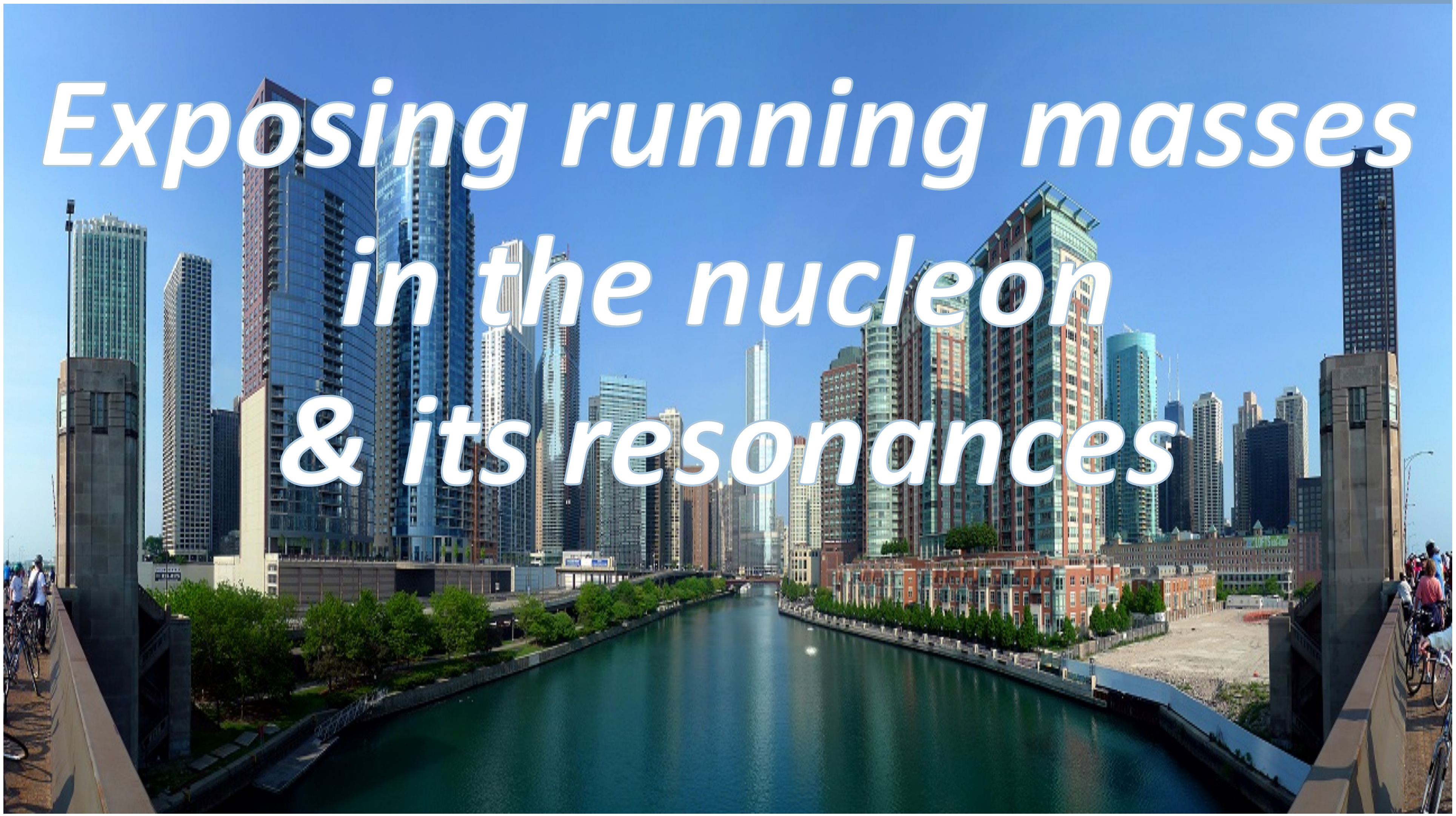
Argonne NATIONAL LABORATORY

Exposing running masses in the nucleon & its resonances



Craig Roberts, Physics Division

U.S. DEPARTMENT OF ENERGY

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Overarching Science Challenge for the coming decade

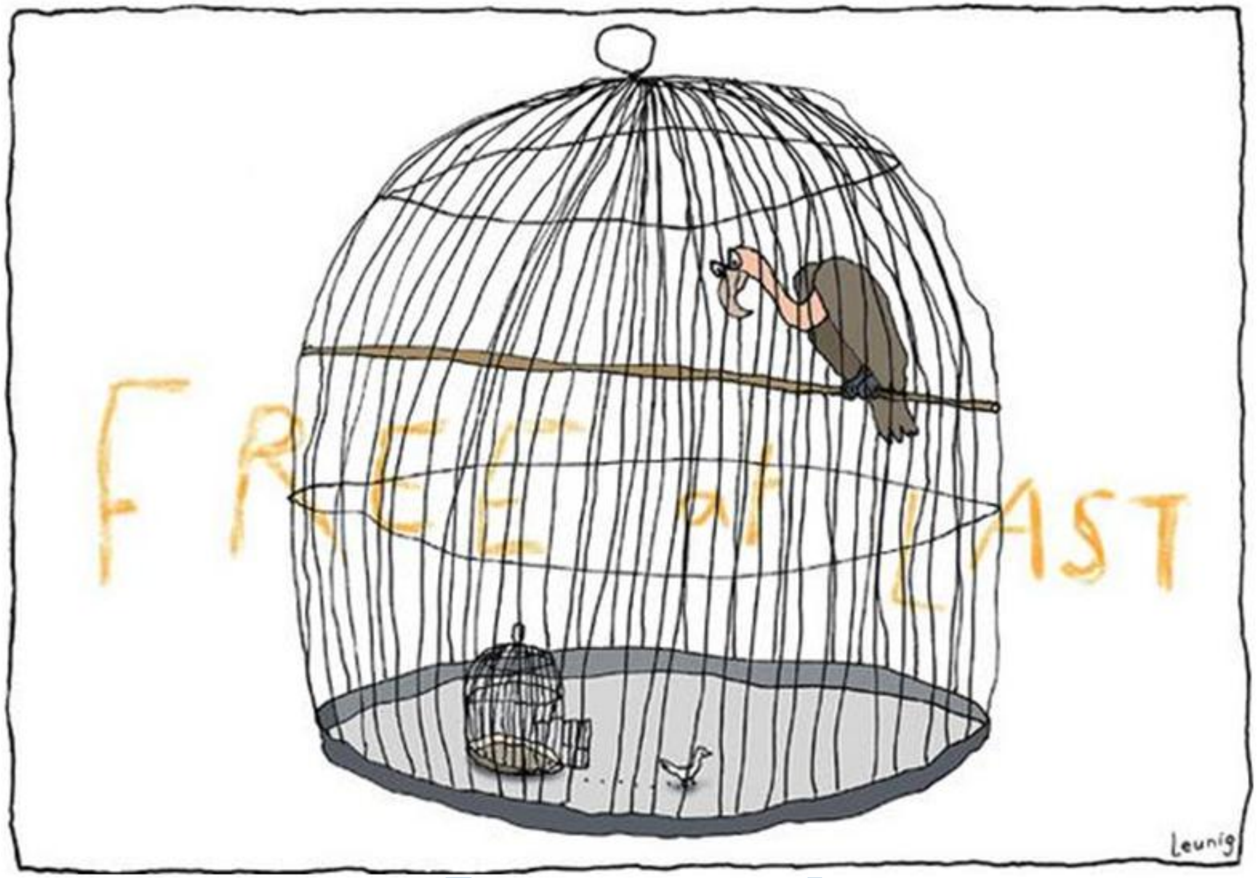
Discover meaning of confinement, its relationship to DCSB – the Origin of Visible Mass – and the connection between them

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?

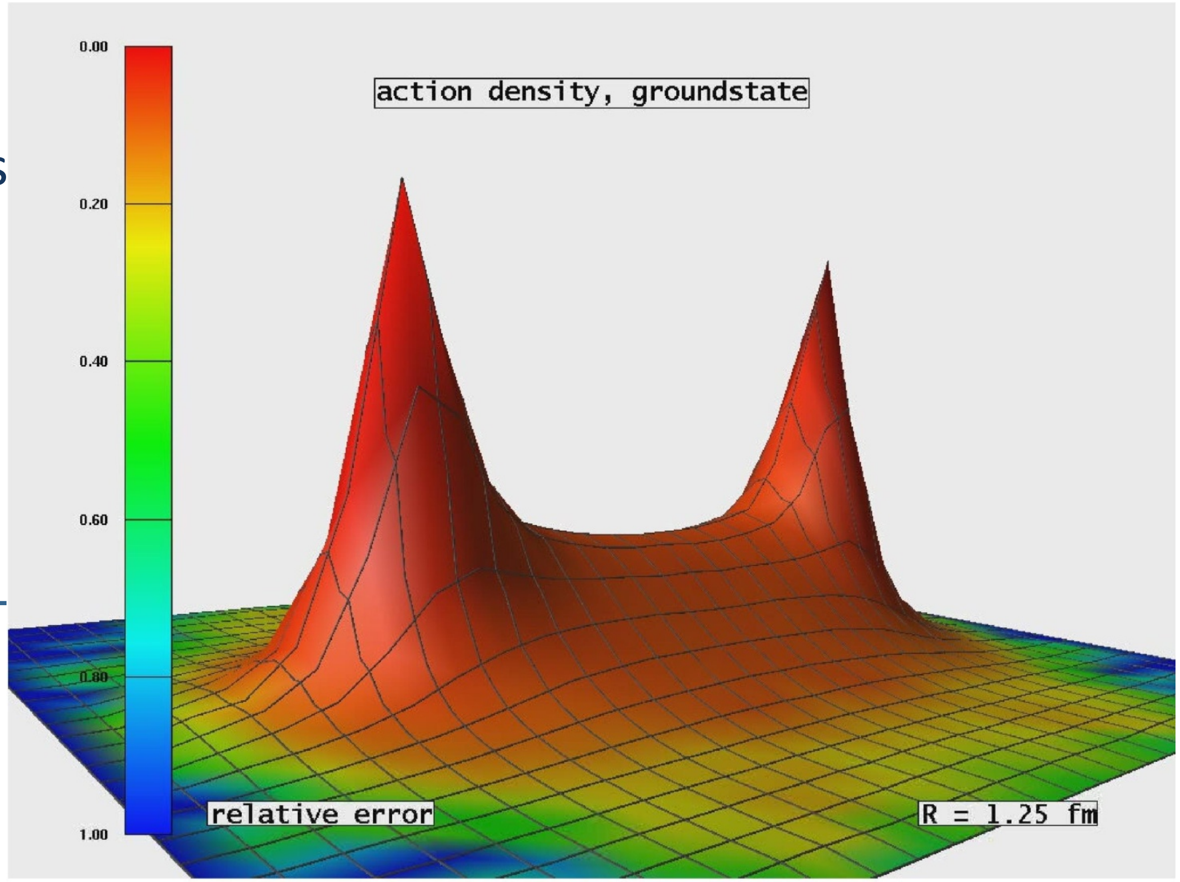
Light quarks & Confinement

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

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

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

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



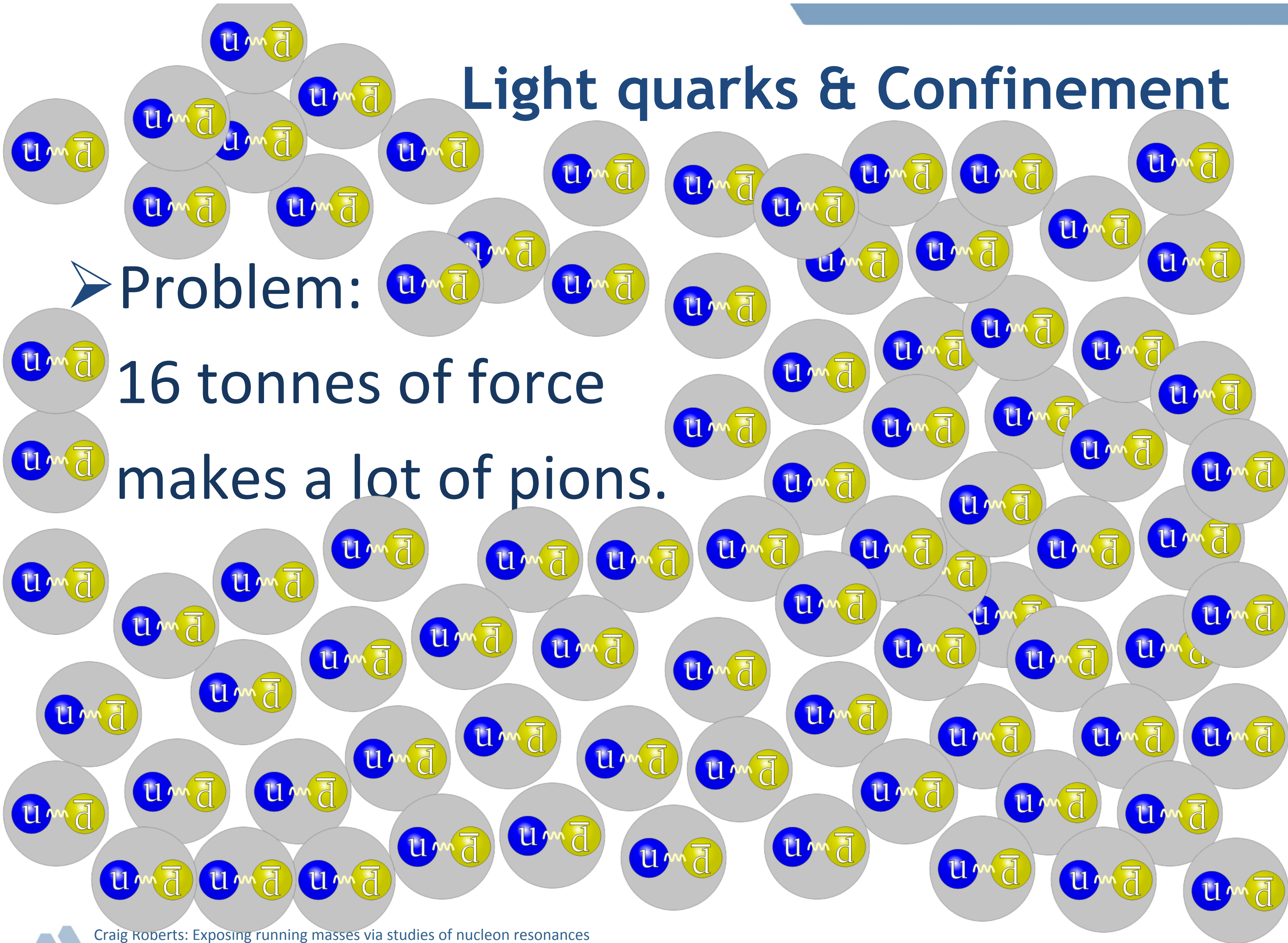
Light quarks & Confinement

- Problem:

  16 tonnes of force

  makes a lot of pions.

Light quarks & Confinement



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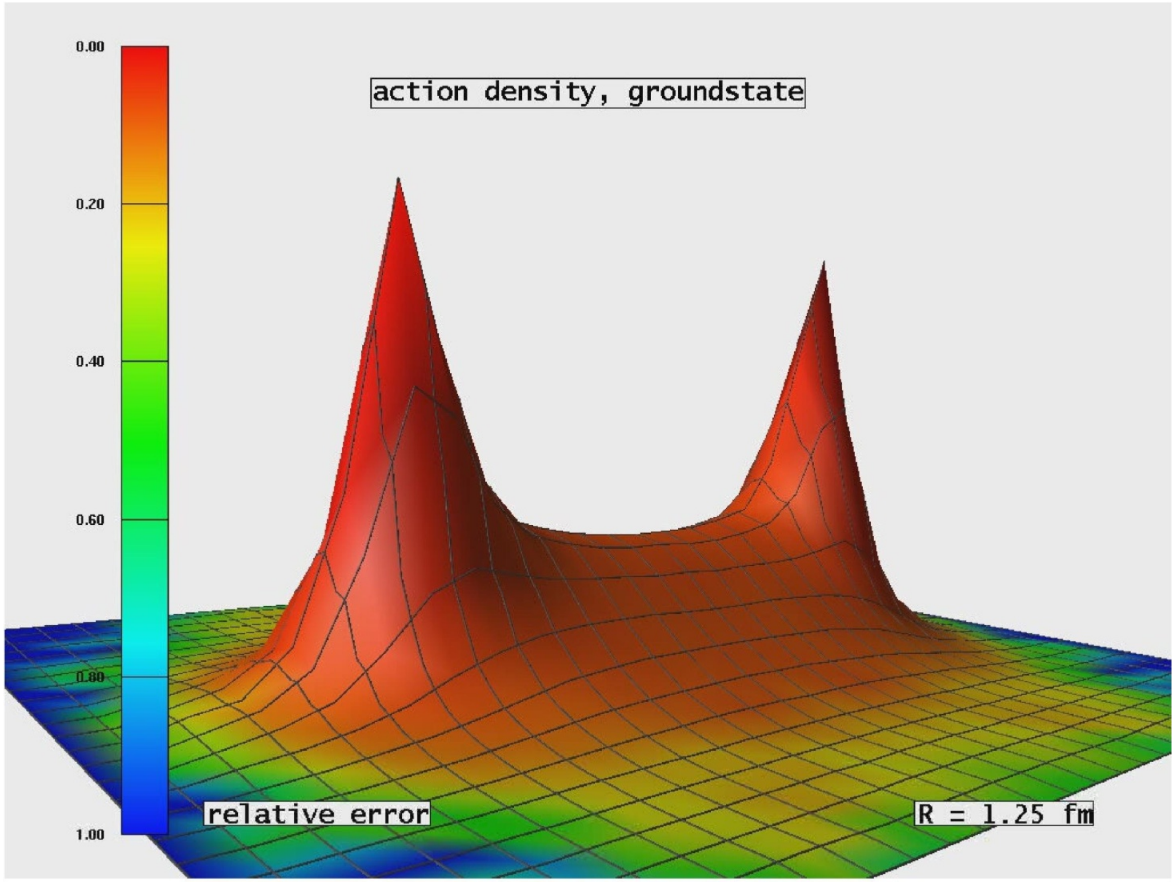
G. *Bali* et al., [*PoS LAT2005 (2006) 308*]

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***



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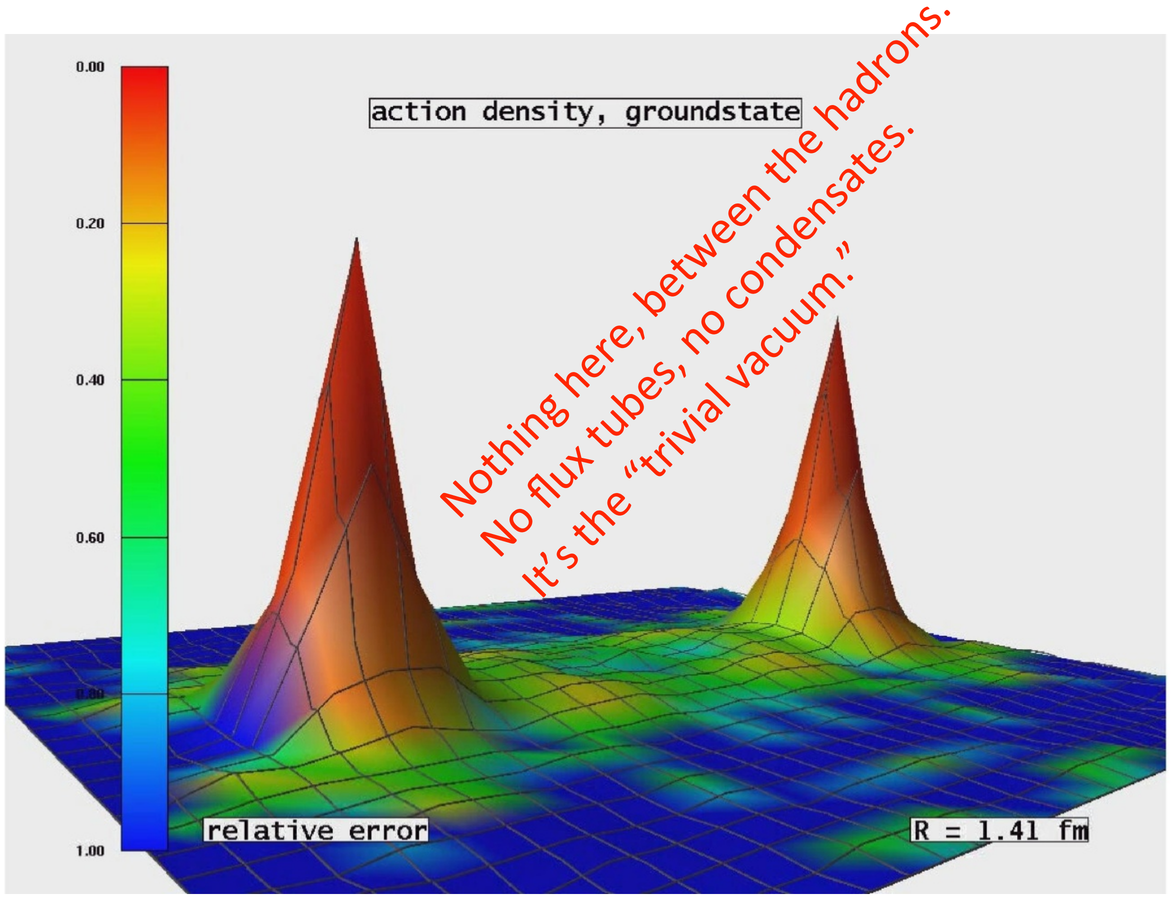
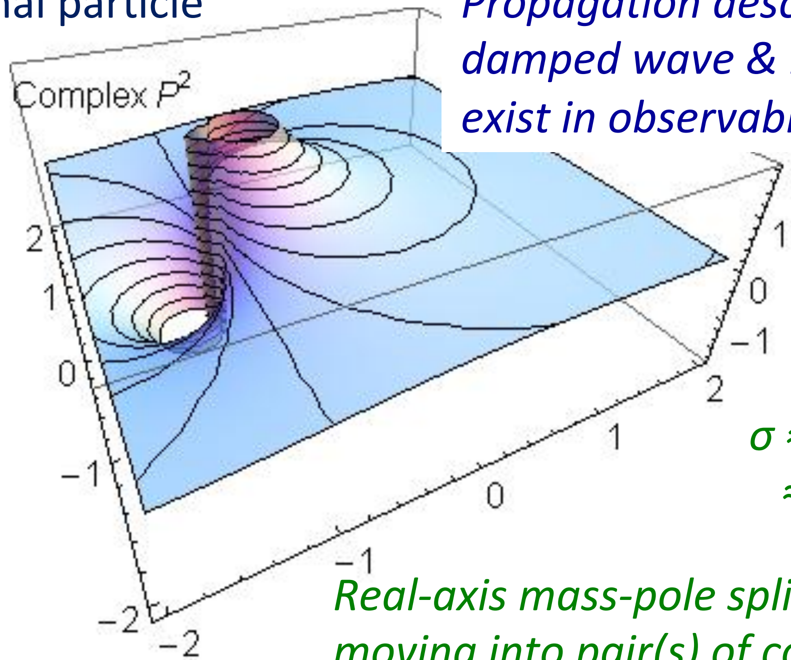


Confinement

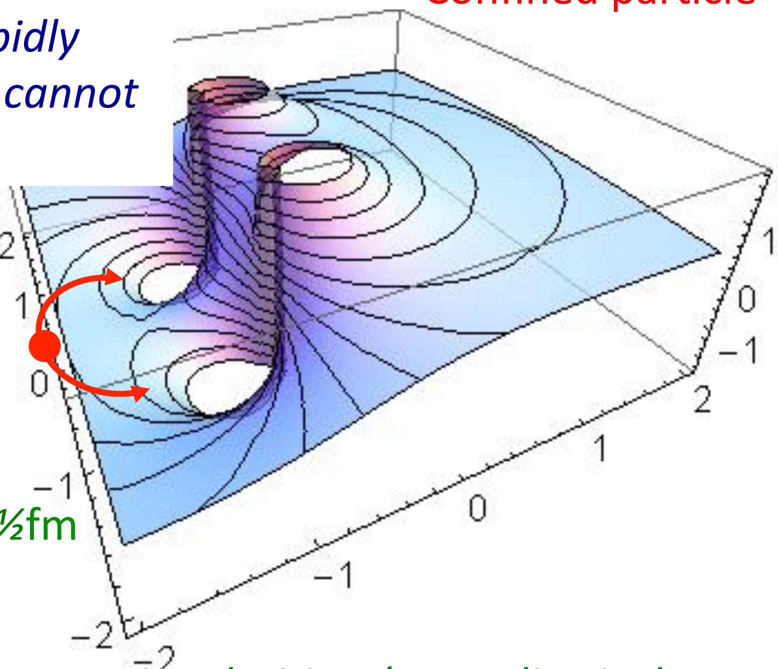
- QFT Paradigm:
  - Confinement is expressed through a *dramatic* change in the analytic structure of propagators for coloured states
  - It can be read from a plot of the dressed-propagator for a coloured state

Normal particle



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

Confined particle

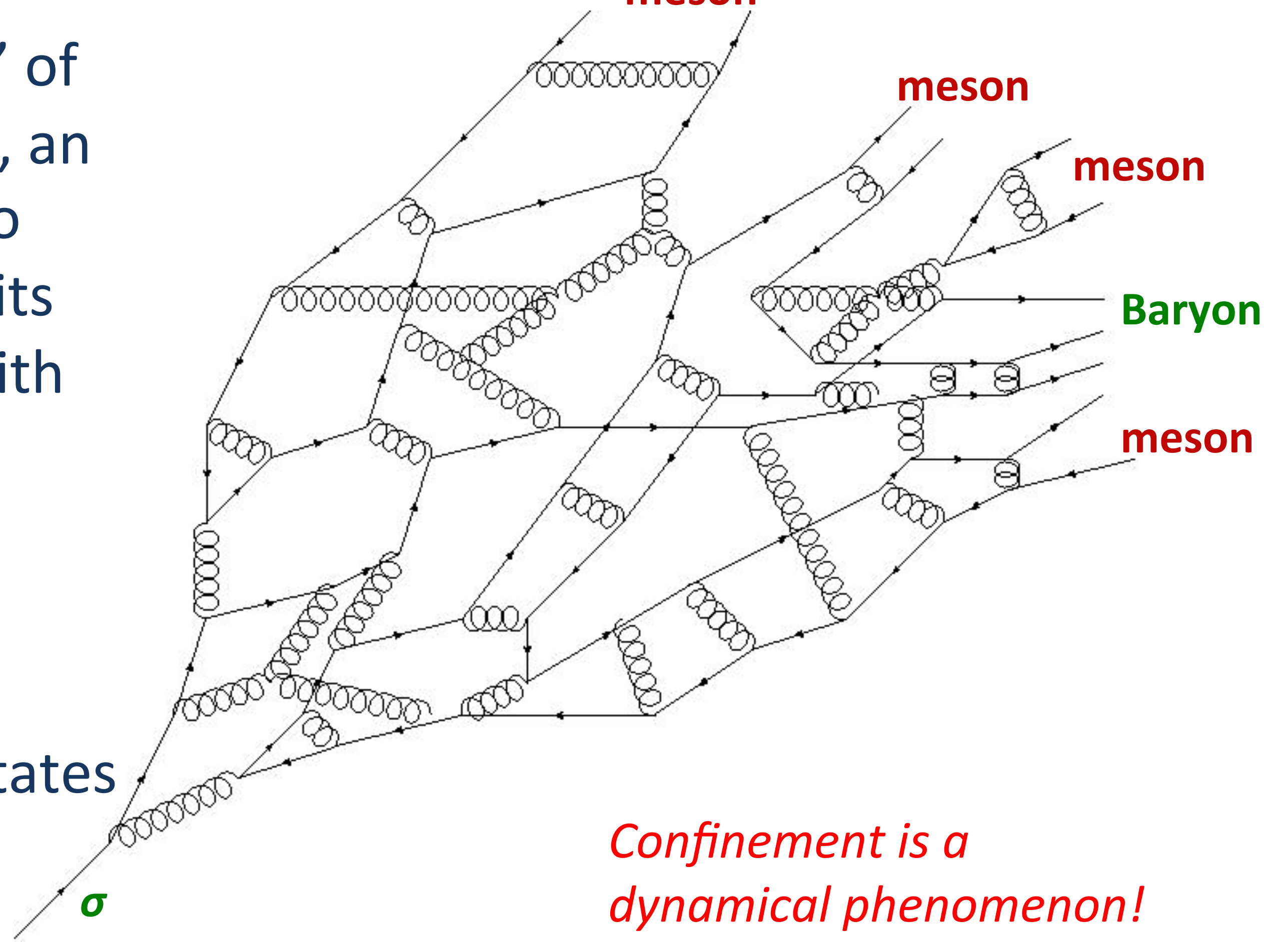


$\sigma \approx 1/Im(m)$
$\approx 1/2\Lambda_{QCD} \approx$ ½fm

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

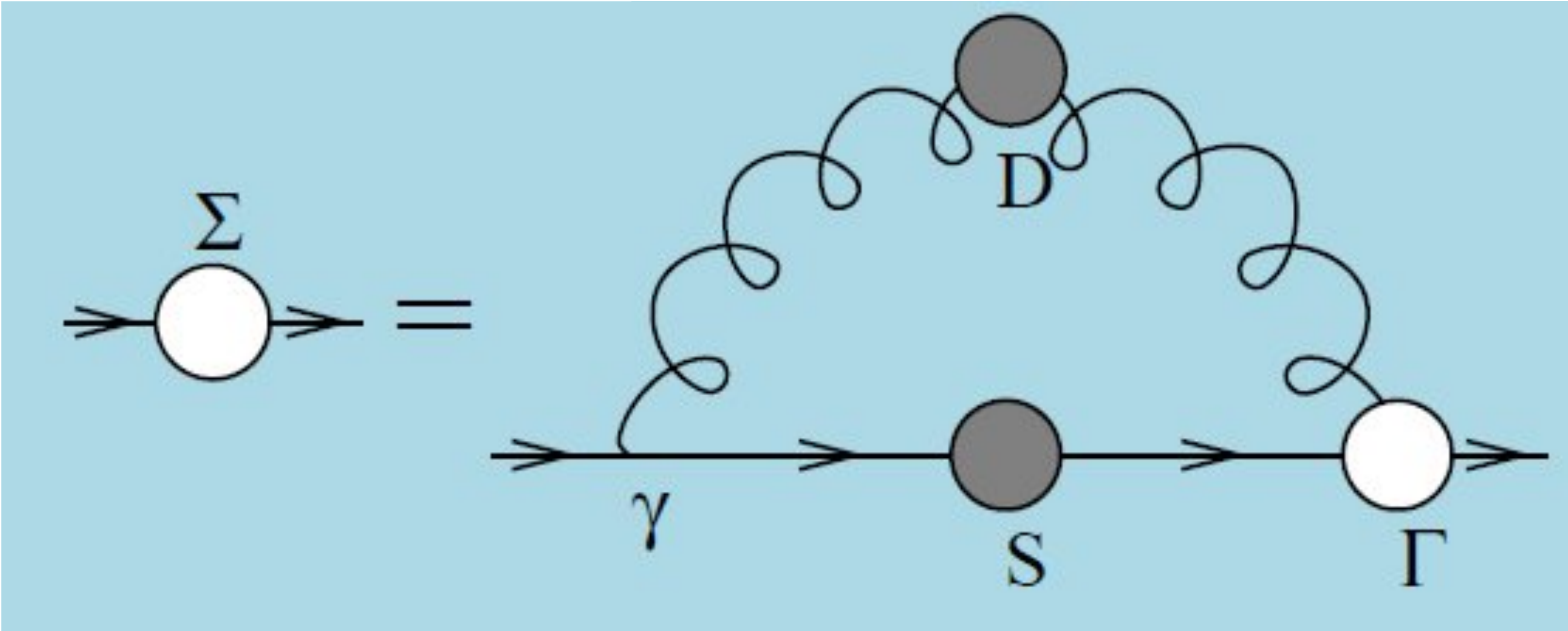
Quark Fragmentation

- 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

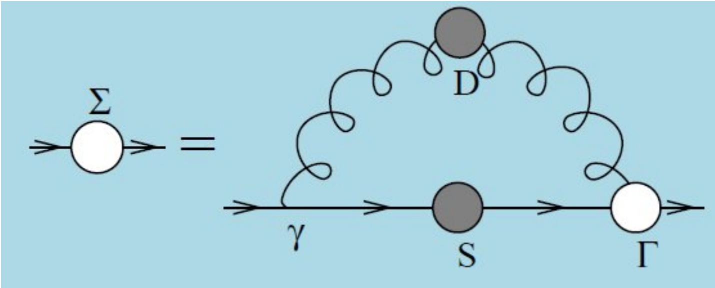


Confinement is a dynamical phenomenon!

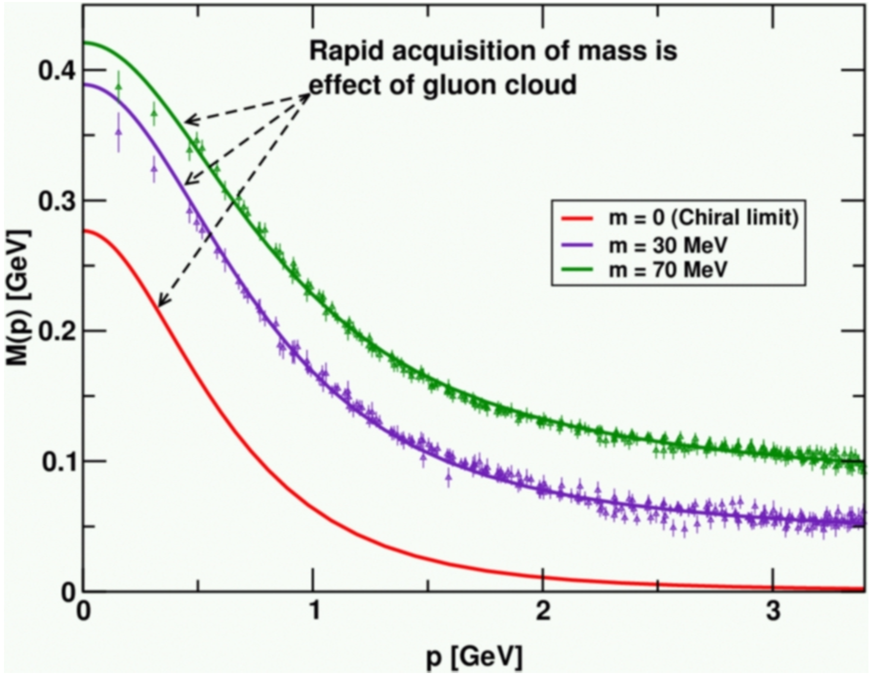
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



Quark Gap Equation



Dynamical Chiral Symmetry Breaking



- ***DCSB is a fact in QCD***
  - ***Dynamical***, not spontaneous
    - Add nothing to *QCD* ,

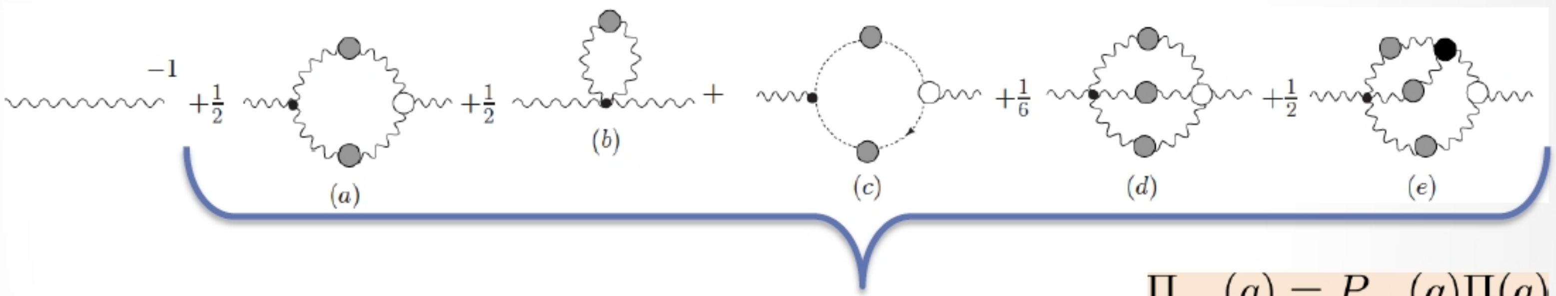
      No Higgs field, nothing!

      Effect achieved purely through quark+gluon dynamics.
  - It's the most important mass generating mechanism for visible matter in the Universe.
    - Responsible for ≈98% of the proton's mass.
    - Higgs mechanism is (*almost*) irrelevant to light-quarks.

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!

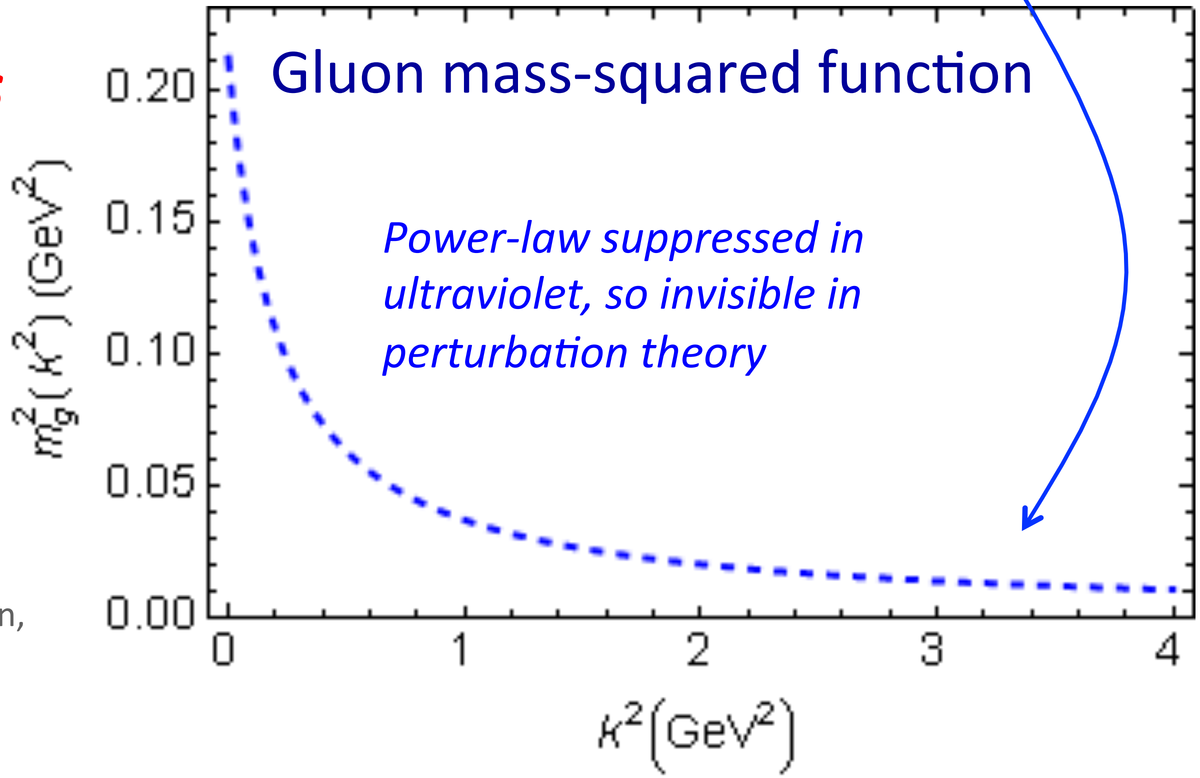
- Running gluon mass

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

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

- 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

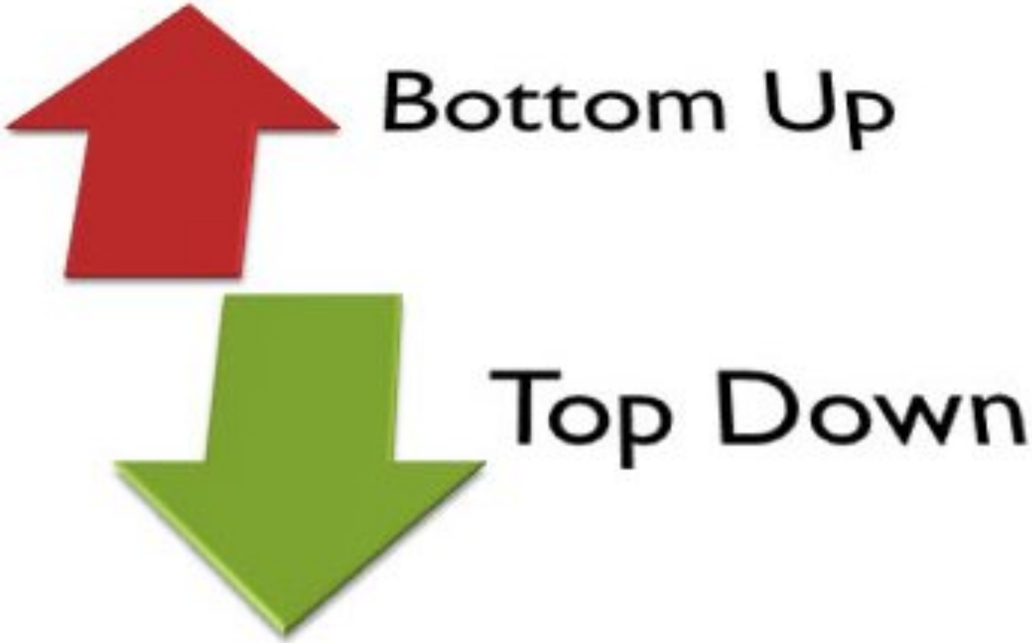
- Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
  - Gluons and quarks with

    wavelength $\lambda > 2$/mass ≈ 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

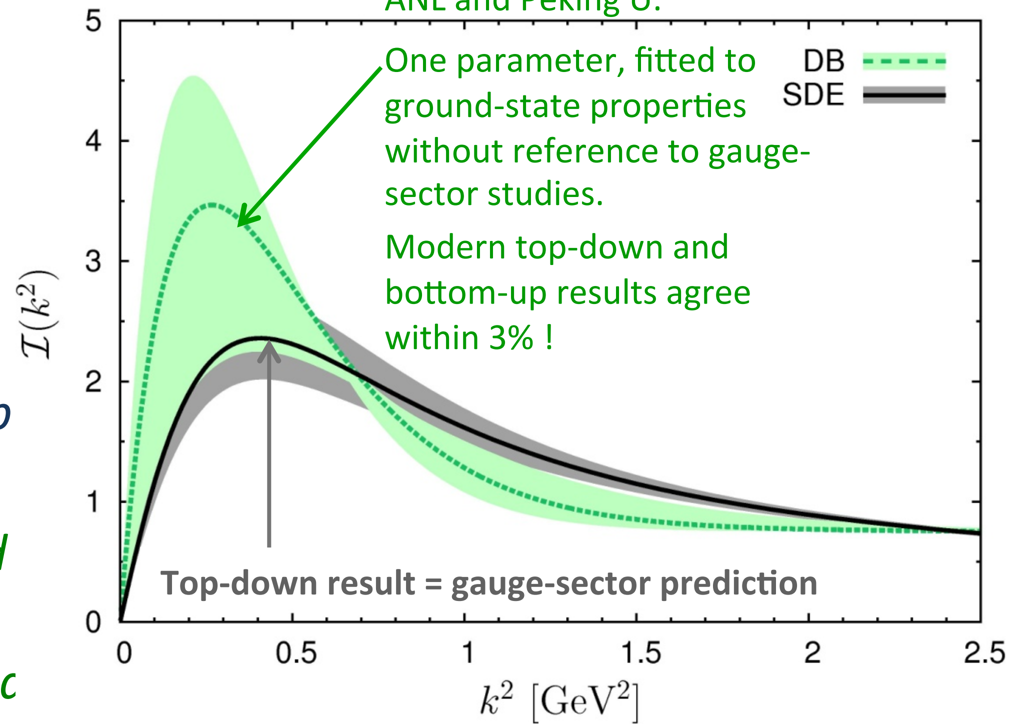
Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

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

- *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

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C. D. Roberts (US), arXiv:1412.4782 [nucl-th] , *Phys. Lett. B* ***742*** *(2015) 183*

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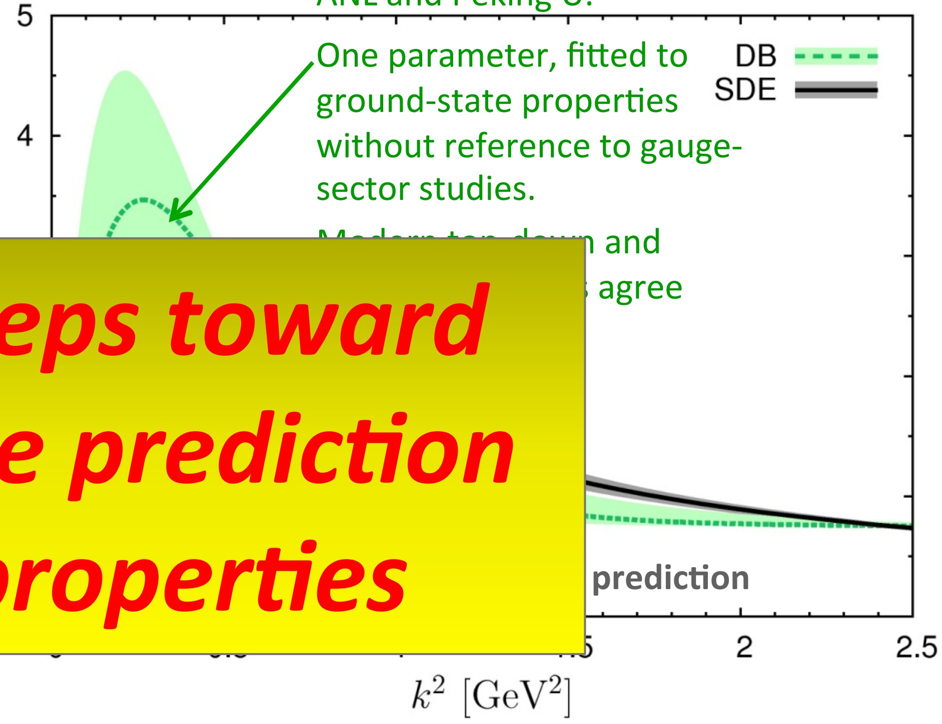
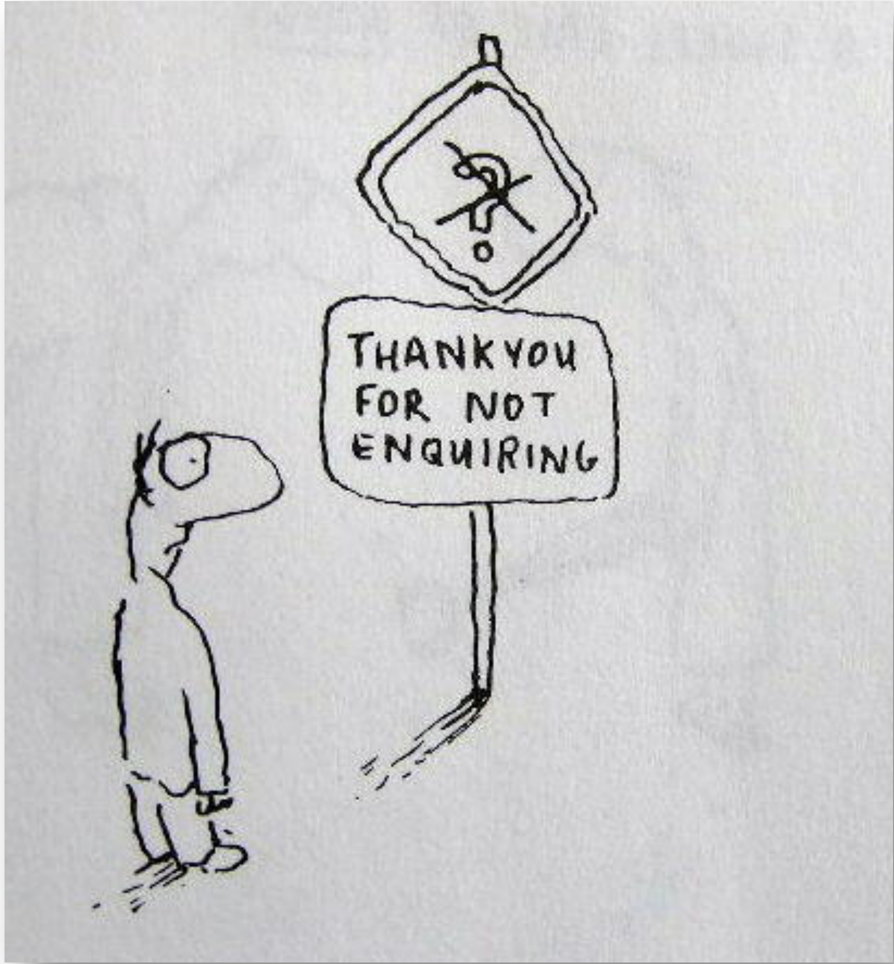


Significant steps toward parameter-free prediction of hadron properties



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

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

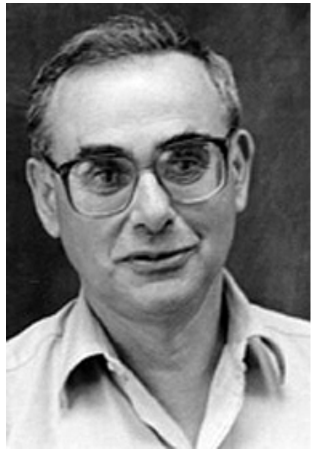
This identity is why the pion is massless in the chiral limit

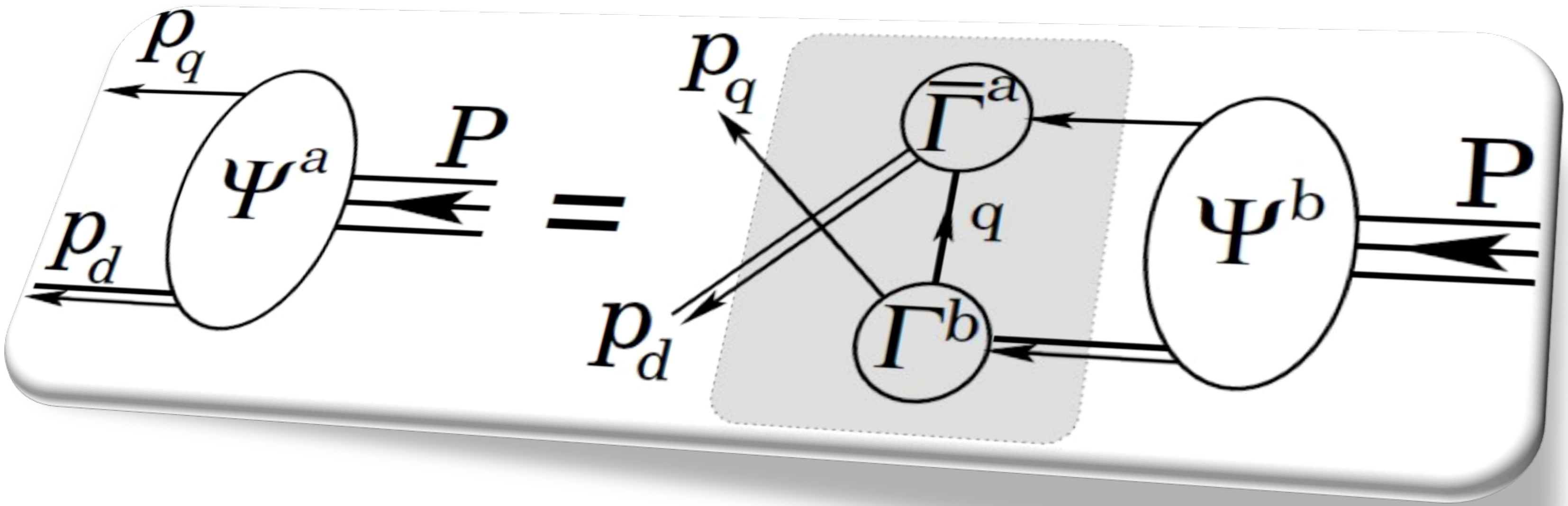
Enigma of mass

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

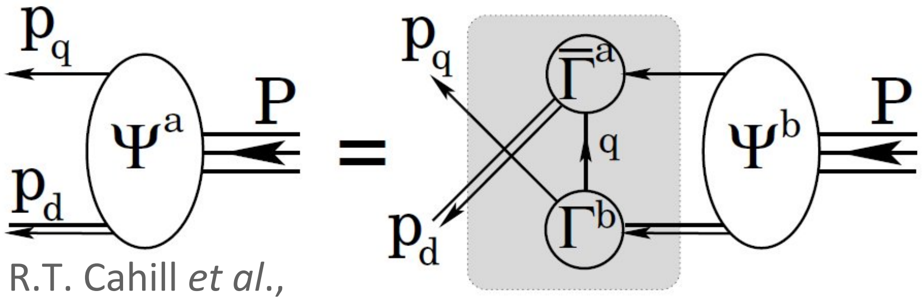
  Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

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





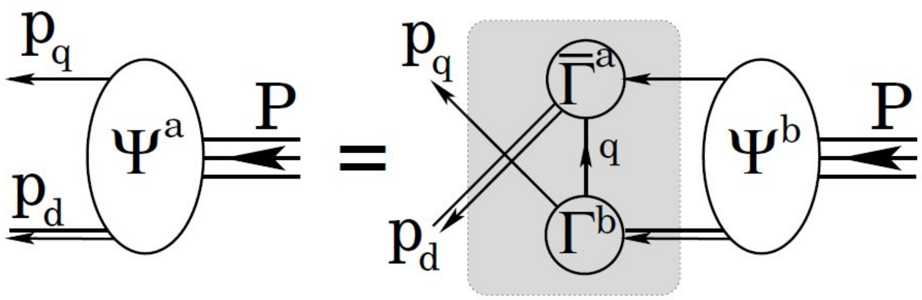
Spectrum & Structure of Baryons



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

Baryon Structure

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



Diquarks

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

Other clusters are negligible in J^+ states

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

Proton Faddeev Amplitude

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

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

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

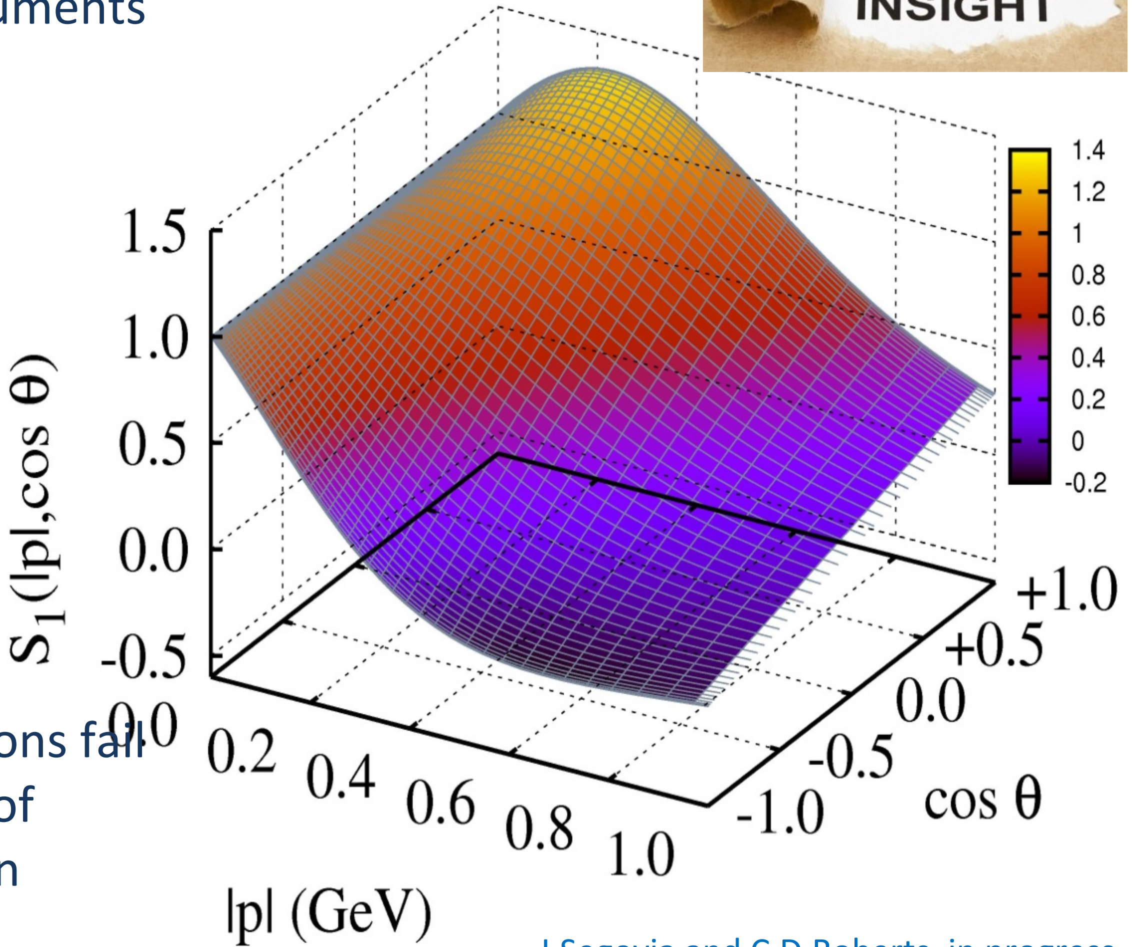
  i.e., *natural* rel-momentum = 0

  $\cos\vartheta = -1$, 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



J.Segovia and C.D.Roberts, in progress

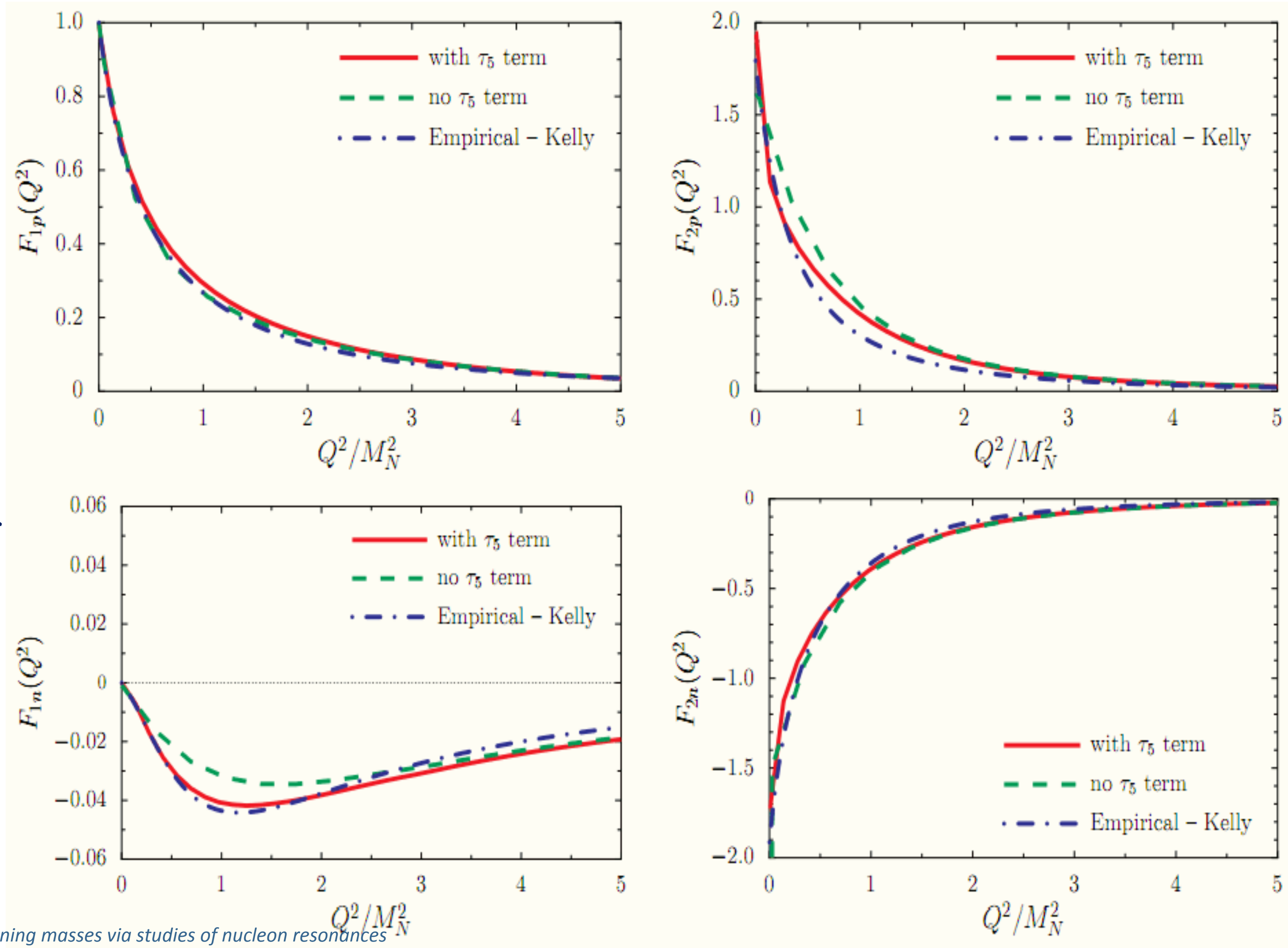
Survey of nucleon electromagnetic form factors
I.C. Cloët et al, arXiv:0812.0416 [nucl-th],
Few Body Syst. **46** (2009) pp. 1-36

Nucleon Form Factors

Unification of meson and nucleon form factors.

Very good description.

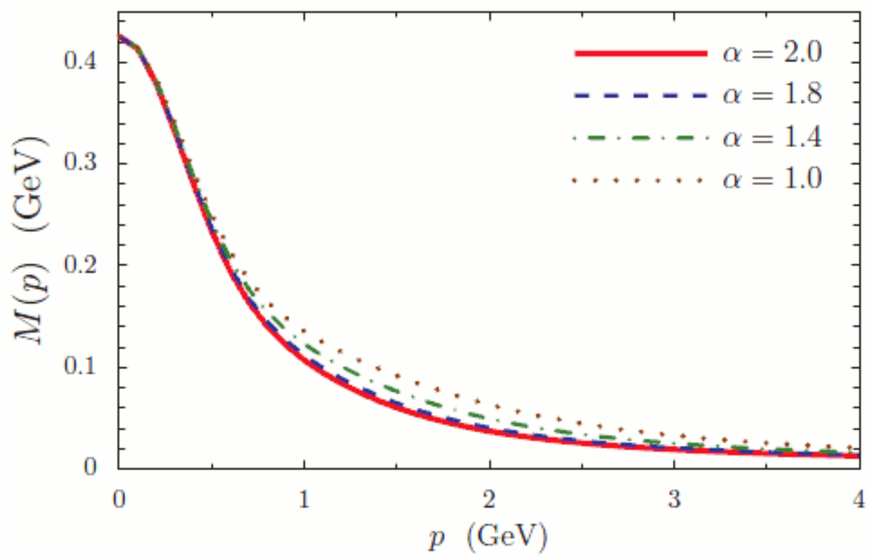
Quark's momentum-dependent anomalous magnetic moment has observable impact & materially improves agreement in all cases.

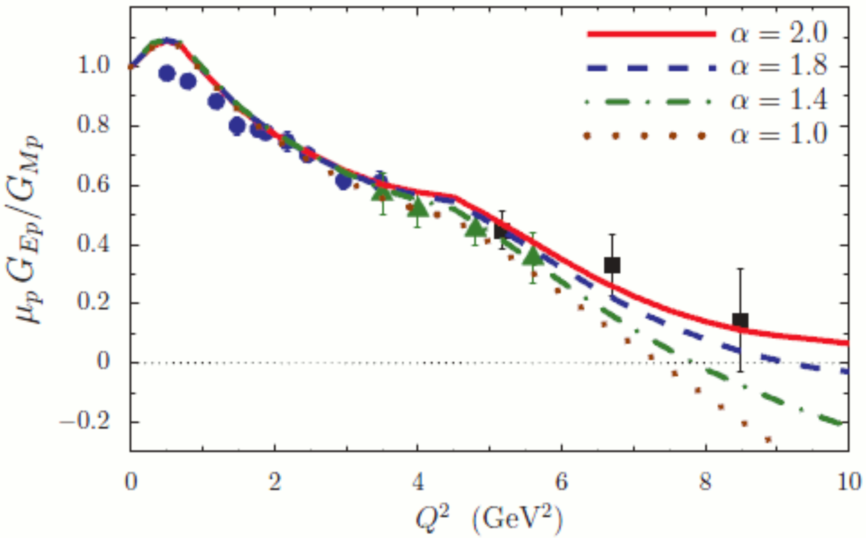


I.C. Cloët, C.D. Roberts, A.W. Thomas: Revealing dressed-quarks via the proton's charge distribution,
arXiv:1304.0855 [nucl-th], Phys. Rev. Lett. **111** (2013) 101803

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

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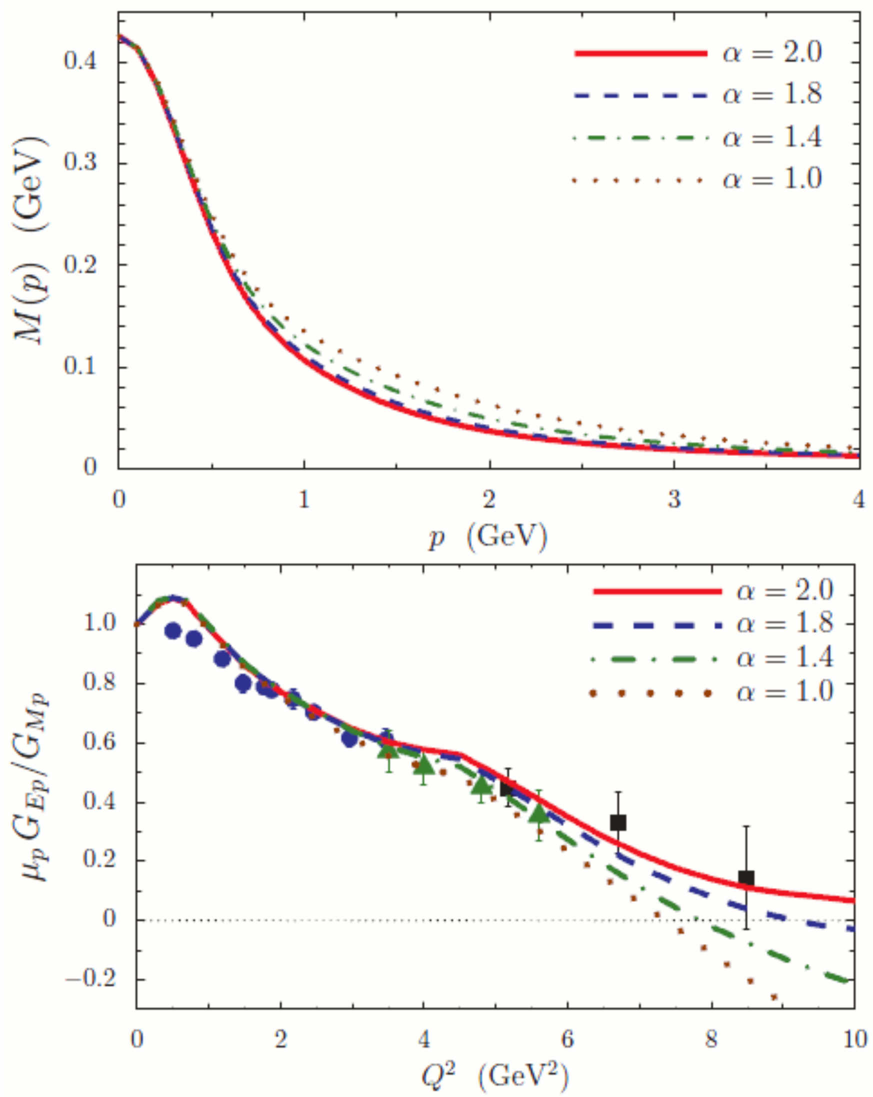


- Follows that the
  - ✓ possible existence
  - ✓ and location

  of a zero in the ratio of proton elastic form factors

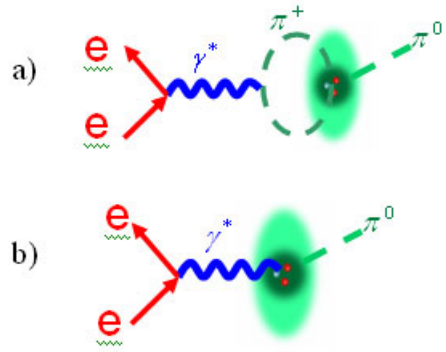
  $[\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)]$

  are a direct measure of the nature of the quark-quark interaction in the Standard Model.

What's missing?

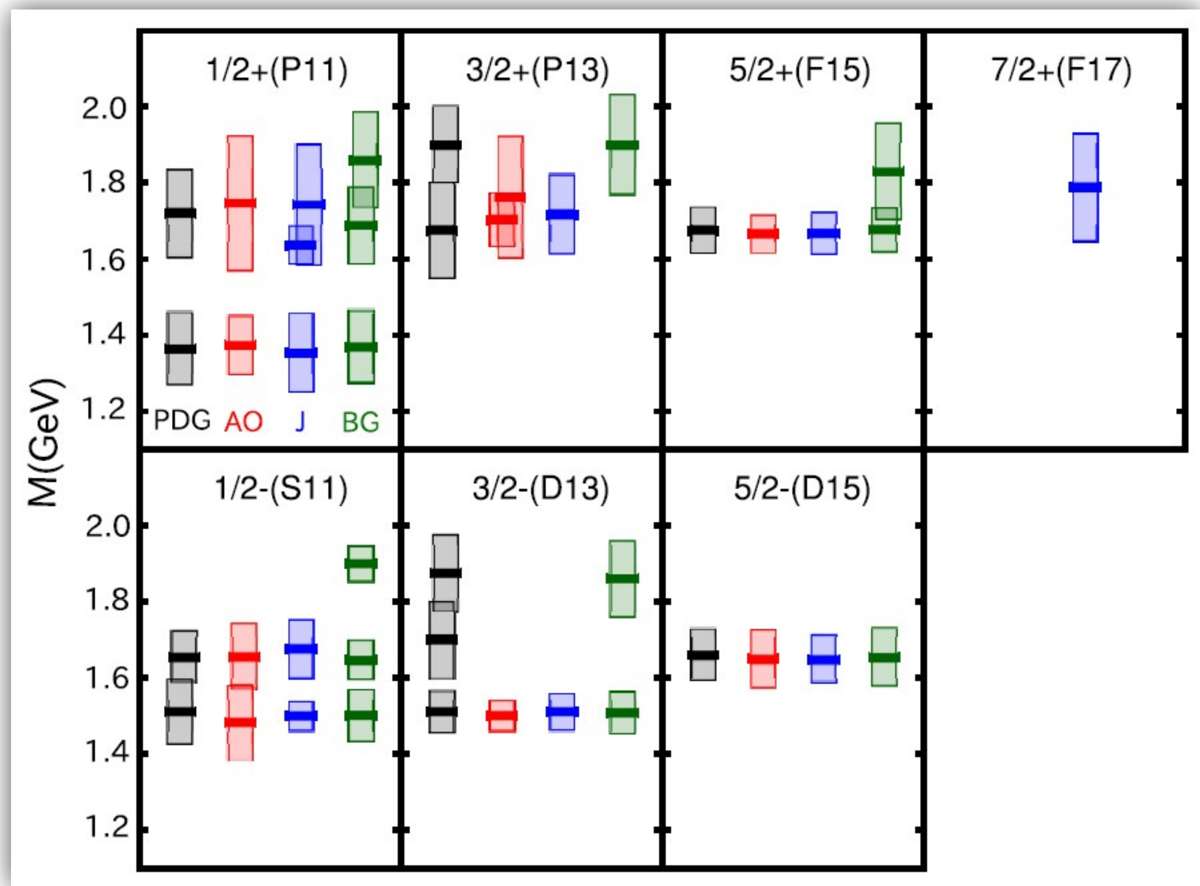
H.L.L. Roberts, L. Chang, I.C. Cloët and C.D. Roberts,
arXiv:1101.4244 [nucl-th], Few Body Syst. **51** (2011) pp. 1-25

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



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.

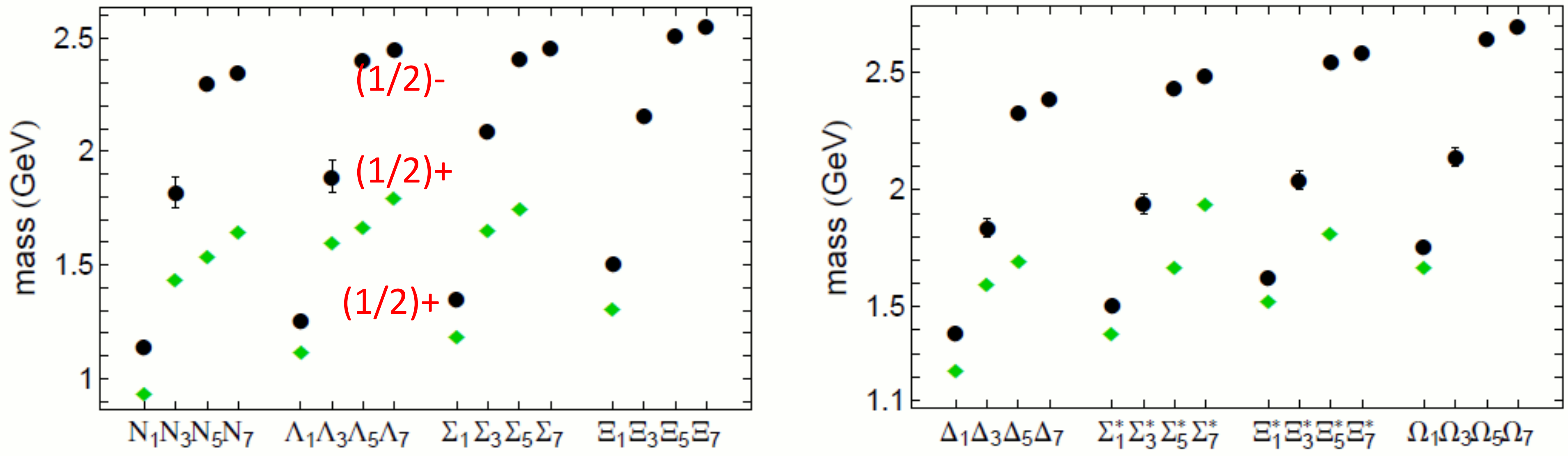


Fig. 4 Left panel: Pictorial representation of octet masses in Table 6. *Circles* – computed masses; and *diamonds* – empirical masses. On the horizontal axis we list a particle name with a subscript that indicates its row in the table; e.g., N_1 means nucleon column, row 1. In this way the labels step 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

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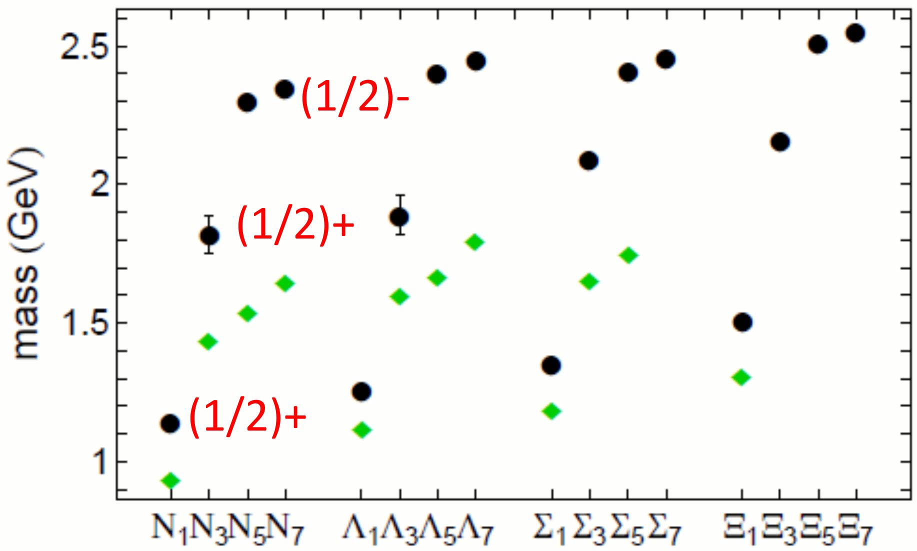


Fig. 4 Left panel: Pictorial representation of octet
diamonds – empirical masses. On the horizontal axis
its row in the table; e.g., N_1 means nucleon column, r
radial excitation, parity partner, parity partner's radial
masses in Table 6.

- 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

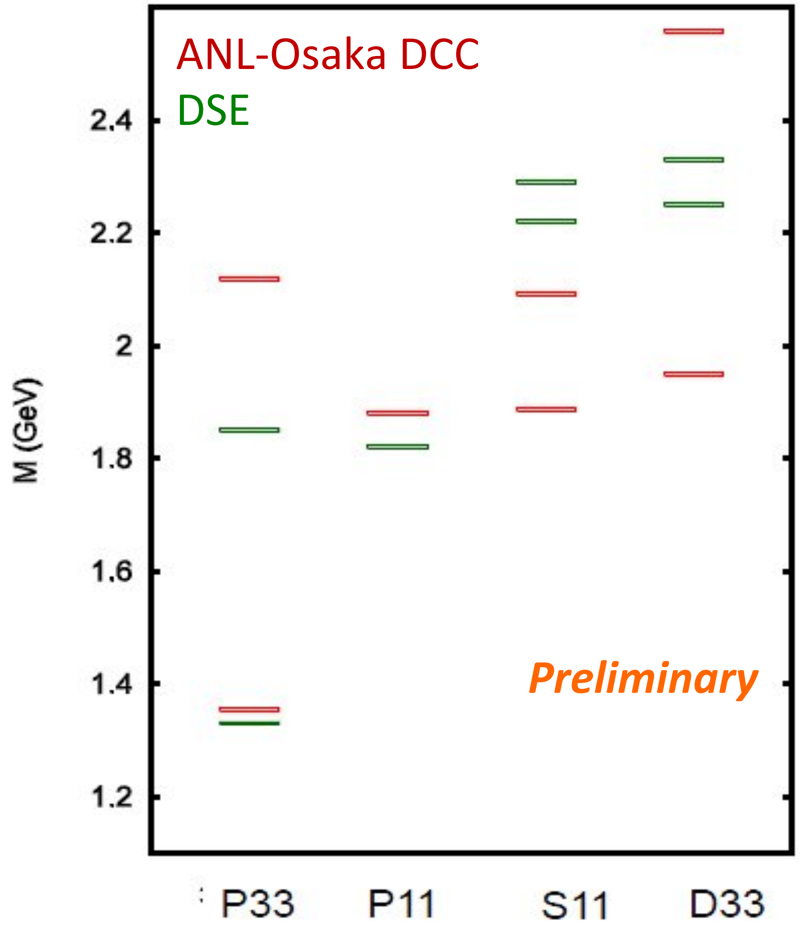
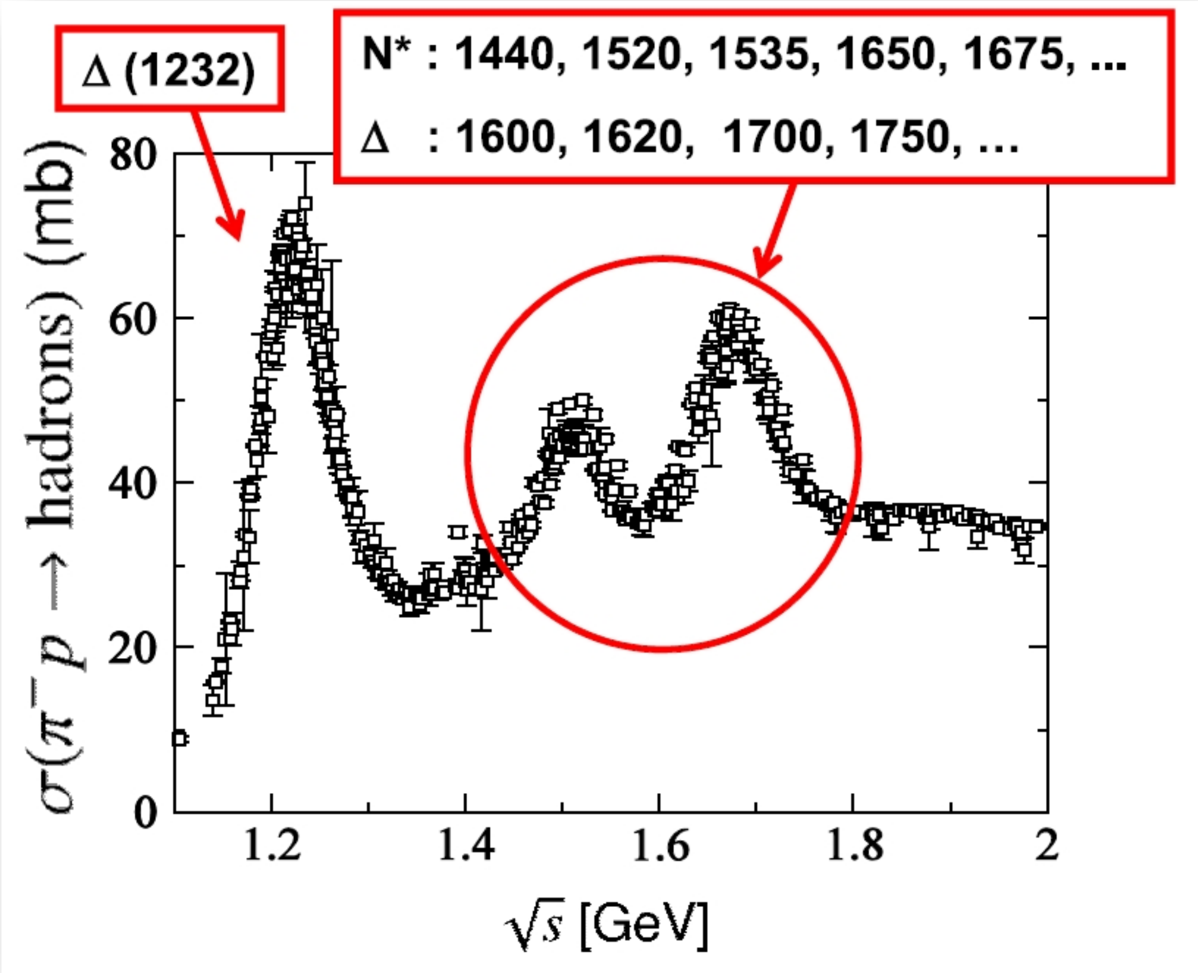


Image courtesy of T. Sato, H. Kamano, S. Nakamura and T.-S. H. Lee



Nucleon Resonances

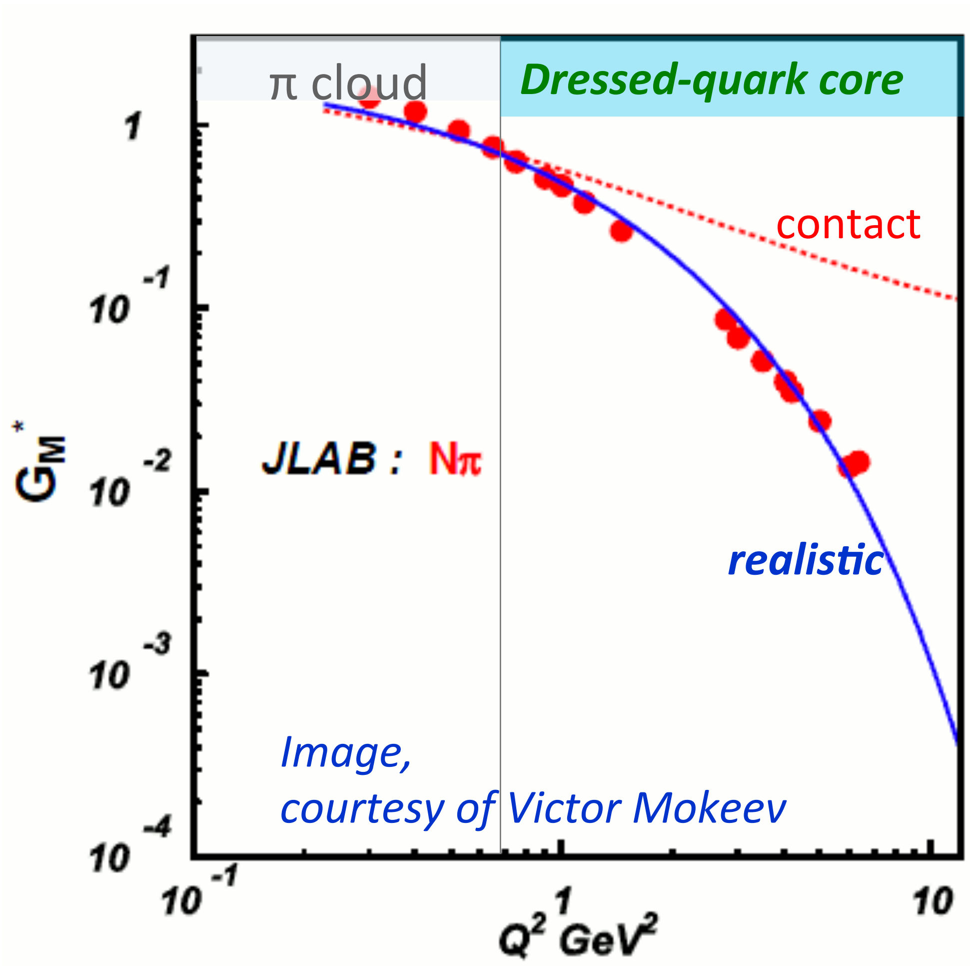
γ N → Resonance

- 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]

$\gamma N \to \Delta$

- 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***



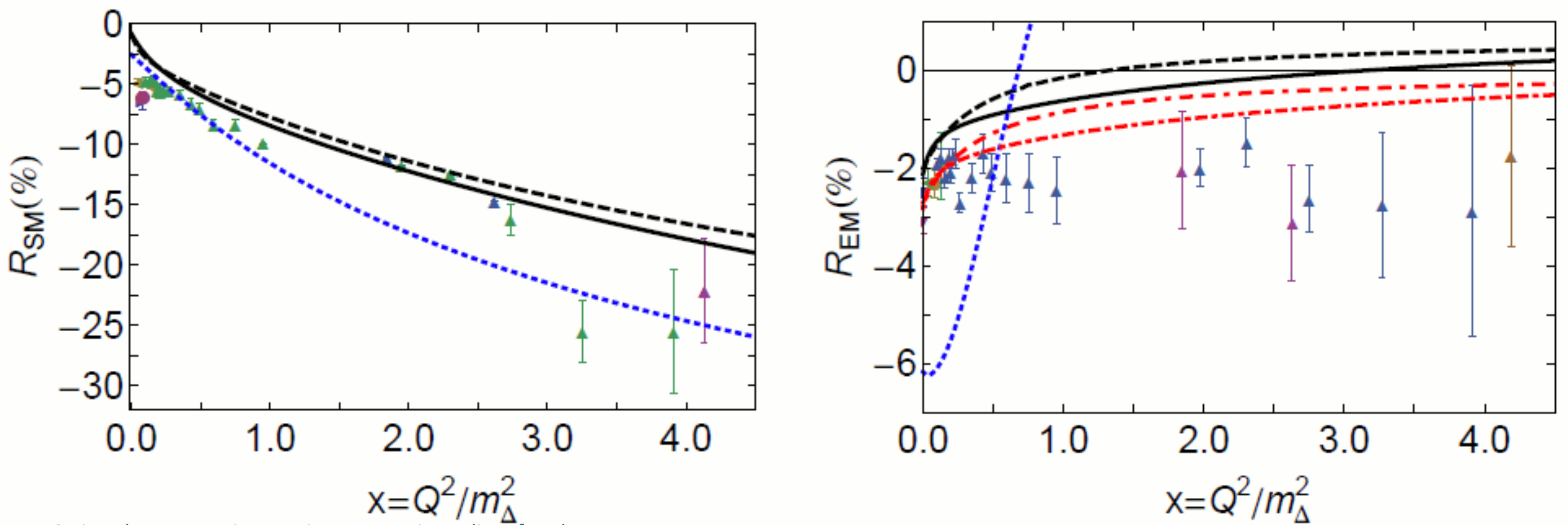
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222
[on-line]

$\gamma\, N \to \Delta$

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

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

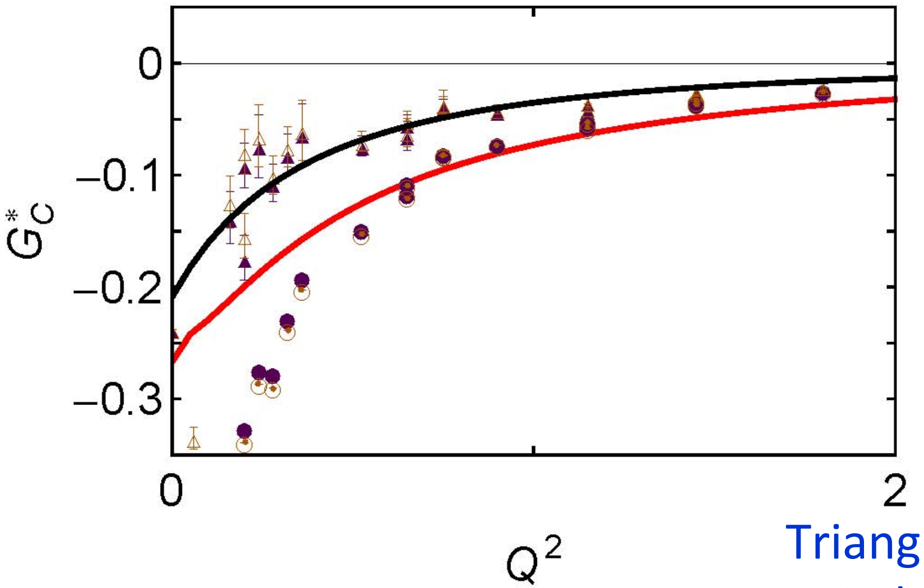
  – Available data suggest that it's not happening yet

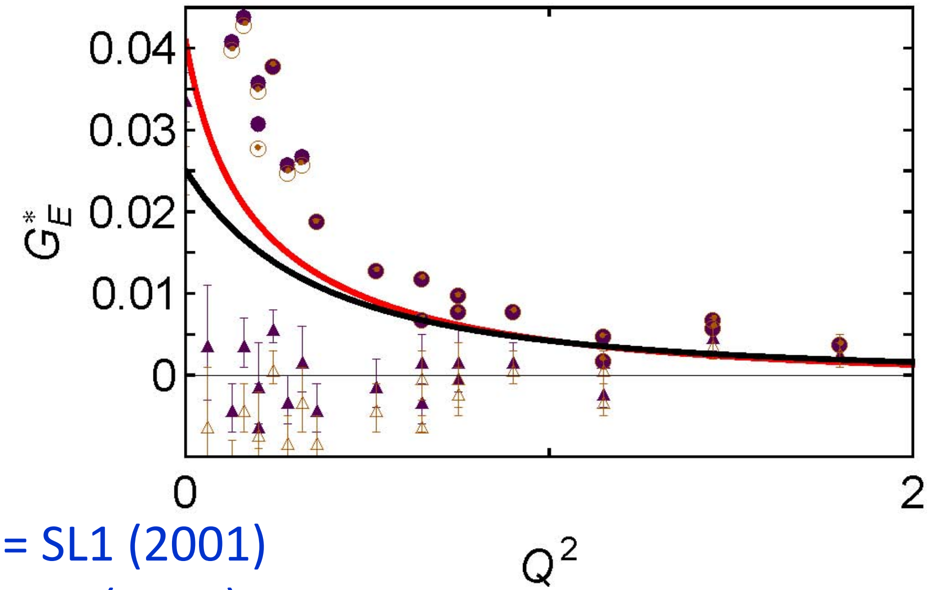


J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt:
Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222
[on-line]

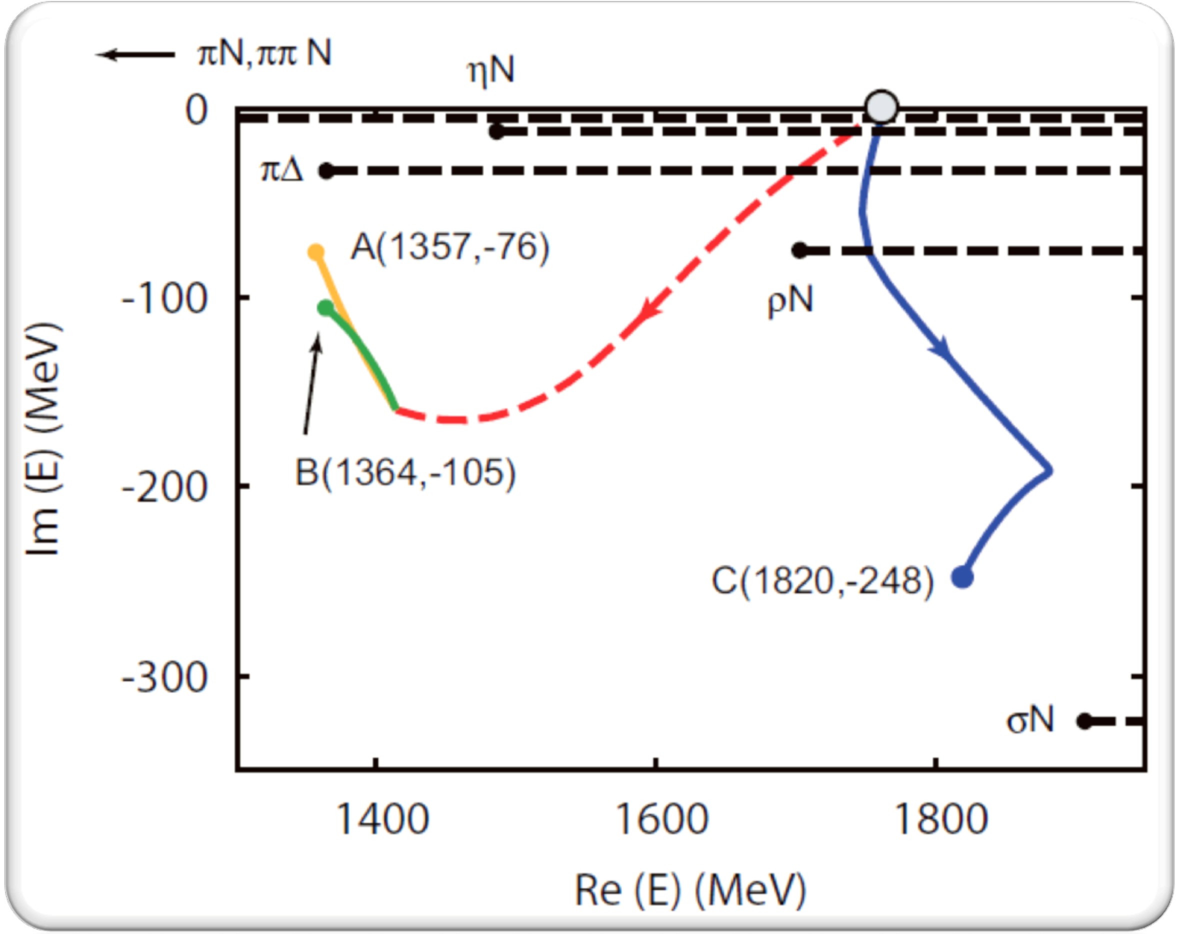
$\gamma N \rightarrow \Delta$

- Very probably, that is because pion cloud is masking the zero on the currently accessible domain
- Judge that because our dressed-quark core results agree very well with Sato-Lee's meson-*undressed* electric and Coulomb form factors … determined from data fits more than 7 years ago





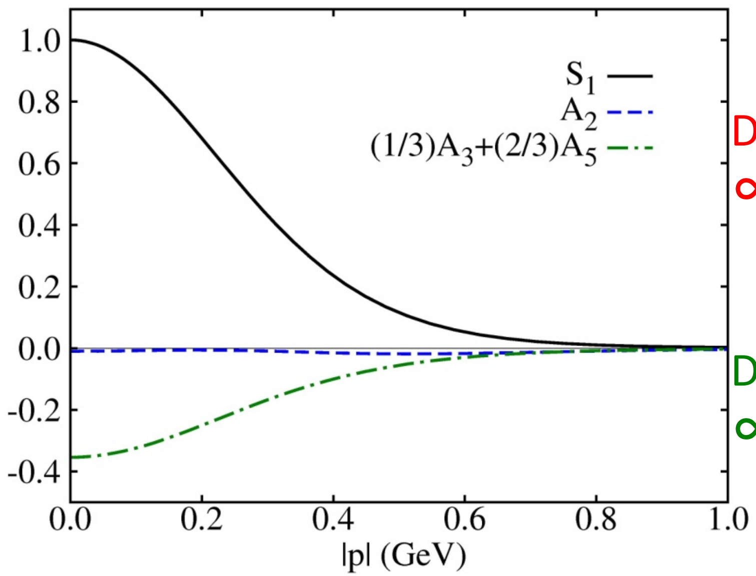
Triangles = SL1 (2001)
Circles = SL2 (2007)



Roper Resonance

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

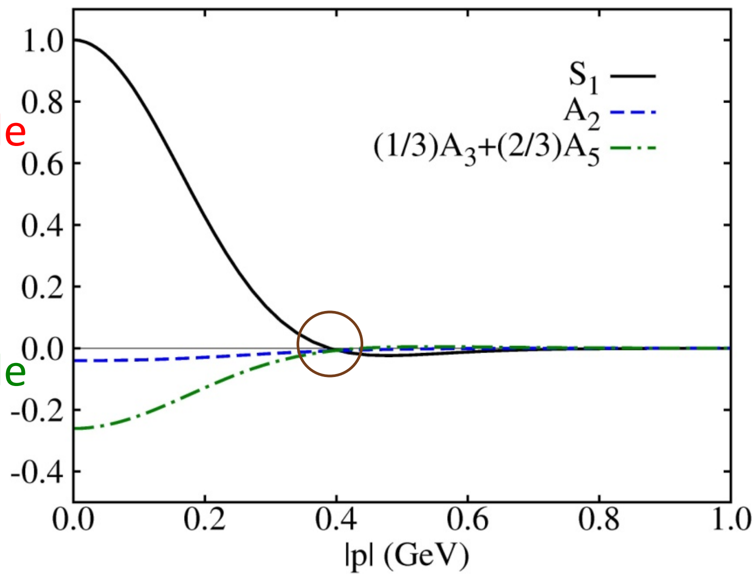


Dominant 0+ amplitude

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

Dominant 1+ amplitude

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



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

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

Roper Resonance

- Precisely same framework as employed for nucleon and *Δ*; viz.
  - dressed-quark mass function
  - diquark amplitudes , masses, propagators
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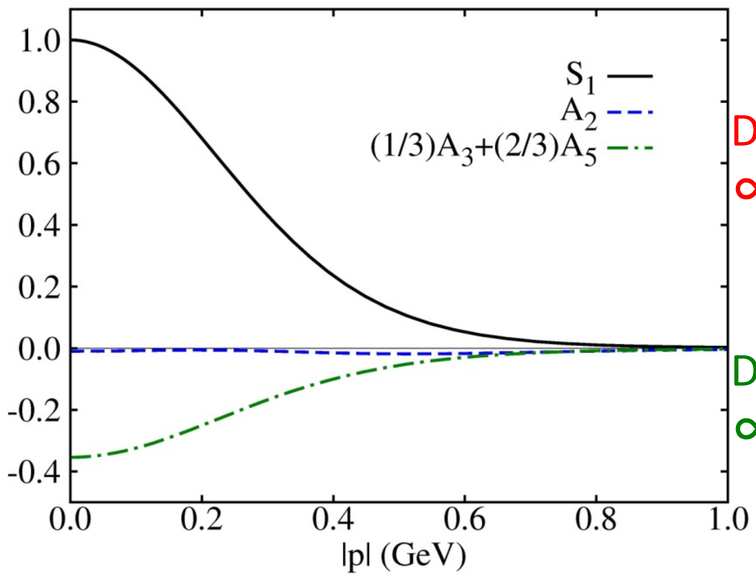
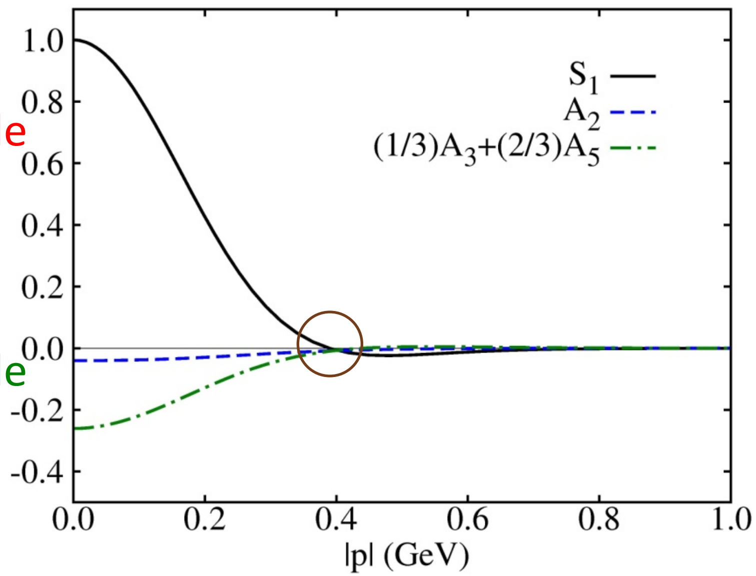


Dominant 0+ amplitude
$\propto C\,I\,\tau_2$

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



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

n

Meson-baryon final-state interactions

N.B. ,

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 Roper

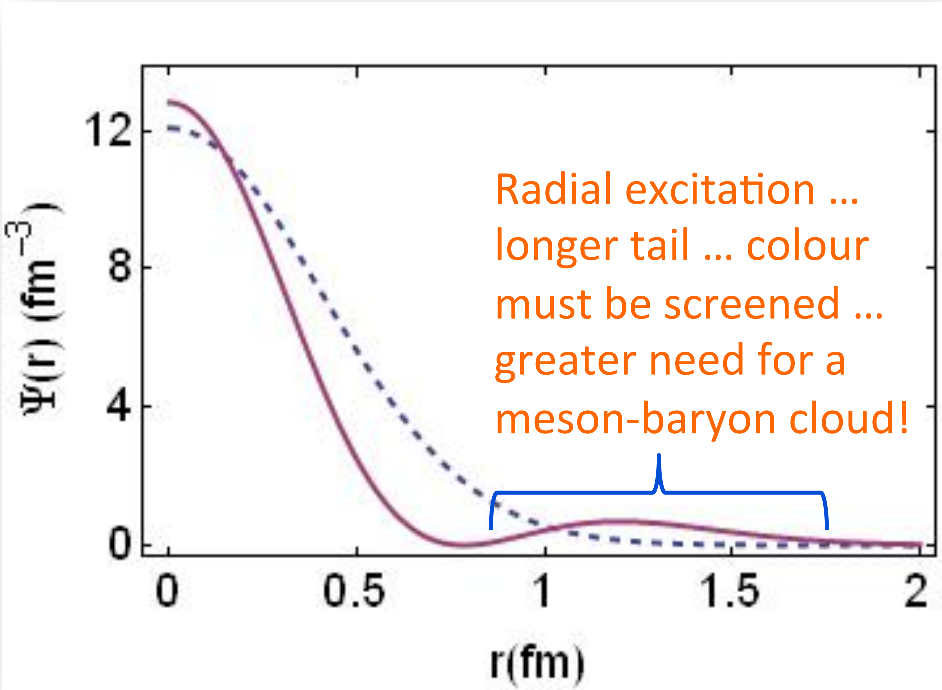
	Nucleon	Roper	Image-Nucleon
$P_{J=0x0}$	62%	62%	30%
$P_{J=0x1\&1x1}$	38%	38%	70%

  – "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]

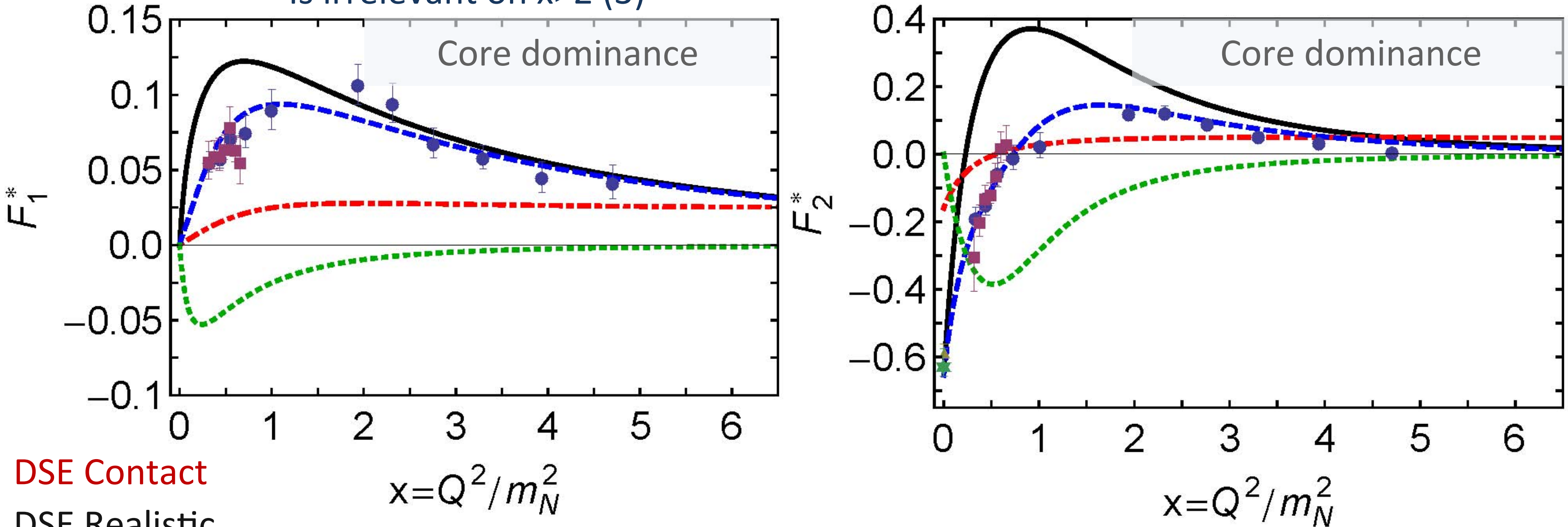
Roper Resonance



- 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)



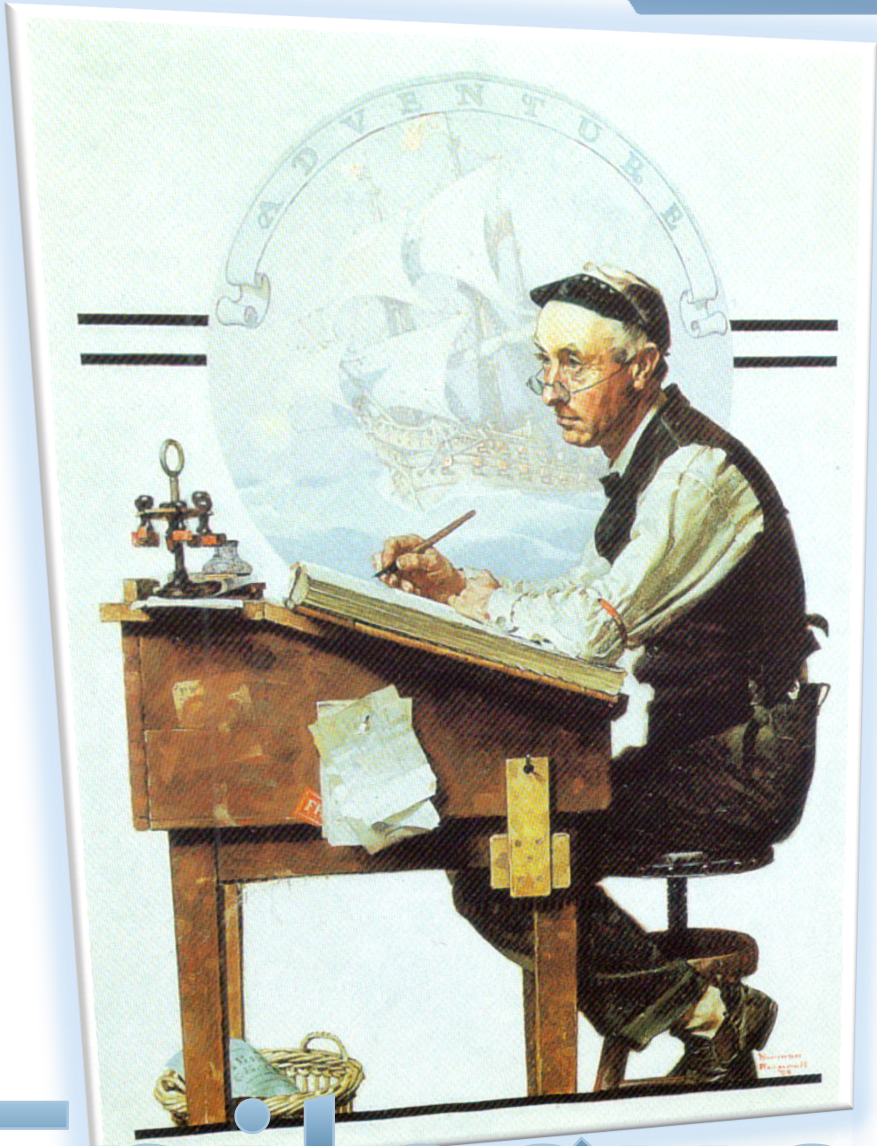
DSE Contact

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 mass dynamically*, those masses are momentum dependent, with large values in the infrared $m_g \propto 500$ MeV & $M_q \propto 350$ MeV … this underlies DCSB and has numerous observable consequences
- In a Universe with light quarks, confinement is a dynamical phenomenon … *no linear potentials, no Regge trajectories*
- Top-down and bottom-up DSE analyses agree on RGI interaction in *continuum-QCD ⇒ parameter-free prediction of hadron properties*
- *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 → Δ* ... understood
- *Nucleon → Roper* ... understood

This is just the beginning

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"*

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Properties of Regge trajectories

Alfred Tang* and Joh...

Physics Department, University of Wisconsin ... 3201

(Receive...

Early Chew-Fra... ...ies 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... ...y, 12.40.Nn, 14.20.−c, 14.40.−n

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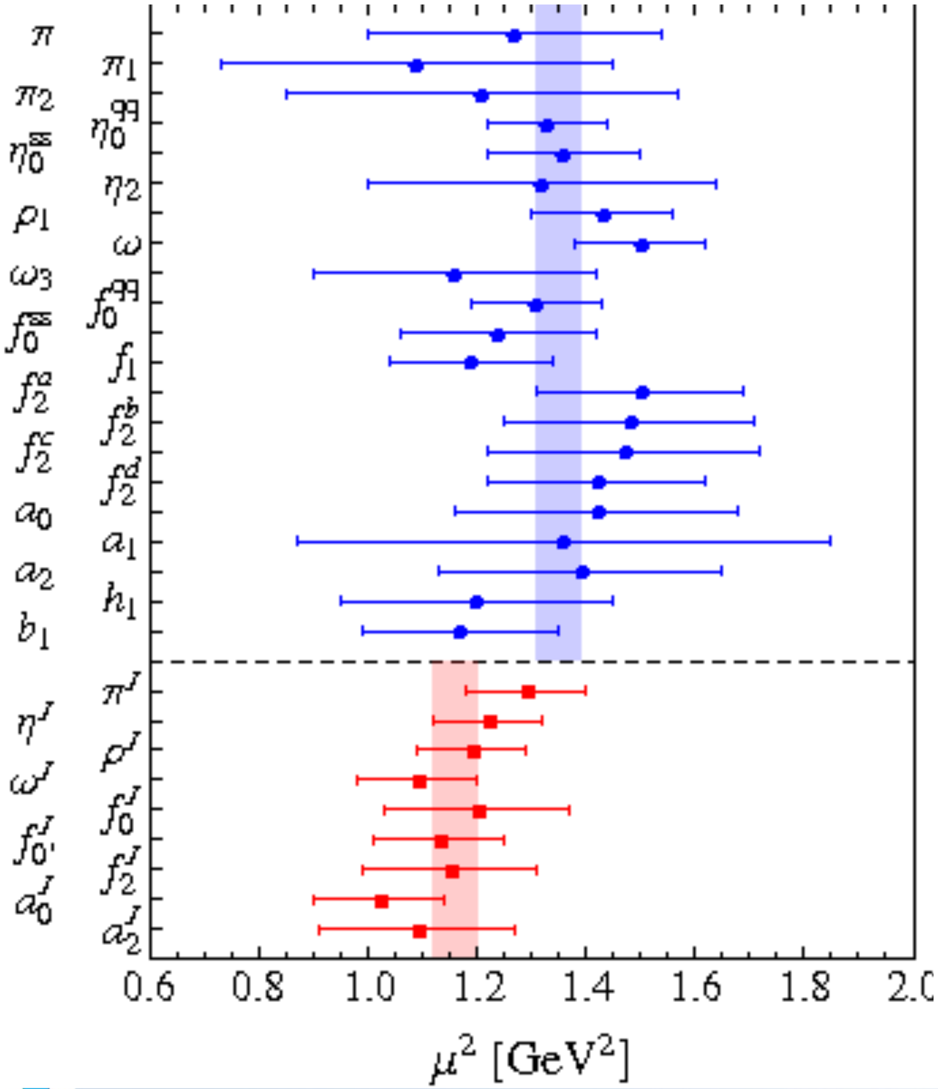
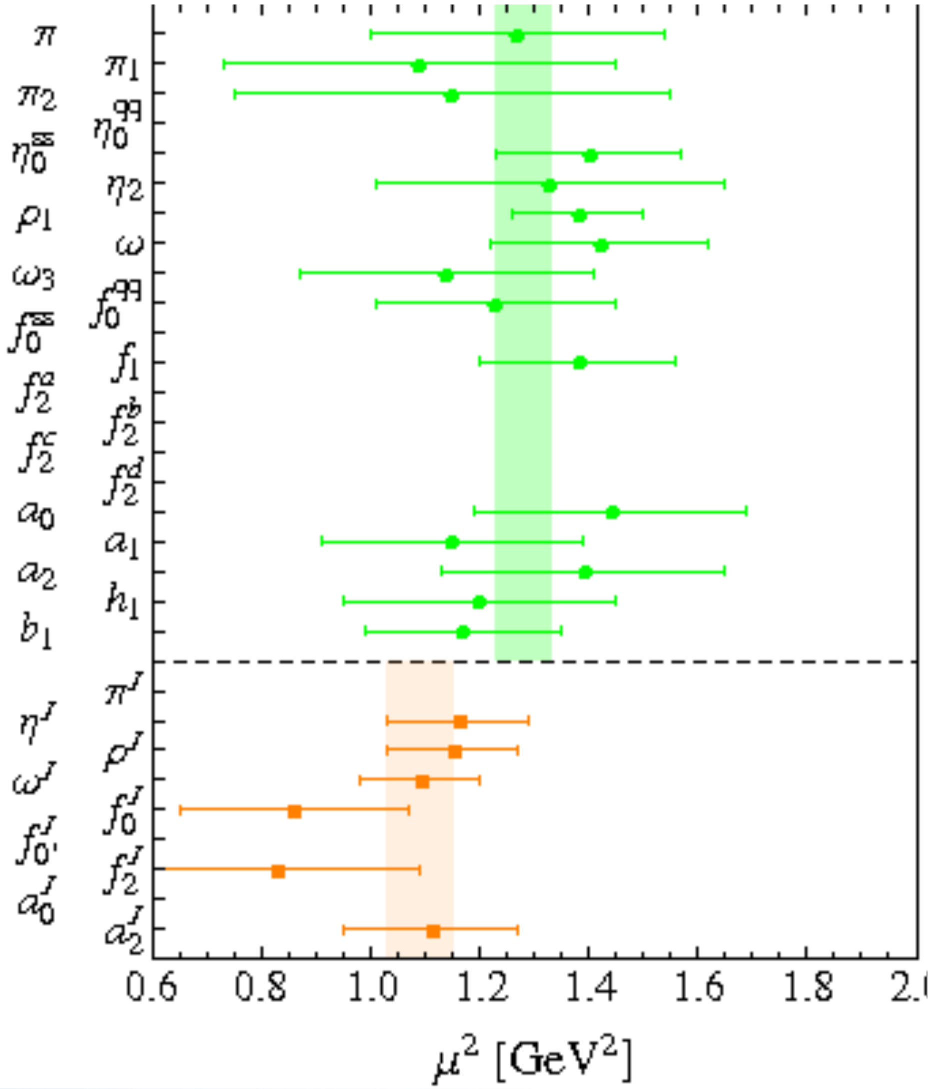
"Systematics of radial and angular-momentum Regge trajectories of light non-strange qqbar-states," Masjuan, Ruiz Arriola, Broniowski. arXiv:1305.3493 [hep-ph]

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



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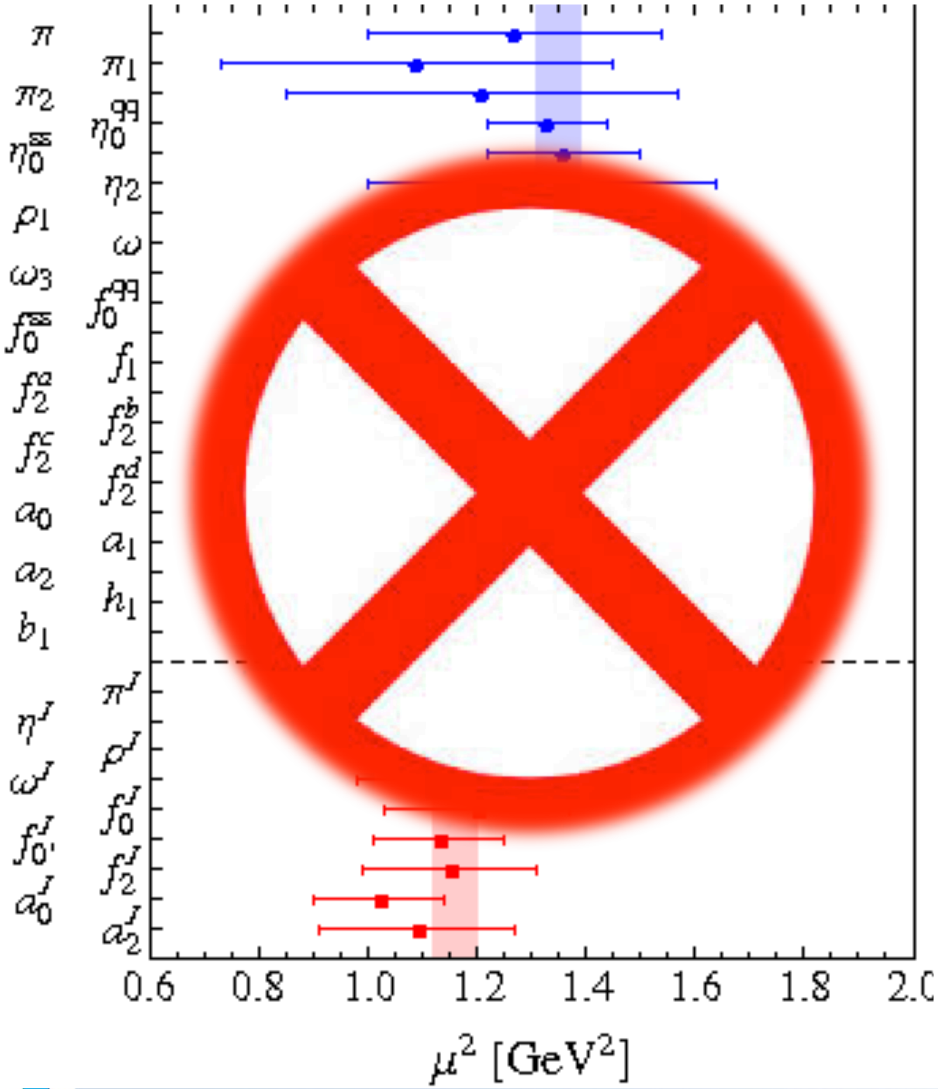
If all points take the same value, then $M^2 \propto J,n$ … Method 1



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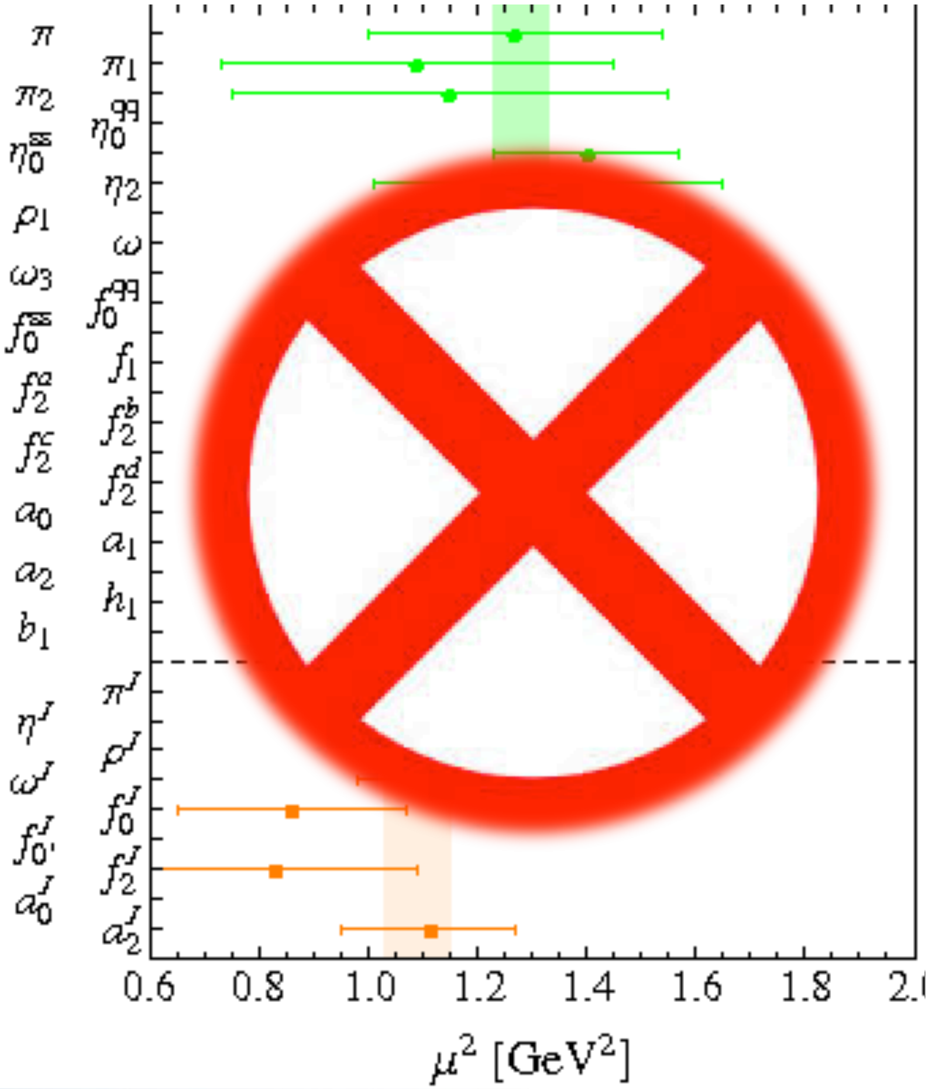
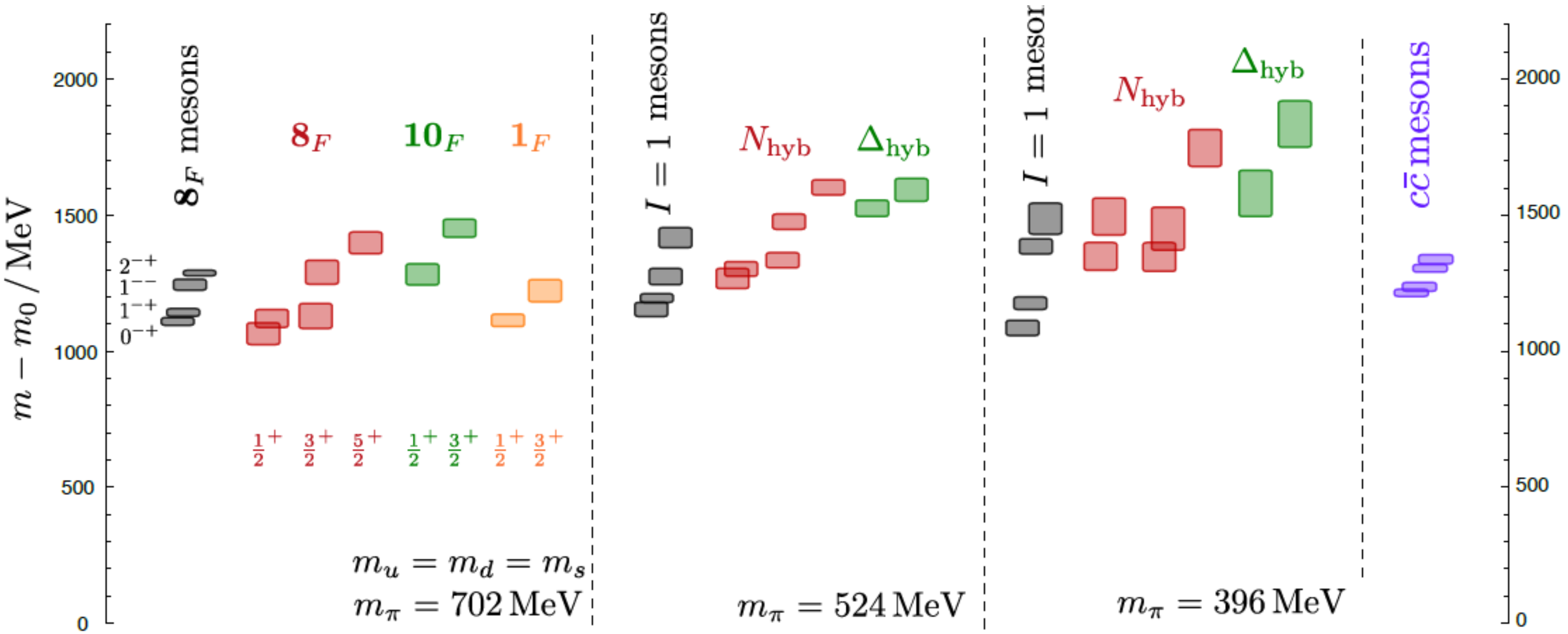


Hybrid Hadrons & Lattice QCD
- Robert Edwards, Baryons13

arXiv:1104.5152, 1201.2349

- Heavy pions … so, naturally, constituent-quark like spectra
- To which potential does it correspond?



Hybrid meson models – Robert Edwards, Baryons13

arXiv:1104.5152, 1201.2349

With minimal quark content, $q\bar{q}G$ gluonic field can in a color singlet or octet

- `constituent' gluon in S-wave

  $G \sim 1_{\mathbf{8}}$

  $(0,1,2)^{++}, 1^{+-}$

  $0^{--}, (1^{-+})^3, 3^{-+} \ldots$

- bag model

  `constituent' gluon in P-wave

  $G \sim 1_{\mathbf{8}}^{+-}$

  $q\bar{q}_{L=0}$ $(0,1,2)^{-+}, 1^{--}$

  $q\bar{q}_{L=1}$ $0^{+-}, (2^{+-})^2 \ldots$

- flux-tube model

  $(0,1,2$ … $, (0,1,2)^{+-}, 1^{++}$

Hybrid baryon models - Robert Edwards, Baryons13

arXiv:1104.5152, 1201.2349

Minimal quark content, $qqqG$, gluonic field can be in color singlet, octet or decuplet

Now must take into account ***permutation*** symmetry of quarks and gluonic field

- bag model $G \sim 1^{+}_{\mathbf{8_c}}$ $(N\frac{1}{2}^{+})^2, (N\frac{3}{2}^{+})^2, (\Delta\frac{1}{2}^{+}), (\Delta\frac{3}{2}^{+}), (N\frac{5}{2}^{+})$

- flux-tube model $(N\frac{1}{2}^{+})^2, \ldots^{+}), (\Delta\frac{3}{2}^{+}), (\Delta\frac{5}{2}^{+})$

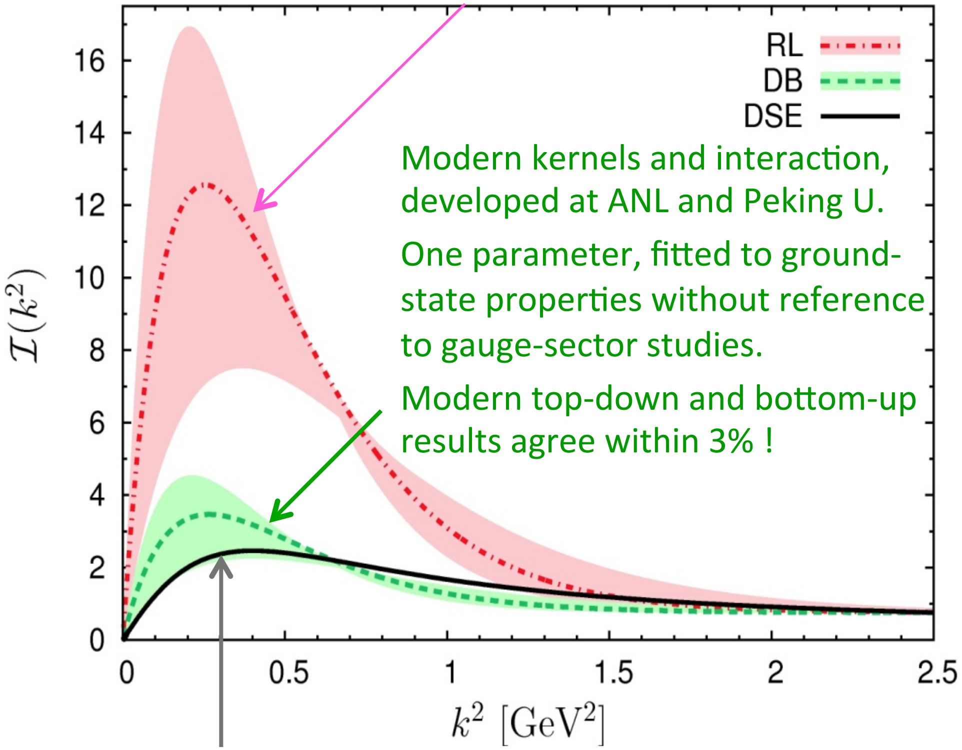
Bridging a gap between continuum-QCD
& ab initio predictions of hadron observables

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

- *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*

Top down & Bottom up

"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

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

DSEs & Baryons

- *Dynamical chiral symmetry breaking* (DCSB)
  – has enormous impact on meson properties.
  - *Must be included in description and prediction of baryon properties*.
- *DCSB* is essentially a quantum field theoretical effect.
  In quantum field theory
  - Meson appears as pole in four-point quark-antiquark Green function → Bethe-Salpeter Equation
  - *Nucleon appears as a pole in a six-point quark Green function → Faddeev Equation*.
- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Tractable equation is based on the observation that an interaction which describes colour-singlet mesons also generates *nonpointlike* quark-quark (diquark) correlations in the colour-antitriplet channel

$SU_c(3)$: $3 \otimes 3 = \bar{3} \oplus 6$

Proton Faddeev Amplitude

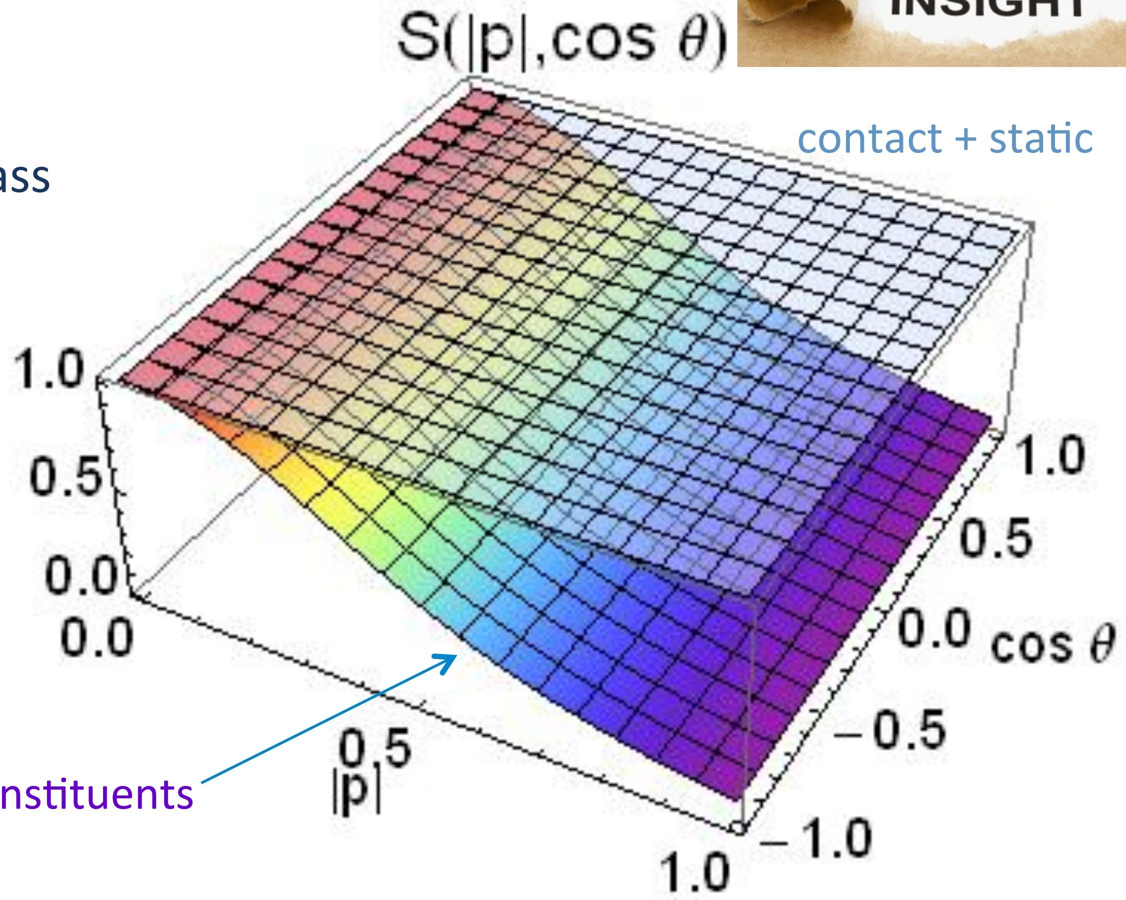
- Eight terms in Faddeev amplitude
- Plot the dominant scalar-diquark component
- Published treatments of a contact-interaction (static-approximation) produce

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

- In a bound-state with equal mass constituents,

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

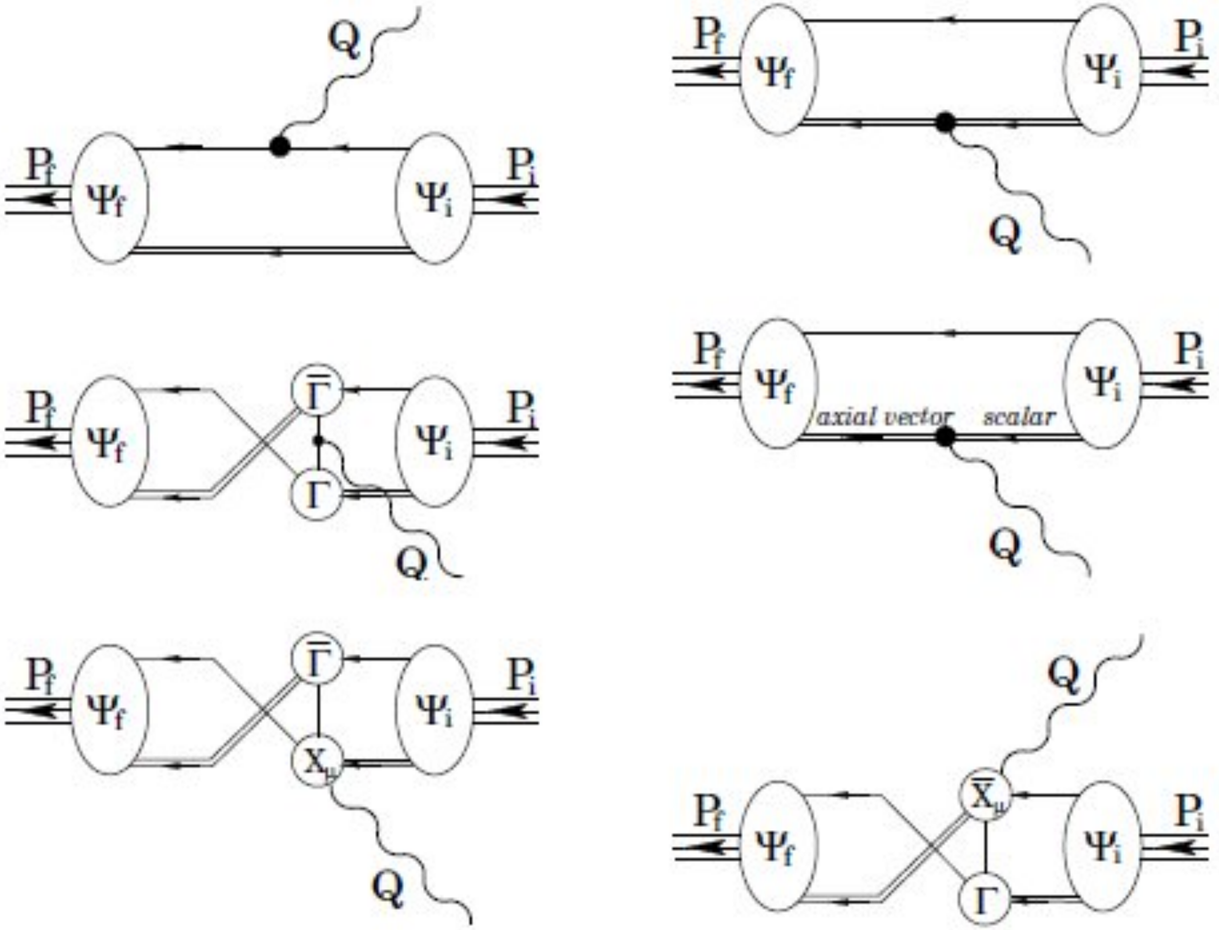
  i.e., independent of *cos ϑ*



J.Segovia and C.D.Roberts, in progress

Photon-nucleon current

- Composite nucleon must interact with photon via nontrivial current constrained by Ward-Green-Takahashi identities
- DSE → BSE → Faddeev equation plus current → nucleon elastic and transition form factors



Oettel, Pichowsky, Smekal
Eur.Phys.J. A8 (2000) 251-281

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

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

Abstract | References | Citing Articles (11)

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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

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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

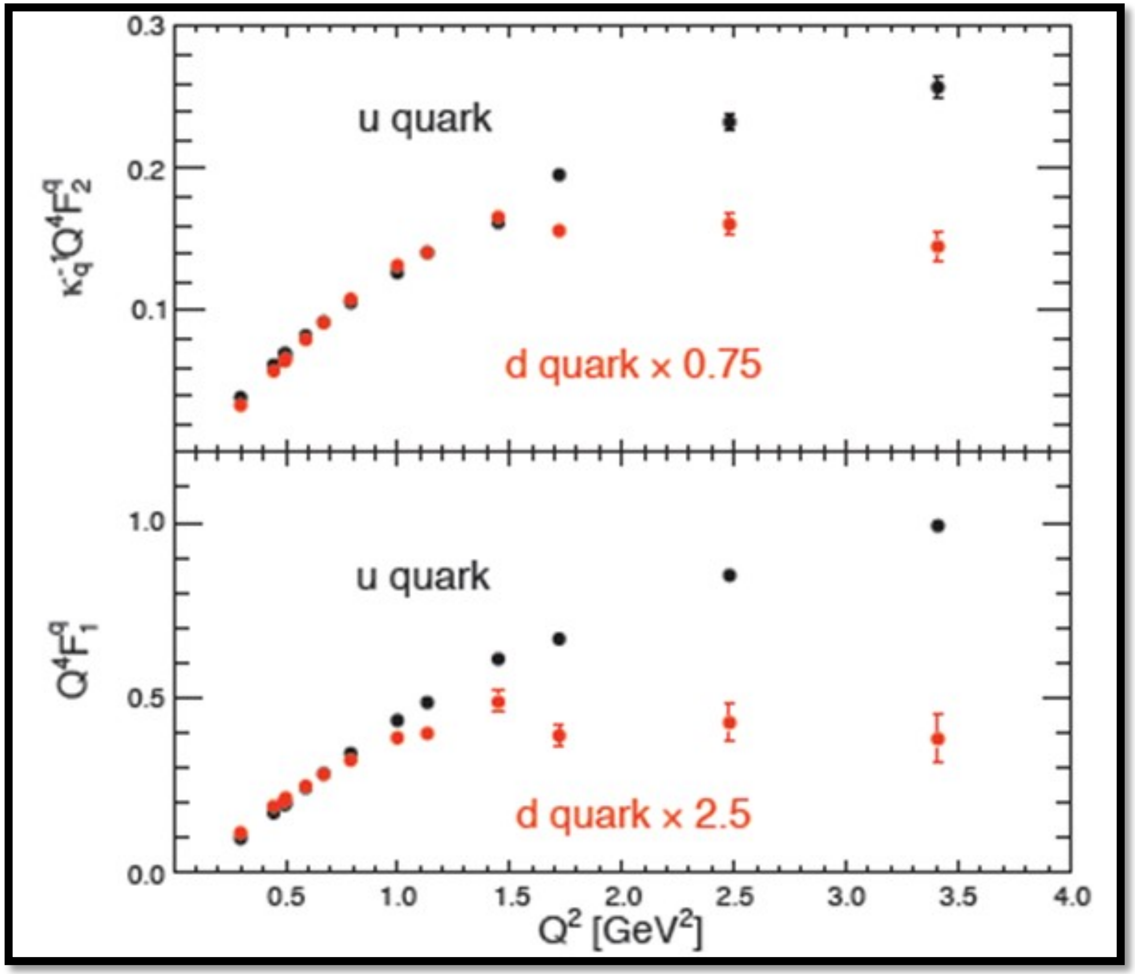
Discovering Diquarks

Flavor separation of proton form factors

$Q^4F_2^q/\kappa$

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

$Q^4 F_1^q$

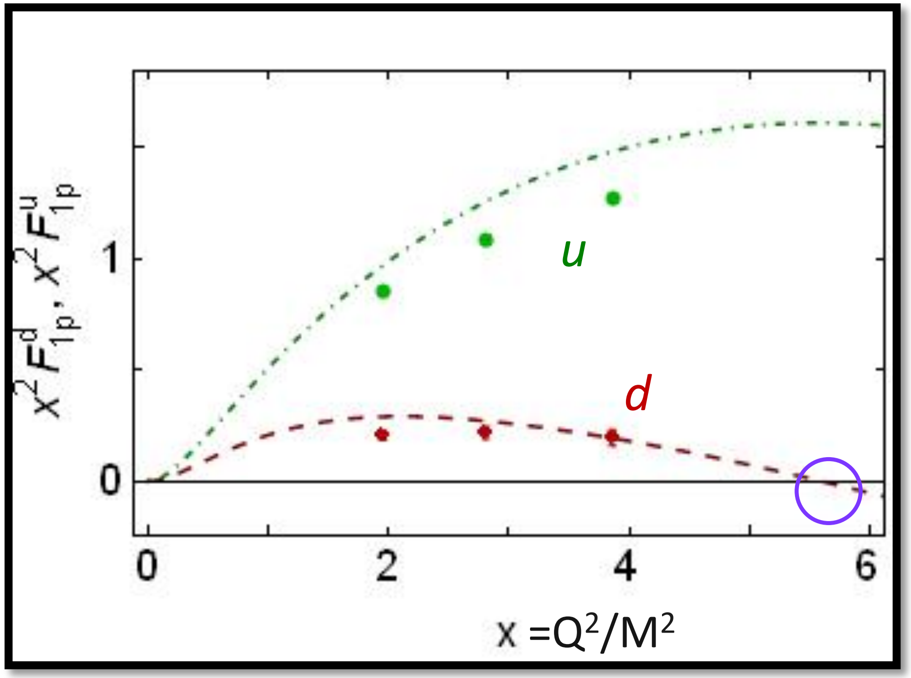


- Very different behavior for *u* & *d* quarks

  Means apparent scaling in proton F2/F1 is *purely accidental*

Cloët, Eichmann, El-Bennich, Klähn, Roberts, Few Body Syst. 46 (2009) pp.1-36
Wilson, Cloët, Chang, Roberts, PRC 85 (2012) 045205

Diquark correlations!



- Poincaré covariant Faddeev equation
  - Predicts scalar and axial-vector diquarks
- Proton's singly-represented *d*-quark more likely to be struck in association with *1⁺* diquark than with *0⁺*
  - form factor contributions involving *1⁺* diquark are softer
- Doubly-represented *u*-quark is predominantly linked with harder *0⁺* diquark contributions
- Interference produces zero in Dirac form factor of *d*-quark in proton
  - Location of the zero depends on the relative probability of finding 1⁺ & 0⁺ diquarks in proton
  - Correlated, e.g., with valence *d/u* ratio at x=1

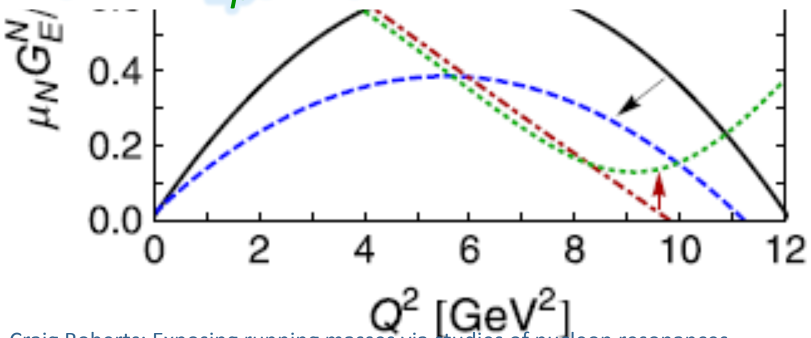
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) 1185 [on-line]

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 $Q^2 > 4GeV^2$

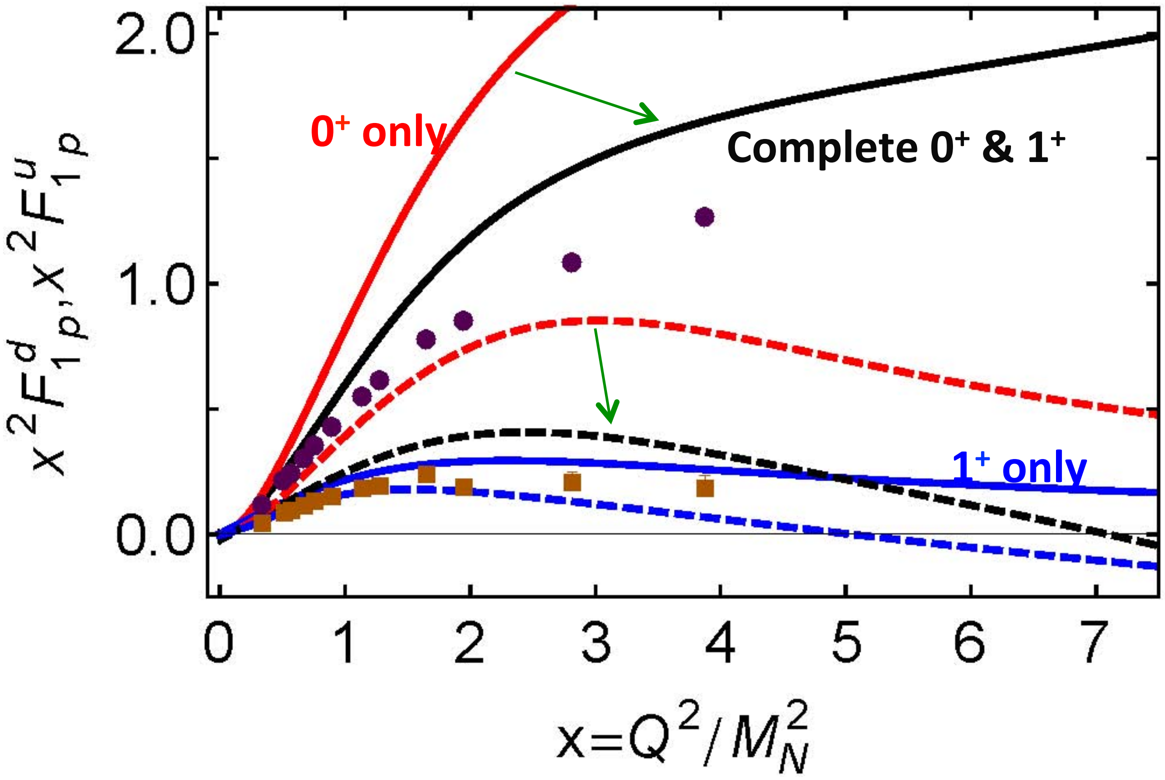


- These features entail that at x≈ 5 the electric form factor of the neutral neutron will become larger than that of the unit-charge proton!
- JLab12 will probe this prediction

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]

Diquark correlations

- u-quark = solid
- d-quark = dashed
- Plainly ,
  - presence of axial-vector diquark is crucial to agreement with data and is the origin of zero in F_1^d
  - scalar diquark alone
    - cannot describe data
    - does not produce a zero



J. Segovia et al., in progress

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