Strangeness Content of the Nucleon

Anthony W. Thomas
Asia-Pacific Few Body Conference
SUT, Thailand : July 26th, 2005
Outline

• The QCD Vacuum
• Quarks to Hadrons
• Measurements of Nucleon Form Factors
• Latest Results on Strangeness
• A Precise Theoretical Calculation of $G_M^s$
• What needs measuring?
Topology of QCD Vacuum

Leinweber: see CSSM web pages
Powerful Qualitative New Insights From Lattice QCD

QCD sum rules:

\[
\left\langle 0 \left| \frac{\alpha_s}{\pi} \, G_{\mu\nu}^i \, G_{i\mu\nu}^{\mu\nu} \right| 0 \right\rangle = \left\langle 0 \left| \frac{2\alpha_s}{\pi} \left( B^2 - E^2 \right) \right| 0 \right\rangle = (350 \pm 30 \text{ MeV})^4,
\]

- Non-trivial topological structure of vacuum linked to dynamical chiral symmetry breaking
- There are regions of positive and negative topological charge
- BUT they clearly are NOT spherical
- NOR are they weakly interacting!
Quark Condensate

\[
\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = \langle \bar{s}s \rangle = -(225 \pm 25 \text{ MeV})^3
\]

at a renormalization scale of about 1 GeV.

- commutator measures chiral symmetry breaking
  \[ \approx \text{valence} + \text{pion cloud} + \]
  volume \(\times (\text{difference of condensate in \& out of N})\)

and last term is as big as 20 MeV (or more)

i.e. presence of nucleon “cleans out” vacuum to some extent

Hence:  Model independent LO term for in-medium condensate

\[
\frac{Q(\rho_B)}{Q_0} \approx 1 - \frac{\sigma_N}{f_\pi^2 m_\pi^2} \rho_B
\]

BUT this has no new physics at all!
QCD and the Origin of Mass

\[ u + u + d = \text{proton} \]

mass: \[ 0.003 + 0.003 + 0.006 \neq 0.938 \]

HOW does the rest of the proton mass arise?
χ’al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon

FRR give same answer to <<1% systematic error!

Leinweber et al., PRL 92 (2004) 242002

Leinweber et al., PRL 92 (2004) 242002

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Convergence from LNA to NLNA is Rapid – Using Finite Range Regularization

<table>
<thead>
<tr>
<th>Regulator</th>
<th>LNA</th>
<th>NLNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp</td>
<td>968</td>
<td>961</td>
</tr>
<tr>
<td>Monopole</td>
<td>964</td>
<td>960</td>
</tr>
<tr>
<td>Dipole</td>
<td>963</td>
<td>959</td>
</tr>
<tr>
<td>Gaussian</td>
<td>960</td>
<td>960</td>
</tr>
<tr>
<td>Dim Reg</td>
<td>784</td>
<td>884</td>
</tr>
</tbody>
</table>

$M_N$ in MeV
Comparison with $\chi$ QSM

Goeke et al., hep-lat/0505010
Analysis of pQQCD $\rho$ data from CP PACS

\[ \sqrt{(M_V^{\text{deg}})^2 - \Sigma_{TOT}} = (a_0^{\text{cont}} + X_1 a + X_2 a^2) + a_2 (M_{PS}^{\text{deg}})^2 + a_4 (M_{PS}^{\text{deg}})^4 + a_6 (M_{PS}^{\text{deg}})^6 \]
Infinite Volume Unitary Results

All 80 data points drop onto single, well defined curve

Allton, Young et al., hep-lat/0504022

777 ± 7 MeV
JLAB: Unique Capabilities for Investigating QCD in the Non-Perturbative Regime

JLab is a world leader in SRF technology: SNS, 12 GeV Upgrade, FEL, RIA, and others in the Office of Science 20-Year Facilities Outlook

Superconducting rf (SRF) technology makes the circulating accelerator feasible

Providing ~2300 international users with a unique electron beam, three experimental halls, and computational and theory support

High luminosity, high resolution detectors in Halls A, B, and C.
Precision Tests of Nucleon Structure

- Astonishing discovery concerning proton electric form factor

- But what about contribution from non-valence quarks
  - especially strange quarks?
Strangeness Widely Believed to Play a Major Role – Does It?

- As much as 100 to 300 MeV of proton mass:

\[ M_N = \langle N(P) \rangle - \frac{9\alpha_s}{4\pi} \text{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u \bar{\psi}_u \psi_u + m_d \bar{\psi}_d \psi_d + m_s \bar{s} \psi_s |N(P)\rangle \]

\[ \Delta M_N^{s-\text{quarks}} = \frac{ym_s}{m_u + m_d} \sigma_N \]

\[ y = 0.2 \pm 0.2 \]

\[ 45 \pm 8 \text{ MeV (or 70?)} \]

Hence \( 110 \pm 110 \text{ MeV} \) (increasing to 180 for higher \( \sigma_N \))

- Through proton spin crisis:
  As much as 10% of the spin of the proton

- HOW MUCH OF THE MAGNETIC FORM FACTOR?
G0 Experiment at Jefferson Lab

detectors

magnet

beam line

target service vessel
World Data @ $Q^2 = 0.1 \text{ GeV}^2$

$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

\pm 0.62 \ 2\sigma$

Contours

-1\sigma, 2\sigma

68.3, 95.5\% CL

Theories

1. Leinweber, et al.
   PRL 94 (05) 212001

2. Lyubovitskij, et al.
   PRC 66 (02) 055204

3. Lewis, et al.
   PRD 67 (03) 013003

   PRD 65 (01) 014016
Simple Fits to World Hydrogen Data

- Fit

\[ G_E^s(Q^2) + \eta(Q^2, E_i) G_M^s(Q^2) = \]

\[ \frac{4\pi\alpha\sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^p + \tau G_M^p}{\varepsilon G_E^p (1 + R_V^{(0)})} \left( A_{phys} - A_{NVS}(Q^2, E_i) \right) \]

with simple forms for \( G_E^s, G_M^s \)

\[ G_E^s(Q^2) = \frac{c_2 Q^4}{1 + d_1 Q^2 + d_2 Q^4 + d_3 Q^6} \]  

à la Kelly

\[ G_M^s(Q^2) = \frac{G_M^s(Q^2 = 0)}{\left(1 + Q^2 / \Lambda_M^s \right)^2} \]

with

\[ G_M^s(Q^2 = 0) = 0.81 \]  

from \( Q^2 = 0.1 \) GeV\(^2\) plot, dipole ff
“Fit” to World Hydrogen Data

\[ c_2 = -0.51 \pm 0.25 \]
\[ d_1 = -8.5 \pm 0.9 \]
\[ d_2 = 24 \pm 6 \]
\[ d_3 = 1 \]
\[ \Lambda_M^2 = \Lambda^2 / 1.3 \]

Remember the factor of -1/3
Significance & Comparison with Lattice QCD

• Size and sign of the strange magnetic moment is astonishing!

• Experimental isoscalar nucleon moment is 0.88 \( \mu_N \)
  c.f. this result which is (Beck) - 0.54 \( \mu_N \) : i.e. - 60% !!

• Also remarkable versus lattice QCD which gives

  +0.03 \( \pm \) 0.01 \( \mu_N \) (Leinweber et al., PRL 94 (2005) 212001)

• Sign would require violation of universality of
  valence quark moments by \( \sim \) 70% !
Magnetic Moments within QCD

\[ p = \frac{2}{3} u^p - \frac{1}{3} d^p + O_N \]
\[ n = -\frac{1}{3} u^p + \frac{2}{3} d^p + O_N \]
\[ \Sigma^+ = \frac{2}{3} u^\Sigma - \frac{1}{3} s^\Sigma + O_\Sigma \]
\[ \Sigma^- = -\frac{1}{3} u^\Sigma - \frac{1}{3} s^\Sigma + O_\Sigma \]

HENCE:
\[ O_N = \frac{1}{3} \left[ 2p + n - \left( \frac{u^p}{u^\Sigma} \right) (\Sigma^+ - \Sigma^-) \right] \]

Just these ratios from Lattice QCD

OR
\[ O_N = \frac{1}{3} \left[ n + 2p - \left( \frac{u^n}{u^\Sigma} \right) (\Xi^0 - \Xi^-) \right] \]
Constraint from Charge Symmetry

\[ O_N = \frac{2}{3} \ell G_M^u - \frac{1}{3} \ell G_M^d - \frac{1}{3} \ell G_M^s \]

\[ = \frac{1}{3} (\ell G_M^d - \ell G_M^s) \]

\[ = \frac{\ell G_M^s}{3} \left( \frac{1 - \ell R_d^s}{\ell R_d^s} \right) \]

\[ G_M^s = \left( \frac{\ell R_d^s}{1 - \ell R_d^s} \right) \left[ 3.673 - \frac{u_P}{u_{\Sigma^+}} \right] (3.618) \]

\[ G_M^s = \left( \frac{\ell R_d^s}{1 - \ell R_d^s} \right) \left[ -1.033 - \frac{u_n}{u_{\Xi^0}} \right] (-0.599) \]

$u^p_{\text{valence}}$ : QQCD Data Corrected for Full QCD Chiral Coeff’s

\[ a_0 + a_2 m_\pi^2 + a_4 m_\pi^4 + \chi 'al \text{ loops} \]

New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

c.f. CQM
\[ 2/3 \ 940/540 \sim 1.18 \]
$u^\Sigma_{\text{valence}}$
Check: Octet Magnetic Moments

Leinweber et al., hep-lat/0406002
Convergence LNA to NLNA Again Excellent (Effect of Decuplet)
## State of the Art Magnetic Moments

<table>
<thead>
<tr>
<th></th>
<th>QQCD</th>
<th>Valence</th>
<th>Full QCD</th>
<th>Expt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>2.69 (16)</td>
<td>2.94 (15)</td>
<td>2.86 (15)</td>
<td>2.79</td>
</tr>
<tr>
<td>n</td>
<td>-1.72 (10)</td>
<td>-1.83 (10)</td>
<td>-1.91 (10)</td>
<td>-1.91</td>
</tr>
<tr>
<td>Σ⁺</td>
<td>2.37 (11)</td>
<td>2.61 (10)</td>
<td>2.52 (10)</td>
<td>2.46 (10)</td>
</tr>
<tr>
<td>Σ⁻</td>
<td>-0.95 (05)</td>
<td>-1.08 (05)</td>
<td>-1.17 (05)</td>
<td>-1.16 (03)</td>
</tr>
<tr>
<td>Λ</td>
<td>-0.57 (03)</td>
<td>-0.61 (03)</td>
<td>-0.63 (03)</td>
<td>-0.613 (4)</td>
</tr>
<tr>
<td>Ξ⁰</td>
<td>-1.16 (04)</td>
<td>-1.26 (04)</td>
<td>-1.28 (04)</td>
<td>-1.25 (01)</td>
</tr>
<tr>
<td>Ξ⁻</td>
<td>-0.65 (02)</td>
<td>-0.68 (02)</td>
<td>-0.70 (02)</td>
<td>-0.651 (03)</td>
</tr>
<tr>
<td>u⁺</td>
<td>1.66 (08)</td>
<td>1.85 (07)</td>
<td>1.85 (07)</td>
<td>1.81 (06)</td>
</tr>
<tr>
<td>u⁻</td>
<td>-0.51 (04)</td>
<td>-0.58 (04)</td>
<td>-0.58 (04)</td>
<td>-0.60 (01)</td>
</tr>
</tbody>
</table>
Accurate Final Result for $G_M^s$

Yields: $G_M^s = -0.046 \pm 0.019 \, \mu_N$

Leinweber et al., (PRL June ’05) hep-lat/0406002
Parity Violating Studies on $^1$H and $^4$He

3 GeV beam in Hall A

$\theta_{\text{lab}} \sim 6^\circ$  
$Q^2 \sim 0.1 \,(\text{GeV/c})^2$

<table>
<thead>
<tr>
<th>target</th>
<th>$A_{PV}$ $G^s = 0$ (ppm)</th>
<th>Stat. Error (ppm)</th>
<th>Syst. Error (ppm)</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>-1.6</td>
<td>0.08</td>
<td>0.04</td>
<td>$\delta(G^s_E + 0.08G^s_M) = 0.010$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>+7.8</td>
<td>0.18</td>
<td>0.18</td>
<td>$\delta(G^s_E) = 0.015$</td>
</tr>
</tbody>
</table>

Septum magnets (not shown)
High Resolution Spectrometers detectors

Brass-Quartz integrating detector

Elastic Rate:
$^1$H: 120 MHz
$^4$He: 12 MHz

Background $\leq 3\%$
Special Mentions......

Derek Leinweber

Ross Young

Stewart Wright
"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them."

S. Harris
• Lattice data (from MILC Collaboration) : red triangles
• Green boxes: fit evaluating $\sigma$’s on same finite grid as lattice
• Lines are exact, continuum results

$\Delta (\text{QQCD})$

$N (\text{QQCD})$

$\alpha_N + \beta_N \ m_\pi^2 + \text{self-energies (LNA+NLNA)}$

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_N$</th>
<th>$\beta_N$</th>
<th>$\alpha_\Delta$</th>
<th>$\beta_\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL</td>
<td>1.24 (2)</td>
<td>0.92 (5)</td>
<td>1.43 (3)</td>
<td>0.75 (8)</td>
</tr>
<tr>
<td>QQCD</td>
<td>1.23 (2)</td>
<td>0.85 (8)</td>
<td>1.45 (4)</td>
<td>0.71 (11)</td>
</tr>
</tbody>
</table>

Young et al., hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Jefferson Lab
Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Office of Science
U.S. Department of Energy
FRR Mass well determined by data

\[ \sqrt{(M_{V}^{\text{deg}})^2 - \Sigma_{TOT}} = (a_0^{\text{cont}} + X_1 a + X_2 a^2) + a_2(M_{PS}^{\text{deg}})^2 + a_4(M_{PS}^{\text{deg}})^4 + a_6(M_{PS}^{\text{deg}})^6 \]
Quark Condensate In-Medium

Free space:

\[ \langle \bar{u}u \rangle = \langle \bar{d}d \rangle = \langle \bar{s}s \rangle = -(225 \pm 25 \text{ MeV})^3 \]

at a renormalization scale of about 1 GeV.

- commutator measures chiral symmetry breaking
  \[ \approx \text{valence} + \text{pion cloud} + \]
  \[ \text{volume} \times (\text{difference of condensate in} \& \text{out of N}) \]

and last term is as big as 20 MeV (or more)

i.e. presence of nucleon “cleans out” vacuum to some extent

Hence: Model independent LO term for in-medium condensate

\[ \frac{Q(\rho_B)}{Q_0} \approx 1 - \frac{\sigma_N}{f^2_m^2} \rho_B \]

BUT this has no new physics at all!
Lattice QCD Simulation of Vacuum Structure

Leinweber, Signal et al.

$<r> = 0.16 \text{ fm}$