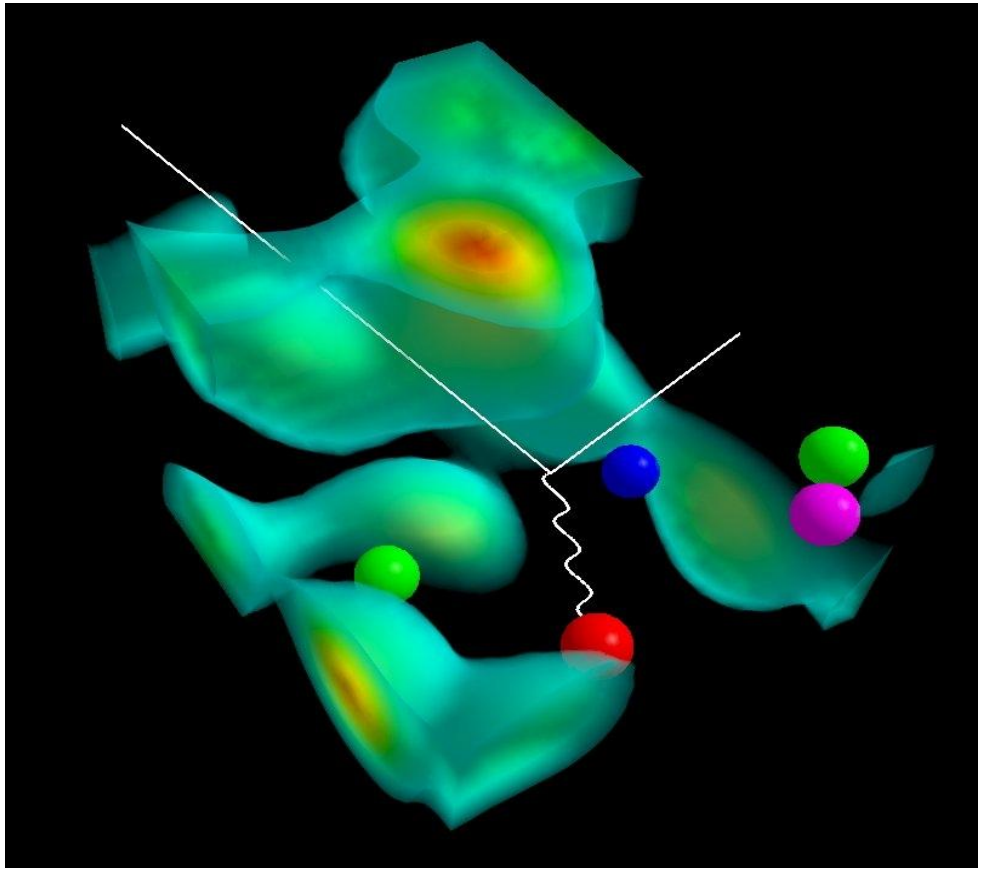
Physics of the Proton Spin Problem



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Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

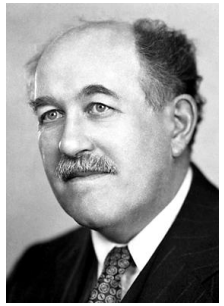
10th Circum-Pan-Pacific Symposium on High Energy Spin Physics
Academia Sinica : October 6th 2015

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Background

- The structure of the proton is a fundamental challenge

- Not an elementary Dirac particle known since 1930's through anomalous magnetic moment



Stern

- Now understand its mass at 2% level from lattice QCD

- What about its spin?

  - yes it's one half

- But how is that one half obtained?

Outline

- A reminder: the proton "spin crisis" is *not* the same as the "spin problem": $L^q + S^q + J^g = 0.5$

- Progress *was* driven/diverted by search for a huge value of $\Delta G \sim 4$ – eventually much smaller!

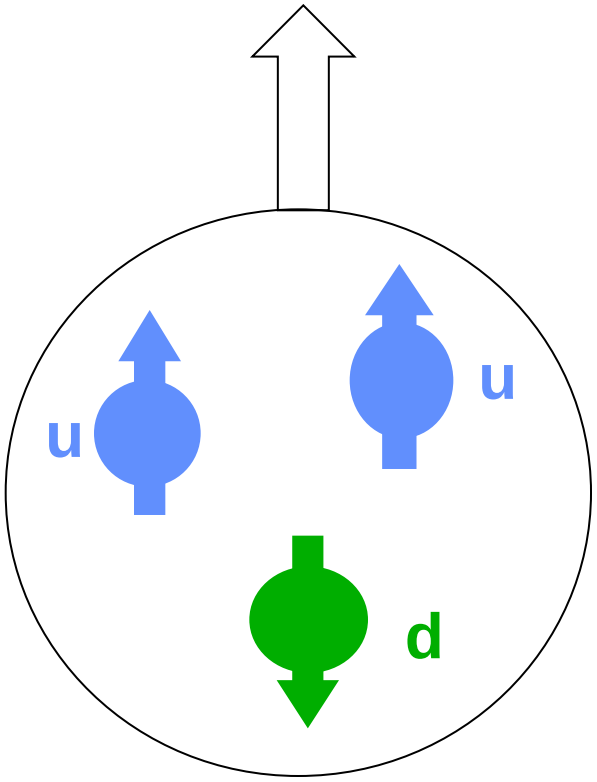
- The resolution of the problem
  - one-gluon-exchange
  - the pion cloud
  - input from lattice QCD

- The spin is primarily quark orbital angular momentum!

- What more do we need to know?

What do we expect ?

Most quark models start with 3 quarks in the 1s-state of a confining potential: proton spin is ALL carried by its quarks: $\Sigma = 100\%$



N.B. Given low values of $m_{u,d}$ the quark motion is relativistic and lower Dirac components have spin down: $\Sigma \sim 65\%$

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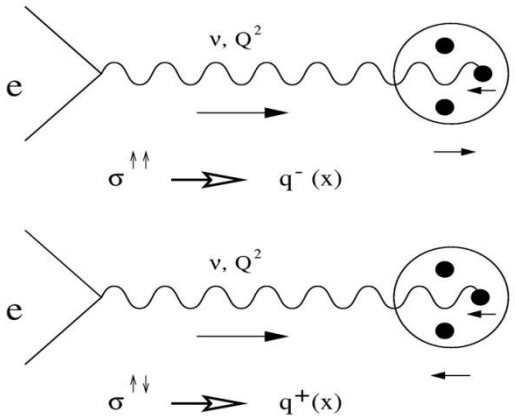
The EMC "Spin Crisis"



Up to standard pQCD coefficients (series in $\alpha_s(Q^2)$):

$$\int_0^1 dx\, g_1^p(x) = (\Delta u - \Delta d)/12 + (\Delta u + \Delta d - 2\Delta s)/36$$

$$+ (\Delta u + \Delta d + \Delta s)/9$$

(up to QCD radiative corrections)

g^3_A : from β decay of n

naively fraction of proton 'spin' carried by its quarks

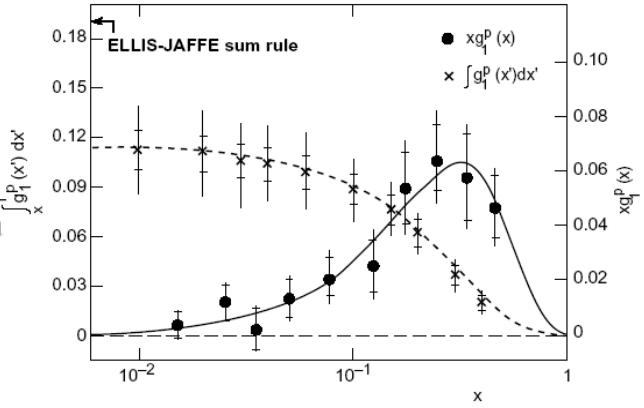
g^8_A : hyperon β decay

$\Sigma_{inv} = \Sigma(Q^2 = \infty)$

Δ u = fraction of proton spin carried by u and anti-u quarks, etc..

The Beginning

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988



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 [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(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 and *possibly none*

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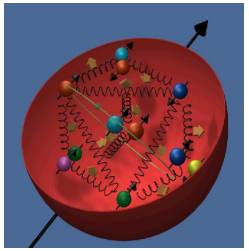
Possible Role of Polarized Glue in the Proton

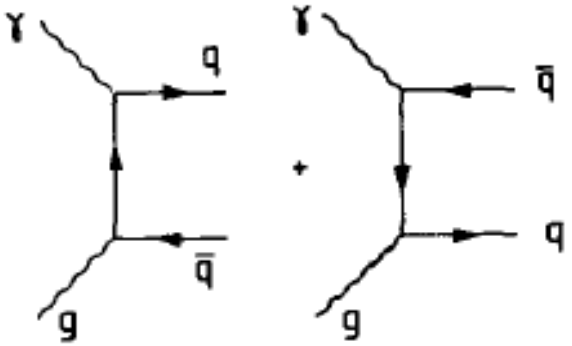
$$\Sigma_{naïve} \rightarrow \Sigma_{naïve} - N_f \alpha_s(Q^2) \frac{\Delta G(Q^2)}{2\pi}$$

and



QCD evolution: $\alpha_s(Q^2)\,\Delta G(Q^2)$ does not vanish as $Q^2 \rightarrow \infty$

and polarized gluons would resolve crisis



Required ΔG ~ +4…. no physical explanation of such a huge value (8 times proton spin) offered !

This spurred a tremendous experimental effort

- **DIS measurements of spin structure functions of polarized p, d, ^{3}He (and ^{6}Li) at SLAC, CERN, Hermes, JLab**

- **Direct search for high-p_T hadrons as well as inclusive jet and π^0 production at Hermes, COMPASS, RHIC to directly search for effects of polarized glue in the p**

- **This effort has lasted the past 25 years, with great success**

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: $g^D_1 = 0$ to $x = 10^{-4}$**
  - **A_{LL} (π^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 very small role in explaining the spin crisis**

- **Return to alternate explanation lost in 1988 in rush to explore the anomaly**

One-Gluon-Exchange Correction

PHYSICAL REVIEW D VOLUME 38, NUMBER 5 1 SEPTEMBER 1988

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the accelerated schedule, publication is not delayed for receipt of corrections unless requested by the author or noted by the editor.

Spin structure functions and gluon exchange

F. Myhrer
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A. W. Thomas
Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5000, Australia
*and Department of Theoretical Physics, Oxford University, Oxford OX1 3NP, Oxfordshire, England**
(Received 13 June 1988)

Two-quark correlations due to gluon exchange give corrections to both the proton and neutron spin-dependent structure functions in the Bjorken sum rule. They are found to be as large as the pionic corrections in the cloudy bag model of the nucleon. While still not enough to explain the result published recently by the European Muon Collaboration, it is compatible with the reanalysis of the data by Close and Roberts.

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One Gluon Exchange (OGE) Hyperfine Interaction

- **Essentially <u>every quark model needs this QCD based interaction for hadron spectroscopy</u> – beginning with de Rujula et al.; De Grand et al. ; Isgur & Karl……..**

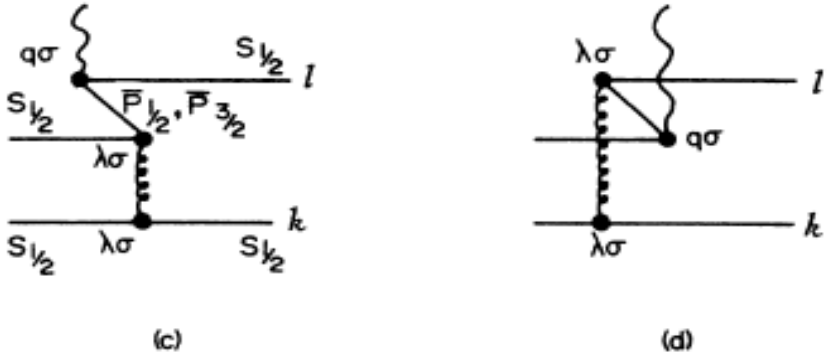
- **N-Δ, Σ-Λ splitting etc…**
  (MIT bag, constituent quark model(s))

- **As soon as this is included one must also calculate the corresponding exchange current corrections**

- **First done for magnetic moments and non-singlet axial charges by Hogaasen and Myhrer**

OGE Exchange Current : Spin Problem

- The dominant exchange current correction, shown below, reduces G_A by ~4%



- BUT it has a much bigger effect on Σ:

$$\Sigma \rightarrow \Sigma - 3G \text{ ; with } G \sim 0.05$$
$$\text{i.e. } \Sigma \rightarrow 0.65 - 0.15 = 0.5$$

- Effect is to transfer quark spin to quark (relativity) and anti-quark (OGE) orbital angular momentum

Myhrer-Thomas, Phys Rev D38 (1988);
and most recent: Altenbuchinger et al., EPJ arXiv:1012.4409

The Pion Cloud of the Nucleon

Volume 215, number 1 PHYSICS LETTERS B 8 December 1988

SPIN DEPENDENT STRUCTURE FUNCTIONS IN THE CLOUDY BAG MODEL

A.W. SCHREIBER AND A.W. THOMAS

Department of Physics and Mathematical Physics, University of Adelaide, North Terrace, Adelaide, South Australia 5000, Australia

Received 17 May 1988

We derive expressions for the integrals of the spin dependent structure functions $g_1(x)$ for the proton and the neutron in the context of the cloudy bag model. We find that the neutron contributes 5–10% to the Bjorken sum rule, while there is a corresponding decrease for the proton's contribution. It is difficult to reconcile these results with those reported in a recent experiment.

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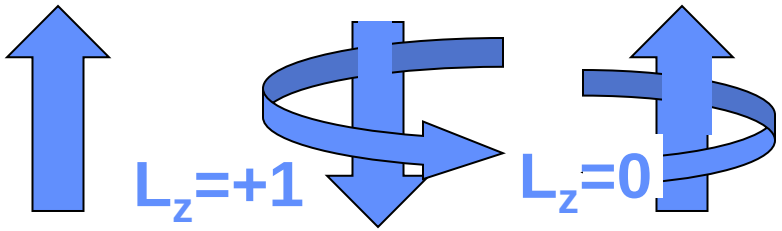
Effect of the Pion Cloud/ Chiral Symmetry

- Probability to find a bare N is Z ~ 70%

- Biggest Fock Component is N π ~ 20-25% and 2/3 of the time N spin points down



Z $\quad \frac{2}{3} P_{N\pi} \quad \frac{1}{3} P_{N\pi}$

- Next biggest is $\Delta \pi$ ~ 5-10%

- To this order (i.e. including terms which yield LNA and NLNA contributions):

- Spin gets renormalized by a factor :

$$Z - 1/3\, P_{N\pi} + 15/9\, P_{\Delta\pi} \sim 0.75 - 0.8$$

$$\text{Hence: } \Sigma = 0.65 \rightarrow 0.49 - 0.52$$

Schreiber-Thomas, Phys Lett B215 (1988)

Final Result for Quark Spin

$$\Sigma = (Z - P_{N\pi}/3 + 5\, P_{\Delta\pi}/3)\ \ (0.65 - 3\, G)$$

$$= (0.7,0.8) \text{ times } (0.65 - 0.15) = (0.35, 0.40)$$

c.f. Experiment: 0.33 ± 0.03 ± 0.05

- **ALL effects, relativity and OGE and the pion cloud**

swap quark spin for valence orbital angular momentum

and anti-quark orbital angular momentum

(>60% of the spin of the proton)

Myhrer & Thomas, hep-ph/0709.4067

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The Balance Sheet – fraction of total spin

	$2\,L_{u+ubar}$	$2\,L_{d+dbar}$	Σ
Non-relativistic			1.0
Relativity (e.g. Bag)	0.46	-0.11	0.65
Plus OGE	0.52	-0.02	0.50
Plus pion	0.50	0.12	0.38

At model scale: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$

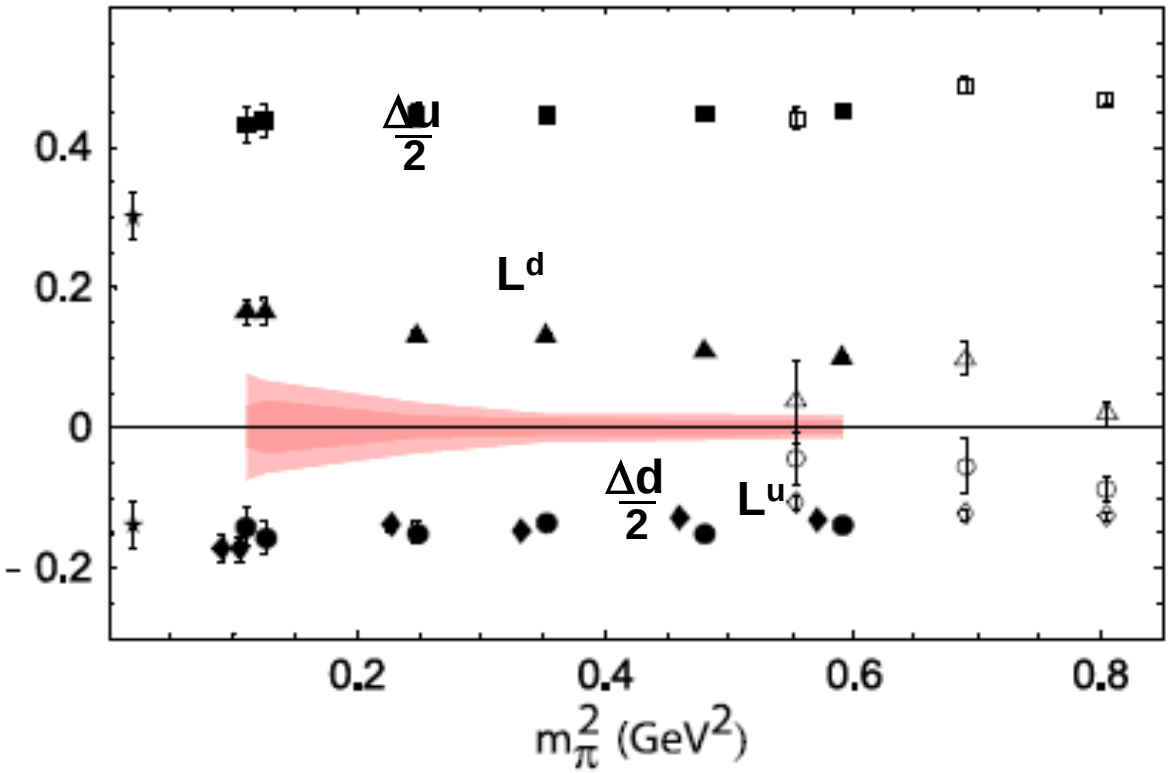
$: L_d + S_d = 0.06 - 0.22 = -0.16 = J_d$

AW Thomas, Phys Rev Lett, 101 (2008) 102003

LHPC Lattice Results

- At first glance shocking :

$L^u \sim -0.1$ and $L^d \sim +0.1$
(c.f. + 0.25 and +0.06 in our model)



LHPC: hep-lat/0610007

However $J^{u,d}$ are not RGI – what scale?

- Known since mid-70s (Le Yaouanc et al., Parisi, etc.) that connection between quark models and QCD must be at low-Q^2

- This is because momentum fraction carried by quarks is monotonically decreasing with Q^2 " and in models quarks carry nearly all the momentum (used by Glück-Reya to model HERA data to very low x - $\mu^2 = 0.23\ GeV^2$ at LO – Phys Lett 359, 205 (1995))

e.g. Schreiber et al., PR D42, 2226 (1990) : $\mu = 0.5$ GeV

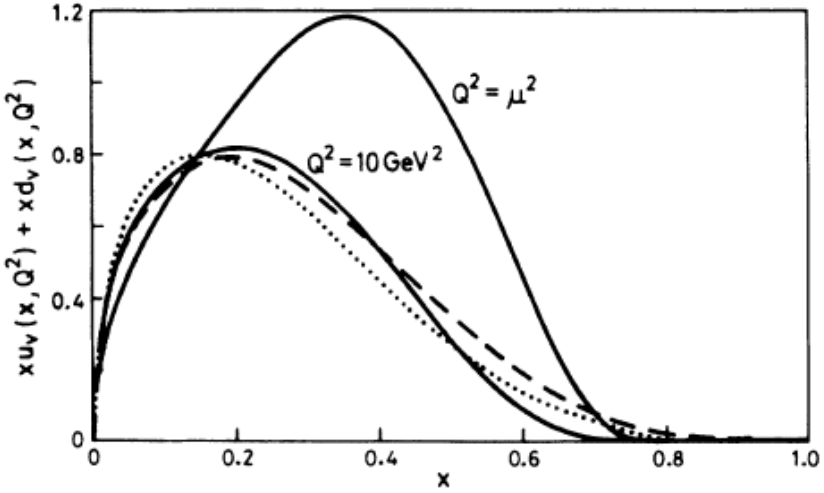
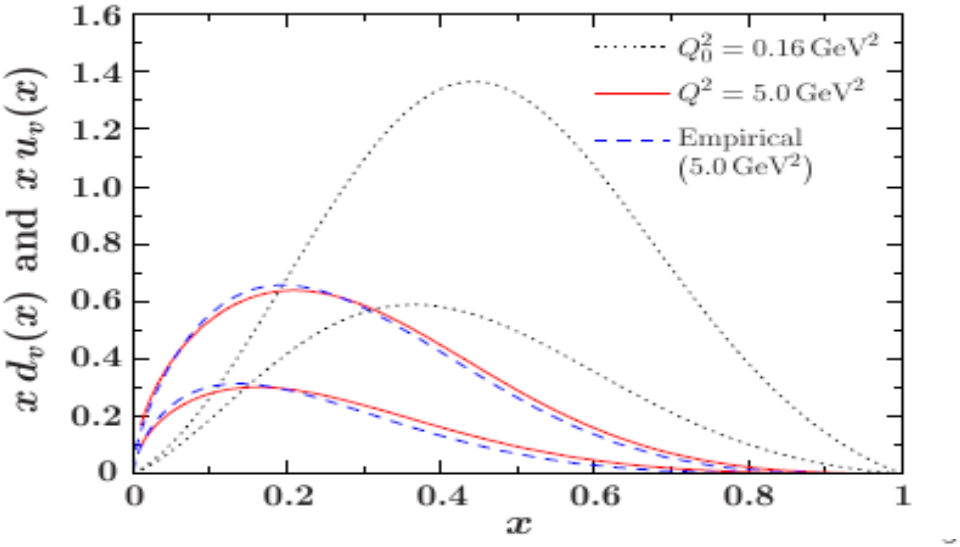
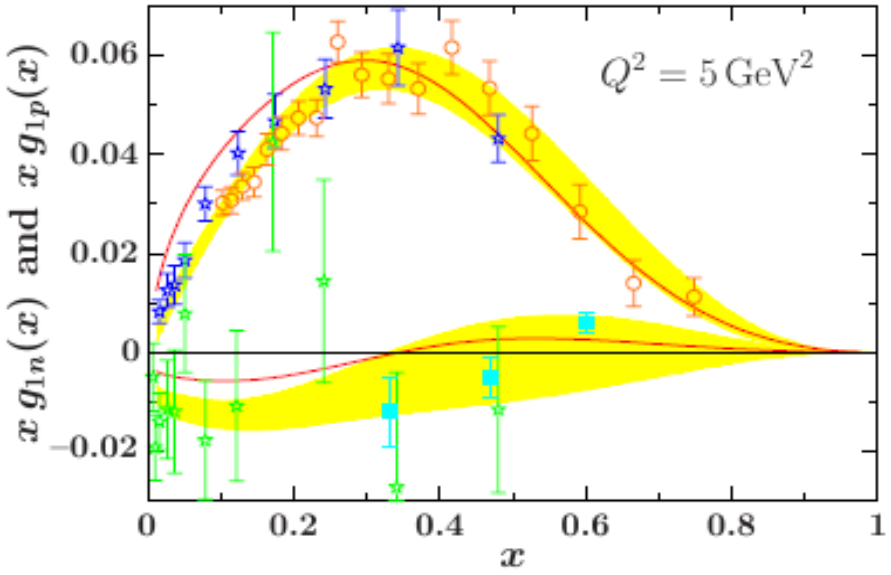


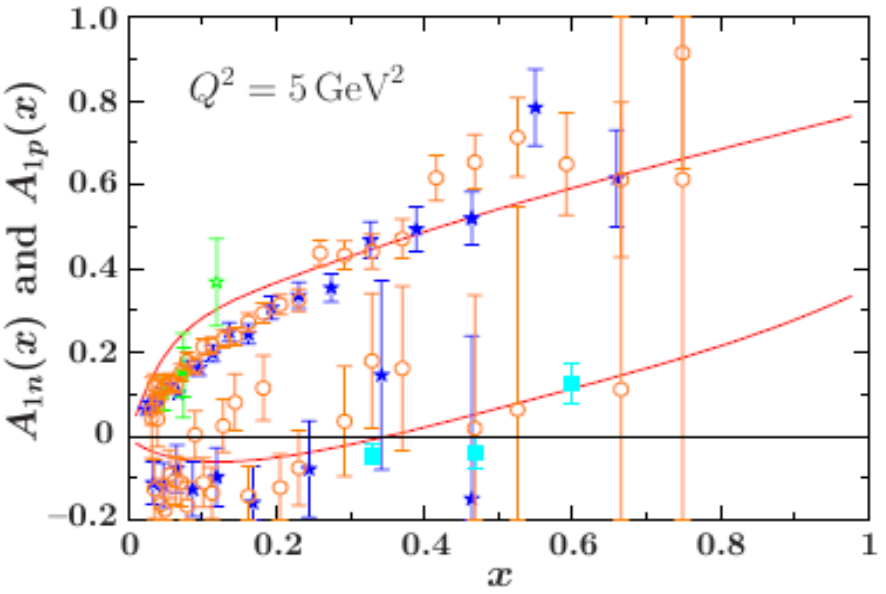
FIG. 1. $xu_v(x,Q^2)+xd_v(x,Q^2)$ at the model scale $Q^2=\mu^2$ and at $Q^2=10\ GeV^2$ (solid lines). The dashed and dotted lines correspond to the Duke-Owens and Martin-Roberts-Stirling parametrizations of $xu_v(x,Q^2=10\ GeV^2)+xd_v(x,Q^2=10\ GeV^2)$,

More Modern (Confining) NJL Calculations

Cloet et al.,
Phys. Lett. B621, 246 (2005)

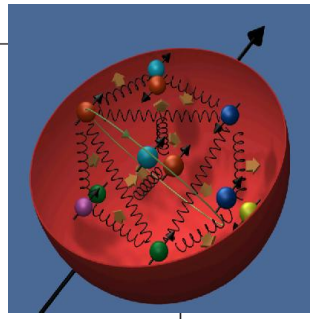






NLO Evolution

Remarkable agreement between model and LQCD



Fix : $J^u + J^d = 0.26$ at 4 GeV^2 : sets model scale

Find: $J^u = 0.32$ (LO); 0.30 (NLO)

$J^d = 0.06$ (LO); 0.04 (NLO)

c.f. Kroll (today) $J^u \sim (0.23, 0.26)$, $J^d \sim (0, 0.04)$

LHPC (PR D82 (2010) 094502): $J^u \sim 0.26$, $J^d \sim 0.0$

- Bass and Thomas, Phys Lett 684 (2010) 216
& AWT, Casey & Matevosyan, E P J A46 (2010) 325

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Update (used in preceding slide)

- Update including K and η loops to check g_A^8 and ensure that g_A^3 is correct
- $g_A^8 = 0.46 \pm 0.05$ (not 0.57 : 20% SU(3) breaking)
- This implies that the value of Σ extracted from experiment (needs g_A^8) should be $0.36 \pm 0.03 \pm 0.05$
- To be compared with calculated $\Sigma = 0.42 \pm 0.07$ (no polarized gluon correction included)
- Note that $\Delta s \sim -0.01$
  - agrees QCDSF Phys.Rev.Lett. 108 (2012) 222001 : $\Delta s = -0.02 \pm 0.01$

Bass-AWT Phys Lett B684 (2010) 216

What were we trying to learn?

- **Ellis-Jaffe sum rule:**
  - **based on intuition of quark models, Δs small and hence $a_0 = a_8$**
  - **and deduce a_8 assuming SU(3) breaking small**

- **Indeed, we have a great deal of intuition within quark models (CQM, MIT bag, cloudy bag, χQSM etc.) based on spectroscopy, form factors, transition rates etc.**

  BUT these, as valence dominated models, must be matched to QCD at a low scale (which becomes part of the model) – e.g. Le Yaounanc *et al*., Bell, Jaffe, Signal, AWT, Glück, Reya, Vogt....

Again: at what scale do we want the composition of the proton spin?

- **In low energy quark models, where intuition (including Ellis-Jaffe) was built, gluons are integrated out**

- **As shown CBM gives a consistent, physical interpretation of the spin decomposition (AT LOW SCALE) where spin is dominated by the orbital angular momentum of quarks and anti-quarks**

- **After evolution the results are consistent with modern lattice QCD calculations and GPD fits**

END OF CHALLENGE FOR ME!

What physics remains?

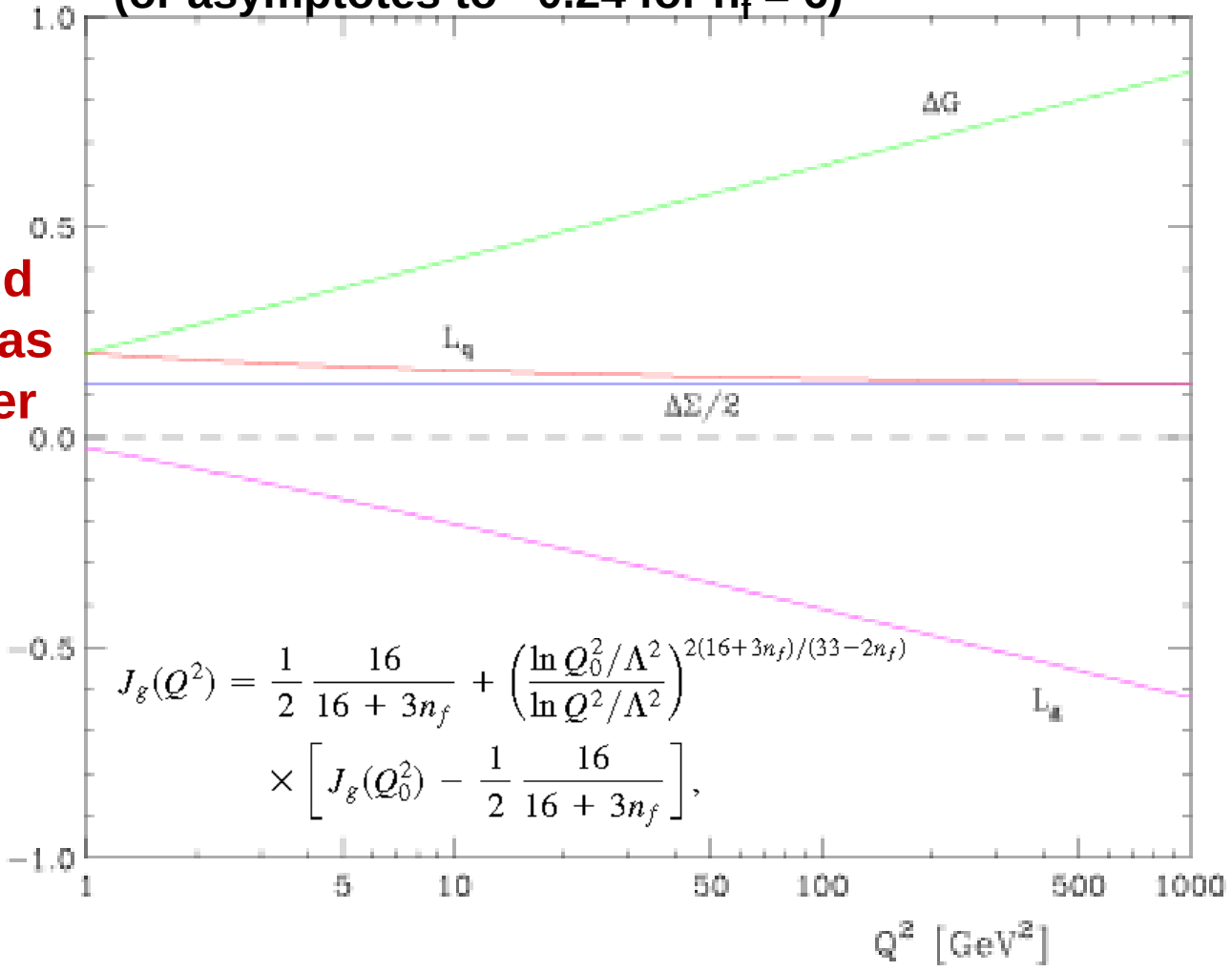
- **CBM not accurate enough to rule out (say) 10% of spin carried by gluons at a low scale**

- **BUT ΔG by itself is largely irrelevant (now we know it is small) to the proton spin problem**

ΔG is a moving target and largely irrelevant

J_g increases <u>mildly</u> from ~ 0.24 to 0.32 from 4 GeV² to ∞ (n_f = 3)
(or asymptotes to ~0.24 for n_f = 6)

BUT ΔG and L_g diverge as Same power of ln Q²



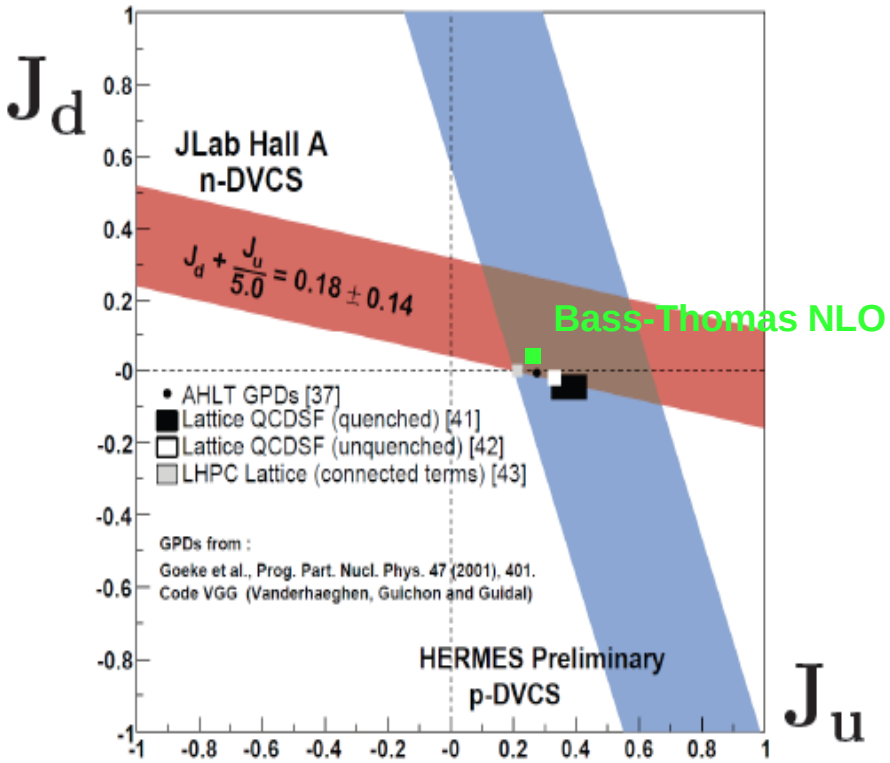
$L_g \equiv J_g - \Delta G$

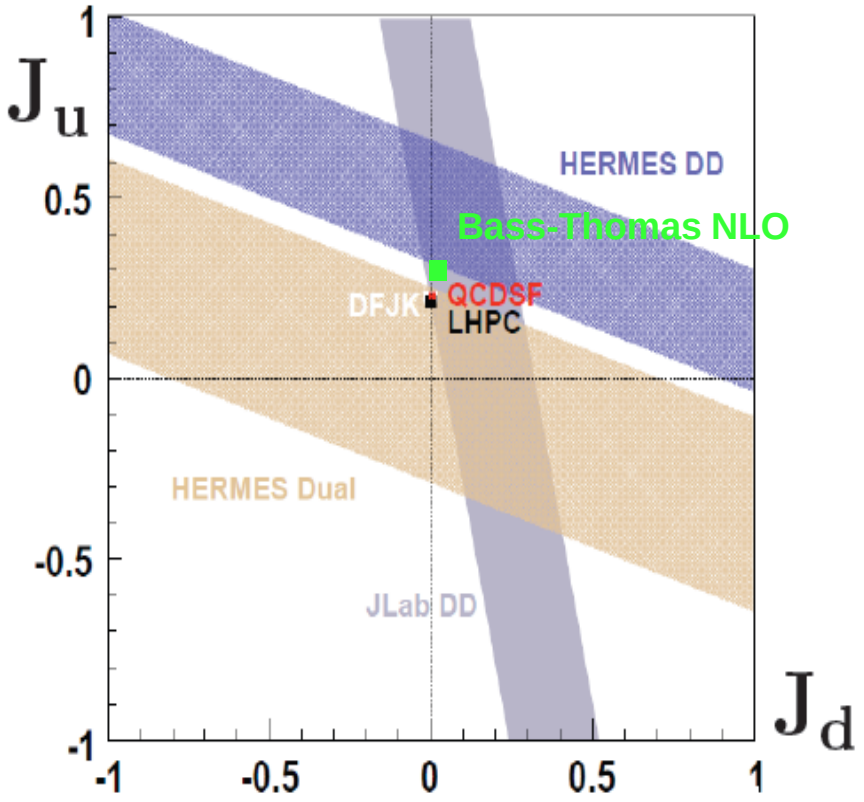
Calculations (unpublished) based on: Ji, PRL 78 (1997) 610

Experimental effort just beginning!

For the moment the analysis is model dependent ....

- ... from DVCS: (**JLAB** PRL 99 (2007) 242501 and **HERMES** JHEP 0806:066 (2008)





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**

	MIT Bag	MIT Bag + OGE	MIT Bag + M. Cloud	MIT Bag + OGE + M. Cloud	Model	Lattice
N	65.4	53.8	51.9	43.8	1.0	1.0
Λ	77.1	67.3	66.4	58.9	1.35 (1.33)	-
Σ	61.5	50.8	50.5	42.6	0.97 (0.98)	0.92 (13)
Ξ	80.9	72.3	72.0	65.2	1.49 (1.44)	1.61 (33)

- **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!**

Shanahan et al., Phys Rev Lett 110 (2013) 202001

Summary

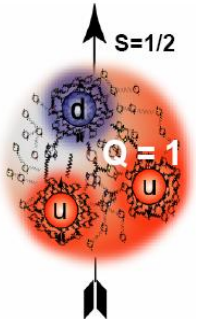
- Two decades of experiments have given us important new insight into spin structure of the p

- U(1) axial anomaly appears to play little role in resolving the problem
  - not as severe as in original EMC paper

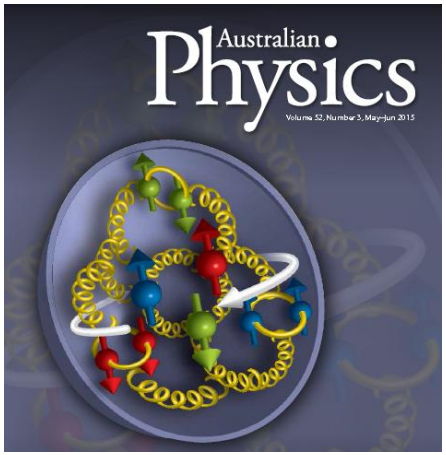
- Instead, important details of the non-perturbative structure of the nucleon DO resolve the "crisis"
  - OGE hyperfine interaction
  - chiral symmetry: pion cloud
  - relativistic motion of quarks

} Ingredients of a minimal description of proton structure

Summary (cont.)



- Important consequence for quark model:
  a large fraction of the proton spin is carried as orbital angular momentum by valence quarks and by anti-quarks in the proton



- Effect of QCD Evolution is to:
  - flip ordering of L^u and L^d
  - reduce size of orbital angular momentum
  - restore agreement between data, LQCD and the CBM explanation

- Of course, there are many fascinating spin problems to be addressed by experimental facilities, including GPDs, TMDs (Sivers and Collins) and even precise value of ΔG

BUT spin problem is understood!


We look forward to welcoming delegates to
Adelaide, Australia for INPC 2016
September 11-16 2016
exceptional!
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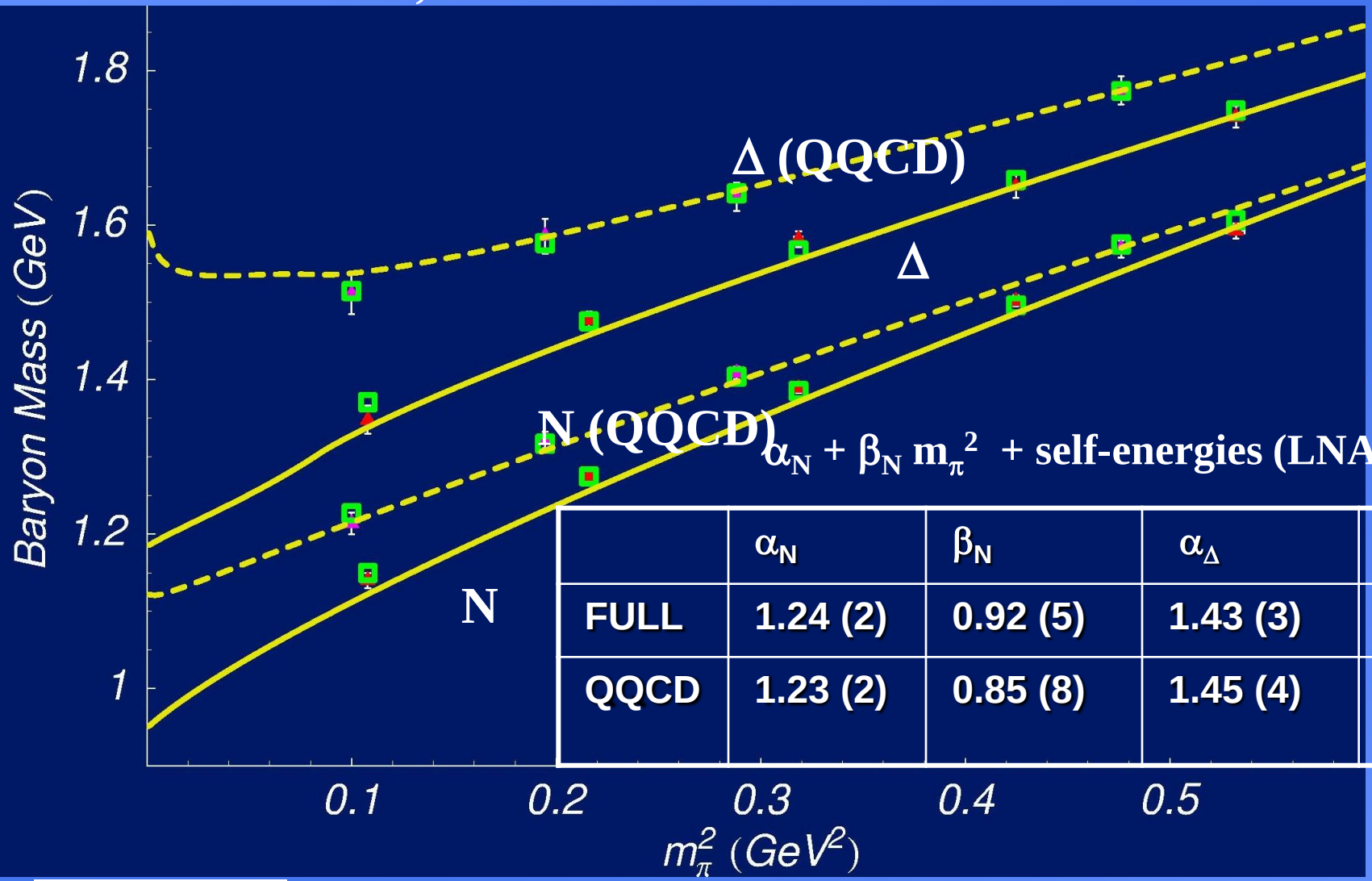
- Lattice data (from MILC Collaboration) : red triangles
- Green boxes: fit evaluating σ's on same finite grid as lattice
- Lines are exact, continuum results

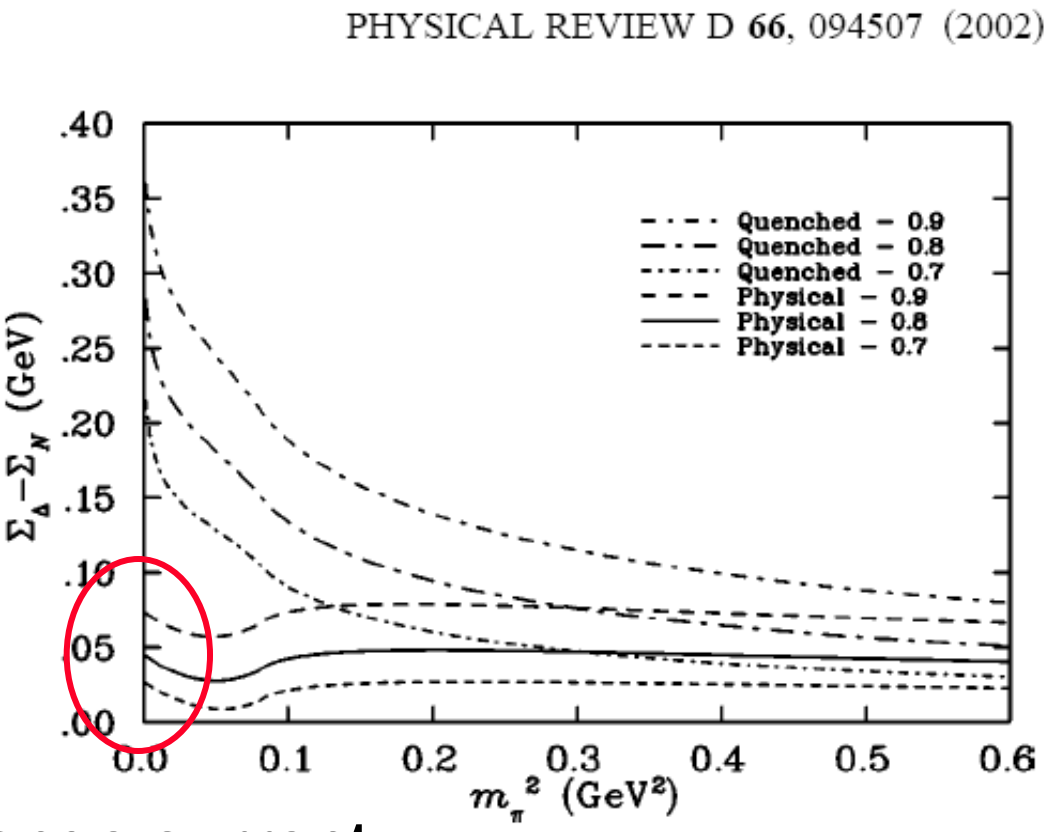


	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

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

Nucleon - Δ Splitting

Lattice analysis implies pions give 40 ± 20 MeV



- **Hence most of the N-Δ splitting comes from OGE – as in most quark models**

- **Thus the value of α_s used in the bag model calculation of the exchange current correction is more or less unchanged**

and… one can <u>add</u> the pion and OGE corrections without significant double counting

Modern value of Δs

- **The value suggested by the Bass-Thomas analysis (also 1989 work of Yamaguchi et al.) is Δs is between -0.01 and - 0.02**

- **Then Σ and g_A^8 differ by only ~ 0.06 (modulo minor effects of glue through the anomaly)**

- **Latest careful evaluation* of strange polarization in a careful lattice study of "disconnected" term, by**

  Bali et al. [QCDSF], arXiv:1112.3324 ***indeed*** **yields**

  $\Delta s = -0.02 \pm 0.010 \pm 0.004$ (MSbar at 7.4 GeV²)

*Essential to take into account flavor mixing – lattice artifact