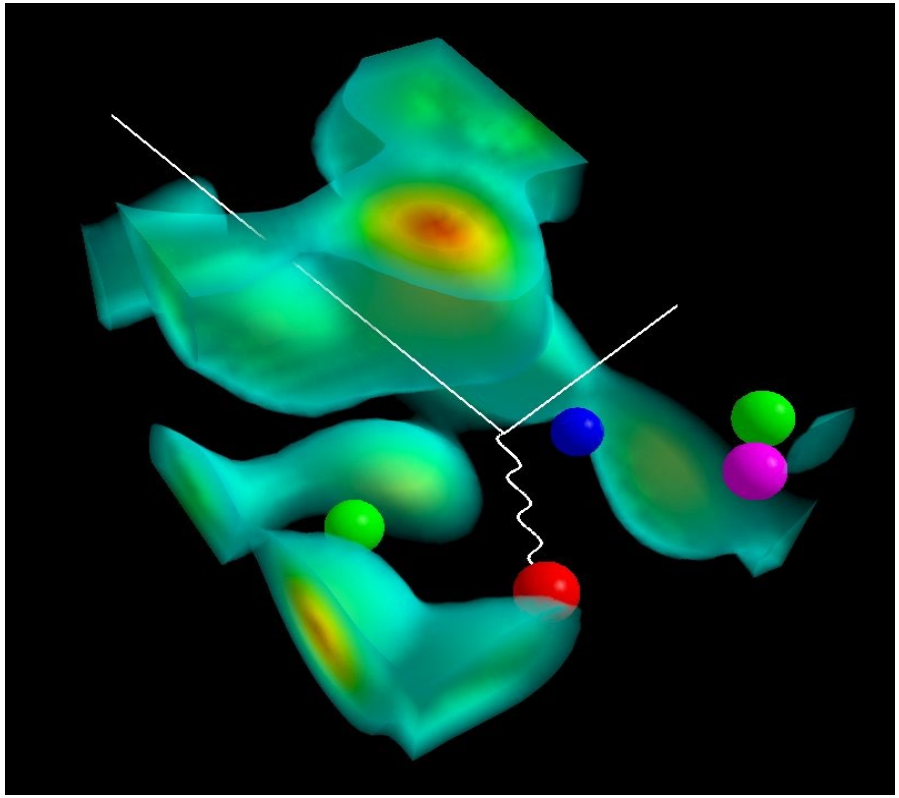
The Nature of Baryon Resonances in QCD



Anthony W. Thomas

BARYONS 2025 : Jeju Korea

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

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

II. Quark States versus Dynamically Generated States

III. New Insight into the Quark Model

- The Λ(1405) IS a $\overline{K}$ - N bound state
- The Roper IS generated by πN-σN re-scattering with the 2s state nearer 1.9 GeV
- Similar story form the 1st and 2nd excited states of the Δ
- But not all states are dynamically generated e.g. N(1535)!

IV. The Quark Model is not so bad!

ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

A brief and very incomplete history

- Dalitz began to develop quark model before quarks were “real”
- Chodos, Jaffe, Johnson &Thorn, 1974+: MIT bag
- De Rujula, Georgi & Glashow, 1975: color hyperfine gluon exchange
- Isgur and Karl, 1977+: developed “shell model” description of baryons using harmonic oscillator with color hyperfine
  - but no role for chiral symmetry
- Capstick *et al.* : relativistic extension of Isgur-Karl

History cont.

- **Dyson-Schwinger equations: Roberts *et al.***
- **Coupled channels work: ANL, Jülich, Kyoto, Tokyo IT, Valencia…**
- **χPT; holographic "QCD"**
- **Hundreds of others (apologies) with an excellent recent review by Dȍring, Haidenbauer, Mai and Sato, *arXiv: 2505.02745 (123 pp.)***
- **Tremendous amount of photo- and electro-production data from Bonn, CLAS…**
- **Recent reviews of experimental data:**
  - **Thiel *et al., PPNP 125 (2022) 103949***
  - **Ireland *et al., PPNP 111 (2019) 103752***

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 – but the lattice is less so….

- Everything is stable on the lattice
  – 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 as excited states involve <u>many</u> coupled channels

Lüscher approach does not solve the key problem

- **This procedure gives no more information than we get from a phase shift analysis of experimental data**

- **It provides no new insight into the nature of the excited states**

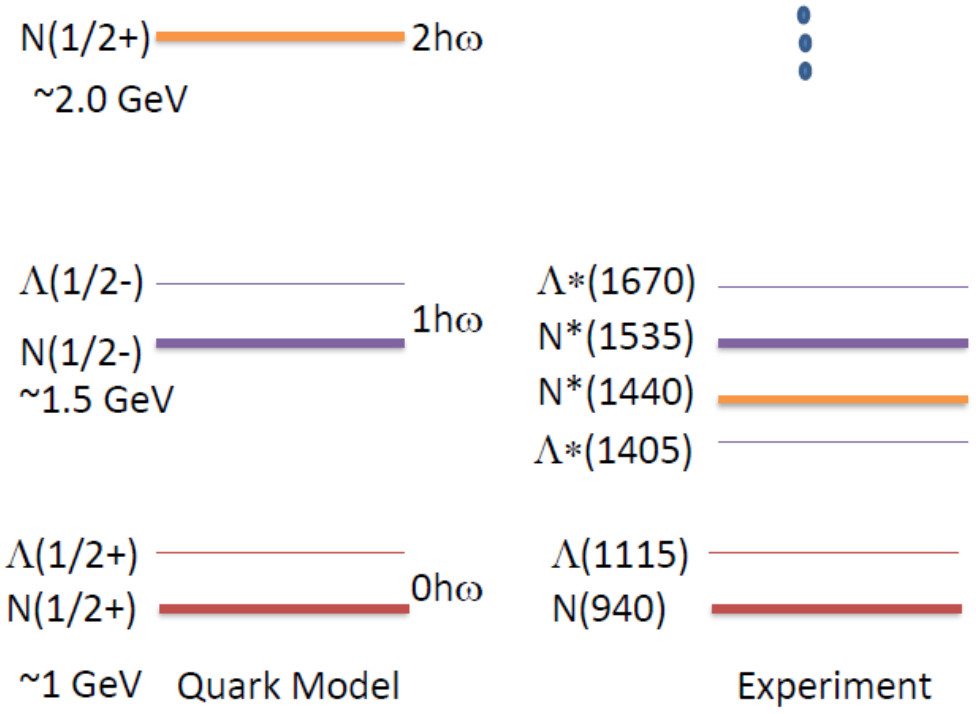
Longstanding Challenges

Quark Model looks WRONG

First +ve parity state occurs before first –ve parity state

Excited state with a heavier strange quark occurs below even the first nucleon excited state

A number of expected excited states are not observed

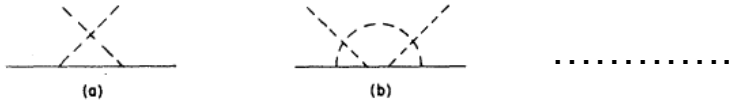


ADELAIDE UNIVERSITY AUSTRALIA
DARK MATTER PARTICLE PHYSICS
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Quark Model vs Dynamically Generated States

Δ(1232): A Classic Illustration

- **Before the quark model, the Δ was understood in terms of the Chew-Low model**



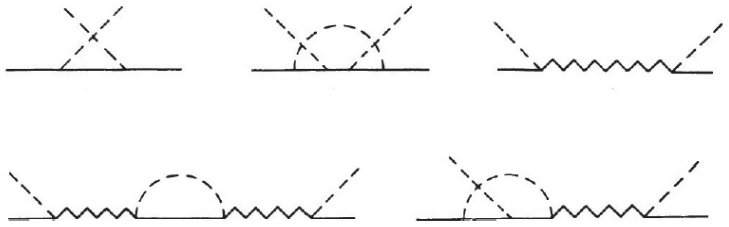
- **Provided the πN vertex allows sufficiently high momentum this series generates a resonance**

- **But the quark model also gave a resonance: S=3/2 3-quark state**

- **Should there be two resonances?**

- **Solution given in cloudy bag model (Théberge *et al.*): $u(k) \sim 3j_1(kR)/(kR)$**

  AT BOTH $N \rightarrow N\pi$ and $\Delta \rightarrow N\pi$ vertices



The Δ(1232) is Essentially a Quark Model State

- When scattering data is fit, WITH THE CONSTRAINT THAT FORM FACTORS ARE THE SAME, there is just one resonance*

- At the resonance pole over 80% of the strength of the scattering amplitude is associated with the three-quark Δ

- As a result, even though the resonance couples to πN it is natural to identify it as a quark state
  - Do NOT have a resonance if 3-quark state is removed

- On the other hand, if meson-baryon channel(s) dominate at the resonance it should be interpreted as dynamically generated
  - Note that the underlying theoretical constraint was critical

- This serves as the archetypical example BUT now we also have lattice QCD data, as a function of quark mass, as additional information

* Théberge et al., Phys Rev D22 (1980) 2838

Λ(1405)

ADELAIDE UNIVERSITY AUSTRALIA
SUB CRUCE LUMEN
DARK MATTER PARTICLE PHYSICS
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

The Λ(1405)

- We have unambiguous evidence that it is a $\overline{K}$ - 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 to BOTH experimental and lattice data

  – shown to be equivalent for phase shifts*
  – BUT <u>also provides information on eigenstates</u>

This along with negative parity nucleon resonances and photo- and electro-production will be discussed by Zhan-Wei Liu on Friday

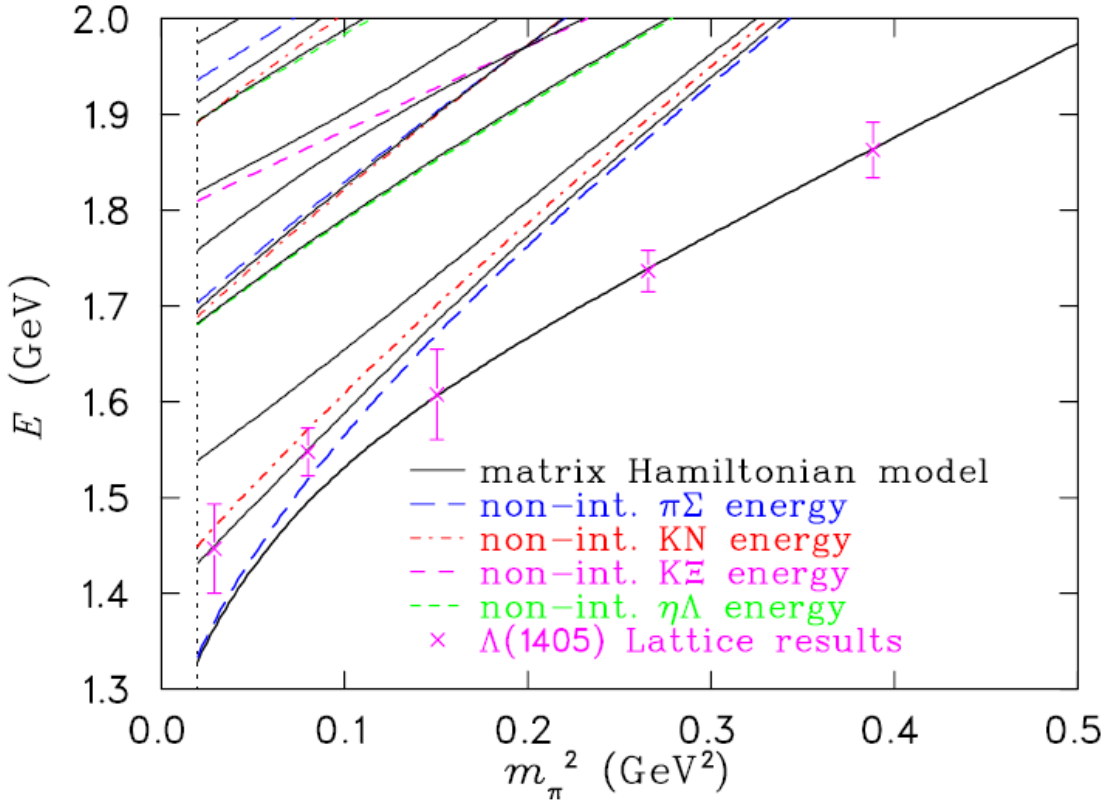
* Wu et al., Phys. Rev. C 90 (2014) 5, 055206

ADELAIDE UNIVERSITY AUSTRALIA
DARK MATTER PARTICLE PHYSICS
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

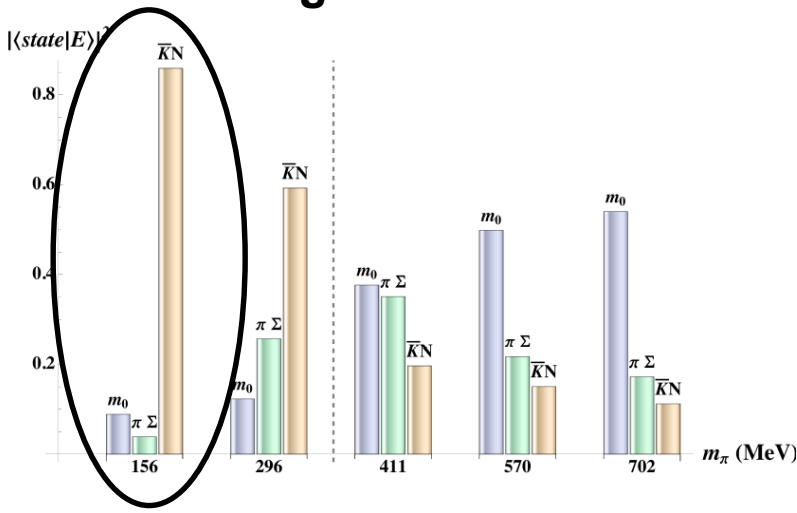
Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state

Dashed lines: free energy levels; solid: eigenstates of Hamiltonian



Hamiltonian approach allows one to examine the eigenstates:



ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

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

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*

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

Roper Resonance (1450)

– David Roper celebrating his 90th birthday in December

Roper Resonance (Discovered 1964)

Investigating the nature of $N(1535)$ and $\Lambda(1405)$ in a quenched chiral quark model

Yue Tan[a], Zi-Xuan Ma[b], Xiaoyun Chen[c], Xiaohuang Hu[d], Youchang Yang[e], Qi Huang[b], Jialun Ping[b]*
[a]*Department of Physics, Yancheng Institute of Technology, Yancheng 224000, People's Republic of China*
[b]*Department of Physics, Nanjing Normal University, Nanjing 210023, People's Republic of China*
[c]*College of Science, Jinling Institute of Technology, Nanjing 211169, People's Republic of China*
[d]*Department of Physics, Changzhou Vocational Institute of Engineering, Changzhou 213164, People's Republic of China and*
[e]*Department of Physics, Guizhou University of Engineering Science, Bijie 551700, People's Republic of China.*
(Dated: March 7, 2025)

2503.04586

In this work, we systematically study $N(1440)$, $N(1535)$, and $\Lambda(1405)$ in both the quenched three-quark and five-quark frameworks using the Gaussian Expansion Method (GEM) within the chiral quark model. Our calculations show that $N(1535)$ can be reproduced as a three-quark state ($N(1P)$), while $N(1440)$ and $\Lambda(1405)$ cannot be accommodated as the three-quark candidates, ($N(2S)$ and $\Lambda(1P)$), respectively. In the five-quark framework, we find that the ΛK state for $N(1535)$ can not form a bound state, while in the $N\bar{K}$ channel there will $\Lambda(1405)$ form a shallow bound state. Based

For the Roper this mirrors conclusion of Jülich group two decades ago

PHYSICAL REVIEW C, VOLUME 62, 025207

What is the structure of the Roper resonance?

O. Krehl,[1,*] C. Hanhart,[2] S. Krewald,[1] and J. Speth[1]
[1]*Institut für Kernphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*
[2]*Department of Physics and INT, University of Washington, Seattle, Washington 98195*
(Received 30 November 1999; published 24 July 2000)

We investigate the structure of the nucleon resonance $N^*(1440)$ (Roper) within a coupled-channel meson exchange model for pion-nucleon scattering. The coupling to $\pi\pi N$ states is realized effectively by the coupling to the σN, $\pi\Delta$, and ρN channels. The interaction within and between these channels is derived from an effective Lagrangian based on a chirally symmetric Lagrangian, which is supplemented by well known terms for the coupling of the Δ isobar, the ω meson, and the ''σ,'' which is the name given here to the strong correlation of two pions in the scalar-isoscalar channel. In this model the Roper resonance can be described by meson-baryon dynamics alone; no genuine $N^*(1440)$ (three quark) resonance is needed in order to fit πN phase shifts and inelasticities.

ADELAIDE UNIVERSITY AUSTRALIA

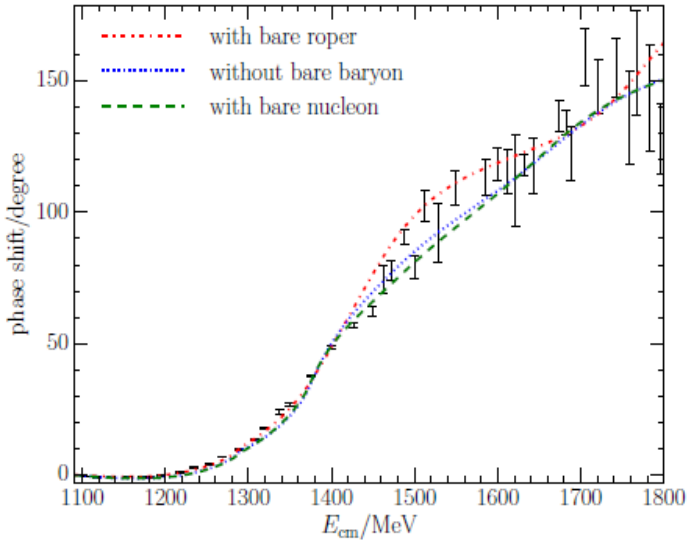
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

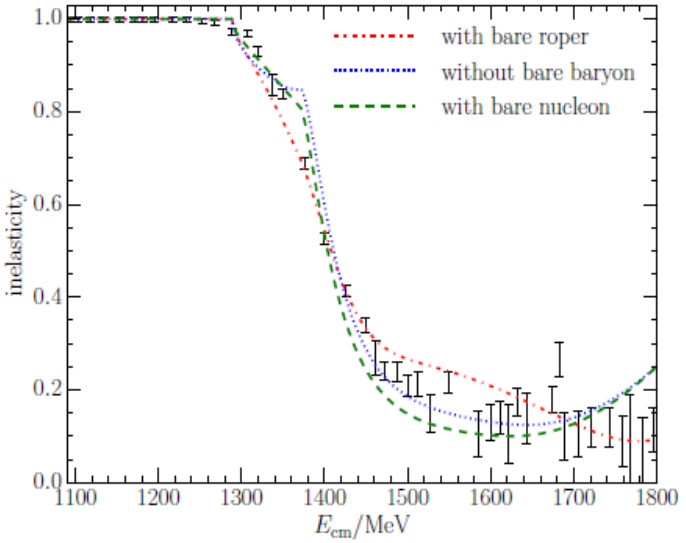
Roper Resonance and Lattice QCD

This has long been a challenge for the quark model, as it is the 1st positive parity excited state and lies below 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.

Wu et al., Phys. Rev. D 97 (2018) 9, 094509
- use Hamiltonian Effective Field Theory (HEFT)

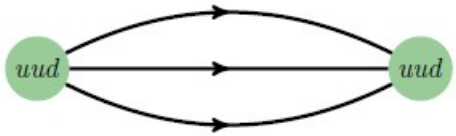
ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

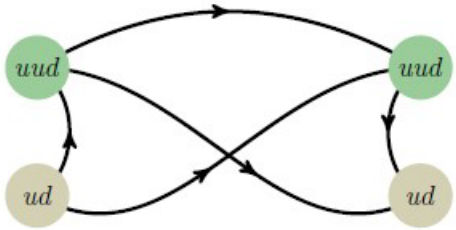
ARC CENTRE OF EXCELLENCE FOR THE SUBATOMIC STRUCTURE OF MATTER

3-quark correlator mainly yields a localized state

This is useful in understanding the nature of a resonance



Need explicit meson-baryon correlator to efficiently excite composite states

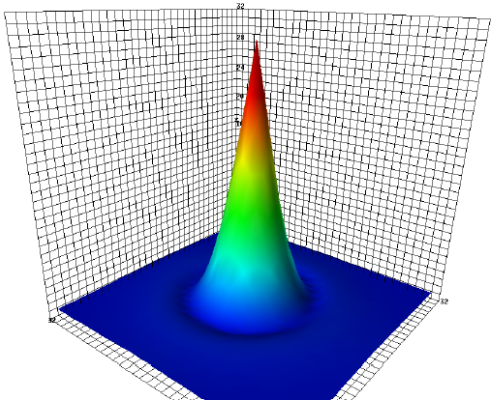


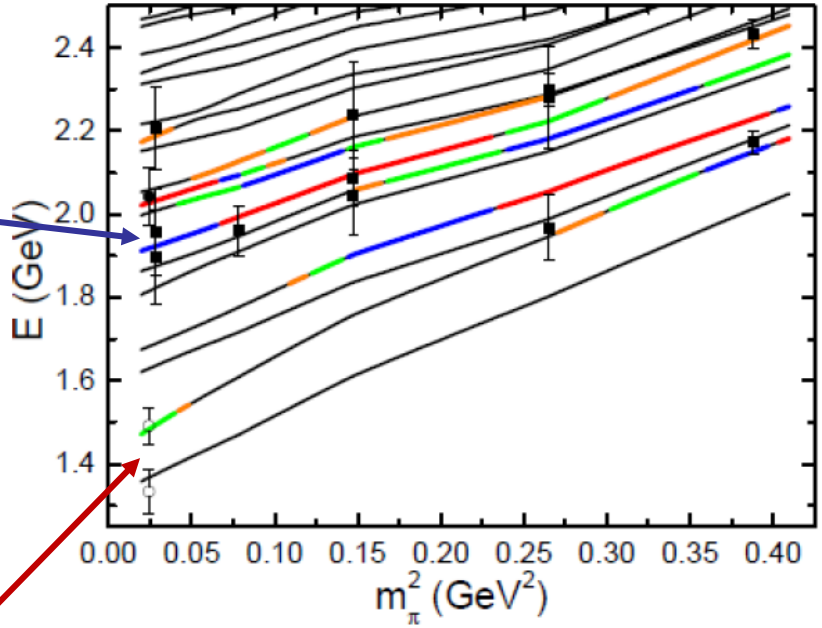
Leskovec, Lang, Padmanath and Prelovsek, 1806.02363
only saw a state in Roper region with explicit Nσ included

ADELAIDE UNIVERSITY AUSTRALIA
DARK MATTER PARTICLE PHYSICS
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Comparison of HEFT Results with Lattice Energy Levels

- Blue indicates high "bare state" (i.e. 3-quark) content: this matches the lowest excited state found with a 3-quark interpolating field and looks Like a 2s state





- Lattice calculations of Padmanath, Lang et al., Phys. Rev. D 95, 014510 (2017), using baryon-meson interpolating fields, especially Nσ, crucial to finding state In Roper mass region

- 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.

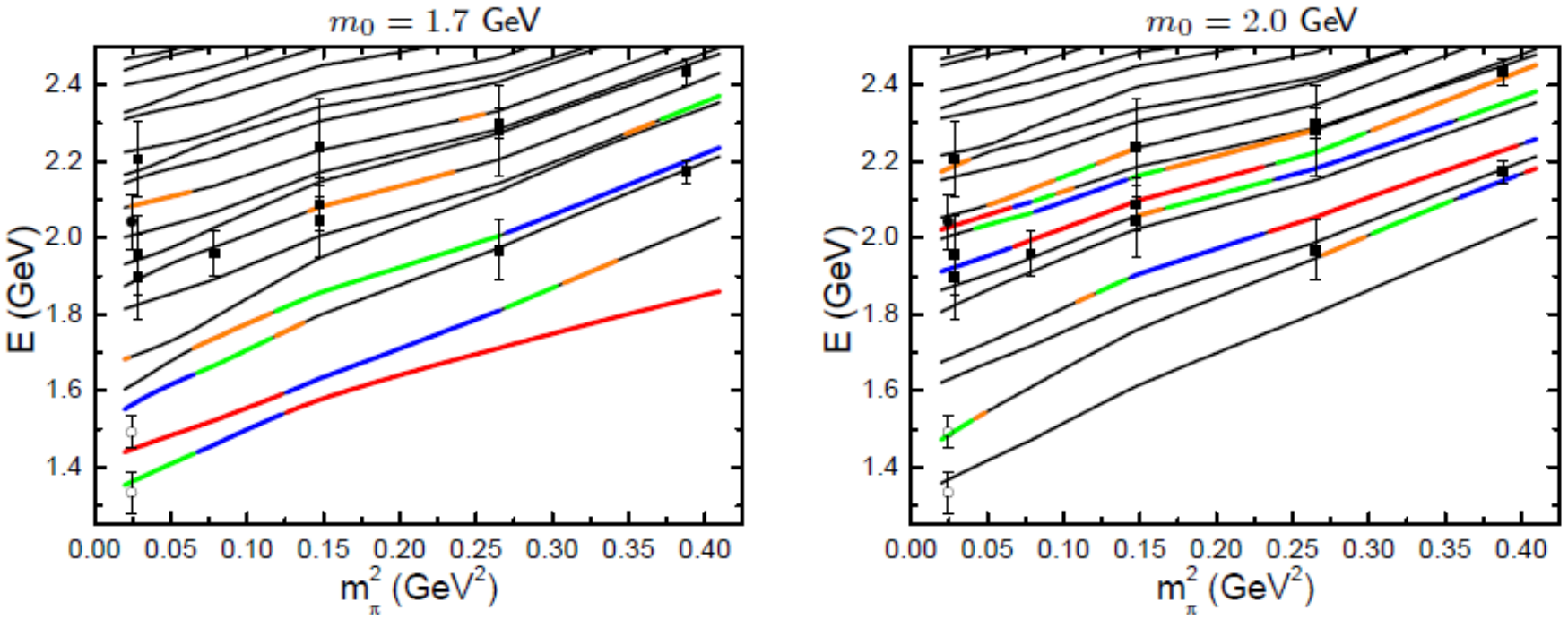
Wu et al., Phys. Rev. D 97 (2018) 9, 094509

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.

ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

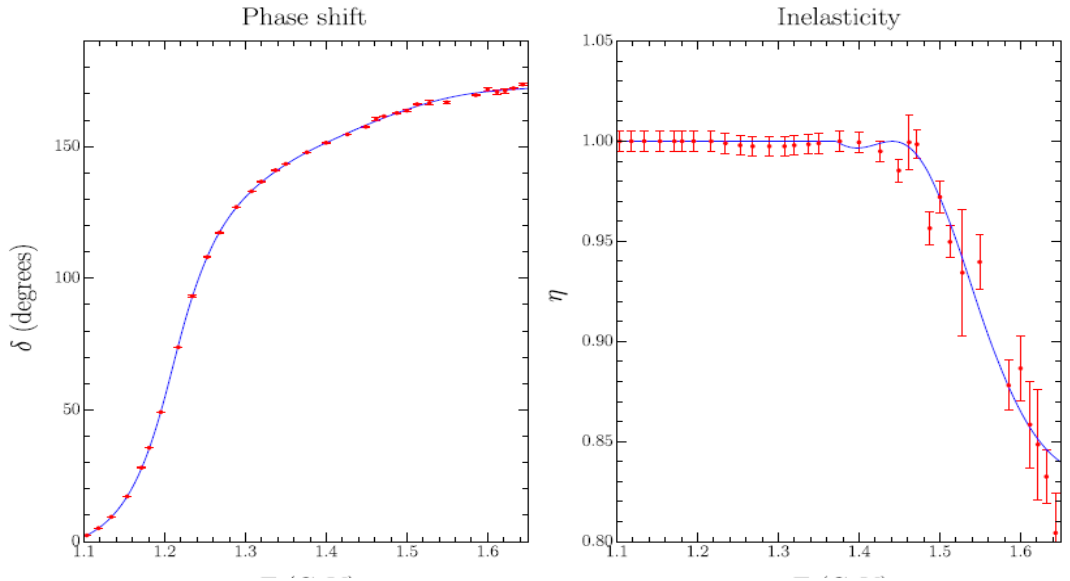
Slide from Derek Leinweber

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

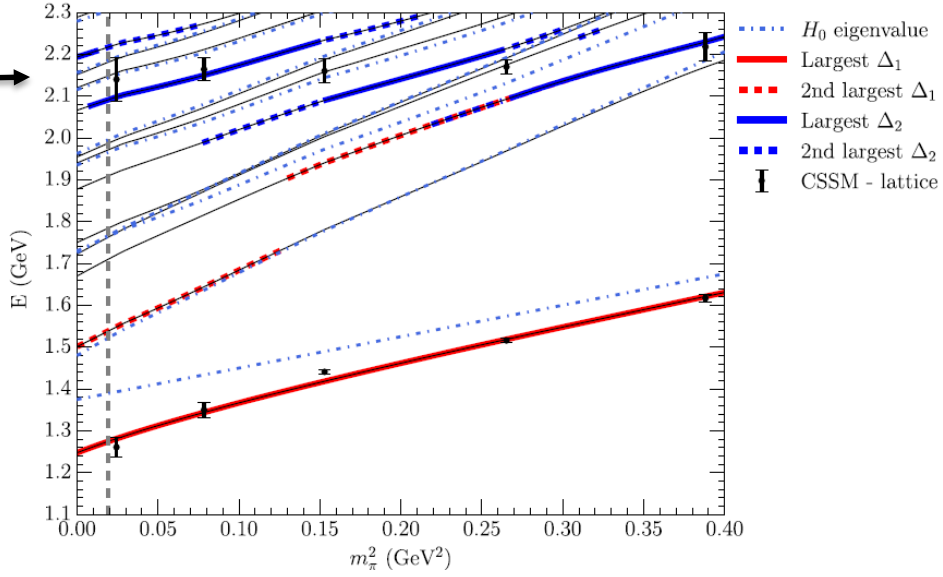
Clear conclusion is that the Roper is dynamically generated by coupling of the Nσ to the Nπ channel

What about the excited states of the Δ ?

Like the Roper the Δ(1600) is also dynamically generated



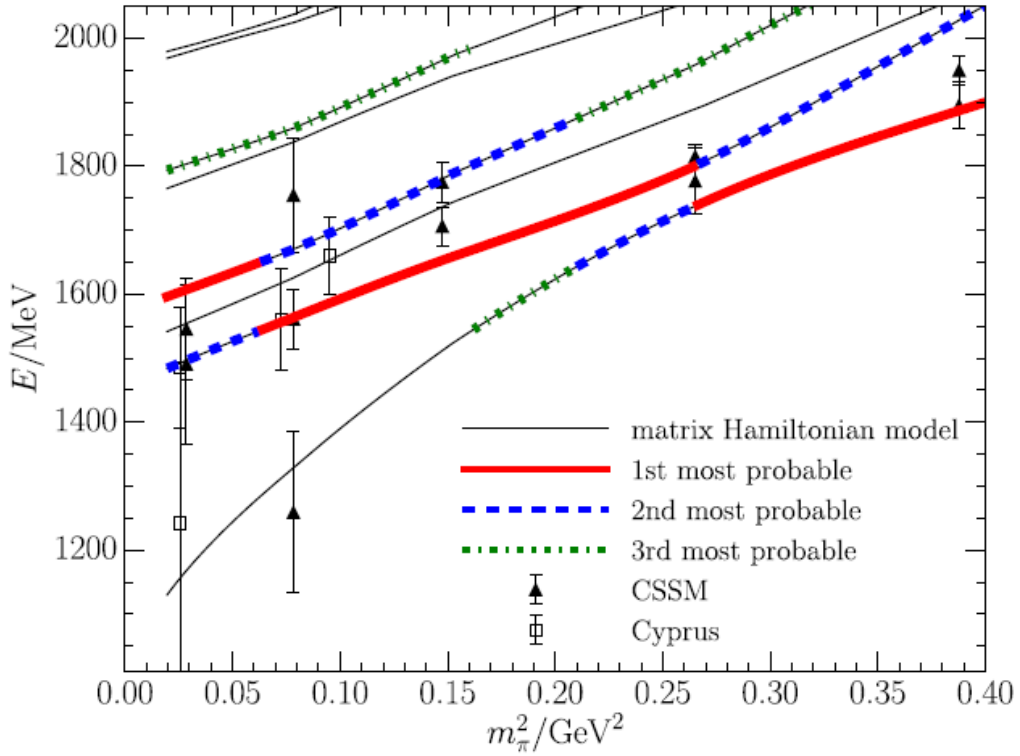
State dominated by 3-quark (2s) excitation near 2.1 GeV



Are all states like this?

NO: The N(1535) is a quark state

Lattice 3-quark states (L=2.9 fm) match bare-state dominated eigenstates in HEFT calculation

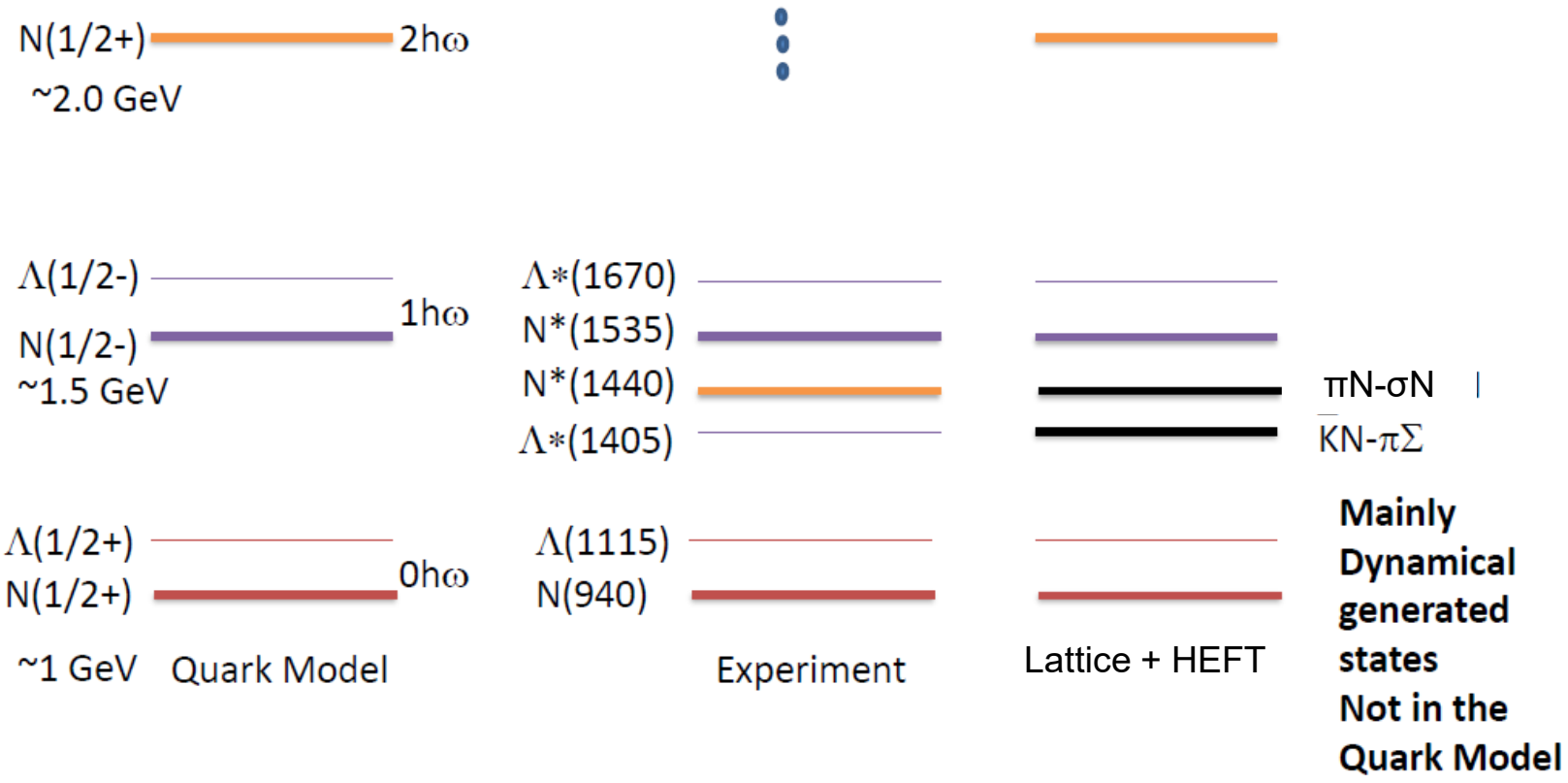


Same conclusion regarding Roper and N(1535) in Tan et al., 2503.04586

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

Once the nature of key states becomes clear

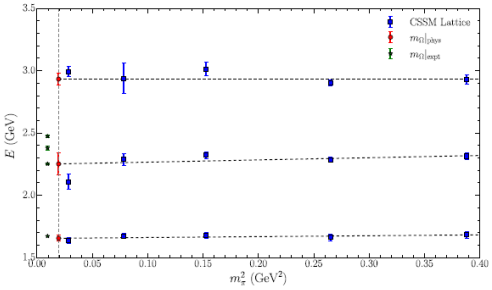
the quark model makes sense

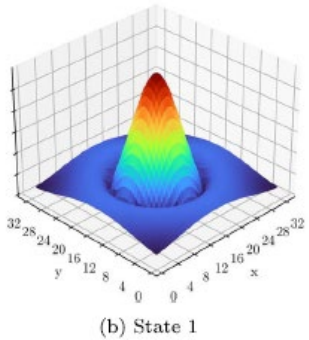


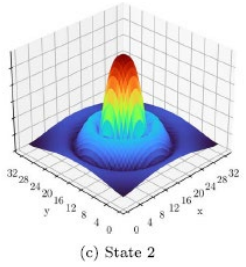
Wu, Leinweber et al., Physical Review D97, 094509 (2018)

Recent Extension to Ω excited States

PDG			Lattice		
Resonance	J^P	m (MeV)	J^P	$m_\Omega\|_{\text{phys}}$ (MeV)	Nodes
$\Omega^-(1672)$	$3/2^+$	1672.5 ± 0.3	$3/2^+$	1656 ± 23	0
$\Omega^-(2012)$	$?^-$	2012.4 ± 0.9	$1/2^-$	2041 ± 55	0
			$3/2^-$	2051 ± 45	0
$\Omega^-(2250)$	$?^?$	2252 ± 9	$3/2^+$	2252 ± 91	1
$\Omega^-(2380)$	$?^?$	2380 ± 17	$1/2^+$	2341 ± 140	0
$\Omega^-(2470)$	$?^?$	2474 ± 12	$1/2^-$	2562 ± 184	1
			$3/2^-$	2646 ± 76	1
			$3/2^+$	2933 ± 48	2
			$1/2^+$	2970 ± 138	1
			$3/2^-$	3339 ± 218	2
			$1/2^-$	3485 ± 178	2




(b) State 1


(c) State 2

Hockley *et al.*, J Phys G 52 (2025) 065103
(lattice calculations at CSSM)

Summary

- New techniques (HEFT/coupled channels) applied to lattice QCD provide hitherto unimagined insights into hadron structure

- Neither the Λ(1405) nor the Roper (nor the Δ(1600)) are predominantly three-quark states

- The quark model has new life with ordering of major shells as expected

- These insights may help to resolve “missing state” problem - as the 3-quark excited states occur at higher energy

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

ADELAIDE UNIVERSITY AUSTRALIA
DARK MATTER PARTICLE PHYSICS
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER


ADELAIDE
UNIVERSITY
AUSTRALIA
SUB CRUCE LUMEN


DARK
MATTER
PARTICLE PHYSICS

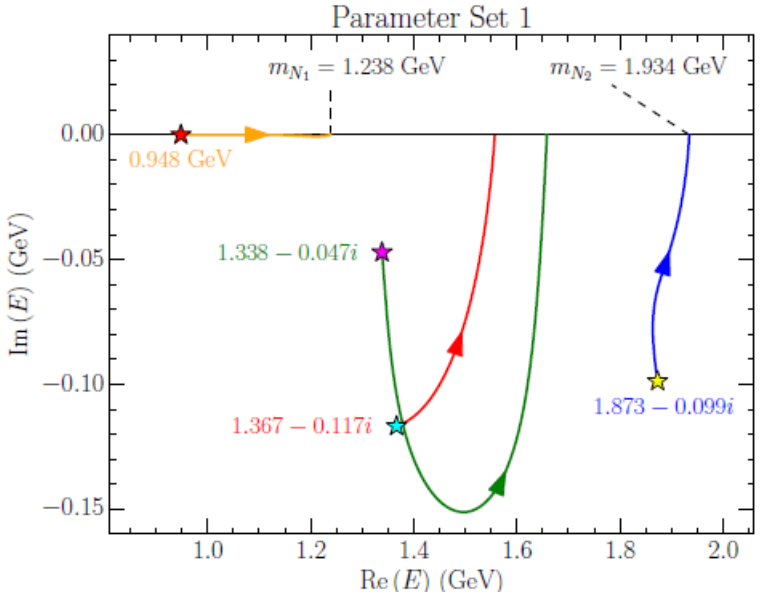

SPECIAL RESEARCH
CENTRE FOR THE
SUBATOMIC
STRUCTURE OF MATTER

Movement of Poles is Model Dependent

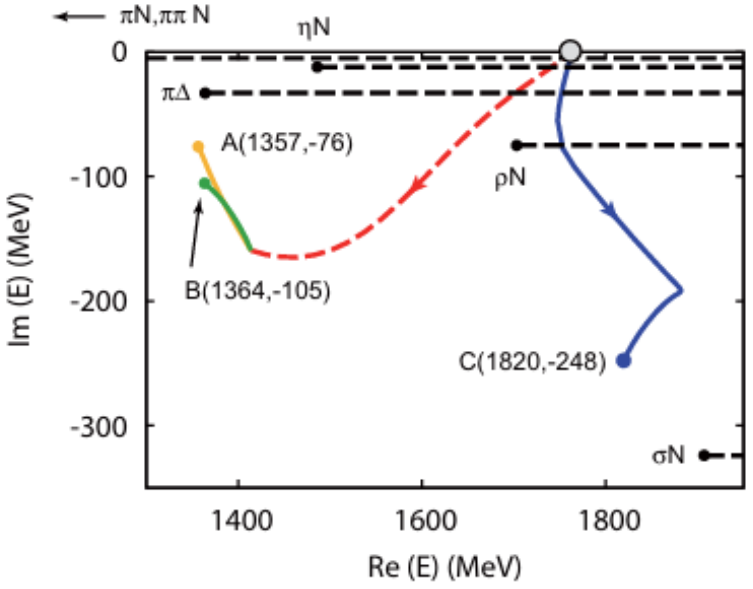
Set	Location	Our value (GeV)	PDG value (GeV)
1	$\{u,p,p,u\}$	$1.367-0.117i$	$1.365(15)-0.095(15)i$
	$\{u,u,p,u\}$	$1.338-0.047i$	
	$\{u,u,u,u\}$	$1.873-0.099i$	$1.860(40)-0.115(25)i$
2	$\{u,p,p,u\}$	$1.363-0.120i$	$1.365(15)-0.095(15)i$
	$\{u,u,p,u\}$	$1.344-0.056i$	
	$\{u,u,u,u\}$	$1.867-0.107i$	$1.860(40)-0.115(25)i$

{πN, πΔ, ηN, σN}

As interactions are turned off the movement of poles is unpredictable



Owa et al., 2503.09940



Suzuki et al., PRL 111 (2010) 042302

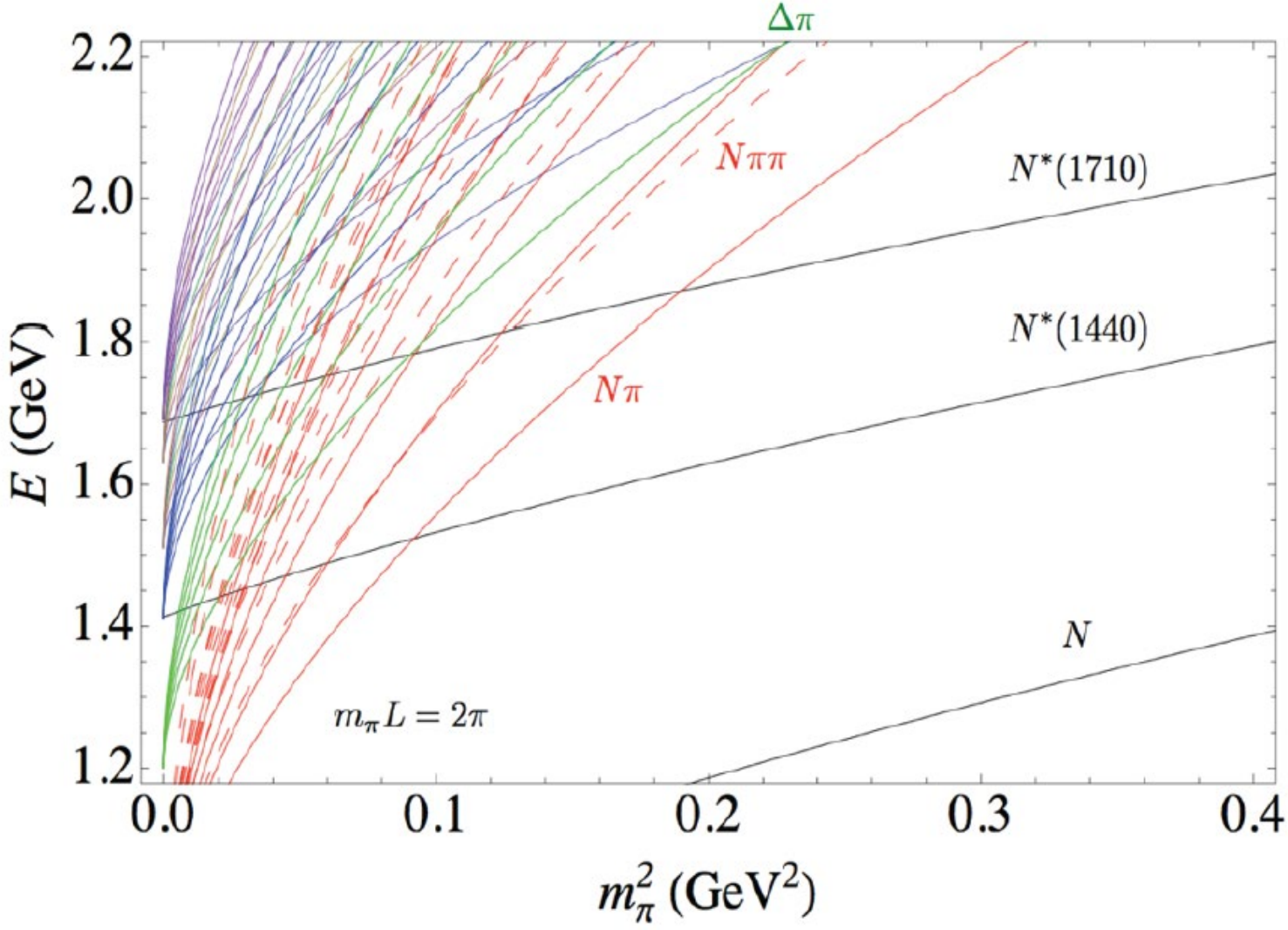
ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

In General: Multiple open channels

Illustration of multiple non-interacting energy levels on a lattice



and then there are: σN, ωN, ρN etc....

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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.

But now, through the lattice, we can use QCD itself

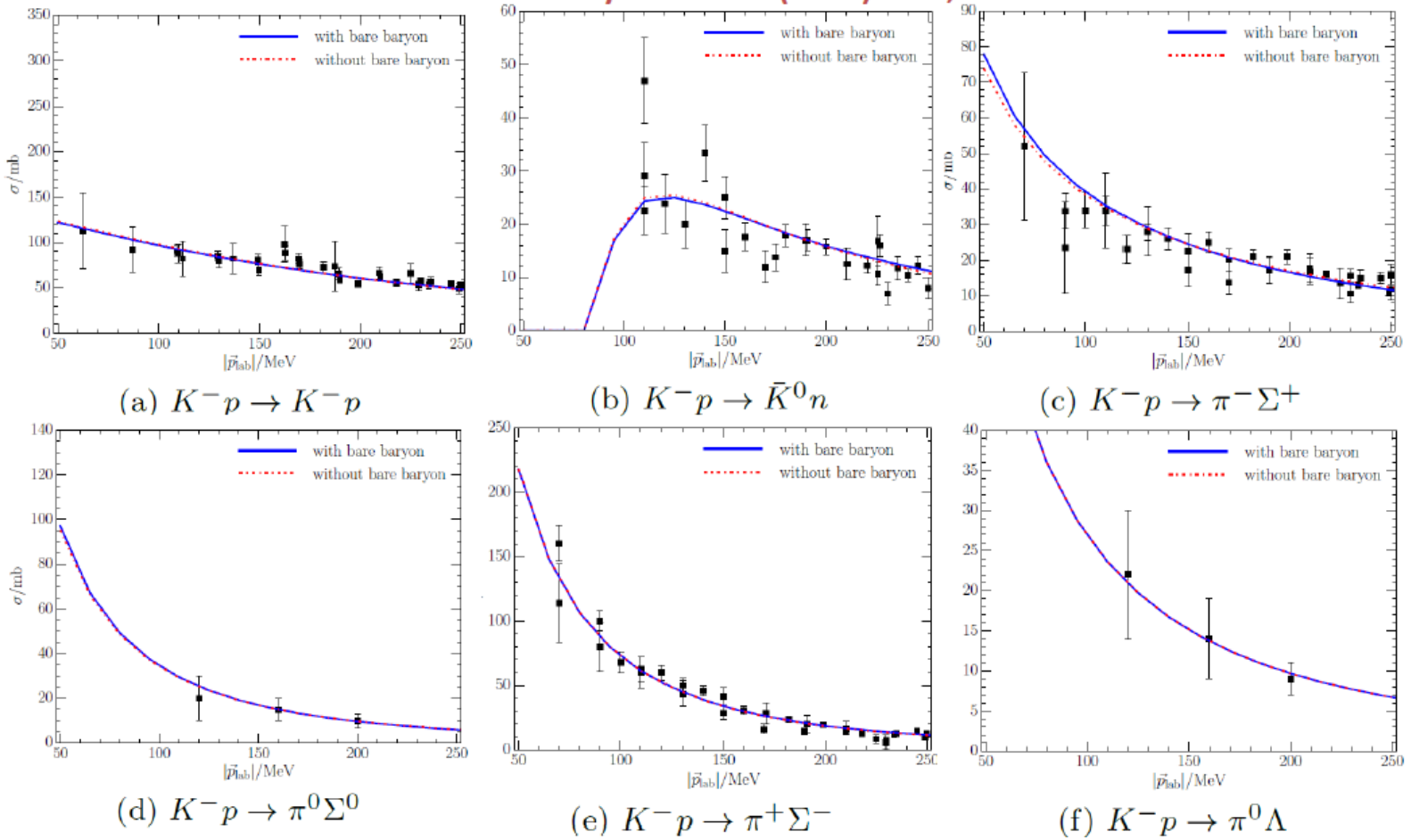
ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

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



Include πΣ, $\bar{K}$N, ηΛ and KΞ channels

Similar work by Valencia, Bonn, JLab and other groups

Find the same two-pole structure as other analyses

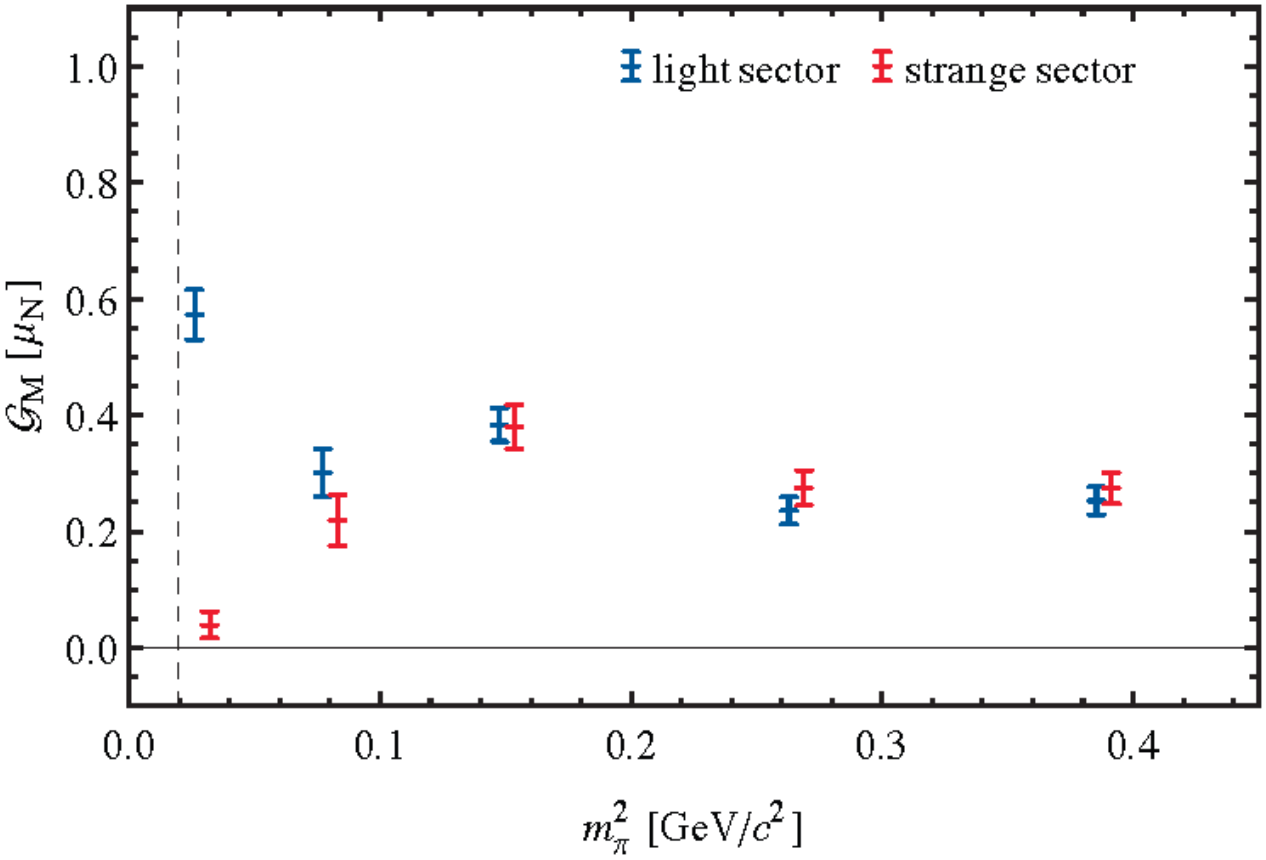
ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Lattice Magnetic Form Factor Calculations

- **Calculation of the individual quark contributions to the magnetic form factor confirms that it is a $\overline{K}$ - N bound state**



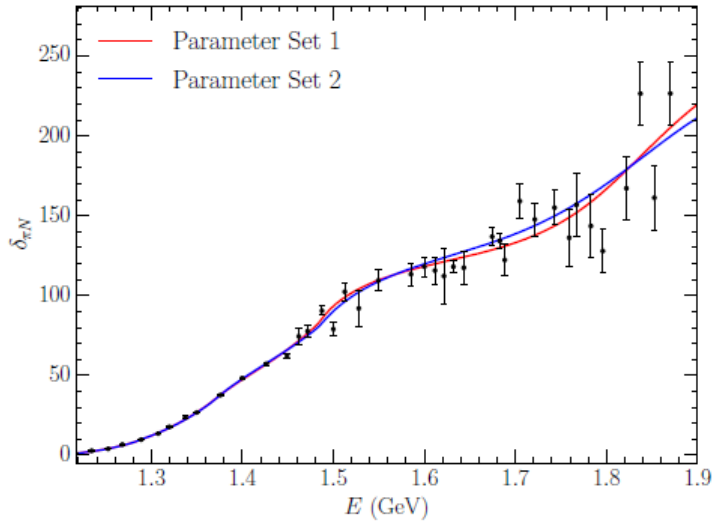
Only an L=0 $\overline{K}$ - N state gives vanishing strange moment

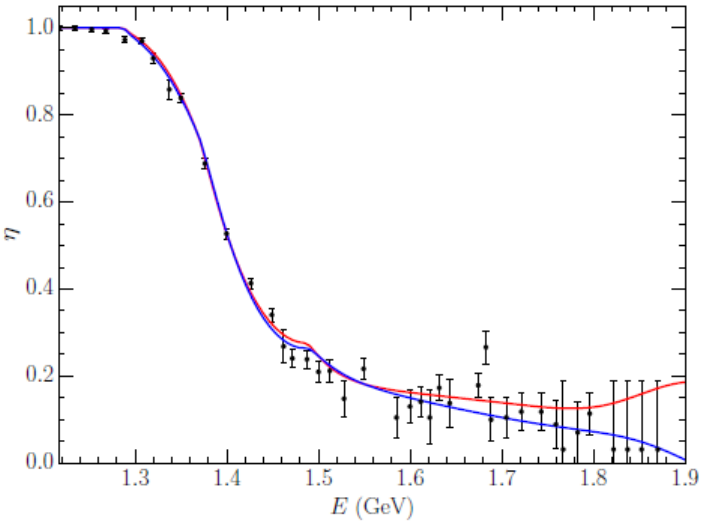
Hall *et al.*, Phys. Rev. *D* 95 (2017) 5, 054510

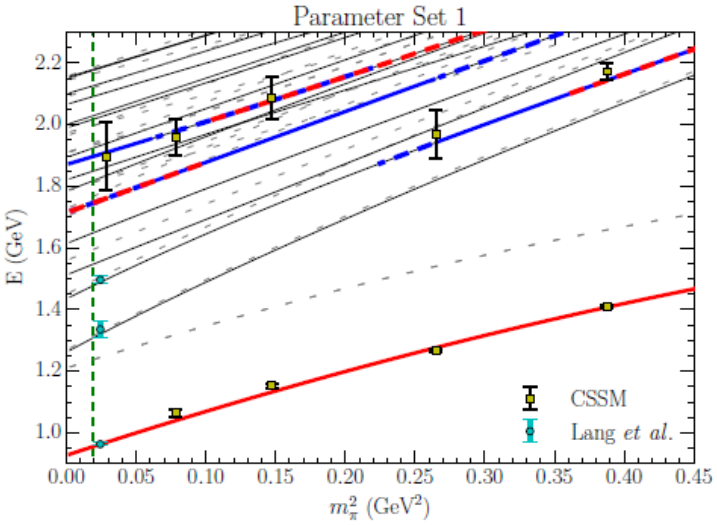
ADELAIDE UNIVERSITY AUSTRALIA

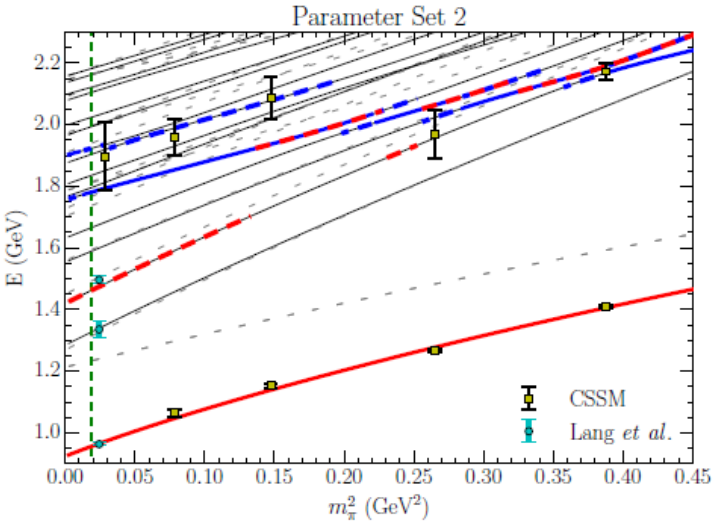
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

More Detail on Roper







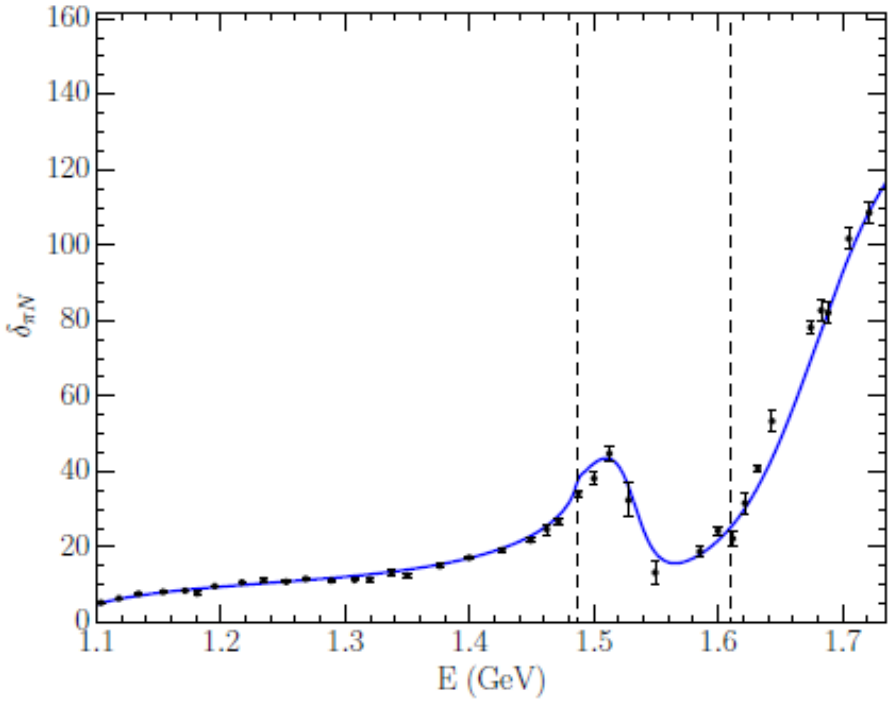


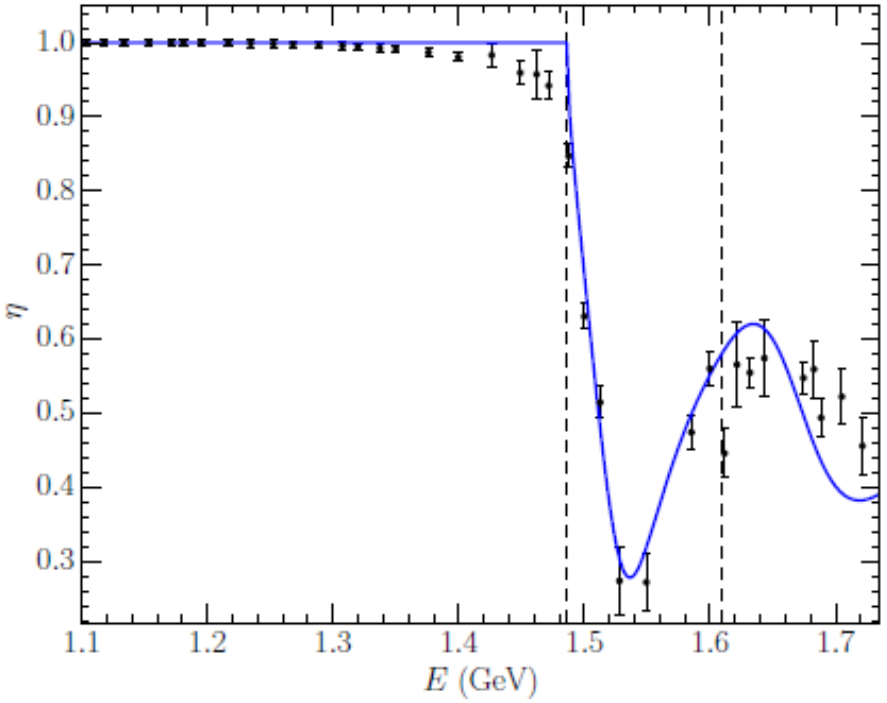
Owa et al., 2503.09945

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.

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


ADELAIDE
UNIVERSITY
AUSTRALIA
SUB CRUCE LUMEN


DARK
MATTER
PARTICLE PHYSICS


SPECIAL RESEARCH
CENTRE FOR THE
SUBATOMIC
STRUCTURE OF MATTER