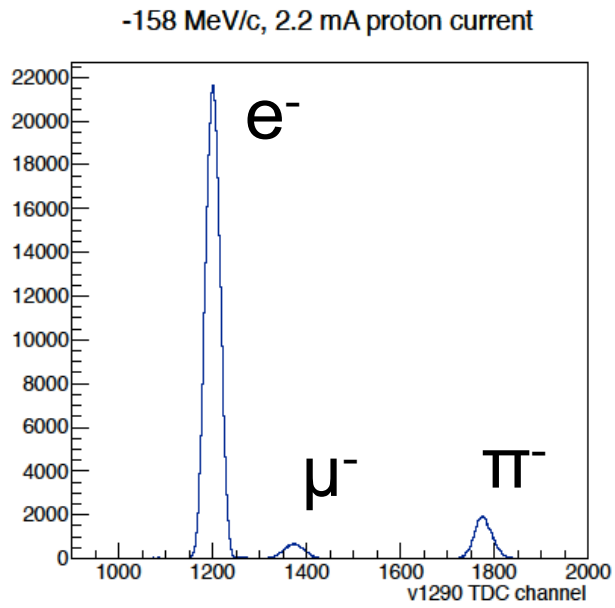


πM1: 100-500 MeV/c
Momentum measurement
RF+TOF separated π, μ, e

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

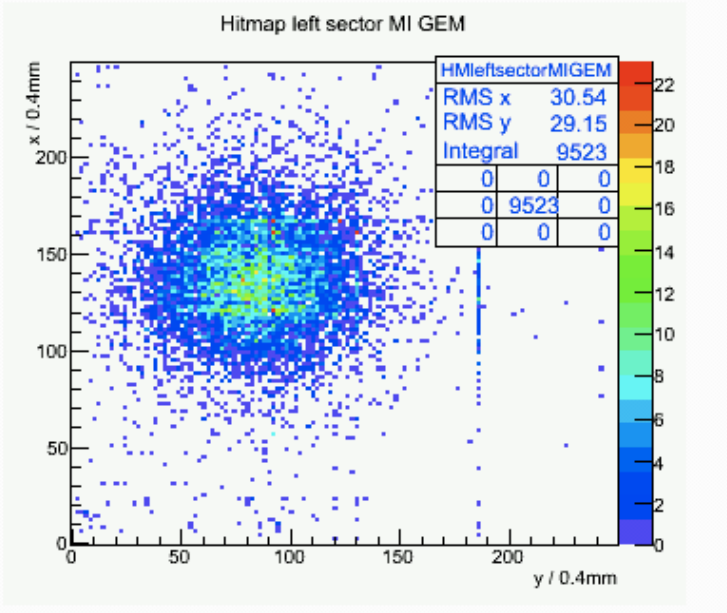
First beam tests

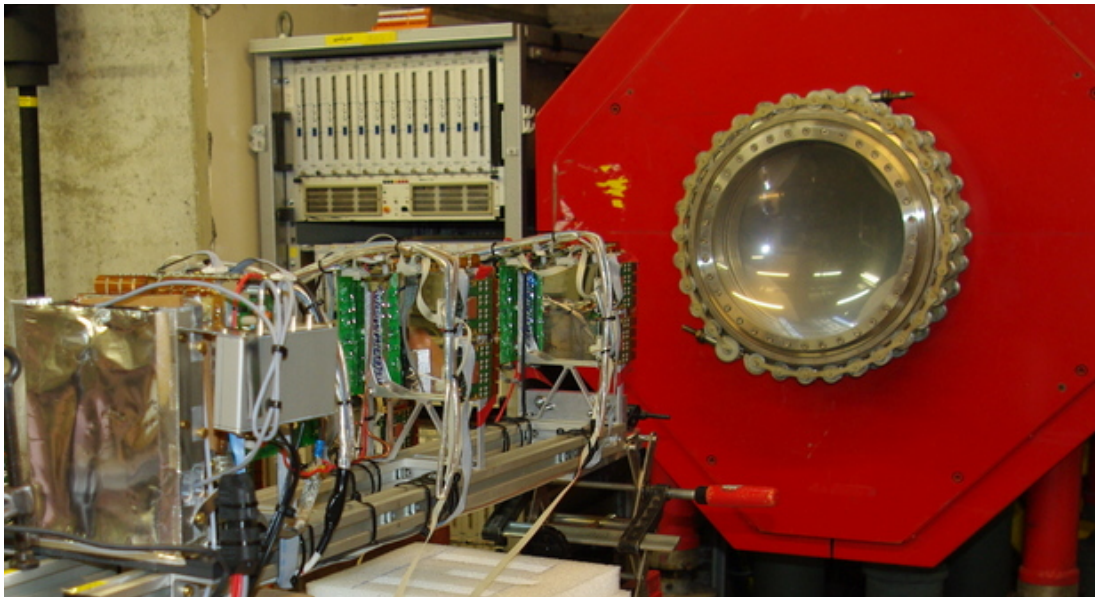




Time of flight relative to RF time (Fall 2012)

Beam spot with GEM telescope – May 13, 2013 (!)



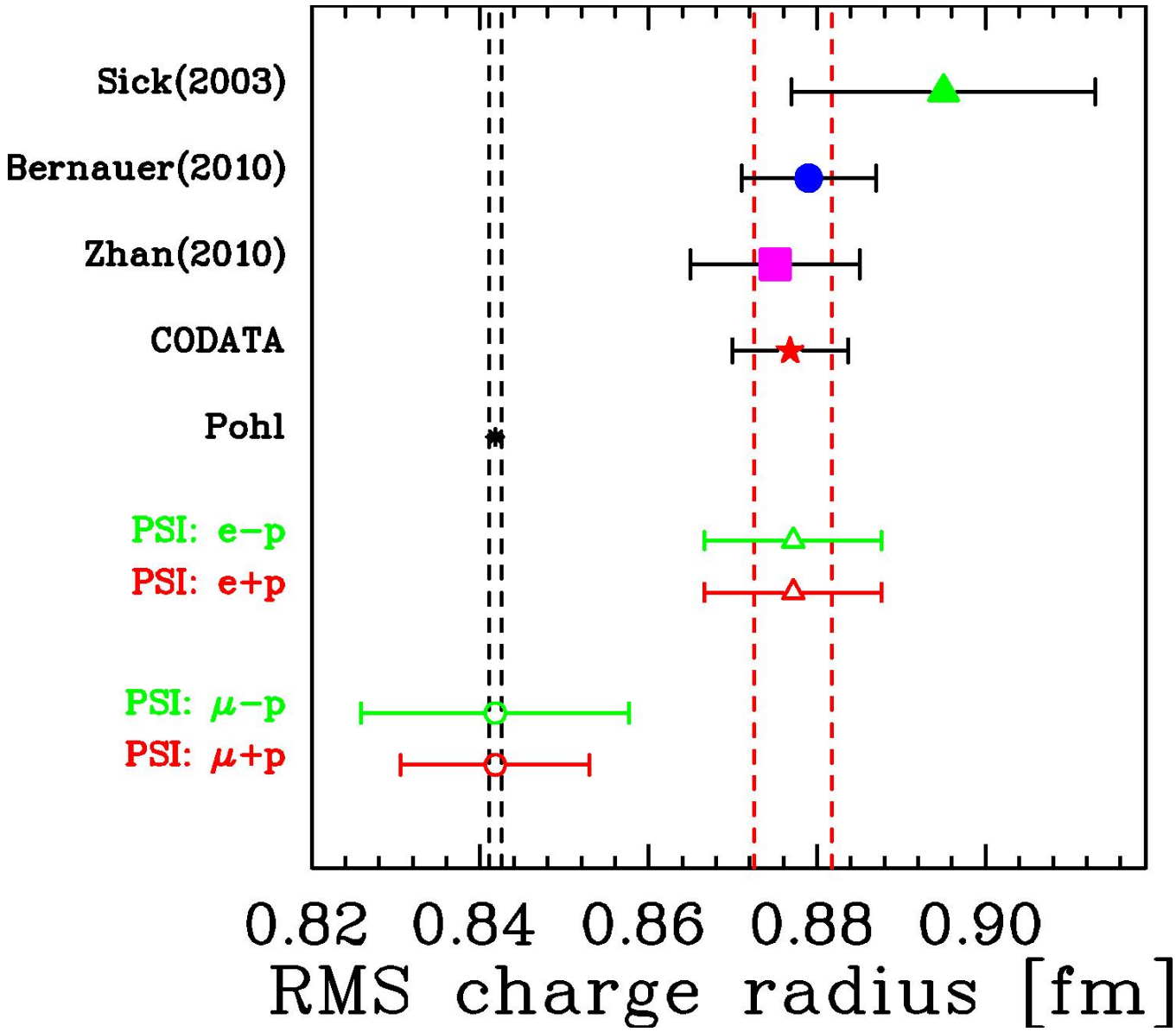


Projected sensitivity

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-, μ+/μ-, and μ/e comparisons



Projected sensitivity

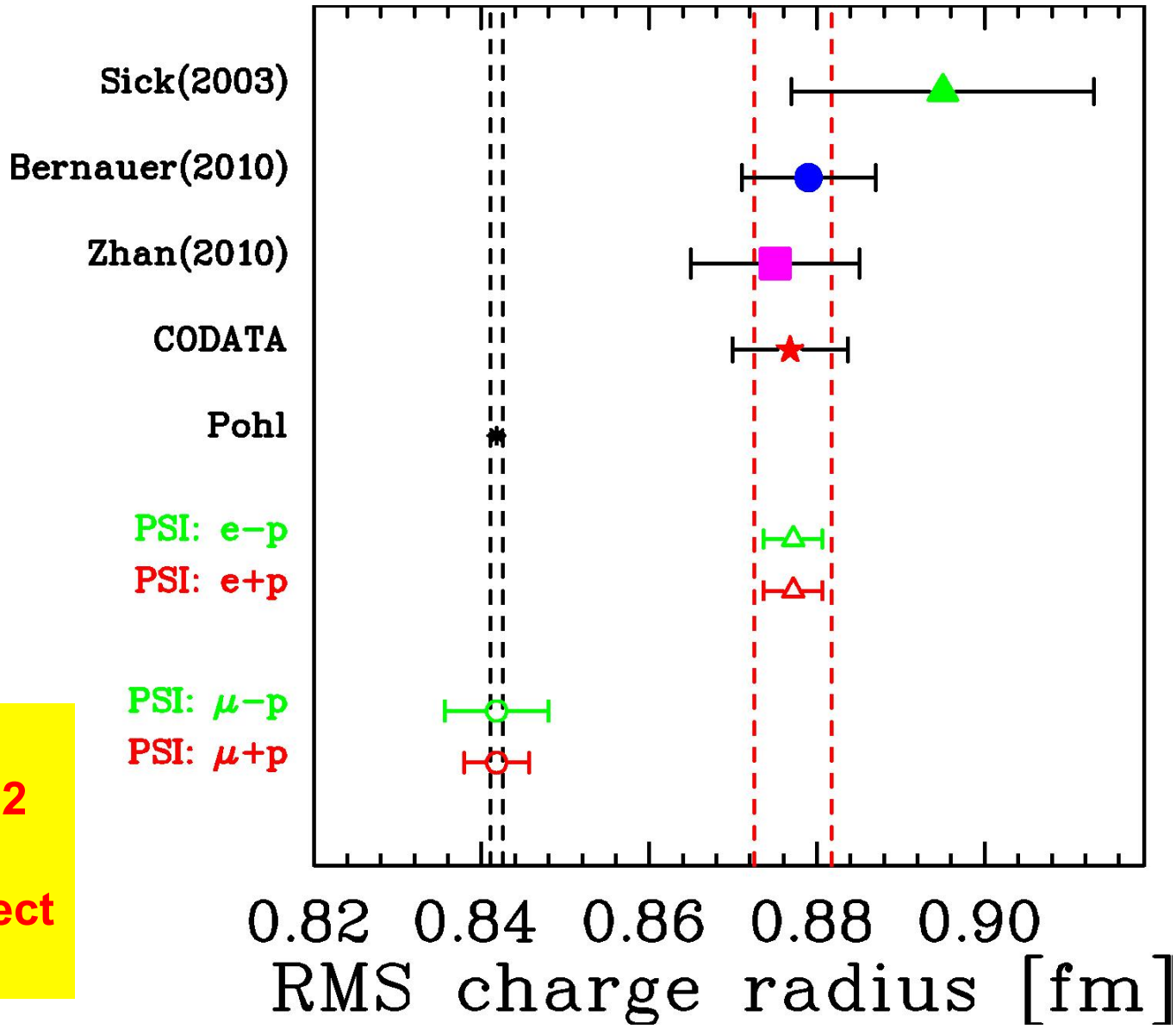
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

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

Relative comparison reduces errors by factor of 2

MUSE suited to verify 7σ effect with similar significance



MUon Scattering Experiment – MUSE

- **Proton Radius Puzzle – still unresolved ~3 years later**
- **MUSE Experiment at PSI**
  - Measure μp and ep scattering and compare directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Timeline**
  - Initial proposal February 2012
  - Technical Review July 2012
  - **Approved in January 2013**
  - Engineering runs 2012–2013
  - Funding & Construction 2013–2015
  - Production running ~2016
- **48 MUSE collaborators from 23 institutions in 6 countries:**
  Argonne National Lab, Christopher Newport University, Technical University of Darmstadt, Duke University, Duquesne University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Old Dominion University, Paul Scherrer Institute, Rutgers University, University of South Carolina, Seoul National University, St. Mary's University, Soreq Nuclear Research Center, Tel Aviv University, Temple University, University of Virginia, Weizmann Institute, College of William & Mary

U(1)-Boson, g_μ-2 and the proton radius

Dark photon: mediator of a dark force with coupling to SM through "kinetic mixing"; motivated by astrophysics, $g_\mu - 2$ and R_p

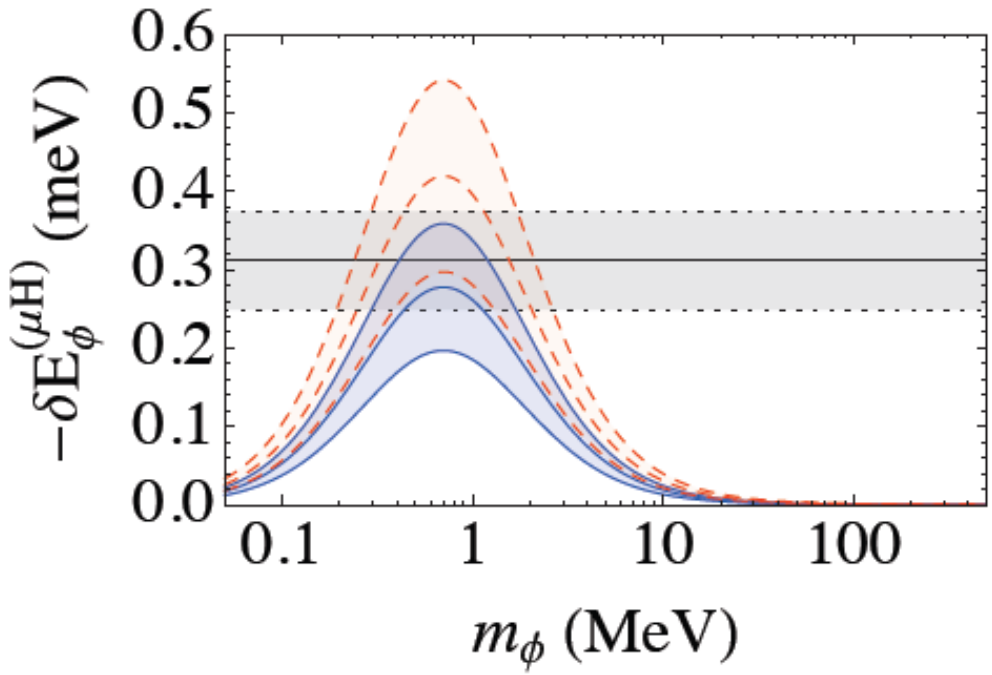
Jaeckel, Roy (arXiv:1008.3536)

- Dark U(1)-photon can reduce charge radius for muonic hydrogen, however effect even larger for regular hydrogen

Tucker-Smith, Yavin (arXiv:1011.4922)
can solve proton radius puzzle

- **Scalar** or **vector particle** in MeV-region with coupling to p and μ (but not e) consistent with g_μ-2

- μ–e non-universality



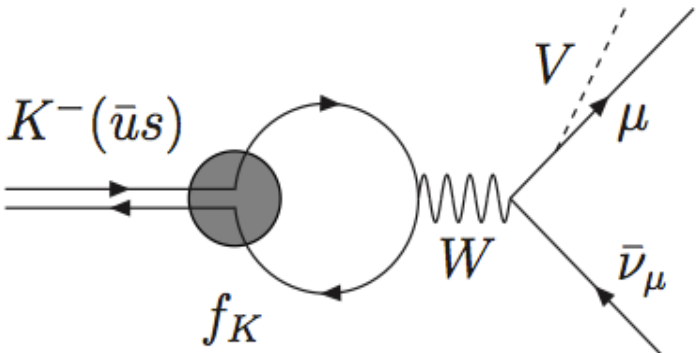
U(1)-Boson, g_μ-2 and the proton radius

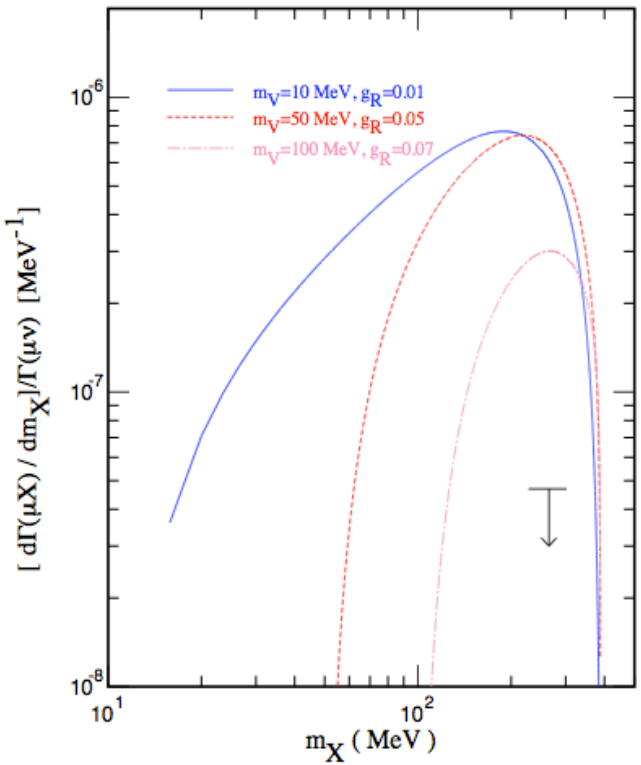
Batell, McKeen, Pospelov (arXiv:1103.0721):
can solve proton radius puzzle

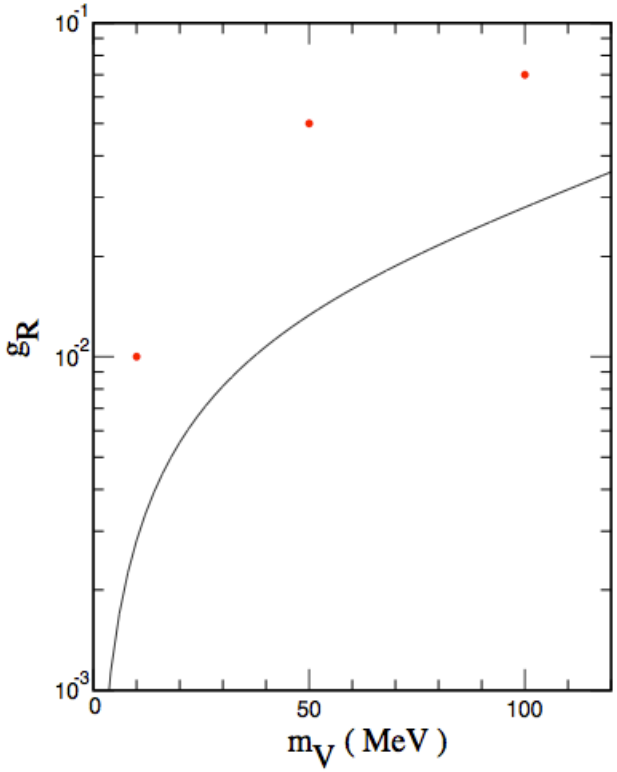
- new e/μ differentiating force consistent with g_μ-2
- <100 MeV gauge boson V or dark photon
- resulting in large PV μp scattering

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

- constrained by K → μν decay (invisible only)

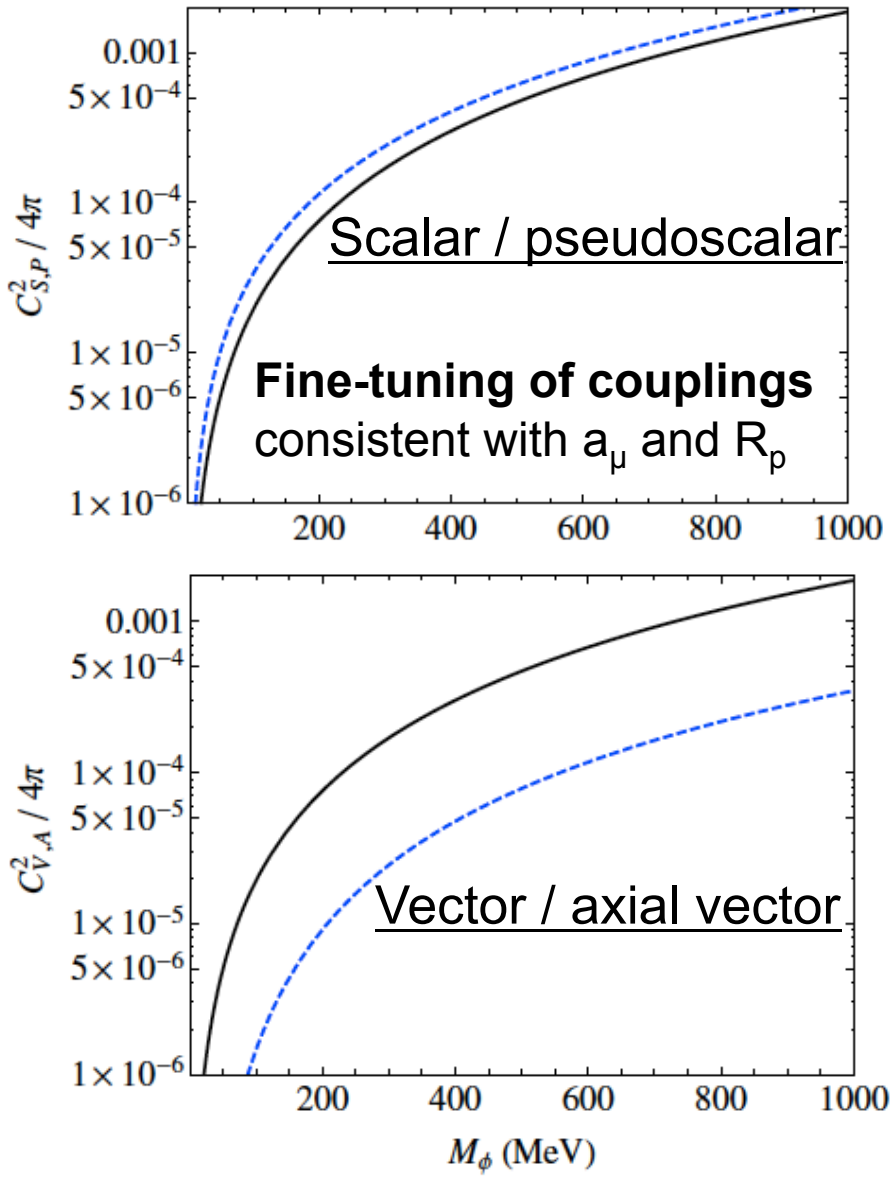


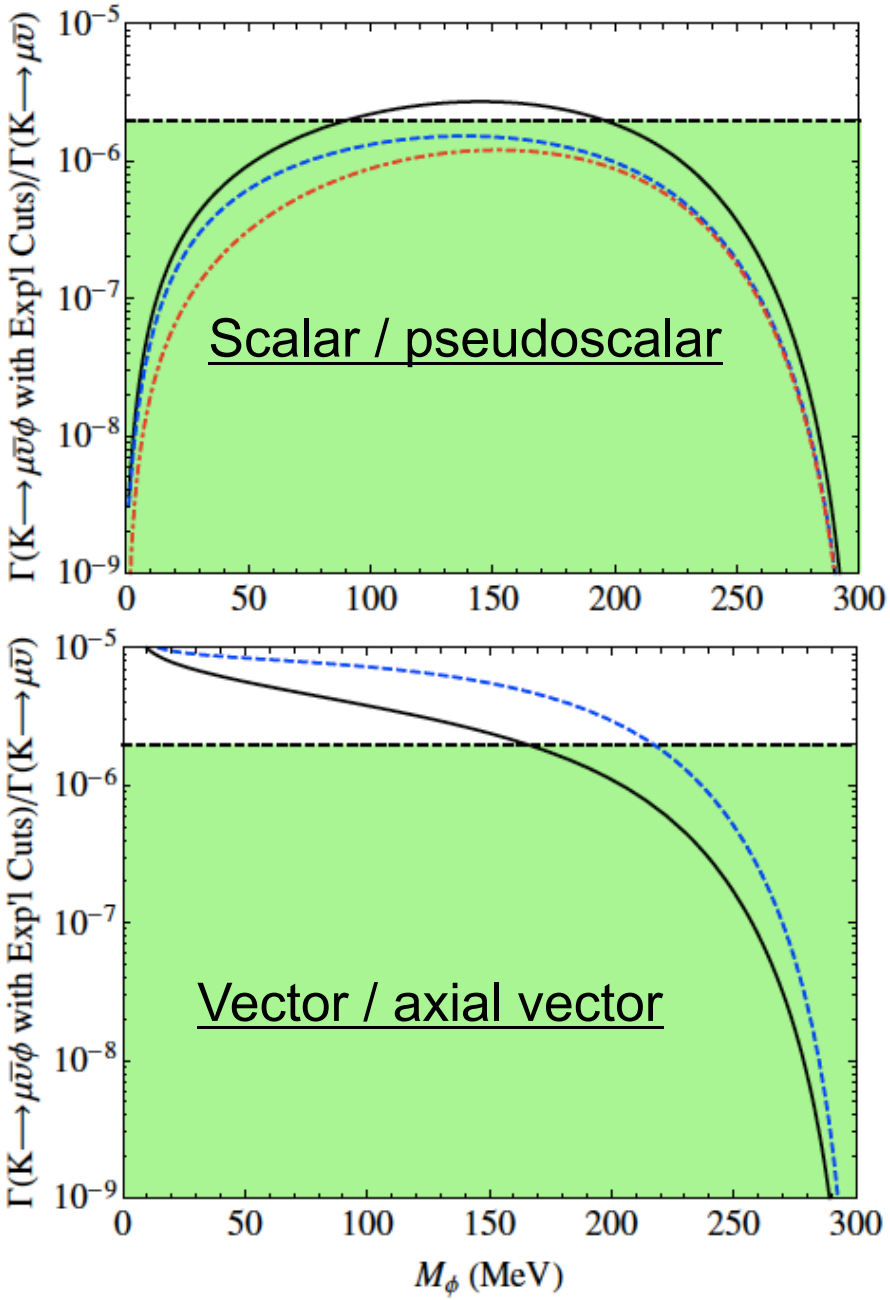




U(1)-Boson, g_μ-2 and the proton radius

C. Carlson and B. Rislow, 1206.3587v2 [hep-ph]





Experimental limit (invisible decay): Bevatron experiment with stopped K

C. Pang, R. Hildebrand, G. Cable, and R. Stiening, Phys. Rev. D8, 1989 (1973)

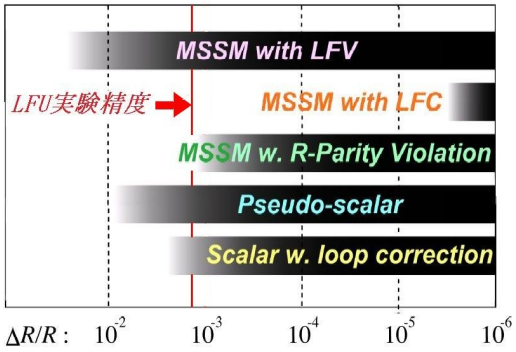
The TREK program at J-PARC

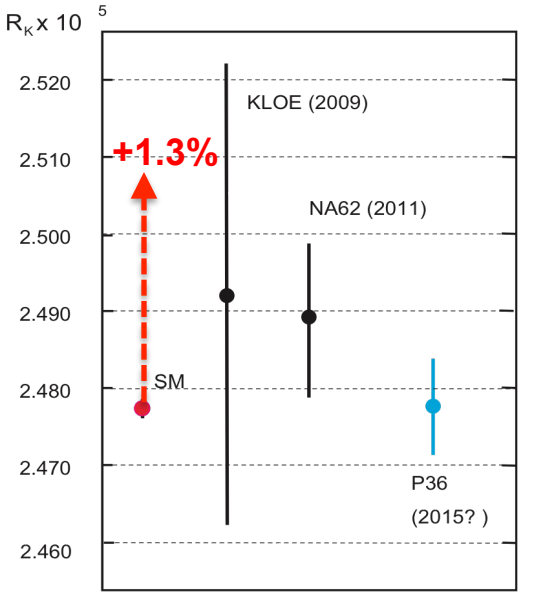
E06: Search for T-violating transv. muon polarization in $K_{\mu 3}$ decays

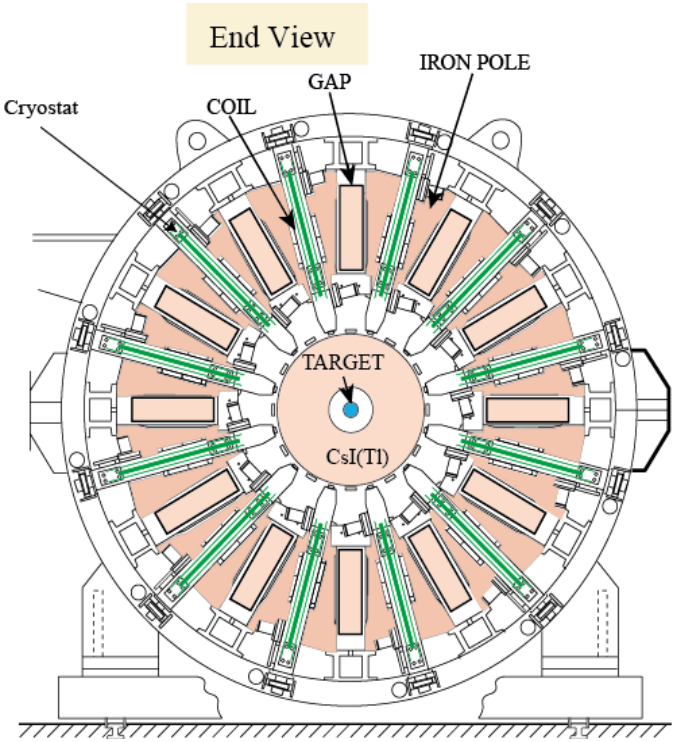
Precision measurement:
Test of lepton universality
in $BR(K_{e2})/BR(K_{\mu 2})$

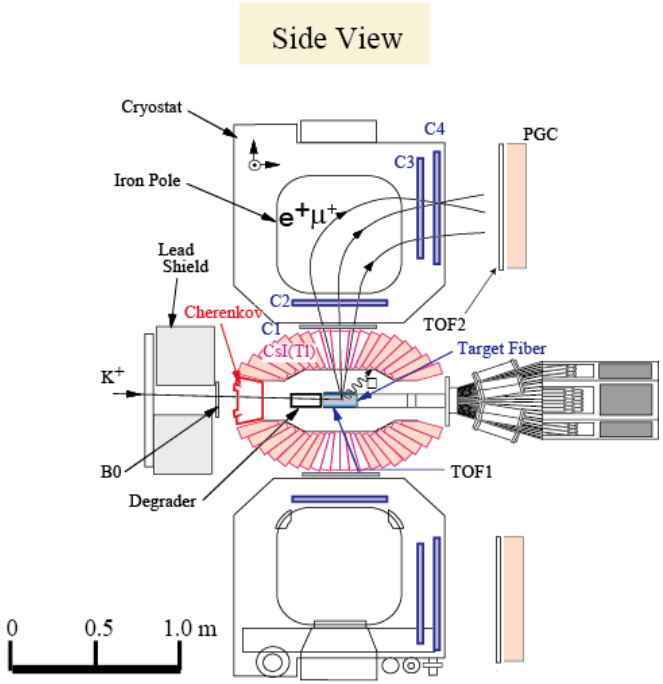
E36

Parasitic searches:
Heavy sterile neutrinos
Dark photons / U(1) bosons





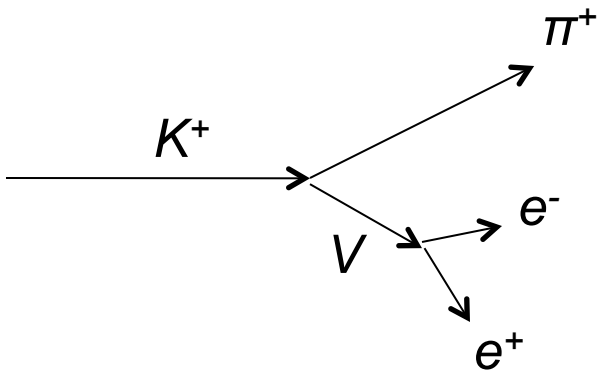




E36 data taking planned in 2014-2015

Search for light bosons in K^+ decays

- Dark photon: mediator of a dark force with coupling to SM through "kinetic mixing"; motivated by astrophysics, $g_\mu - 2$ and R_p
- Detect all charged particles; Search for peak in spectrum of the e^+e^- invariant mass at 0-300 MeV

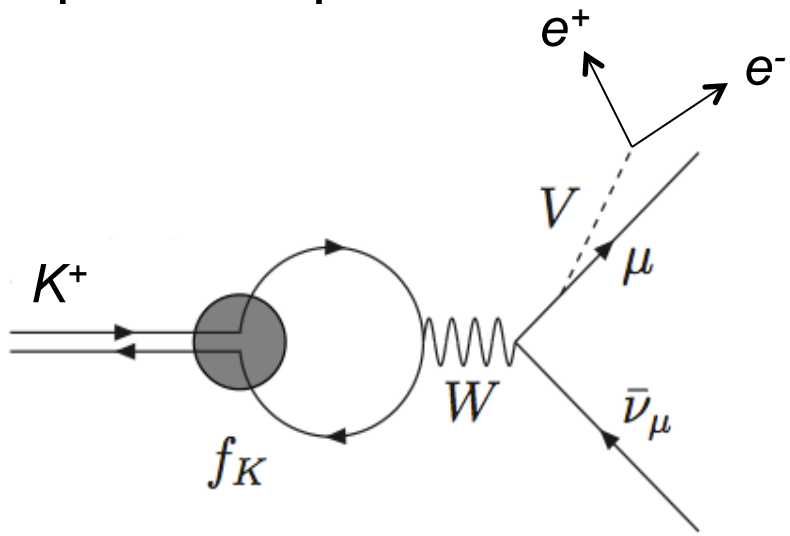


$K^+ \to \pi^+ e^+ e^-$ *(ΔS = 1)*

$K_{\pi 2}$: $K^+ \to \pi^+ \pi^0$ (~10^{10} events)

Signal: BR($K^+ \to \pi^+ V$) ~10^{-8}
$V \to e^+e^-$ (~100 events)

Background:
BR($K^+ \to \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7}



$K_{\mu 2}$: $K^+ \to \mu^+ \nu$ (~10^{10} events)

$K_{\mu 2\gamma}$: $K^+ \to \mu^+ \nu \gamma$ (~10^7 events)

Signal: BR($K^+ \to \mu^+ \nu V$) ~10^{-8}
$V \to e^+e^-$ (~100 events)

Background:
BR($K^+ \to \mu^+ \nu e^+ e^-$) ~ 2.5 x 10^{-5}

Summary

- **The Proton Radius Puzzle has been standing since 2010**
  - **Muonic hydrogen Lamb shift:**
    Proton rms radius 7σ smaller than with
    electronic hydrogen and electron scattering
  - **No theoretical explanation within given frameworks**
  - **Additional experiments necessary**
    (scattering – JLAB, Mainz, PSI; spectroscopy – Munich, PSI)
  - **MUon Scattering Experiment MUSE**
  - **New Physics remains a possibility**

The nine muses

Thank you!

Enjoy HUGS2013!