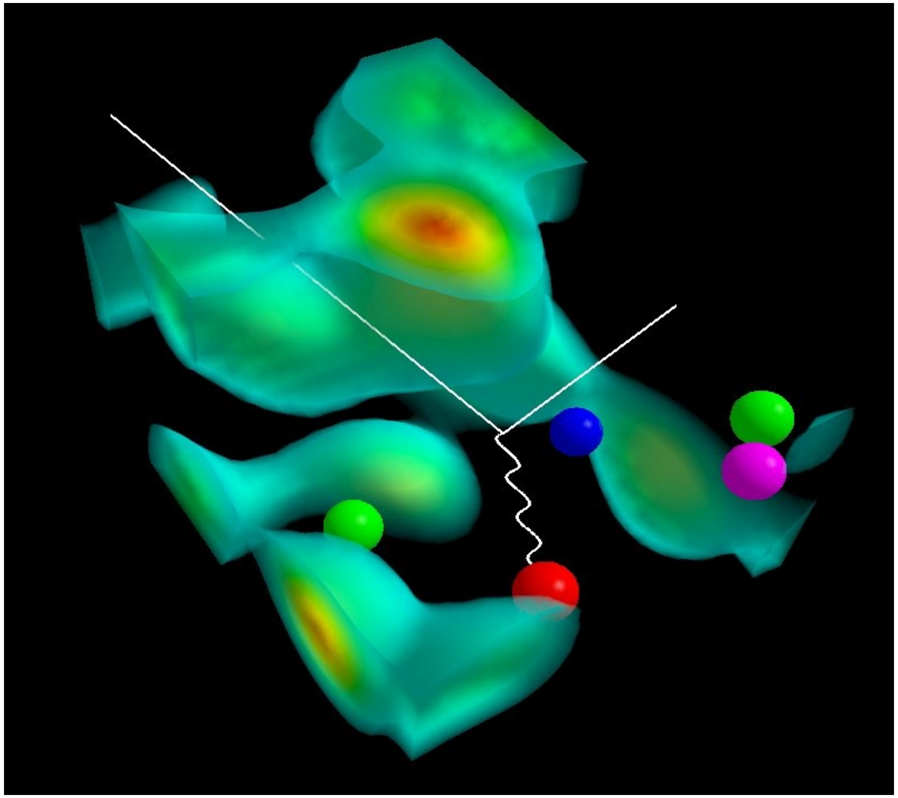
Chiral Structure of the Nucleon



Anthony W. Thomas

ANPhA Symposium 2024
Huizhou-IMP : November 15th 2024

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

QCD

1964: Quarks, Aces, Partons…

1973: Fritzsch, Gell-Mann and Leutwyler: Phys Lett B67, 345

From my point of view:

Gell-Mann at ICOHEPANS Los Alamos 1974

Gave one hour lecture on QCD – second Nobel Prize?

November 1974: J/Ψ

But it took a long time to realize that this was c-cbar in spite of GIM

e.g. CERN TH Division 1975-76: "Another resonance discovered!"

Chiral Symmetry

- **Near massless quarks $\Longrightarrow$ near degeneracy of opposite parity states**
- **BUT not so in Nature N(940) and nearest negative parity is N(1535) !**
- **Alternative: Goldstone's theorem implies a massless pion**
- ***Such a light pion completely undermines the conventional picture of confinement***
- **Chiral limit crucial but bizarre**
  - **e.g., p and n charge radii infinite in chiral limit (more later)**

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Chiral Symmetry in Context of QCD

- Of course, chiral symmetry was known before QCD
- Current algebra was known and widely used in 60's
- Soft pion theorems also very powerful and phenomenologically useful
- But how to combine with the quark and gluon structure of real hadrons (and nuclei)?

The Cloudy Bag Model (1979+)

with Miller and Théberge: For a review see Adv Nucl Phys 13 (1984) 1-137

Restore chiral symmetry to theory of confined quarks – the Cloudy Bag Model

$$\mathscr{L}(x) = (i\bar{q}\partial\!\!\!/ q - B)\theta_v - \tfrac{1}{2}\bar{q}e^{i\underset{\sim}{\tau}\cdot\underset{\sim}{\phi}\gamma_5/f}q\delta_s + \tfrac{1}{2}(D_\mu\underset{\sim}{\phi})^2$$

Linearize the theory (proven for R ≥ 0.8 fm)

$$\mathscr{L}_{\rm CBM}(x) = \mathscr{L}_{\rm MIT}(x) + \mathscr{L}_\pi(x) + \mathscr{L}_{\rm int}(x)$$

Work with non-exotic colorless baryon states

$$P = \sum_{\substack{\alpha = \text{nonexotic} \\ \text{baryons}}} |\,\alpha\rangle\langle\alpha\,|$$

$$Q = \underset{\sim}{1} - P$$

P is a projection operator onto nonexotic bag states and non-interacting states of pions plus bags

so that:

$$H_{\rm MIT} \simeq PH_{\rm MIT}P = \sum_\alpha |\,\alpha\rangle m_\alpha{}^{(\rm b)}\langle\alpha\,|$$

Interactions

$$PH_{\text{int}}P = \frac{i}{2f}\sum_{\alpha,\beta}\int d^3x\,\langle\beta \mid \bar{q}(x)\underset{\sim}{\tau}\cdot\underset{\sim}{\phi}(\underset{\sim}{x})\gamma_5 q(x)\mid\alpha\rangle\delta_s\beta^+\alpha$$

and there is the free pion field: $H_\pi = \sum_i \int d\underset{\sim}{k}\; w_{\underset{\sim}{k}} a^+_{\underset{\sim}{k}i} a_{\underset{\sim}{k}i}$

This is the ONLY way to ensure the correct infrared behavior (i.e. chiral symmetry) of the theory

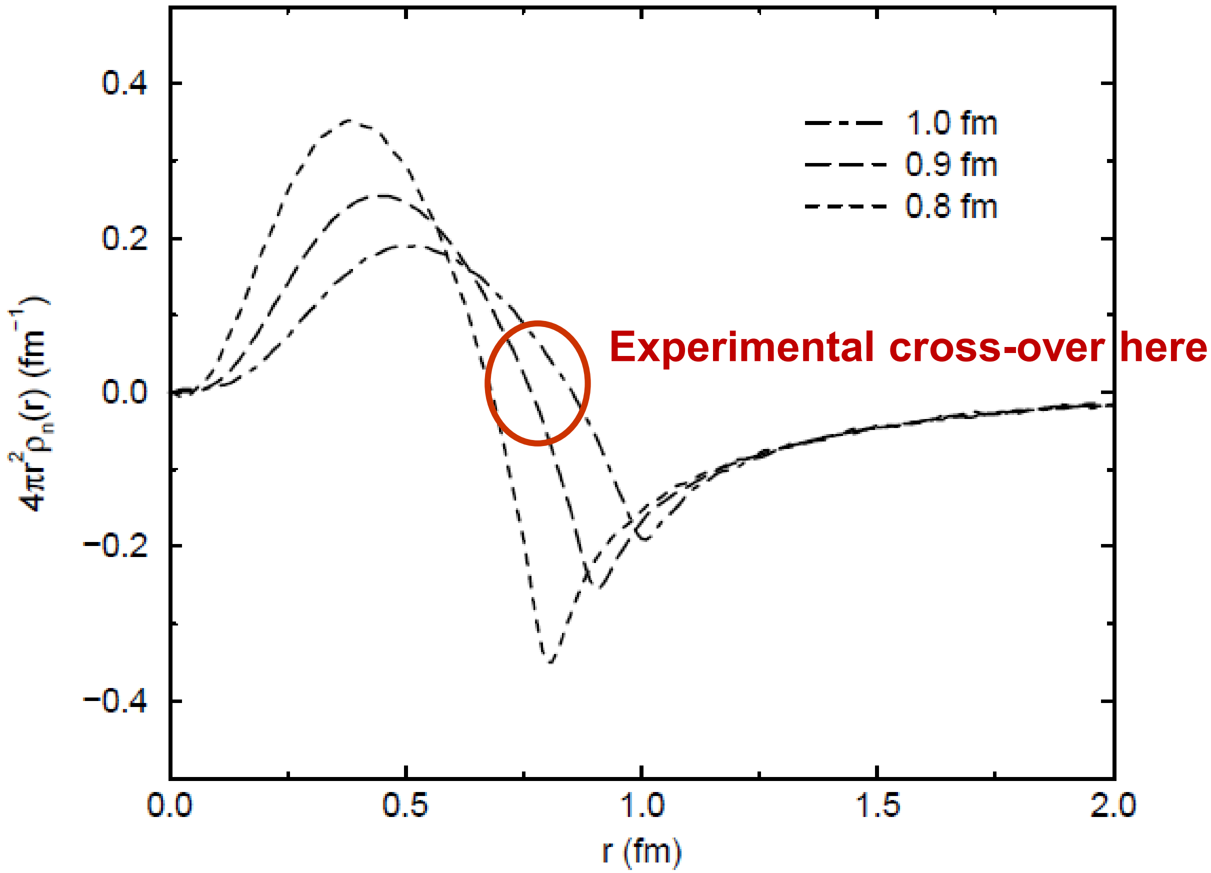
Not projecting onto colorless states is why the chiral quark model of Manohar and Georgi gives incorrect non-analytic behavior

Baryons are then clusters of confined quarks dressed by pions (and kaons in SU(3))

e.g. for the nucleon:

$$\tilde{N}\rangle \simeq Z^{1/2}\mid N\rangle + c\mid N\pi\rangle + c'\mid \Delta\pi\rangle$$

Neutron Charge Radius: Size of Confinement Region



To leading order results from $|p\ \pi^- >$ component of the neutron wave function

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Remarkable Consequences in Chiral Limit

- As light quark masses go from a few MeV to zero:

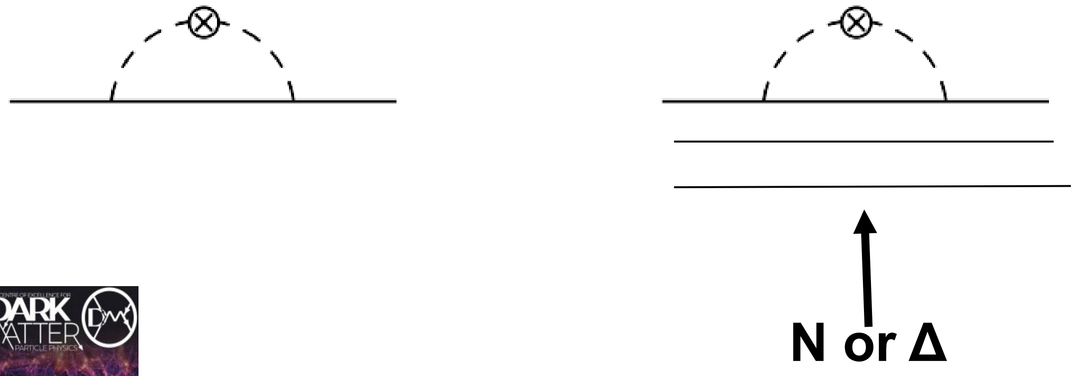
  the charge radius of the proton goes to infinity

  the charge radius^2 of the neutron to minus infinity

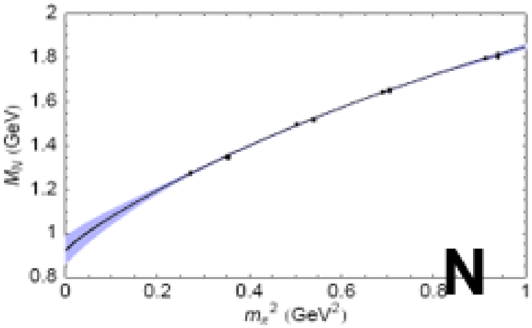
- Both like $\ln m_\pi \sim \ln m_q$

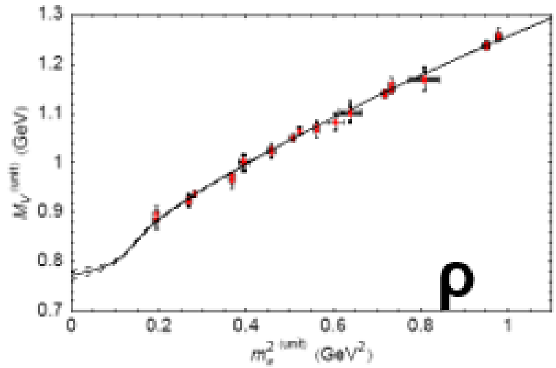
  the magnetic moments behave like $m_\pi \sim m_q^{1/2}$

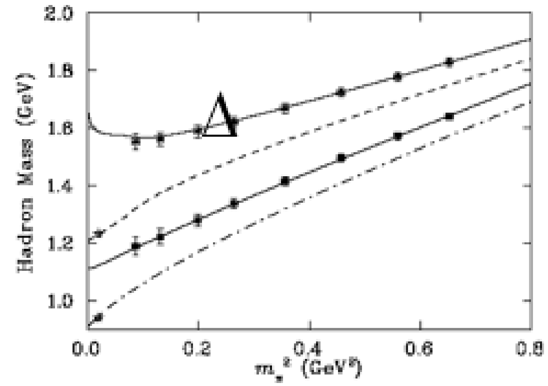
- One <u>cannot</u> describe this correctly in a chiral <u>quark</u> model

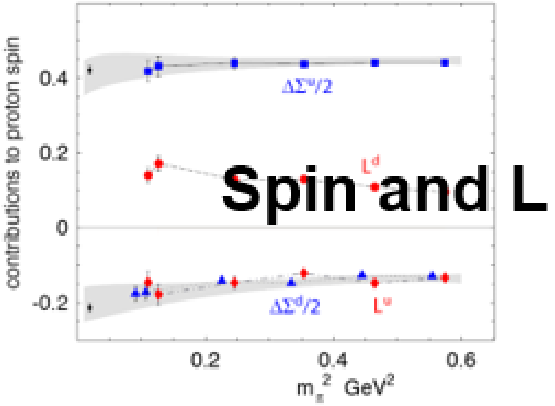


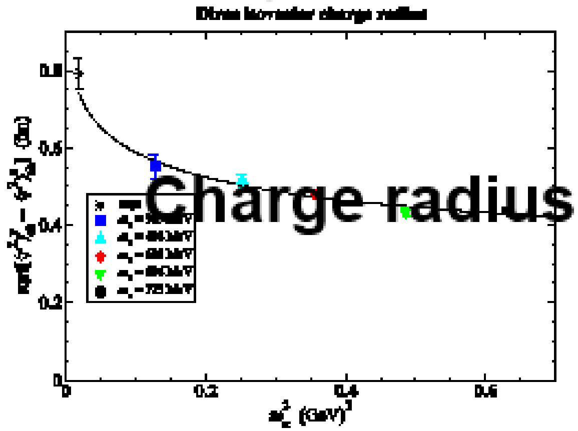
Simplicity: Pion loops suppressed at large quark mass

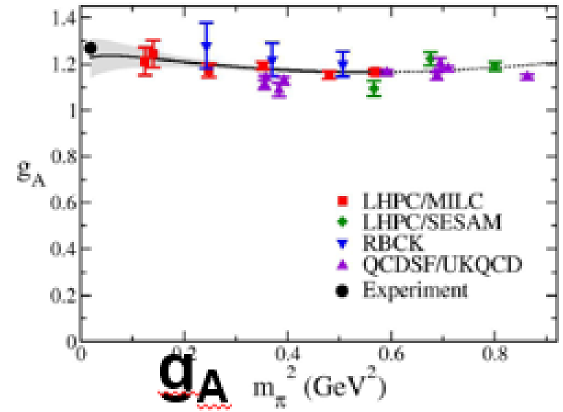


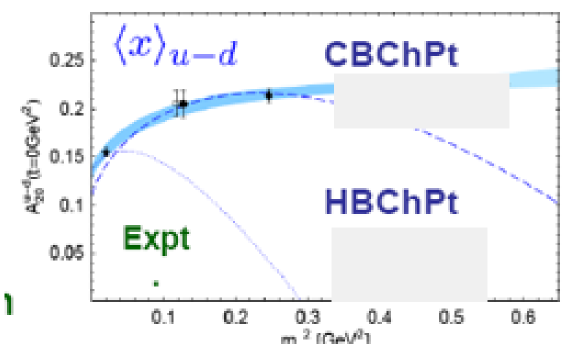












Is it believable that smooth behavior for m_π above 400 MeV is a result of a <u>different</u> accidental cancellation in every case??

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

Very simple lesson / universal feature of lattice data

- Meson loops are suppressed once the meson mass exceeds ~0.4 GeV (good place to build a CQM)

- This corresponds to a remarkably small current mass
  – m_q ~ 40 MeV

- Maybe a scale intrinsic to instantons or in a chiral quark model (like CBM) the finite size of hadron suppresses loops – implemented through a finite range regulator: FRR

- Very real insights from study of hadrons in QCD as a function of quark mass – especially in spectroscopy

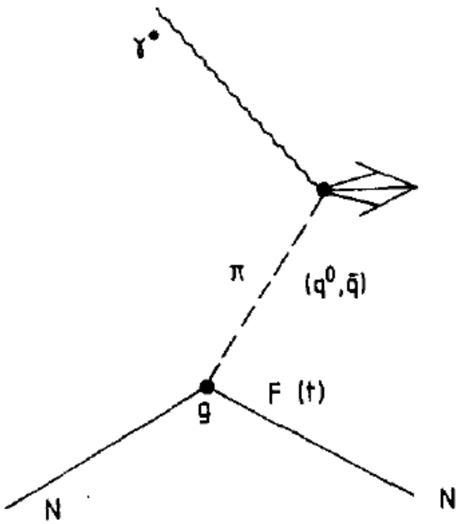
- But usual χpt methods fail outside power counting region – meson mass above 0.3 GeV

Major Results of the Chiral Approach

Anti-Matter Asymmetry 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."

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**

- **<u>Predicted</u> violation of Gottfried sum-rule not confirmed for 10 years**

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

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

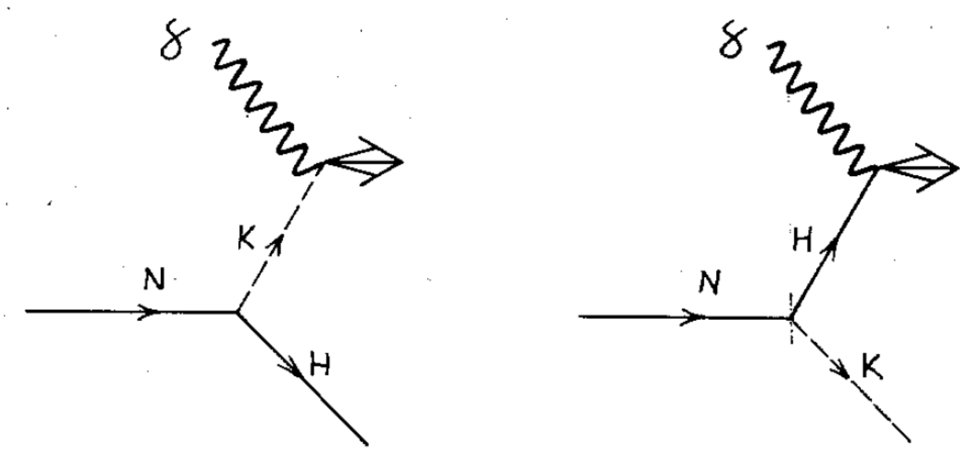
- **Consistent with range predicted by the pion cloud....**

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

$$\varepsilon\ 0.11 - 0.15$$

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: e.g. BSM physics (Wang and Thomas: 2403.07327)

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

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Power of Tracking Non-Analytic Behavior

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!

Strange and Charm Still a Major Issue

- **Knowledge of strange and charm PDFs is still totally inadequate for BSM tests:**
  e.g. 4% uncertainty lowers scale for new BSM physics from 11 to 6 TeV

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

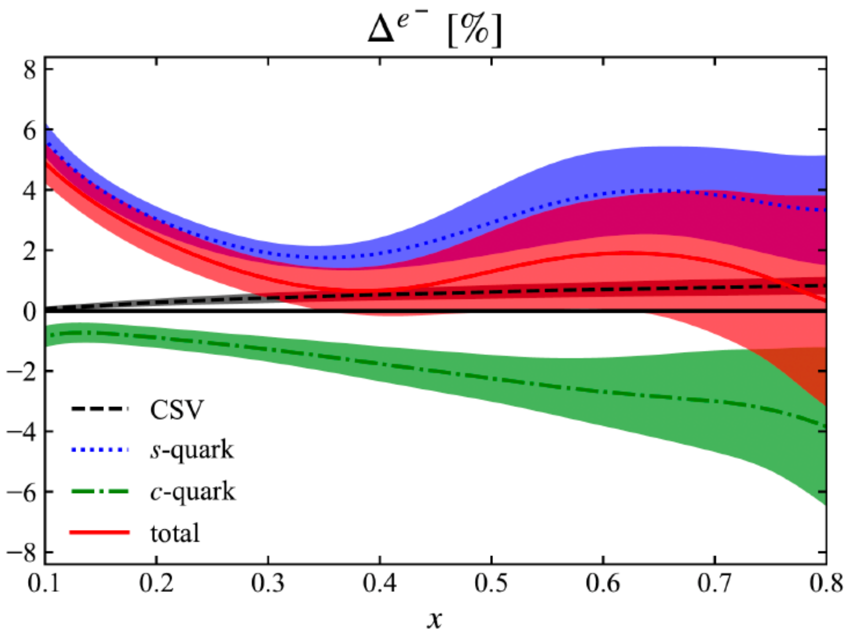
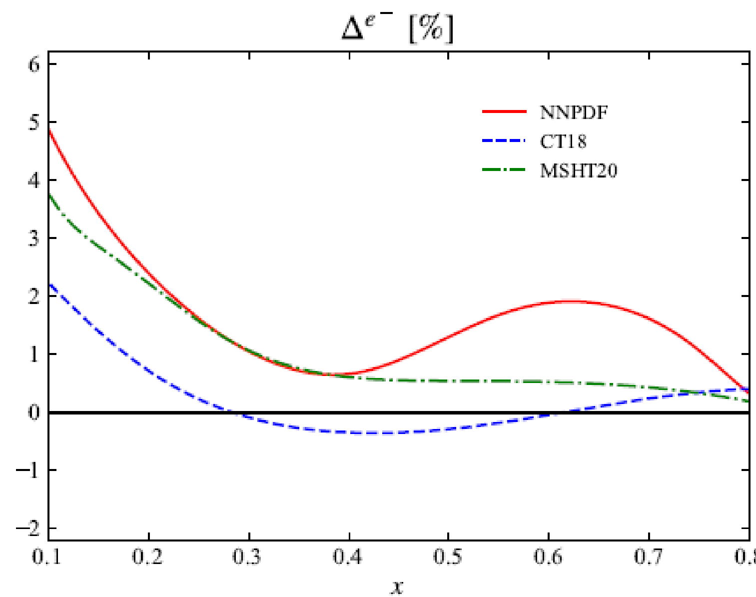


Figure 2. Corrections to $A_{RL,d}^{e^-}$ (in percentage) at $Q^2 = 10$ GeV^2 for $y = 0.5$.



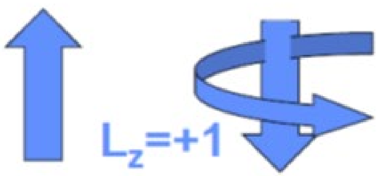
Xuangong Wang and AWT, arXiv: 2403.07327

The Spin "Crisis"

The pion cloud naturally coverts quark spin to pion orbital angular momentum

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

- 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%)



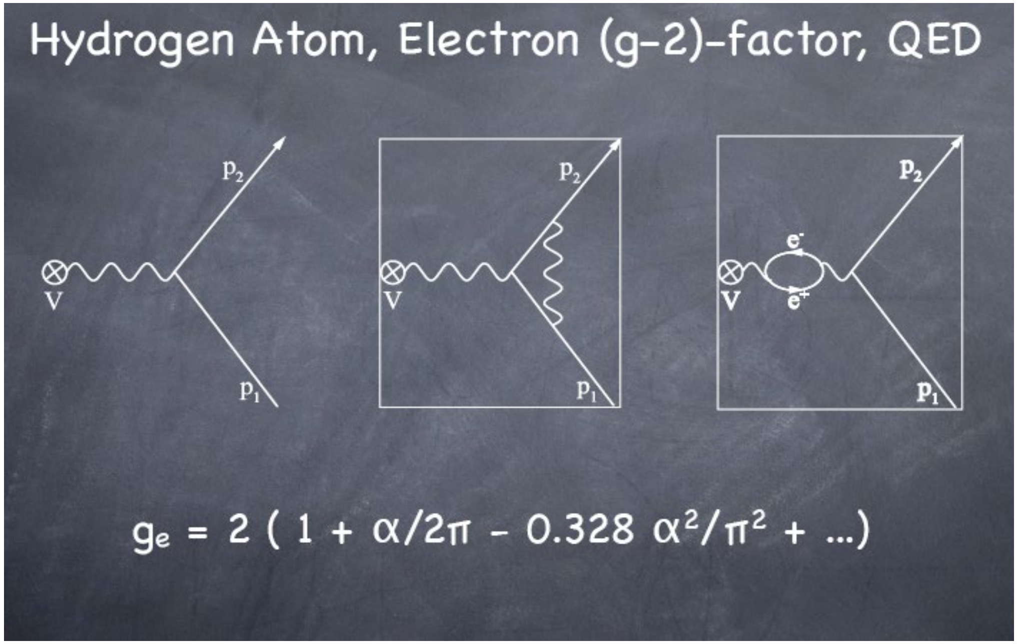
More recent discussion and importance of resolution (Q^2)

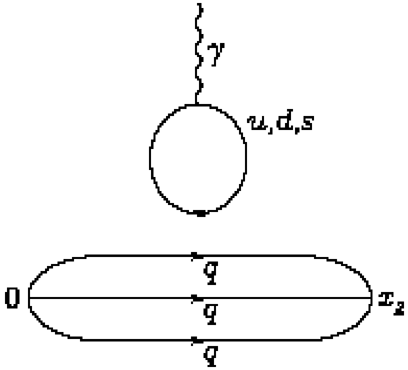
AWT, PRL 101 (2008) 102003 and Myhrer and AWT, Phys. Lett. B 663 (2008) 302

QCD Lamb Shift

QCD Analogue of the Lamb Shift

- Strangeness contribution is a vacuum polarization effect, analogous to Lamb shift in QED



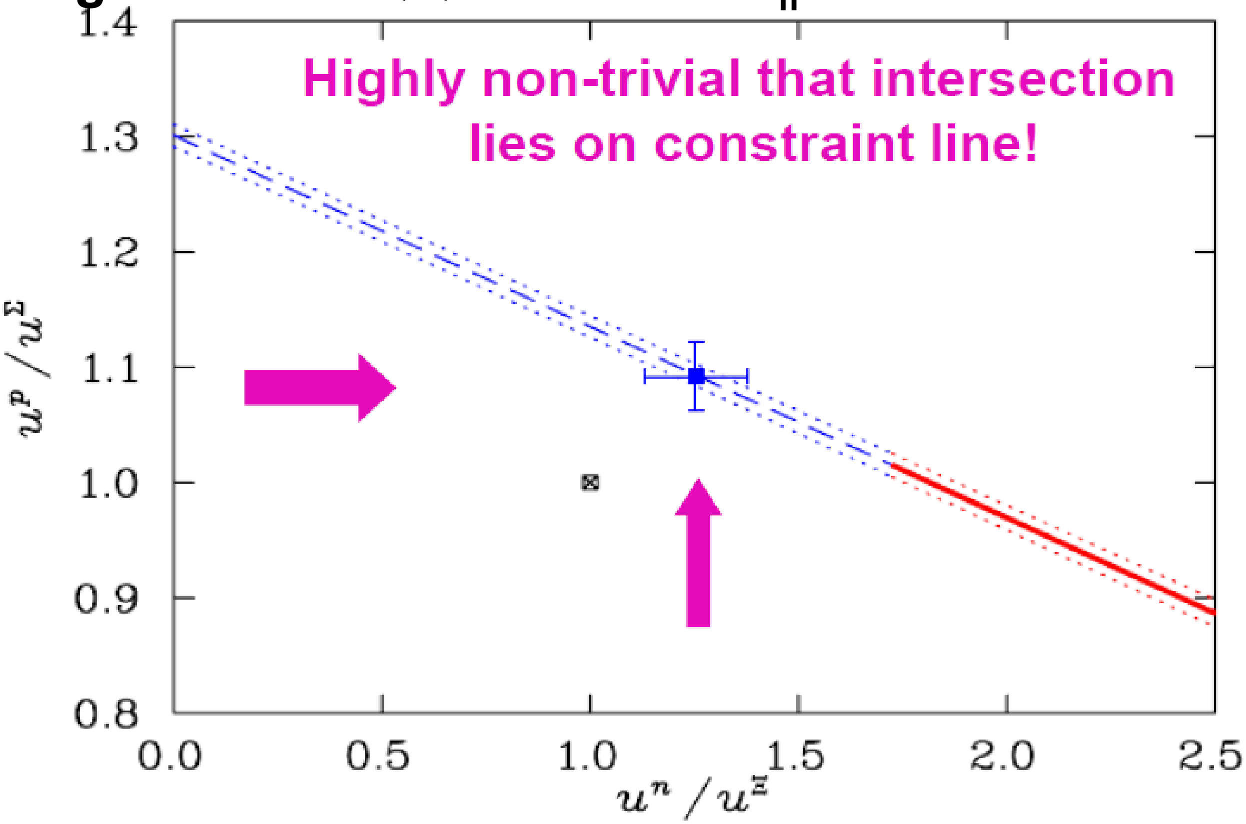


- It is a fundamental test of non-perturbative QCD

First Accurate Determination of G_M^s from QCD

Using FRR with QQCD data at m_π above 400 MeV!

1.10±0.03



1.25±0.12

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

CoEPP

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Leinweber et al., PRL 94 (2005) 212001

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC

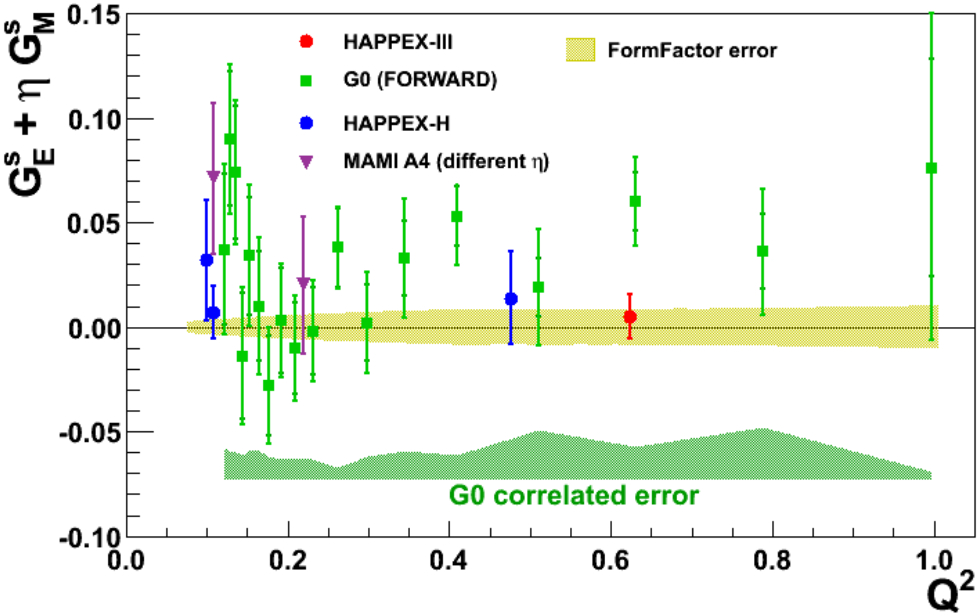
Strange Quarks in the Proton

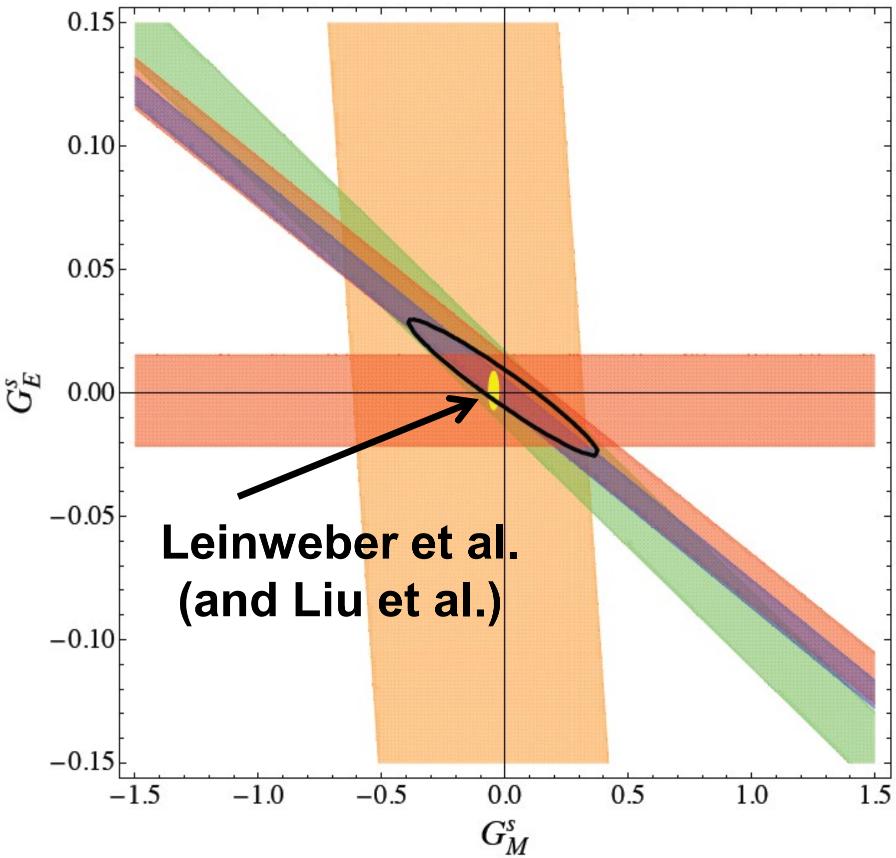
There have been a number of major steps forward in past 20 years, both theory and experiment :

- Calculation of $G_{E,M}^s\ (Q^2)$:
  - Direct: Kentucky then many other calculations
  – see e.g., Alexandrou et al., 2112.06750
- Experimental determination of $G_{E,M}^s\ (Q^2)$
  - G0 and Happex
  - Mainz PVA4 (and earlier Bates)
- Strangeness sigma commutator
- But 2005 FRR calculation based on unquenching QQCD agrees with the best modern results

Global Analysis of PVES Data

$Q^2 = 0.1\ GeV^2$





➢ **QCD analogue of Lamb shift works beautifully !**

See also Alexandrou et al., 2112.06750

Global analysis: Young et al., PRL 99 (2007)122003 and Young, arXiv 1004.5163 [nucl-th]

Spectroscopy

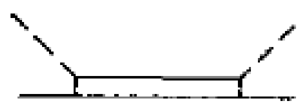
- how do excited states emerge from QCD ?
- what are the fundamental degrees of freedom ?
- Lattice QCD provides extremely valuable information

CBM was inspired by two explanations of the Δ

Miller, Thomas, Théberge, Phys Lett B91 (1980) 192
– preprint just 4 years after quarks were real!

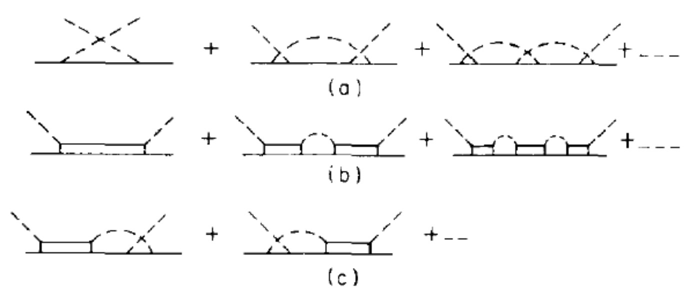
The Chew-Low Model where it is dynamically generated

and the quark model, where is it a 3-quark state



The CBM resolves this because the underlying theory yields the same form factor shape for the $NN\pi$ and $\Delta N\pi$ vertices

ANSWER: It is predominantly 3-quark with small contribution from Chew-Low type processes:



The Λ(1405) : A Clear Anomaly

- **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 <u>also provides information on eigenstates</u>**

- **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

First calculation after QCD was invented 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

E. A. Veit* and B. K. Jennings
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

A. W. Thomas
Physics Department, University of Adelaide, Adelaide, South Australia 5001

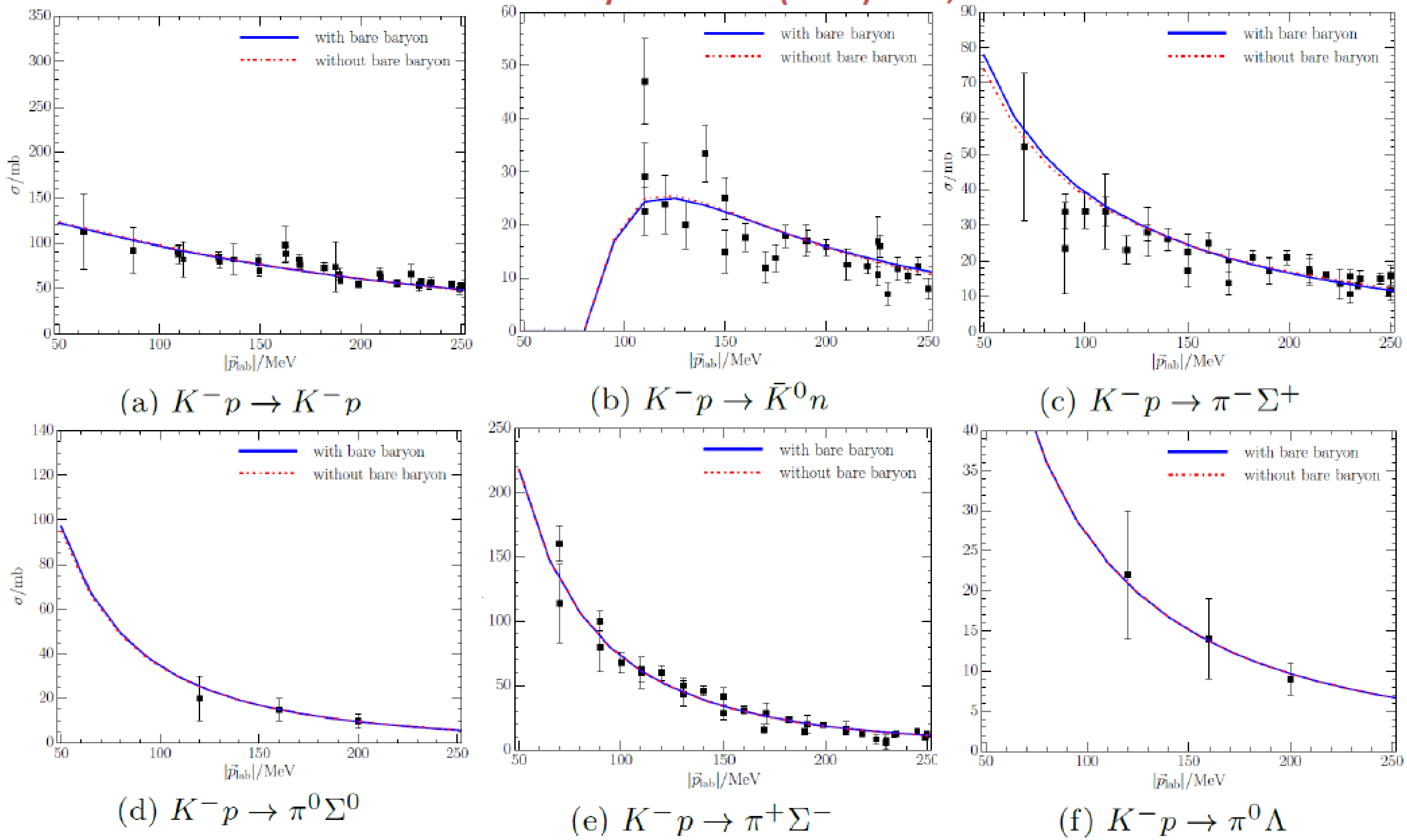
R. C. Barrett
Physics Department, University of Surrey, Guildford GU2 5XH, United Kingdom
(Received 8 June 1984)

The cloudy bag model (CBM) is extended to incorporate chiral SU(3)$\times$SU(3) symmetry, in order to describe S-wave KN and $\bar{K}N$ 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 $\bar{K}N$ 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



Include $\pi\Sigma$, $\overline{K}N$, $\eta\Lambda$ and $K\Xi$ channels

Similar work by Valencia, Bonn, JLab and other groups

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SUB CRUCE LUMEN

DARK MATTER PARTICLE PHYSICS

Find the same two-pole structure as other analyses

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Note that Lattice QCD allows us

to study hadron structure IN QCD as a

function of quark mass – a powerful tool

Chiral Extrapolation of Hadronic Observables

A. W. Thomas[a]

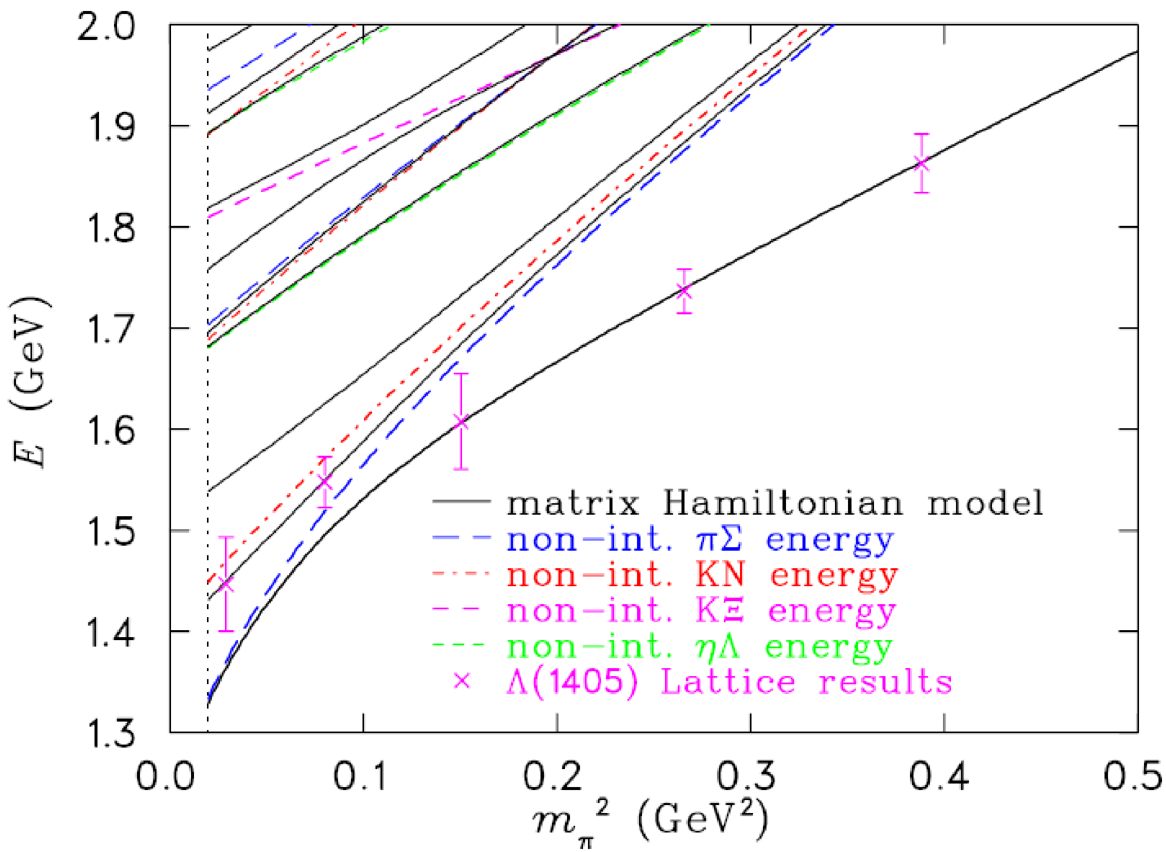
Nuclear Physics B (Proc. Suppl.) 119 (2003) 50–58

In combination with the very successful techniques for chiral extrapolation, which we have illustrated by just a few examples, lattice QCD will finally yield accurate data on the consequences of non-perturbative QCD. Furthermore, the physical insights obtained from the study of hadron properties as a function of quark mass will guide the development of new quark models and hence a much more realistic picture of hadron structure.

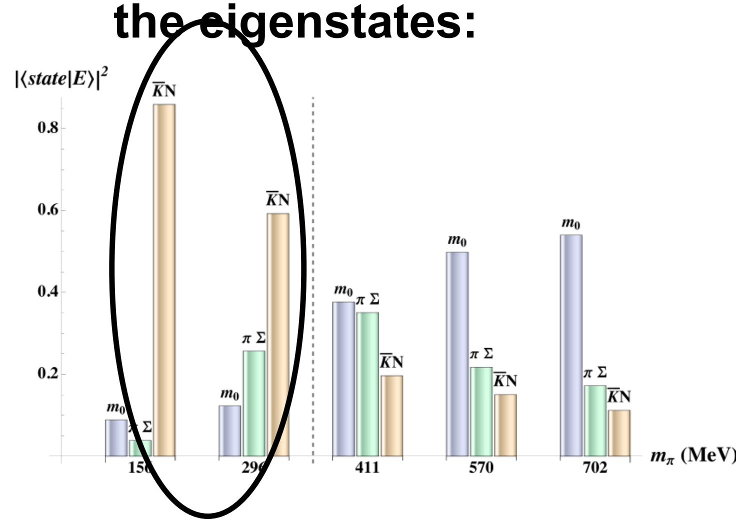
Proceedings Lattice 2002

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

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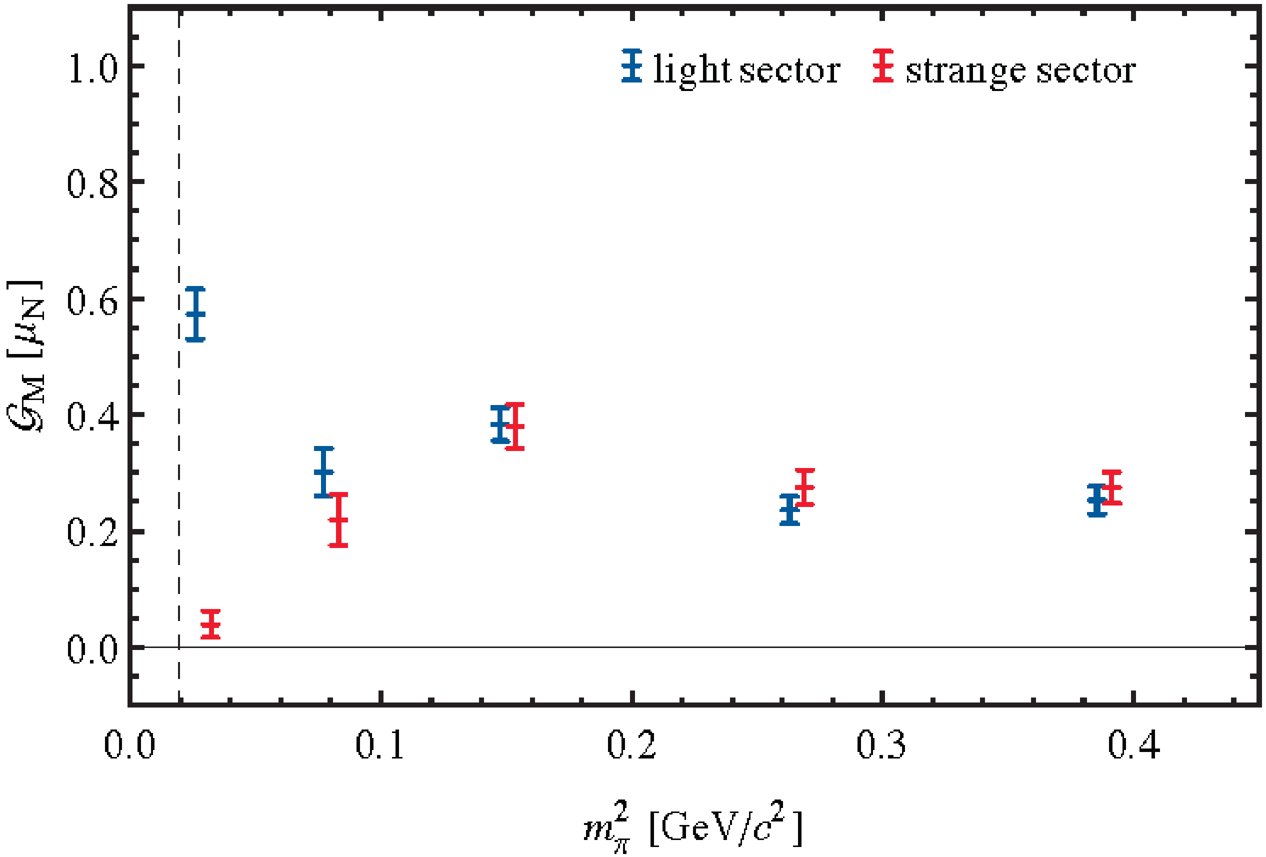
Lattice Magnetic Form Factor Calculations

- **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

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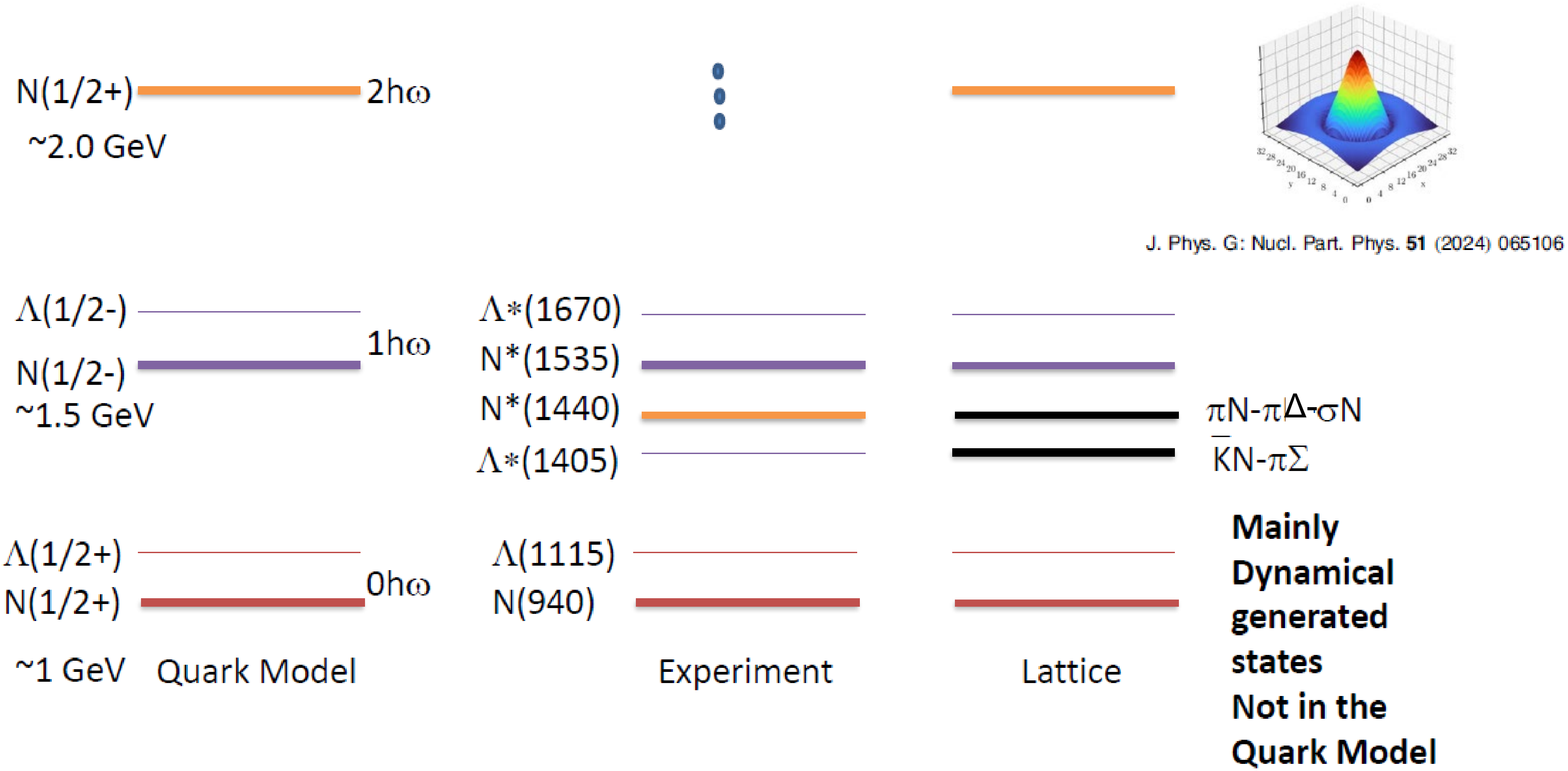
Hall *et al.*, Phys. Rev. *D* 95 (2017) 5, 054510

Once the nature of key states becomes clear

the quark model makes sense*



* Wu *et al.*, 1805.05066

Our challenges

- Discover how the properties of hadrons, nuclei and neutron stars emerge as non-perturbative products of this beautiful, non-linear theory, with its fascinating chiral properties

- Test that it is indeed fully correct
  - − precision

- Develop our physical insight – a picture of how it works

- Our capacity to win new physical insight into how Nature works is what makes it worthwhile to get out of bed in the morning!