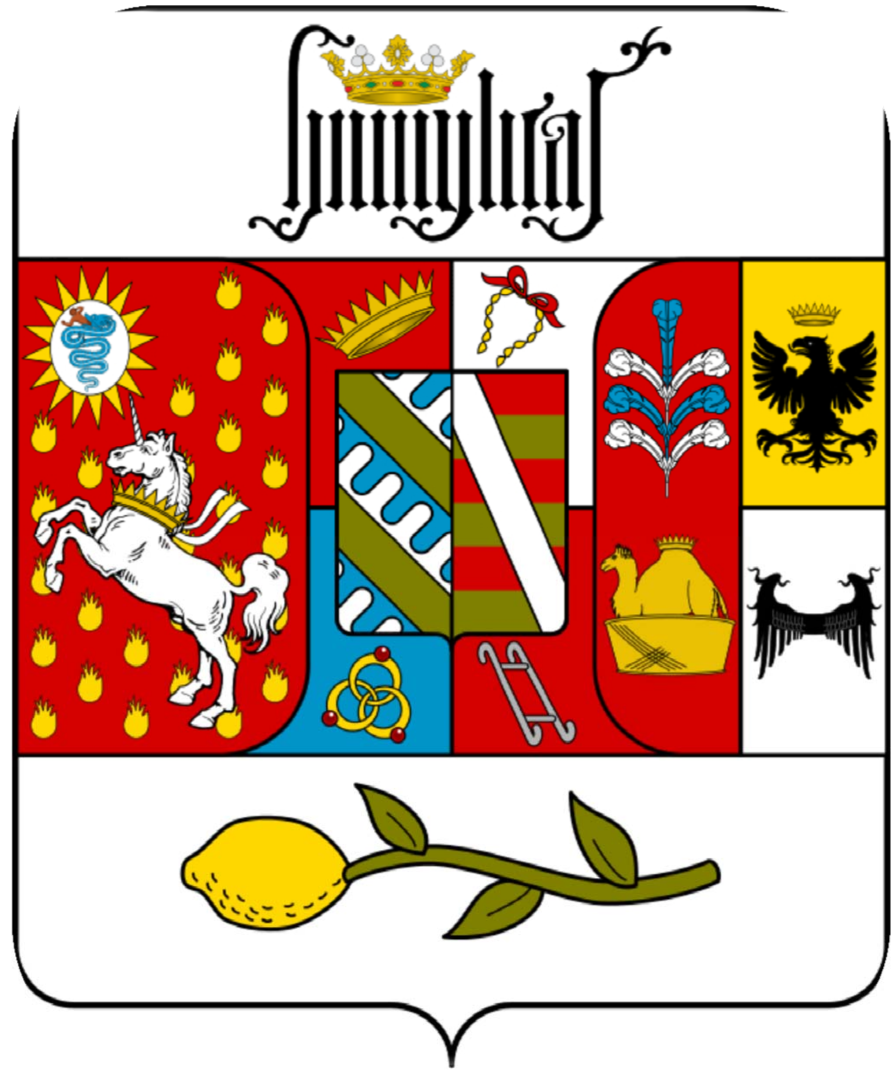
Baryons and the Borromeo



Craig Roberts, Physics Division

Abstract

- The kernels in the tangible matter of our everyday experience are composed of light quarks. At least, they are light classically; but they don't remain light. Dynamical effects, novel forces, within the Standard Model of Particle Physics change them in remarkable ways, so that in some configurations they appear nearly massless but in others possess masses on the scale of light nuclei. Modern experiment and theory are exposing the mechanisms responsible for these remarkable transformations.

Abstract

- 

- The prize is $1-million if we can combine the emerging sketches into an accurate picture of confinement, the eternal imprisonment of quarks, which is such a singular feature of the Standard Model; and looming larger amongst the emerging ideas is a perspective, which I will outline, that leads to a Borromean picture of the proton and its excited states.

Collaborators: 2012-Present

Students, Postdocs, Asst. Profs.

1. *Shi CHAO (Nanjing U) ;*
2. *Ming-hui DING (PKU);*
3. *Fei GAO (PKU) ;*
4. *S. HERNÁNDEZ (U Michoácan);*
5. *Cédric MEZRAG (CEA, Saclay) ;*
6. *Khépani RAYA (U Michoácan);*
7. *Chien-Yeah SENG (UM-Amherst) ;*
8. *Kun-lun WANG (PKU);*
9. *Shu-sheng XU (Nanjing U) ;*
10. *Chen CHEN (USTC);*
11. *J. Javier COBOS-MARTINEZ (U Michoácan)*
12. *L. Xiomara. GUTIERREZ-GUERRERO (U.Sonora);*
13. *Mario PITSCHMANN (Vienna);*

- *Si-xue QIN (ANL, U. Frankfurt am Main, PKU);*
- *Jorge SEGOVIA (TU-München);*

16. *David WILSON (ODU);*
17. *Lei CHANG (U. Adelaide, FZJ, ANL, PKU) ;*
18. *Ian CLOËT (ANL) ;*

- *Bruno EL-BENNICH (São Paulo);*
- Adnan BASHIR (U Michoácan);
- Daniele BINOSI (ECT*)

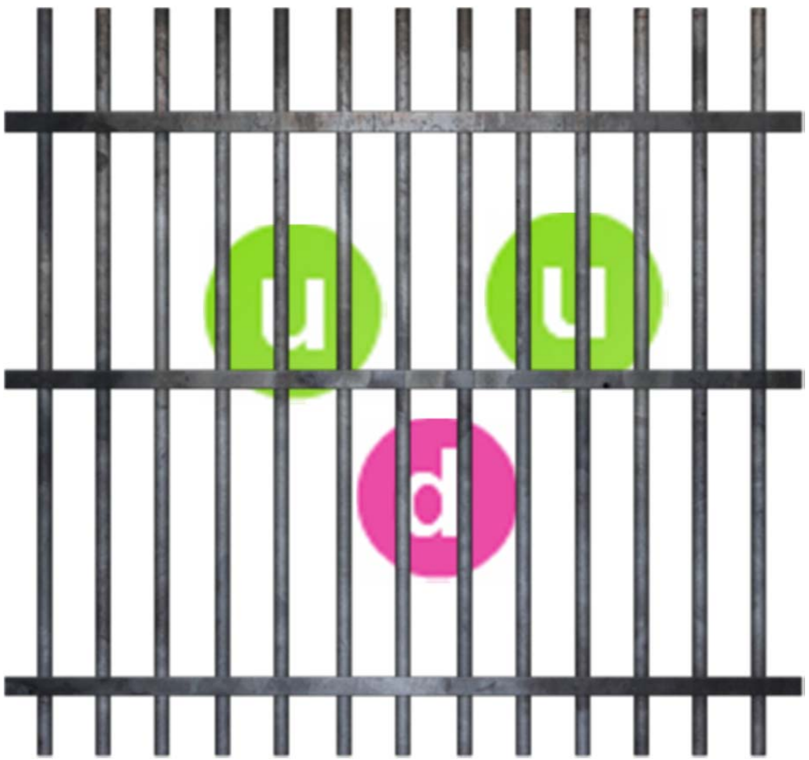
22. Stan BRODSKY (SLAC);
23. Roy HOLT (ANL);
24. G. KREIN (São Paulo IFT)
25. Yu-xin LIU (PKU);
26. Hervé MOUTARDE (CEA, Saclay) ;
27. Joannis PAPAVASILLIOU (U.Valencia)
28. Michael RAMSEY-MUSOLF (UM-Amherst) ;
29. Alfredo RAYA (U Michoácan);

- Jose RODRIGUEZ QINTERO (U. Huelva) ;

31. Sebastian SCHMIDT (IAS-FZJ & JARA);
32. Robert SHROCK (Stony Brook);
33. Peter TANDY (KSU);
34. Tony THOMAS (U.Adelaide) ;
35. Shaolong WAN (USTC) ;
36. Hong-Shi ZONG (Nanjing U)

2013: Higgs and Englert

- “The Higgs boson is often said to give mass to everything. However, that is wrong. It only gives mass to some very simple particles, accounting for only one or two percent of the mass of more complex things like atoms, molecules and everyday objects, from your mobile phone to your pet llama.”
- *“The vast majority of mass comes from the energy needed to hold quarks together inside nuclei.”*



confinement

News › Science › Particle physics **theguardian**

One year on from the Higgs boson find, has physics hit the buffers?

Despite the success of the Large Hadron Collider, evidence for the follow-up theory – supersymmetry – has proved elusive

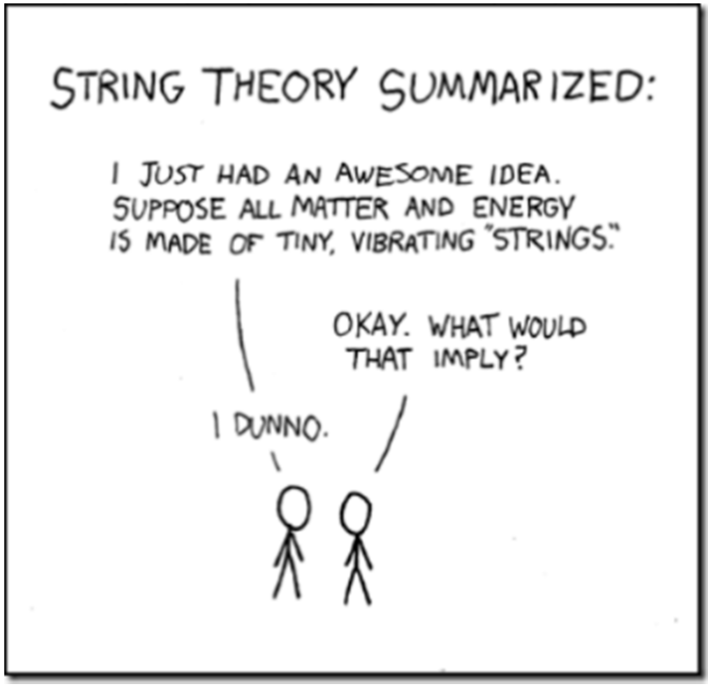
A little over a year ago, physicists put the finishing touches to the most successful scientific theory of all time: the Standard Model of particle physics. When the Higgs boson was found at the Large Hadron Collider in July 2012, it was the final piece in our picture of the universe at the smallest, subatomic scales.

Champagne corks flew in physics labs around the world at this vindication of quantum field theory, which had been more than 80 years and dozens of Nobel prizes in the making.

Inevitably, a hangover followed. The leading idea for how to push physics beyond the Standard Model – and explain the many remaining mysteries of the universe – is looking shaky. Thousands of physicists have spent their career carefully constructing the theory, called supersymmetry. It has taken almost four decades. But, so far, the most powerful particle accelerator ever built – the Large Hadron Collider (LHC) at Cern, near Geneva – has not found any hard evidence to back up the theory.

This conspicuous lack of proof has led a growing number of physicists, particularly those who are less invested in supersymmetry, to publicly call time on the idea. Perhaps, despite all the work, the theory is just plain wrong.

Death of Super-String Theory?



Problems in Theory

www.nature.com/news/scientific-method-defend-the-integrity-of-physics-1.16535

- Faced with difficulties in applying fundamental theories to the observed Universe, some researchers have called for a change in how theoretical physics is done.
- They begin to argue — explicitly — that if a theory is sufficiently elegant and explanatory, it need not be tested experimentally ...
- Chief among the "elegance will suffice" advocates are some string theorists and cosmologists …
- This is NOT science …

Scandal in Academia

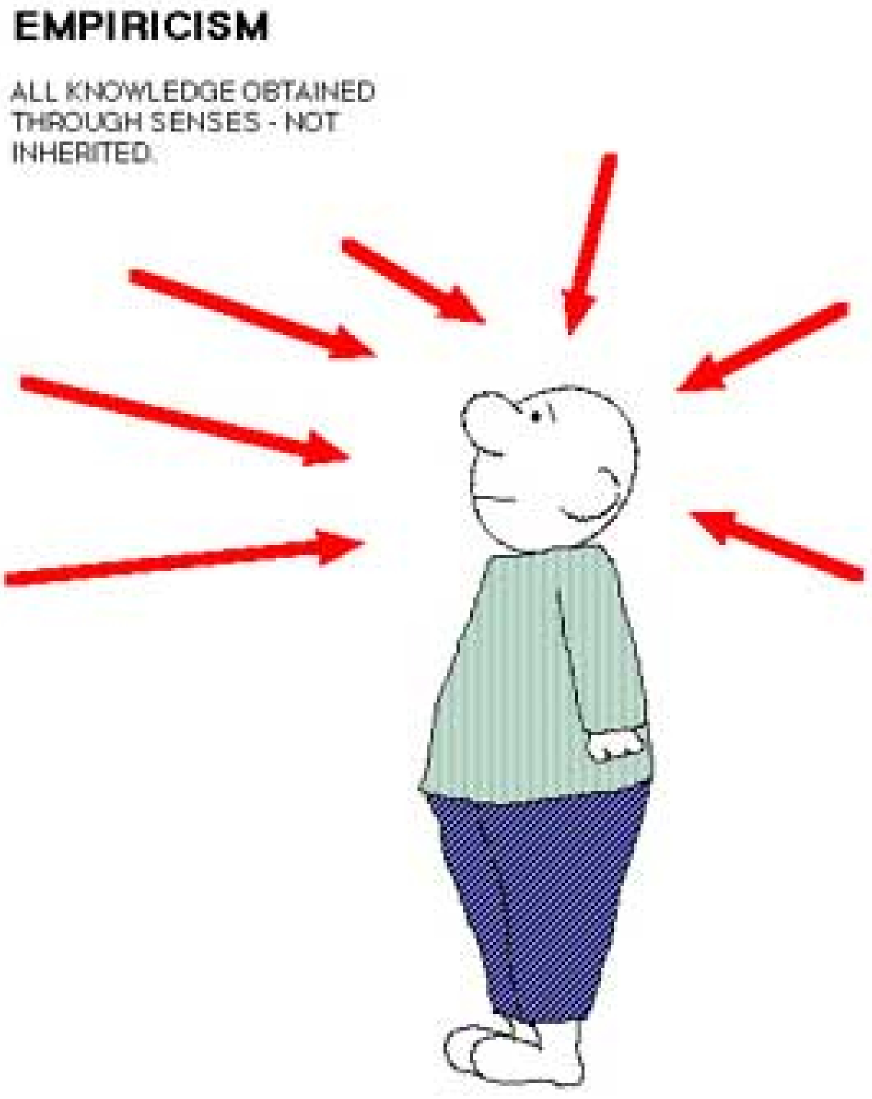
"THE PIPE WAS STILL BETWEEN HIS LIPS."

- "I have no data yet.

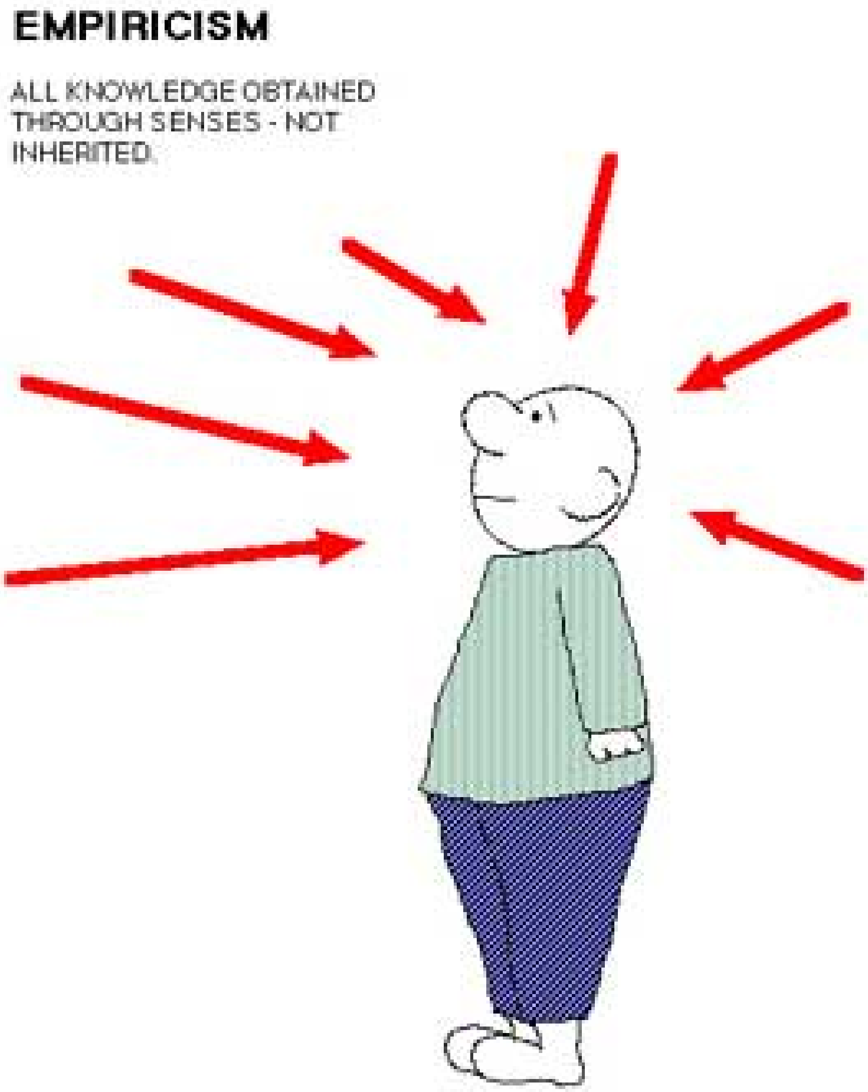
  It is a capital mistake to theorize before one has data.

  Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

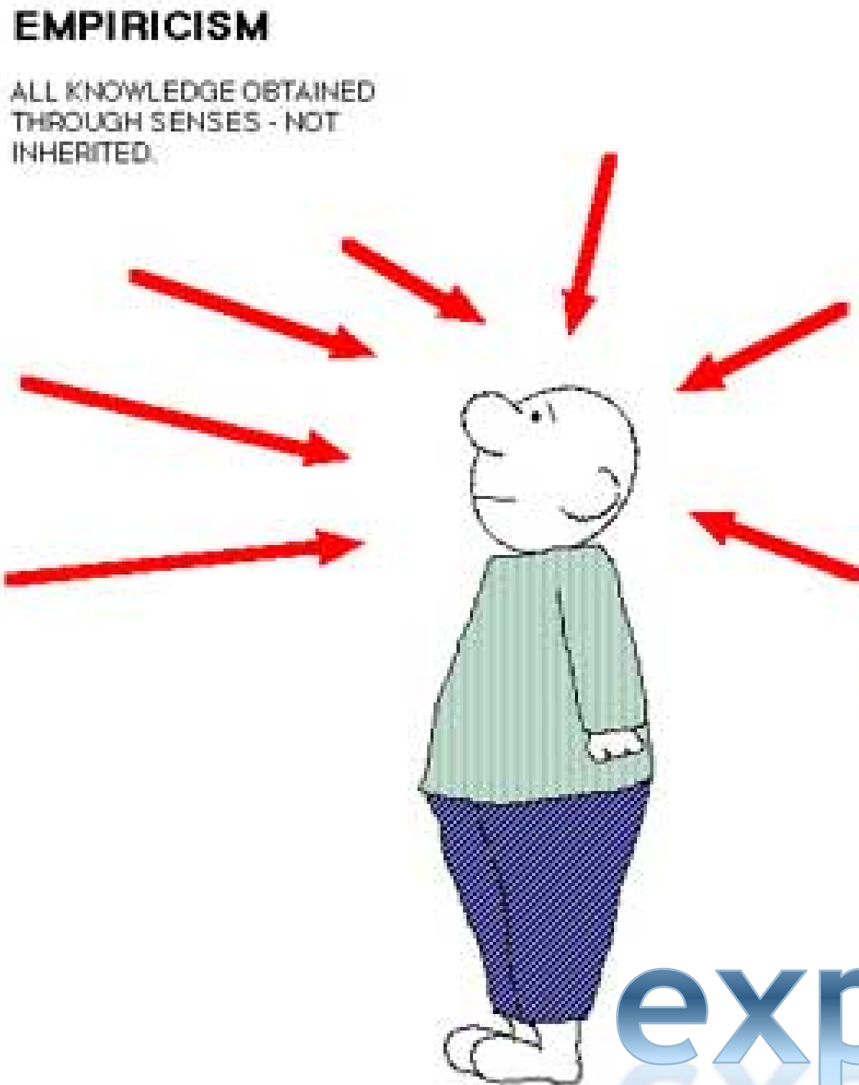
  Sherlock Holmes



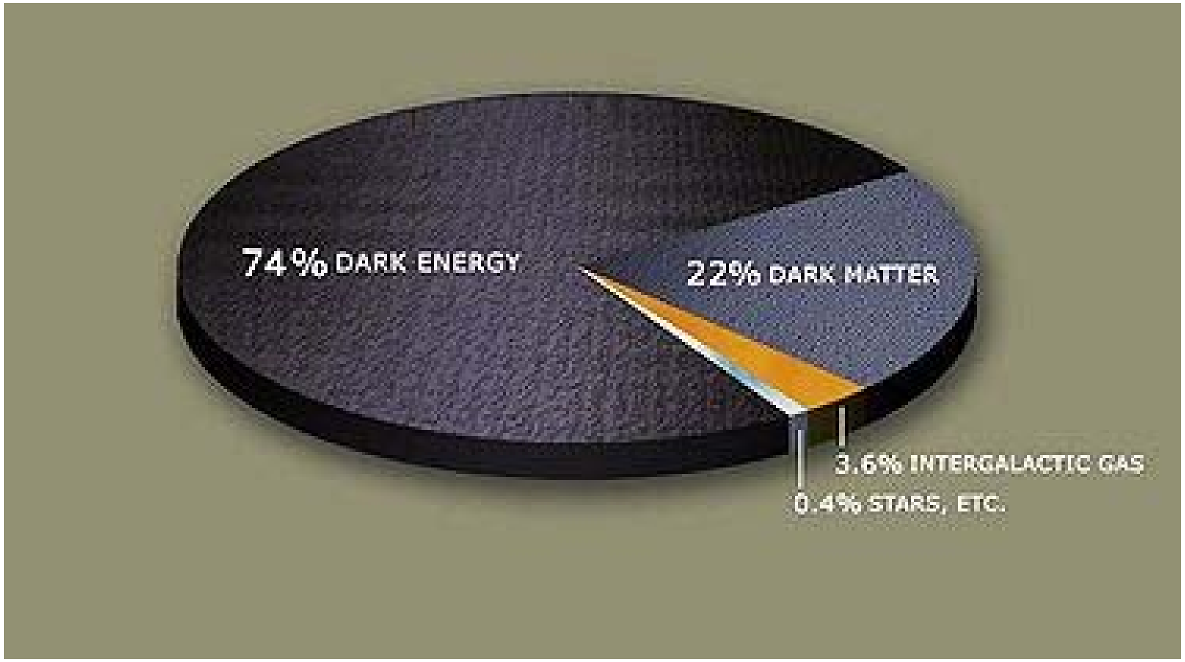
Physics is an empirical science



It's not physics unless it can be tested empirically.



It’s not proven unless it’s verified experimentally.



Top Open Questions in Physics

Excerpt from the top-10

- ***Can we quantitatively understand quark and gluon confinement in quantum chromodynamics and the existence of a mass gap?***

    Quantum chromodynamics is the theory describing the strong nuclear force. Carried by gluons, it binds quarks into particles like protons and neutrons. Apparently, the tiny subparticles are permanently confined: one can't pull a quark or a gluon from a proton because the strong force gets stronger with distance and snaps them right back inside.

Overarching Science Challenge for the coming decade

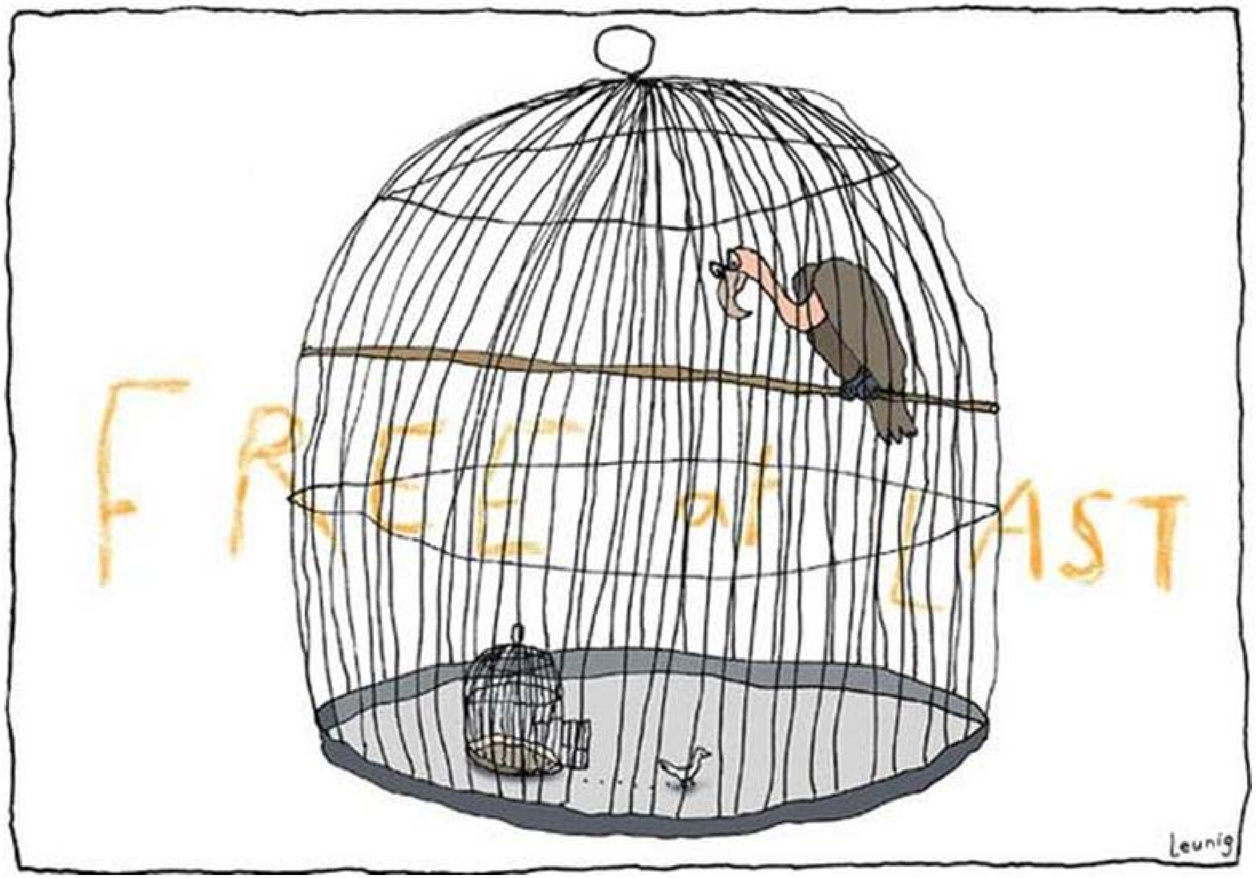
Discover meaning of confinement, its relationship to DCSB – the Origin of Visible Mass – and the connection between them

Recent News

- Novel understanding of gluon and quark confinement and its consequences is emerging from quantum field theory
- Arriving at a clear picture of how hadron masses emerge dynamically in a universe with light quarks

  Dynamical Chiral Symmetry Breaking (DCSB)

- Realistic computations of ground-state hadron wave functions with a direct connection to QCD are now available
  - Quark-quark correlations are crucial in hadron structure
  - Accumulating empirical evidence in support of this prediction



What is Confinement?

CLAY MATHEMATICS INSTITUTE

Millennium prize of $1,000,000 for proving that $SU_c(3)$ gauge theory is mathematically well-defined, which will necessarily prove or disprove the confinement conjecture

YANG–MILLS EXISTENCE AND MASS GAP. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

5. Comments

An important consequence of the existence of a mass gap is clustering: Let $\vec{x} \in \mathbb{R}^3$ denote a point in space. We let H and $\vec{P}$ denote the energy and momentum, generators of time and space translation. For any positive constant $C < \Delta$ and for any local quantum field operator $\mathcal{O}(\vec{x}) = e^{-i\vec{P}\cdot\vec{x}}\mathcal{O}e^{i\vec{P}\cdot\vec{x}}$ such that $\langle\Omega, \mathcal{O}\Omega\rangle = 0$, one has

$$|\langle\Omega, \mathcal{O}(\vec{x})\mathcal{O}(\vec{y})\Omega\rangle| \leq \exp(-C|\vec{x} - \vec{y}|), \tag{2}$$

as long as $|\vec{x} - \vec{y}|$ is sufficiently large. Clustering is a locality property that, roughly speaking, may make it possible to apply mathematical results established on $\mathbb{R}^4$ to any 4-manifold, as argued at a heuristic level (for a supersymmetric extension of four-dimensional gauge theory) in [**49**]. Thus the mass gap not only has a physical significance (as explained in the introduction), but it may also be important in mathematical applications of four-dimensional quantum gauge theories to geometry. In addition the existence of a uniform gap for finite-volume approximations may play a fundamental role in the proof of existence of the infinite-volume limit.

There are many natural extensions of the Millennium problem. Among other things, one would like to prove the existence of an isolated one-particle state (an upper gap, in addition to the mass gap), to prove confinement, to

Confinement?

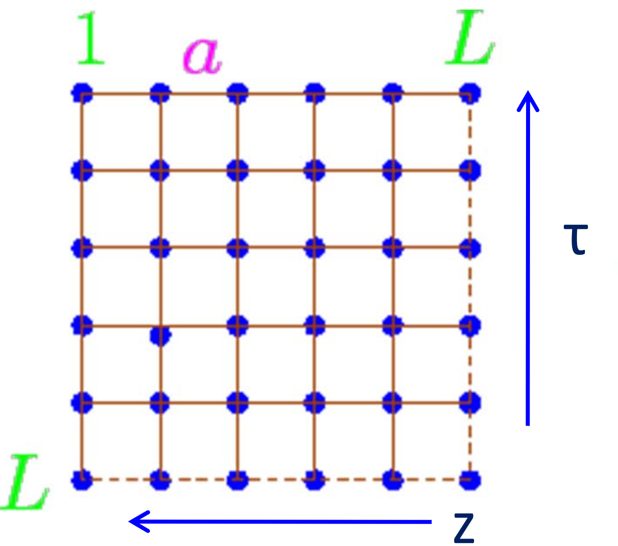
Confinement of quarks*

Kenneth G. Wilson
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 12 June 1974)

A mechanism for total confinement of quarks, similar to that of Schwinger, is defined which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and treating the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free quarks. There is unfortunately no Lorentz (or Euclidean) invariance in the strong-coupling limit. The strong-coupling expansion involves sums over all quark paths and sums over all surfaces (on the lattice) joining quark paths. This structure is reminiscent of relativistic string models of hadrons.

Wilson Loop & the Area Law

$$W_C := \mathrm{Tr}\left(\mathcal{P}\exp i\oint_C A_\mu dx^\mu\right)$$



periodic lattice

- C is a closed curve in space,
  P is the path order operator
- Now, place static (infinitely heavy) fermionic sources of *any* charge at positions

  $z_0=0$ & $z=½L$
- Then, evaluate $<W_C(z, \tau)>$ as a functional integral over gauge-field configurations
- In the strong-coupling limit, the result can be obtained algebraically; viz.,

  $<W_C(z, \tau)> = \exp(-V(z)\,\tau)$

  where $V(z)$ is the potential between the static sources, which behaves as $V(z) = \sigma z$

Linear potential
σ = String tension

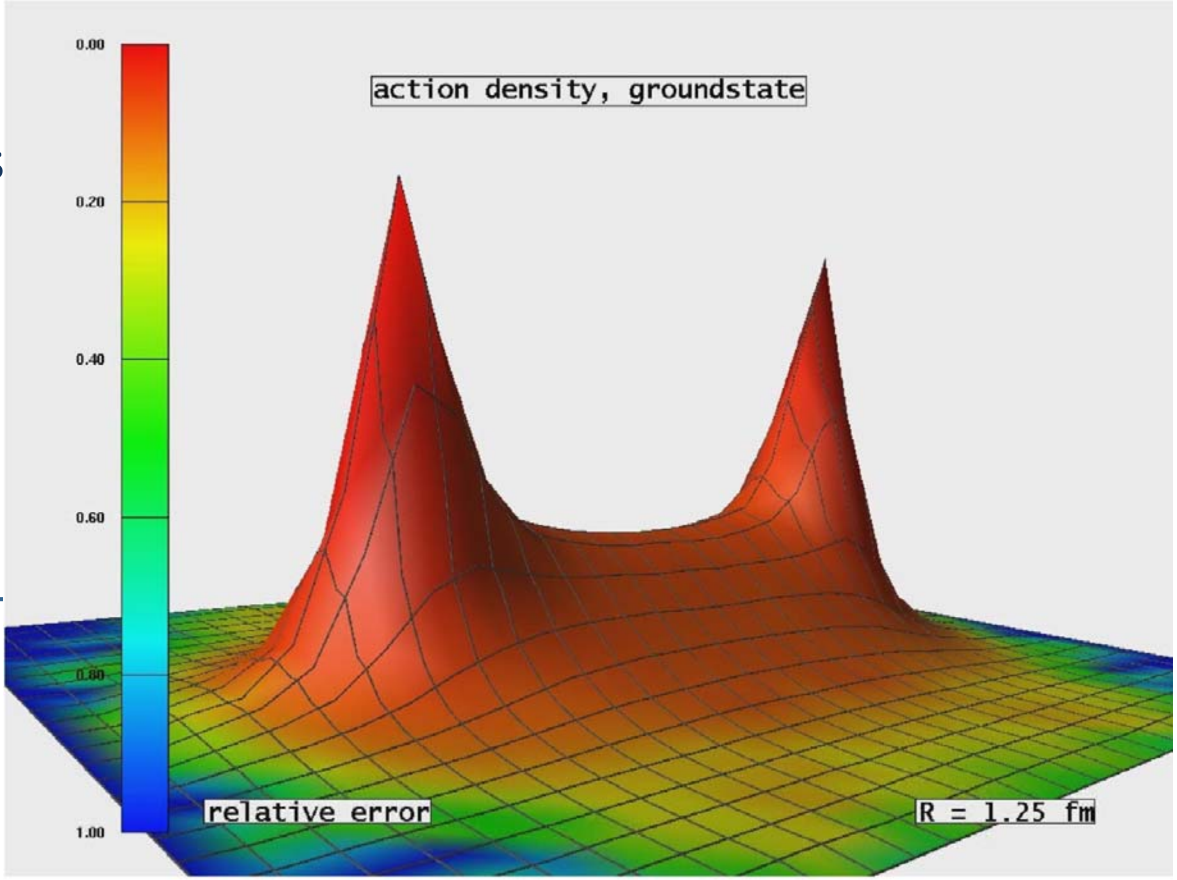
Light quarks & Confinement

- Folklore … *JLab 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:

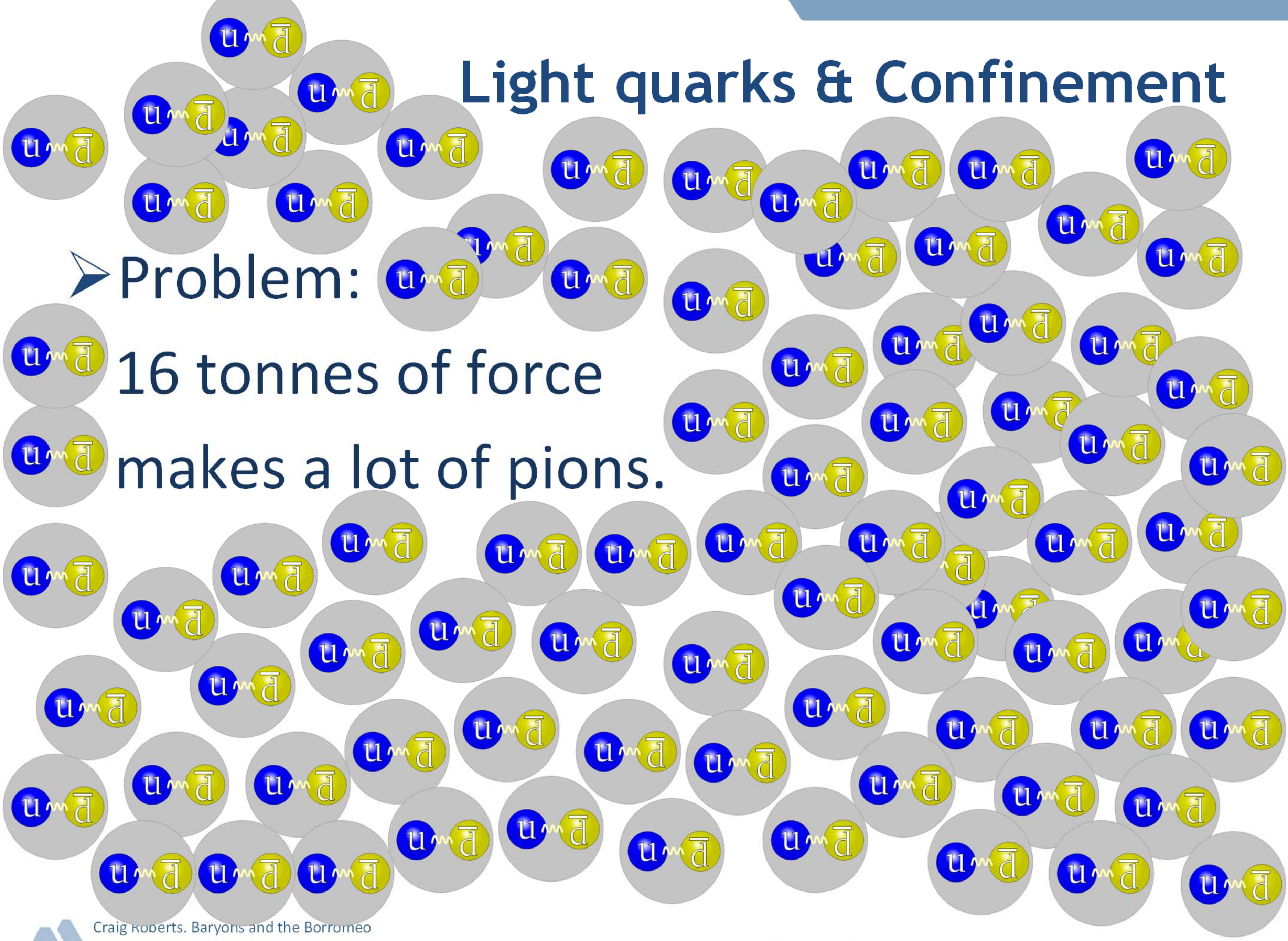
  Pions

  They're extremely, *unnaturally* light

  16 tonnes of force

  makes a lot of them.

Light quarks & Confinement



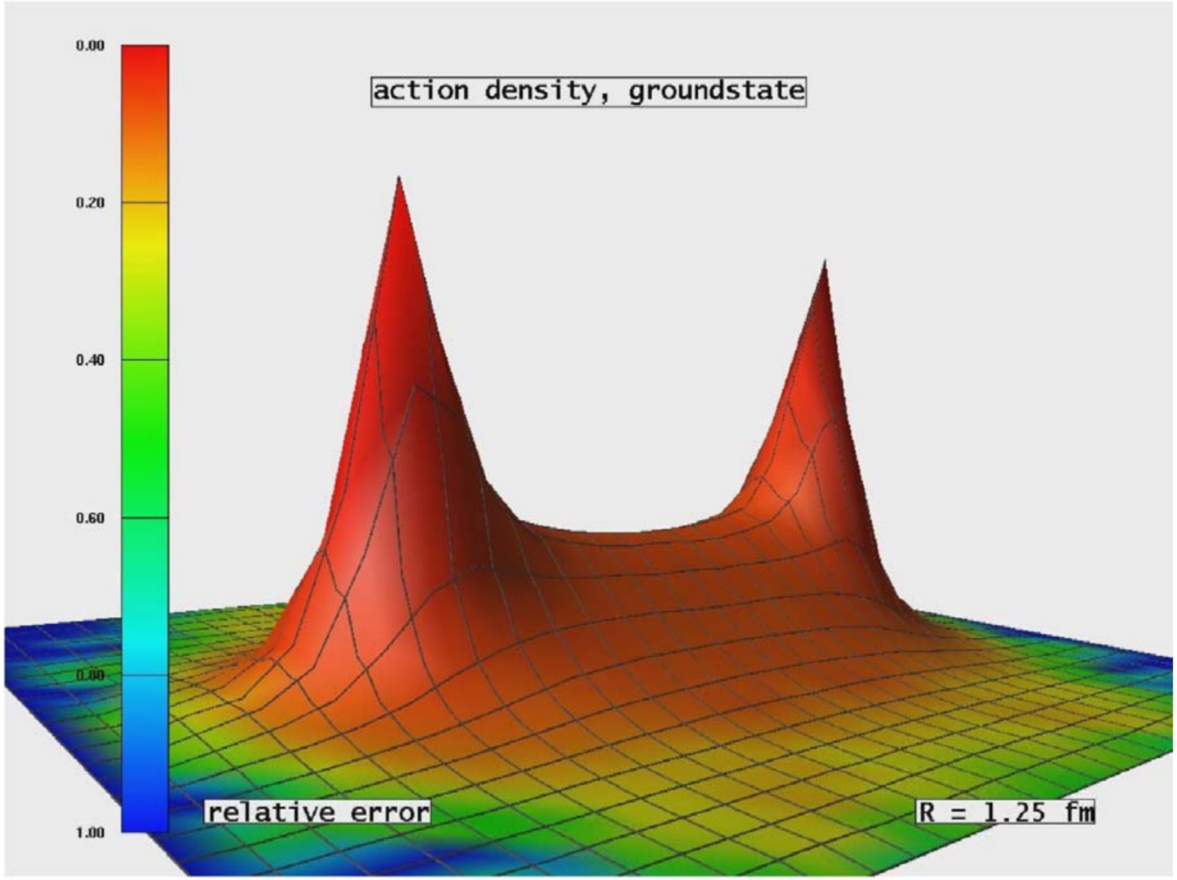
- Problem:

16 tonnes of force

makes a lot of pions.

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



1993: *"for elucidating the quantum structure of electroweak interactions in physics"*

Regge Trajectories?

- Martinus Veltmann, "Facts and Mysteries in Elementary Particle Physics" (World Scientific, Singapore, 2003):

  In time the Regge trajectories thus became the cradle of string theory. Nowadays the Regge trajectories have largely disappeared, not in the least because these higher spin bound states are hard to find experimentally. At the peak of the Regge fashion (around 1970) theoretical physics produced many papers containing families of Regge trajectories, with the various (hypothetically straight) lines based on one or two points only!

Properties of Regge trajectories

Alfred Tang* and John W. Norbury†
Physics Department, University of Wisconsin–Milwaukee, P. O. Box 413, Milwaukee, Wisconsin 53201
(Received 30 November 1999; published 8 June 2000)

Early Chew-Frautschi plots show that meson and baryon Regge trajectories are approximately linear and non-intersecting. In this paper, we reconstruct all Regge trajectories from the most recent data. Our plots show that meson trajectories are non-linear and intersecting. We also show that all current meson Regge trajectories models are ruled out by data.

PACS number(s): 11.55.Jy, 12.40.Nn, 14.20.−c, 14.40.−n

Phys.Rev. D **62** (2000) 016006 [9 pages]

1993: *"for elucidating the quantum structure of electroweak interactions in physics"*

Regge Trajectories?

- Martinus Veltmann, "Facts and Mysteries in Elementary Particle Physics" (World Scientific, Singapore, 2003):

  In time the Regge trajectories thus became the cradle of string theory. Nowadays the Regge trajectories have largely disappeared, not in the least because these higher spin bound states are hard to find experimentally. At the peak of the Regge fashion (around 1970) theoretical physics produced many papers containing families of Regge trajectories, with the various (hypothetically straight) lines based on one or two points only!

Properties of Regge trajectories

Alfred Tang* and Joh

Physics Department, University of Wisconsi ... *3201*

(Receive

Early Chew-Fra ... es are approximately linear and non-int ... from the most recent data. Our plots show that me ... we also show that all current meson Regge trajectories models ...

PACS nu ... .Jy, 12.40.Nn, 14.20.−c, 14.40.−n

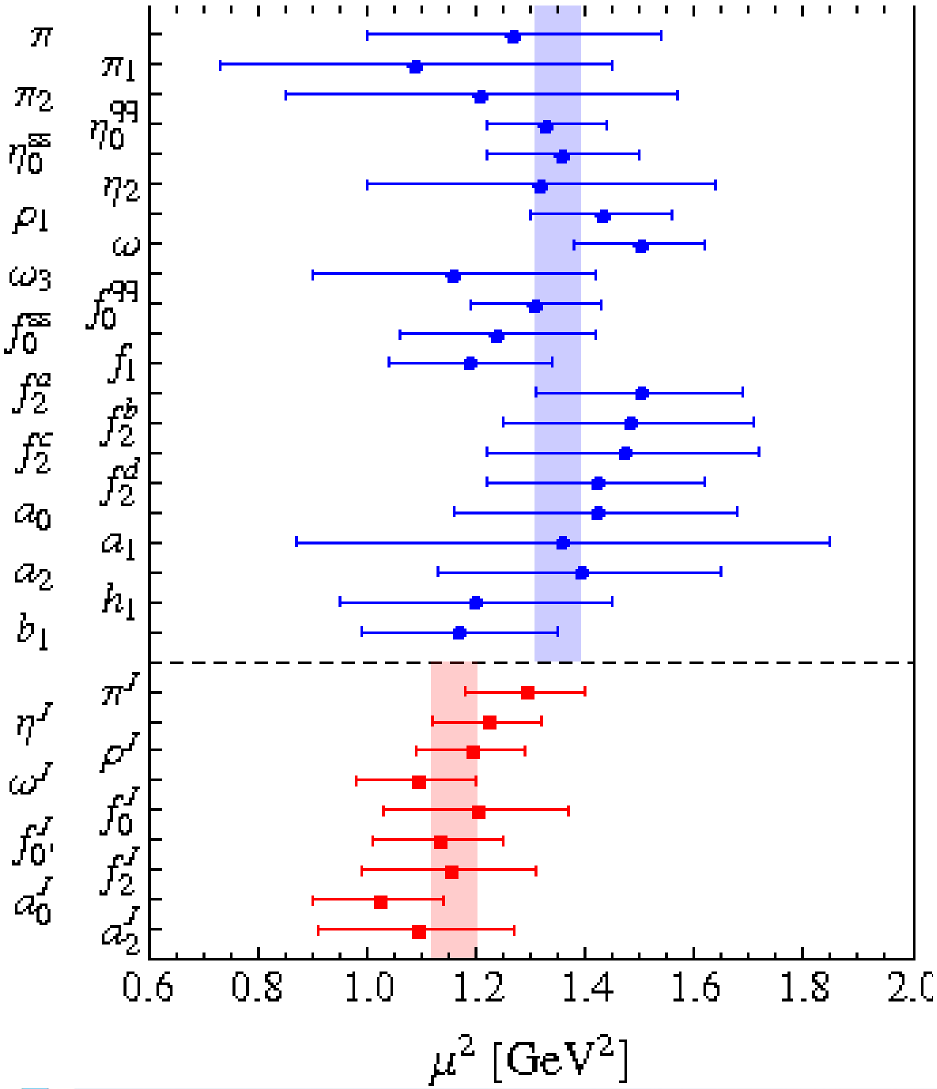
We show that all current meson Regge trajectory models are ruled out by data

Phys.Rev. D **62** (2000) 016006 [9 pages]

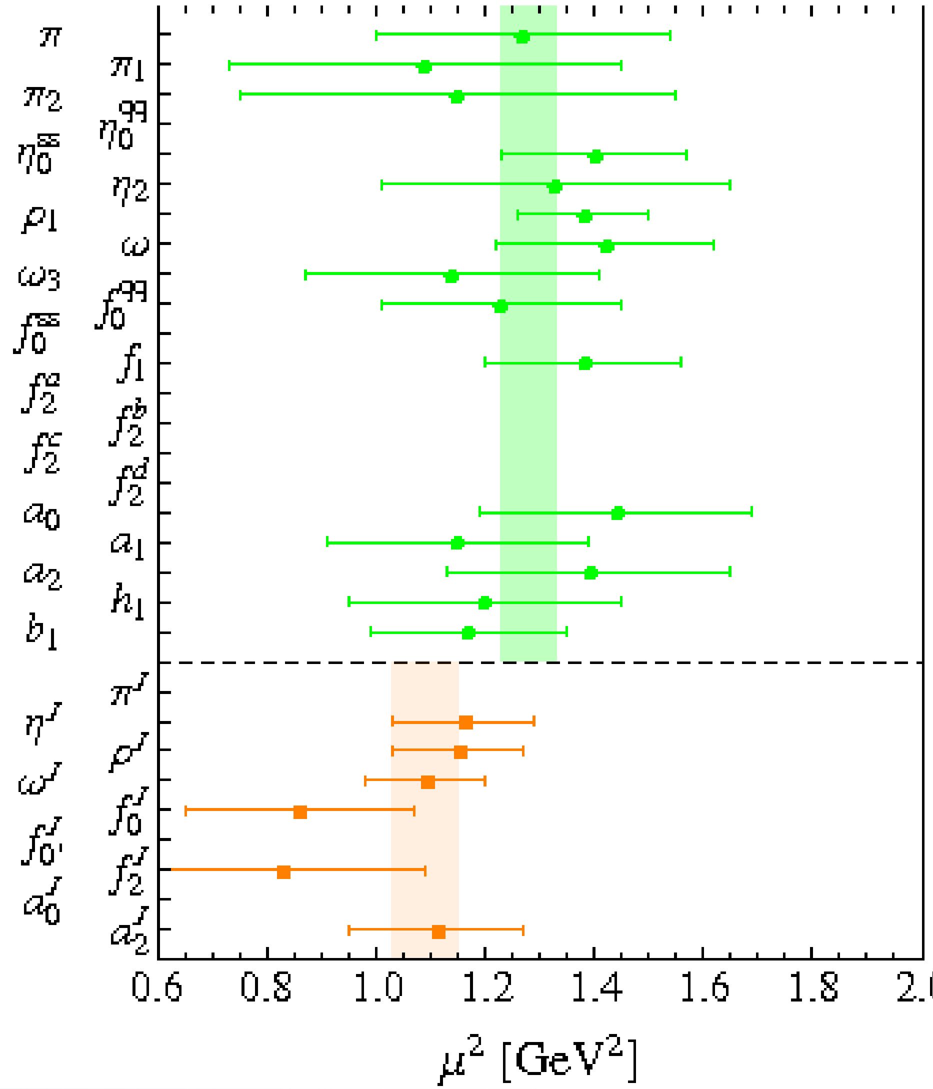
Empirically: Regge Trajectories

"Systematics of radial and angular-momentum Regge trajectories of light non-strange qqbar-states," Masjuan, Ruiz Arriola, Broniowski. [arXiv:1305.3493 [hep-ph]]

If all points take the same value, then $M^2 \propto J,n$ … Method 1

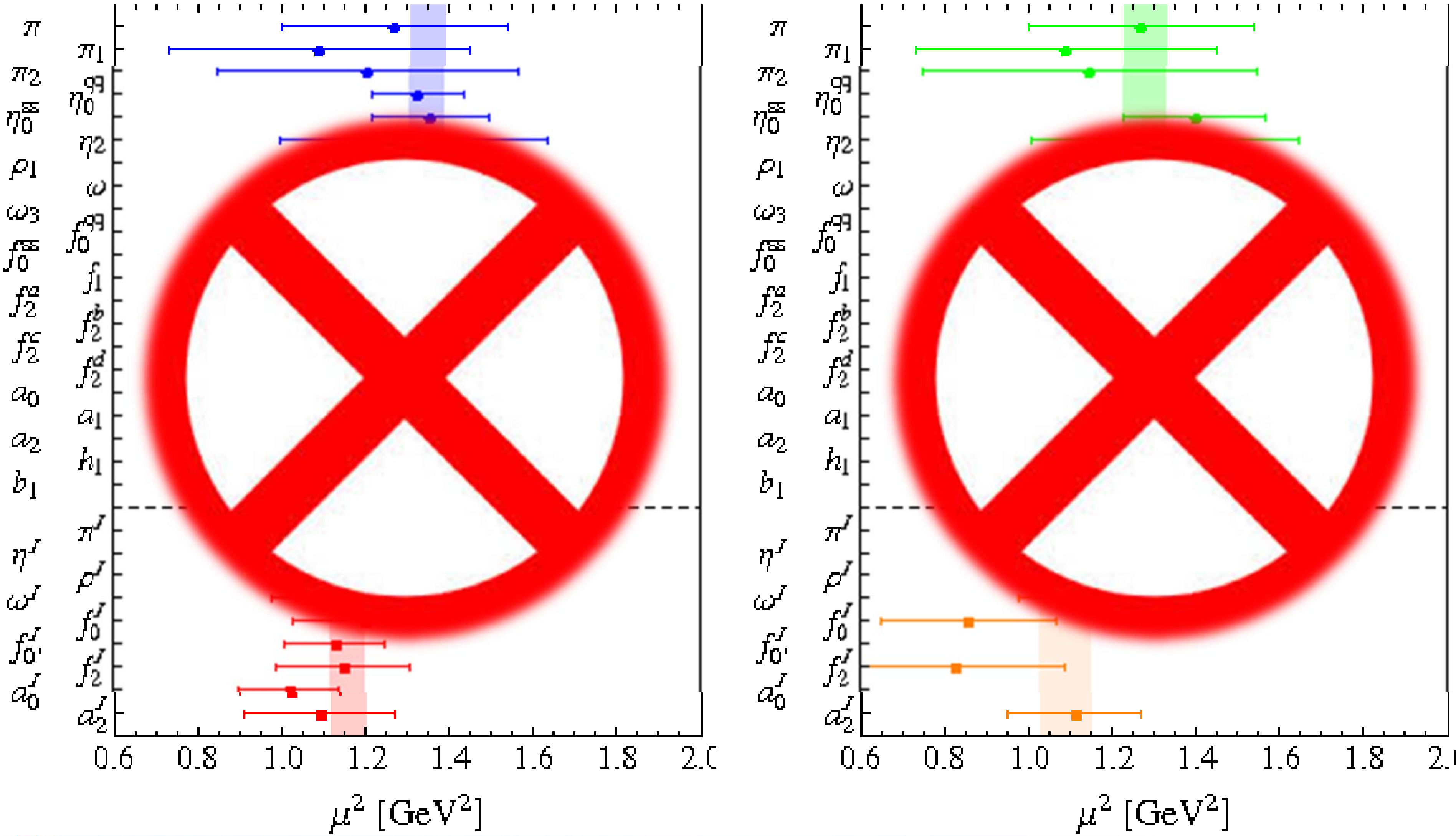


If all points take the same value, then $M^2 \propto J,n$ … Method 2



Our joint linear-regression analysis in the (*n,J,M2) Regge planes indicates, at a statistically significant level of 4.5 standard deviations, that the slopes of the radial Regge trajectories are larger than the angular-momentum slopes.*

Thus no strict universality of slopes occurs in the light non-strange meson spectra.



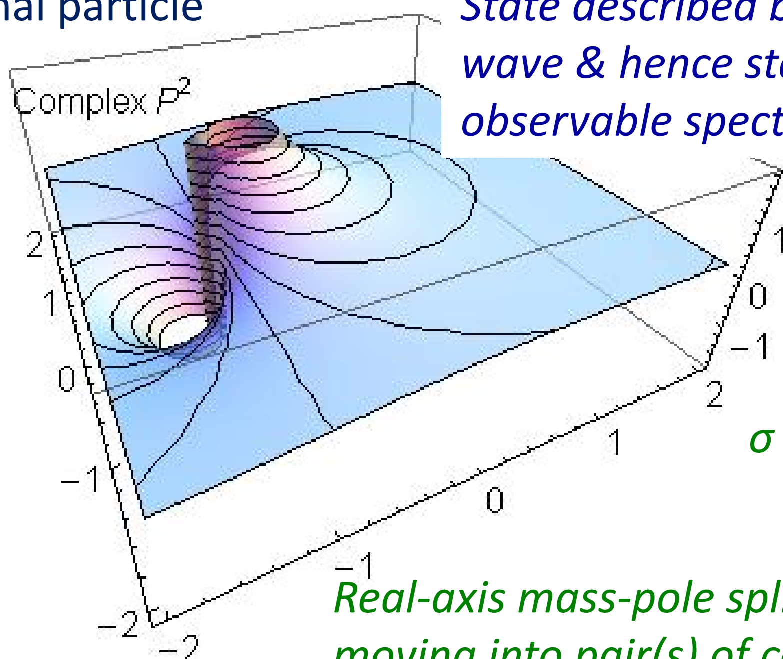
Regge Trajectories?

- Regge trajectories are a property of quantum mechanical models
- The curvature of the trajectories depends on the
  - a) potential used
  - b) form of dynamics, *e.g*.
    - Schrödinger equation: $r^{2/3} \Rightarrow M^2 \propto J,n$ for large M
    - Instant-form with relativistic kinetic energy:
      linear potential $\Rightarrow M^2 \propto J,n$
    - Point-form: harmonic-oscillator potential $\Rightarrow M^2 \propto J,n$
- All models predict infinitely many trajectories.
- No known mechanism for this pattern of masses in relativistic quantum field theory … particle number nonconservation and unnaturally light pion mass make static potential-model picture unrealistic
- *Having one isolated Regge trajectory or a few approximately-linear and approximately parallel Regge trajectories ≡ half-pregnant*

Confinement

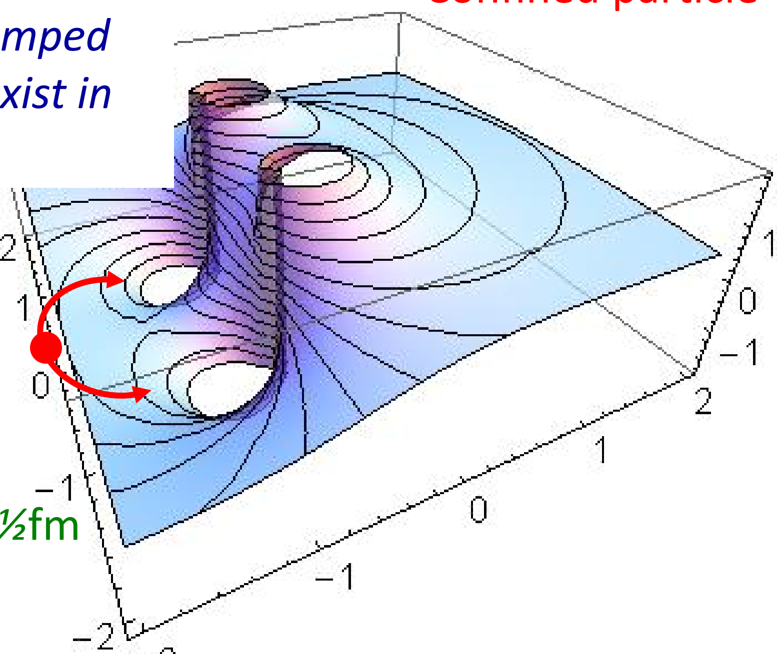
- QFT Paradigm:
  - Confinement is expressed through a *dramatic* change in the analytic structure of propagators for coloured states
  - It can almost be read from a plot of the dressed-propagator for a coloured state

Normal particle



State described by rapidly damped wave & hence state cannot exist in observable spectrum

Confined particle

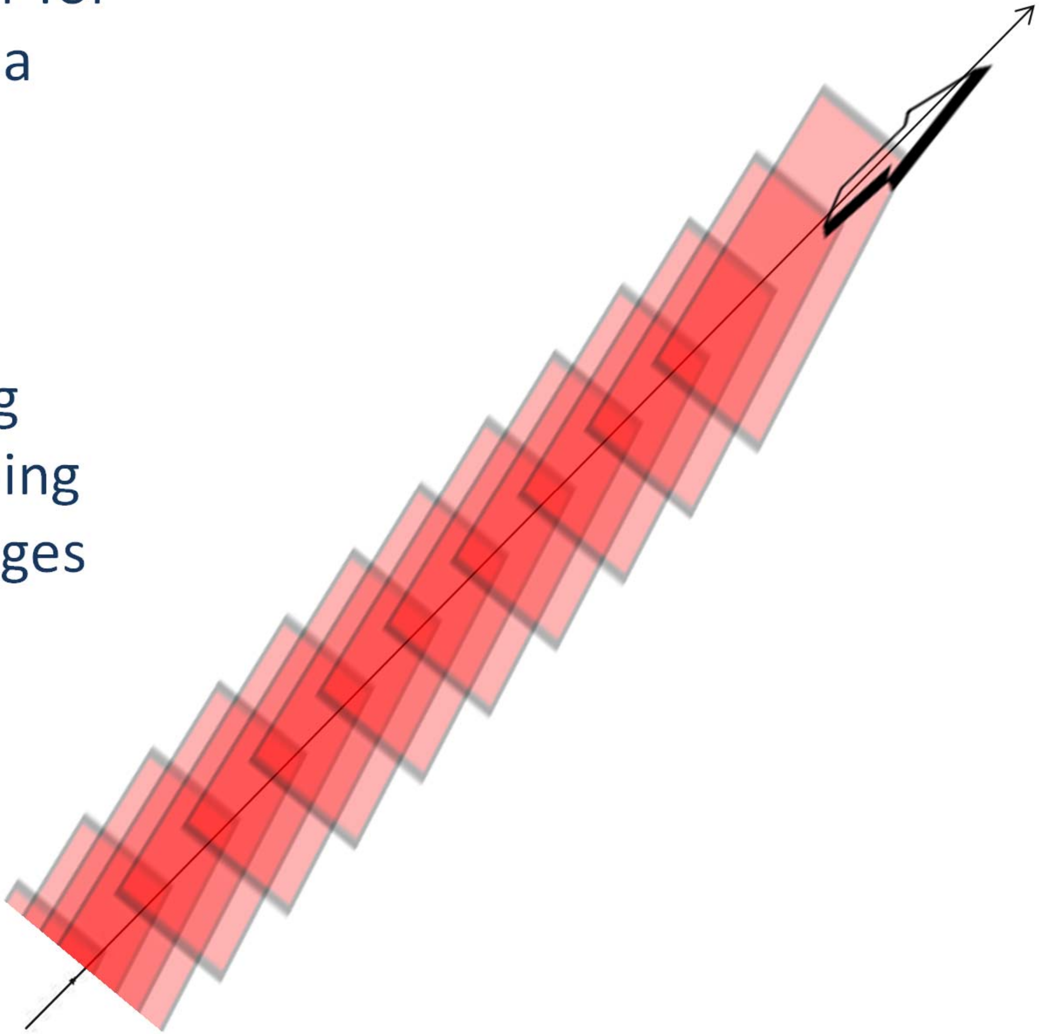


$\sigma \approx 1/\mathrm{Im}(m)$
$\approx 1/2\Lambda_{QCD} \approx$ ½fm

Real-axis mass-pole splits,
moving into pair(s) of complex conjugate singularities, (or qualitatively analogous structures chracterised by a dynamically generated mass-scale)

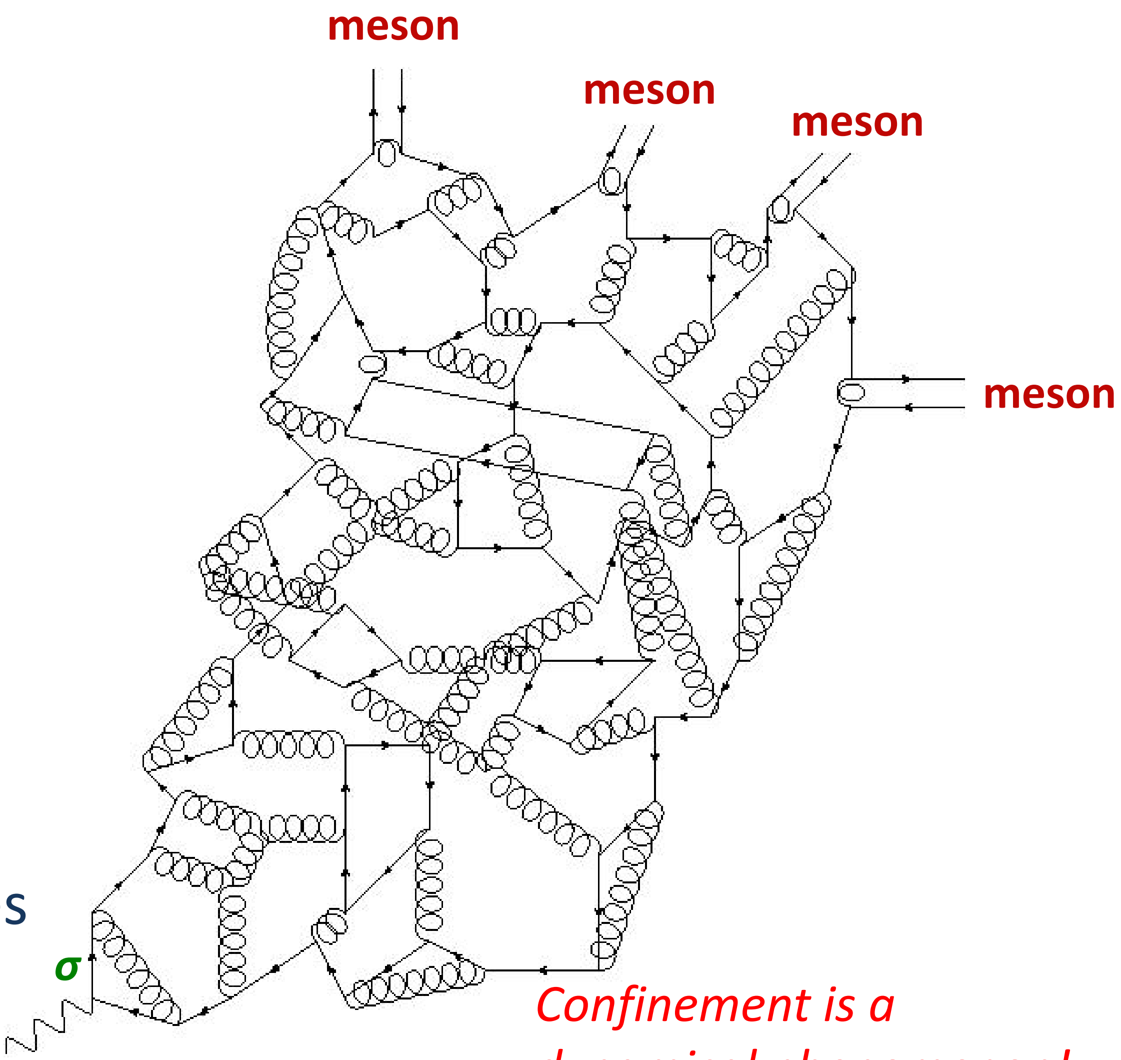
Plane wave propagation

- Feynman propagator for a fermion describes a Plane Wave
- A fermion begins to propagate
- It can proceed a long way before undergoing any qualitative changes



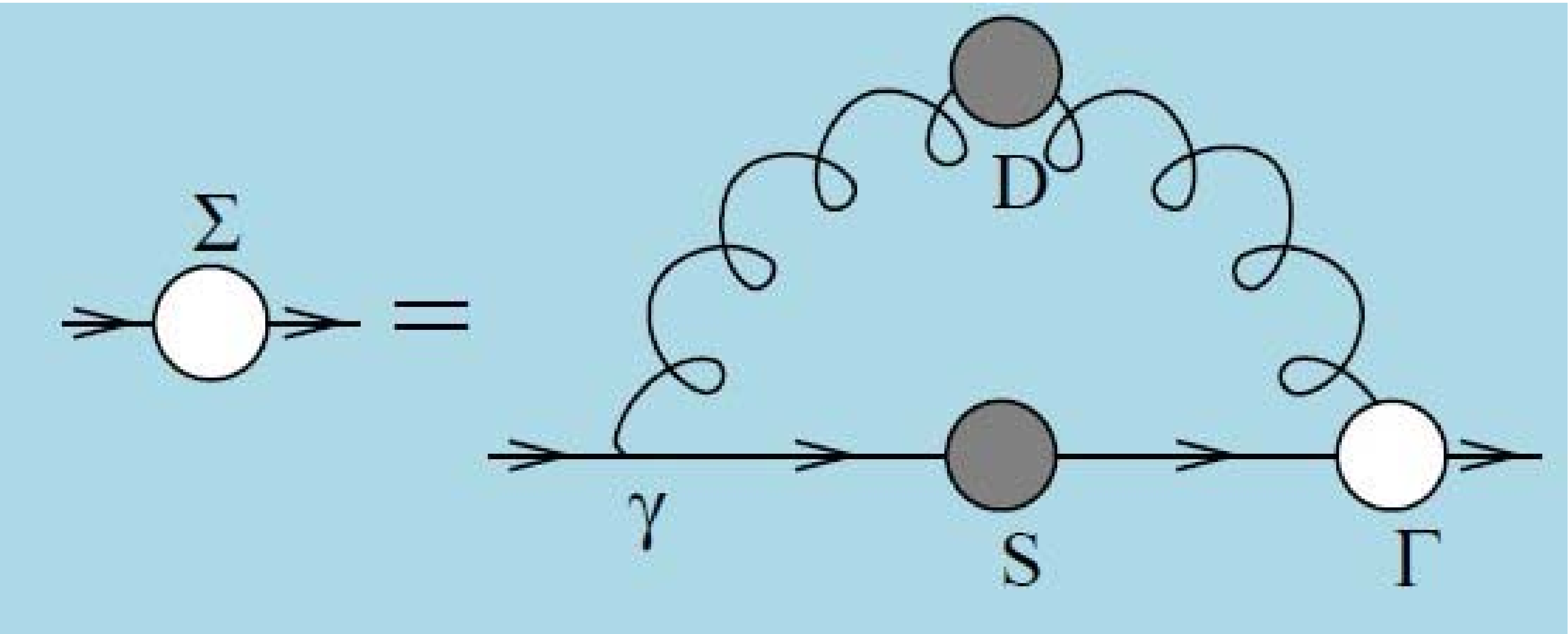
Quark Fragmentation

- 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!

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

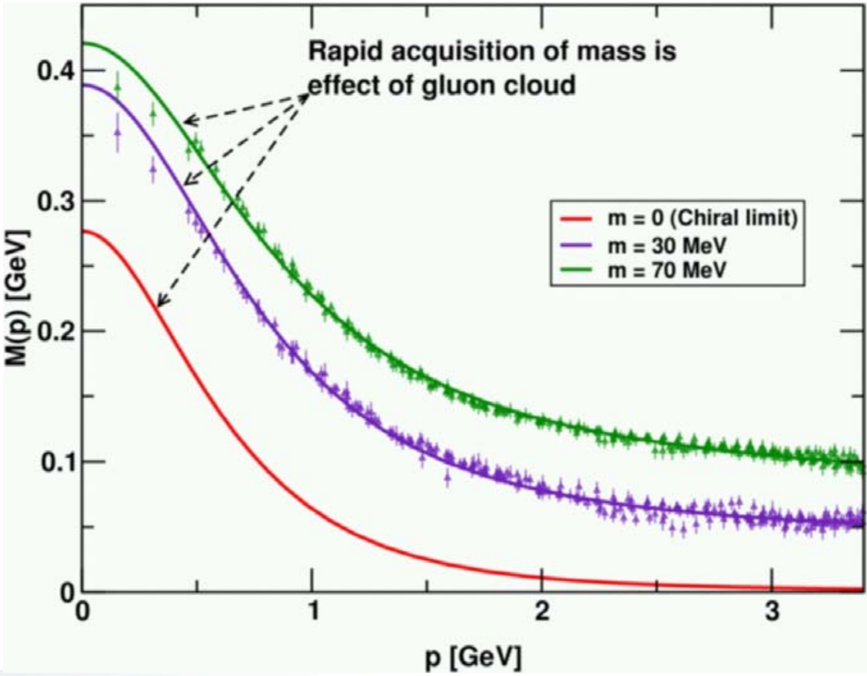


Quark Gap Equation

DCSB

- Dynamical chiral symmetry breaking (DCSB) is another of QCD's emergent phenomena
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory argues 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* ,

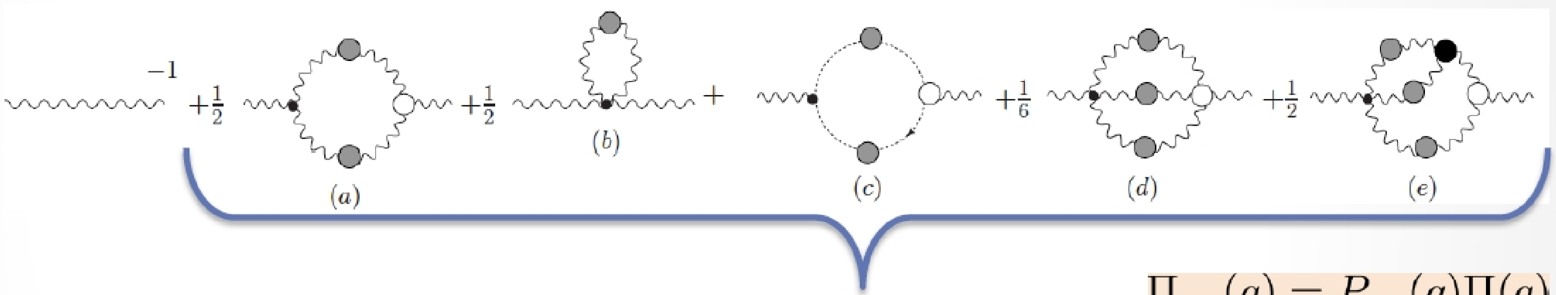
    No Higgs field, nothing! Effect achieved purely through quark+gluon dynamics.



Non-perturbative comparison of QCD effective charges, A.C. Aguilar, D. Binosi, J. Papavassiliou and J. Rodriguez-Quintero, Phys. Rev. D80 (2009) 085018

Gluons, too, have a gap equation

$$\Delta_{\mu\nu}^{-1}(q) =$$



$$\Pi_{\mu\nu}(q)$$

$$\Pi_{\mu\nu}(q) = P_{\mu\nu}(q)\Pi(q)$$

$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

- Pinch-technique + background field method … reordering of diagrammatic summations in the self-energy – $\Pi_{\mu\nu}$ – ensures that subclusters are individually transverse and gluon-loop and ghost-loop contributions are separately transverse
- STIs → WGTIs
- Enables systematic analysis and evaluation of truncations and straightforward comparison of results with those of lQCD

Bridging a gap between continuum-QCD and ab initio predictions of hadron observables, D. Binosi, L. Chang, J.Papavassiliou, C.D. Roberts, arXiv:1412.4782 [nucl-th], Phys. Lett. B742 (2015) 183-188

In QCD: Gluons also become massive!

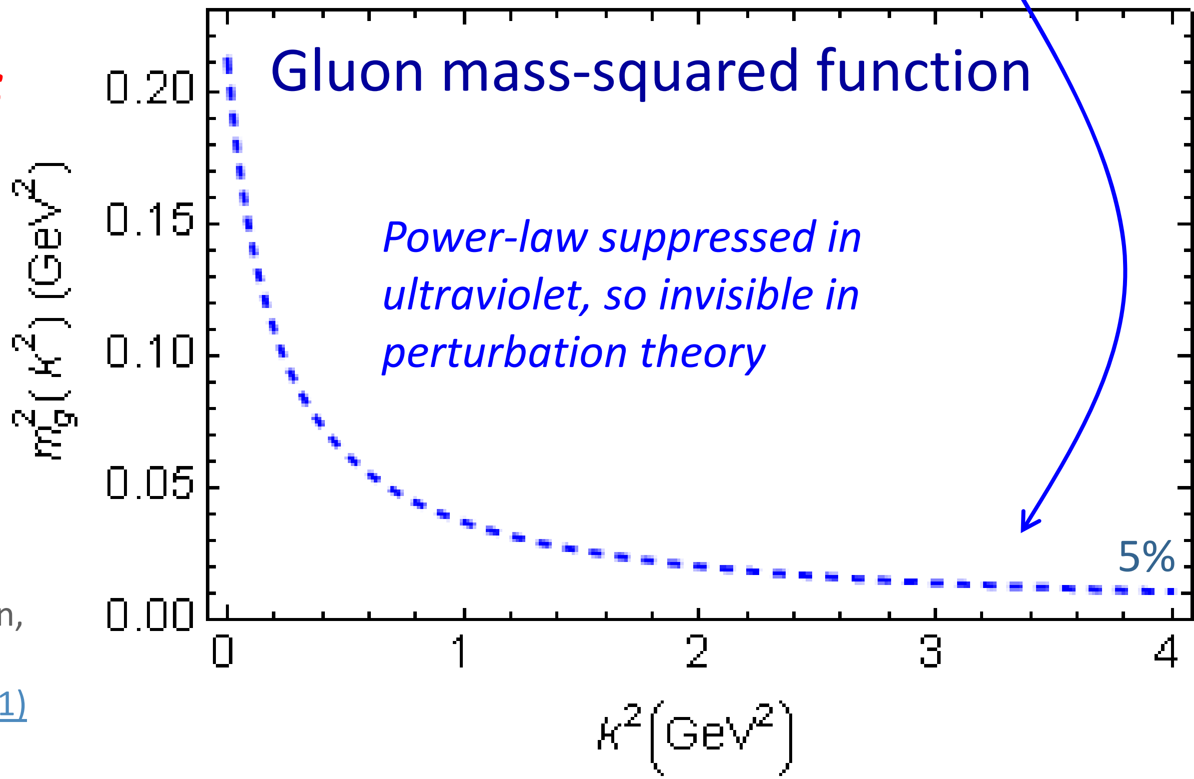
- Running gluon mass

$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

$$\alpha_s(0) = 2.77 \approx 0.9\pi\,,\ m_g^2(0) = (0.46\,\text{GeV})^2$$

- Gluons are ***cannibals*** – a particle species whose members become massive by eating each other!

$$m_g^2(k^2) = \frac{\mu_g^4}{\mu_g^2 + k^2}$$



Interaction model for the gap equation, S.-x.Qin, L.Chang, Y-x.Liu, C.D.Roberts and D. J. Wilson, arXiv:1108.0603 [nucl-th], Phys. Rev. C **84** (2011) 042202(R) [5 pages]

Massive Gauge Bosons!

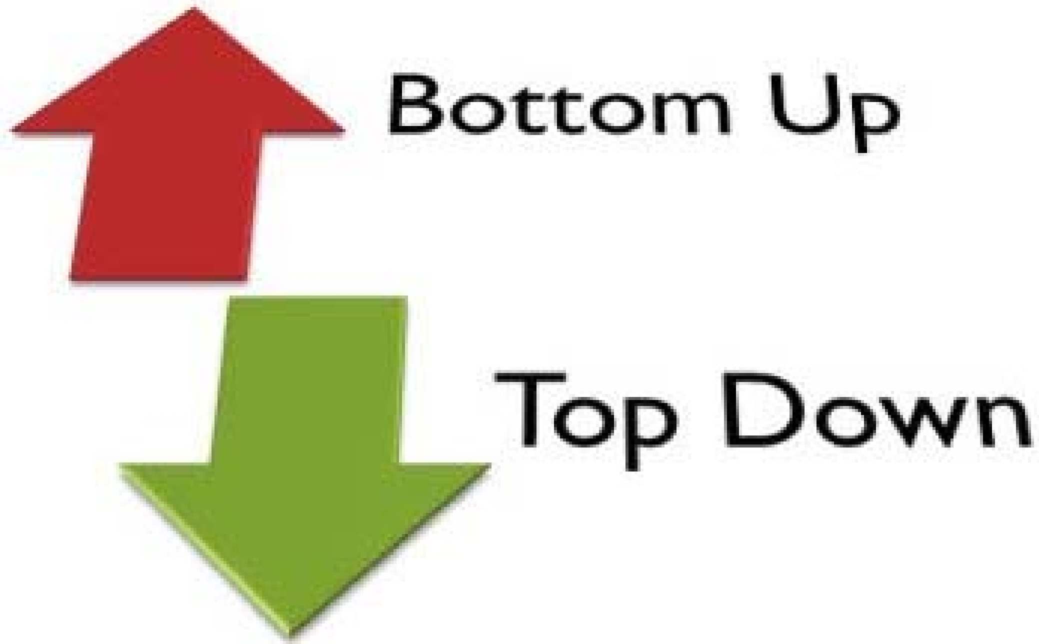
- Gauge boson cannibalism

  … a new physics frontier … within the Standard Model
- Asymptotic freedom means
  … ultraviolet behaviour of QCD is controllable
- Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
  - Gluons and quarks with

    wavelength $\lambda > 2/\text{mass} \approx 1$ fm

    decouple from the dynamics … ***Confinement?!***
- How does that affect observables?
  - It will have an impact in
    any continuum study
  - Must play a role in gluon saturation ...
    In fact, perhaps it's a harbinger of gluon saturation?

Electron Ion Collider: The Next QCD Frontier



Continuum-QCD & ab initio predictions

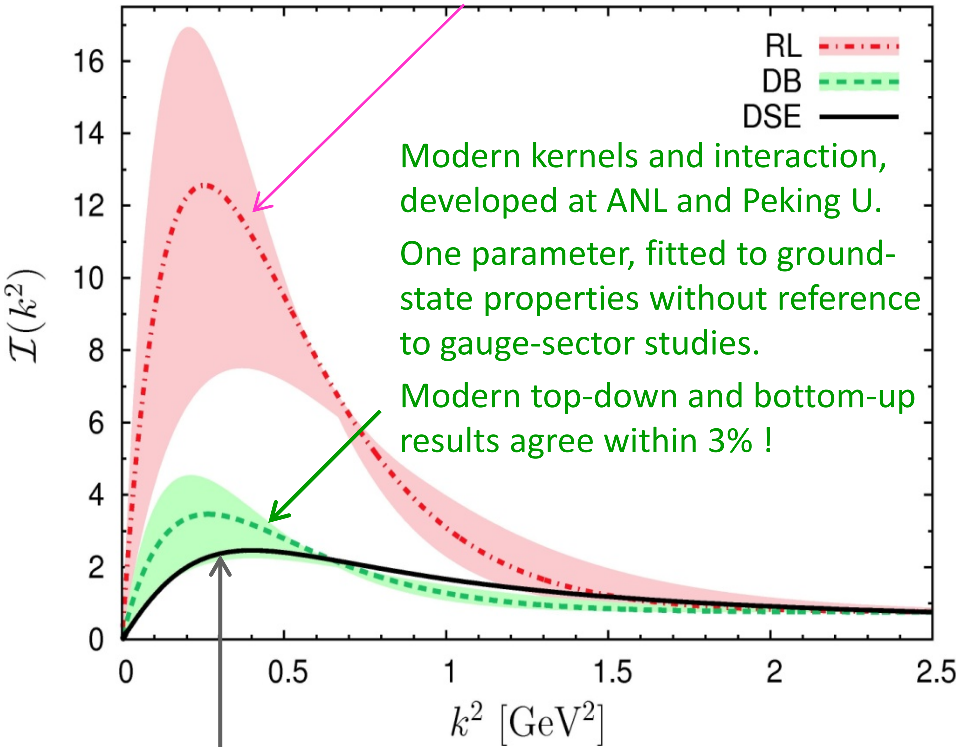
Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
C. D. Roberts (US), [arXiv:1412.4782 [nucl-th]](), *Phys. Lett. B* ***742*** *(2015) 183*

Top down & Bottom up

- *<u>Bottom-up scheme</u> – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.*
- *<u>Top-down approach</u>* – ab initio *computation of the interaction via direct analysis of the gauge-sector gap equations*
- *Serendipitous collaboration, conceived at one-week ECT* Workshop on* DSEs in Mathematics and Physics*, has united these two approaches*

"Maris-Tandy" interaction. Developed at ANL & KSU in 1997-1998. More-than 600 citations – *but* quantitative disagreement with gauge-sector solution.



Top-down result = gauge-sector prediction

– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

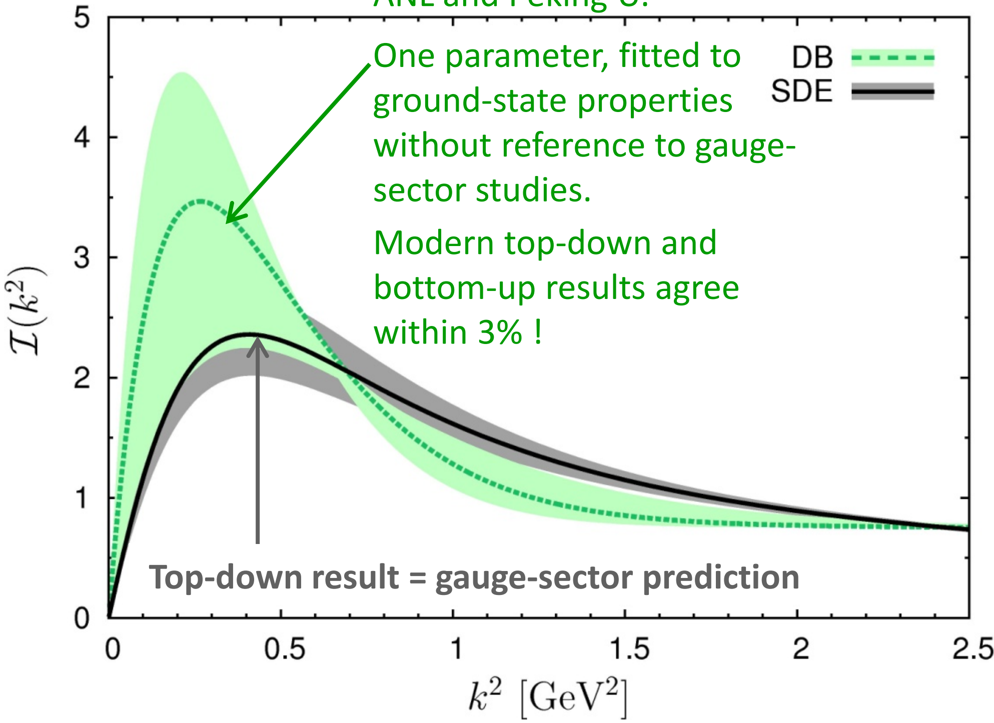
Bridging a gap between continuum-QCD
& ab initio *predictions of hadron observables*

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
C. D. Roberts (US), arXiv:1412.4782 [nucl-th] , *Phys. Lett. B* ***742*** *(2015) 183*

Top down & Bottom up

- *Bottom-up scheme – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.*
- *Top-down approach* – ab initio *computation of the interaction via direct analysis of the gauge-sector gap equations*
- *Serendipitous collaboration, conceived at one-week ECT* Workshop on* DSEs in Mathematics and Physics*, has united these two approaches*

Modern kernels and interaction, developed at ANL and Peking U.



– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

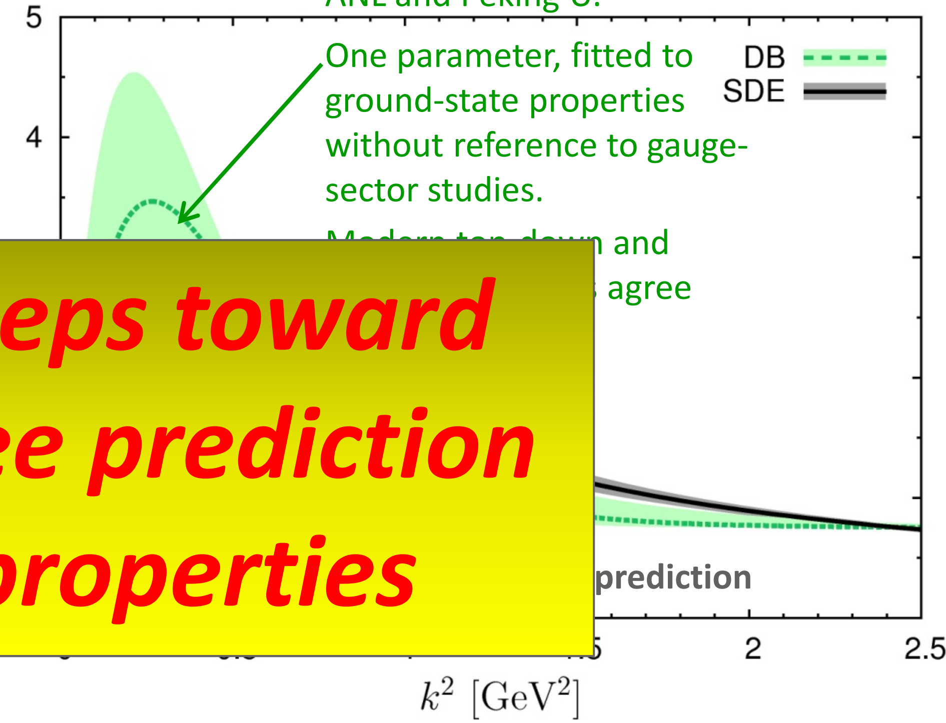
Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
C. D. Roberts (US), arXiv:1412.4782 [nucl-th], *Phys. Lett. B* ***742*** *(2015) 183*

Top down & Bottom up

- *Bottom-up scheme – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.*
- *Top-down* ... computat... direct and ... equations...
- *Serendipit...* at one-we... in Mathematics and Physics, *has united these two approaches*

Modern kernels and interaction, developed at ANL and Peking U.

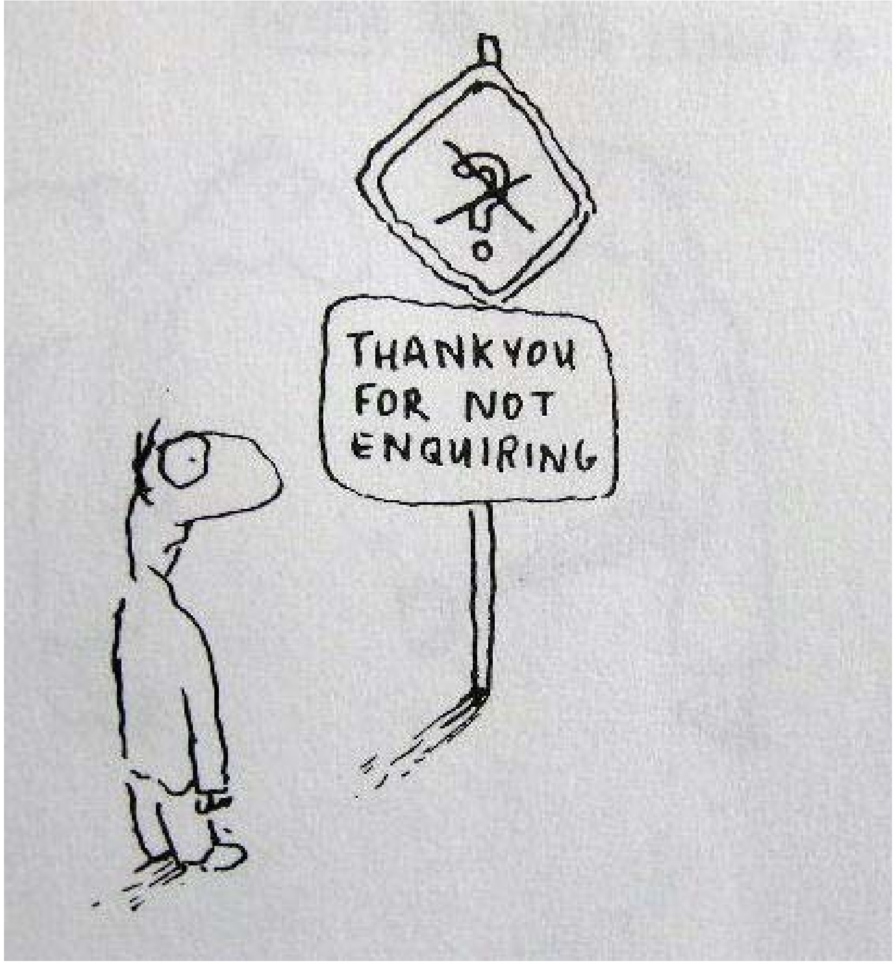


Significant steps toward parameter-free prediction of hadron properties

– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

DCSB at Sub-Critical Couplings

- *Symmetries* demand a dressed quark-gluon vertex, with transverse terms
- *Feedback* induced by the dressed quark-gluon vertex *guarantees DCSB* in the presence of a gluon mass, $m_g \approx 500$ MeV, and a coupling that runs slowly away from a finite infrared value, $\alpha(0) \approx 0.9\,\pi$
- *Solution* of *gauge sector* gap equations is all that is *required*
- Some fictitious *effective propagator,* completely unrelated to the propagation of a standard quantum field, is *entirely unnecessary* in QCD



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

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

- 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**

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

The most fundamental expression of Goldstone's Theorem and DCSB

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

This is why $m_\pi=0$ in the absence of a Higgs mechanism

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

But $m_\pi=0$ is insufficient … QCD predicts $m_\pi^2 \propto m_u+m_d$

If this is missing, then it's not QCD

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

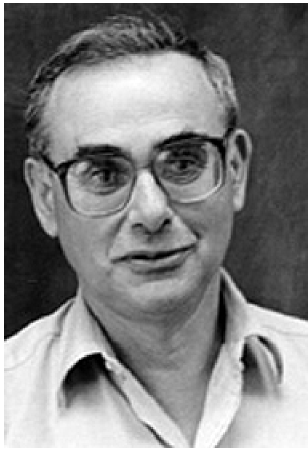
Enigma of mass

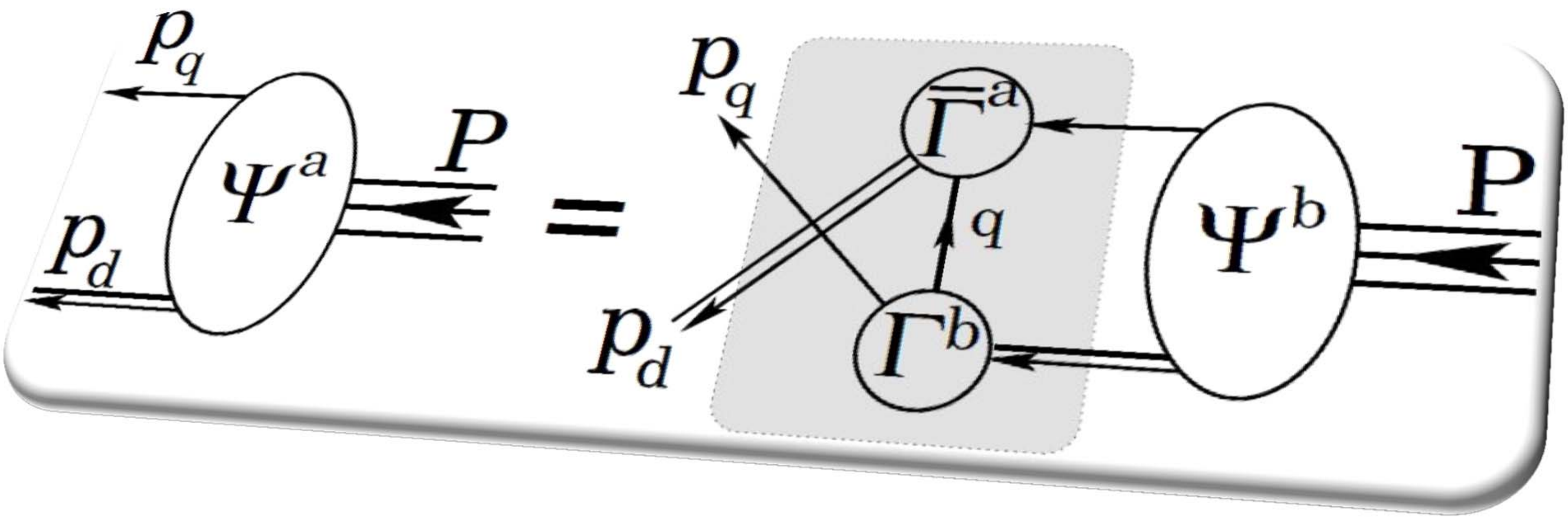
This algebraic identity is why QCD's pion is massless in the chiral limit

- 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.





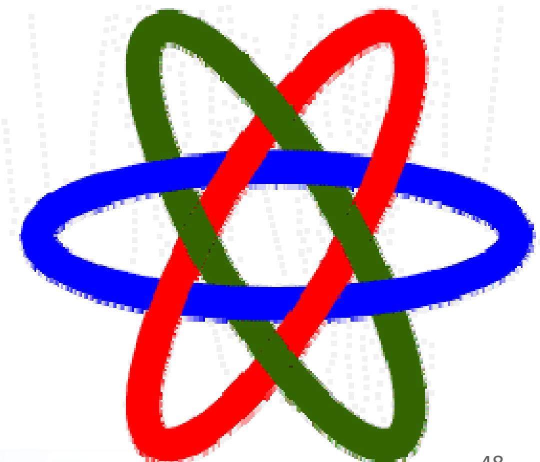
Baryon Structure

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys.Lett. B ***750*** *(2015) pp. 100-106*

Proton

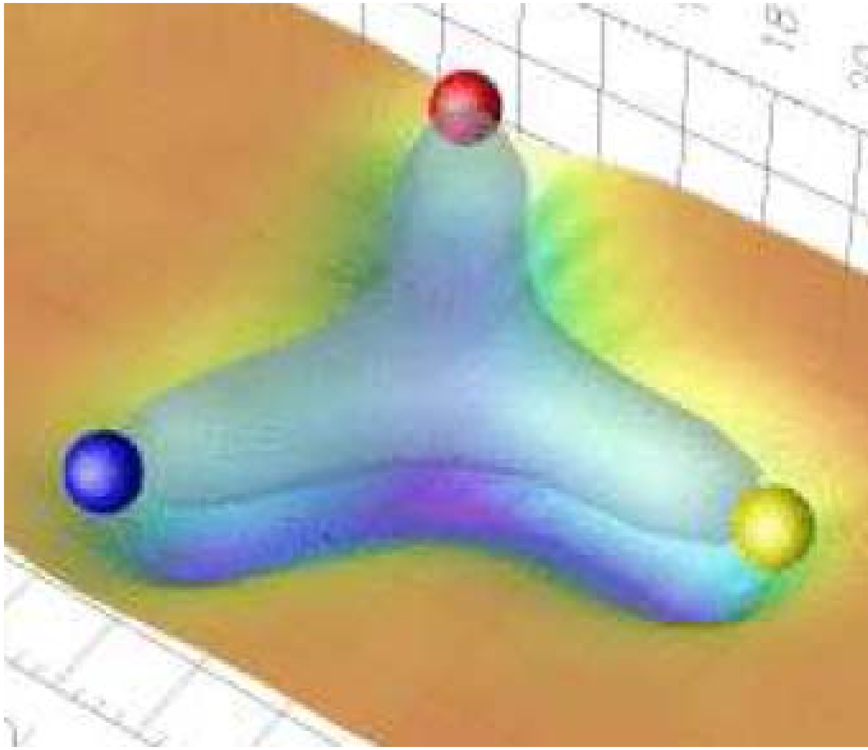
- Proton can be viewed as Borromean bound-state, *viz*. system constituted from three bodies, no two of which can combine to produce an independent two-body bound-state.
- Naturally, in QCD the complete picture of the proton is more complicated owing, in large part, to the loss of particle number conservation in quantum field theory.
- Notwithstanding that, the Borromean analogy provides an instructive perspective from which to consider both quantum mechanical models and continuum treatments of the nucleon bound-state problem in QCD.
- Borromean perspective poses a crucial question:

  Whence binding between the valence quarks in the proton?



Whence binding in the proton?

- Numerical simulations of lattice-regularised QCD (lQCD) that use static sources to represent the proton's valence-quarks produce a ``Y-junction'' flux-tube picture of nucleon structure
- Might be viewed as originating in the three-gluon vertex, which signals the non-Abelian character of QCD and is the source of asymptotic freedom
- Such results and notions would suggest a key role for the three-gluon vertex in nucleon structure *if* they were equally valid in real-world QCD wherein light dynamical quarks are ubiquitous.
- As we have seen, however, they are not; and so a different explanation of binding within the nucleon must be found.

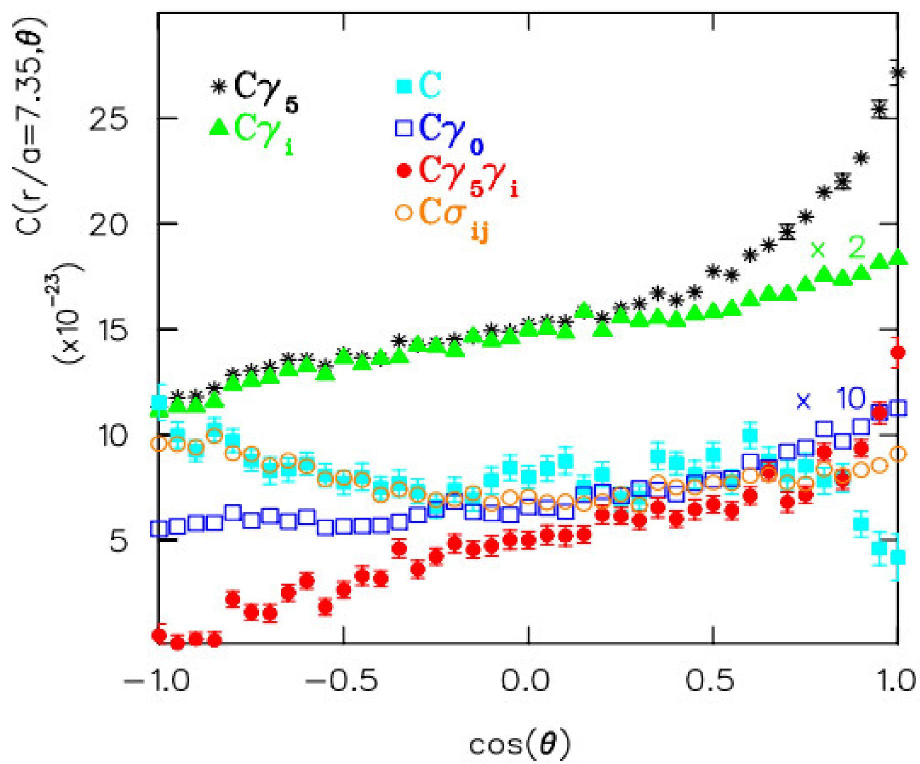


Corollary of DCSB (*little-known*)

- Any interaction that is capable of creating pseudo-Goldstone modes as bound-states of a light dressed-quark and -antiquark, and reproduce the measured value of their leptonic decay constant, will necessarily also generate strong correlations between any two dressed quarks contained within a nucleon.
- This assertion is based on an accumulated body of evidence gathered in nearly two decades of studying two- and three-body bound-state problems in hadron physics
- No realistic counter examples are known.

Corollary of DCSB (*little-known*)

- The existence of such diquark correlations is supported, too, by numerical simulations of lQCD
  - Alexandrou:2006cq
  - Babich:2007ah
- Correlations in scalar and pseudo vector diquark channels are strong
- Correlations in pseudoscalar and vector channels are smaller by a factor of 10



SU(2)-colour

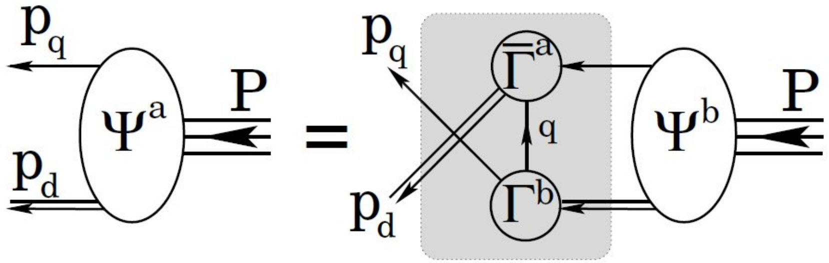
- In a dynamical theory based on SU(2)-colour, diquarks would be colour-singlets.
- They would exist as asymptotic states and form mass-degenerate multiplets with mesons composed from like-flavoured quarks.
- Consequently, the $[ud]_{0+}$ diquark would be massless in the presence of DCSB, matching the pion.
- These properties are a manifestation of Pauli-Gürsey symmetry
- Such identities are lost in changing the gauge group to SU(3)-colour; but strong and instructive similarities between mesons and diquarks remain

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
*arXiv: 1506.05112 [nucl-th], Phys.Lett. B **750** (2015) pp. 100-106*

Strong running coupling - α_S

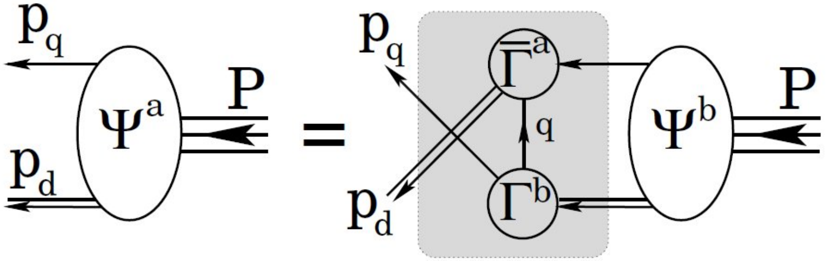
- Bulk of QCD's particular features can be traced to evolution of α_S
- Characteristics are primarily determined by three-gluon vertex:
  - four-gluon vertex doesn't contribute dynamically at leading order in perturbative analyses of matrix elements;
  - nonperturbative continuum analyses of gauge sector indicate that satisfactory agreement with lQCD gluon propagator is typically obtained without reference to dynamical contributions from four-gluon vertex

- Three-gluon vertex is therefore the dominant factor in producing the class of renormalisation-group-invariant running interactions that have provided both successful descriptions of and predictions for many hadron observables
- This class of interactions generates strong attraction between two quarks ⇒ tight diquark correlations in analyses of the three valence-quark scattering problem.



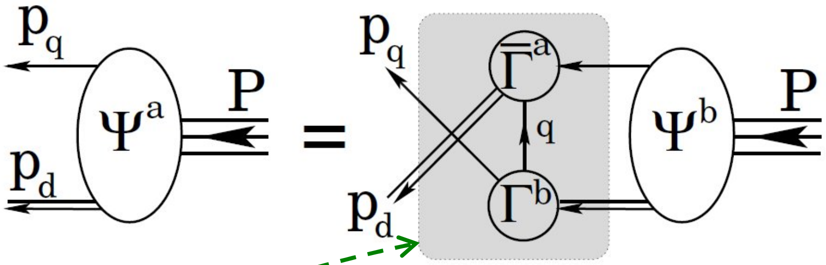
Baryon Structure

- Existence of tight diquark correlations simplifies analyses of baryon bound states … reduces task to solving Poincaré covariant Faddeev equation
- Three gluon vertex … not explicitly part of bound-state kernel
- Instead, one uses fact that phase-space factors and combinatorics enhance 2-body interactions over *n≥3*-body interactions & exploits dominant role played by diquark correlations in the 2-body subsystems
- The dominant effect of non-Abelian multi-gluon vertices is expressed in the formation of diquark correlations
- Baryon is then a compound system whose observable properties and interactions are primarily determined by the quark+diquark structure

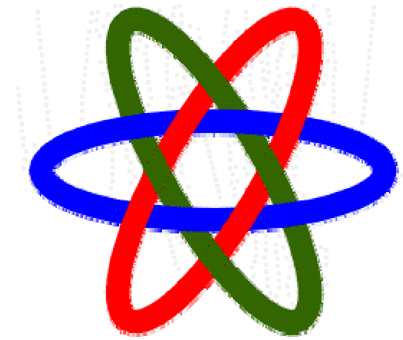


Baryon Structure

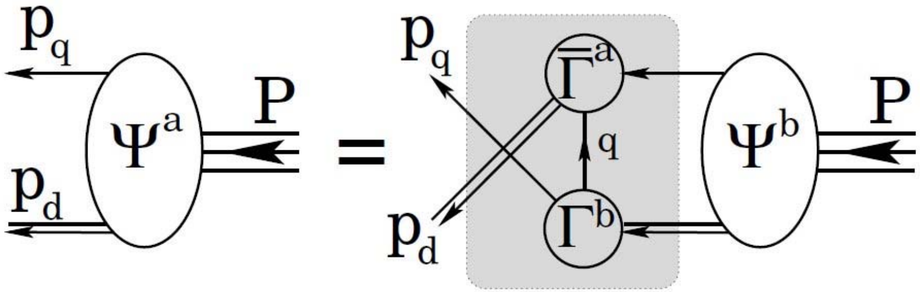
- Both scalar-isoscalar and pseudovector-isotriplet diquark correlations feature within a nucleon.
- Any study that neglects pseudovector diquarks is unrealistic because no self-consistent solution of the Faddeev equation can produce a nucleon constructed solely from a scalar diquark
- The relative probability of scalar versus pseudovector diquarks in a nucleon is a dynamical statement.
  - Realistic computations predict a scalar diquark strength of approximately 60%
  - This prediction can be tested by contemporary experiments.



Baryon Structure



- A nucleon (and kindred baryons) described by the Poincaré-covariant Faddeev equation is a Borromean bound-state, the binding within which has two contributions:
  - One part is expressed in the formation of tight diquark correlations, originating in non-Abelian nature of QCD
  - That is augmented, by attraction generated by the quark exchange depicted in the shaded area
  - This exchange ensures that diquark correlations within the nucleon are fully dynamical: no quark holds a special place because each one participates in all diquarks to the fullest extent allowed by its quantum numbers.
  - The continual rearrangement of the quarks guarantees, *inter alia*, that the nucleon's dressed-quark wave function complies with Pauli statistics.



Diquarks

- **Not your grandfather's diquarks!**
- Dynamically generated correlations
- Two particle sub-cluster is not frozen
  - 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

Proton Faddeev Amplitude

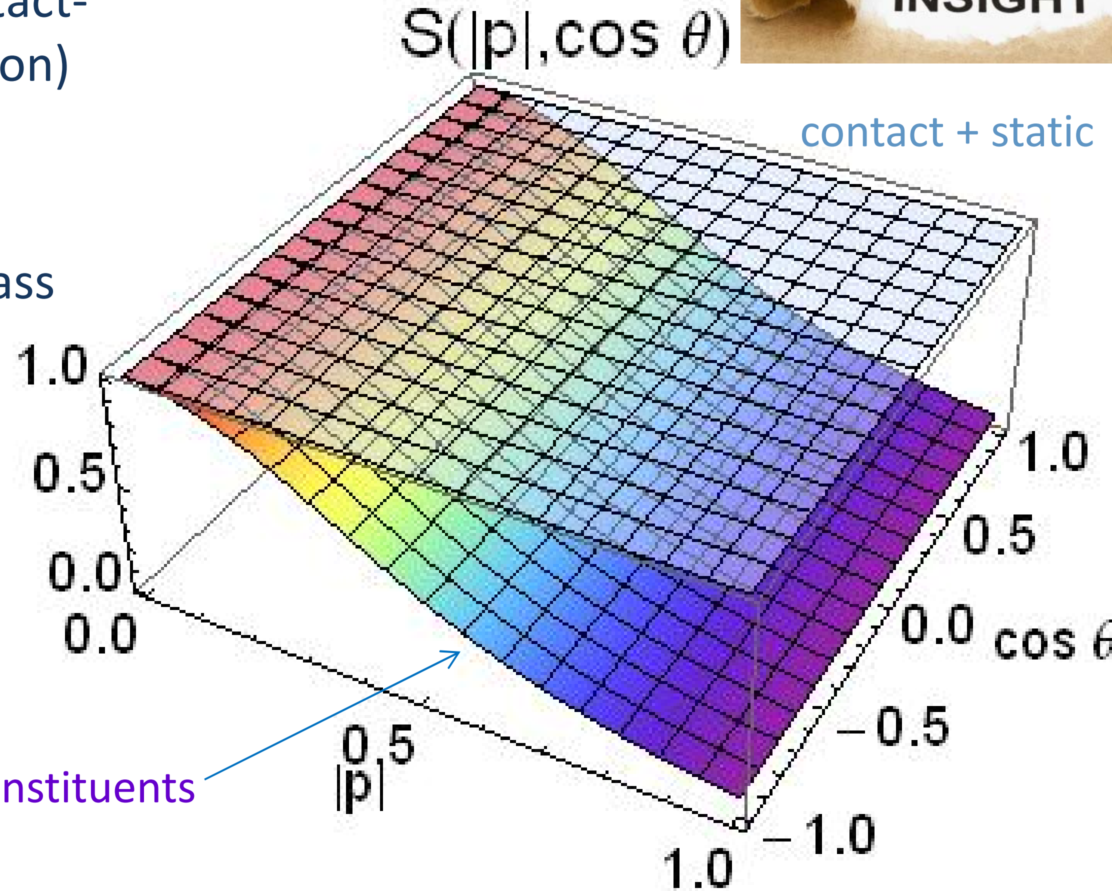
- Eight terms in Faddeev amplitude
- Plot the dominant scalar-diquark component
- Published treatments of a contact-interaction (static-approximation) produce

  $S(|p|, \cos\vartheta) = constant$

- In a bound-state with equal mass constituents,

  $S(|p|, \cos\vartheta) = f(|p|^2)$

  i.e., independent of $\cos\vartheta$



Equal mass constituents

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys.Lett. B ***750*** *(2015) pp. 100-106*

Proton Faddeev Amplitude

- Eight terms in Faddeev amplitude
- Plot the dominant scalar-diquark component: $S_1(|p|, \cos\vartheta)$
- **Realistic solution of Faddeev equation**
- Strong variation with *both* arguments
- Peaks at

  $|p| \approx m_N/6$, $\cos\vartheta \approx +1$

  $\Rightarrow k_q \approx P/2$, $k_{qq} \approx P/2$

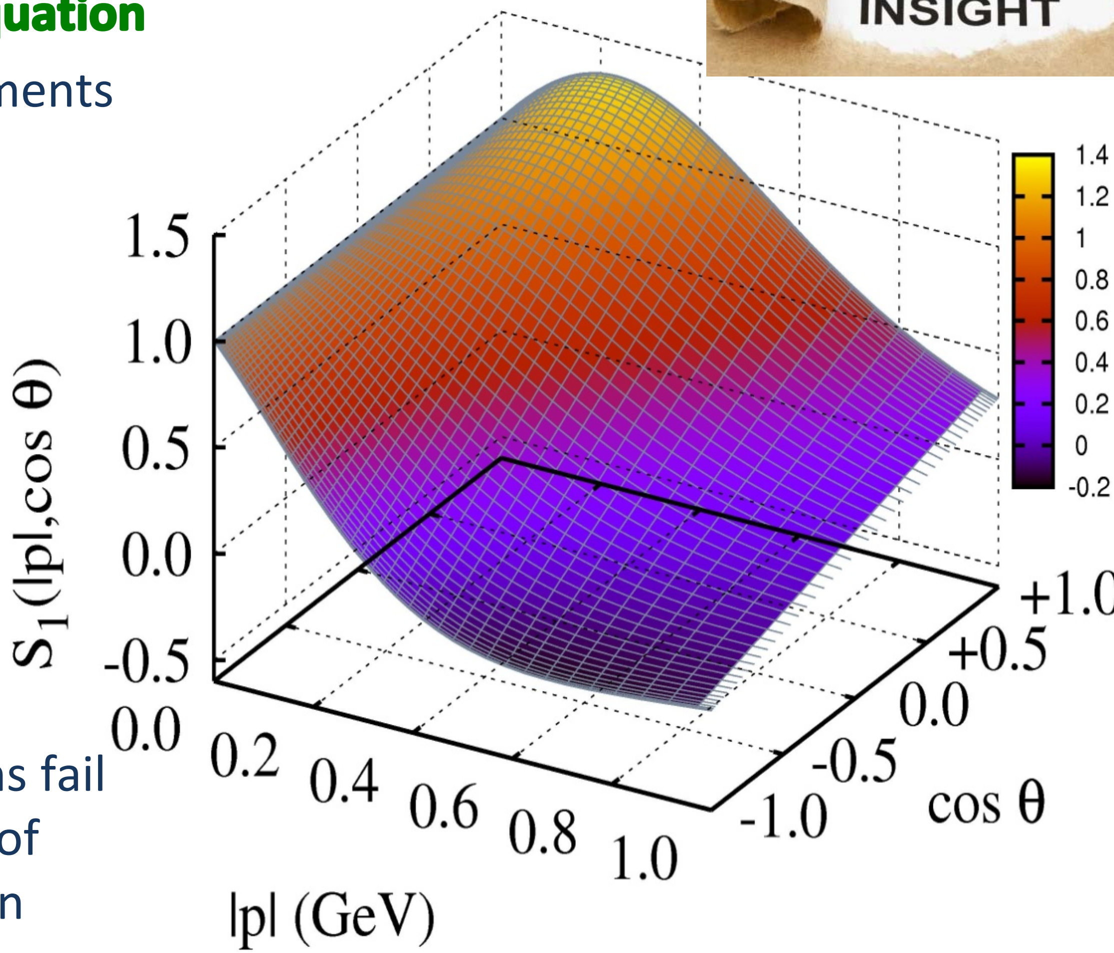
  i.e., *natural* rel-momentum = 0

  $\cos\vartheta = -1$, maximum at $|p| = 0$,

  $\Rightarrow k_q \approx P/3$, $k_{qq} \approx (2/3)P$

  Support concentrated in forward direction:

  $\cos\vartheta > 0$; *i.e.* $k \parallel P$
- Simple interactions & truncations fail to capture sophisticated profile of nucleon's Faddeev wave function



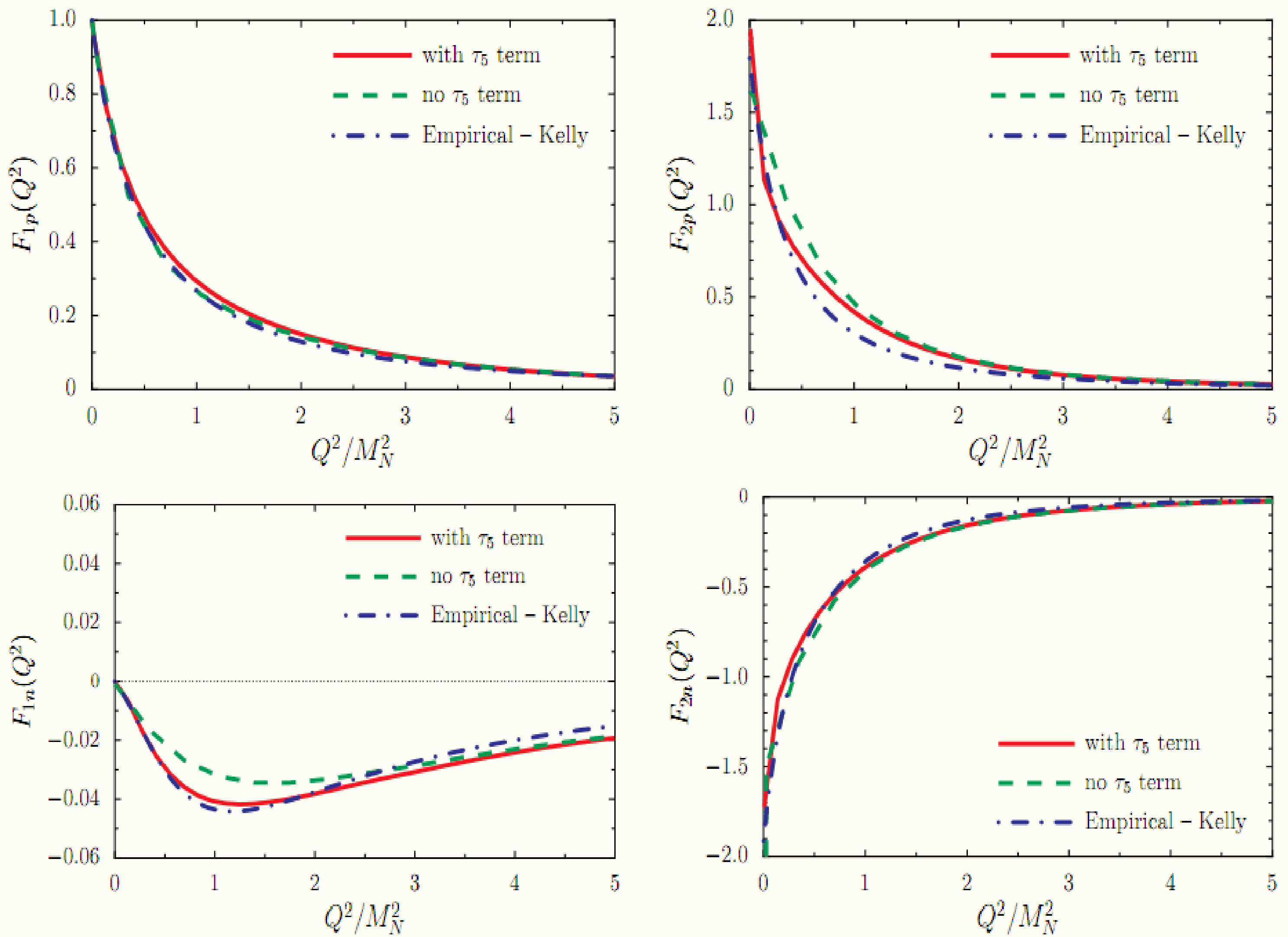
Survey of nucleon electromagnetic form factors
I.C. Cloët et al, arXiv:0812.0416 [nucl-th],
Few Body Syst. **46** (2009) pp. 1-36

Nucleon Form Factors

Unification of meson and nucleon form factors.

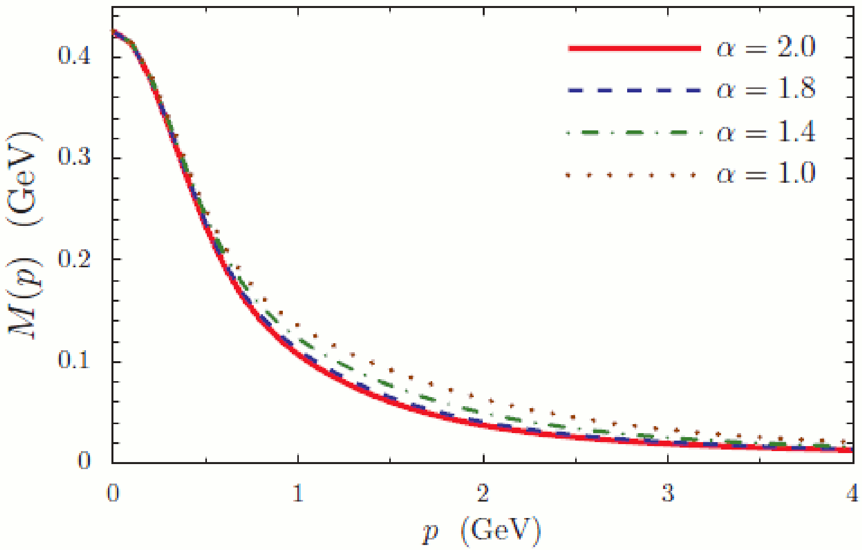
Very good description.

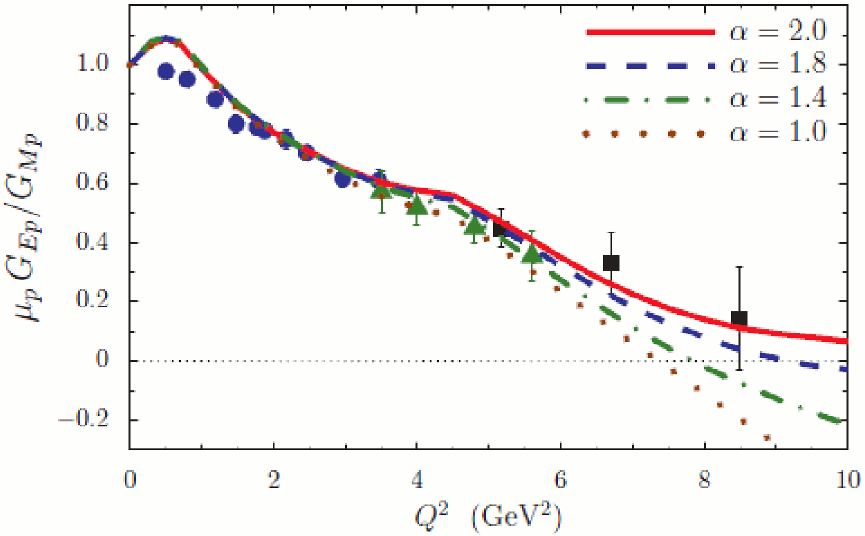
Quark's momentum-dependent anomalous magnetic moment has observable impact & materially improves agreement in all cases.



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



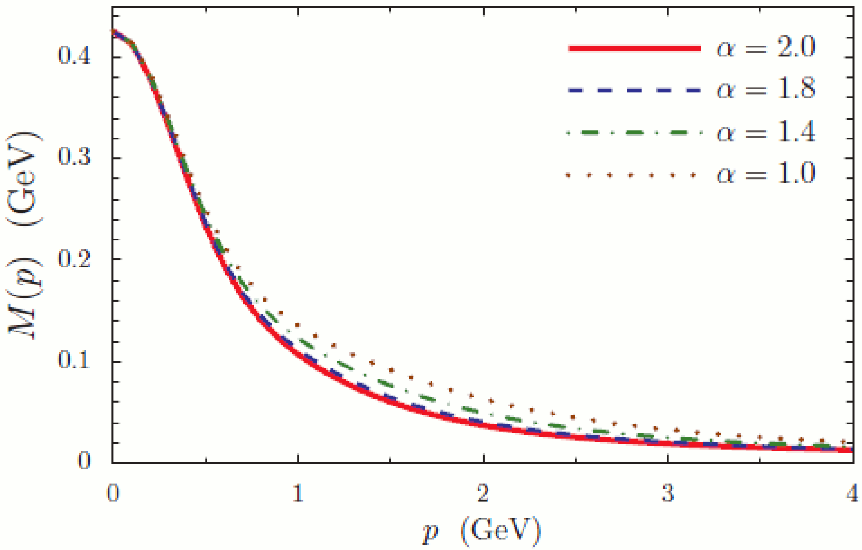


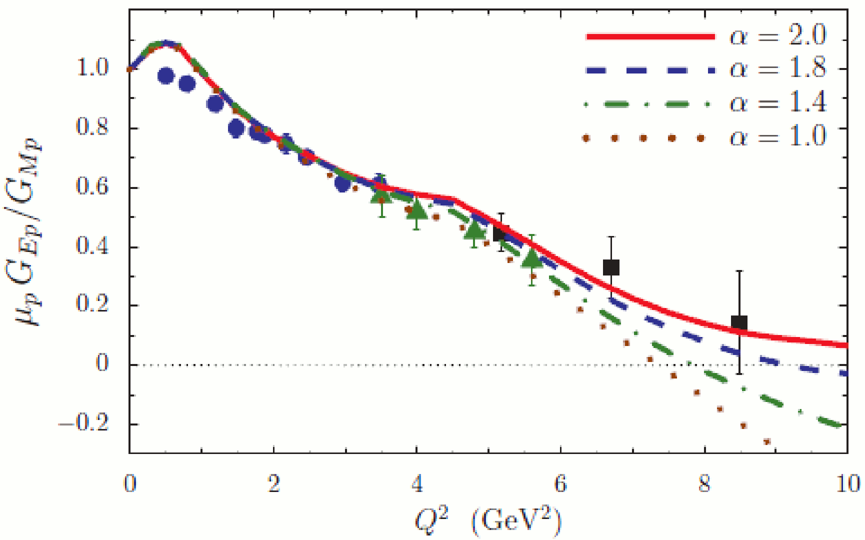
$$S(p) = \frac{Z(p^2)}{i\gamma\cdot p + M(p^2)}$$

- Apparently small changes in M(p) within the domain 1<p(GeV)<3 have striking effect on the proton’s electric form factor
- The possible existence and location of the zero is determined by behaviour of $Q^2F_2^p(Q^2)$, proton’s Pauli form factor
- Like the pion’s PDA, $Q^2F_2^p(Q^2)$ measures the rate at which dressed-quarks become parton-like:
  - ✓ $F_2^p=0$ for bare quark-partons
  - ✓ Therefore, G_E^p can’t be zero on the bare-parton domain

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





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

- Follows that the
  - ✓ 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 nature of the quark-quark interaction in the Standard Model.

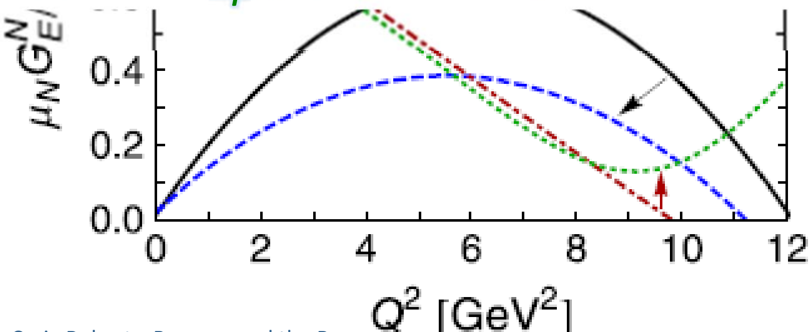
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) 1185 [on-line]

Electric Charge

- Proton: if one accelerates the rate at which the dressed-quark sheds its cloud of gluons to become a parton, then zero in G_{ep} is pushed to larger Q^2
- Opposite for neutron!
- Explained by presence of diquark correlations

Leads to *Prediction neutron:proton*

$G_{En}(Q^2) > G_{Ep}(Q^2)$ at $Q^2 > 4GeV^2$



- These features entail that at x≈ 5 the electric form factor of the neutral neutron will become larger than that of the unit-charge proton!
- JLab12 will probe this prediction

Phys. Rev. Lett. 106, 252003 (2011) [4 pages]

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

Abstract | References | Citing Articles (11)

Download: PDF (200 kB) Buy this article   Export: BibTeX or EndNote (RIS)

G. D. Cates[1], C. W. de Jager[2], S. Riordan[3], and B. Wojtsekhowski[2,*]
[1]University of Virginia, Charlottesville, Virginia 22903, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[3]University of Massachusetts, Amherst, Massachusetts 01003, USA

Received 8 March 2011; published 22 June 2011

Article Available via CHORUS Pilot
Download Accepted Manuscript

The u- and d-quark contributions to the elastic nucleon electromagnetic form factors have been determined by using experimental data on G_E^n, G_M^n, G_E^p, and G_M^p. Such a flavor separation of the form factors became possible up to negative four-momentum transfer squared Q^2=3.4 GeV^2 with recent data on G_E^n from Hall A at Jefferson Lab. For Q^2 above 1 GeV^2, for both the u and the d quark, the ratio of the Pauli and Dirac form factors, F_2/F_1, was found to be almost constant in sharp contrast to the behavior of F_2/F_1 for the proton as a whole. Also, again for Q^2>1 GeV^2, both F_2^d and F_1^d are roughly proportional to $1/Q^4$, whereas the dropoff of F_2^u and F_1^u is more gradual.

© 2011 American Physical Society

URL: http://link.aps.org/doi/10.1103/PhysRevLett.106.252003
DOI: 10.1103/PhysRevLett.106.252003
PACS: 14.20.Dh, 13.40.Gp, 24.70.+s, 25.30.Bf

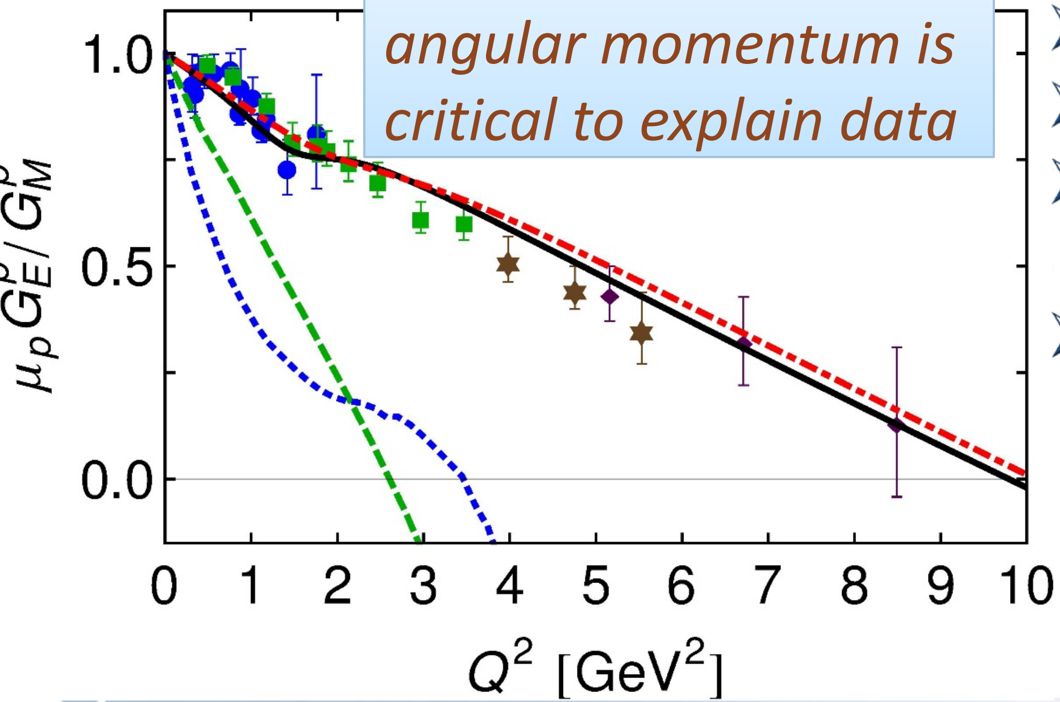
Discovering Diquarks

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt, arXiv: 1506.05112 [nucl-th],
*Phys.Lett. B **750** (2015) pp. 100-106*

Visible Impacts of diqarks

- Behaviour of the ratio, and location of zero is primarily determined by behavior of quarks in presence of scalar diquark correlation
- Hard scattering from the u-quark is dominant

u-quark orbital angular momentum is critical to explain data

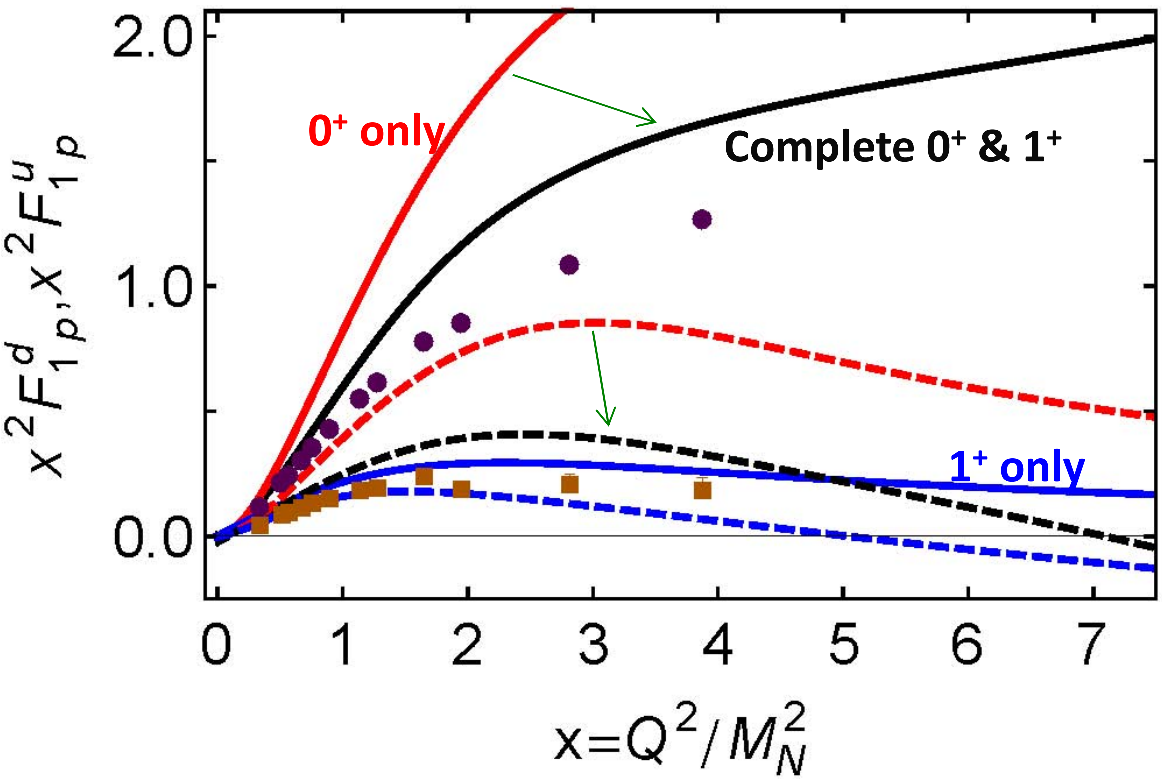


- Black = full calculation
- Red = scalar diquark only
- Blue = pseudovector diquark only
- Green = *S*-wave component of scalar diquark

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt, arXiv: 1506.05112 [nucl-th],
*Phys.Lett. B **750** (2015) pp. 100-106*

Diquark correlations

- u-quark = solid
- d-quark = dashed
- Plainly,
  - axial-vector diquark is crucial to agreement with data
  - scalar diquark alone cannot describe data
  - F_1^d possesses a zero because a zero is present in each of its separated contributions.



Location of the predicted zero depends on the strength of interference with the scalar diquark part of the proton.

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt, arXiv: 1506.05112 [nucl-th],
Phys.Lett. B ***750*** *(2015) pp. 100-106*

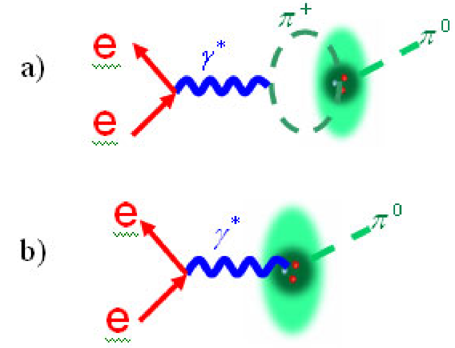
Borromean proton

- Poincaré covariance demands presence of dressed-quark orbital angular momentum in the nucleon
- α_S expressed, *e.g*. in momentum-dependence of dressed-quark mass; and existence of strong, electromagnetically-active 0^+ and 1^+ qq-correlations in nucleon ⇒ big differences between properties associated with doubly- and singly-represented valence-quarks
- Clear evidence that measured behaviour of nucleon form factors is primarily determined by presence of strong diquark correlations
- Planned experiments are capable of validating this picture of nucleon and placing tight constraints, *e.g*. on rate at which dressed-quarks transform into partons, and relative probability of finding scalar and pseudovector diquarks within the nucleon.

What's missing?

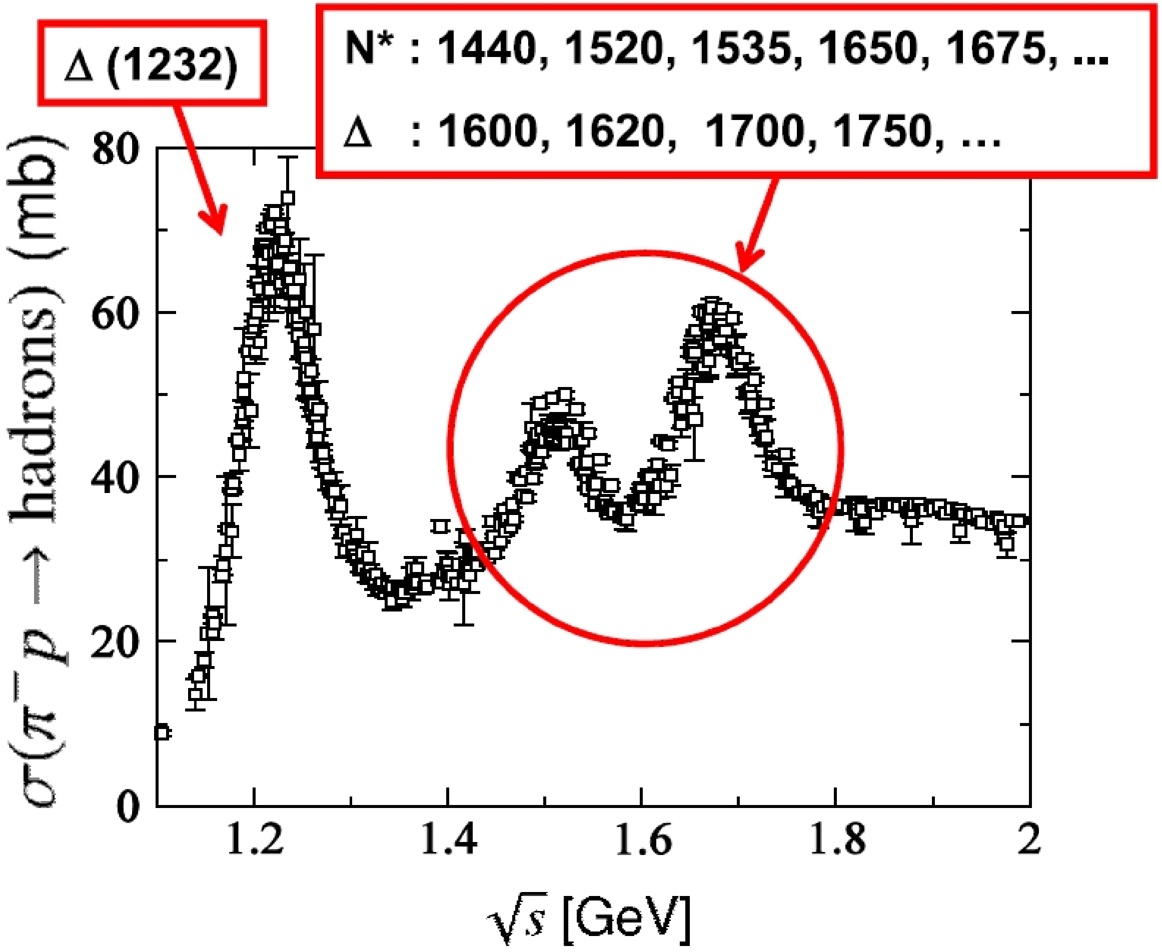
H.L.L. Roberts, L. Chang, I.C. Cloët and C.D. Roberts, arXiv:1101.4244 [nucl-th], Few Body Syst. **51** (2011) pp. 1-25

Pion cloud



- Kernels constructed in widely-used truncations do not contain any long-range interactions
  - These kernels are built only from dressed-quarks and -gluons
- But, QCD produces a very potent long-range interaction; namely that associated with the pion and other mesons
- Contemporary kernels produces the hadron's

  dressed-quark core
- The contribution from mesons is omitted. It can be added without "double counting"
- The meson contributions must be thoughtfully considered before any comparison can be made with real-world data
- Inclusion of a "meson cloud" improves quantitative agreement with data on small-Q^2 domain; but it does not qualitatively affect other salient features of the form factors



Nucleon Resonances

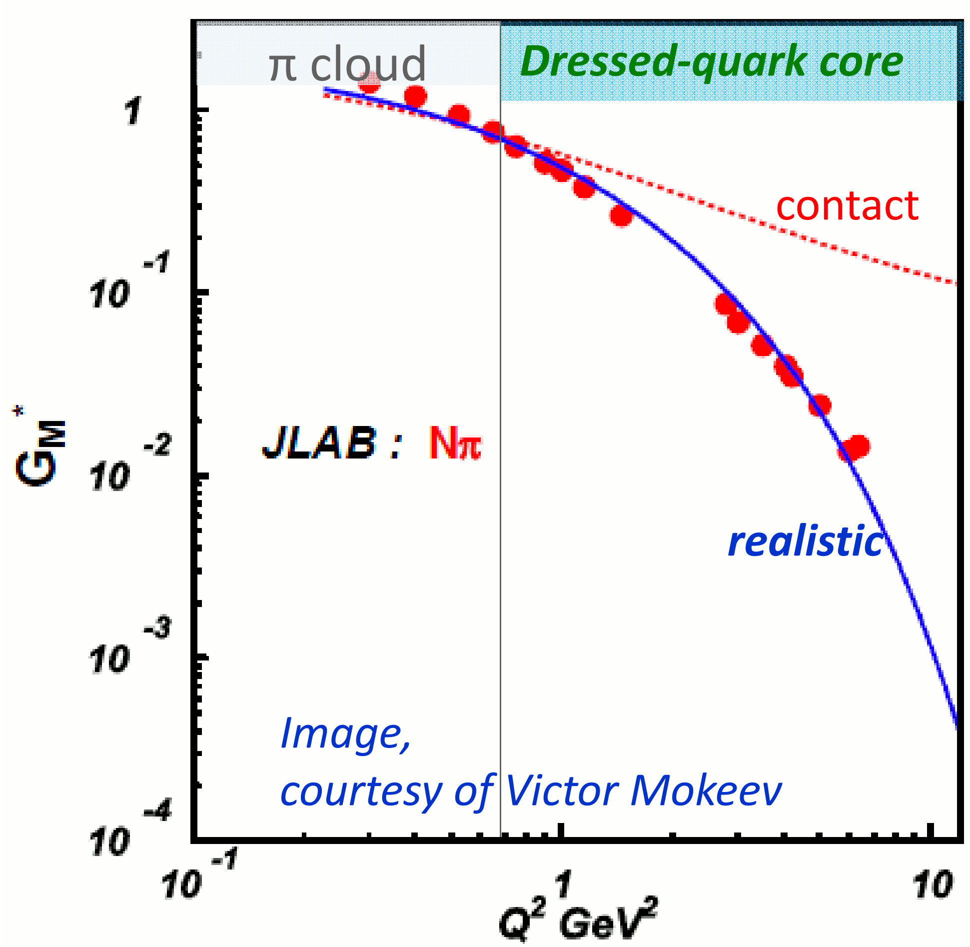
γ N → Resonance

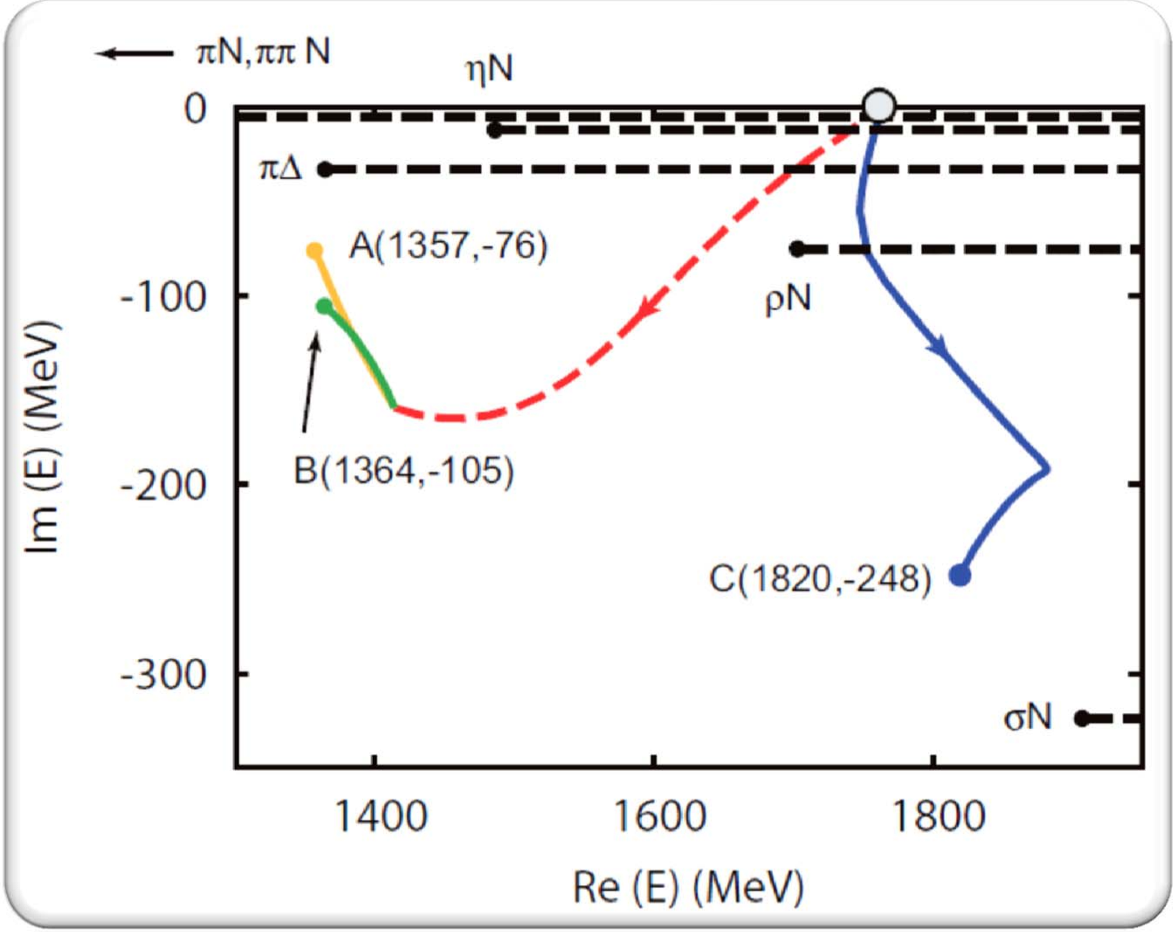
- Prediction and measurement of ground-state elastic form factors is insufficient to chart the infrared behaviour of the strong interaction
- There are numerous nucleon → resonance transition form factors. The challenge of mapping their Q^2-dependence provides many new ways to probe the infrared behaviour of the strong interaction
- Completed unified study of nucleon, Δ & N(1440) $\frac{1}{2}^+$ elastic and transition form factors:
  - Identical propagators and vertices are sufficient to describe all properties
  - Establishes conclusively that experiments are sensitive to the momentum dependence of the running couplings and masses in the strong interaction sector of the Standard Model
  - Highlights that key to describing hadron properties is use of the full machinery of relativistic quantum field theory so that, e.g., a veracious expression of DCSB is guaranteed in bound-state problem.

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 pion valence-quark PDF***)
  - 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***



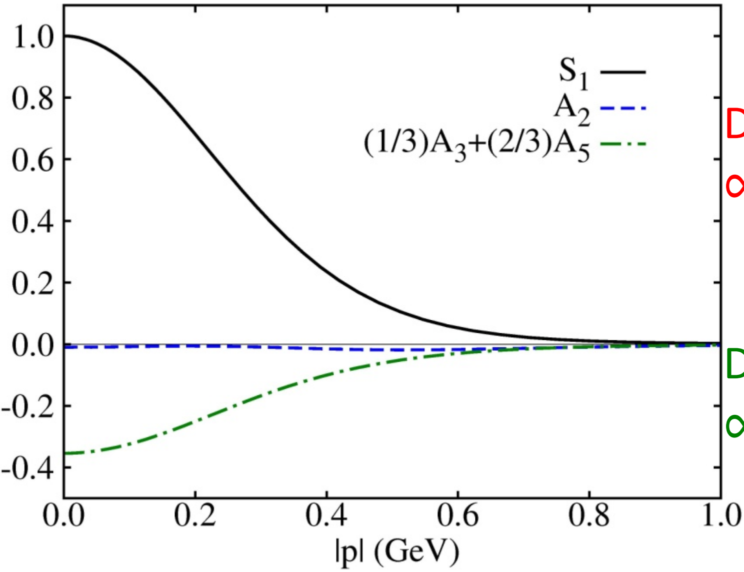


Roper Resonance

Completing the picture of the Roper resonance, Jorge Segovia, Bruno El-Bennich, Eduardo Rojas, Ian C. Cloët, Craig D. Roberts, Shu-Sheng Xu and Hong-Shi Zong, arXiv:1504.04386 [nucl-th]

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

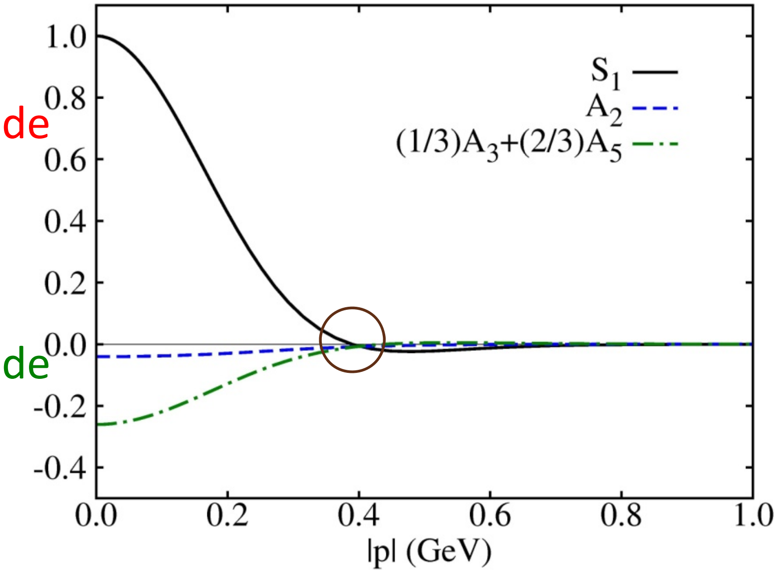


Dominant 0+ amplitude

$\propto C\, I\, \tau_2$

Dominant 1+ amplitude

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



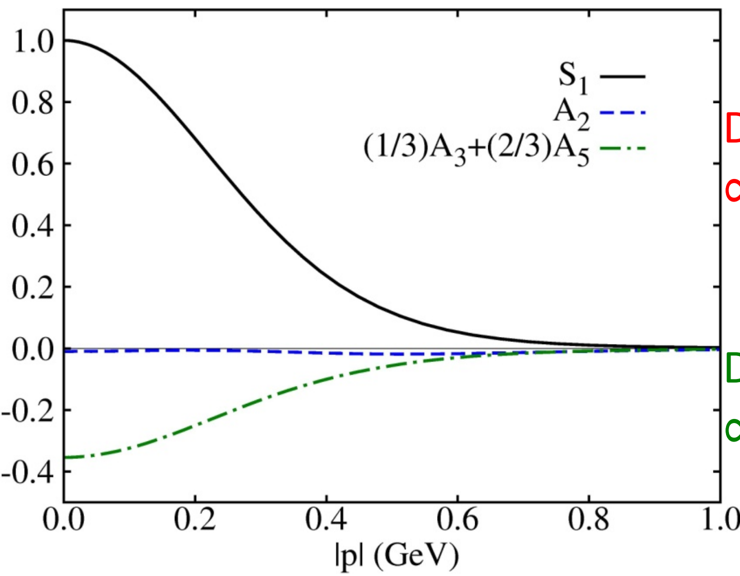
- $M_{\text{Excited QQQ}}$ = 1.73 GeV … amplitudes typically possess a zero
  ⇒ lightest excitation of the nucleon is radial excitation

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

Completing the picture of the Roper resonance, Jorge Segovia, Bruno El-Bennich, Eduardo Rojas, Ian C. Cloët, Craig D. Roberts, Shu-Sheng Xu and Hong-Shi Zong, arXiv:1504.04386 [nucl-th]

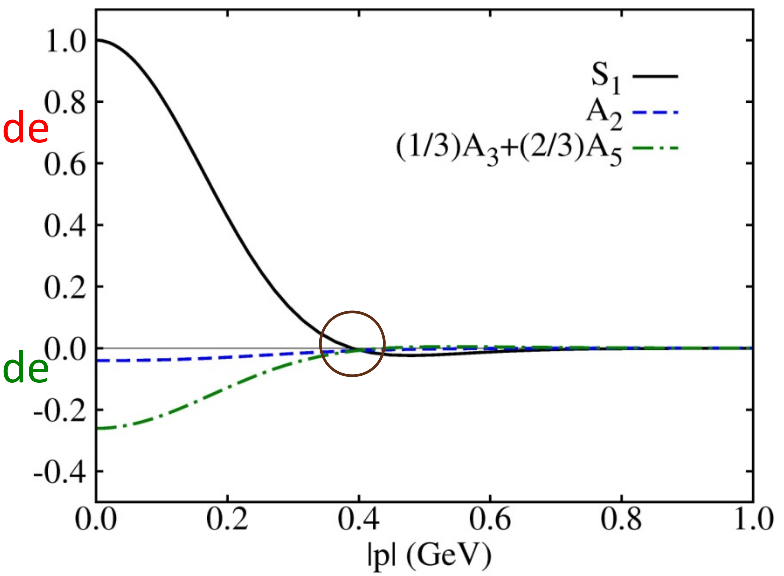
Roper Resonance

- 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
$\propto C\,\mathbf{I}\,\tau_2$

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



- $M_{\text{Excited QQQ}}$ = 1.73 GeV … amplitudes typically possess a zero

N.B.

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

Completing the picture of the Roper resonance, Jorge Segovia, Bruno El-Bennich, Eduardo Rojas, Ian C. Cloët, Craig D. Roberts, Shu-Sheng Xu and Hong-Shi Zong, arXiv:1504.04386 [nucl-th]

Roper Resonance

- Diquark content: Nucleon vs Radial Excitation

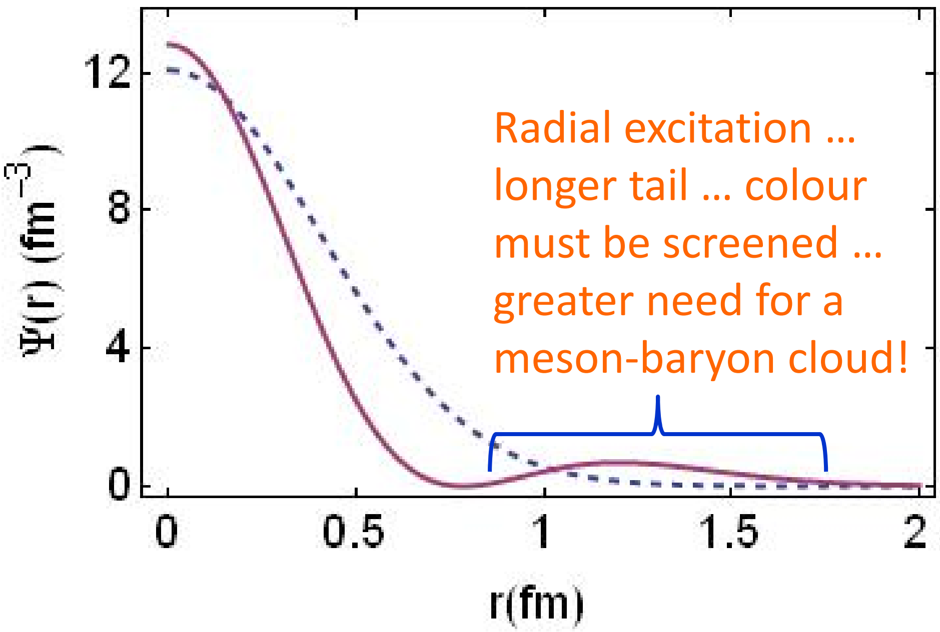
	Nucleon	Radial excitation	Image-Nucleon
$P_{J=0x0}$	62%	62%	30%
$P_{J=0x1\&1x1}$	38%	38%	70%

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

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

Completing the picture of the Roper resonance, Jorge Segovia, Bruno El-Bennich, Eduardo Rojas, Ian C. Cloët, Craig D. Roberts, Shu-Sheng Xu and Hong-Shi Zong, arXiv:1504.04386 [nucl-th]

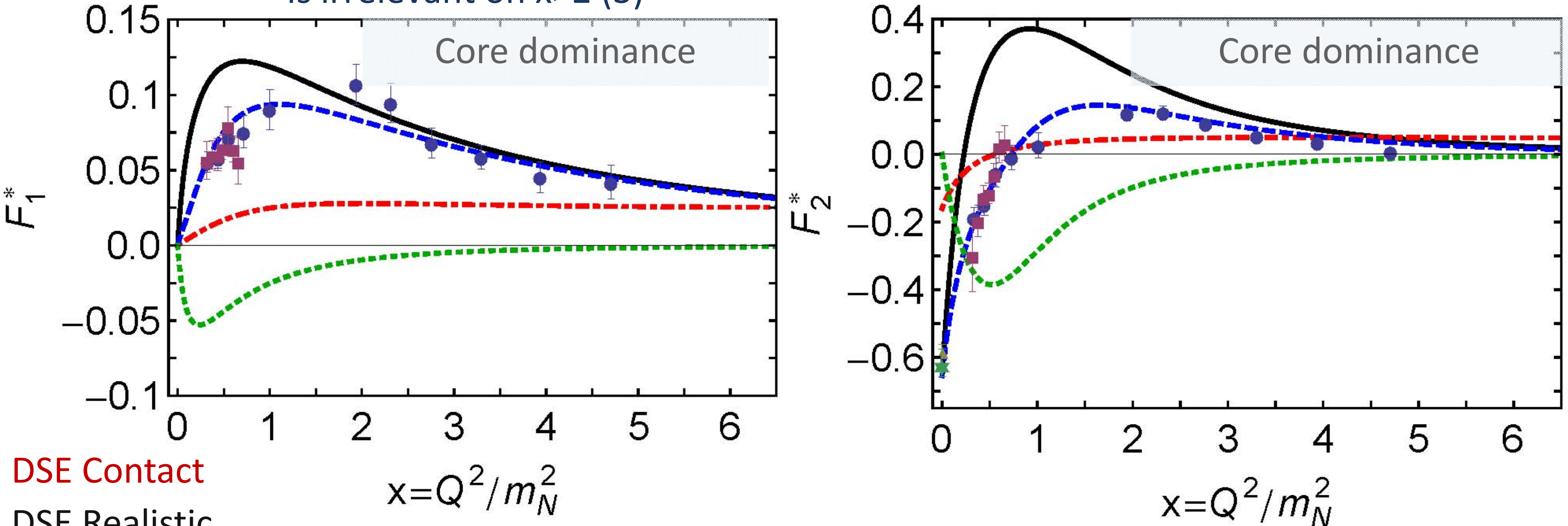
Roper Resonance



- Ratio of charge radii for the quark+diquark core of the Radial excitation 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 radial excitation

γ N → Roper

- Predicted transition form factors
  - 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

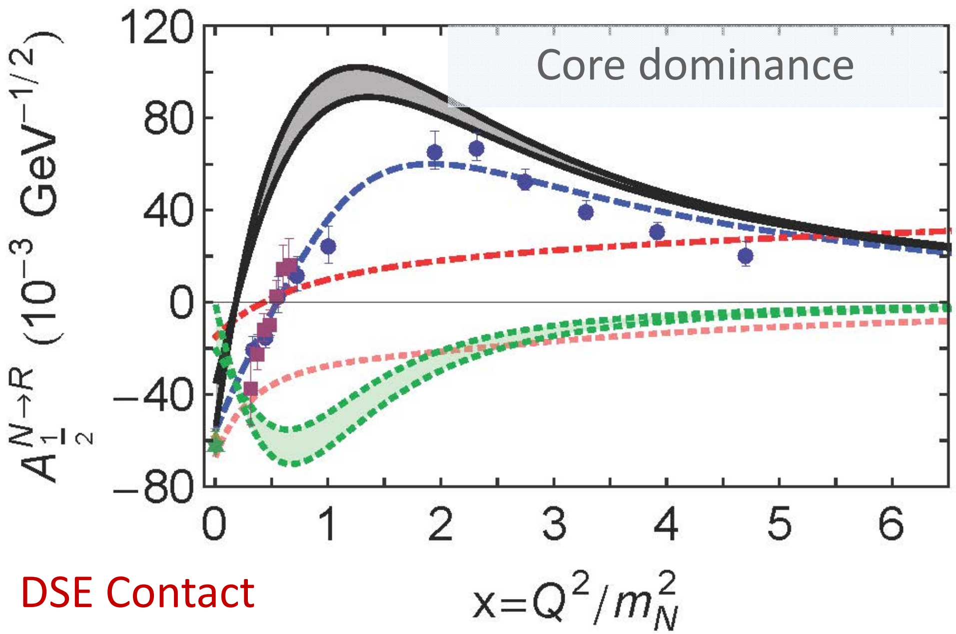
Completing the picture of the Roper resonance, Jorge Segovia *et al.*,,
arXiv:1504.04386 [nucl-th]

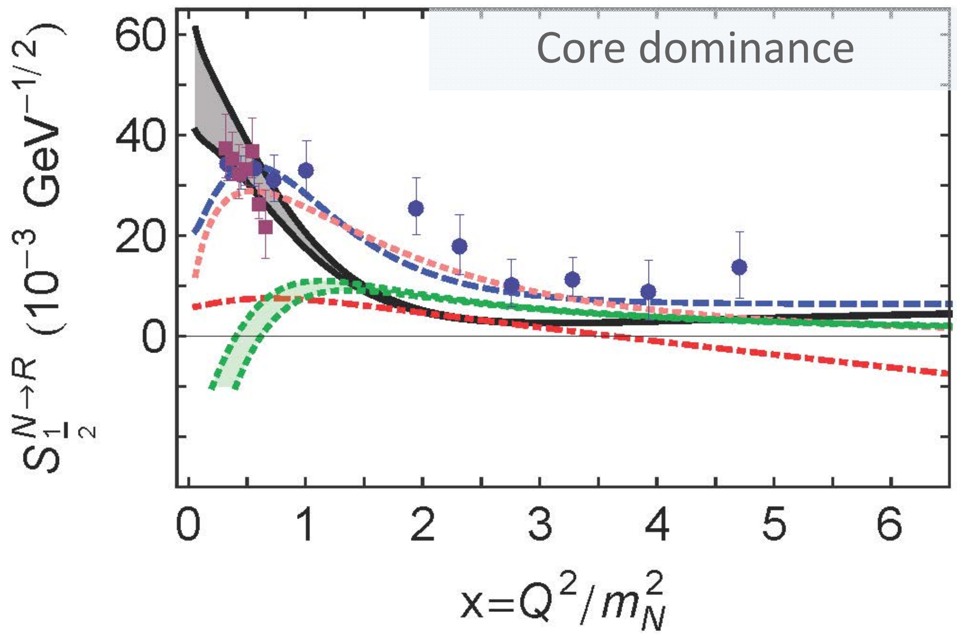
γ N → Roper

- Predicted helicity amplitudes
  - Agreement with data on *x>2 (3)*
  - Like *γN → Δ*, room for meson cloud on *x<2*
    - EBAC and DSE cloud agree on *x>2*
    - For $S_{1/2}$ … very different on *x<3*

$$A_{\frac{1}{2}}(Q^2) = c(Q^2)\,[F_{1*}(Q^2) + F_{2*}(Q^2)]\,, \quad (11a)$$

$$S_{\frac{1}{2}}(Q^2) = -\frac{q_{\rm CMS}}{\sqrt{2}} c(Q^2) \left[-F_{1*}(Q^2) \frac{m_R + m_N}{Q^2} + \frac{F_{2*}(Q^2)}{m_R + m_N} \right], \quad (11b)$$





DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

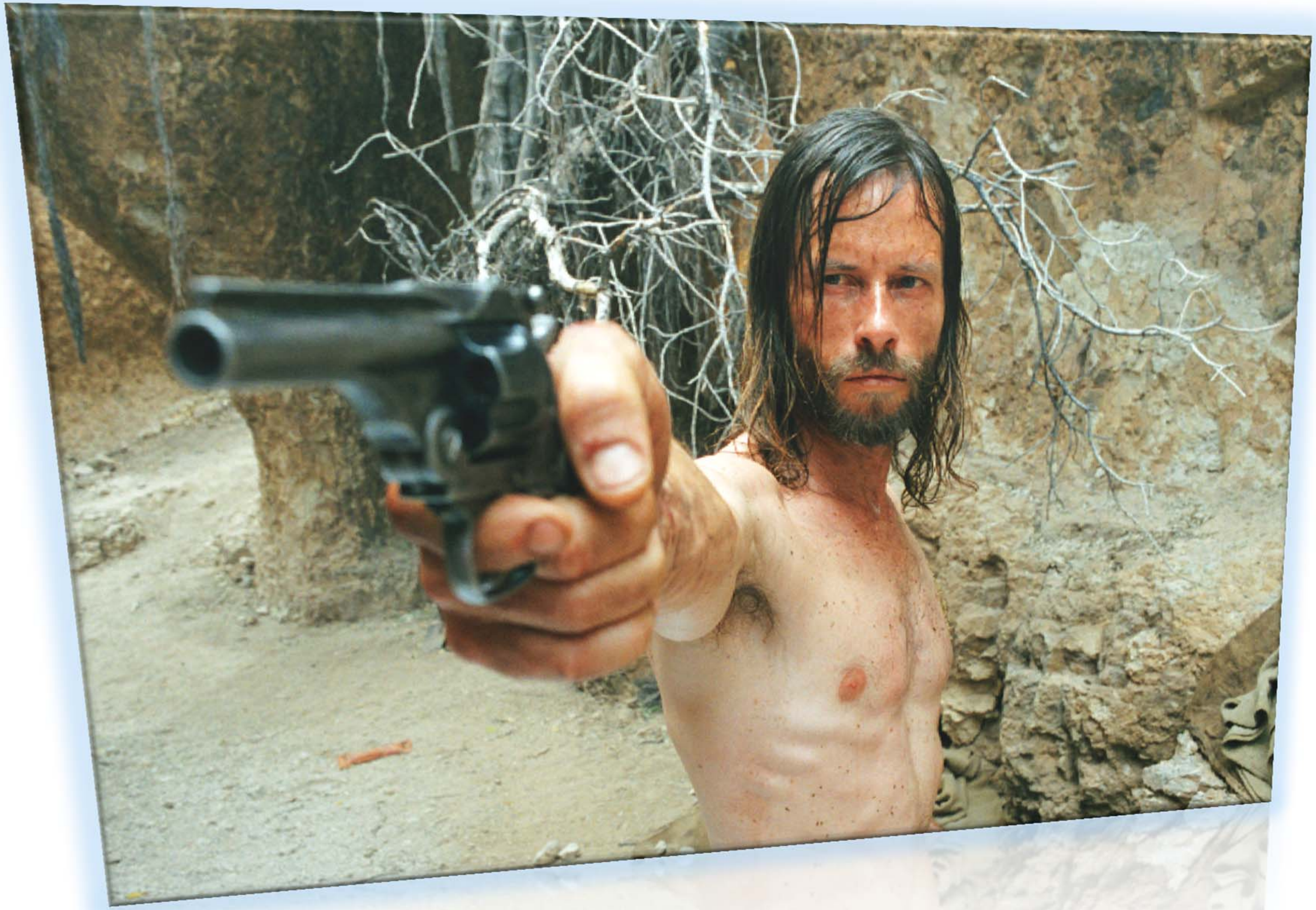
EBAC inference for cloud

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

Roper

- Range of properties of the dressed-quark core of the proton's radial excitation computed
- In all cases they provide an excellent understanding and description of data on the proton-Roper transition and related quantities derived using dynamical coupled channels models.
- Analysis based on a sophisticated continuum framework for the three-quark bound-state problem; all elements employed possess an unambiguous link with analogous quantities in QCD; and no parameters were varied in to achieve success.
- These results suggest strongly that the observed Roper resonance is at heart the nucleon's first radial excitation:
  - consists of a well-defined dressed-quark core augmented by a meson cloud that reduces its (Breit-Wigner) mass by approximately 20%.
- Analysis shows that a meson-cloud obscures the dressed-quark core from long-wavelength probes; but that it is revealed to probes with $Q^2 > 3m_N^2$.

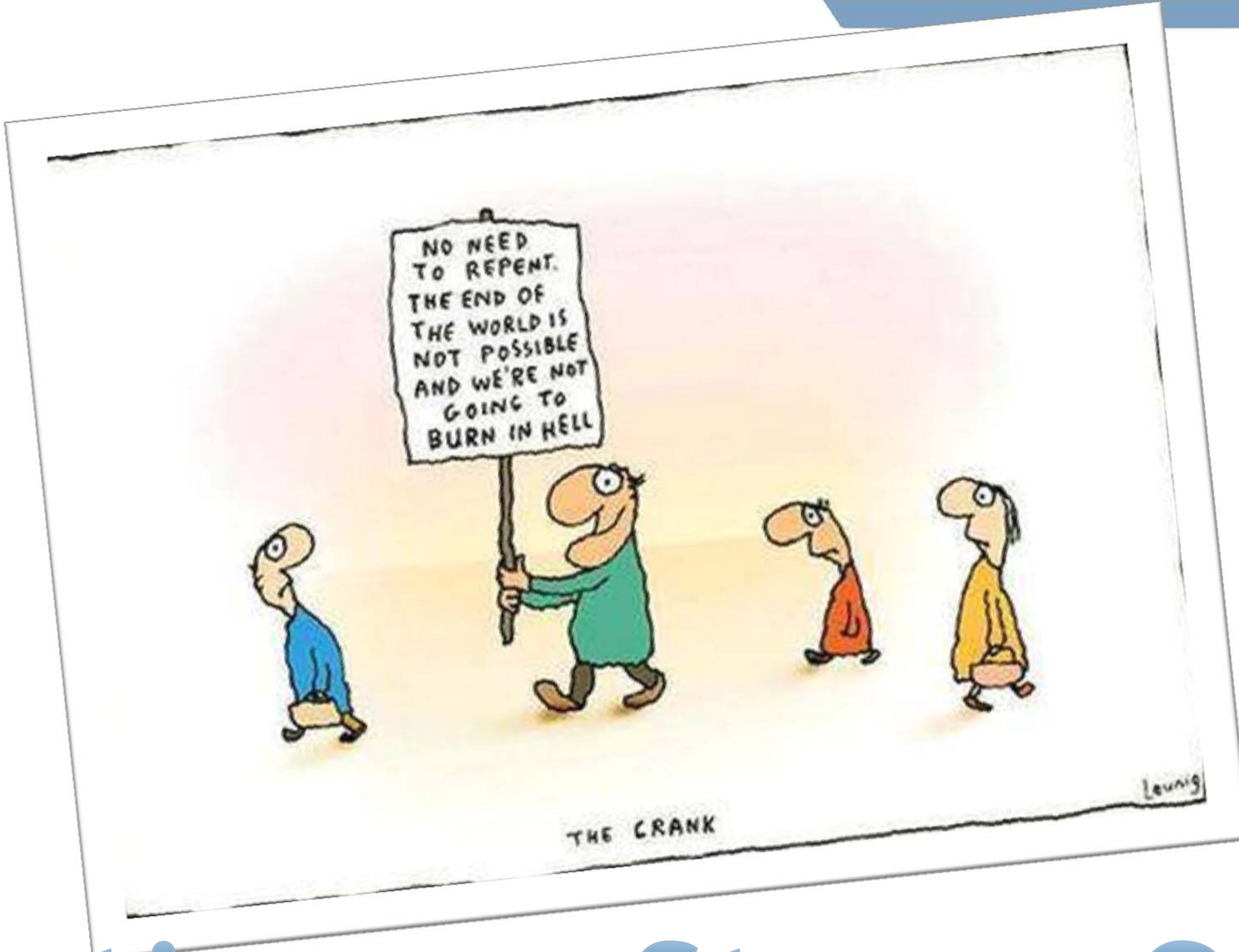
These features are typical of nucleon-resonance transitions; and hence measurements of resonance electroproduction on this domain can serve as an incisive probe of quark-gluon dynamics within the Standard Model, assisting greatly in mapping the evolution between the nonperturbative and perturbative domains of QCD.



Epilogue

Epilogue

- Conformal anomaly ... *gluons and quarks acquire momentum-dependent masses*, values are large in the infrared $m_g \propto 500$ MeV & $M_q \propto 350$ MeV
  ... underlies DCSB and has numerous observable consequences
- In a Universe with light quarks, confinement is a dynamical phenomenon ... *no linear potentials, no tower of linear, nonintersecting "Regge" trajectories*
- Top-down and bottom-up DSE analyses agree on RGI interaction in *continuum-QCD* $\Rightarrow$ *parameter-free prediction of hadron properties*
- Not many good reasons left which justify using rainbow-ladder truncation
  ... pointwise forms of interaction and propagators are simply wrong
- *Diquarks are a reality* ... their existence does not alter the number of baryon states in any obvious way
- DSE quark core has same level ordering as experiment and ongoing work with ANL-Osaka collaboration suggests
  meson cloud does not alter level ordering in baryon spectrum
- *Nucleon → Nucleon* ... *Nucleon → Δ* ... *Nucleon → Roper* ... understood



Continuum Strong QCD is not just a dream