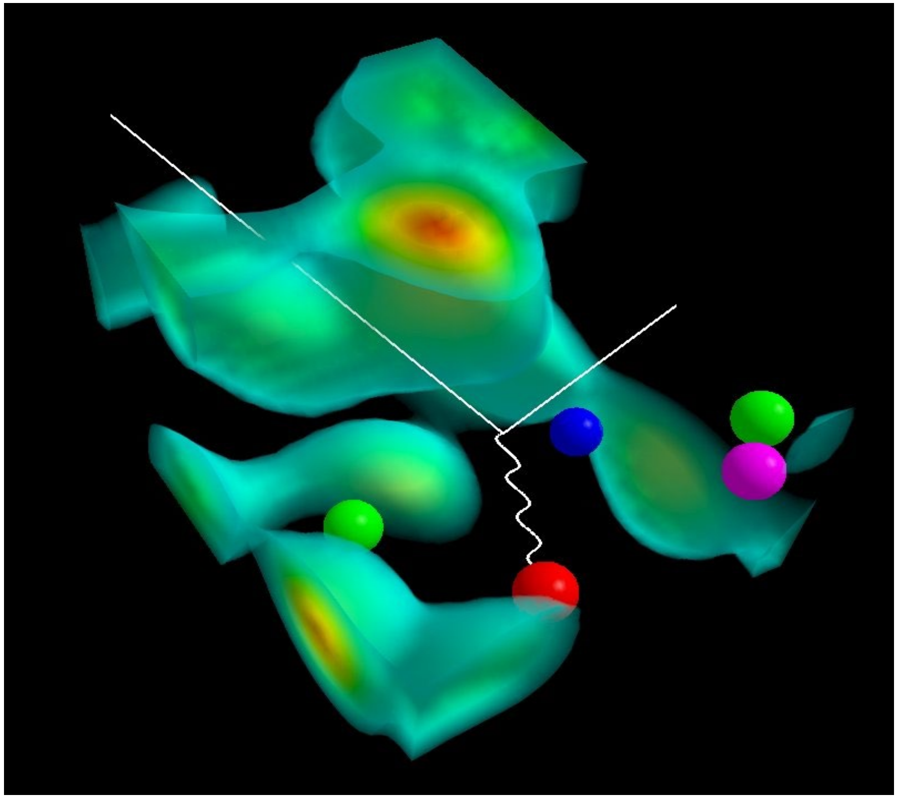
Baryon Excited States: Quark Model versus Reality



Anthony W. Thomas

International Pacific-Spin 2024 Conference
Heifei, China: November 9-12 2024

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Before we start

PHYSICAL REVIEW LETTERS 133, 161901 (2024)

New Data-Driven Constraints on the Sign of Gluon Polarization in the Proton

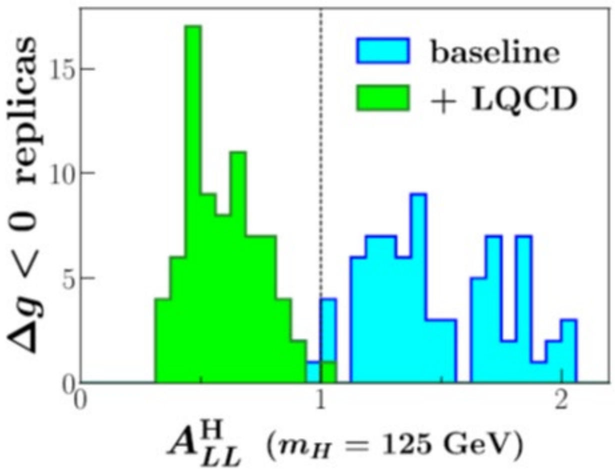
N. T. Hunt-Smith,[1] C. Cocuzza,[2] W. Melnitchouk,[3] N. Sato,[3] A. W. Thomas,[1] and M. J. White[1]

(JAM Collaboration-Spin PDF Analysis Group)

- **Work by Karpie *et al*., (Phys. Rev. D109 (2024) 036031) showed that negative solutions for Δg(x) were allowed**

- **Criticised by de Florian *et al*., (Phys. Rev. D109 (2024) 074007) as giving unphysical Higgs production**

- **But when lattice data (Hadstruc: Phys. Rev. D 106, 094511) constrains the PDFs contradiction disappears**



ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Additional Experimental Data at Large-x

- Lowering W^2 cut to 4 GeV^2 adds 1370 data points, primarily from JLab but also HERMES and SLAC
- When this is added to the baseline (10 GeV^2) and lattice data
- Negative $\Delta g(x)$ solution is excluded:

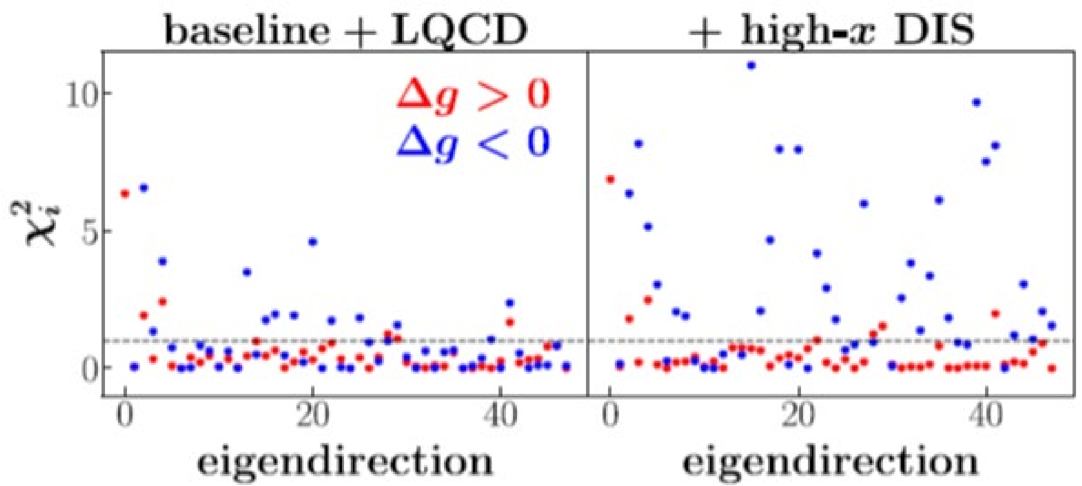


FIG. 2. Comparison of χ^2 contributions for positive (red dots) and negative (blue dots) Δg mean theory predictions for LQCD data versus eigendirection; χ_i^2 represents the ith lattice data point.

PHYSICAL REVIEW LETTERS **133,** 161901 (2024)

New Data-Driven Constraints on the Sign of Gluon Polarization in the Proton

N. T. Hunt-Smith,[1] C. Cocuzza,[2] W. Melnitchouk,[3] N. Sato,[3] A. W. Thomas,[1] and M. J. White[1]

(JAM Collaboration-Spin PDF Analysis Group)

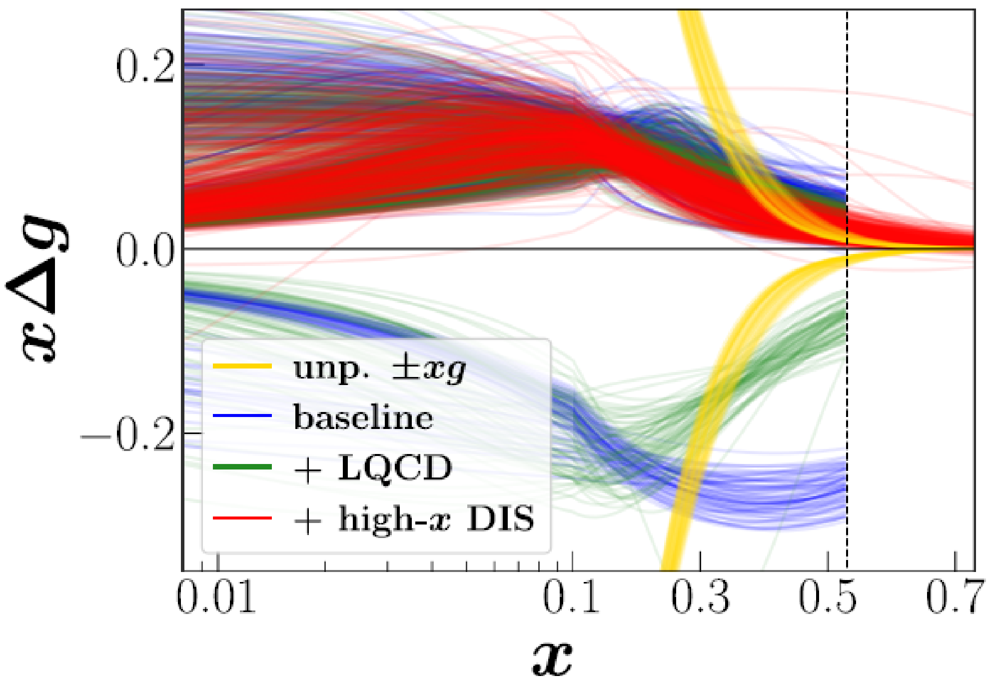


FIG. 3. Monte Carlo replicas for the polarized gluon PDF $x\Delta g$ and the unpolarized gluon PDF xg at $Q^2 = 10$ GeV^2. The "baseline" and "+LQCD" cases are cut off at $x \approx 0.53$, corresponding to a $W^2 > 10$ GeV^2 cut for polarized DIS.

Outline

I. Excitations of the nucleon are a vital piece of the challenge to understand how hadrons are made in QCD

II. New Insight into the Quark Model

- The Λ(1405) IS a Kbar-N bound state
- The Roper IS generated by πN-σN-πΔ rescattering
- But not all states are dynamically generated e.g. N(1535)!

III. The Quark Model is not so bad!

Spectroscopy

– how do excited states emerge from QCD ?

– what are the fundamental degrees of freedom ?

– Lattice QCD provides extremely valuable information

Resonances are very complicated − and the lattice is not

- **Everything is stable – an eigenstate of the QCD Hamiltonian**

- **Whereas real resonances decay like crazy.....**

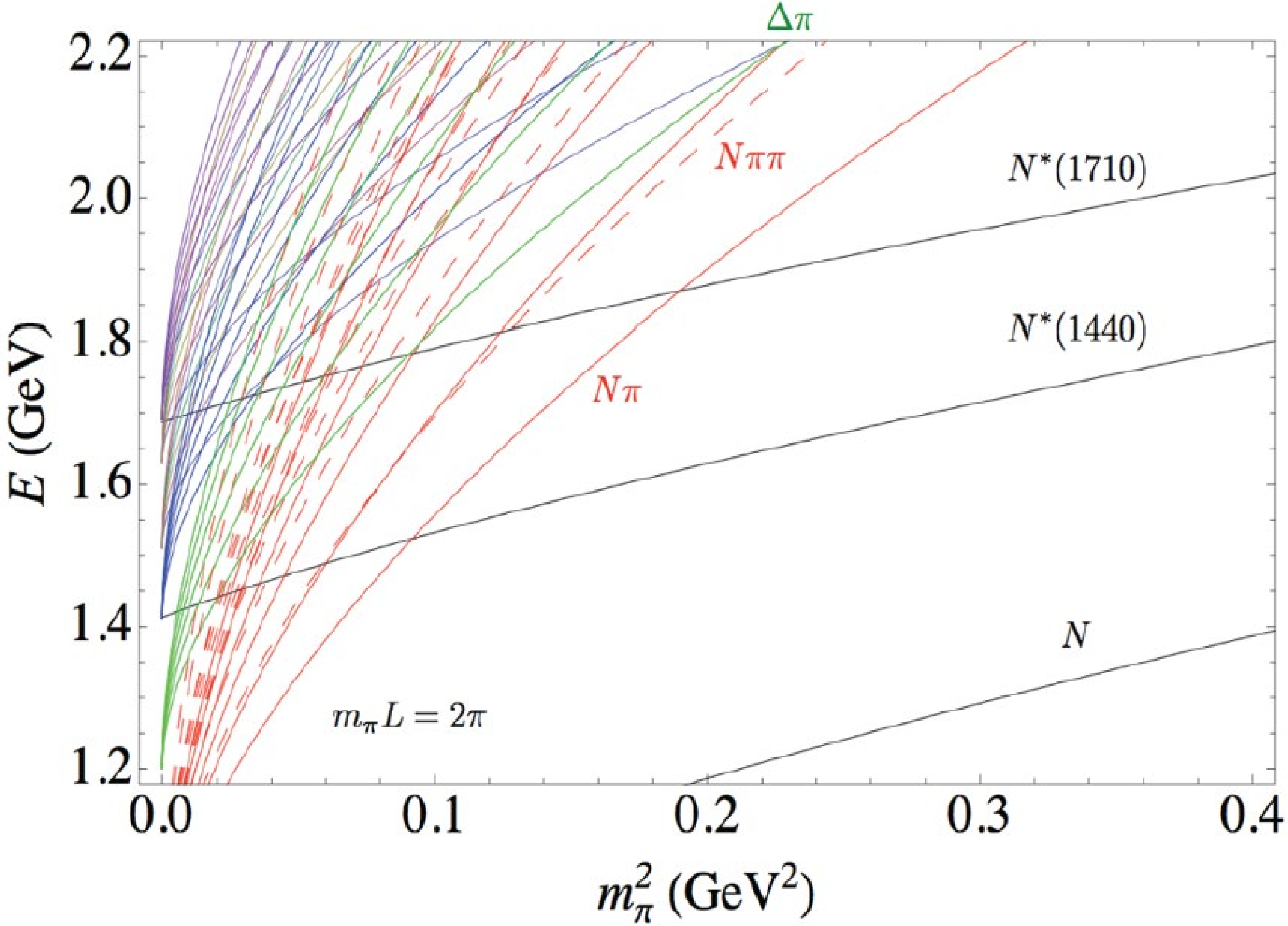
- **Lüscher has a method to derive phase shifts at discrete energies when there is one open channel**

- **That approach has been generalized to coupled channels by Hansen and Sharpe (Phys. Rev. D86 (2012) 016007) and Lellouch and Lüscher (Comm. Math. Phys., 219 (2011) 31), as well as moving frames, e.g. Li et al.,(Phys. Rev. D 103 (2021) 094518) BUT it becomes very complicated**

Interesting cases have many open channels

– at least at realistic quark masses

In General: Multiple open channels



and then there is: σN, ωN, ρN etc....

But Lüscher does not solve all our problems

- This procedure gives no more information than we get from a phase shift analysis of experimental data
- That is, it provides no new insight into the nature of the excited states

Interesting cases

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**

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

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)×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.

ADELAIDE UNIVERSITY AUSTRALIA

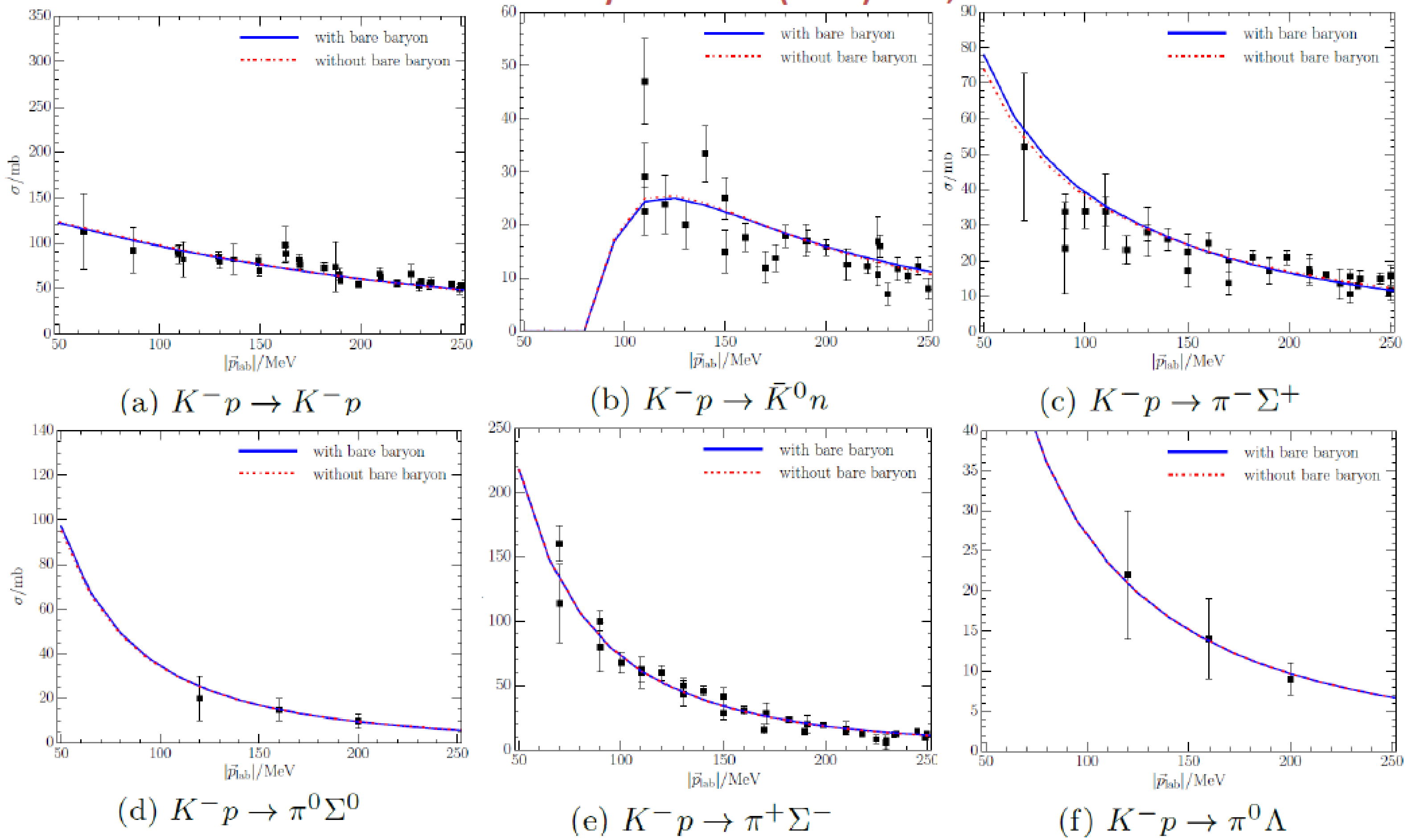
DARK MATTER

But now we can use QCD itself

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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, $\overline{\text{K}}$N, ηΛ and KΞ channels

Similar work by Valencia, Bonn, JLab and other groups

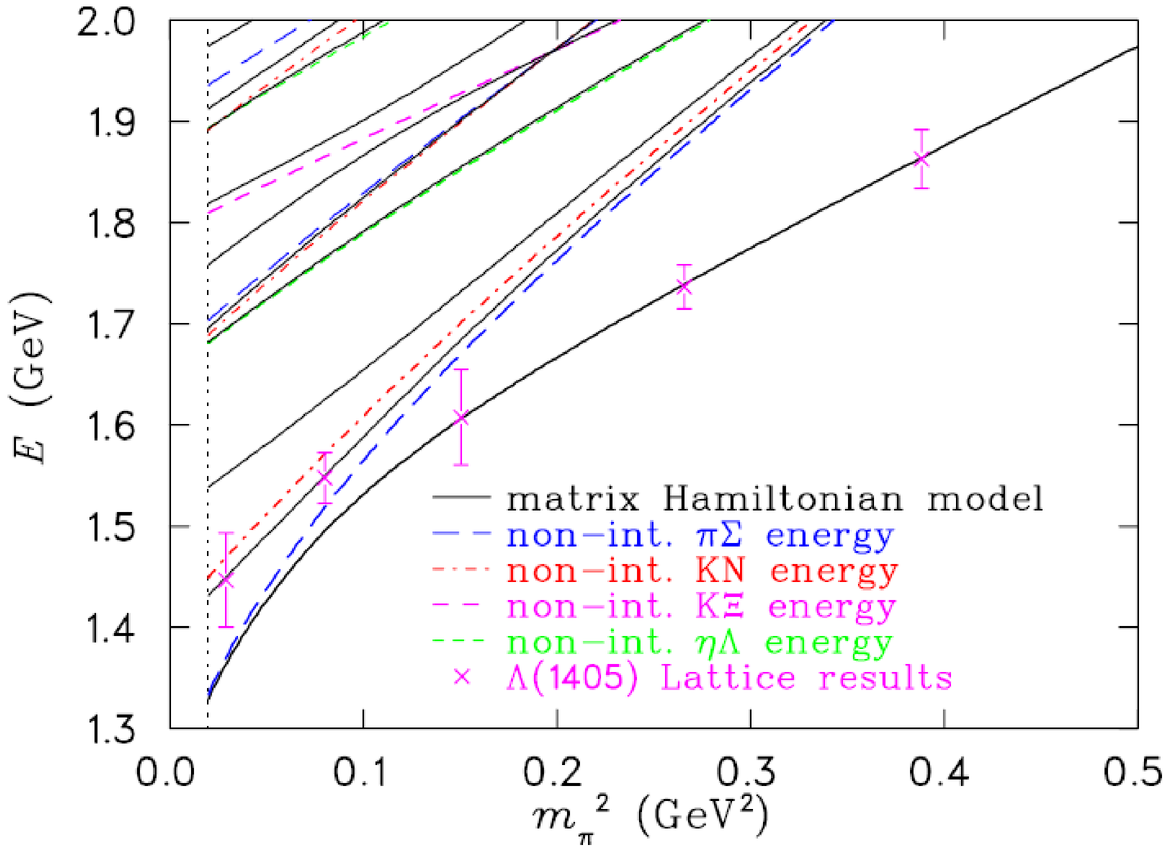
ADELAIDE UNIVERSITY AUSTRALIA

Find the same two-pole structure as other analyses

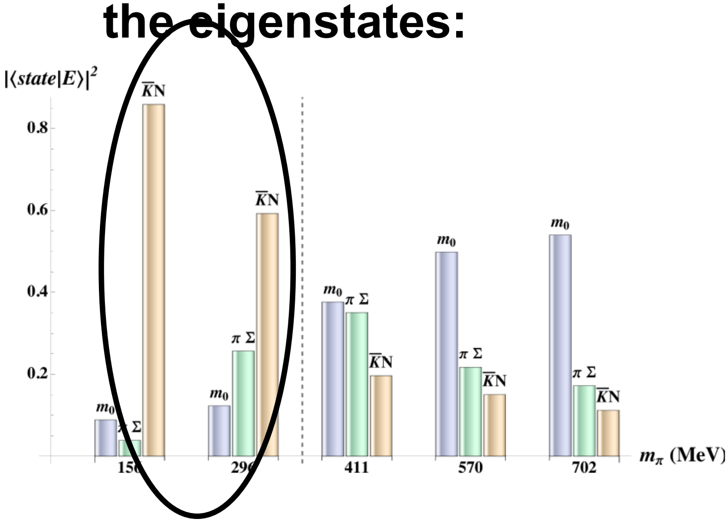
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state



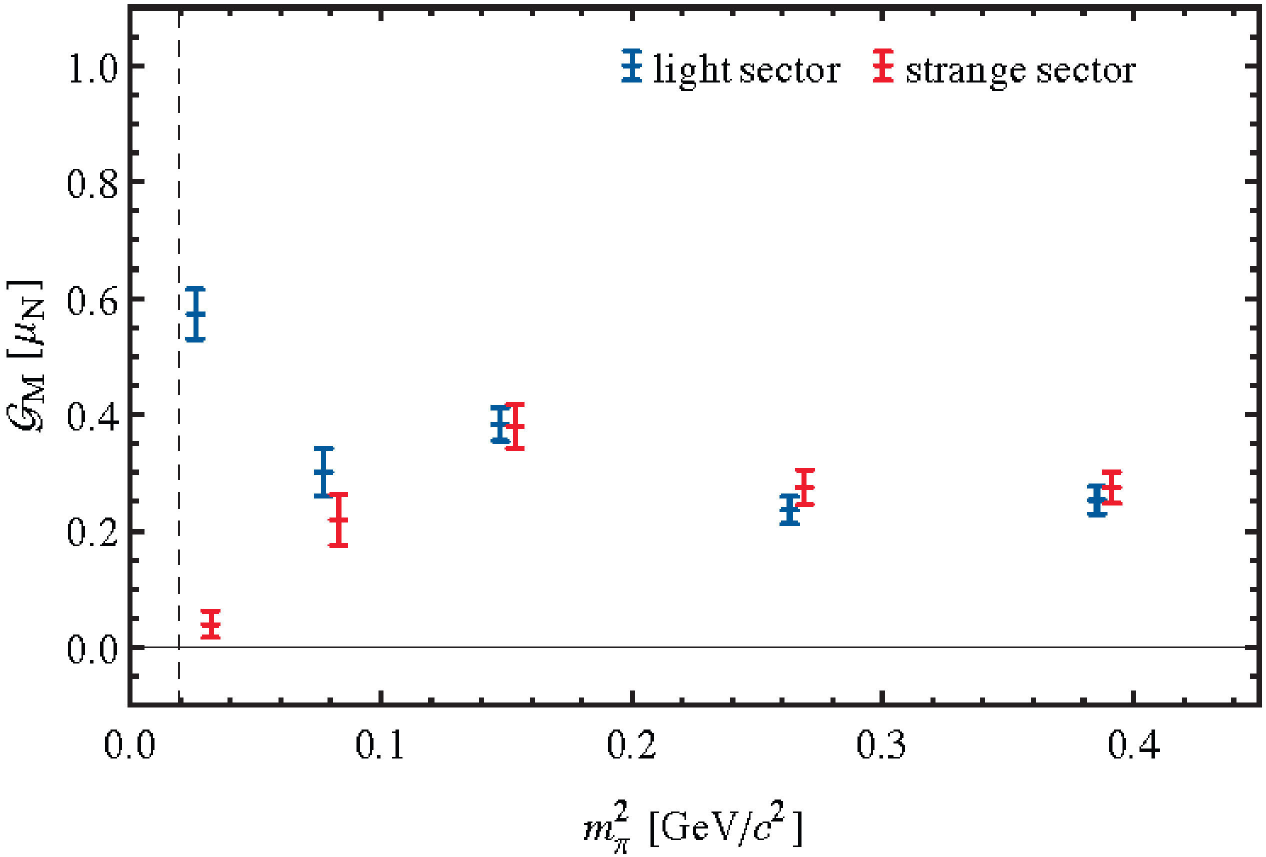
Hamiltonian approach allows one to examine the eigenstates:



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

ADELAIDE UNIVERSITY AUSTRALIA

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

Note that Lattice QCD allows

us to study hadron structure IN QCD as a

function of quark mass – a powerful tool*

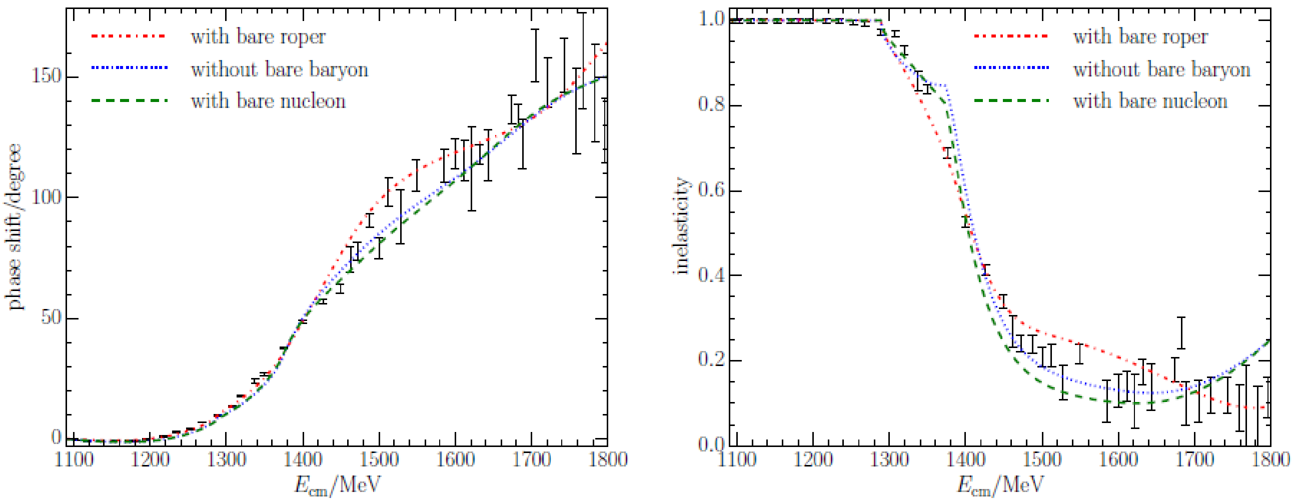
*AWT, Nucl. Phys. B Proc. Suppl. 119 (2003) 50

Roper Resonance

Again this has <u>long been a challenge for the quark model</u>, as it is the 1st positive parity excited state and lies <u>below</u> the N(1535), the 1st negative parity state

Bare Roper Case: $m_0 = 2.03$ GeV

- Consider πN, $\pi\Delta$ and σN channels, dressing a bare state.
- Fit to phase shift and inelasticity



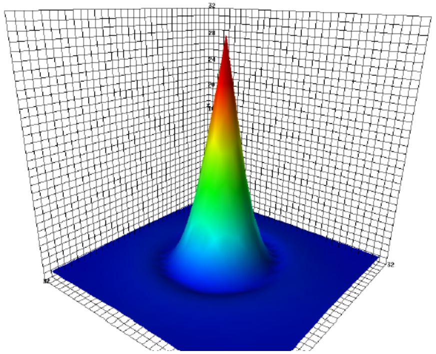
- Fit yields a pole at 1380 $- i\,87$ MeV.
- Compare PDG estimate $1365 \pm 15 - i\,95 \pm 15$ MeV.

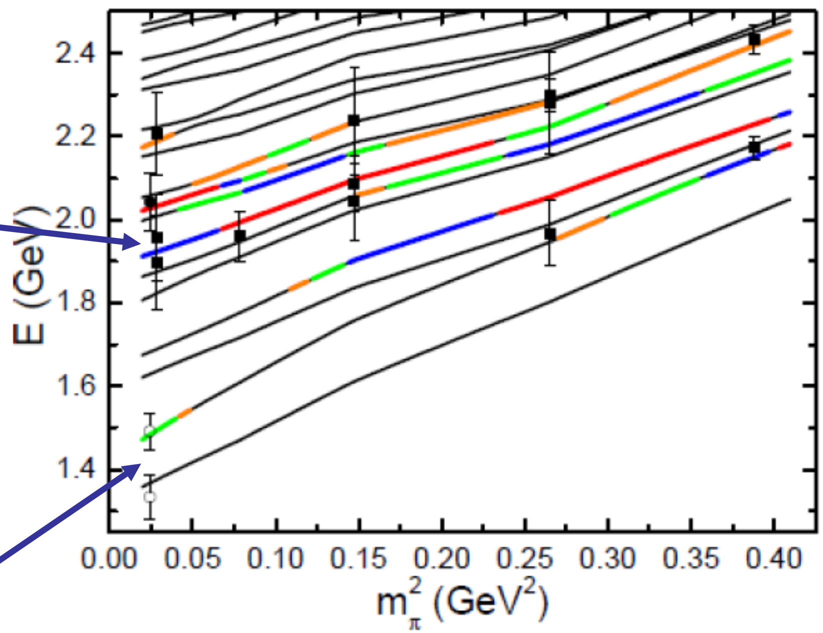
ADELAIDE UNIVERSITY AUSTRALIA

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

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 and looks Like a 2s state**





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.

- **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**

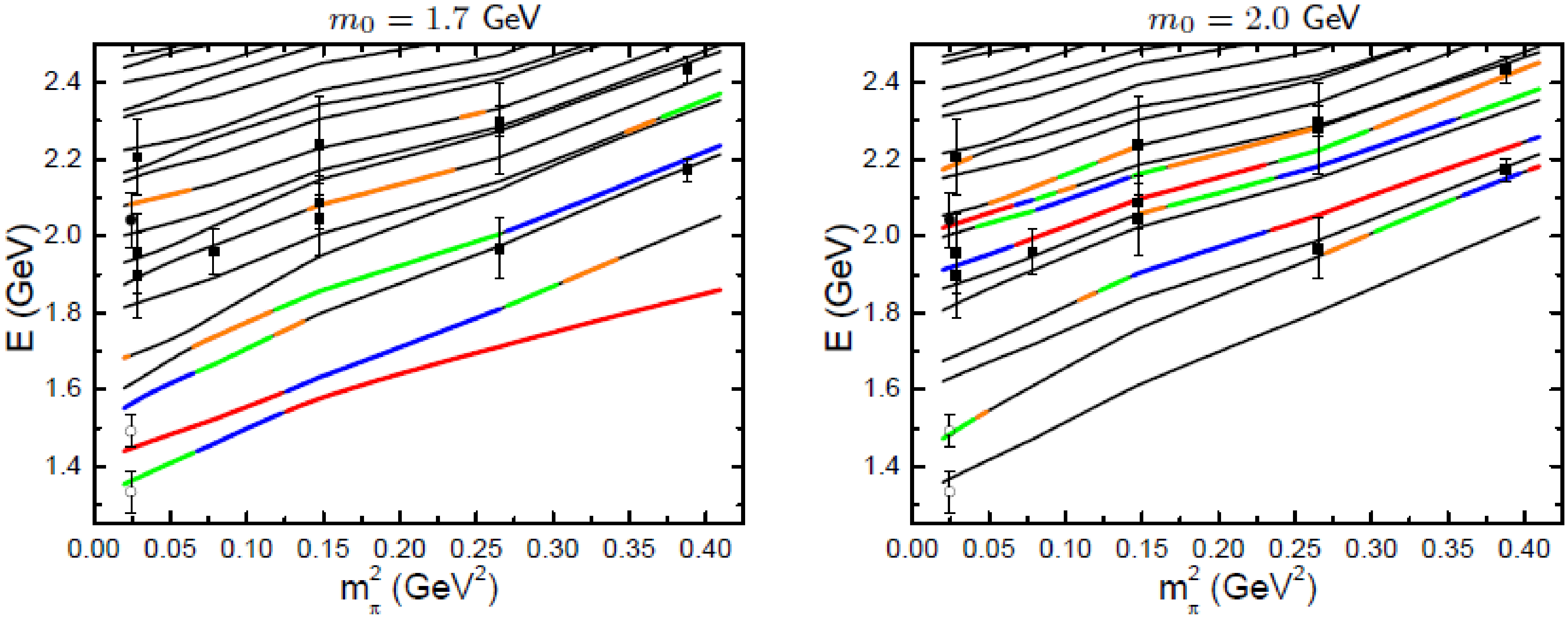
Wu et al., Phys. Rev. D 97 (2018) 9, 094509

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

To emphasise the point

Two different descriptions of the Roper resonance



(left) Meson dressings of a quark-model like core.

(right) Resonance generated by strong rescattering in meson-baryon channels.

Slide from Derek Leinweber

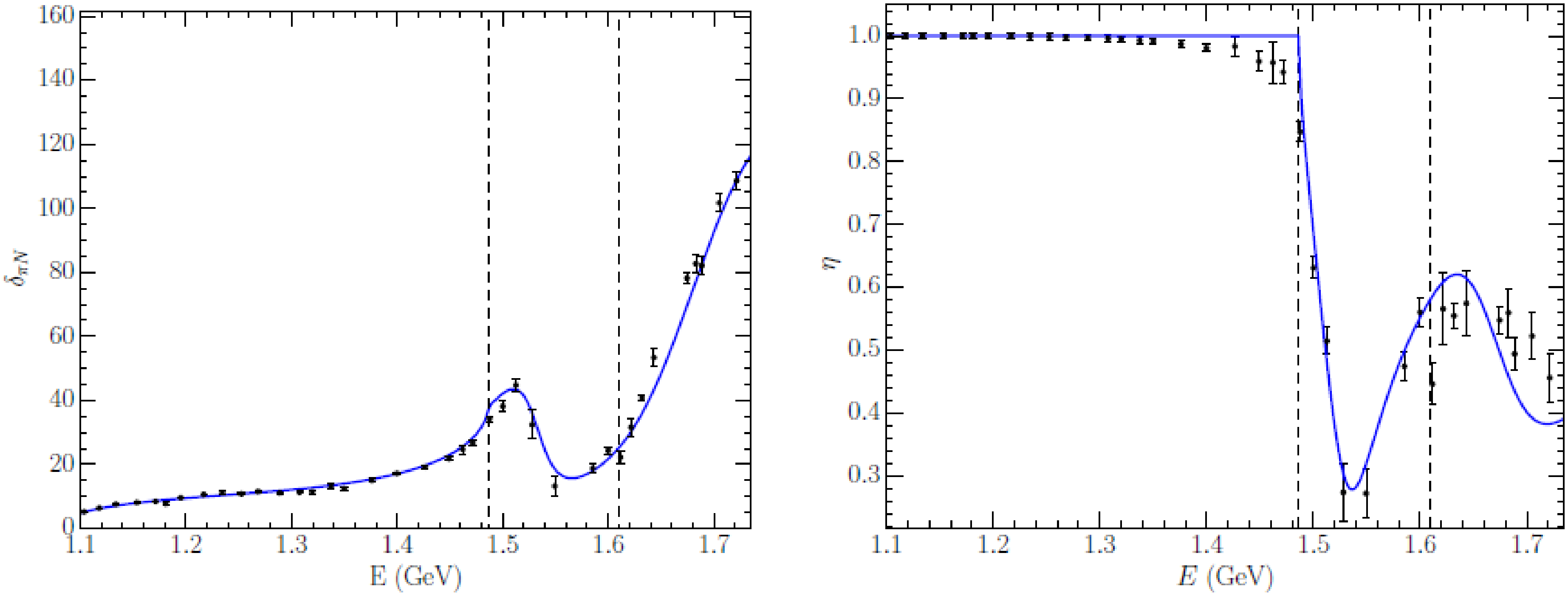
Clear conclusion is that the Roper is dynamically generated by coupling to the Nσ and Δπ channels

Are all states like this?

NO: The N(1535) *is* a 3-quark state

First construct a Hamiltonian to accurately describe experimental data

Pole at 1531 ± 29 - i 88 ± 2 MeV



- WI08 single-energy data from SAID.
- Vertical lines indicate the opening of the ηN and $K\Lambda$ thresholds.

ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER

Liu *et al.*, PRL 116 (2016) 082004

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Analysis of eigenstates

Lattice 3-quark states match bare-state dominated eigenstates in HEFT calculation

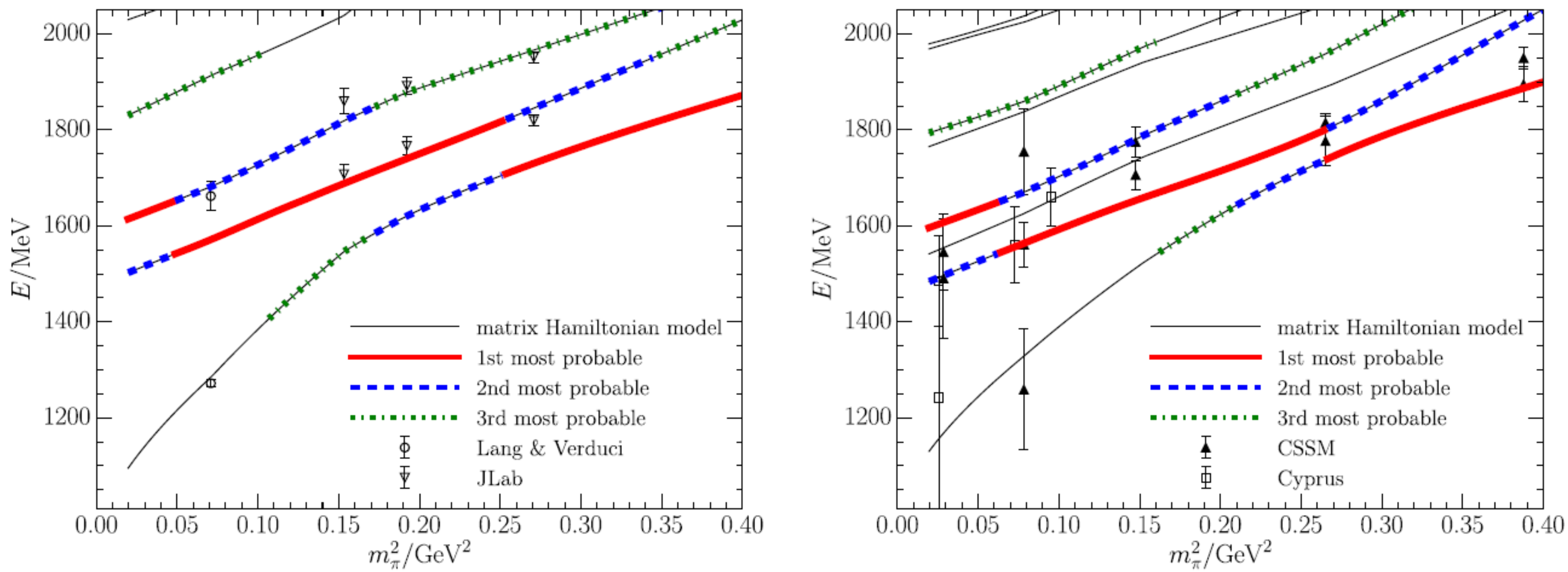


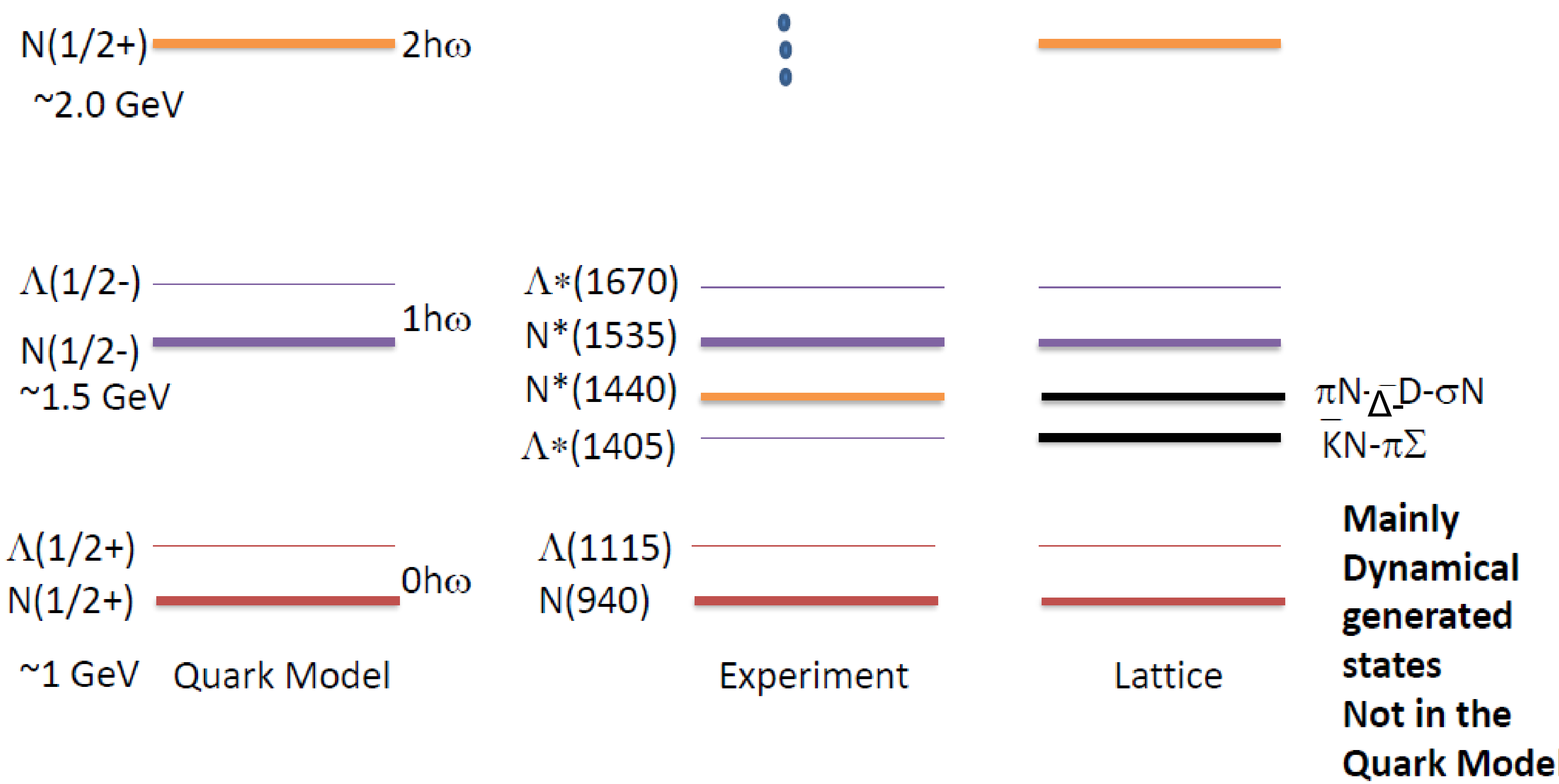
FIG. 2. The pion mass dependence of the $L \simeq 1.98$ fm (left) and $L \simeq 2.90$ fm (right) finite-volume energy eigenstates. The different line types and colors indicate the strength of the bare basis state in the Hamiltonian model eigenvector.

ADELAIDE UNIVERSITY AUSTRALIA

Liu *et al.*, PRL 116 (2016) 082004

Once the nature of key states becomes clear

the quark model makes sense



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

Summary

- New techniques applied to lattice QCD provide hitherto unimagined insights into hadron structure
- Neither the Λ(1405) nor the Roper are predominantly three-quark states
- The quark model has new life with ordering of major shells as expected
- These insights may well resolve "missing state" problem

Acknowledgements: Derek Leinweber, Zhan-Wei Liu,
Jon Hall, Curtis Abell, Jiajun Wu, Waseem Kamleh, Liam Hockley