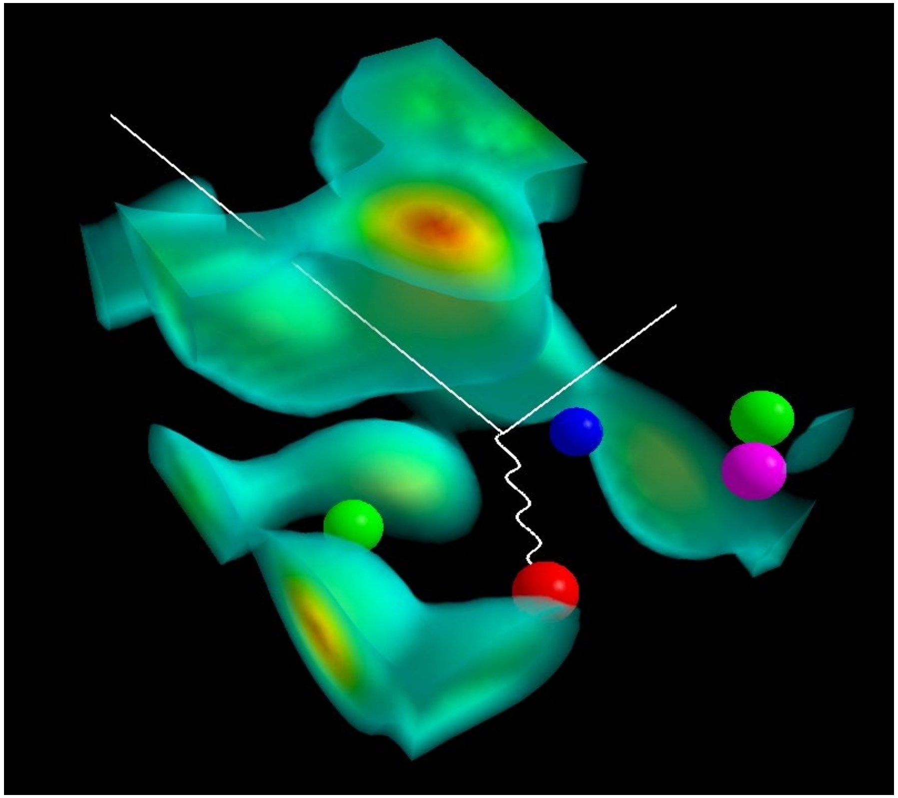
Some Outstanding Questions



Anthony W. Thomas

Workshop on Hadron Tomography with Hard Exclusive Reactions
ECT * Trento – August 8th 2024

Outline

I. **Strangeness and charm in the sea: effect on BSM searches**

II. **Baryon spectroscopy re-examined:**
how does QCD work for hadrons?

III. **QCD from atomic nuclei to neutron stars:**
how does QCD work for nuclei?

FONDAZIONE
BRUNO KESSLER

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

ADELAIDE
UNIVERSITY
AUSTRALIA

SPECIAL RESEARCH
CENTRE FOR THE
SUBATOMIC
STRUCTURE OF MATTER

Charm and Strangeness in the Nucleon

Knowledge of these features is totally unsatisfactory

- **s + sbar very uncertain:**

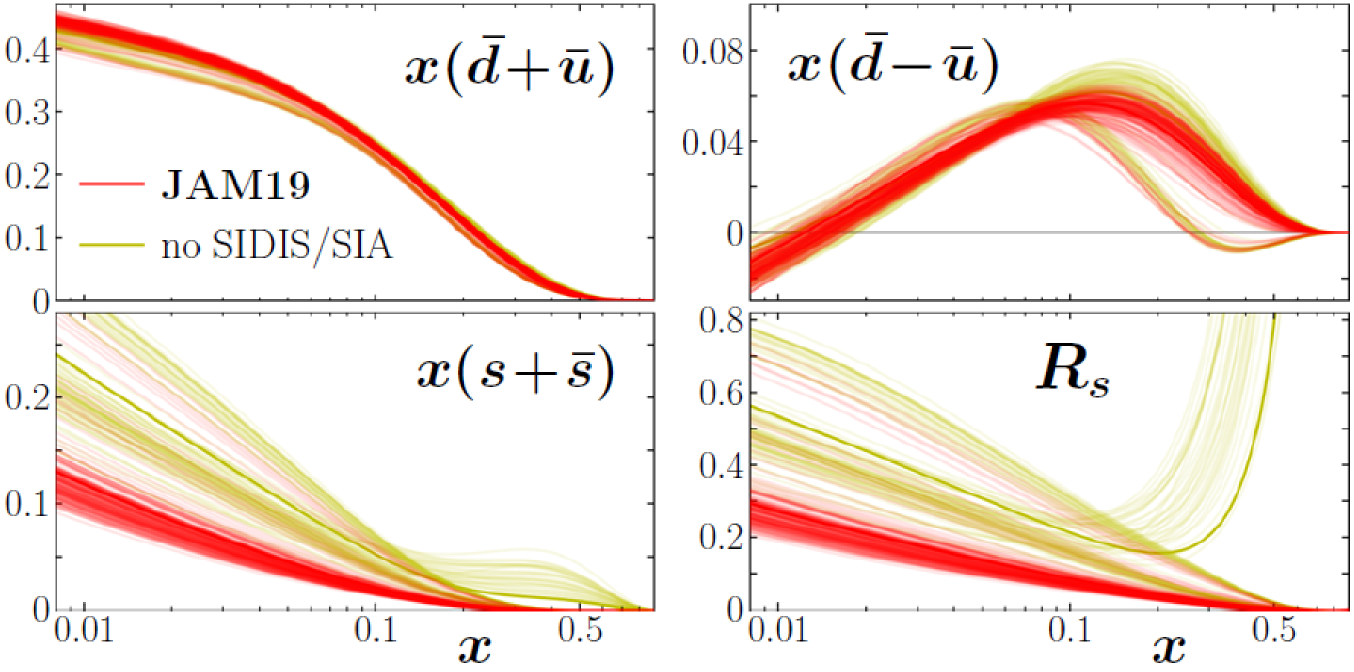
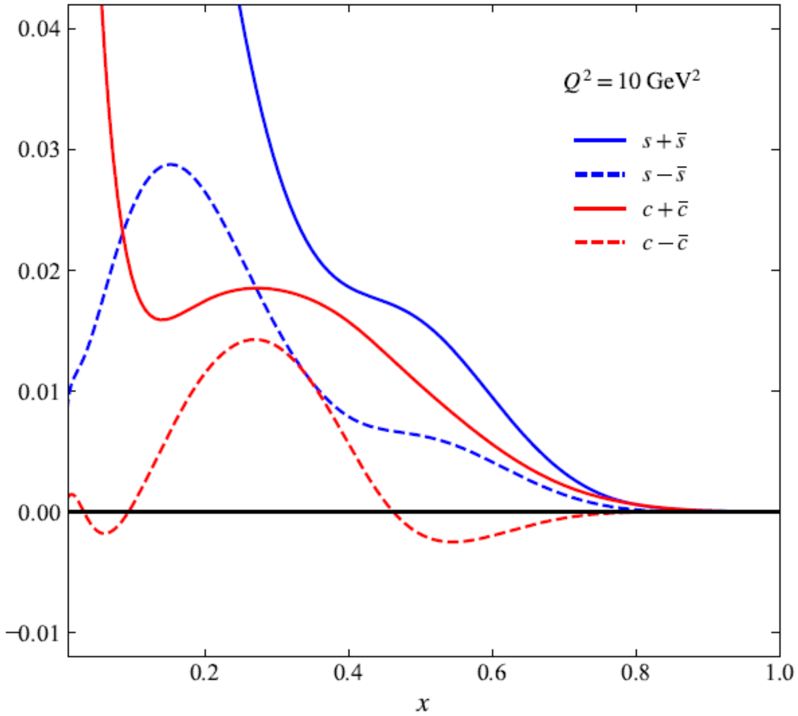


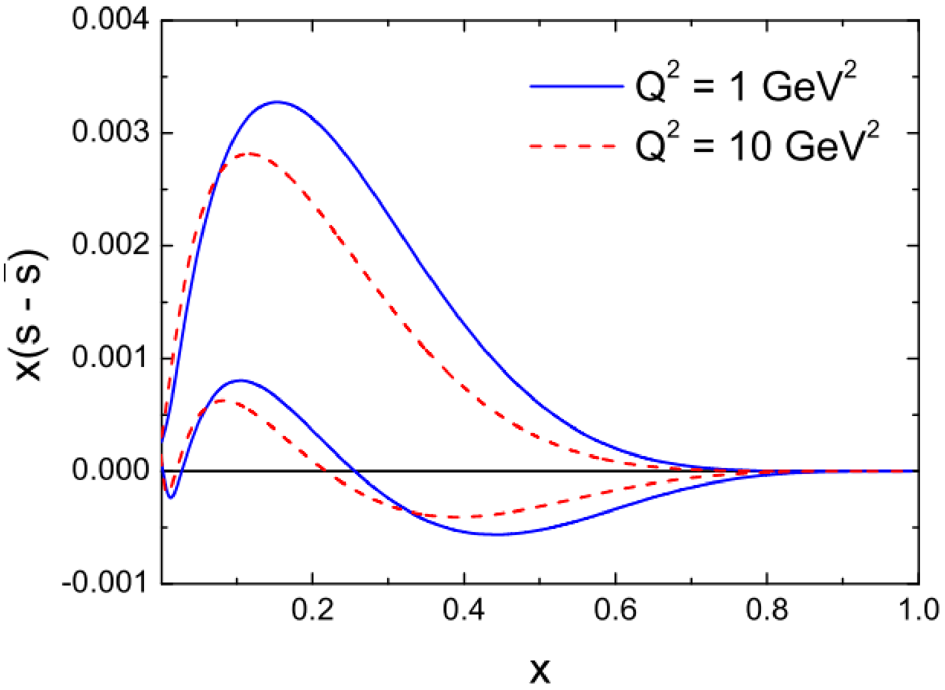
Fig. 4 Comparison of the light and strange sea quark PDFs in the JAM19 Monte Carlo global QCD analysis (red lines), with fits excluding SIDIS and SIA data (yellow lines) at the input scale, $Q = m_c =$

Melnitchouk and Owens: Eur. Phys. J. A (2021) 57:311

Strangeness extraction: Note difference in scale!



NNPDF: 2311.00743



X.G. Wang et al. / Physics Letters B 762 (2016) 52–56

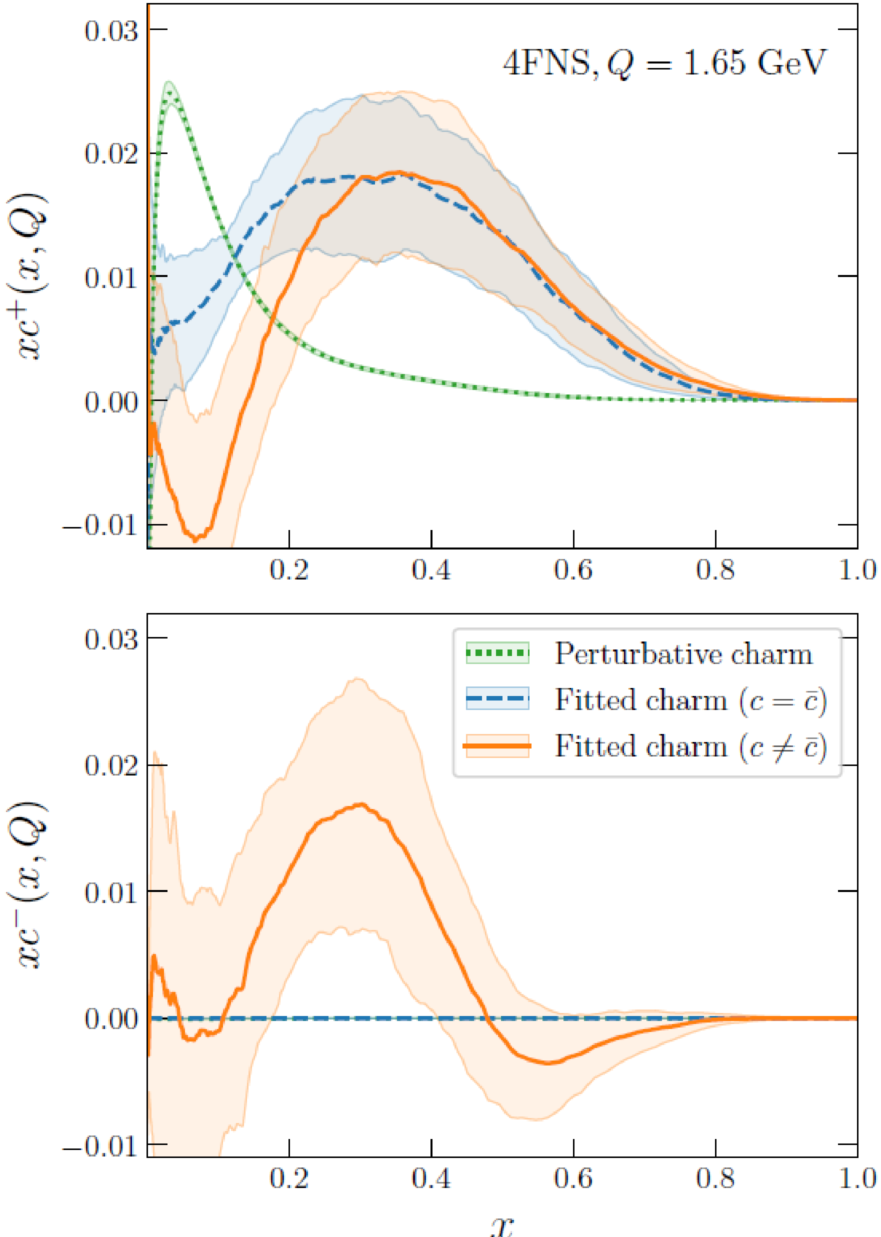
Wang et al., is based on chiral calculation: N to K Λ etc.

The same approach that originally predicted dbar > ubar (AWT Phys Lett B126 (1983) 97) and also first predicted s not equal to sbar (Signal and Thomas Phys Lett B191 (1987) 205)

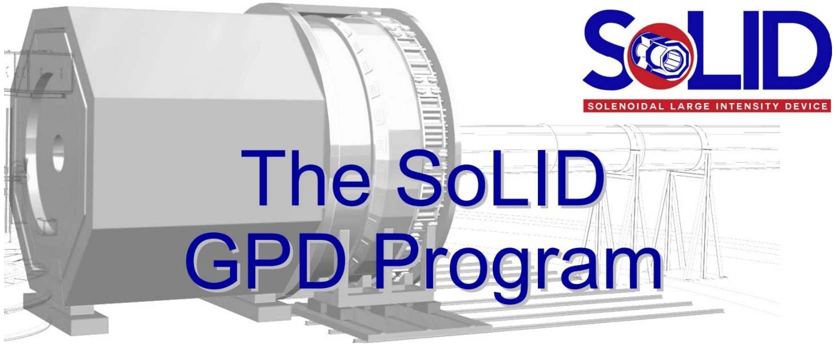
Recent NNPDF Extraction of charm

- Claim evidence for intrinsic charm
- Also claim to extract C-odd combination c – cbar

Ball et al., 2311.00743

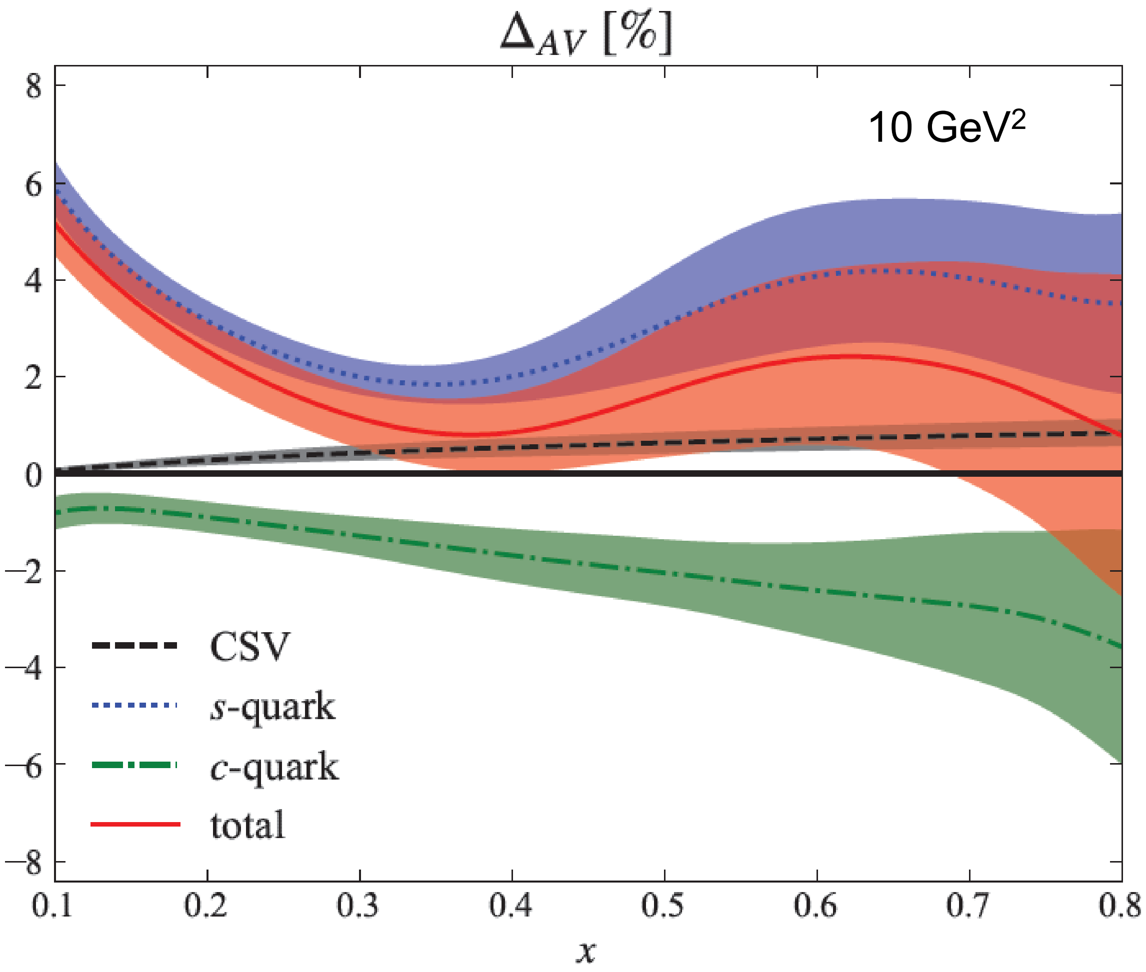


Crucial for tests of BSM Physics in PV DIS



The SoLID
GPD Program

Test of BSM Physics in PV DIS



$$A^{e^-}_{RL,d} = \frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}\Big[(2g^{eu}_{AV} - g^{ed}_{AV})(1+\Delta_{AV}) + R_V Y(2g^{eu}_{VA} - g^{ed}_{VA})(1+\Delta_{VA})\Big]$$

$$\Delta^{\mathrm{CSV}}_{AV} = \frac{2(g^u_V + 2g^d_V)(\delta u^+ - \delta d^+)}{5(2g^u_V - g^d_V)(u^+ + d^+)},$$

$$\Delta^{s}_{AV} = -\frac{4(g^u_V + 2g^d_V)s^+}{5(2g^u_V - g^d_V)(u^+ + d^+)},$$

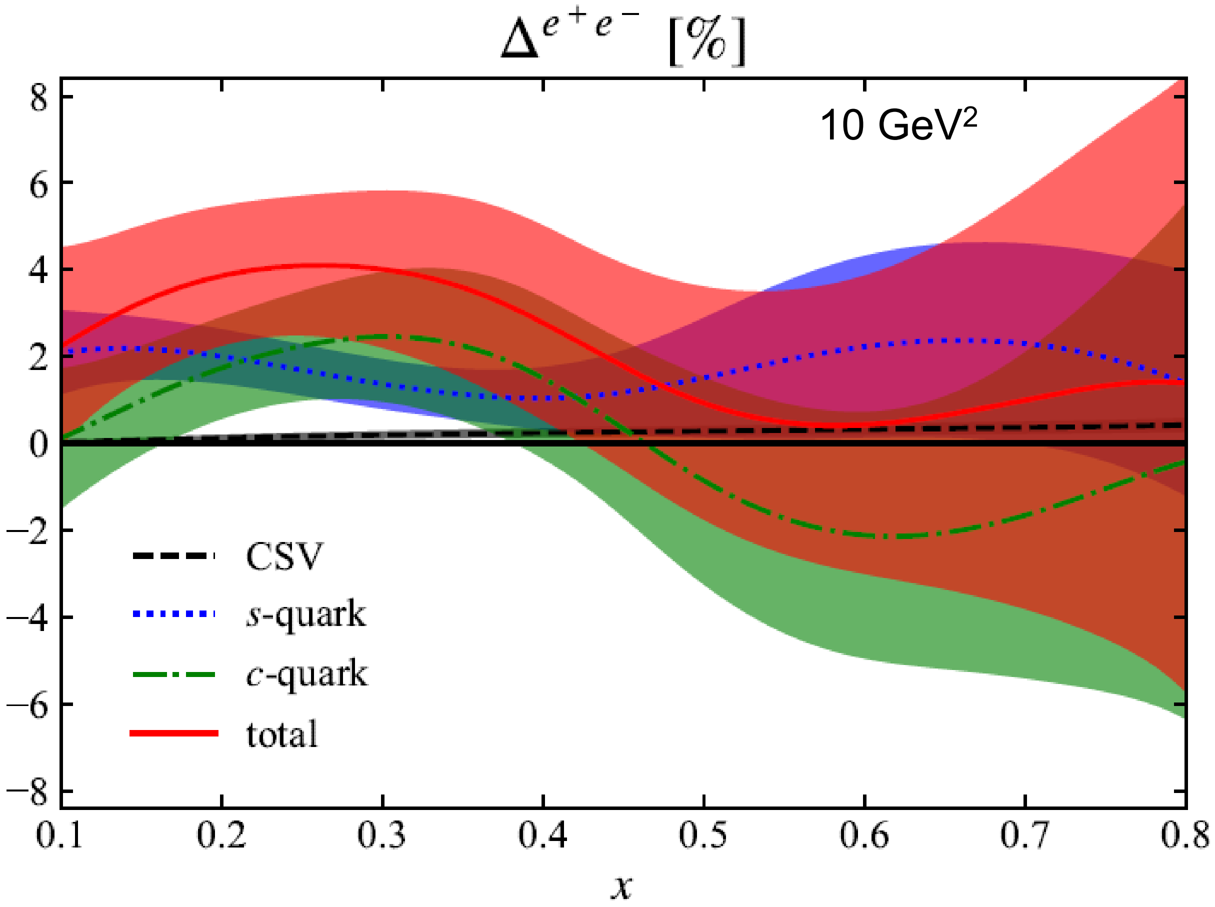
$$\Delta^{c}_{AV} = \frac{4(g^u_V + 2g^d_V)c^+}{5(2g^u_V - g^d_V)(u^+ + d^+)},$$

Big cancellation between s$^+$ and c$^+$

X-G Wang and AWT, 2403.07327
Using NNPDF NNLO parton distributions

PV DIS e^+ - e^- asymmetry on D: Tests AA uniquely

$$A_d^{e^+e^-} = -\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\,\frac{1-(1-y)^2}{1+(1-y)^2}\,\frac{R_V(2g_{AA}^{eu}-g_{AA}^{ed})}{5+4R_c+R_s}\left(1+\Delta^{e^+e^-}\right)$$



$$\Delta_s^{e^+e^-} = -\frac{2g_A^d s_V}{(2g_A^u - g_A^d)(u_V + d_V)},$$

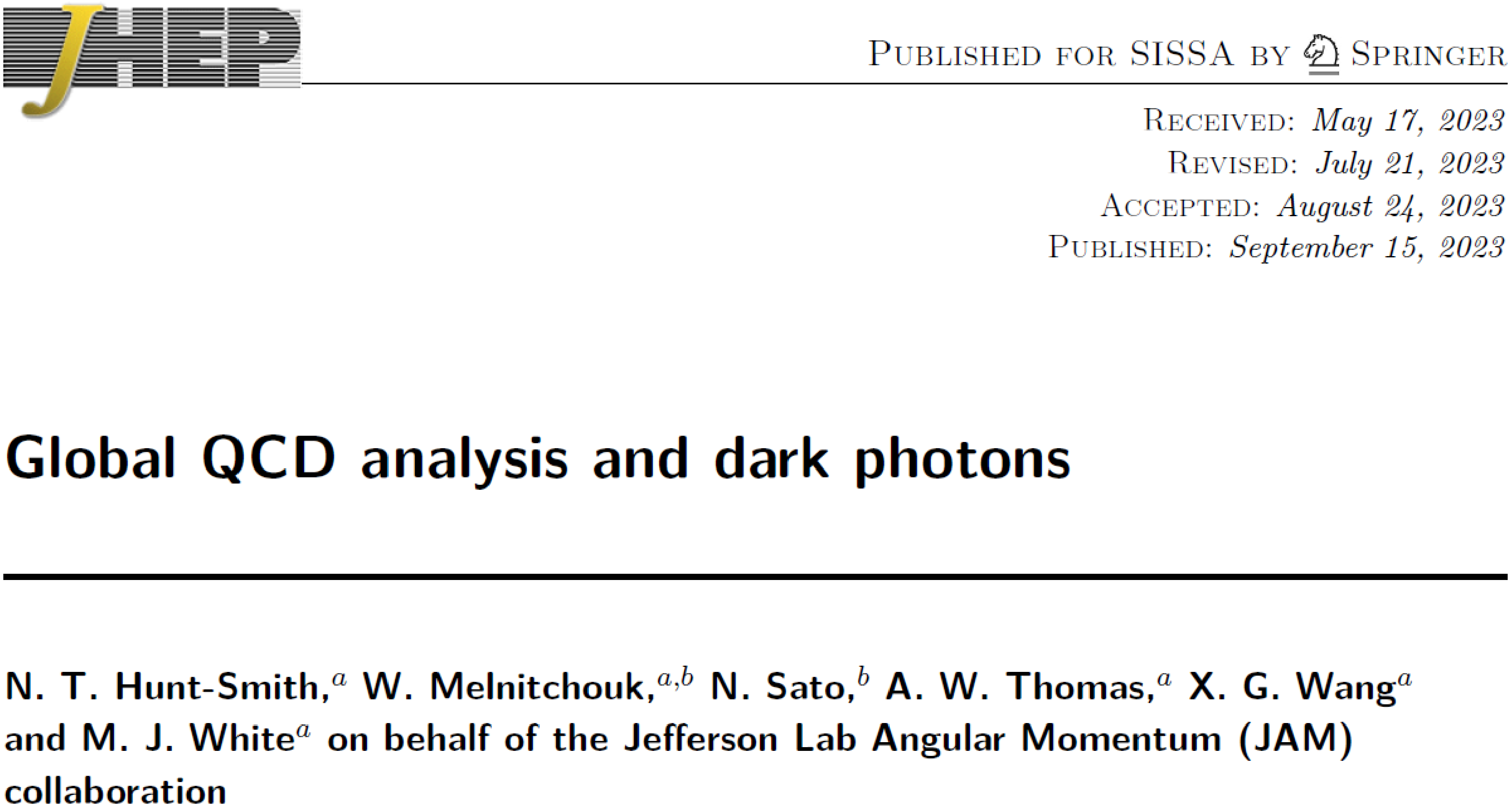
$$\Delta_c^{e^+e^-} = \frac{4g_A^u c_V}{(2g_A^u - g_A^d)(u_V + d_V)}.$$

Only C-odd terms: s and c add at low-x and cancel at large-x

Uncertainties in c and s imply many TeV reduction in exclusion limits

- **Reduction from 10.7 GeV to 6.2 TeV for $(2g^{eu}_{AA} - g^{ed}_{AA})$ with uncertainties shown**
- **But the C-odd strange and charm PDFs are essentially undetermined experimentally**
- **Errors could be much bigger**
- **Could mimic effects on new physics, such as a dark photon**

JAM Collaboration Analysis of World DIS Data



Published for SISSA by Springer

Received: *May 17, 2023*
Revised: *July 21, 2023*
Accepted: *August 24, 2023*
Published: *September 15, 2023*

Global QCD analysis and dark photons

N. T. Hunt-Smith,[a] W. Melnitchouk,[a,b] N. Sato,[b] A. W. Thomas,[a] X. G. Wang[a] and M. J. White[a] on behalf of the Jefferson Lab Angular Momentum (JAM) collaboration

https://doi.org/10.1007/JHEP09(2023)096

Allow for Existence of a Dark Photon: SURPRISE

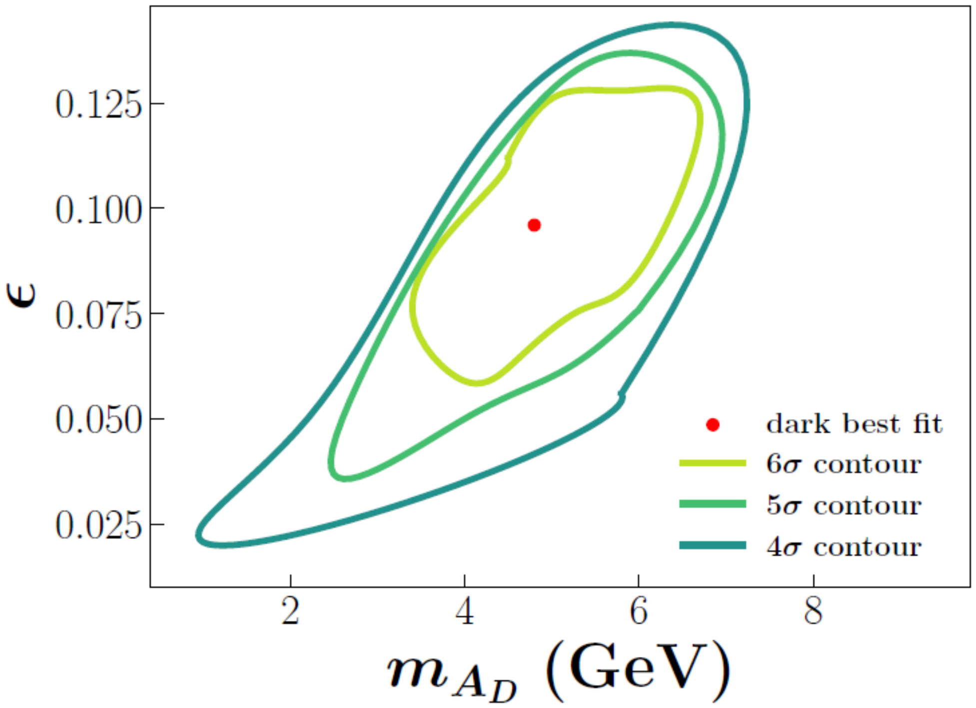
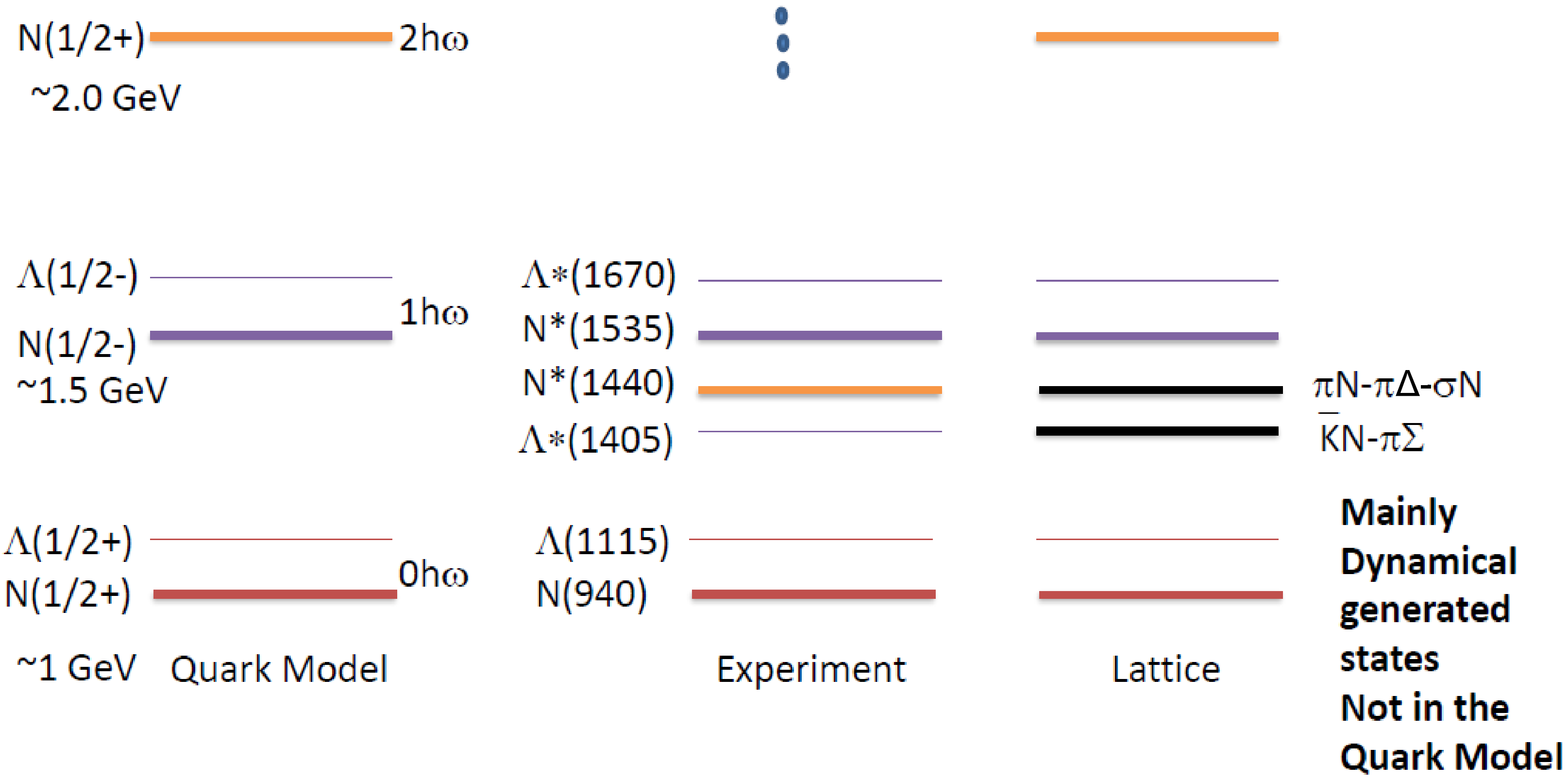


Figure 3: Results of an hypothesis test for the likelihood that the SM is the correct theory to describe this data, compared with the case where a dark photon is included. The hypothesis that the SM is the correct theory is excluded at 6.5σ for the best dark photon fit at the red point.

Testing new ideas in Baryon Spectroscopy

Recent suggestions from CSSM that old mysteries in the quark model have been clarified by lattice QCD and HEFT

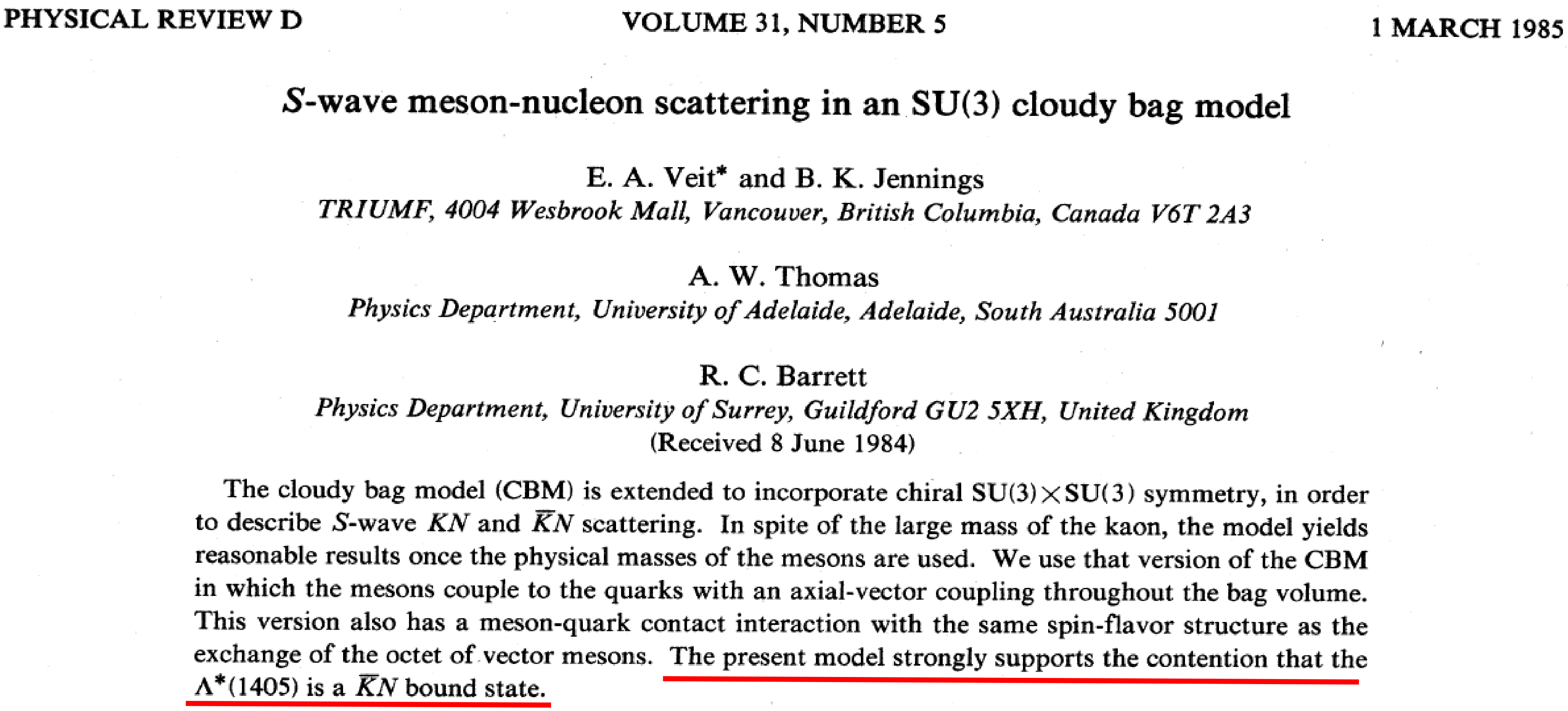


Mainly Dynamical generated states Not in the Quark Model

Wu, Leinweber et al., Physical Review D97, 094509 (2018)

Example: Λ(1405)

First calculation after QCD incorporating chiral symmetry



PHYSICAL REVIEW D VOLUME 31, NUMBER 5 1 MARCH 1985

S-wave meson-nucleon scattering in an SU(3) cloudy bag model

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TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

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Physics Department, University of Adelaide, Adelaide, South Australia 5001

R. C. Barrett
Physics Department, University of Surrey, Guildford GU2 5XH, United Kingdom

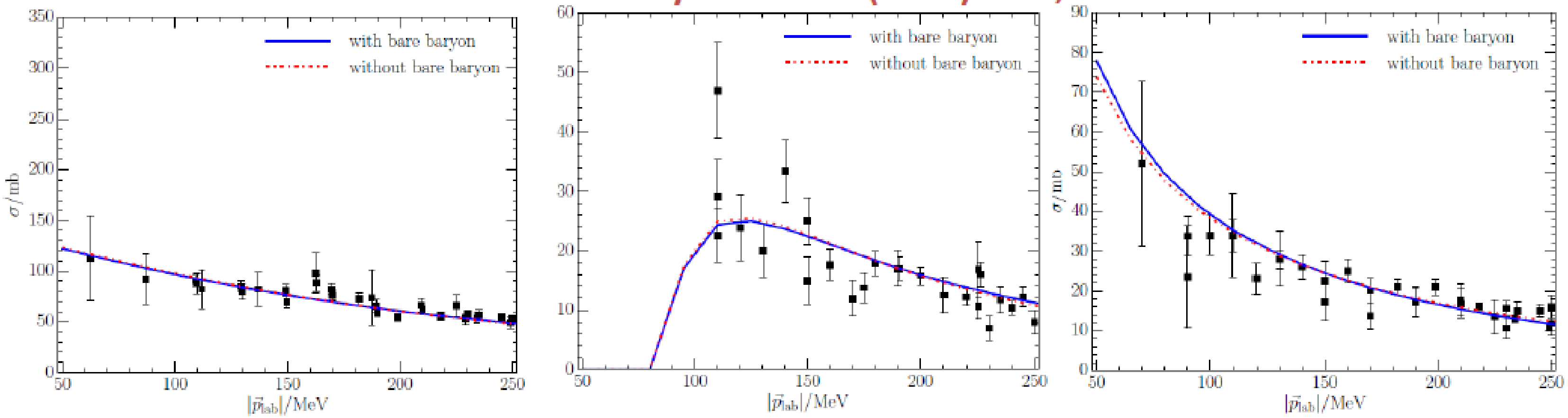
(Received 8 June 1984)

The cloudy bag model (CBM) is extended to incorporate chiral SU(3)×SU(3) symmetry, in order to describe S-wave KN and $\overline{K}N$ scattering. In spite of the large mass of the kaon, the model yields reasonable results once the physical masses of the mesons are used. We use that version of the CBM in which the mesons couple to the quarks with an axial-vector coupling throughout the bag volume. This version also has a meson-quark contact interaction with the same spin-flavor structure as the exchange of the octet of vector mesons. The present model strongly supports the contention that the $\Lambda^*(1405)$ is a $\overline{K}N$ bound state.

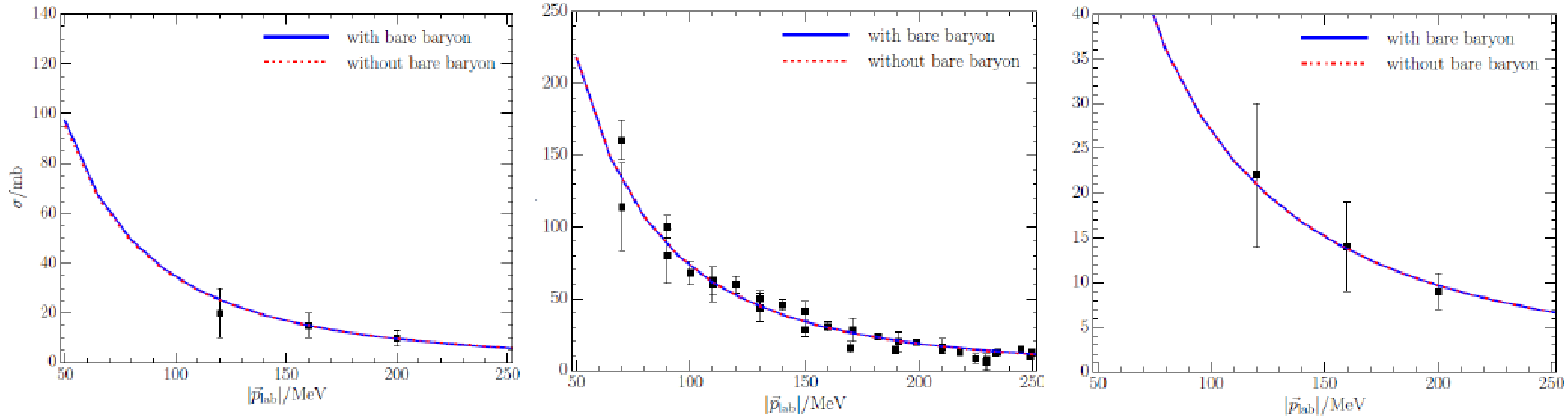
But now we can use QCD itself

Hamiltonian fit to existing data

Zhan-wei Liu etc. Phys.Rev. D95 (2017) no.1, 014506



(a) $K^- p \to K^- p$ (b) $K^- p \to \bar{K}^0 n$ (c) $K^- p \to \pi^- \Sigma^+$



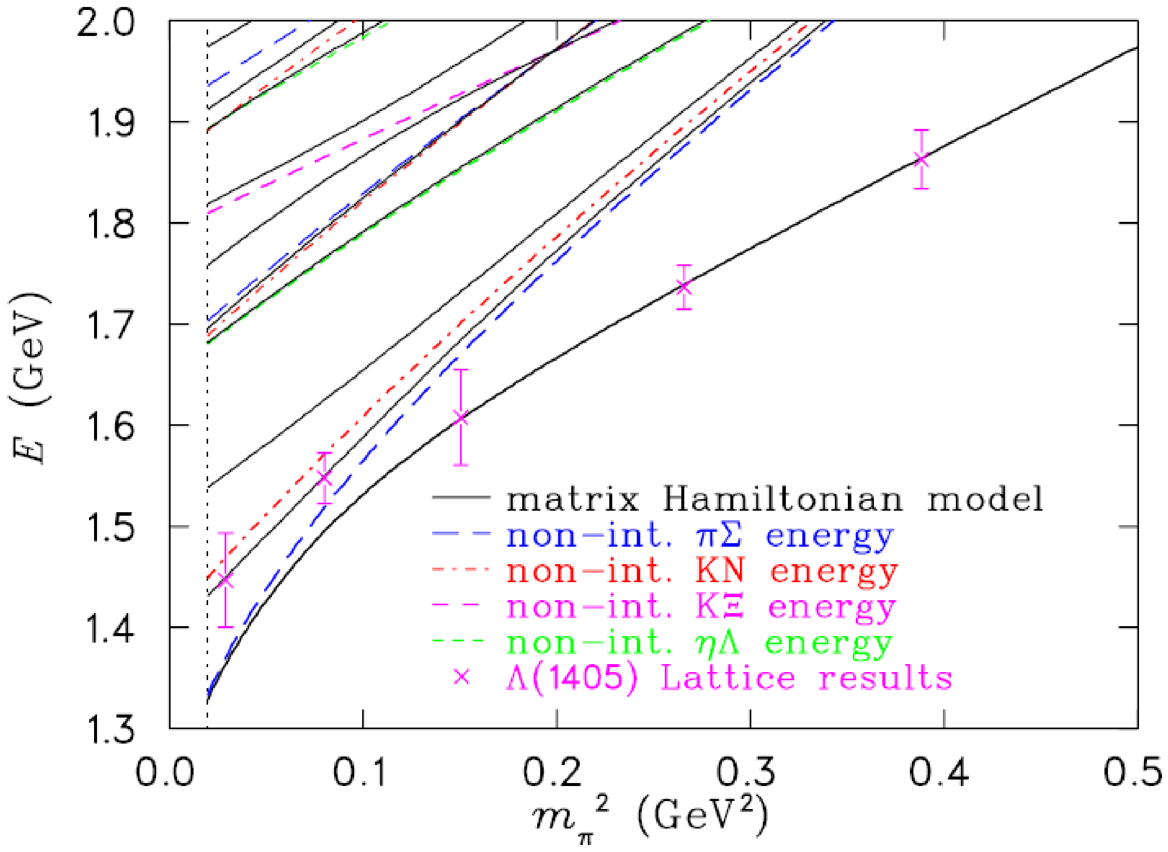
(d) $K^- p \to \pi^0 \Sigma^0$ (e) $K^- p \to \pi^+ \Sigma^-$ (f) $K^- p \to \pi^0 \Lambda$

Include πΣ, KbarN, ηΛ and KΞ channels

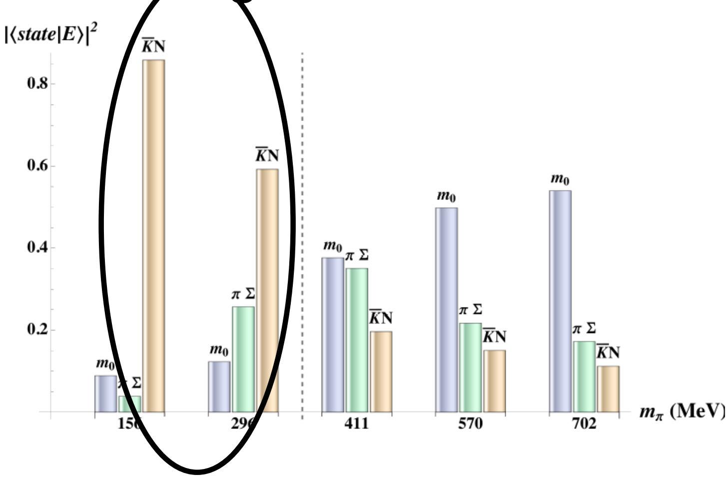
Similar work by Valencia, Bonn, JLab and other groups

Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state



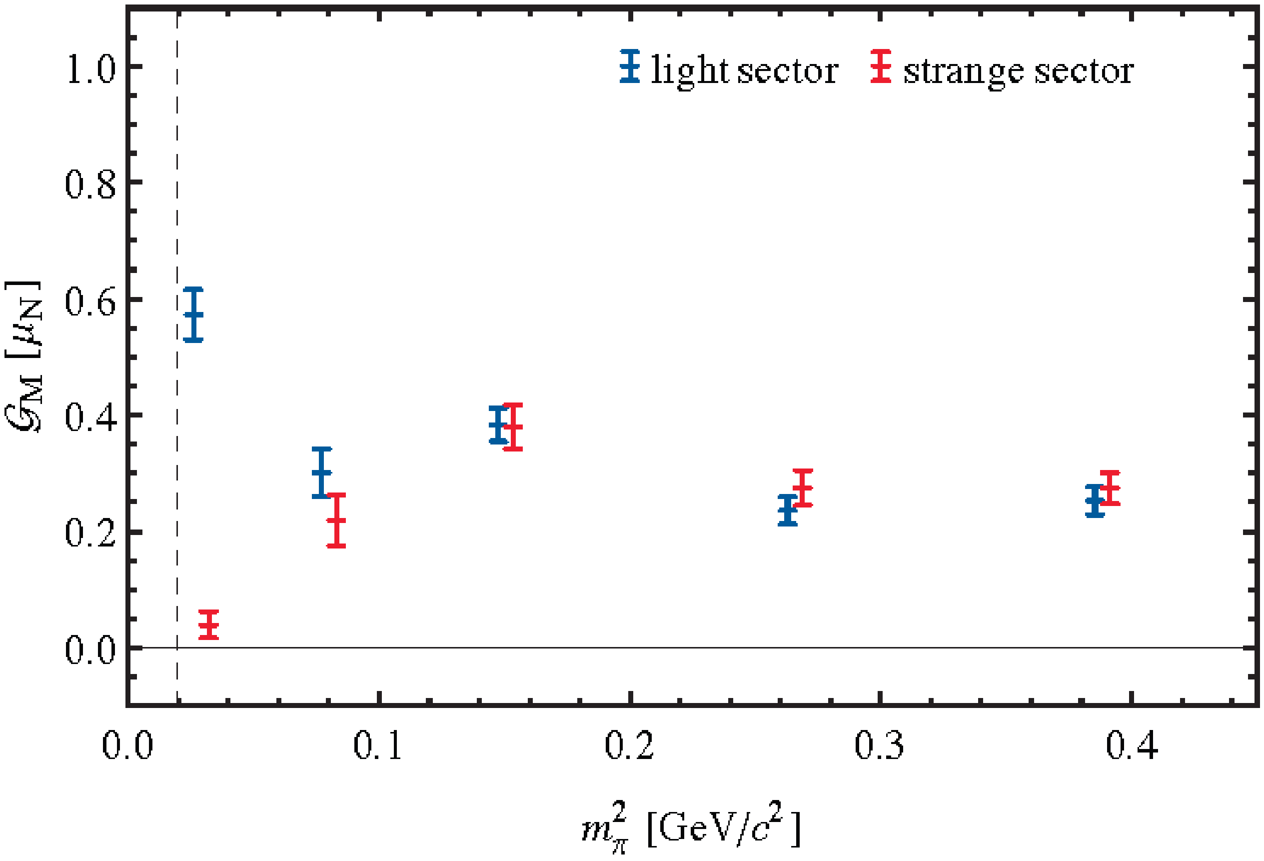
Hamiltonian approach allows one to examine the eigenstates:



Hall, Leinweber, Menadue, Young, AWT – Phys. Rev. Lett. 114 (2015) 13

Lattice Magnetic Form Factor Calculations

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



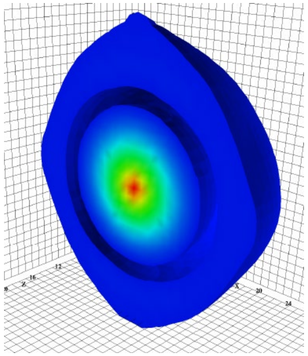
Only an L=0 Kbar-N state gives vanishing strange moment

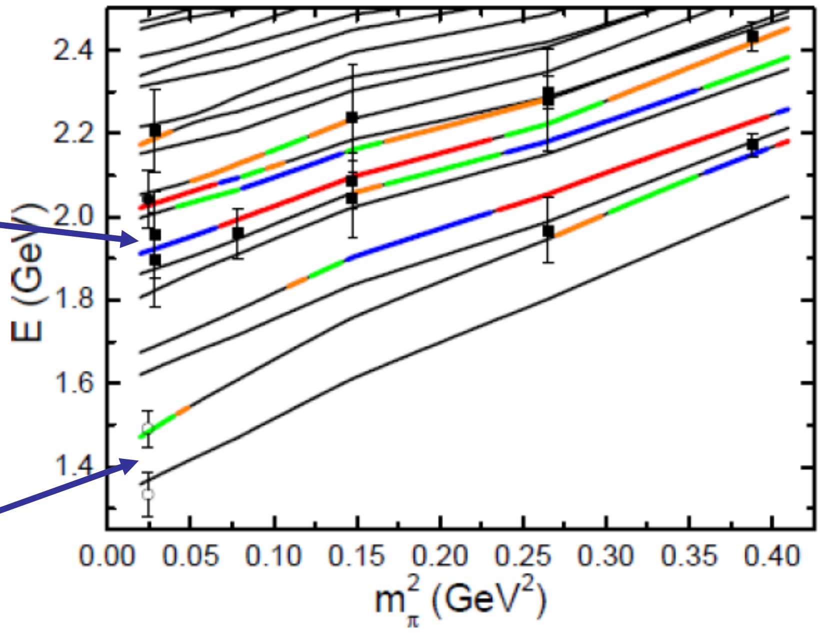
Hall *et al.*, Phys. Rev. *D* 95 (2017) 5, 054510

Similar (more controversial) conclusion for Roper

Comparison of HEFT Results with Lattice Energy Levels

- **Blue indicates high "bare state" (i.e. 3-quark) content. This matches the lowest state found with a 3-quark interpolating field**





- **Lattice calculations of Lang et al., Phys. Rev. D 95, 014510 (2017), using baryon-meson interpolating fields, especially Nσ**

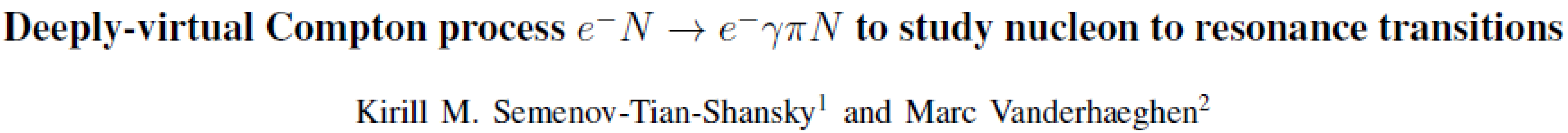
- **Matched by Hamiltonian levels but with little or no 3-quark content**

The first scenario with a bare state for P11 around the pole at 2.0 GeV can fit both Lattice data and experimental data well, it indicates that N*(1440) seems a molecule state, and first radial excitation of nucleon should be around 2.0 GeV.

Wu et al., Phys. Rev. D 97 (2018) 9, 094509

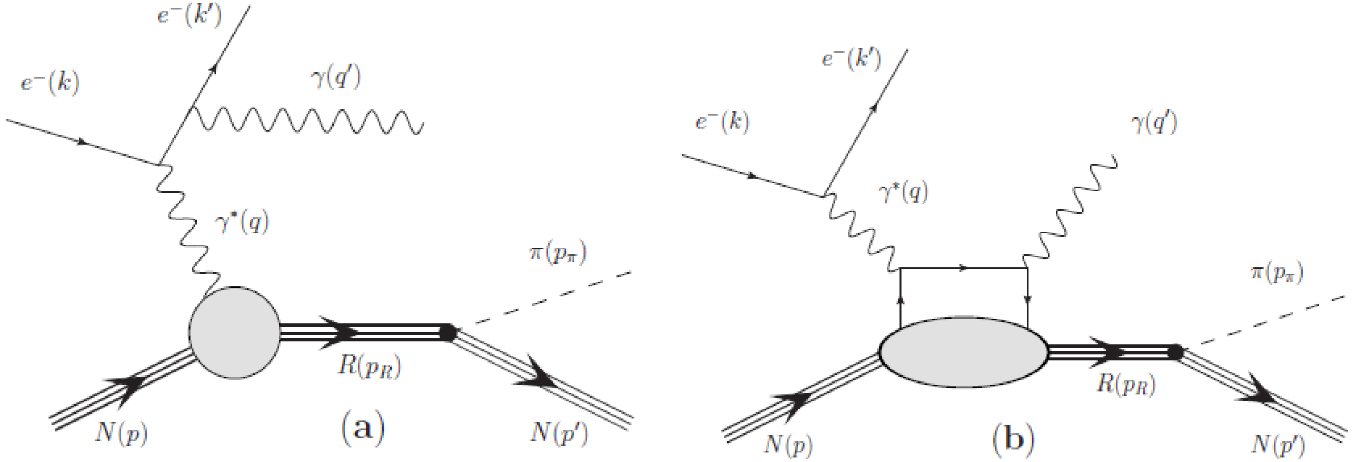
How can we test this experimentally?

- **New suggestion:** **2303.00119**



Deeply-virtual Compton process $e^- N \to e^- \gamma \pi N$ to study nucleon to resonance transitions

Kirill M. Semenov-Tian-Shansky[1] and Marc Vanderhaeghen[2]



May provide a way to test the molecular idea……

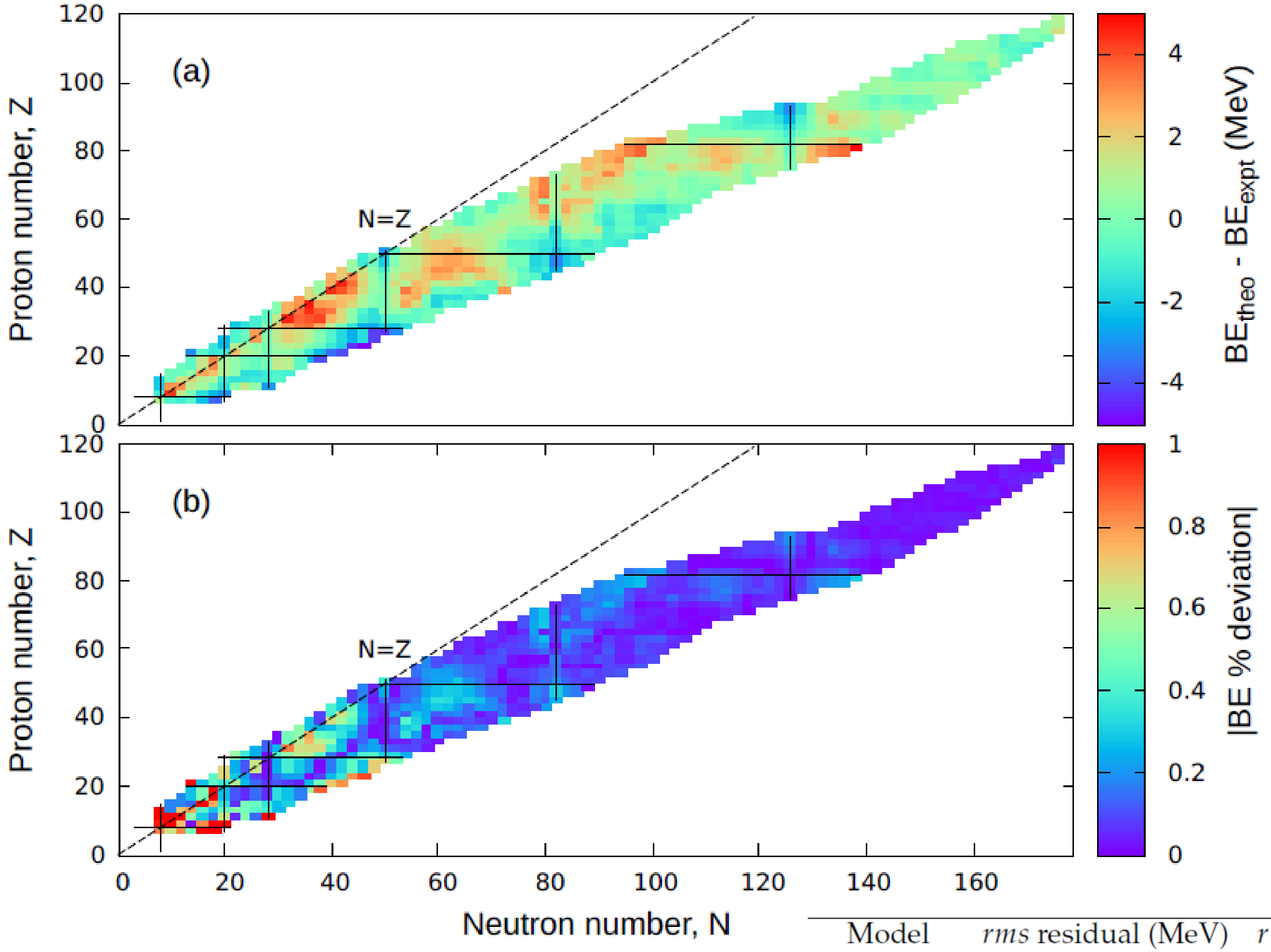
A new paradigm for nuclear physics

— anathema to traditional nuclear physicists!

Quark structure of nucleon changes in-medium

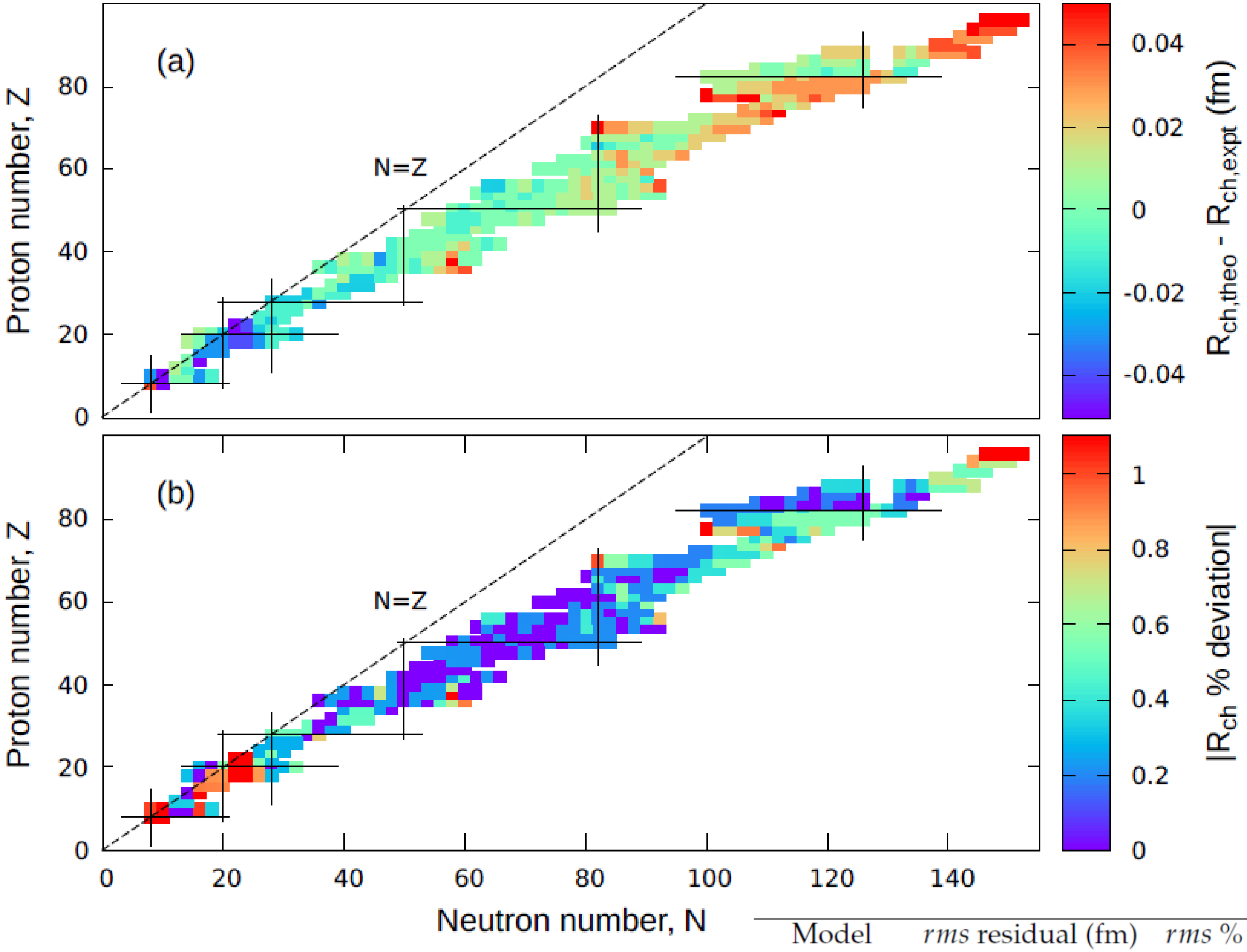
- **Nuclear matter has strong Lorentz scalar mean-field**
- **Comparable with the mass of the nucleon**
- **This naturally modifies the quark structure of the bound nucleon** **(Guichon et al., PPNP 100 (2018) 262)**
- **Know since 1980s that this naturally explains the EMC effect** **(Thomas et al., Phys Lett B 233 (1989) 43)** **and recently using covariant NJL model** **(Cloët et al., Phys Lett B642 (2006) 210)**
- **Has been used to generate a remarkably successful EDF with just 5 parameters** **(Martinez et al., PR C102 (2020) 065801)**

Binding Energies – All Known Even-Even Nuclei



Model	*rms* residual (MeV)	*rms* % deviation
QMCπ-III	1.59	0.29
QMCπ-II	2.34	0.39
QMCπ-I	2.78	0.50
QMC-I	3.84	0.69
SV-min	3.64	0.38
UNEDF1	2.06	0.55
DD-MEδ	2.41	0.42
FRDM	0.89	0.18

Charge Radii

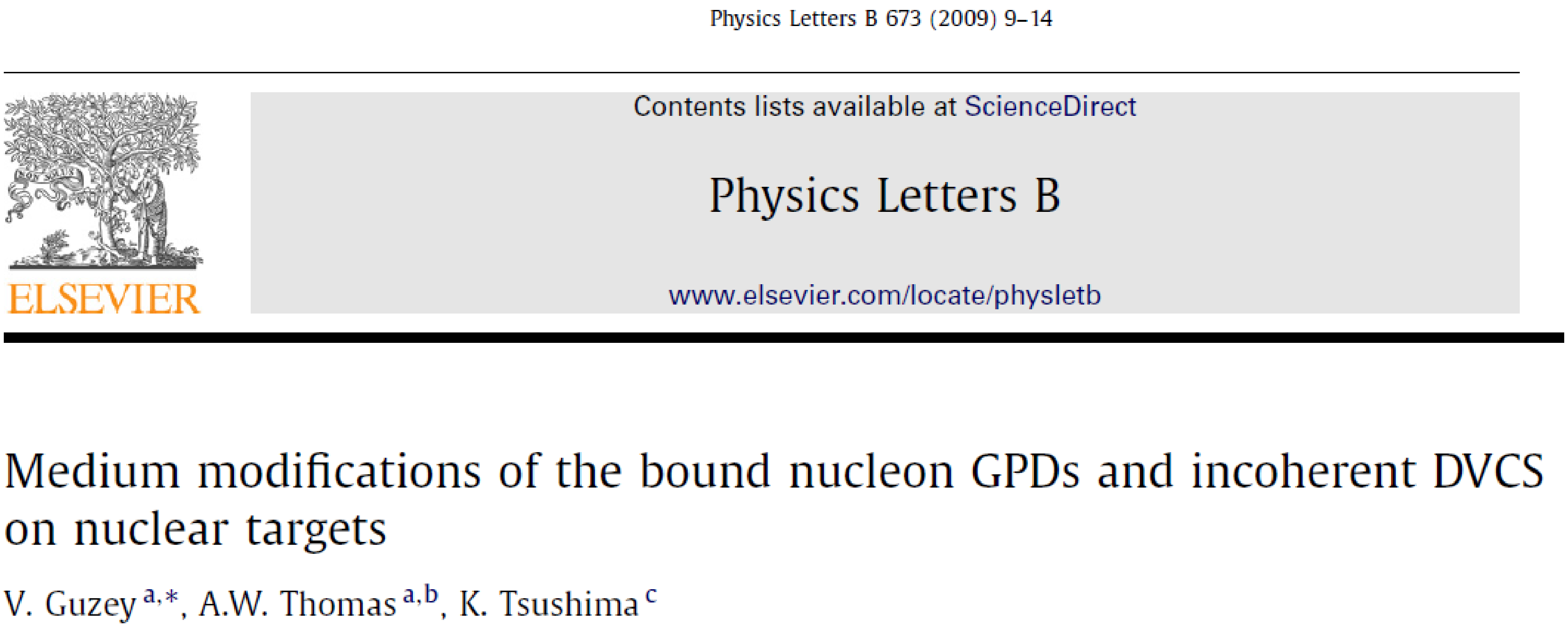


Model	*rms* residual (fm)	*rms* % deviation
QMCπ-III	0.024	0.50
QMCπ-II	0.029	0.66
QMCπ-I	0.028	0.65
QMC-I	0.030	0.66
SV-min	0.024	0.61
UNEDF1	0.029	0.65
DD-MEδ	0.035	0.78

Ways to test this new paradigm:

- Coulomb sum rule
- Spin dependent EMC effect
- Parity violating DIS on nuclei
- But what about GPDs?   e.g. 4He

Incoherent DVCS on ^{4}He



Physics Letters B 673 (2009) 9–14

Contents lists available at ScienceDirect

Physics Letters B

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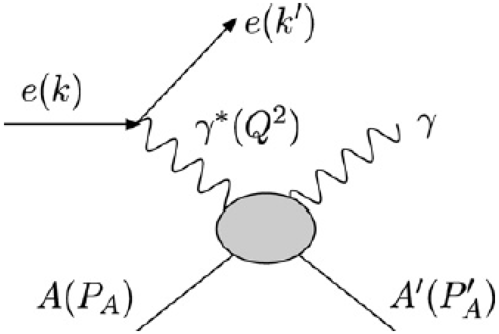
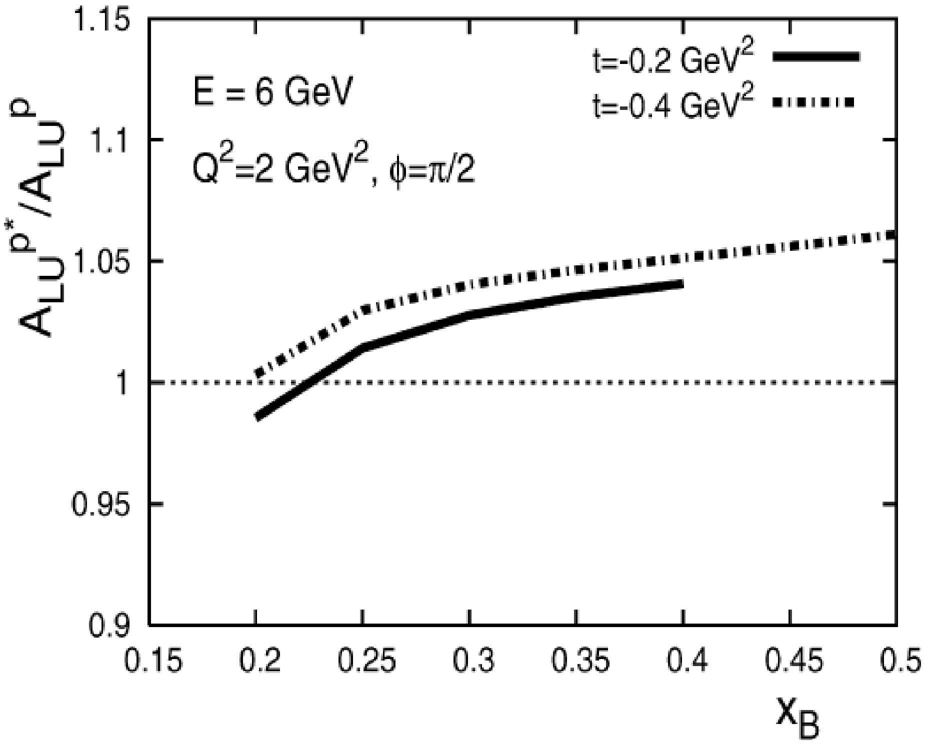
Medium modifications of the bound nucleon GPDs and incoherent DVCS on nuclear targets

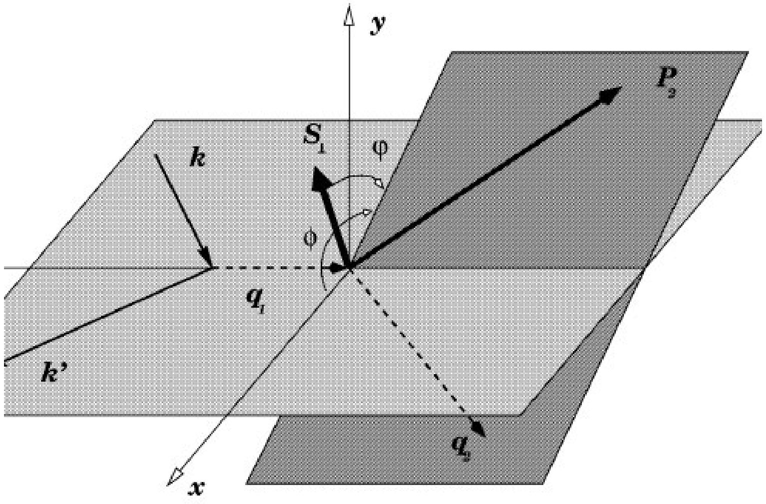
V. Guzey [a,*], A.W. Thomas [a,b], K. Tsushima [c]



New opportunity to probe medium modifications

$$A_{\mathrm{LU}}(\phi) \propto \mathrm{Im}\Big(F_1^{p^*}\mathcal{H}^{p^*} + \frac{x_B}{2-x_B}\big(F_1^{p^*}+F_2^{p^*}\big)\tilde{\mathcal{H}}^{p^*} - \frac{t}{4m_N^2}F_2^{p^*}\mathcal{E}^{p^*}\Big)\Big/ f\big(F_1^{p^*},F_2^{p^*}\big)\sin\phi,$$





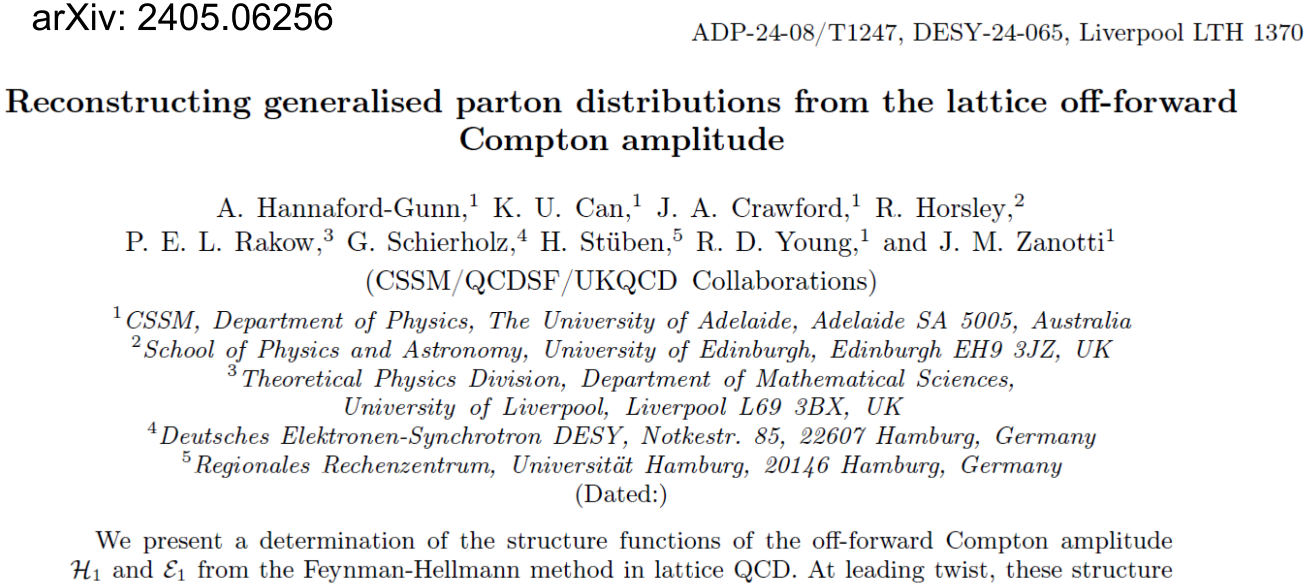
A.V. Belitsky et al. / Nuclear Physics B 629 (2002) 323–392

More recent work theoretical Liuti and experimental work see talk of Stepanyan

Guzey *et al.*, Phys Lett B673 (2009) 9

Finally: A different lattice method

arXiv: 2405.06256



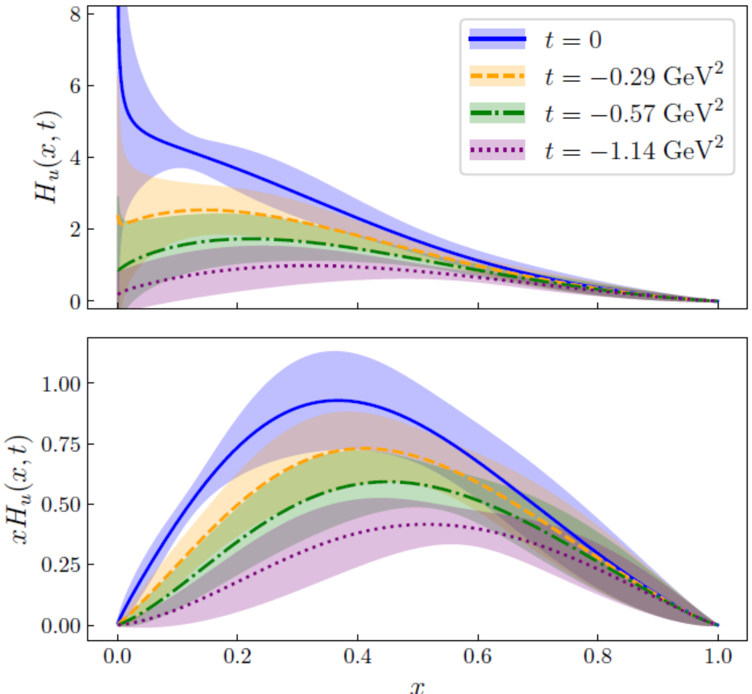
ADP-24-08/T1247, DESY-24-065, Liverpool LTH 1370

Reconstructing generalised parton distributions from the lattice off-forward Compton amplitude

A. Hannaford-Gunn,[1] K. U. Can,[1] J. A. Crawford,[1] R. Horsley,[2]
P. E. L. Rakow,[3] G. Schierholz,[4] H. Stüben,[5] R. D. Young,[1] and J. M. Zanotti[1]
(CSSM/QCDSF/UKQCD Collaborations)
[1] *CSSM, Department of Physics, The University of Adelaide, Adelaide SA 5005, Australia*
[2] *School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, UK*
[3] *Theoretical Physics Division, Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, UK*
[4] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[5] *Regionales Rechenzentrum, Universität Hamburg, 20146 Hamburg, Germany*

(Dated:)

We present a determination of the structure functions of the off-forward Compton amplitude $\mathcal{H}_1$ and $\mathcal{E}_1$ from the Feynman-Hellmann method in lattice QCD. At leading twist, these structure



Summary

- Our knowledge of s and sbar and c and cbar is very poor
  - This hampers searches for BSM physics: must be fixed!
- DVCS to excited baryon states: possible insight into how QCD works
- Studies of GPDs in nuclei may provide insight into changes of structure of bound nucleons

Remarkable given uncertainty in s^+ let alone s^-

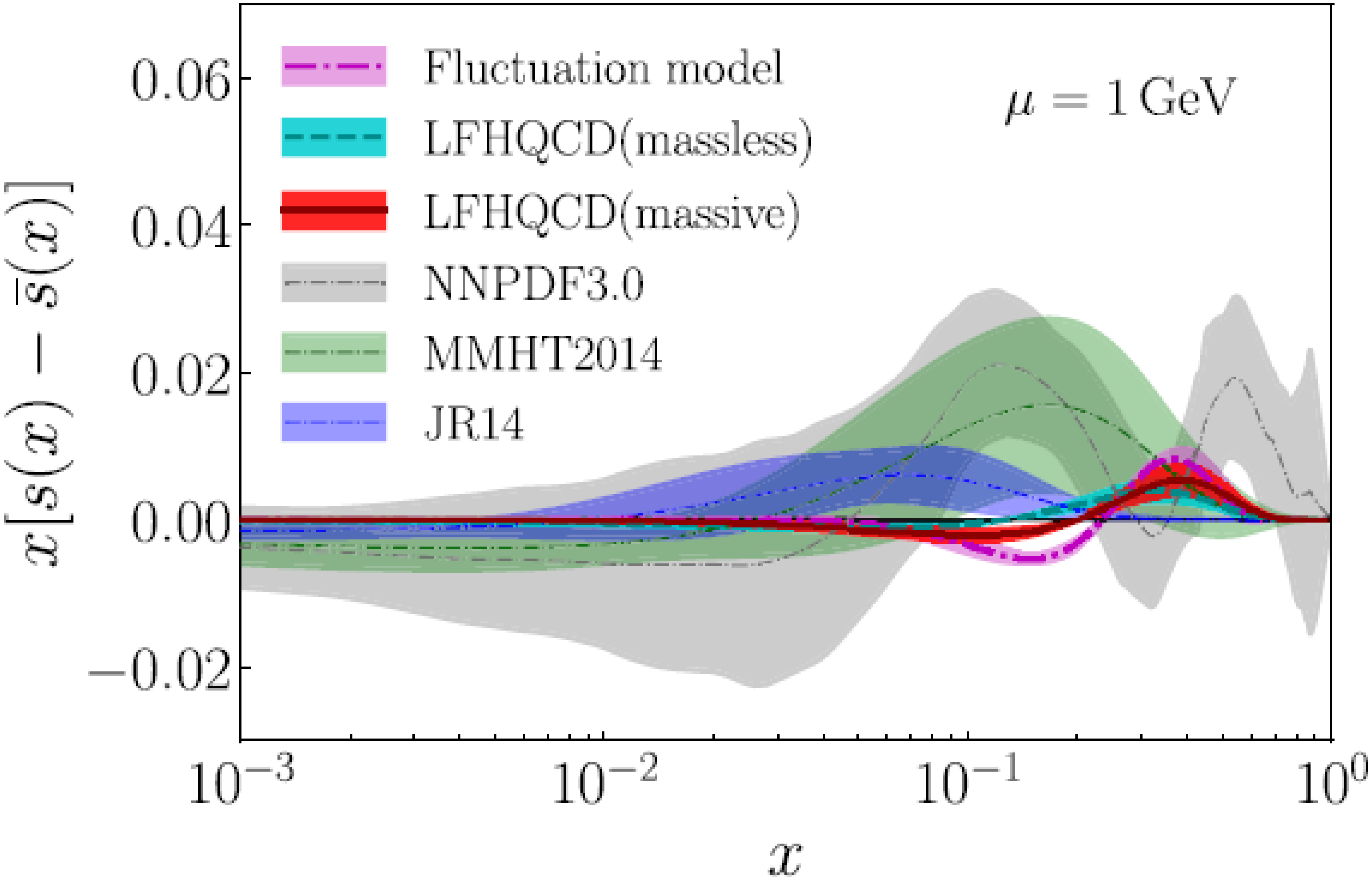
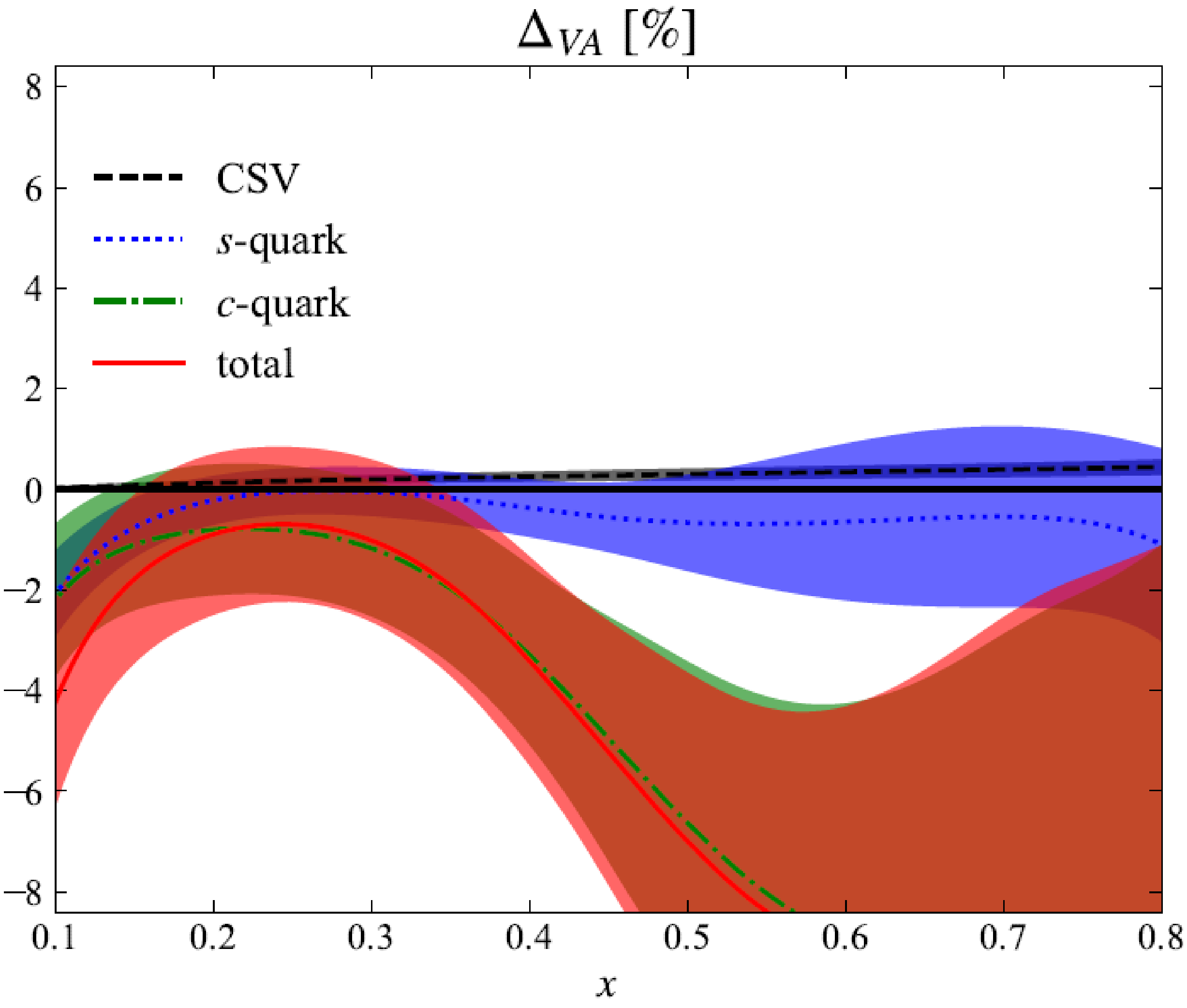


Illustration from Sufian et al., PRD 98 (2018) 114004

PV DIS cont. Δ_{VA}



$$\Delta_{VA}^{\mathrm{CSV}} = \frac{-2g_A^u\,\delta d_V + g_A^d\,\delta u_V}{(2g_A^u - g_A^d)(u_V + d_V)} + \frac{4\delta d^+ + \delta u^+}{5(u^+ + d^+)},$$

$$\Delta_{VA}^{s} = -\frac{2g_A^d s_V}{(2g_A^u - g_A^d)(u_V + d_V)} - \frac{2s^+}{5(u^+ + d^+)},$$

$$\Delta_{VA}^{c} = \frac{4g_A^u c_V}{(2g_A^u - g_A^d)(u_V + d_V)} - \frac{8c^+}{5(u^+ + d^+)}.$$

Charm dominates and C-odd charm (c_v) contributes

The Λ(1405)

- **We have unambiguous evidence that it is a Kbar-N bound state!**
  50 years after speculation by Dalitz *et al*.

- **To be fair Dalitz had no quark model then so there was not much else it could be at that time.**

- **Rather than the Lüscher method we apply Hamiltonian Effective Field Theory**
  - **shown to be equivalent for phase shifts[*]**
  - **BUT also provides information on eigenstates**

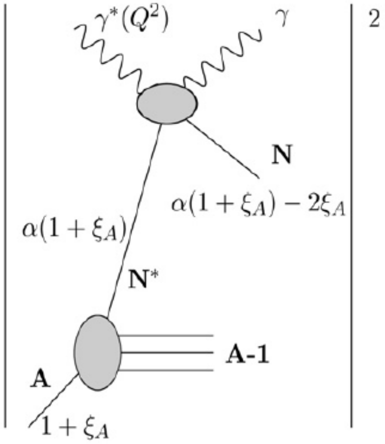
- **Carry out a Hamiltonian analysis of lattice data**

- **Examine the strange magnetic form factor of Λ(1405)**

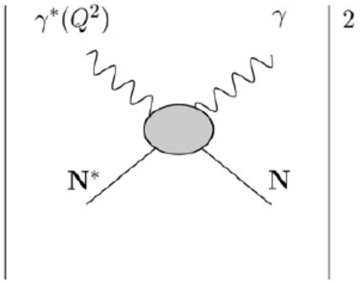
[*] **Wu et al., Phys. Rev. C 90 (2014) 5, 055206**

DVCS on a bound nucleon

- **Calculate incoherent DVCS in terms of DVCS from a bound nucleon:**



$$= \int \frac{d\alpha}{\alpha} \rho_A^N(\alpha,\lambda) \Sigma_\lambda$$



- **Assume:**

$$H^{q/p^*}(x,\xi,t,Q^2) = \frac{F_1^{p^*}(t)}{F_1^p(t)} H^q(x,\xi,t,Q^2),$$

$$E^{q/p^*}(x,\xi,t,Q^2) = \frac{F_2^{p^*}(t)}{F_2^p(t)} E^q(x,\xi,t,Q^2),$$

$$\tilde{H}^{q/p^*}(x,\xi,t,Q^2) = \frac{G_1^*(t)}{G_1(t)} \tilde{H}^q(x,\xi,t,Q^2),$$

with modification of bound nucleon form factors calculated in the QMC model

(e.g. Lu *et al*., Phys Lett B417 (1998) 217)

Nuclear DIS Structure Functions : The EMC Effect

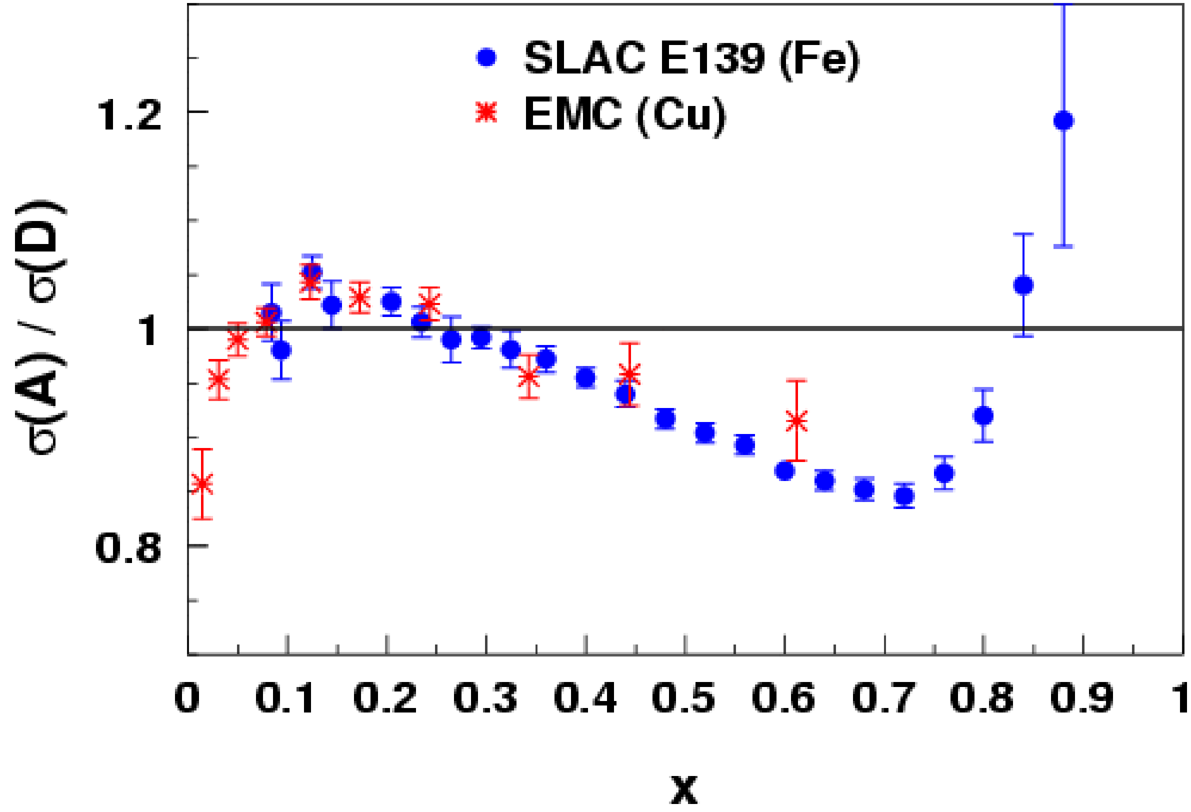
The QMC approach is ideal as one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– there are no other examples.....

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 39 years ago

- 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)

See also: Higinbotham *et al*., CERN Courier 2013

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

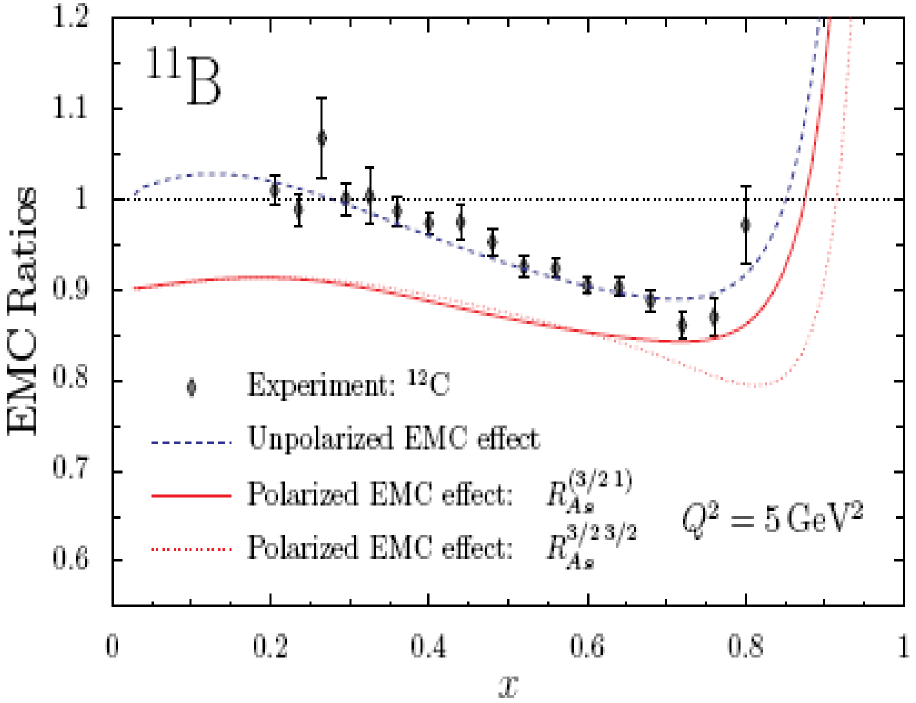


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

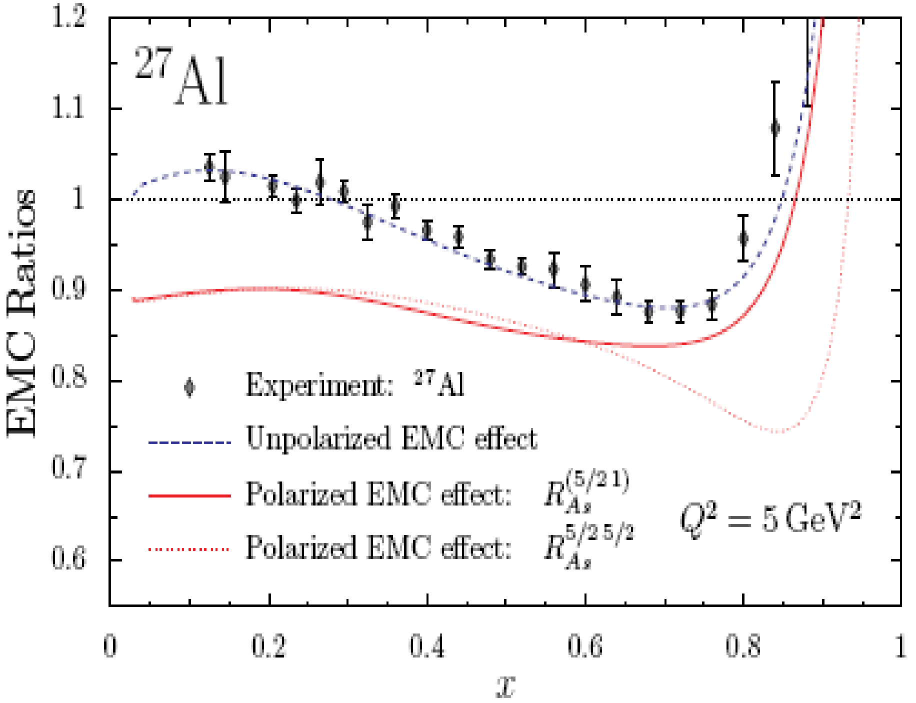


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

Spin-EMC Effect is a crucial test

- **Tensor correlations leading to high momentum components in nuclear wave function have been proposed as an alternate explanation of the EMC effect**

- **The tensor force scatters $^3S_1$ pairs almost entirely into $^3D_1$ at high momentum (~84% at p > 400 MeV/c)**

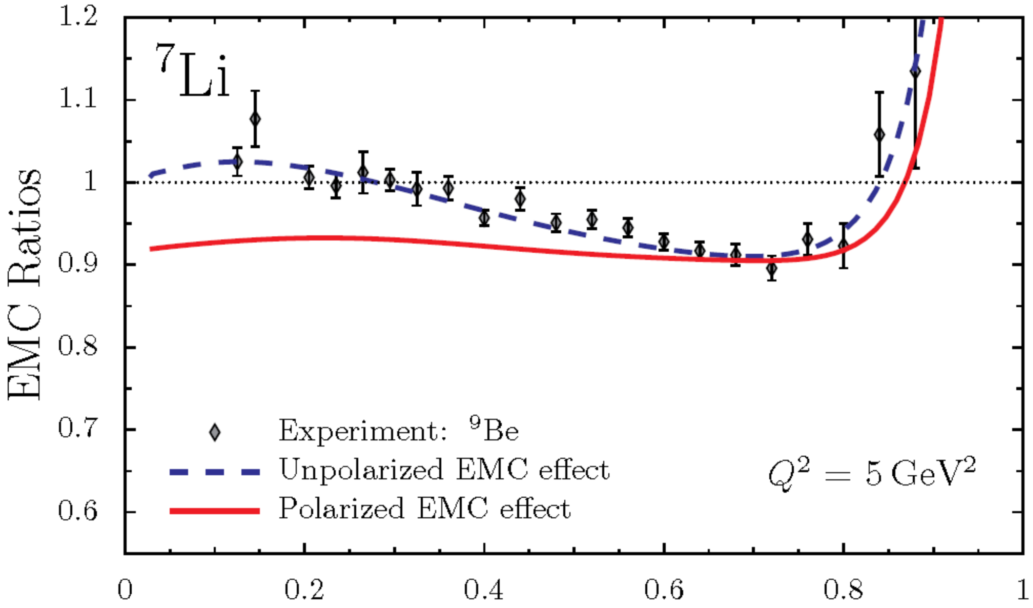
- **Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect**

- **That is, SRC idea gives essentially NO spin-EMC effect**

AWT - Int J Mod Phys 27 (2018) 1840001 (Ernest Henley Memorial)

Approved JLab Experiment

- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*



Other tests (e.g. Isovector EMC effect)