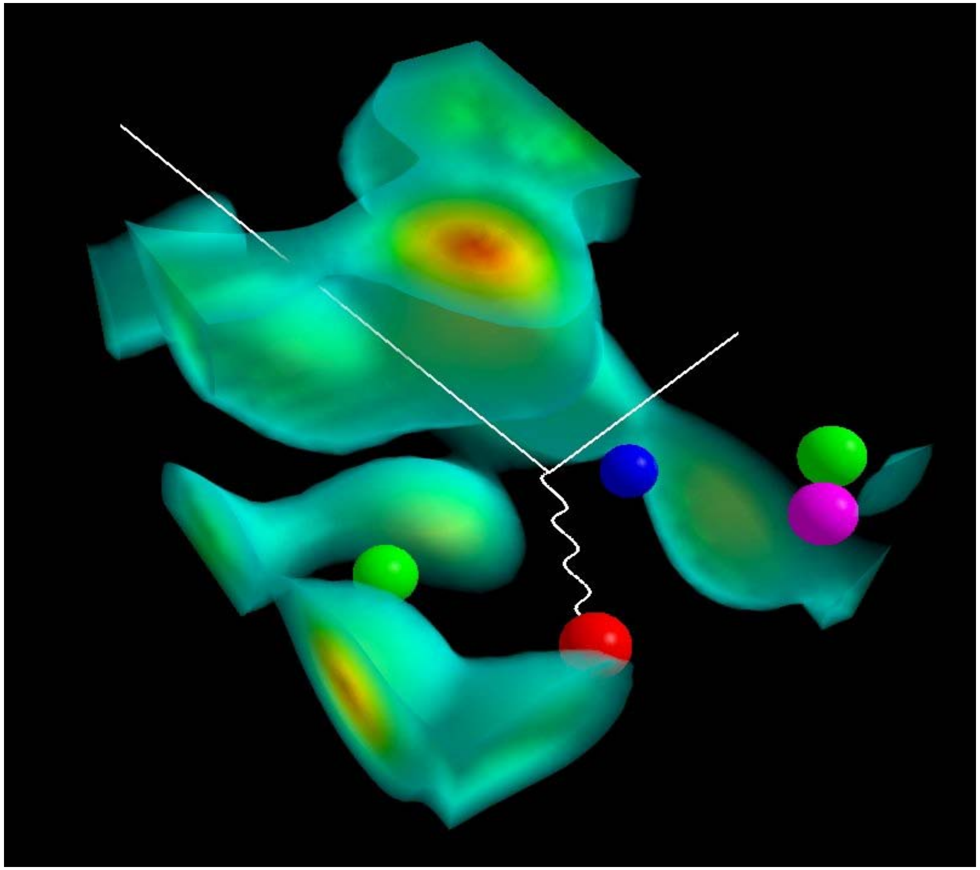
Challenges in the Spin and Flavour Structure of PDFs



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Anthony W. Thomas

POETIC : Universidad Técnica Federico Santa María
Valparaiso, Chile – March 5th 2013

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Outline

- **Chiral symmetry of QCD : asymmetries**
  - **$\bar{d} \neq \bar{u}$; $s \neq \bar{s}$**

- **Charge Symmetry Violation**

- **NuTeV "anomaly"**

- **Test of the QCD origin of nuclei : isovector EMC effect**

- **Resolution of the NuTeV "anomaly"**

- **Nucleon spin and quark angular momentum**

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Asymmetries in the Sea:

– from Chiral Symmetry

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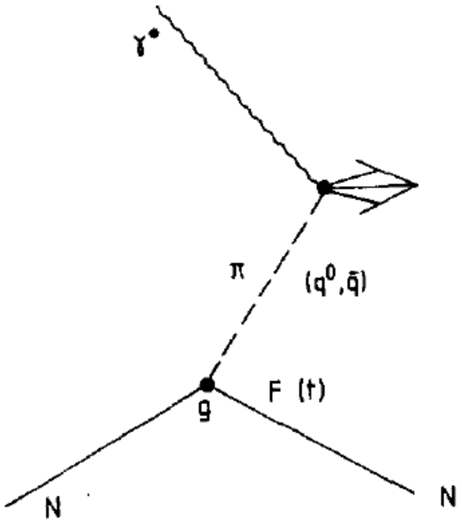
Symmetry Breaking in the Nucleon Sea

- **Role of pion cloud in DIS first investigated by (Feynman) and Sullivan**

- **Generally ignored until:**

Volume 126B, number 1,2 PHYSICS LETTERS



A LIMIT ON THE PIONIC COMPONENT OF THE NUCLEON THROUGH SU(3) FLAVOUR BREAKING IN THE SEA

A.W. THOMAS
CERN, Geneva, Switzerland

Dominant role of π^+ for proton predicts violation of Gottfried sum-rule

"Clearly the pion exchange process of fig. 1 does predict that the excess of $\bar{D}$ to $\bar{U}$ should be in the ratio 5 to 1 in the proton."

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Pion Cloud (cont.)

- It only makes sense to consider this as a separate process *provided there is a significant rapidity gap*

- Often forgotten later when investigators added ρ and heavier mesons

- Probably πΔ Fock component makes sense but nothing much heavier

- Predicted violation of Gottfried sum-rule not confirmed for 10 years

Gottfried Sum Rule: NMC 1994: $S_G = 0.258 \pm 0.017\ [Q^2 = 4\,\text{GeV}^2]$

$$S_G = \int_0^1 \frac{dx}{x}\,[F_{2p}(x) - F_{2n}(x)] = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,\left[\bar{d}(x) - \bar{u}(x)\right]$$

- Consistent with range predicted by the pion cloud....

$$\int_0^1 dx\,[\,\bar{d} - \bar{u}\,] = 2\,P_{N\pi}/3 - P_{\Delta\pi}/3$$

$$\varepsilon\ 0.11 - 0.15$$

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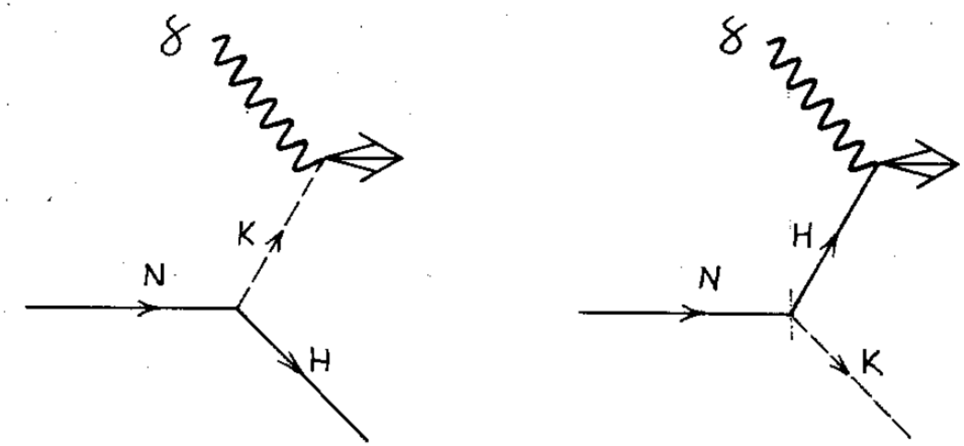
Strange Sea of the Nucleon

Similar mechanism for kaons implies s – $\bar{s}$ 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 *STILL* not been measured experimentally....**

− but it *does* matter!

Signal and Thomas, Phys. Lett. 191B (1987) 205

Dependence of s- $\bar{s}$ on assumed cross-over

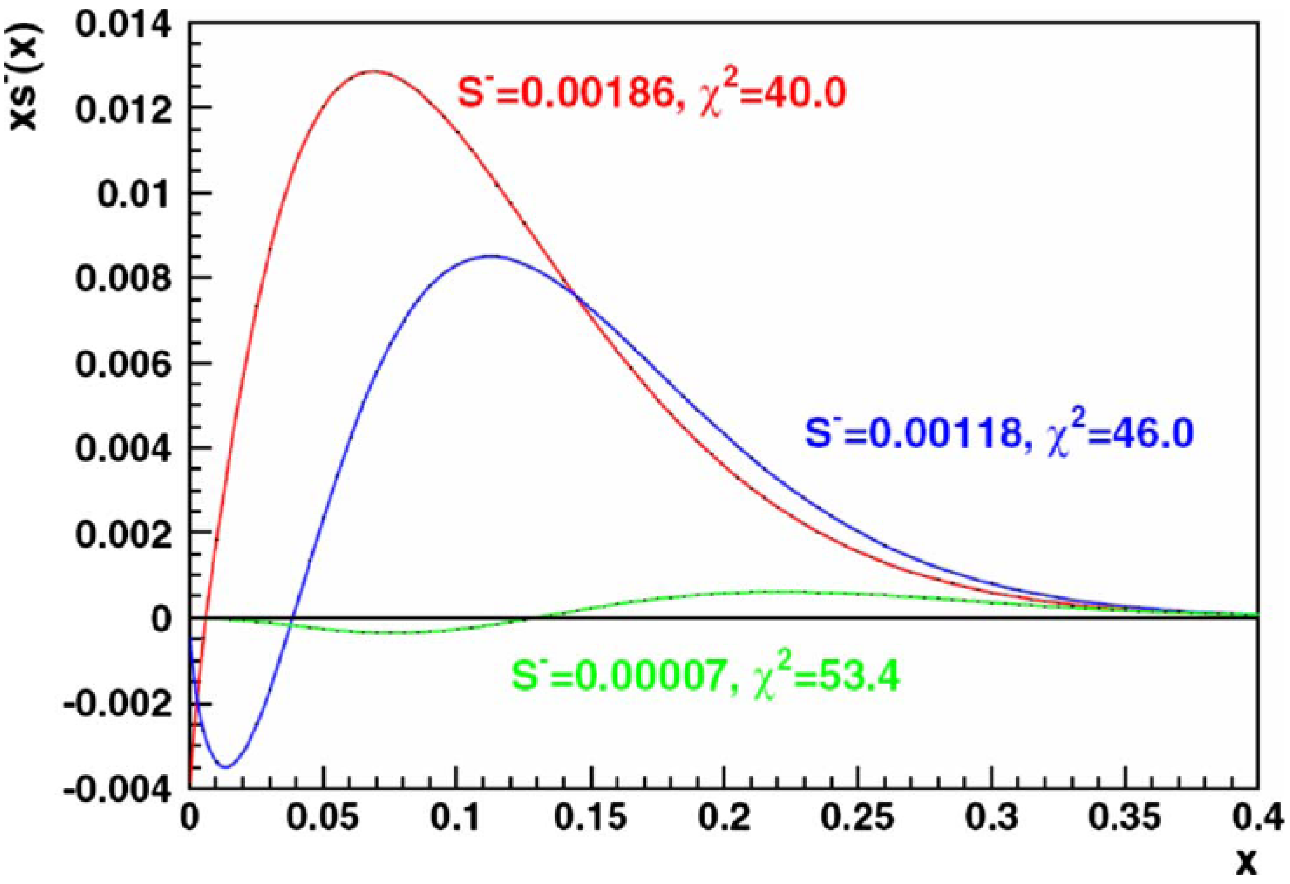


FIG. 16. (Color online) The quantity $xs^{-}(x) = x[s(x) - \bar{s}(x)]$ vs x, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The χ^2 value is listed for each curve. From Mason *et al.*, 2007.

Dynamical Symmetry Breaking in the Sea of the Nucleon

A. W. Thomas,[1] W. Melnitchouk,[1,2] and F. M. Steffens[3]

$$(S - \bar{S})^{(n)} = \int_0^1 dx\, x^n [s(x) - \bar{s}(x)] = V_\Lambda^{(n)} \cdot f_{\Lambda K}^{(n)} - V_K^{(n)} \cdot f_{K\Lambda}^{(n)}$$

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

nth moment of $\bar{s}$ is of order $m_K^{2n+2} \log m_K^2$

LNA contribution to the nth 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 and therefore s – $\bar{s}$ has to be non-zero as a matter of principle!

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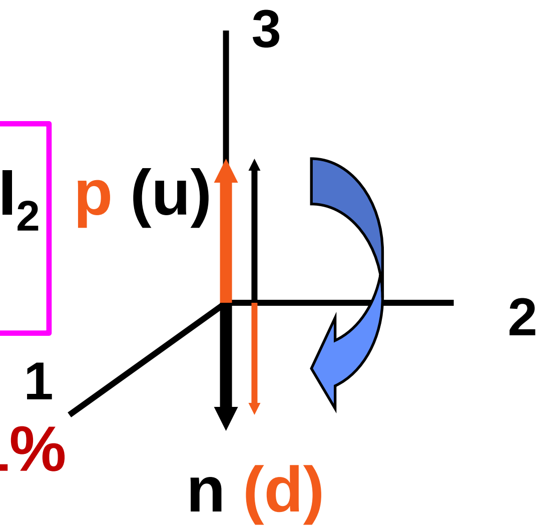
Violation of Charge Symmetry

P-W Sum Rule Assumes Charge Symmetry

Traditionally there is NO label “p” on PDF’s !

Its assumed that charge symmetry: $e^{i \pi I_2}$ is exact.



Good at < 1% : e.g. $(m_n - m_p) / m_p \sim 0.1\%$

That is: $u \equiv u^p = d^n$

$d \equiv d^p = u^n$ **etc.**

Hence:

$$F_2^{\,n} = 4/9 \times (d(x) + \bar{d}(x)) + 1/9 (u(x) + \bar{u}(x))$$

up-quark in n **down-quark in n**

Charge Symmetry is almost universally *assumed* in the analysis of PDFs and it is vital to establish how accurately it is satisfied.

Non-Perturbative Structure of Nucleon

To calculate PDFs need to evaluate non-perturbative matrix elements

Using either : i) lattice QCD or ii) Model

i) Lattice QCD can only calculate low moments of $u^p - d^p$

quite a lot has been learnt....

BUT nothing about CSV until December 2010 – see later

Estimates of Charge Symmetry Violation*

- see Londergan et al., Rev Mod Phys 82 (2010) 2009-2052 for modern review

- Origin of effect is $m_d \neq m_u$

- Unambiguously predicted : $\delta d_V - \delta u_V > 0$

- Biggest % effect is for minority quarks, i.e. δd_V

- Same physics that gives : d_V / u_V small as $x \rightarrow 1$

  and : g^p_1 and $g^n_1 > 0$ at large x

Close & Thomas, Phys Lett B212 (1988) 227

i.e. mass difference of quark pair spectators to hard scattering

* Sather, Phys Lett B274 (1992) 433;
Rodionov et al., Mod Phys Lett A9 (1994) 1799

Di-quark Spectator States Dominate Valence

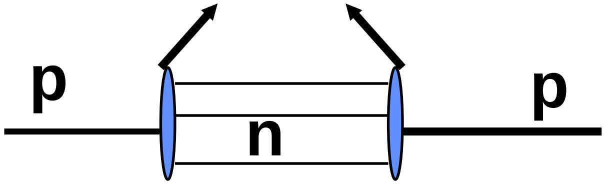
For s-wave valence quarks, most likely three-momentum is zero :

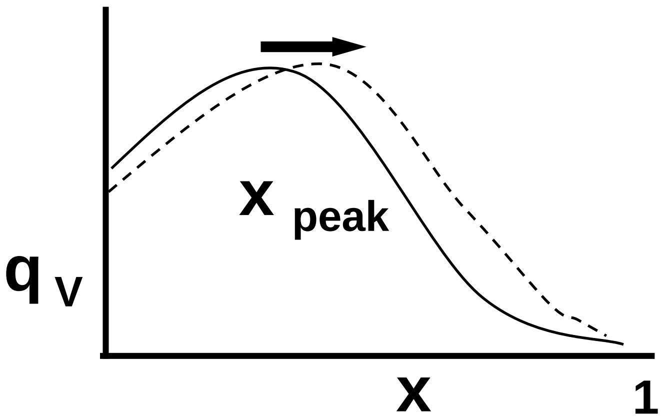
$\delta(M (1 - x) - m_n)$ determines x where $q (x, Q^2_0)$ is maximum

i.e. $x_{peak} = (M - m_n) / M$ and hence lowest $m_n \rightarrow$ large – x behaviour

Natural choice is two-quark state

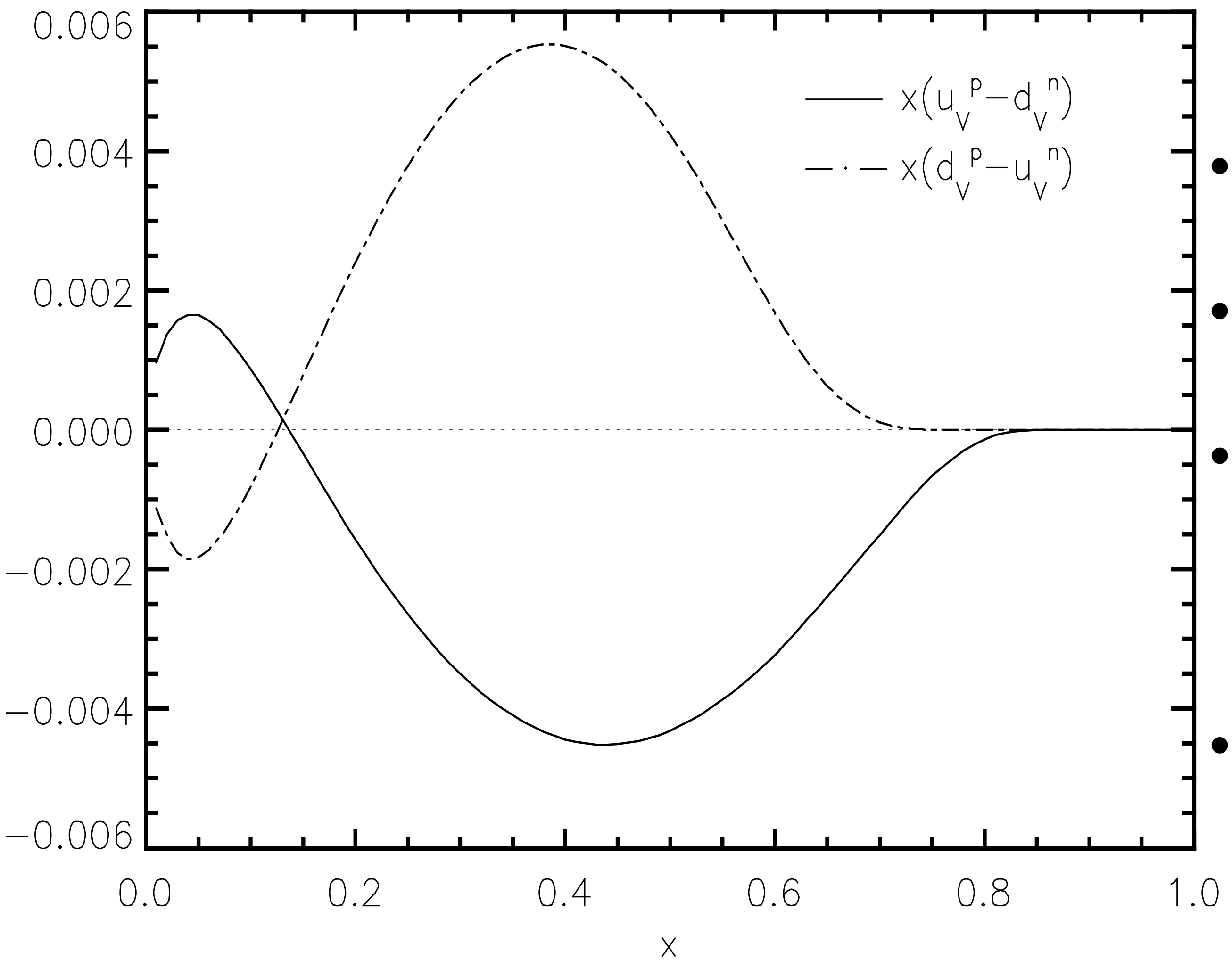
$m_2 / M = 2/3$ (CQM);
= 3/4 MIT bag ➡ $x_{peak} \sim 1/4$ to $1/3$





If $m_2 \downarrow$: x_{peak} moves to right

Application to Charge Symmetry Violation



- **d in p : uu left**
- **u in n : dd left**
- **Hence m_2 lower by about 4 MeV for d in p than u in n**
- **Hence $d^p > u^p$ at large x.**

This amount of CSV reduces NuTeV anomaly by ~1σ

From: Rodionov et al., Mod Phys Lett A9 (1994) 1799

Remarkably Similar to MRST Fit a Decade Later

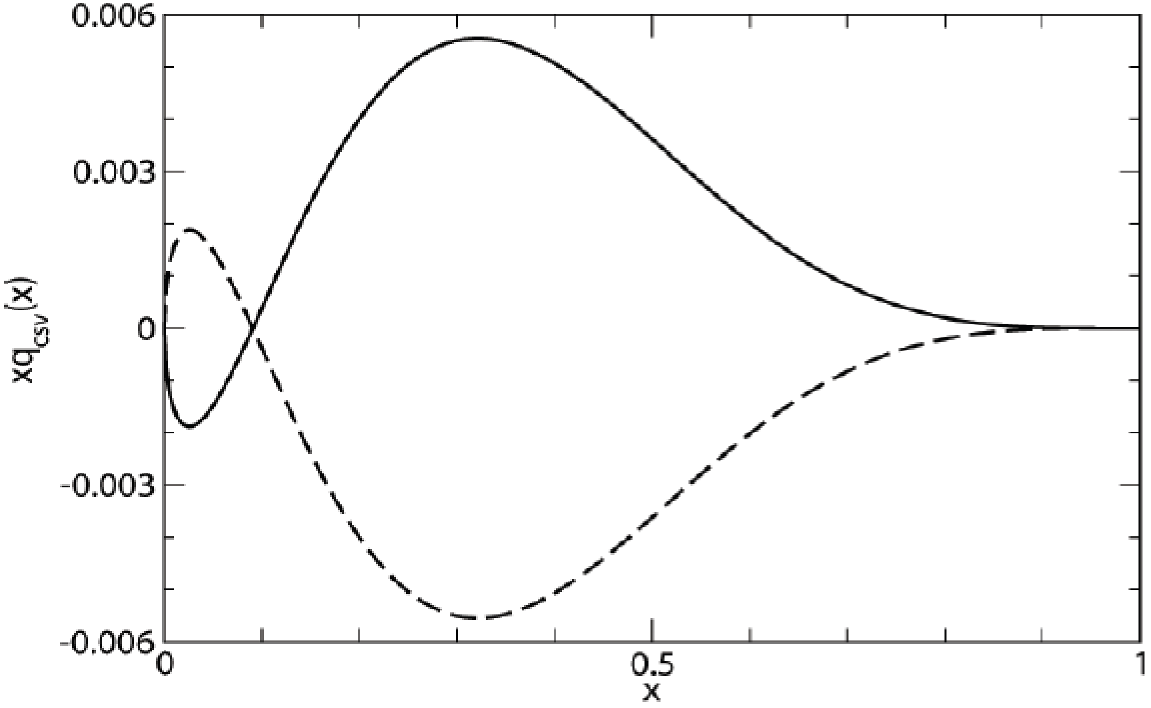
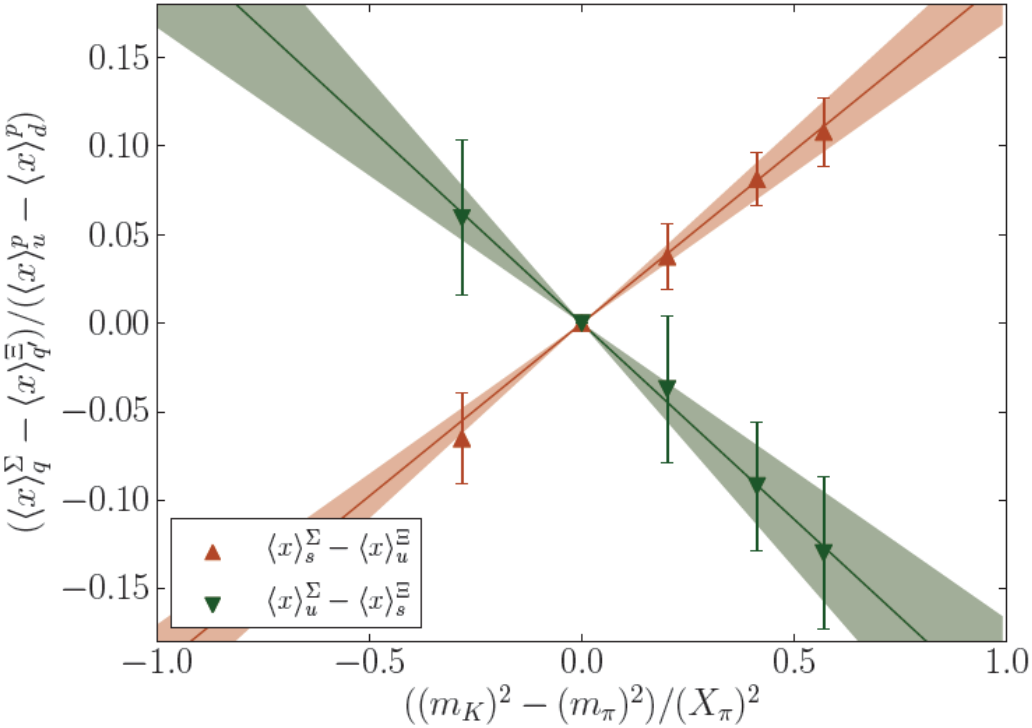


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_{\rm v}$; dashed curve: $x\delta u_{\rm v}$.

Eur. Phys. J. C39 (2005) 155-161

Strong support from 2011 lattice QCD calculation

Study moments of octet baryon PDFs



$$\frac{\delta u}{\langle x\rangle_{u-d}^p} = \frac{m_\delta}{\overline{m}_q}\frac{(\langle x\rangle_u^{\Sigma^+} - \langle x\rangle_s^{\Xi^0})/\langle x\rangle_{u-d}^p}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

$$\frac{\delta d}{\langle x\rangle_{u-d}^p} = \frac{m_\delta}{\overline{m}_q}\frac{(\langle x\rangle_s^{\Sigma^+} - \langle x\rangle_u^{\Xi^0})/\langle x\rangle_{u-d}^p}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

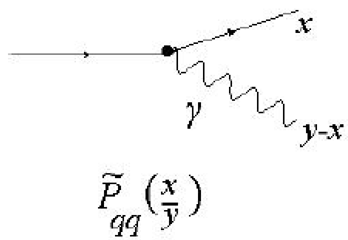
Deduce: $\delta u^+ = -0.0023(6), \quad \delta d^+ = 0.0020(3)$

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

Horsley et al., Phys. Rev. D83 (2011) 051501

An additional source of CSV

- **In addition to the u-d mass difference, MRST (Eur Phys J C39 (2005) 155) and Glück et al (PRL 95 (2005) 022002) suggested that "QED splitting":**



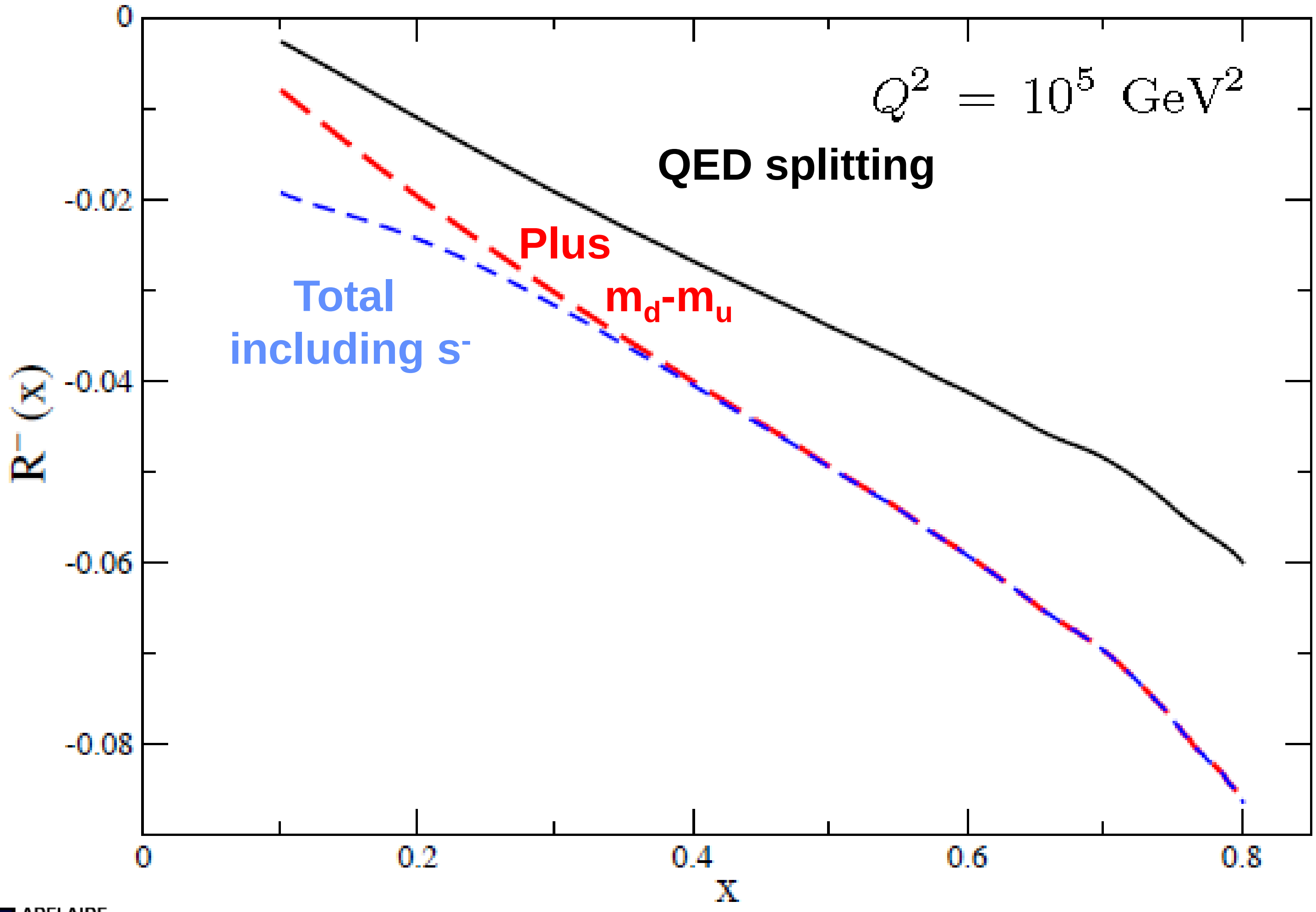
- **which is obviously larger for u than d quarks, would be an additional source of CSV. Assume zero at some low scale and then evolve – so CSV from this source grows with Q^2**

- **Effect on NuTeV is exactly as for regular CSV and magnitude but grows logarithmically with Q^2**

- **For NuTeV it gives:** $\Delta R^{\mathrm{QED}} = -0.0011$ **to which we assign 100% error**

Test at Future EIC or LHeC – σ_{CC}

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)}$$

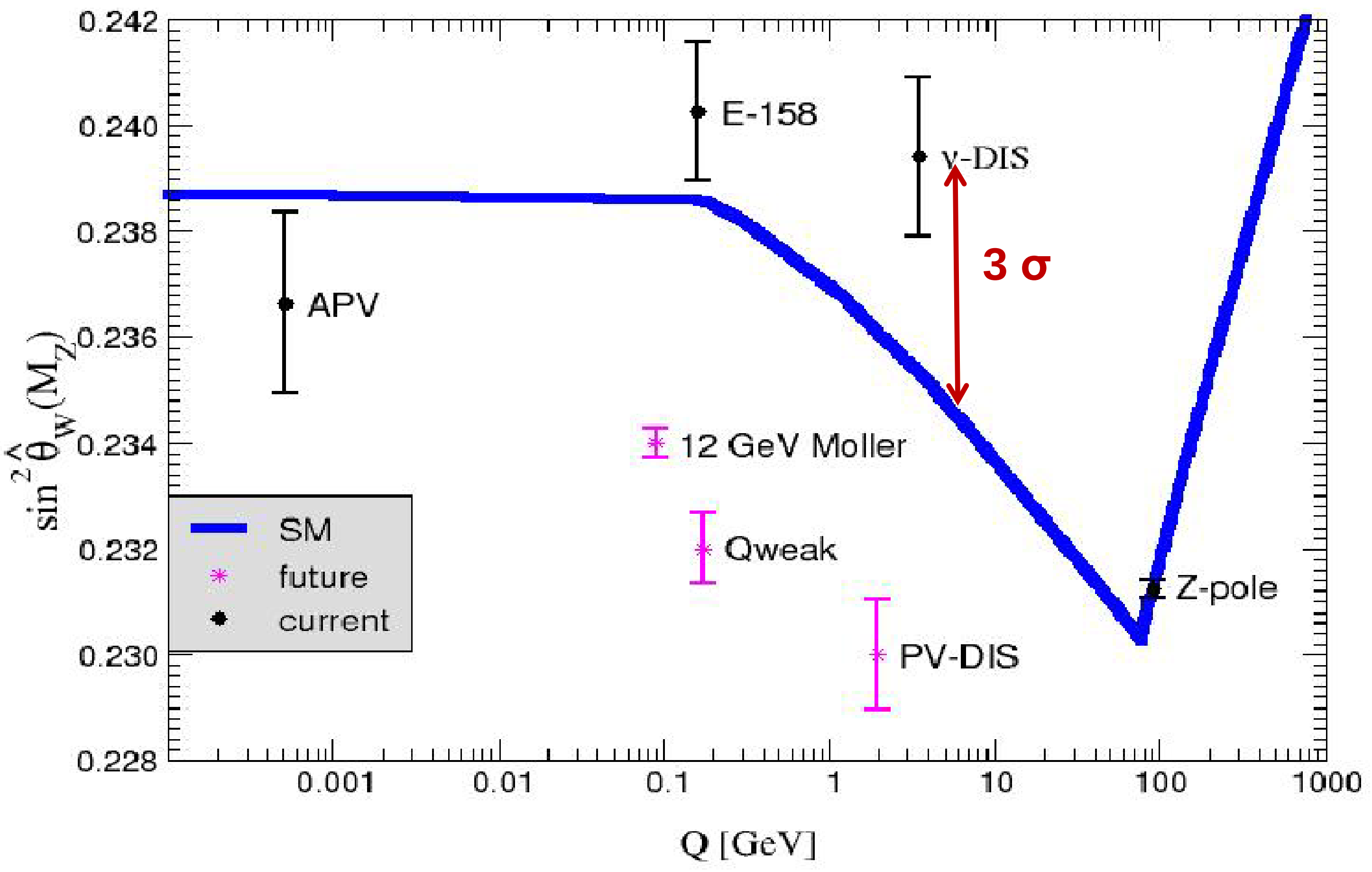


Hobbs et al., arXiv 1101.3923 [hep-ph]

NuTeV “Anomaly”

Radiative Corrections: Test of Weak Neutral Current

Not so long ago….



SM line: Erler & Ramsey-Musolf, Phys.Rev.D72:073003,2005

Paschos-Wolfenstein Ratio: Isoscalar Target

NuTeV measured (approximately) P-W ratio:

$$R^{PW} = \frac{\sigma(\nu\, Fe \rightarrow \nu\, X) - \sigma(\bar{\nu}\, Fe \rightarrow \bar{\nu}\, X)}{\sigma(\nu\, Fe \rightarrow \mu^-\, X) - \sigma(\bar{\nu}\, Fe \rightarrow \mu^+\, X)} = \frac{NC}{CC} \text{ ratio}$$

$$= \tfrac{1}{2} - \sin^2\theta_W$$

NuTeV

$\sin^2\theta_W = 1 - M_W^2/M_Z^2 \quad = \quad 0.2277 \pm 0.0013 \pm 0.0009$

other methods

c.f. Standard Model $= \quad 0.2227 \pm 0.0004$

(c.f. 1978: 0.230 ± 0.015)

NuTeV Anomaly

Phys. Rev. Lett. 88 (2002) 091802 : 400+ citations since….

Fermilab press conference, Nov. 7, 2001:

"We looked at $\sin^2 \theta_W$," said Sam Zeller. The predicted value was 0.2227. The value we found was 0.2277…. might not sound like much, but the room full of physicists fell silent when we first revealed the result."

"3 σ discrepancy : 99.75% probability ν are not like other particles…. only 1 in 400 chance that our measurement is consistent with prediction ," MacFarland said.

Isovector EMC Effect :

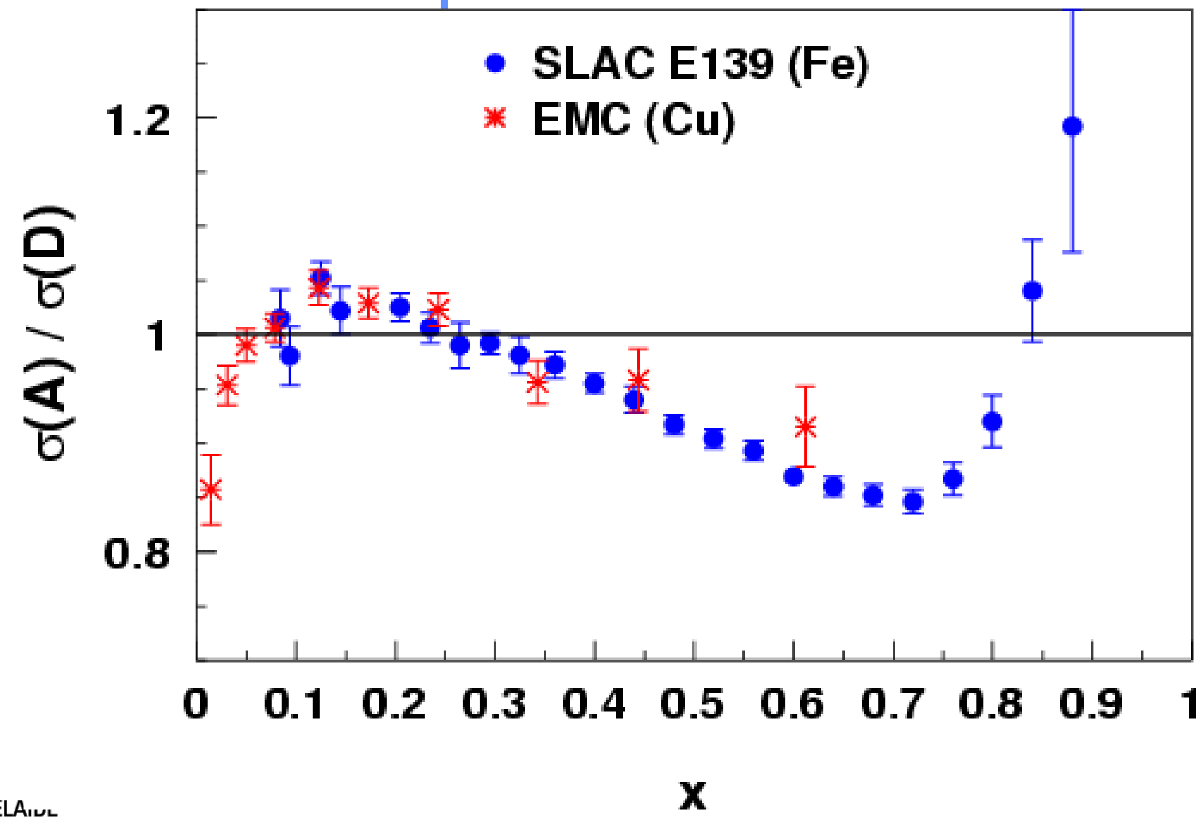
A Handle on Nuclear Binding in QCD

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the
  HEP and Nuclear communities 20 years ago

- Nearly 1,000 papers have been generated…..

- What is it that alters the quark momentum in the nucleus?

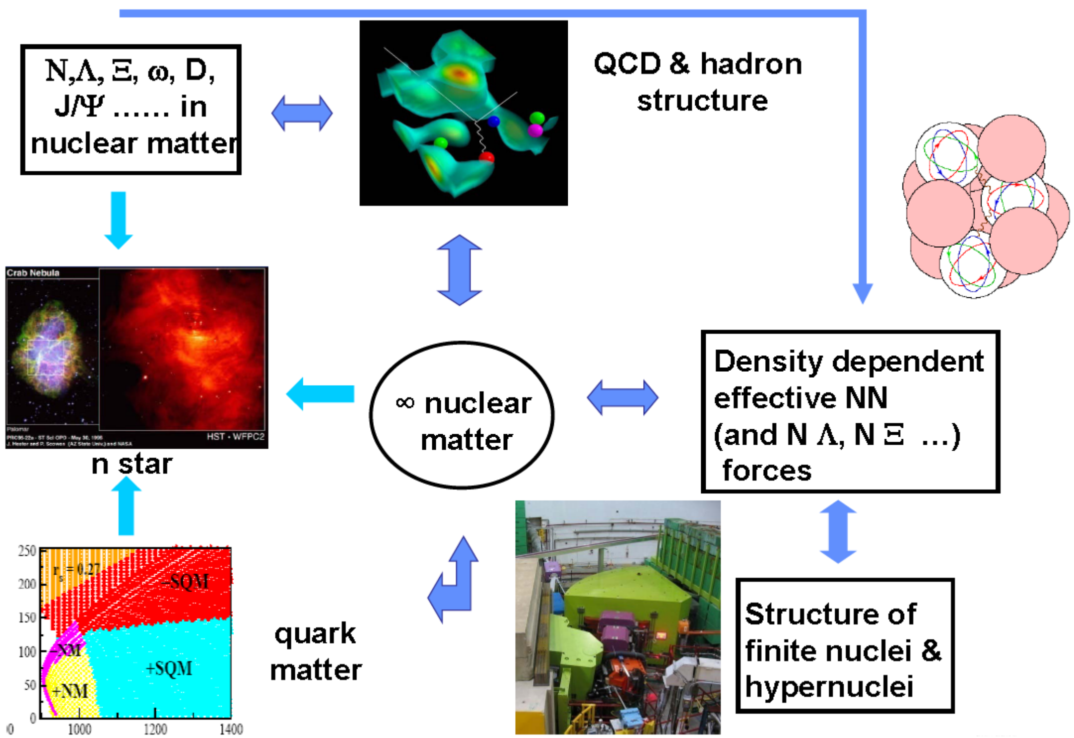


J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

Nuclei within QCD

Driven by EMC effect and inspired by an idea of Pierre Guichon (Phys.Lett. B200 (1988) 235; see key development in Nucl.Phys. A601 (1996) 349-379) over the last 25 years we have built a surprisingly realistic description of nuclear structure based on the self-consistent modification of nucleon structure in-medium



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Check directly vs nuclear data

- **That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (exactly as for common Skyrme forces)**

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

~ 4%

~ 1%

- **Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:**

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[\frac{-3\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\sigma}{2\,(1 + d\rho\,G_\sigma)} + \frac{3\,G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[\frac{5\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

○ highlights scalar polarizability

See Nucl. Phys. A772 (2006) 1

Recent global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

M. Dutra, O. Lourenço, J. S. S. Martins, and A. Delfino

Departamento de Física - Universidade Federal Fluminense,

Av. Litorânea s/n, 24210-150 Boa Viagem, Niterói RJ, Brazil

J. R. Stone

Department of Physics, University of Oxford,

OX1 3PU Oxford, United Kingdom and

Department of Physics and Astronomy,

University of Tennessee, Knoxville, Tennessee 37996, USA

C. Providência

Centro de Física Computacional,

Department of Physics,

University of Coimbra,

P-3004-516 Coimbra, Portugal

These authors test over 200 widely used Skyrme forces against ~10 standard nuclear properties

Furthermore, we considered weaker constraints arising from giant resonance experiments on isoscalar and isovector effective nucleon mass in SNM and BEM, Landua parameters and low-mass neutron stars. If these constraints are taken into account, the number of CSkP reduces to to 9, GSkI, GSkII, KDE0v1, LNS, NRAPR, QMC700, QMC750 and SKRA, the CSkP* list.

Phys.Rev. C85 (2012) 035201

Model Describes EMC Effect for Finite Nuclei

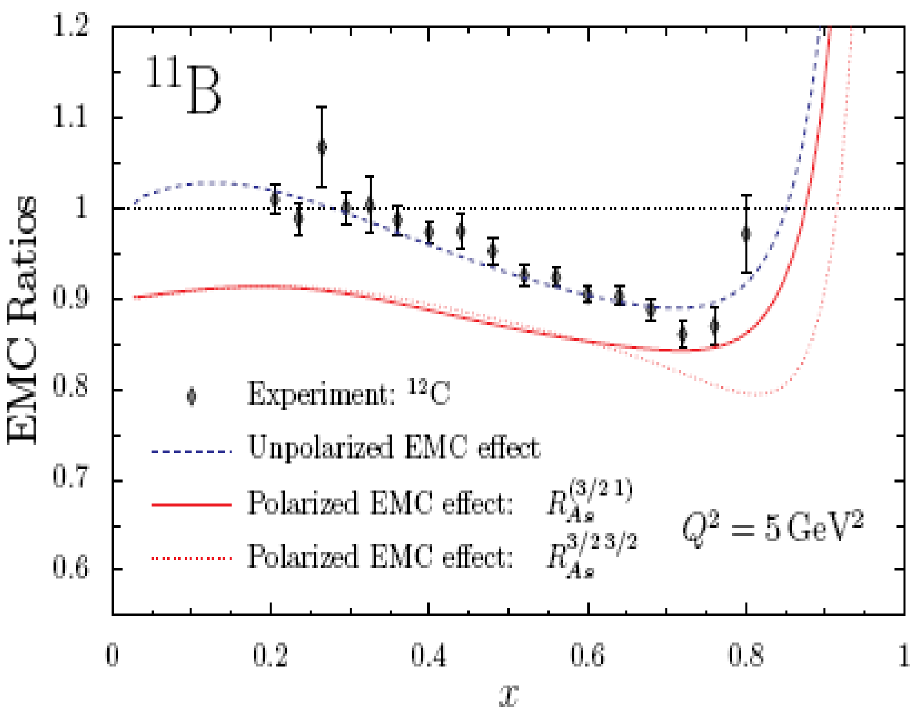


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

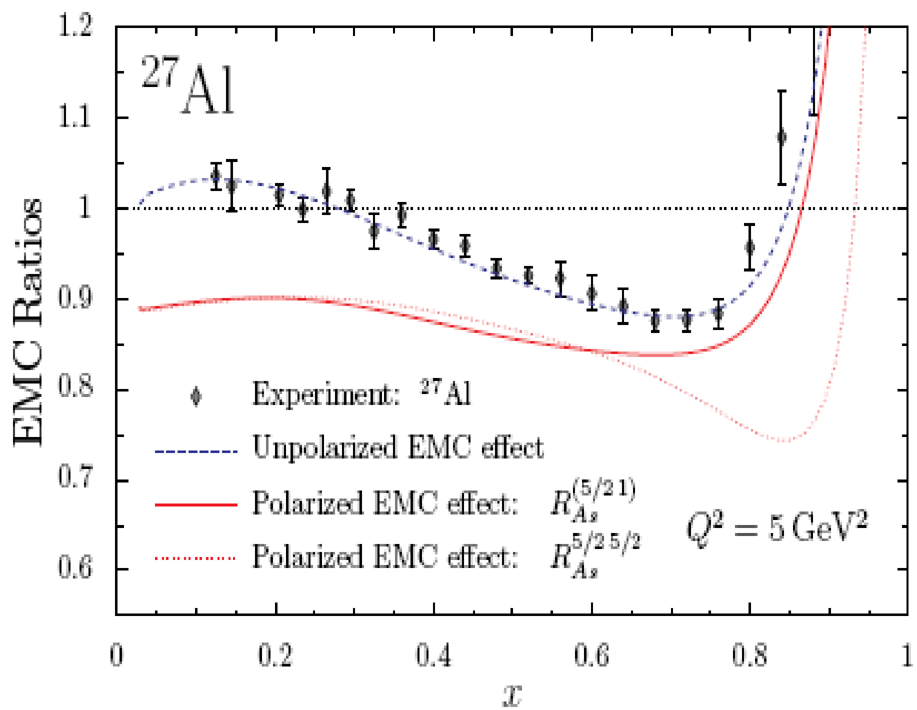


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

(Spin dependent EMC effect TWICE as large as unpolarized)

Cloet et al., Phys. Lett. B642 (2006) 210

Observable Consequence : isovector EMC Effect

- **New realization concerning EMC effect:**
  - **isovector force in nucleus (like Fe) with N≠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 $m_u \neq m_d$**

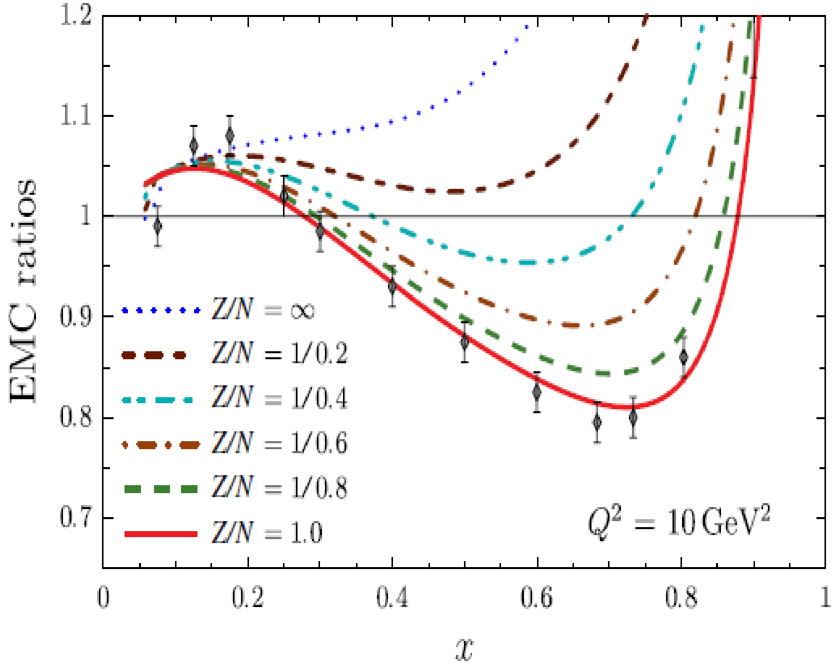
- **Sign and magnitude of both effects exhibit little model dependence**

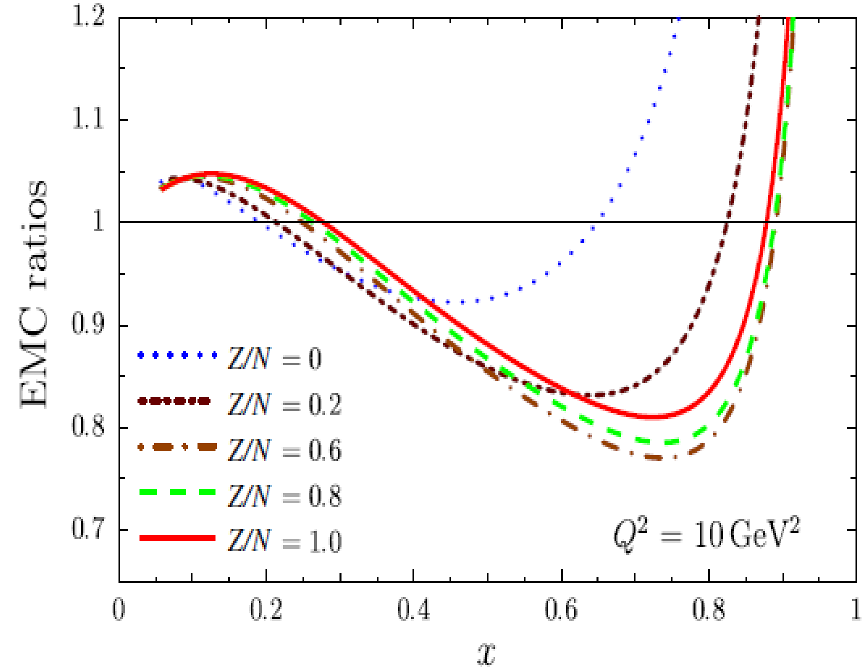
Cloet et al., arXiv: 0901.3559v1;
Londergan et al., Phys Rev D67 (2003) 111901

Isovector EMC Effect

Cloet, Bentz,Thomas

PRL **102,** 252301 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009





Means that excess neutrons in Fe shift momentum from <u>all</u> u- to <u>all</u> d-quarks and subtracting their direct contribution does not remove this effect

This has similar implications for the NuTeV anomaly as CSV

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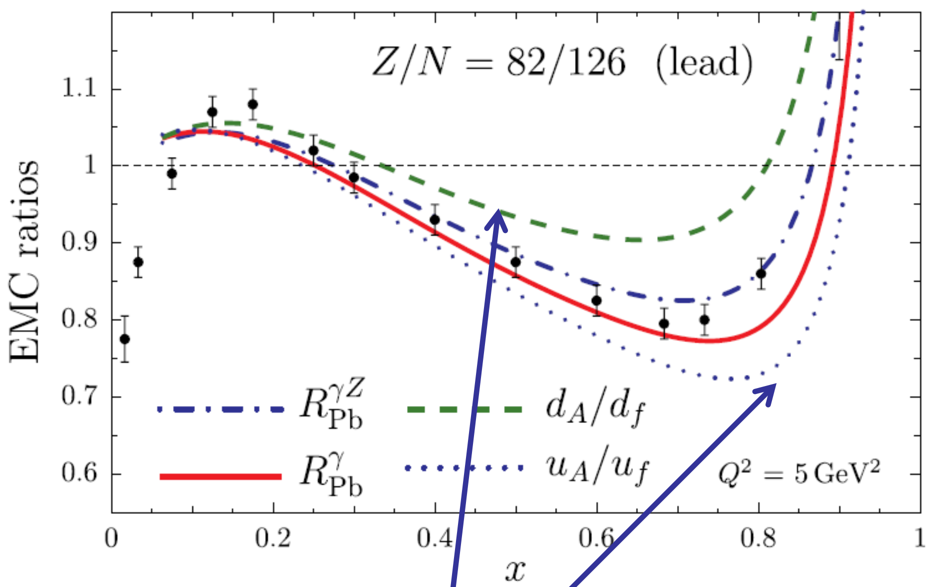
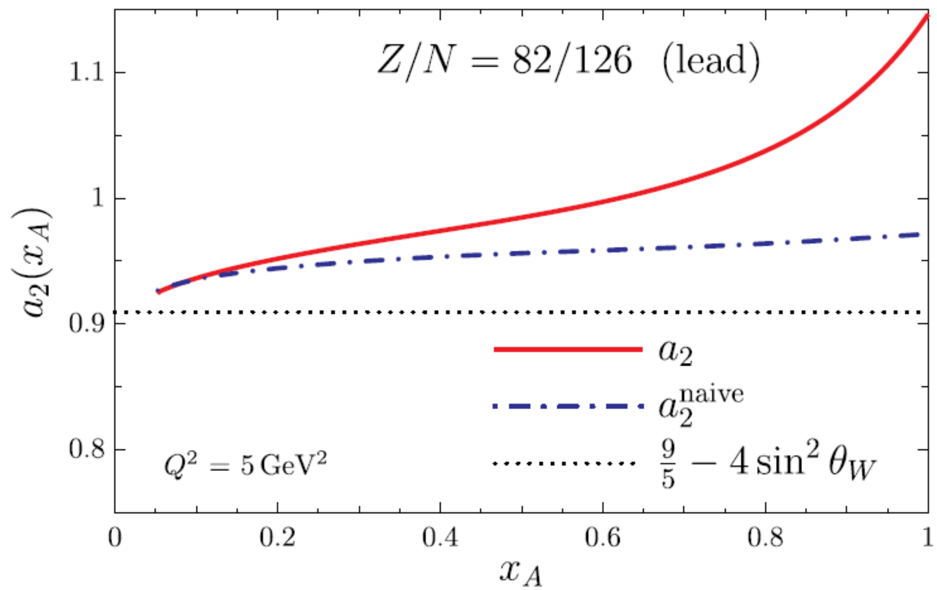
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[1]



$$A_{\rm PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\rm em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$



Can also be tested at EIC with CC reactions

Parity violating EMC maybe tested at Jlab 12 GeV

Resolution of the NuTeV "Anomaly"

Correction to Paschos-Wolfenstein from CSV

- **General form of the correction is:**

$$\Delta R_{\mathrm{PW}} \simeq \left(1 - \frac{7}{3} s_W^2\right) \frac{\langle x_A\, u_A^- - x_A\, d_A^- - x_A\, s_A^- \rangle}{\langle x_A\, u_A^- + x_A\, d_A^- \rangle}$$

- **$u_A = u^p + u^n$; $d_A = d^p + d^n$ and hence**

  $u_A - d_A = (u^p - d^n) - (d^p - u^n) \equiv \delta u - \delta d$

- **N.B. In general the corrections are C-odd and so involve only valence distributions: $q^- = q - \bar{q}$**

- **Also the $x_A\, s_A^-$ term means that the asymmetry between strange and anti-strange quarks adds a correction**

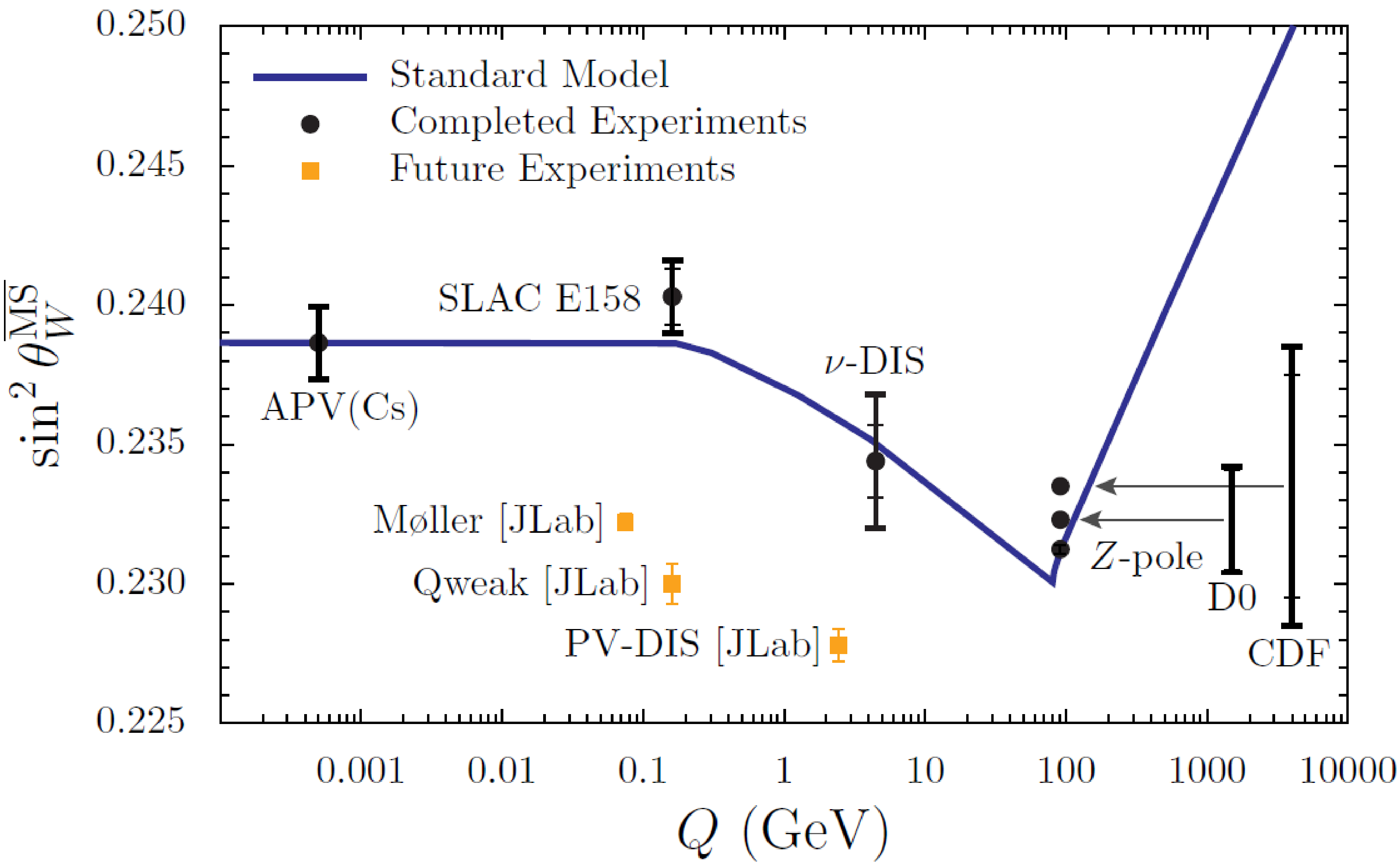
Davidson *et al*., hep-ph/0112302

Summary of Corrections to NuTeV Analysis

- **Isovector EMC effect:** $\Delta R^{\rho^0} = -0.0019 \pm 0.0006$
  - **using NuTeV functional**
- **CSV:** $\Delta R^{\mathrm{CSV}} = -0.0026 \pm 0.0011$
  - **again using NuTeV functional**
- **Strangeness:** $\Delta R^{s} =$ - 0.0011 ± 0.0014
  - **this is largest uncertainty (systematic error) ; desperate need for an accurate determination of $s^-(x)$, e.g. semi-inclusive DIS?**
- **Final result:** $\sin^2\theta_W = 0.2221 \pm 0.0013(\mathrm{stat}) \pm 0.0020(\mathrm{syst})$
  - **c.f. Standard Model:** $\sin^2\theta_W = 0.2227 \pm 0.0004$

Bentz et al., Phys Lett B693 (2010) 462 (arXiv: 0908.3198)

The Standard Model works… again



Bentz et al., Phys Lett B693 (2010) 462 (arXiv: 0908.3198)

Nucleon spin and quark orbital angular momentum

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)

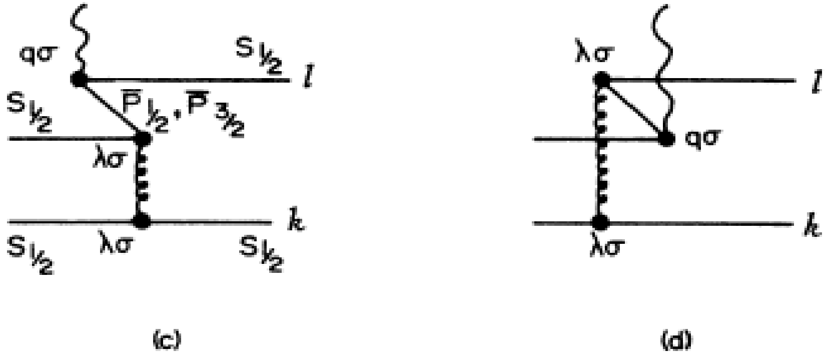
- In addition, there is little or no polarized glue
  - COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$
  - A_{LL} (π^0 and jets) at PHENIX & STAR: $\Delta G \sim 0$
  - Hermes, COMPASS and JLab: $\Delta G / G$ small

- 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

OGE Exchange Current : Spin Problem

- Further reduces the fraction of spin carried by the quarks in the bag model (naively 0.65)



$$\Sigma \rightarrow \Sigma - 3G \text{ ; with } G \sim 0.05$$

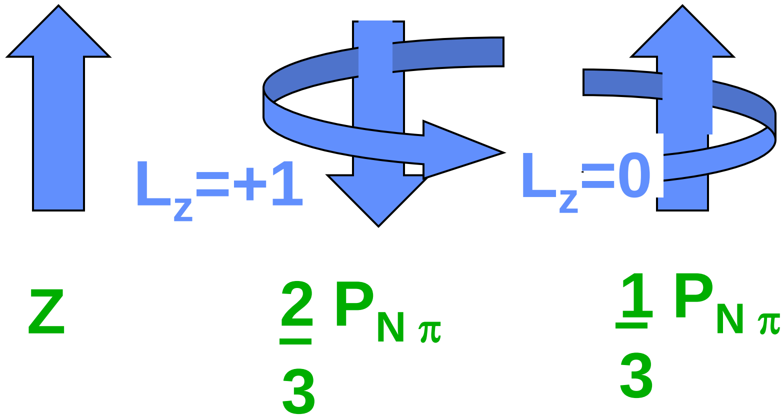
$$\Sigma \rightarrow 0.65 - 0.15 = 0.5$$

- 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

Effect of the Pion Cloud

- 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



- 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 :

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

Hence: $\Sigma = 0.65 \rightarrow 0.49 - 0.52$

Schreiber-Thomas, Phys Lett B215 (1988)

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Final Result for Quark Spin

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

$= (0.7,0.8)$ 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

	$2\,L_{u+ubar}$	$2\,L_{d+dbar}$	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: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$

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

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Phys Rev Lett, 101 (2008) 102003

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Recent Result on 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 CBM model that worked so well for the nucleon applied to whole octet**

- **Agreement remarkably good... Suppression is not universal!**

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Shanahan et al., arXiv:1302.6300

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Summary

- Chiral symmetry has remarkable consequences for asymmetries in the sea ($\bar{d} > \bar{u}$; $s \neq \bar{s}$) − *EIC may resolve the latter*

- Charge symmetry violation is theoretically unavoidable.
  For $m_u \neq m_d$ lattice QCD strongly supports phenomenology.

- Need experimental confirmation of CSV, including photon radiation
  − *ideal experiment for an EIC*

- Establishing iso-vector EMC effect (d_A / d much larger (~25%) than u_A /u in a nucleus like Pb or Au) would also drive a dramatic new picture of nuclear structure
  − *ideal experiment for an EIC*

- These effects naturally resolve the NuTeV anomaly

- Octet spin fractions from lattice QCD offer new insight into the proton spin crisis

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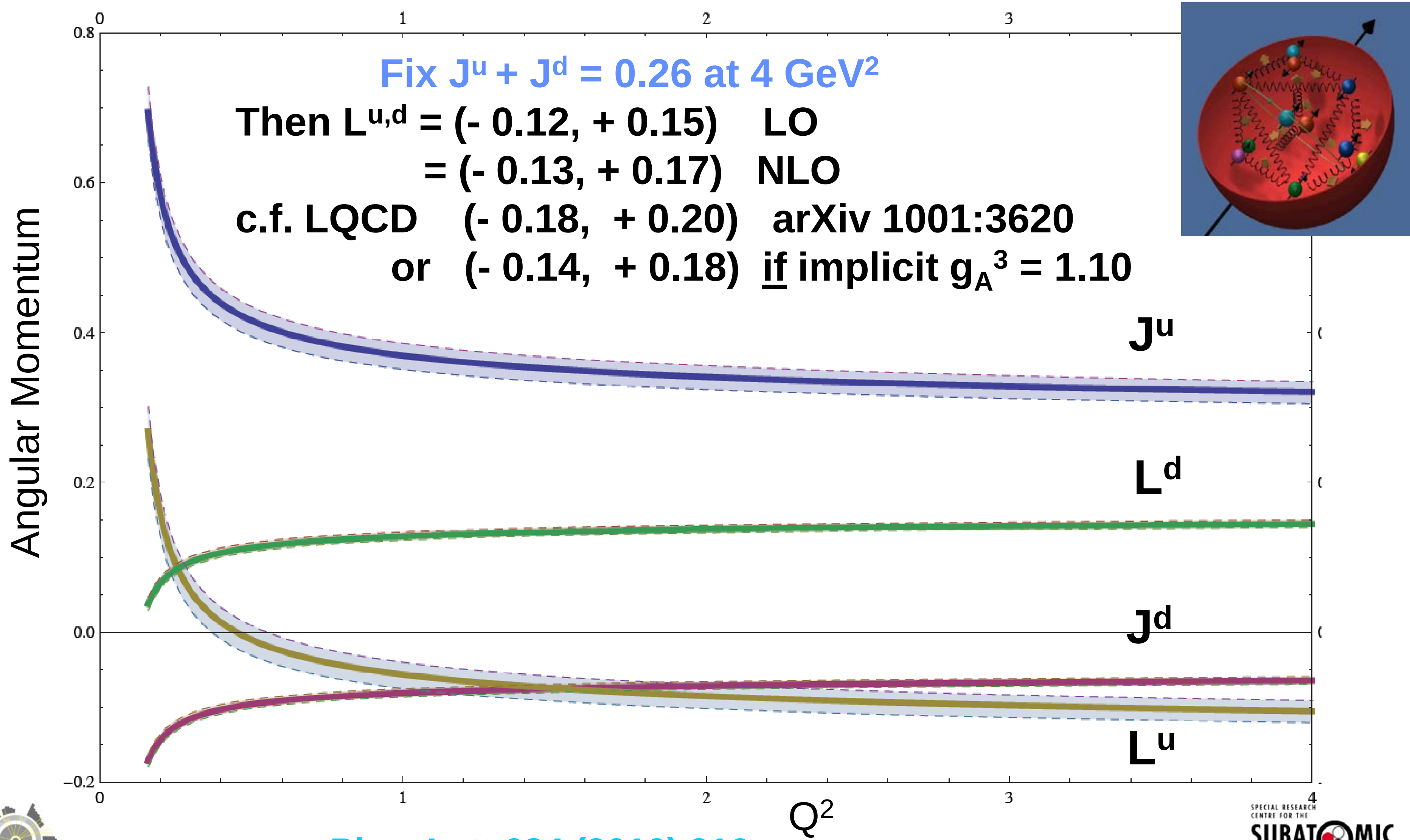
NLO Evolution – using Bass-Thomas update

Remarkable agreement between model and LQCD



- Phys Lett 684 (2010) 216

& AWT, Casey & Matevosyan, E P J A46 (2010) 325

Experimental effort just beginning!

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

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