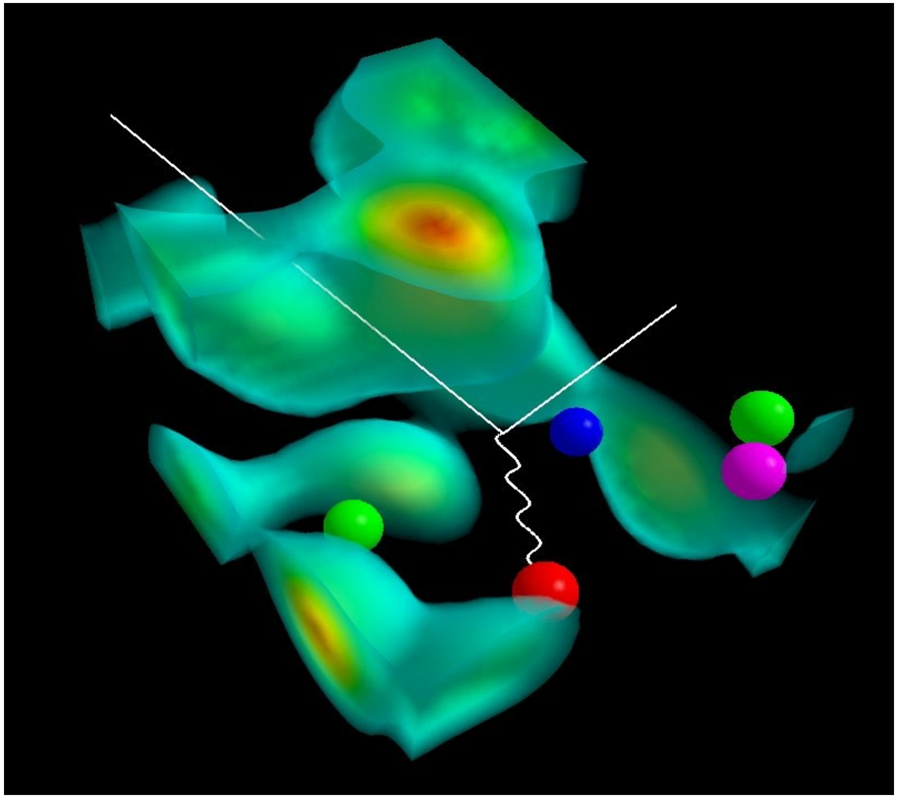
Half a Century of Quantum Chromodynamics



Anthony W. Thomas

Half a Century of Quantum Chromodynamics
Kolymbari : August 29th 2024

ADELAIDE UNIVERSITY AUSTRALIA

DARK MATTER

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?

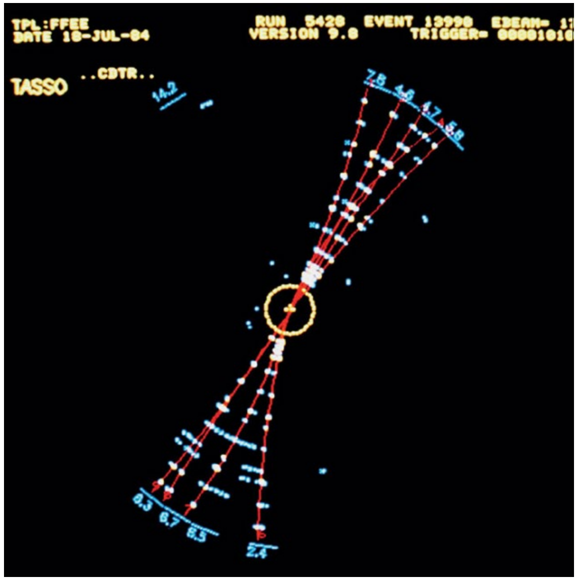
November 1974: J/Ψ

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!”

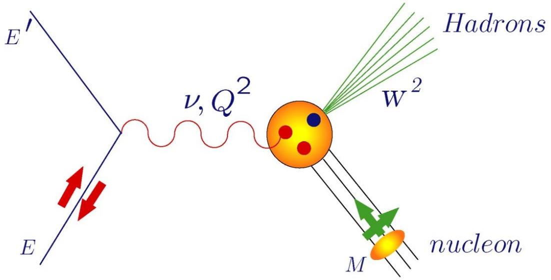
DESY 1978-79

e^+- e^- annihilation to jets: 3 gluon vertex



Deep Inelastic Scattering

- At high energy and momentum transfer in inelastic electron (muon and neutrino) scattering one directly measures the momentum distribution of the quarks



- Polarised electrons also enable the spin of the quarks to be determined

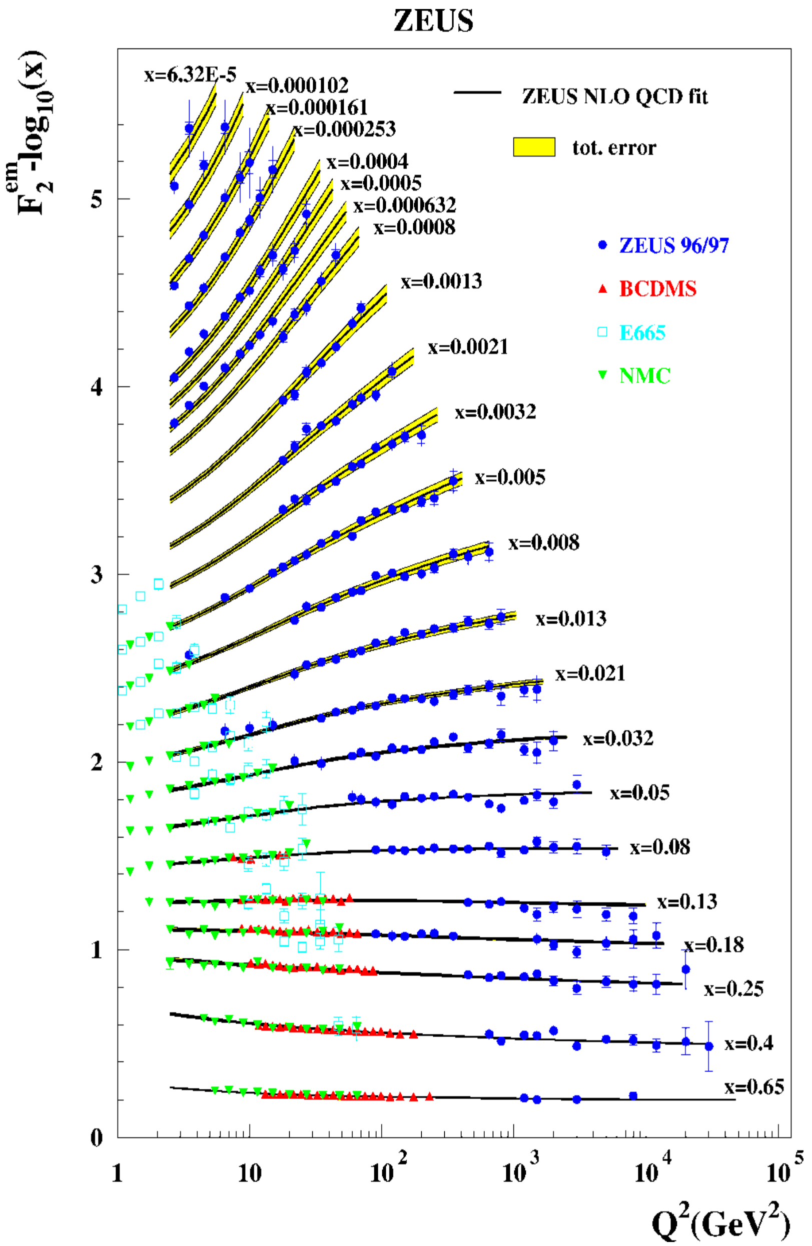
- Later Drell-Yan (quark-anti-quark) annihilation added crucial new information

Unpolarized Structure Function F_2

- **Bjorken Scaling**
- **Scaling Violation**
- **Gluon radiation –**
- **QCD evolution**

  NLO: Next-to-Leading-Order

  …….
- **One of the best experimental tests of perturbative QCD**



SLAC
CERN
FNAL
DESY

Lattice QCD

- **Tremendous step forward by Wilson 1974**

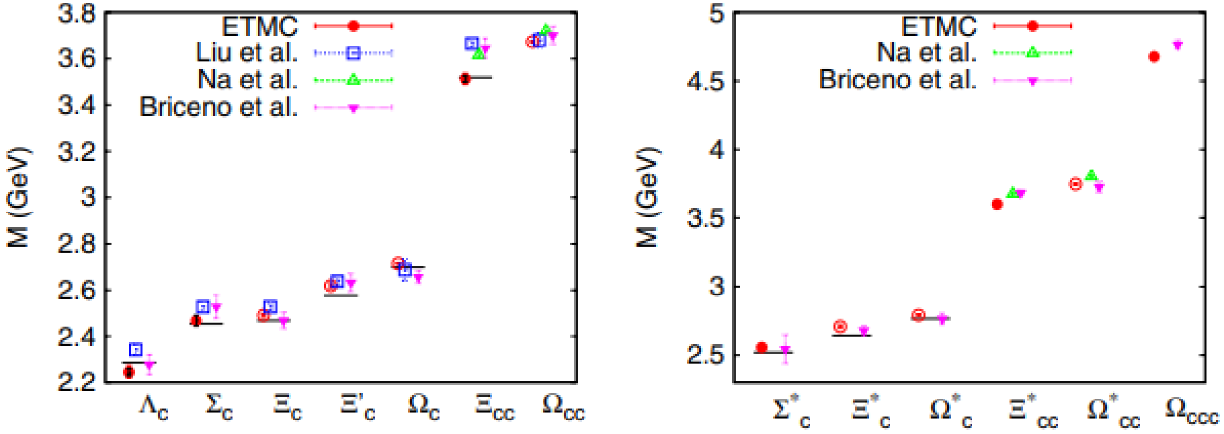
  but computing requirements needed another 30-40 years

- **Personal note:**

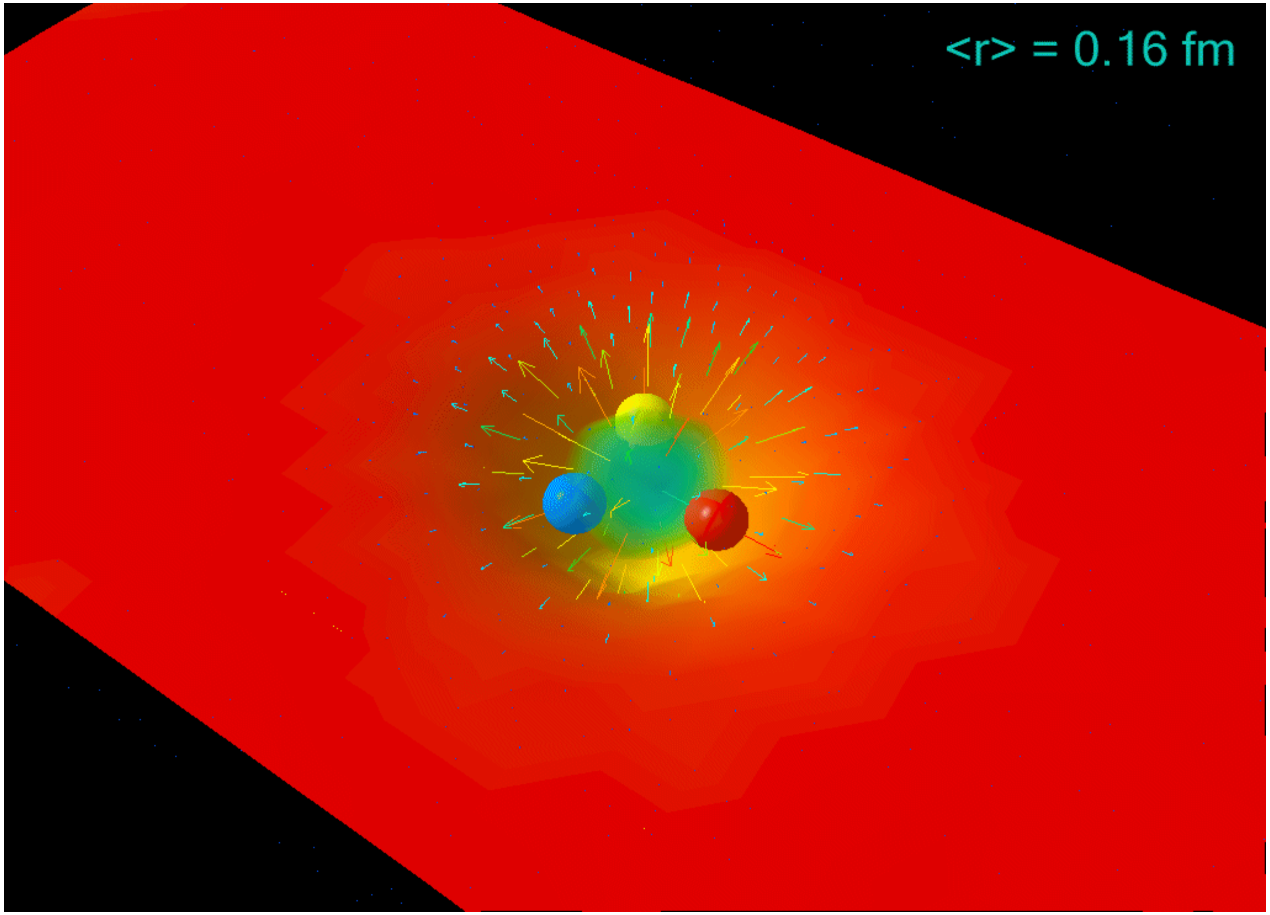
  Sasha Migdal 1975 at CERN

STRANGE AND CHARM BARYON MASSES WITH TWO ...

PHYSICAL REVIEW D **86,** 114501 (2012)



Confinement for infinitely heavy quarks?



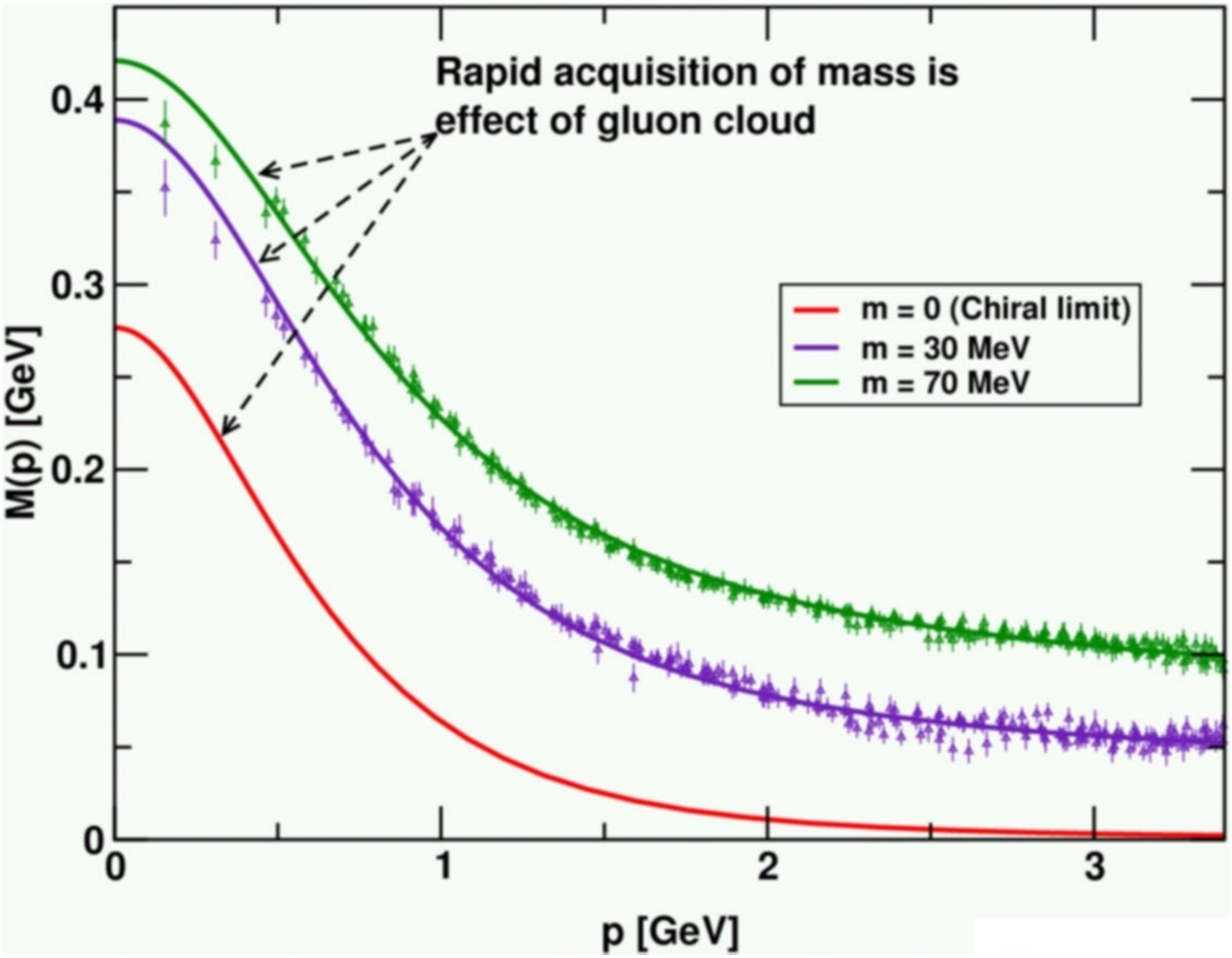
www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/ImprovedOperators/index.html

Chiral Symmetry

Chiral Symmetry

- **Near massless quarks → 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)**

Quark mass function through χSB



From:
2007 US LRP

$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

Lattice studies & Dyson-Schwinger modelling in excellent agreement

− χSB is origin of constituent quark mass

Chiral Symmetry in Context of QCD

- Of course, chiral symmetry was known before QC
- 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

$$\mathscr{L}(x) = (i\bar{q}\not{\partial} q - B)\theta_v - \tfrac{1}{2}\bar{q}e^{i\underset{\sim}{\tau}\cdot\underset{\sim}{\phi}\gamma_5/f}q\delta_s + \tfrac{1}{2}(D_\mu\underset{\sim}{\phi})^2$$

Linearize the theory (proven for R ≥ 0.8 fm)

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

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:

$$\begin{aligned} H_{\mathrm{MIT}} &\simeq P H_{\mathrm{MIT}} P \\ &= \sum_{\alpha} |\,\alpha\rangle m_{\alpha}{}^{(\mathrm{b})}\langle\alpha\,| \end{aligned}$$

Interactions

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

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

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

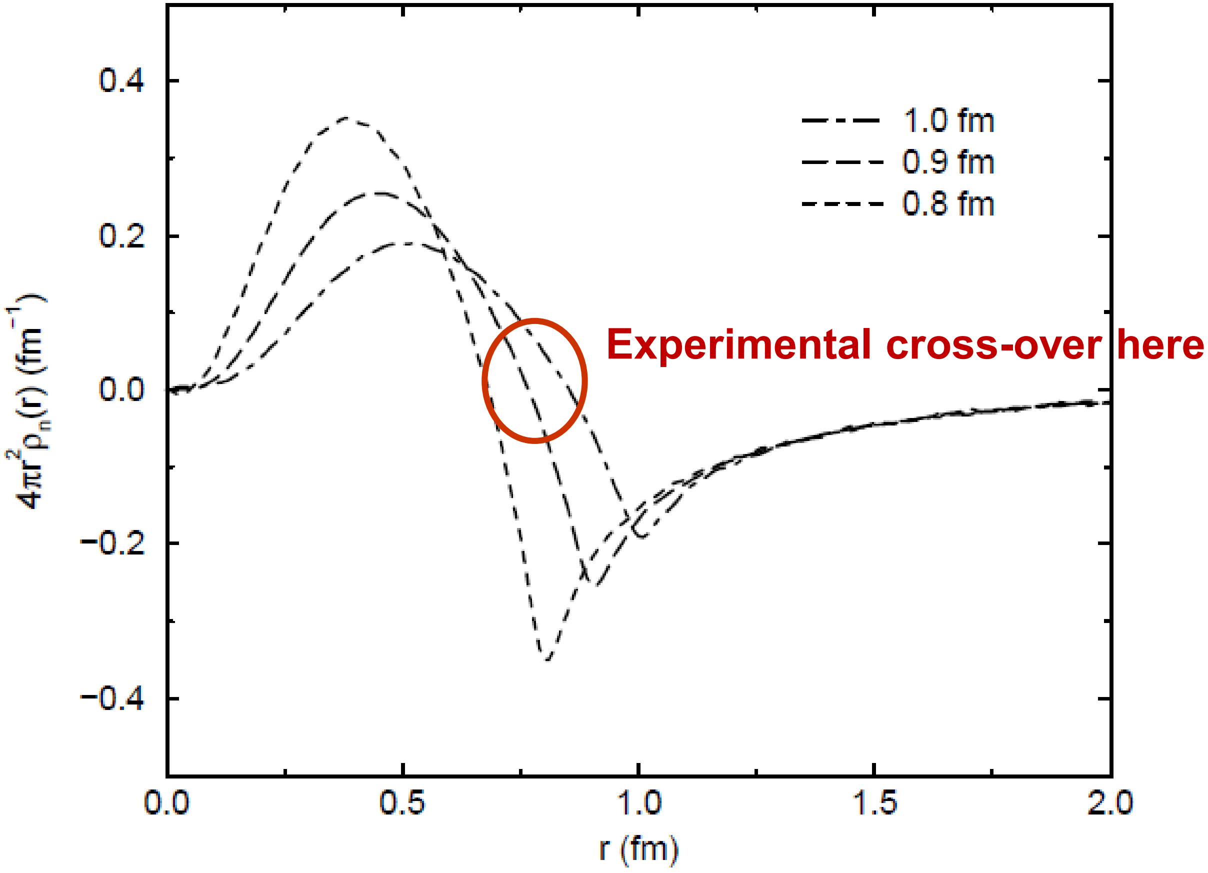
Not projecting onto colorless states is why the chiral quark model of Manohar and Georgi gives incorrect non-analytic behavior

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

e.g. for the nucleon:

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

Neutron Charge Radius: Size of Confinement Region



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

Remarkable Consequences in Chiral Limit

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

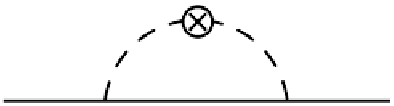
  the charge radius of the proton goes to infinity

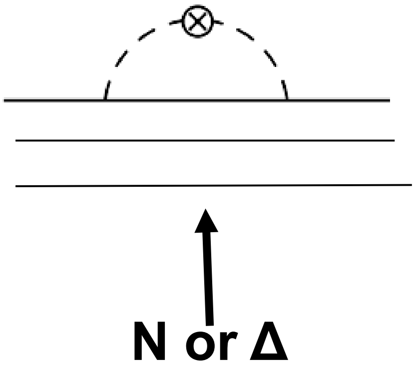
  the charge radius^2 of the neutron to minus infinity

- Both like ln m_π ~ ln m_q

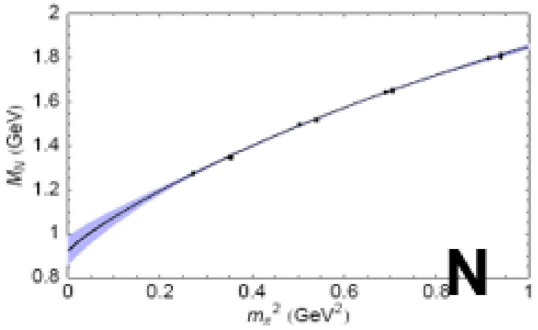
  the magnetic moments behave like $m_\pi \sim m_q^{1/2}$

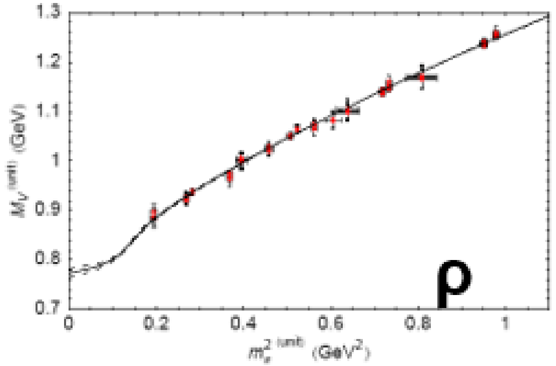
- One <u>cannot</u> describe this correctly in a chiral <u>quark</u> model

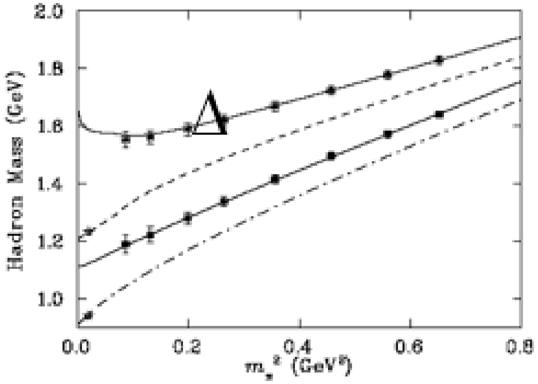


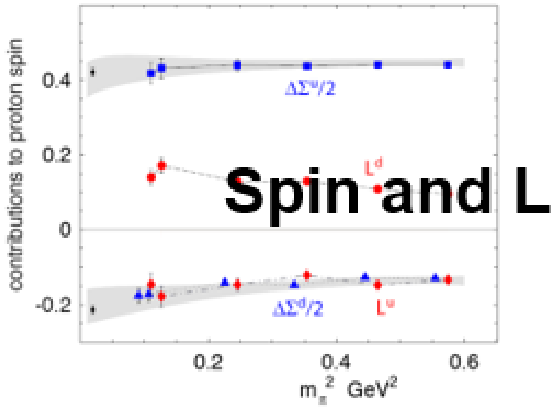


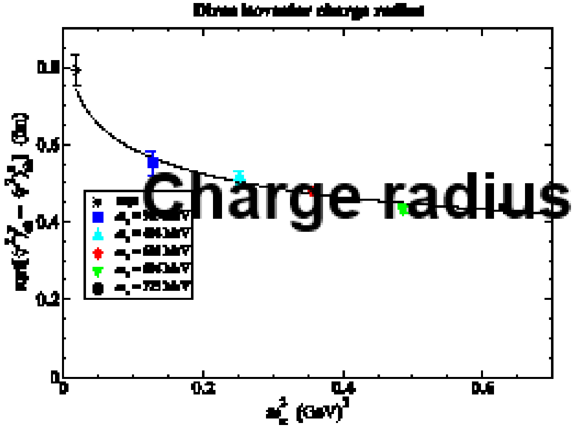
Simplicity: Pion loops suppressed at large quark mass

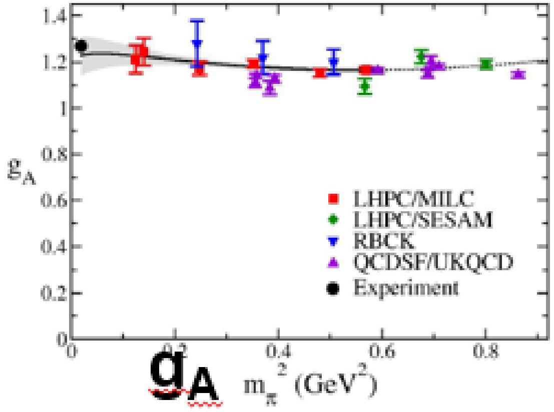


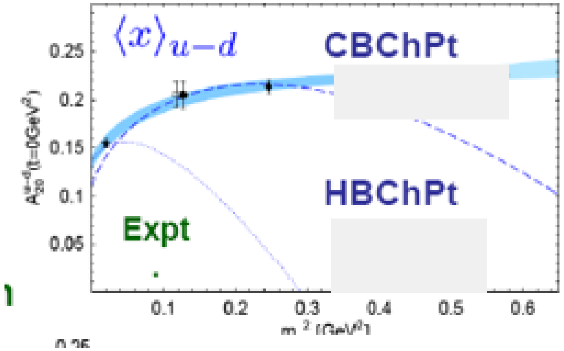












Is it believable that smooth behavior for m_π above 400 MeV is a result of a different accidental cancellation in every case??

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

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**
  - **$m_q \sim 40$ 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**

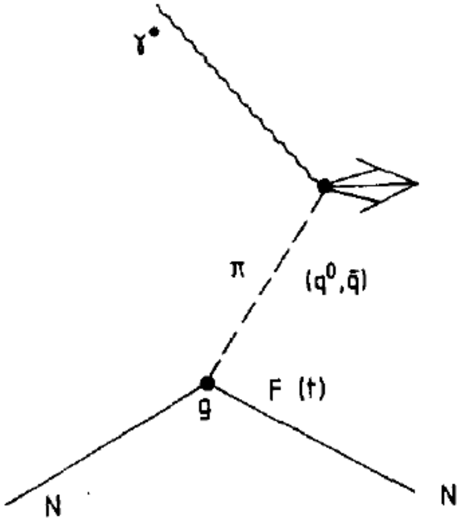
- **But usual χpt methods fail outside power counting region – meson mass above 0.3 GeV**

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."

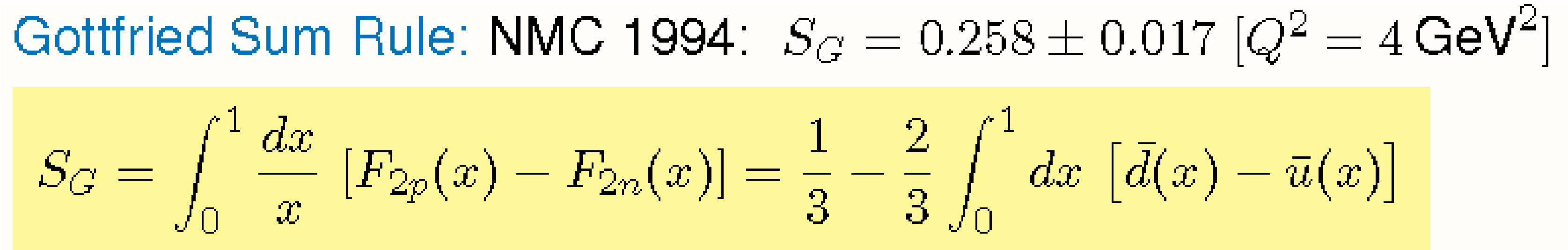
Pion Cloud (cont.)

- 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

- Predicted violation of Gottfried sum-rule not confirmed for 10 years



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

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

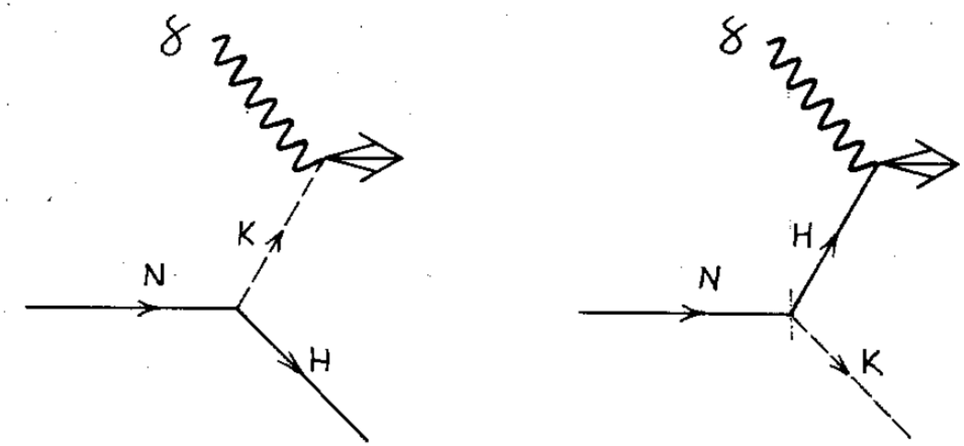
- Consistent with range predicted by the pion cloud....

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

$$\varepsilon\ 0.11 - 0.15$$

Strange Sea of the Nucleon

Similar mechanism for kaons implies $s - \bar{s}$ goes through zero for x of order 0.10



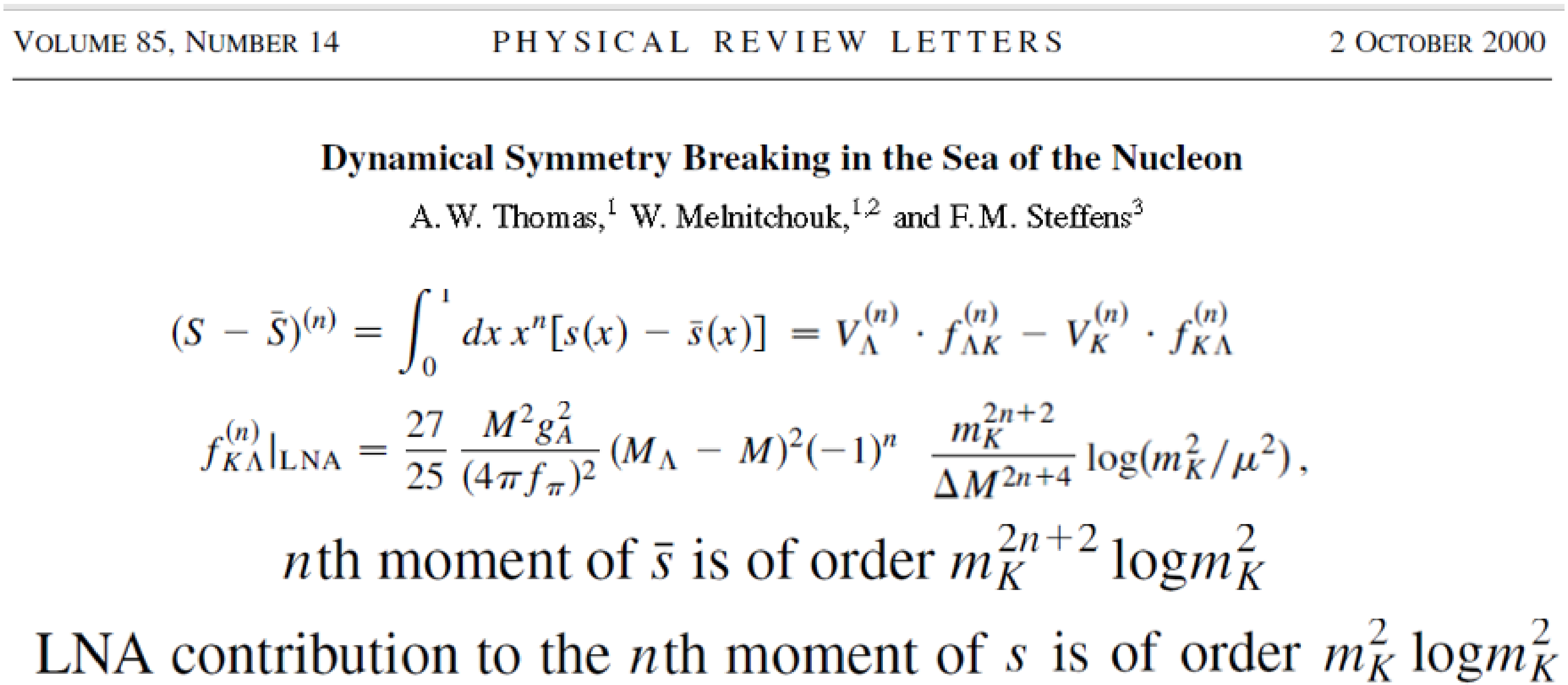
- **Later, naive 5-quark additions often (implicitly) violate parity**

- **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)

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

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 $m_K^{2n+2}\log m_K^2$

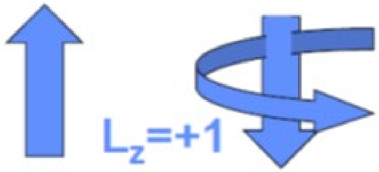
LNA contribution to the nth moment of s is of order $m_K^2\log m_K^2$

- **i.e. Non-analytic behaviour of s and $\bar{\text{s}}$ are different and therefore s – $\bar{\text{s}}$ has to be non-zero as a matter of principle!**

The Spin “Crisis”

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

- Biggest Fock Component is N π ~ 20-25% and 2/3 of the time N spin points down (next biggest is Δ π ~ 5-10%)

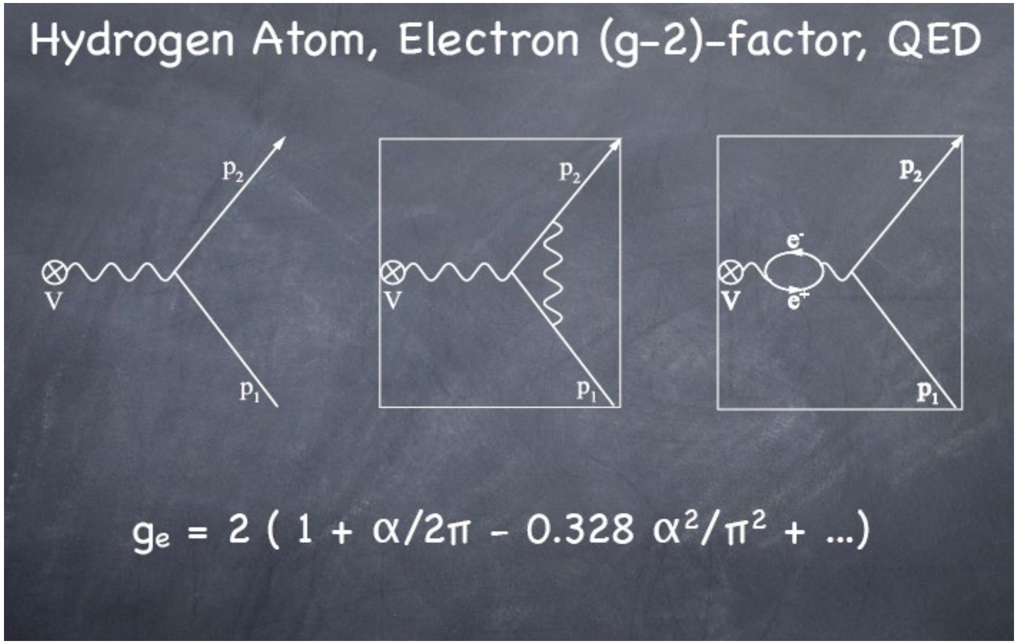


Schreiber-Thomas, Phys Lett B215 (1988)
and Myhrer-Thomas, Phys Lett (1988)

QCD Lamb Shift

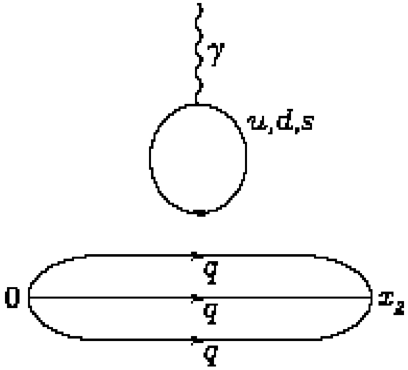
QCD Analogue of the Lamb Shift

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



Hydrogen Atom, Electron (g-2)-factor, QED

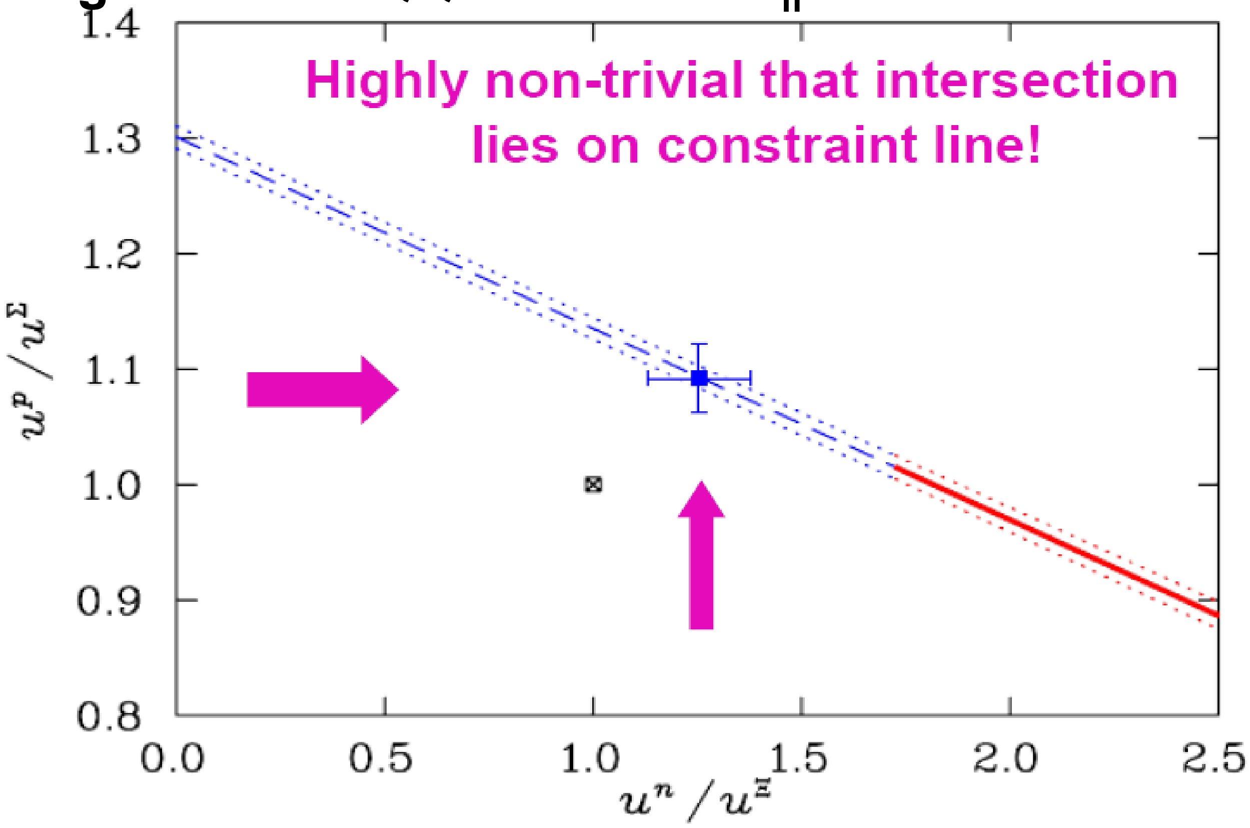
$$g_e = 2\,(\,1 + \alpha/2\pi - 0.328\,\alpha^2/\pi^2 + \ldots)$$



- 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!



Highly non-trivial that intersection lies on constraint line!

1.10±0.03

1.25±0.12

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

Leinweber et al., PRL 94 (2005) 212001

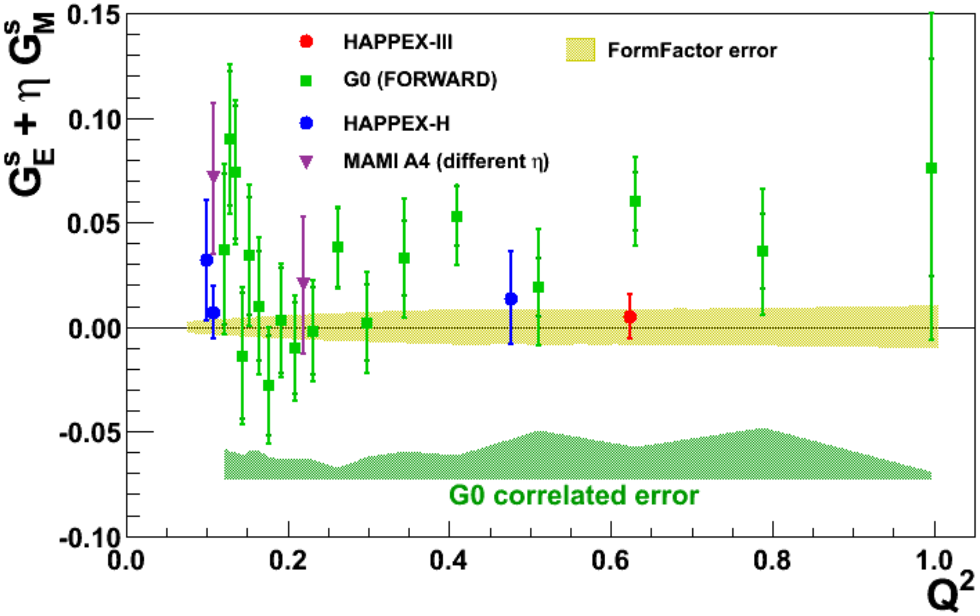
Strange Quarks in the Proton

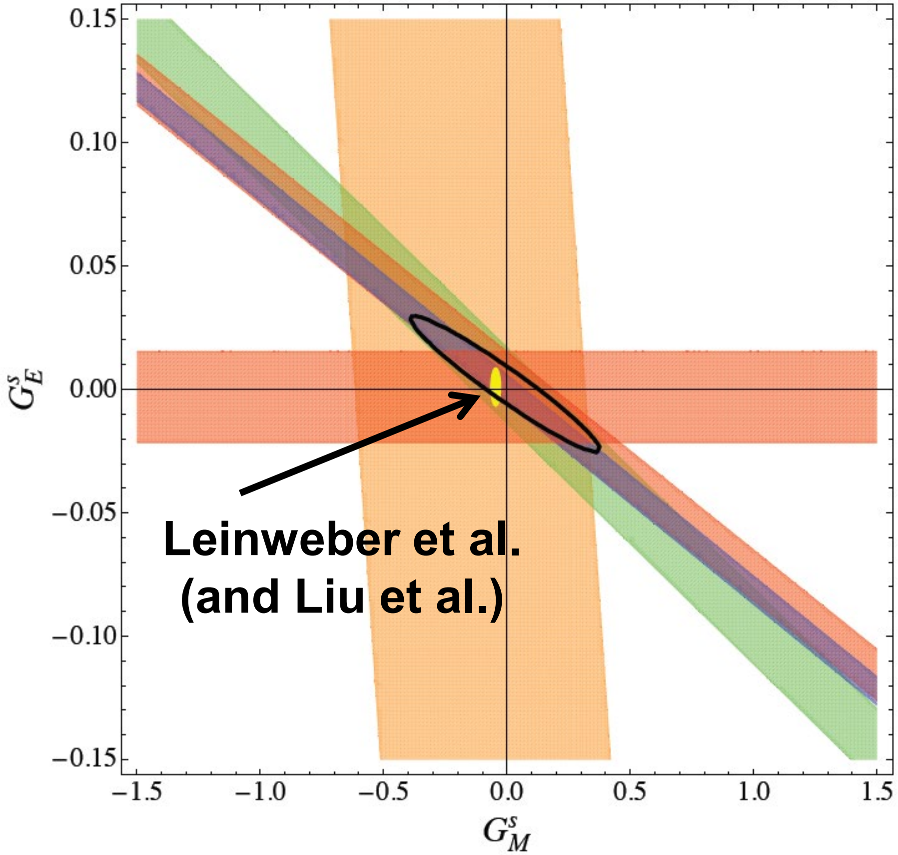
There have been a number of major steps forward in past 20 years, both theory and experiment :

- 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

$Q^2 = 0.1\ \mathrm{GeV}^2$





Leinweber et al.
(and Liu et al.)

- **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 ?

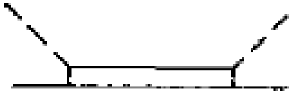
- Lattice QCD provides extremely valuable information

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!

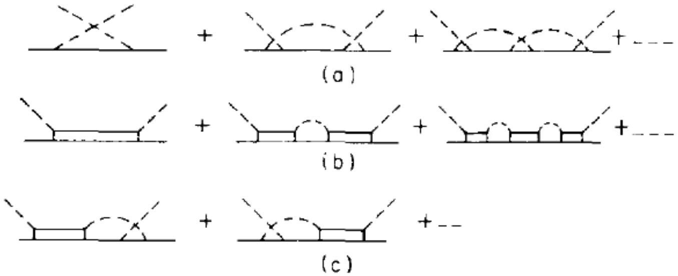
The Chew-Low Model where it is dynamically generated

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 NNπ and ΔNπ vertices

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

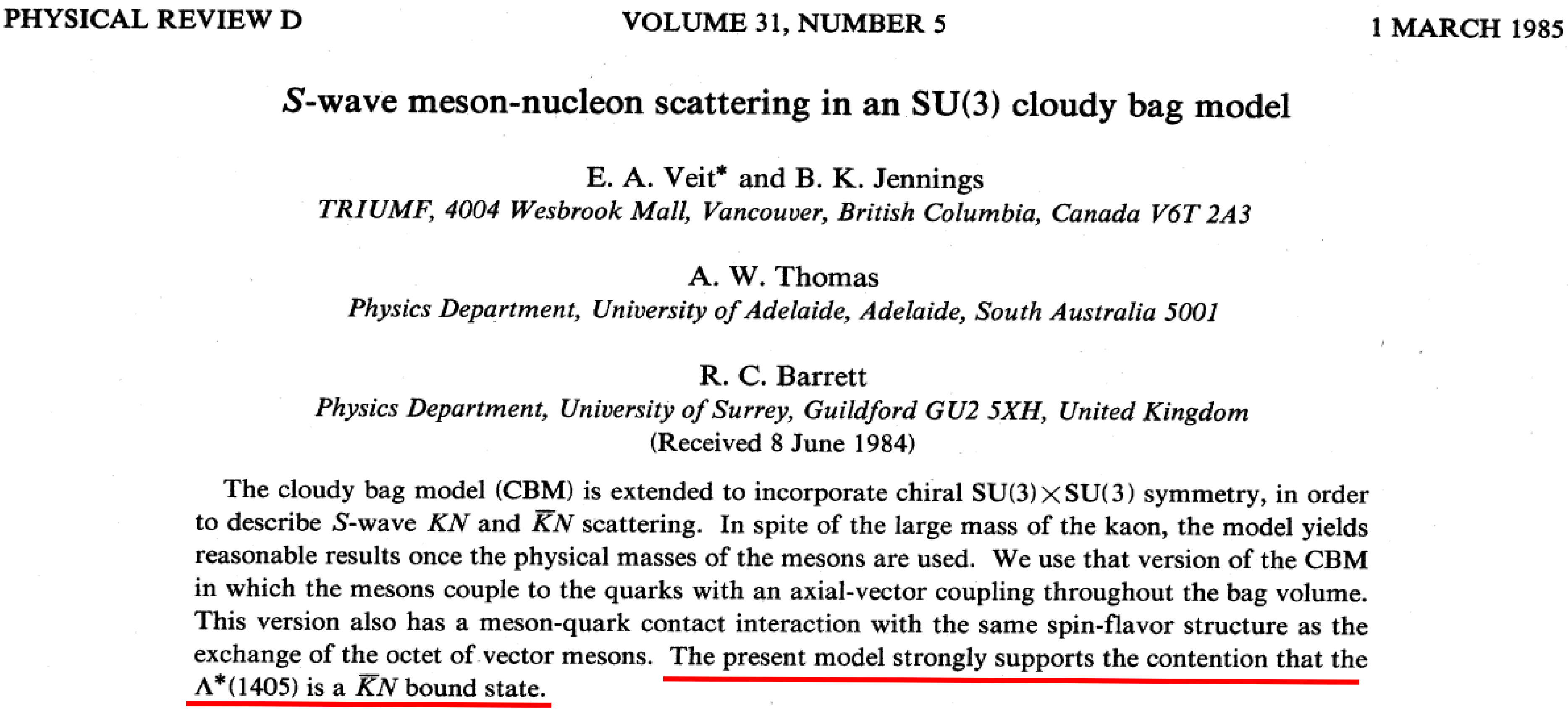


The Λ(1405) : A Clear Anomaly

- **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 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 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

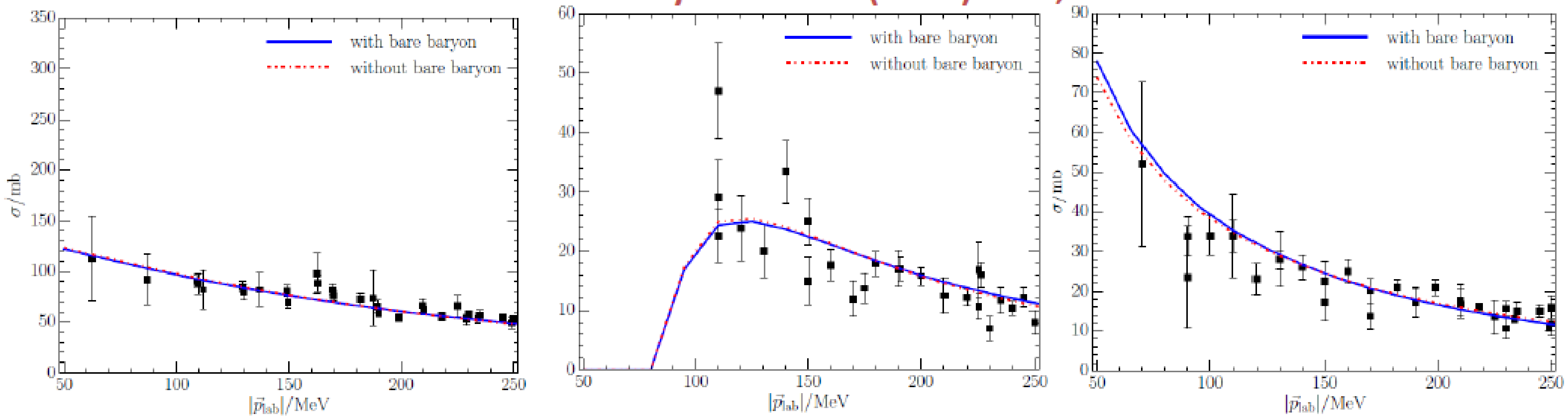
(Received 8 June 1984)

The cloudy bag model (CBM) is extended to incorporate chiral SU(3)×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.

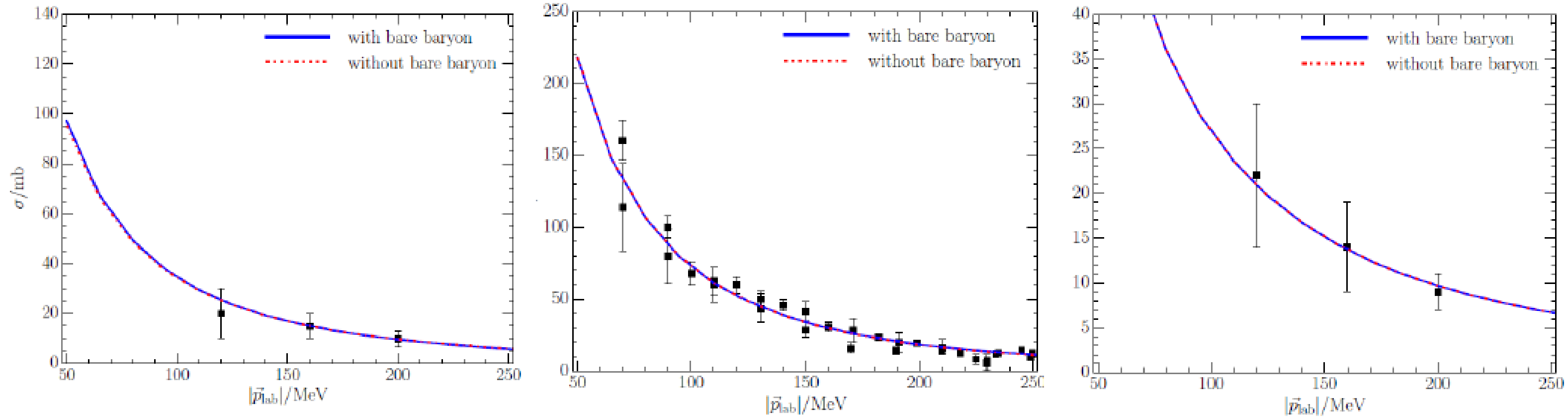
But now we can use QCD itself

Hamiltonian fit to existing data

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



(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) $K^-p \to \pi^0\Lambda$

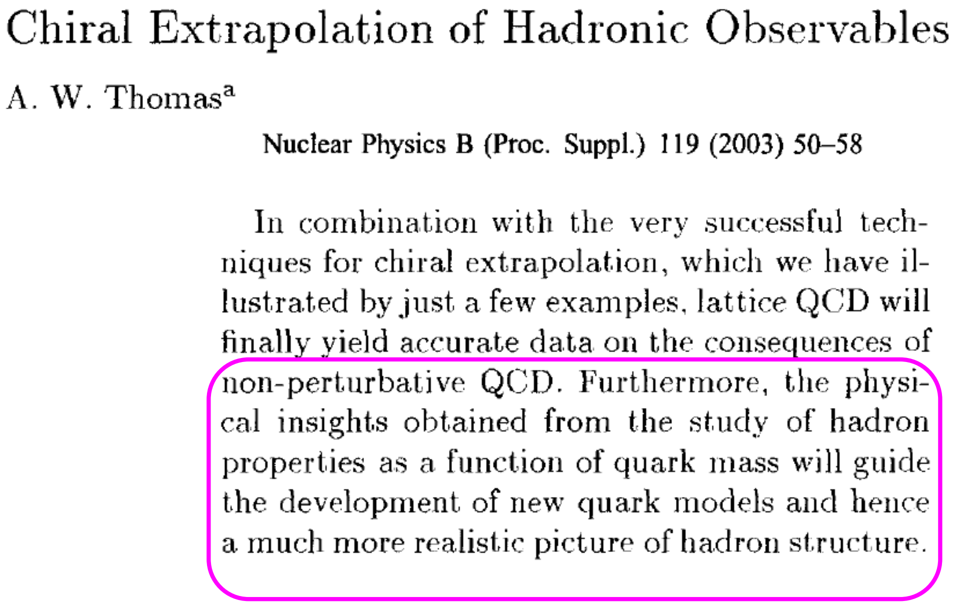
Include πΣ, $\overline{\text{K}}$N, ηΛ and KΞ channels

Similar work by Valencia, Bonn, JLab and other groups

Find the same two-pole structure as other analyses

Note that Lattice QCD allows us to study hadron structure IN QCD as a function of quark mass – a powerful tool

Proceedings Lattice 2002



Chiral Extrapolation of Hadronic Observables

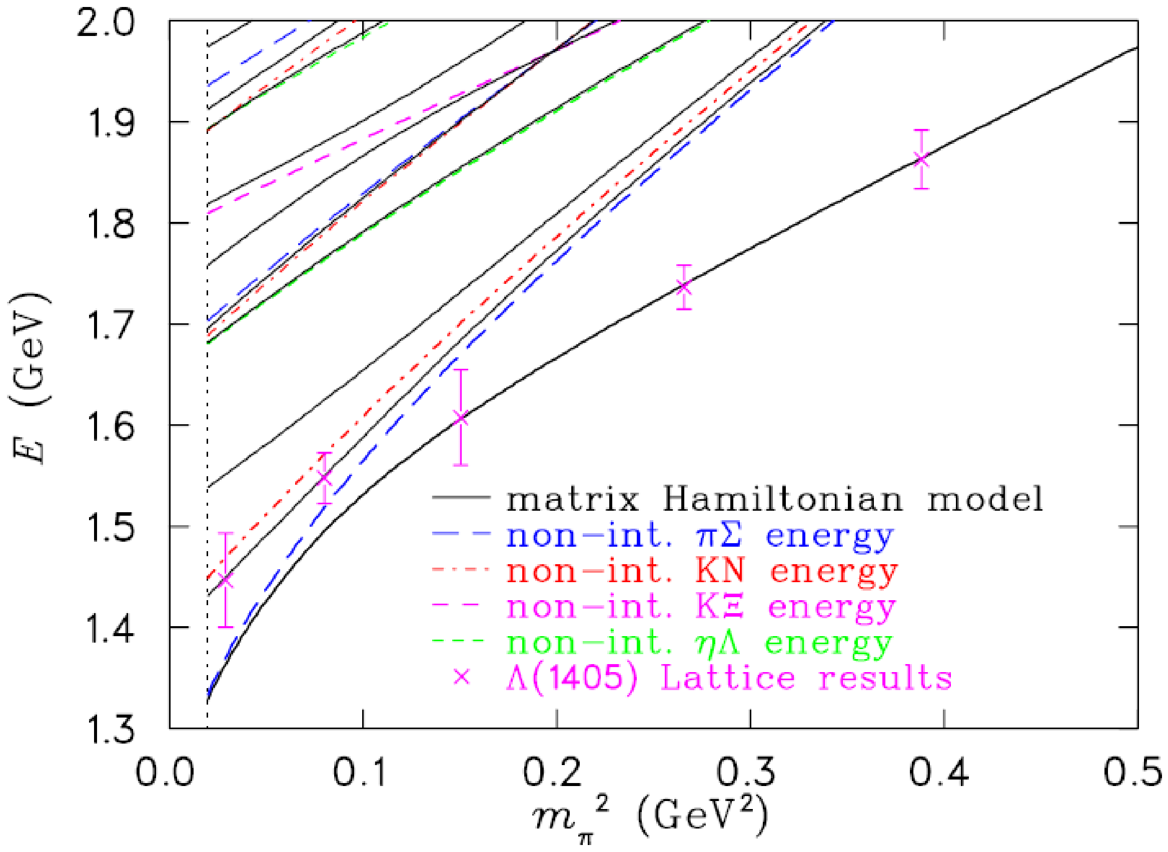
A. W. Thomas[a]

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

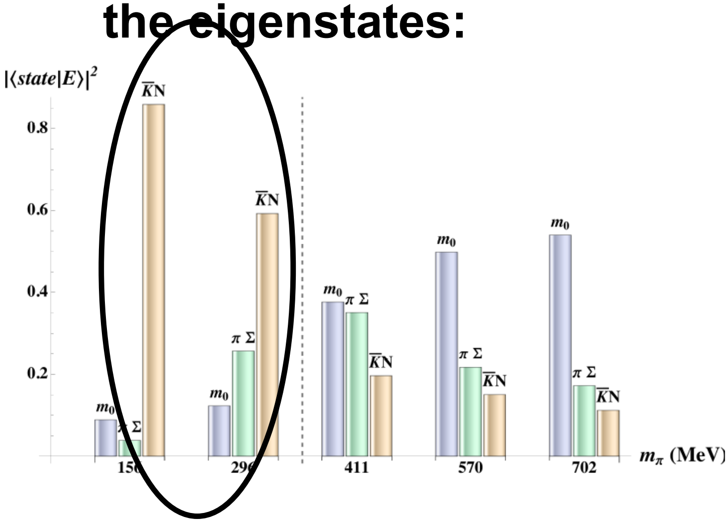
In combination with the very successful techniques for chiral extrapolation, which we have illustrated by just a few examples, lattice QCD will finally yield accurate data on the consequences of non-perturbative QCD. Furthermore, the physical insights obtained from the study of hadron properties as a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

Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state



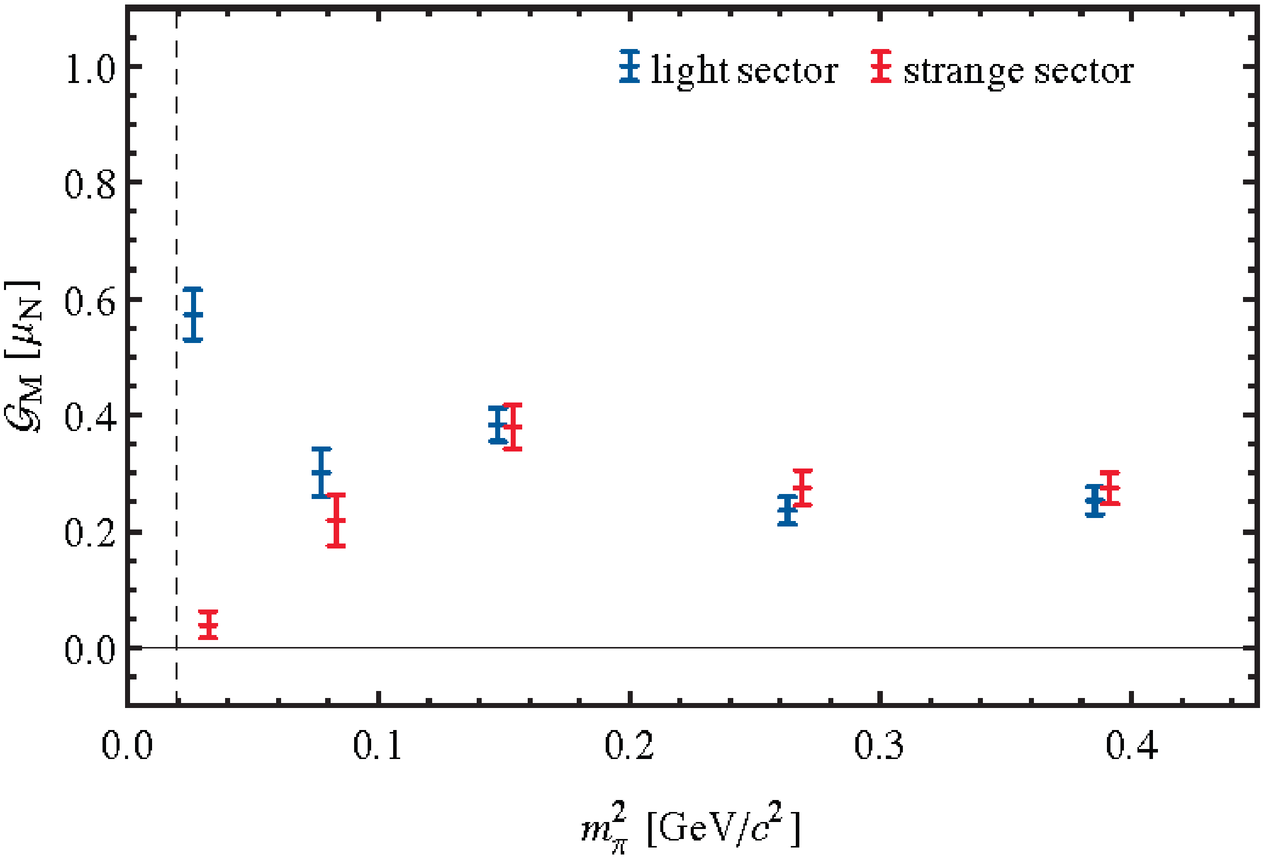
Hamiltonian approach allows one to examine the eigenstates:



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

Lattice Magnetic Form Factor Calculations

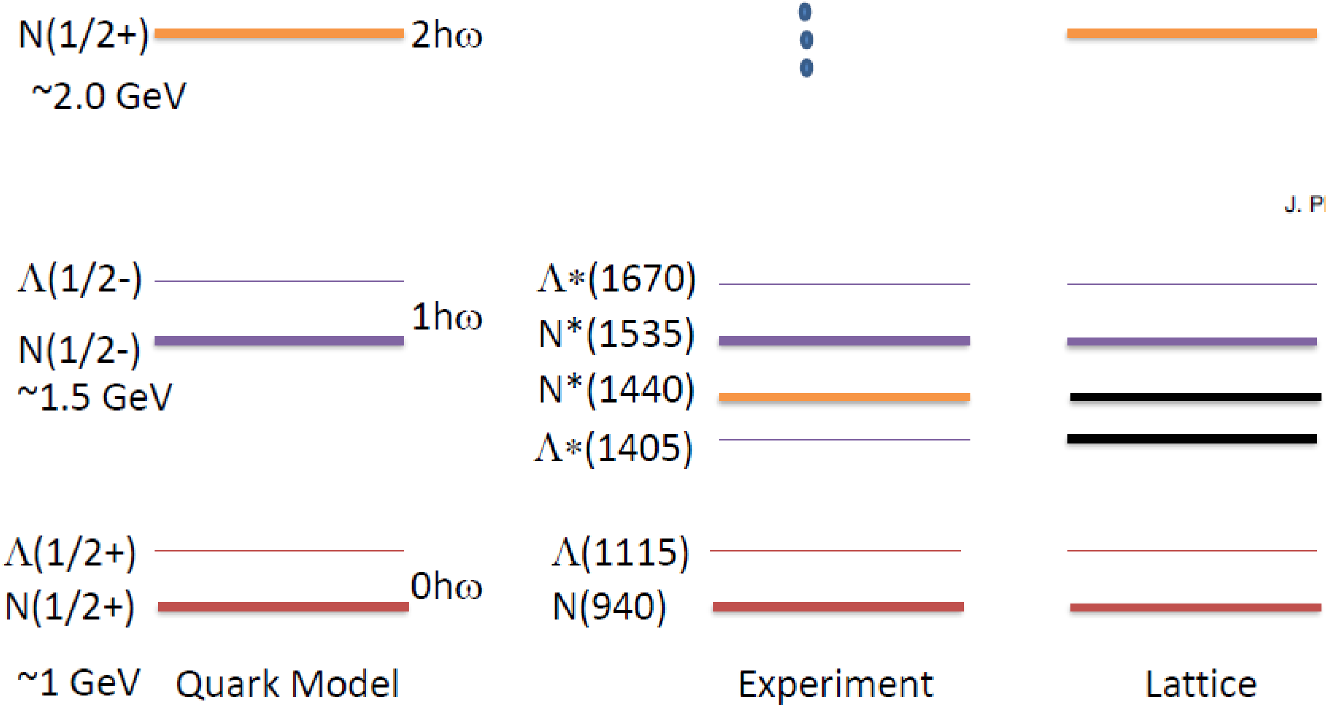
- **Calculation of the individual quark contributions to the magnetic form factor confirms that it is a Kbar-N bound state**

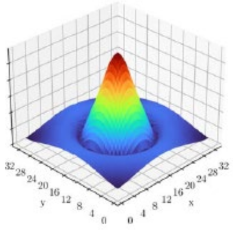


Only an L=0 Kbar-N state gives vanishing strange moment

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

Once the nature of key states becomes clear the quark model makes sense*





J. Phys. G: Nucl. Part. Phys. **51** (2024) 065106

Mainly Dynamical generated states Not in the Quark Model

* Wu *et al.*, 1805.05066

Atomic Nuclei

- **Since the neutron was discovered by Chadwick, nuclei have been built from neutrons and protons, *with exactly the same properties in-medium as outside*, interacting through the exchange of pions and other mesons**

- **BUT is that the whole story?**

- **After all, along came QCD in the 1970s!**

BUT it is widely regarded as irrelevant to nuclear structure............

Quark Structure matters/doesn't matter

- **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning (EIC motivation)**

  OR

- **"Considering quarks is in contrast to our modern understanding of nuclear physics… the basic degrees of freedom of QCD (quarks and gluons) have to be considered only at higher energies. The *energies relevant for nuclear physics are only a few* MeV"**

What do we know?

- Since 1970s: Dispersion relations → intermediate range NN attraction is a strong Lorentz scalar
- In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field on a nucleon ~300 to 500 MeV!!
- *This is not small* – up to half the nucleon mass
  - death of "wrong energy scale" arguments
- Largely cancelled by large vector mean field BUT these have totally different dynamics: ω^0 just shifts energies,
  σ seriously modifies internal hadron dynamics
- Structure of bound nucleons is changed!
  Naturally explains the EMC effect

Suggests a different approach: QMC Model

(Guichon 1988, Guichon, Saito, Tsushima et al., Rodionov et al., Stone - see Saito *et al*., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Guichon *et al*., Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- **Start with quark model (MIT bag/NJL...) for all hadrons**

- **Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks**

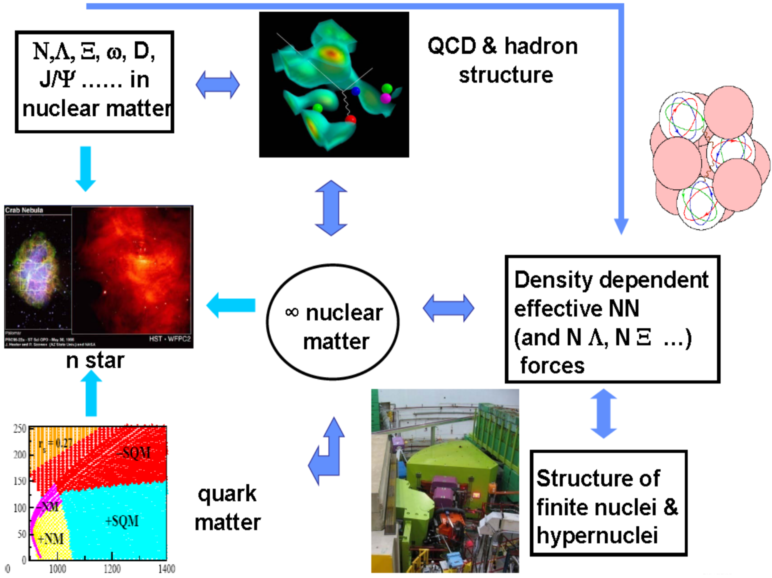
- **Hence, initially only 4 parameters**

  $(m_\sigma , g^{\sigma,\omega,\rho}{}_q)$

  − determine by fitting to:

  ρ_0 , E/A and symmetry energy

  − same in dense matter & finite nuclei



N,Λ, Ξ, ω, D, J/Ψ ...... in nuclear matter

QCD & hadron structure

n star

∞ nuclear matter

Density dependent effective NN (and N Λ, N Ξ ...) forces

quark matter

Structure of finite nuclei & hypernuclei

- **Must solve self-consistently for the internal structure of baryons in-medium: generating many-body forces for all baryons**

Latest Nuclear Structure Results

Includes some unpublished results for QMC π-III from

PhD thesis of Kay Martinez

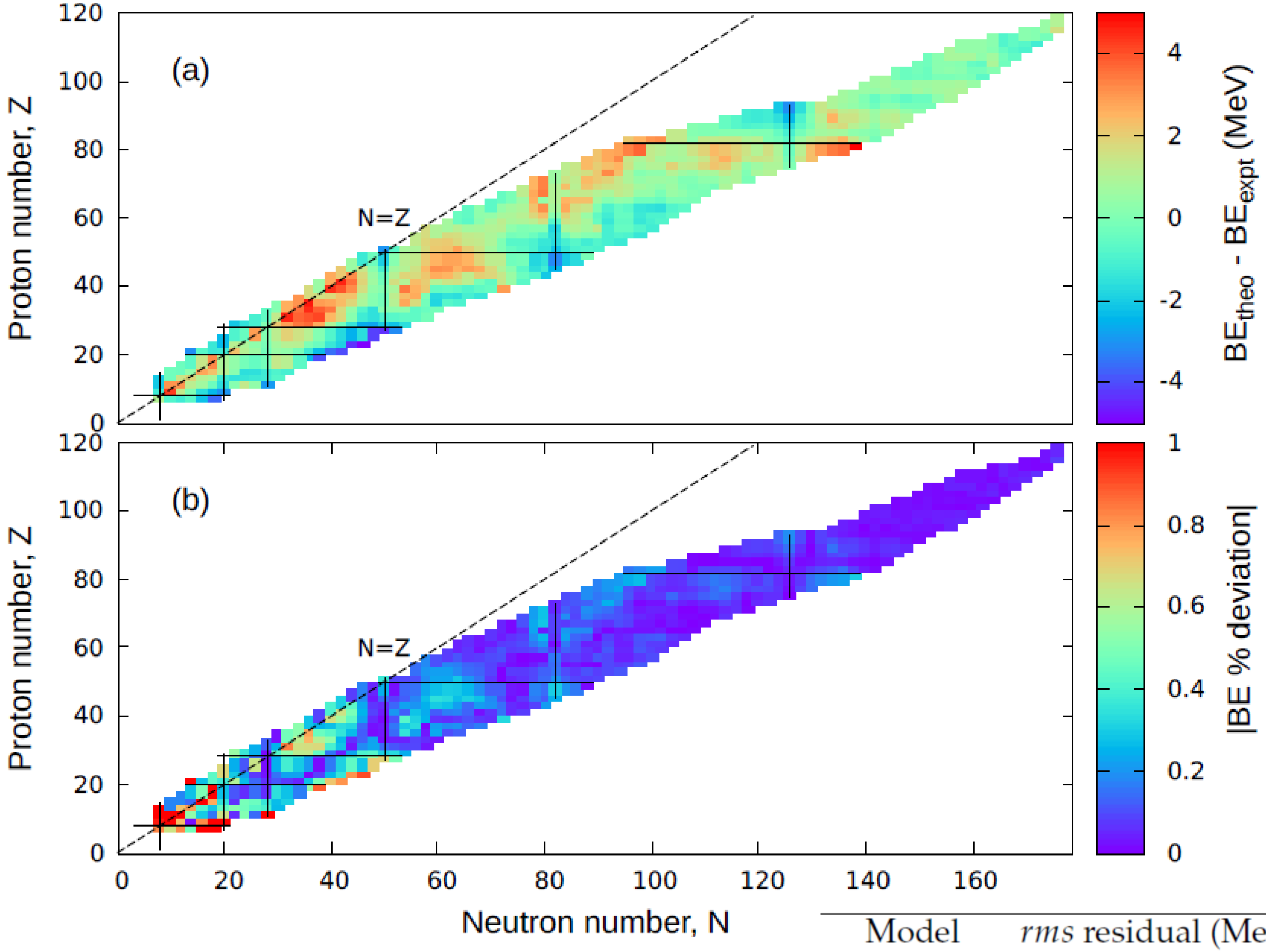
- now at Silliman University (Philippines)
(publications in preparation)

- in collaboration with Pierre Guichon and Jirina Stone

QMC π-II and III incorporate a much more accurate evaluation of H^{σ}

Binding Energies – 820 Known Even-Even Nuclei

2020



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

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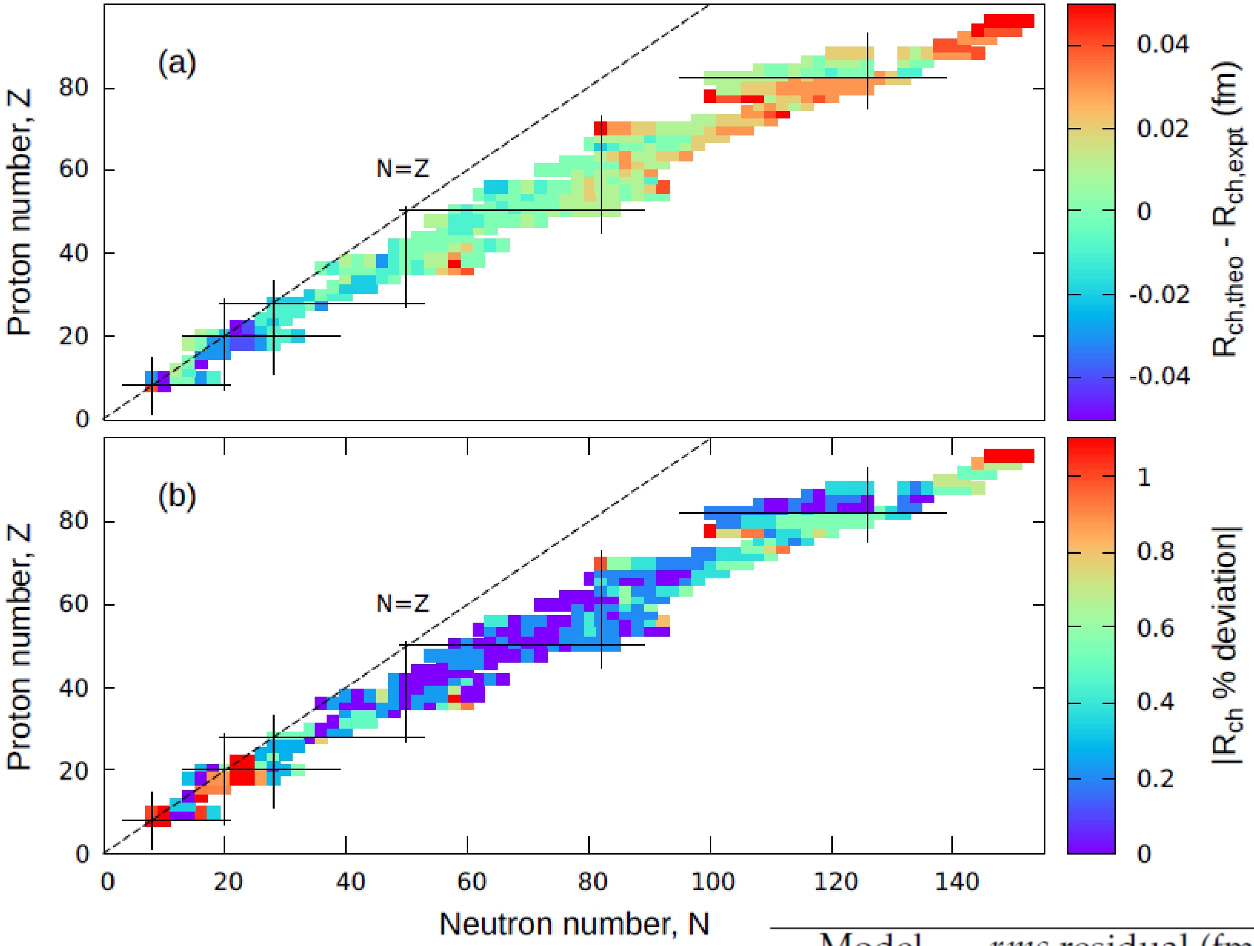
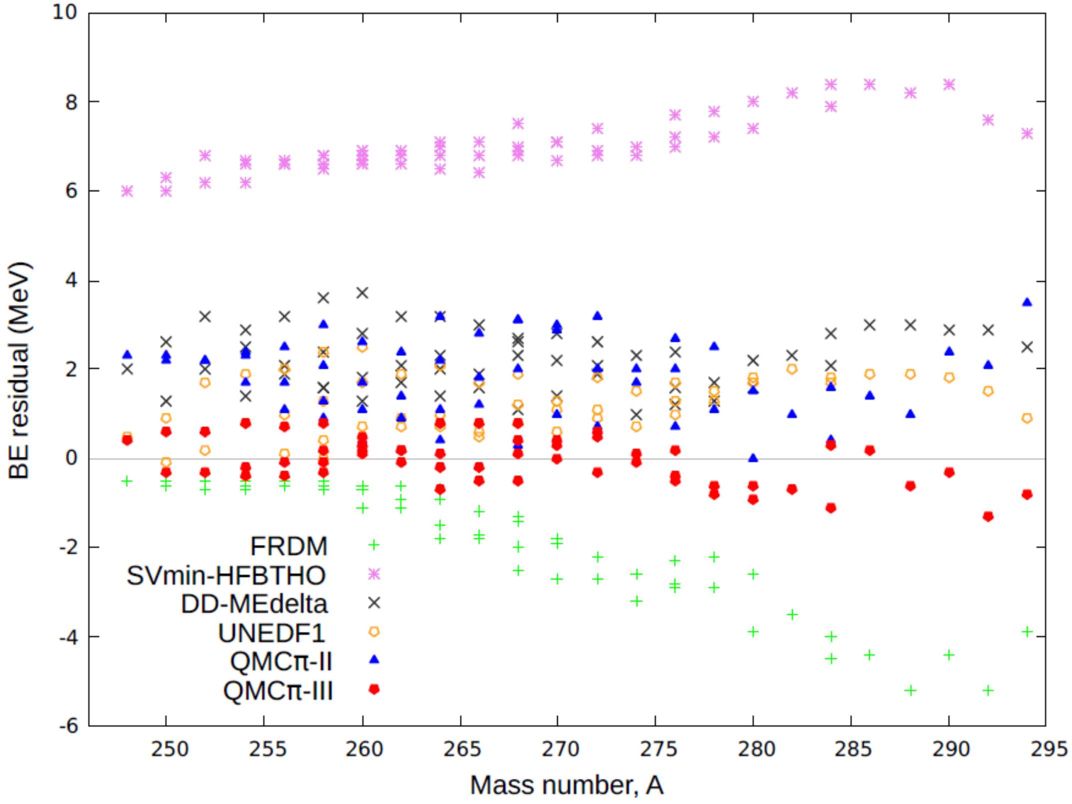
Charge Radii



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

Binding Energies of Superheavy Nuclei

Martinez et al (TBP) and PHYSICAL REVIEW C **100**, 044302 (2019)



	rms % deviation	*rms* residual (MeV)
QMCπ-III	0.03	0.52
QMCπ-II [54]	0.11	2.04
QMCπ-I [53]	0.12	2.42
QMC-I [8]	0.08	1.50
FRDM [23]	0.11	2.25
SV-min [24]	0.36	6.99
UNEDF1 [28]	0.07	1.31
DD-MEδ [66]	0.12	2.28

Outstanding agreement

Neutron Stars

The most dense matter in the Universe

- **Heaviest stars have central densities up to 6-7 times ρ_0**

  What is the EoS?

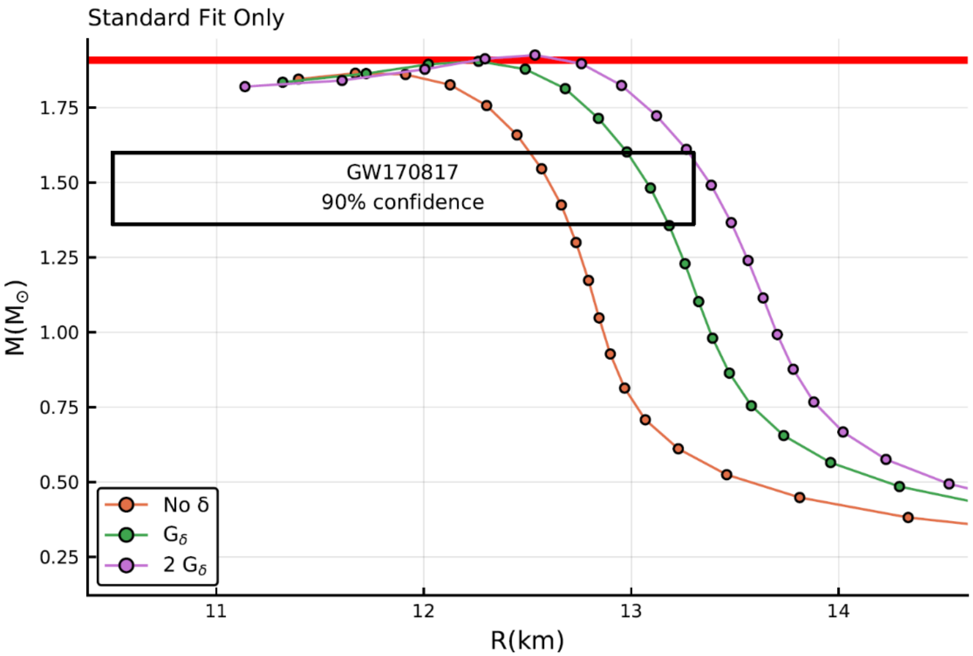
- **Do we have deconfined quark matter?**

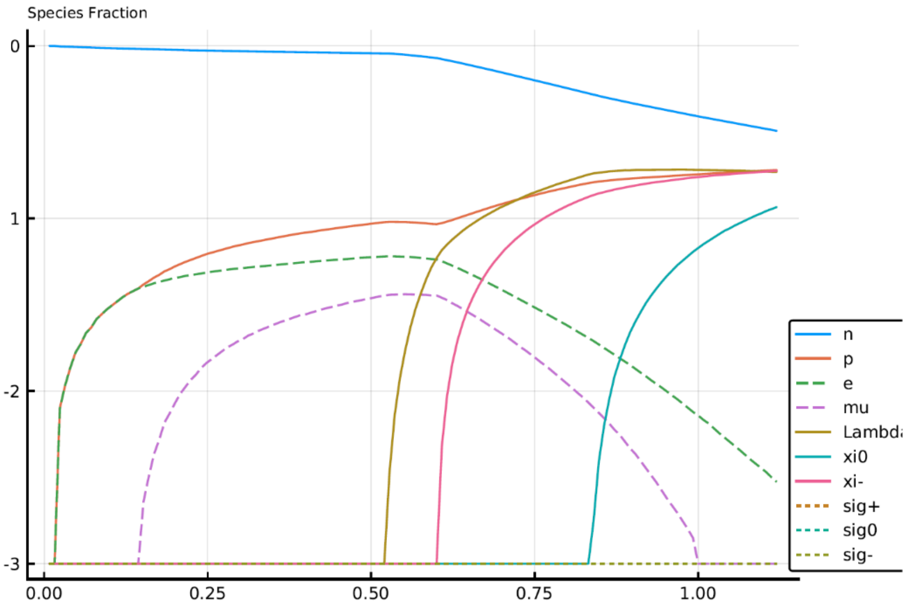
- **Hyperons must play a role in some stars**

  and

- **At present all data (gravitational waves, NICER satellite data etc.) is consistent with purely hadronic matter – including hyperons**

Neutron Stars with hyperons in β-equilibrium



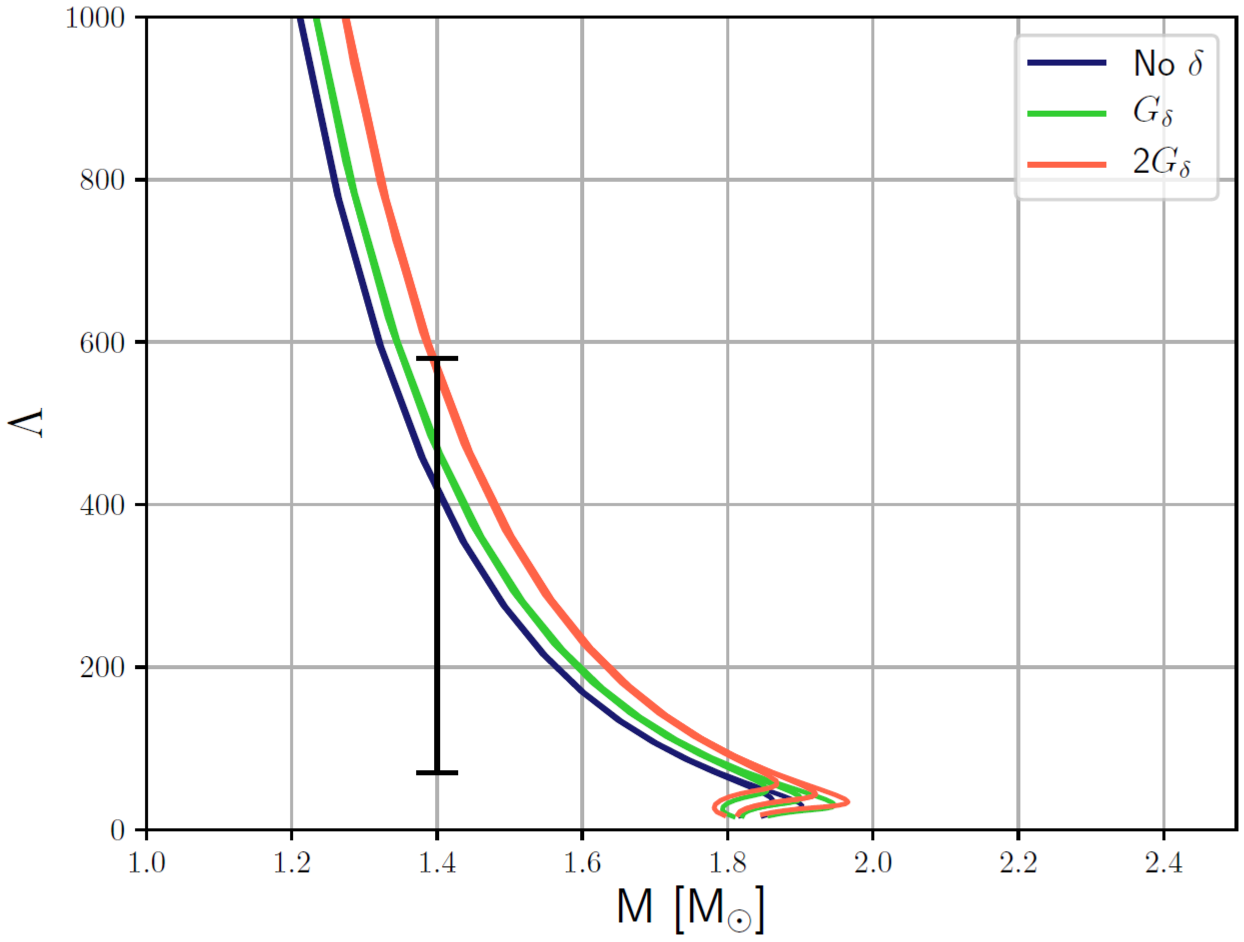


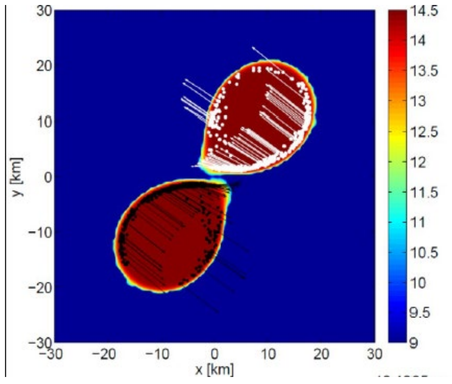
$\mathbf{n_B}$

Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

Tidal deformability

- **Band deduced by LIGO-Virgo analysis of GW170817**

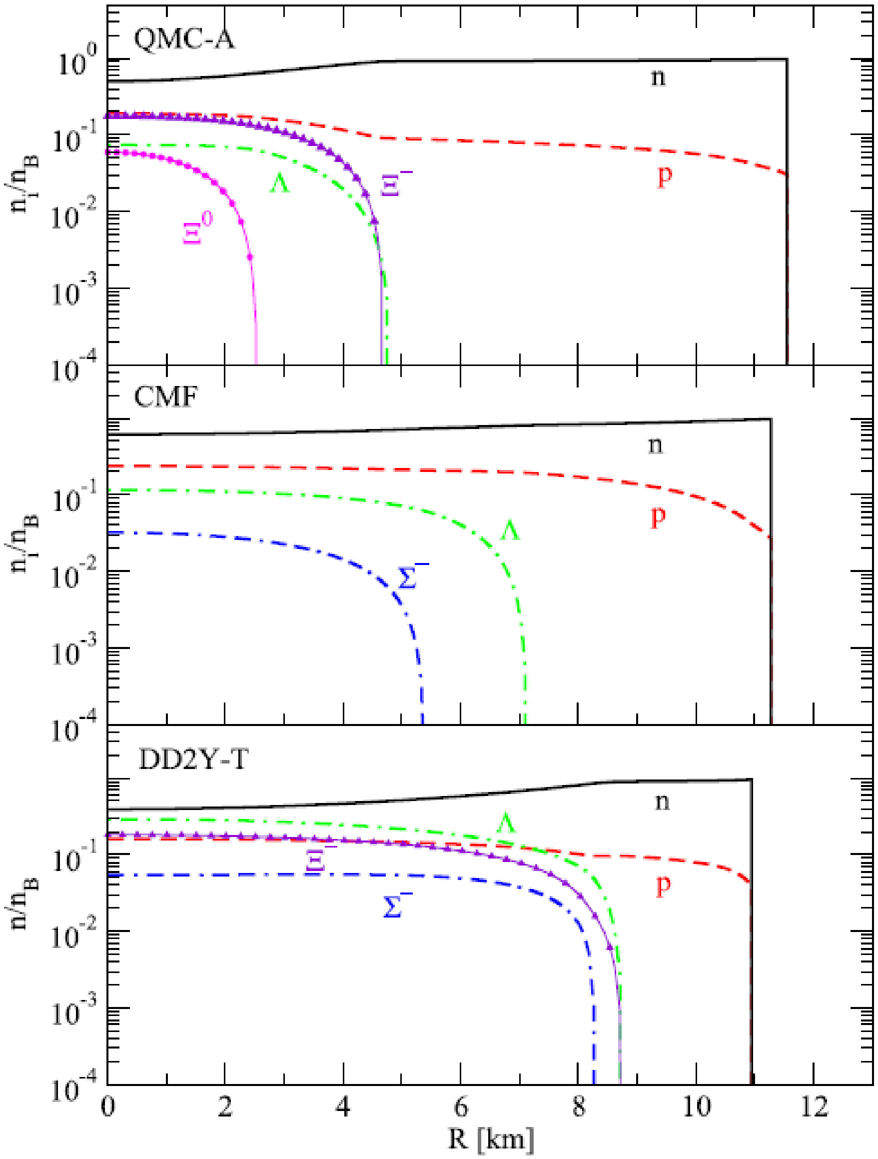




$$Q_{ij} = -\lambda(M)\,E_{ij}$$

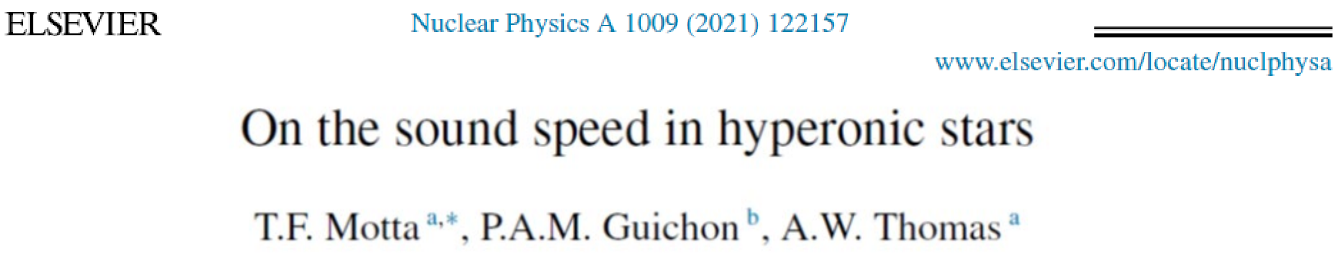
Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

Radial Distribution of Hyperons (T=0)



In heaviest stars

Stone *et al.*, MNRAS **502,** 3476–3490 (2021)



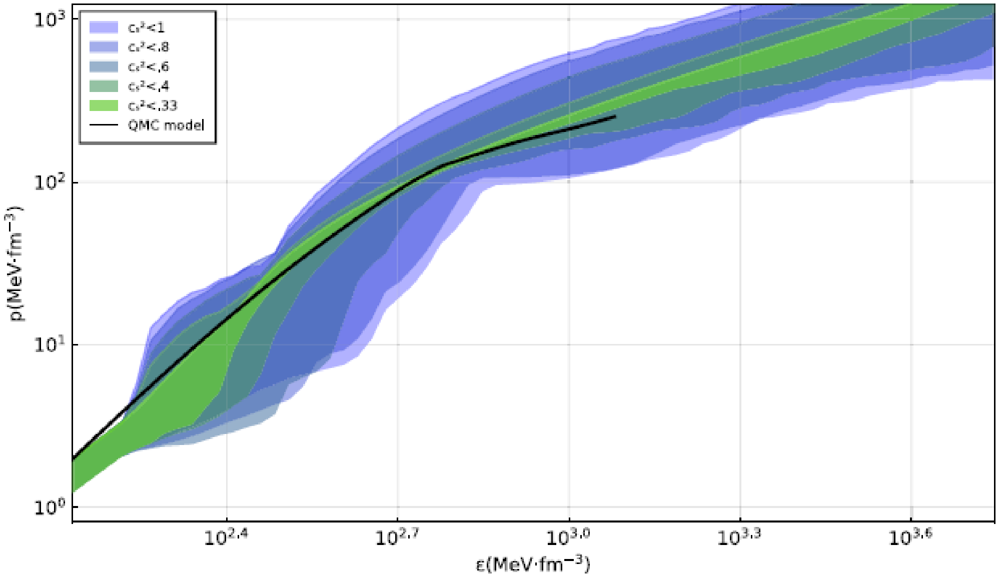
ELSEVIER

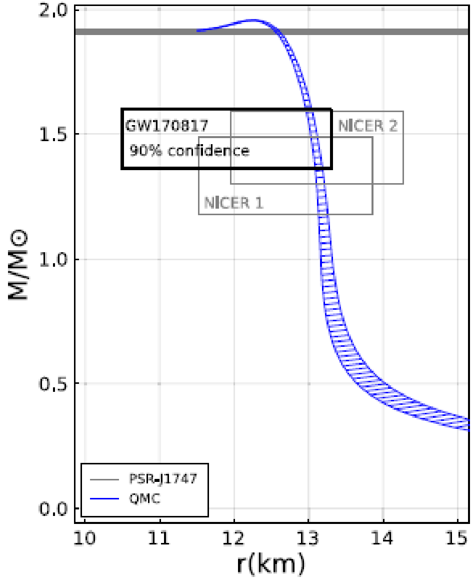
Nuclear Physics A 1009 (2021) 122157

www.elsevier.com/locate/nuclphysa

On the sound speed in hyperonic stars

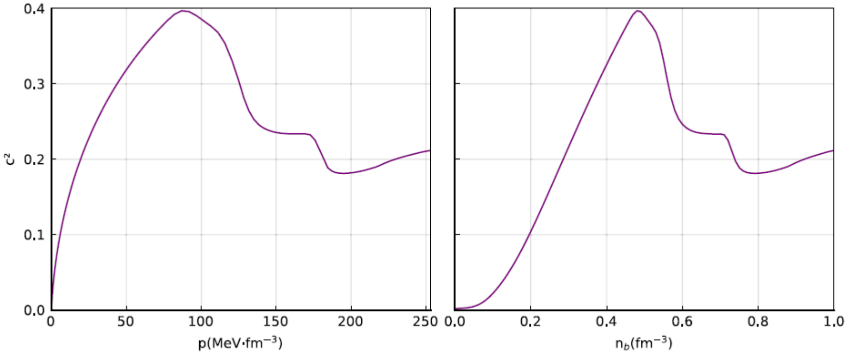
T.F. Motta [a,*], P.A.M. Guichon [b], A.W. Thomas [a]





Follow up on Annala et al., Nature Physics (2020) model independent EoS based on speed of sound interpolation between low and high density

- claim low value implies quark matter



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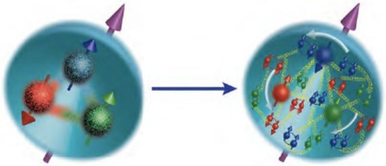
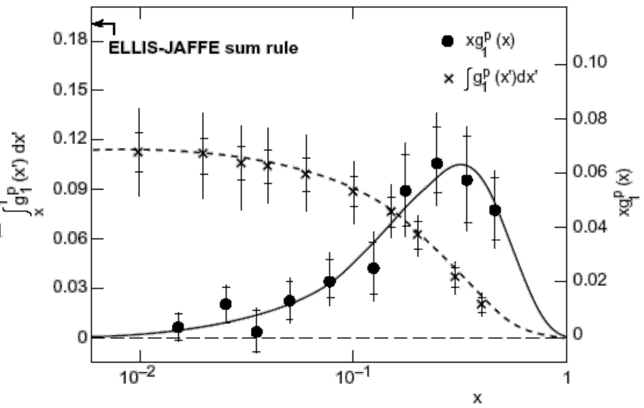
Our challenges

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

The Spin Crisis

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988





A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxford, Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(93 authors)

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range $(0.01 < x < 0.7)$. The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

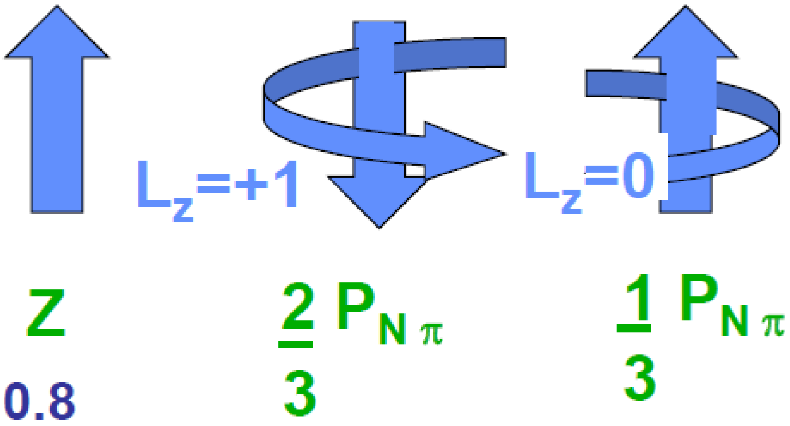
$\Sigma = 14 \pm 3 \pm 10$ % :

i.e. 86% of spin of p NOT carried by its quarks

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%)



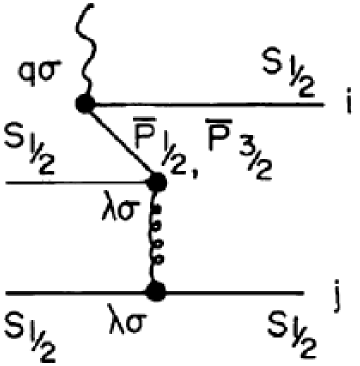
- Spin gets renormalized by a factor :

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

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

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

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



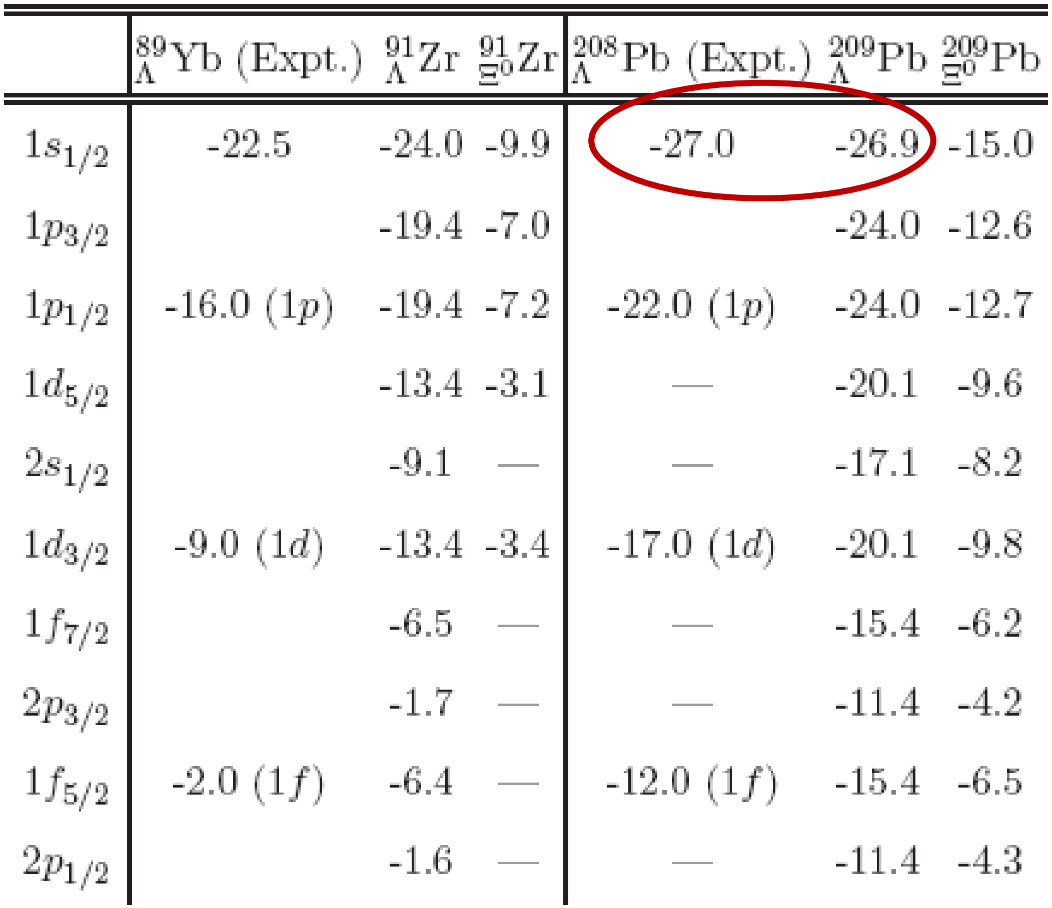
Schreiber-Thomas, Phys Lett B215 (1988)
and Myhrer-Thomas, Phys Lett (1988)

Hypernuclei

No new parameters as σ, ω and ρ
mesons do not couple to the strange quark.

One could add extra mesons with more
free parameters but let's see what we find…..

Λ- and Ξ-Hypernuclei in QMC



	$^{89}_{\Lambda}$Yb (Expt.)	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb (Expt.)	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-22.5	-24.0	-9.9	-27.0	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.0 ($1p$)	-19.4	-7.2	-22.0 ($1p$)	-24.0	-12.7
$1d_{5/2}$		-13.4	-3.1	—	-20.1	-9.6
$2s_{1/2}$		-9.1	—	—	-17.1	-8.2
$1d_{3/2}$	-9.0 ($1d$)	-13.4	-3.4	-17.0 ($1d$)	-20.1	-9.8
$1f_{7/2}$		-6.5	—	—	-15.4	-6.2
$2p_{3/2}$		-1.7	—	—	-11.4	-4.2
$1f_{5/2}$	-2.0 ($1f$)	-6.4	—	-12.0 ($1f$)	-15.4	-6.5
$2p_{1/2}$		-1.6	—	—	-11.4	-4.3

Also predicts Ξ – hypernuclei bound by 5-15 MeV − being tested at J-PARC

"The first evidence of a bound state of Ξ^{-} ^{14}N system",
K. Nakazawa et al.,
Prog. Theor. Exp. Phys. (2015)

Guichon *et al*., Nucl.Phys. A814 (2008) 66; see also 1998

Finite Temperature

As we have heard at this meeting (e.g. Perego and Kochankovski) after BNS mergers the temperature in time-frame relevant to Gravitational Waves is 10-100 MeV

The composition is then very different from a cold star

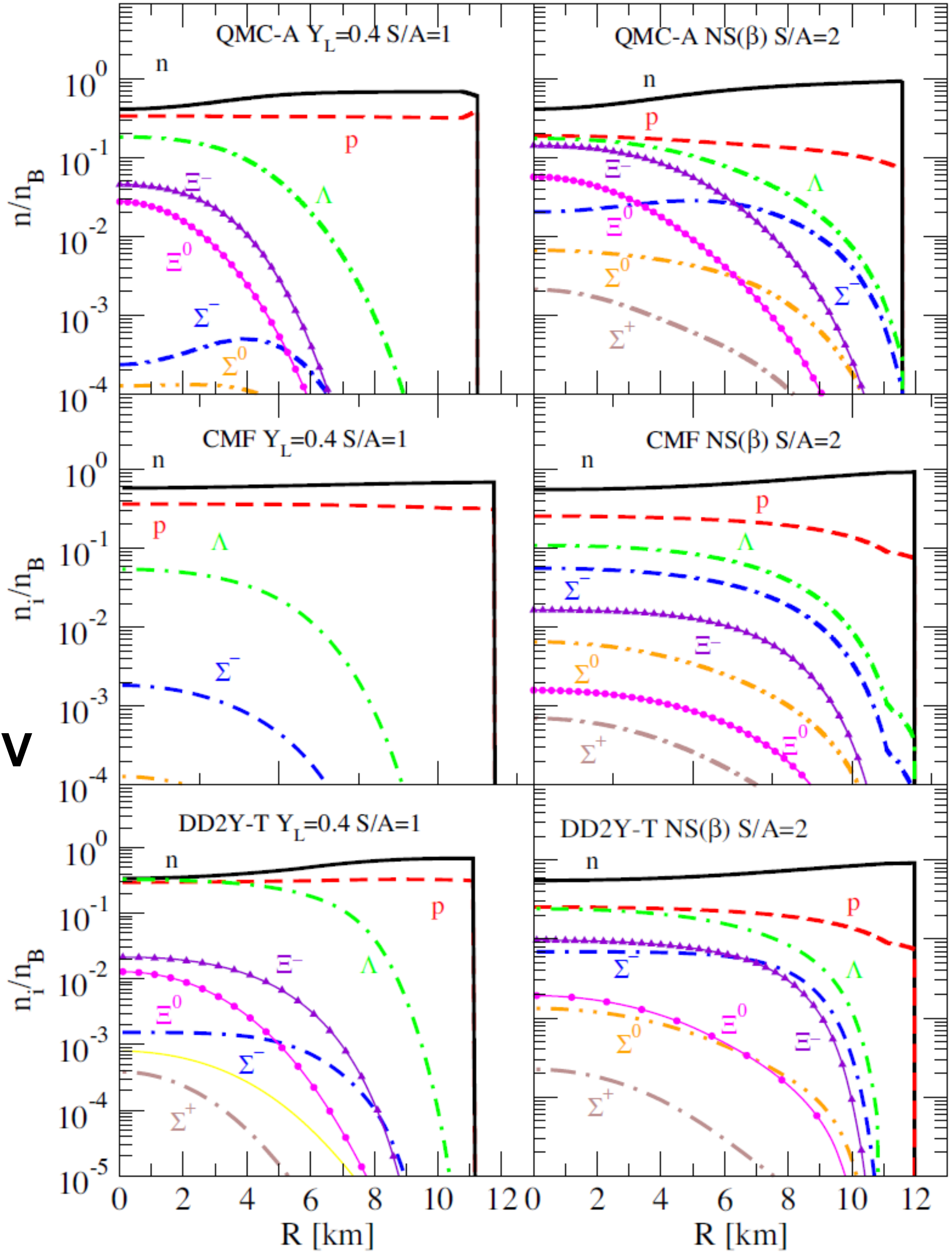
For example, Σ hyperons which play no role in QMC at T=0 because of the enhancement of the color hyperfine repulsion play an important role

See:

Stone *et al*., MNRAS **502**, 3476–3490 (2021)

Hyperon content at finite Temperature

T = 10-20 MeV



T = 20-40 MeV