A Unified Treatment of the Nucleon, Delta and Roper Resonance

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XVI International Conference on Hadron Spectroscopy

Marriott at City Center, Newport News, VA

13-18 September, 2015

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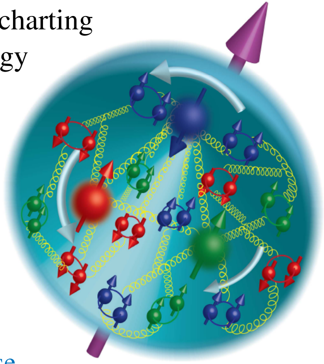
Roads to Discovery

- Understanding hadron structure (& QCD) means charting and computing the distribution of matter and energy within hadrons and nuclei
  - mapping correlations and exposing their influence are the hallmark of nuclear physics
  - but *a priori* have no idea what QCD can produce



- Solving QCD will have profound implications
  - it will explain how massless gluons and light quarks bind together to form hadrons & thereby explain the origin of $\sim$98% of the mass in the visible universe
  - *however given QCD's complexity, the best promise for progress is a strong interplay between experiment and theory*
- A key pathway is to exploit opportunities provided by new data on nucleon elastic and transition form factors
  - help chart the infrared evolution of QCD's coupling and dressed-masses
  - reveal correlations that are key to nucleon structure e.g. *diquarks*

Discover the meaning of *confinement* and its relation to *dynamical chiral symmetry breaking*

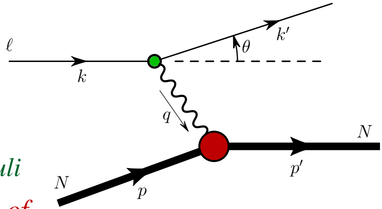
– origin of visible mass –

Nucleon Electromagnetic Form Factors

- Nucleon electromagnetic current

$$\langle J^\mu \rangle = \bar{u}(p') \left[\gamma^\mu \, F_1(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2\,M} \, F_2(Q^2) \right] u(p)$$

Dirac *Pauli*



- *Provide vital information on the distribution of charge and magnetization within the most basic element of nuclear physics*
  - form factors also directly probe confinement at all energy scales

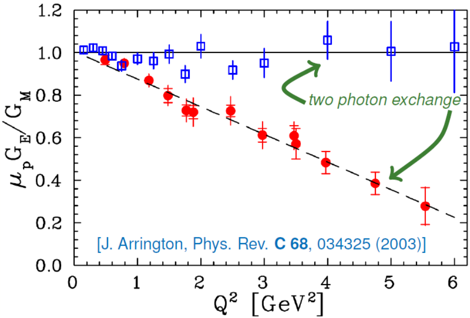
- Today accurate form factor measurements are creating a paradigm shift in our understanding of nucleon structure:
  - proton radius puzzle
  - $\mu_p \, G_{Ep}/G_{Mp}$ ratio and a possible zero-crossing
  - flavour decomposition and evidence for diquark correlations
  - meson-cloud effects
  - seeking verification of perturbative QCD scaling predictions & scaling violations

Nucleon Sachs Form Factors

- Experiment gives Sachs form factors: $G_E = F_1 - \frac{Q^2}{4\,M^2}\,F_2 \quad G_M = F_1 + F_2$

- Until the late 90s Rosenbluth separation experiments found that the $\mu_p\, G_{Ep}/G_{Mp}$ ratio was flat

- Polarization transfer experiments completely altered our picture of nucleon structure
  - distribution of charge and magnetization are not the same



- Proton charge radius puzzle $[7\sigma]$

$$\langle r_E^2 \rangle = -6\,\frac{\partial}{\partial Q^2}\,G_E(Q^2)\Big|_{Q^2=0}$$

$r_{Ep} = 0.84087 \pm 0.00039$ fm

muonic hydrogen [Pohl *et al.* (2010)]

$r_{Ep} = 0.8775 \pm 0.0051$ fm

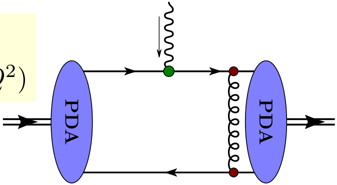
CODATA: $e\,p$ + e-hydrogen

  - one of the most interesting puzzles in hadron physics
  - so far defies explanation

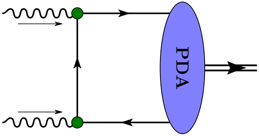
Form Factors in Conformal Limit ($Q^2 \to \infty$)

- At asymptotic energies hadron form factors factorize into *parton distribution amplitudes* & a hard scattering kernel [Farrar, Jackson; Lepage, Brodsky]
  - only the valence Fock state ($\bar{q}q$ or qqq) can contribute as $Q^2 \to \infty$
  - both confinement and asymptotic freedom in QCD are important in this limit
- Most is known about $\bar{q}q$ bound states, e.g., for the pion:

$$Q^2\, F_\pi(Q^2) \to 16\pi\, f_\pi^2\, \alpha_s(Q^2)$$



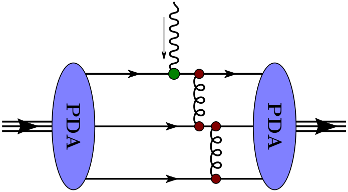
$$Q^2\, F_{\gamma^*\gamma\pi}(Q^2) \to 2\, f_\pi$$



- For the nucleon, normalization is not known

$$G_{E,M}(Q^2 \to \infty) \propto \alpha_s^2(Q^2)/Q^4$$

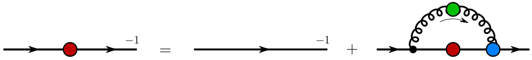
  - orbital angular momentum effects approach



- *Gluons play a critical role – formalism must reflex this!*

QCD's Dyson-Schwinger Equations

- The equations of motion of QCD $\Longleftrightarrow$ QCD's Dyson–Schwinger equations
  - an infinite tower of coupled integral equations
  - tractability $\Longrightarrow$ must implement a symmetry preserving truncation
- The most important DSE is QCD's gap equation $\Longrightarrow$ quark propagator

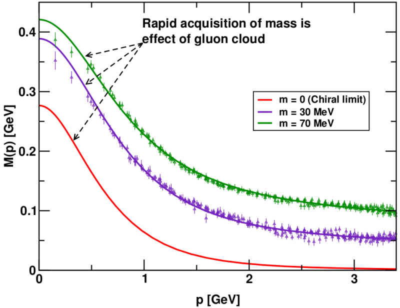


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

$$S(p) = \frac{Z(p^2)}{i\not p + M(p^2)}$$

- $S(p)$ has correct perturbative limit
- mass function, $M(p^2)$, exhibits dynamical mass generation
- complex conjugate poles
  - no real mass shell $\Longrightarrow$ confinement

[M. S. Bhagwat *et al.*, Phys. Rev. **C 68**, 015203 (2003)]



Nucleon Structure

- A robust description of the nucleon as a bound state of 3 dressed-quarks can only be obtained within an approach that respects Poincaré covariance
- Such a framework is provided by the Poincaré covariant Faddeev equation

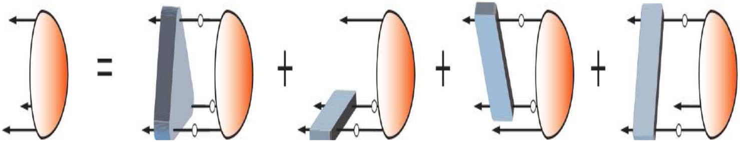


image from
Gernot Eichmann

  - sums all possible interactions between three dressed-quarks
  - much of 3-body interaction can be absorbed into renormalized 2-body interactions
  - *Faddeev eq. has solutions at discrete values of* $p^2\ (= M^2) \implies$ *baryon spectrum*

- A *prediction* of these approaches is that owing to DCSB in QCD – strong diquark correlations exist within baryons
  - any interaction that describes colour-singlet mesons also generates *non-pointlike* diquark correlations in the colour-$\bar{3}$ channel
  - where *scalar* (0^+) *& axial-vector* (1^+) *diquarks* most important for the nucleon

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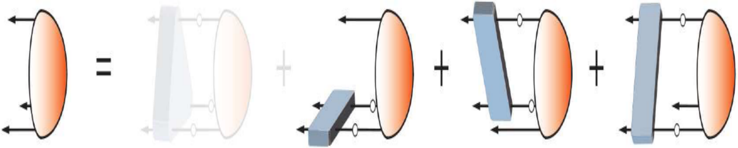

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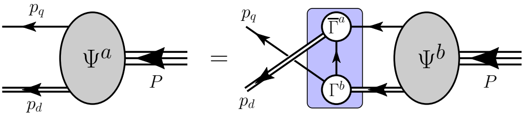
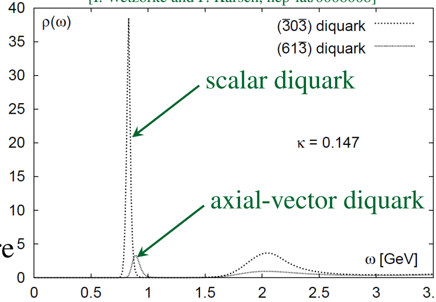
- Diquarks are dynamically generated correlations between quarks inside baryons



  - typically diquark sizes are similar to analogous mesons: $r_{0^+} \sim r_\pi$, $r_{1^+} \sim r_\rho$
- These dynamic qq correlations are not the static diquarks of old
  - all quarks participate in all diquark correlations
  - in a given baryon the Faddeev equation predicts a probability for each diquark cluster
  - for the nucleon: scalar $(0^+) \sim 70\%$
    axial-vector $(1^+) \sim 30\%$
- *Faddeev equation spectrum has significant overlap with constituent quark model and limited relation to Lichtenberg's quark+diquark model*
- Mounting evidence from hadron structure (e.g. PDFs, form factors) and lattice

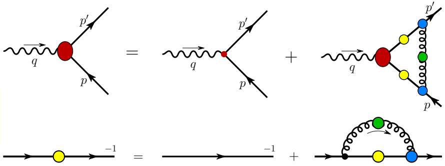
[I. Wetzorke and F. Karsch, hep-lat/0008008]



Nucleon EM Form Factors from DSEs

- A robust description of form factors is only possible if *electromagnetic gauge invariance* is respected; equivalently all relevant *Ward-Takahashi identities* (WTIs) must be satisfied

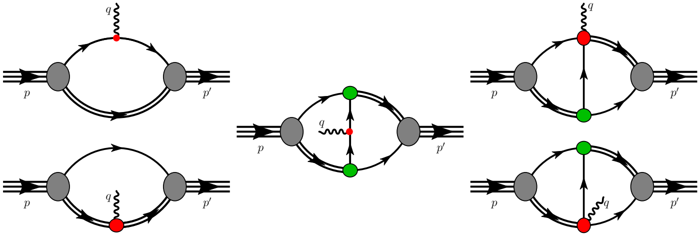
- For quark-photon vertex WTI implies:



$$q_\mu\, \Gamma^\mu_{\gamma qq}(p',p) = \hat{Q}_q \left[S_q^{-1}(p') - S_q^{-1}(p)\right]$$

  - transverse structure unconstrained

- Diagrams needed for a gauge invariant nucleon EM current in DSEs



- Feedback with experiment can shed light on elements of QCD via DSEs

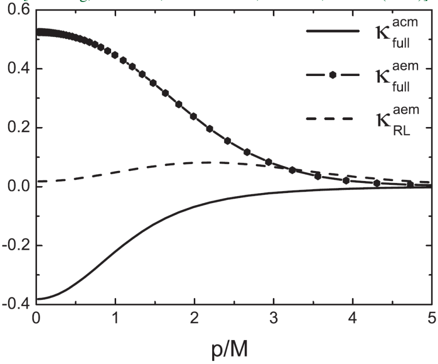
Beyond Rainbow Ladder Truncation

- Include *"anomalous chromomagnetic"* term in quark-gluon vertex

$$\frac{1}{4\pi}\, g^2\, D_{\mu\nu}(\ell)\, \Gamma_\nu(p',p) \quad \to \quad \alpha_{\text{eff}}(\ell)\, D^{\text{free}}_{\mu\nu}(\ell)\, [\gamma_\nu + i\sigma^{\mu\nu} q_\nu\, \tau_5(p',p) + \ldots]$$

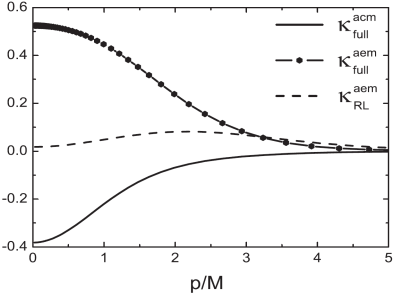
- In chiral limit *anomalous chromomagnetic* term can only appear through DCSB – since operator flips quark helicity
- EM properties of a spin-$\frac{1}{2}$ point particle are characterized by two quantities:
  - charge: e & magnetic moment: μ
- Expect strong gluon dressing to produce non-trivial electromagnetic structure for a dressed quark
  - recall dressing produces – from massless quark – a $M \sim 400\,\text{MeV}$ dressed quark
- Large anomalous chromomagnetic moment in the quark-gluon vertex – *produces a large quark anomalous electromagnetic moment*
  - *dressed quarks are not point particles!*

[L. Chang, Y. -X. Liu, C. D. Roberts, PRL **106**, 072001 (2011)]

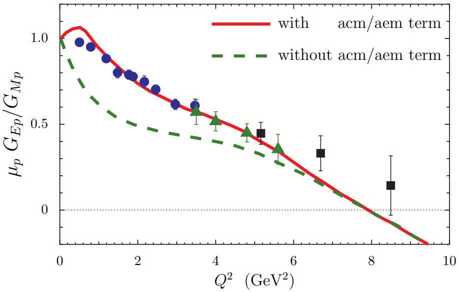


Proton G_E/G_M Ratio

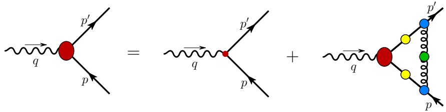
[L. Chang, Y. -X. Liu, C. D. Roberts, Phys. Rev. Lett. **106**, 072001 (2011)]



[I. C. Cloët, C. D. Roberts, Prog. Part. Nucl. Phys. **77**, 1 (2014)]



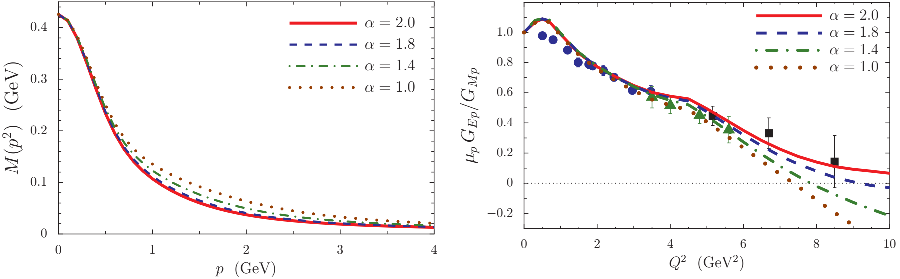
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
  - power law suppressed at large Q^2



- Illustrates how feedback with EM *form factor measurements* can help constrain the *quark–photon vertex* and therefore the *quark–gluon vertex* within the DSE framework
  - knowledge of quark–gluon vertex provides $\alpha_s(Q^2)$ within DSEs $\Leftrightarrow$ confinement

Proton G_E form factor and DCSB

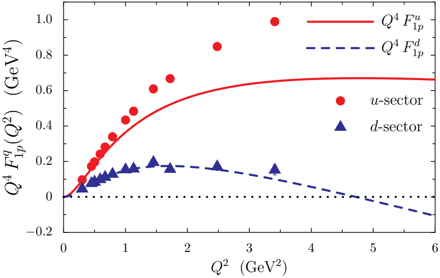
[I. C. Cloët, C. D. Roberts and A. W. Thomas, Phys. Rev. Lett. **111**, 101803 (2013)]

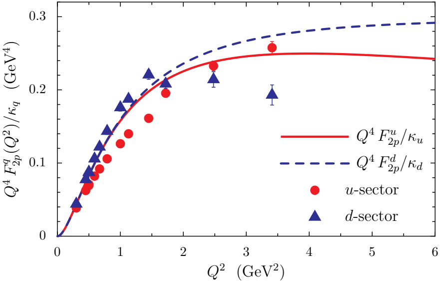


- Find that slight changes in $M(p^2)$ on the domain $1 \lesssim p \lesssim 3\,\mathrm{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
  - *strong indication that position of a zero is very sensitive to underlying dynamics and the nature of the transition from nonperturbative to perturbative QCD*
- Zero in $G_E = F_1 - \frac{Q^2}{4\,M_N^2}\,F_2$ largely determined by evolution of $Q^2\,F_2$
  - F_2 is sensitive to DCSB through the dynamically generated quark anomalous electromagnetic moment – *vanishes in perturbative limit*
  - the quicker the perturbative regime is reached the quicker $F_2 \to 0$

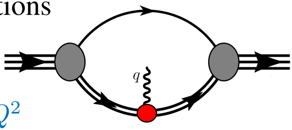
Flavour separated proton form factors

[I. C. Cloët, W. Bentz, A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]





- Prima facie, these experimental results are remarkable
  - u and d quark sector form factors have very different scaling behaviour
- However, when viewed in context of diquark correlations results are straightforward to understand
  - in proton (uud) the d quark is "bound" inside a scalar diquark $[ud]$ 70% of the time; $u[ud]$ diquark $\implies 1/Q^2$

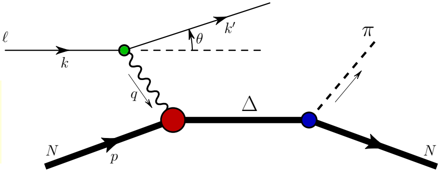


- Zero in F^d_{1p} a result of interference between scalar and axial-vector diquarks
  - location of zero indicates relative strengths – correlated with d/u ratio as $x \to 1$

Nucleon to Resonance Transitions

- Given the challenges posed by non-perturbative QCD it is insufficient to study hadron ground-states alone
- Nucleon transition form factors provide a critical extension to elastic form factors – providing more windows into and different perspectives on quark-gluon dynamics
  - e.g. nucleon resonances are more sensitive to long-range effects in QCD than the properties of ground states . . . analogous to exotic and hybrid mesons
- Important example is $N \to \Delta$ transition – parametrized by three form factors
  - $G_E^*(Q^2), \quad G_M^*(Q^2), \quad G_C^*(Q^2)$
  - if both N and Δ were purely S-wave then $\quad G_E^*(Q^2) = 0 = G_C^*(Q^2)$
- When analyzing the $N \to \Delta$ transition it is common to construct the ratios:

$$R_{EM} = -\frac{G_E^*}{G_M^*}, \qquad R_{SM} = -\frac{|\boldsymbol{q}|}{2\,M_\Delta}\,\frac{G_C^*}{G_M^*}$$



$N \to \Delta$ *form factors from the DSEs*

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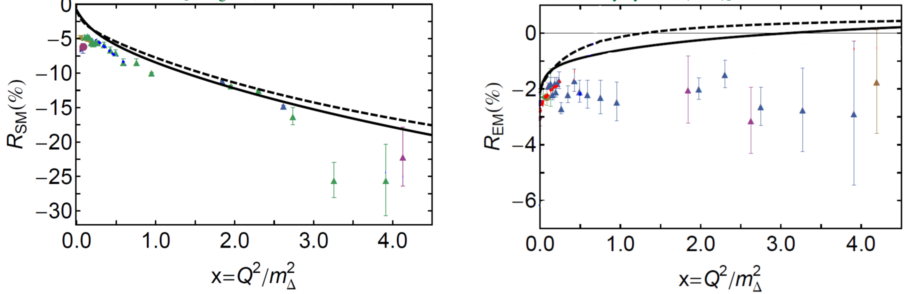
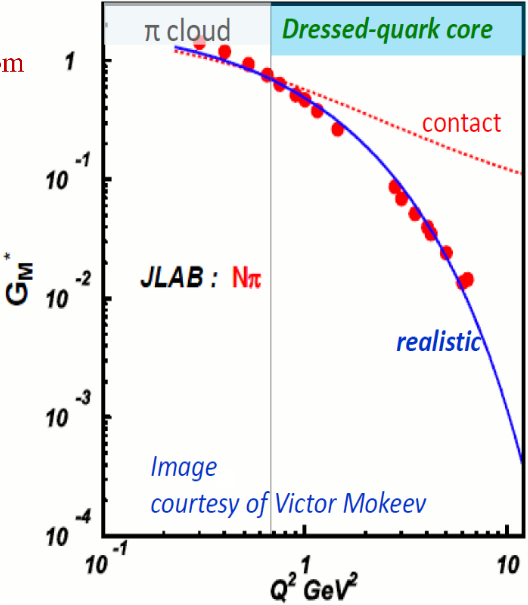
[J. Segovia, I. C. Cloët, C. D. Roberts and S. M. Schmidt, Few Body Syst. **57**, (2014)]



- For $R_{SM} = -\frac{|\boldsymbol{q}|}{2\,M_\Delta}\frac{G_C^*}{G_M^*}$ DSEs reproduces rapid fall off with Q^2
- Find that $R_{EM} = -\frac{G_E^*}{G_M^*}$ is a particular sensitive measure of *quark orbital angular momentum* within the nucleon and Δ
- At large Q^2 helicity conservation demands: $R_{SM} \to$ constant, $R_{EM} \to 1$
  - however these asymptotic results are not reached until incredibility large Q^2 – which will not be accessible at any present or foreseeable facility
- Comparison with Argonne-Osaka results for $N \to \Delta$ suggest that the pion cloud is masking expected zero-crossing in R_{EM}

$N \to \Delta$ magnetic form factor

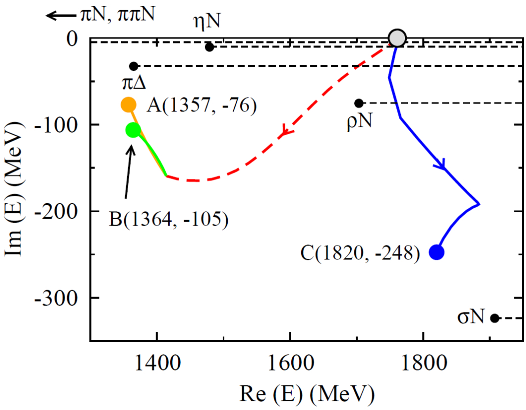
- Results are indistinguishable from data for $Q^2 \gtrsim 0.7\,\mathrm{GeV}^2$
- With same set of inputs provide a unified description of nucleon, Delta and $N \to \Delta$ form factors
- For example, same
  - quark propagators
  - diquark masses and amplitudes
  - Faddeev kernel
  - electromagnetic current operator



Three poles, each seeded by a single dressed quark core:

Two poles associated with Roper resonance and the third with the next higher P_{11} resonance

[H. Kamano, *et al.*, Phys. Rev. C **88**, no. 3, 035209 (2013)]

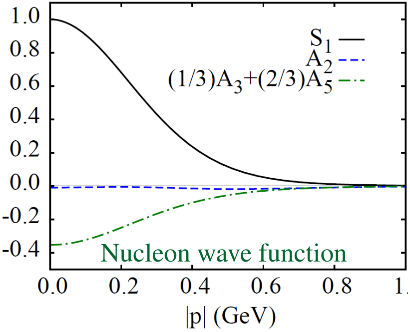


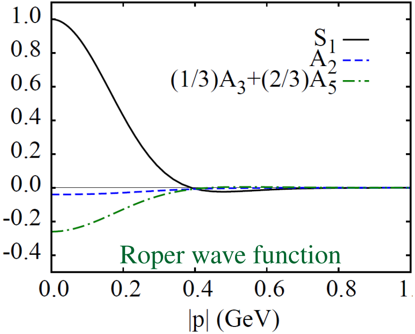
- The Excited Baryon Analysis Center (EBAC), resolved a fifty-year puzzle by demonstrating that the Roper resonance is the proton's first radial excitation
  - its lower-than-expected mass owes to a dressed-quark core shielded by a dense cloud of pions and other mesons

  [Decadal Report on Nuclear Physics: Exploring the Heart of Matter]

Roper Resonance from the DSEs

[J. Segovia, B. El-Bennich, E. Rojas, I. C. Cloët, C. D. Roberts, S. S. Xu and H. S. Zong, arXiv:1504.04386 [nucl-th]]

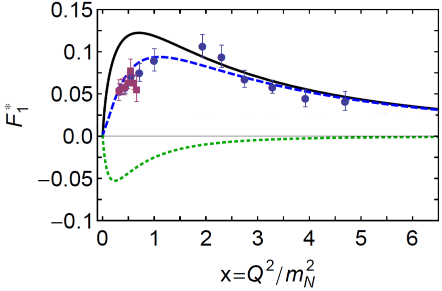


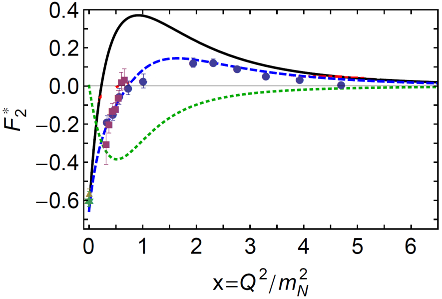


- The Faddeev equation that produces the nucleon also gives its excited states
  - amplitudes for the lightest excited state typically possess a zero
  - therefore lightest nucleon excited state is a radial excitation $\Longleftrightarrow$ Roper resonance
  - "quark core" mass: $M_R = 1.73\,\text{GeV}$; c.f. Argonne-Osaka group $M_R = 1.76\,\text{GeV}$
- Now have a unified description of the nucleon, Delta and Roper baryons
- Find e.g. that the Roper charge radius is 80% larger than the nucleon's

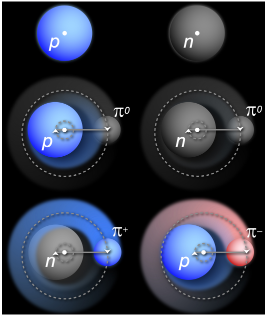
Nucleon → Roper transition form factors

[J. Segovia, B. El-Bennich, E. Rojas, I. C. Cloët, C. D. Roberts, S. S. Xu and H. S. Zong, arXiv:1504.04386 [nucl-th]]





- Results agree well with data for $Q^2 \gtrsim 2\,m_N^2$ & at the real photon point
- However contemporary kernels just produce a hadron's *dressed-quark core*
  - pion cloud contributions are absent from our calculation, however these are inferred from the deviation with data
  - on domain $0 < Q^2 \lesssim 2\,m_N^2$ pion cloud contributions should be negative and deplete the transition form factors

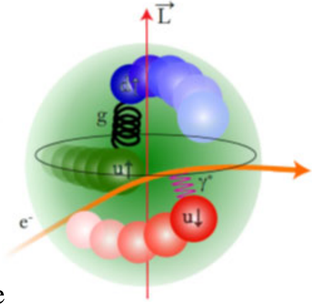


Looking to the Future

- The DSEs are primarily a hadron structure tool
  - a detailed study of the hadron spectrum is (currently) beyond the scope of the approach
  - need much more sophisticated kernels with explicit resonance contributions

- However, studies are underway to determine the "*quark core*" contributions to other low-lying nucleon to resonance transitions:
  e.g., $N(1535) - J^P = \frac{1}{2}^-$ & $N(1520) - J^P = \frac{3}{2}^-$
- More broadly we are beginning a detailed study of nucleon generalized and transverse momentum dependent PDFs
  - an aim is to predict a large amount of hadron structure data and relate it to a single universal quark-gluon vertex
  - constraints from experiment & lattice will result in significantly improved kernels
- DSEs can then be used to study domains not explored by experiment and not reachable by lattice

Conclusion

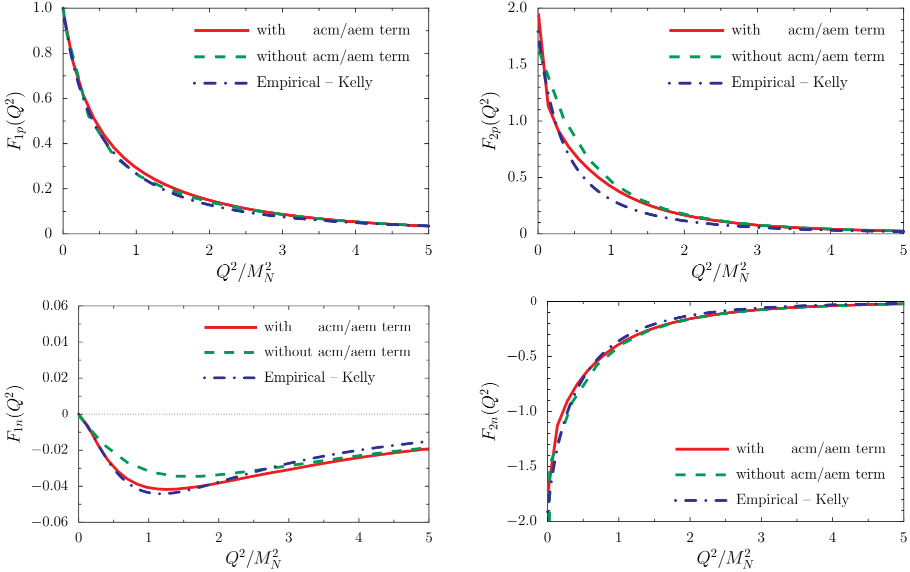


- QCD will only be solved by deploying a diverse array of experimental and theoretical methods
  - must define and solve the problems of confinement and its relationship with DCSB
- These are two of the most important challenges in fundamental Science
- Nucleon elastic and transition form factors provide an important avenue with which to address these critical questions
- We have provided a unified treatment of the nucleon, Delta and Roper elastic and transition form factors
  - demonstrating e.g. that the location of zero's in form factors – e.g. G_{Ep}, F_{1p}^{d} – provide tight constraints on QCD dynamics
- *Continuum-QCD approaches are essential; are at the forefront of guiding experiment & provide rapid feedback; building intuition & understanding*

Backup Slides

Nucleon Dirac & Pauli form factors

[ICC, G. Eichmann, B. El-Bennich, T. Klahn and C. D. Roberts,, Few Body Syst. **46**, 1 (2009)]



- quark aem term has important influence on Pauli form factors at low Q^2

Neutron G_E/G_M Ratio

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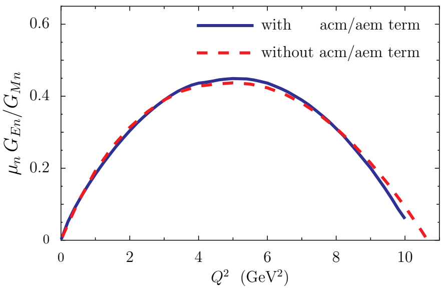
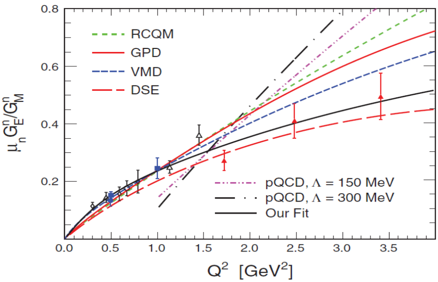
[ICC, C. D. Roberts, Prog. Part. Nucl. Phys. **77**, 1 (2014)]



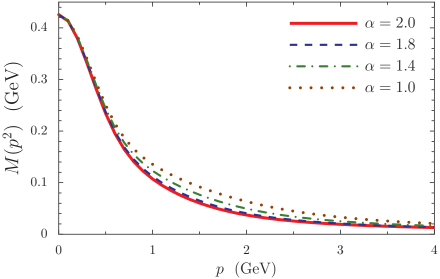
[S. Riordan *et al*, Phys. Rev. Lett. **105**, 262302 (2010)]

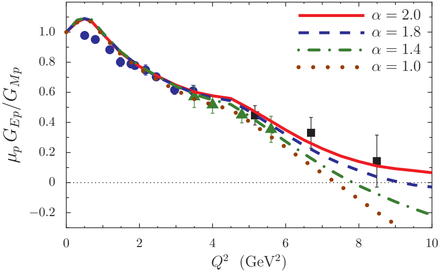


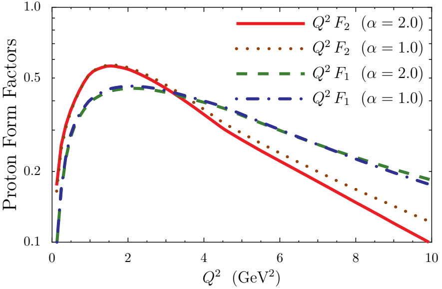
- Quark anomalous chromomagnetic moment – which drives the large anomalous electromagnetic moment – has only a minor impact on neutron Sachs form factor ratio
- Predict a zero-crossing in G_{En}/G_{Mn} at $Q^2 \sim 11\,\mathrm{GeV}^2$
- DSE *predictions* were confirmed on domain $1.5 \lesssim Q^2 \lesssim 3.5\,\mathrm{GeV}^2$

Proton G_E form factor and DCSB

[I. C. Cloët, C. D. Roberts and A. W. Thomas, Phys. Rev. Lett. **111**, 101803 (2013)]







- Recall: $G_E = F_1 - \frac{Q^2}{4\,M_N^2}\,F_2$
- Only G_E is senitive to these small changes in the mass function
- *Accurate determination of zero crossing would put important contraints on quark-gluon dynamics within DSE framework*