Exposing the Mass at the Heart of Visible Matter

Craig Roberts, Physics Division

Collaborators: 2013-Present

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45. Peter Tandy (KSU);
46. Tony Thomas (U.Adelaide) ;
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Baryon Structure

$$\mathcal{L}_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} \qquad) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Baryon Structure

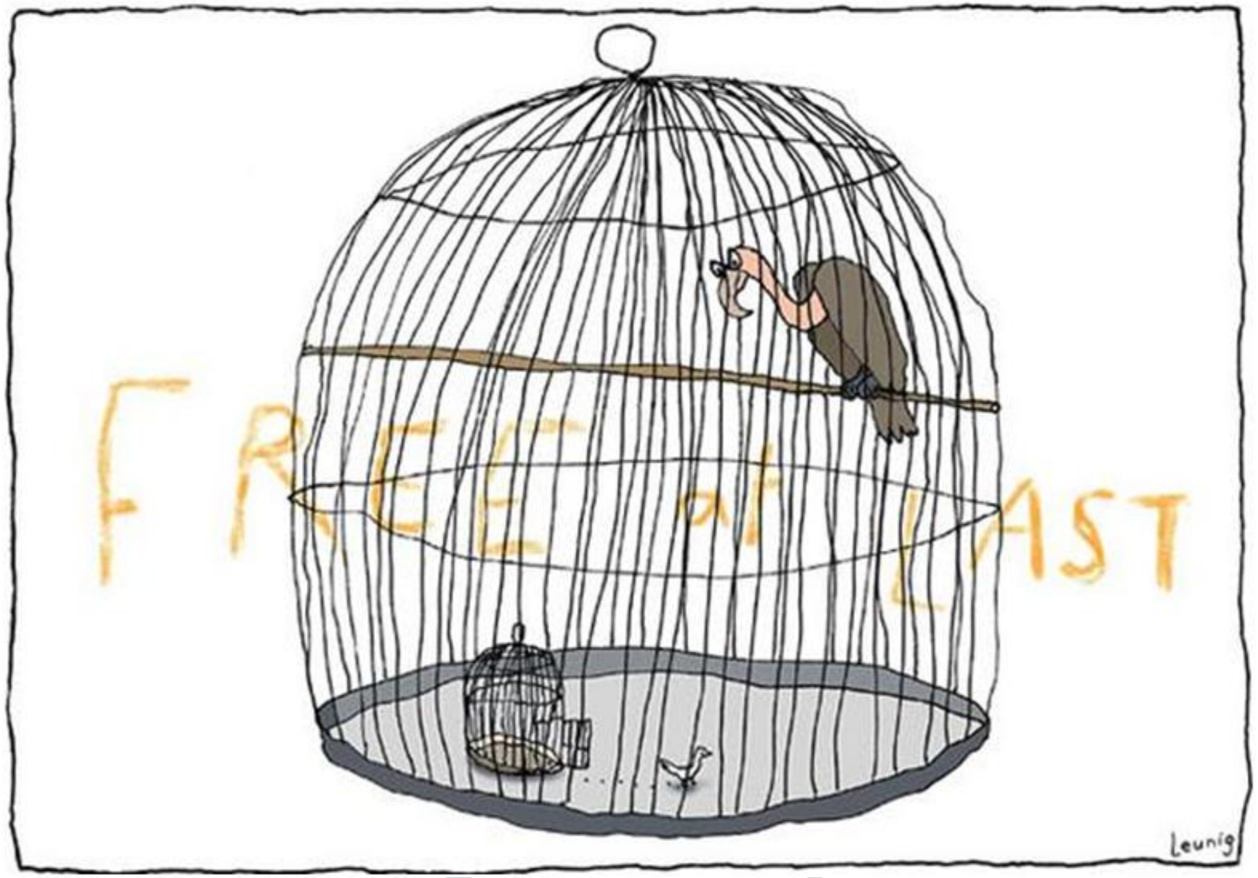
Why?

- Classical chromdynamics … non-Abelian local gauge theory
- Remove the current mass … no energy scale left
- *No dynamics in a scale-invariant theory*; only kinematics … the theory looks the same at all length-scales … there can be no clumps of anything … *hence bound-states are impossible*.
- *Our Universe can't exist*
- *Higgs boson doesn't solve this problem* … normal matter is constituted from light-quarks & the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce
- *Where did it all begin?*

  … becomes … Where did it all come from?

Overarching Science Challenge for the coming decade

Discover nature of confinement, its relationship to DCSB – the Origin of Visible Mass – and the connection between them



What is Confinement?

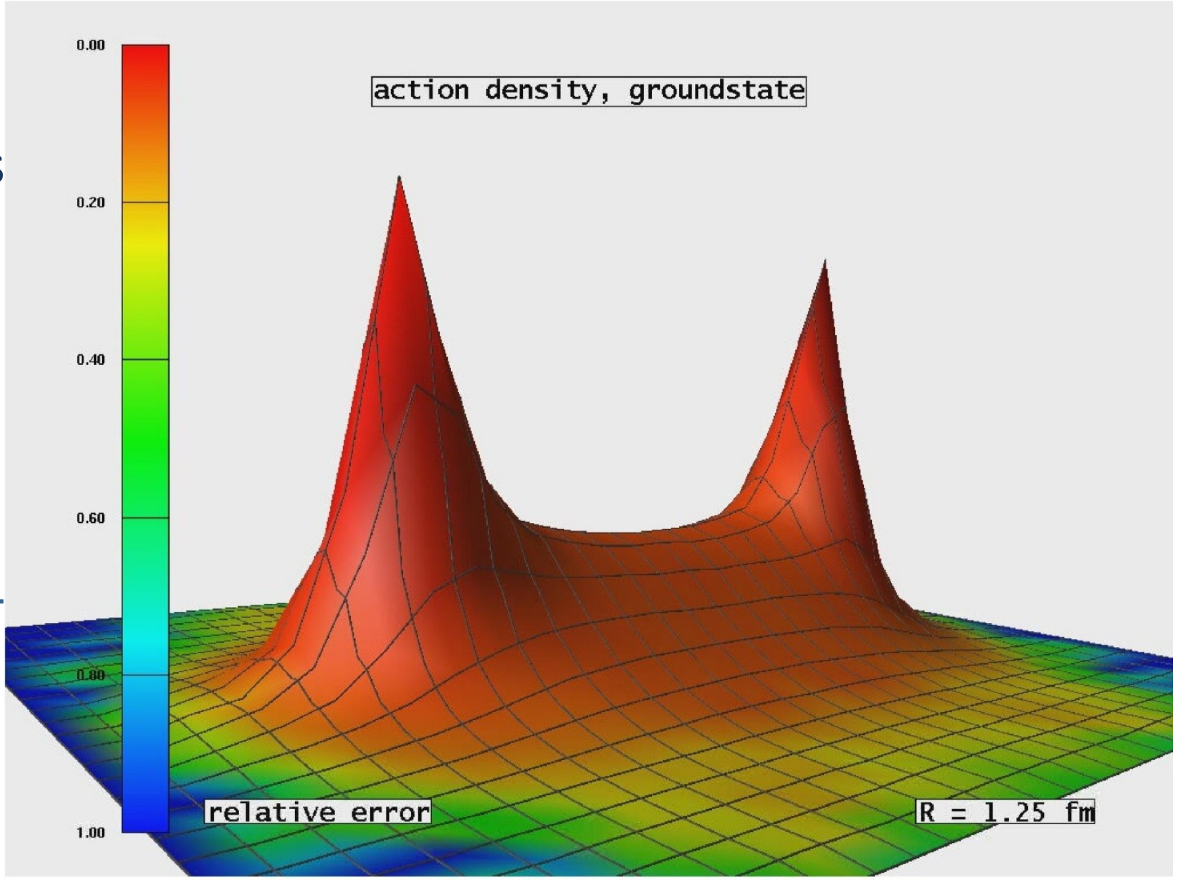
Light quarks & Confinement

- Folklore … *Hall-D Conceptual Design Report(5)*

  "The color field lines between a quark and an anti-quark form flux tubes.

  A unit area placed midway between the quarks and perpendicular to the line connecting them intercepts a constant number of field lines, independent of the distance between the quarks.

  This leads to a constant force between the quarks – and a large force at that, equal to about 16 metric tons."



Light quarks & Confinement

- Problem:
  16 tonnes of force
  makes a lot of pions.

Light quarks & Confinement

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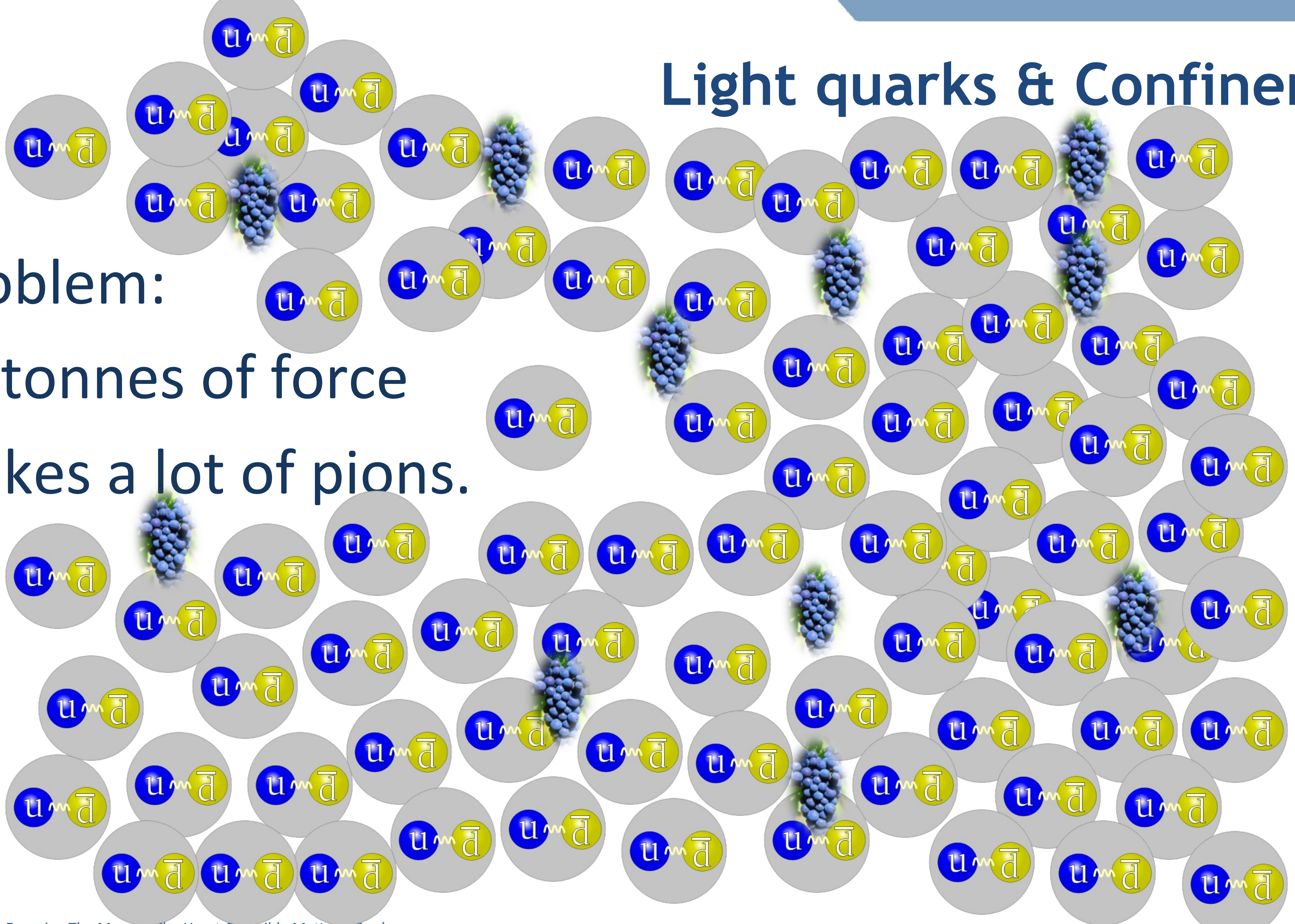
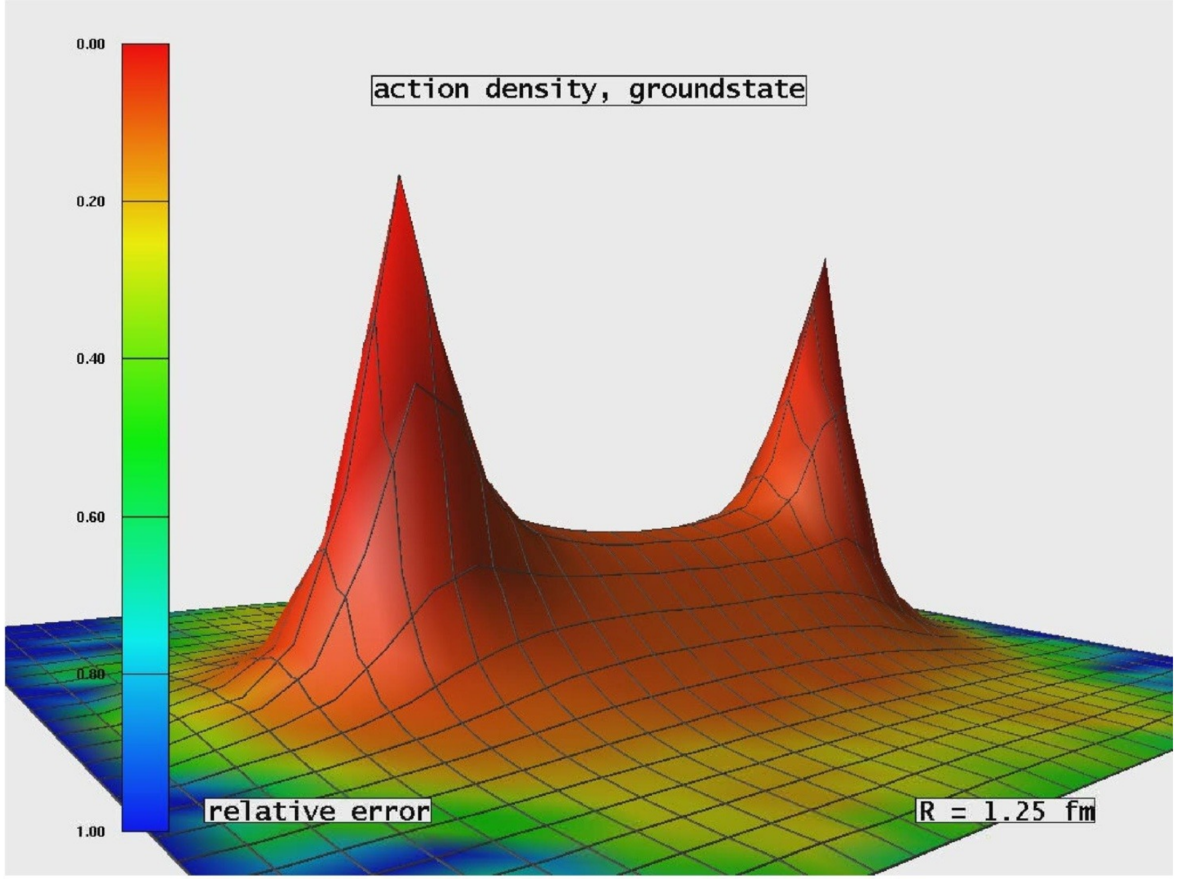


G. Bali et al., [PoS LAT2005 (2006) 308](PoS LAT2005 (2006) 308)

Light quarks & Confinement

- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***



Light quarks & Confinement

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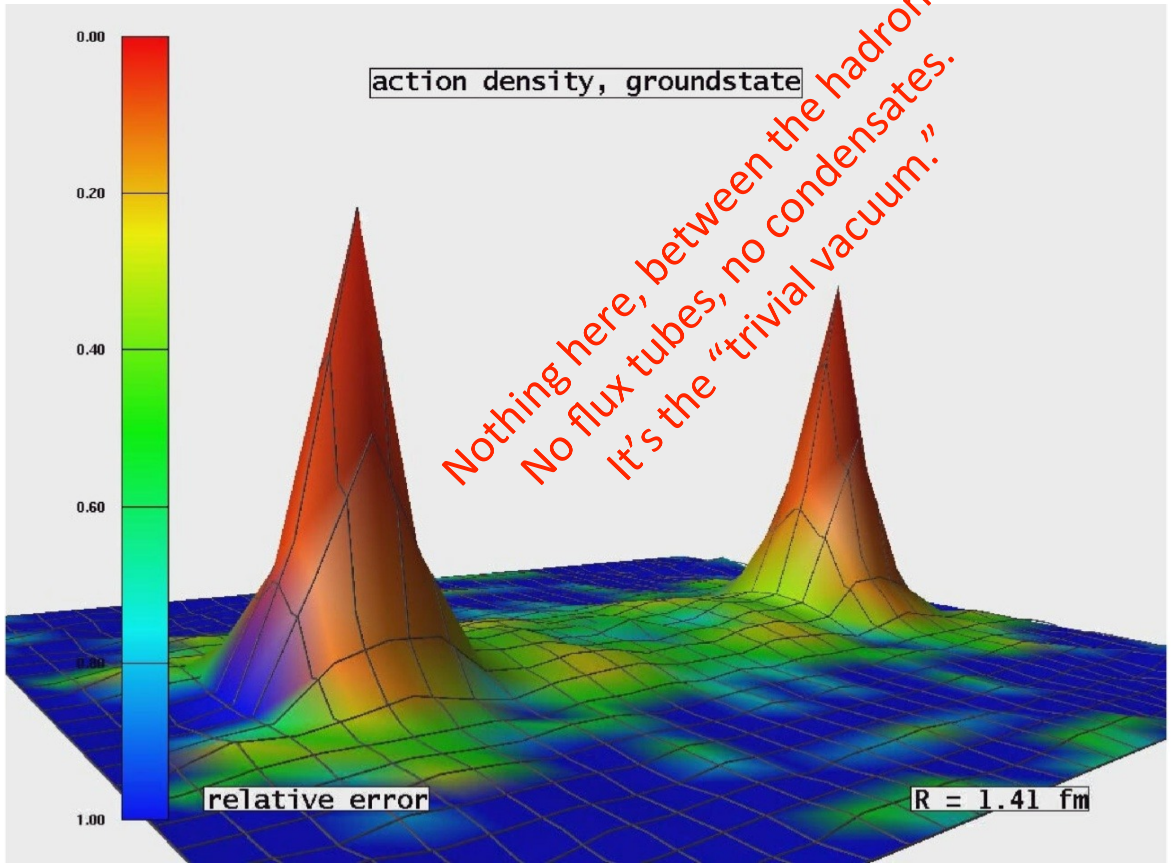
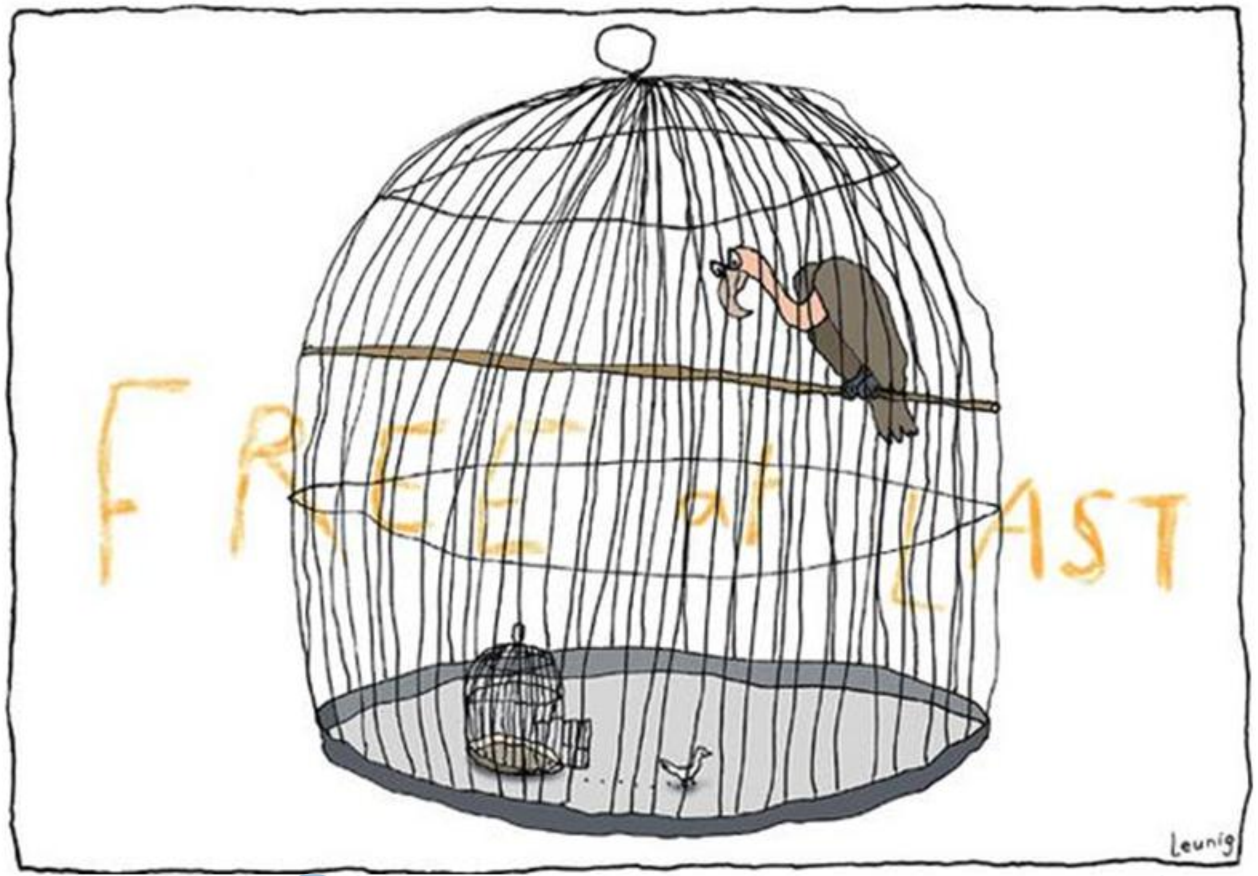
Confinement contains condensates
Brodsky, Roberts, Shrock,Tandy
arXiv:1202.2376 [nucl-th], Phys. Rev. C**85** (2012) 065202





Confinement is dynamical

Confinement

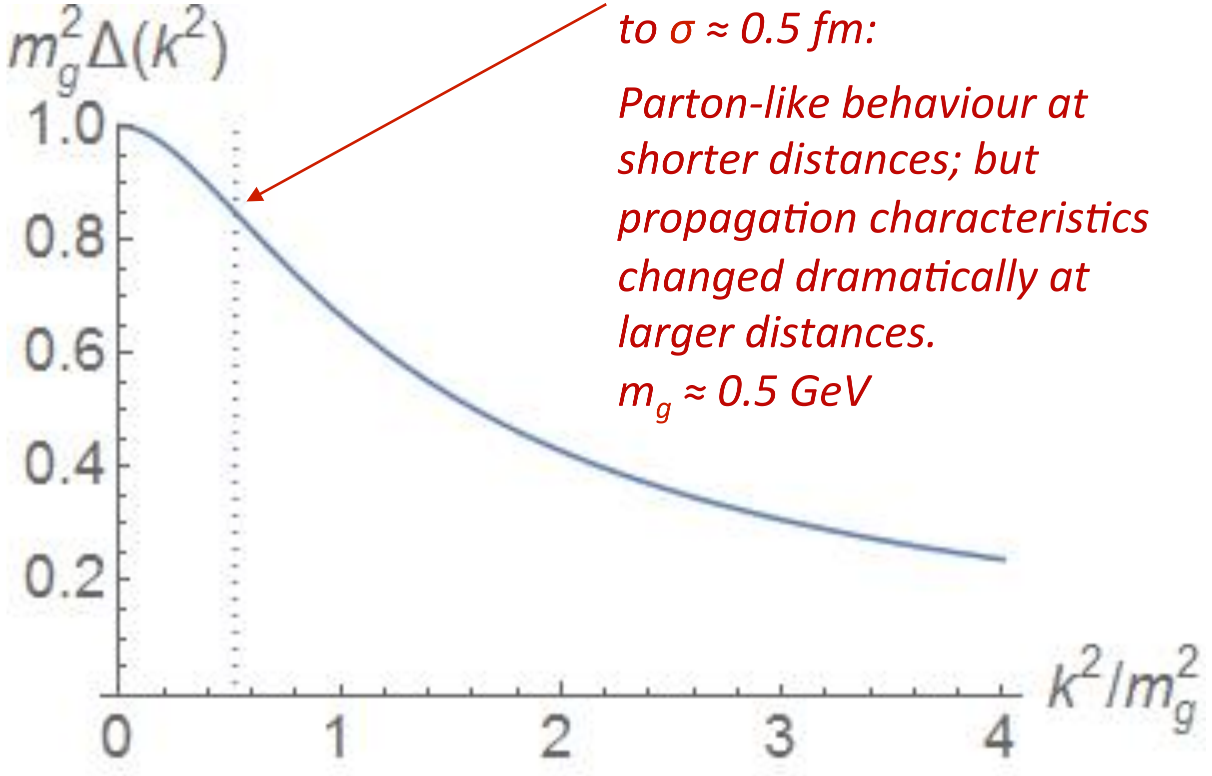
- All continuum and lattice predictions for Landau-gauge gluon & quark propagators exhibit an inflection point in k^2

$\Rightarrow$ Violate reflection positivity = sufficient for confinement

$\Rightarrow$ Such states have negative norm

$\Rightarrow$ Negative norm states are not observable

$\Rightarrow$ Observable states of a physical Hamiltonian have positive norm



Inflexion point corresponds to $\sigma \approx 0.5$ fm:

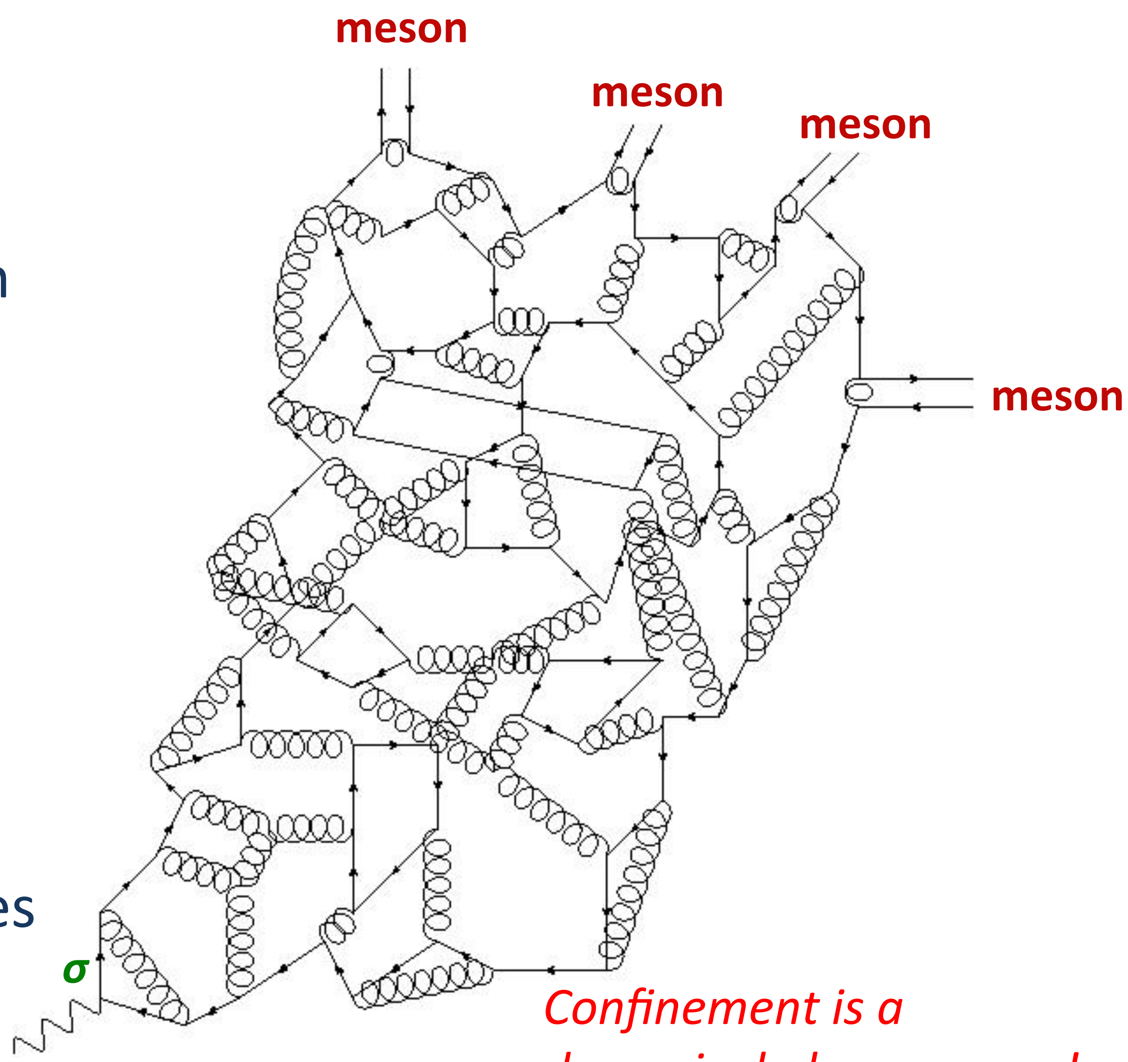
Parton-like behaviour at shorter distances; but propagation characteristics changed dramatically at larger distances.

$m_g \approx 0.5$ GeV

Test: compute fragmentation functions & TMDs ⇒ compare with data

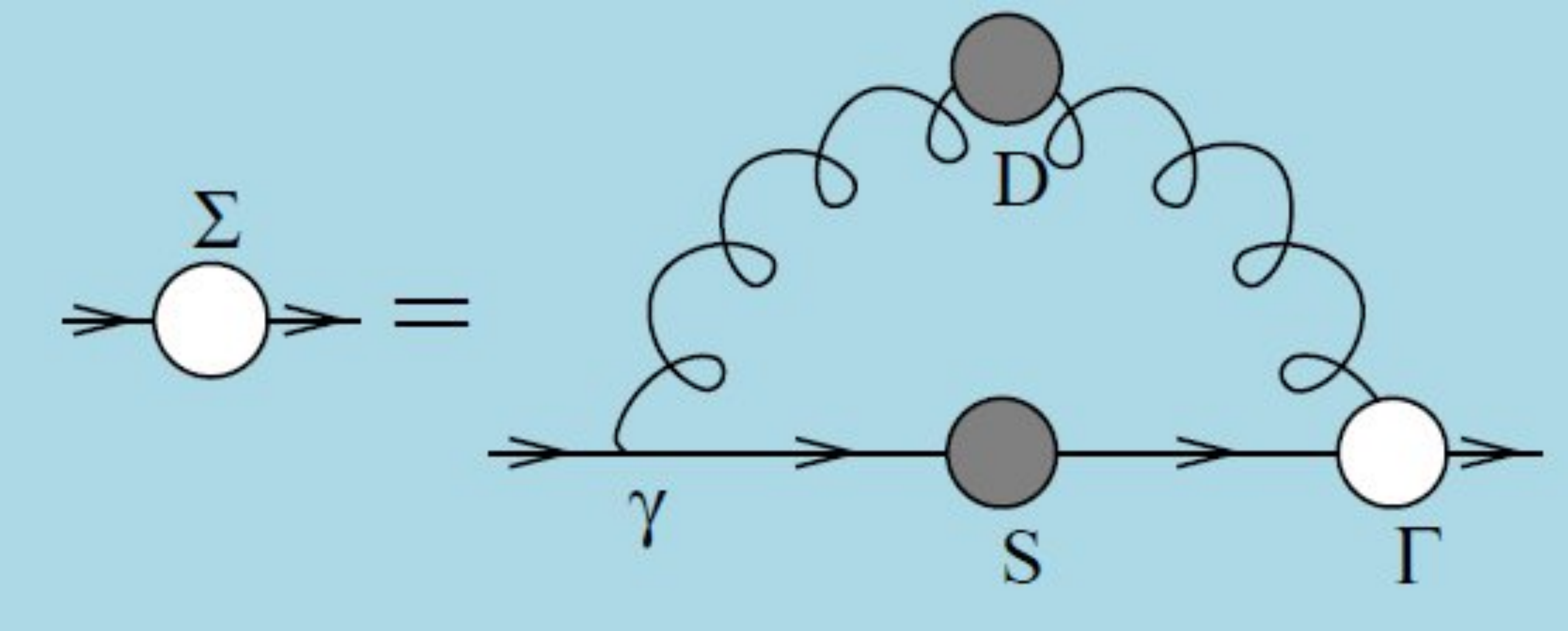
Quark Fragmentation

- A quark begins to propagate
- But after each "step" of length ***σ***, on average, an interaction occurs, so that the quark *loses* its identity, sharing it with other partons
- Finally, a cloud of partons is produced, which coalesces into colour-singlet final states



Confinement is a dynamical phenomenon!

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

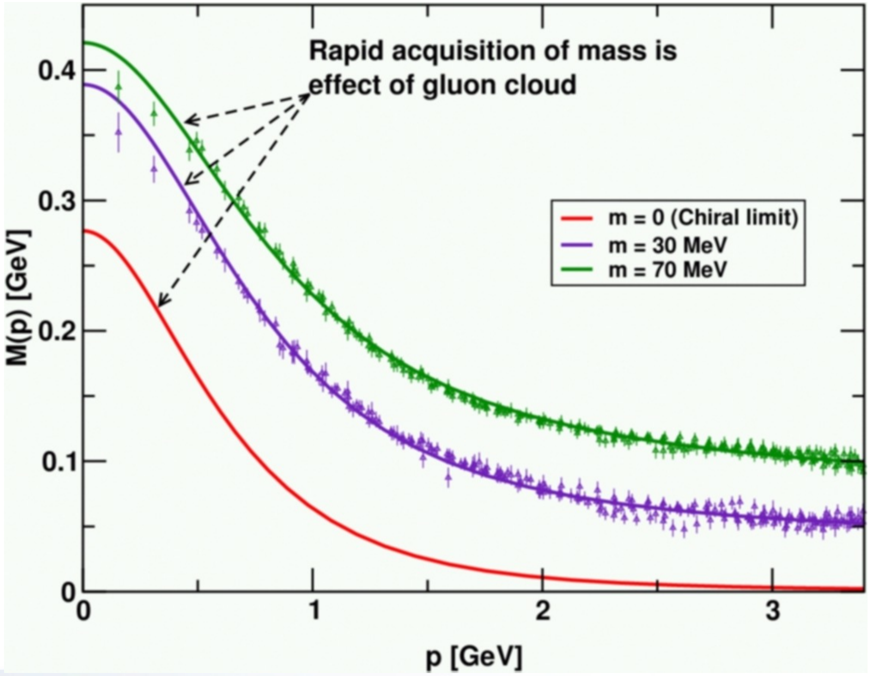


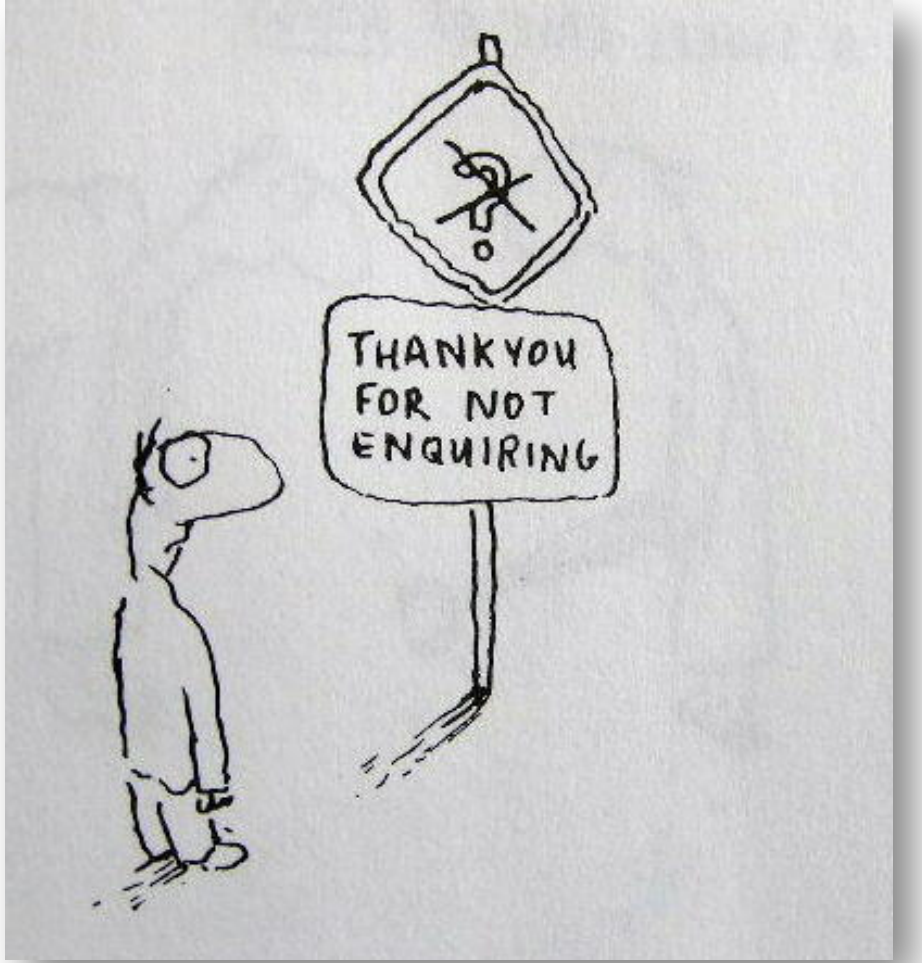
DCSB Paradigm

DCSB

- Dynamical chiral symmetry breaking (DCSB) is a crucial emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory indicates that it is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of *mass from nothing*.
- ***Dynamical***, not spontaneous
  - Add nothing to *QCD* ,

    No Higgs field, nothing! Effect achieved purely through quark+gluon dynamics.





Enigma of Mass

Maris, Roberts and Tandy
*nucl-th/9707003, Phys.Lett. B**420** (1998) 267-273*

Pion's Goldberger -Treiman relation

- Pion's Bethe-Salpeter amplitude

  Solution of the Bethe-Salpeter equation

$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5 \Big[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P) + \sigma_{\mu\nu}\, k_\mu P_\nu\, H_\pi(k;P) \Big]$$

- Dressed-quark propagator $S(p) = \dfrac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$

- Axial-vector Ward-Takahashi identity entails

$$f_\pi E_\pi(k;P=0) = B(k^2)$$

Owing to DCSB & Exact in Chiral QCD

***Miracle*: two body problem solved, almost completely, once solution of one body problem is known**

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

$$f_\pi E_\pi(p^2) = B(p^2)$$

The most fundamental expression of Goldstone's Theorem and DCSB in SM

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

$$f_\pi E_\pi(p^2) \Leftrightarrow B(p^2)$$

Pion exists if, and only if, mass is dynamically generated

$$f_\pi E_\pi(p^2) = B(p^2)$$

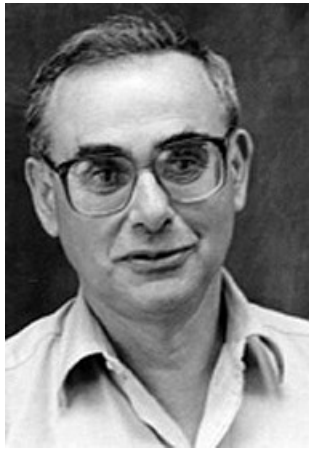
This algebraic identity is why QCD's pion is massless in the chiral limit

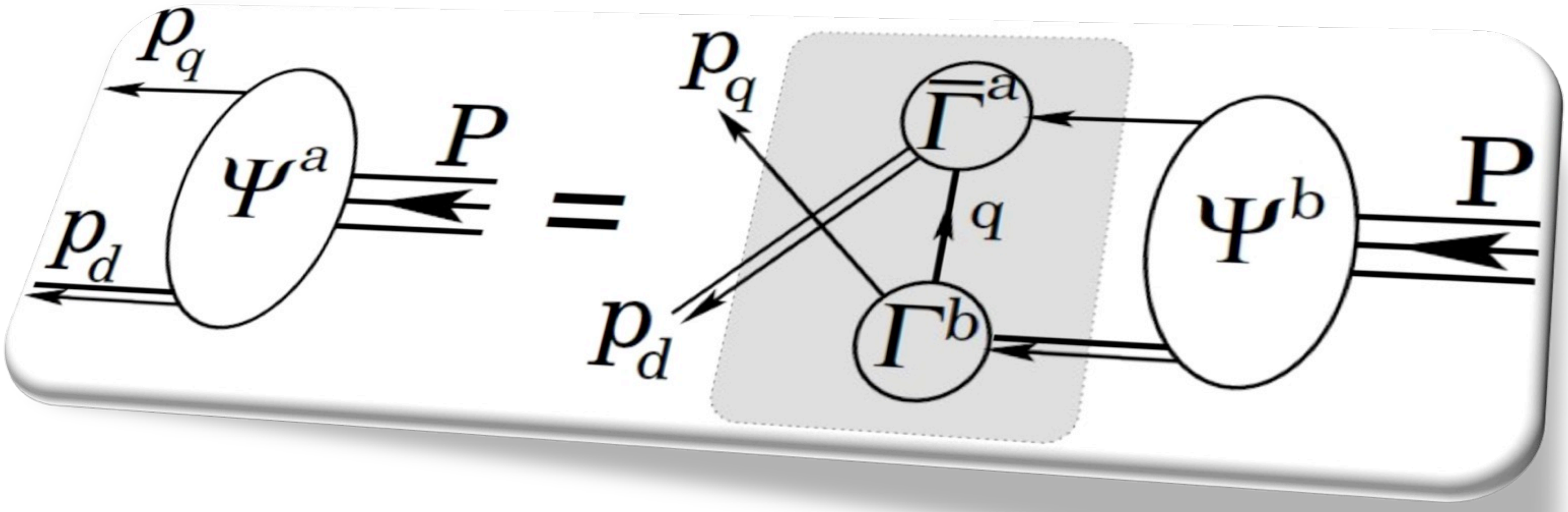
Enigma of mass

- The quark level Goldberger-Treiman relation shows that DCSB has a very deep and far reaching impact on physics within the strong interaction sector of the Standard Model; viz.,

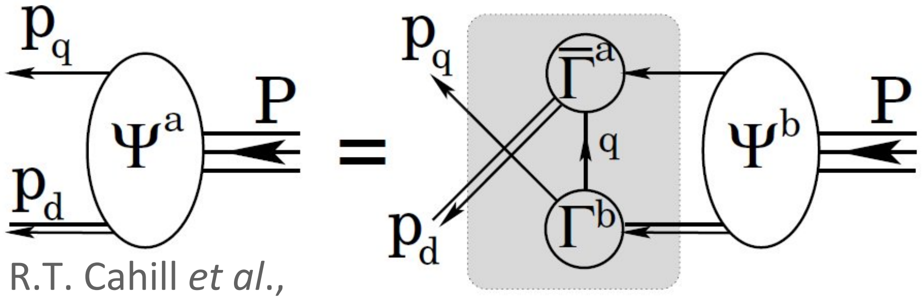
  Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

- This emphasises that Goldstone's theorem has a pointwise expression in QCD
- Hence, pion properties are an almost direct measure of the dressed-quark mass function.
- Thus, enigmatically, the properties of the *massless* pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.





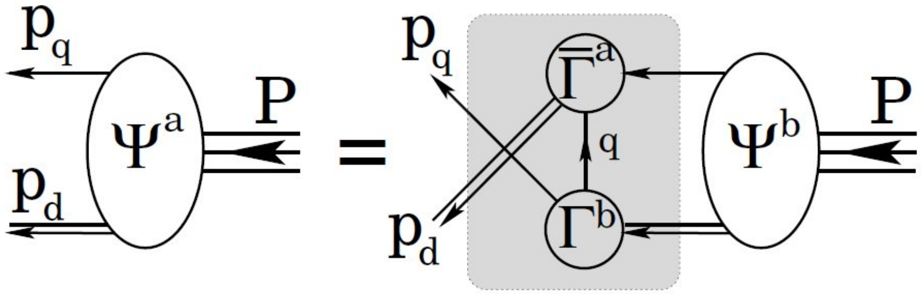
Spectrum & Structure of Baryons



R.T. Cahill *et al.*,
[Austral. J. Phys. 42 (1989) 129-145]

Baryon Structure

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Confinement and DCSB are readily expressed
- ***Prediction***: owing to *DCSB in QCD, strong diquark correlations exist within baryons*
- Diquark correlations are not pointlike
  - Typically, $r_{0+} \sim r_{\pi}$ & $r_{1+} \sim r_{\rho}$ (actually 10% larger)
  - They have soft form factors



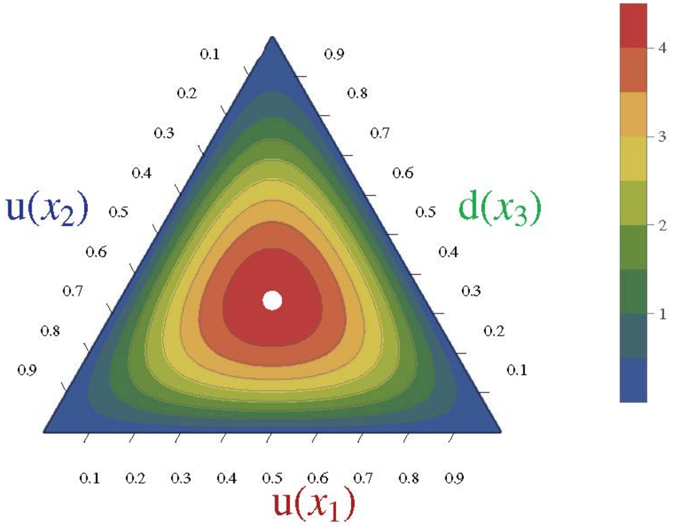
Baryon Structure

- Poincaré … Faddeev equation sums all possible exchanges and interactions that ca… …een three dressed-quarks
- Confineme… …ily expressed
- ***Prediction***: strong… …exist within baryons as a dynamical consequence of DCSB i…
  - T… … pion from two dynamically-massive c… …tion b… …lour-antitriplet channels within a…
- Diqu… …intlike
  - T… (actually 10% larger)
  - T…

Nucleon wave function can be calculated … prediction of nucleon properties is possible

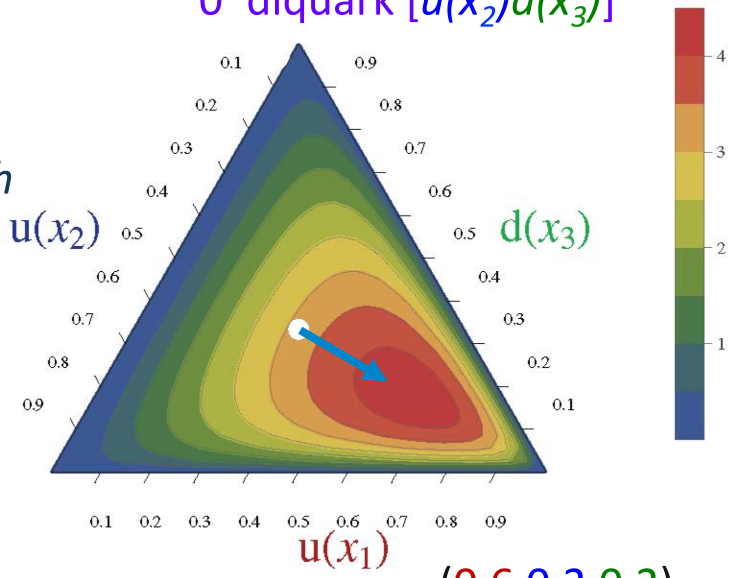
Nucleon Parton Distribution Amplitudes

- Computations underway. First results available.



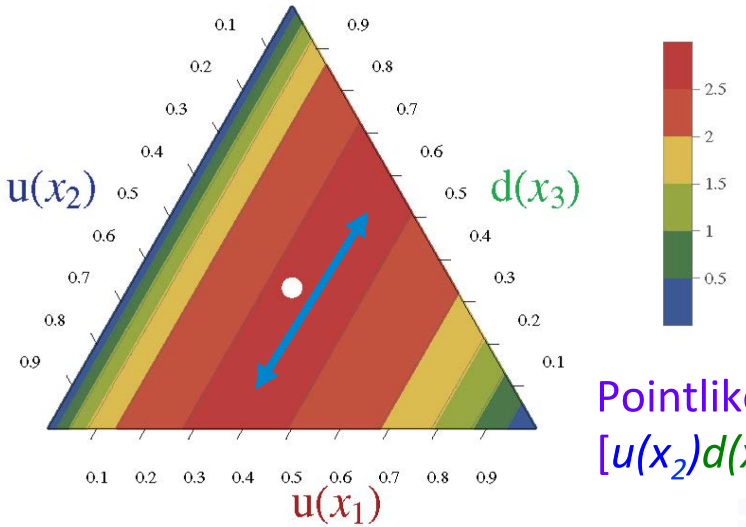
Diquark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton's light-front momentum

Realistic, finite size (0.7fm)
0^+ diquark [*u(x_2)d(x_3)*]



(0.6,0.2,0.2)

conformal limit:
120 $x_1x_2x_3$
$\langle x_i \rangle$ =⅓ … peak of the distribution



Pointlike 0^+ diquark
[*u(x_2)d(x_3)*]

Light-cone distribution amplitudes of the nucleon and negative parity nucleon resonances from lattice QCD
V. M. Braun *et al.*, Phys. Rev. D 89 (2014) 094511

Light-cone distribution amplitudes of the baryon octet
G. S. Bali *et al*. JHEP 1602 (2016) 070

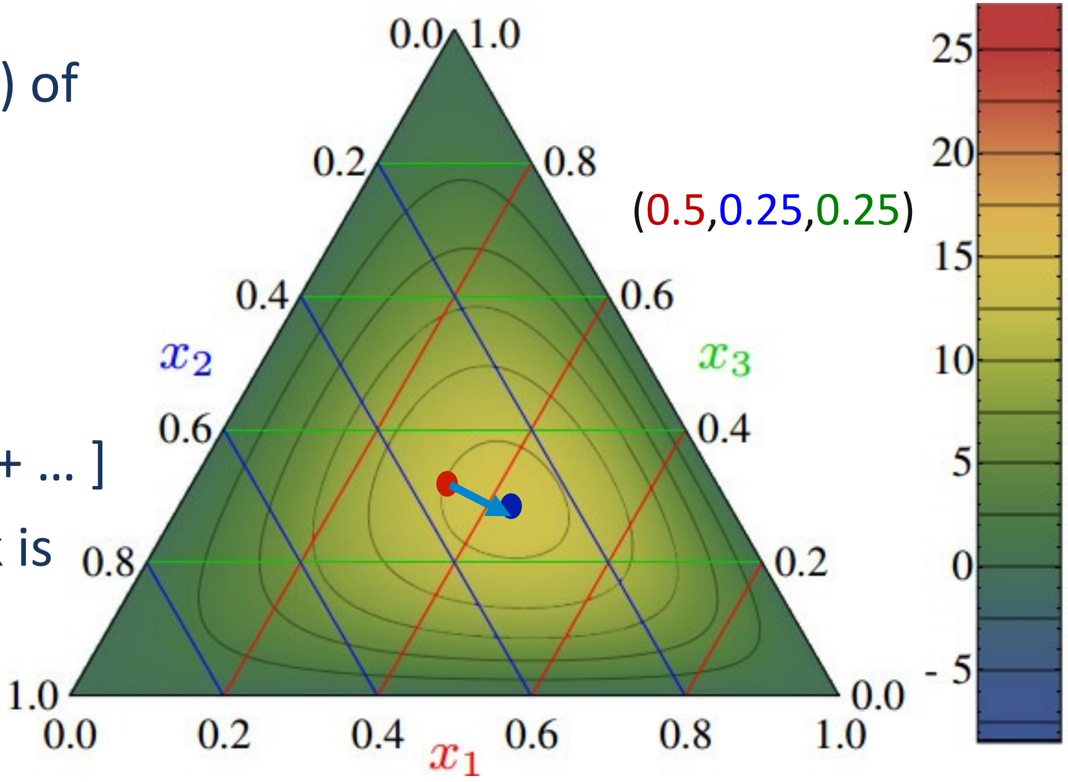
Nucleon PDAs & lQCD

- First lQCD results for n=0, 1 moments of the leading twist PDA of the nucleon are available
- Used to constrain strength (a_{11}) of the leading-order term in a conformal expansion of the nucleon's PDA:

$\Phi(x_1,x_2,x_3)$

$= 120\, x_1\, x_2\, x_3\, [\, 1 + a_{11}\, P_{11}(x_1,x_2,x_3) + \ldots\,]$

- Shift in location of central peak is consistent with existence of diquark correlations within the nucleon



Far valence domain

$x \simeq 1$

Nucleon spin structure at very high-x
Craig D. Roberts, Roy J. Holt and Sebastian M. Schmidt
arXiv:1308.1236 [nucl-th], Phys. Lett. B 727 (2013) pp. 249–254
Contact-interaction Faddeev equation and, inter alia, proton tensor charges, Shu-Sheng Xu et al., *arXiv:1509.03311 [nucl-th], Phys. Rev. D 92 (2015) 114034/1-21*

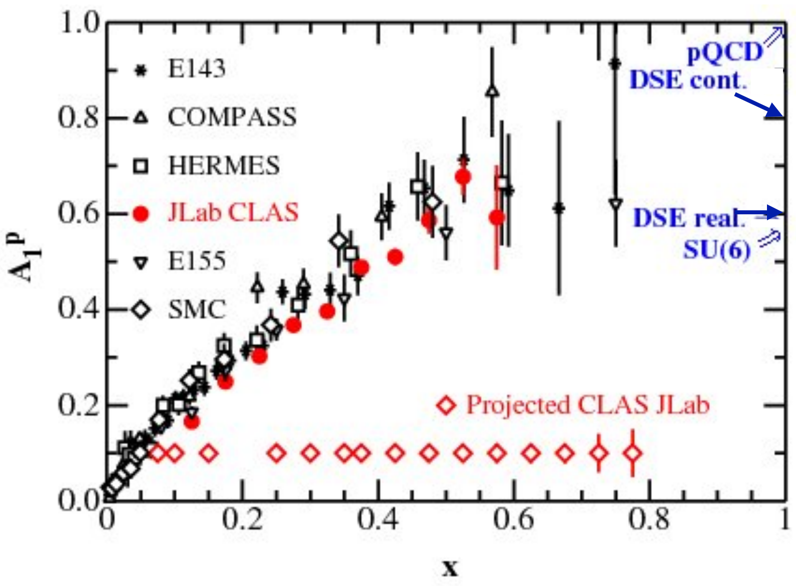
Nucleon PDFs at large Bjorken-x

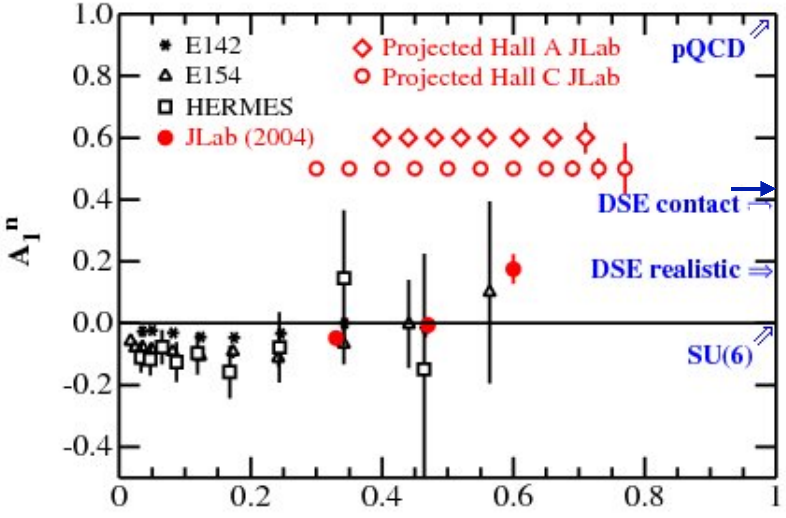
- Correlations between dressed-quarks within the proton have an enormous impact on nucleon flavor & spin structure

	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-realistic [21]	0.50	0.29	−0.12	0.67	−0.29	0.16	0.61
DSE-contact-S [37]	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
DSE-contact-D	0.38	0.14	−0.05	0.83	−0.33	0.43	0.79
$0^+_{[ud]}$-frozen	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

No two frameworks make the same predictions for F_{2n}/F_{2p}, A_{1p}, A_{1n}

Quark helicity at large Bjorken-x

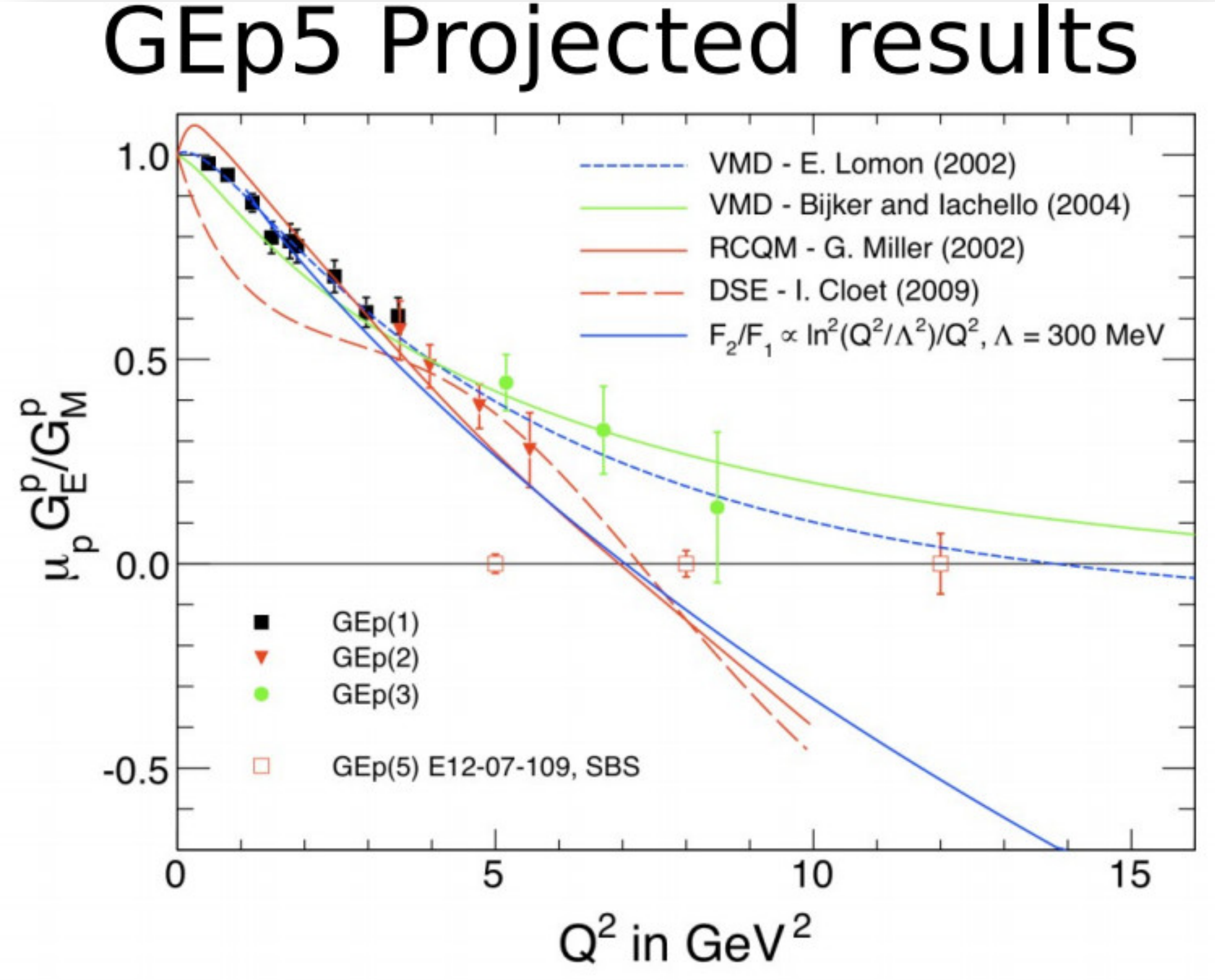




Craig Roberts. Exposing The Mass At The Heart Of Visible Matter (49pp)

- Existing data cannot distinguish between modern pictures of nucleon structure
- Empirical results for nucleon longitudinal spin asymmetries on $x \simeq 1$ promise to add greatly to our capacity for discriminating between contemporary pictures of nucleon structure.

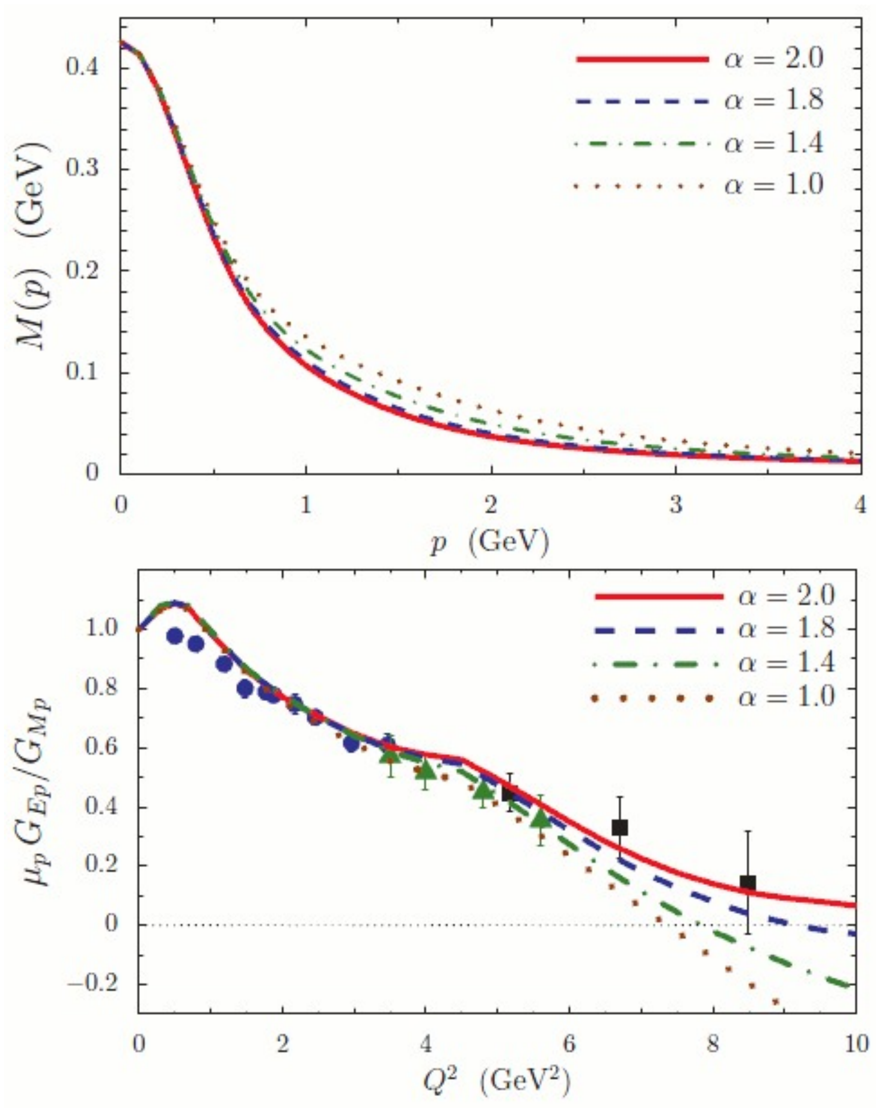
Electron Ion Collider: The Next QCD Frontier



Nucleon Elastic FFs

I.C. Cloët, C.D. Roberts, A.W. Thomas: Revealing dressed-quarks via the proton's charge distribution,
arXiv:1304.0855 [nucl-th], Phys. Rev. Lett. **111** (2013) 101803

Visible Impacts of DCSB



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

- Possible existence and location of a zero in the ratio of proton elastic form factors

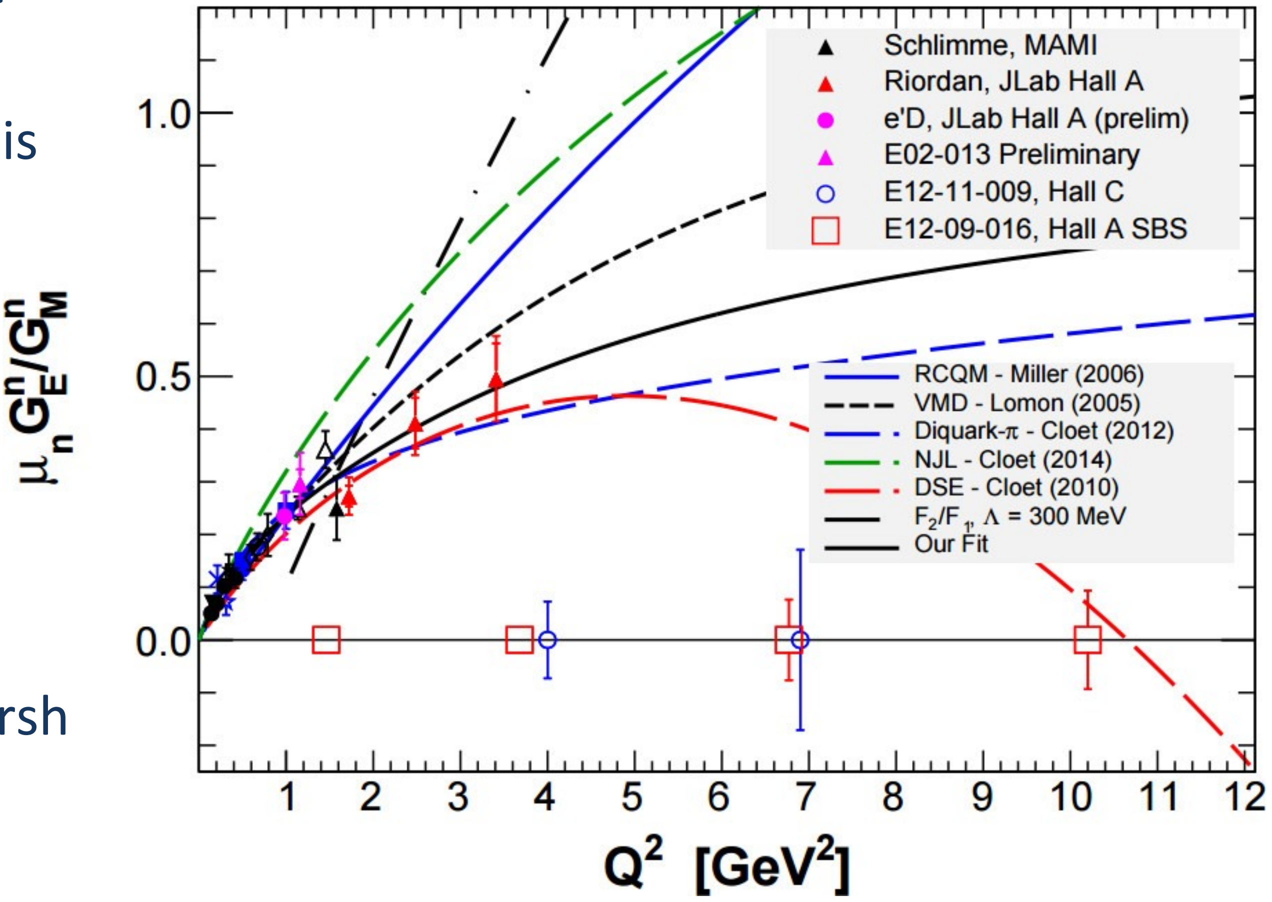
  $[\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)]$

  are a direct measure of the rate at which dressed-quarks become partons again,

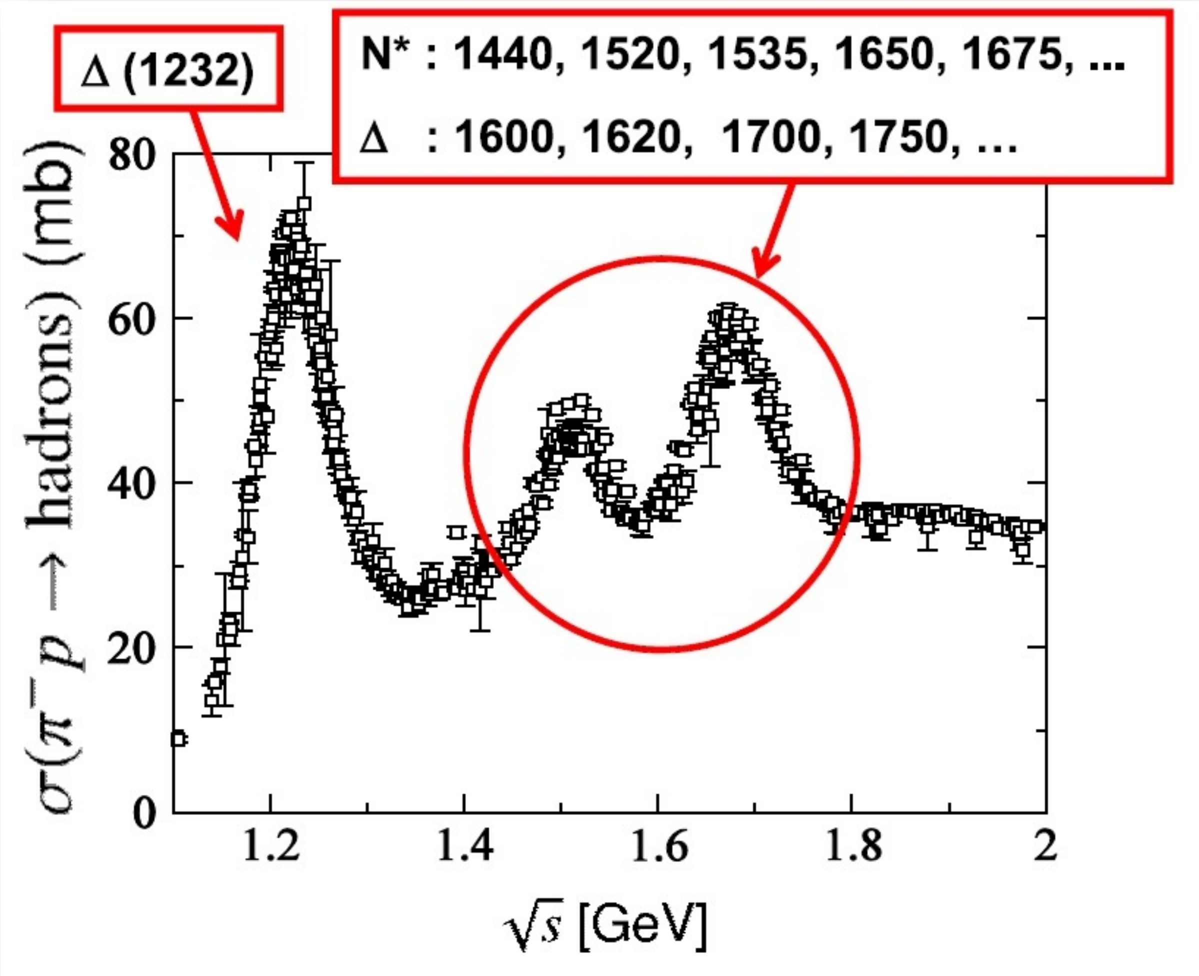
  i.e. character of strong interactions in the Standard Model.

G_{En}

- Numerous calculations on this figure; but only one viable prediction
- DSE result (2008/2010) is not fitted to any data
  - Predicts zero in G_{En}
  - Owes to presence of running quark-mass & strong diquark correlations
  - Verifiable at JLab12
- G_{En} promises to be a harsh discriminator between descriptions of nucleon structure



Seamus Riordan, ECT, April 2016*



Nucleon Resonances

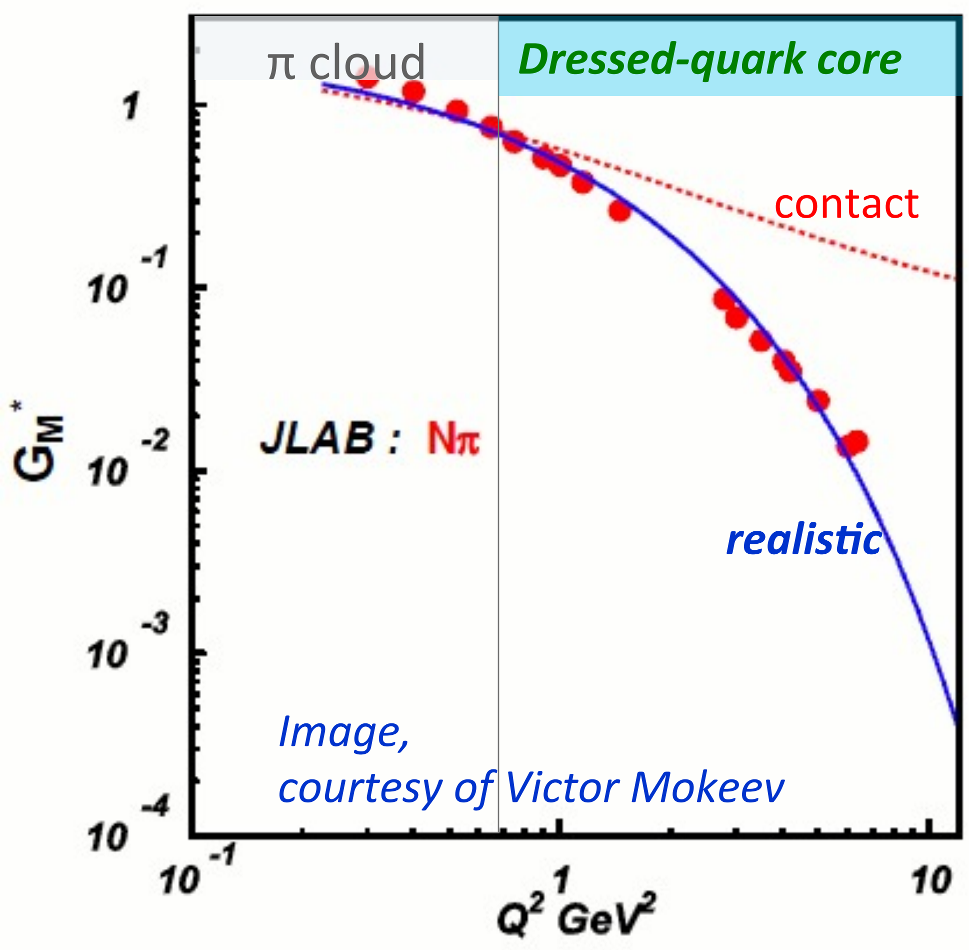
$\gamma N \rightarrow$ Resonance

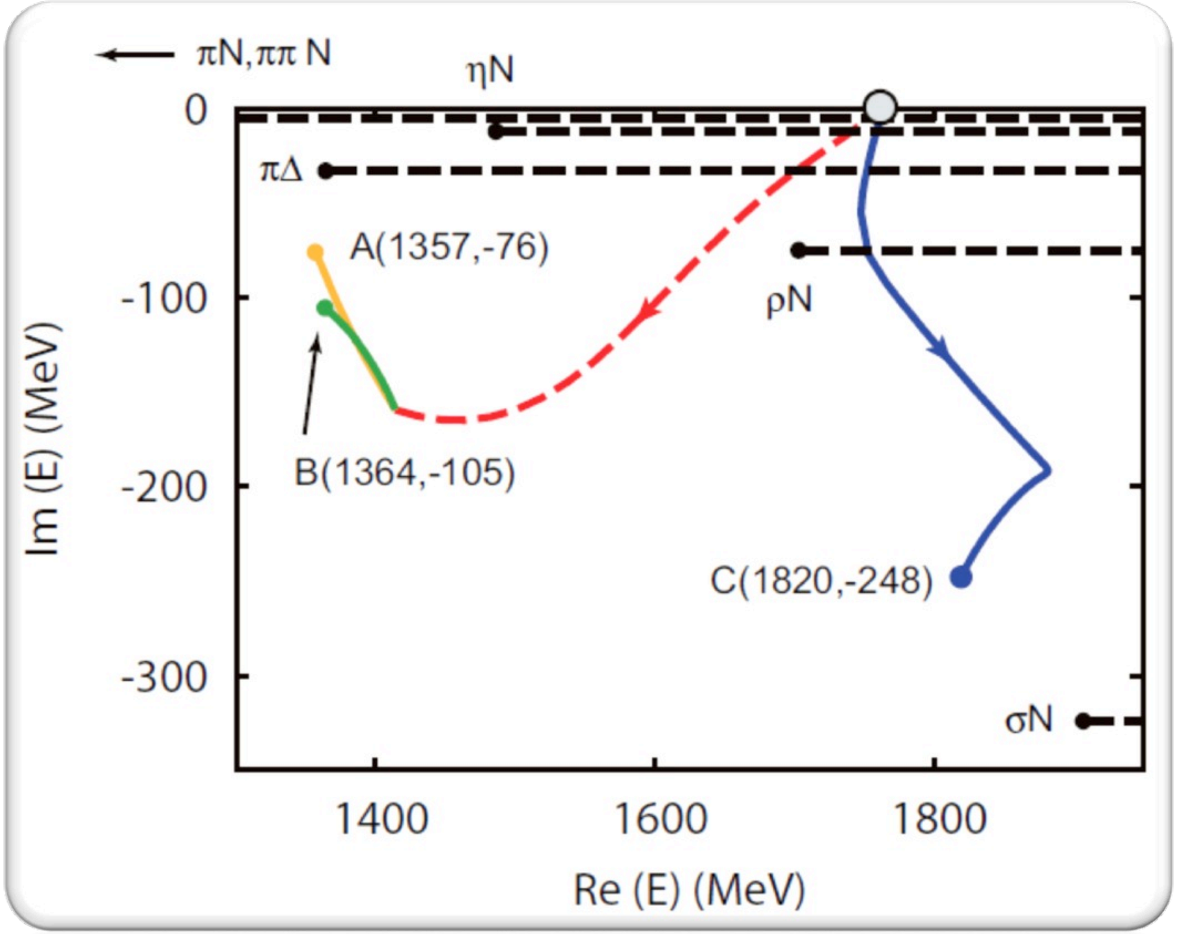
- Prediction and measurement of ground-state elastic form factors is essential to increasing our understanding of strong-interaction
- However, alone, it is insufficient to chart the infrared behaviour of the strong interaction
  - the hydrogen ground-state didn't give us QED
- There are numerous nucleon → resonance transition form factors.
  - The challenge of mapping their Q^2-dependence provides a vast array of novel ways to probe the infrared behaviour of the strong interaction, including the environment and energy sensitivity of correlations

J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222
[on-line]

$\gamma N \rightarrow \Delta$

- Jones-Scadron convention – simplest direct link to helicity conservation in pQCD
- Single set of inputs …
  - dressed-quark mass function (***same as that which predicted meson properties***)
  - diquark amplitudes , masses, propagators
  - same current operator for elastic and transition form factors
- ***Prediction N→Δ transition is indistinguishable from data on Q^2>0.7 GeV^2***





Roper Resonance

H. Kamano , S.X. Nakamura, T. -S. H. Lee , T. Sato,
Phys.Rev. C **88** (2013) 035209

Roper Resonance

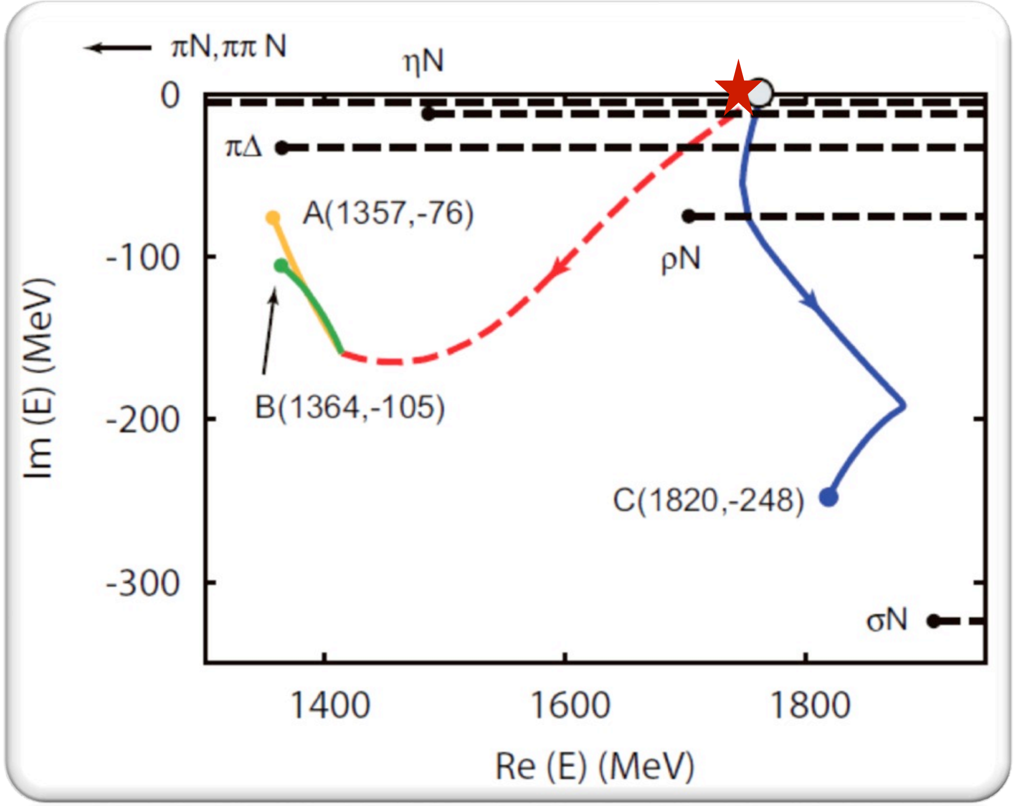
- Constituent-Quark Model brought order to Particle Zoo in the '60s
- But, the "Roper Resonance" didn't fit the pattern. It baffled nuclear and particle physicists for more than 50 years.
- Discovered in 1963 by L. David Roper while working on his Ph.D. at M.I.T. The Roper is just like the proton, except 50% heavier.
- 1st problem was its *mass*: until recently, it could not be explained from QCD by any available theoretical method.
- EBAC/Argonne-Osaka pushed nuclear physics towards a solution
  - Highly advanced, dynamical coupled channels analysis of resonance production, 8 channels: γN, πN, ηN, $K\Lambda$, $K\Sigma$, $\pi\Delta$, σN, ρN
  - Excellent description of 22,348 *independent data points*, representing *complete array of partial waves*

H. Kamano , S.X. Nakamura, T. -S. H. Lee , T. Sato, Phys.Rev. C **88** (2013) 035209

J. Segovia *et al*, Phys. Rev. Lett. **115** (2015) 171801

Roper Resonance

- Argonne-Osaka:
  - *Bare Roper state must be included in the DCC analysis*
  - *Without it, impossible to achieve description of all available data*
  - Bare mass = 1.76 GeV
  - Adding Meson-Baryon FSIs, this bare state metamorphoses into thee distinct features in the P_{11} partial wave = two associated with the "Roper" and the third with $N^*(1710)$
- DSE prediction for mass of the quark core of the nucleon's first radial excitation = 1.73 GeV



Agreement between two completely unrelated approaches to the same problem is very unlikely to be an accident

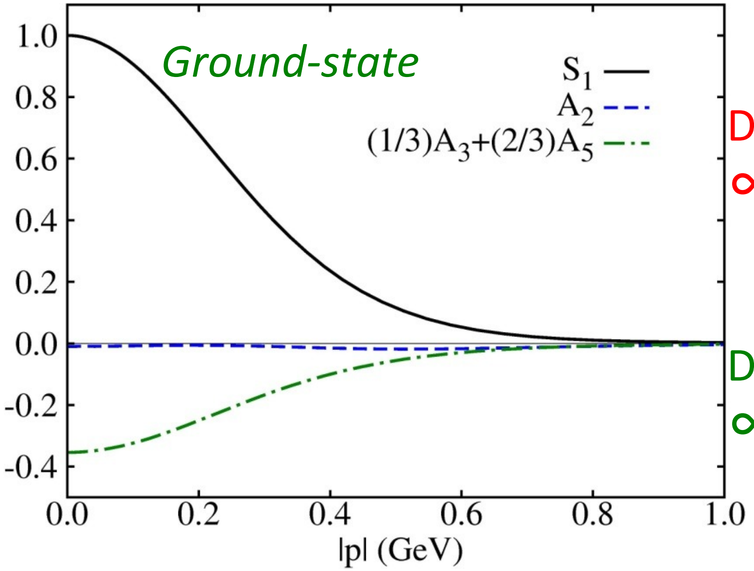
Roper Resonance

- An explanation of how and where the Roper resonance fits into the spectrum of hadrons cannot rest on a description of its mass alone.
- Instead, it must combine a prediction of the Roper mass with detailed descriptions of its structure and how that structure is revealed in the momentum dependence of the transition form factors.
- Moreover, it must combine all this with a similarly complete picture of the proton, from which the Roper resonance is produced.
- Last decade ⇒ precise data on p→Roper electroproduction transition form factors, reaching to momentum transfers $Q^2 \approx 4$ GeV^2.
- This scale probes into domain upon which valence-quark degrees-of-freedom could be expected to determine their behaviour
- *Real Test: Unified description of proton, Δ, Roper, and their associated electromagnetic form factors (elastic and transition)*

Completing the picture of the Roper resonance, Jorge Segovia *et al.*,,
arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

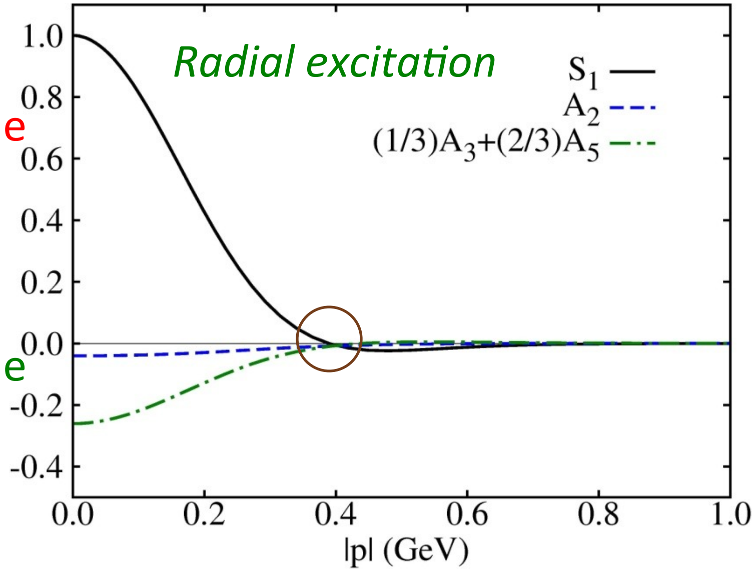
Roper Resonance

- Precisely same framework as employed for nucleon and *Δ*; viz.
  - dressed-quark mass function
  - diquark amplitudes, masses, propagators
  - same current operator for elastic and transition form factors



Dominant 0+ amplitude
$\propto C\, I\, \tau_2$

Dominant 1+ amplitude
$\propto C\gamma_5\gamma_\mu\, \tau_{+,0}$



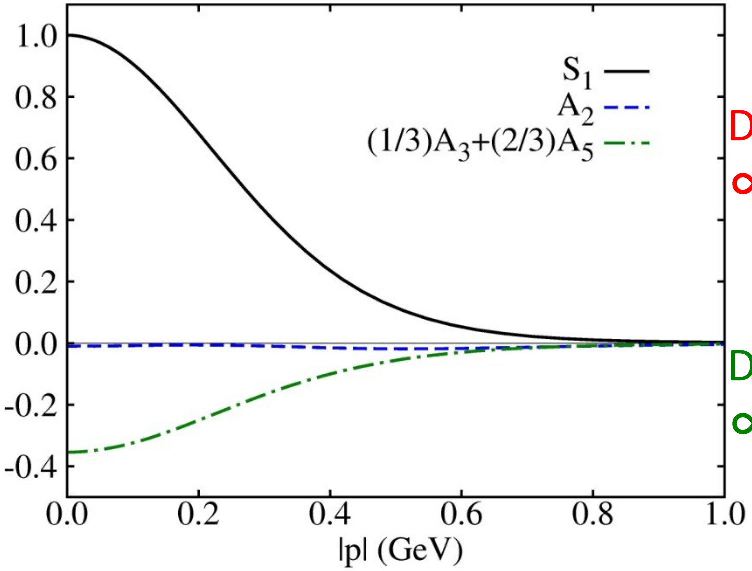
- $M_{\text{radial-QQQ}}$ = 1.73 GeV … amplitudes typically possess a zero
  $\Rightarrow$ lightest excitation of the nucleon is radial excitation

N.B. Argonne-Osaka $M_{\text{Roper-cloud-removed}}$ = 1.76 GeV

Completing the picture of the Roper resonance, Jorge Segovia *et al*.,, arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

Roper Resonance

- Precisely same framework as employed for nucleon and *Δ*; viz.
  - dressed-quark mass function
  - diquark amplitudes, masses, propagators
  - same current operator for elastic and transition form factors



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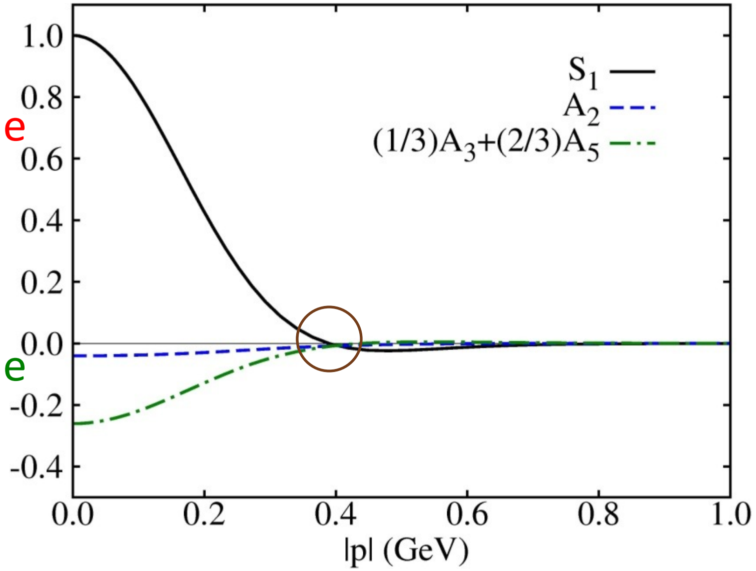


- $M_{Roper,QQQ}$ = 1.73 GeV … amplitudes typically possess a zero

n

N.B. /

Meson-baryon final-state interactions reduce core mass by 20%

Completing the picture of the Roper resonance, Jorge Segovia *et al*.,,
arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

Roper Resonance

- Diquark content: Nucleon vs Roper

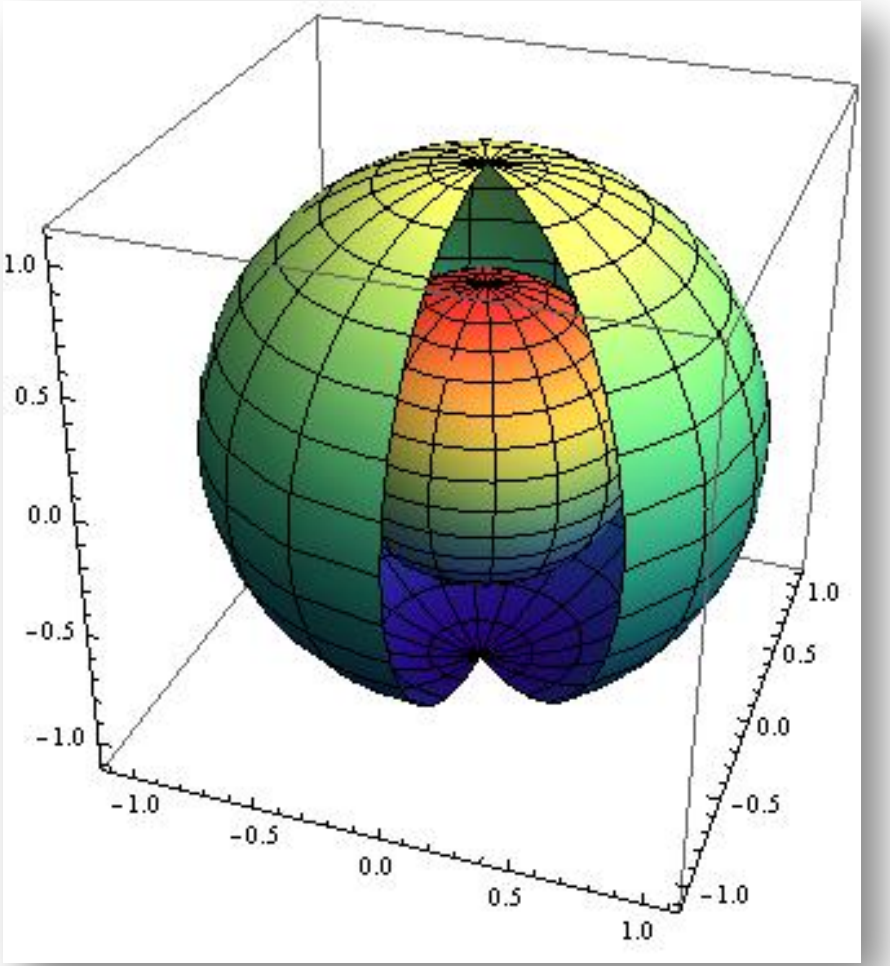
	Nucleon	Roper	Image-Nucleon
$P_{J=0}$	62%	62%	30%
$P_{J=1}$	38%	38%	70%

  - "Image"-nucleon = orthogonal solution of Faddeev equation at the Roper mass, with eigenvalue $\lambda>1$

- Roper & Nucleon have *same* diquark content
  - Completely different to prediction of contact-interaction, wherein $P_{J=0} \approx 0$
  - With richer kernel, orthogonality of ground and excited states is achieved differently

Completing the picture of the Roper resonance, Jorge Segovia *et al.*,,
arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

Roper Resonance



- Ratio of charge radii for the quark+diquark core of the Roper compared with that of the nucleon = 1.8
- Harmonic Oscillator result ($L=0$): $r_{n=1}/r_{n=0}$ = 1.53
- Significant angular momentum and spin-orbit repulsion introduced via relativity, which increases size of core, for nucleon and Roper

Completing the picture of the Roper resonance, Jorge Segovia *et al.*,,
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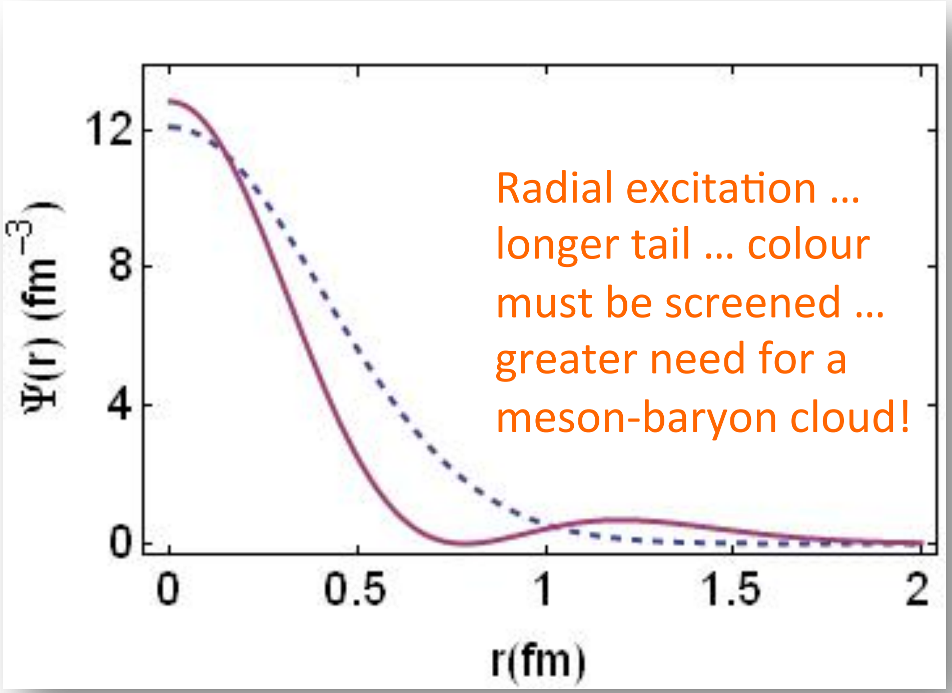
Roper Resonance



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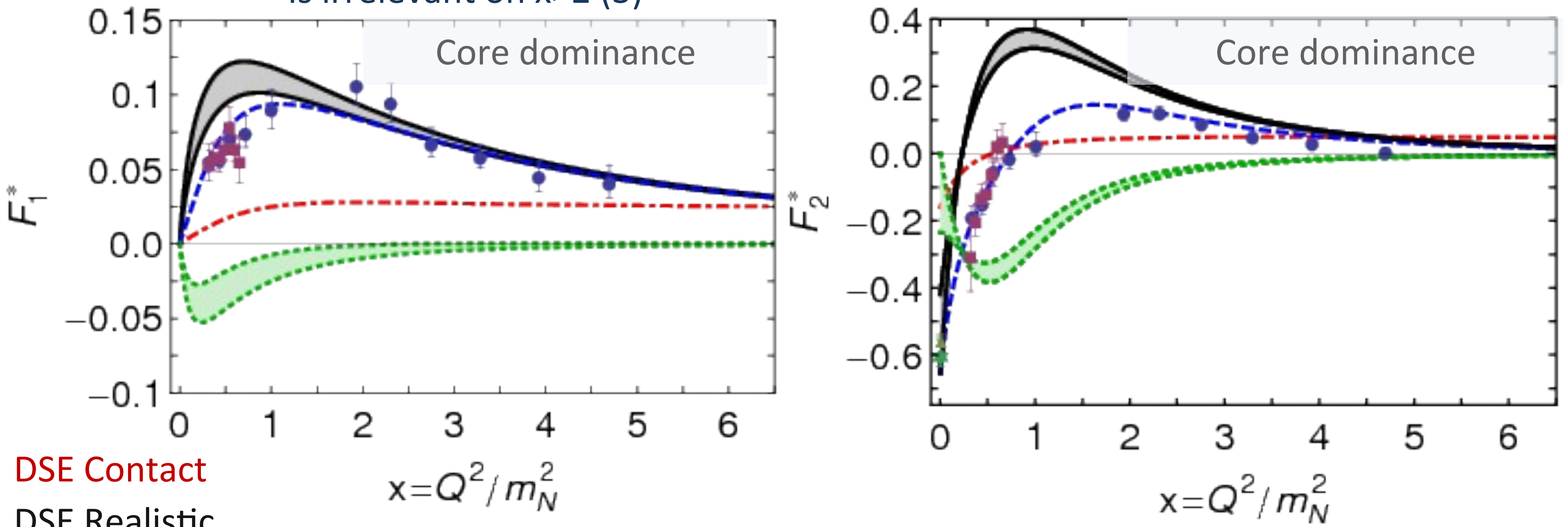
Completing the picture of the Roper resonance, Jorge Segovia *et al*.,,
arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

γ N → Roper

- Predicted transition form factors
  - Excellent agreement with data on *x>2 (3)*
  - Like *γN* → *Δ*, room for meson cloud on *x<2* … appears likely that cloud
    - Is a negative contribution that depletes strength on *0<x<2*
    - Has nothing to do with existence of zero; but is influential in shifting the zero in F_2* from *x=¼* to *x=1*
    - Is irrelevant on x>2 (3)



DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

M. Dugger *et al*., Phys. Rev. C79, 065206 (2009).
I. Aznauryan *et al*., Phys. Rev. C80, 055203 (2009).
I. G. Aznauryan *et al*., arXiv:1108.1125 [nucl-ex].
V. I. Mokeev *et al*., Phys. Rev. C86 (2012) 035203

[1] arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** 132001 (2013) [5 pages]

Roper Resonance

- Sophisticated continuum framework for the 3-quark bound-state problem
  - all elements possess unambiguous link with analogous quantities in QCD
  - no parameters varied in order to achieve success.
- No material improvement in these results can be envisaged before either:
  - novel spectral function methods introduced in Ref. [1] have been extended and applied to the entire complex of nucleon, Δ and Roper properties
  - or numerical simulations of lattice-regularised QCD become capable of reaching the same breadth of application and accuracy
- *Conclusion*
  - *Observed Roper resonance is at heart the proton's first radial excitation*
    - *Consists of a well-defined dressed-quark core*
    - *Augmented by a meson cloud that reduces its mass by approximately 20% and materially alters its electroproduction form factors on $Q^2 < 2m_p^2$*

Baryons & their Resonances

Nucleon and Δ elastic and transition form factors
Jorge Segovia *et al.*, arXiv:1408.2919 [nucl-th],
Few Body Syst. **55** (2014) pp. 1185-1222 [on-line]

Completing the picture of the Roper resonance
Jorge Segovia *et al.* arXiv:1504.04386 [nucl-th],
Phys. Rev. Lett. **115** (2015) 171801

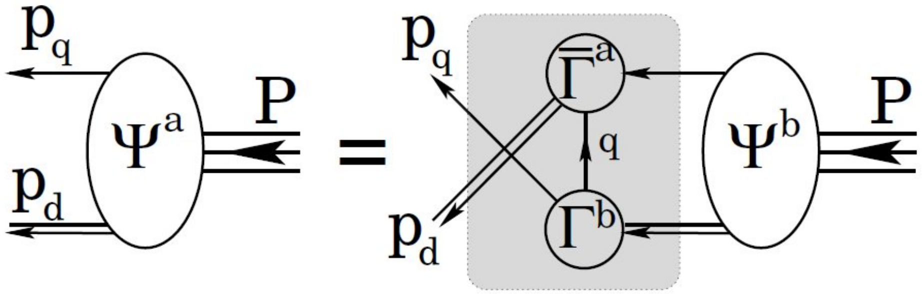
- Critical issues:
  - is there an environment sensitivity of DCSB and the dressed-quark mass function?
  - are quark-quark correlations an essential element in the structure of all baryons?
- Properties of nucleons alone can't answer such questions
- Detailed knowledge of resonances and their electroproduction is necessary
- Existing feedback between experiment and theory indicates absence of environment sensitivity for the nucleon, *Δ*-baryon and Roper resonance:
  - DCSB in these systems is expressed in ways that can readily be predicted once its manifestation is understood in the pion, and this includes the generation of diquark correlations with the same character in each of these baryons.

Epilogue

Epilogue

Thankyou!

- Conformal anomaly ... *gluons & quarks acquire momentum-dependent masses*, values large in the infrared $m_g \propto 500$ MeV & $M_q \propto 350$ MeV … underlies DCSB, origin of hadron masses: many observable consequences
- *Diquarks are a reality* … their existence does not affect the number of baryon states in any obvious way & their presence leads to many verifiable predictions … no contradictions yet; but stern tests on the horizon
- *Nucleon PDAs* … programme underway; PDFs … large-*x*, theoretically "easy" but *x*-dependence harder
  - Sound computation of PDAs and PDFs are necessary precursor to reliable computation of GPDs and TMDs
- How universal is $M(p^2)$? How robust are diquark correlations?
  - Electroproduction of baryon resonances is one excellent way to tackle questions such as these …
    - *Nucleon → Nucleon … Nucleon → Δ … Nucleon → Roper* … understood with no environment sensitivity
    - *meson cloud does not alter level ordering in baryon spectrum*
  - *Computation alone can/will reveal verifiable signals in observables*



Diquarks

- **Not your grandfather's diquarks!**
- Dynamically generated correlations
- Two particle sub-cluster is not frozen
  - All quarks participate in all diquark clusters
  - There is a predicted probability for each given cluster within a given J^P baryon
  - Nucleon: $1^+/0^+ \approx 60\%$

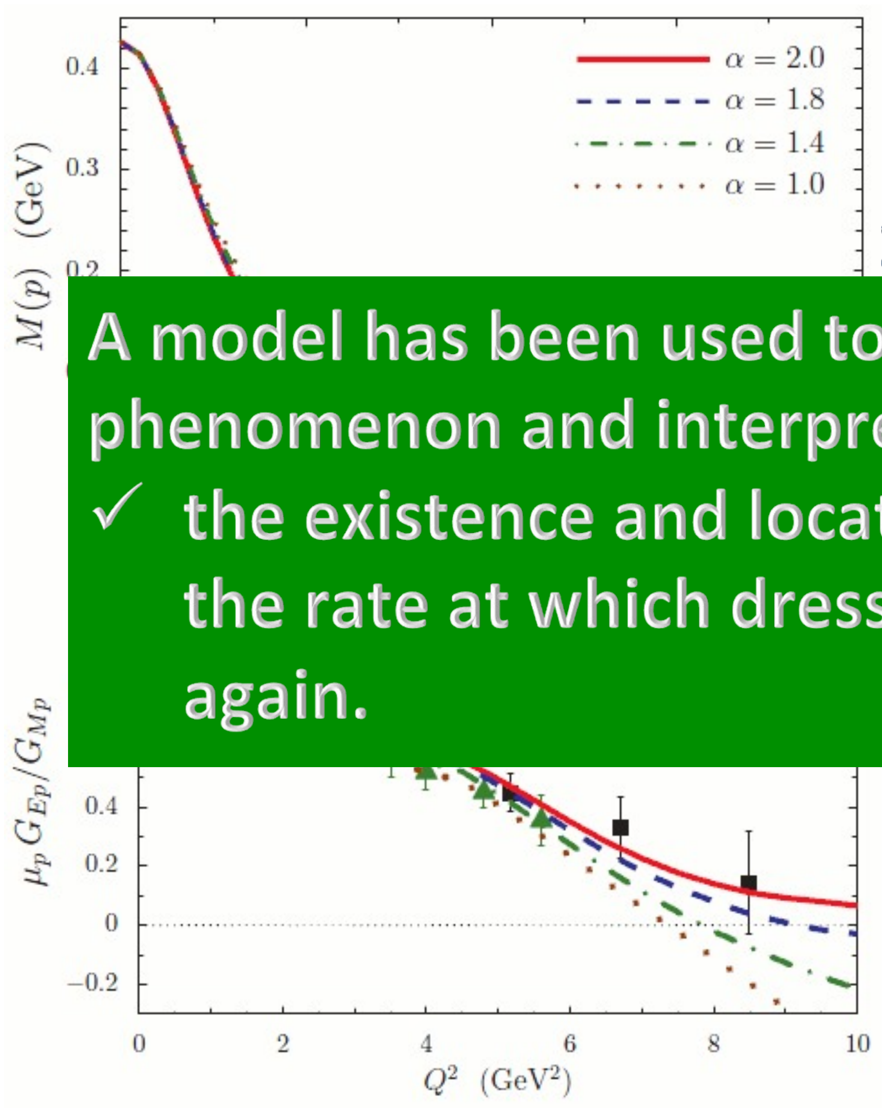
Other clusters are negligible in J^+ states

- Faddeev equation baryon spectrum must have significant overlap with that of the three-constituent quark model and no relation to the Lichtenberg-Tassie quark+diquark model

I.C. Cloët, C.D. Roberts, A.W. Thomas: Revealing dressed-quarks via the proton's charge distribution,
[arXiv:1304.0855 [nucl-th]](), [Phys. Rev. Lett. **111** (2013) 101803]()

Visible Impacts of DCSB

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



- Possible existence and location

A model has been used to illustrate the effect; but the phenomenon and interpretation are model-independent

✓ the existence and location of a zero is a measure of the rate at which dressed-quarks become partonic again.

i.e. character of strong interactions in the Standard Model.

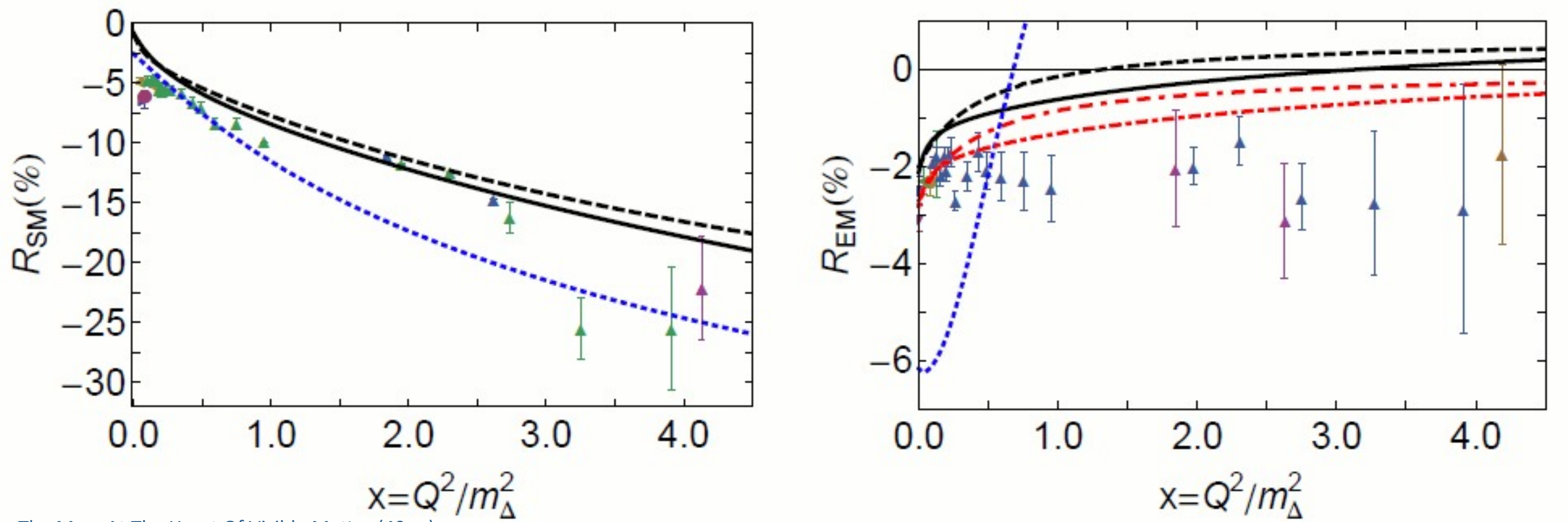
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt:
Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222 [on-line]

γ N → Δ

- Three form factors describe $N \to \Delta$: G_M^*, G_E^*, G_C^*
- Ratios $R_{EM} \propto G_E^*/G_M^*$ & $R_{SM} \propto G_C^*/G_M^*$ are a particularly sensitive measure of correlations and dressed-quark orbital angular momentum
- Helicity conservation demands that

  $R_{EM} \to 100\%$ at some (very large?) x.

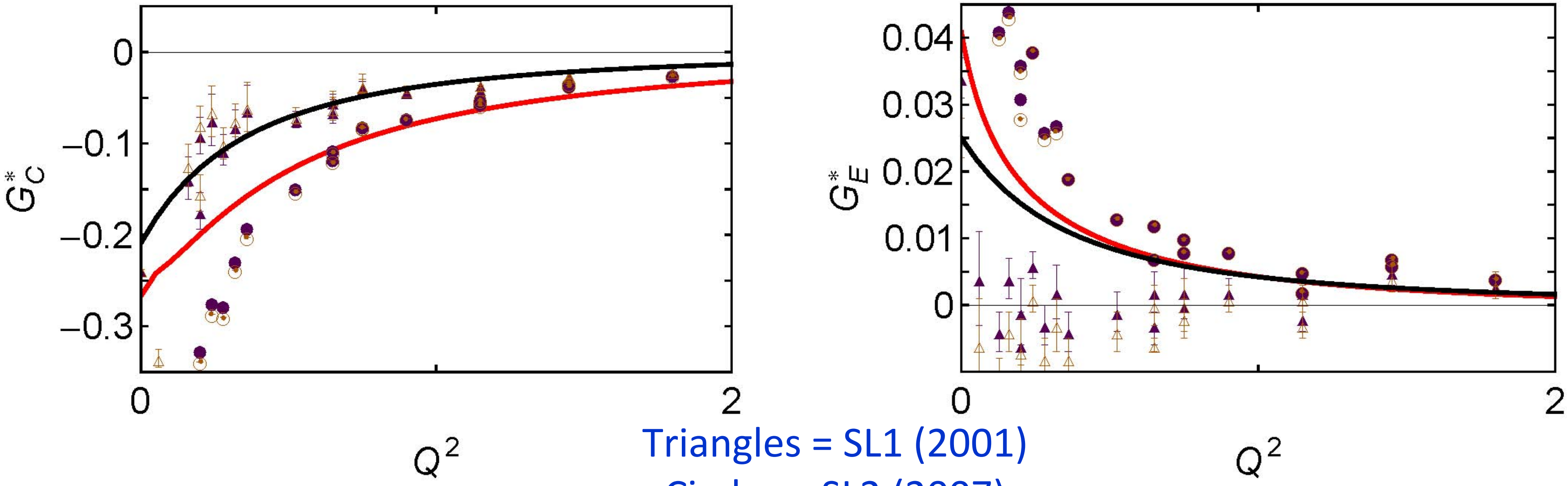
  – Available data suggest that it's not happening yet



J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt:
Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222
[on-line]

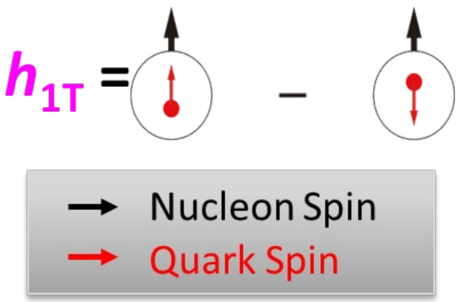
$\gamma N \to \Delta$

- Very probably, that's because pion cloud is masking the zero on the currently accessible domain
- Judge that because dressed-quark core results agree very well with Sato-Lee's meson-*undressed* electric and Coulomb form factors … determined from data fits more than 8 years ago … long before DSE results were available



Triangles = SL1 (2001)
Circles = SL2 (2007)

Direction of motion



TMDs …
Transversity … Tensor Charge

$$\delta q = \int_0^1 dx\, \left(h_1^q(x) - h_1^{\bar{q}}(x)\right)$$

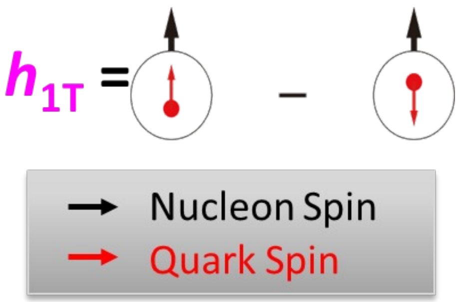
- Intrinsic, defining property of the nucleon

  … just as significant as axial-charge
- No gluon transversity distribution
- Value of tensor charge places constraints on some extensions of the Standard Model <PRD85 (2012) 054512>
- Current knowledge of transversity:

  SIDIS @HERMES, COMPASS, JLab
- Future SIDIS at JLab (SoLId), EIC, …

Electron Ion Collider: The Next QCD Frontier

Direction of motion



Contact-interaction Faddeev equation and, inter alia, proton tensor charges
Shu-Sheng Xu et al., *arXiv:1509.03311 [nucl-th], Phys. Rev. D 92 (2015) 114034/1-21*

TMDs …
Transversity … Tensor Charge

$$\delta q = \int_0^1 dx\, (h_1^q(x) - h_1^{\bar{q}}(x))$$

- Presence of diquark correlations in the proton wave function suppresses δu by ⅓-½ cf. SU(6) quark model prediction
- Axial-vector correlation is crucial, e.g.: δd is only measurably nonzero because the proton wave function contains axial-vector correlations; and axial-vector suppresses δu