Argonne NATIONAL LABORATORY

Proton as a Borromean Bound-State

Craig Roberts, Physics Division

U.S. DEPARTMENT OF ENERGY

Collaborators: 2012-Present

Students, Postdocs, Asst. Profs.

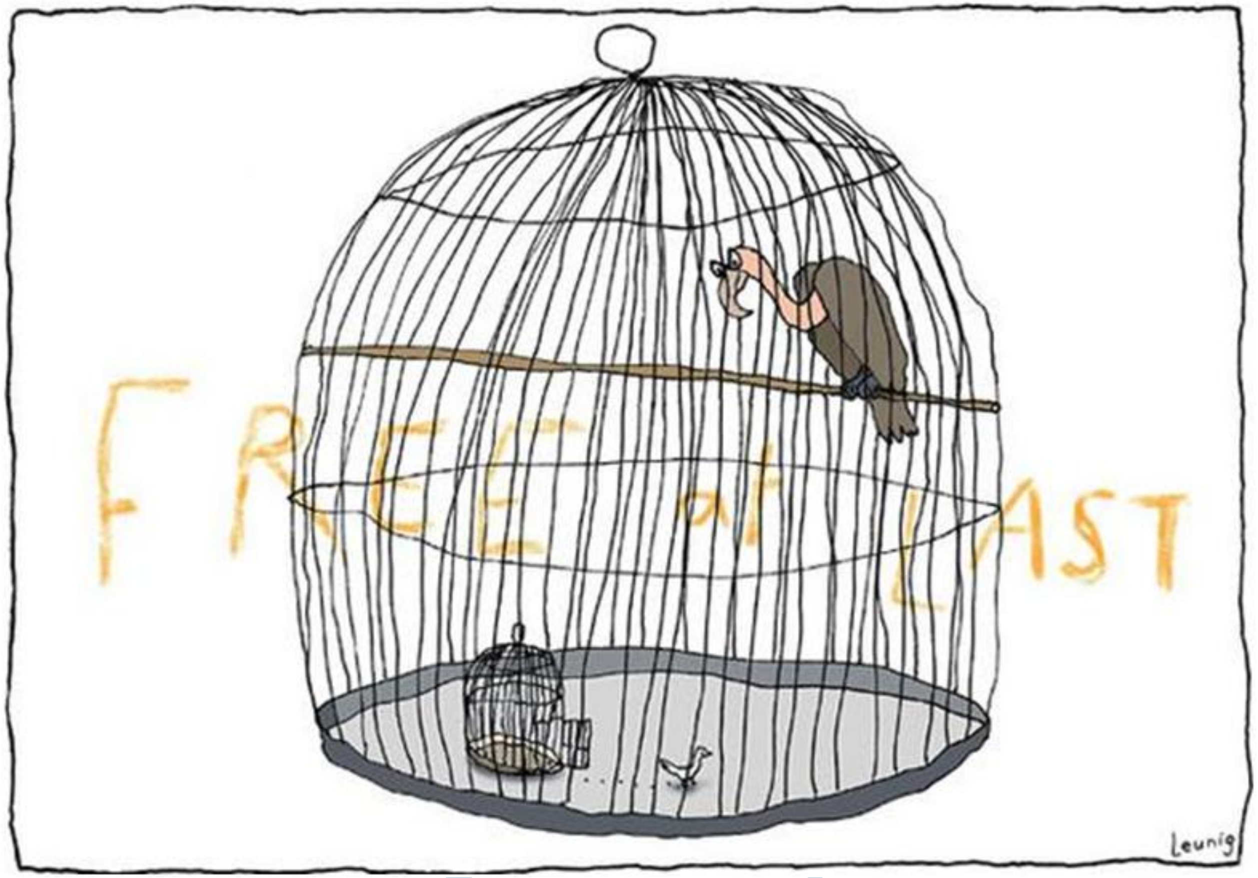
1. *Shi CHAO (Nanjing U) ;*
2. *Ming-hui DING (PKU);*
3. *Fei GAO (PKU) ;*
4. *S. HERNÁNDEZ (U Michoácan);*
5. *Cédric MEZRAG (CEA, Saclay) ;*
6. *Khépani RAYA (U Michoácan);*
7. *Chien-Yeah SENG (UM-Amherst) ;*
8. *Kun-lun WANG (PKU);*
9. *Shu-sheng XU (Nanjing U) ;*
10. *Chen CHEN (USTC);*
11. *J. Javier COBOS-MARTINEZ (U.Sonora);*
12. *Mario PITSCHMANN (Vienna);*
13. *Si-xue QIN (ANL, U. Frankfurt am Main, PKU);*
14. *Jorge SEGOVIA (Salamanca);*
15. *David WILSON (ODU);*
16. *Lei CHANG (U. Adelaide, FZJ, ANL, PKU) ;*
17. *Ian CLOËT (ANL) ;*
18. *Bruno EL-BENNICH (São Paulo);*
19. Adnan BASHIR (U Michoácan);
20. Daniele BINOSI (ECT*)
21. Stan BRODSKY (SLAC);
22. Roy HOLT (ANL);
23. G. KREIN (São Paulo IFT)
24. Yu-xin LIU (PKU);
25. Hervé MOUTARDE (CEA, Saclay) ;
26. Joannis PAPAVASILLIOU (U.Valencia)
27. Michael RAMSEY-MUSOLF (UM-Amherst) ;
28. Alfredo RAYA (U Michoácan);
29. Jose RODRIGUEZ QINTERO (U. Huelva) ;
30. Sebastian SCHMIDT (IAS-FZJ & JARA);
31. Robert SHROCK (Stony Brook);
32. Peter TANDY (KSU);
33. Tony THOMAS (U.Adelaide) ;
34. Shaolong WAN (USTC) ;
35. Hong-Shi ZONG (Nanjing U)

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 link to QCD are now available
  - Quark-quark correlations are unavoidable
  - Accumulating empirical evidence in support of prediction that they are crucial in determining hadron properties



What is Confinement?

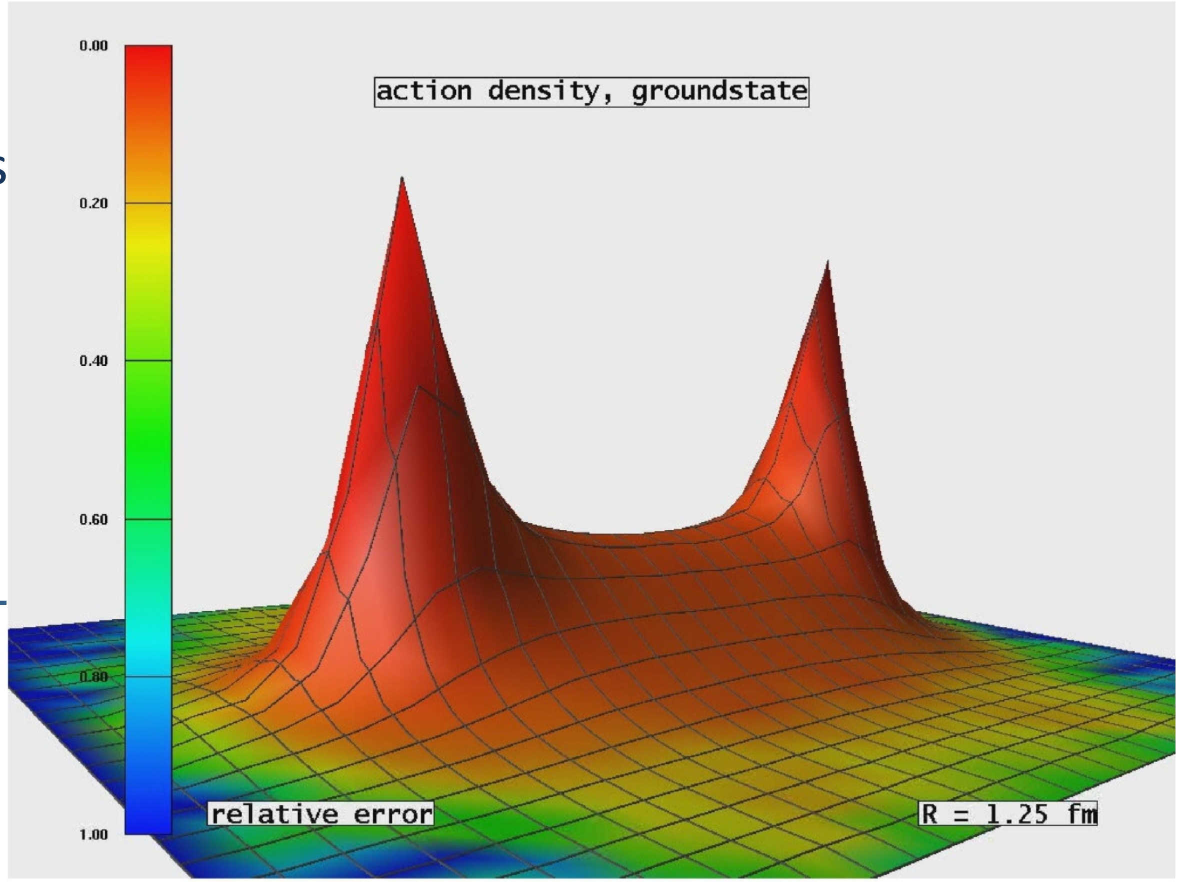
Light quarks & Confinement

- 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."



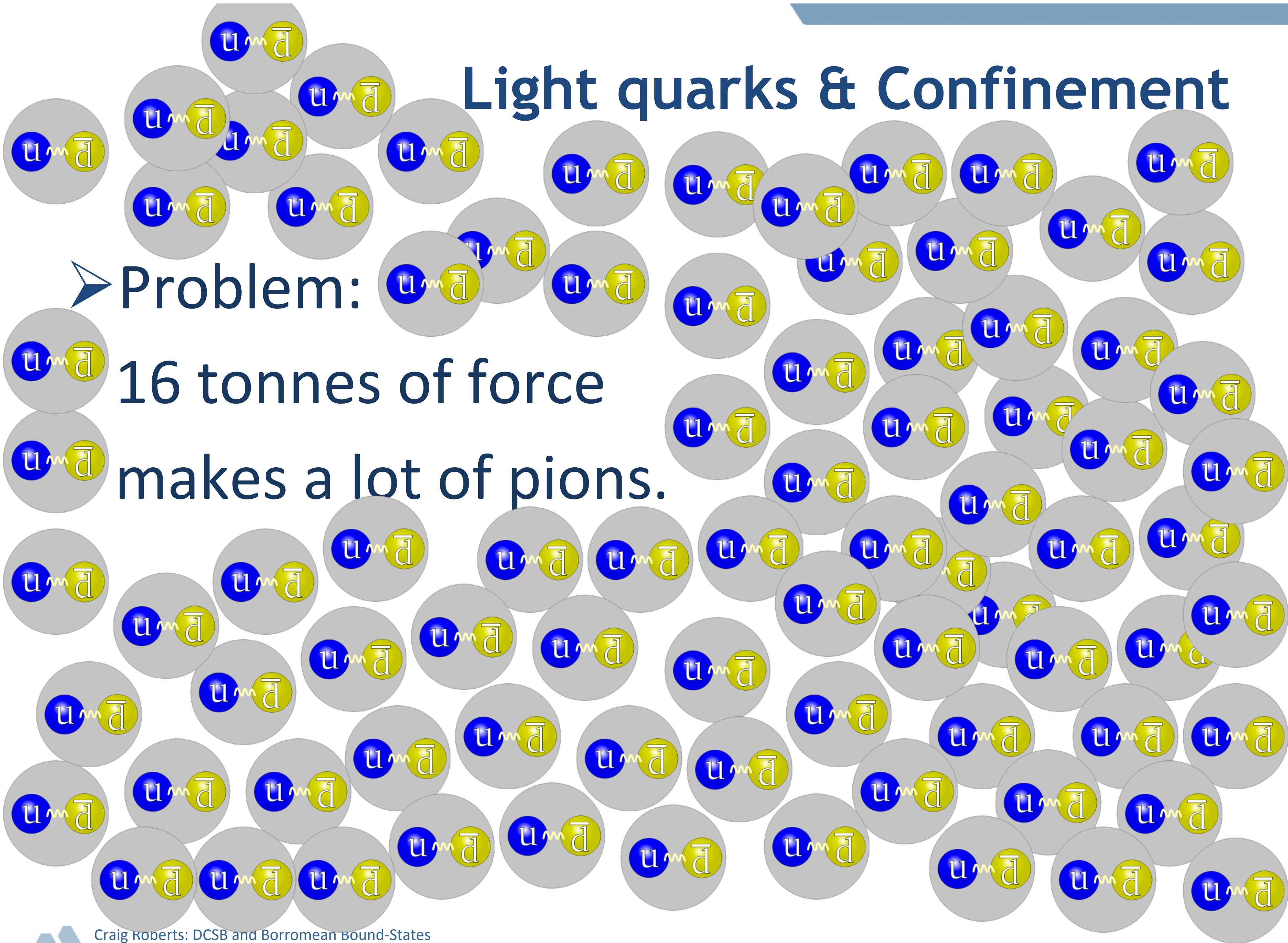
Light quarks & Confinement

- Problem:

  16 tonnes of force

  makes a lot of pions.

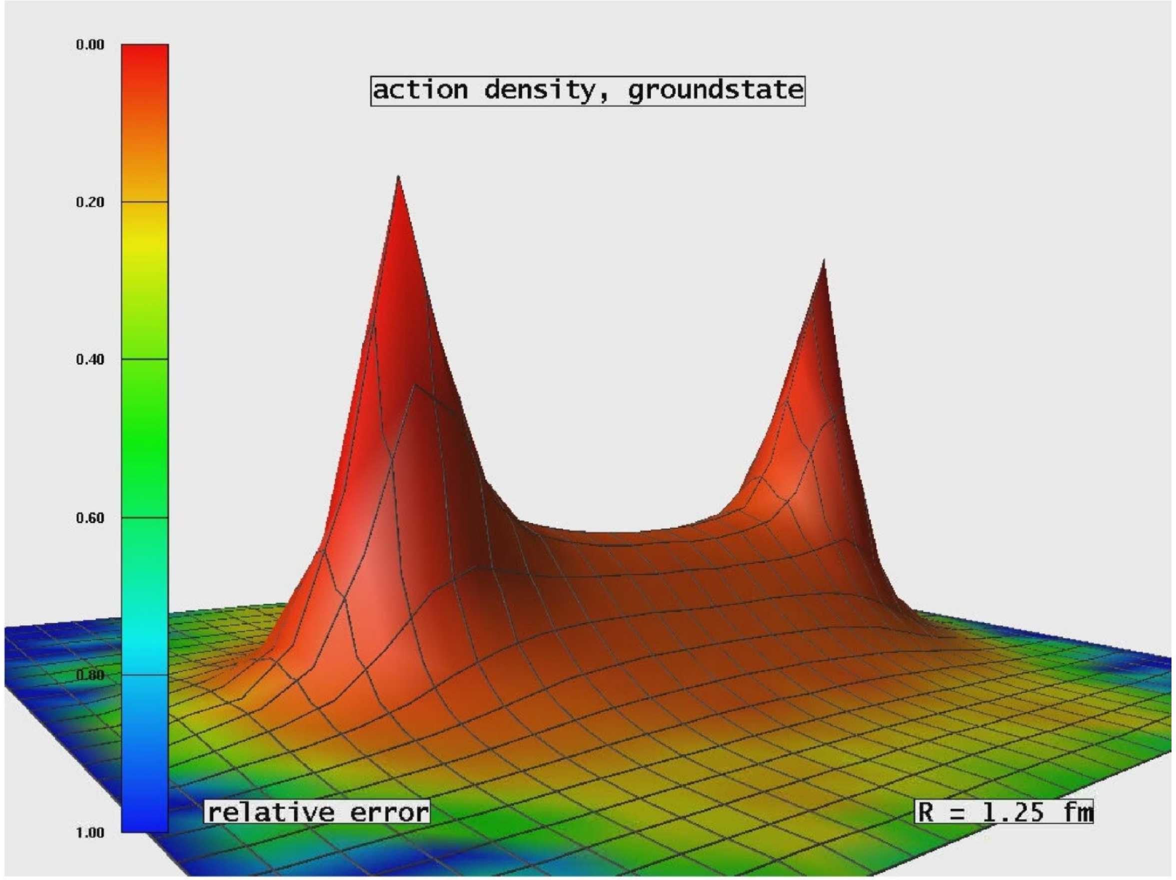
Light quarks & Confinement



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

Light quarks & Confinement

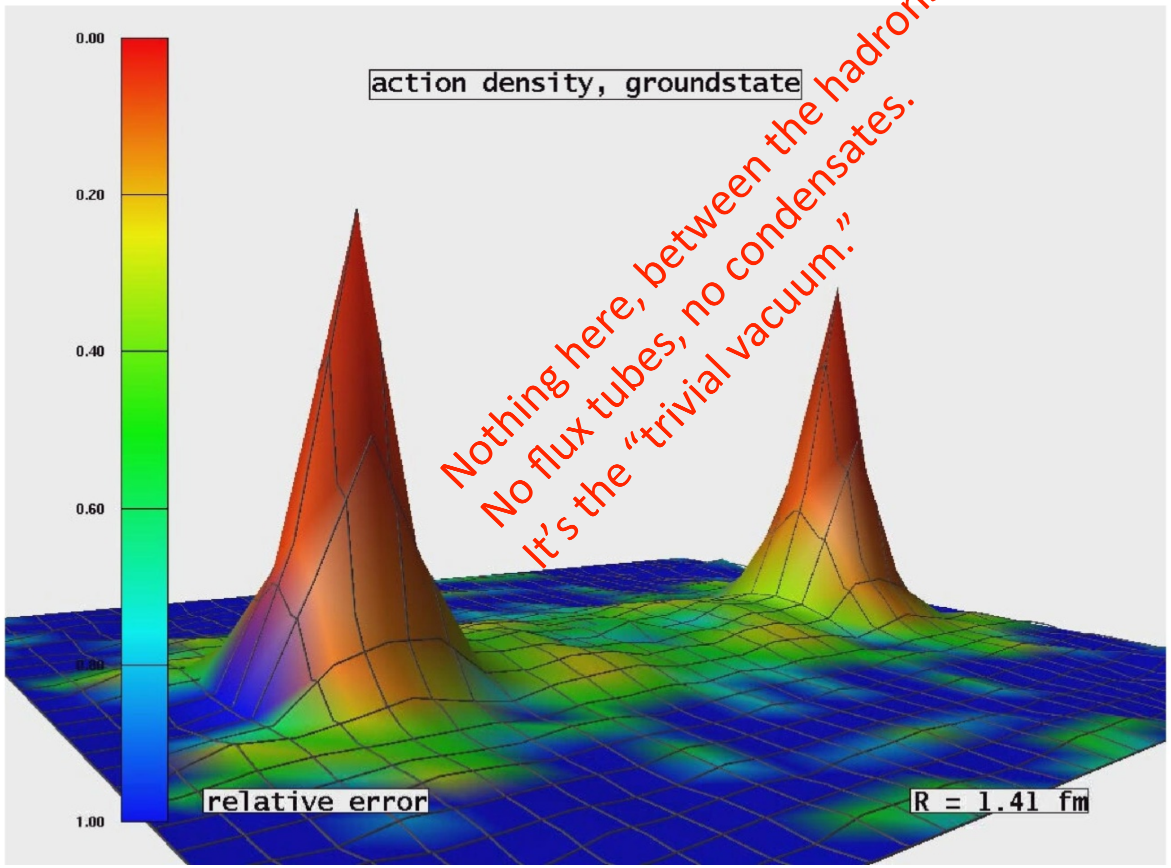
- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***



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

Light quarks & Confinement

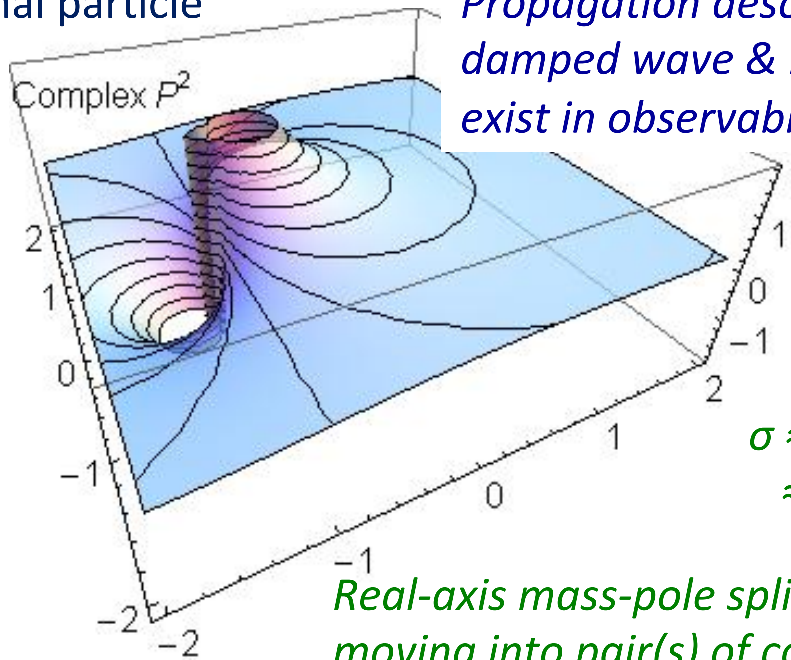
- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***



Confinement

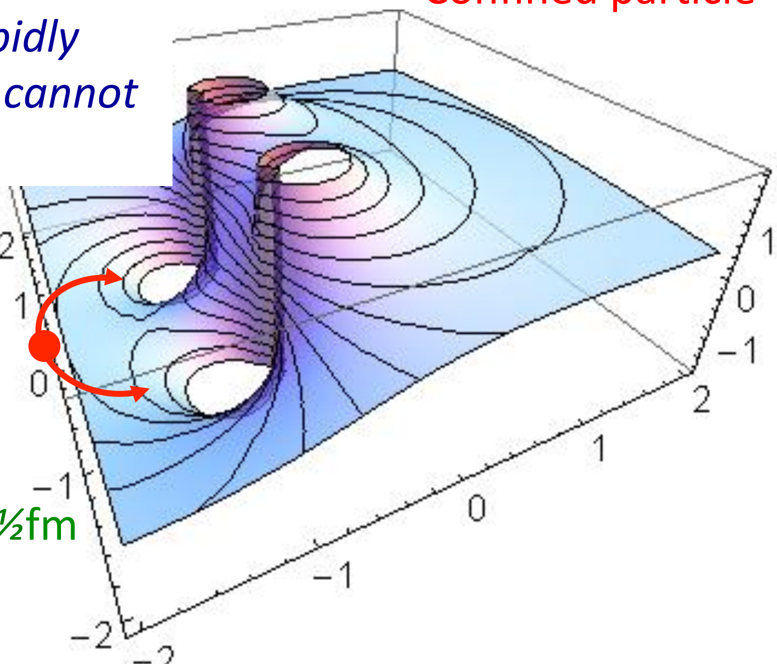
- QFT Paradigm:
  - Confinement is expressed through a *dramatic* change in the analytic structure of propagators for coloured states
  - It can be read from a plot of the dressed-propagator for a coloured state

Normal particle



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

Confined particle

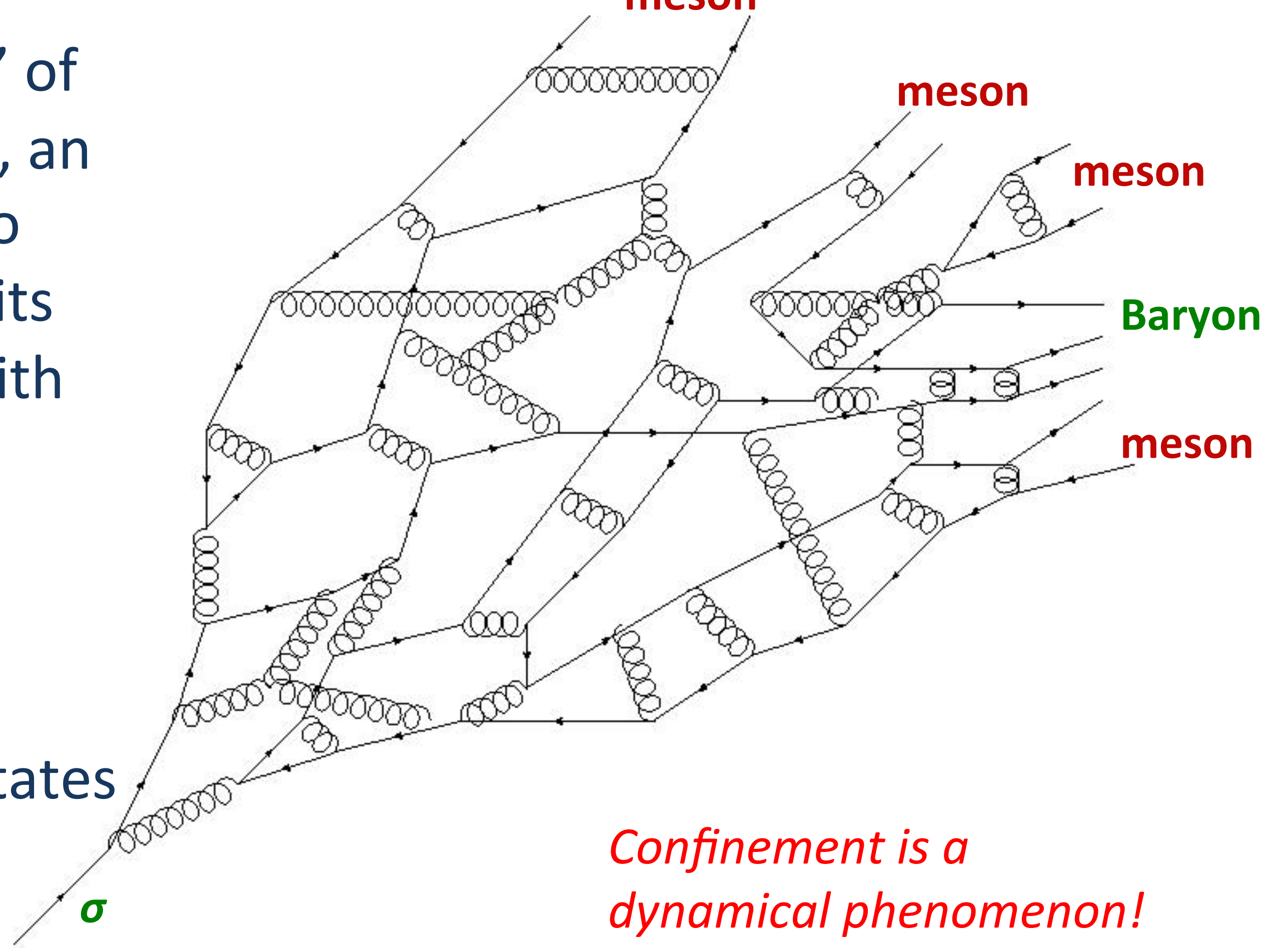


$\sigma \approx 1/Im(m)$
$\approx 1/2\Lambda_{QCD} \approx$ ½fm

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

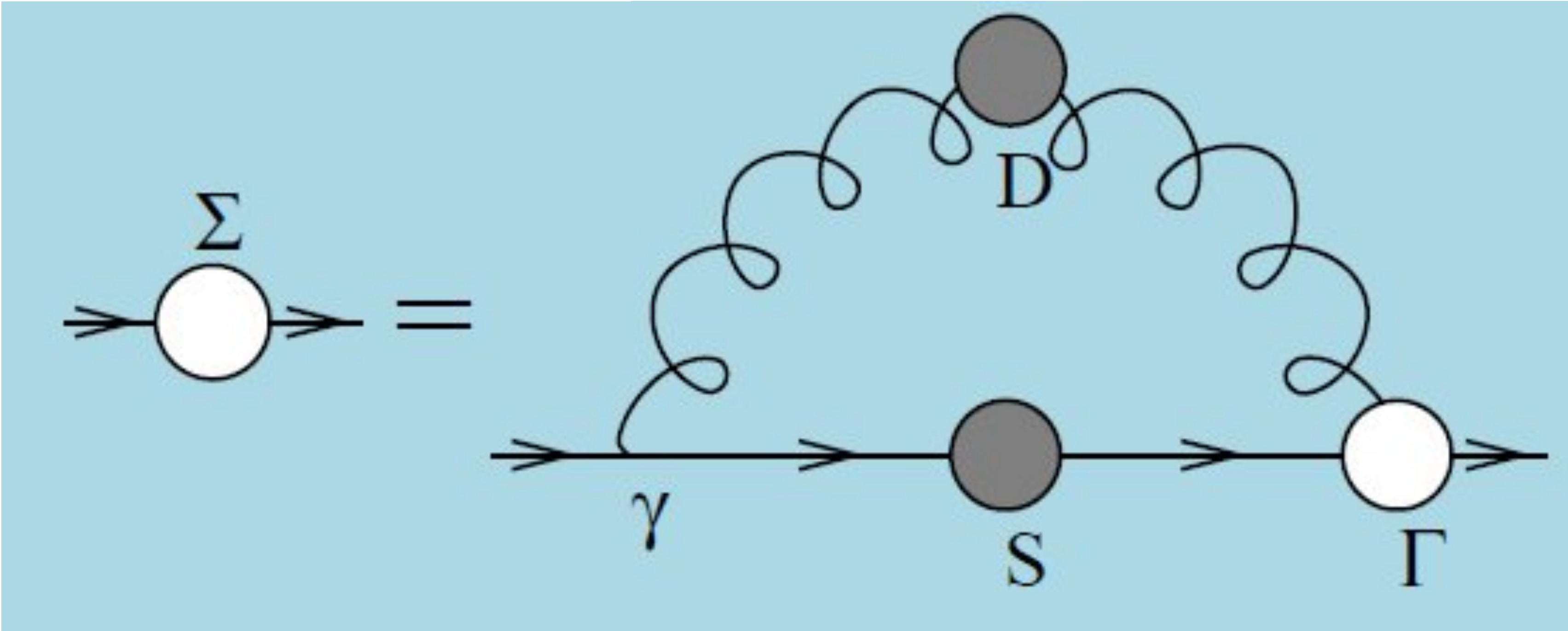
Quark Fragmentation

- 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!

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

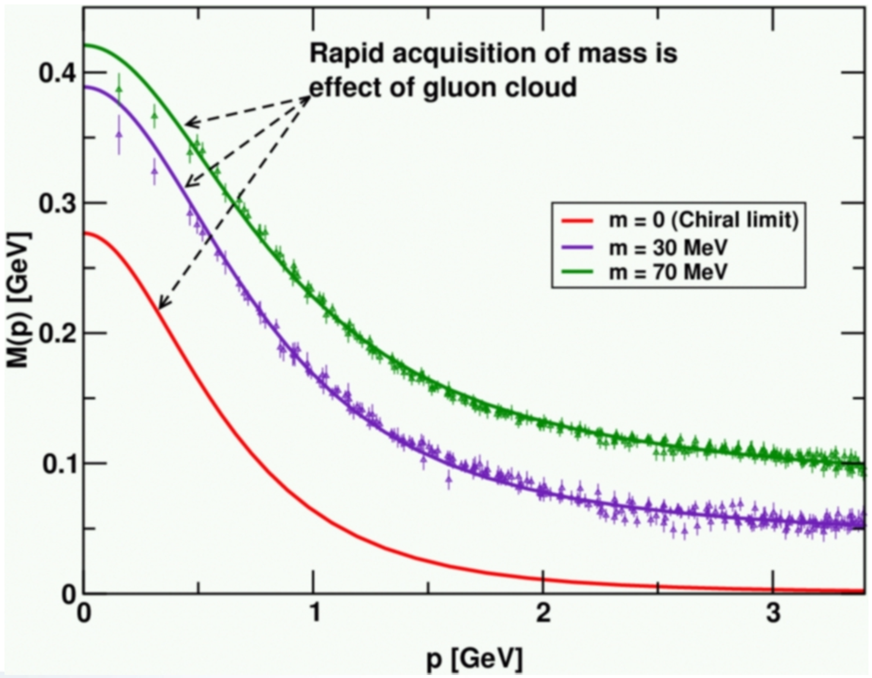


Quark Gap Equation

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.

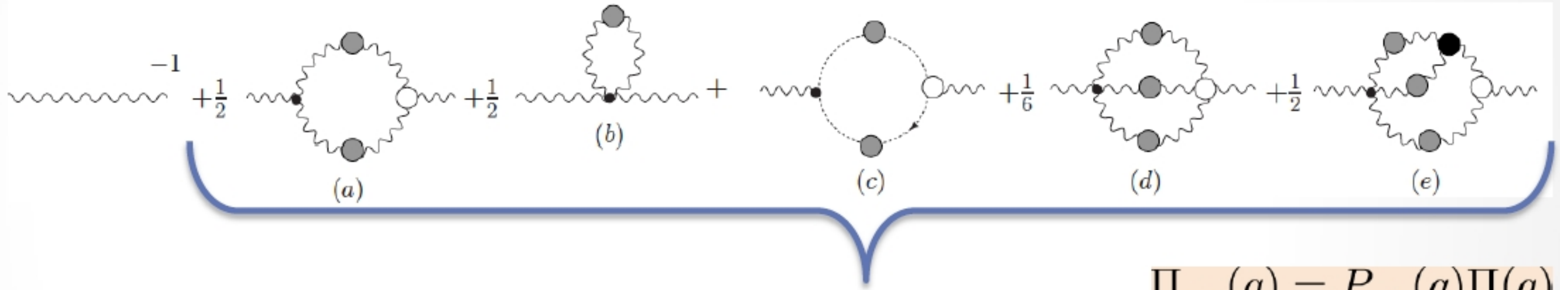


Cristina

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

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



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

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

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

- 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!

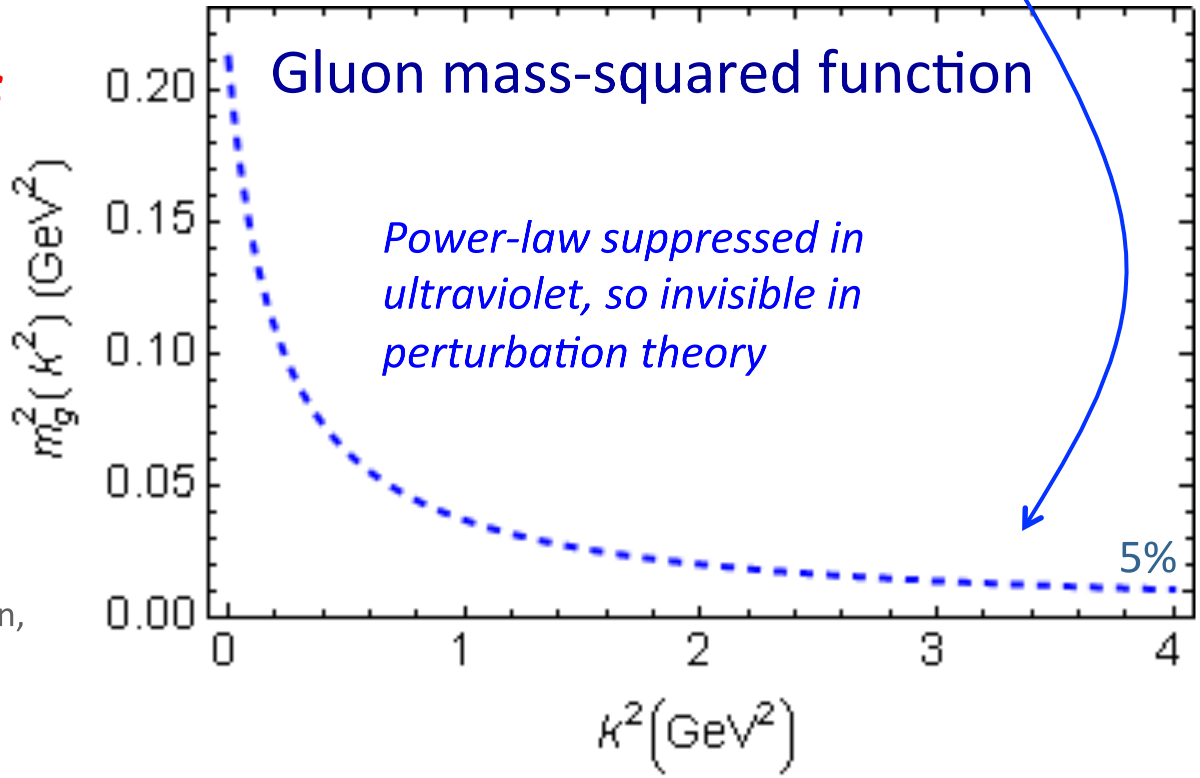
- Running gluon mass

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

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

- 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

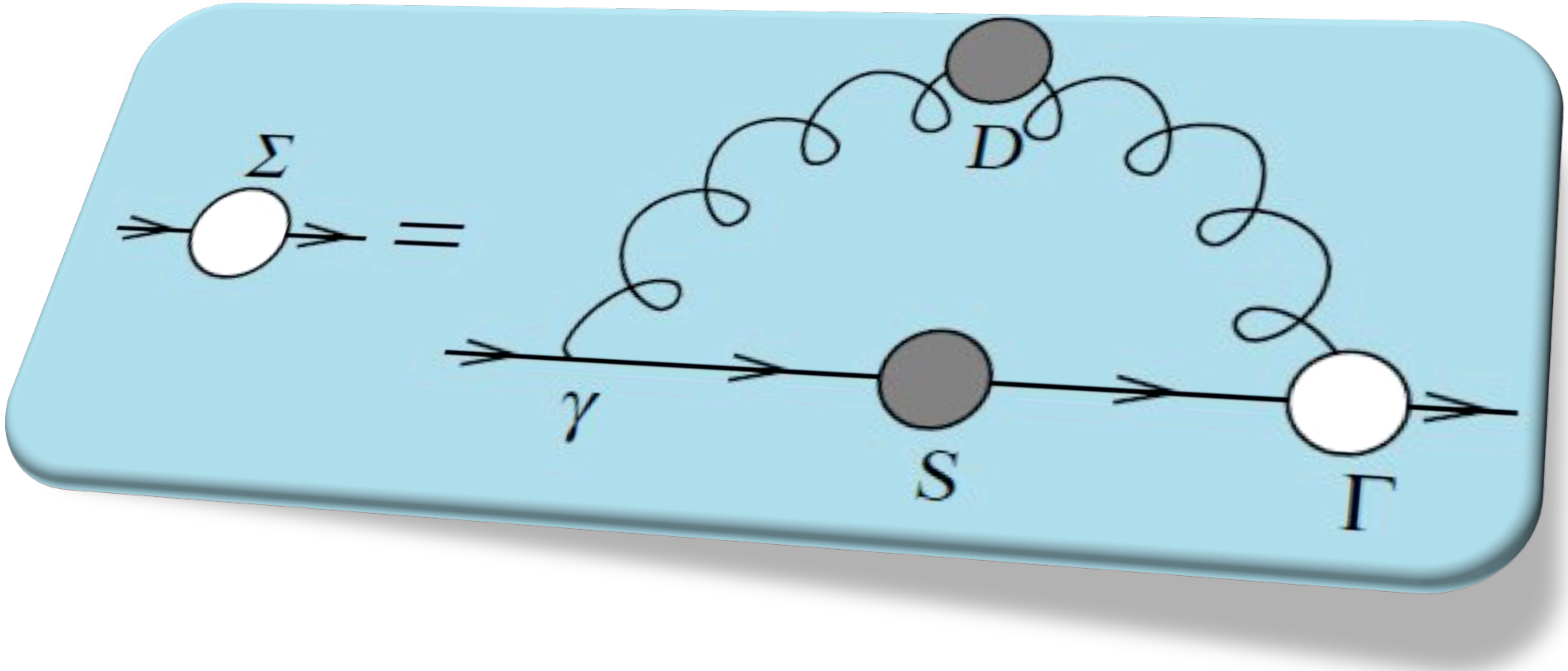
- Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
  - Gluons and quarks with

    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



Gap Equation
- Critical open question

What is Γ_μ?

Ward-Green-Takahashi Identities

LETTERS TO THE EDITOR

…udies and the latter in studying atmospheric ionization at ground level. These increases in ionization are considered to be due to radioactive matter brought down with the rain. Between 0935 and 1900 hr. GMT on November 29 at Ottawa precipitation was falling. The precipitation started as snow and changed to rain about 1400 hr. Compared with the results of Doan and Wait and McNish the 35 percent increase in the soft component registered at Ottawa by counters seems too high to be explained in the same way, unless there was an exceptionally high density of radioactive matter in the atmosphere at the time. An alternative, but not very likely explanation, might be that there was a burst of hard gamma-rays or some other radiation which would increase the number of soft shower particles without any appreciable effect on the hard component.

An interesting feature of the November 19 increase is the difference between the measurements at the various stations, particularly between Resolute and Godhaven (geomagnetic latitude 80°). These two stations are about 900 miles apart and the differences confirm previous indications that sudden increments in cosmic-ray intensity occur over a limited area. The lack of a sudden decrease after the increment is unusual, since a decrease has been reported on previous occasions.

The cooperation of the Department of Transport of the Government of Canada is appreciated for supplying facilities at Resolute and for weather information.

[1] A. Dauvillier, Comptes Rendus 229, 1096 (1949).
[2] Forbush, Stinchcomb, and Schein, Bull. Am. Phys. Soc. 25, No. 1, 15 (1950).
[3] I. L. Chakraborty and S. D. Chatterjee, Ind. J. Phys. 23, 525 (1949).
[4] Forbush, Gill, and Vallarta, Rev. Mod. Phys. 21, 44 (1949).
[5] R. L. Doan, Phys. Rev. 49, 107 (1936).
[6] G. R. Wait and A. G. McNish, Monthly Weather Rev. 62, 1 (1934).

An Identity in Quantum Electrodynamics

J. C. Ward
The Clarendon Laboratory, Oxford, England
February 27, 1950

It has been recently proved by Dyson[1] that all divergencies in the S-matrix of electrodynamics may be removed by a renormalization of mass and charge. Dyson defines certain fundamental divergent operators Γ_μ, S_F', D_F' and gives a procedure for the calculation of their finite parts $\Gamma_{\mu 1}$, S_{F1}', D_{F1}' by a process of successive approximation. It is then shown that

$$\Gamma_\mu = Z_1^{-1}\Gamma_{\mu 1}(e_1),\quad S_F' = Z_2 S_{F1}(e_1),\quad D_F' = Z_3 D_{F1}(e_1),$$
$$e_1 = Z_1^{-1} Z_2 Z_3^{\frac{1}{2}} e,$$

where Z_1, Z_2, and Z_3 are certain infinite constants and e_1 is the renormalized electronic charge. Dyson conjectured that $Z_1 = Z_2$, and it is proposed here to give a formal proof of this relation.

In the first place, with any proper electron self-energy part W, may be associated a set of proper vertex parts V^i obtained by inserting a photon line in one of the electron lines of W. Now consider the operators $\Lambda_\mu(V^i, p, p)$ in which the two external electron momentum variables p have been set equal, and the external photon variable made to vanish. Then $\Lambda_\mu(V^i, p, p)$ may be obtained from $\Sigma(W, p)$ by replacing S_F by $S_F\gamma_\mu S_F$ at one electron line of W. Because of the identity

$$-(1/2\pi)\partial S_F/\partial p_\mu = S_F\gamma_\mu S_F,$$

on summing $\Lambda_\mu(V^i, p, p)$ over all vertex parts V^i associated with W, one finds

$$\Sigma_{V^i}\Lambda_\mu(V^i, p, p) = -(1/2\pi)(\partial\Sigma(W, p)/\partial p_\mu).$$

(One can verify that any closed loop in W gives zero total effect.) Finally summing over all proper electron self-energy parts W, one finds

$$\Lambda_\mu(p, p) = -(1/2\pi)(\partial\Sigma^*(p)/\partial p_\mu).$$

Now substitute this identity into Eqs. (91) and (95) of reference 1. One finds

$$\Lambda_\mu = Z_1^{-1}[(1-Z_1)\gamma_\mu + \Lambda_{\mu c}],\ \Sigma^* = Z_2^{-1}[(Z_2-1)S_F^{-1} + S_F^{-1}S_C/2\pi].$$

We have

$$-(1/2\pi)Z_2^{-1}\{(Z_2-1)2\pi\gamma_\mu + \gamma_\mu S_C + (\gamma_\lambda p_\lambda - iK_0)(\partial S_C/\partial p_\mu)\}$$
$$= Z_1^{-1}\{(1-Z_1)\gamma_\mu + \Lambda_{\mu c}(p, p)\}.$$

Now put

$$\gamma_\lambda p_\lambda = iK_0,\quad (p_\lambda)^2 = -K_0^2.$$

The convergent parts of these equations then vanish and there is left the relation

$$-(1/2\pi)Z_2^{-1}(Z_2-1)2\pi\gamma_\mu = Z_1^{-1}(1-Z_1)\gamma_\mu$$

which reduces immediately to $Z_1 = Z_2$.

[1] F. J. Dyson, Phys. Rev. 75, 1736 (1949).

The Partial Molal Entropy of Superfluid in Pure He[4] below the λ-Point

O. K. Rice
Department of Chemistry, University of North Carolina, Chapel Hill, North Carolina
March 3, 1950

In a recent article[1] (the notation of which is retained here, except that subscripts $4n$ and $4s$ refer to normal fluid and superfluid, respectively, in place of 1 and 2), I have considered the thermodynamics of liquid helium on the two-fluid theory, taking account of the fact that if two "phases" or "components," the normal fluid and the superfluid, exist together they must be in equilibrium with each other. On this basis, using the assumed relation[2] which states that the total molal entropy S at any temperature is the mole fraction x_{4n} of normal fluid times the molal entropy S_λ at the λ-point

$$S = x_{4n}S_\lambda = (1-x_{4s})S_\lambda, \tag{1}$$

using the empirical relation for S as a function of temperature

$$S = S_\lambda(T/T_\lambda)^r \tag{2}$$

(with $r\sim 5.6$), and assuming that the partial molal enthalpy of superfluid, $\bar{H}_{4s}$, is independent of temperature (at essentially constant pressure), and independent of x_{4s} (i.e., there is no heat of mixing), I derived the equation for the partial molal entropy of superfluid

$$\bar{S}_{4s} = S_\lambda x_{4n}/(r+1). \tag{3}$$

However, as I remarked in reference 1, there are some approximations involved in this procedure. Equation (1) is based on the assumption that below T_λ the entropy is contributed solely by the normal fluid, whose molal entropy is always set equal to the constant S_λ, thus neglecting any temperature dependence. Furthermore, there is an implied inconsistency, since Eq. (1) assumes no entropy of mixing while Eq. (3) implies that there is a mixing entropy. In fact, in the following letter we shall show that we may derive a somewhat different expression for S from Eq. (3). We shall, therefore, discard Eq. (1) and turn to a consideration of the enthalpies.

If $\bar{H}_{4s}$ is independent of x_{4s}, then $\bar{H}_{4n}$ must be also, and we have $\bar{H}_{4n} = H_{4n}$, where H_{4n} is the enthalpy of pure normal helium. We can write for the total molal enthalpy[3]

$$H = x_{4n}H_{4n}. \tag{4}$$

We will now proceed to derive an expression for $\bar{S}_{4s}$ in a somewhat more direct way than in reference 1, using Eq. (4) in place of Eq. (1). Since $F = H - TS$ and $\mu_{4s} = \bar{H}_{4s} - T\bar{S}_{4s} = -T\bar{S}$… the condition for internal equilibrium, $F = \mu_{4s}$, gives

$$\bar{S}_{4s} = S - H/T.$$

H.J. Munczek, Phys. Rev. D **52** (1995) 4736
A. Bender, C.D. Roberts and L. von Smekal, Phys.Lett. B **380** (1996) 7

Lei Chang and C.D. Roberts, Phys. Rev. Lett. 103 (2009) 081601

Longitudinal Axial-Vector Ward-Green-Takahashi Identity

$$P_\mu \Gamma^l_{5\mu}(k;P) \; = \; \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5\,\mathcal{S}^{-1}(k_-)$$

$$-M_\zeta\, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\,M_\zeta$$

Axial-Vector vertex Satisfies an inhomogeneous Bethe-Salpeter equation

Quark propagator satisfies a gap equation

Kernels of these equations are completely different
But they must be intimately related

- This class of identities have been known for more than 60 years
- They have been used for 19 years in order to construct a symmetry-preserving kernel for the Bethe-Salpeter equation
- ***For the last 5 years we've known how to construct a symmetry preserving kernel given an arbitrary quark-gluon vertex***

. Takahashi. (1985), Canonical quantization and generalized Ward relations: Foundation of nonperturbative approach, Print-85-0421 (Alberta).

Transverse Ward-Takahashi identity, anomaly and Schwinger-Dyson equation - Kondo, Kei-Ichi Int.J.Mod.Phys. A12 (1997) 5651-5686 hep-th/9608100 CHIBA-EP-94, OUTP-96-30-P

Transverse Ward-Takahashi identity for the fermion boson vertex in gauge theories - He, Han-Xin *et al.* Phys.Lett. B480 (2000) 222-228

Transverse vector vertex function and transverse Ward-Takahashi relations in QED - He, Han-Xin Commun.Theor.Phys. 46 (2006) 109-112

Transverse Ward-Takahashi relation for the fermion-boson vertex function in four-dimensional Abelian gauge theory - He, Han-Xin Int.J.Mod.Phys. A22 (2007) 2119-2132

Nonperturbative fermion boson vertex function in gauge theories - He, Han-xin hep-th/0202013

Checking the transverse Ward-Takahashi relation at one loop order in 4-dimensions - Pennington, M.R. *et al.* J.Phys. G32 (2006) 2219-2234 hep-ph/0511254 DCPT-05-130, IPPP-05-65

Transverse Ward-Takahashi relation for the fermion-boson vertex to one-loop order - He, Han-Xin *et al.* I.J.Mod.Phys. A21 (2006) 2541-2551

Transverse Ward-Green-Takahashi Identities

Physics Letters B
Volume 722, Issues 4–5, 24 May 2013, Pages 384–388

Practical corollaries of transverse Ward–Green–Takahashi identities

Si-xue Qin[a, b], Lei Chang[c], Yu-xin Liu[a], Craig D. Roberts[d, e], Sebastian M. Schmidt[f]

- Longitudinal WGT identity expresses properties of the divergence of the vertex

$$q_\mu \Gamma_\nu(k,p) - q_\nu \Gamma_\mu(k,p) = S^{-1}(p)\sigma_{\mu\nu} + \sigma_{\mu\nu} S^{-1}(k) + 2im\Gamma_{\mu\nu}(k,p) + t_\lambda \varepsilon_{\lambda\mu\nu\rho}\Gamma^A_\rho(k,p) + A^V_{\mu\nu}(k,p),$$

- Transverse identities relate to its *curl* (as Faraday's law of induction involves an electric field)

$$q_\mu \Gamma^A_\nu(k,p) - q_\nu \Gamma^A_\mu(k,p) = S^{-1}(p)\sigma^5_{\mu\nu} - \sigma^5_{\mu\nu} S^{-1}(k) + t_\lambda \varepsilon_{\lambda\mu\nu\rho}\Gamma_\rho(k,p) + V^A_{\mu\nu}(k,p),$$

- The last two terms in each identity arise in computing the momentum space expression of a nonlocal axial-vector/vector vertex, whose definition involves a gauge-field-dependent line integral
- But … practical progress can be made without knowing their precise forms

Physics Letters B

Volume 722, Issues 4–5, 24 May 2013, Pages 384–388

Practical corollaries of transverse Ward–Green–Takahashi identities

Si-xue Qin[a, b], Lei Chang[c], Yu-xin Liu[a], Craig D. Roberts[d, e], Sebastian M. Schmidt[f]

- Using symmetries alone, it is readily established that DCSB forces dressed fermions to possess anomalous chromo- and electro-magnetic moments, which are large on the domain within which DCSB is effective
- This is the "final" word.
- Evidence had slowly been accumulating since 1985

Anomalous Magnetic Moment Of Light Quarks And Dynamical Symmetry Breaking - Singh, J.P. Phys.Rev. D31 (1985) 1097-1108

Anomalous quark chromomagnetic moment induced by instantons - Kochelev, N.I. Phys.Lett. B426 (1998) 149-153 hep-ph/9610551 KOBE-FHD-96-01, C96-09-02.3

The Anomalous magnetic moment of quarks - Bicudo, Pedro J.A. *et al.* Phys.Rev. C59 (1999) 1107-1112 hep-ph/9806243

Dressed-quark anomalous magnetic moments - Chang, Lei *et al.* Phys.Rev.Lett. 106 (2011) 072001 arXiv:1009.3458 [nucl-th]

Dynamical chiral symmetry breaking and the fermion--gauge-boson vertex - Bashir, A. *et al.* Phys.Rev. C85 (2012) 045205 arXiv:1112.4847 [nucl-th]

Dressed-quark anomalous magnetic moments
Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1009.3458 [nucl-th],
Phys. Rev. Lett. **106** (2011) 072001

Dynamically generated AMM

- Simple vertex in perturbation theory $\Gamma_\mu = \gamma_\mu$
  → 12 distinct terms when strong interactions are turned on
- Amongst them, one with a unique structure; i.e., an anomalous magnetic moment term

$$\propto \sigma_{\mu\nu} k_\nu \frac{dB(k^2)}{dk^2}$$

- Follows, algebraically, that gauge theories coupled to fermions with a dynamically generated mass MUST possess an anomalous (chromo/electro)-magnetic moment, whose magnitude is driven by the strength of DCSB

Rapid Communication

Modern $\Gamma_\mu(q;k)$

Tracing masses of ground-state light-quark mesons

Phys. Rev. C **85**, 052201(R) – Published 7 May 2012

Lei Chang and Craig D. Roberts

- Describes the best-informed vertex available today
  - Contains all the Ball-Chiu terms

    They are the unique kinematic-singularity-free solution of the longitudinal vector WGT identity
  - And two of the terms critical for expressing the CAMMs

$$\Gamma_\mu^{\rm acm}(p_1,p_2) = \Gamma_\mu^{\rm acm_4}(p_1,p_2) + \Gamma_\mu^{\rm acm_5}(p_1,p_2)\,, \quad (8)$$

with $(k = p_1 - p_2,\ T_{\mu\nu} = \delta_{\mu\nu} - k_\mu k_\nu/k^2,\ a_\mu^{\rm T} := T_{\mu\nu} a_\nu)$

$$\Gamma_\mu^{\rm acm_4} = [\ell_\mu^{\rm T} \gamma\cdot k + i\gamma_\mu^{\rm T} \sigma_{\nu\rho}\ell_\nu k_\rho]\tau_4(p_1,p_2)\,, \quad (9)$$

$$\Gamma_\mu^{\rm acm_5} = \sigma_{\mu\nu}k_\nu \tau_5(p_1,p_2)\,, \quad (10)$$

$$\tau_4 = \frac{2\tau_5(p_1,p_2)}{\mathcal{M}(p_1^2,p_2^2)}\,, \quad (11)$$

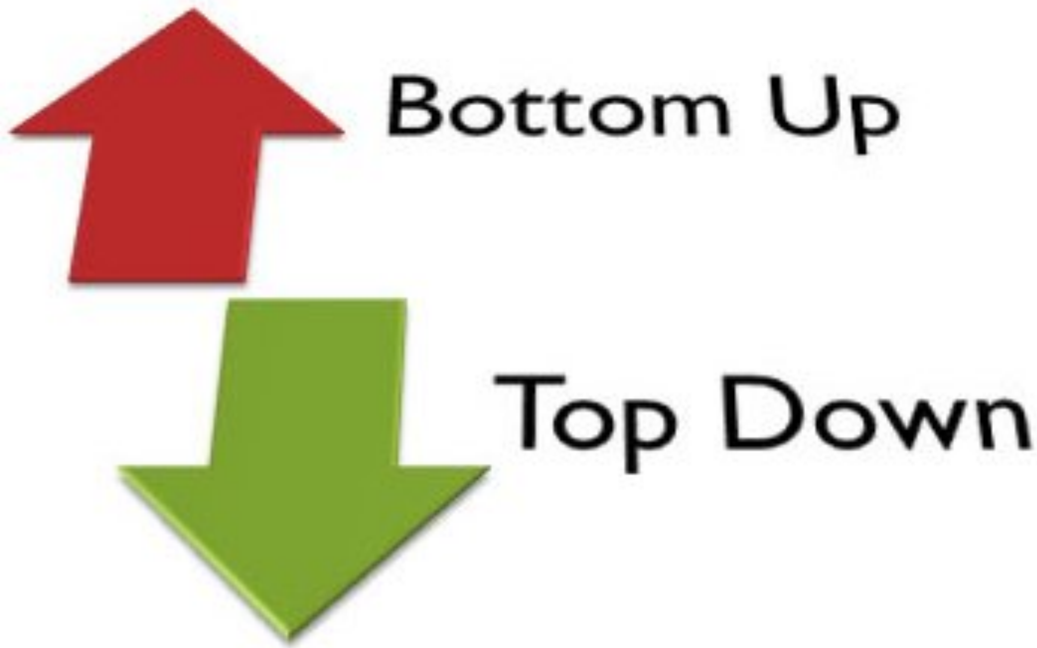
- The chromo AMM is crucial to explaining the splitting between parity partners, such as a_1-ρ mass splitting, and connecting it with DCSB

Mesons and Rainbow-Ladder Truncation: *Requiescat in Pace*

- For reasons that are fully understood, Rainbow-Ladder truncation provides accurate results (15% over ≈ 100 observables) for properties of ground-states in the π, ρ, K, $Q_{bar}Q$, N, Δ channels
- Equally, however, we know it is critically flawed for
  - scalar, axial-vector and tensor mesons
  - excited states in all channels
  - exotic states
  - heavy-light systems
  - etc.
- Like quenched lattice-QCD

the time for RL analyses is passing

Daniele



Continuum-QCD & ab initio predictions

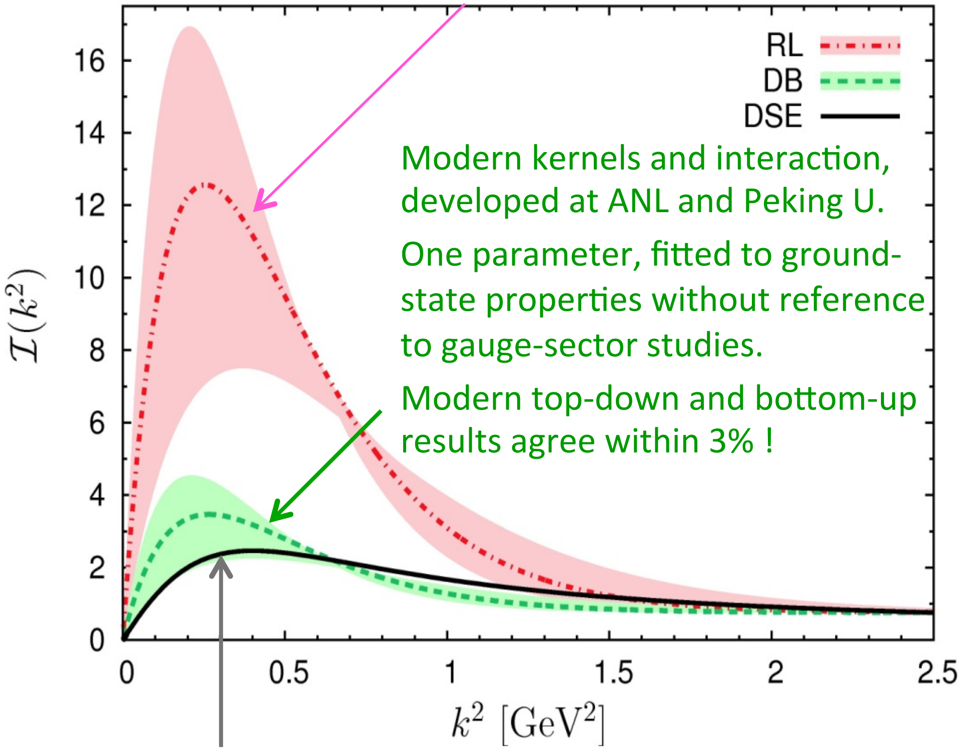
Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

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

- *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*

"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

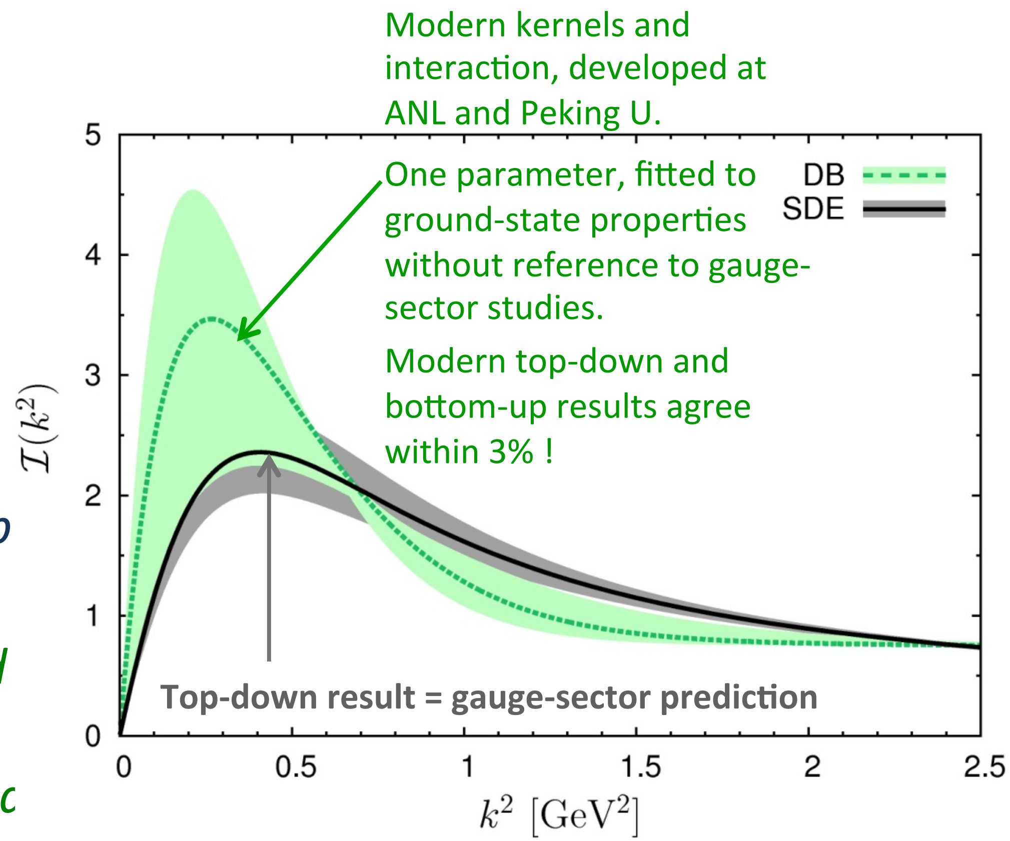
– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

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 unitec these two approaches*



– 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

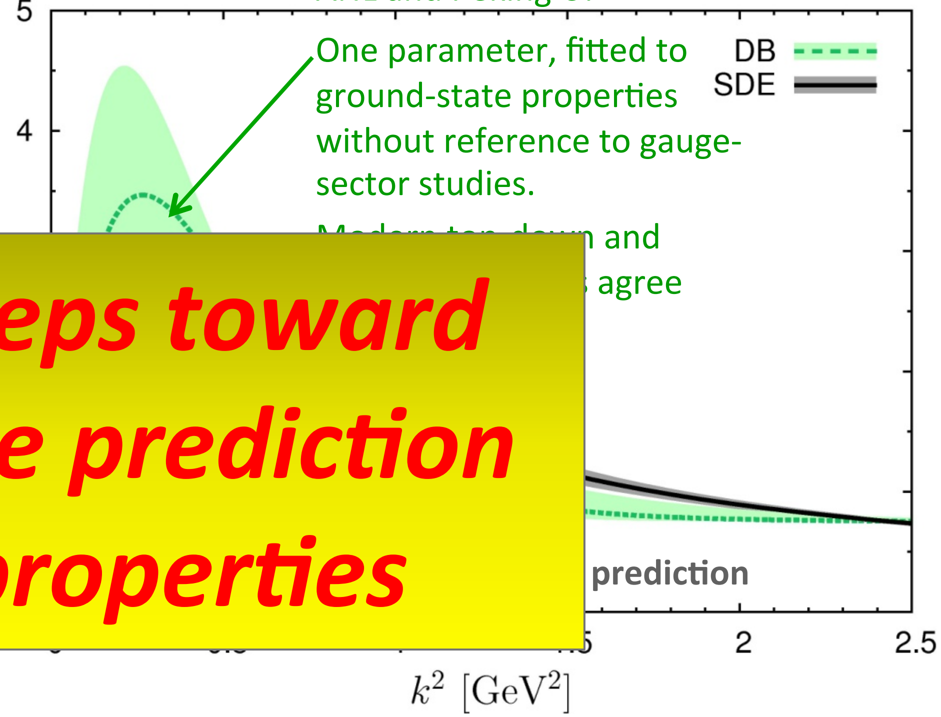
D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
C. D. Roberts (US), arXiv:1412.4782 [nucl-th] , *Phys. Lett. B* ***742*** *(2015) 183*

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 unitec these two approaches*

– 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

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

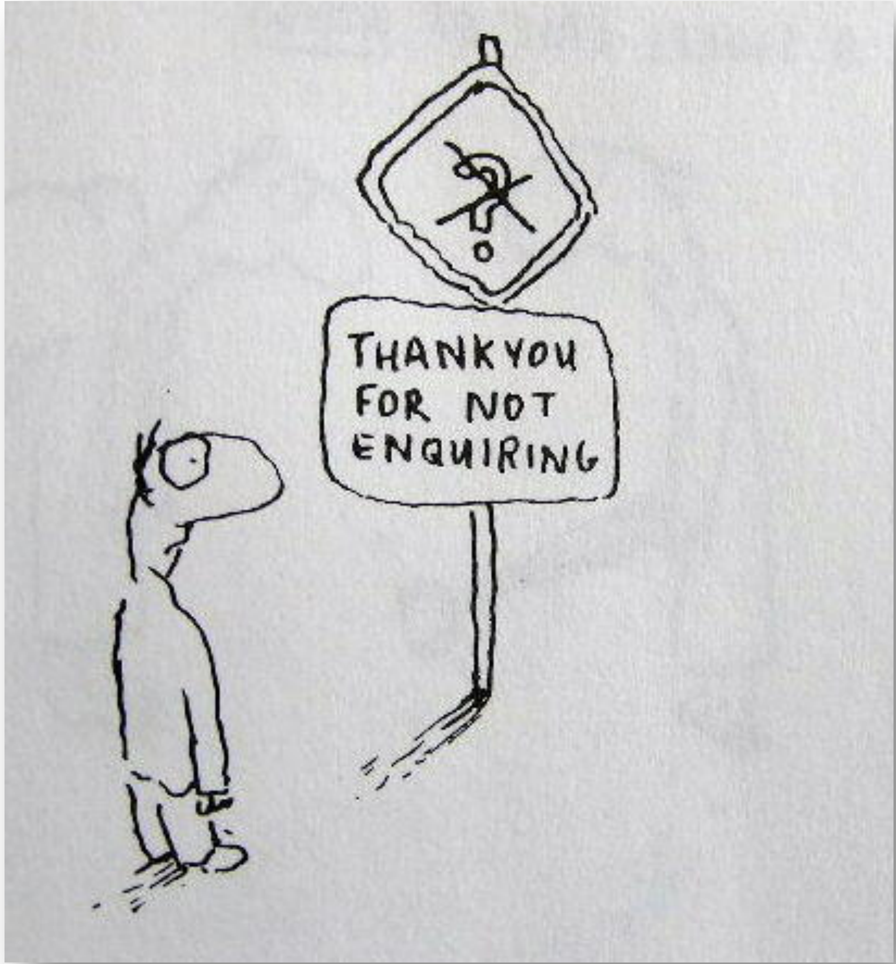


Significant steps toward parameter-free prediction of hadron properties

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

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

- 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**

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

The most fundamental expression of Goldstone's Theorem and DCSB

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

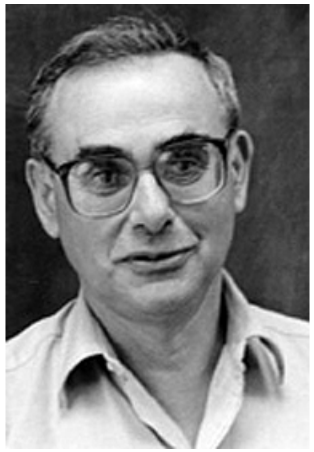
This algebraic identity is why QCD's pion is massless in the chiral limit

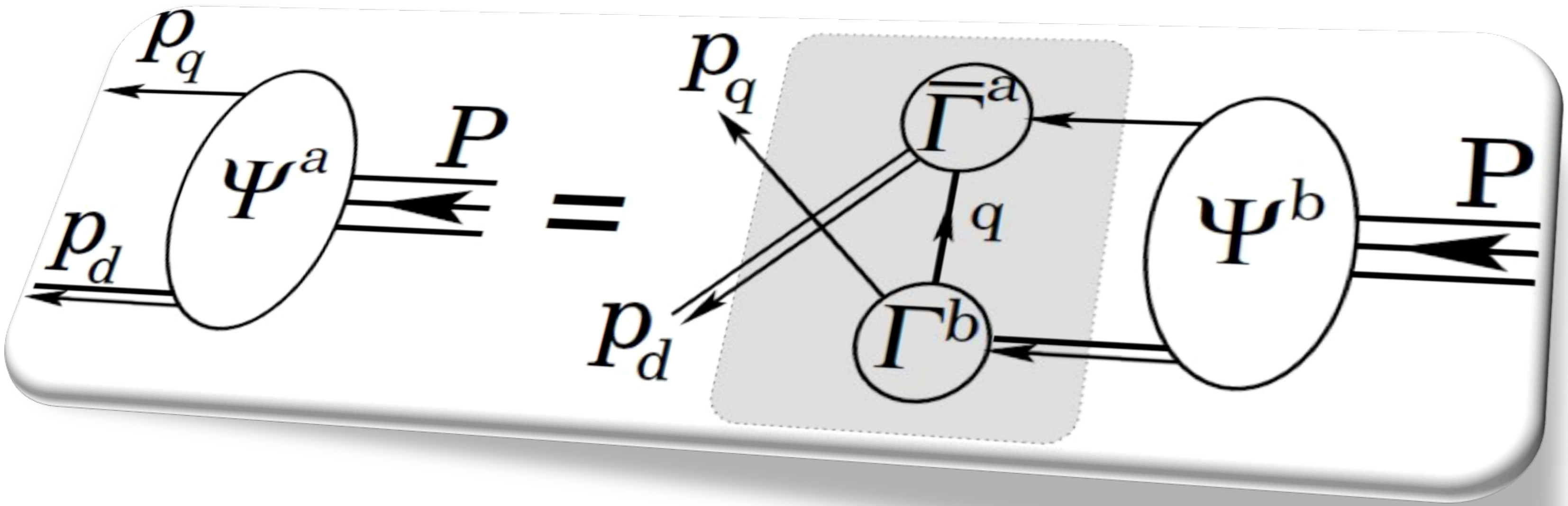
Enigma of mass

- 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.





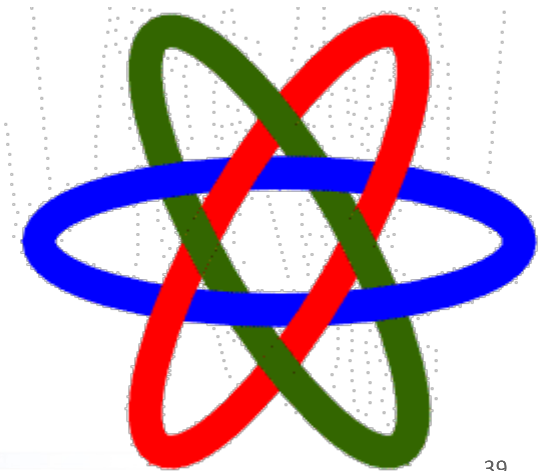
Baryon Structure

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys. Lett. B in press

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?



Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys. Lett. B in press

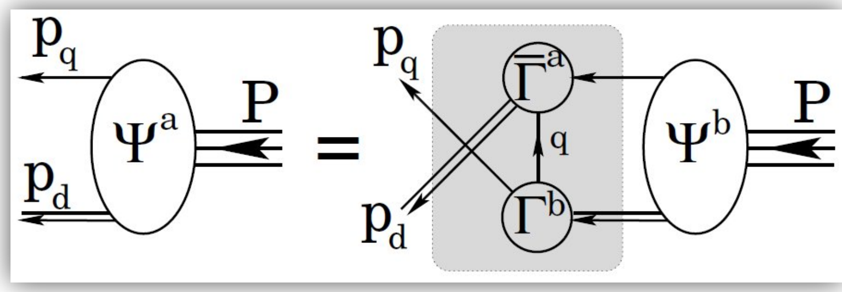
Strong running coupling - α_s

- 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.

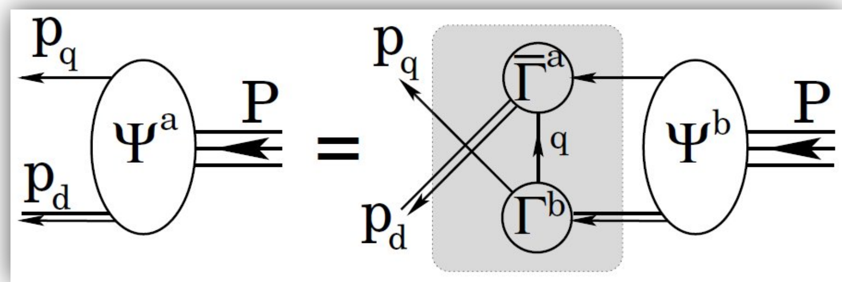
Corollary of DCSB (*little-known*)

- 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 two decades of studying two- and three-body bound-state problems in hadron physics
- No realistic counter examples are known.



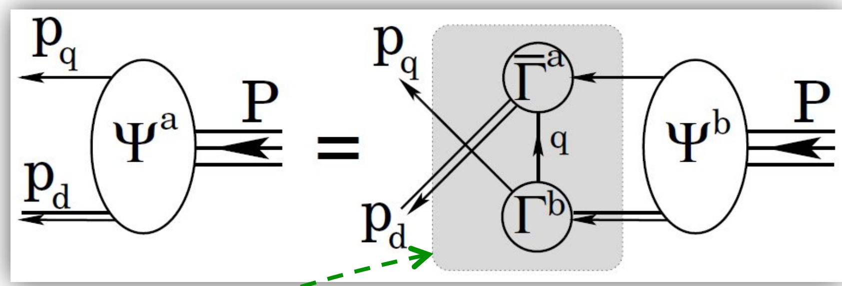
Baryon Structure

- 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 enhance 2-body interactions over $n \geq 3$-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

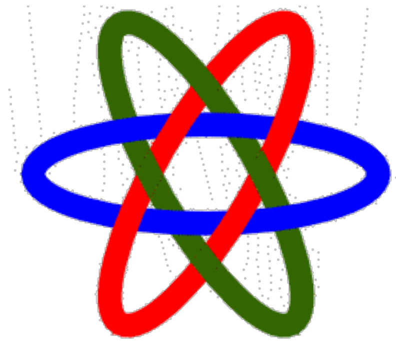


Baryon Structure

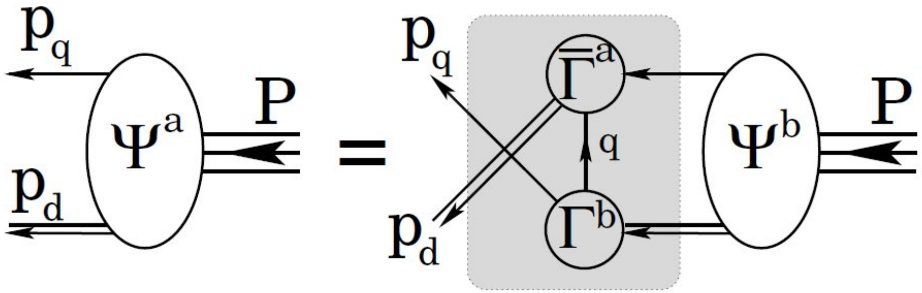
- Both scalar-isoscalar and pseudovector-isotriplet diquark correlations feature within a nucleon.
- Any study that neglects pseudovector diquarks is unrealistic because no self-consistent solution of the Faddeev equation can produce a nucleon constructed solely from a scalar diquark
- The relative probability 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: $S_1(|p|, \cos\vartheta)$
- **Realistic solution of Faddeev equation**
- Strong variation with *both* arguments
- Peaks at

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

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

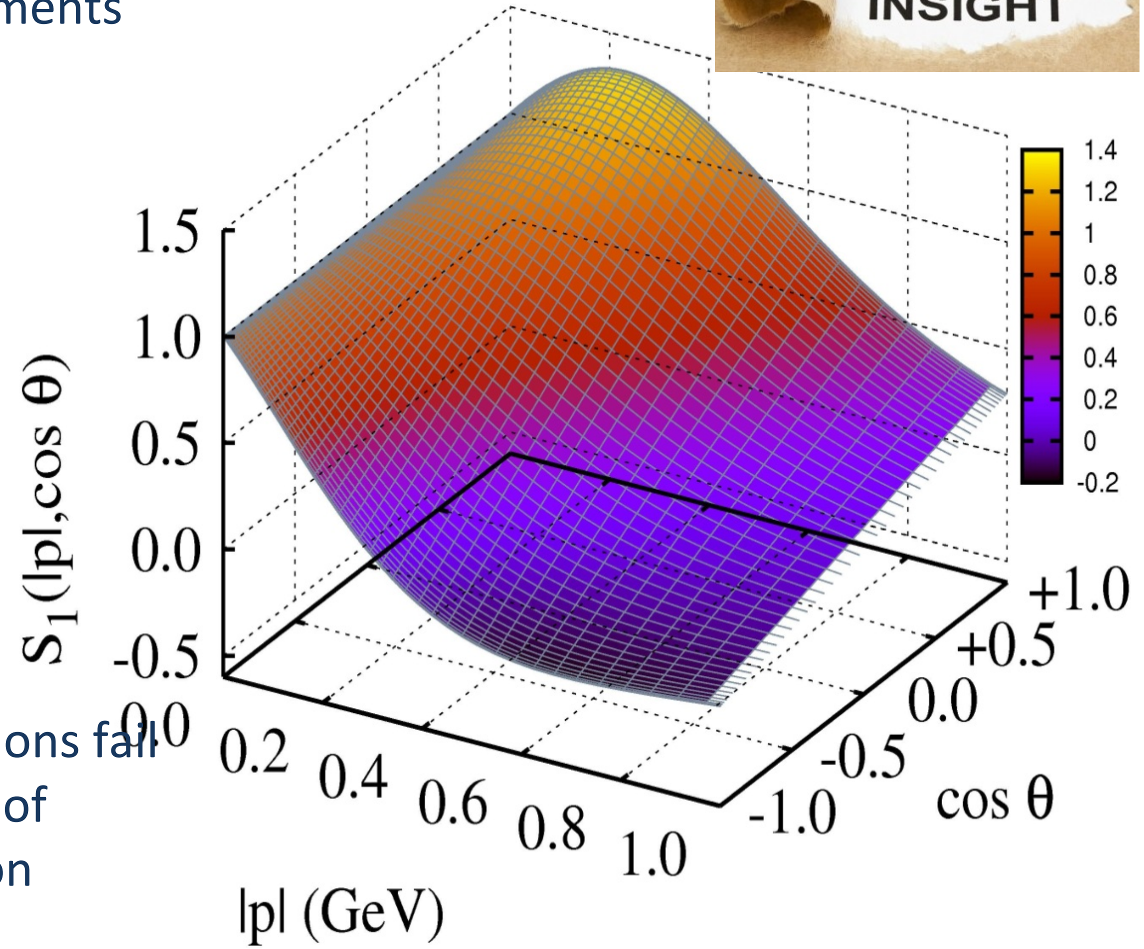
  i.e., *natural* rel-momentum = 0

  $\cos\vartheta = -1$, 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.* $k \,//\, P$
- Simple interactions and truncations fail to capture sophisticated profile of nucleon's Faddeev wave function



Ian

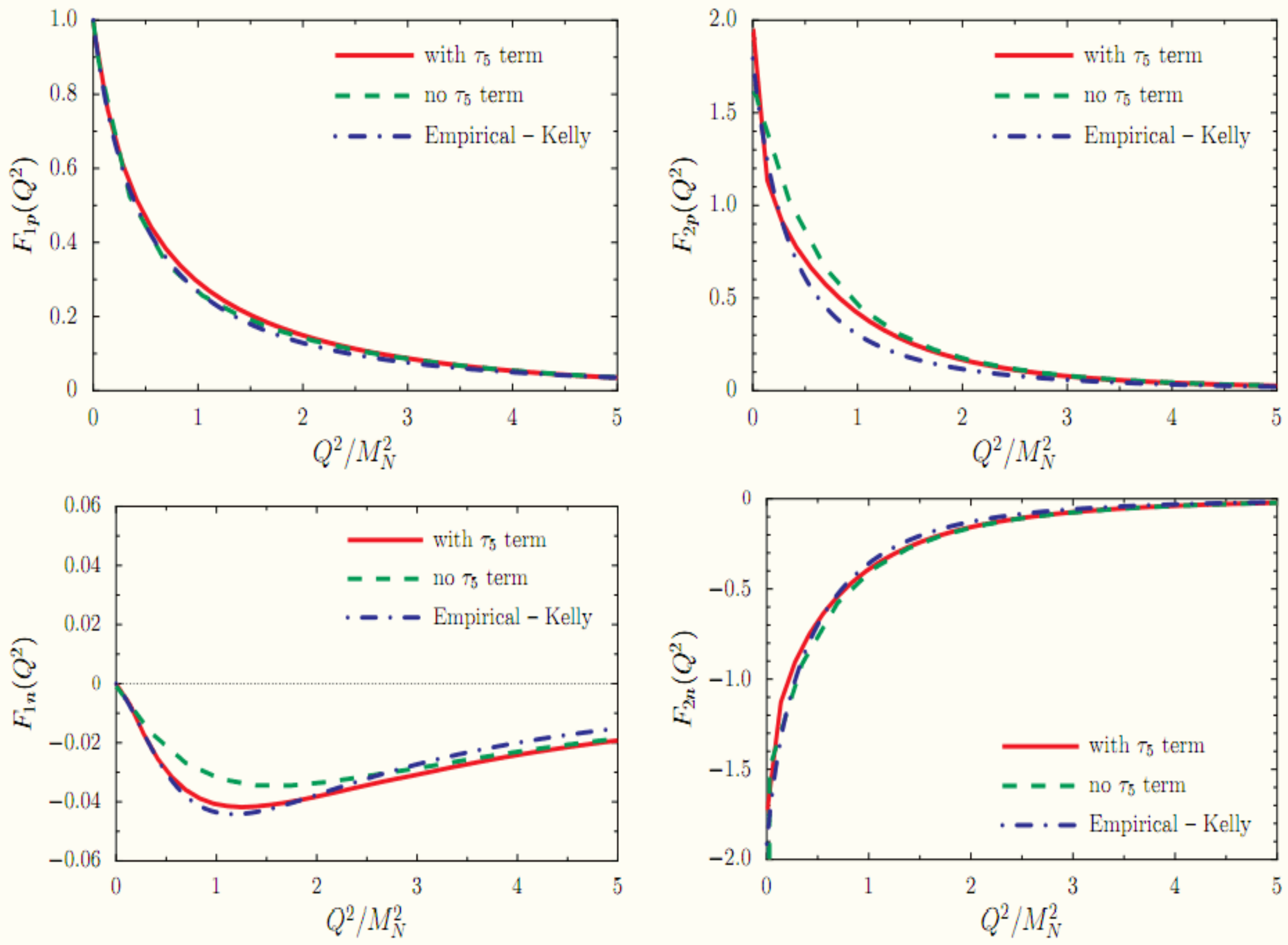
Survey of nucleon electromagnetic form factors
I.C. Cloët et al, arXiv:0812.0416 [nucl-th],
Few Body Syst. **46** (2009) pp. 1-36

Nucleon Form Factors

Unification of meson and nucleon form factors.

Very good description.

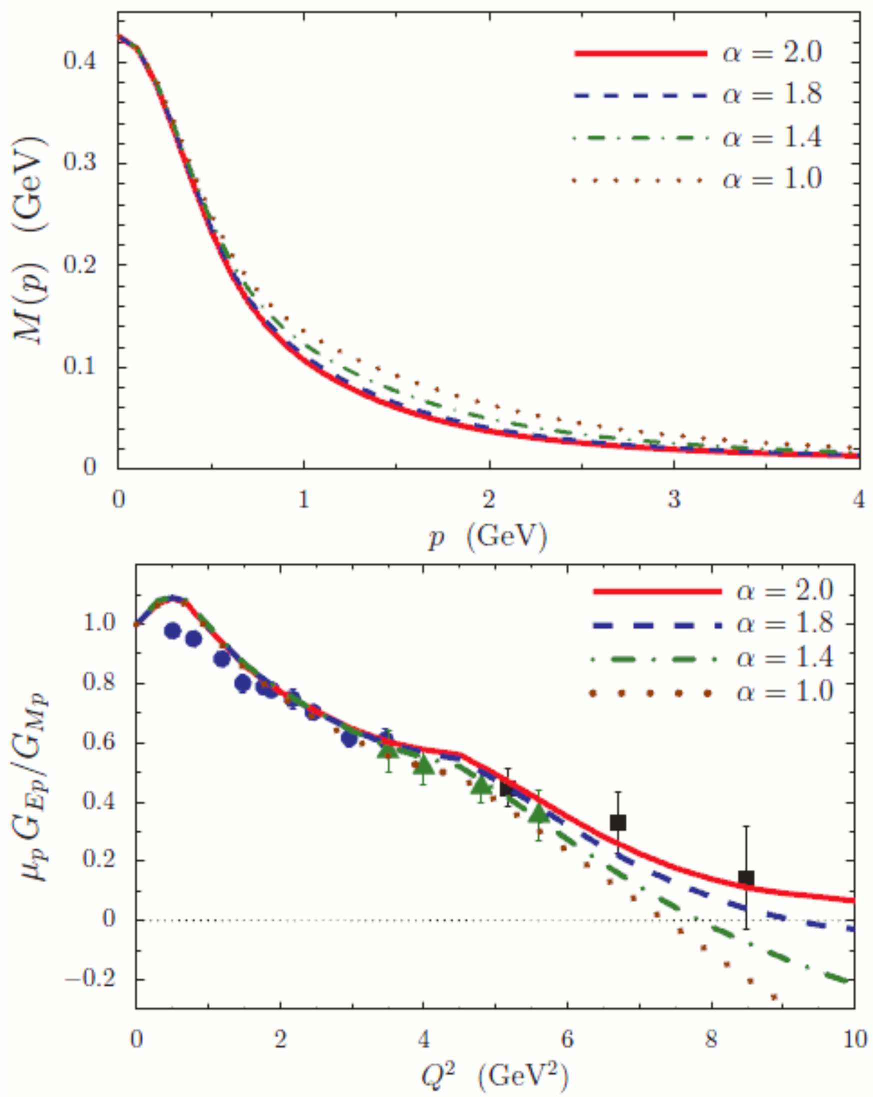
Quark's momentum-dependent anomalous magnetic moment has observable impact & materially improves agreement in all cases.



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

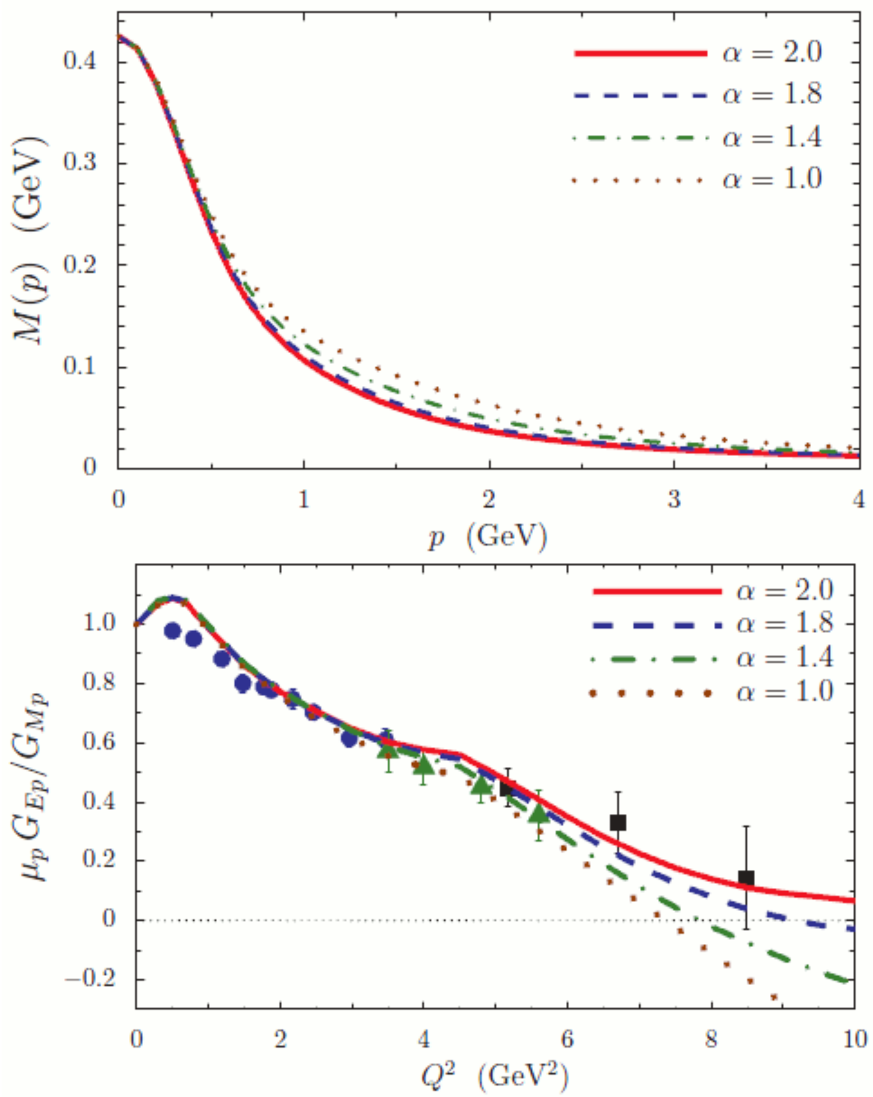
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



- 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.

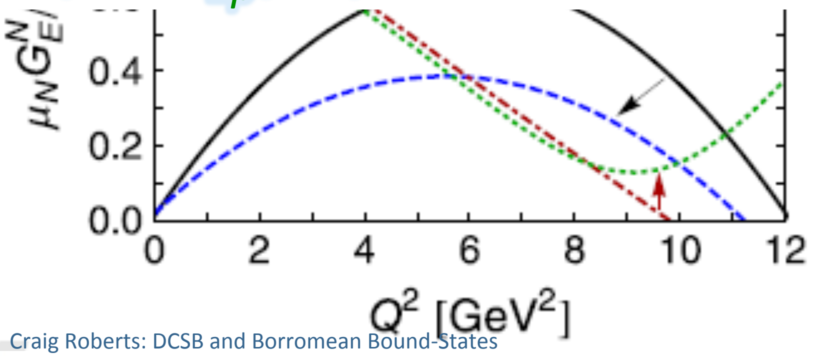
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors, arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) 1185 [on-line]

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.

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

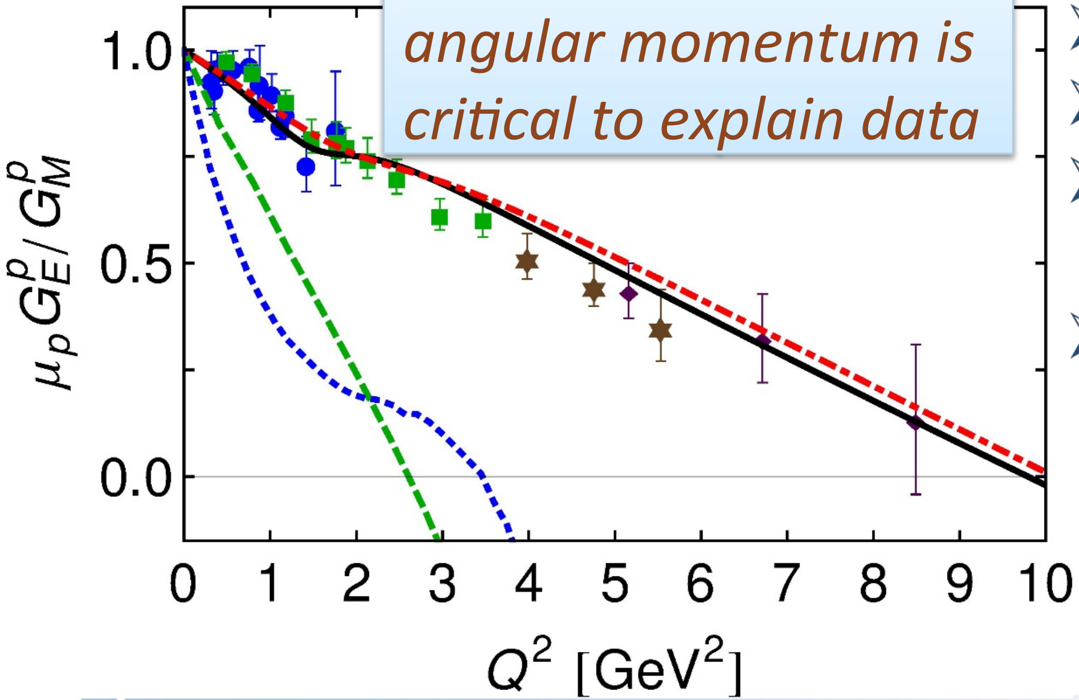
Discovering Diquarks

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys. Lett. B in press

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

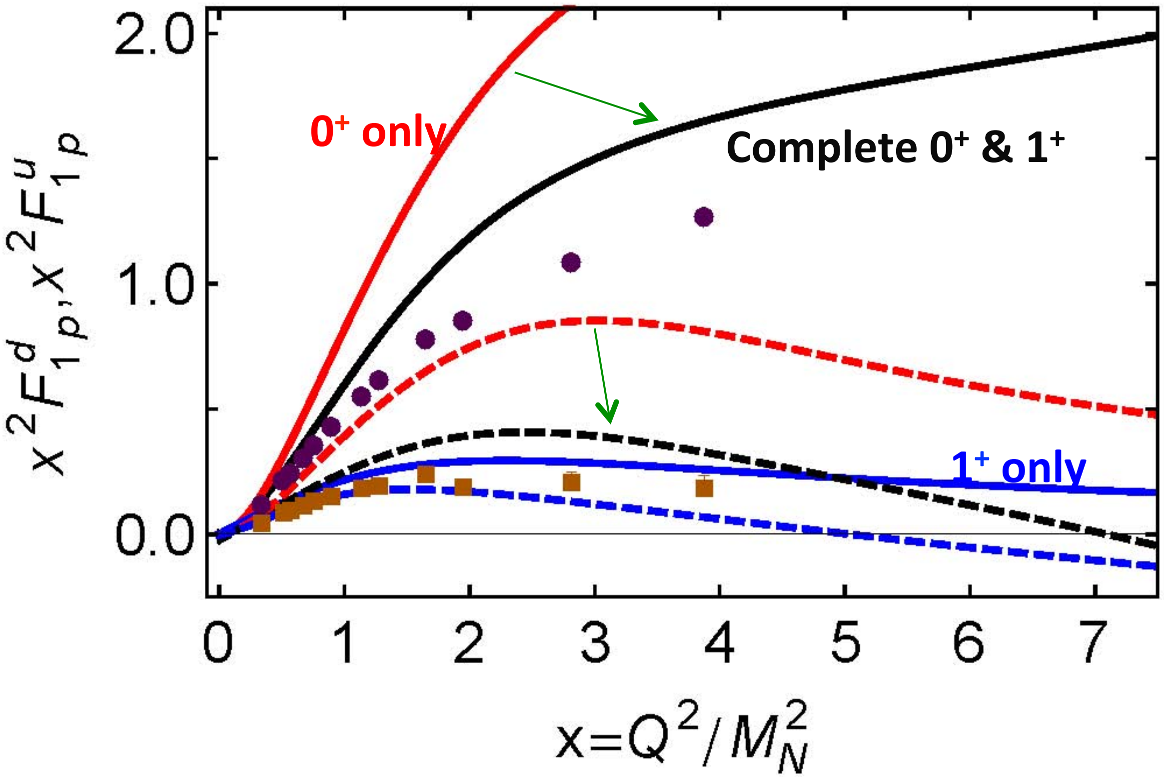


- Black = full calculation
- Red = scalar diquark only
- Blue = pseudovector diquark only
- Green = *S*-wave component of scalar diquark

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys. Lett. B in press

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.

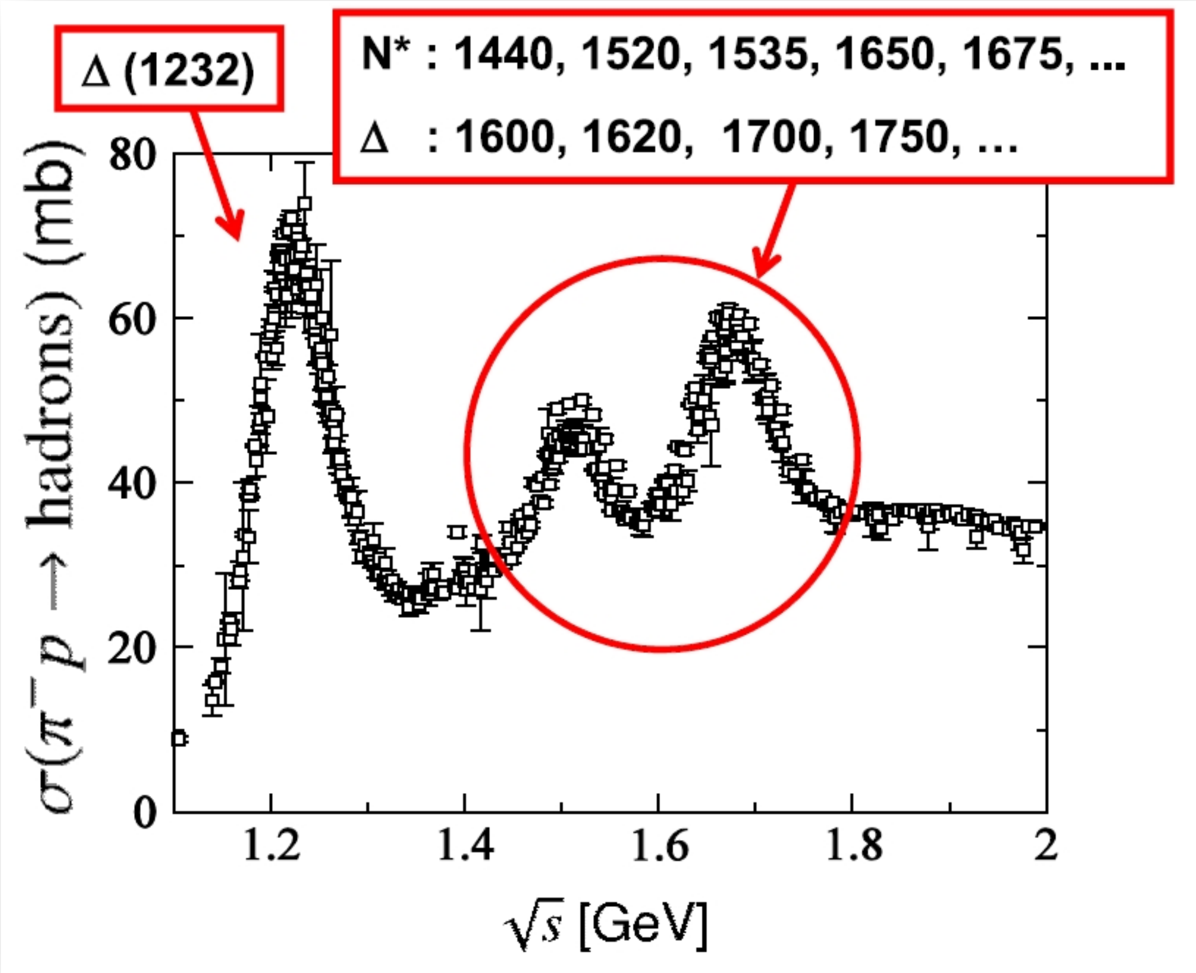


Location of the predicted zero depends on the strength of interference with the scalar diquark part of the proton.

Understanding the nucleon as a Borromean bound-state,
J. Segovia, C.D. Roberts, S.M. Schmidt,
arXiv: 1506.05112 [nucl-th], Phys. Lett. B in press

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
- 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
- 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.



Nucleon Resonances

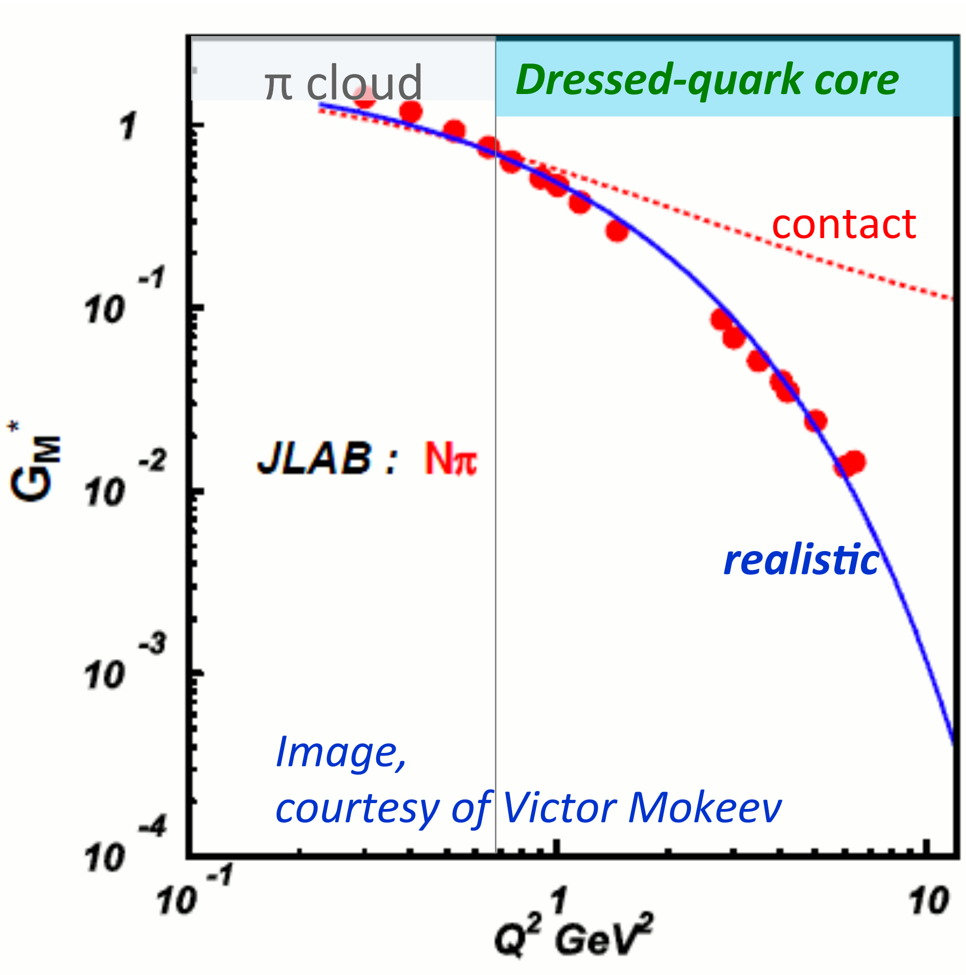
γ N → Resonance

- 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.

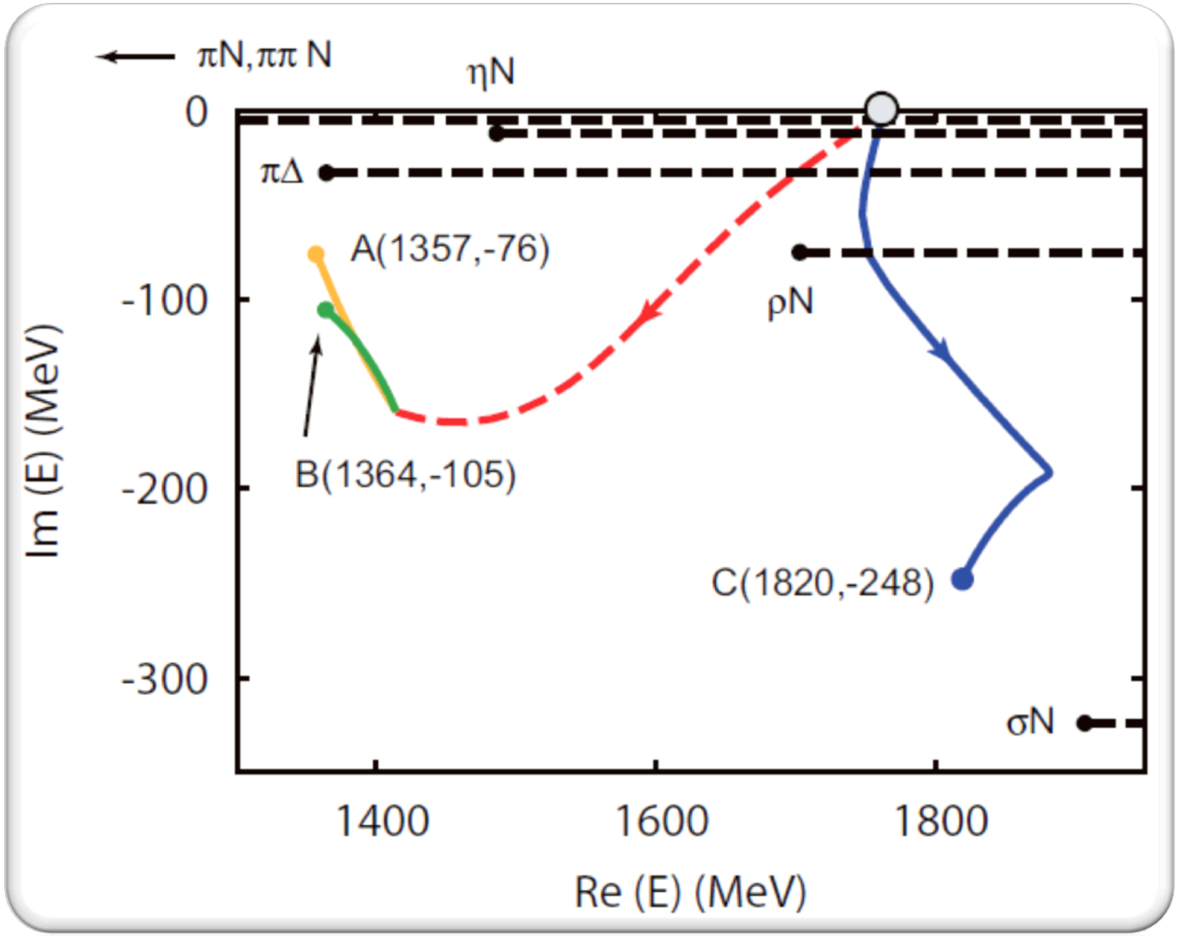
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: *Nucleon and Δ Elastic and Transition Form Factors*, arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222 [on-line]

$\gamma N \rightarrow \Delta$

- 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 $Q^2>0.7\ GeV^2$***



Bruno

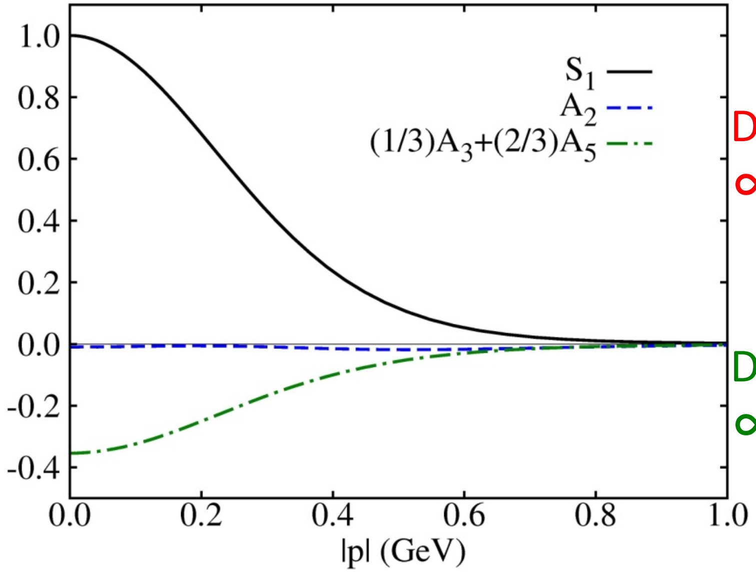


Roper Resonance

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]

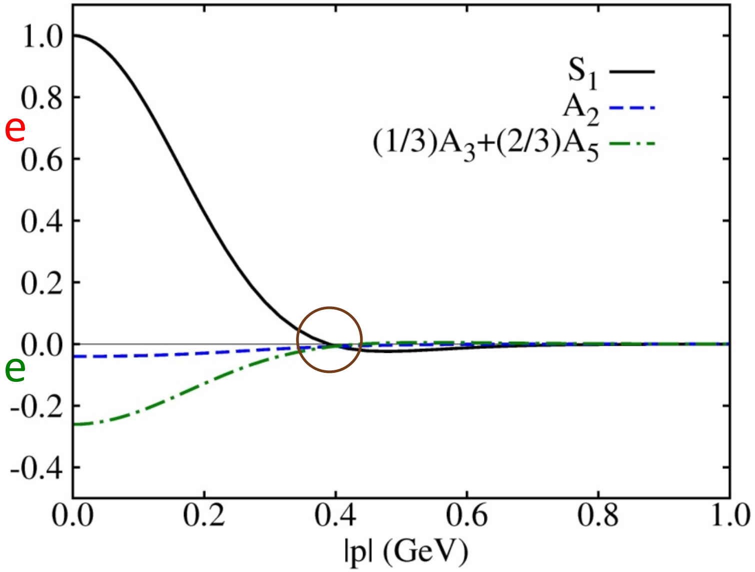
Roper Resonance

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



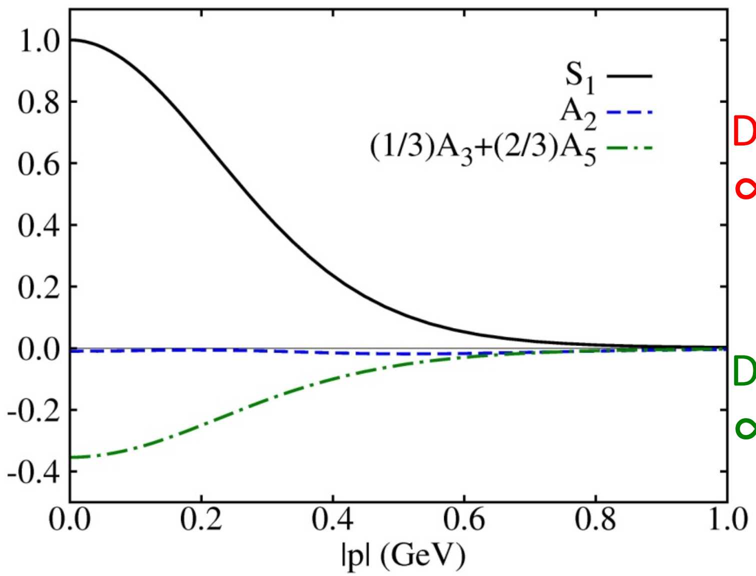
- $M_{\text{Roper QQQ}}$ = 1.73 GeV … amplitudes typically possess a zero
  $\Rightarrow$ lightest excitation of the nucleon is radial excitation

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]

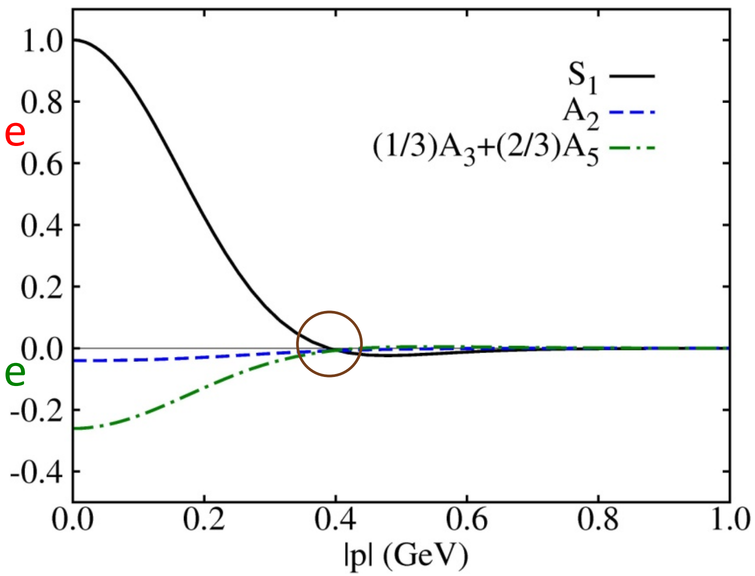
Roper Resonance

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

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



- $M_{Roper\ ooo}$ = 1.73 GeV … amplitudes typically possess a zero

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

n

N.B.

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 Roper

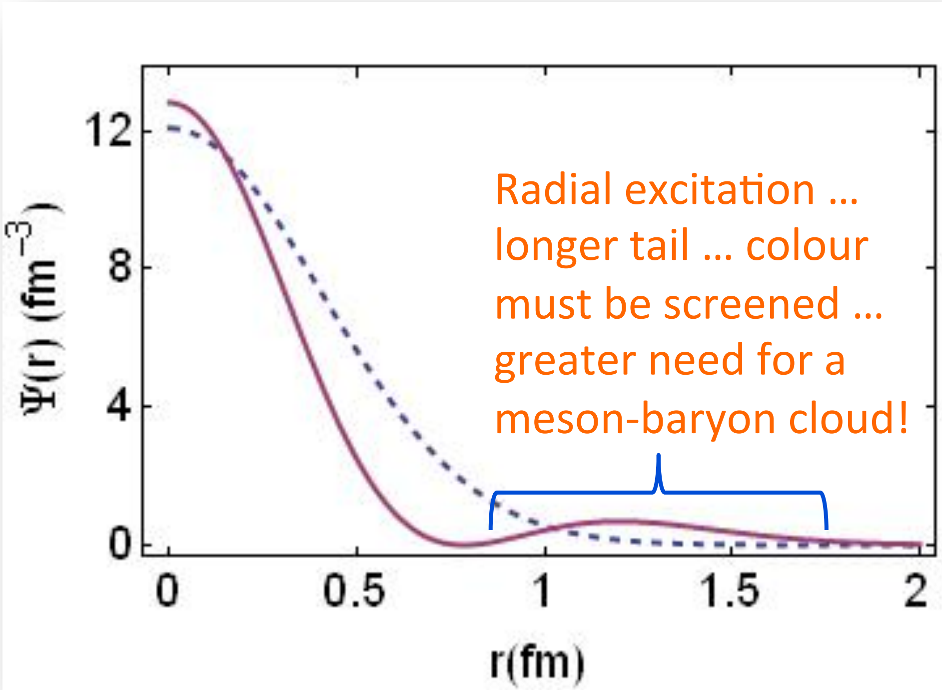
	Nucleon	Roper	Image-Nucleon
$P_{J=0x0}$	62%	62%	30%
$P_{J=0x1\&1x1}$	38%	38%	70%

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

- Roper & 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]

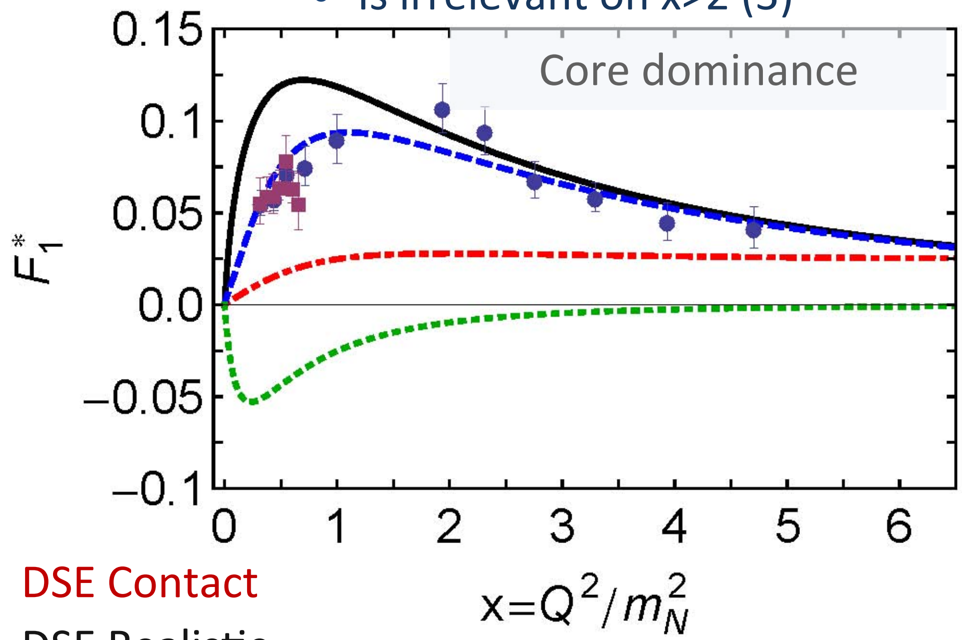
Roper Resonance

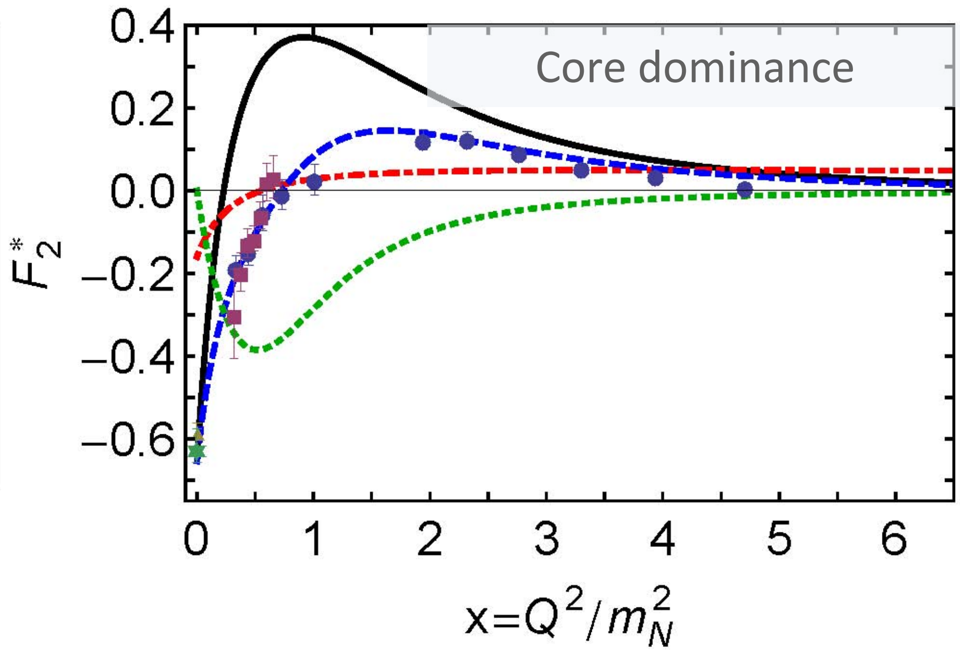


- Ratio of charge radii for the quark+diquark core of the Roper compared with that of the nucleon = 1.8
- Harmonic Oscillator result (*L=0*): $r_{n=1}/r_{n=0} = 1.53$
- Significant angular momentum and spin-orbit repulsion introduced via relativity, which increases size of core, for nucleon and Roper

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

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 ⇒ 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* … there 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

QCD in the continuum is not just a dream

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]

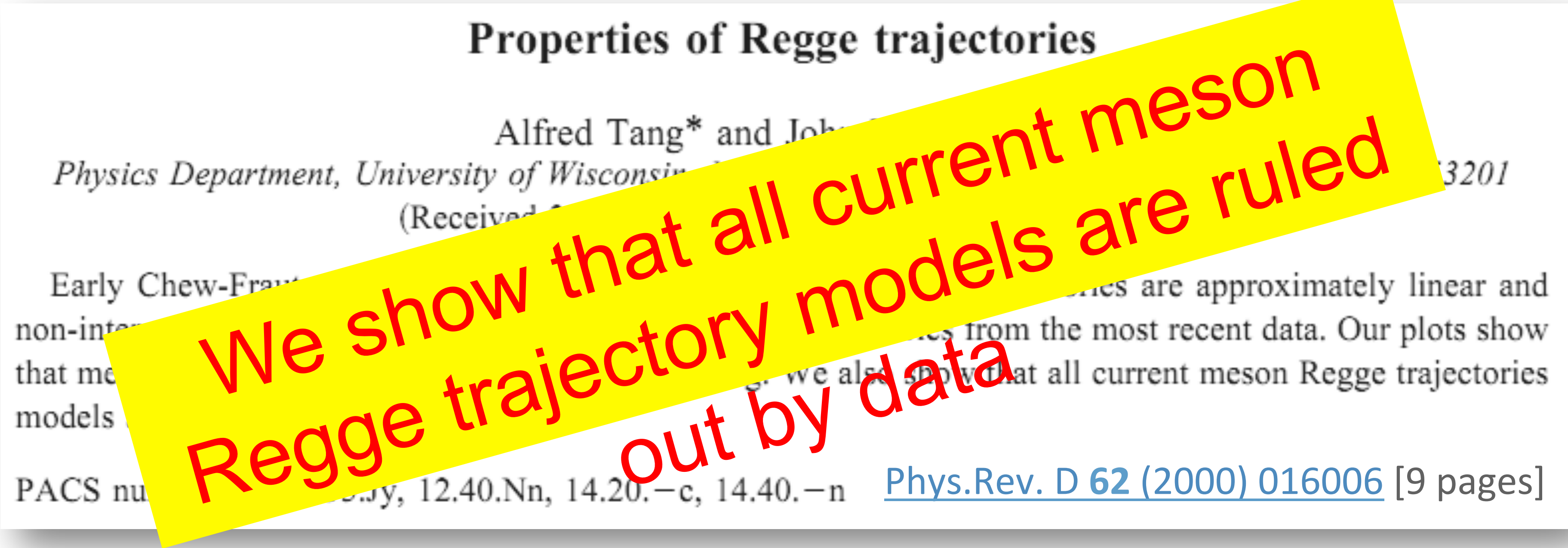
Systematics of radial and angular-momentum Regge trajectories of light non-strange qqbar-states" P. Masjuan, E. Ruiz Arriola, W. Broniowski. arXiv:1305.3493 [hep-ph]

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!



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

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

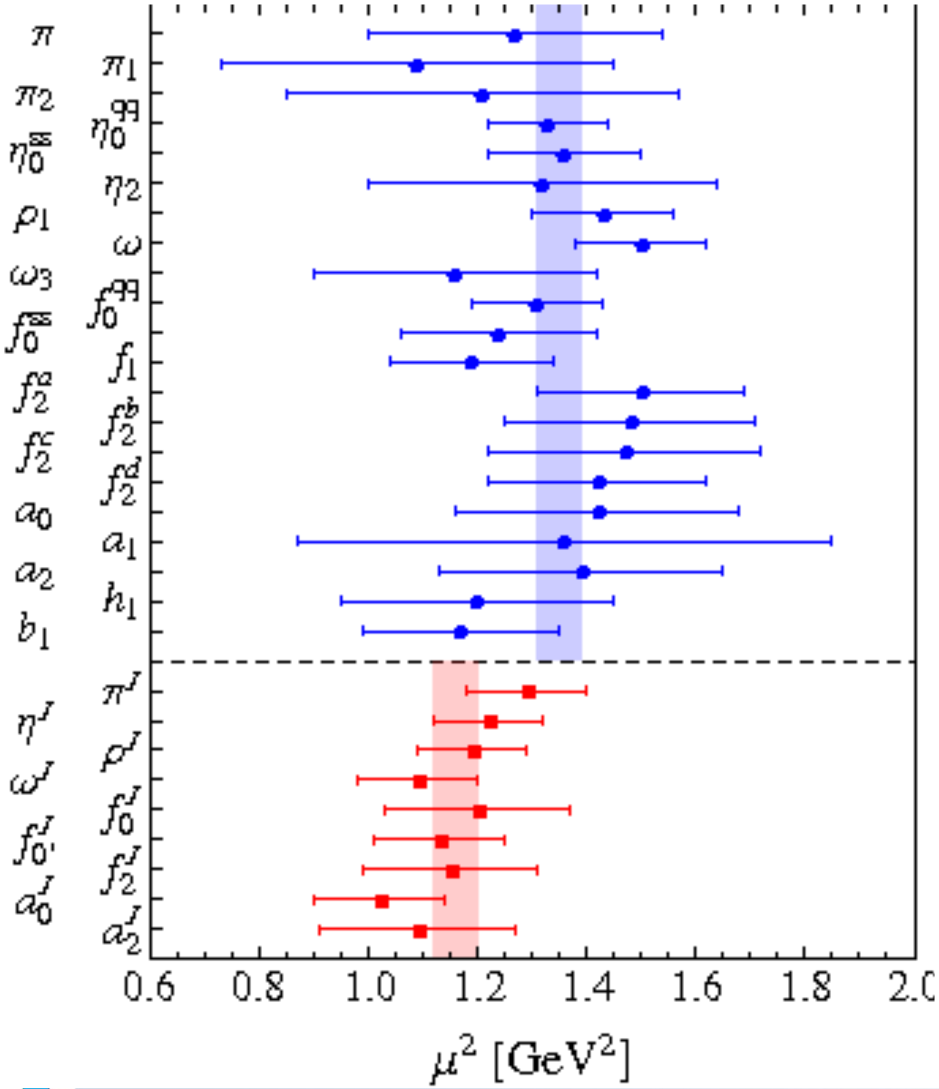
Regge Trajectories?

- 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 makes potential-model picture unrealistic
- *Having one isolated Regge trajectory or a few approximately-linear Regge trajectories ≡ half-pregnant*

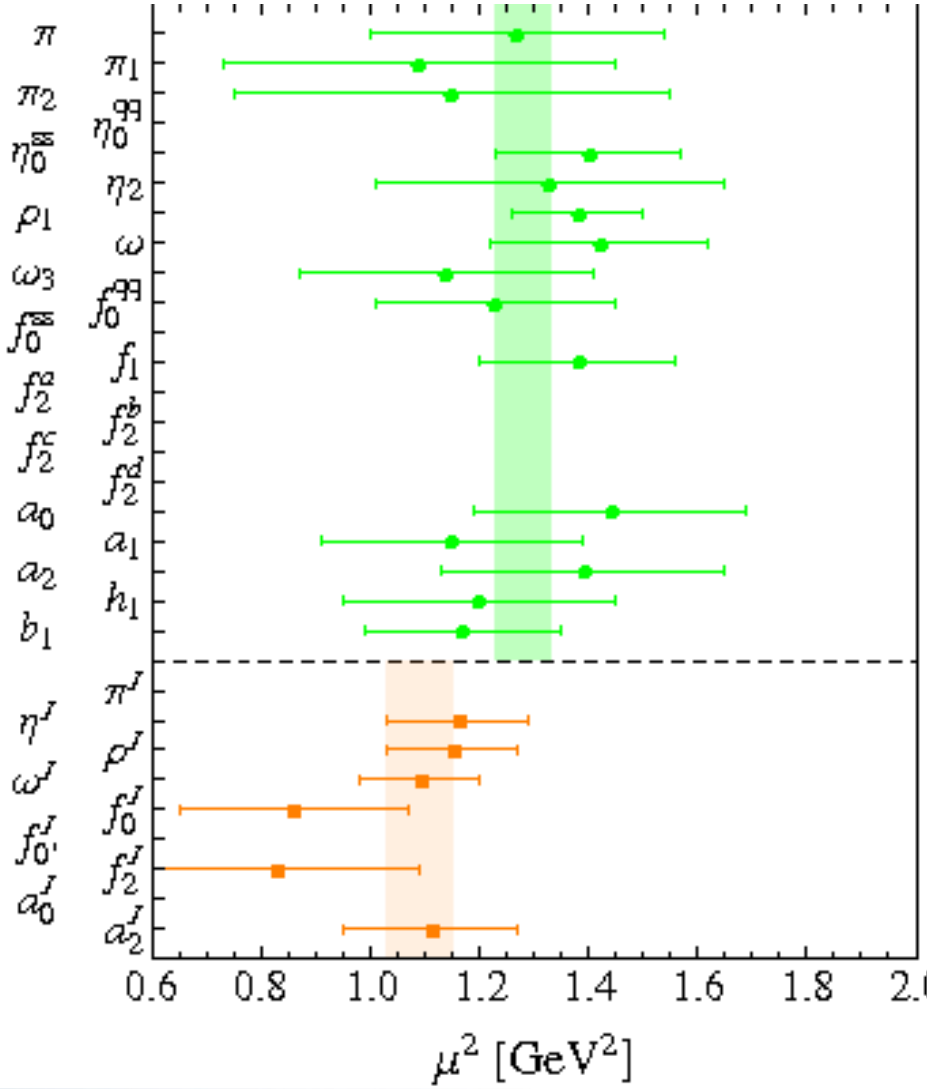
"Systematics of radial and angular-momentum Regge trajectories of light non-strange qqbar-states," Masjuan, Ruiz Arriola, Broniowski. arXiv:1305.3493 [hep-ph]

Empirically: Regge Trajectories

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

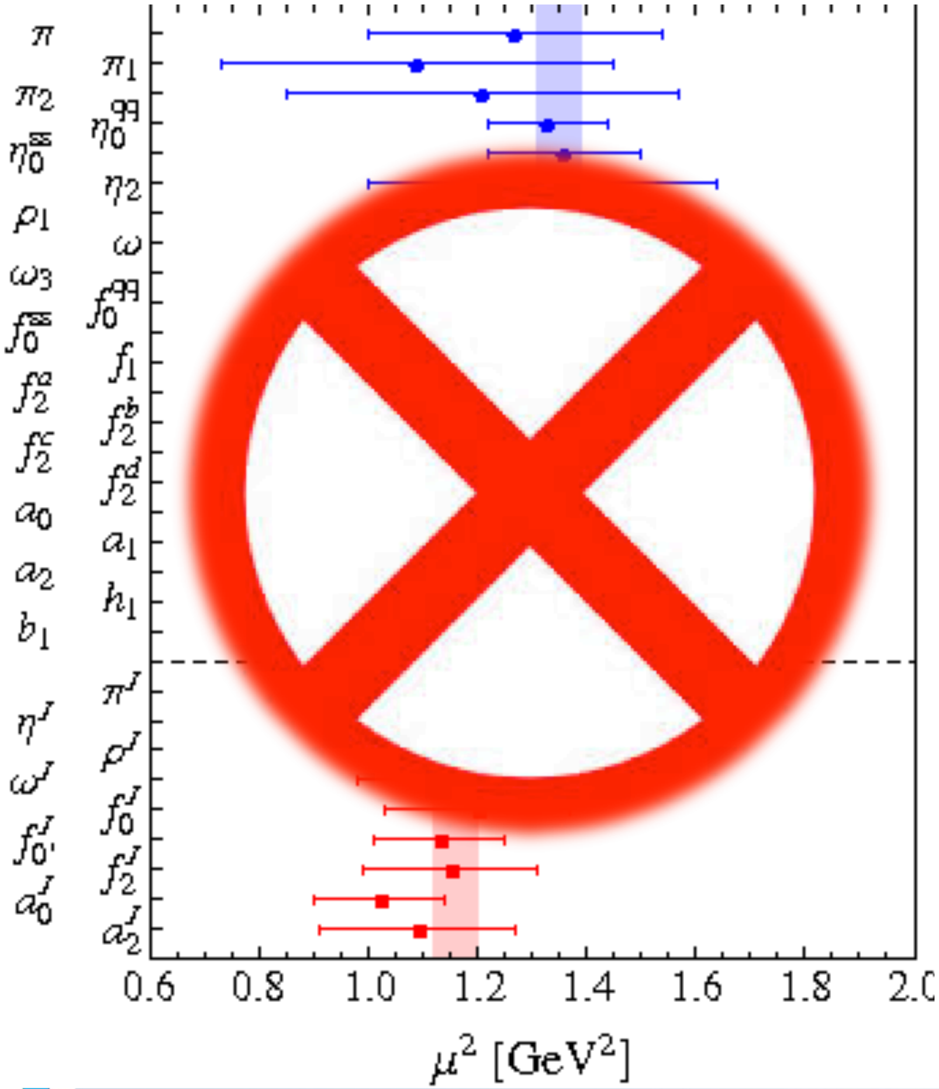


If all points take the same value, then $M^2 \propto J,n$ … Method 2

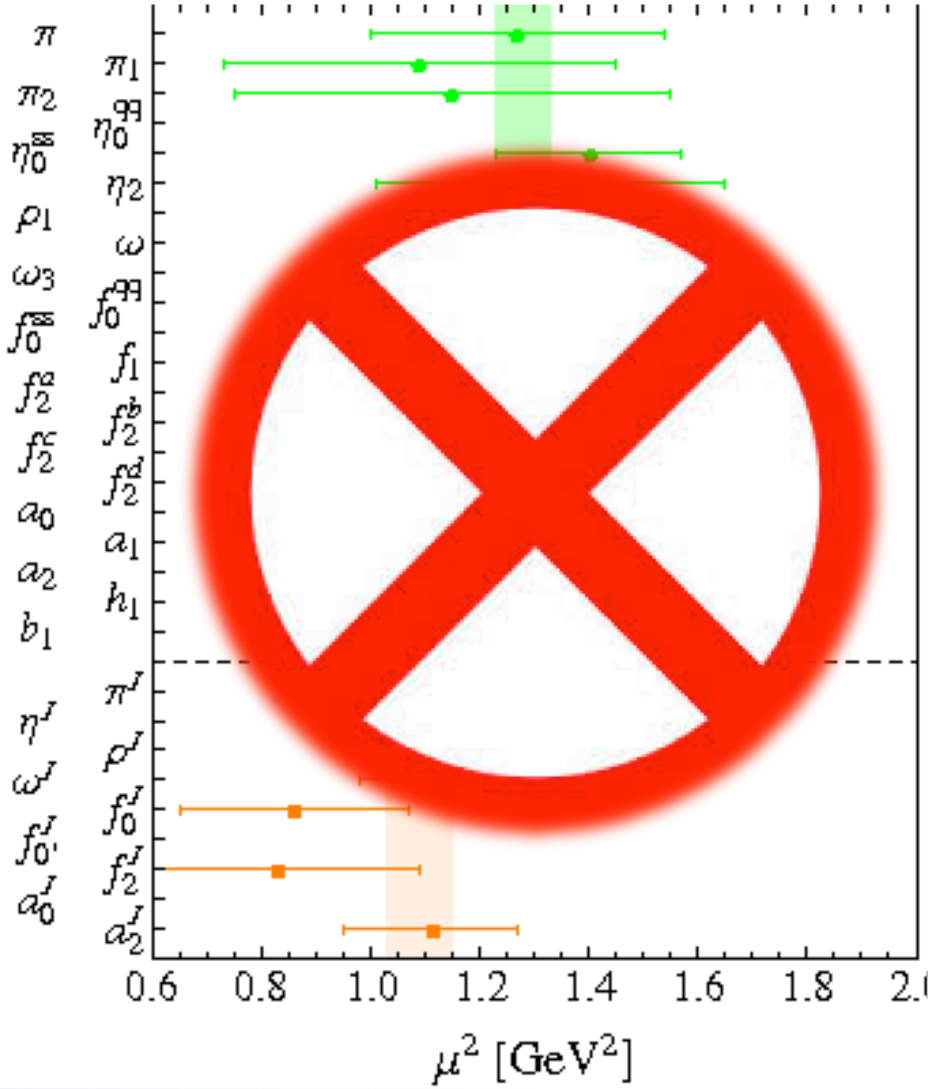


Empirically: Regge Trajectories

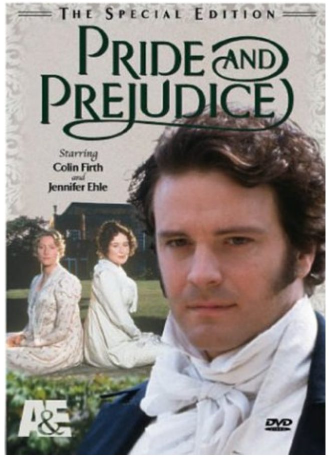
If all points take the same value, then $M^2 \propto J,n$ … Method 1



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



Dynamical Chiral Symmetry Breaking
Vacuum Condensates?



Universal *Conventions*

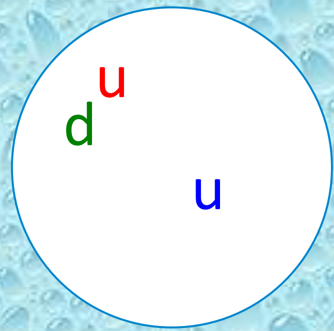
- Wikipedia: (http://en.wikipedia.org/wiki/QCD_vacuum)

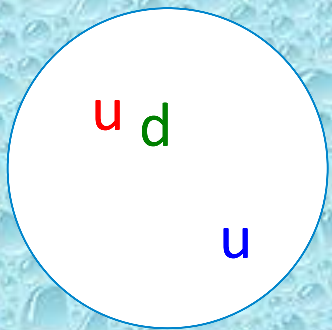
  "The QCD vacuum is the vacuum state of quantum chromodynamics (QCD). It is an example of a non-perturbative vacuum state, characterized by many non-vanishing condensates such as the gluon condensate or the quark condensate. These condensates characterize the normal phase or the confined phase of quark matter."

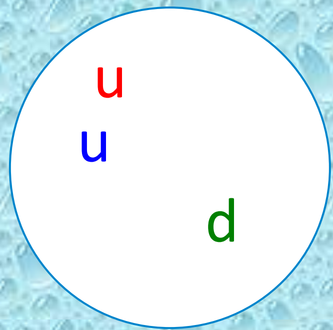
"Orthodox Vacuum"

- Vacuum = "frothing sea"
- Hadrons = bubbles in that "sea",

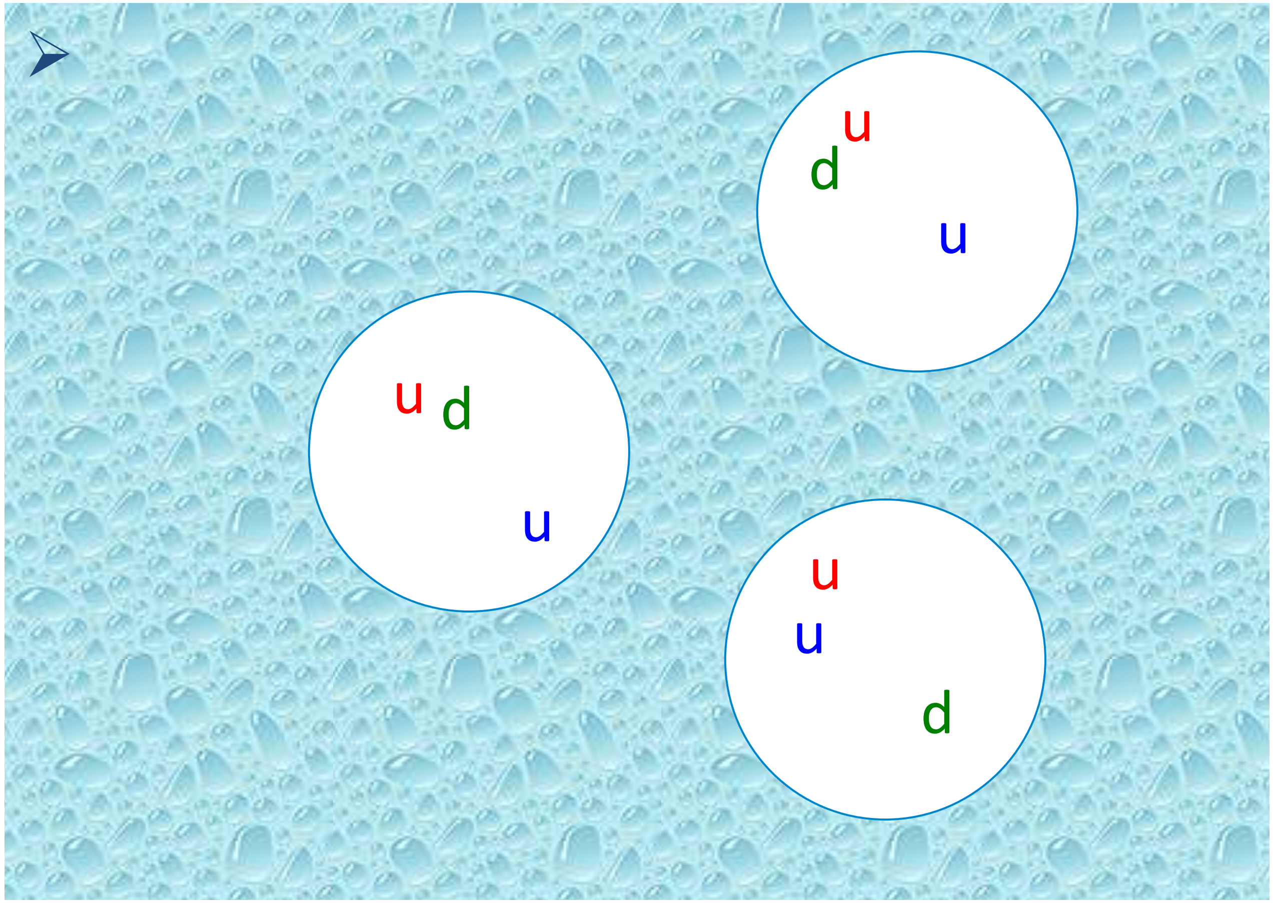
  containing nothing but quarks & gluons interacting perturbatively, unless they're near the bubble's boundary, whereat they feel they're trapped!





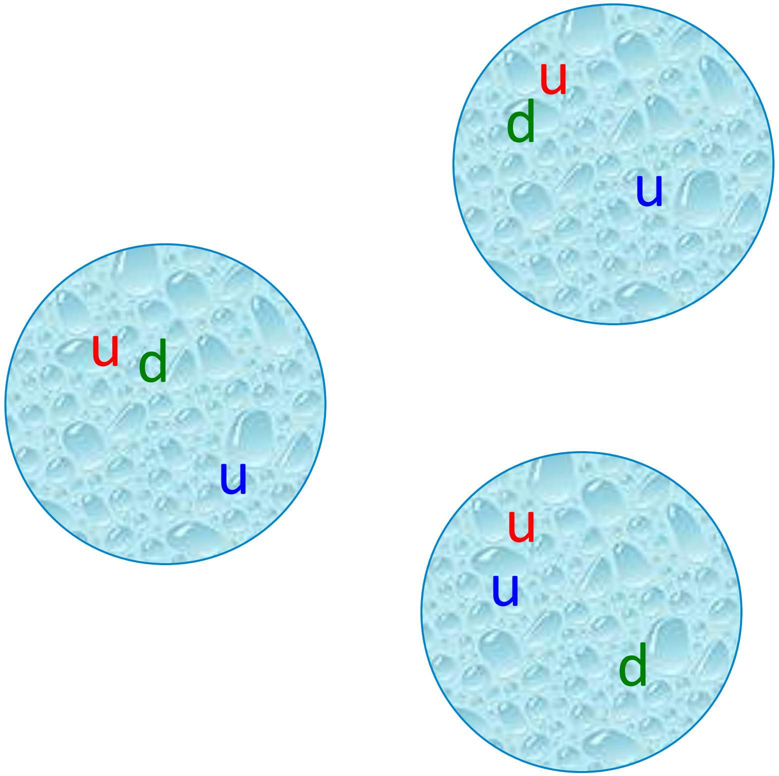


“Orthodox Vacuum”

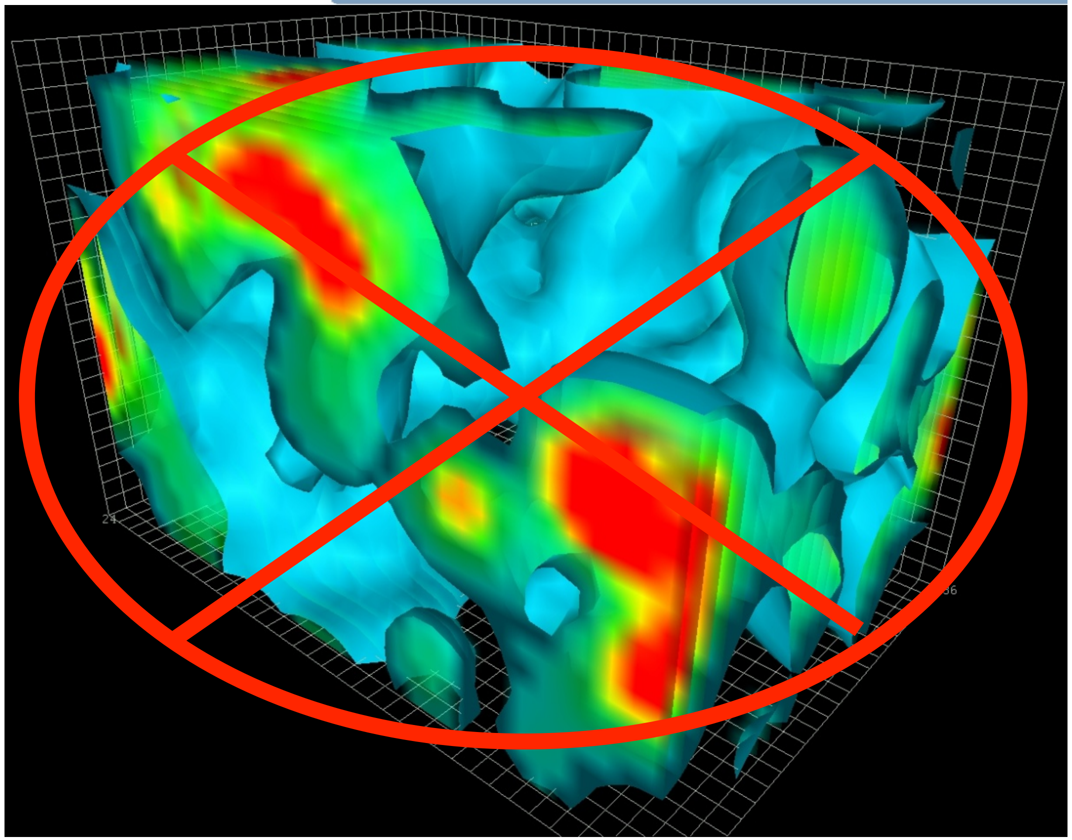


"Orthodox Vacuum"

➢



Historically, DCSB has come to be associated with the presumed existence of *spacetime-independent condensates* that *permeate the Universe*.



However, just like gluons and quarks, and for the same reasons:
Condensates are confined within hadrons.
There are *no* vacuum condensates.

PHYSICAL REVIEW C **85**, 065202 (2012)

Confinement contains condensates

Stanley J. Brodsky,[1,2] Craig D. Roberts,[3,4] Robert Shrock,[5] and Peter C. Tandy[6]

[1]*SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA*
[2]*Centre for Particle Physics Phenomenology: CP³-Origins, University of Southern Denmark, Odense 5230 M, Denmark*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616, USA*
[5]*C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[6]*Center for Nuclear Research, Department of Physics, Kent State University, Kent, Ohio 44242, USA*

(Received 27 February 2012; published 21 June 2012)

Dynamical chiral symmetry breaking and its connection to the generation of hadron masses has historically been viewed as a vacuum phenomenon. We argue that confinement makes such a position untenable. If quark-hadron duality is a reality in QCD, then condensates, those quantities that have commonly been viewed as constant empirical mass scales that fill all space-time, are instead wholly contained within hadrons; i.e., they are a property of hadrons themselves and expressed, e.g., in their Bethe-Salpeter or light-front wave functions. We explain that this paradigm is consistent with empirical evidence and incidentally expose misconceptions in a recent Comment.

DOI: 10.1103/PhysRevC.85.065202 PACS number(s): 12.38.Aw, 11.30.Rd, 11.15.Tk, 24.85.+p

Confinement contains condensates

PHYSICAL REVIEW VOLUME 175, NUMBER 5 25 NOVEMBER 1968

Behavior of Current Divergences under $SU_3 \times SU_3$*†

MURRAY GELL-MANN
California Institute of Technology, Pasadena, California 91109

AND

R. J. OAKES
Northwestern University, Evanston, Illinois 60201

AND

B. RENNER‡
California Institute of Technology, Pasadena, California 91109

(Received 22 July 1968)

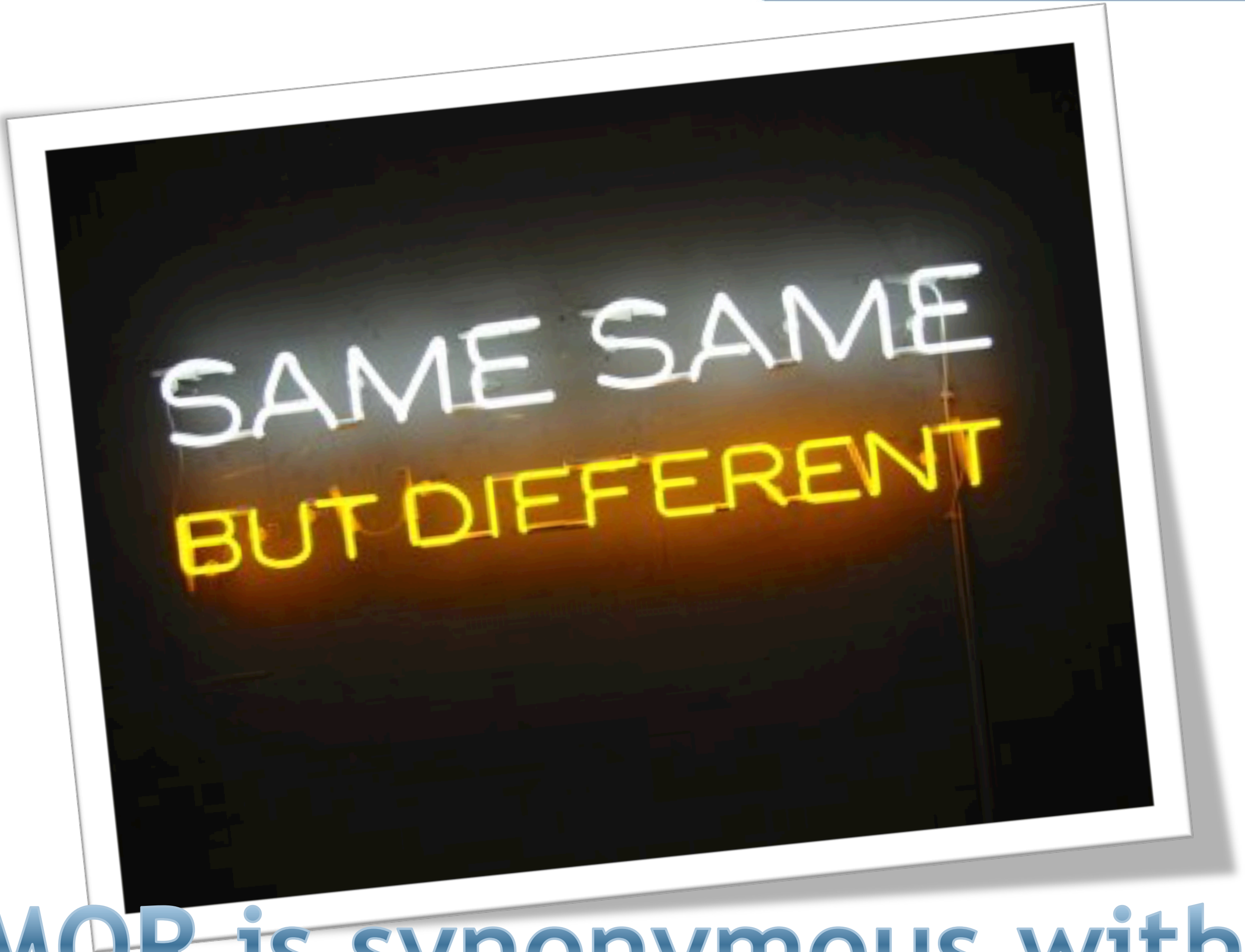
GMOR Relation

GMOR Relation

- Valuable to highlight the precise form of the Gell-Mann–Oakes–Renner (GMOR) relation: Eq. (3.4) in Phys.Rev. 175 (1968) 2195

$$m_\pi^2 = \lim_{P'\to P\to 0} \langle \pi(P') | \mathcal{H}_{\chi\mathrm{sb}} | \pi(P) \rangle$$

  - *m_π is the pion's mass*
  - *$H_{\chi sb}$ is that part of the* hadronic Hamiltonian density which explicitly breaks chiral symmetry.
- The operator expectation value in this equation is evaluated between pion states.
- Un-approximated form of the GMOR relation doesn't make any reference to a vacuum condensate



GMOR is synonymous with "Vacuum Quark Condensate"

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **85**, 012201(R) (2012)

Expanding the concept of in-hadron condensates

Lei Chang,[1] Craig D. Roberts,[1,2,3] and Peter C. Tandy[4]

[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

Department of Physics, Center for High Energy Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

[3] *Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616-3793, USA*

[4] *Center for Nuclear Research, Department of Physics, Kent State University, Kent, Ohio 44242, USA*

(Received 13 September 2011; published 23 January 2012)

The in-pseudoscalar-meson condensate can be represented through the pseudoscalar meson's scalar form factor at zero-momentum transfer. With the aid of a mass formula for scalar mesons, revealed herein, the analog is shown to be true for in-scalar-meson condensates. The concept is readily extended to all hadrons so that, via the zero-momentum-transfer value of any hadron's scalar form factor, one can readily extract the value for a quark condensate in that hadron which is a measure of dynamical chiral symmetry breaking.

DOI: 10.1103/PhysRevC.85.012201 PACS number(s): 12.38.Aw, 11.30.Rd, 11.15.Tk, 24.85.+p

Concept of in-hadron condensates

Gell-Mann Oakes Renner Relation

- Demonstrated algebraically that the so-called Gell-Mann – Oakes – Renner relation is the following statement

$$\forall m_{ud} \sim 0\,,\; m_{\pi^\pm}^2 = m_{ud}^\zeta\, \mathcal{S}_\pi^\zeta(0)\,,$$
$$\mathcal{S}_\pi^\zeta(0) = -\langle \pi(P)| \tfrac{1}{2}(\bar{u}u + \bar{d}d)|\pi(P)\rangle$$

Namely, the mass of the pion is completely determined by the pion's scalar form factor at zero momentum transfer $Q^2 = 0$.

viz., by ***the pion's scalar charge***

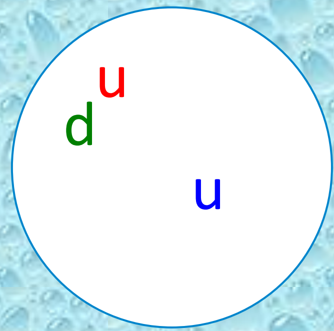
Hadron Charges

$$\langle H(p')|\bar{q}\mathcal{O}q|H(p)\rangle$$

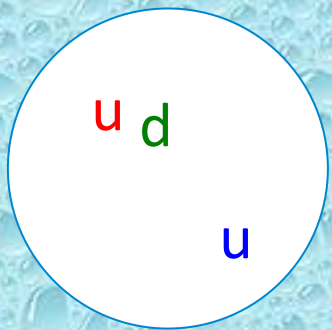
- Matrix elements associated with hadron form factors
- *Scalar charge of a hadron is an intrinsic property of that hadron … no more a property of the vacuum than the hadron's electric charge, axial charge, tensor charge, etc. …*

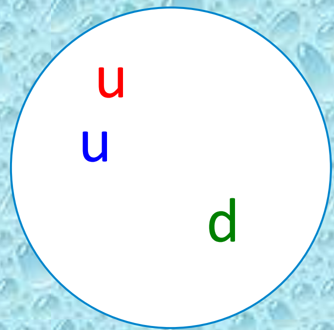
“Orthodox Vacuum”

- Vacuum = “frothing sea”
- Hadrons = bubbles in that “sea”,



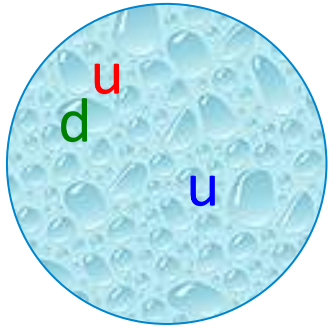
containing nothing but quarks & gluons interacting perturbatively, unless they’re near the bubble’s boundary, whereat they feel they’re trapped!

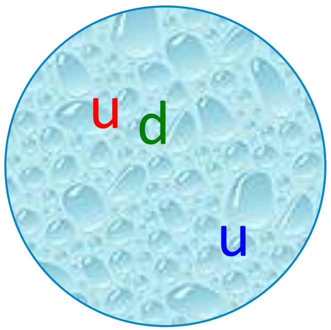


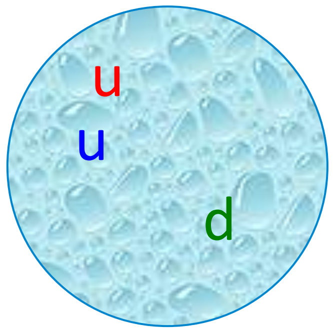


New Paradigm

- Vacuum = perturbative hadronic fluctuations
  but no nonperturbative condensates
- Hadrons = complex, interacting systems
  within which perturbative behaviour is
  restricted to just 2% of the interior







Paradigm shift:
In-Hadron Condensates

"Void that is truly empty solves dark energy puzzle"
Rachel Courtland, New Scientist 4th Sept. 2010

"The biggest embarrassment in theoretical physics."

"EMPTY space may really be empty. Though quantum theory suggests that a vacuum should be fizzing with particle activity, it turns out that this paradoxical picture of nothingness may not be needed. A calmer view of the vacuum would also help resolve a nagging inconsistency with dark energy, the elusive force thought to be speeding up the expansion of the universe."

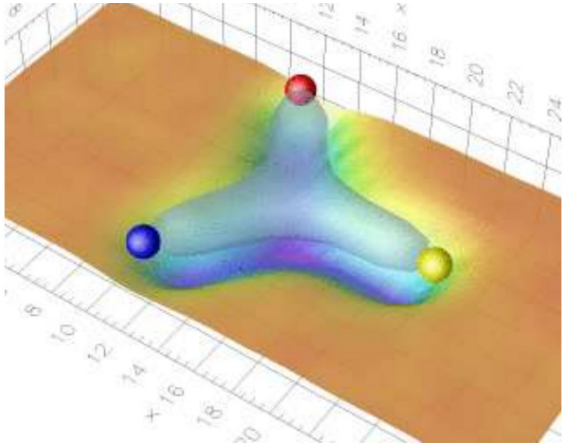
$$\Omega_{QCD-condensates} = 8\pi G_N \frac{\Lambda_{QCD}^4}{3H_0^2} \cong 10^{46} * \text{experiment}$$

Cosmological Constant:

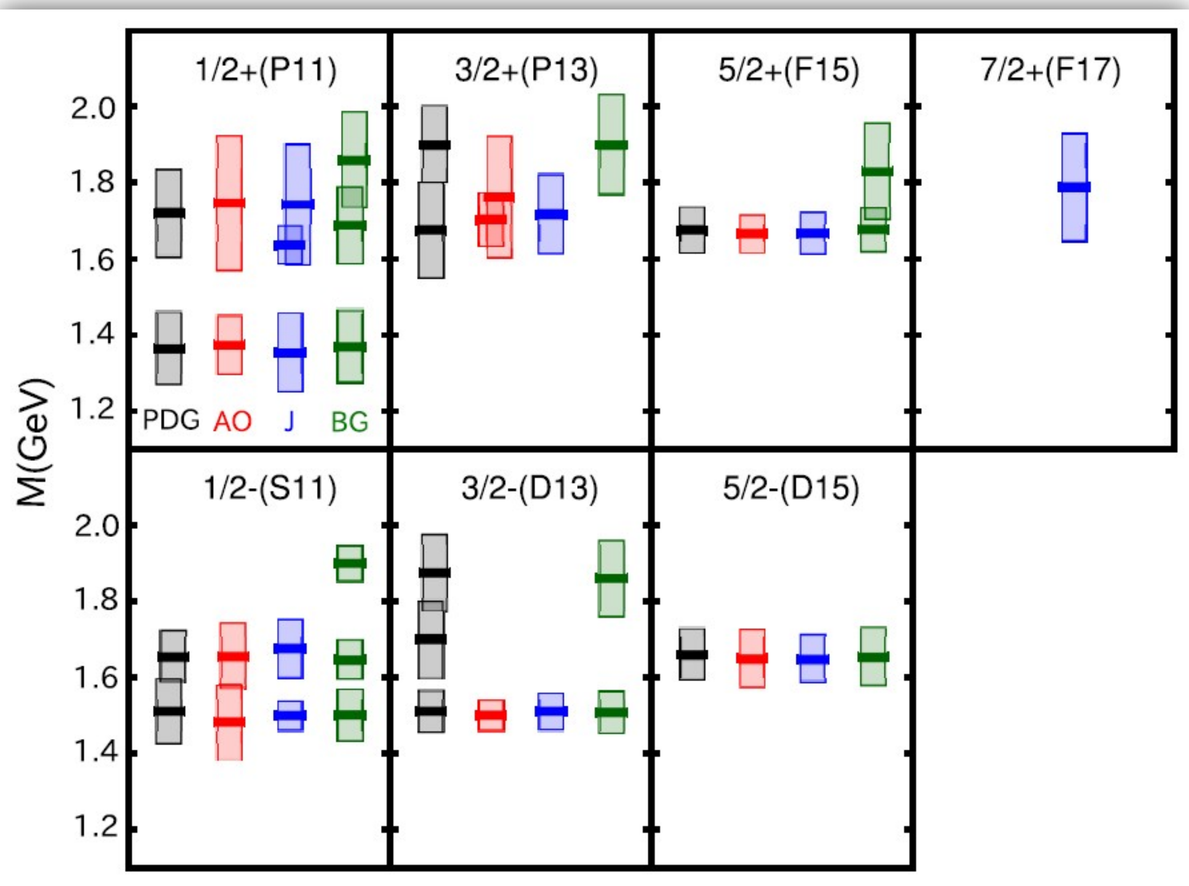
- ✓ ***Putting QCD condensates back into hadrons reduces the mismatch between experiment and theory by a factor of 10^{46}***
- ✓ ***Possibly by far more, if technicolour-like theories are the correct paradigm for extending the Standard Model***

Proton

- Numerical simulations of lattice-regularised QCD (lQCD) that use static (infinitely heavy) sources to represent the proton's valence-quarks produce a ``Y-junction'' flux-tube picture of nucleon structure
- This 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 notions would suggest an existential role for the dressed three-gluon vertex in nucleon structure if they were equally valid in real-world QCD wherein light dynamical quarks are ubiquitous.
- *However, as we have seen, they are not; and so a different explanation of binding within the nucleon must be found*



Faddeev Equation Spectrum

arXiv:1204.2553 [nucl-th], *Spectrum of hadrons with strangeness,* Chen Chen, L. Chang, C.D. Roberts, Shaolong Wan and D.J. Wilson

Bethe-Salpeter amplitudes

- Bethe-Salpeter amplitudes are couplings in Faddeev Equation

Table 3 The structure of meson Bethe-Salpeter amplitudes is described in Sect. 2.2.1 and App. B. Here we list the canonically normalised amplitude associated with each of the BSE eigenstates in Table 2. Only pseudoscalar mesons involve two independent amplitudes when a vector×vector contact interaction is treated systematically in rainbow-ladder truncation.

		m_π	m_K	m_ρ	m_{K^*}	m_ϕ	m_σ	m_κ	m_{a_1}	m_{K_1}	m_{f_1}
n=0	$E_{q\bar q}$	3.60	3.86	1.53	1.62	1.74	0.47	0.47	0.31	0.31	0.31
	$F_{q\bar q}$	0.48	0.60								
n=1	$E_{q\bar q}$	0.83	0.76	0.72	0.70	0.66	0.34	0.35	0.28	0.28	0.28
	$F_{q\bar q}$	0.05	1.18								

- Magnitudes for diquarks follow precisely the meson pattern

Table 5 The structure of diquark Bethe-Salpeter amplitudes is described in Sect. 2.2.2 and App. B. Here we list all canonically normalised amplitudes that are relevant to the baryons we consider. Only scalar diquarks involve two independent amplitudes.

	$[u,d]_{0^+}$	$[s,u]_{0^+}$	$\{u,u\}_{1^+}$	$\{s,u\}_{1^+}$	$\{s,s\}_{1^+}$	$[u,d]_{0^-}$	$[s,u]_{0^-}$	$\{u,u\}_{1^-}$	$\{s,u\}_{1^-}$	$\{s,s\}_{1^-}$
E_{qq}	2.74	2.91	1.30	1.36	1.42	0.40	0.39	0.27	0.27	0.26
F_{qq}	0.31	0.40								

Owing to DCSB, FE couplings in ½⁻ channels are 25-times weaker than in ½⁺ !

arXiv:1204.2553 [nucl-th], *Spectrum of hadrons with strangeness*, Chen Chen, L. Chang, C.D. Roberts, Shaolong Wan and D.J. Wilson

Spectrum of Hadrons with Strangeness

- Solved all Faddeev equations, obtained masses and eigenvectors of the octet and decuplet baryons.

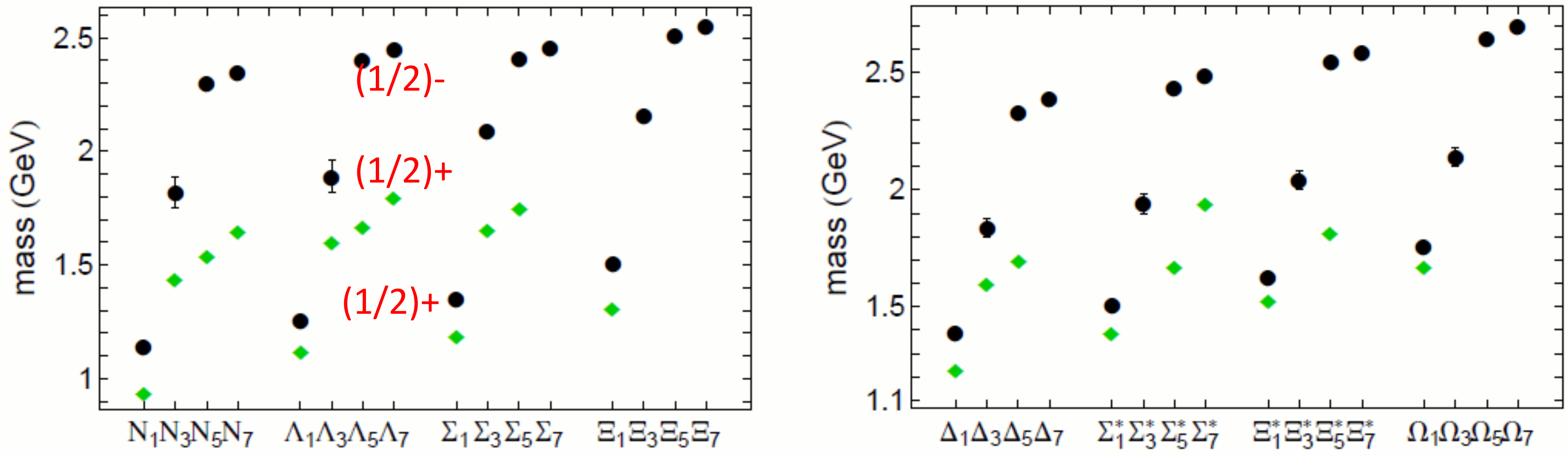


Fig. 4 Left panel: Pictorial representation of octet masses in Table 6. *Circles* – computed masses; and *diamonds* – empirical masses. On the horizontal axis we list a particle name with a subscript that indicates its row in the table; e.g., N_1 means nucleon column, row 1. In this way the labels step through ground-state, radial excitation, parity partner, parity partner's radial excitation. Right panel: Analogous plot for the decuplet masses in Table 6.

arXiv:1204.2553 [nucl-th], *Spectrum of hadrons with strangeness,* Chen Chen, L. Chang, C.D. Roberts, Shaolong Wan and D.J. Wilson

Spectrum of Hadrons with Strangeness

- Solved all Faddeev equations, obtained masses and eigenvectors of the octet and decuplet baryons.

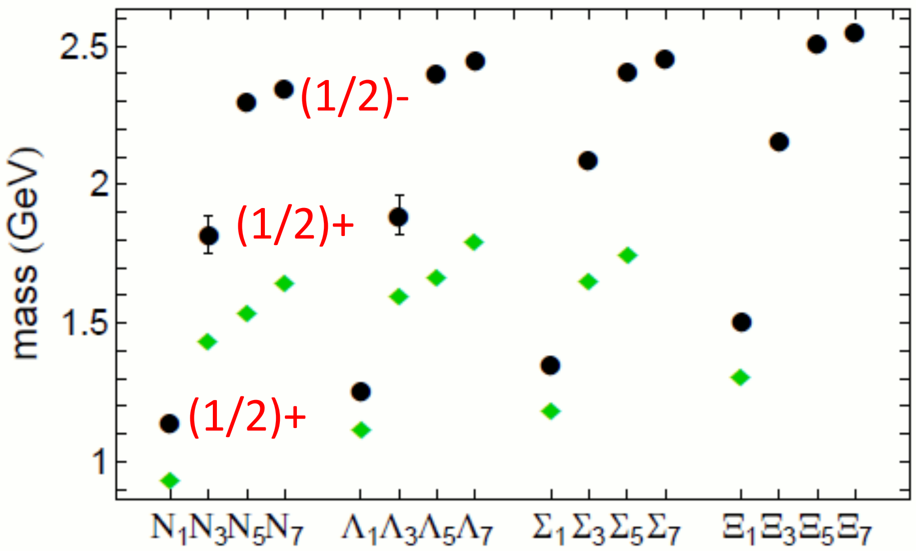


Fig. 4 Left panel: Pictorial representation of octet *diamonds* – empirical masses. On the horizontal axis its row in the table; e.g., N_1 means nucleon column, r radial excitation, parity partner, parity partner's radial masses in Table 6.

- This level ordering has long been a problem in CQMs with linear or HO confinement potentials
- *Correct ordering owes to DCSB*
    - *Positive parity diquarks have Faddeev equation couplings 25-times greater than negative parity diquarks*
- Explains why approaches within which DCSB cannot be realised (CQMs) or simulations whose parameters suppress DCSB will both have difficulty reproducing experimental ordering

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]

Quark core masses

- Argonne Osaka DCC model: Preliminary attempt to identify quark-core mass by isolating and removing meson-cloud contribution
- Semi-quantitative agreement: Cloud-subtracted masses

  ≈ DSE dressed-quark core masses
- Level ordering is particularly interesting:

  Cloud-substracted & DSE core masses agree on

  ½⁺ … ½⁺ … ½⁻

  Level ordering for core masses;

  Evidently, adding cloud does not change ordering

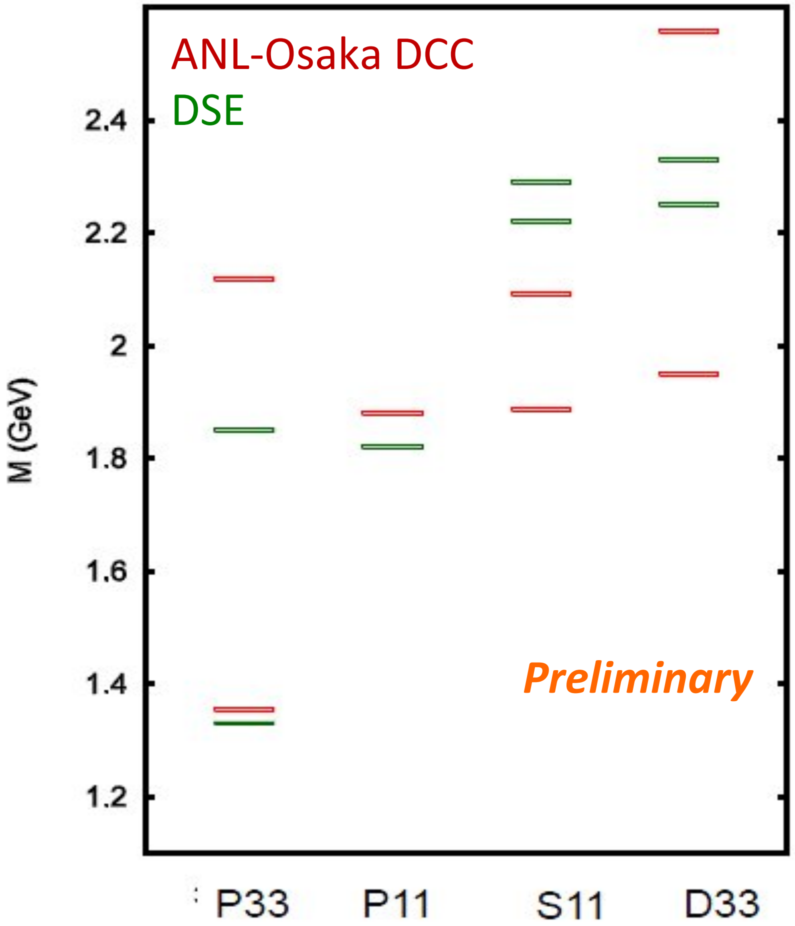


Image courtesy of T. Sato, H. Kamano, S. Nakamura and T.-S. H. Lee

Contents