Baryon Structure and Properties

Anthony W. Thomas

Electron-Nucleus Scattering XIII
Isola d’Elba – June 23rd 2014
Outline

• QCD and Hadronic Physics
  – confinement & chiral symmetry breaking

• Spectroscopy – especially the interpretation of lattice data

• Form factors: $\sigma_s; G_E / G_M$; strangeness …

• Structure functions: d/u; flavour structure; CSV
  : resolution of proton spin problem

• Single spin asymmetries
Our challenges

• Discover how the properties of hadrons emerge as non-perturbative properties of QCD

• Test that it is indeed fully correct – precision

• Develop our physical insight – a picture of how it works

• Investigate the role of hadron structure for atomic nuclei, dense matter, etc.
Spectroscopy

- how do excited states emerge from QCD?
- what are the fundamental degrees of freedom?
Impressive results on excited states: lattice QCD

- Recent results from JLab ($m_\pi = 391$ MeV)

Edwards et al., arXiv:1212.5236 (JLab)
....and from CSSM

(Adelaide plot...)

$N^{1/2+}$

$M$ (GeV) vs. $m^2_\pi$ (GeV$^2$)

Mahbub et al., arXiv:1302.2987
Experiment: N/Δ spectrum in PDG 2012

Experiments at JLab and Mainz: new baryonic states

All new candidate states need confirmation in independent analyses
More detailed information coming – experiment & lattice!

e.g. Nature of the Roper – 1450 MeV

Leinweber et al., arXiv:1304.0325

Burkert et al., CLAS
Hybrid Baryons in LQCD

T. Barnes and F.E. Close, PLB128, 277 (1983)

Hybrid states have same J^P values as Q^3 baryons. How to identify them?
- Overpopulation of N1/2^+ and N3/2^+ states compared to QM projections?
- Transition form factors in electro-production (different Q^2 dependence)

Hybrid states are clustered in mass at 1.3 GeV.

Regular states
Hybrid states
The $\Lambda(1405)$

- 50 years after speculation by Dalitz, we have unambiguous evidence that it is a Kbar-N bound state!
- need Hamiltonian analysis of lattice data
- and Strange magnetic form factor of $\Lambda(1405)$
Hamiltonian analysis

- In a finite periodic volume, momentum is quantised to \( n \left( \frac{2\pi}{L} \right) \).
- Working on a cubic volume of extent \( L \) on each side, it is convenient to define the momentum magnitudes
  \[
  k_n = \sqrt{n_X^2 + n_Y^2 + n_Z^2} \frac{2\pi}{L},
  \]
  with \( n_i = 0, 1, 2, \ldots \) and integer \( n = n_X^2 + n_Y^2 + n_Z^2 \).
- The non-interacting Hamiltonian \( H_0 \) has diagonal entries corresponding to the relativistic non-interacting meson-baryon energies available on the finite periodic volume at total three-momentum zero.
- The four octet meson-baryon interaction channels of the \( \Lambda(1405) \) are included: \( \pi \Sigma, \bar{K}N, K\Xi \) and \( \eta\Lambda \).

Similar work by Valencia, Bonn, JLab and other groups
Low lying negative parity state: $\Lambda(1405)$

Clear evidence that it is a $K\bar{N}$ bound state

Hall, Leinweber, Menadue, Young, AWT – in preparation
Lattice Magnetic Form Factor Calculations

- Calculation of the individual quark contributions to the magnetic form factor confirms that it is a Kbar-N bound state.

Only an L=0 Kbar-N state gives vanishing strange moment.
Scalar form factors

– especially the strange $\sigma$ commutator
Sigma Commutators

These are a direct measure of the breaking of chiral symmetry

- \( \sigma_{\pi N} = \langle N | m_l (\bar{u}u + \bar{d}d) |N\rangle \sim 45-65 \text{ MeV} \)
  
  (Gasser, Leutwyler, Sainio...)

- \( \sigma_s = \langle N | m_s \bar{s}s |N\rangle \sim 300 \text{ MeV} \)
  
  (Kaplan, Manohar, early lattice...)

These are the measure of the contribution of the masses of the quarks to the nucleon mass

\[
m_l = \frac{m_u + m_d}{2}
\]
Can use lattice QCD to measure these

• Feynman-Hellmann theorem:

\[ \sigma_{\pi N} = m_l \frac{\partial M_N}{\partial m_l} \]

\[ \sigma_s = m_s \frac{\partial M_N}{\partial m_s} \]

• Hence IF we have a reliable parameterization of the mass of the nucleon vs \( m_\pi \) and \( m_K \) we can evaluate the \( \sigma \)-terms by differentiation
Octet Baryon Masses - LHPC Data

(lattice data: Walker-Loud et al., arXiv:0806.4549)

Comparison with physical masses

\[ m_B^2 \text{ (GeV)} \]

Young et al., arXiv:0901.3559 [nucl-th]
Additional Test

Fit these points (as shown above) and extrapolate to these

Comparison (data of Bietenholz et al.) is excellent (arXiv:1102.5300) – not a fit!
Summary of Results of Combined Fits  
(of 2008 LHPC & PACS-CS data)

<table>
<thead>
<tr>
<th>B</th>
<th>Mass (GeV)</th>
<th>Expt.</th>
<th>$\bar{\sigma}_{B\ell}$</th>
<th>$\bar{\sigma}_{Bs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>0.945(24)(4)(3)</td>
<td>0.939</td>
<td>0.050(9)(1)(3)</td>
<td>0.033(16)(4)(2)</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1.103(13)(9)(3)</td>
<td>1.116</td>
<td>0.028(4)(1)(2)</td>
<td>0.144(15)(10)(2)</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>1.182(11)(2)(6)</td>
<td>1.193</td>
<td>0.0212(27)(1)(17)</td>
<td>0.187(15)(3)(4)</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>1.301(12)(9)(1)</td>
<td>1.318</td>
<td>0.0100(10)(0)(4)</td>
<td>0.244(15)(12)(2)</td>
</tr>
</tbody>
</table>

$\bar{\sigma}_{Bq} = \left( \frac{m_q}{M_B} \right) \frac{\partial M_B}{\partial m_q}$

Of particular interest:

$\sigma$ commutator well determined: $\sigma_{\pi N} = 47 \ (9) \ (1) \ (3) \text{ MeV}$

(unchanged over a decade of lattice analysis: e.g. Leinweber et al., Phys Lett B482 (2000) 109)

and strangeness sigma commutator small

$m_s \frac{\partial M_N}{\partial m_s} = 31 \ (15) \ (4) \ (2) \text{ MeV} \ - \text{now } 21 \pm 6 \text{ MeV}$

NOT several 100 MeV !

Profound Consequences for Dark Matter Searches
Evolution of Knowledge of $\sigma_s$ with time

- Fukugita et al. (1995)
- Dong et al. (1996)
- SESAM (1998)
- JLQCD (2008)
- Young & Thomas (2009)
- Toussaint & Freeman (2009)
- JLQCD (2011)
- Dürr et al. (2011)
- QCDSF (2012)
- QCDSF–UKQCD (2012)
- Toussaint & Freeman (2012)
- Engelhardt (2012)
- Alexandrou et al. (2013)
- JLQCD (2013)
- Shanahan et al. (2013)
- Ren et al. (2014)

$\sigma_s$ (MeV)

- $N_f = 0$
- $N_f = 2$
- $N_f = 2+1$
Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter

John Ellis,¹,* Keith A. Olive,²,† and Christopher Savage²,‡

we find a variation by a factor $\sim 2$ in the spin-dependent cross section. Since the spin-independent cross section may now be on the verge of detectability in certain models, and the uncertainty in the cross section is far greater, we appeal for a greater, dedicated effort to reduce the experimental uncertainty in the $\pi$-nucleon $\sigma$ term $\Sigma_{\pi N}$. This quantity is not just an object of curiosity for those interested in the structure of the nucleon and non-perturbative strong-interaction effects: it may also be key to understanding new physics beyond the Standard Model.

$$\mathcal{L} = \alpha_2 i \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q}_i \gamma^\mu \gamma^5 q_i + \alpha_3 i \bar{\chi} \chi \bar{d}_i q_i$$

Neutralino (0.3 GeV / cc : WMAP )

Even if $\sigma_{\pi N}$ perfect

$$\Delta \sigma_s = \frac{m_s}{2m_l} \Delta \sigma_0 \sim 90 \text{ MeV}$$
cMSSM Predictions for Dark Matter $\sigma$

Cross section accurately fixed (e.g. “New CMSSM scenario C”) through DIRECT measure of $\sigma_s$

c.f. using old relation to unknown $\pi N$ sigma commutator (“Old cMSSM scenario C”)

Giedt, Thomas & Young, arXiv:0907.4177v1
PRL 103 (2009) 201802

Much larger $\sigma_s$ in $\Xi$ has important consequences for Dark Matter capture by heavy neutron stars
n-p mass difference, CSV etc.
Quark Mass contributions to Baryon Masses

\[ M_B = M^{(0)} + \delta M_B^{(1)} + \delta M_B^{(3/2)} + \ldots \]

\[ \delta M_B^{(1)} = -C_{\bar{B}l}^{(1)} Bm_l - C_{\bar{B}s}^{(1)} Bm_s. \]

\[ \delta M_B^{(3/2)} = -\frac{1}{16\pi f^2} \sum_\phi \left[ \chi_{\bar{B}\phi} I_R(m_\phi, 0, \Lambda) + \chi_{T\phi} I_R(m_\phi, \delta, \Lambda) \right] \]

<table>
<thead>
<tr>
<th>( B )</th>
<th>( C_{\bar{B}u}^{(1)} )</th>
<th>( C_{\bar{B}d}^{(1)} )</th>
<th>( C_{\bar{B}s}^{(1)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>( \frac{5}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
<td>( 2\sigma )</td>
</tr>
<tr>
<td>( n )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
<td>( \frac{5}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
<td>( 2\sigma )</td>
</tr>
<tr>
<td>( \Sigma^+ )</td>
<td>( \frac{2}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
<td>( 2\sigma )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
</tr>
<tr>
<td>( \Sigma^- )</td>
<td>( 2\sigma )</td>
<td>( \frac{5}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
</tr>
<tr>
<td>( \Xi^0 )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
<td>( 2\sigma )</td>
<td>( \frac{5}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
</tr>
<tr>
<td>( \Xi^- )</td>
<td>( 2\sigma )</td>
<td>( \frac{1}{3} \alpha + \frac{4}{3} \beta + 2\sigma )</td>
<td>( \frac{5}{3} \alpha + \frac{2}{3} \beta + 2\sigma )</td>
</tr>
</tbody>
</table>
Quark mass dependence of $M_p - M_n$

Shanahan et al., 1312.4990

\[
\begin{align*}
M_n - M_p &= (\omega/m_{\pi(\text{phys})}^2)(16.6 \pm 1.2) \text{ MeV} \\
M_{\Sigma^-} - M_{\Sigma^+} &= (\omega/m_{\pi(\text{phys})}^2)(48.9 \pm 1.7) \text{ MeV} \\
M_{\Xi^-} - M_{\Xi^0} &= (\omega/m_{\pi(\text{phys})}^2)(32.2 \pm 1.6) \text{ MeV}
\end{align*}
\]

QCDSF case
Electromagnetic Mass Difference n-p

Clearly must find the e-m contribution in order to find $m_u/m_d$

Apply the Walker-Loud-Carlson-Miller approach which corrected an ambiguity in Cottingham sum-rule: $1.30 \pm 0.47$ MeV (instead of $0.76 \pm 0.30$).

Almost entire error from $\beta_{p-n}$ ($\beta_{p-n} = (-1 \pm 1) \times 10^{-4}$ fm$^3$).

Use finite volume chiral analysis of RBC lattice data to give:

$$\beta_{p-n} = (-1.12 \pm 0.40) \times 10^{-4} \text{ fm}^3$$

and hence

$$\delta M_{p-n}^\gamma = 1.04 \pm 0.11 \text{ MeV}$$

Thomas et al., 1406.4579
**EM Mass Difference of n-p**

Shanahan et al., 1312.4990

Thomas et al., 1406.4579 (and BMW 1406.4088)

\[ B m_u = m_{\pi(\text{phys})}^2 / 2 - \omega \]
\[ B m_d = m_{\pi(\text{phys})}^2 / 2 + \omega \]

\[ M_n - M_P = \left( \omega / m_{\pi(\text{phys})}^2 \right) (16.6 \pm 1.2) \text{ MeV} \]
\[ M_{\Sigma^-} - M_{\Sigma^+} = \left( \omega / m_{\pi(\text{phys})}^2 \right) (48.9 \pm 1.7) \text{ MeV} \]
\[ M_{\Xi^-} - M_{\Xi^0} = \left( \omega / m_{\pi(\text{phys})}^2 \right) (32.2 \pm 1.6) \text{ MeV} \]
Electromagnetic form factors
G_E/G_M and Potential link to $\chi$SB

- Small changes in M(p) within the domain 1<p(GeV)<3 have striking effect on the electric form factor

- Ratio $[\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)]$ provides information on the nature of the quark-quark interaction in the transition region from pQCD to non-perturbative QCD

\[
S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}
\]

Strange Form Factors – A Fundamental Test of QCD

Experimental program took three major laboratories 20 years!

CSSM – JLab calculation – culmination of 12 years work!

Thomas Jefferson National Accelerator Facility (G0 and Happex expts) plus Mainz & MIT Bates
Latest Extraction from CSSM-QCDSF/UKQCD
Shanahan et al., arXiv:1403.65

Electric

Magnetic

Blue are calculated values

This work: 0.26 GeV²
A4: 0.23 GeV²
G0: 0.23 GeV²

Dark: 1σ
Light: 2σ

Red stars: G0, SAMPLE, HAPPEX, A4.

Role of diquark correlations
$F_i^s$ small: allows separation of flavour form factors

Very different behavior for $u$ & $d$ quarks suggests apparent scaling in proton $F_2/F_1$ may be accidental
Confining NJL Studies

• Tell us about the interplay of di-quark correlations and pions

Data from Cates et al., PRL 106 (2011) 252003

Lattice QCD is also giving hyperon information
Hyperon magnetic form factors

At \((m_\pi = 310, m_K = 510)\) MeV – connected only

Doubly represented

Singly represented

Shanahan et al., CSSM-QCDSF/UKQCD
Electric Form Factors

Extrapolated to physical quark masses

Shanahan et al., 1403.1965
Structure Functions
Deep Inelastic Scattering

- At high energy and momentum transfer in inelastic electron (muon and neutrino) scattering one directly measures the momentum distribution of the quarks.

- Polarised electrons also enable the spin of the quarks to be determined.

- Later Drell-Yan (quark-anti-quark) annihilation added crucial new information.
Charge Symmetry Violation from lattice QCD

Study moments of octet baryon PDFs

\[
\frac{\delta u}{\langle x \rangle_{u-d}^p} = \frac{m_\delta}{m_q} \frac{\langle x \rangle_{u}^{\Sigma^+} - \langle x \rangle_{s}^{\Xi^0}}{(m_K^2 - m_{\pi}^2)/X_{\pi}^2}
\]

\[
\frac{\delta d}{\langle x \rangle_{u-d}^p} = \frac{m_\delta}{m_q} \frac{\langle x \rangle_{s}^{\Xi^0} - \langle x \rangle_{u}^{\Sigma^+}}{(m_K^2 - m_{\pi}^2)/X_{\pi}^2}
\]

Deduce: \( \delta u^+ = -0.0023(7) \) \( \delta d^+ = 0.0017(4) \)

- in excellent agreement with phenomenological estimates of Rodionov et al. \( \delta u^- = -0.0014 \) and \( \delta d^- = 0.0015 \)

and update by: Shanahan et al., arXiv:1303.4806
Remarkable agreement

CSV distributions from lattice moment (2013)

Original bag model calculation of Rodionov et al (1994)
Strange Sea of the Nucleon

Chiral mechanism for kaons implies $s - s^-$ goes through zero for $x$ of order 0.10

- Later, naive 5-quark additions often (implicitly) violate parity

- This predicted asymmetry in the strange sea has \textit{STILL} not been measured experimentally....

- but it \textit{does} matter!

FIG. 16. (Color online) The quantity $x s^{-}(x) = x [s(x) - \bar{s}(x)]$ vs $x$, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The $\chi^2$ value is listed for each curve. From Mason et al., 2007.
Dynamical Symmetry Breaking in the Sea of the Nucleon

A. W. Thomas,¹ W. Melnitchouk,¹,² and F.M. Steffens³

\[(S - \bar{s})^{(n)} = \int_0^1 dx x^n [s(x) - \bar{s}(x)] = V^{(n)}_\Lambda \cdot f^{(n)}_{\Lambda K} - V^{(n)}_K \cdot f^{(n)}_{K\Lambda}\]

\[f^{(n)}_{K\Lambda}|_{\text{LNA}} = \frac{27}{25} \frac{M^2 g_A^2}{(4\pi f_{\pi})^2} (M_\Lambda - M)^2 (-1)^n \frac{m_K^{2n+2}}{\Delta M^{2n+4}} \log(m_K^2/\mu^2),\]

\[n\text{th moment of } \bar{s} \text{ is of order } m_K^{2n+2} \log m_K^2\]

LNA contribution to the \(n\)th moment of \(s\) is of order \(m_K^2 \log m_K^2\)

• i.e., non-analytic behaviour of \(s\) and \(\bar{s}\) are different

Hence, from theoretical point of view, \(s - \bar{s}\) has to be non-zero as a matter of principle!
Experimentally knowledge of strange sea is a mess

- Much has been made of Hermes result (Phys Lett B666 (2008) 446)
  - low $Q^2$, LO analysis, dubious fragmentation functions (see next slide)

- Lattice studies of Liu et al. suggest $<x_S> = 0.024$ at 4 GeV$^2$ (Phys. Rev. D79 (2009) 094502)

- Blumlein et al. (2014) $<x_S>/2<x_d> \sim 0.6$ (arXiv:1404.6469)

- Later publication by Hermes (arXiv:1312.7028) shows zero above $x=0.10$ (within errors)
Still much to learn about fragmentation

e.g. It’s commonly assumed that for these *unfavoured* fragmentation functions $D^{K^+}_{d} = D^{K^+}_{s}$ and $D^{\pi^+}_{d} = D^{\pi^+}_{s}$: WRONG

see: Matevosyan et al., AIPCP 1374 (2011) 387
for this and other examples of NJL jet-model (Ito et al., Phys.Rev. D80 (2009) 074008) predictions
CSV & Strange Asymmetry: Critical for Standard Model Test(s)

(arXiv: 0908.3198)
Recent New Results for Sivers Effect in Di-Hadron Production

\[
\frac{d\sigma}{d^2 T d^2 R} = C(x, Q^2) \left( \sigma_U + S_T \left[ \sigma_T \frac{T}{M} \sin(\varphi_T - \varphi_S) + \sigma_R \frac{R}{M} \sin(\varphi_R - \varphi_S) \right] \right), \quad R = (P_{1T} - P_{2T})/2
\]

Kotzinian, Matevosyan and Thomas, arXiv:1403.5562
Recent COMPASS results appear to Confirm this
The Proton Spin Crisis/Problem
A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION $g_1$ IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxford, Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN, B. BADELEK, G. BAUM, J. BEAUFAYS, C. P. BEE, C. BENCHOUK

(93 authors)

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large $x$ range ($0.01 < x < 0.7$). The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over $x$ found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of $g_1$ for the neutron. These values for the integrals of $g_1$ lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

$$\Sigma = 14 \pm 3 \pm 10 \% :$$

i.e. 86% of spin of p NOT carried by its quarks
Testing $\Delta G \sim 4$ in pol. pp collisions

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \cdot \hat{a}_{LL}^{f_a f_b \rightarrow fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \otimes D_f^h}$$

Double longitudinal spin asymmetry $A_{LL}$ is sensitive to $\Delta G$

Polarized pp collider at RHIC
Where is the Spin of the proton?

- Modern data (Hermes, COMPASS) yields: $\Sigma = 0.33 \pm 0.03 \pm 0.05$
  
  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- In addition, there is little or no polarized glue
  - COMPASS: $g_D^D = 0$ to $x = 10^{-4}$
  - $A_{LL}$ ($\pi^0$ and jets) at PHENIX & STAR: $\Delta G \sim 0$
  - Hermes, COMPASS and JLab: $\Delta G / G$ small

- Hence: **axial anomaly plays at most a small role in explaining the spin crisis**

- Suggests alternate explanation lost in the rush to explore the anomaly:
  - chiral symmetry and gluon exchange
The Pion Cloud & Gluon Hyperfine Interaction

• Probability to find a bare N is $Z \sim 70\%$

• Biggest Fock Component is $N\pi \sim 20\%-25\%$ and $2/3$ of the time N spin points down (next biggest is $\Delta \pi \sim 5\%-10\%$)

• Spin gets renormalized by a factor:
  $$Z - \frac{1}{3} P_{N\pi} + \frac{15}{9} P_{\Delta \pi} \sim 0.75 - 0.8$$
  Hence: $\Sigma = 0.65 \rightarrow 0.49 - 0.52$

• In addition the effect of the one-gluon-exchange “exchange current” correction:
  $$\Sigma \rightarrow \Sigma - 3G ; \text{ with } G \sim 0.05$$

The Balance Sheet – fraction of total spin

<table>
<thead>
<tr>
<th></th>
<th>$2 L_{u+ubar}$</th>
<th>$2 L_{d+dbar}$</th>
<th>$\Sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-relativistic</td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Relativity (e.g. Bag)</td>
<td>0.46</td>
<td>-0.11</td>
<td>0.65</td>
</tr>
<tr>
<td>Plus OGE</td>
<td>0.52</td>
<td>-0.02</td>
<td>0.50</td>
</tr>
<tr>
<td>Plus pion</td>
<td>0.50</td>
<td>0.12</td>
<td>0.38</td>
</tr>
</tbody>
</table>

At model scale: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$
$\therefore L_d + S_d = 0.06 - 0.22 = -0.16 = J_d$

Fix \( J^u + J^d = 0.26 \) at 4 GeV\(^2\)

Then \( L^{u,d} = (-0.12, +0.15) \) LO

\( = (-0.13, +0.17) \) NLO

c.f. LQCD \( (-0.18, +0.20) \) arXiv 1001:3620

or \( (-0.14, +0.18) \) if implicit \( g_A^3 = 1.10 \)

Remarkable agreement between model and LQCD

• Phys Lett 684 (2010) 216

& AWT, Casey & Matevosyan, E P J A46 (2010) 325
Recent Test using Quark Spins for the Octet

• Rather than experimental measurements on the octet, we now have lattice QCD - in this case QCDSF (Phys. Rev. D 84, 054509 (2011) and Phys. Lett. B 714, 97 (2012)) – see final column

<table>
<thead>
<tr>
<th></th>
<th>MIT Bag</th>
<th>MIT Bag + OGE</th>
<th>MIT Bag + M. Cloud</th>
<th>MIT Bag + OGE + M. Cloud</th>
<th>Model</th>
<th>Lattice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>65.4</td>
<td>53.8</td>
<td>51.9</td>
<td>43.8</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>77.1</td>
<td>67.3</td>
<td>66.4</td>
<td>58.9</td>
<td>1.35 (1.33)</td>
<td>-</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>61.5</td>
<td>50.8</td>
<td>50.5</td>
<td>42.6</td>
<td>0.97 (0.98)</td>
<td>0.92 (13)</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>80.9</td>
<td>72.3</td>
<td>72.0</td>
<td>65.2</td>
<td>1.49 (1.44)</td>
<td>1.61 (33)</td>
</tr>
</tbody>
</table>

• The other columns show the results for the cloudy bag model that worked so well for the nucleon applied to whole octet

• Agreement remarkably good... suppression is not universal!

Measuring $\Delta G$ not enough

- Measurements of $\Delta G$ becoming more precise
- But $\Delta G$ increases linearly with $\ln Q^2$ and so does $\Delta L^g$ but opposite sign
- Get a bigger $\Delta G$ at larger $Q^2$ but learn nothing about spin crisis
- By taking lattice $J^g$ and evolving back to model scale, we know it is very small, possibly zero
- Hence transfer of quark spin to quark orbital angular momentum is the solution......
Summary

- We have a wealth of exciting and fundamental questions to address

- Lattice QCD, phenomenology and experiment working beautifully together
  - Hamiltonian methods promising: e.g. $\Lambda(1405)$
  - $\sigma_{\pi N}$ and $\sigma_{s}$ now well known: aids Dark Matter searches
  - QCD survives critical test through $G_{s}\chi_{M}$ and $G_{s}\chi_{E}$
  - accurate lattice results for hyperon form factors
  - powerful new results on CSV in PDFs (No NuTeV anomaly)

- Proton spin crisis understood as replacement of quark spin by quark and anti-quark orbital angular momentum
We look forward to welcoming delegates to Adelaide, Australia for INPC 2016

September 11-16 2016
Summary of Corrections to NuTeV Analysis

• Isovector EMC effect:  $\Delta R^{\rho^0} = -0.0019 \pm 0.0006$
  – using NuTeV functional

• CSV:  $\Delta R^{\text{CSV}} = -0.0026 \pm 0.0011$
  – again using NuTeV functional

• Strangeness:  $\Delta R^s = -0.0011 \pm 0.0014$
  – this is largest uncertainty (systematic error); desperate need for an accurate determination of $s^{-}(x)$, e.g. semi-inclusive DIS?

• Final result:  $\sin^2 \theta_W = 0.2221 \pm 0.0013 \text{(stat)} \pm 0.0020 \text{(syst)}$
  – c.f. Standard Model:  $\sin^2 \theta_W = 0.2227 \pm 0.0004$

(arXiv: 0908.3198)
Model Describes EMC Effect for Finite Nuclei

FIG. 7: The EMC and polarized EMC effect in $^{11}$B. The empirical data is from Ref. [31].

FIG. 9: The EMC and polarized EMC effect in $^{27}$Al. The empirical data is from Ref. [31].

(Spin dependent EMC effect TWICE as large as unpolarised)

Observable Consequence: isovector EMC Effect

- New realization concerning EMC effect:
  - isovector force in nucleus (like Fe) with \( N \neq Z \)
  - effects ALL \( u \) and \( d \) quarks in the nucleus
  - subtracting structure functions of extra neutrons is not enough
  - *there is a shift of momentum from all \( u \) to all \( d \) quarks*

- This has same sign as charge symmetry violation associated with \( m_u \neq m_d \)

- Sign and magnitude of both effects exhibit little model dependence

Cloët et al., arXiv: 0901.3559v1;
Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët, W. Bentz, and A. W. Thomas

\[ A_{PV} = \frac{G_{F}Q^{2}}{4\sqrt{2}\pi\alpha_{em}} \left[ a_{2}(x_{A}) + \frac{1 - (1 - y)^{2}}{1 + (1 - y)^{2}} a_{3}(x_{A}) \right] \]

Ideally tested at EIC with CC reactions

Parity violating EMC maybe tested at Jlab 12 GeV