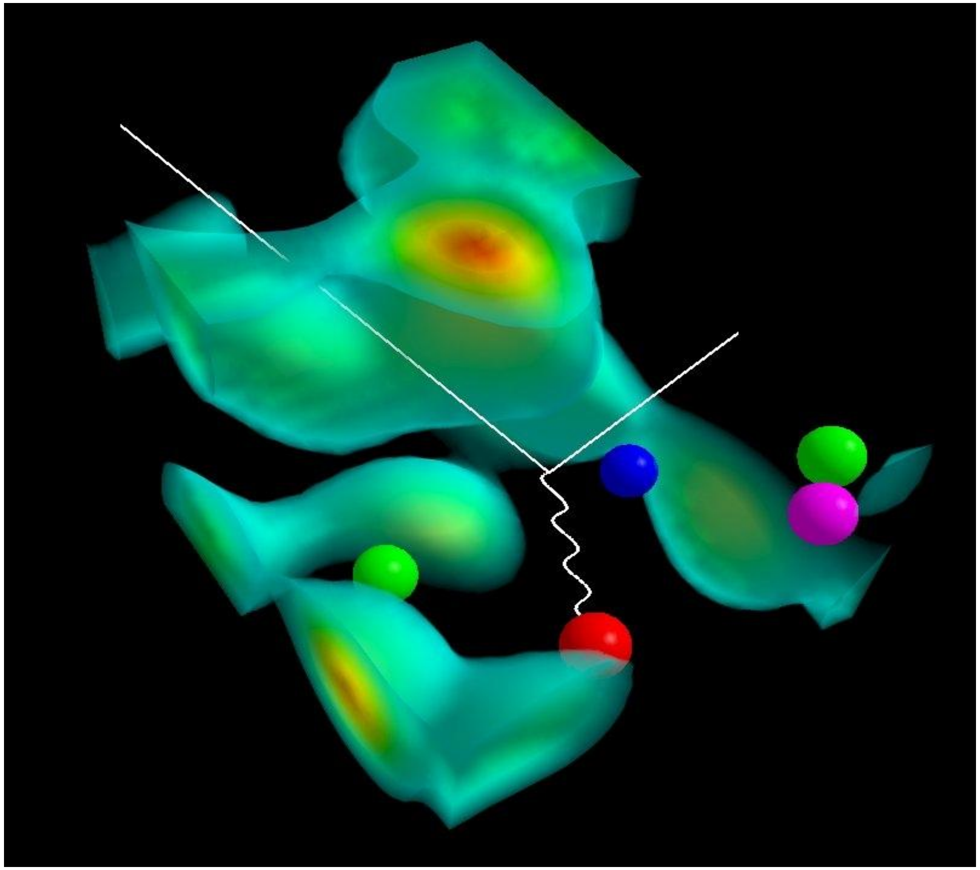
The Spin and Flavour Dependence of the Deep Structure of Hadrons



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ARC Centre of Excellence for Particle Physics at the Terascale

Australian Government
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Anthony W. Thomas

Seminar : CEA Saclay
Orme des Merisiers - May 23rd 2013

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Big Picture

- Focus on *understanding* some aspects of QCD

- Especially beautiful examples where subtle violations of fundamental symmetries teach us about QCD

- Today's selection emphasises examples where an EIC offers unique access to this physics

Outline

- Chiral symmetry of QCD : asymmetries
  - $d \neq u$; $s \neq s$
- Charge Symmetry Violation
- Test of the QCD origin of nuclei : isovector EMC effect
- Resolution of the NuTeV "anomaly"
- Nucleon spin and quark angular momentum
  - spin crisis is *understood*

Asymmetries in the Sea:

– from Chiral Symmetry

Symmetry Breaking in the Nucleon Sea

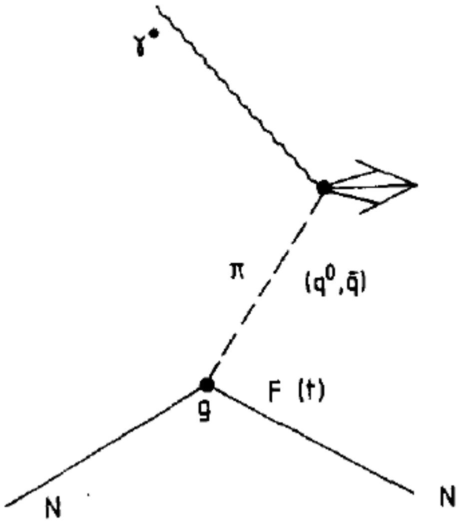
- **Role of pion cloud in DIS first investigated by (Feynman) and Sullivan**

- **Generally ignored until:**

Volume 126B, number 1,2 (1983) 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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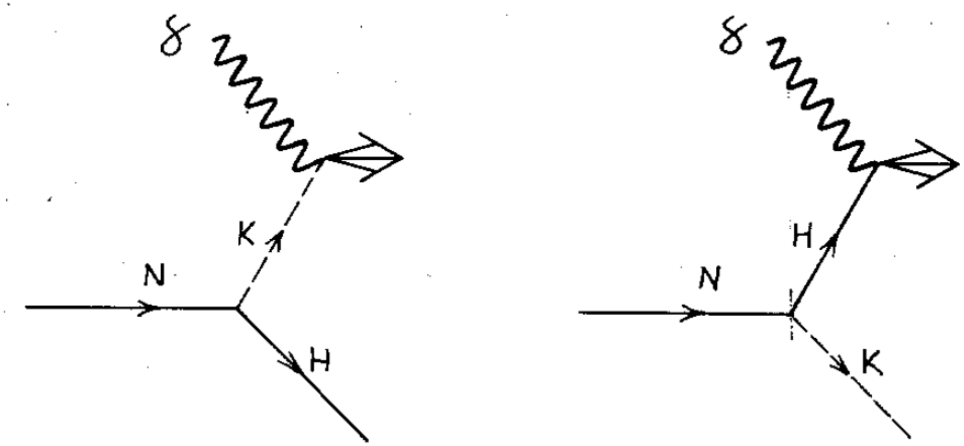
Strange Sea of the Nucleon

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

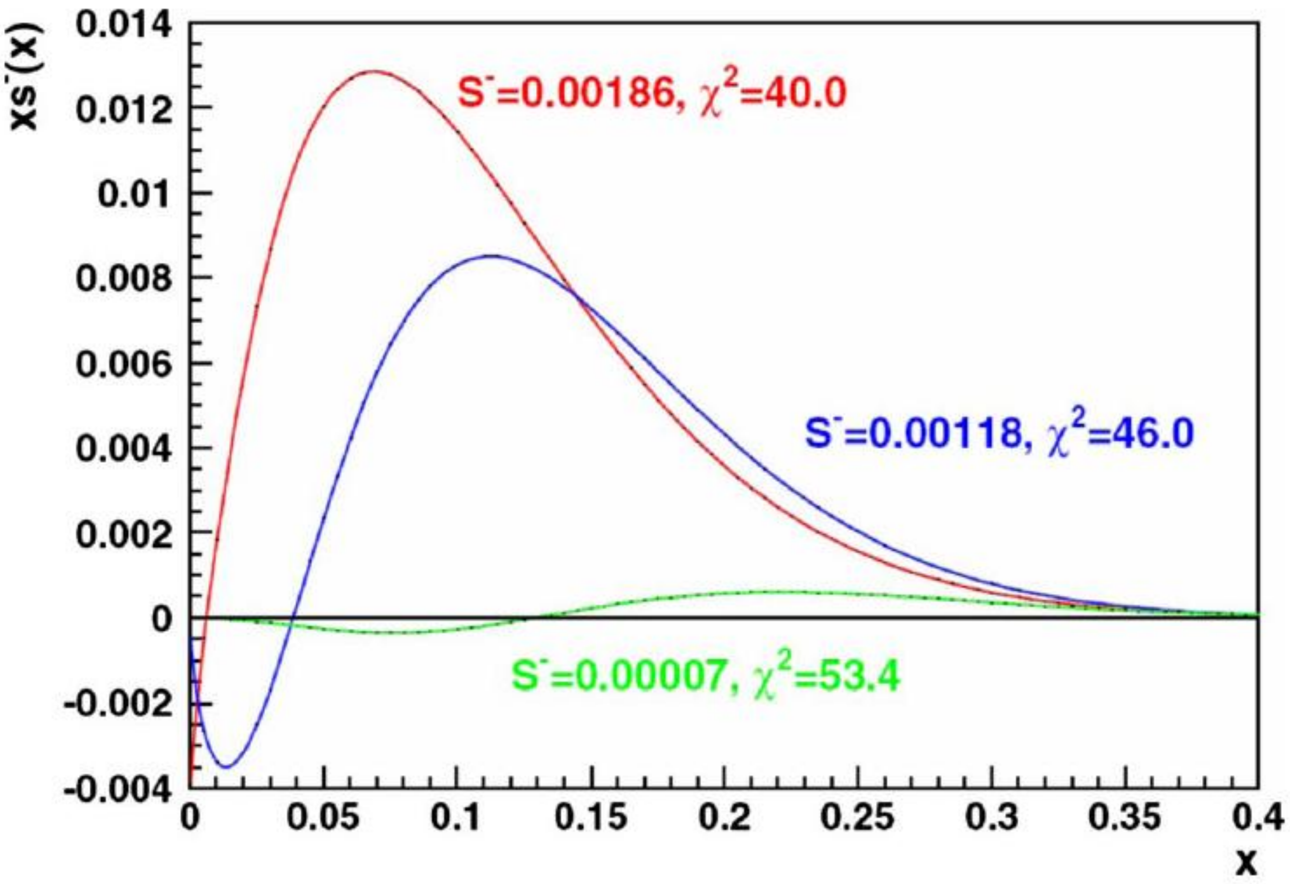


FIG. 16. (Color online) The quantity $xs^{-}(x) = x[s(x) - \bar{s}(x)]$ vs x, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The χ^2 value is listed for each curve. From Mason *et al.*, 2007.

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

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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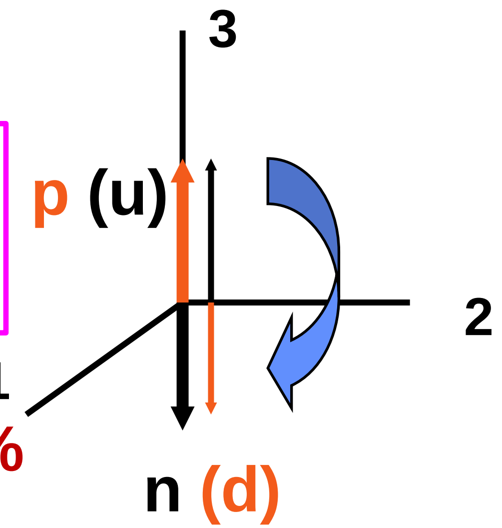
Violation of Charge Symmetry

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**

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Charge Symmetry is almost universally *assumed* in the analysis of PDFs

- **it is vital to establish how accurately it is satisfied.**

Role of Di-quark Correlations

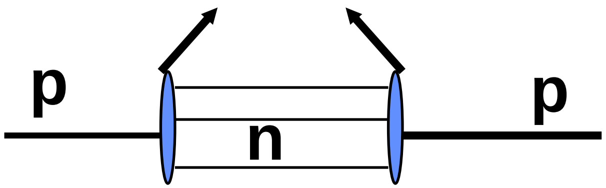
On general grounds (conservation of energy & momentum) :

in the *ground state* of a baryon the peak of the valence PDF

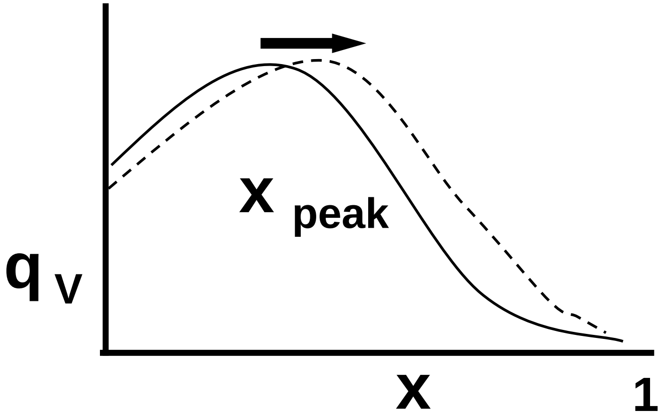
Is determined by:

$$x_{peak} = (M - m_2) / M$$

where m_2 is the mass of the di-quark spectator to the struck quark



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



If $m_2 \downarrow$: x_{peak} moves to right
***enhancing large-x* distribution**

Effect of "Hyperfine" Interaction

Δ – N mass splitting) S=1 "di-quark" mass is 0.2 GeV greater S=0

SU(6) wave function for proton :

hit d-quark : ONLY S=1 left

c.f. hit u-quark : 50% S=0 and 50% S=1

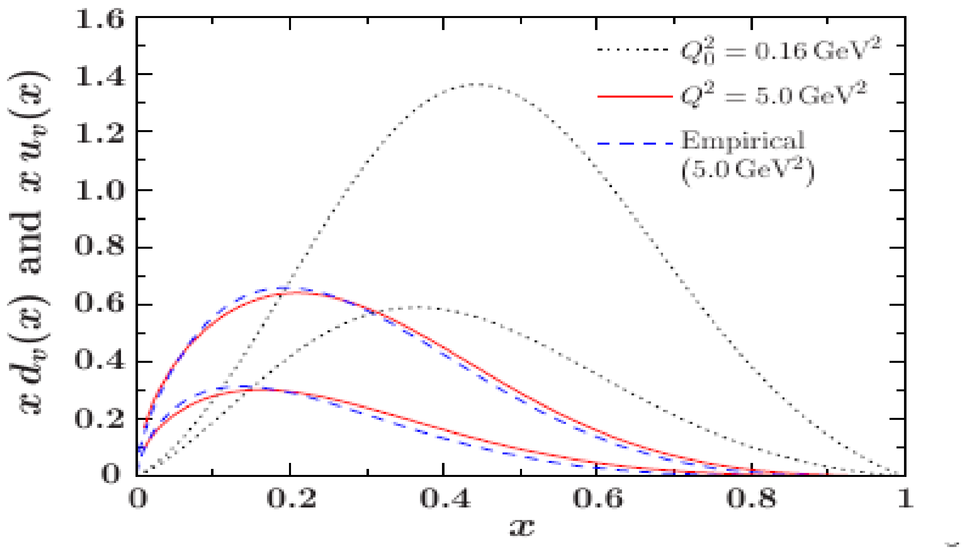
Hence*:

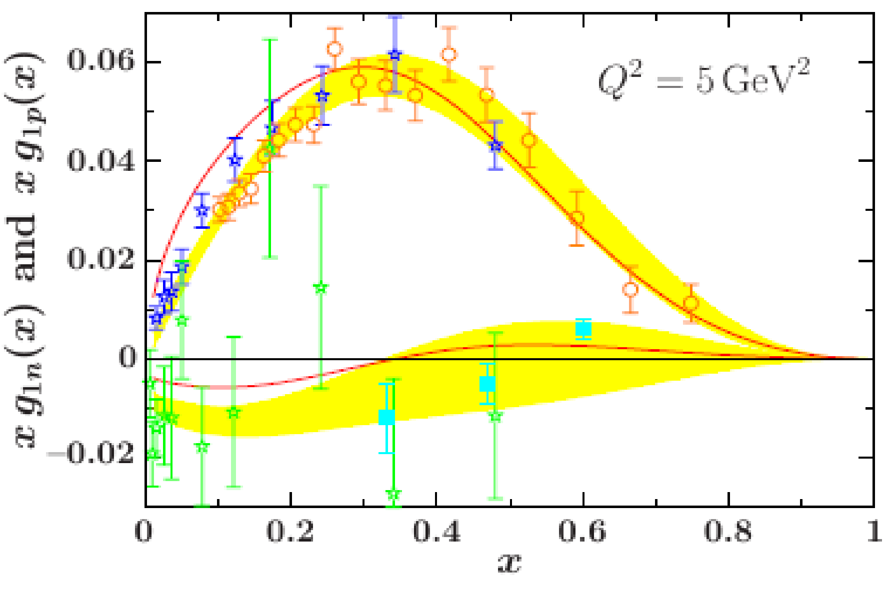
- **u(x) dominates over d(x) for x > 0.3**
- **u↑ dominates over u↓ at large x**
  and hence: $g^p_1(x) > 0$ at large x
- **Similarly $g^n_1(x) > 0$ at large x**

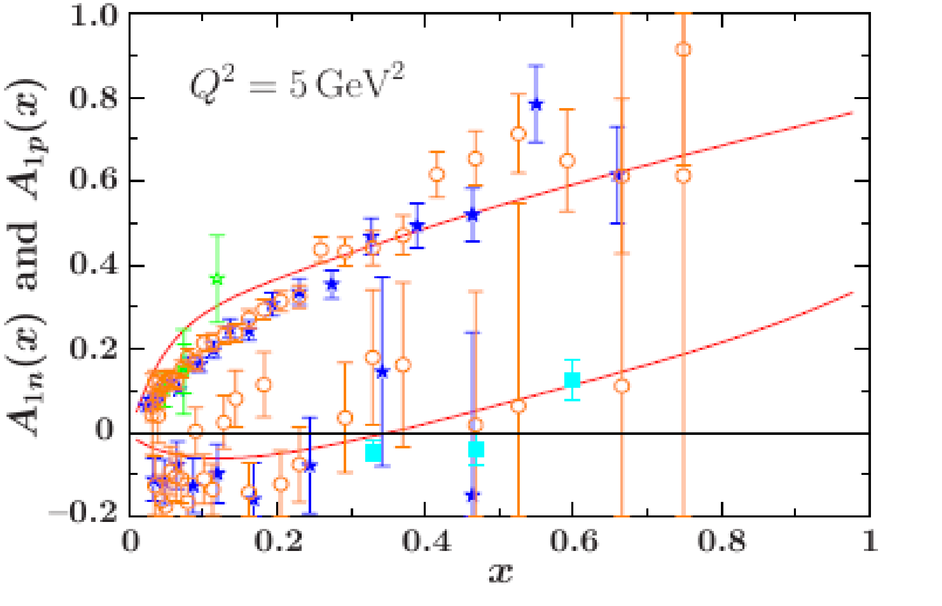
***Close & Thomas: 1988**

More Modern (Confining) NJL Calculations

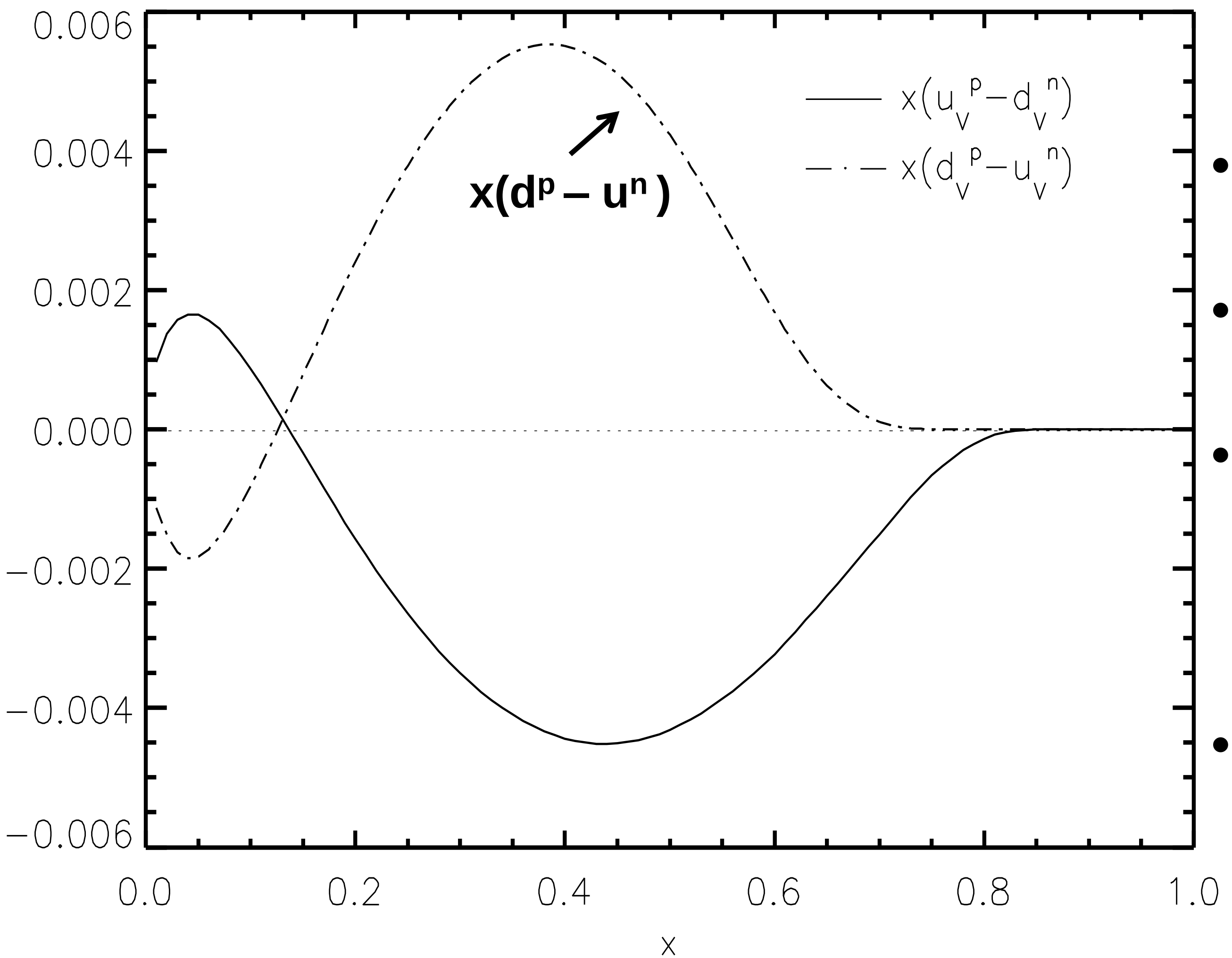
Cloët et al.,
Phys. Lett. B621, 246 (2005)
(μ = 0.4 GeV)







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 would reduce NuTeV anomaly by ~1σ

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

Remarkably Similar to MRST Fit a Decade Later

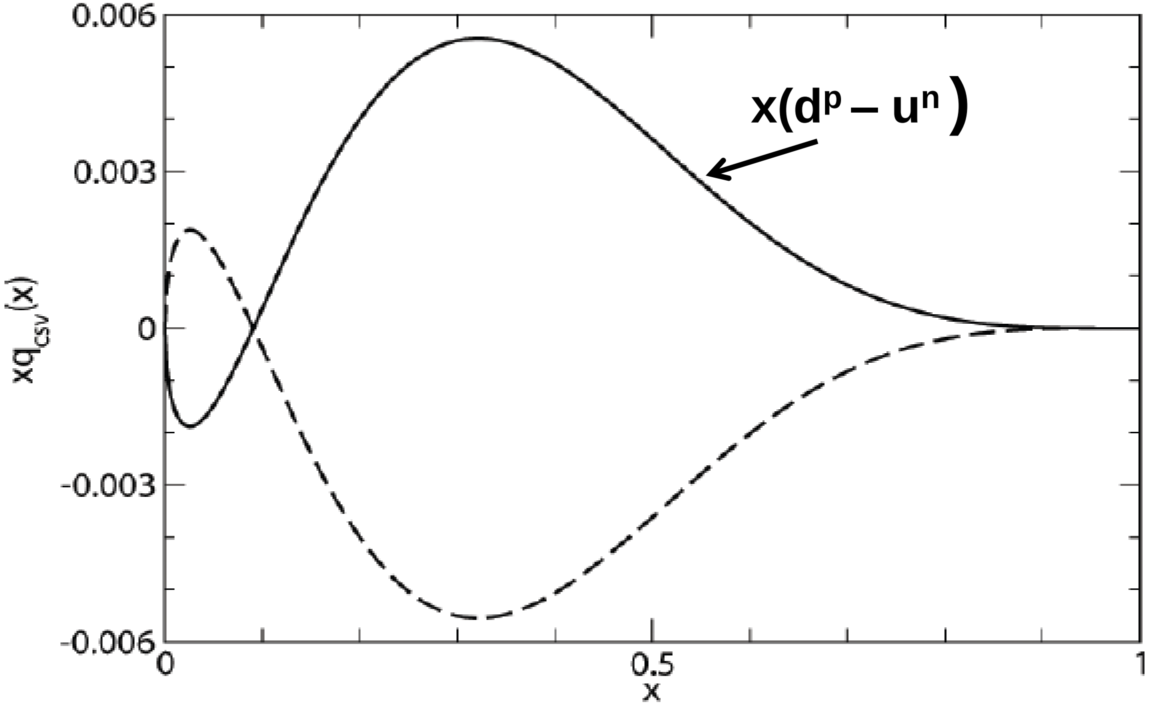


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_v$; dashed curve: $x\delta u_v$.

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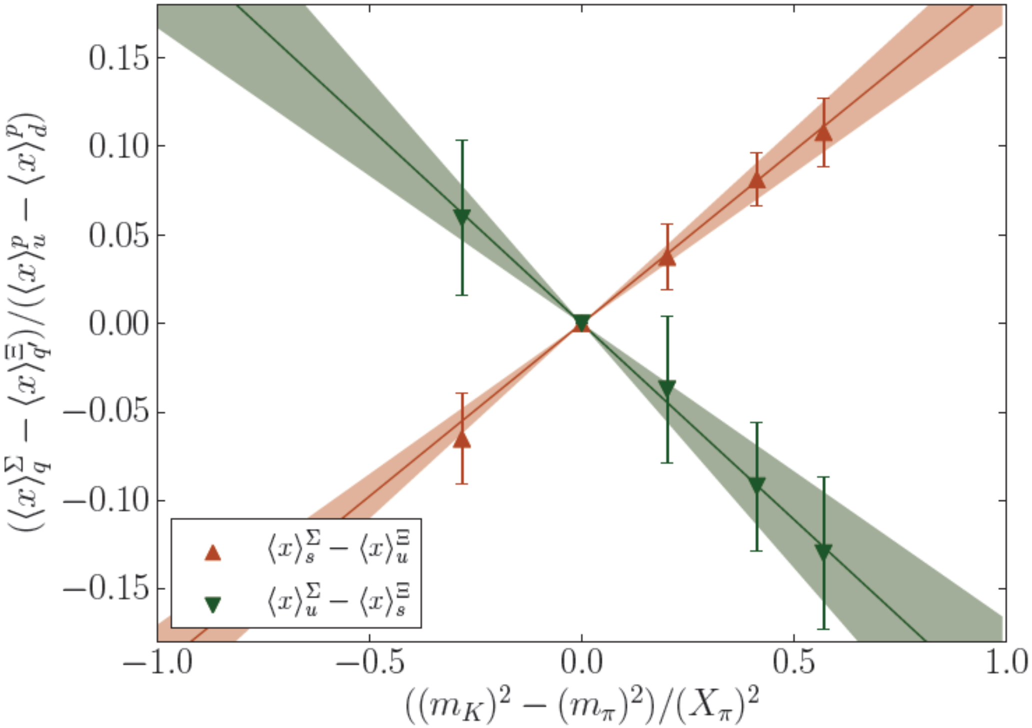
Eur. Phys. J. C39 (2005) 155-161

Strong support from 2011 lattice QCD calculation

Study moments of octet baryon PDFs



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

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

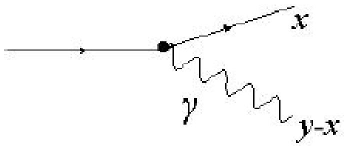
Deduce: $\delta u^+ = -0.0023(7)$ $\delta d^+ = 0.0017(4)$

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

Horsley et al., Phys. Rev. D83 (2011) 051501
and update by: Shanahan *et al*., arXiv:1303.4806

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":**



$\widetilde{P}_{qq}\left(\frac{x}{y}\right)$

- **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**

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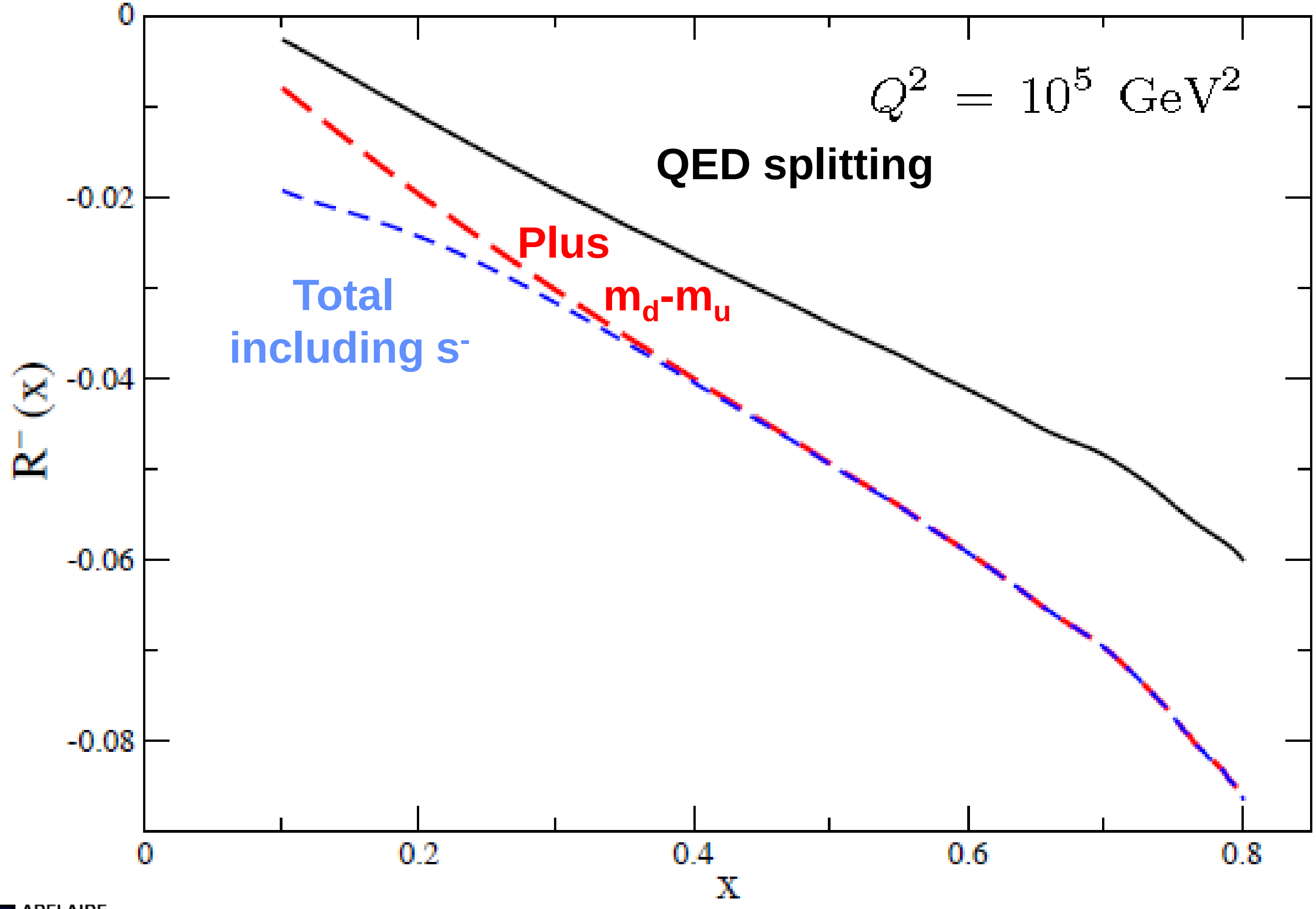
Test at Future EIC or LHeC – σ_{CC}

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



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

Nuclear Binding : A Consequence of the Modification of Nucleon Structure In-Medium

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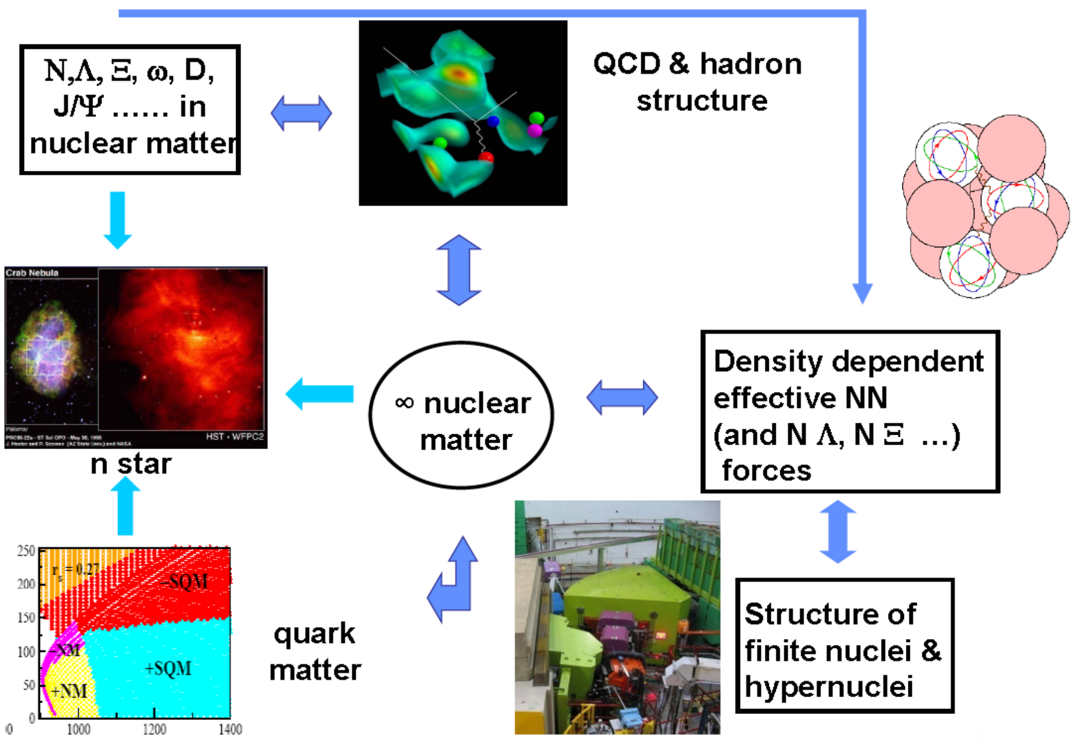
Nuclei within QCD

Driven by EMC effect and inspired by an idea of Pierre Guichon (Phys. Lett. B200 (1988) 235; see also 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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Fundamental Question: "What is the Scalar Polarizability of the Nucleon?"

Nucleon response to a chiral invariant scalar field is then a nucleon property of great interest…

$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2$$

Non-linear dependence through the scalar polarizability

d ~ 0.22 R in original QMC (MIT bag)

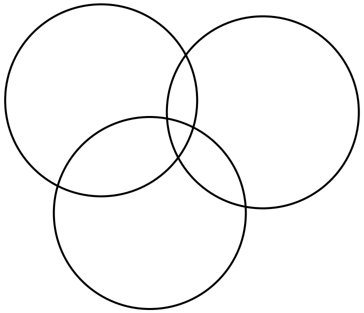
Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the ONLY place the response of the internal structure of the nucleon enters.

Summary : Scalar Polarizability

- **Can always rewrite non-linear coupling as linear coupling plus non-linear scalar self-coupling – likely physical origin of non-linear versions of QHD**

- **In nuclear matter this is the only place the internal structure of the nucleon enters in MFA**

- **Consequence of polarizability in atomic physics is many-body forces:**



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

- **Expect same consequence in nuclear matter**

Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work in nuclear theory is based upon effective forces

- **Used for everything from nuclear astrophysics to collective excitations of nuclei**

- **Skyrme Force: Vautherin and Brink**

Paper I: Phys. Rev. Lett. 93, 132502 (2004)

explicitly obtained effective force, 2- plus 3- body, of Skyrme type

- equivalent to QMC model

Paper II: Nucl. Phys. A772 (2006) 1
density dependent effective force

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 Guichon et al., Nucl. Phys. A772 (2006) 1

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SUBATOMIC STRUCTURE OF MATTER

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.

Dutta et al., Phys.Rev. C85 (2012) 035201

Isovector EMC Effect :

Insight into Nuclear Binding in QCD

Model Describes EMC Effect for Finite Nuclei

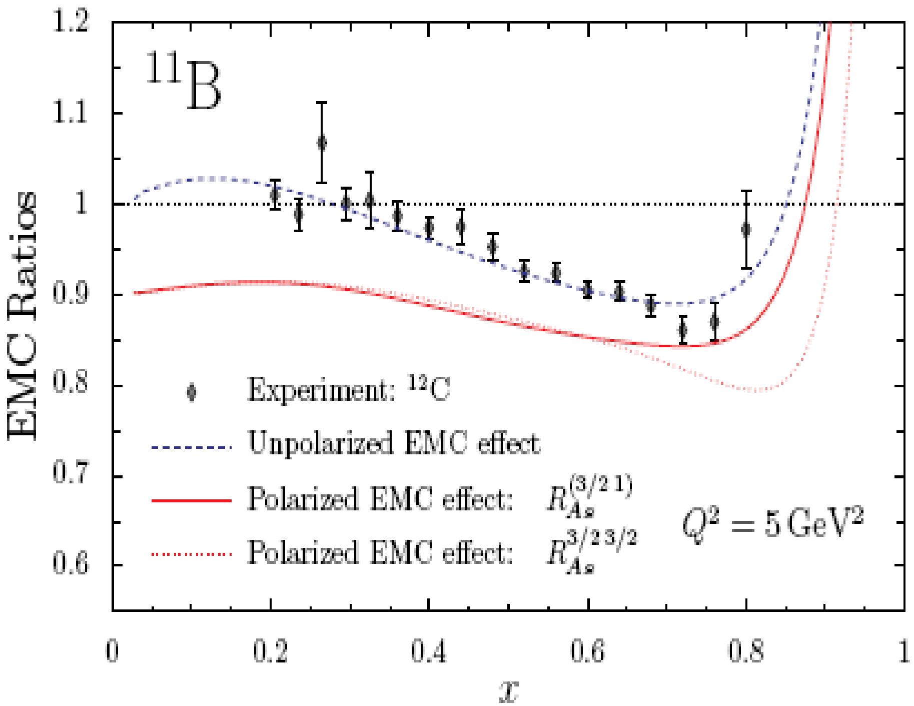

FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

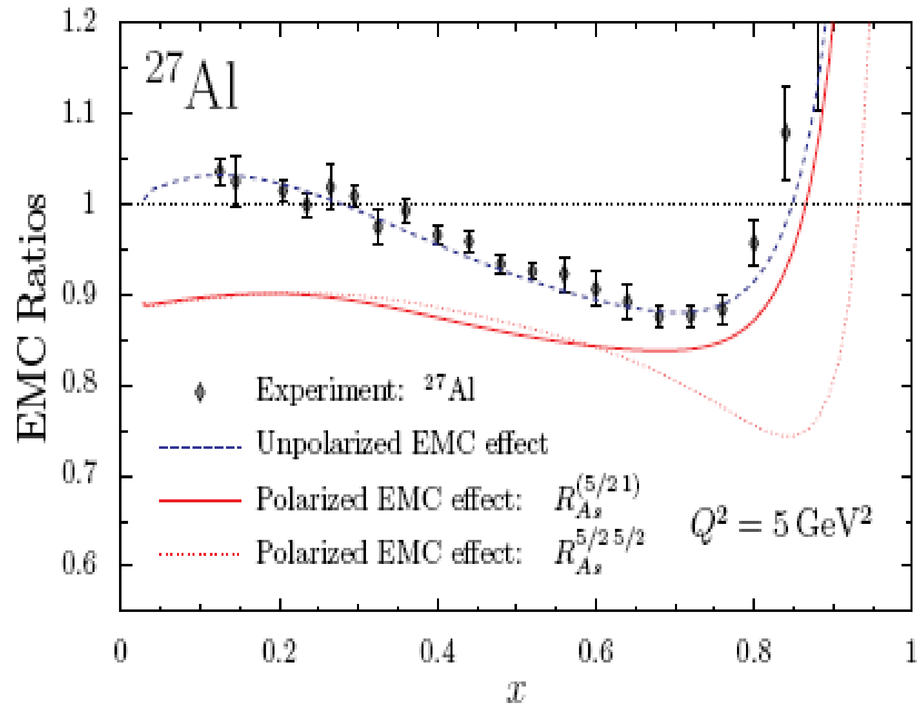

FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

(Spin dependent EMC effect TWICE as large as unpolarised)

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

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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 $m_u \neq m_d$**

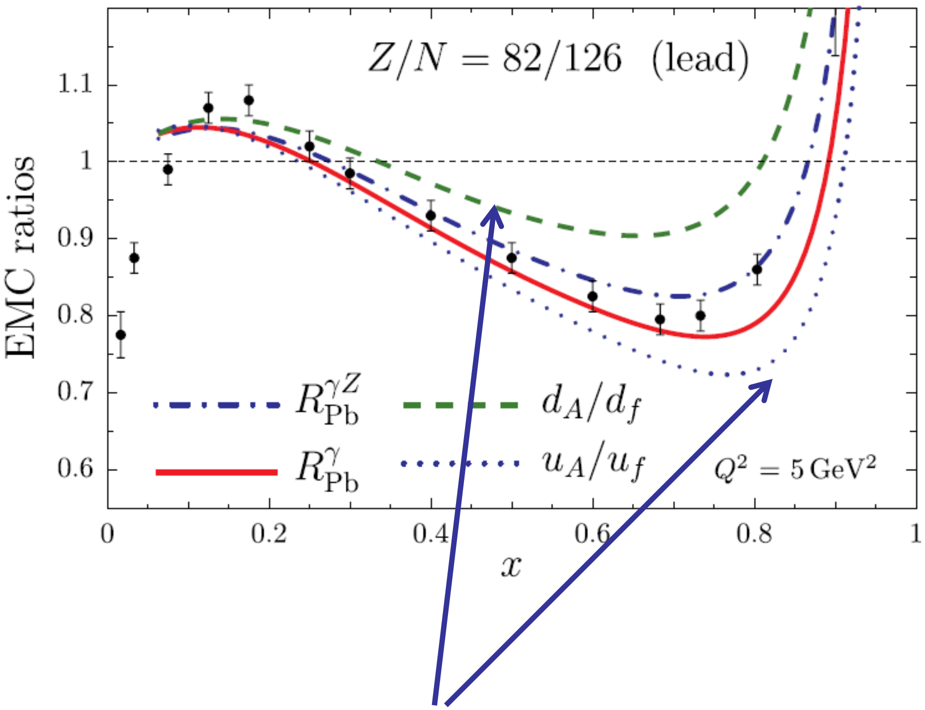
- **Sign and magnitude of both effects exhibit little model dependence**

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

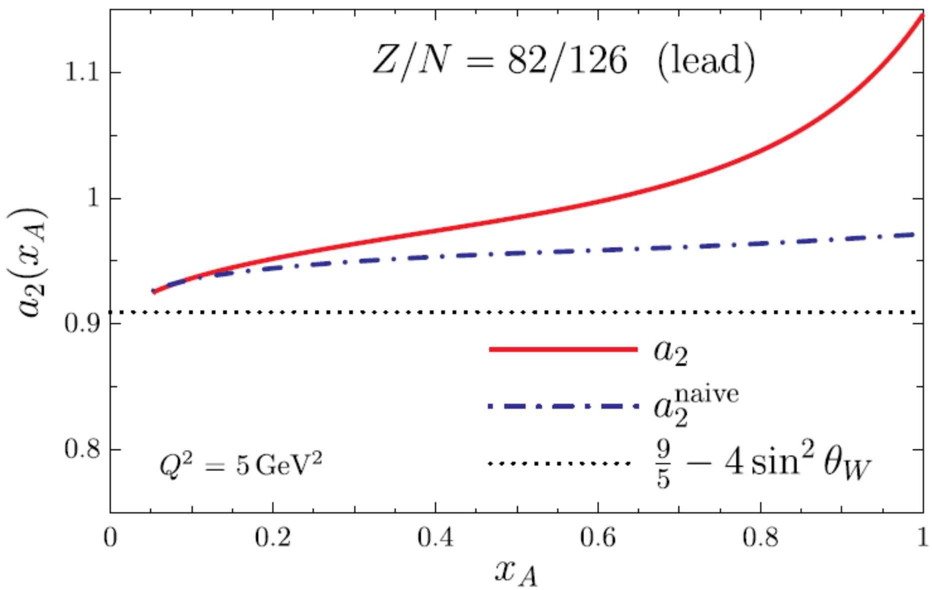
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]



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



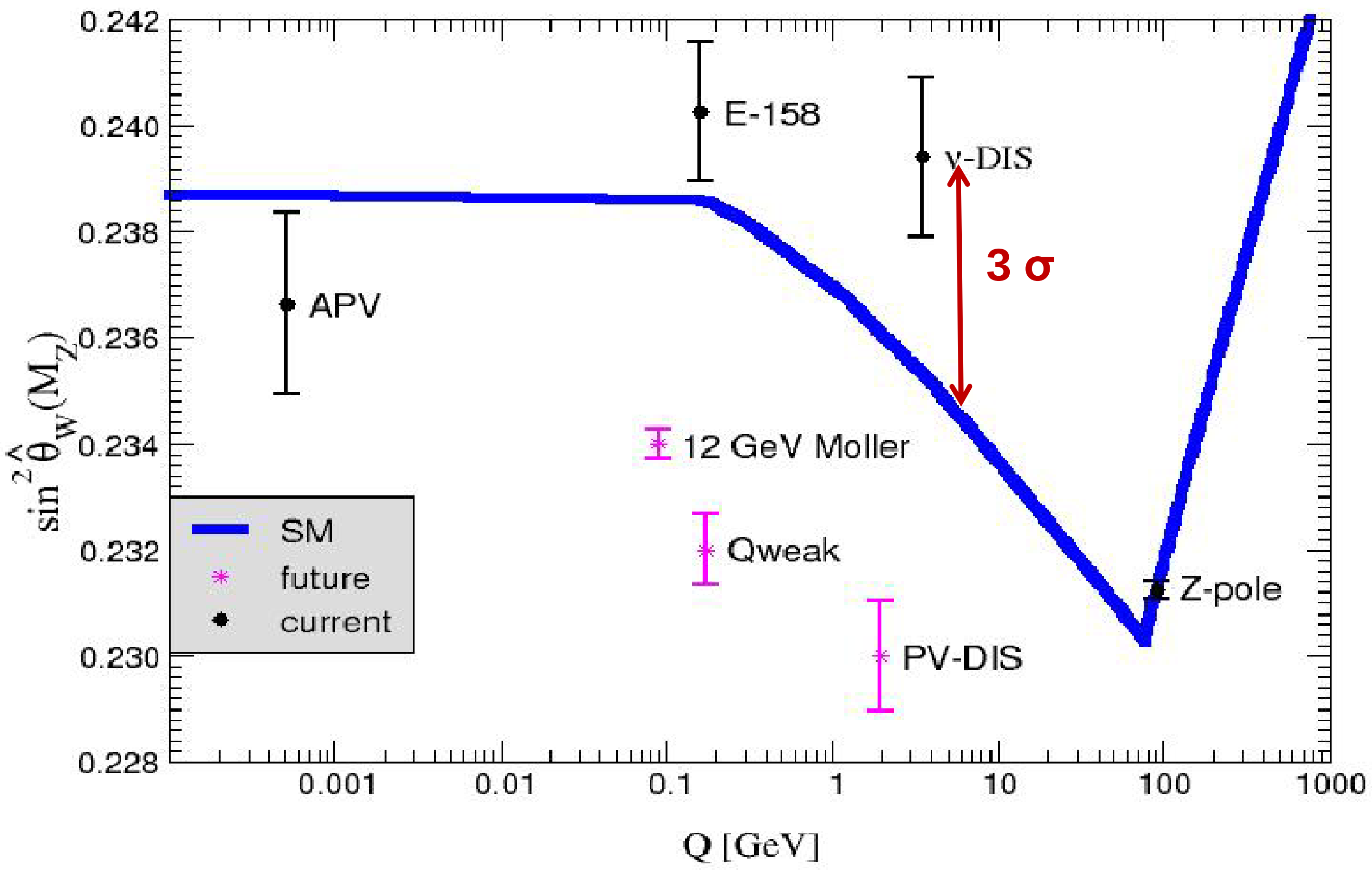
Ideally tested at EIC with CC reactions

Parity violating EMC maybe tested at Jlab 12 GeV

Resolution of the NuTeV “Anomaly”

Radiative Corrections: Test of Weak Neutral Current

Not so long ago….



SM line: Erler et al., Phys.Rev.D72:073003,2005

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.

Paschos-Wolfenstein Ratio: Isoscalar Target

NuTeV measured (approximately) P-W ratio:

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

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

NuTeV

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

other methods

c.f. Standard Model = 0.2227 ± 0.0004

(c.f. 1978: 0.230 ± 0.015)

Correction to Paschos-Wolfenstein from CSV

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

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

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

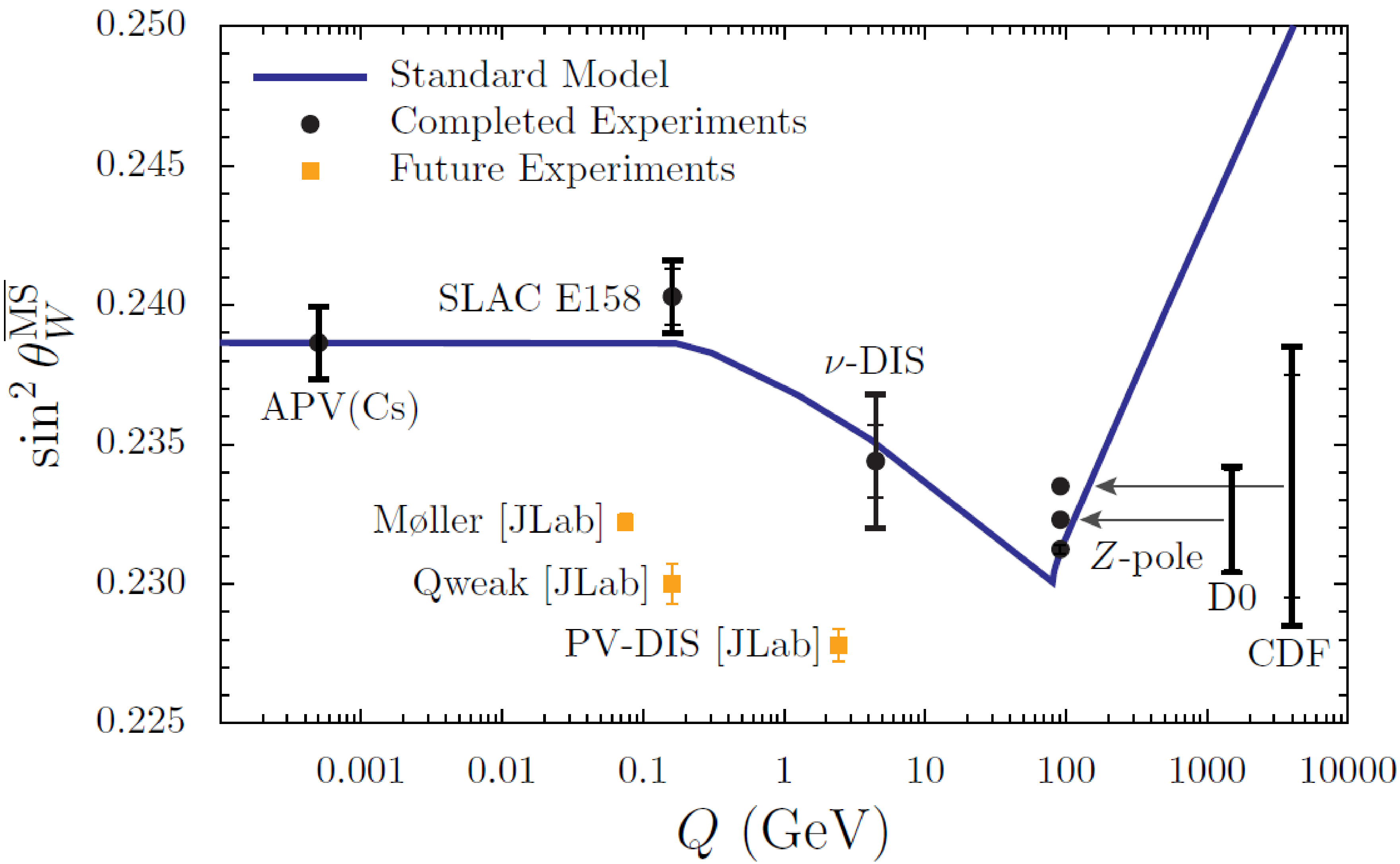
- **CSV:** $\Delta R^{\mathrm{CSV}} = -0.0026 \pm 0.0011$
  - **again using NuTeV functional**

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

- **Final result:** $\sin^2\theta_W = 0.2221 \pm 0.0013(\mathrm{stat}) \pm 0.0020(\mathrm{syst})$
  - **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 ± 0.03 ± 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

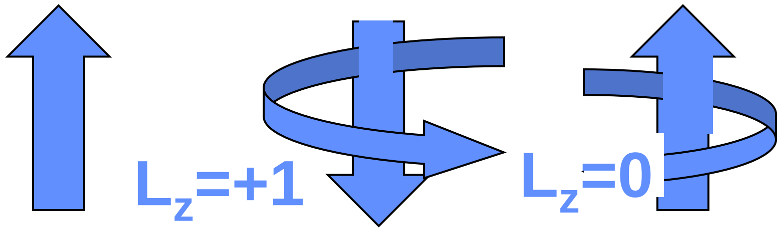
- Hence: axial anomaly plays at most a small role in explaining the spin crisis

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

The Pion Cloud & Gluon Hyperfine Interaction

- 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%)



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

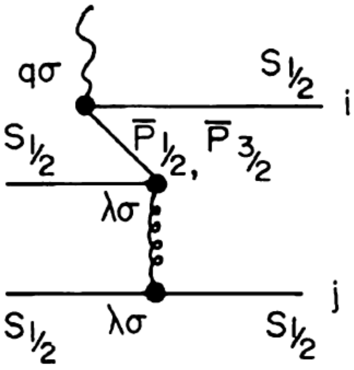
- Spin gets renormalized by a factor :

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

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

- In addition the effect of the one-gluon-exchange | "exchange current" correction :

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



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Schreiber-Thomas, Phys Lett B215 (1988) and Myhrer-Thomas, Phys Lett (1988)

Final Result for Quark Spin

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

$= (0.7,0.8)$ 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

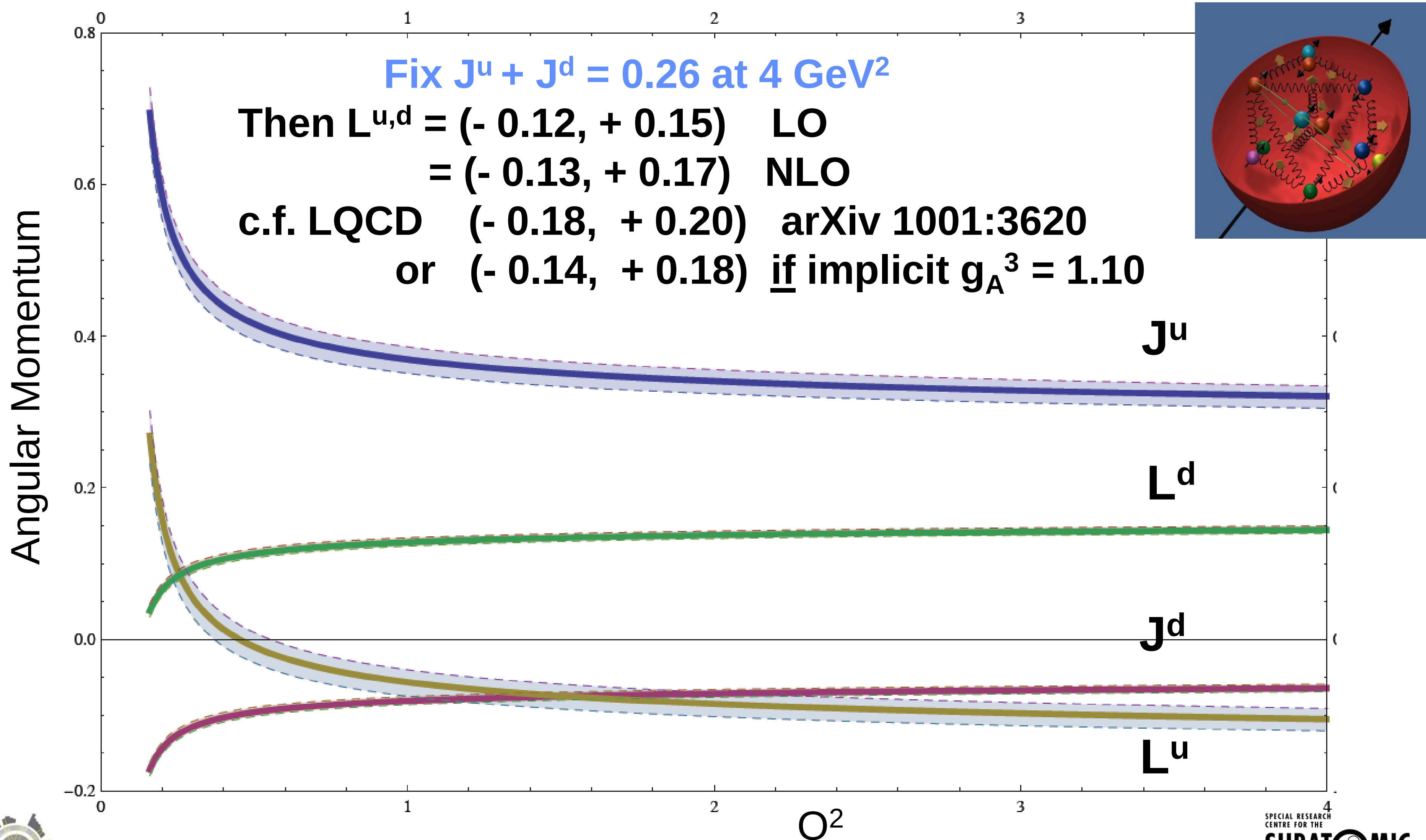
At model scale: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$

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

AWT, Phys Rev Lett, 101 (2008) 102003

NLO Evolution – using Bass-Thomas update

Remarkable agreement between model and LQCD

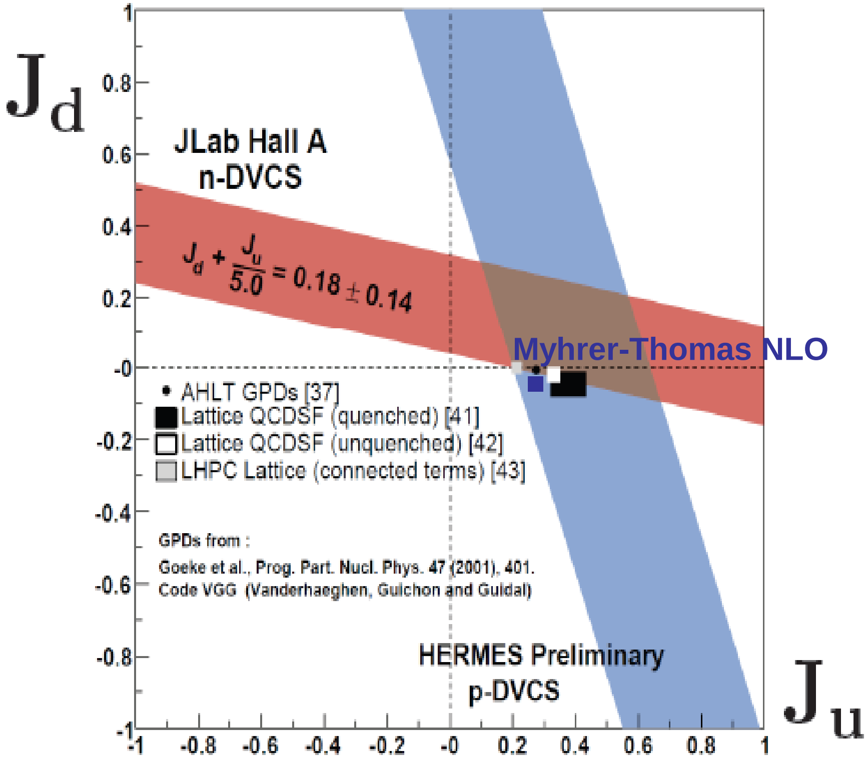


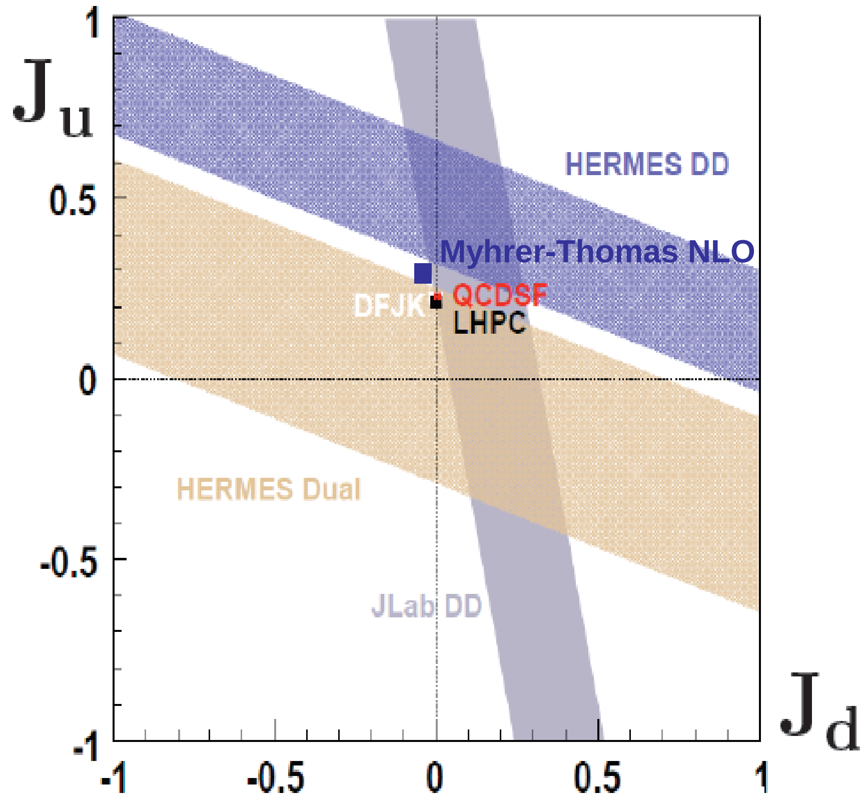
Bass, AWT, Phys Lett 684 (2010) 216; AWT, PRL 101 (2008) 102003
& AWT et al., E P J A46 (2010) 325

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)





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 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., PRL 110 (2013) 202001 (arXiv:1302.6300)

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 – which is solved in CBM

Separate Neutrino and Anti-Neutrino Ratios

- **Biggest criticism of this explanation was that NuTeV actually measured R^ν and $R^{\bar\nu}$, separately: Claim we should compare directly with these.**

- **Have done this:**

$$\delta R^\nu = \frac{2\left(3\, g_{Lu}^2 + g_{Ru}^2\right)\langle x_A\, u_A^- - x_A\, d_A^-\rangle}{\langle 3\, x_A\, u_A + 3\, x_A\, d_A + x_A\, \bar u_A + x_A\, \bar d_A + 6\, x_A\, s_A\rangle}$$

$$\delta R^{\bar\nu} = \frac{-2\left(3\, g_{Rd}^2 + g_{Ld}^2\right)\langle x_A\, u_A^- - x_A\, d_A^-\rangle}{\langle x_A\, u_A + x_A\, d_A + 3\, x_A\, \bar u_A + 3\, x_A\, \bar d_A + 6\, x_A\, \bar s_A\rangle}$$

- **Then R^ν moves from 0.3916 ± 0.0013 c.f. 0.3950 in the Standard Model to 0.3933 ± 0.0015;**

  $R^{\bar\nu}$ moves from 0.4050 ± 0.0027 to 0.4034 ± 0.0028, c.f. 0.4066 in SM

- **This is tremendous improvement : χ^2 changes from 7.2 to 2.6 for the two ratios!**

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

Strange Quark Asymmetry

- **Required in principle by chiral symmetry (s and $\bar{s}$ have different chiral behaviour*)**

- **Experimental constraint primarily through opposite sign di-muon production with neutrinos (CCFR & NuTeV)**

	$\langle x\, s^- \rangle$	ΔR^s	ΔR^{total}	$\sin^2\theta_W \pm$ syst.
Mason *et al.* [8]	0.00196 ± 0.00143	-0.0018 ± 0.0013	-0.0063 ± 0.0018	0.2214 ± 0.0020
NNPDF [9]	0.0005 ± 0.0086	-0.0005 ± 0.0078	-0.0050 ± 0.0079	$0.2227 \pm large$
Alekhin *et al.* [31]	$0.0013 \pm 0.0009 \pm 0.0002$	$-0.0012 \pm 0.0008 \pm 0.0002$	-0.0057 ± 0.0015	0.2220 ± 0.0017
MSTW [32]	$0.0016^{+0.0011}_{-0.0009}$	$-0.0014^{-0.0010}_{+0.0008}$	-0.0059 ± 0.0015	0.2218 ± 0.0018
CTEQ [33]	$0.0018^{+0.0016}_{-0.0004}$	$-0.0016^{+0.0014}_{-0.0004}$	$-0.0061^{+0.0019}_{-0.0013}$	$0.2216^{+0.0021}_{-0.0016}$
This work (Eq. (10))	0.0 ± 0.0020	0.0 ± 0.0018	-0.0045 ± 0.0022	0.2232 ± 0.0024

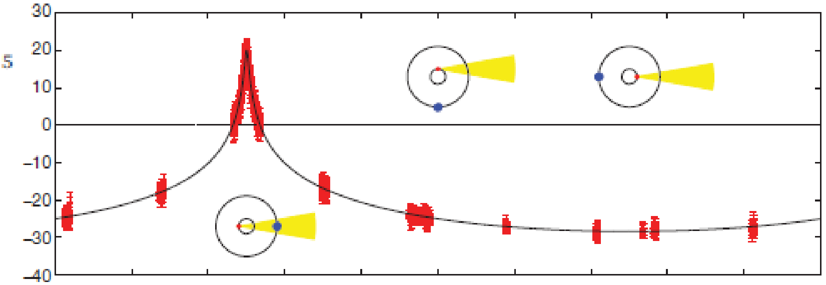
*** Signal & Thomas, Phys. Lett. B191 (1987) 205; Thomas et al., PRL 85 (2000) 2892**

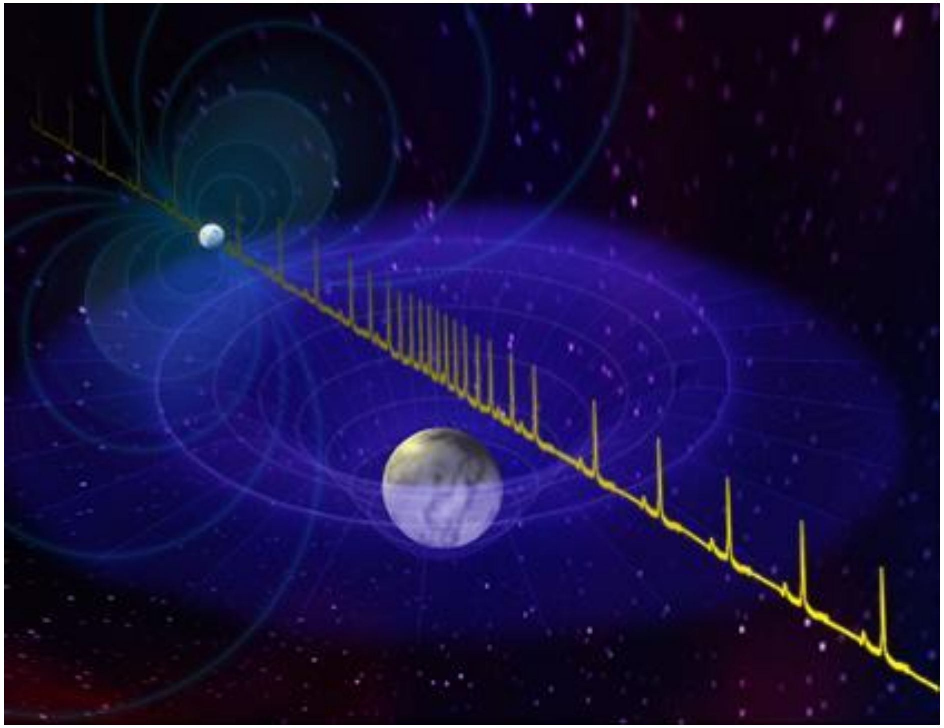
LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]



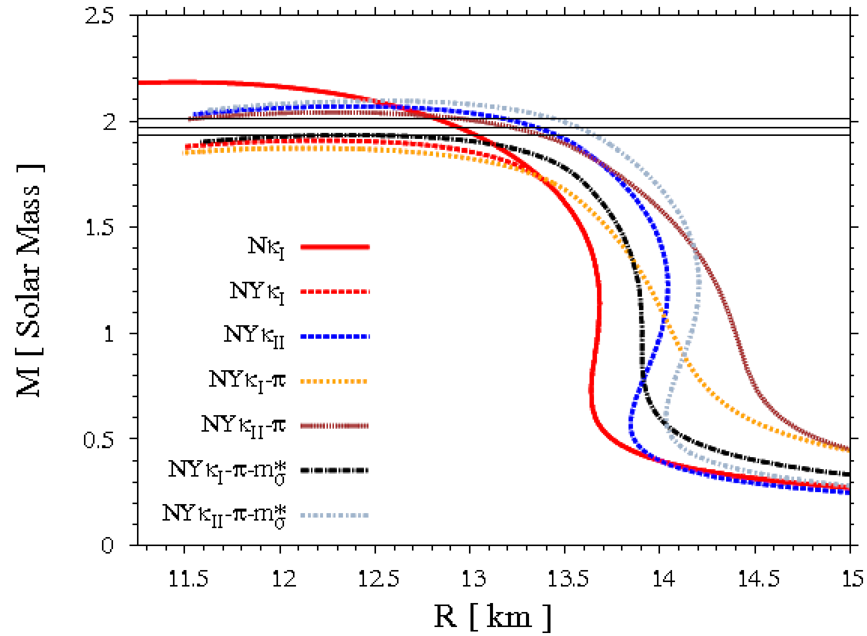


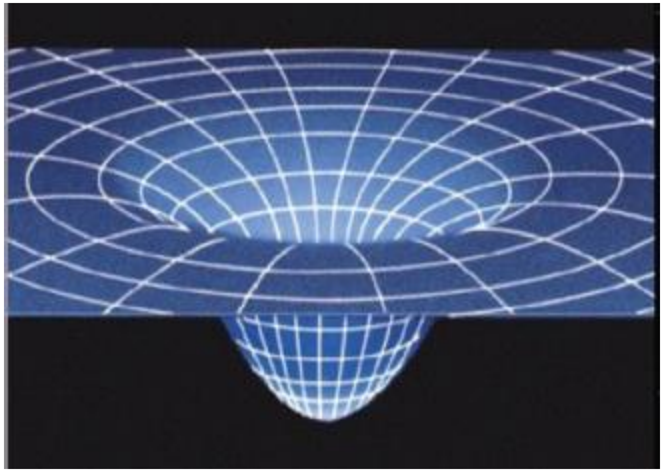
Report a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim it rules out hyperons (particles with strange quarks)

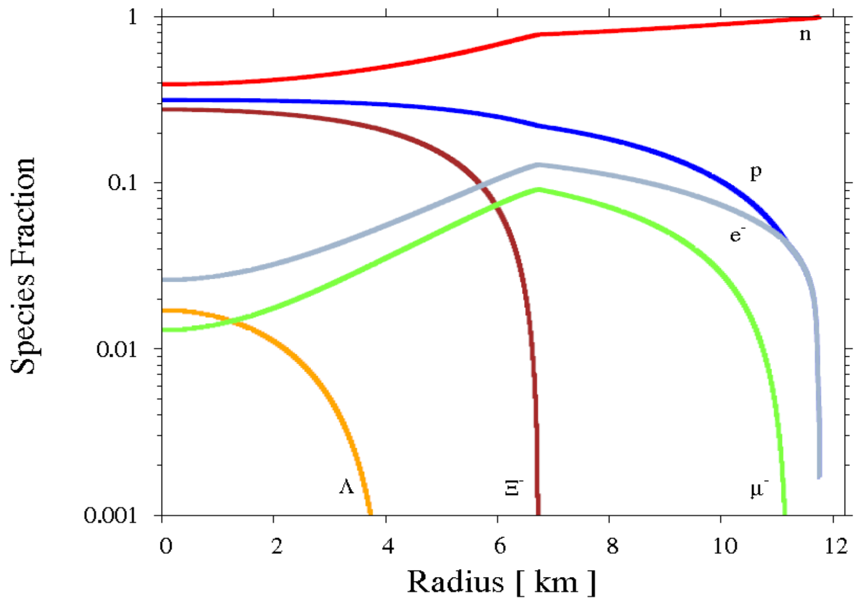
J1614-2230

Whittenbury et al. – arXiv:1204.2614 [nucl-th]





Data represents an Important constraint but does NOT forbid hyperons – indeed they are required and compatible!



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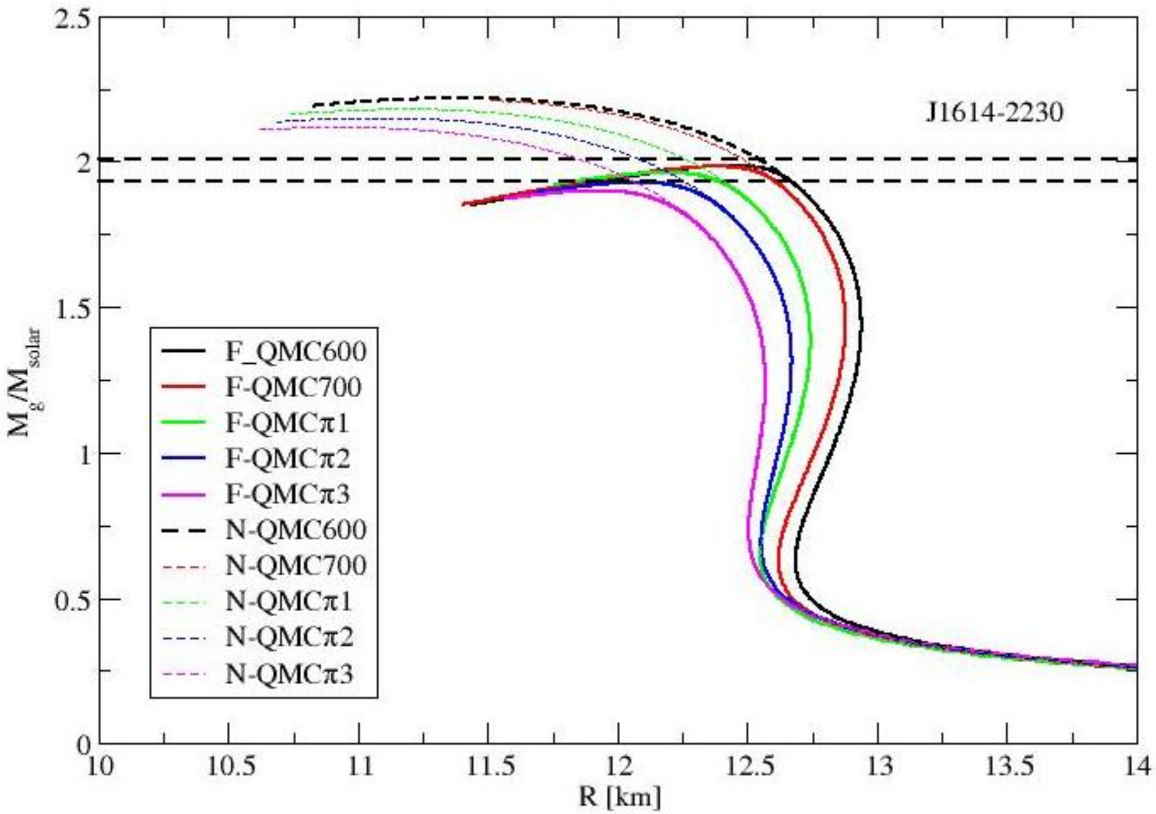
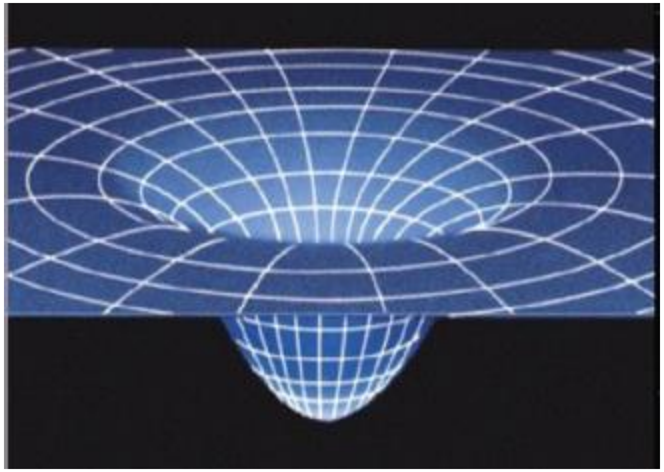
Conclusion incorrect





We conclude that the Demorest et al. result, if confirmed, is very significant for neutron star physics and does indeed rule out all EoS which predict a mass-radius curve that does not intersect the J1614-2230 mass line. However, it does not provide any constraint on the possible `exotic' composition of the high-density neutron star matter.

- Guichon et al., Nucl. Phys. A814 (2008) 66
  - result of an on-going collaboration between CSSM & CEA France with Jirina Stone (Oxford)

Physical Origin of Density Dependent Force of the Skyrme Type within the Quark Meson Coupling Model

P.A.M. Guichon[1], H.H. Matevosyan[2,3], N. Sandulescu[1,4,5] and A.W. Thomas[2]

Paper II: N P A772 (2006) 1 (nucl-th/0603044)

No longer need to expand around < σ > = 0

m_σ(MeV)	t_0(fm^2)	t_1(fm^4)	t_2(fm^4)	t_3(fm$^{5/2}$)	x_0	W_0(fm^4)	Deviation
600	-12.72	2.64	-1.12	74.25	0.17	0.6	33%
650	-12.48	2.21	-0.77	71.73	0.13	0.56	18%
700	-12.31	1.88	-0.49	69.8	0.1	0.53	18%
750	-12.18	1.62	-0.28	68.28	0.08	0.51	38%
SkM*	-13.4	2.08	-0.68	79	0.09	0.66	0%

Table 2: Comparison of the SkM* parameters with the QMC predictions for several values of m_σ

BUT density functional not exactly the same – QMC yields rational forms

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Modeling Valence Distribution

Formally, using OPE ($A_+ = 0$ gauge) *:

$$q(x, Q^2_0) = 1/4\,\pi \int_{-1}^{1} dz \exp[-i M x z] <p| \psi_+^{+} (z;00-z)\, \psi_+(0) |p>$$

Insert complete set of states : $\sum_n \int d^3 p_n |n><n| = 1$

and do $\int dz$ using translational invariance)

$$q(x, Q^2_0) = \sum_n \int d^3 p_n \; | < n | \psi_+(0) | p > |^2 \delta (M (1 - x) - p^{+}_n)$$

$$\text{with } p^+_n = (m_n^2 + \bar{p}_n^2)^{1/2} + p_z > 0$$

* Q^2_0 is the scale at which nucleon momentum is carried by predominantly valence quarks: below 1 GeV^2