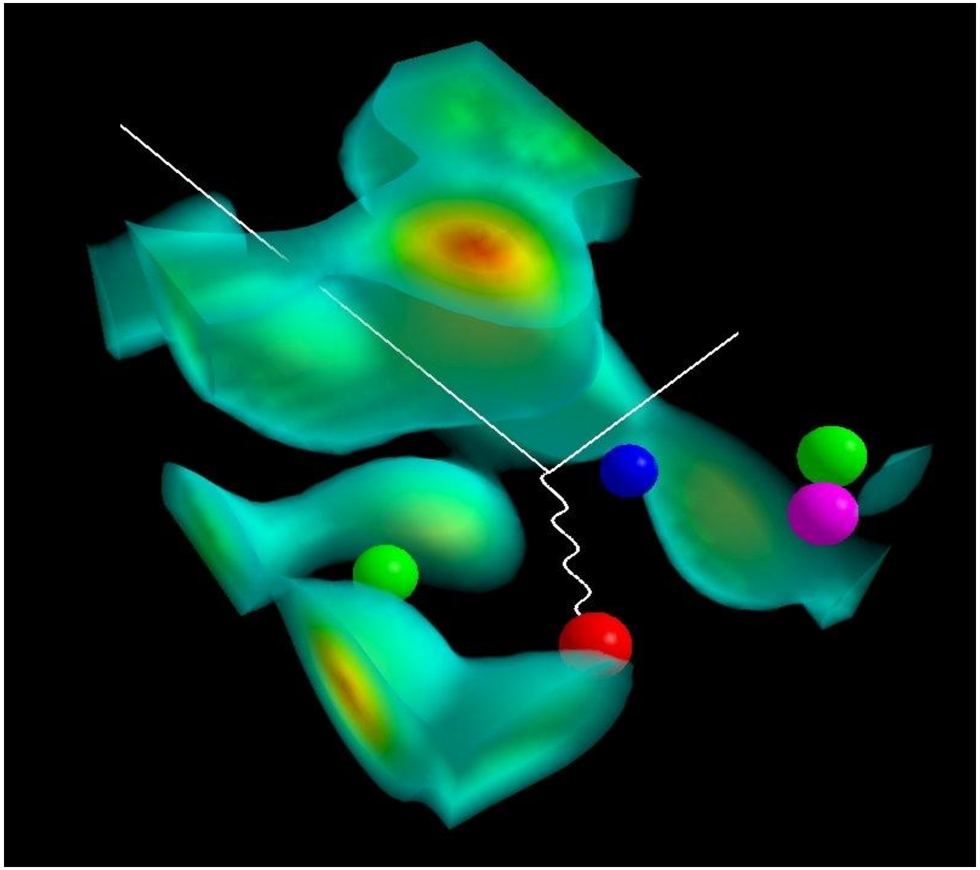
New Insights into Hadron Structure



Anthony W. Thomas

UK Annual Theory Meeting
Durham : Dec 19th 2008

Outline

- Octet Masses and Sigma terms

- Strangeness in the Nucleon

  and…. Dark Matter Searches

- Solution of the Proton Spin Problem

  (Nuclei in the Framework of QCD)

  (Significance for dense matter)

Open Questions for Hadron Spectroscopy

- Does lattice QCD precisely reproduce the best experimental data
  - spectroscopy, form factors, DIS, GPDs?

- Are some observables more likely to yield interesting constraints than others?

- What physical insight can LQCD yield into how QCD works?

- Are we able to take the lessons learnt in hadron structure and use them to understand nuclear structure better?

Formal Chiral Expansion

Formal expansion of Hadron mass:

$$M_N = c_0 + c_2\, m_\pi^2 + c_{LNA}\, m_\pi^3 + c_4\, m_\pi^4 + c_{NLNA}\, m_\pi^4 \ln m_\pi + O(m_\pi^5)$$

Mass in chiral limit

No term linear in m_π (in FULL QCD…… there is in QQCD)

First (hence "leading") non-analytic term ~ $m_q^{3/2}$ (LNA)

Source: N → N π → N

c_{LNA} MODEL INDEPENDENT

Another branch cut from N → Δ π → N

- **higher order in m_π**
- **hence "next-to-leading" non-analytic (NLNA)**

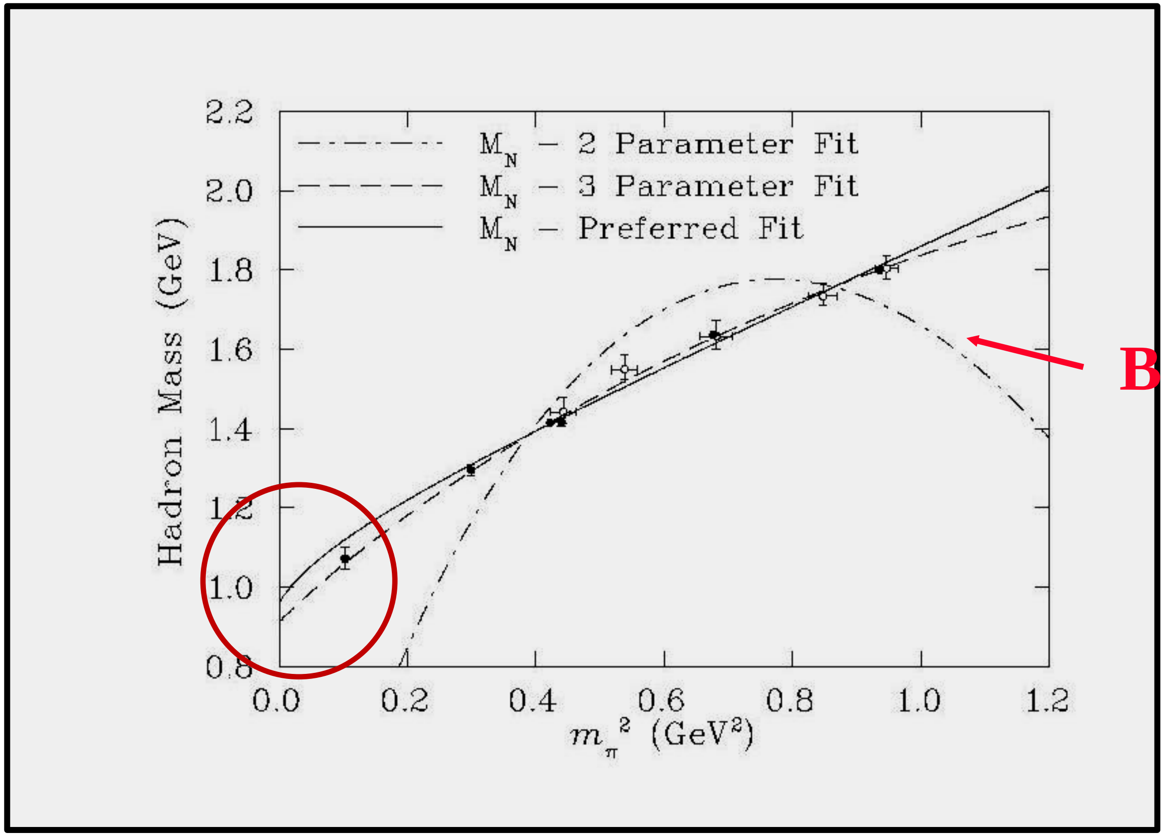
c_{NLNA} MODEL INEPENDENT

Convergence?

Convergence!

Knowing χ PT , fit with: $\alpha + \beta\, m_\pi^2 + \gamma\, m_\pi^3$ (dashed curve)

$m_\pi^2|_{phys}$=0.02

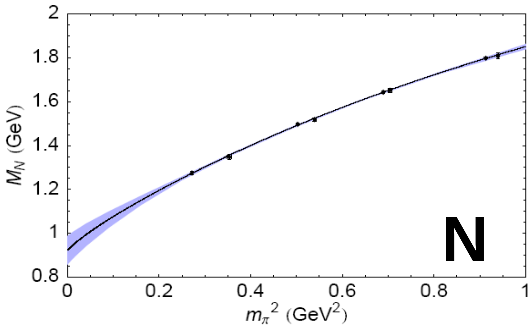


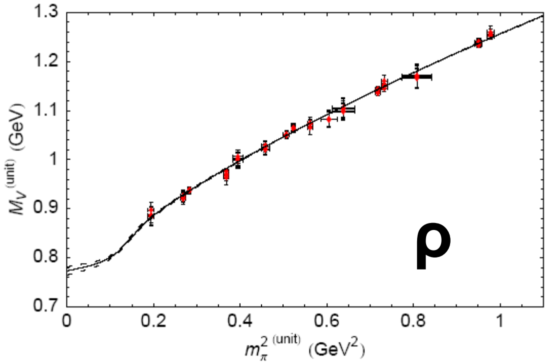
Best fit with γ as in χ P T

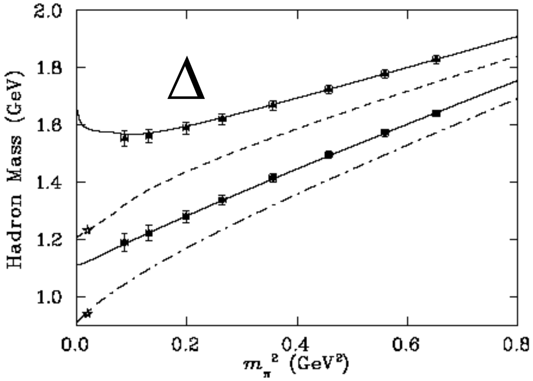
Problem: γ = - 0.76 c.f. model independent value -5.6 !!

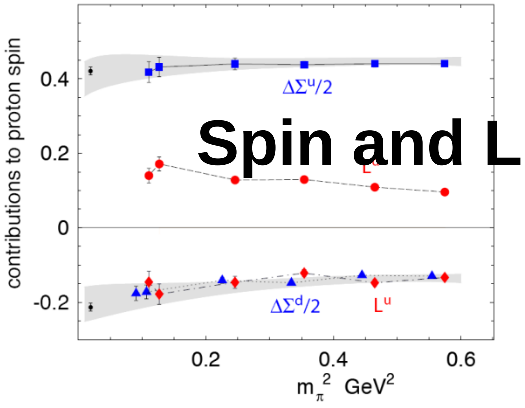
(From: Leinweber *et al*., Phys. Rev., D61 (2000) 074502)

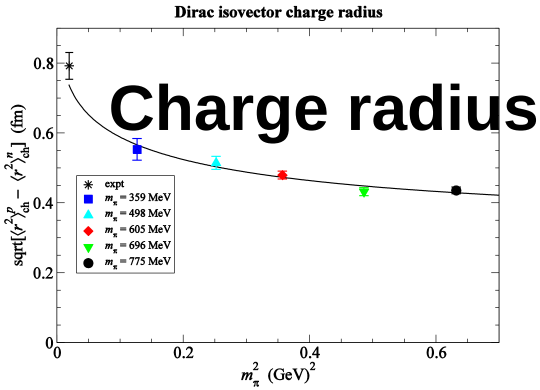
The “big picture”

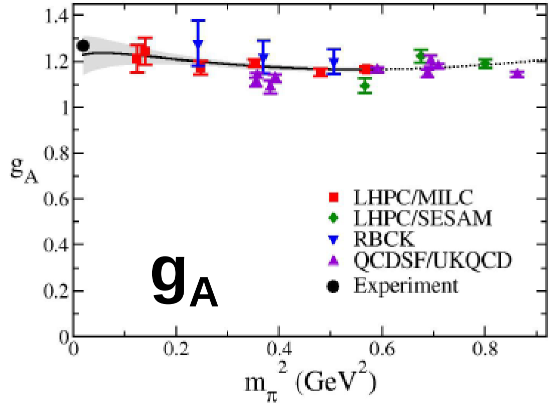


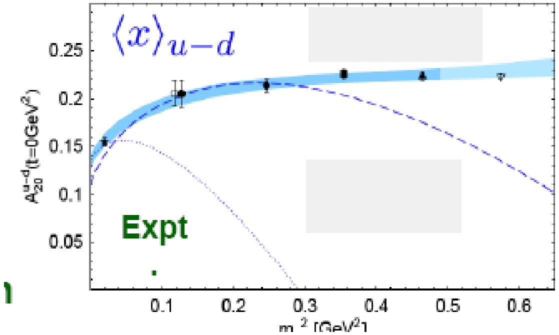












Is it believable that smooth behavior for m_π above 400 MeV is a result of a <u>different</u> accidental cancellation in every case??

$$a + b\, m_\pi^2 + c\, m_\pi^3 + d\, m_\pi^4 \ln m_\pi + m_\pi^5 + \ldots.$$

No: FRR explains this because…

It preserves model independent LNA and NLNA behavior
and

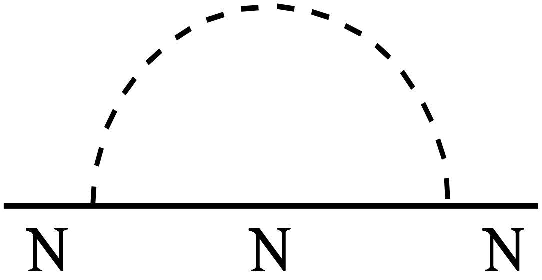
- For <u>sound physical reasons</u>, FRR suppresses meson loops once m_π exceeds about 0.4 GeV

- Yields convergent series expansion over mass region covered by lattice data

- Form factor naturally yields GT discrepancy of right sign and magnitude – and therefore correct m_π^5 term!
  - i.e. correct NNLNA behavior

- N.B. Usual EFT yields this term only at two loops

Some details of FRR



= $c_{LNA}\, I_\pi$; $c_{LNA} = -3\, g_A{}^2/(32\, \pi\, f_\pi{}^2)$

$$I_\pi = \frac{2}{\pi}\int_0^\infty dk\, \frac{k^4\, u^2(k)}{k^2+m_\pi^2}$$

$$I_\pi^{\rm DIP} = \frac{\Lambda^5(m_\pi^2+4m_\pi\Lambda+\Lambda^2)}{16(m_\pi+\Lambda)^4} \sim \frac{\Lambda^3}{16} - \frac{5\Lambda}{16}m_\pi^2 + m_\pi^3 - \frac{35}{16\Lambda}m_\pi^4 + \ldots$$

(with dipole regulator; /// closed forms for other regulators)

Pion cloud and sea quark flavor asymmetry in the impact parameter representation

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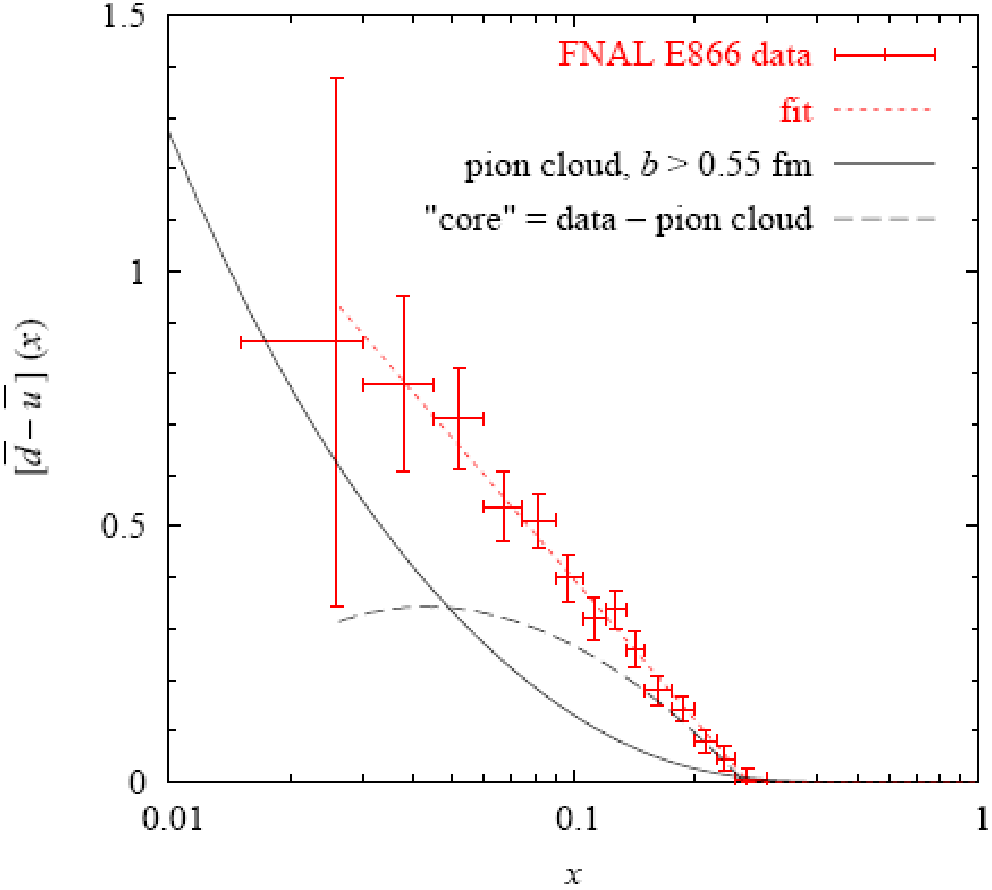


- Prediction of $\bar{d} - \bar{u} > 0$ from pion cloud 1983

  (AWT, Phys. Lett. B126, 97)

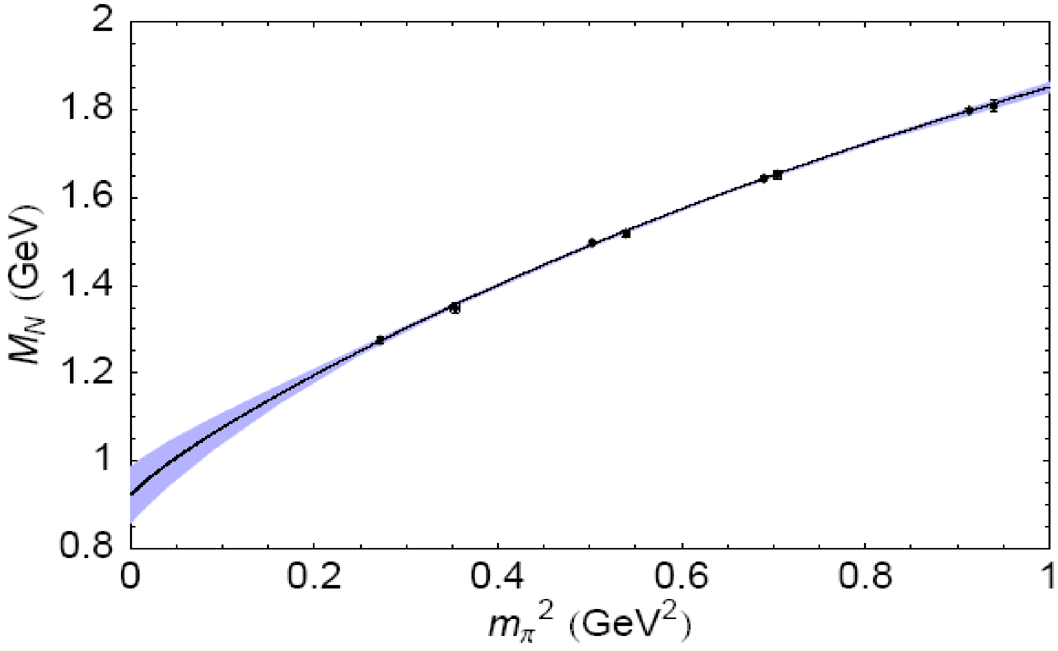
- Here analysis establishes model independent piece, for b>0.55fm

- Inside is "non-chiral" core

- m_π > 400 MeV : pion cannot be distinguished from "core"

- chiral behavior disappears

χ'al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon



Status in 2004

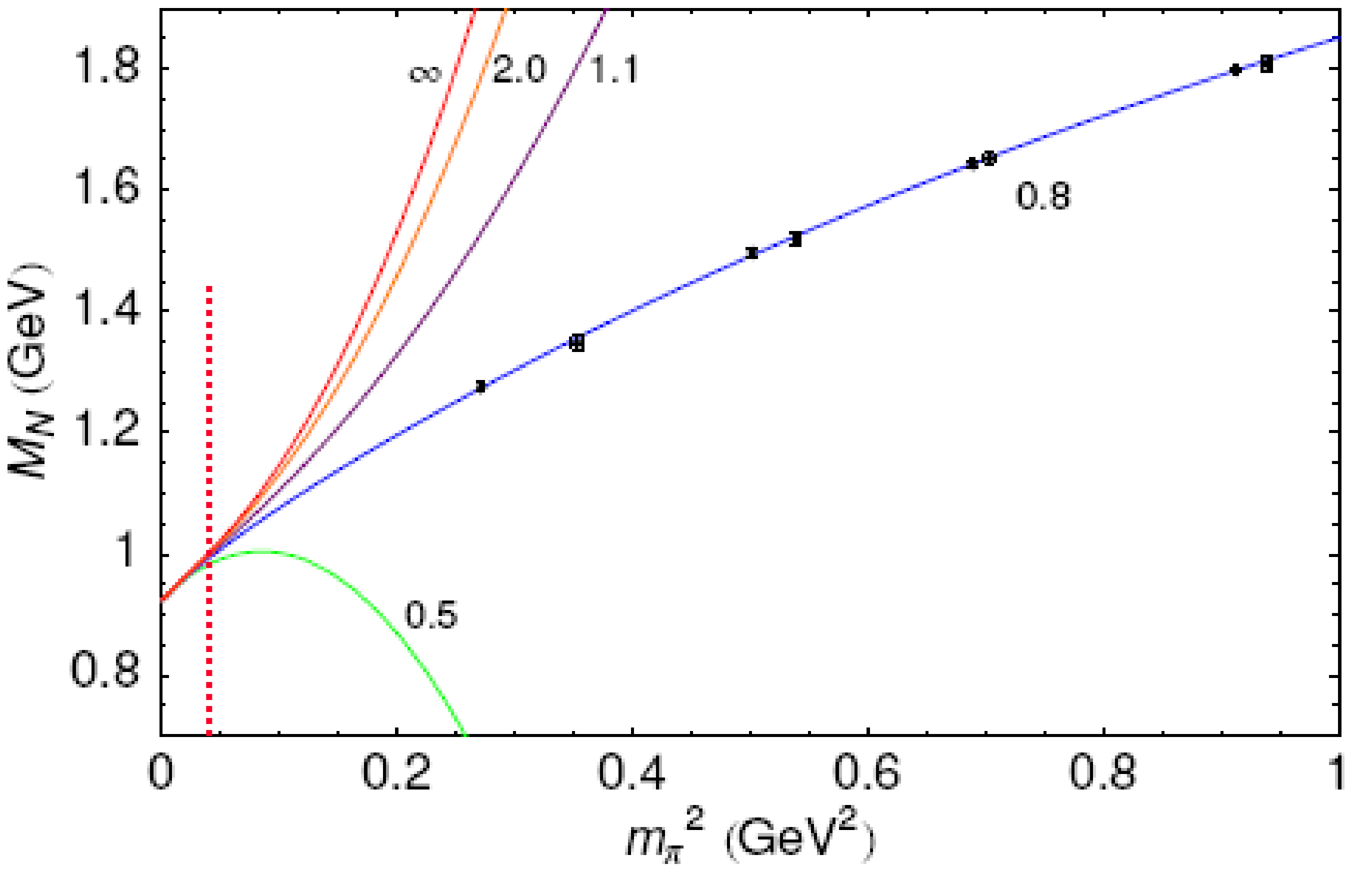
FRR give same answer to <<1% systematic error!

	Bare Coefficients				Renormalized Coefficients			
Regulator	a_0^Λ	a_2^Λ	a_4^Λ	Λ	c_0	c_2	c_4	m_N
Monopole	1.74	1.64	−0.49	0.5	0.923(65)	2.45(33)	20.5(15)	0.960(58)
Dipole	1.30	1.54	−0.49	0.8	0.922(65)	2.49(33)	18.9(15)	0.959(58)
Gaussian	1.17	1.48	−0.50	0.6	0.923(65)	2.48(33)	18.3(15)	0.960(58)
Sharp cutoff	1.06	1.47	−0.55	0.4	0.923(65)	2.61(33)	15.3(8)	0.961(58)
Dim. Reg. (BP)	0.79	4.15	+8.92	–	0.875(56)	3.14(25)	7.2(8)	0.923(51)

Leinweber et al., PRL 92 (2004) 242002

Power Counting Regime

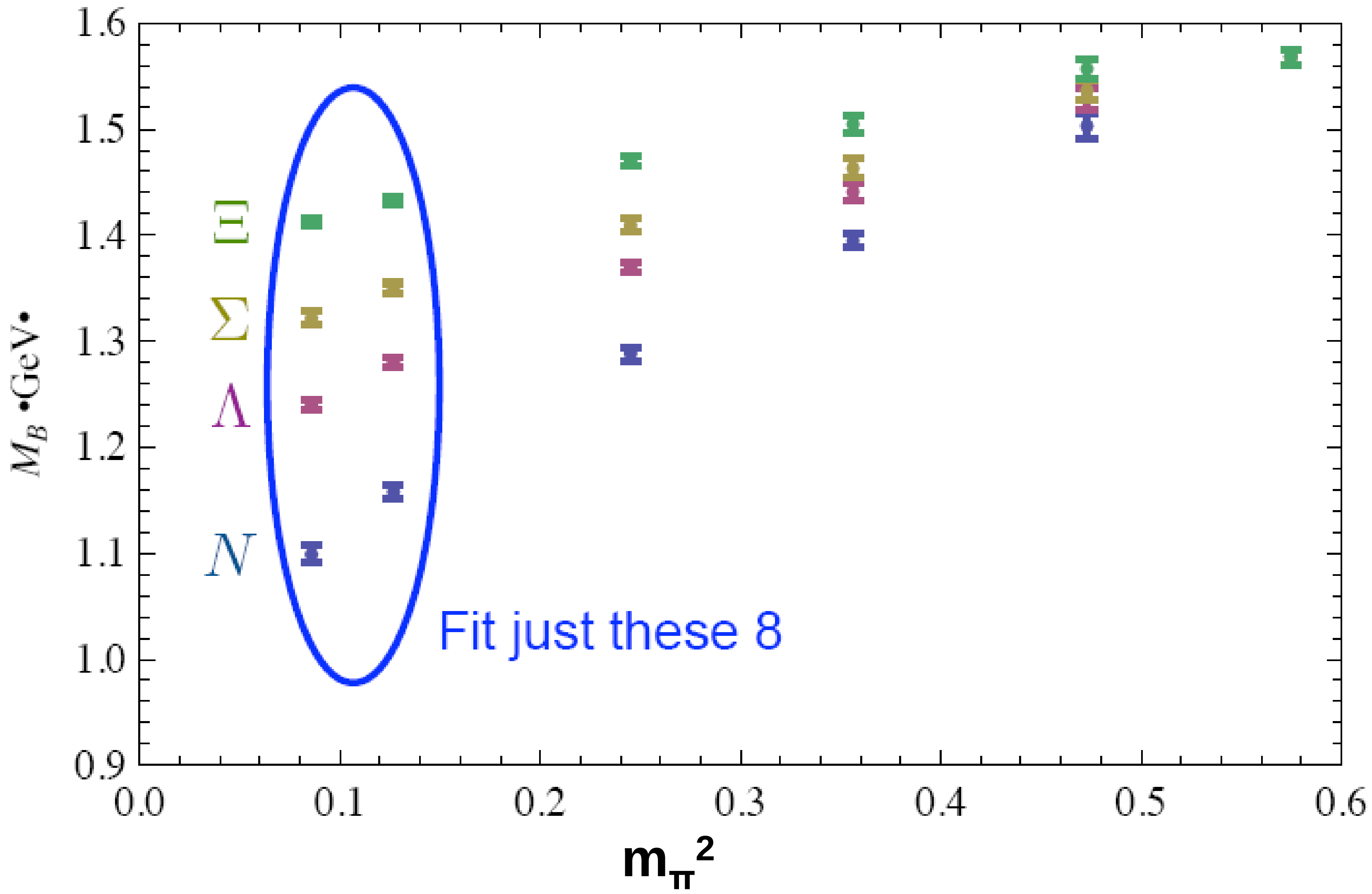
Ensure coefficients c_0 , c_2 , c_4 all identical to 0.8 GeV fit



Leinweber, Thomas & Young, hep-lat/0501028

Lattice Simulation Results: LHPC

Now to 2008



Fit just these 8

Octet-baryon masses

We fit using SU(3) expansions plus FRR loops (π, η and K)

- Leading-order expansion $O(1)$

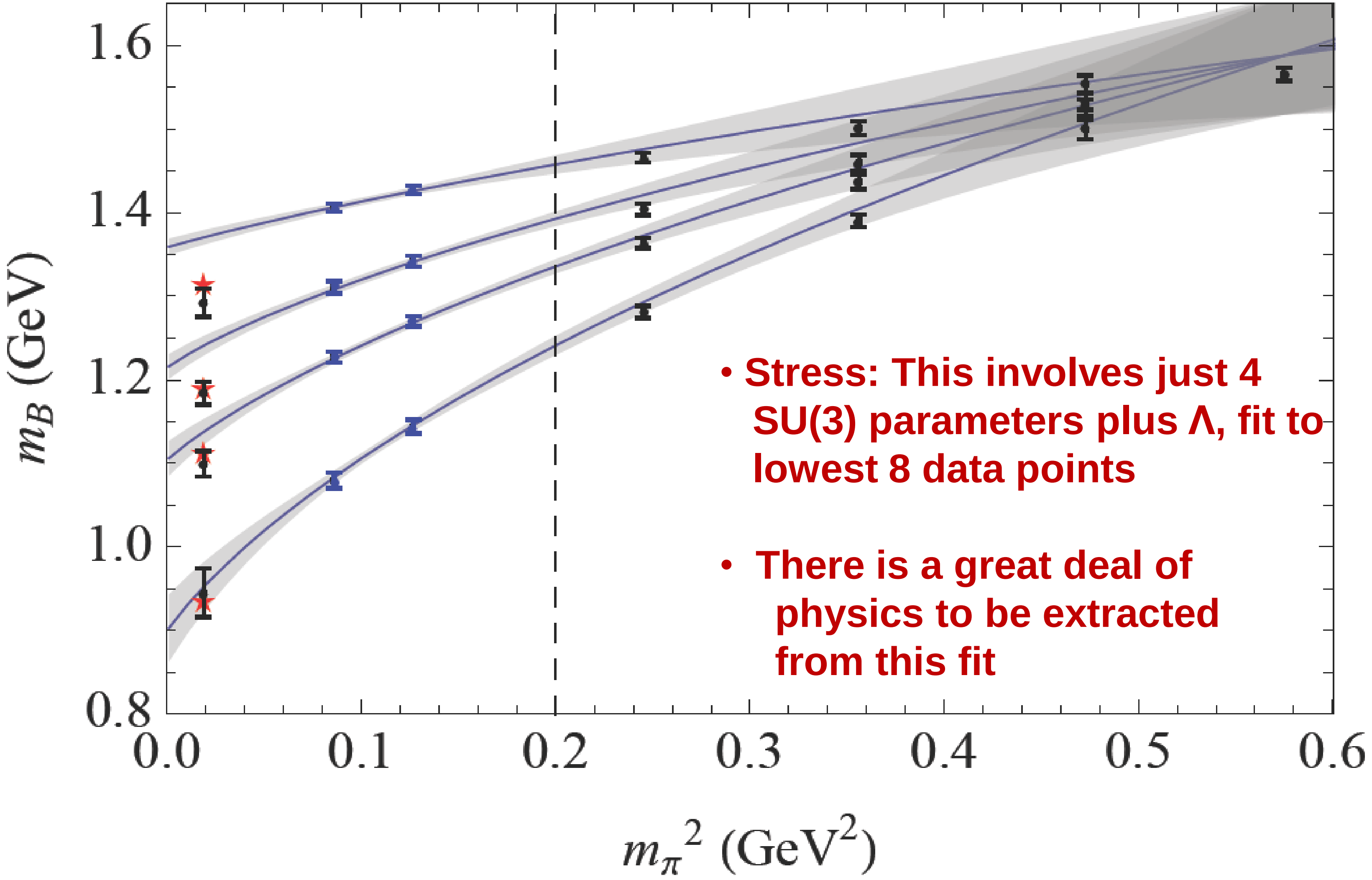
$$\begin{aligned}
M_N &= M_0 + 2(\alpha_M + \beta_M)m_q + 2\sigma_M(2m_q + m_s) \\
M_\Lambda &= M_0 + (\alpha_M + 2\beta_M)m_q + \alpha_M m_s + 2\sigma_M(2m_q + m_s) \\
M_\Sigma &= M_0 + \frac{1}{3}(5\alpha_M + 2\beta_M)m_q + \frac{1}{3}(\alpha_M + 4\beta_M)m_s + 2\sigma_M(2m_q + m_s) \\
M_\Xi &= M_0 + \frac{1}{3}(\alpha_M + 4\beta_M)m_q + \frac{1}{3}(5\alpha_M + 2\beta_M)m_s + 2\sigma_M(2m_q + m_s)
\end{aligned}$$

$$m_\pi^2 = 2Bm_q \quad m_K^2 = B(m_q + m_s)$$

$$m_q \to \frac{m_\pi^2}{2B}, \quad m_s \to \frac{2m_K^2 - m_\pi^2}{2B} \qquad \{\alpha, \beta, \sigma\} \to B\{\alpha', \beta', \sigma'\}$$

LHPC Data

(Walker-Loud et al.. arXiv:0806.4549)

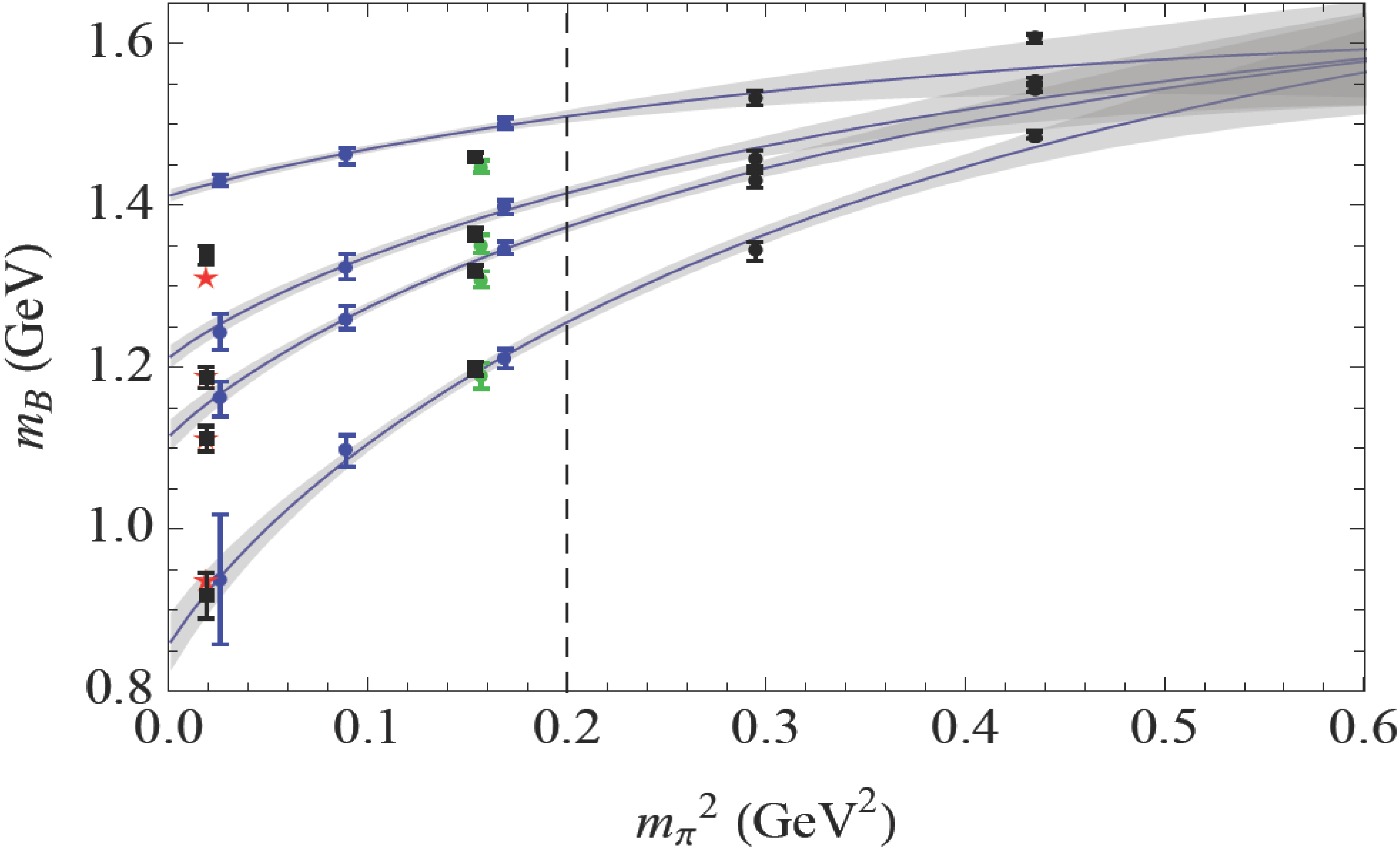


- Stress: This involves just 4 SU(3) parameters plus Λ, fit to lowest 8 data points
- There is a great deal of physics to be extracted from this fit

Young & Thomas, in preparation

PACS-CS Data

(Aoki et al., arXiv:0807.1661[hep-lat])



Young & Thomas, in preparation

Summary of Results of Combined Fits

(of 2008 LHPC & PACS-CS data)

B	Mass (GeV)	$\bar{\sigma}_{Bl}$	$\bar{\sigma}_{Bs}$
N	0.939(19)(4)(2)	0.054(7)(2)(2)	0.020(11)(7)(3)
Λ	1.108(11)(10)(1)	0.0296(31)(5)(10)	0.138(11)(2)(2)
Σ	1.185(9)(2)(1)	0.0221(20)(7)(7)	0.176(11)(6)(2)
Ξ	1.321(9)(20)(0)	0.0095(7)(4)(0)	0.236(11)(4)(3)

$$\bar{\sigma}_{Bq} = (m_q/M_B)\partial M_B/\partial m_q$$

N. B. Masses are absolute calculations based upon heavy quark potential, which involves no chiral physics

Strangeness Has Been Widely Believed to Play a Major Role in N Structure– Does It??

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

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

y=0.2 ± 0.2 ?

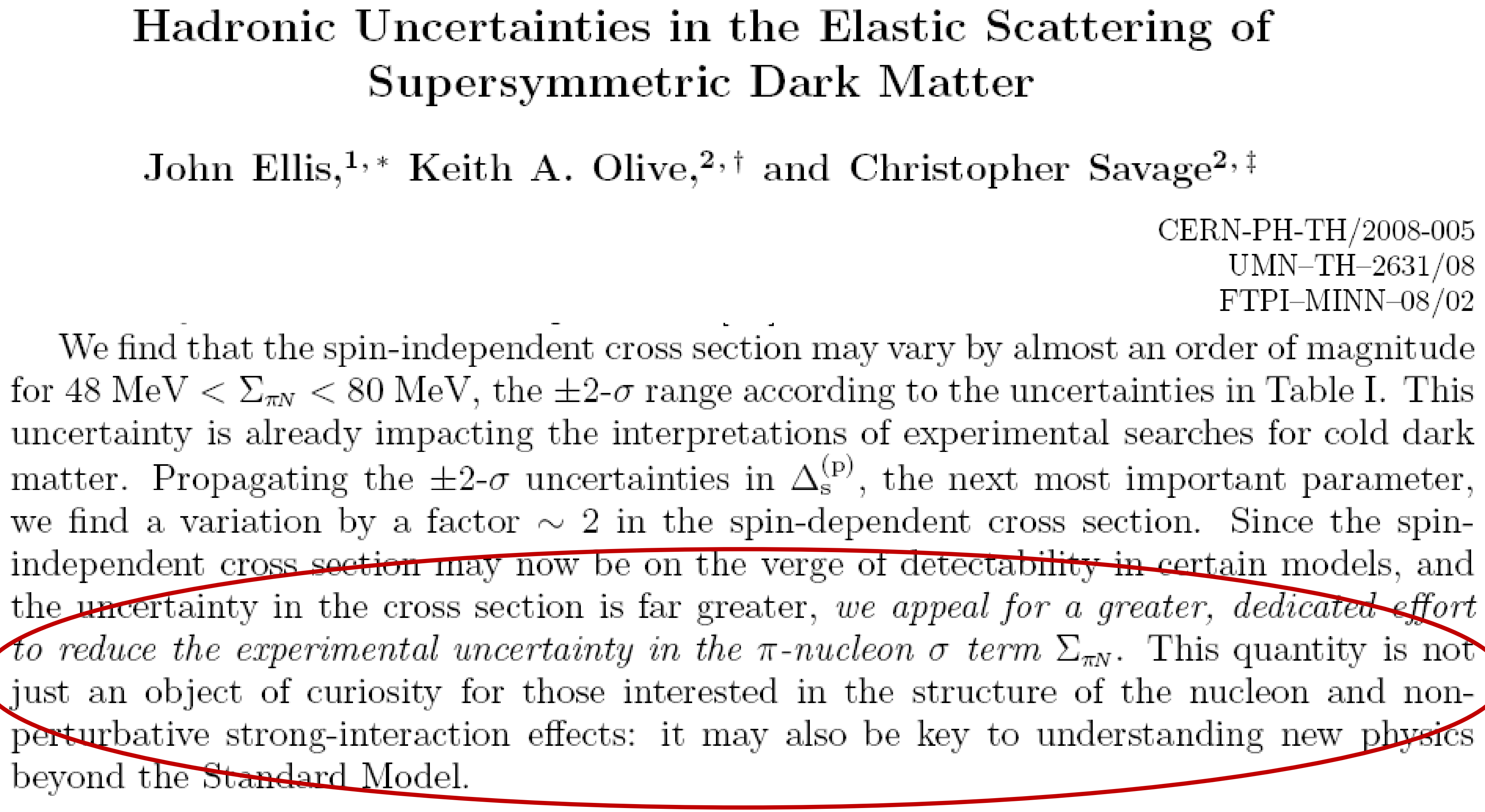
$$\Delta M_N^{s-\mathrm{quarks}} = \frac{y m_s}{m_u + m_d}\,\sigma_N$$

45 ± 8 MeV (or 70?)

Hence 110 ± 110 MeV (increasing to 180 ± 180 for higher σ_N)

As much as half the deuteron magnetic moment?

As much as 10% of the spin of the proton?



Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter

John Ellis,[1,*] Keith A. Olive,[2,†] and Christopher Savage[2,‡]

CERN-PH-TH/2008-005
UMN–TH–2631/08
FTPI–MINN–08/02

We find that the spin-independent cross section may vary by almost an order of magnitude for 48 MeV $< \Sigma_{\pi N} <$ 80 MeV, the ± 2-σ range according to the uncertainties in Table I. This uncertainty is already impacting the interpretations of experimental searches for cold dark matter. Propagating the ± 2-σ uncertainties in $\Delta_s^{(p)}$, the next most important parameter, we find a variation by a factor ~ 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 π-nucleon σ 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.

spin

σ terms

$$\mathcal{L} = \alpha_{2i}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}_i\gamma_{\mu}\gamma^{5}q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

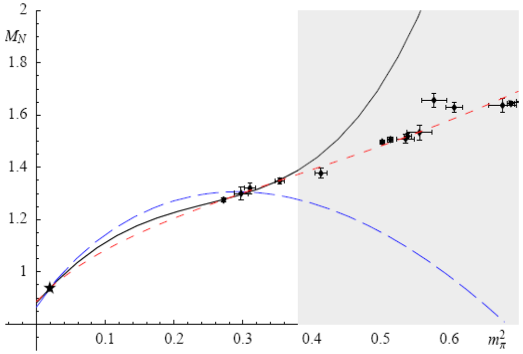
Neutralino (0.3 GeV / cc :WMAP)

McGovern & Birse

First to calculate two-loop, dim-reg χ PT

(hep:lat/0608002)

- Major correction is m_π dependence of $g_{\pi NN}$
  i.e. origin of GT discrepancy : $g_{\pi NN} \neq g_A/f_\pi$



- Leads to large Order (m_π^5) term

- Agree that convergence of formal chiral expansion is hopeless where current lattice data exists

$$M_N = 0.885 + 3.20m_\pi^2 – 5.6m_\pi^3 + 34\ m_\pi^4 – (50\text{-}110)m_\pi^5 \ldots$$

c.f. FRR fit required to include physical nucleon mass:

$$M_N = 0.897 + 2.83m_\pi^2 – 5.6m_\pi^3 + 22m_\pi^4 – (44 \pm 18)m_\pi^5 \ldots$$

Leinweber et al., Lect. Notes in Phys. 663 (2005) 113

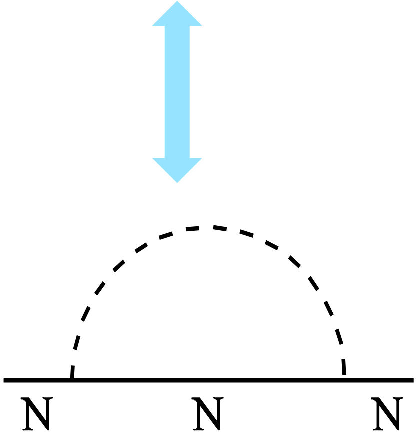
Sigma Commutator

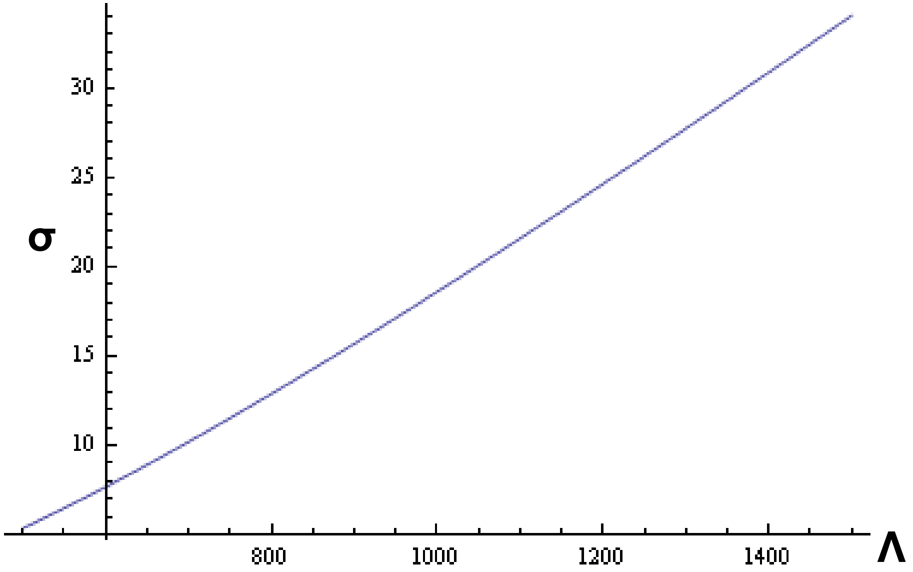
$$\sigma = < N \,|\, (m_u + m_d)\,(\bar{u}\,u + \bar{d}\,d)/2 \,|\, N > \equiv m_q\, \partial M_N / \partial m_q$$

$$= \sigma_{val} + \sigma_{sea}$$

LNA

$$\delta\sigma = 35\,\Lambda - 23 + \frac{9.6}{\Lambda} - \frac{3}{\Lambda^2} + \frac{0.8}{\Lambda^3} + \ldots = 18\text{ MeV } (\Lambda = 1\text{GeV})$$





Naïve Expansion Traditionally Used to Extract σ Terms is Hopeless!

- Leading-order expansion $O(1)$

$$
\begin{aligned}
M_N &= M_0 + 2(\alpha_M + \beta_M)m_q + 2\sigma_M(2m_q + m_s) \\
M_\Lambda &= M_0 + (\alpha_M + 2\beta_M)m_q + \alpha_M m_s + 2\sigma_M(2m_q + m_s) \\
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M_\Xi &= M_0 + \frac{1}{3}(\alpha_M + 4\beta_M)m_q + \frac{1}{3}(5\alpha_M + 2\beta_M)m_s + 2\sigma_M(2m_q + m_s)
\end{aligned}
$$

Need $O(m_\pi^6)$ to get accurate light quark σ term

While for strange condensate expansion is useless !

BUT through FRR have closed expression and can evaluate ….

Summary of Results of Combined Fits

(of 2008 LHPC & PACS-CS data)

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$$\bar{\sigma}_{Bq} = (m_q/M_B)\partial M_B/\partial m_q$$

Of particular interest:

σ commutator well determined : $\sigma_{\pi N}$= 51 (6) (2) (2) MeV

and strangeness sigma commutator <u>small</u>

$m_s\ \partial M_N/\ \partial\ m_s$ = 18 (10) (6) (3) MeV

NOT several 100 MeV !

Profound Consequences for Dark Matter Searches

Additional Comments

- Strangeness content (condensate) is more than an order of magnitude smaller than naively assumed

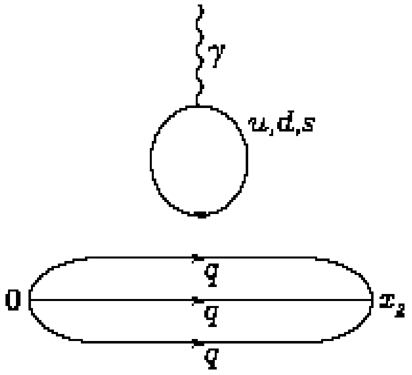
- Strangeness term usually dominates estimates of dark matter cross section - it should NOT!

- In addition, tentatively seems that $\bar{u}\,u$ and $\bar{d}\,d$ condensates should be approximately equal

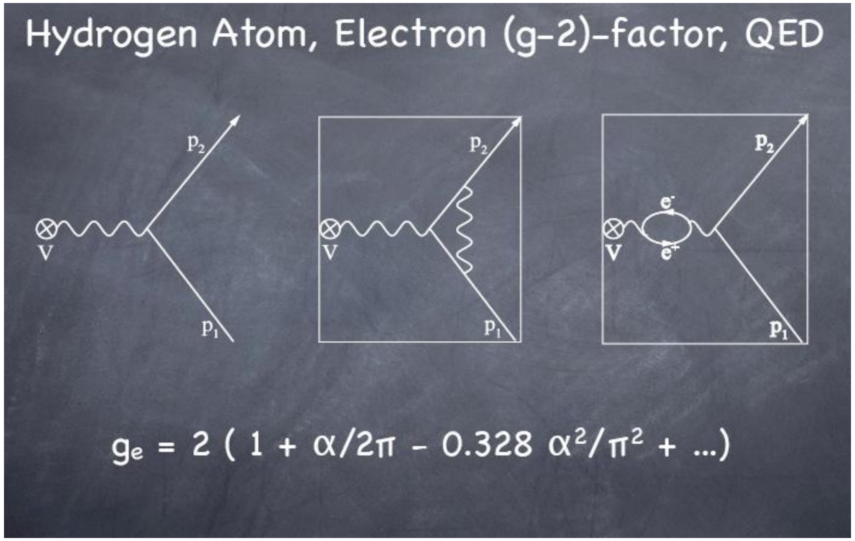
(c.f. usual assumption of 1 : 1.49 : Chen 1989)

Strangeness & Electromagnetic Form Factors

Experiment: Need Parity Violation



Theory: Disconnected diagram

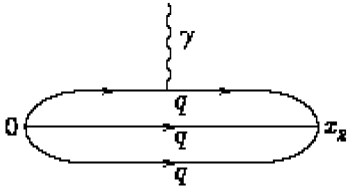


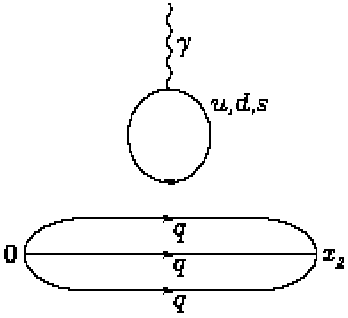
Hydrogen Atom, Electron (g-2)-factor, QED

$$g_e = 2\ (\ 1 + \alpha/2\pi\ -\ 0.328\ \alpha^2/\pi^2\ +\ ...)$$

Magnetic Moments within QCD

(Leinweber and Thomas, Phys Rev D62 (2000)





CS

$$p = 2/3\ u^p - 1/3\ d^p + O_N$$

$$n = -1/3\ u^p + 2/3\ d^p + O_N$$

$$2p + n = u^p + 3\ O_N$$

$$(\text{and } p + 2n = d^p + 3\ O_N\ )$$

$$\Sigma^+ = 2/3\ u^\Sigma - 1/3\ s^\Sigma + O_\Sigma$$

$$\Sigma^- = -1/3\ u^\Sigma - 1/3\ s^\Sigma + O_\Sigma$$

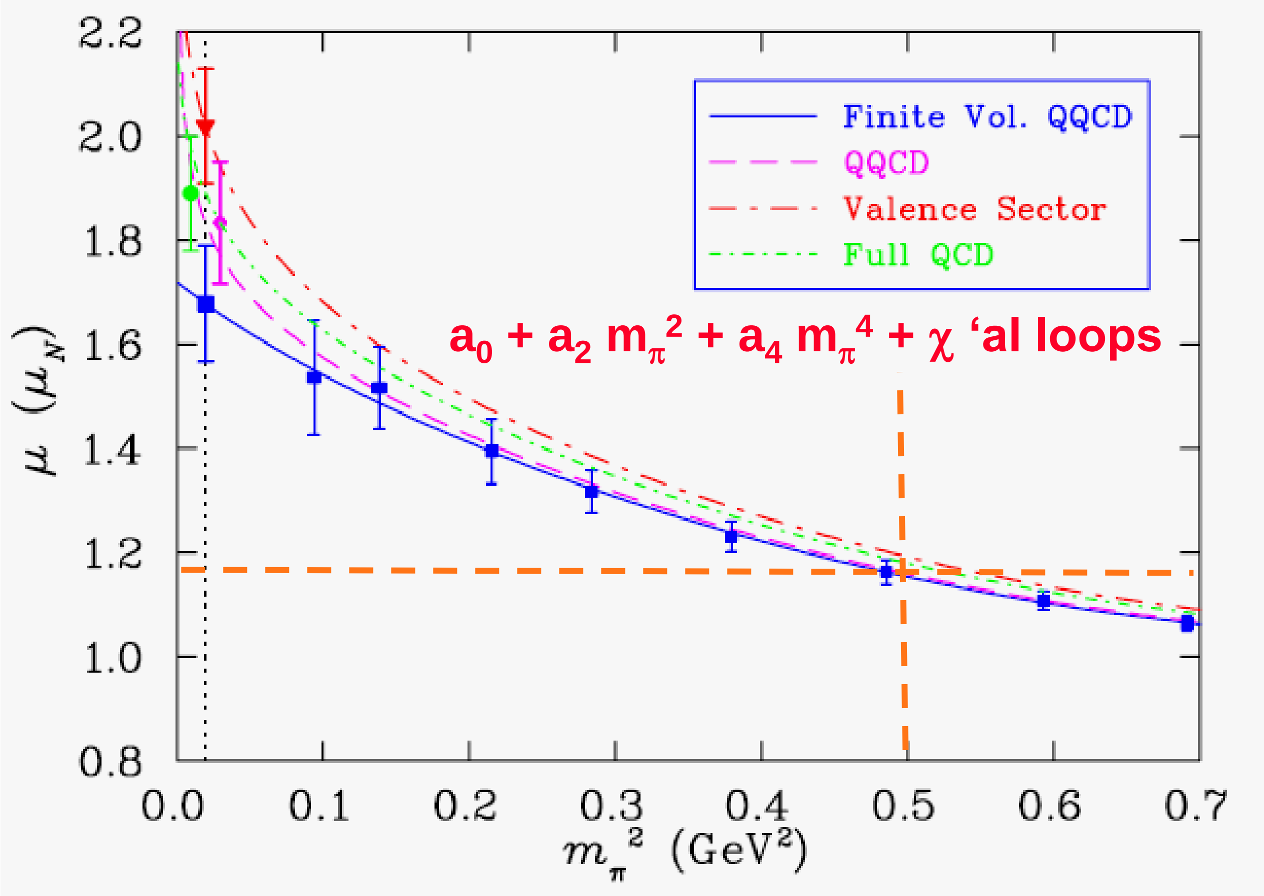
$$\Sigma^+ - \Sigma^- = u^\Sigma$$

HENCE: $O_N = 1/3\ [\ 2p + n - (\ u^p / u^\Sigma\ )\ (\Sigma^+ - \Sigma^-)\ ]$

Just these ratios from Lattice QCD

$$O_N = 1/3\ [\ n + 2p - (\ u^n / u^\Xi\ )\ (\Xi^0 - \Xi^-)\ ]$$

$u^p_{valence}$: QQCD Data Corrected for Full QCD Chiral Coefficients

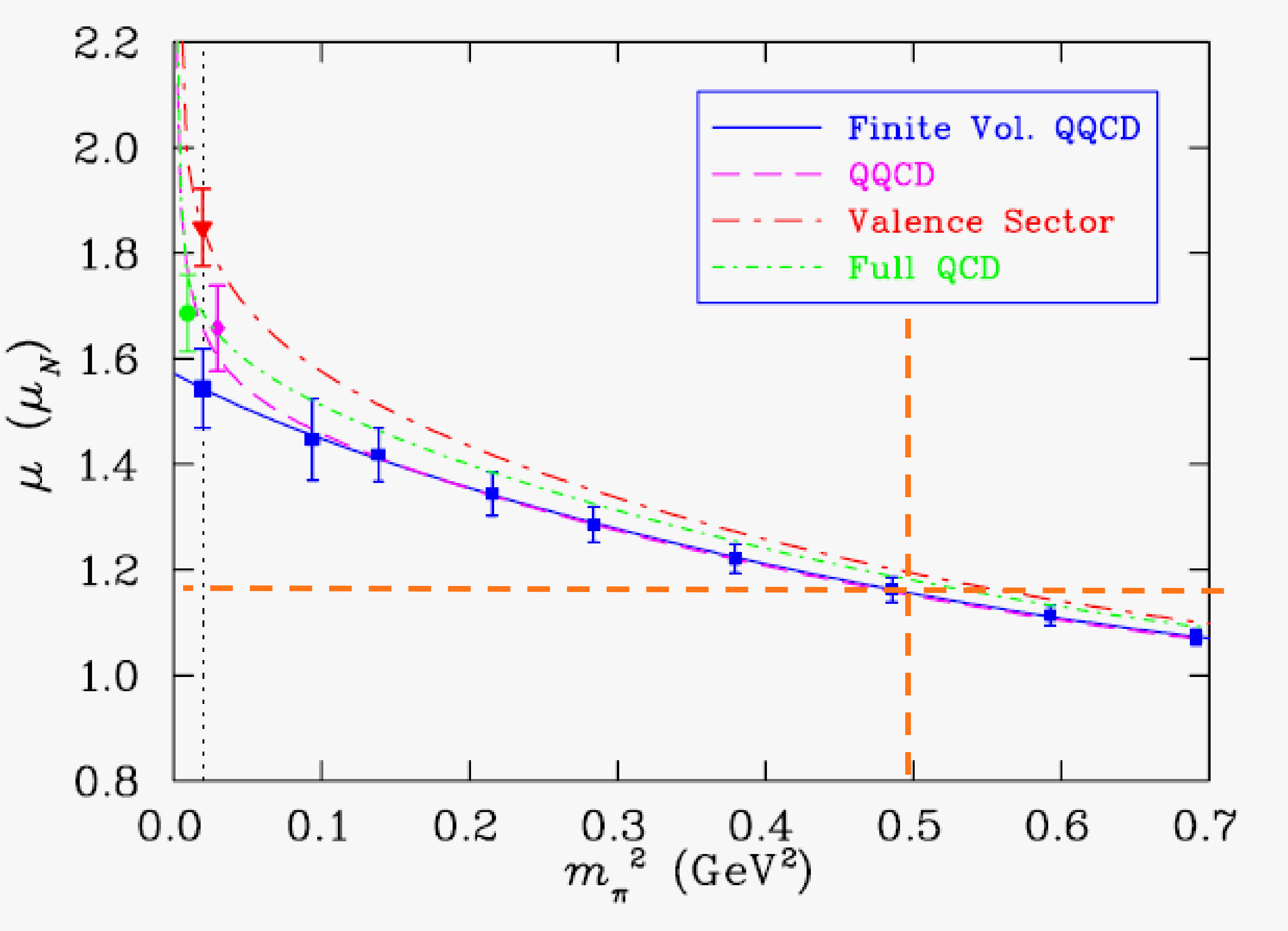


$a_0 + a_2\, m_\pi^2 + a_4\, m_\pi^4 + \chi$ ‘al loops

c.f. CQM
2/3 940/540
$\sim$ 1.18

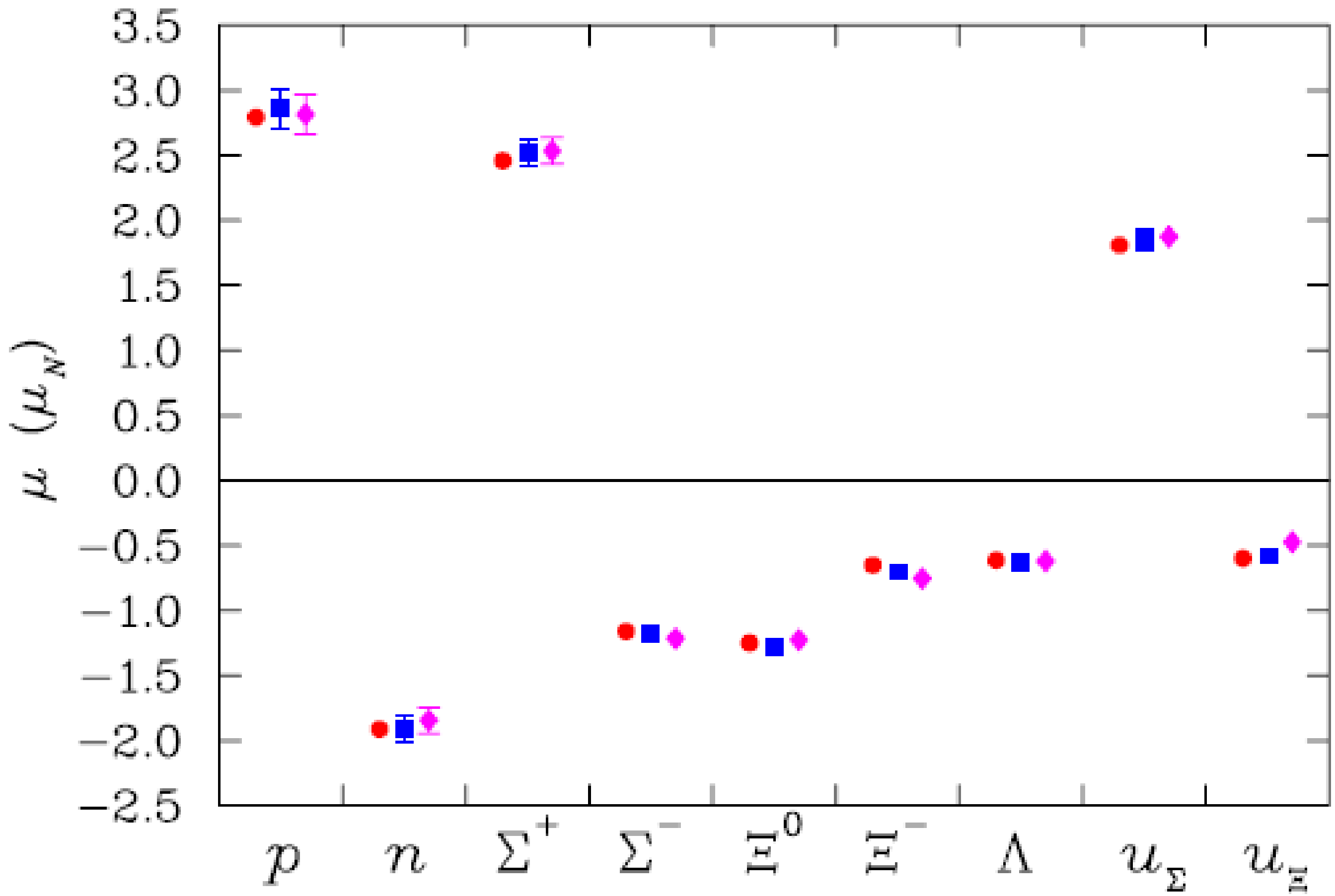
Lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

u^{Σ} valence



Universal Here!

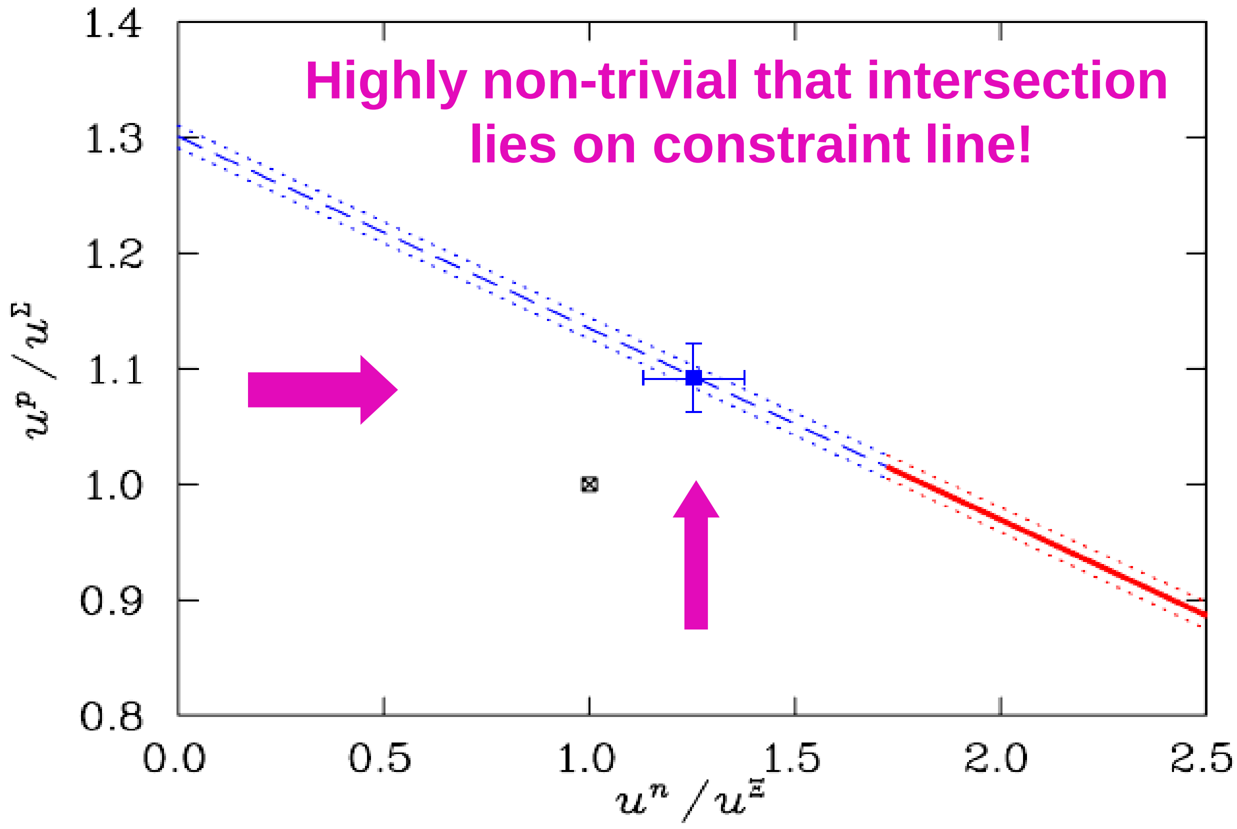
Convergence LNA to NLNA Again Excellent (Effect of Decuplet)



State of the Art Magnetic Moments

	QQCD	Valence	Full QCD	Expt.
p	2.69 (16)	2.94 (15)	2.86 (15)	2.79
n	-1.72 (10)	-1.83 (10)	-1.91 (10)	-1.91
Σ^+	2.37 (11)	2.61 (10)	2.52 (10)	2.46 (10)
Σ^-	-0.95 (05)	-1.08 (05)	-1.17 (05)	-1.16 (03)
Λ	-0.57 (03)	-0.61 (03)	-0.63 (03)	-0.613 (4)
Ξ^0	-1.16 (04)	-1.26 (04)	-1.28 (04)	-1.25 (01)
Ξ^-	-0.65 (02)	-0.68 (02)	-0.70 (02)	-0.651 (03)
u^p	1.66 (08)	1.85 (07)	1.85 (07)	1.81 (06)
u^Ξ	-0.51 (04)	-0.58 (04)	-0.58 (04)	-0.60 (01)

Accurate Final Result for G_M^s



Highly non-trivial that intersection lies on constraint line!

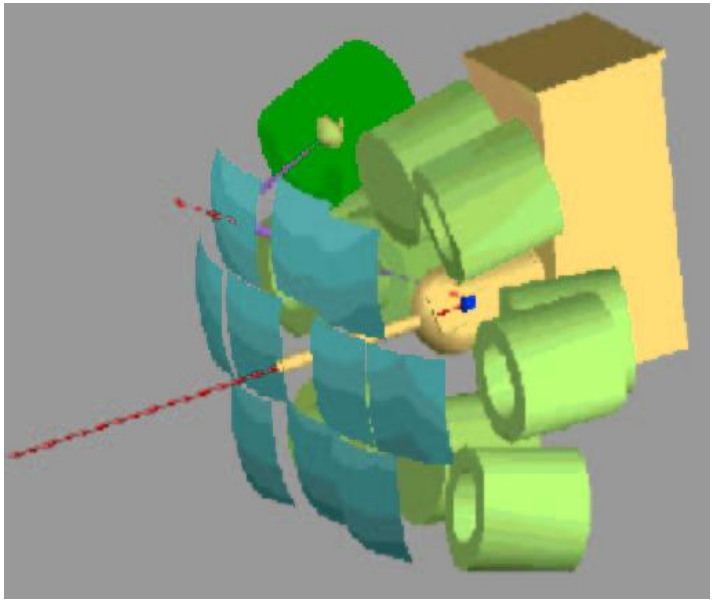
1.10 0.03

1.25 0.12

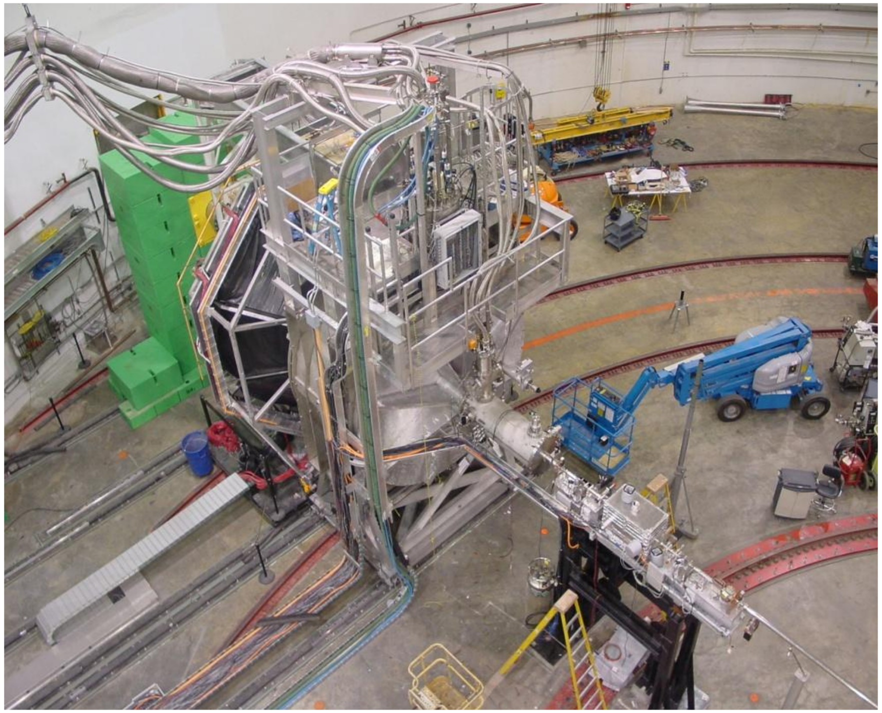
Yields :$G_M{}^s = -0.046 \quad 0.019\ \mu_N$

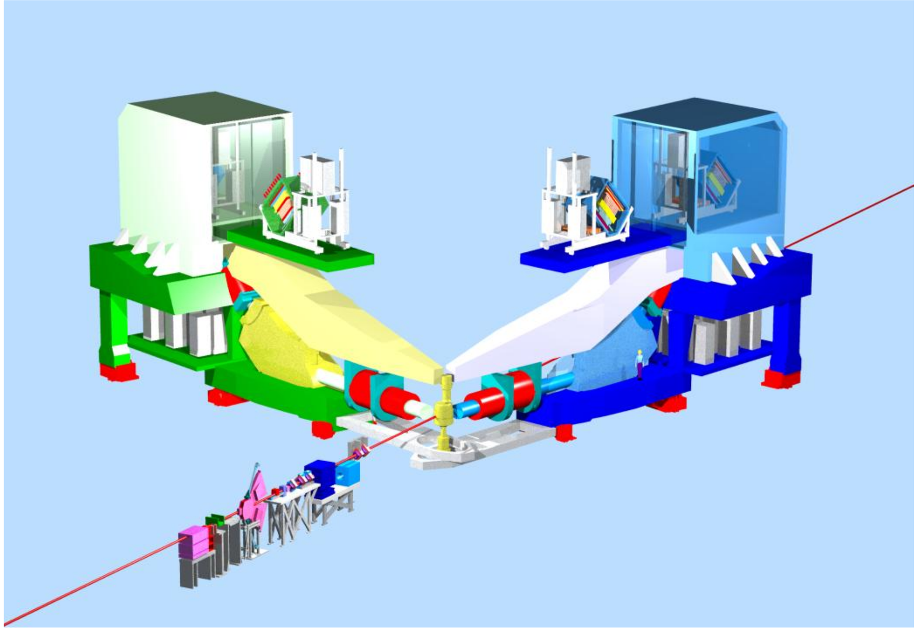
Leinweber et al., (PRL June ’05) hep-lat/0406002

MIT-Bates & A4 at Mainz

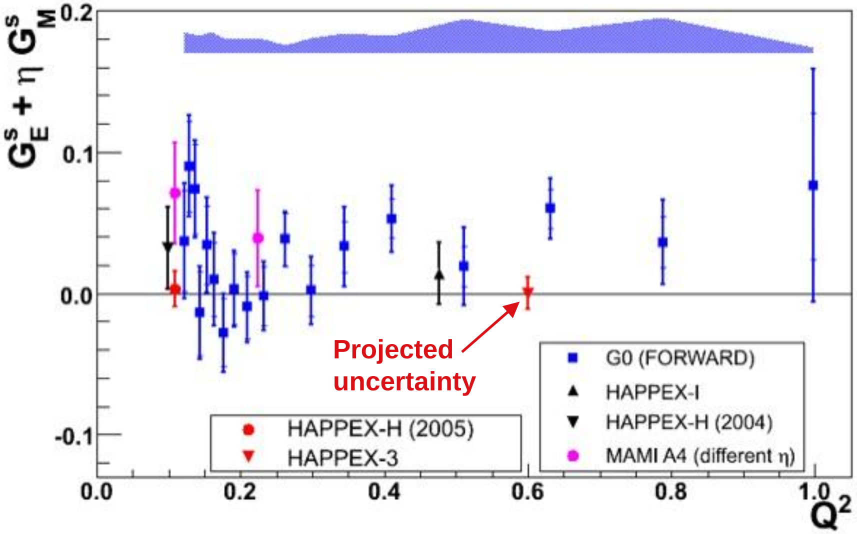


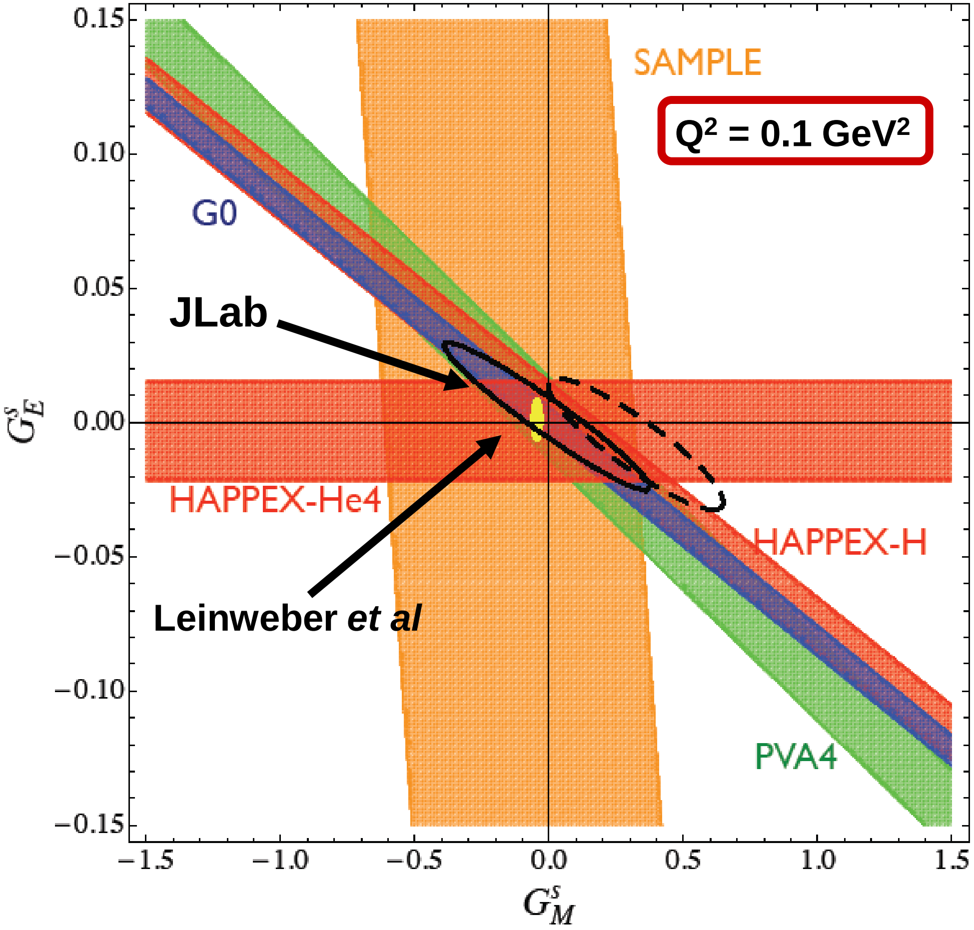
G0 and HAPPEx at Jlab





Exploring the Strangeness Content of the Proton

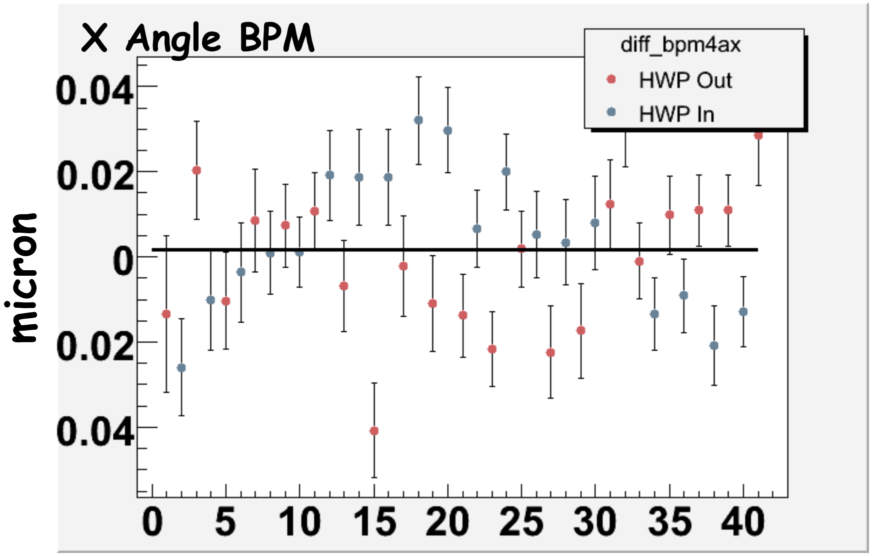


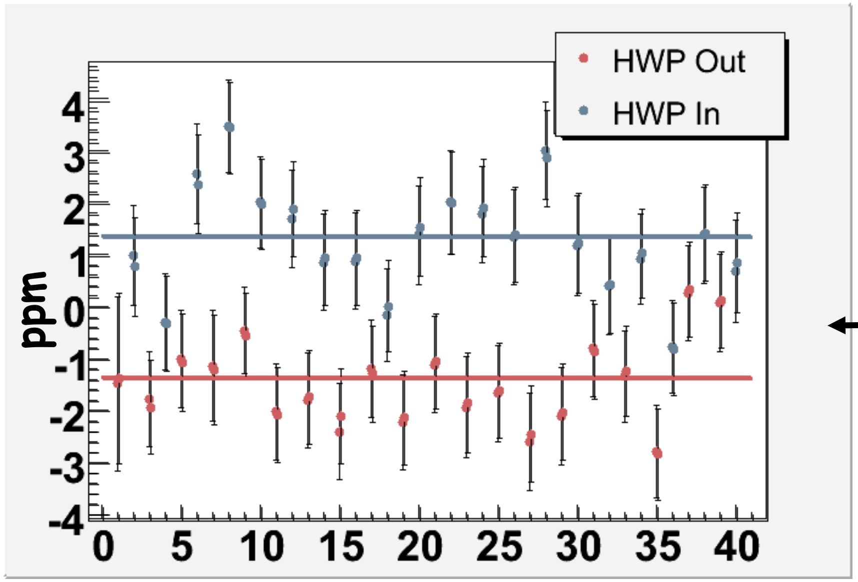


- ➢**Proton not all that strange**
- ➢**Separation possible at 0.1 GeV^2**
- ➢**New data coming at 0.23 and 0.6 GeV^2 (PVA4, G0, HAPPEx III)**

Jefferson Lab Today

Latest HAPPEx Run : Outstanding Achievement !





Surpassed Beam Asymmetry Goals for Hydrogen Run

Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

Y Angle: <1 nm

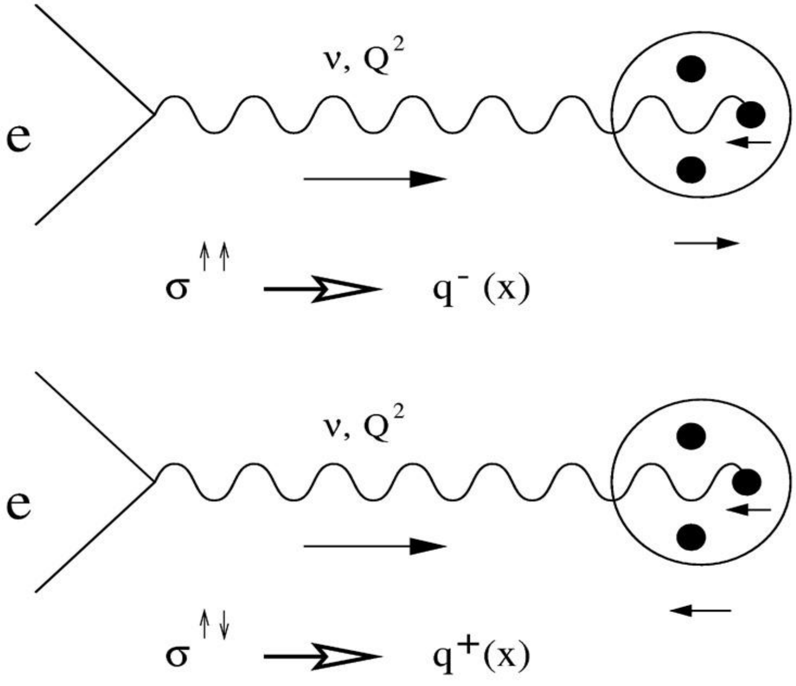
Corrected and Raw

Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

from Kent Paschke

Resolution of the Proton Spin Crisis

Spin Structure Function $g_1(x)$



$$A_{||} = \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}}$$

$x = Q^2 / 2\,M_N\,\nu$

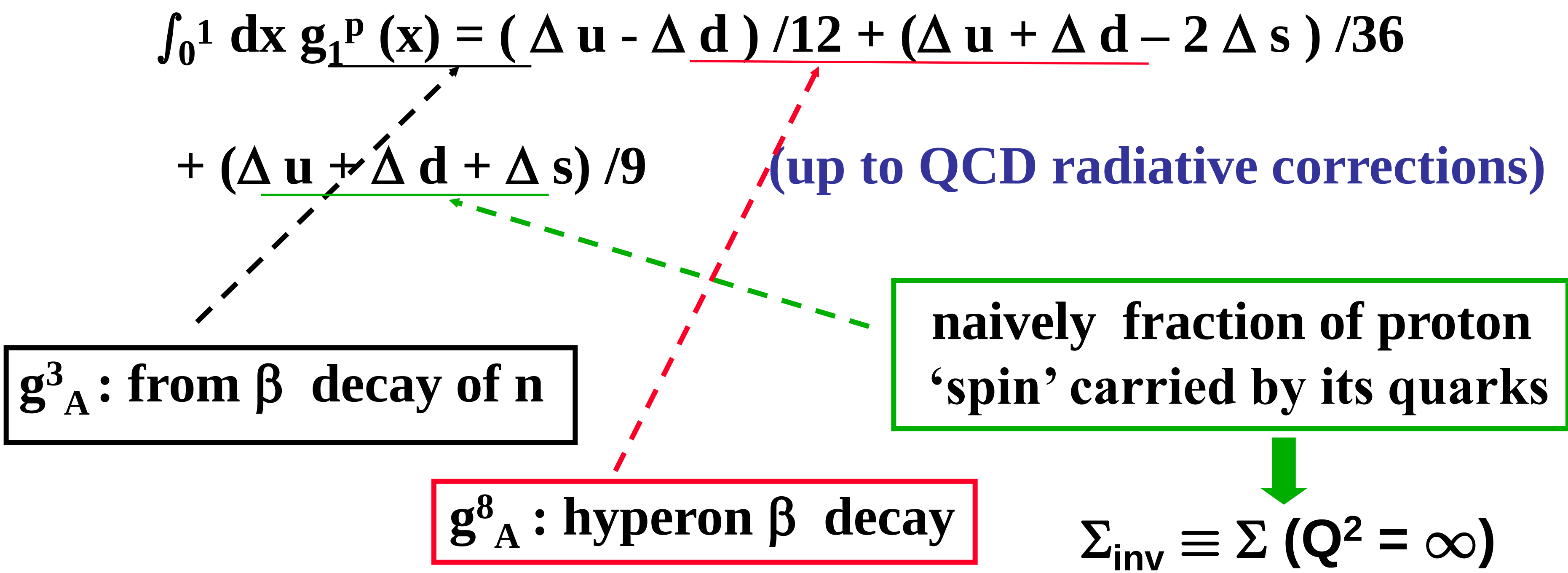
= fraction of proton momentum carried by the quark

$$\boxed{g_1(x) = \frac{1}{2}\sum_q e_q^2\left(q^+(x) - q^-(x)\right) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)}$$

N.B. At Q^2 sufficiently high (>2 GeV^2) the dependence on Q^2 is logarithmic and described by perturbative QCD (scaling)

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)

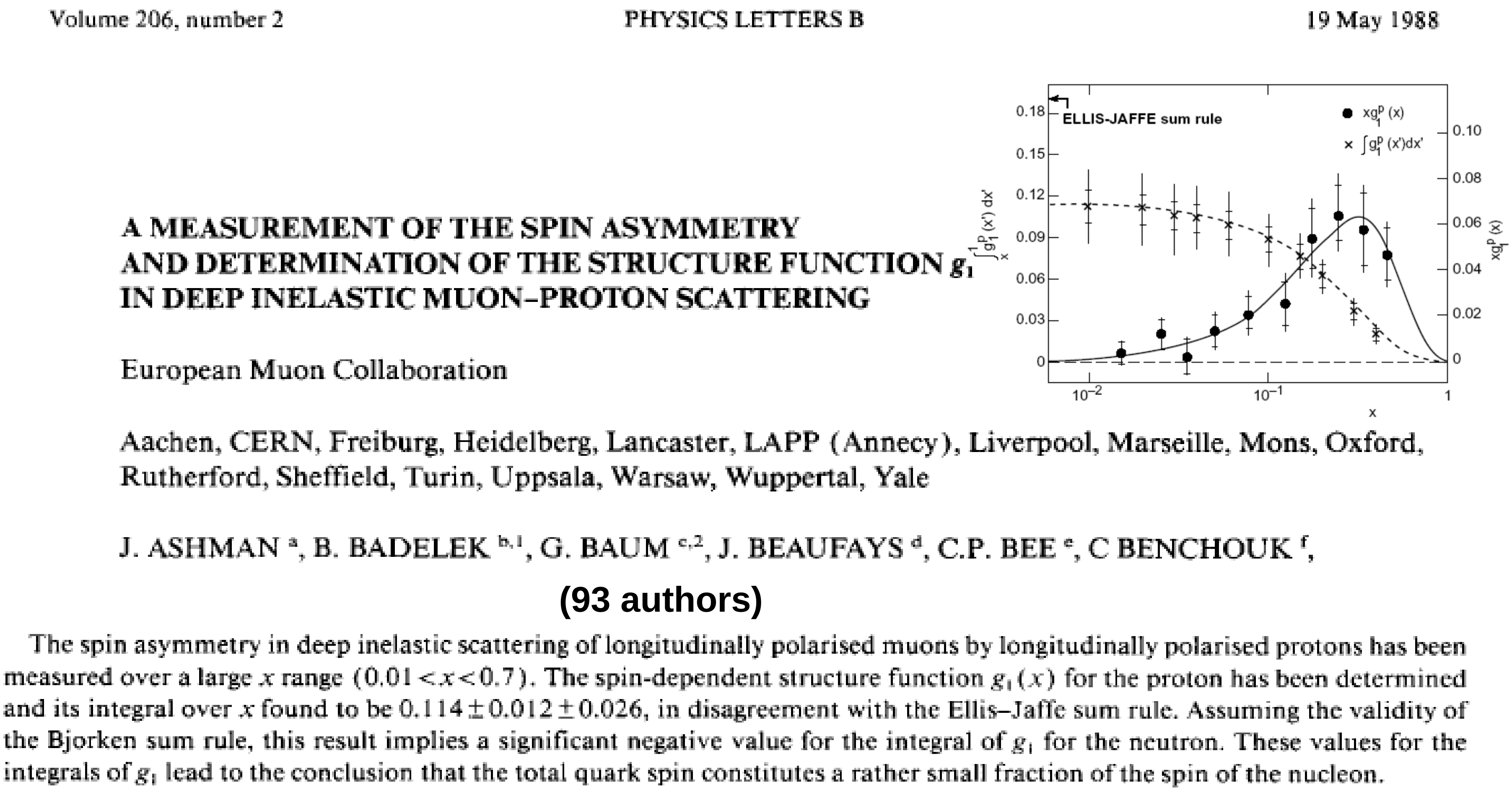
naively fraction of proton ‘spin’ carried by its quarks

g^3_A : from β decay of n

g^8_A : hyperon β decay

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

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



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

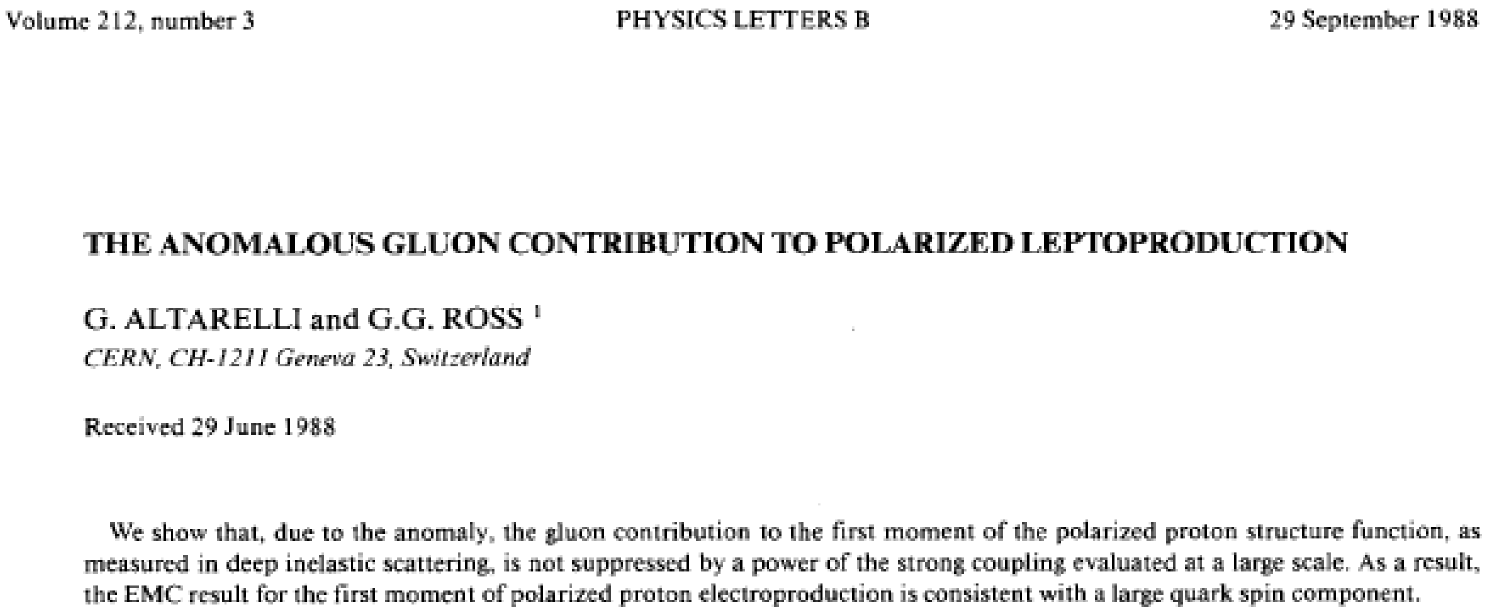
J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(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



Volume 212, number 3 PHYSICS LETTERS B 29 September 1988

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS [1]
CERN, CH-1211 Geneva 23, Switzerland

Received 29 June 1988

We show that, due to the anomaly, the gluon contribution to the first moment of the polarized proton structure function, as measured in deep inelastic scattering, is not suppressed by a power of the strong coupling evaluated at a large scale. As a result, the EMC result for the first moment of polarized proton electroproduction is consistent with a large quark spin component.

$\Sigma_{\text{naïve}} \rightarrow \Sigma_{\text{naïve}} - N_f\, \alpha_s$ (Q

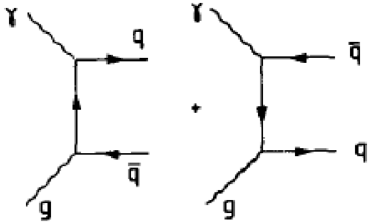


Fig. 1. Diagrams contributing to a finite mixing of order α_s between g_1^p and the polarized gluon parton density.

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

HOW MUCH?

Scale of the Gluon Contribution

At 3 GeV^2 $\alpha_s \sim 0.3$

and $N_f = 3$, so IF all of the

N spin carried by quarks is

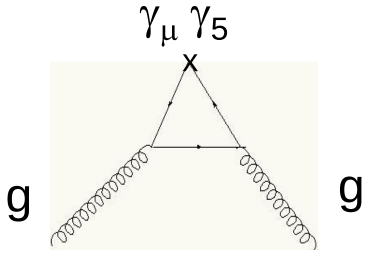
cancelled by gluons:

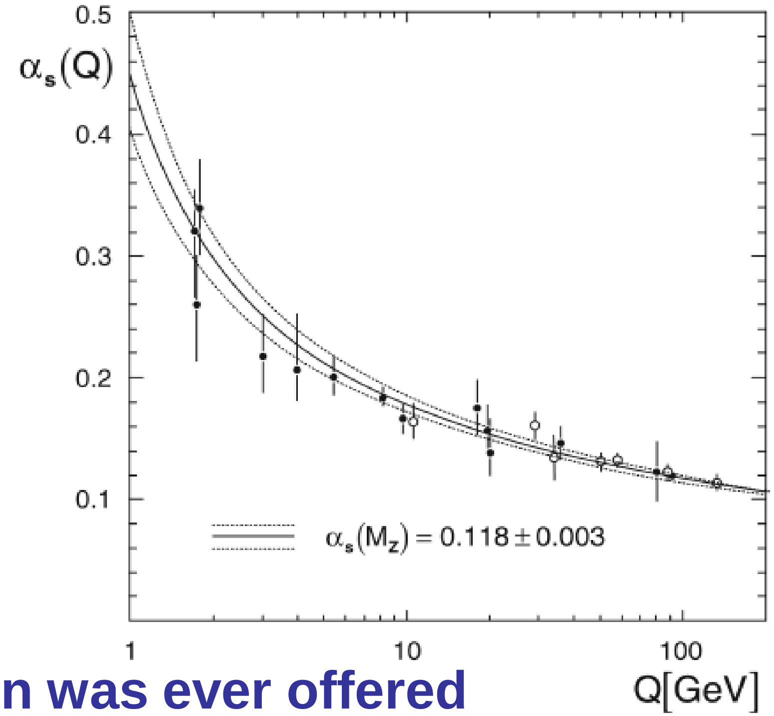
$$\Delta G = \frac{+\,2 * \pi * 1}{3 * 0.3} \sim +6$$

…actually $\Delta G \sim +4$ better

- a truly remarkable result

for which no physical explanation was ever offered





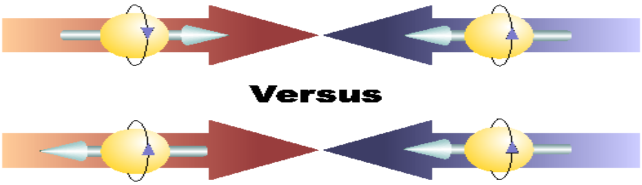
This spurred a tremendous experimental effort

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

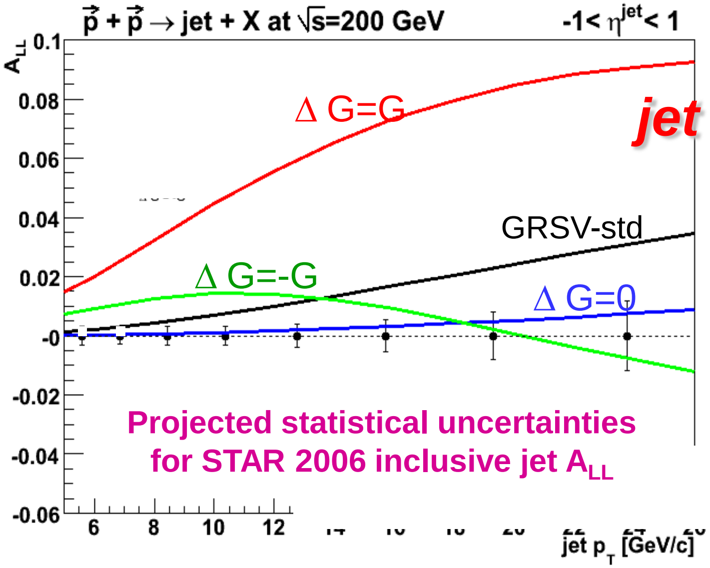
- Direct search for high-p_T hadrons at Hermes, COMPASS, RHIC to directly search for effects of polarized glue in the p

- This effort has lasted the past 20 years, with great success

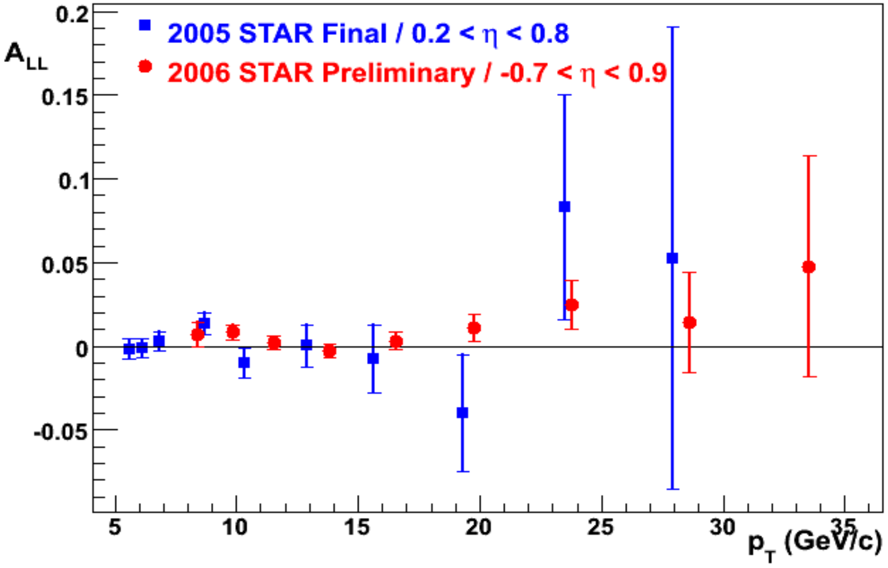
Latest STAR result - Sarsour DNP Oct 07



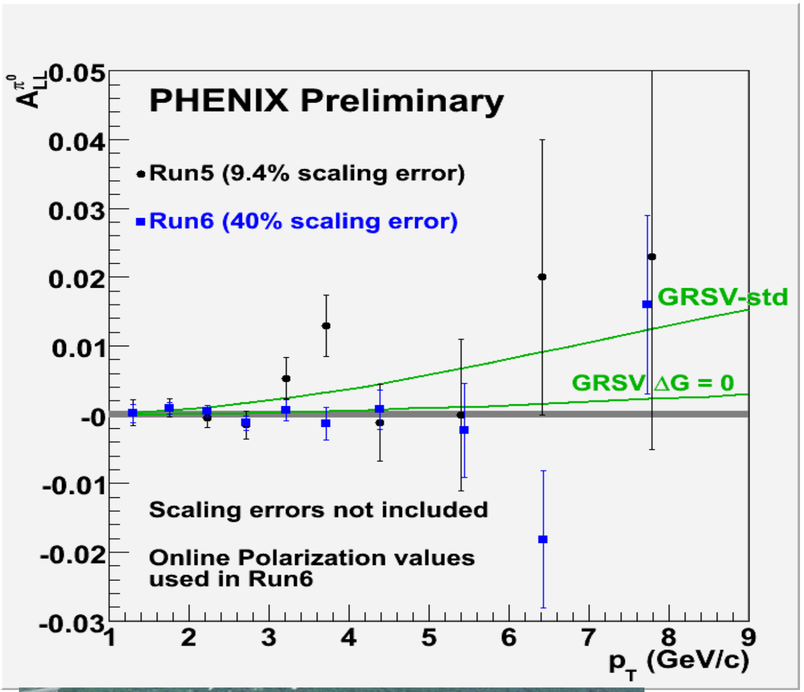
- NLO pQCD describes inclusive jet cross section at RHIC
- Within GRSV framework, 2005 results constrain ΔG to less than 65% of the proton spin with 90% confidence
- Significant increase in precision in Run 2006 data provides even stronger constraints on gluon polarization

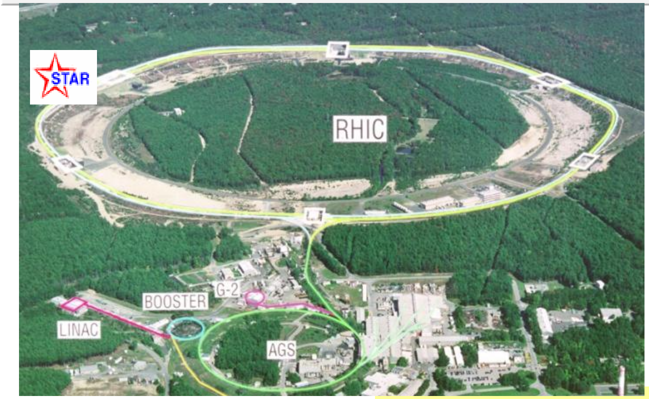


Projected statistical uncertainties for STAR 2006 inclusive jet A_{LL}



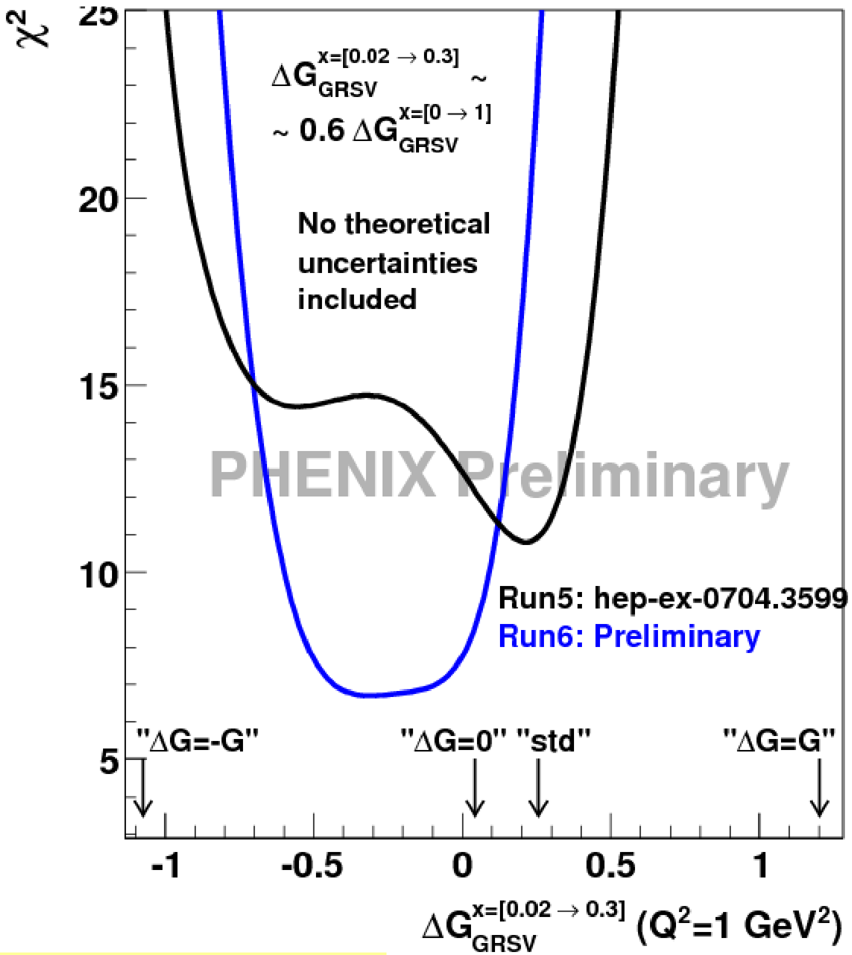
Latest PHENIX Result: From A_{LL} to ΔG





$\Rightarrow$

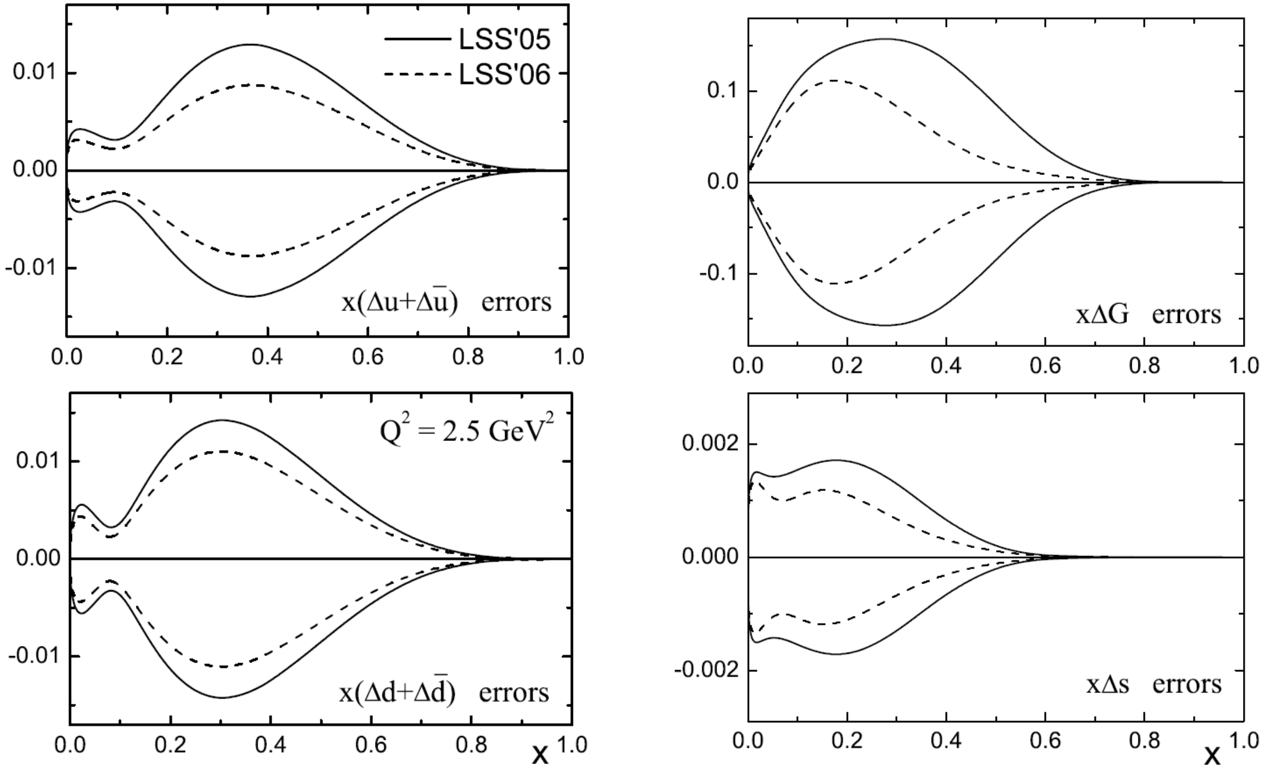
Calc. by W.Vogelsang and M.Stratmann



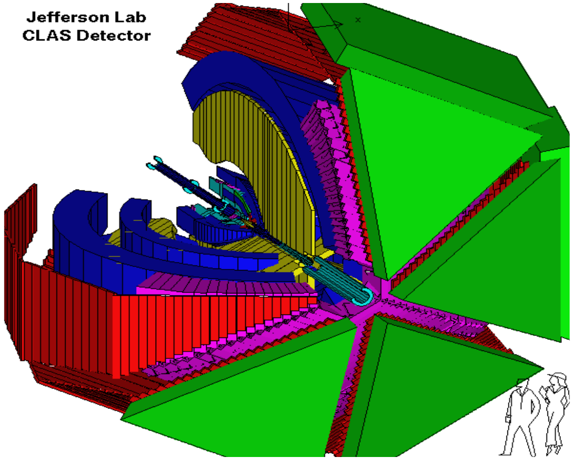
"std" scenario, $\Delta G(Q^2=1GeV^2)=0.4$, is excluded by data on >3 sigma level

Impact of CLAS Precision Data on Parton Distribution Functions

CLAS precision data more than doubled the data points in the DIS region from 30 years of high energy polarized structure function measurements.



At moderate x = 0.4, the relative uncertainty of xΔG is reduced by a factor 3 and of Δs-Δs by a factor 2.



The dashed lines include the CLAS data in the analysis (LSS'06).

E. Leader, A. Sidorov, D. Stamenov, Phys.Rev.D75:074027,200

Conclude
|Δ G | < 0.3
at $Q^2 = 1$ GeV^2

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 small role in explaining the spin crisis

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

Ancient History of the Spin Crisis

• EMC Spin Paper:	22 Dec 87 - 19 May 88
• Brodsky et al. Skyrme:	22 Feb 88 - 19 May 88
• Schreiber-Thomas CBM:	17 May 88 - 8 Dec 88
• Myhrer-Thomas OGE:	13 June 88 - 1 Sept 88

(neither paper could explain reduction to only 14%!)

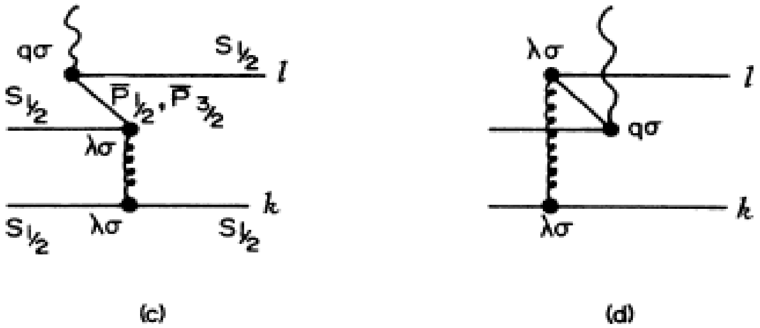
- Efremov-Teryaev Anomaly: 25 May 88
- Altarelli-Ross Anomaly: 29 June 88 - 29 Sept 88

One-Gluon-Exchange Correction

- **Has the effect of further reducing the fraction of spin carried by the quarks in the bag model (naively 0.65) because of lower Dirac component of wave function (/// result in any relativistic model - e.g. recent work of Cloet et al., hep-ph/0708.3246, 0.67 in confining NJL model)**

- **$\Sigma \to \Sigma - 3G$; with G $\sim$ 0.05**

  $\Sigma \to 0.65 - 0.15 = 0.5$



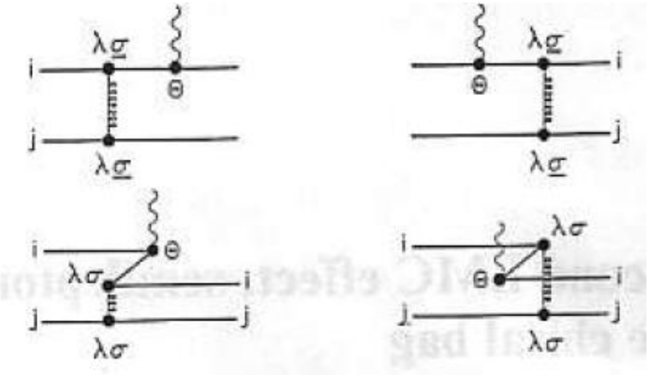
(c) (d)

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

Myhrer & Thomas, Phys R ev D38 (1988)

OGE Correction for Hyperon β-decay

- All correction terms proportional to G = α_s times bag matrix elements
- Very nicely accounts for deviations from SU(3) symmetry



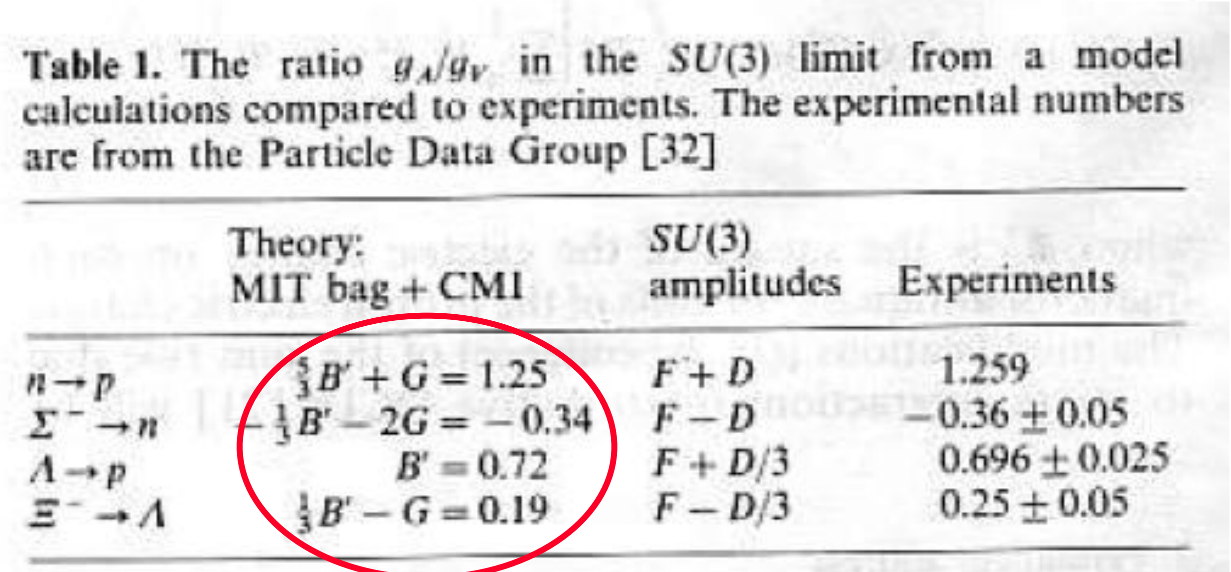


Table 1. The ratio g_A/g_V in the $SU(3)$ limit from a model calculations compared to experiments. The experimental numbers are from the Particle Data Group [32]

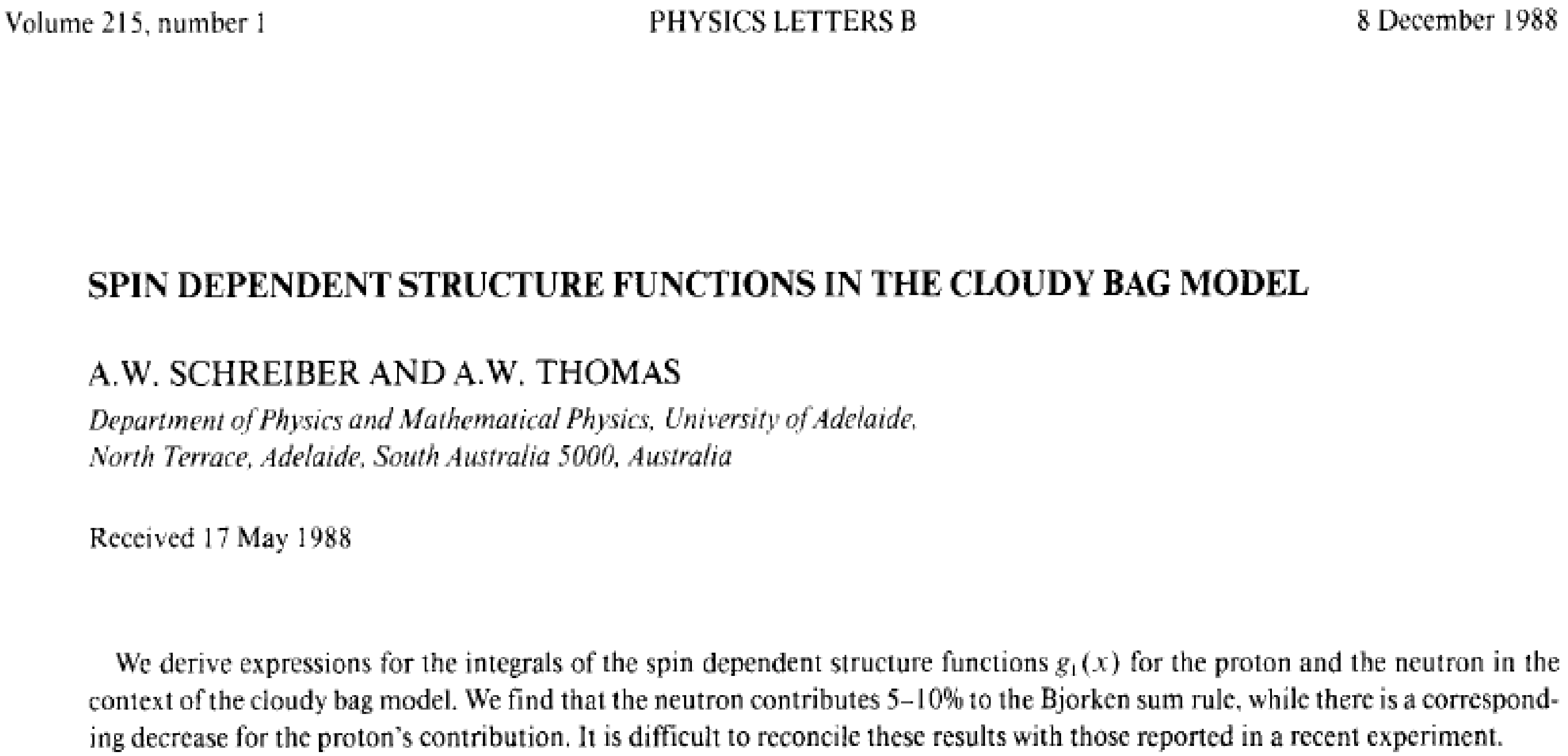
	Theory: MIT bag + CMI	$SU(3)$ amplitudes	Experiments
$n \rightarrow p$	$\frac{5}{3}B' + G = 1.25$	$F + D$	1.259
$\Sigma^- \rightarrow n$	$-\frac{1}{3}B' - 2G = -0.34$	$F - D$	-0.36 ± 0.05
$\Lambda \rightarrow p$	$B' = 0.72$	$F + D/3$	0.696 ± 0.025
$\Xi^- \rightarrow \Lambda$	$\frac{1}{3}B' - G = 0.19$	$F - D/3$	0.25 ± 0.05

F = 0.45 (fixed)
D = 0.81
D = 0.74
D = 0.60

Without OGE correction
MIT bag gives F = 2B′ /3, D = B′

Hogaasen & Myhrer, Z. Phys. C48 (1990) 295
Yamaguchi et al., Nucl. Phys. A 500 (1989) 429

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

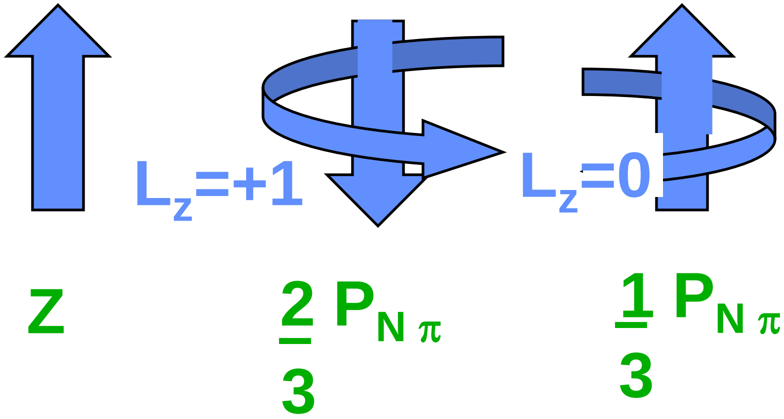
Received 17 May 1988

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.

Effect of the Pion Cloud

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

- **Biggest Fock Component is N $\pi \sim$ 20-25% and 2/3 of time N spin points down**



- **Next biggest is $\Delta\,\pi \sim$ 5-10%**

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

- **Spin gets renormalized by a factor :**

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

$$\Rightarrow \Sigma = 0.65 \rightarrow 0.49 - 0.52$$

Final Result for Quark Spin

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

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

c.f. Experiment: $0.33 \pm 0.03 \pm 0.05$

- 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

The Balance Sheet – fraction of total spin

	L_{u+ubar}	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: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$

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

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 “resolution”)

- N.B. Disconnected terms missing → no anomaly, sea wrong

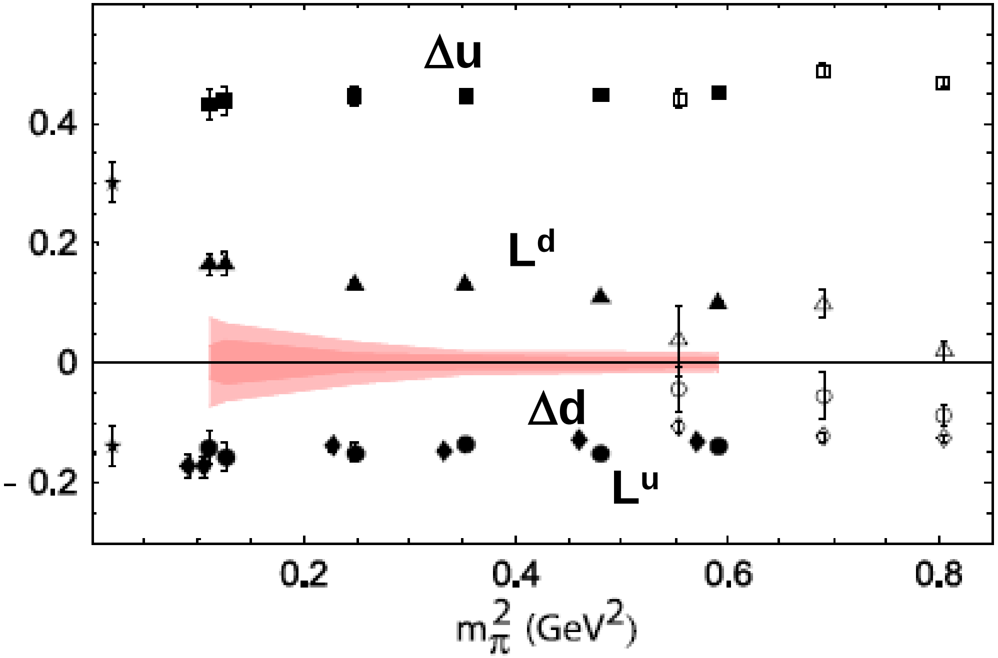


Figure 16: Nucleon spin decomposition by flavor. Squares denote $\Delta\Sigma^u/2$, diamonds denote $\Delta\Sigma^d/2$, triangles denote L^u, and circles denote L^d.

LHPC: hep-lat/0610007

Indeed L_z is not scale invariant – 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 $Q^2 \uparrow$ 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

(N.B. Using LO rather than NLO QCD changes μ not the results at 5-10 GeV^2)

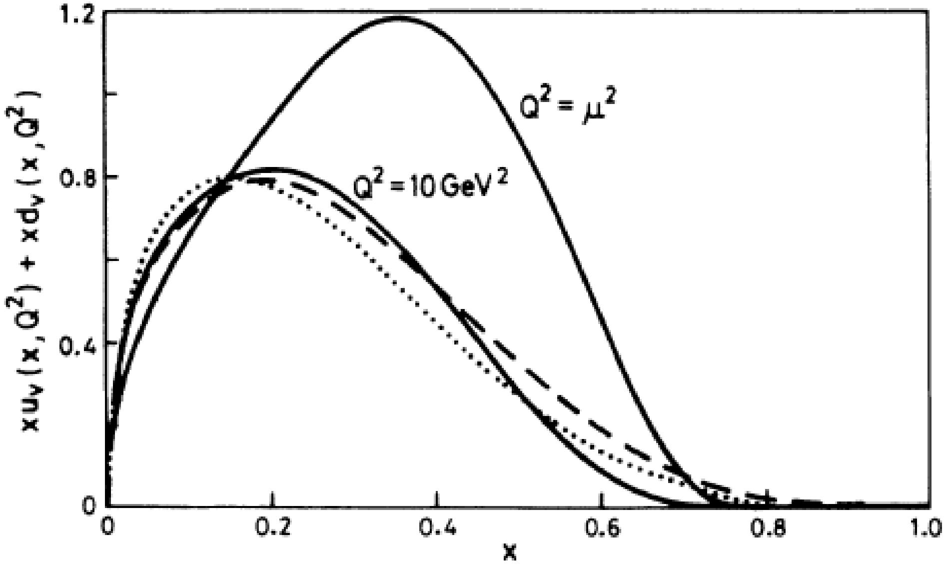
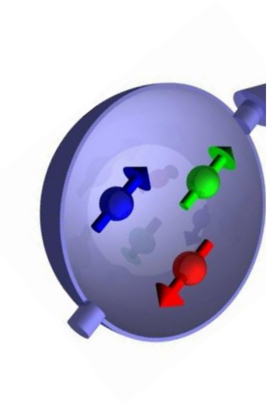


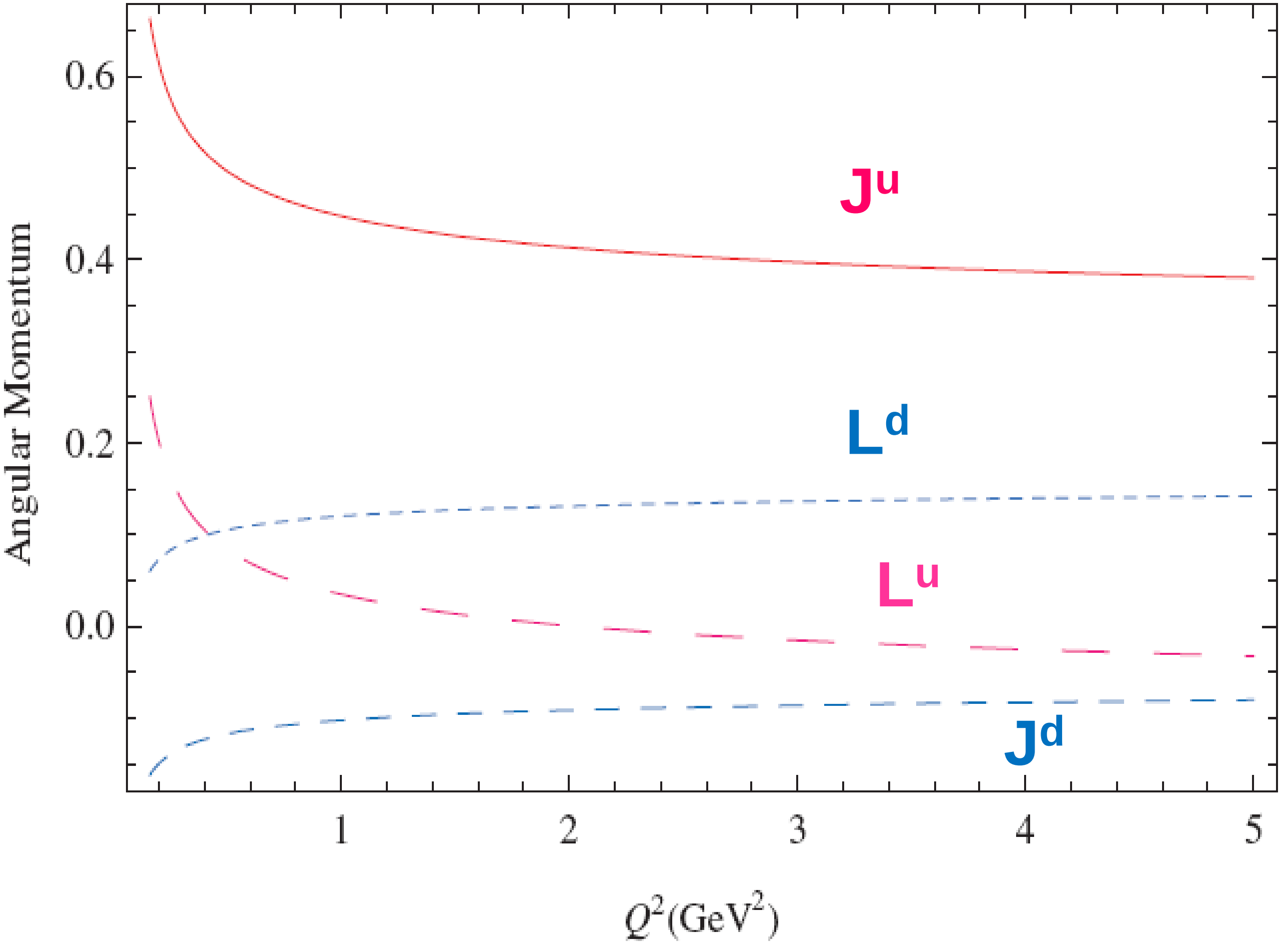
FIG. 1. $xu_v(x,Q^2)+xd_v(x,Q^2)$ at the model scale $Q^2=\mu^2$ and at $Q^2=10$ GeV^2 (solid lines). The dashed and dotted lines correspond to the Duke-Owens and Martin-Roberts-Stirling parametrizations of $xu_v(x,Q^2=10$ GeV$^2)+xd_v(x,Q^2=10$ GeV$^2)$,

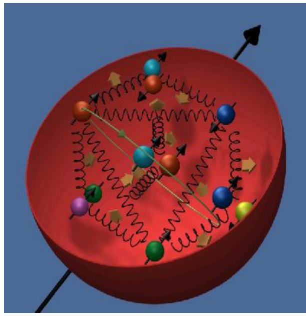
Solution of the Evolution Equations

L^u and L^d both small and cross-over rapidly: AWT, PRL 101 (2008) 102003

- model independent !

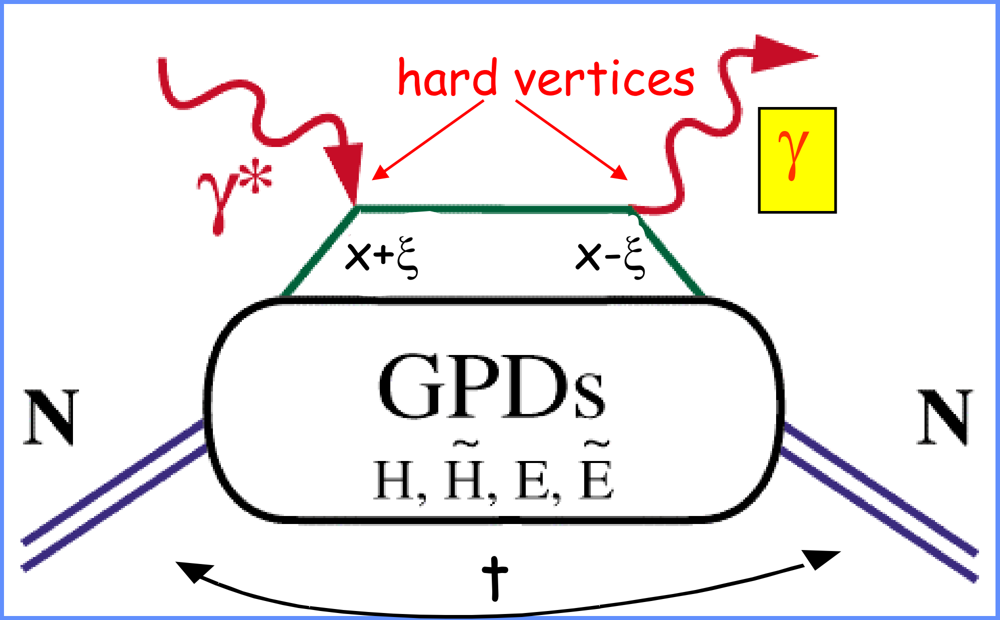






GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

At large Q^2 : QCD factorization theorem → hard exclusive process can be described by 4 transitions (Generalized Parton Distributions) :

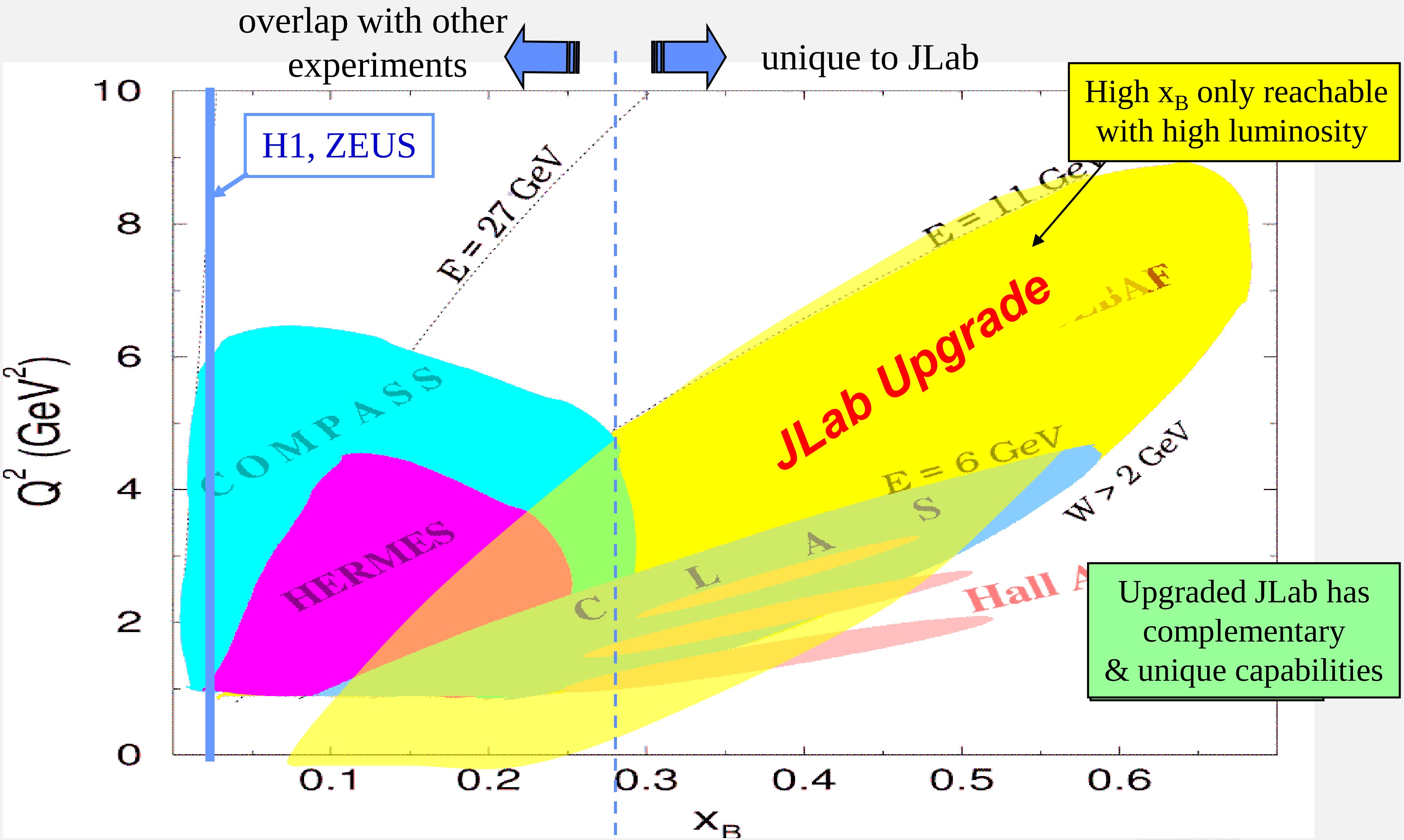
Vector : $H(x, \xi, t)$

Tensor : $E(x, \xi, t)$

Axial-Vector : $\tilde{H}(x, \xi, t)$

Pseudoscalar : $\tilde{E}(x, \xi, t)$

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



High x_B only reachable with high luminosity

Upgraded JLab has complementary & unique capabilities

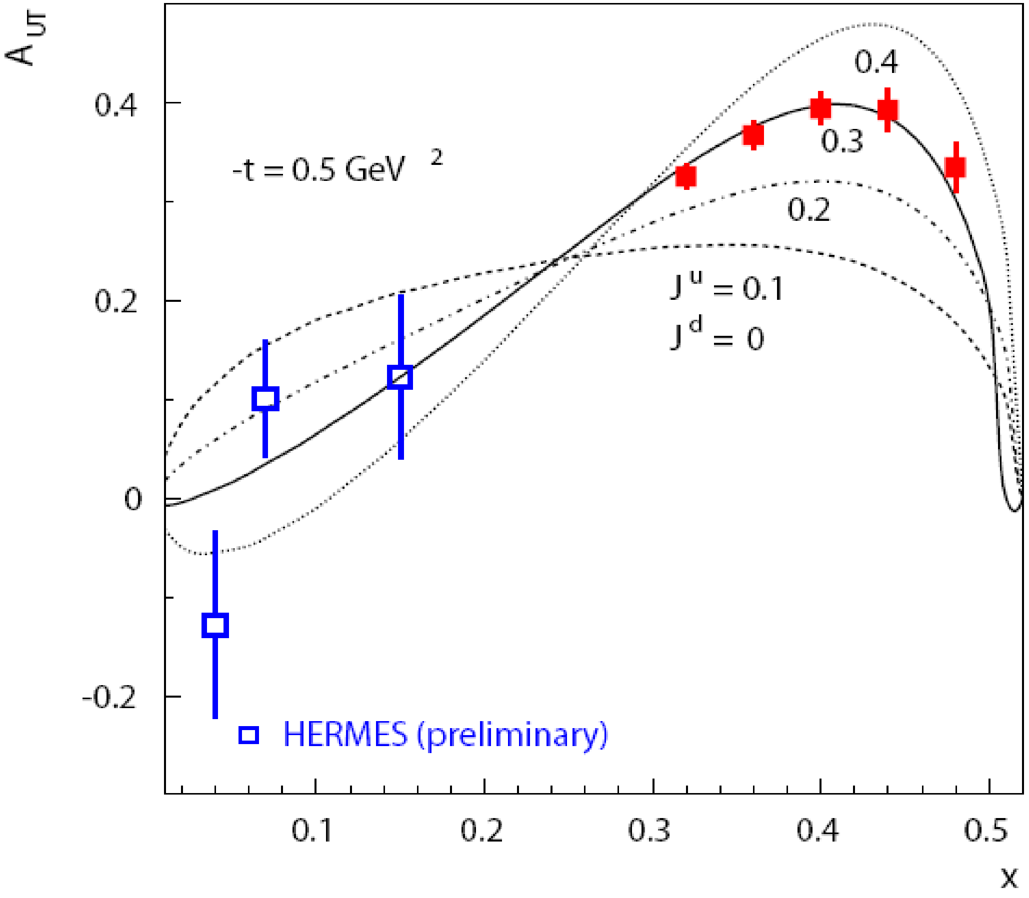
At 12 GeV: e.g. Exclusive ρ^0 with transverse target expect to determine quark orbital angular momentum

$$A_{UT} = -\frac{2\Delta \{\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

$\boxed{\rho^0}$

$A \sim (2H^u + H^d)$

$B \sim (2E^u + E^d)$



$Q^2 = 5\mathrm{GeV}^2$

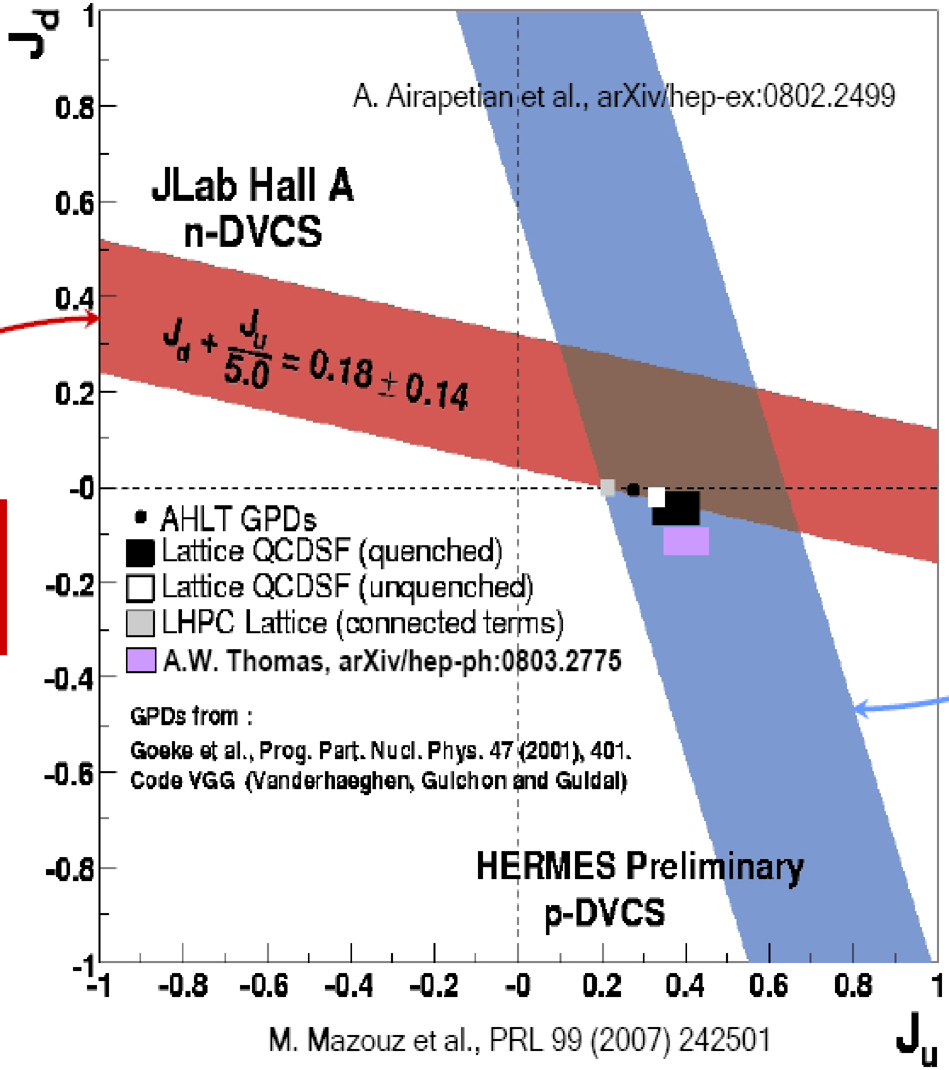
Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

K. Goeke, M.V. Polyakov,
M. Vanderhaeghen, 2001

Model Dependent Quark Angular Momenta

$$\chi^2_{\min} \le \chi^2(J_u,J_d) = \sum_i \frac{\left(\Im m\left[C_n^I(\mathcal{F})\right]^{\exp}(t_i) - \Im m\left[C_n^I(\mathcal{F})\right]^{J_u,J_d}_{VGG}(t_i)\right)^2}{\left[\delta^{\exp}_{stat}(t_i)\right]^2+\left[\delta^{\exp}_{syst}(t_i)\right]^2} \le \chi^2_{\min}+1$$

From Eric Voutier (ECT* June 08)



A. Airapetian et al., arXiv/hep-ex:0802.2499

M. Mazouz et al., PRL 99 (2007) 242501

Measurements off **neutron** are sensitive to J_d (**u** quark in the **neutron**)

Measurements off **proton** are sensitive to J_u (**u** quark in the **proton**)

Electromagnetic Calorimeter

- These experiments show the **complementarity** between **neutron** and **proton** data, and

Additional Observation

- Recall that polarized glue is generated by pQCD evolution

$$-\frac{N_f\,\alpha_s(Q^2)}{2\pi}\Delta G(Q^2) \rightarrow -N_f\frac{8\Sigma}{\beta_0^2 t_0}$$

- This yields a correction of order -0.11 from Σ to Σ_{inv}

$\Rightarrow \ \Sigma_{inv} \in (0.25, 0.29)$

$\Rightarrow \Delta$ s $\sim$ -0.04 (primarily through axial anomaly)

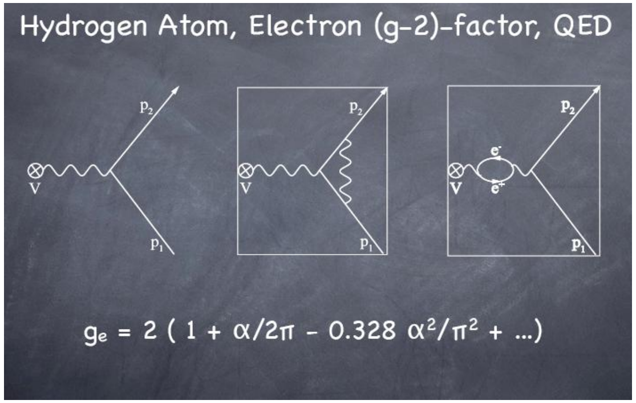
- Still in excellent agreement with experiment

Conclusion

- Extremely impressive results for absolute masses of baryon octet using FRR
- σ commutator very accurate: 51 ± 7 MeV
- $B_u : B_d \approx 1 : 1$ (*not* 1.49)
- Strangeness σ commutator *order of magnitude smaller than usual*, naïve SU(3) analysis : 18 ± 12 MeV (c.f. 330 MeV)
- Major importance for dark matter searches

Conclusion (cont.)

- Strange content of N small
  - Less than 5% of μ^p and $< r^2 >_{ch}^p$
- Theory agrees well but order of magnitude more accurate
- Major success of QCD : direct insight into "disconnected diagrams"
  - analogue of Lamb shift



Conclusion (cont.)

- Proton spin problem appears to be resolved — relativistic motion, OGE, chiral symmetry

- Large fraction of the spin is carried as quark orbital angular momentum
- Caution not RGI: this inverts L^u and L^d
- Future experiments at JLab, using DVCS should test this quantitatively
- Initial investigations promising