The Proton Radius Puzzle

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Introduction: The proton radius puzzle

Form Factors

- Matrix element of EM current between nucleon states give rise to two form factors ($q = p_f - p_i$)

$$\langle N(p_f)|\sum_q e_q\,\bar{q}\gamma^\mu q|N(p_i)\rangle = \bar{u}(p_f)\left[\gamma^\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}}{2m}F_2(q^2)q^\nu\right]u(p_i)$$

- Sachs electric and magnetic form factors

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_p^2}F_2(q^2) \qquad G_M(q^2) = F_1(q^2) + F_2(q^2)$$

$$G_E^p(0) = 1 \qquad G_M^p(0) = \mu_p \approx 2.793$$

- The slope of G_E^p

$$\boxed{\langle r^2\rangle_E^p = 6\frac{dG_E^p}{dq^2}\bigg|_{q^2=0}}$$

determines the charge radius $r_E^p \equiv \sqrt{\langle r^2\rangle_E^p}$

- The proton *magnetic* radius

$$\langle r^2\rangle_M^p = \frac{6}{G_M^p(0)}\frac{dG_M^p(q^2)}{dq^2}\bigg|_{q^2=0}$$

Charge radius from atomic physics

$$\langle p(p_f)| \sum_q e_q \, \bar{q}\gamma^\mu q | p(p_i)\rangle = \bar{u}(p_f)\left[\gamma^\mu F_1^p(q^2) + \frac{i\sigma_{\mu\nu}}{2m} F_2^p(q^2) q^\nu\right] u(p_i)$$

- For a point particle amplitude for $p + \ell \to p + \ell$

$$\mathcal{M} \propto \frac{1}{q^2} \quad \Rightarrow \quad U(r) = -\frac{Z\alpha}{r}$$

- Including q^2 corrections from proton structure

$$\mathcal{M} \propto \frac{1}{q^2} q^2 = 1 \quad \Rightarrow \quad U(r) = \frac{4\pi Z\alpha}{6}\delta^3(r)(r_E^p)^2$$

- Proton structure corrections $\left(m_r = m_\ell m_p/(m_\ell + m_p) \approx m_\ell\right)$

$$\boxed{\Delta E_{r_E^p} = \frac{2(Z\alpha)^4}{3n^3} m_r^3 (r_E^p)^2 \delta_{\ell 0}}$$

- **Muonic hydrogen can give the best measurement of r_E^p!**

Charge radius from atomic physics

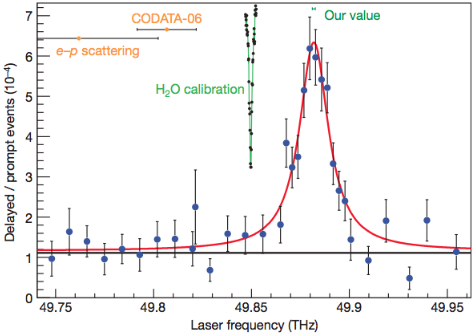
- Lamb shift in muonic hydrogen [Pohl et al. Nature **466**, 213 (2010)]
  $r_E^p = 0.84184(67)$ fm
  more recently $r_E^p = 0.84087(39)$ fm [Antognini et al. Science **339**, 417 (2013)]
- CODATA value [Mohr et al. RMP **80**, 633 (2008)]
  $r_E^p = 0.87680(690)$ fm
  more recently $r_E^p = 0.87510(610)$ fm [Mohr et al. RMP **88**, 035009 (2016)]
  extracted mainly from (electronic) hydrogen
- **5σ discrepancy!**

- This is the proton radius puzzle

Great outreach opportunity!

- Problem easily communicated to general audience

- Example: Detroit high school students using data



[R. Pohl *et al.*, "The size of the proton," Nature **466**, 213 (2010)]

and the approximate formula, $f = 50.59\ \text{THz} - r^2 \dfrac{\text{THz}}{\text{fm}^2}$
to determine $r = 0.84$ fm

What could be the reason for the discrepancy?

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3) New Physics?

Outline

- Introduction: The proton radius puzzle
- Part 1: Proton radii from scattering
- Part 2: Hadronic Uncertainty?
- Conclusions and outlook

Part 1: Proton radii from scattering

Problem with the electronic extraction?

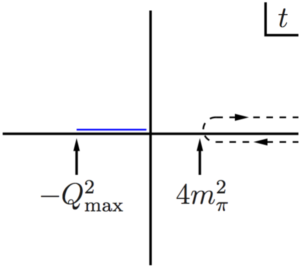
- You can get the proton radius from electron-proton scattering
- Recent development: use of the z expansion
  based on known analytic properties of form factors
  [Hill, GP PRD **82** 113005 (2010)]
- **The** method for **meson** form factors
  [Flavor Lattice Averaging Group, EPJ C **74**, 2890 (2014)]
- Now applied successfully to **baryon** form factors
  to extract $r_E^p, r_M^p, r_M^n, m_A \ldots$

Form Factors: What we do know

- Analytic properties of $G_E^p(t)$ and $G_M^p(t)$ are known
- They are analytic outside a cut $t \in [4m_\pi^2, \infty]$

  [Federbush, Goldberger, Treiman, Phys. Rev. **112**, 642 (1958)]

- $e - p$ scattering data is in $t < 0$ region



- If your form factor doesn't have this analytic structure it's **wrong!** (e.g. singularity at $4m_\pi^2$: why should the Taylor series converge?)

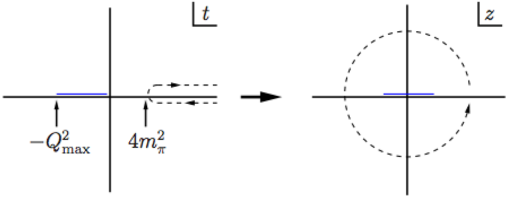
z expansion

- z expansion:

  We can map the domain of analyticity onto the unit circle

$$z(t, t_{\text{cut}}, t_0) = \frac{\sqrt{t_{\text{cut}} - t} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} - t} + \sqrt{t_{\text{cut}} - t_0}}$$

  where $t_{\text{cut}} = 4m_\pi^2$, $z(t_0, t_{\text{cut}}, t_0) = 0$



- Expand $G^p_{E,M}$ in a Taylor series in z: $G^p_{E,M}(q^2) = \sum_{k=0}^{\infty} a_k \, z(q^2)^k$

z expansion

- [Zachary Epstein, GP, Joydeep Roy PRD **90**, 074027 (2014)]

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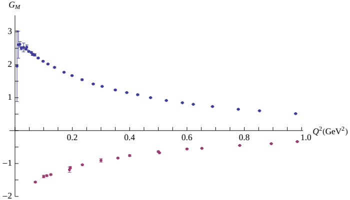
  $G_M(Q^2)$ for proton (blue, above axis) and neutron (red, below axis)



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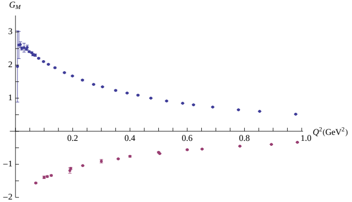

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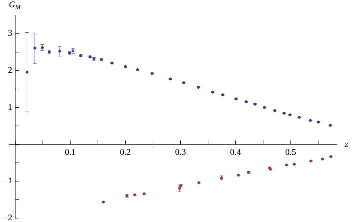


- See also R.J. Hill talk at FPCP 2006 [hep-ph/0606023]

PDG 2016: r_E^p

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

p CHARGE RADIUS

This is the rms electric charge radius, $\sqrt{\langle r_E^2 \rangle}$.

VALUE (fm)			*DOCUMENT ID*		*TECN*	*COMMENT*
0.8751	**±0.0061**		MOHR	16	RVUE	2014 CODATA value
0.84087	**±0.00026**	**±0.00029**	ANTOGNINI	13	LASR	μp-atom Lamb shift
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.895	±0.014	±0.014	[1] LEE	15	SPEC	Just 2010 Mainz data
0.916	±0.024		LEE	15	SPEC	World data, no Mainz
0.8775	±0.0051		MOHR	12	RVUE	2010 CODATA, $e p$ data
0.875	±0.008	±0.006	ZHAN	11	SPEC	Recoil polarimetry
0.879	±0.005	±0.006	BERNAUER	10	SPEC	$e p \to e p$ form factor
0.912	±0.009	±0.007	BORISYUK	10		reanalyzes old $e p$ data
0.871	±0.009	±0.003	HILL	10		z-expansion reanalysis
0.84184	±0.00036	±0.00056	POHL	10	LASR	See ANTOGNINI 13
0.8768	±0.0069		MOHR	08	RVUE	2006 CODATA value
0.844	$^{+0.008}_{-0.004}$		BELUSHKIN	07		Dispersion analysis
0.897	±0.018		BLUNDEN	05		SICK 03 + 2γ correction
0.8750	±0.0068		MOHR	05	RVUE	2002 CODATA value
0.895	±0.010	±0.013	SICK	03		$e p \to e p$ reanalysis

[Hill, GP PRD **82** 113005 (2010)]

[Lee, Arrington, Hill, PRD **92**, 013013 (2015)]

PDG 2016: r_M^p

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

p MAGNETIC RADIUS

This is the rms magnetic radius, $\sqrt{\langle r_M^2 \rangle}$.

VALUE (fm)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.776±0.034±0.017	[1] LEE	15	SPEC	Just 2010 Mainz data
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.914±0.035	LEE	15	SPEC	World data, no Mainz
0.87 ±0.02	EPSTEIN	14		Using ep, en, $\pi\pi$ data
0.867±0.009±0.018	ZHAN	11	SPEC	Recoil polarimetry
0.777±0.013±0.010	BERNAUER	10	SPEC	$ep \to ep$ form factor
0.876±0.010±0.016	BORISYUK	10		Reanalyzes old $ep \to ep$ data
0.854±0.005	BELUSHKIN	07		Dispersion analysis

[1] Authors also provide values for a combination of all available data.

[Epstein, GP, Roy PRD **90**, 074027 (2014)]
[Lee, Arrington, Hill, PRD **92**, 013013 (2015)]

PDG 2016: r_M^n

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

n MAGNETIC RADIUS

This is the rms magnetic radius, $\sqrt{\langle r_M^2 \rangle}$.

VALUE (fm)	*DOCUMENT ID*		*COMMENT*
$\mathbf{0.864^{+0.009}_{-0.008}}$ **OUR AVERAGE**			
0.89 ± 0.03	EPSTEIN	14	Using ep, en, $\pi\pi$ data
$0.862^{+0.009}_{-0.008}$	BELUSHKIN	07	Dispersion analysis

[Epstein, GP, Roy PRD **90**, 074027 (2014)]

Part 2: Hadronic Uncertainty?

[Hill, GP PRD **95**, 094017 (2017), arXiv:1611.09917]

The bottom line

- Scattering:
- World $e-p$ data [Lee, Arrington, Hill '15]
  $r_E^p = 0.918 \pm 0.024$ fm
- Mainz $e-p$ data [Lee, Arrington, Hill '15]
  $r_E^p = 0.895 \pm 0.020$ fm
- Proton, neutron and π data [Hill , GP '10]
  $r_E^p = 0.871 \pm 0.009 \pm 0.002 \pm 0.002\,\mathrm{fm}$

- Muonic hydrogen
- [Pohl et al. Nature **466**, 213 (2010)]
  $r_E^p = 0.84184(67)$ fm
- [Antognini et al. Science **339**, 417 (2013)]
  $r_E^p = 0.84087(39)$ fm

- The bottom line:
  using z expansion scattering disfavors muonic hydrogen

- Is there a problem with muonic hydrogen *theory*?

Muonic hydrogen theory

- Is there a problem with muonic hydrogen *theory*?
- Potentially yes!
  [Hill, GP PRL **107** 160402 (2011)]
- The proton radius arises from **one** photon probe
- Increasing precision requires also a **two** photon probe
  a much more complicated object

Muonic hydrogen theory

- Is there a problem with muonic hydrogen *theory*?

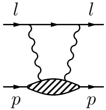
- Potentially yes!
  [Hill, GP PRL **107** 160402 (2011)]

- Muonic hydrogen measures ΔE and translates it to r_E^p

- [Pohl et al. Nature **466**, 213 (2010) Supplementary information]
  $\Delta E = 206.0573(45) - 5.2262(r_E^p)^2 + 0.0347(r_E^p)^3$ meV

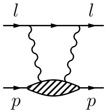
- [Antognini et al. Science **339**, 417 (2013), Ann. of Phy. **331**, 127]
  $\Delta E = 206.0336(15) - 5.2275(10)(r_E^p)^2 + 0.0332(20)$ meV

- In both cases apart from r_E^p need two-photon exchange



Two photon exchange

- Apart from r_E^p we have two-photon exchange (TPE)



- Imaginary part of TPE related to data:
  form factors, structure functions

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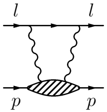


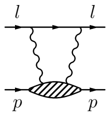
- Imaginary part of TPE related to data:
  form factors, structure functions

- Cannot reproduce it from its imaginary part:
  Dispersion relation requires subtraction

- Need poorly constrained non-perturbative function $W_1(0, Q^2)$

Two photon exchange

- Apart from r_E^p we have two-photon exchange (TPE)



$$W^{\mu\nu} = \frac{1}{2}\sum_s i\int d^4x\, e^{iq\cdot x}\langle \boldsymbol{k}, s| T\{J^\mu_{\rm e.m.}(x) J^\nu_{\rm e.m.}(0)\}|\boldsymbol{k}, s\rangle$$

$$= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) W_1 + \left(k^\mu - \frac{k\cdot q\, q^\mu}{q^2}\right)\left(k^\nu - \frac{k\cdot q\, q^\nu}{q^2}\right) W_2$$

- Dispersion relations ($\nu = 2k\cdot q,\ Q^2 = -q^2$)

$$W_1(\nu, Q^2) = W_1(0, Q^2) + \frac{\nu^2}{\pi}\int_{\nu_{\rm cut}(Q^2)^2}^{\infty} d\nu'^2 \frac{{\rm Im}\, W_1(\nu', Q^2)}{\nu'^2(\nu'^2 - \nu^2)}$$

$$W_2(\nu, Q^2) = \frac{1}{\pi}\int_{\nu_{\rm cut}(Q^2)^2}^{\infty} d\nu'^2 \frac{{\rm Im}\, W_2(\nu', Q^2)}{\nu'^2 - \nu^2}$$

- W_1 requires subtraction...

Two Photon exchange: small Q^2 limit

- *Small* Q^2 limit using NRQED [Hill, GP, PRL **107** 160402 (2011)]
  The photon sees the proton "almost" like an elementary particle

$$W_1(0,Q^2) = 2a_p(2+a_p) + \frac{Q^2}{m_p^2}\left\{\frac{2m_p^3\bar{\beta}}{\alpha} - a_p - \frac{2}{3}\left[(1+a_p)^2 m_p^2 (r_M^p)^2 - m_p^2 (r_E^p)^2\right]\right\} + \mathcal{O}\left(Q^4\right)$$

$$W_1(0,Q^2) = 13.6 + \frac{Q^2}{m_p^2}(-54 \pm 7) + \mathcal{O}\left(Q^4\right)$$

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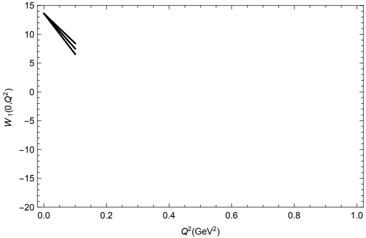

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- *Large* Q^2 limit using Operator Product Expansion (OPE)
  The photon "sees" the quarks and gluons inside the proton

$$W_1(0, Q^2) = c/Q^2 + \mathcal{O}\left(1/Q^4\right)$$

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Received 23 October 1978

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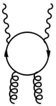
- Collins confirmed the mistake in [J. C. Collins, NPB **915**, 392 (2017)]

Large Q^2 behavior



- Performing the complete calculation, we found a mistake in Collins spin-0 calculation from 1978...

- Collins didn't calculate the spin-0 gluon contribution directly

  He extracted it from another calculation

- For three light quark u, d, s

  Correct result: $\sum_q e_q^2 = (\frac{2}{3})^2 + (\frac{1}{3})^2 + (\frac{1}{3})^2 = \frac{2}{3}$

  Collins: $\sum_q = 3$

  Too large by a factor of 4.5...

Two Photon Exchange: Modeling

- Simple modeling: use OPE for $Q^2 \geq 1$ GeV^2
- Model unknown Q^4: add $\Delta_L(Q^2) = \pm Q^2/\Lambda_L^2$ with $\Lambda_L \approx 500$ MeV
- Model unknown $1/Q^4$: add $\Delta_H(Q^2) = \pm \Lambda_H^2/Q^2$ with $\Lambda_H \approx 500$ MeV

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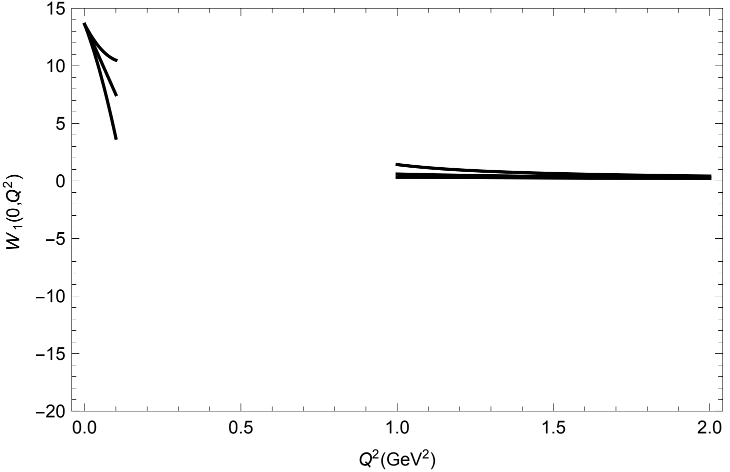
- How to connect the curves?



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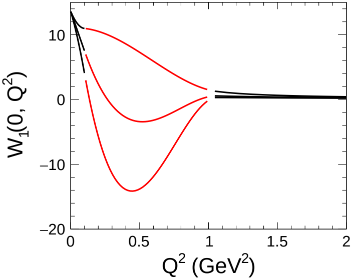

Two Photon Exchange: Modeling

- Simple modeling: use OPE for $Q^2 \geq 1$ GeV^2
- Model unknown Q^4: add $\Delta_L(Q^2) = \pm Q^2/\Lambda_L^2$ with $\Lambda_L \approx 500$ MeV
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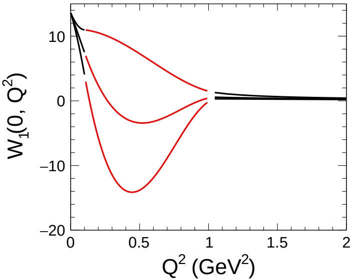
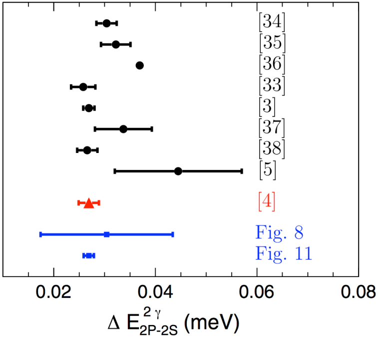


- Energy contribution: $\delta E(2\mathrm{S})^{W_1(0,Q^2)} \in [-0.046\,\mathrm{meV}, -0.021\,\mathrm{meV}]$
  To explain the puzzle need this to be ~ -0.3 meV
- Caveats: OPE might be only valid for larger Q^2
  $W_1(0, Q^2)$ might be different than the interpolated lines

Two Photon Exchange: Other approaches

- Similar results found by other groups



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Experimental test

- How to test? New experiment: $\mu - p$ scattering
  MUSE (MUon proton Scattering Experiment) at PSI
  [R. Gilman et al. (MUSE Collaboration), arXiv:1303.2160]

- Need to connect muon-proton scattering and muonic hydrogen
  can use a new effective field theory: QED-NRQED
  [Hill, Lee, GP, Mikhail P. Solon, PRD **87** 053017 (2013)]
  [Steven P. Dye, Matthew Gonderinger, GP, PRD **94** 013006 (2016)]
  [Steven P. Dye, Matthew Gonderinger, GP, *in progress*]

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- Much more work to do!

- Thank you