The Proton

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“Everything that rises”, Martin Puryear

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Outline

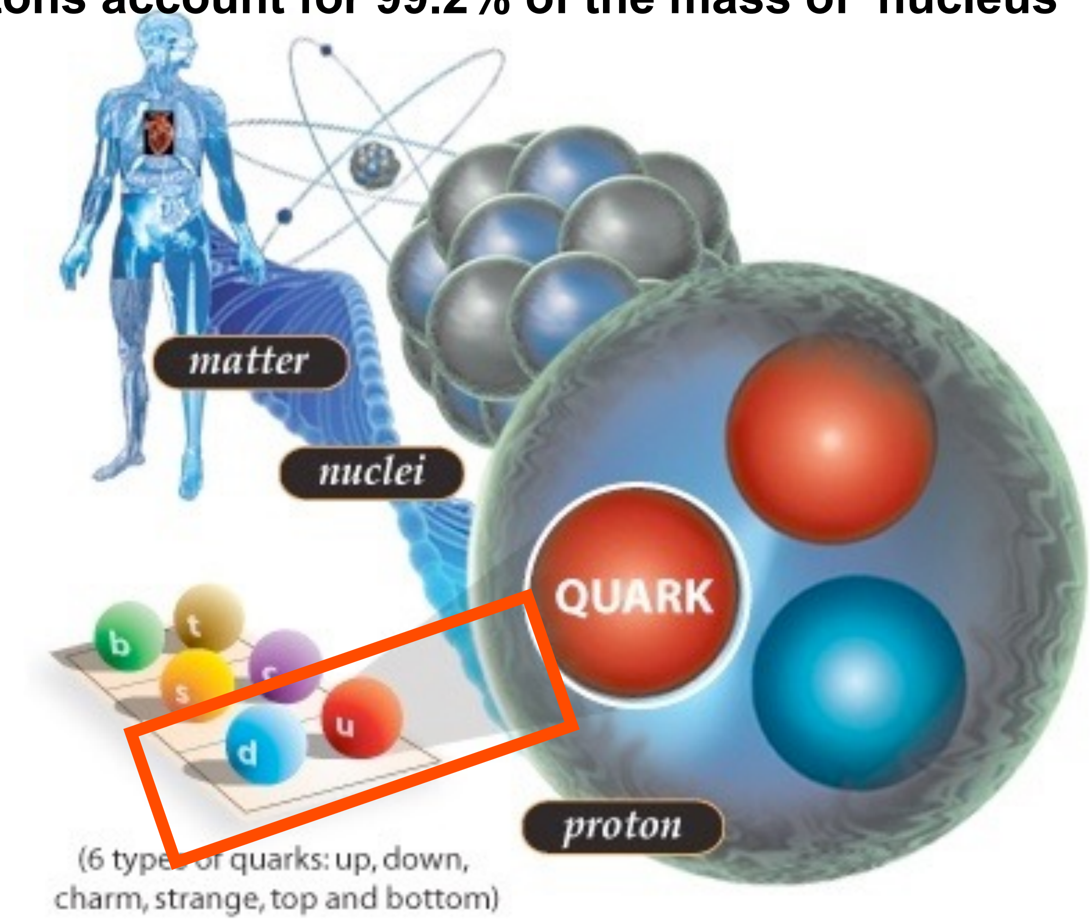
- General information about quark, gluons, QCD
  Motivation for study of proton
  How does the proton spin?
- Phenomenological considerations →
  proton is **not** round.

- How large is the proton: precision <1%?

Cool Facts about Quarks, Gluons (QCD) and Nuclei

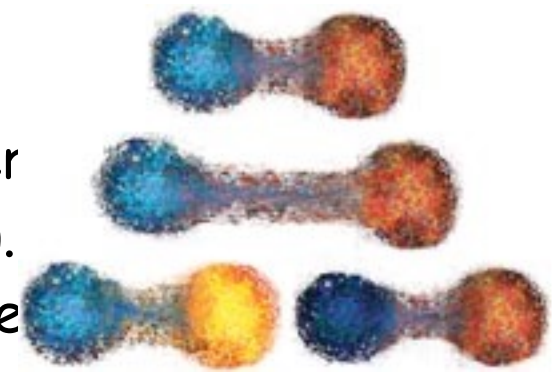
Did you know that … ?

- If an atom was the size of a football field, the (atomic) nucleus would be about the size of a marble.
- Despite its tiny dimensions, the nucleus accounts for 99.9% of an atom's mass. Neutrons and protons account for 99.2% of the mass of nucleus
- Protons and neutrons swirl in a heavy atomic nucleus. Average speed is some ¼ the speed of light. They are "strong-forced" to reside in a small space.
- Quarks (and gluons) are "confined" to the even smaller space inside protons and neutrons. Because of this, they swirl around with the speed of light.



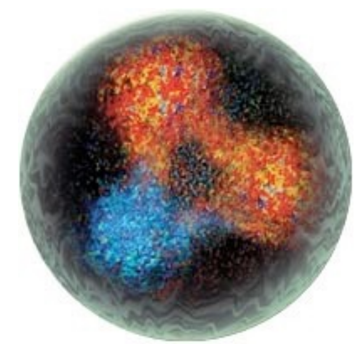
Cool Facts about QCD=strong force

Did you know that … ?



• The strong force is so strong, that you can never find one quark alone (this is called "confinement").

•When pried even a little apart, quarks experience ten tons of force pulling them together again.

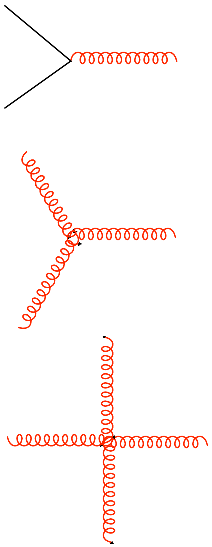


• Quarks and gluons jiggle around at nearly light-speed, and extra gluons and quark/anti-quark pairs pop into existence one moment to disappear the next.

• It is this flurry of activity, fueled by the energy of the gluons, that generates nearly all the mass of protons and neutrons, and thus ultimately of all the matter we see.

• 99% of your mass is due to this stored energy.

QCD the fundamental theory of the strong interaction



QCD Lagrangian: quarks and gluons

We know that QCD works, but theory is difficult to evaluate. Lattice QCD makes big progress now. Exciting prospect: comparing experiment with correctly evaluated fundamental theory.

Why study the nucleon?

- Neutrons protons made of quarks, gluons
- Quantum Chromodynamics QCD
- CONFINEMENT, test QCD lattice
- Size influences atomic physics tests of QED
- How does the nucleon stick together when struck by photon?
- Where is charge and magnetization density located? Origin of angular momentum= spin?
- What is the shape of the proton?

Naive Quark Model of Proton, Neutron (nucleon)

Proton 2 u(2/3), 1 d

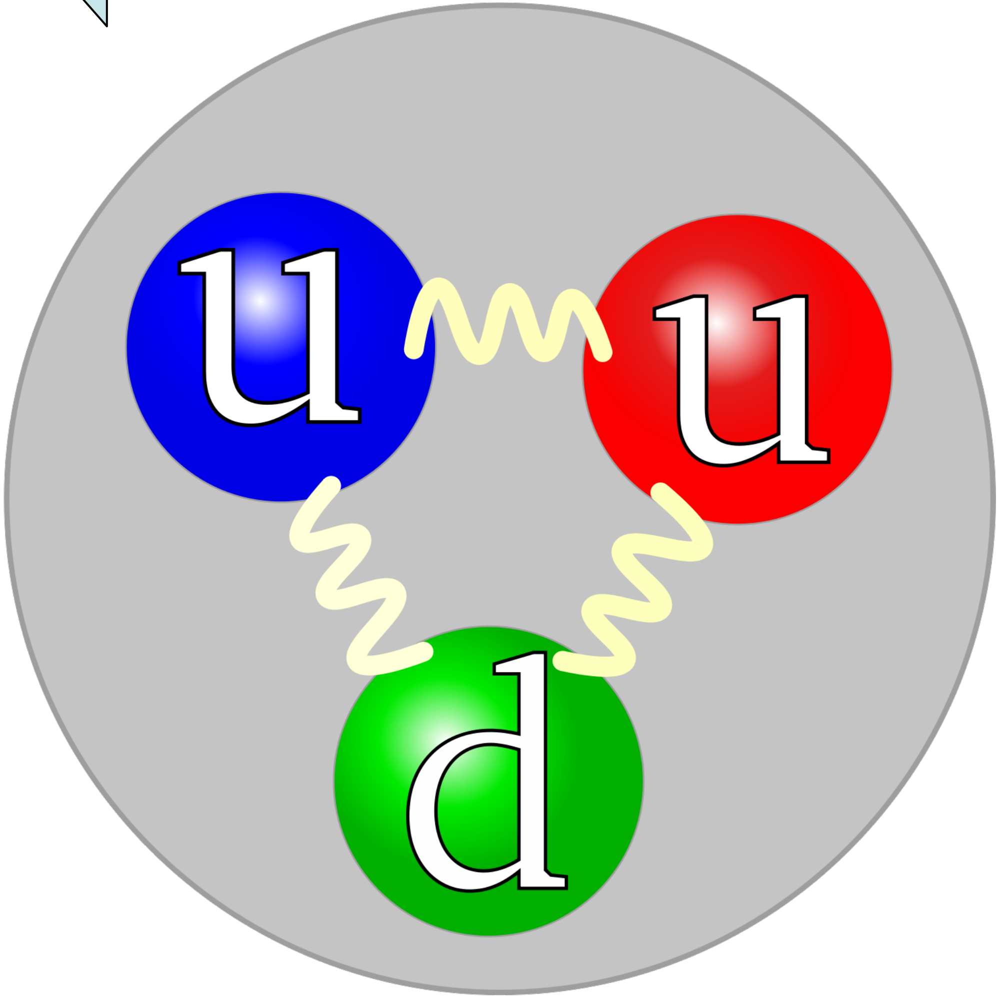
Neutron 2 d(-1/3) 1 u

Confined quarks move with zero orbital angular momentum

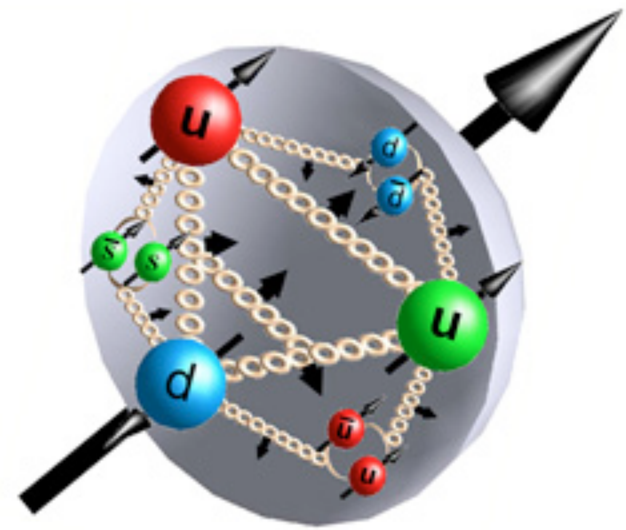
This idea has great success - magnetic moments, spectra of particles, etc

$1.6\ \text{fm} = 1.6 * 10^{-15}\ \text{m}$

Proton has size



Proton has spin



"Spin Crisis"

Proton spin is $1/2\ \hbar$

Experiment shows that the spin of the quark carry only 30 % of $1/2\ \hbar$

Possibilities:

u, d quarks surrounded by strange quark pairs $s\bar{s}$ -RULED OUT

gluons carry spin and orbital angular momentum

quarks carry orbital angular momentum

STATUS?

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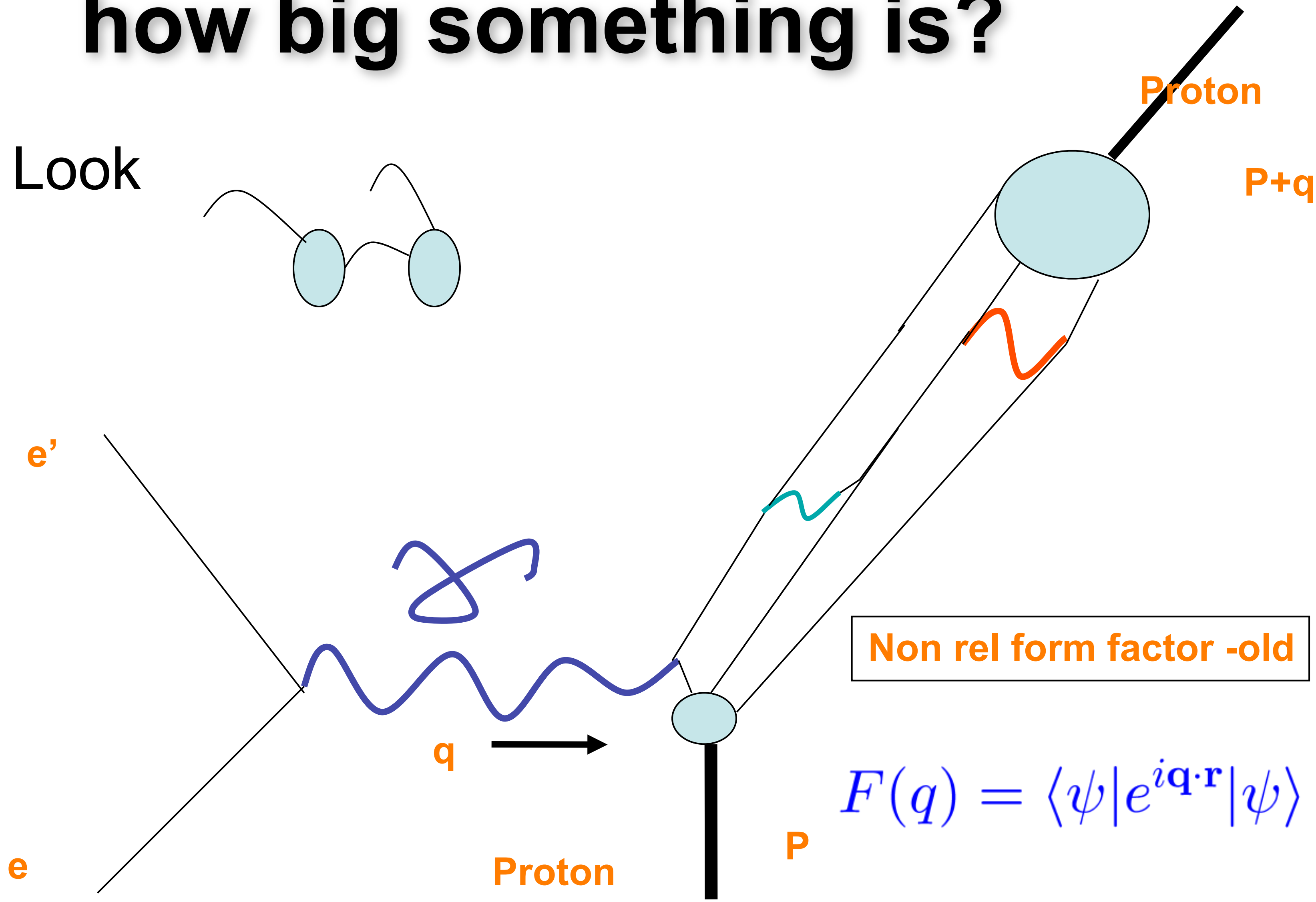
STATUS?

We are still trying to figure out how much of each

Study proton: How to tell how big something is?

- Look

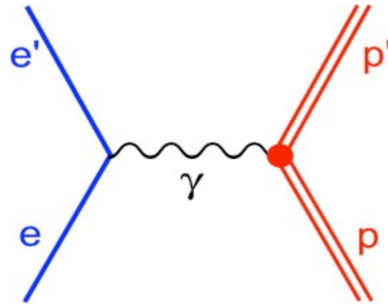


$$F(q) = \langle \psi | e^{i\mathbf{q}\cdot\mathbf{r}} | \psi \rangle$$

Structure factor

Electron-nucleon scattering

$j_\mu = \langle e' | \gamma_\mu | e \rangle$

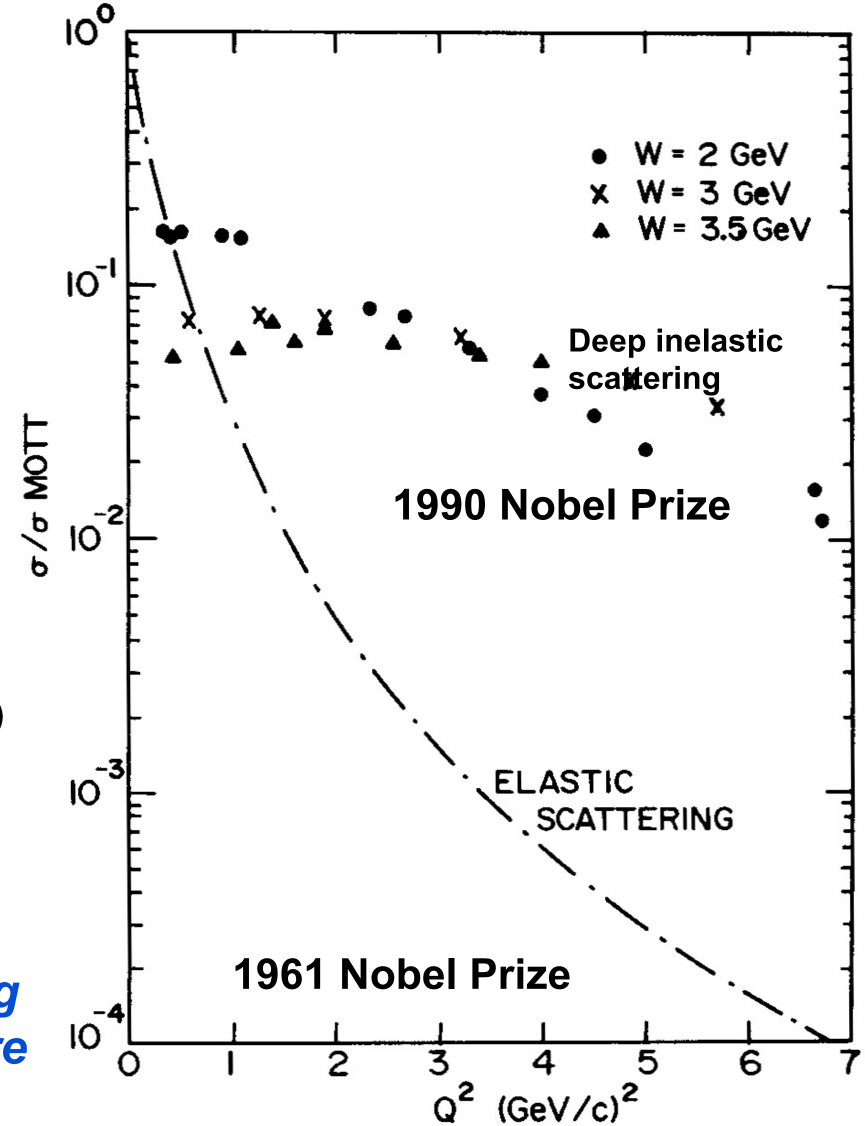


Nucleon vertex:

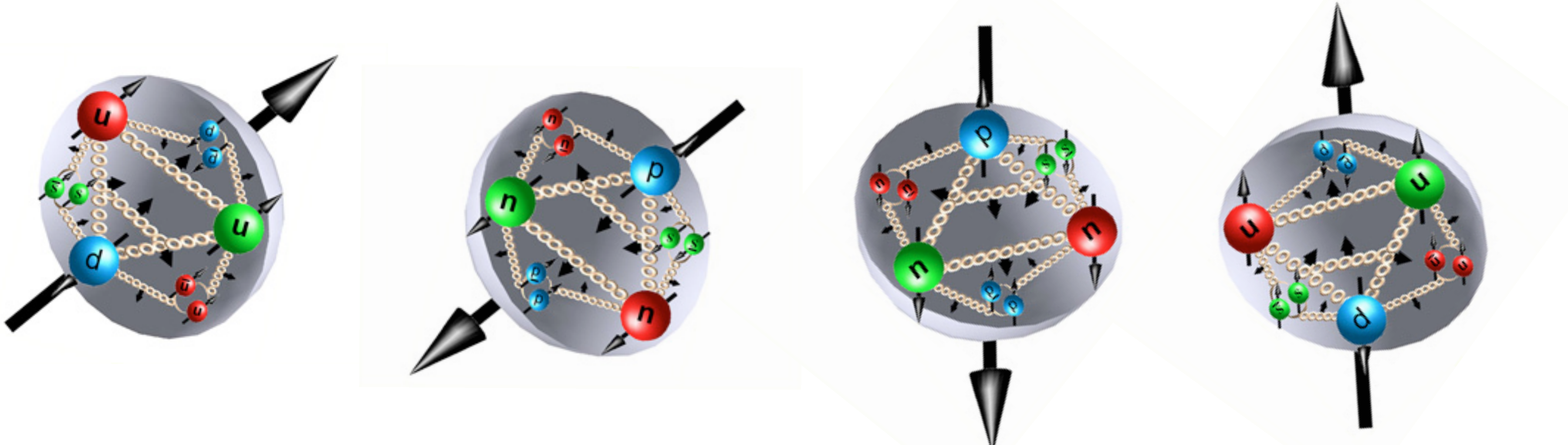
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(G_E^2 + \frac{\tau}{\epsilon} G_M^2\right) / (1 + \tau)$$

Cross section for scattering from a point-like object

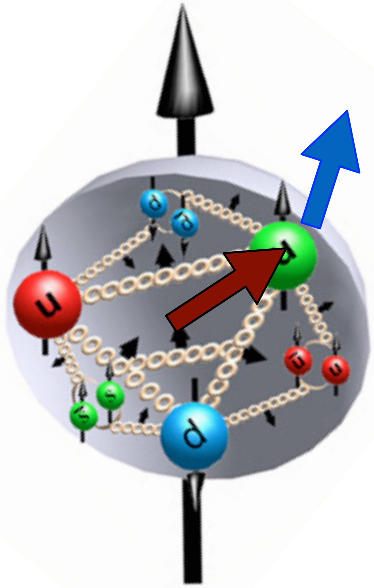
Form factors describing nucleon shape/structure



Shape of proton



Random spin -direction -means no direction proton is spherical



Fix spin direction -three vectors:spin (up) , quark position, direction of quark spin

I: Non-Rel. $p_{1/2}$ proton outside 0^+ core

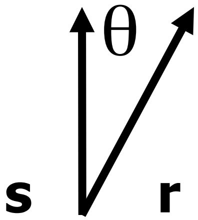
$$\langle \mathbf{r}_p | \psi_{1,1/2s} \rangle = R(r_p) \boldsymbol{\sigma} \cdot \hat{\mathbf{r}}_p | s \rangle$$

$$\rho(r) = \langle \psi_{1,1/2s} | \delta(\mathbf{r} - \mathbf{r}_p) | \psi_{1,1/2s} \rangle = R^2(r)$$

probability proton at $\mathbf{r}$ & spin direction $\mathbf{n}$:

$$\rho(\mathbf{r}, \mathbf{n}) = \langle \psi_{1,1/2s} | \delta(\mathbf{r} - \mathbf{r}_p) \frac{(1+\boldsymbol{\sigma} \cdot \mathbf{n})}{2} | \psi_{1,1/2s} \rangle$$

$$= \frac{R^2(r)}{2} \langle s | \boldsymbol{\sigma} \cdot \hat{\mathbf{r}} (1 + \boldsymbol{\sigma} \cdot \mathbf{n}) \boldsymbol{\sigma} \cdot \hat{\mathbf{r}} | s \rangle$$



$\mathbf{n} \parallel \hat{\mathbf{s}}$: $\quad \rho(\mathbf{r}, \mathbf{n} = \hat{\mathbf{s}}) = R^2(r) \cos^2 \theta$

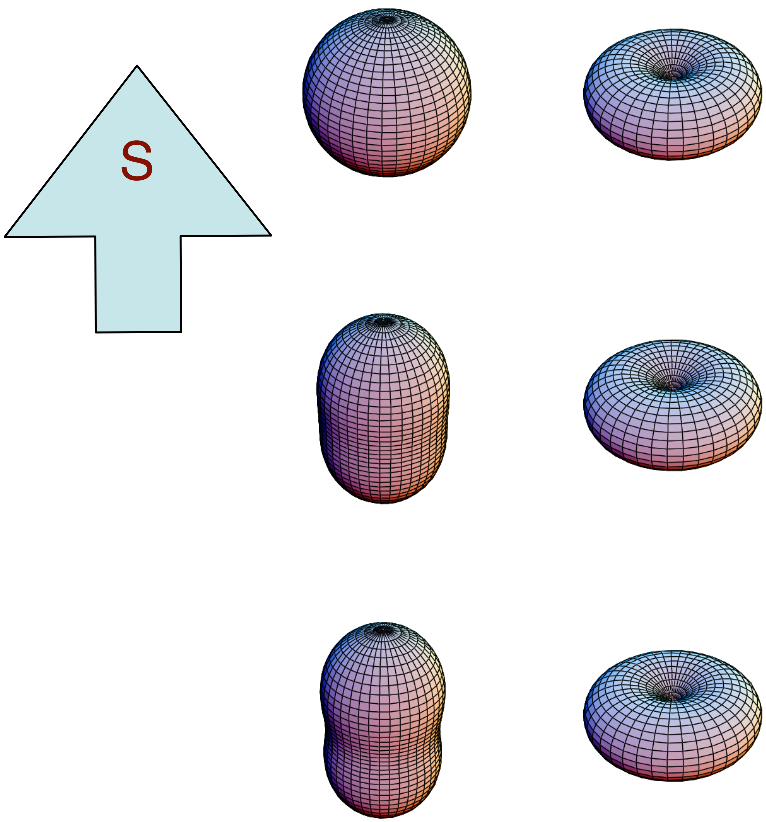
$\mathbf{n} \parallel -\hat{\mathbf{s}}$: $\quad \rho(\mathbf{r}, \mathbf{n} = -\hat{\mathbf{s}}) = R^2(r) \sin^2 \theta$

non-spherical shape depends on spin direction

Shapes of the proton- momentum space

n parallel to S

n anti-parallel to S



three vectors n, K, S

n is quark spin

S is proton spin

Phys.Rev. C68 (2003) 022201

Shapes of the proton- momentum space

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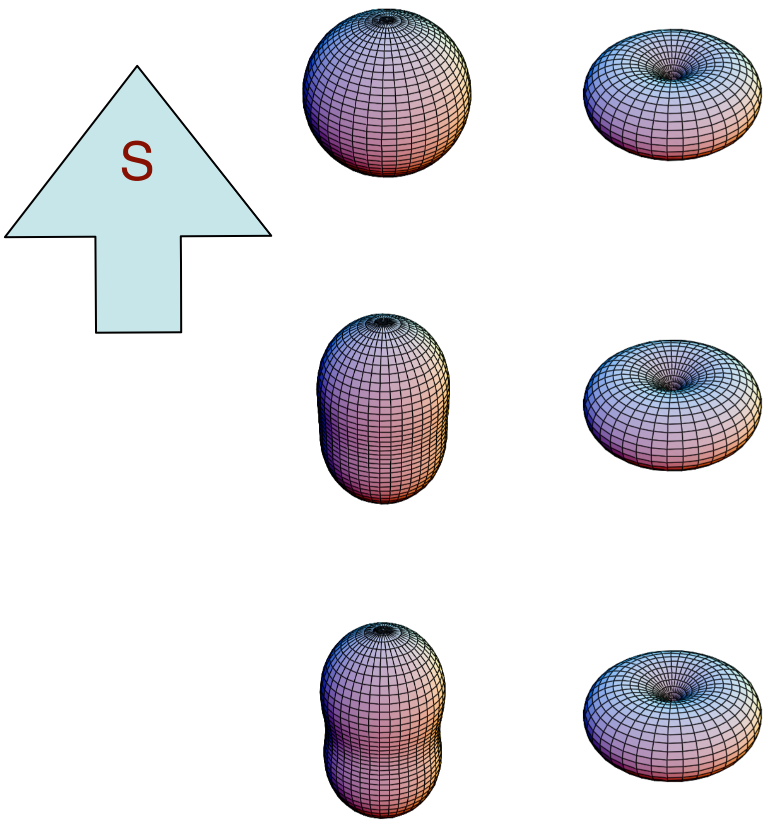

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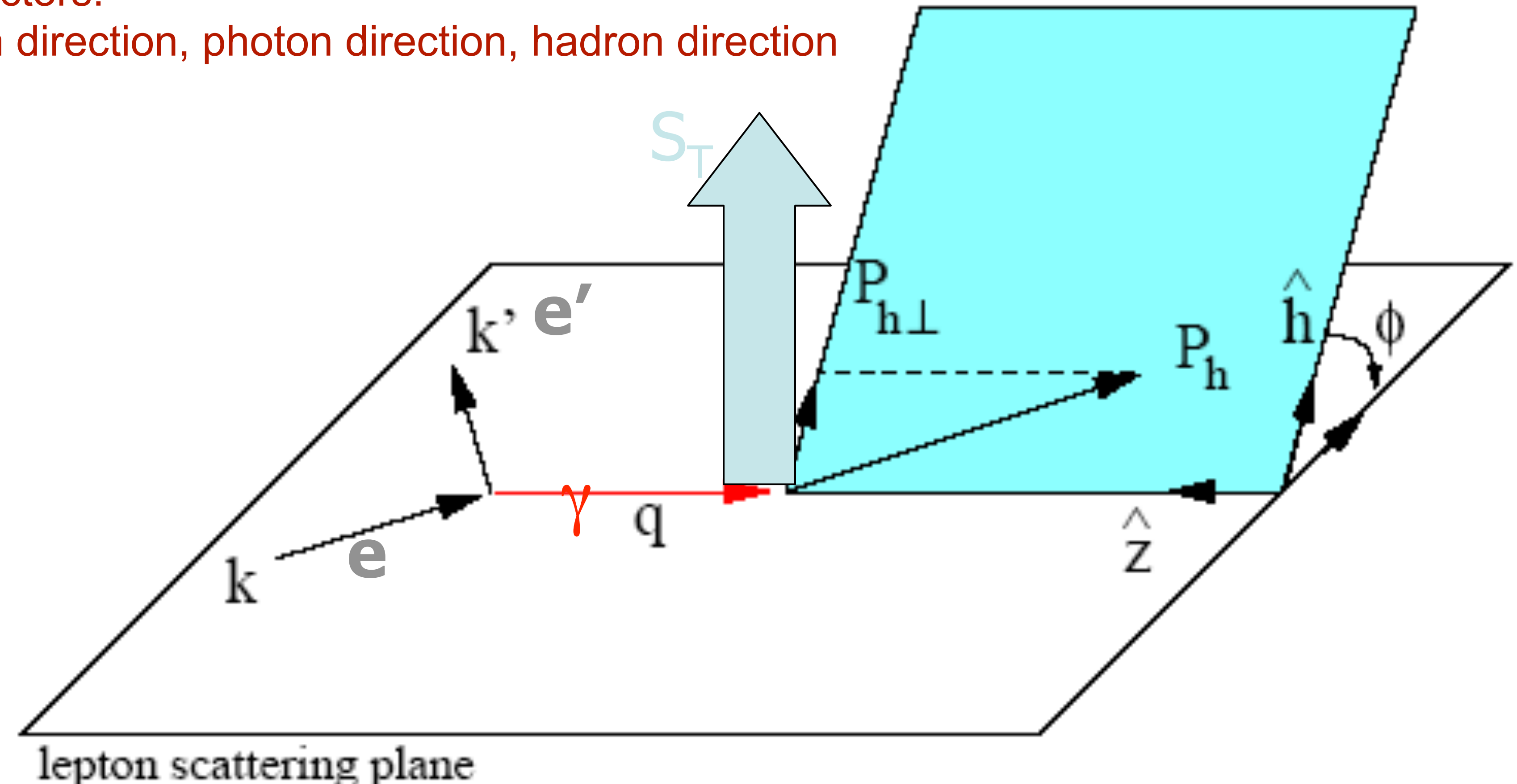
MODEL , HOW TO MEASURE? How to compute fundamentally?

Measure $h_{1T}^{\perp} : e + p(\uparrow) \rightarrow e'\pi X$

3 vectors:
Spin direction, photon direction, hadron direction



Cross section has term proportional to cos 3ϕ

Boer Mulders 1998

Measure $h_{1T}^{\perp} : e + p(\uparrow) \to e'\pi X$

H. Avakian, *et al.* "Transverse Polarization Effects in Hard Scattering at CLAS12 Jefferson Laboratory", LOI12-06-108, and H. Avakian private communication.

3 vectors:
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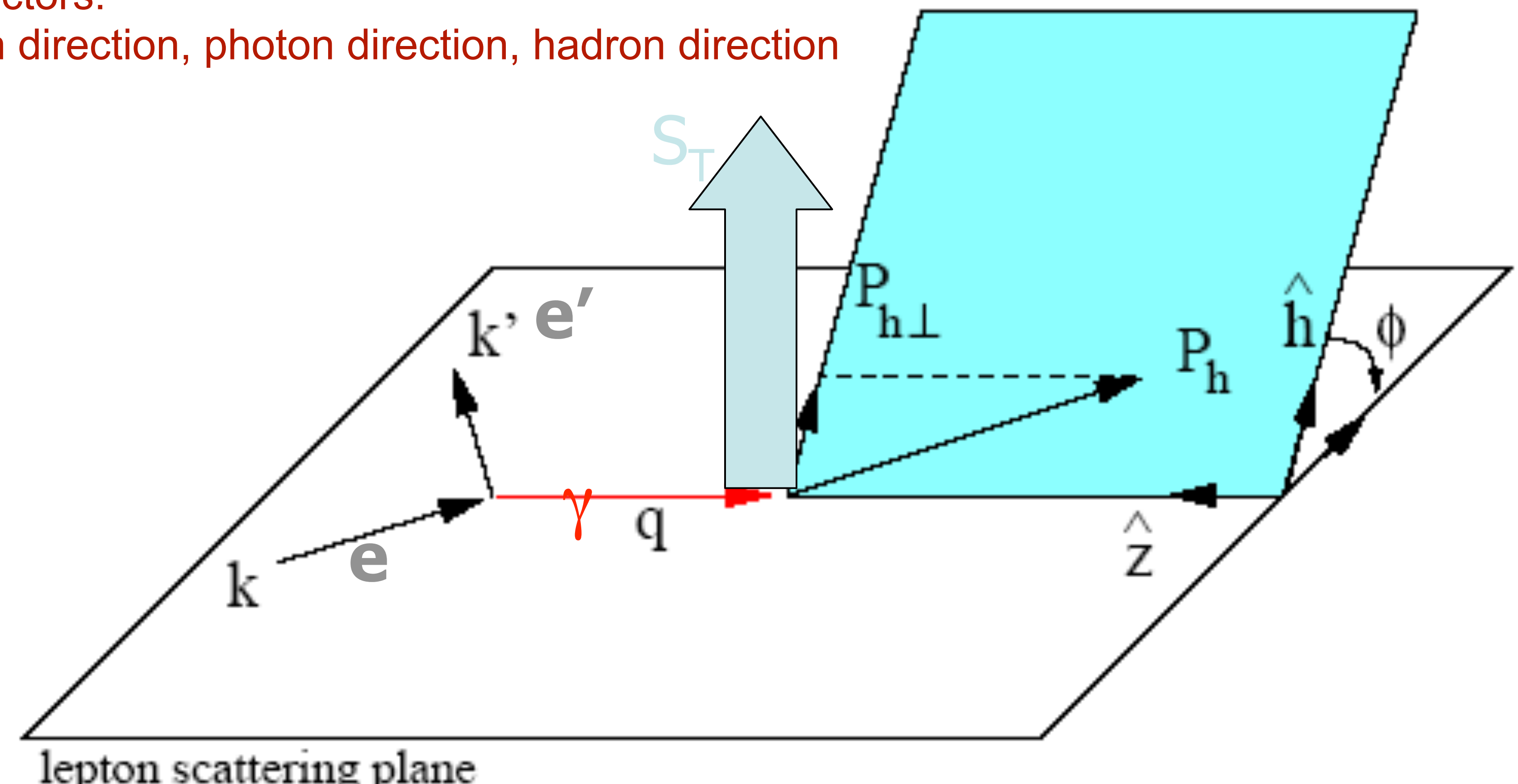

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Summary

- Proton is not round- Theory lattice QCD spin-dependent-density is not zero
- Experiment can whether or not proton is round by measuring still waiting, some indications have been found

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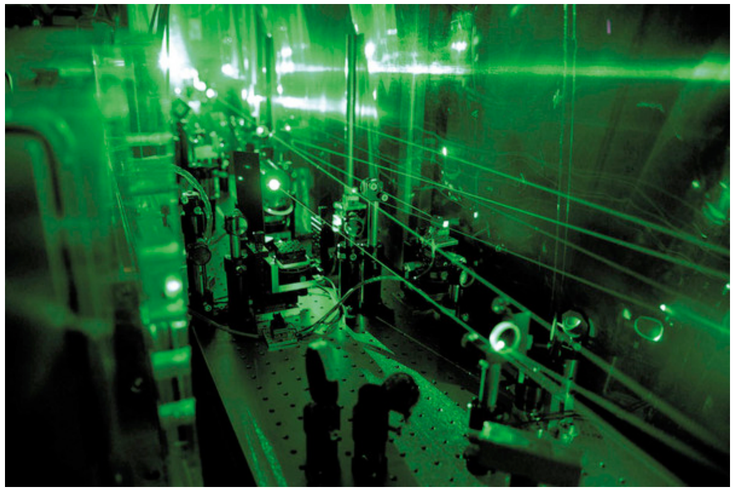
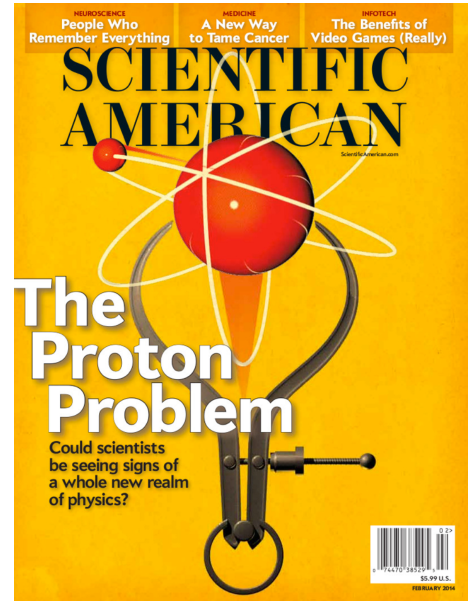
The Proton

Electrophobic scalar boson and muonic puzzles

Gerald A. Miller, University of Washington

Pohl et al Nature 466, 213 (8 July 2010)





Feb. 2014

Pohl, Gilman, Miller, Pachucki (ARNPS63, 2013)

$$r_p^2 \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

muon H r_p =0.84184 (67) fm

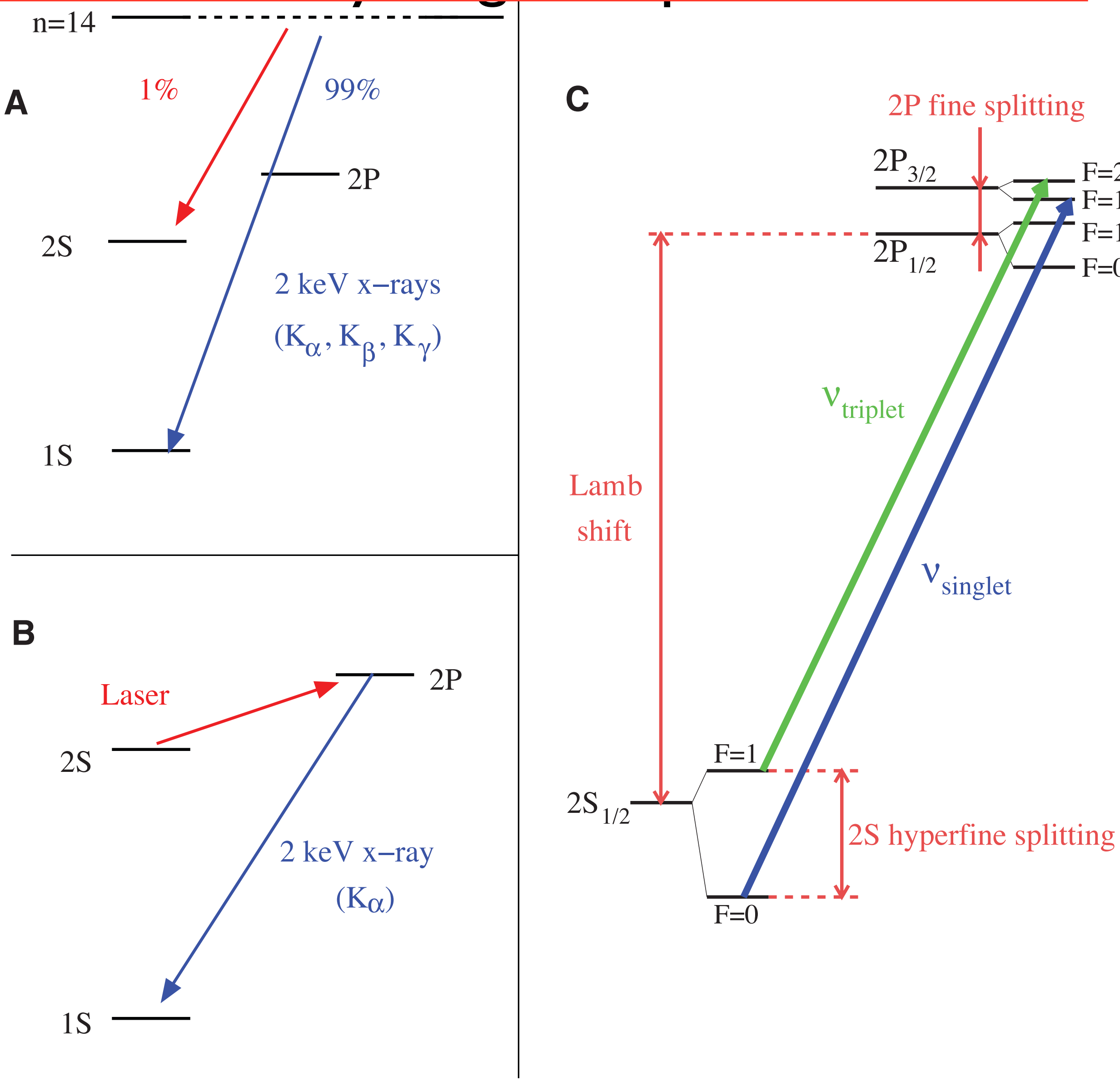
electron H r_p =0.8768 (69)fm

electron-p scattering r_p =0.875 (10)fm

PRad at JLab- lower Q^2

4 % Difference

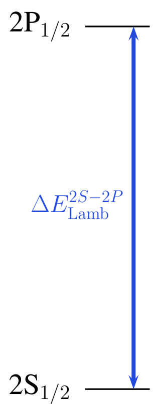
Muonic Hydrogen Experiment



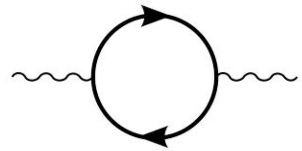
From 2013 Science paper

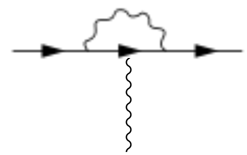
Fig. 1. (**A**) Formation of μp in highly excited states and subsequent cascade with emission of "prompt" $K_{\alpha,\ \beta,\ \gamma}$. (**B**) Laser excitation of the 2S-2P transition with subsequent decay to the ground state with K_α emission. (**C**) 2S and 2P energy levels. The measured transitions ν_s and ν_t are indicated together with the Lamb shift, 2S-HFS, and 2P-fine and hyperfine splitting.

muonic hydrogen experiment



The Lamb shift is the splitting of the degenerate $2S_{1/2}$ and $2P_{1/2}$ eigenstates

Dominant in μH  vacuum polarization 205 of 206 meV

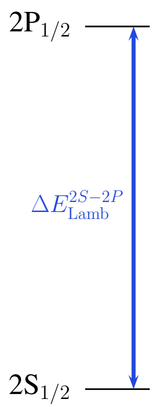
Dominant in eH  electron self-energy

Proton radius in Lamb shift

$$\Delta E = \langle \Psi_S | V_C - V_C^{\rm pt} | \Psi_S \rangle = \frac{2}{3} \pi \alpha |\Psi_S(0)|^2 (-6 G'_E(0))$$

Muon/electron mass ratio 205! 8 million times larger for muon

muonic hydrogen experiment



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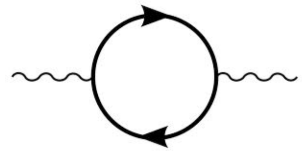

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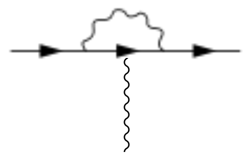

electron self-energy

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Recoil effects included:
interaction computed for moving fermions

4 % in radius: why care?

- Can't be calculated to that accuracy
- 1/2 cm in radius of a basketball

Is the muon-proton interaction the same as the electron-proton interaction? - many possible ramifications

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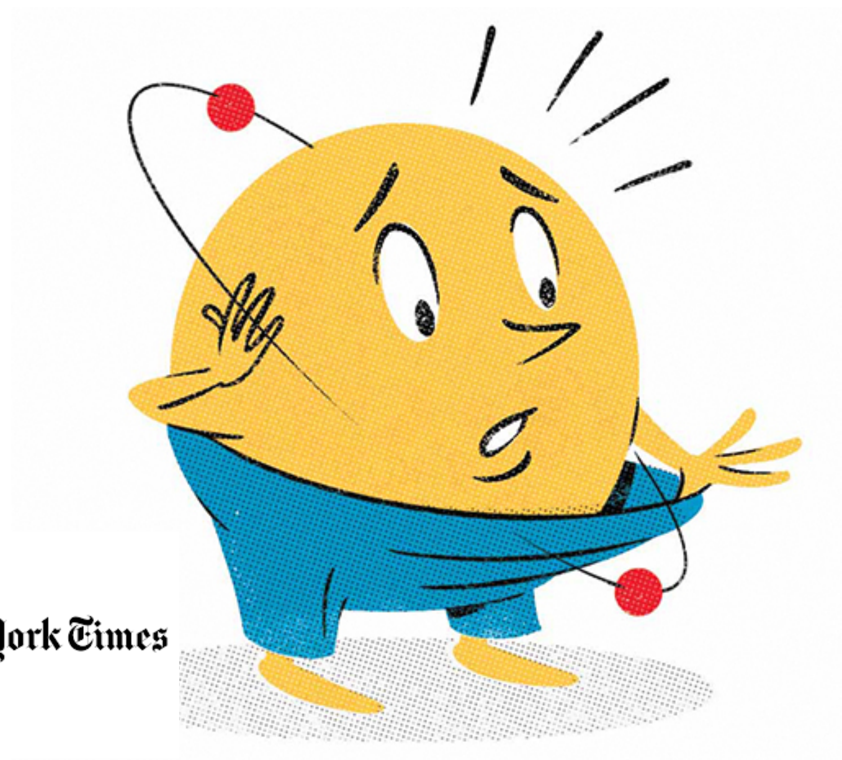


The New York Times

Another muon opportunity-anomalous moment

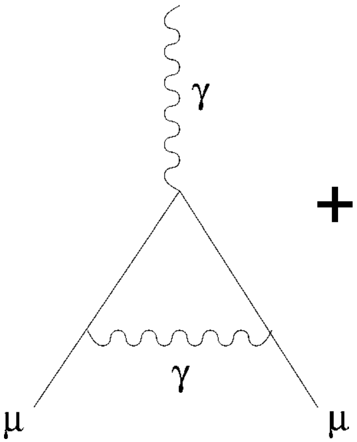
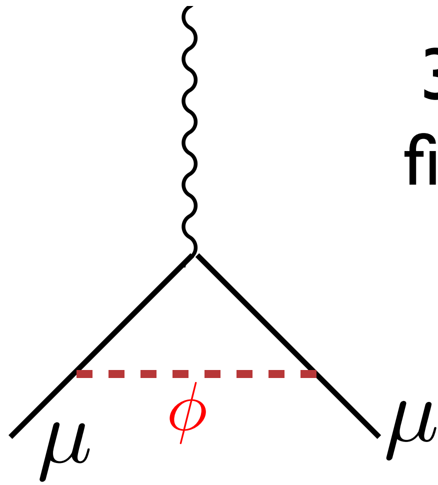


Figure 1 The first-order QED correction to g-2 of the muon.

+

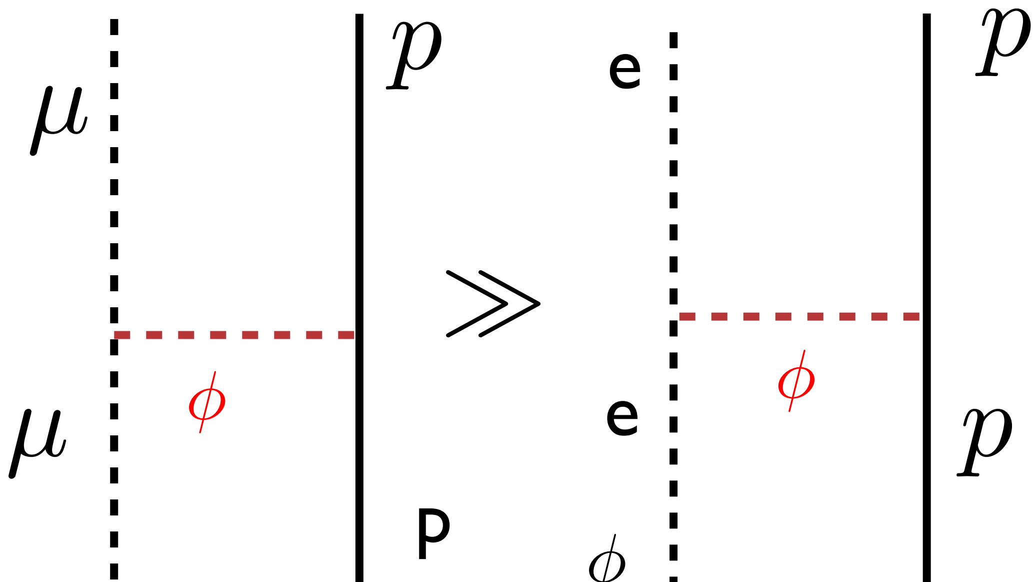


3.6 st. dev anomaly now
fix: add new scalar boson interacts preferentially with muon

Muon data is g-2 - BNL exp't, Hertzog...

Lamb shift

Maybe dark matter, energy particles show up as mediator in muon physics!



Possible resolutions

- QED bound-state calculations not accurate-very unlikely- this includes recoil effects
- Electron experiments not so accurate -new ones ongoing
- other stuff -unlikely
- Muon interacts differently than electron!- scalar boson

Notation

Couplings of ϕ to standard model fermions, f:

$$\mathcal{L} \supset e\epsilon_f \phi \bar{f} f, \ \epsilon_f \equiv g_f/e$$

$e =$ electric charge of the proton, f is particle label.

One scalar boson exchange potential between flavor 1 and 2:

$$V(r) = -\epsilon_{f_1}\epsilon_{f_2}\alpha e^{-m_\phi r}/r$$

Others pursued this idea, using further assumptions:

TuckerSmith (2010) uses $\epsilon_p = \epsilon_\mu$, $\epsilon_n = 0$
Izaguirre (2014), assume mass-weighted couplings & $\epsilon_n = 0$

Here: NO assumptions re signs or magnitudes of coupling constants.
Lamb shift $\rightarrow \epsilon_\mu \epsilon_p > 0$ take ϵ_μ, $\epsilon_p > 0$. Then $\epsilon_{e,\mu}, \epsilon_n$: either sign

- muonic g-2 and Lamb shift

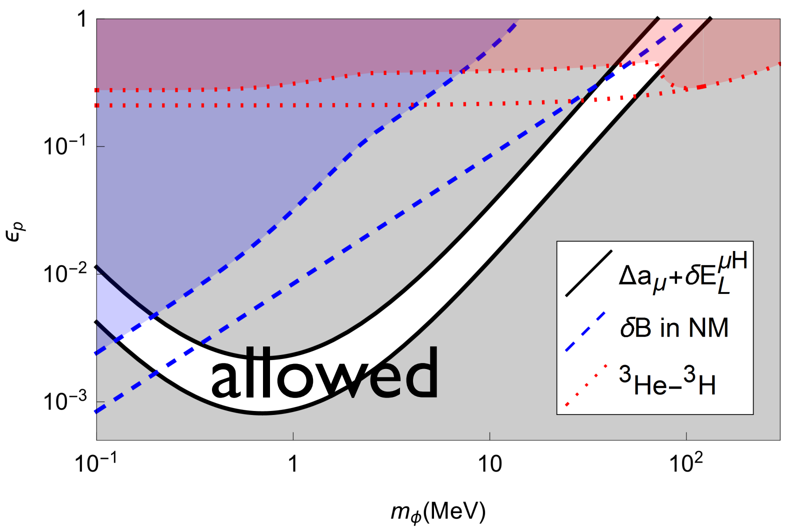
$$\Delta a_\ell = \frac{\alpha \epsilon_\ell^2}{2\pi} \int_0^1 dz \frac{(1-z)^2(1+z)}{(1-z)^2 + (m_\phi/m_\ell)^2 z}.$$

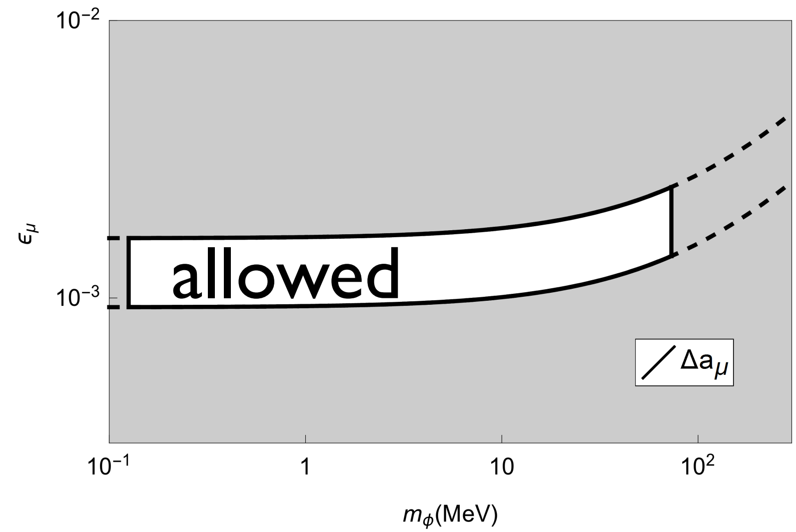
Lamb Shift

$$\delta E_L^{\ell N} = -\frac{\alpha}{2a_{\ell N}} \epsilon_\ell [Z\epsilon_p + (A-Z)\epsilon_n] f(a_{\ell N} m_\phi)$$

$$f(x) = x^2/(1+x)^4$$

$$\Delta a_\mu = 287(80) \times 10^{-11}, \ \delta E_L^{\mu H} = -0.307(56) \ \text{meV}$$





Yavin-&Tucker-Smith assume coupling to neutron = proton

n- Pb(208) impose severe restriction, but why =?

Nuclear Physics Constraints

Low energy n Pb scattering constrains g_N

Charge independence breaking of nucleon-nucleon scattering

$1/2(V_{nn}+V_{pp})-V_{np}$ is constrained to be small via scattering length difference <1.6 fm

Binding energy difference between ^3He and ^3H: $V_{pp}-V_{nn}$ change in binding energy difference < 30 keV

Binding energy in infinite nuclear matter: change in binding energy <1 MeV

Constrain coupling to electron (analysis similar to dark photon)

- anomalous magnetic moment of electron- used to determine α, needs value obtained free of possible scalar boson effects- ratio of Planck constant to mass of Rb: Bouchendira et al PRL 106 080801
- Bhabha (e^+e^-) scattering sensitive to resonance at cm energy = m_ϕ Bhabha scattering in the MeV range Tsertos et al PRD40, 1397
- Beam dump experiments- phi decays to e+e- or $\gamma\gamma$ pairs. We provide exact evaluation of phase space integral
- Lamb shift in hydrogen <14 kHz (Eides reviews)
- Stellar cooling limits see An et al PLB725,190 (we have same limits for masses less than 200 keV). Supernova cooling -g_p large enough to keep scalar trapped

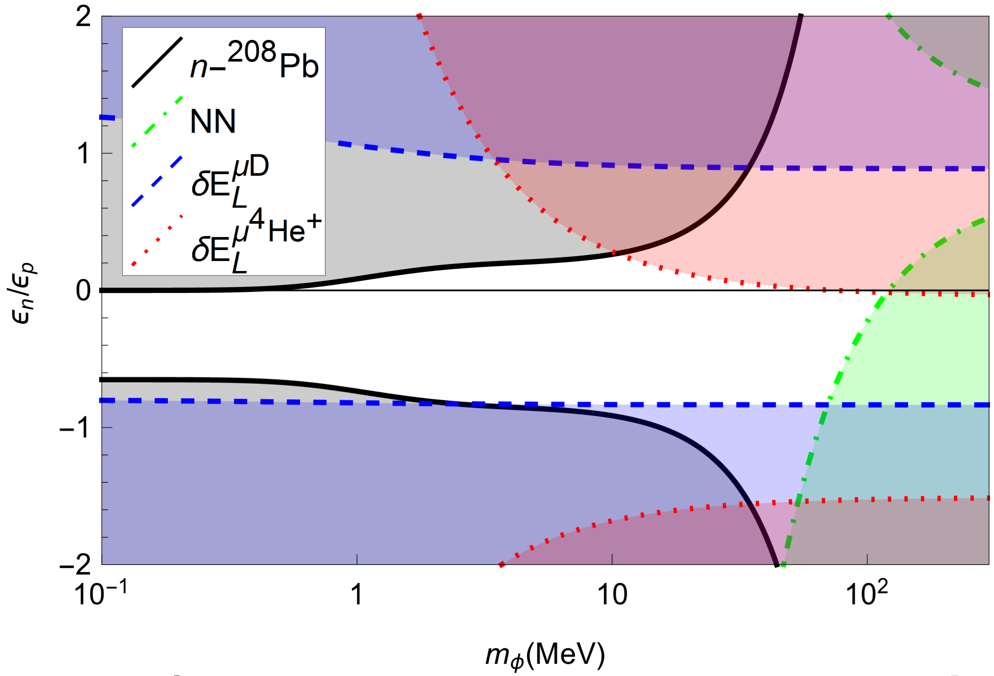
mu D and mu He constraints

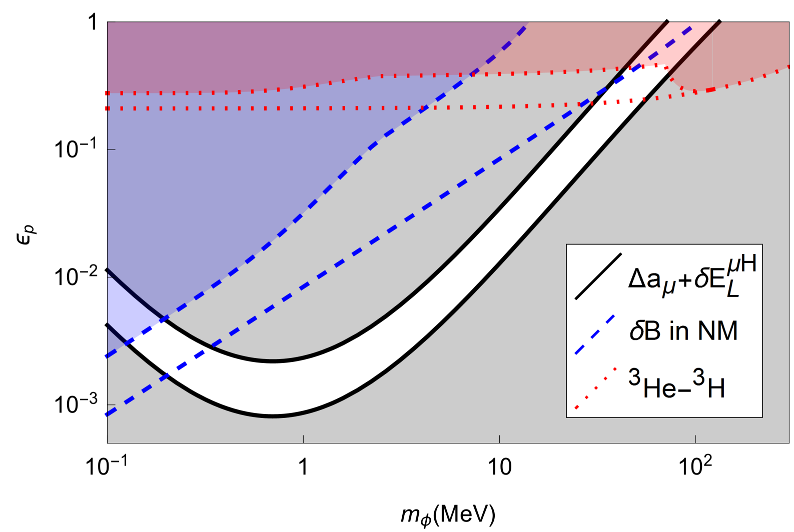
- $\delta E_L^{\mu D} = -0.368\,(78)\,\mathrm{meV}$ (Preliminary) from talk, 3 st. dev.
- $\delta E_L^{\mu He} = -1.4(1.5)\,\mathrm{meV}$ (Preliminary) from talk, 3 st. dev

Combine $\mu H, \mu D, \mu^4 He$ to get ϵ_p/ϵ_n independent of ϵ_μ and ϵ_p

Combining nuclear and muonic atom results

Shaded regions excluded





Allowing opposite sign widens allowed region

Possible new experiments

- Publish muon D and muon 4He results (big impact on soft proton)
- proton and or muon beam dump experiments for large mass region
- low mass region Izaguirre et al underground nuclear decays
- pp to pp phi detect protons
- improve neutron-nucleus experiments
- If scalar boson solves proton radius problem, MUSE will detect same `large radius' for positively and negatively charge electrons and muons
- muon beam dump (COMPASS)
- new muon anomalous moment measurement
- Goudelis et al PRL 116, 211303 particle of mass 1.6 to 20 MeV may provide solution to understanding cosmological abundance of 7Li

Summary of proton size

- If all of the experiments relevant to r_p, and their analyses, are correct some unusual or BSM physics occurs
- new scalar boson
- Searching over a wide range of experiments a new scalar boson could account for both muonic puzzles and exist in the allowed parameter space.

Liu McKeen Miller 1605.04612