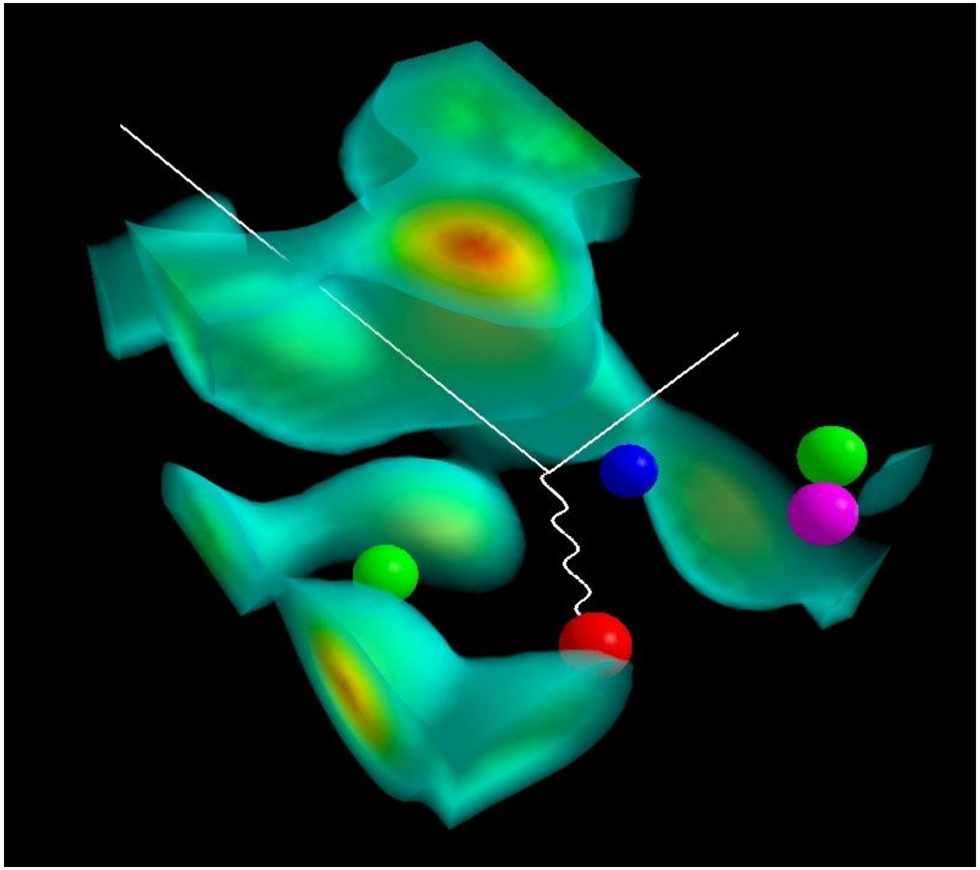
A Vision of Hadronic Physics



ARC Centre of Excellence for Particle Physics at the Terascale

Australian Government

Australian Research Council

Anthony W. Thomas

IFT São Paulo – May 12th 2014

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

My "Vision"

- **What (physics) makes it worthwhile to get out of bed in the morning?**

- ***Our capacity to win new physical insight into how Nature works***

- **My vision for the next decade is that we will *develop a clearer and more satisfying picture of the structure of hadrons and nuclei within the framework of* QCD**

- **Not just new data or higher precision calculations but *new physical insight/understanding* – for which *models* are critical**

Models

- **For some the word "model" is almost an obscenity**
  - **they are *wrong !***

- **Just a few examples of insights that have guided/should guide later work:**

  - **spin-flavour structure of PDFs: diquarks 1970s & 80s**
  - **$\bar{d} > \bar{u}$: CBM 1983**
  - **$\bar{s} \neq s$: CBM 1987**
  - **quark spin $\longrightarrow$ pion and anti-quark orbital angular momentum : CBM 1988**
  - **$\Delta \bar{u} > 0$ and $\Delta \bar{d} < 0$: MIT bag 1991**
  - **charge symmetry violation in PDFs: bag model 1993**
  - **flavour dependence of nuclear structure functions: NJL model 2009**
  - **20% SU(3) breaking in g_A^8 ; Δs small: CBM 2010**

etc.....

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Outline

• QCD and Hadronic Physics
− confinement
& chiral symmetry breaking

• Spectroscopy – especially the interpretation of lattice data

• Electromagnetic form factors : μH; G_E / G_M ; strangeness …

• Structure functions: d/u; proton spin; flavour structure

• *GPDs and TMDs*

QCD within the Standard Model

- **Standard Model is complete with Higgs discovery**

- **Built upon local gauge symmetries**

- **Strong sector is *unique* – fundamental degrees of freedom (*dof*) do not exist outside hadrons!**
  − despite searching everywhere, including moon rocks, deep ocean sediments, cosmic rays....

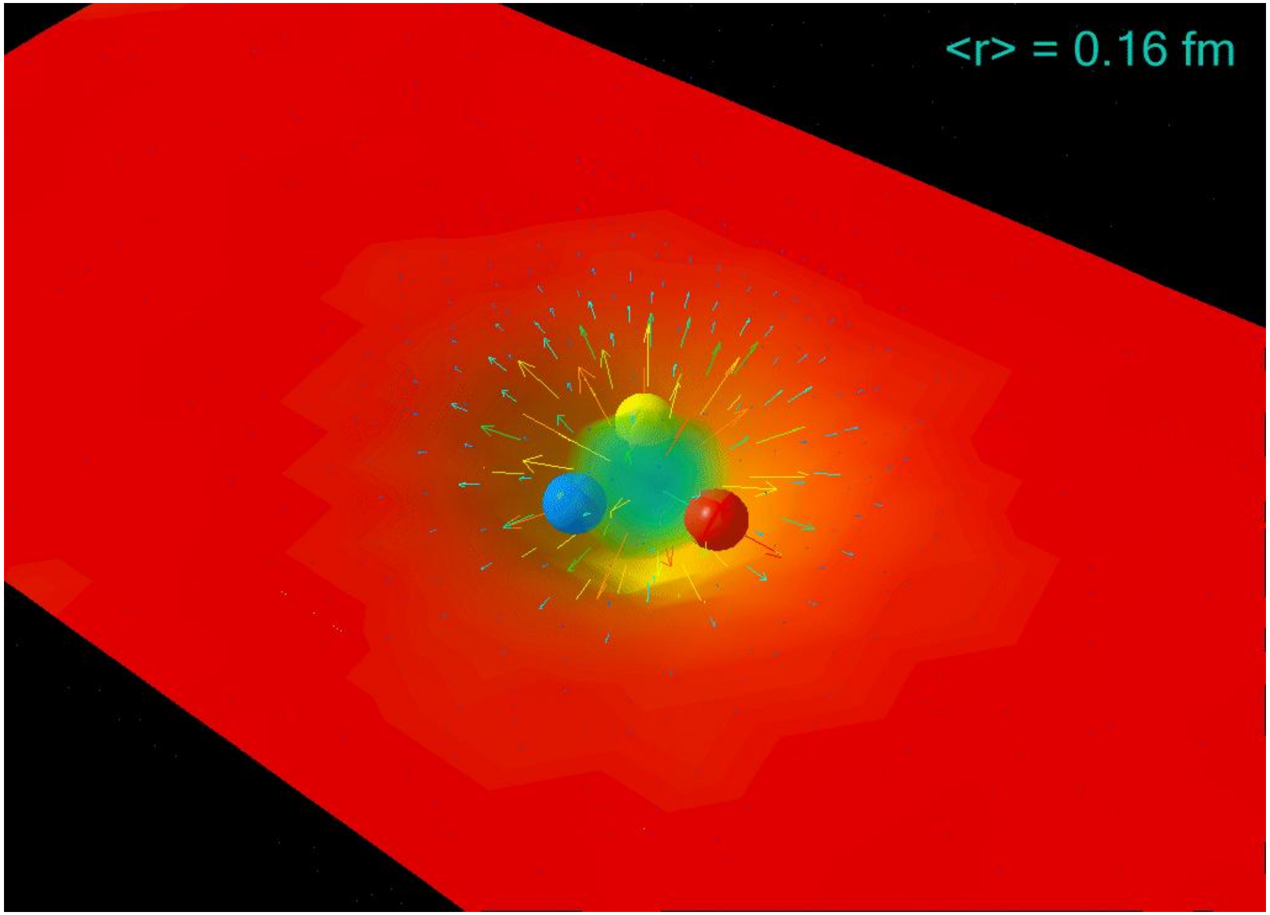
Confinement

- **In our world the fundamental *dof* are almost massless**
  BUT we are not!

Dynamically Broken Chiral Symmetry

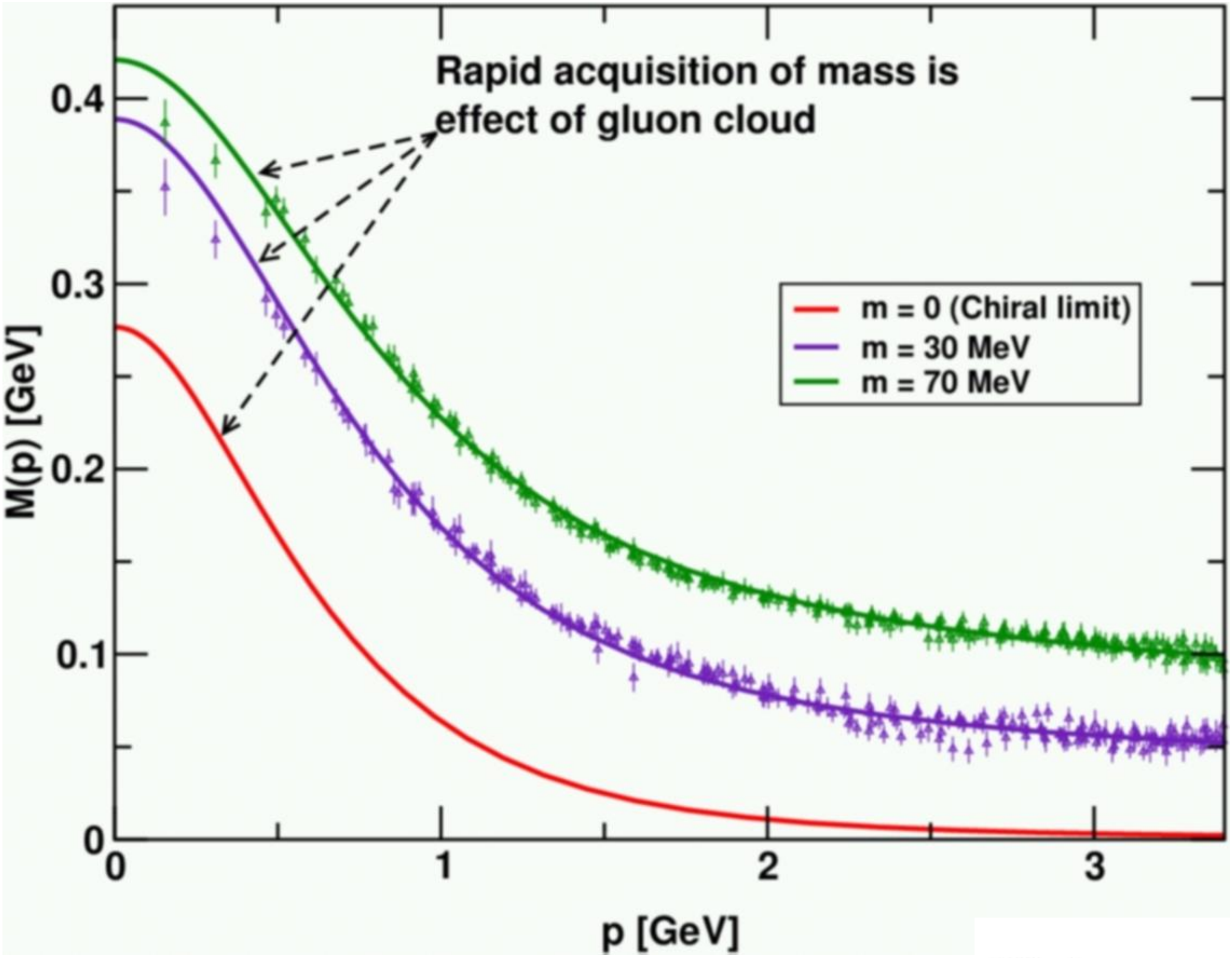
- **Near massless quarks $\Longrightarrow$ near degeneracy of opposite parity states**
- **BUT N(940) and nearest negative parity is N(1535) !**
- **Goldstone's theorem implies near massless pion (and less so the K)**
- **Chiral limit crucial but bizarre**
  - **p *and* n charge radii infinite**
- ***Such a light pion completely undermines the conventional picture of confinement***

Confinement for infinitely heavy quarks?



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

Quark mass function through χSB



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

Lattice studies & Dyson-Schwinger modelling in excellent agreement

– χSB is origin of constituent quark mass

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Our challenges

- **Discover how the properties of hadrons emerge as non-perturbative properties of this beautiful, non-linear theory**
- **Test that it is indeed fully correct**
  − precision
- **Develop our physical insight – a picture of how it works**
- **Investigate the role of hadron structure for atomic nuclei, dense matter, etc.**

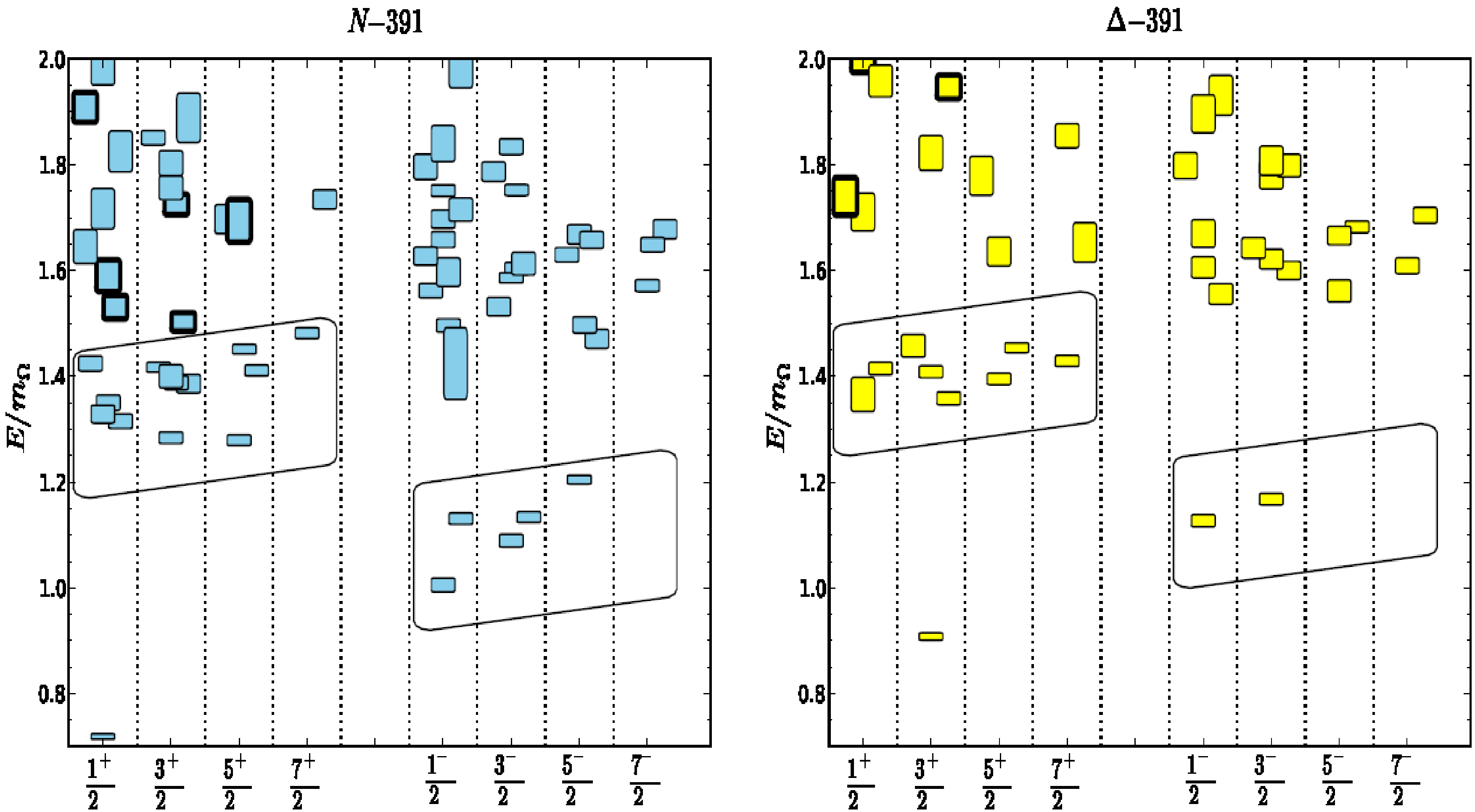
Spectroscopy

− how do excited states emerge from QCD ?

− what are the fundamental degrees of freedom ?

Impressive results on excited states : lattice QCD

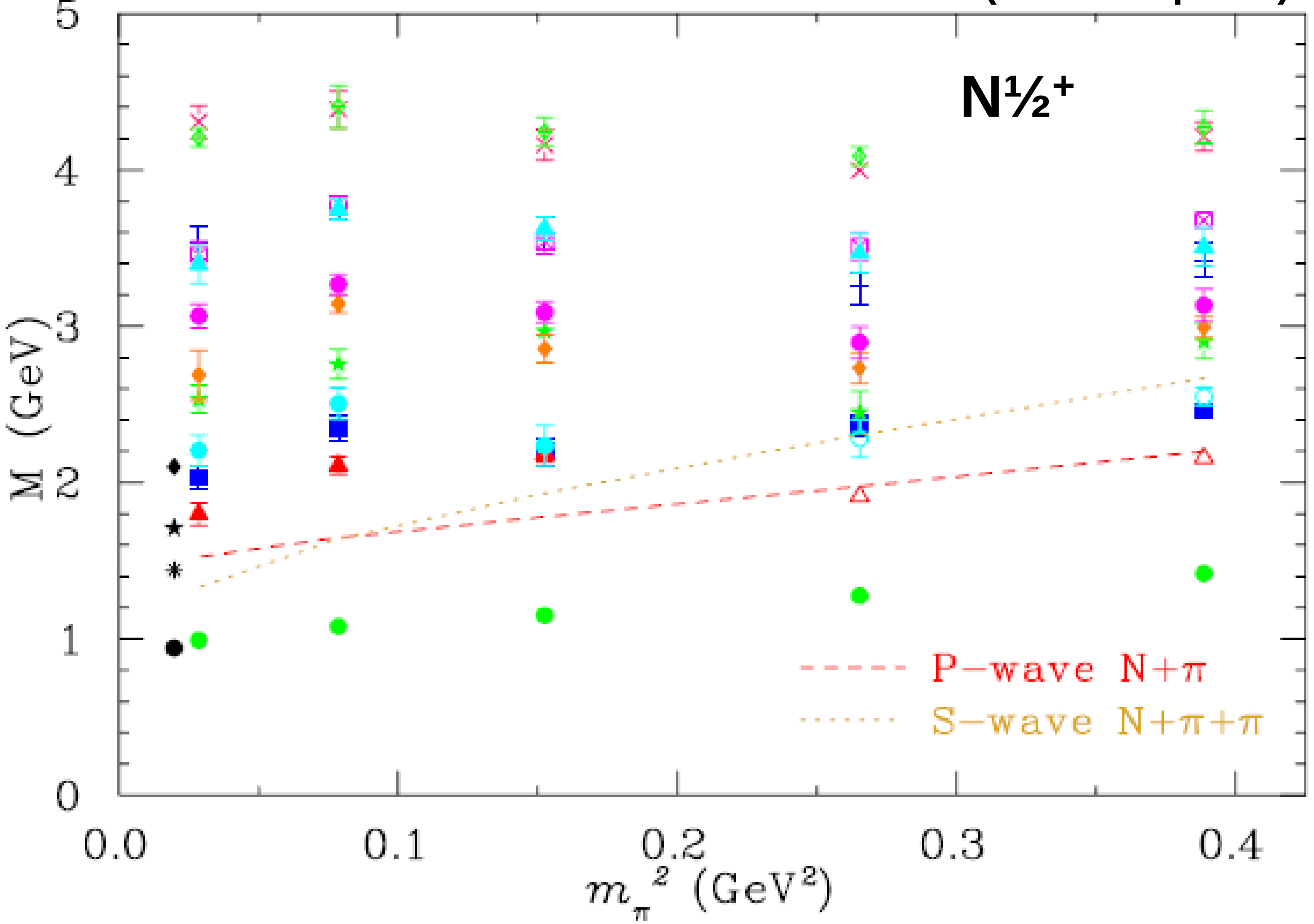
- **Recent results from JLab (m_π = 391 MeV)**



Edwards et al., arXiv:1212.5236 (JLab)

....and from CSSM

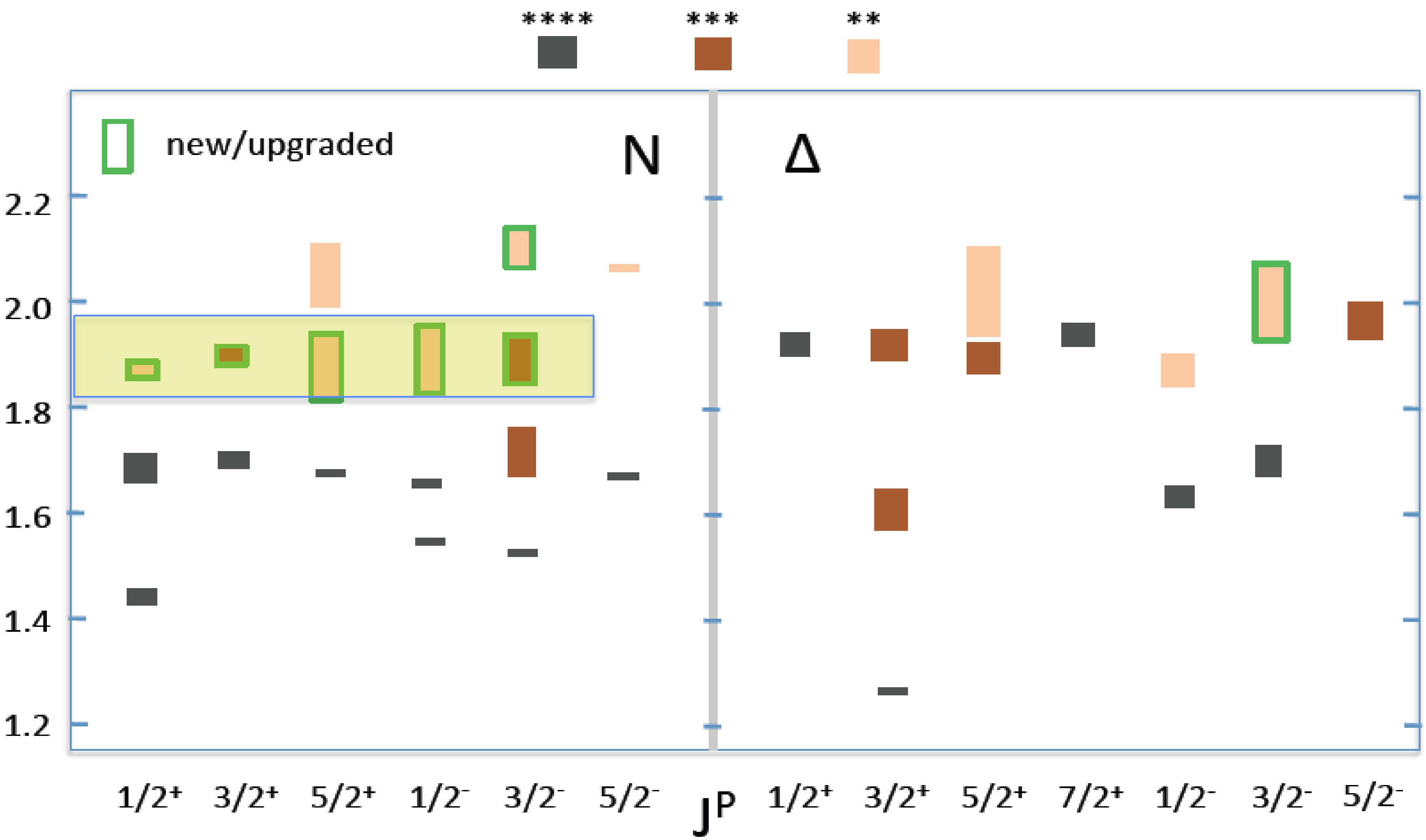
(Adelaide plot...)



Mahbub et al., arXiv:1302.2987

Experiment: N/Δ spectrum in PDG 2012

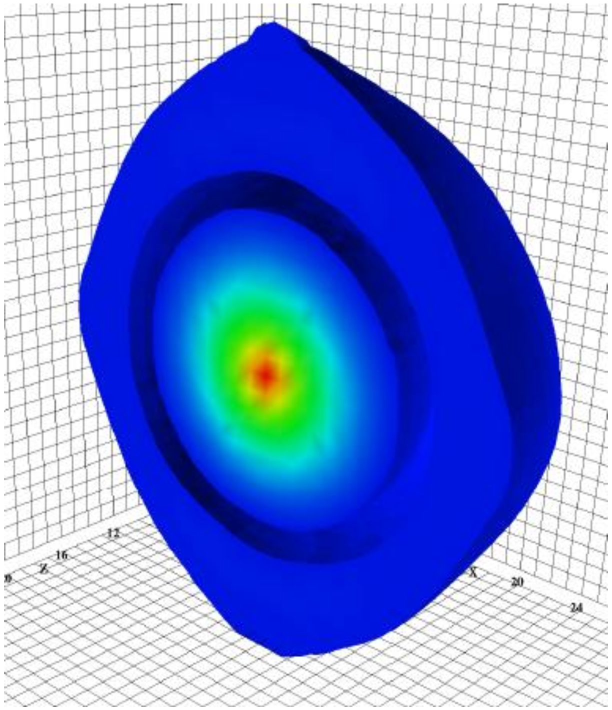
Experiments at JLab and Mainz : new baryonic states



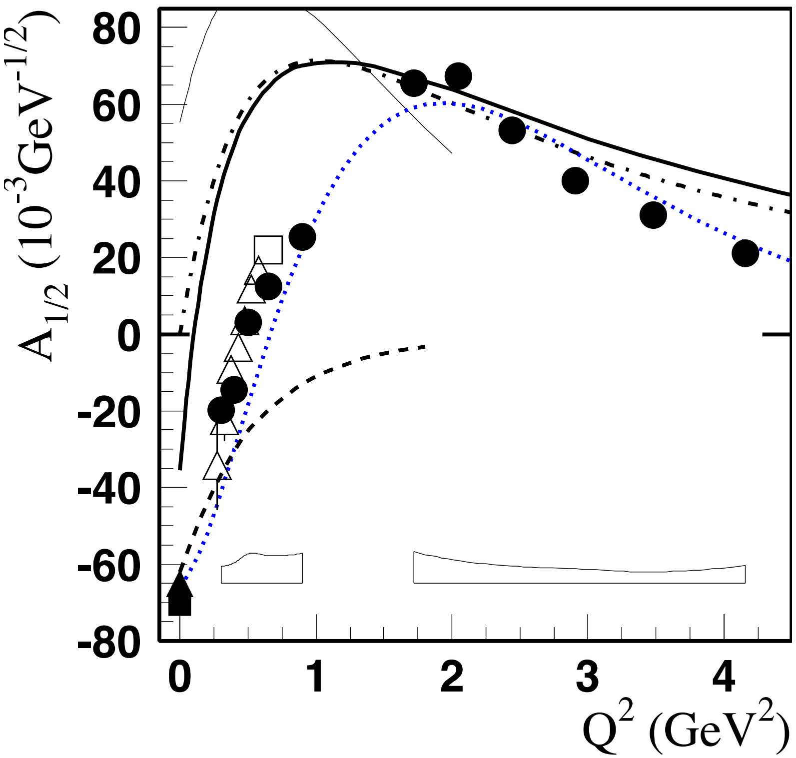
All new candidate states need confirmation in independent analyses

More detailed information coming − experiment & lattice!

e.g. Nature of the Roper − 1450 MeV



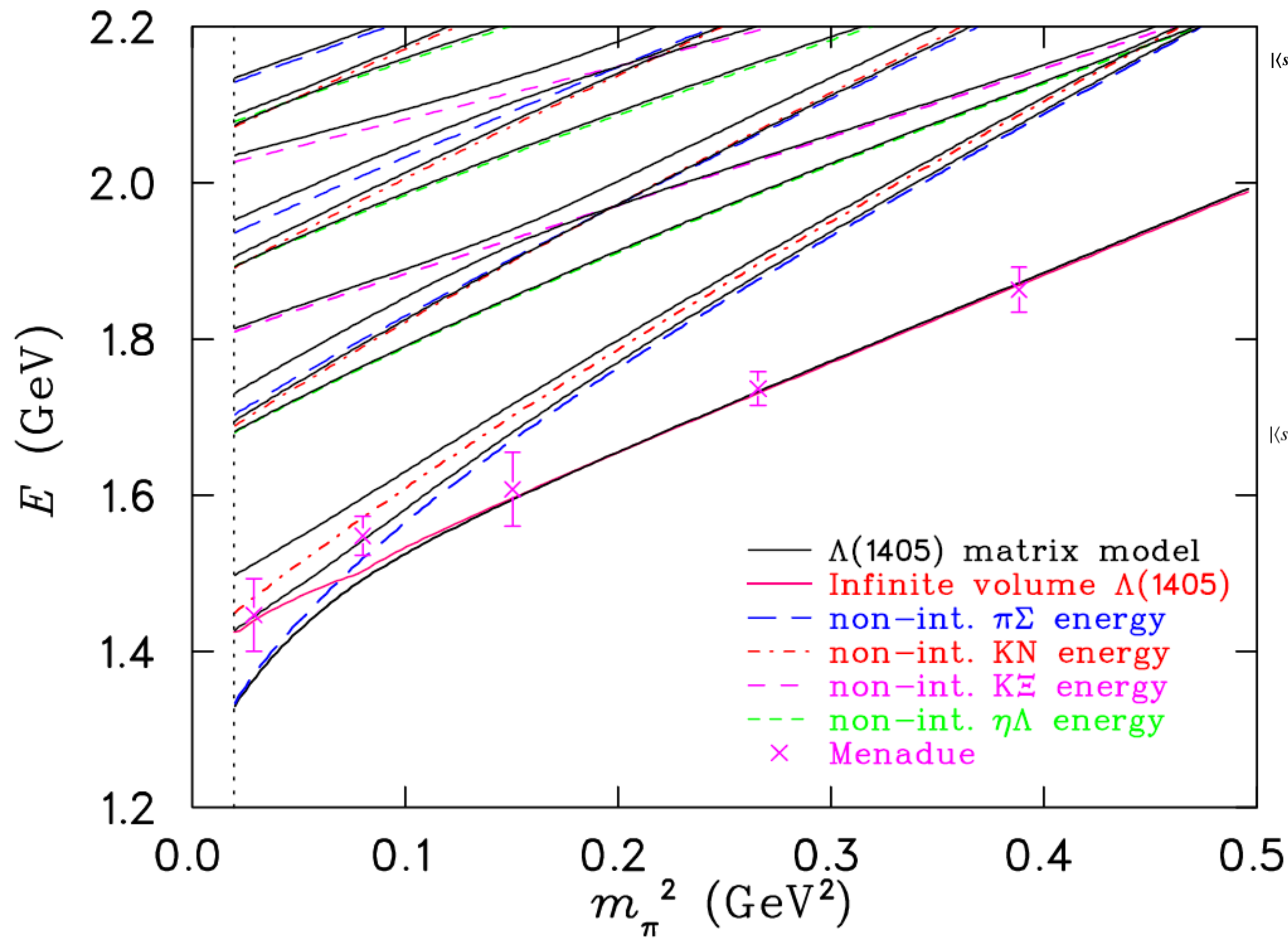
Leinweber et al., arXiv:1304.0325

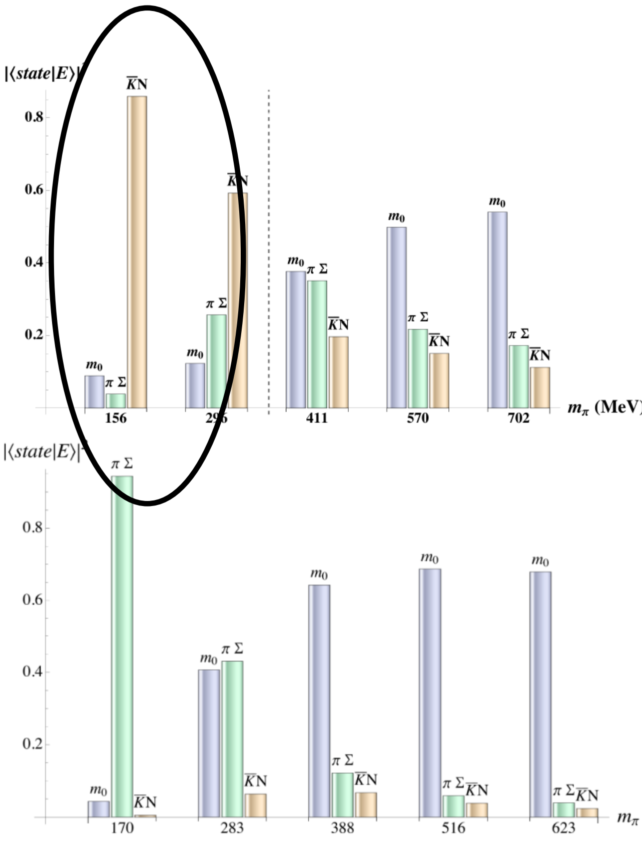


Burkert et al., CLAS

Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state





Hall, Leinweber, Menadue, Young, AWT – in preparation

Return to this topic at the end

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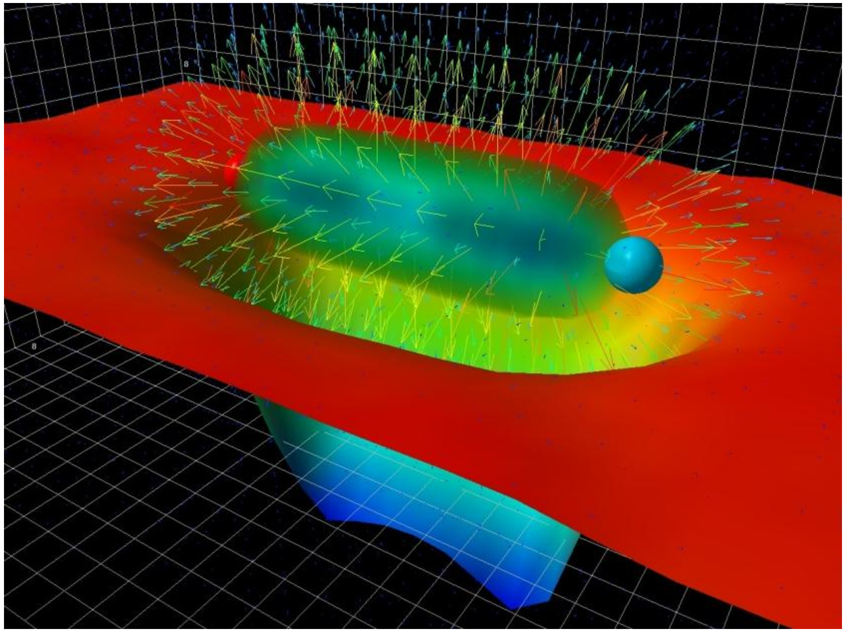
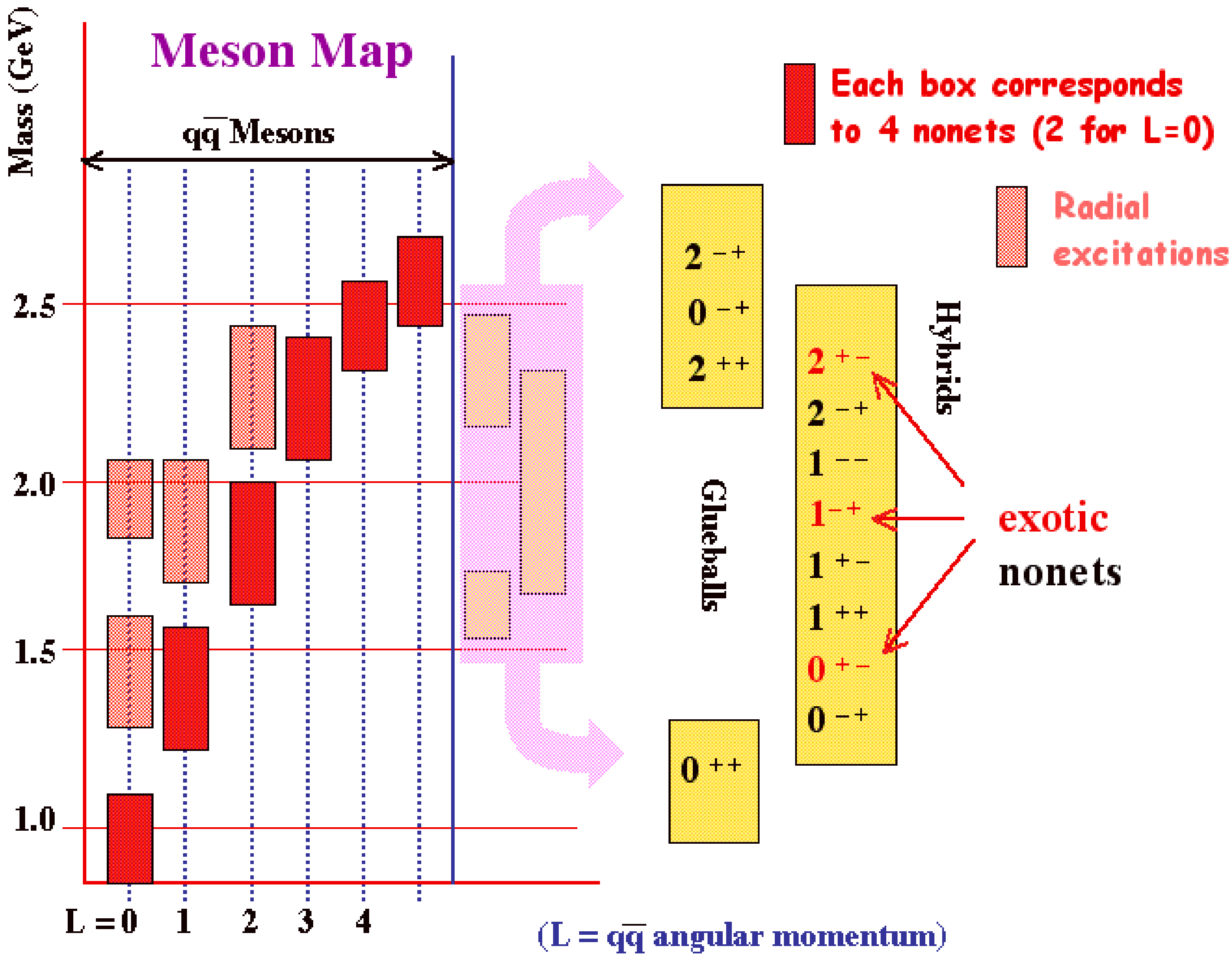
Gluonic Excitations?



QCD predicts (we think) a rich spectrum of as yet to be discovered gluonic excitations

− their experimental verification is crucial for our understanding of QCD in the non-perturbative regime

Glueballs and hybrid mesons : Hall D at Jlab?

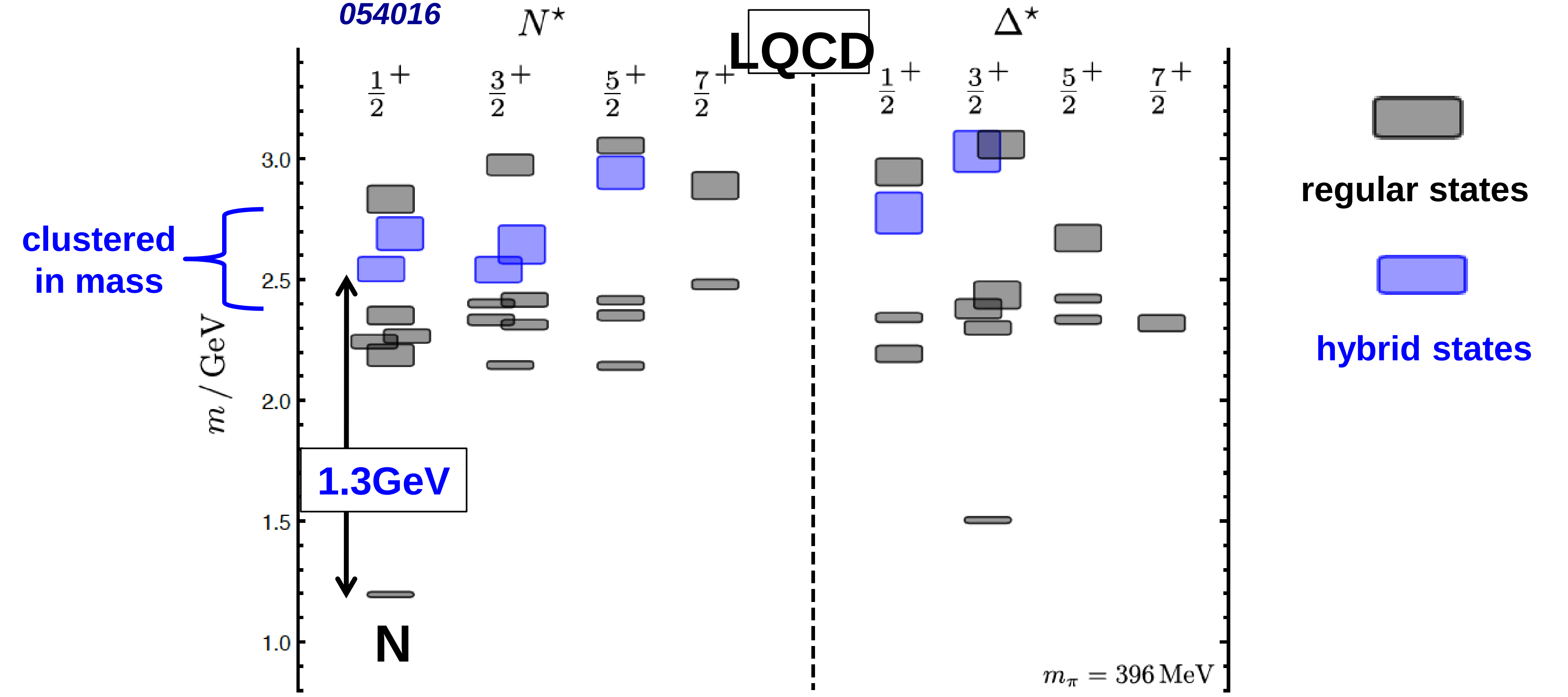


– see also Dudek and Szczepaniak this meeting...

Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016

T. Barnes and F.E. Close, PLB128, 277 (1983)



Hybrid states have same J^P values as Q^3 baryons. How to identify them?

- Overpopulation of N1/2$^+$ and N3/2$^+$ states compared to QM projections?

- Transition form factors in electro-production (different Q^2 dependence)

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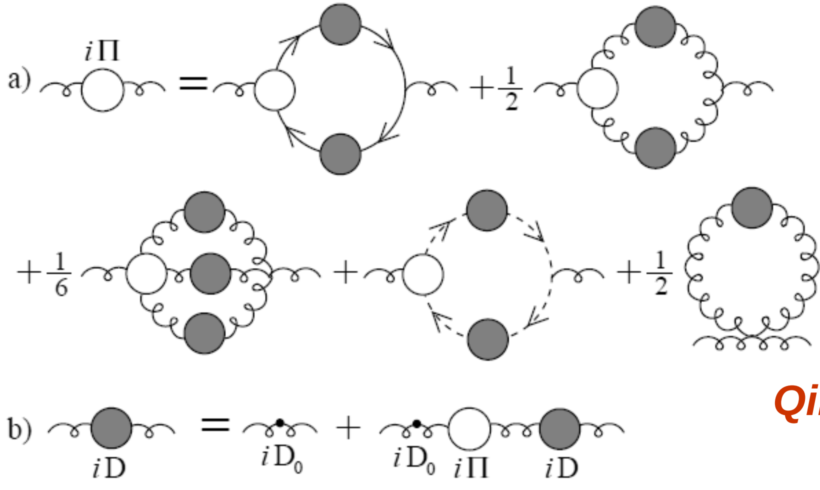
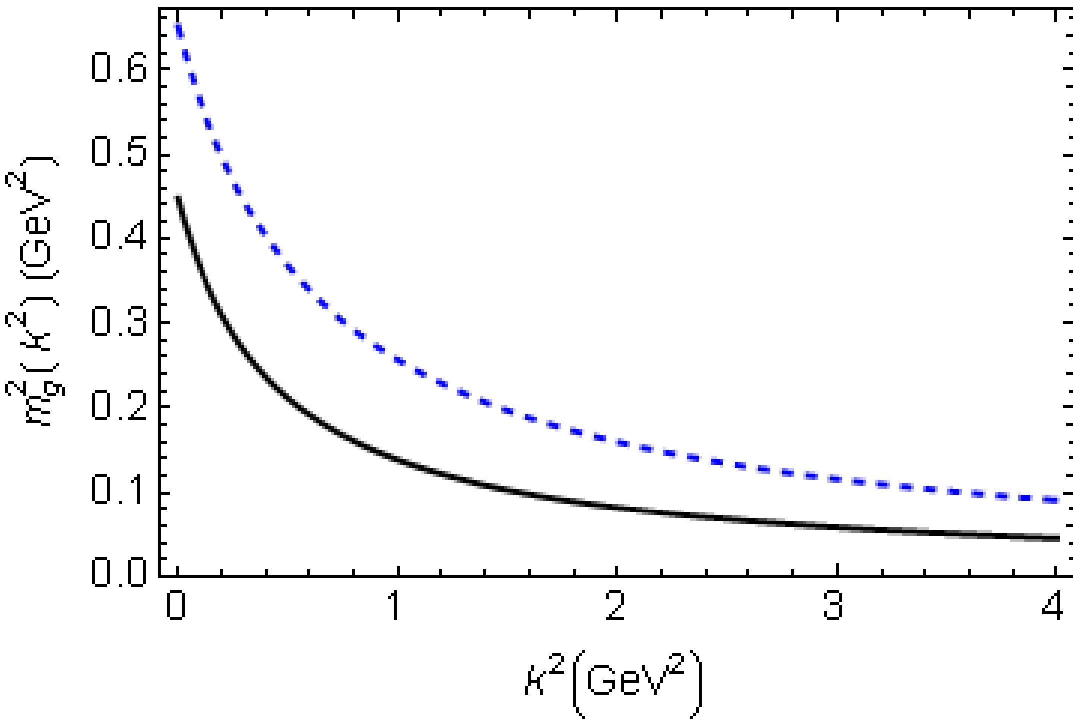
Gluon, too, has non-perturbative mass!



Qin et al., Phys. Rev. C 84 042202(Rapid Comm.) (2011)

$m_G^2(k^2) \approx m_G^4/(k^2+m_G^2)$



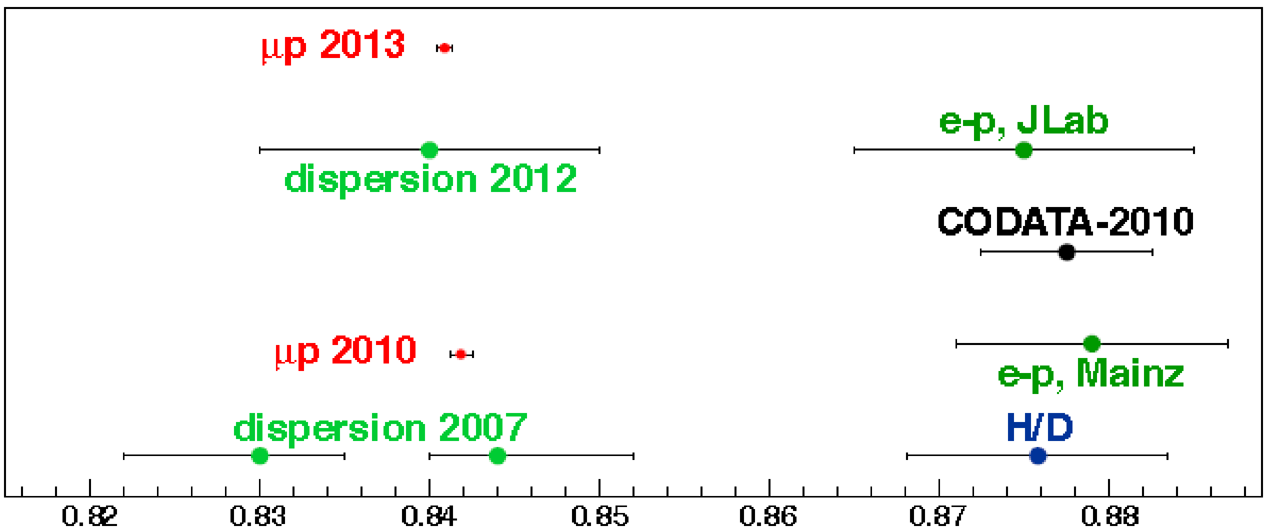
- **Running gluon mass**
  - **Gluon is massless in UV, in agreement with pQCD**
  - **Massive in infrared**
    - **$m_G(0)$ = 0.67-0.81 GeV**

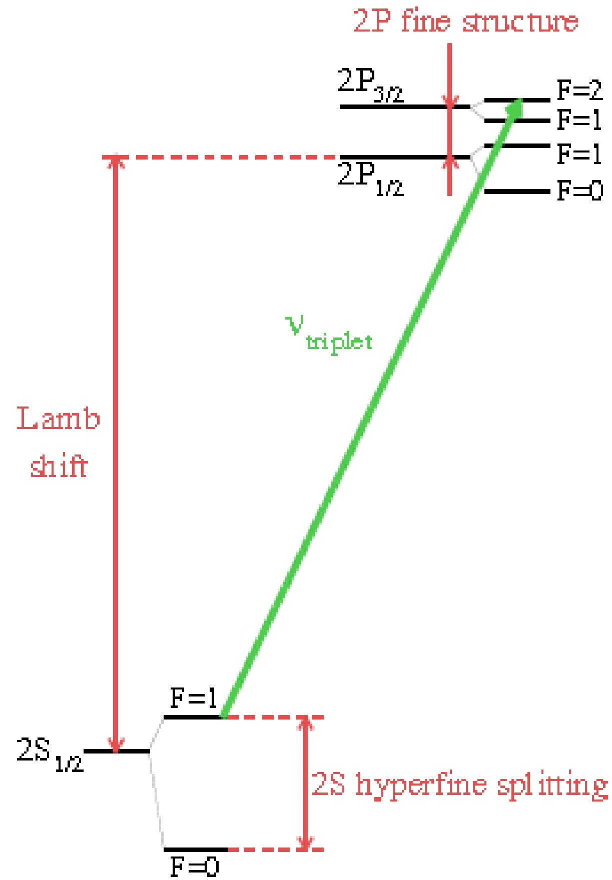
- **DSE prediction confirmed by numerical simulations of lattice-regularised QCD**

Qin et al., P R C84 (2011) 042202
- see also Roberts andSzczepaniak, this meeting

Electromagnetic form factors

Proton Radius Puzzle?





$r_p = 0.84087\,(26)_{exp}\,(29)_{th} = 0.84087\,(39)\,\text{fm}$

R. Pohl *et al.*, Nature 466, 213 (2010).

A. Antognini, RP *et al.*, Science 339, 417 (2013).

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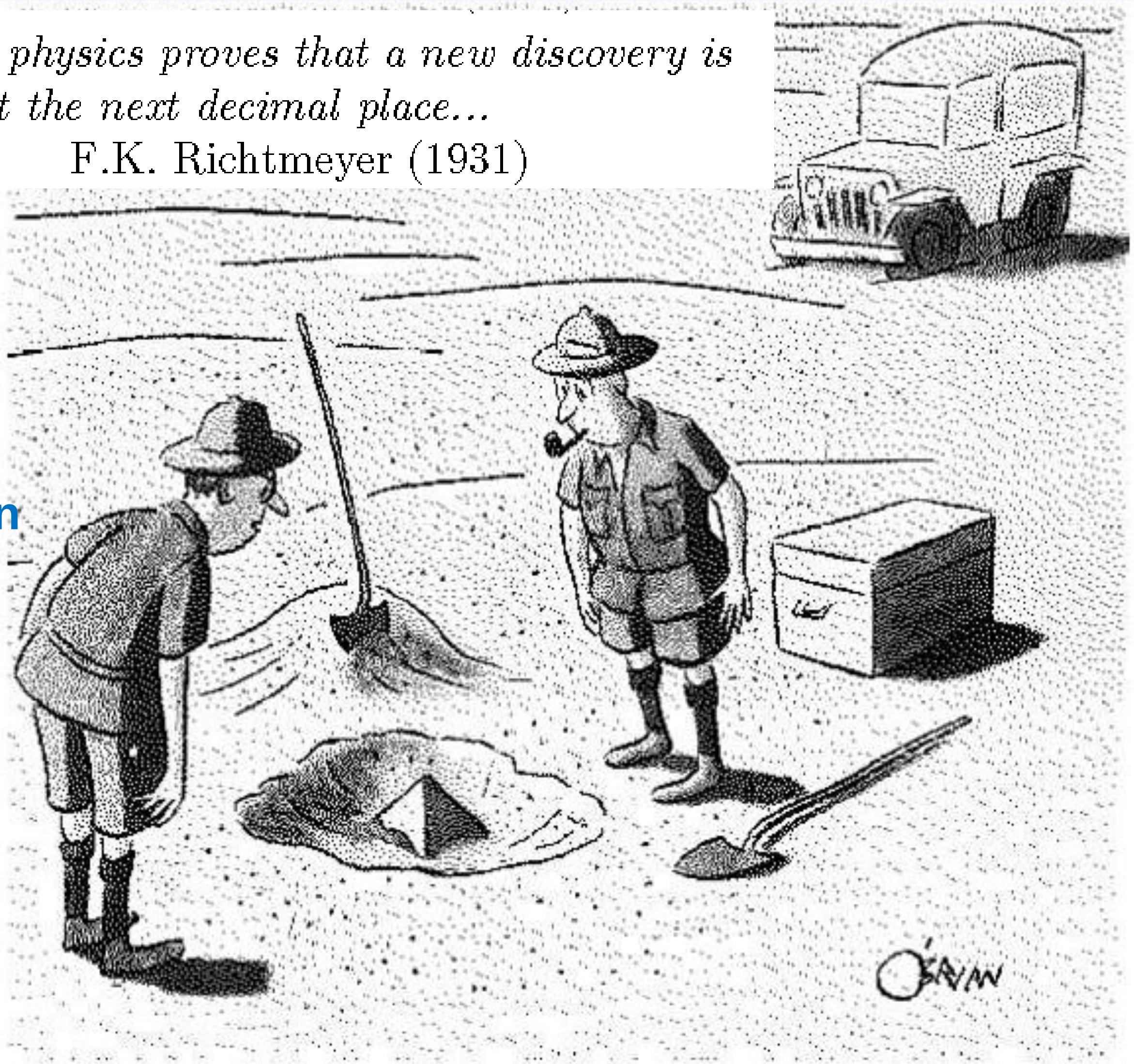
The proton radius puzzle

The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place...

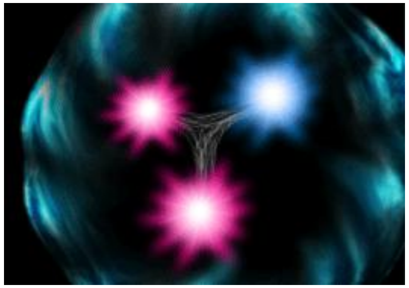
F.K. Richtmeyer (1931)

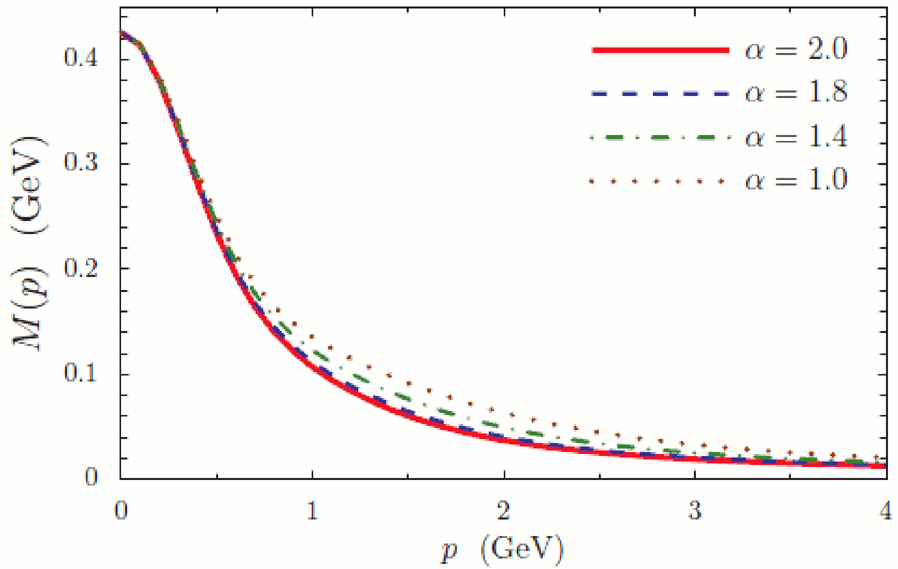
Carlson & Rislow, PRD86: it may be possible to explain both g-2 and muonic hydrogen with new physics but seems highly fine tuned!



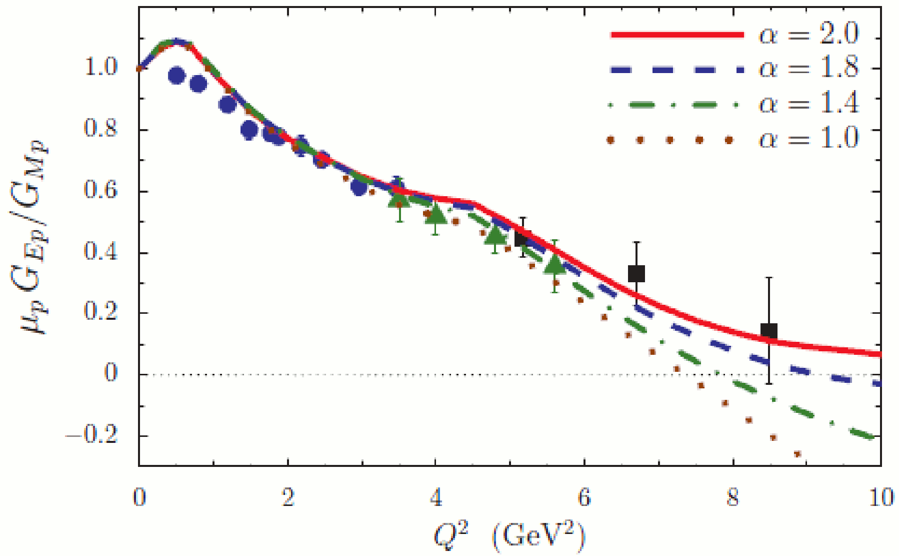
"This could be the discovery of the century. Depending, of course, on how far down it goes."

Potential link to xSB





- **Small changes in M(p) within the domain 1<p(GeV)<3 have striking effect on the electric form factor**



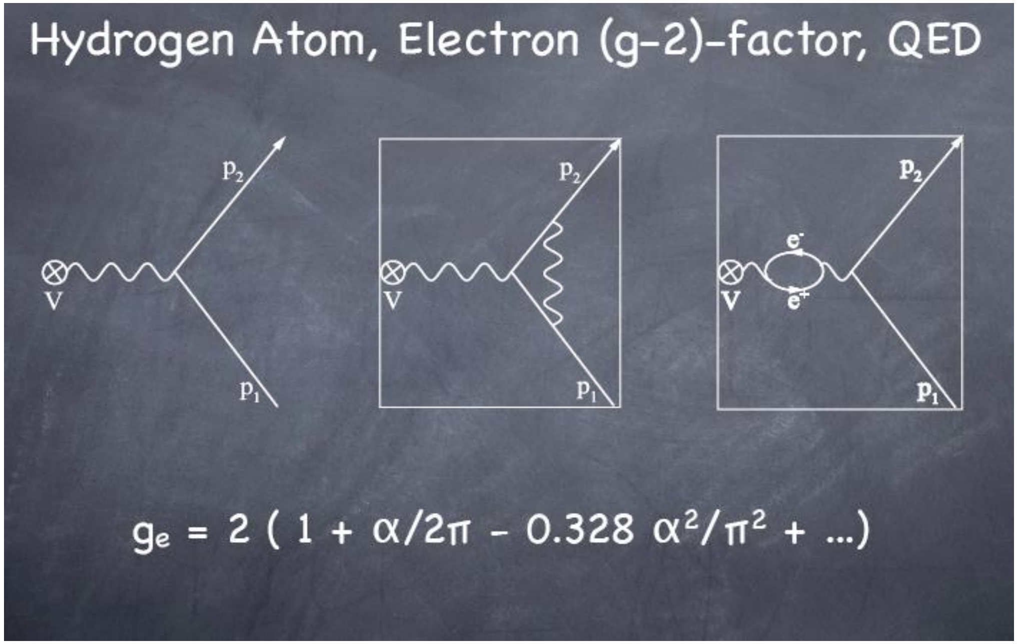
- **Ratio** ***[$\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$]*** **provides information on the nature of the quark-quark interaction in the transition region from pQCD to non-perturbative QCD**

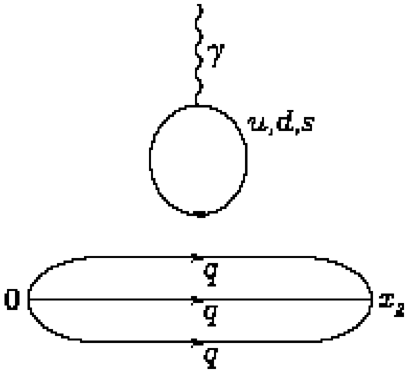
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

I.C. Cloët et al.: **"Revealing dressed-quarks via the proton's charge distribution", arXiv: 1304.0855 (Phys Rev Lett (2013))**

Fundamental Test of Non-Perturbative QCD

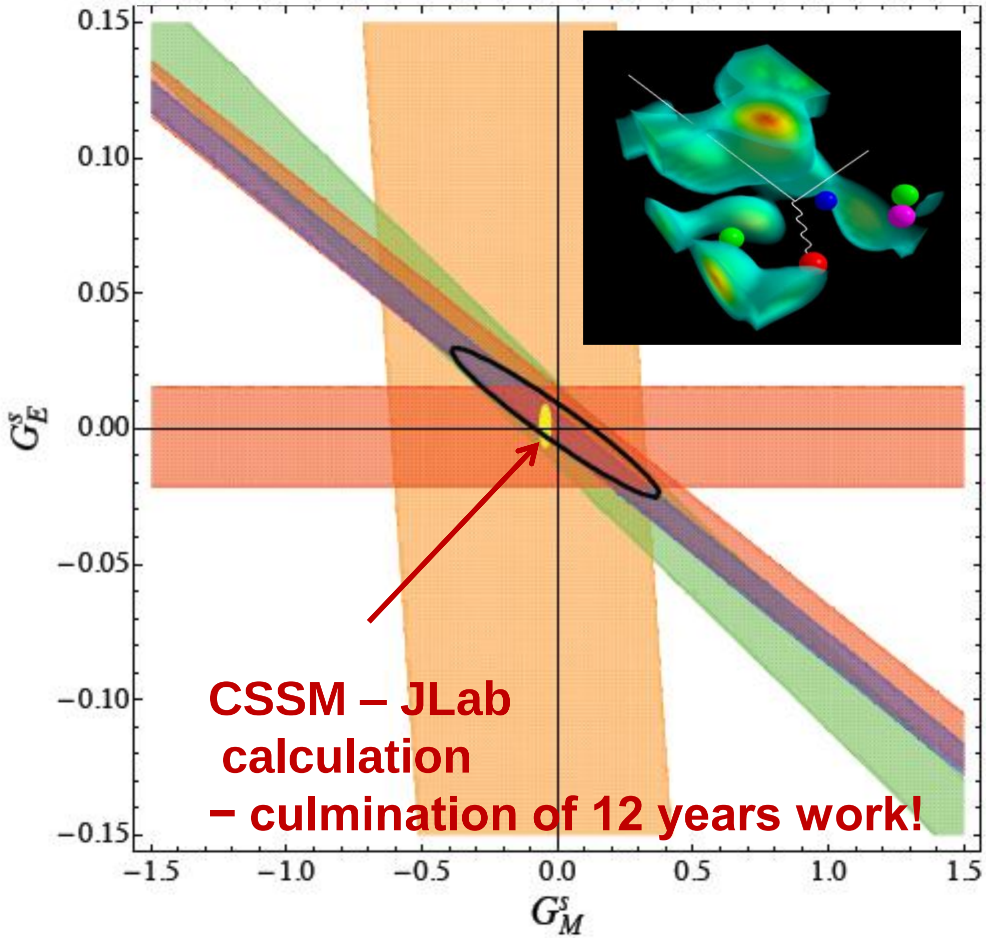
- **Strangeness contribution is a vacuum polarization effect, *analogous to Lamb shift in QED***





It is a fundamental test of QCD

A unique case : theory demanding more accurate than data

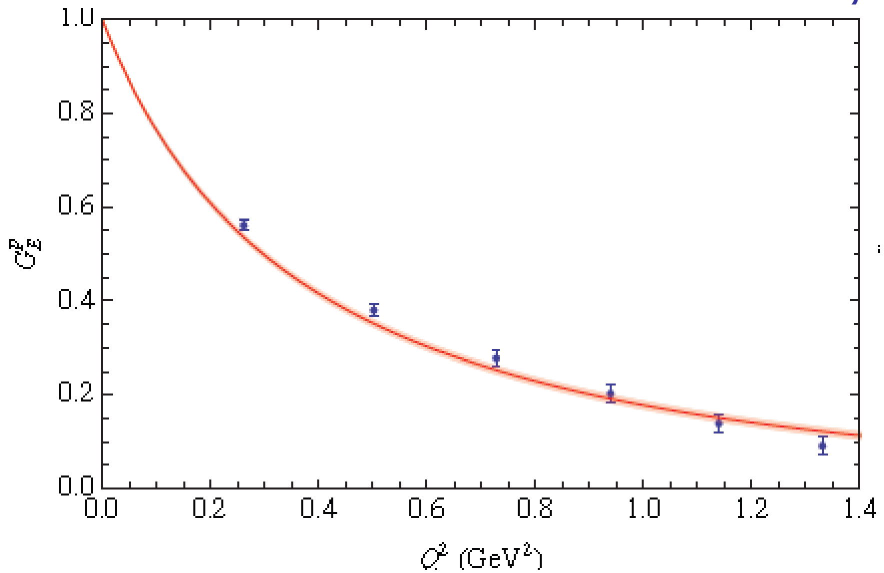


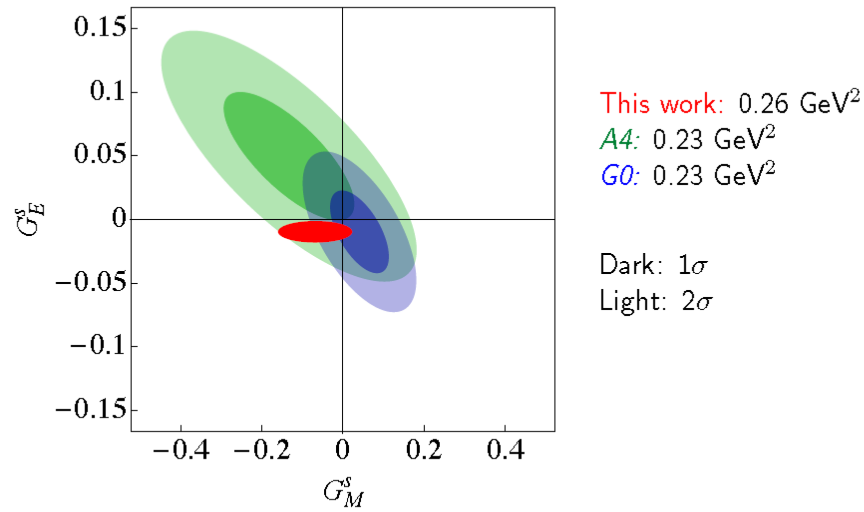
Experimental program took three major laboratories 20 years!

Thomas Jefferson National Accelerator Facility
(G0 and Happex expts)
plus Mainz & MIT Bates

Latest Extraction from CSSM-QCDSF/UKQCD

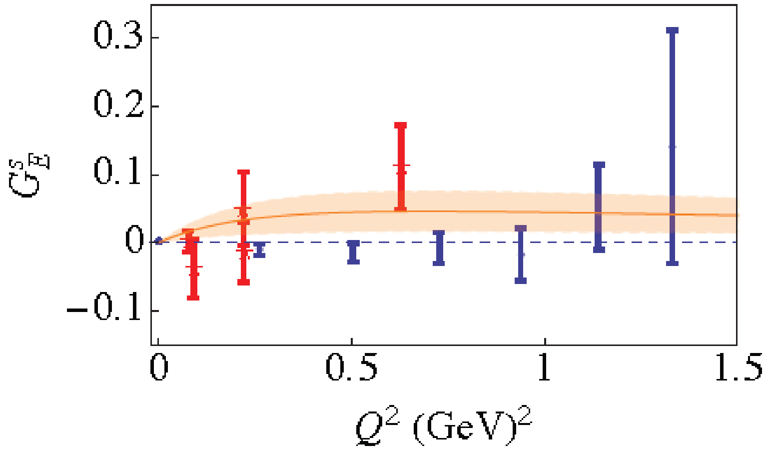
Shanahan et al., arXiv:1403.65

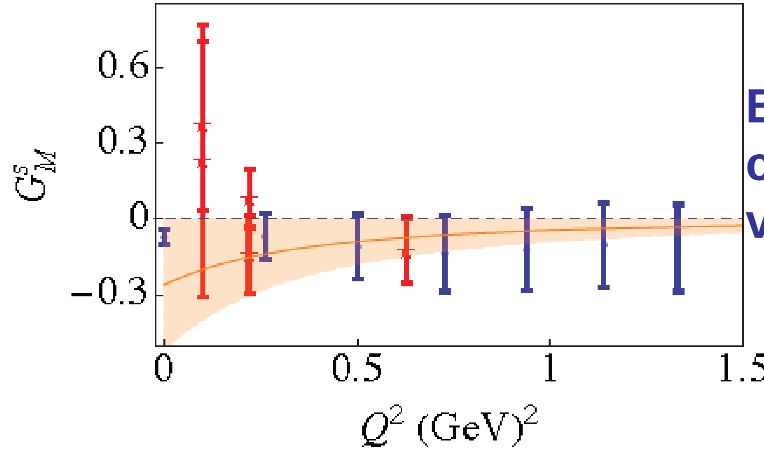




Electric

Magnetic





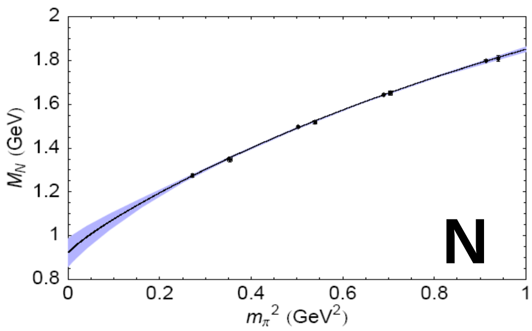
Blue are calculated values

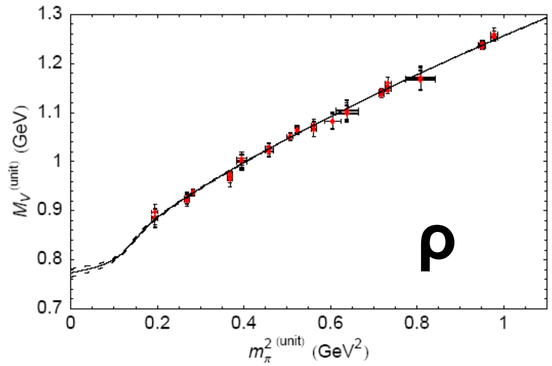
Red stars: *G0, SAMPLE, HAPPEX, A4.*

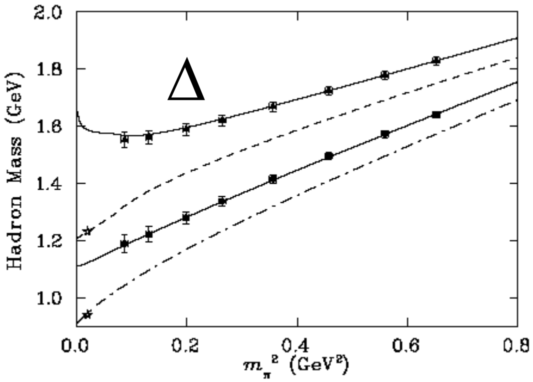
Global fit: R. González-Jiménez, J.A. Caballero, T.W. Donnelly arXiv:1403.5119

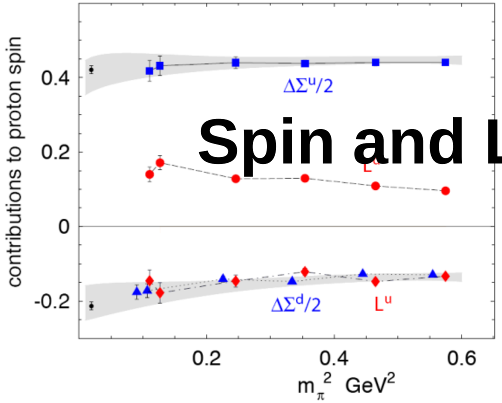
Understanding this result ?

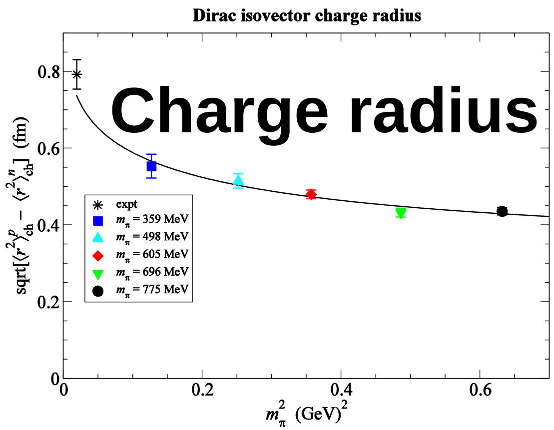
The “Big Picture”

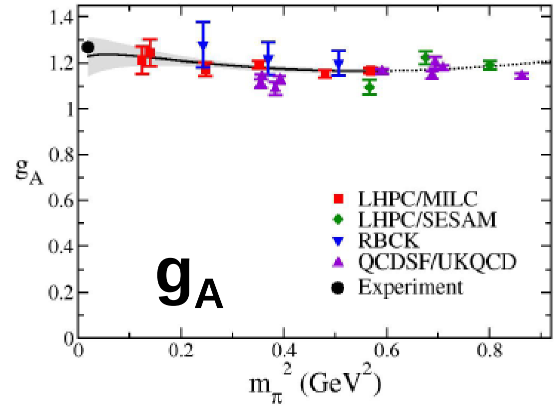


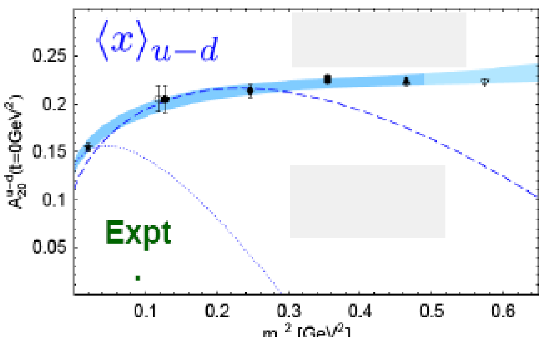












Is it believable that smooth behavior for m_π above 400 MeV is a result of a <u>different</u> accidental cancellation in every case??

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

Very simple lesson / universal feature of lattice data

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

- Physics is that once the Goldstone boson mass is so large that its Compton wavelength is smaller than the interior of the hadron (the "brown muck" of Isgur and Wise) it is no longer a relevant degree of freedom

- The kaon mass is ~0.5 GeV and hence kaon loops and strangeness in the proton are strongly suppressed!

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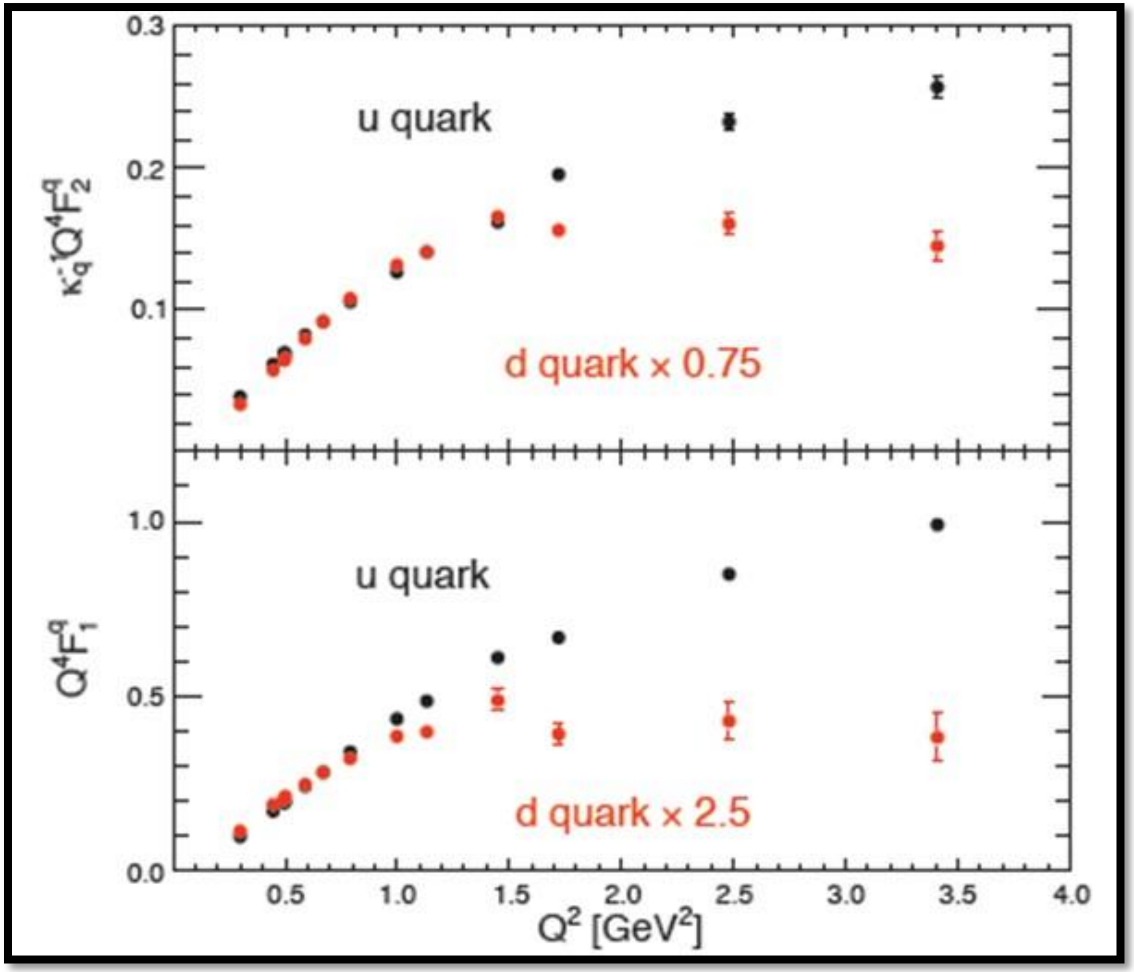
F_i^s small : allows separation of flavour form factors

$Q^4F_2^q/\kappa$

$Q^4 F_1^q$

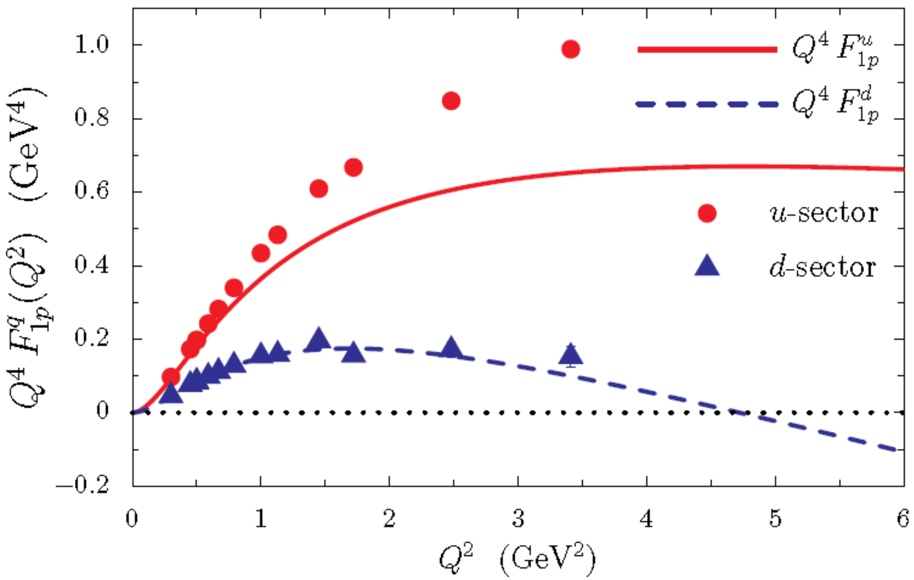
Cates, de Jager, Riordan, Wojtsekhowski, PRL 106 (2011) 252003

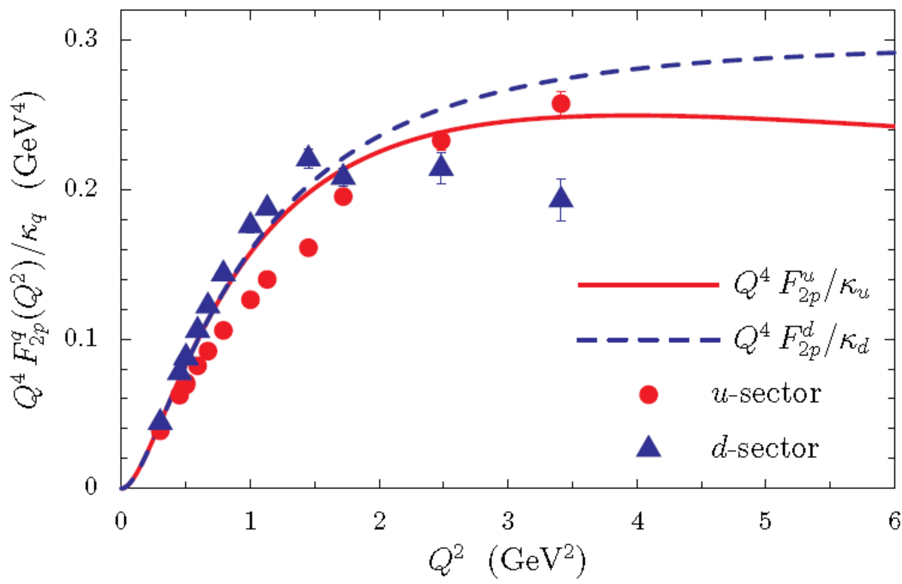


Very different behavior for *u* & *d* quarks suggests apparent scaling in proton F_2/F_1 may be *accidental*

Confining NJL Studies

- **Tell us about the interplay of di-quark correlations and pions**





Data from Cotes et al., PRL 106 (2011) 252003

Theory: Bentz, Cloët and Thomas, to appear

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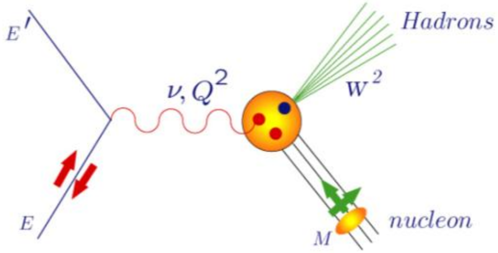
Structure Functions

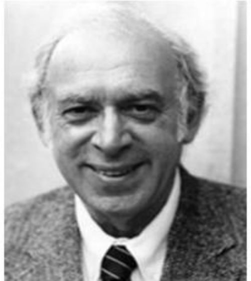
Deep Inelastic Scattering

- 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



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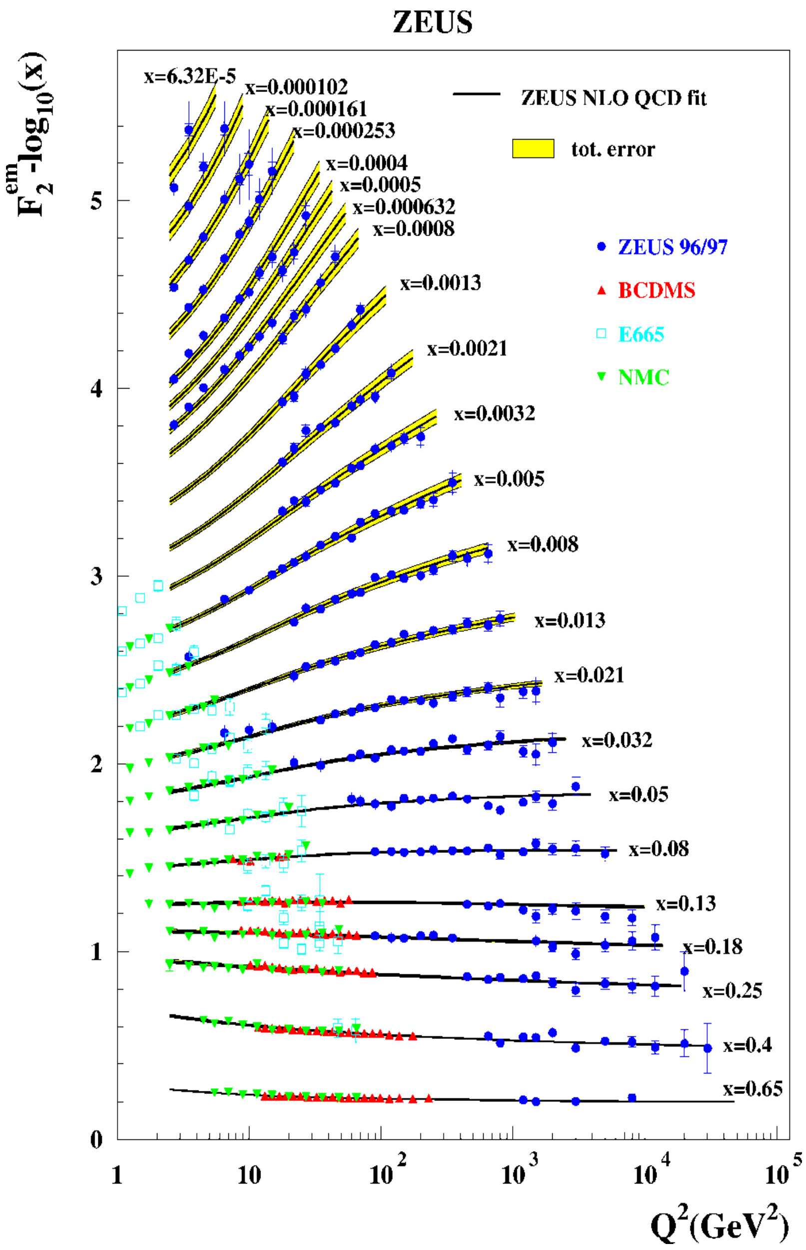
Unpolarized Structure Function F_2

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

  NLO: Next-to-Leading-Order

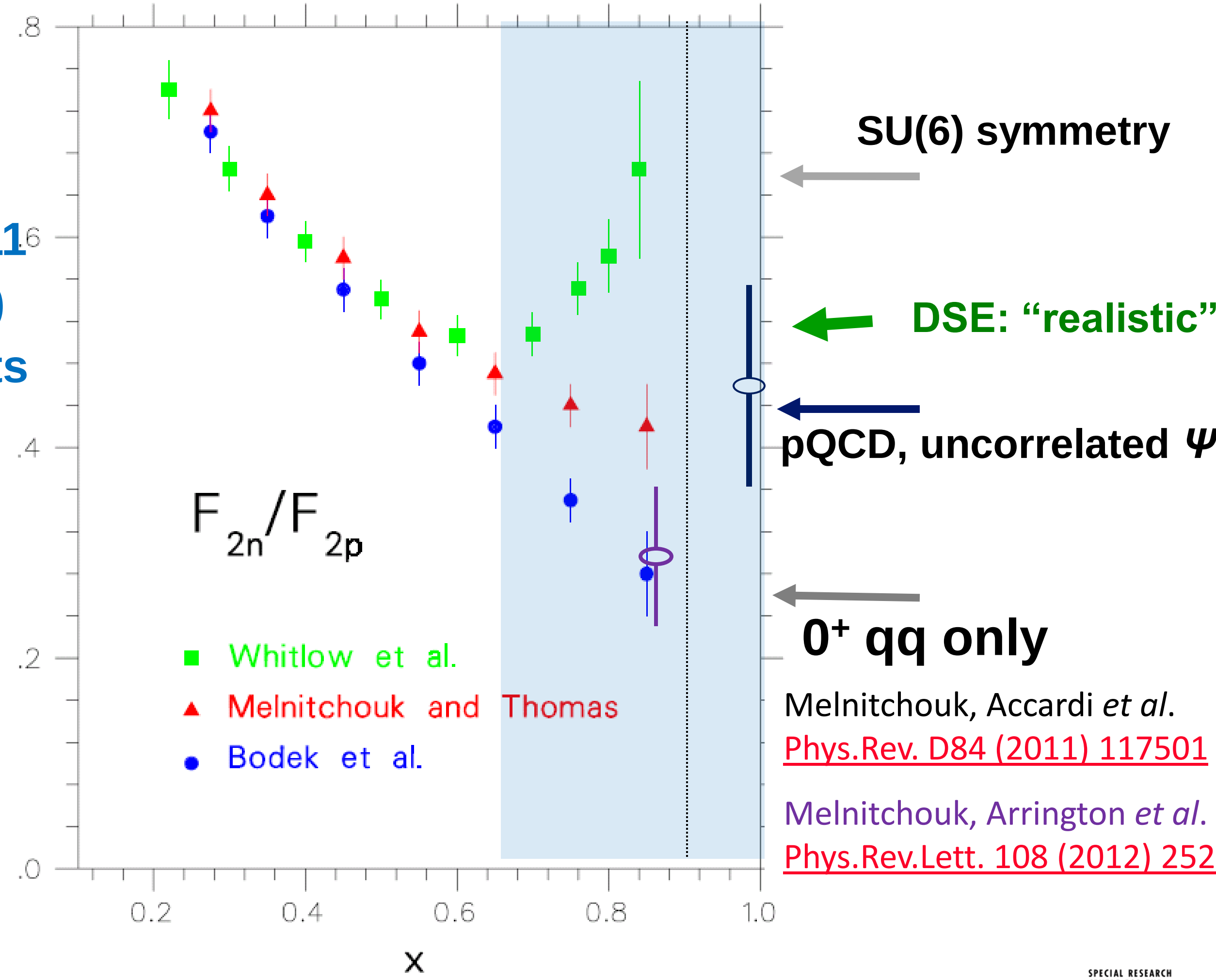
  …….
- One of the best experimental tests of perturbative QCD



SLAC
CERN
FNAL
DESY

Neutron Structure Function at high-x

Reviews:
- **S. Brodsky *et al.* NP B441 (1995)**
- **W. Melnitchouk et al., PL B377 (1996) 11**
- **N. Isgur, PRD 59 (1999)**
- **R.J. Holt & C.D. Roberts RMP (2010)**



I.C. Cloët, C.D. Roberts, *et al*.
Few Body Syst. 46 (2009) 1-36
D. J. Wilson, I. C. Cloët et al.,
Phys. Rev. C85 (2012) 025205

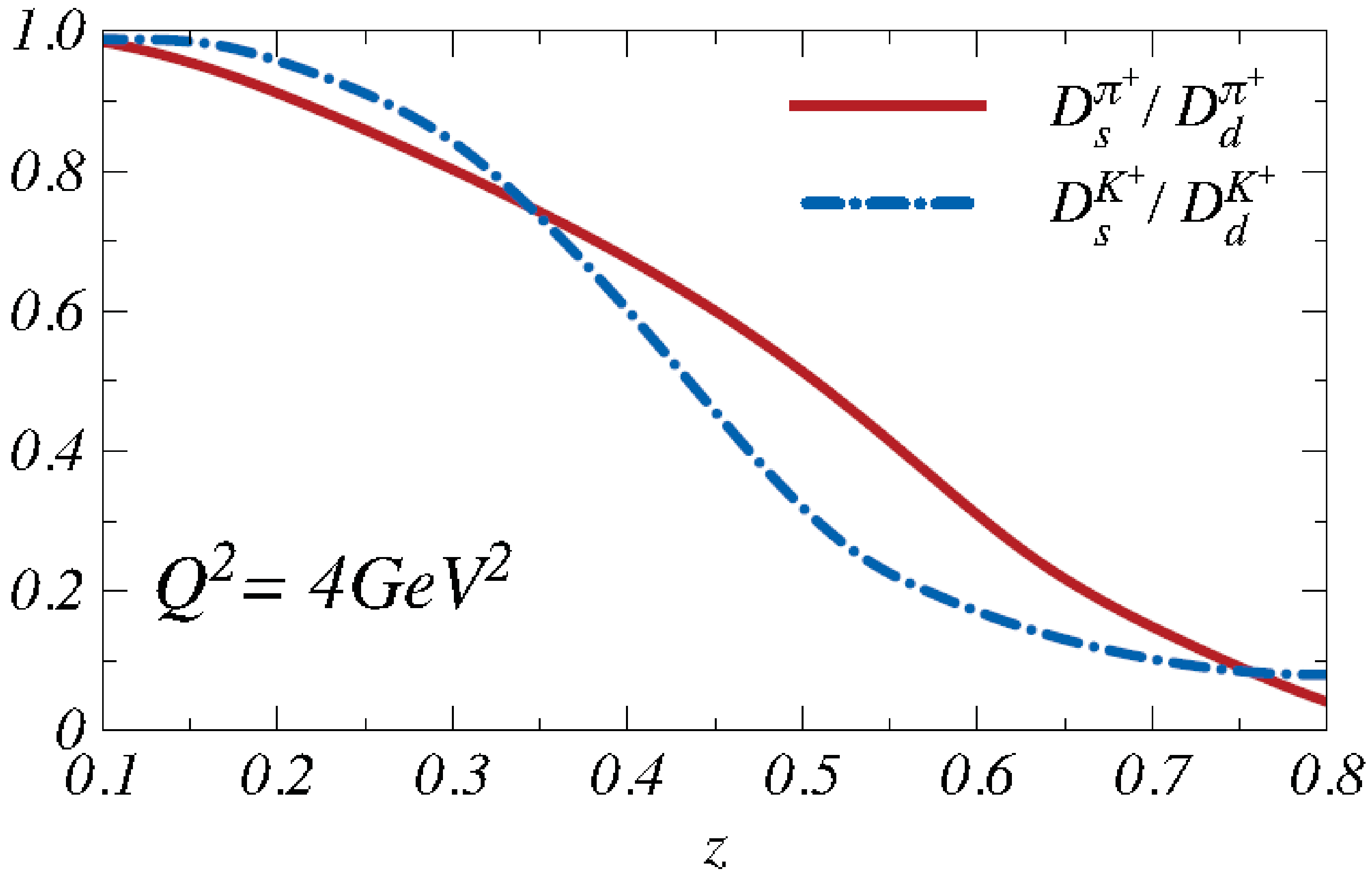
Melnitchouk, Accardi *et al*.
Phys.Rev. D84 (2011) 117501

Melnitchouk, Arrington *et al*.
Phys.Rev.Lett. 108 (2012) 252001

Distribution of neutron's momentum amongst quarks on the valence-quark domain – UNKNOWN!

Still much to learn about fragmentation

e.g. It's commonly assumed that for these *unfavoured* fragmentation functions $D_d^{K^+} = D_s^{K^+}$ **and** $D_d^{\pi^+} = D_s^{\pi^+}$ **: WRONG**



see: Matevosyan et al., AIPCP 1374 (2011) 387
for this and other examples of NJL model predictions

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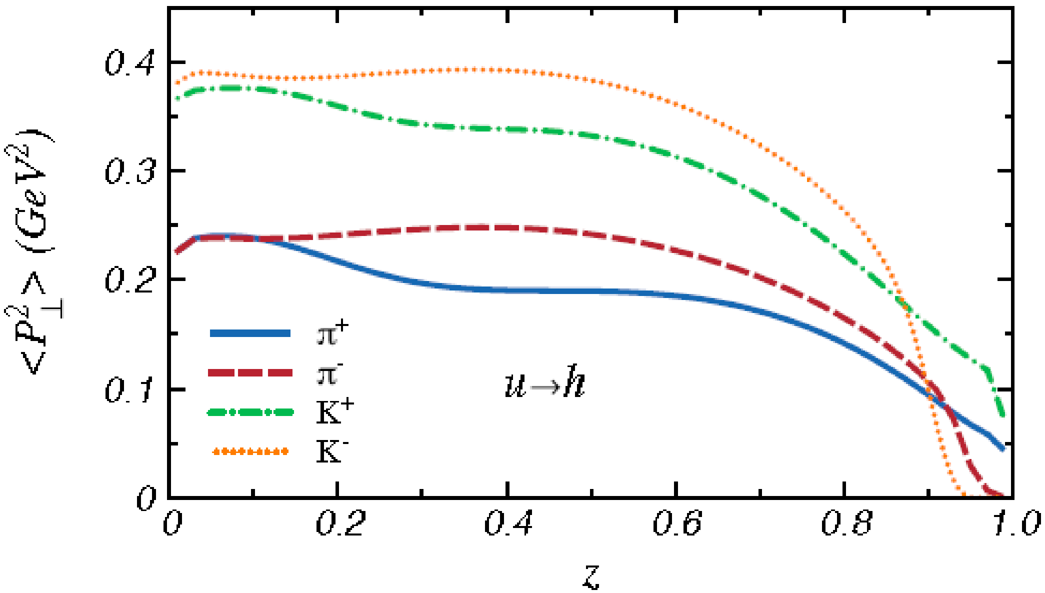
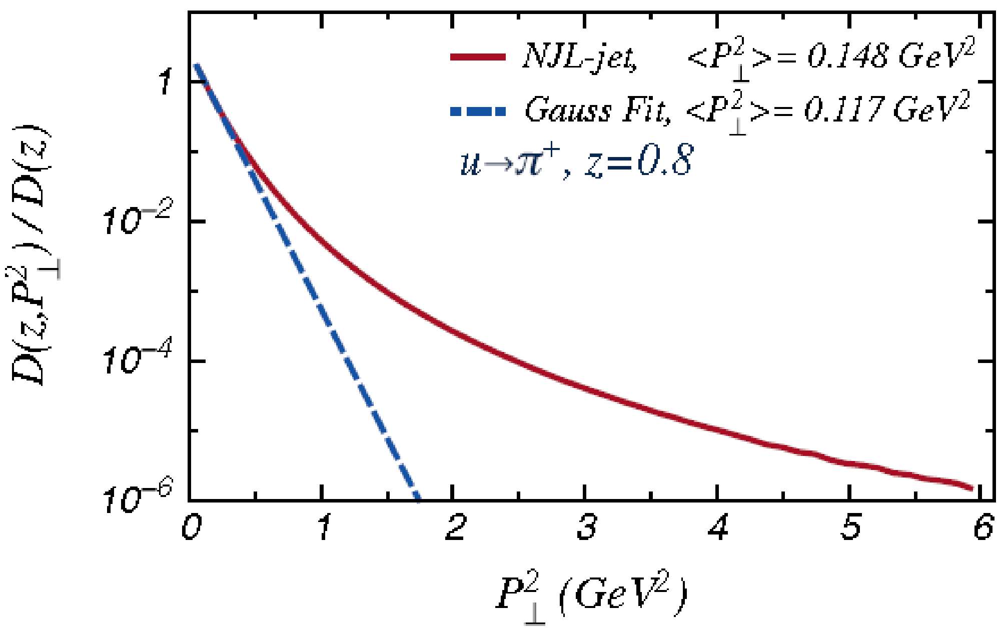
Transverse Momentum – not so simple

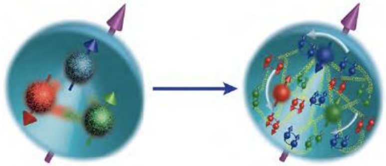


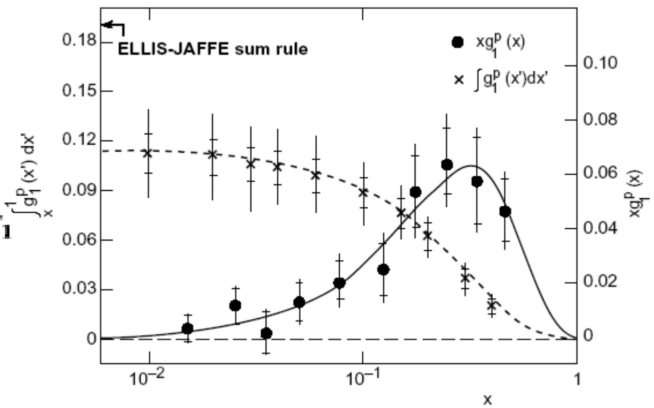
Cloet, Matevosyan et al., P R D85 (2012) 014021



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

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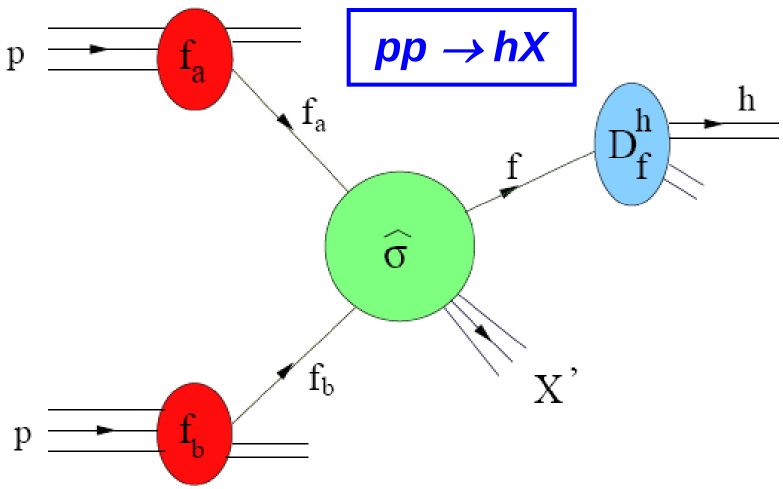
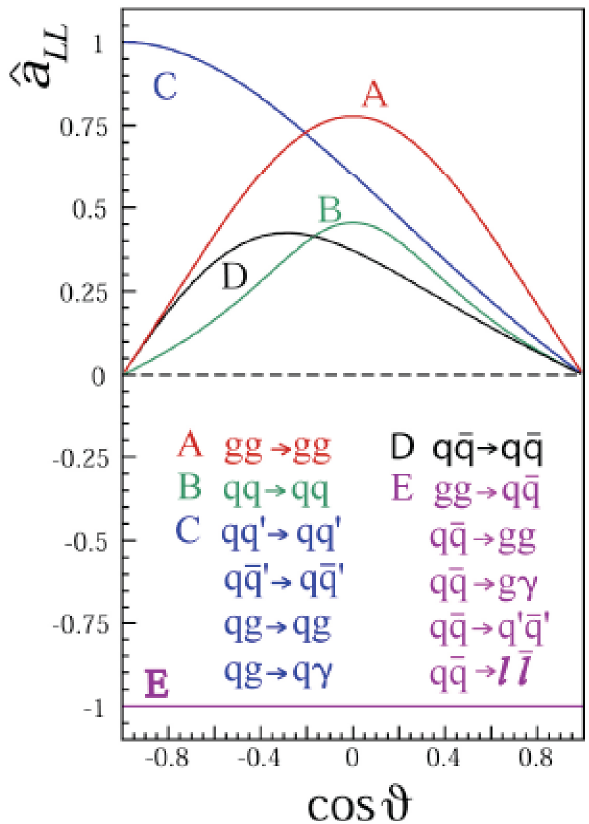
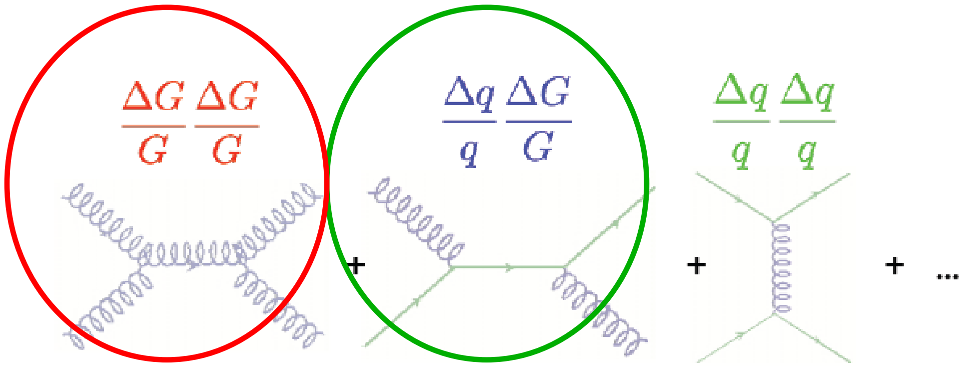
Testing ΔG~4 in pol. pp collisions





$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

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Polarized pp collider at RHIC

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Where is the Spin of the proton?

- Modern data (Hermes, COMPASS) yields:
  $\Sigma = 0.33 \pm 0.03 \pm 0.05$

  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- In addition, there is little or no polarized glue
  - COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$
  - A_{LL} (π^0 and jets) at PHENIX & STAR: $\Delta G \sim 0$
  - Hermes, COMPASS and JLab: $\Delta G / G$ small

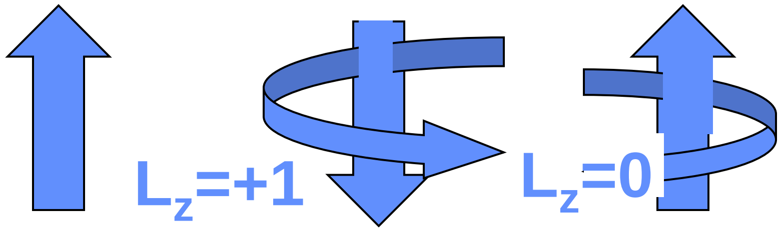
- Hence: <u>axial anomaly plays at most a small role in explaining the spin crisis</u>

- Suggests alternate explanation lost in the rush to explore the anomaly :
  chiral symmetry and gluon exchange

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%)



Z $\qquad \frac{2}{3} P_{N\pi} \qquad \frac{1}{3} P_{N\pi}$

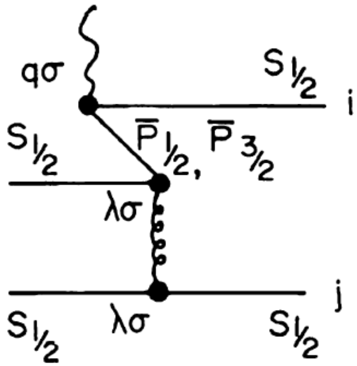
- Spin gets renormalized by a factor :

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

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)

Recent Test using Quark Spins for the Octet

- Rather than experimental measurements on the octet, we now have lattice QCD - in this case QCDSF (Phys. Rev. D 84, 054509 (2011) and Phys. Lett. B 714, 97 (2012)) − see final column

	MIT Bag	MIT Bag + OGE	MIT Bag + M. Cloud	MIT Bag + OGE + M. Cloud	Model	Lattice
N	65.4	53.8	51.9	43.8	1.0	1.0
Λ	77.1	67.3	66.4	58.9	1.35 (1.33)	-
Σ	61.5	50.8	50.5	42.6	0.97 (0.98)	0.92 (13)
Ξ	80.9	72.3	72.0	65.2	1.49 (1.44)	1.61 (33)

- The other columns show the results for the cloudy bag model that worked so well for the nucleon applied to whole octet

- Agreement remarkably good... suppression is not universal!

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Shanahan et al., Phys Rev Lett 110 (2013) 202001

Dependence of s- $\bar{s}$ on assumed cross-over

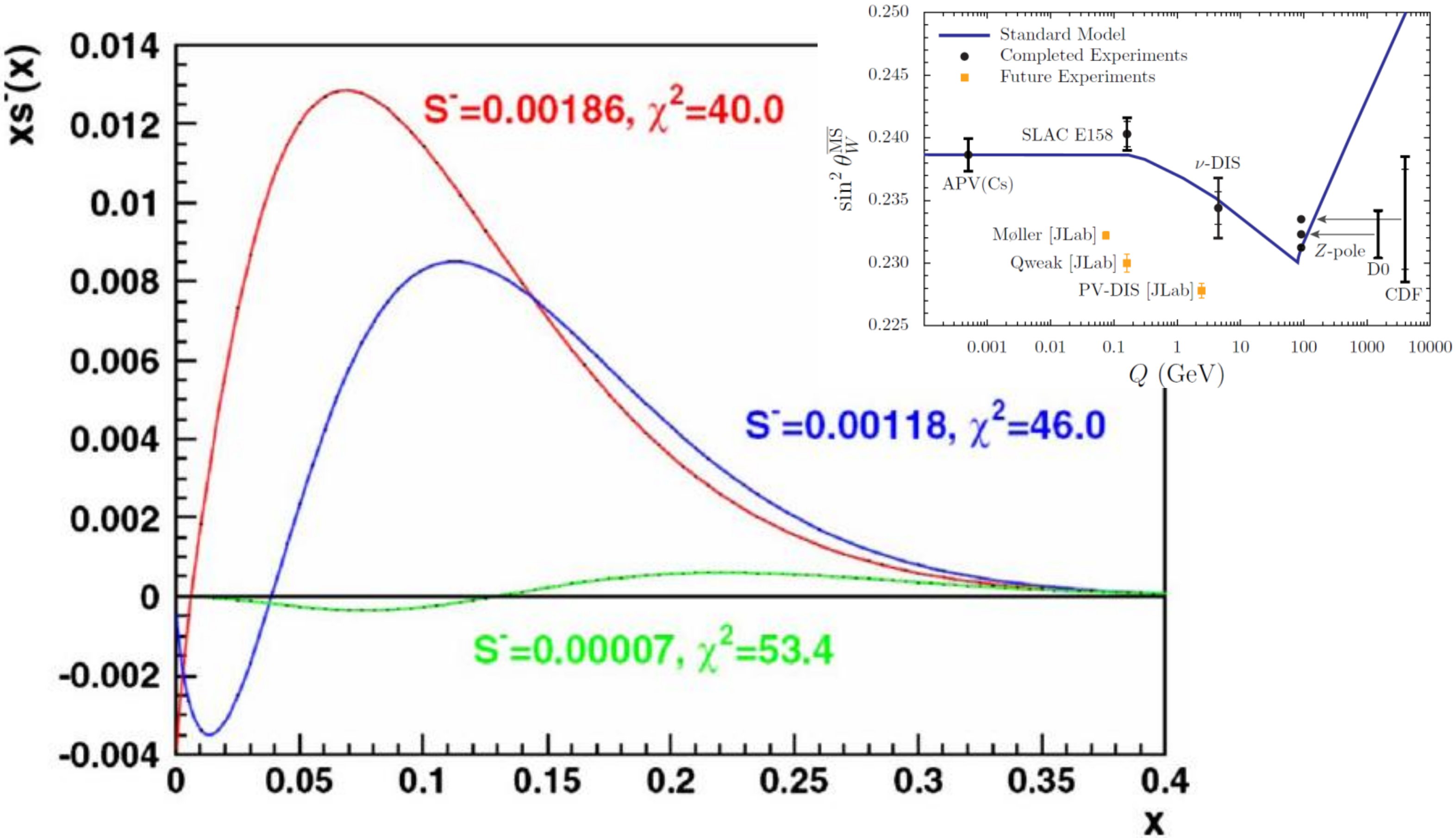
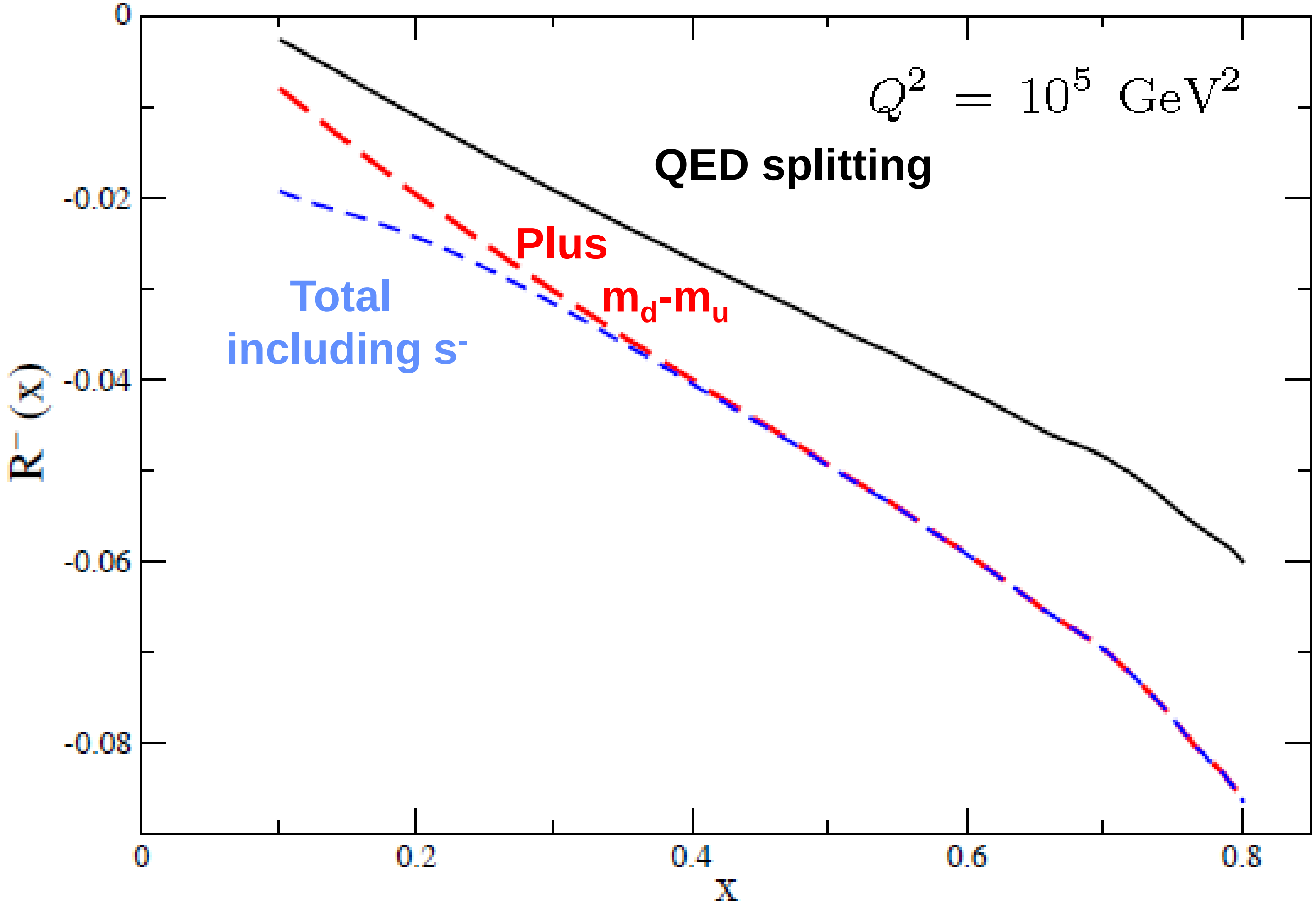


FIG. 16. (Color online) The quantity $xs^{-}(x) = x[s(x) - \bar{s}(x)]$ vs x, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The χ^2 value is listed for each curve. From Mason *et al.*, 2007.

SIDIS and EIC – maybe at LHC

Charge Symmetry : Future EIC or LHeC

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)}$$



Hobbs et al., Phys Lett (arXiv:1101.3923 [hep-ph])

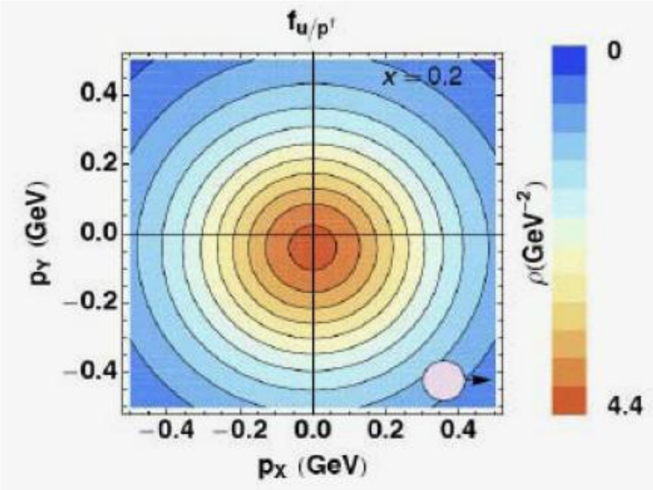
New observables

– 3D imaging of the nucleon

3-D Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

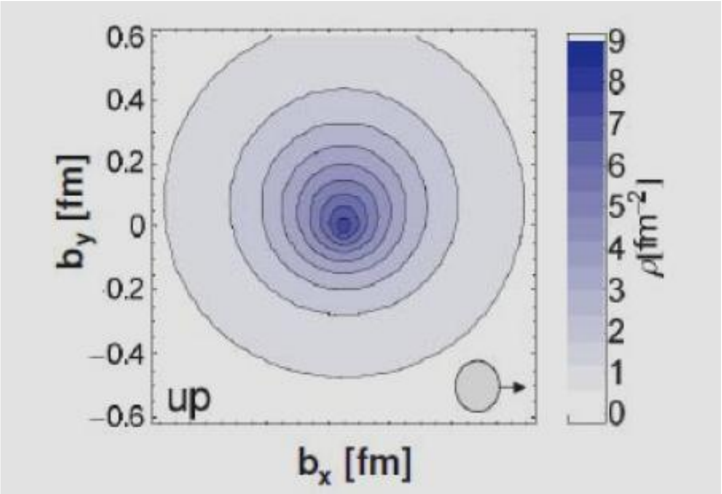


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**



QCDSF collaboration

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

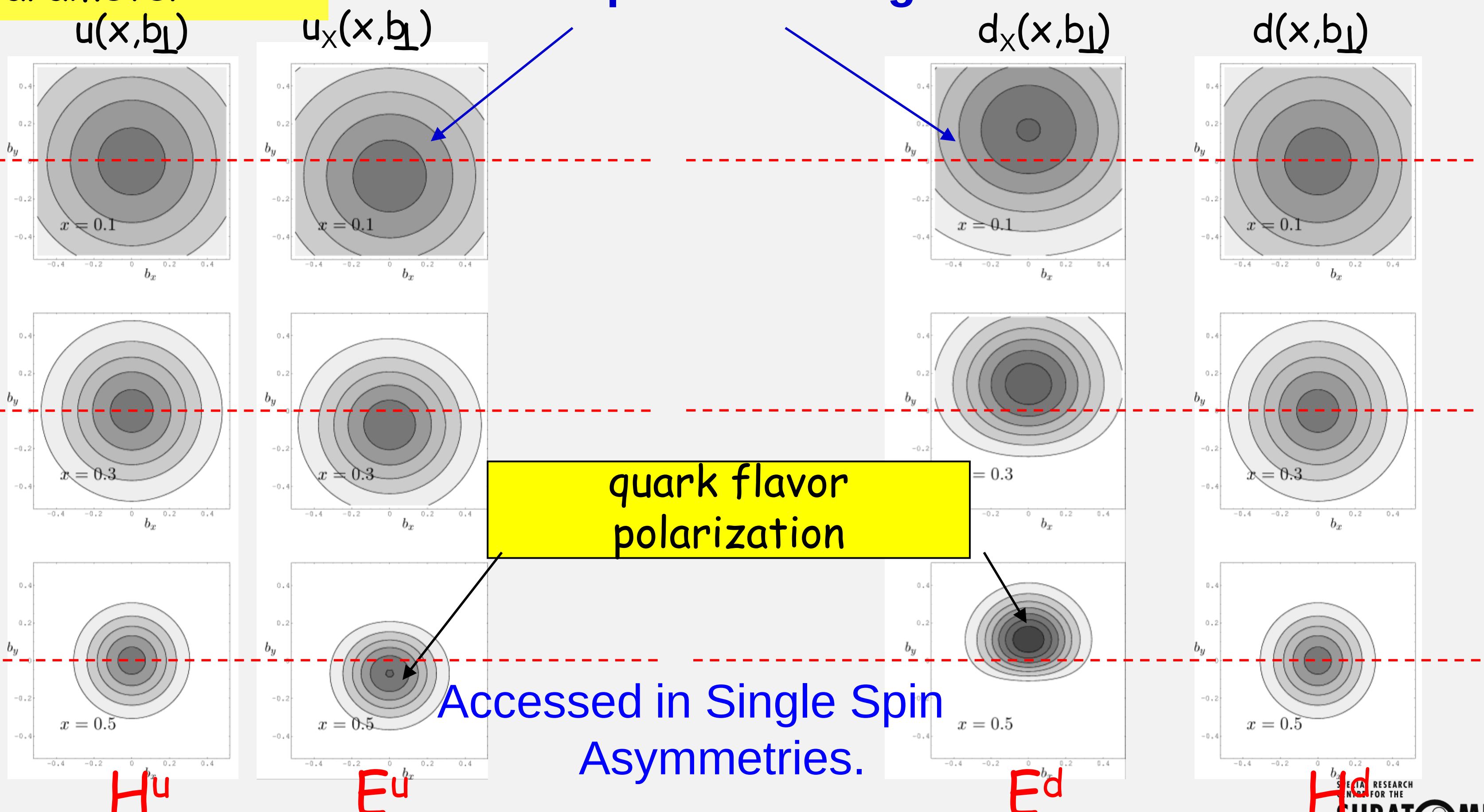
Guidal, Mulders, Niccolai, D'Hose, Sivers, Deshpande.... at this meeting

3D Images of the Proton's Quark Content

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$

$b_\perp$ - Impact parameter

transverse polarized target



Accessed in Single Spin Asymmetries.

M. Burkardt PRD 66, 114005 (2002)

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Detail:

Studies of Resonances using Lattice QCD

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**

Lüscher Method – a simple introduction

(from Ross Young)

- **Assumes that we are measuring two-particle levels**

- Bose symmetry

$$\psi(x) = \psi(-x)$$

- General solution
  - Right $\psi^{(r)}(x) = Ae^{-ikx} + Be^{ikx}$
  - Left $\psi^{(l)}(x) = Ae^{ikx} + Be^{-ikx}$
- Steady-state: conservation of probability $\Rightarrow |B| = |A|$
  - Define $\dfrac{B}{A} = e^{i2\delta}$

$$\Rightarrow \psi^{(r)}(x) = A\left(e^{-ikx} + e^{i2\delta(k)}e^{ikx}\right)$$

Periodic Boundary Conditions in 1D

- Periodic boundary conditions
  - “Box” length L

$$\psi(x+L)=\psi(x)$$

Suppose
$L > 2R$

- Boundary $x = \pm L/2$
  - Continuous: Bose symmetry $\Rightarrow \psi^{(r)}(L/2)=\psi^{(l)}(-L/2)$
  - Smooth

$$-ik\left(Ae^{ikL/2}-Be^{-iKL/2}\right)=ik\left(Ae^{ikL/2}-Be^{-iKL/2}\right),$$

$$\Rightarrow \quad \frac{B}{A}=e^{-ikL}.$$

- Potential defines phase shift through interaction region

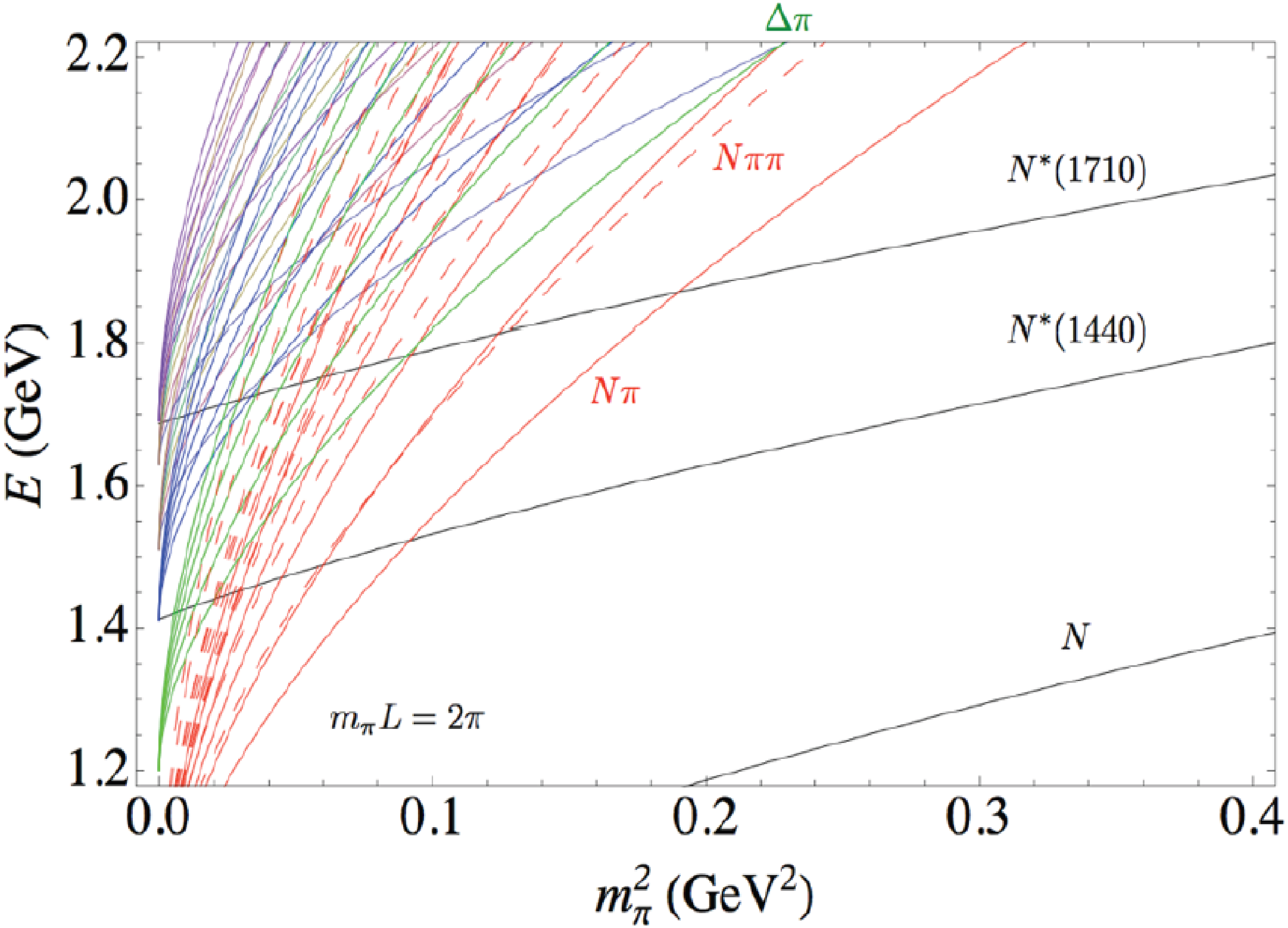
$$e^{i2\delta(k)}=e^{-ikL}$$

- $\Rightarrow$ Eigenvalue equation

$$0=\delta(k)+\frac{kL}{2}+n\pi \quad (n\in\mathbb{Z})$$

Interesting cases have many open channels – at least at realistic quark masses

In General: Multiple open channels



Generalisation of Lüscher method just gives a constraint

- Extension of Lüscher by He, Feng & Liu JHEP(2005)

$$S^{(l)}(E) = \begin{pmatrix} \eta_l e^{2i\delta_1^l} & i\sqrt{1-\eta_l^2}\, e^{i(\delta_1^l+\delta_2^l)} \\ i\sqrt{1-\eta_l^2}\, e^{i(\delta_1^l+\delta_2^l)} & \eta_l e^{2i\delta_2^l} \end{pmatrix}$$

- Scattering parameters as a function of E

$$\delta_1,\ \delta_2,\ \eta$$

- Finite-volume eigenvalue equation (s-wave)

$$\cos(\Delta_1 + \Delta_2 - \delta_1^0 - \delta_2^0) = \eta \cos(\Delta_1 - \Delta_2 - \delta_1^0 + \delta_2^0)$$

$$\Delta_i = \mathcal{M}_{00;00}(q_i^2) = \frac{\mathcal{Z}_{00}(1;q_i^2)}{\pi^{3/2} q_i}$$

See however: Hansen and Sharpe, Phys.Rev. D86 (2012) 016007 and Lellouch and Lüscher , Commun.Math.Phys., 219 (2011) 31, who consider complicated combinations of L and moving frames to get 3 conditions for 2 coupled channels

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Alternative: Effective Hamiltonian on a Finite Volume

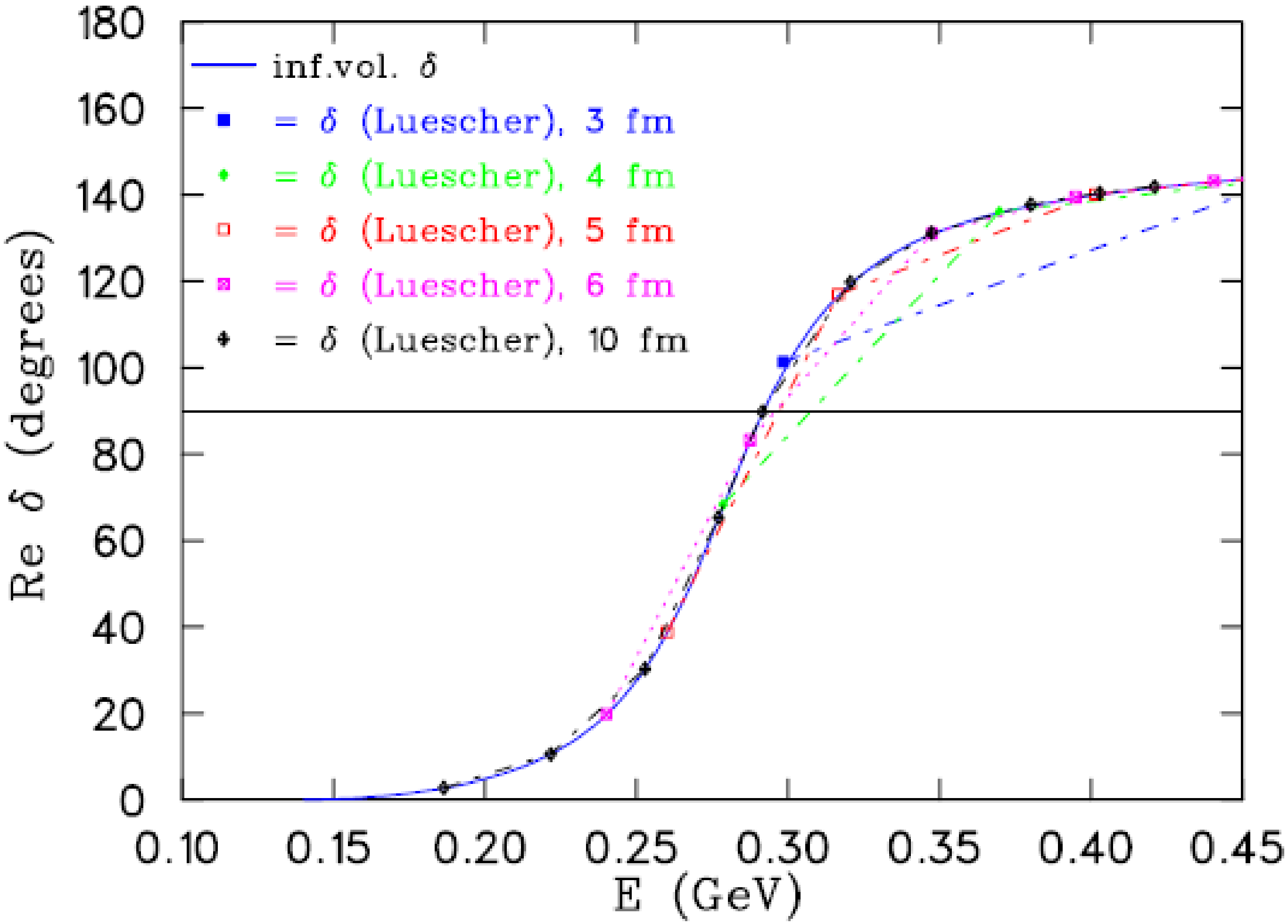
- **We consider the Δ resonance as the classic, well understood case in πN scattering**

- **Use cloudy bag model Hamiltonian** (A W Thomas Adv. Nucl. Phys. 13 (1984) 1)
  – initially $\Delta \to N\pi$ only

$$H_0 = \begin{pmatrix} \Delta_0 & 0 & 0 & \cdots \\ 0 & \omega_\pi(k_1) & 0 & \cdots \\ 0 & 0 & \omega_\pi(k_2) & \\ \vdots & \vdots & & \ddots \end{pmatrix} \qquad H_I = \begin{pmatrix} 0 & g^{\mathrm{fin}}_{\Delta N}(k_1) & g^{\mathrm{fin}}_{\Delta N}(k_2) & \cdots \\ g^{\mathrm{fin}}_{\Delta N}(k_1) & 0 & 0 & \cdots \\ g^{\mathrm{fin}}_{\Delta N}(k_2) & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

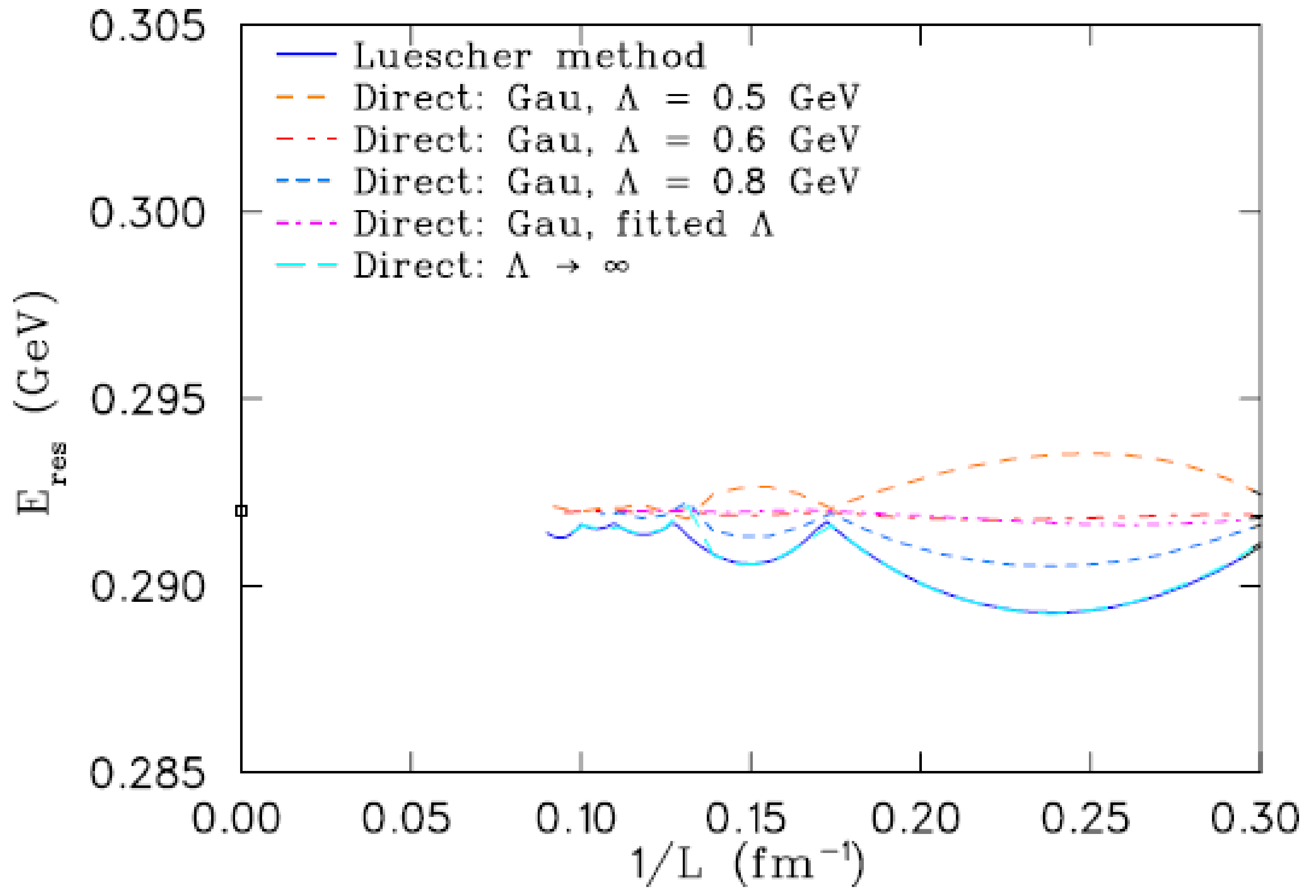
Hall, Hsu, Leinweber, Young, Thomas, arXiv:1303.4157
(Phys Rev D87, 094510 (2013))

Need to match lattice to resonance energy



Alternative to Lüscher's Method

- **Fit parameters of an effective Hamiltonian to the energy levels measured on the lattice**



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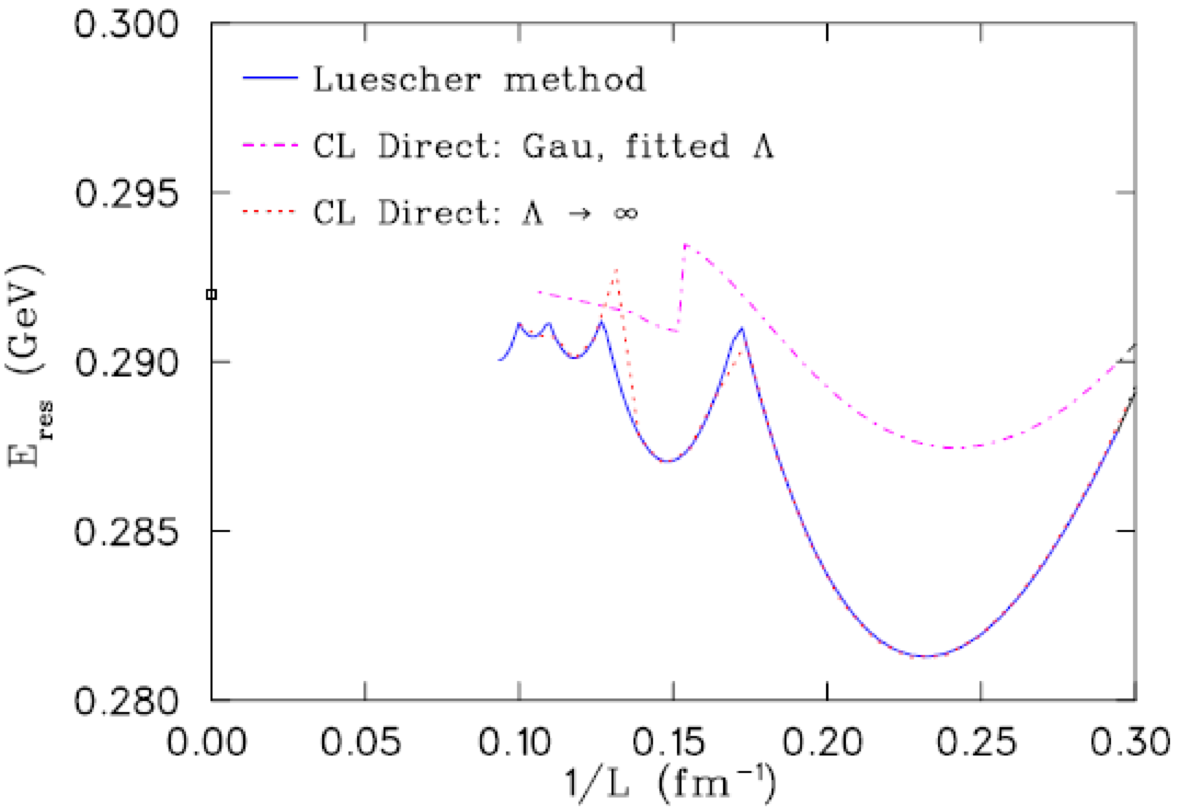
Test on a more complex model

- **Here we include the Chew-Low interaction <u>as well</u>**

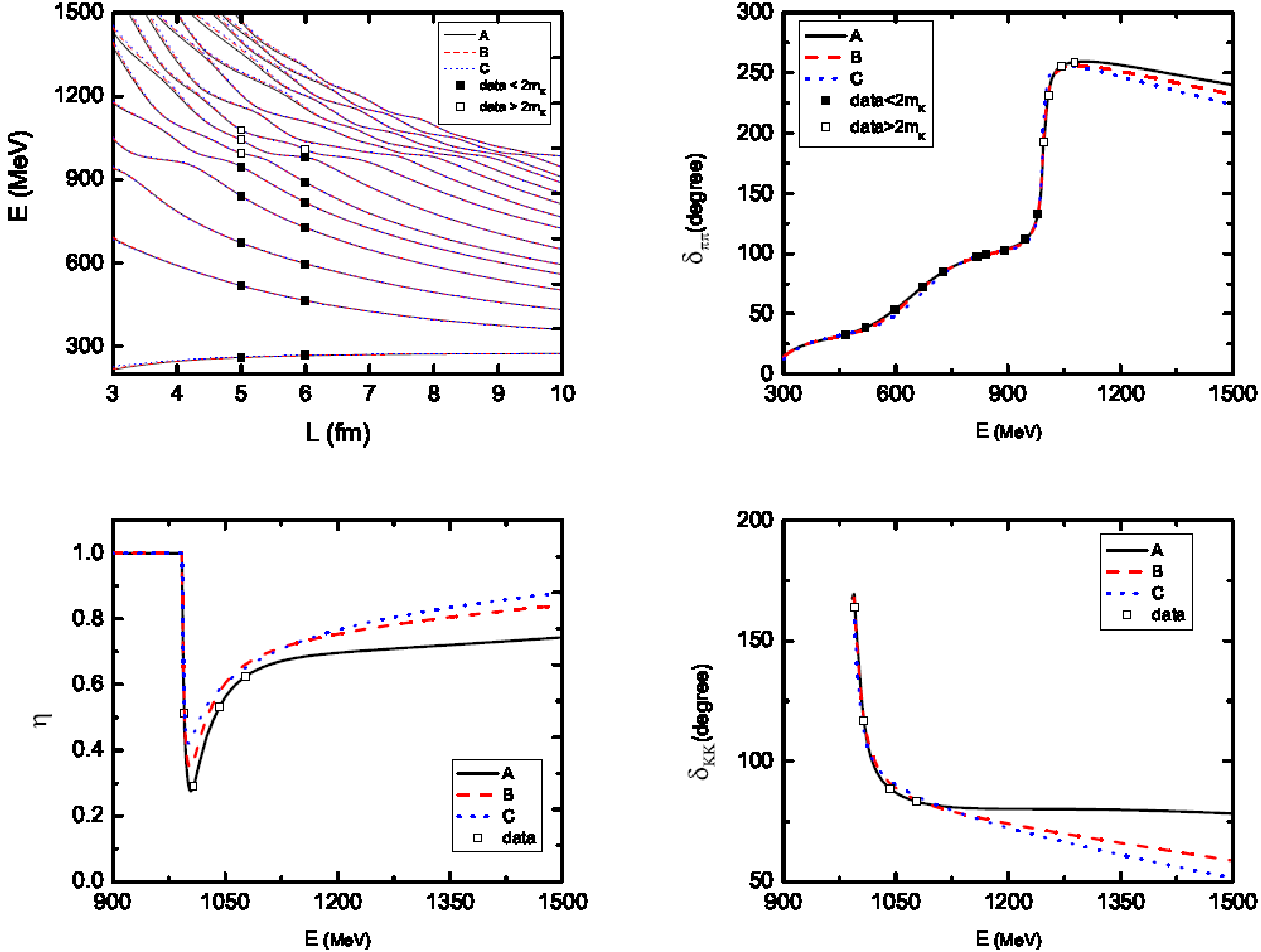
  (Théberge et al., Phys Rev D22 (1980) 2838)

  - **an historical puzzle**



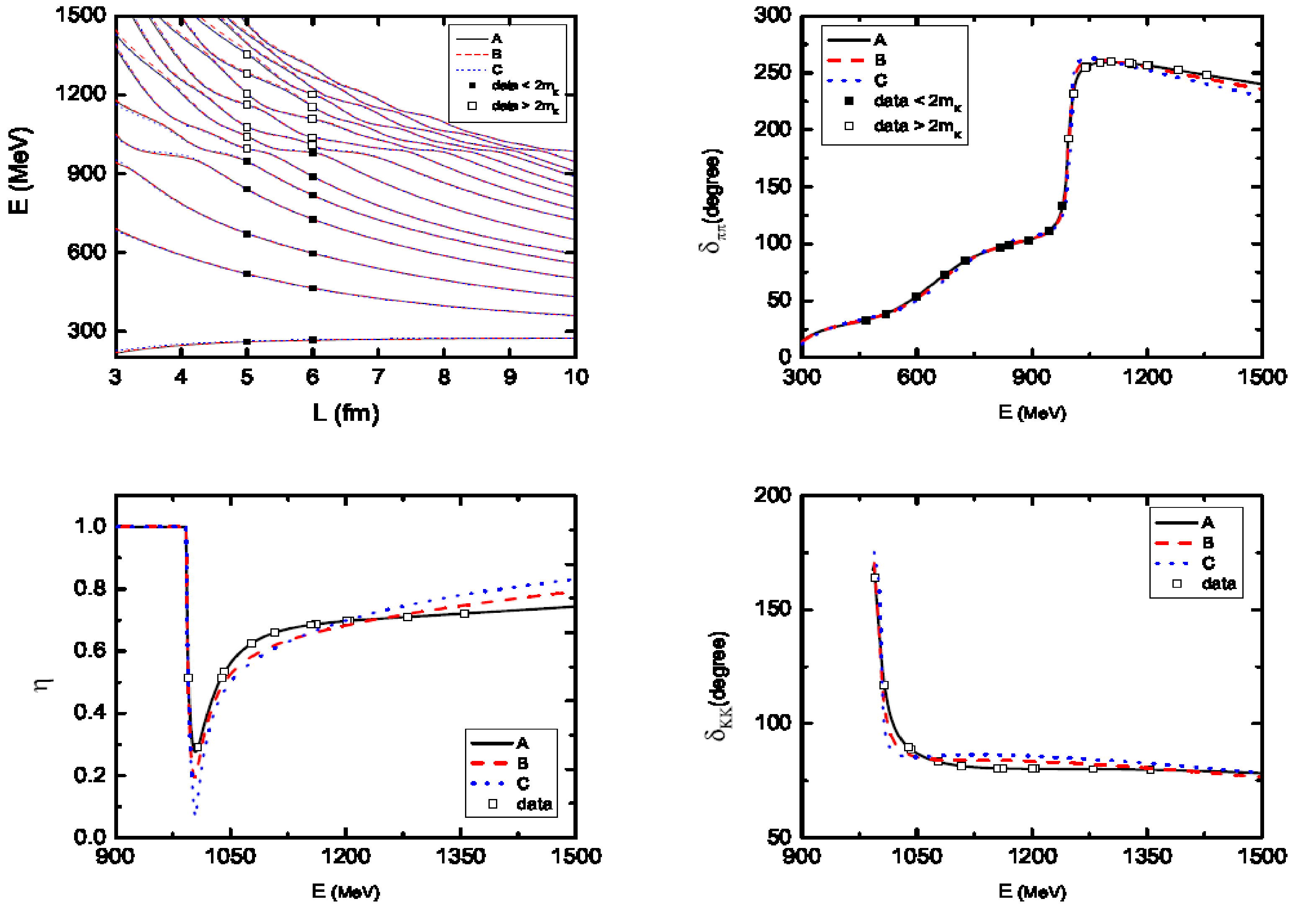
Hall et al., arXiv:1303.4157
(Phys Rev D87, 094510 (2013))

Coupled ππ-KK Study



Wu *et al.*, arXiv:1402.4868

Works well provided we have energy levels



Finally the Λ(1405)

- **50 years after speculation by Dalitz, we prove unambiguously that it is a Kbar-N bound state!**

- **Need Hamiltonian analysis of lattice data**

- **and Strange magnetic form factor**

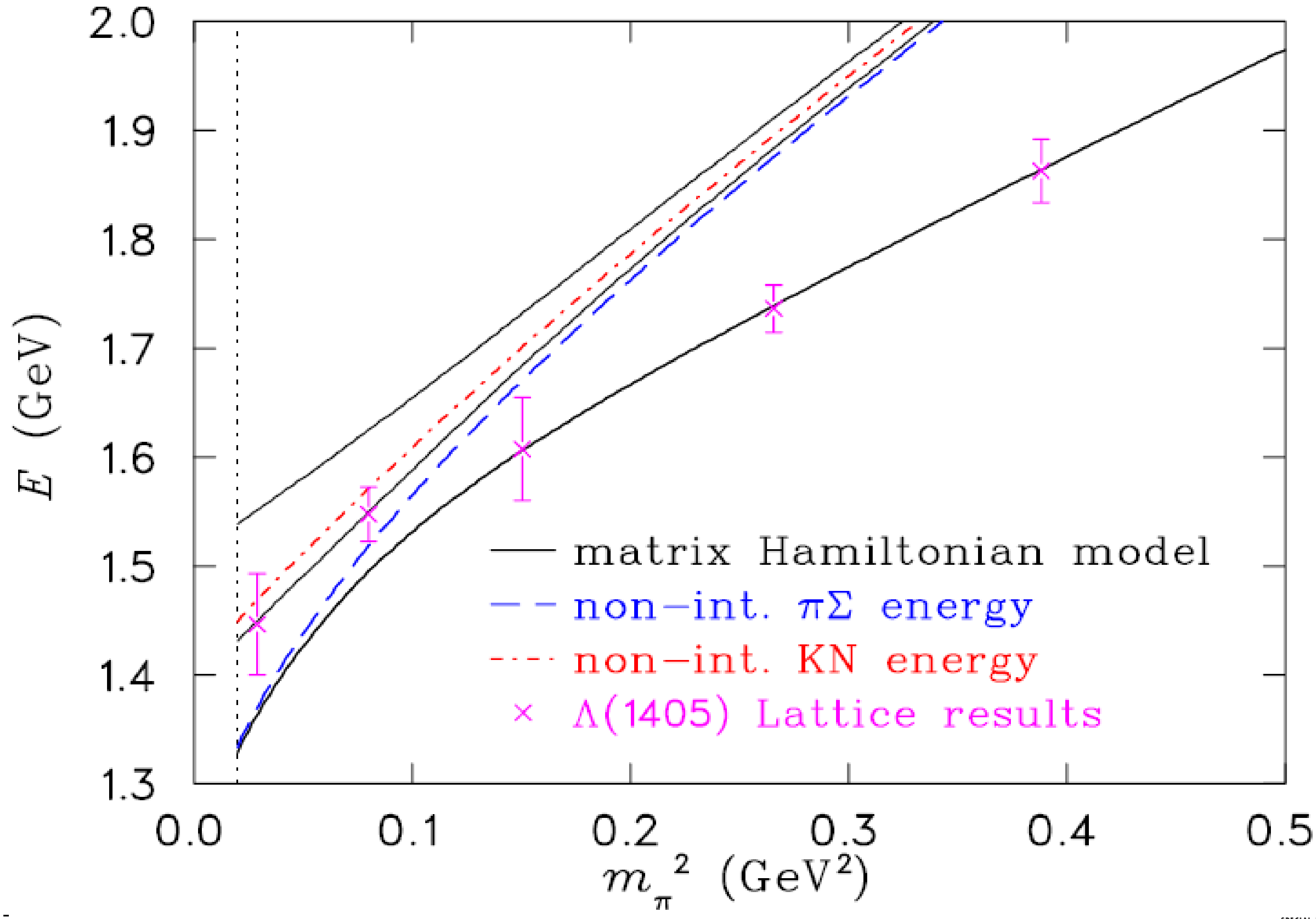
Hamiltonian analysis

- In a finite periodic volume, momentum is quantised to $n\,(2\pi/L)$.
- Working on a cubic volume of extent L on each side, it is convenient to define the momentum magnitudes

$$k_n = \sqrt{n_x^2 + n_y^2 + n_z^2}\,\frac{2\pi}{L}\,,$$

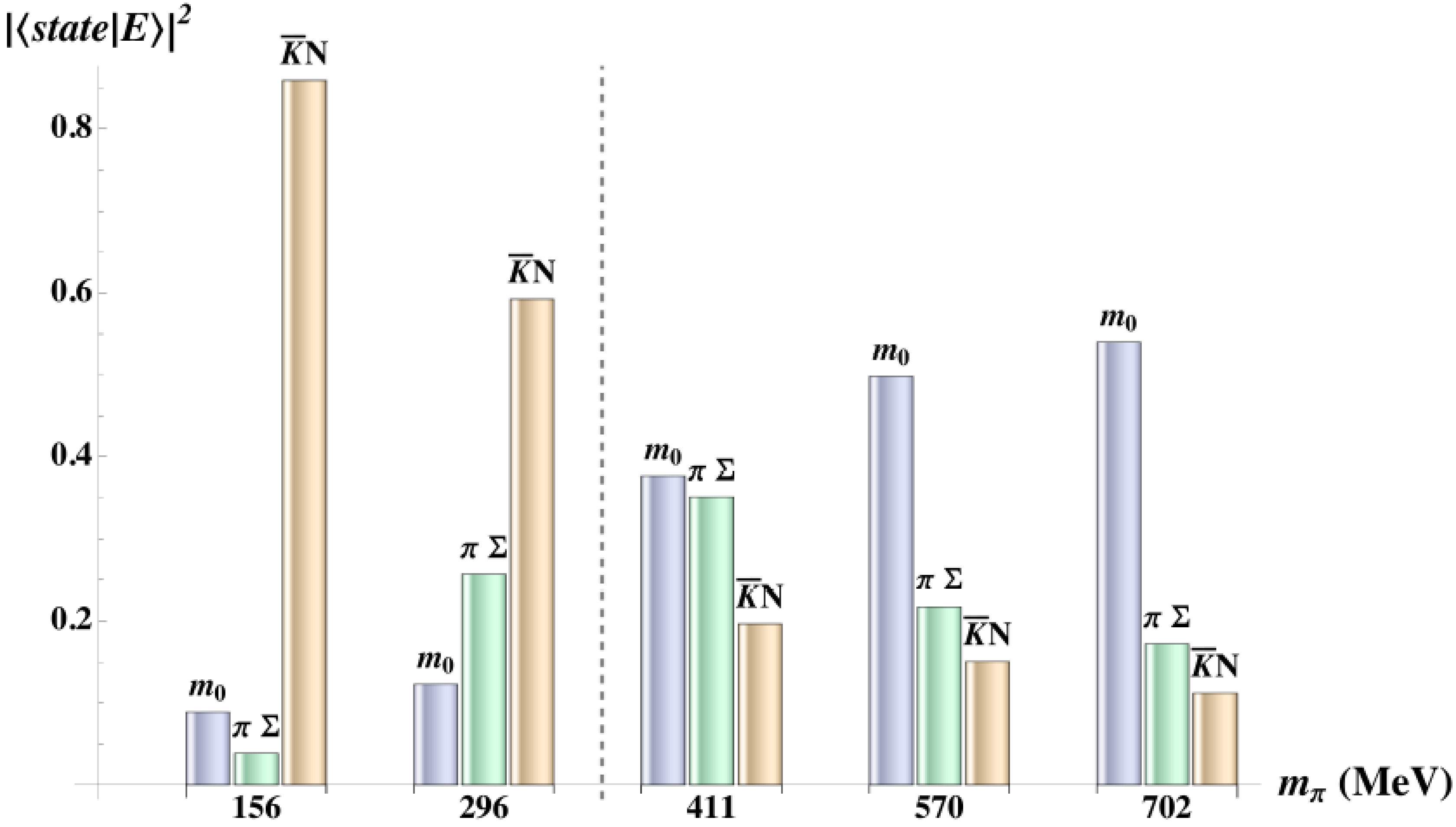
  with $n_i = 0, 1, 2, \ldots$ and integer $n = n_x^2 + n_y^2 + n_z^2$.
- The non-interacting Hamiltonian H_0 has diagonal entries corresponding to the relativistic non-interacting meson-baryon energies available on the finite periodic volume at total three-momentum zero.
- The four octet meson-baryon interaction channels of the $\Lambda(1405)$ are included: $\pi\Sigma$, $\overline{K}N$, $K\Xi$ and $\eta\Lambda$.

Hamiltonian analysis of energy levels



Leinweber *et al.*, to appear

Decomposition of Hamiltonian eigenstates



Leinweber *et al.*, to appear

Summary

- We have a wealth of exciting, fundamental questions to address

- Lattice QCD, phenomenology and experiment working beautifully together
  - Hamiltonian methods promising: e.g. Λ(1405)

- A host of new and upgraded experimental facilities:
  FAIR, JPARC, RHIC;   JLab 12 GeV, EIC(s)

- Let's use all this to build a deeper understanding of how QCD works − how hadron and nuclear structure emerges

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September 11-16 2016

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References for Model Predictions (from slide 3)

Spin-flavour dependence of PDFs:
Phys. Rev. Lett. 35 (1975) 1416;   Phys. Lett. B212 (1988) 227

dbar > ubar: Phys. Lett. B126 (1983) 97

s .neq. sbar: Phys. Lett. B191 (1987) 205

nucleon spin & orbital angular momentum:
Physics Letters B 663 (2008) 302

Delta ubar and Delta dbar: Phys Rev D44 (1990) 2653

CSV in PDFs: Mod Phys. Lett. A9 (1994) 1799

Flavour dependent nuclear SFs: Phys. Lett. B693 (2010) 462

SU(3) breaking in g_A^8: Phys. Lett. B684 (2010) 216-220