Impacts of Dynamical Chiral Symmetry Breaking

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QCD-TNT4

Unraveling the organization of the QCD tapestry

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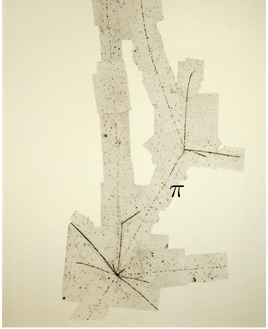
The Pion – Nature's strong messenger

- Hideki Yukawa in 1935 postulated a strongly interacting particle of mass $\sim 100\,\mathrm{MeV}$
  - Yukawa called this particle a "meson"
- Cecil Powell in 1947 discovered the π-meson from cosmic ray tracks in a photographic emulsion – a technique Cecil developed

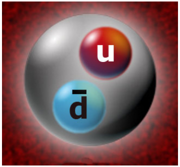
Nuclear Pion Capture

[Nature 160 (1947) 486-492]



- Cavendish Lab had said method is incapable of "*reliable and reproducible precision measurements*"
- The measured *pion* mass was: $130 - 150\,\mathrm{MeV}$
- Both Yukawa & Powell received Nobel Prize – in 1949 and 1950 respectively
- Discovery of pion was beginning of particle physics; before long there was the particle *zoo*

The Pion in QCD



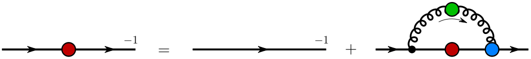
- Today the pion is understood as both a bound state of a *dressed-quark* and a *dressed-antiquark* in QFT and the Goldstone mode associated with DCSB in QCD
- This dichotomous nature has numerous ramifications, e.g.:

$$m_\rho/2 \sim M_N/3 \sim 350\,\text{MeV} \qquad \text{however} \qquad m_\pi/2 \simeq 0.2 \times 350\,\text{MeV}$$

- The pion is unusually light, the key is dynamical chiral symmetry breaking
  - in coming to understand the pion's lepton-like mass, DCSB (and confinement) has been exposed as the origin of more than 98% of the mass in the visible Universe
- QCD is characterized by two emergent phenomena: *confinement & DCSB*
  - it is also the only known example in nature of a fundamental QFT that is innately non-perturbative
- *In the quest to understand QCD must discover the origin of confinement, its relationship to DCSB and understand how these phenomenon influence hadronic observables*

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

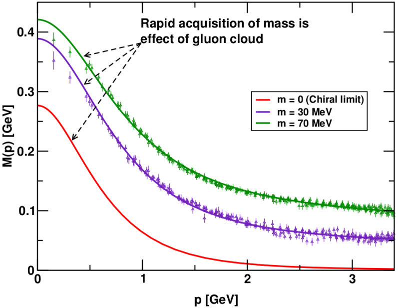


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

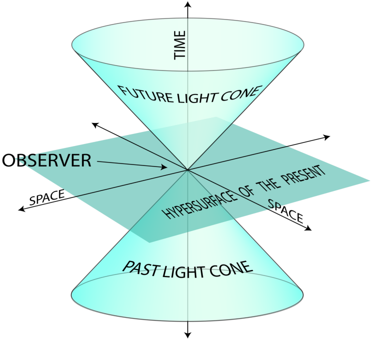
- $S(p)$ has correct perturbative limit
- mass function, $M(p^2)$, exhibits dynamical mass generation
- complex conjugate poles
  - no real mass shell $\Longrightarrow$ confinement

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



Light-Front Wave Functions

- In equal-time quantization a hadron wave function is a frame dependent concept
  - boost operators are dynamical, that is, they are interaction dependent
- In high energy scattering experiments particles move at near speed of light
  - natural to quantize a theory at equal light-front time: $\tau = (t + z)/\sqrt{2}$



- Light-front quantization $\Longrightarrow$ light-front WFs; many remarkable properties:
  - frame-independent; probability interpretation – as close as QFT gets to QM
  - boosts are kinematical – *not dynamical*
- Parton distribution amplitudes (PDAs) are (almost) observables & are related to light-front wave functions

$$\varphi(x) = \int d^2\vec{k}_\perp \; \psi(x, \vec{k}_\perp)$$

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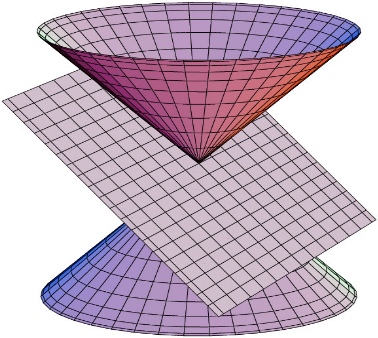

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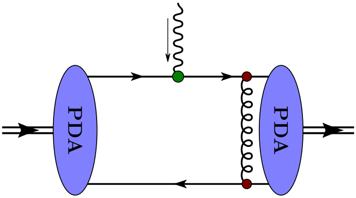
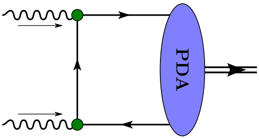
$$\varphi(x) = \int d^2\vec{k}_\perp \; \psi(x, \vec{k}_\perp)$$

Pion's Parton Distribution Amplitude

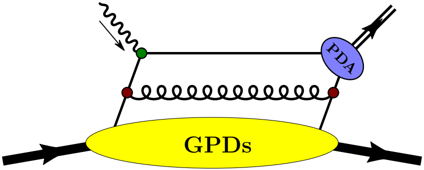
- pion's PDA – $\varphi_\pi(x)$: *is a probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*
  - it's a function of the light-cone momentum fraction $x = \frac{k^+}{p^+}$ and the scale Q^2

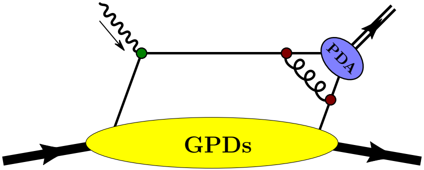


$$Q^2\, F_\pi(Q^2) \to 16\pi\, f_\pi^2\, \alpha_s(Q^2)$$



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





- PDAs enter numerous hard exclusive scattering processes

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  - it's a function of the light-cone momentum fraction $x = \frac{k^+}{p^+}$ and the scale Q^2
- The pion's PDA is defined by

$$f_\pi \, \varphi_\pi(x) = Z_2 \int \frac{d^4k}{(2\pi)^2} \, \delta\left(k^+ - x\, p^+\right) \mathrm{Tr}\left[\gamma^+\gamma_5 \, S(k)\, \Gamma_\pi(k,p)\, S(k-p)\right]$$

- $S(k)\,\Gamma_\pi(k,p)\,S(k-p)$ is the pion's Bethe-Salpeter wave function
  - in the non-relativistic limit it corresponds to the Schrodinger wave function
- $\varphi_\pi(x)$: is the axial-vector projection of the pion's Bethe-Salpeter wave function onto the light-front [at twist-2 also pseudoscalar projection]
- Pion PDA is an essentially nonperturbative quantity whose asymptotic form is known; in this regime governs, e.g., Q^2 dependence of pion form factor

$$Q^2 \, F_\pi(Q^2) \overset{Q^2\to\infty}{\longrightarrow} 16\,\pi\, f_\pi^2 \, \alpha_s(Q^2) \qquad \Longleftrightarrow \qquad \varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$$

QCD Evolution & Asymptotic PDA

- ERBL (Q^2) evolution for pion PDA [c.f. DGLAP equations for PDFs]

$$\mu \frac{d}{d\mu}\,\varphi(x,\mu) = \int_0^1 dy\, V(x,y)\,\varphi(y,\mu)$$

- This evolution equation has a solution of the form

$$\varphi_\pi(x,Q^2) = 6\,x\,(1-x)\left[1 + \sum\nolimits_{n=2,\,4,\ldots} a_n^{3/2}(Q^2)\, C_n^{3/2}(2x-1)\right]$$

  - $\alpha = 3/2$ because in $Q^2 \to \infty$ limit QCD is invariant under the collinear conformal group $SL(2;\mathbb{R})$
  - Gegenbauer-$\alpha = 3/2$ polynomials are irreducible representations $SL(2;\mathbb{R})$

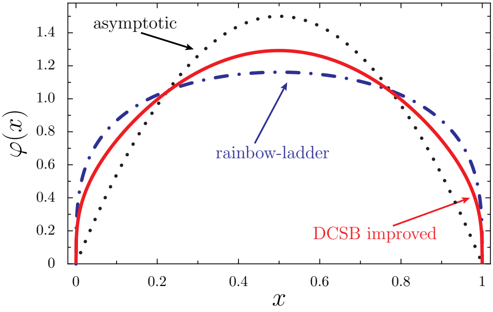
- The coefficients of the Gegenbauer polynomials, $a_n^{3/2}(Q^2)$, evolve logarithmically to zero as $Q^2 \to \infty$: $\varphi_\pi(x) \to \varphi_\pi^{\mathrm{asy}}(x) = 6\,x\,(1-x)$

- At what scales is this a good approximation to the pion PDA?

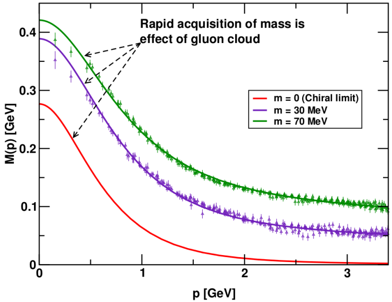
- E.g., AdS/QCD find $\varphi_\pi(x) \sim x^{1/2}\,(1-x)^{1/2}$ at $Q^2 = 1\,\mathrm{GeV}^2$; expansion in terms of $C_n^{3/2}(2x-1)$ convergences slowly: $a_{32}^{3/2} / \, a_2^{3/2} \sim 10\,\%$

Pion PDA from the DSEs

[L. Chang, ICC, *et al.*, Phys. Rev. Lett. **110**, 132001 (2013)]



[C.D. Roberts, Prog. Part. Nucl. Phys. 61 50 (2008)]



- Both DSE results, each using a different Bethe-Salpeter kernel, exhibit a pronounced broadening compared with the asymptotic pion PDA
  - scale of calculation is given by renormalization point $\zeta = 2\,\mathrm{GeV}$
- A realization of DCSB on the light-front
- As we shall see the dilation of pion's PDA will influence the Q^2 evolution of the pion's electromagnetic form factor

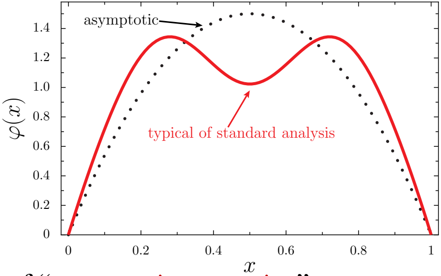
Pion PDA from lattice QCD

- Lattice QCD can only determine one non-trivial moment

$$\int_0^1 dx\,(2\,x-1)^2\varphi_\pi(x) = 0.27 \pm 0.04$$

[V. Braun *et al.*, Phys. Rev. D **74**, 074501 (2006)]

  - scale is $Q^2 = 4\,\text{GeV}^2$



- Standard practice to fit first coefficient of "*asymptotic expansion*" to moment

$$\varphi_\pi(x,Q^2) = 6\,x\,(1-x)\left[1+\sum_{n=2,\,4,\ldots} a_n^{3/2}(Q^2)\,C_n^{3/2}(2x-1)\right]$$

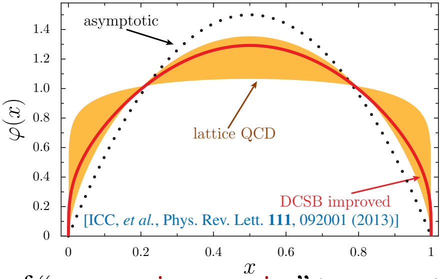
  - however this expansion is guaranteed to converge rapidly only when $Q^2 \to \infty$
  - this procedure results in a *double-humped* pion PDA

- Advocate using a *generalized expansion*

$$\varphi_\pi(x,Q^2) = N_\alpha\,x^\alpha(1-x)^\alpha\left[1+\sum_{n=2,\,4,\ldots} a_n^{\alpha+1/2}(Q^2)\,C_n^{\alpha+1/2}(2x-1)\right]$$

- Find $\varphi_\pi \simeq x^\alpha(1-x)^\alpha,\ \alpha = 0.35^{+0.32}_{-0.24}$; good agreement with DSE: $\alpha \sim 0.52$

Pion PDA from lattice QCD



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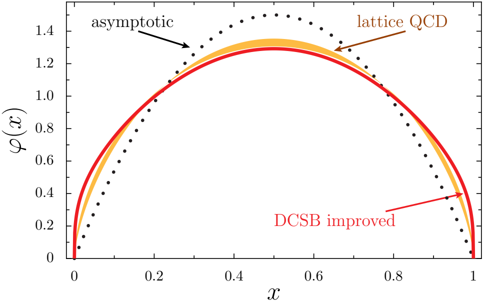
Updated Pion PDA from lattice QCD

- Generalized expansion

$$\varphi_\pi(x) = N_\alpha\, x^\alpha (1-x)^\alpha \left[1 + \sum a_n^{\alpha+}(Q^2)\, C_n^{\alpha+}(2x-1)\right]$$



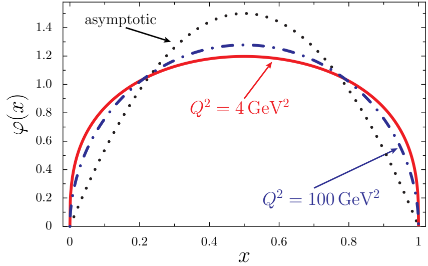
- Updated lattice QCD moment: [V. Braun *et al.*, arXiv:1503.03656 [hep-lat]]

$$\int_0^1 dx\,(2\,x-1)^2 \varphi_\pi(x) = 0.2361\,(41)\,(39)\,(?)$$

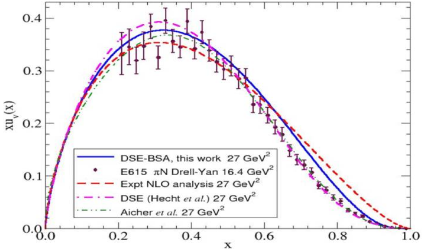
- DSE prediction:

$$\int_0^1 dx\,(2\,x-1)^2 \varphi_\pi(x) = 0.251$$

[I. C. Cloët, *et al.*, Phys. Rev. Lett. **111**, 092001 (2013)]

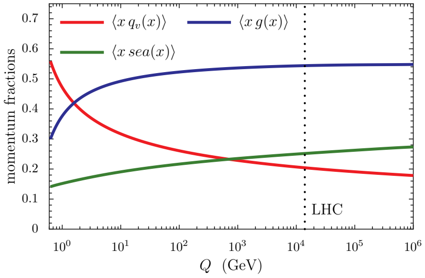


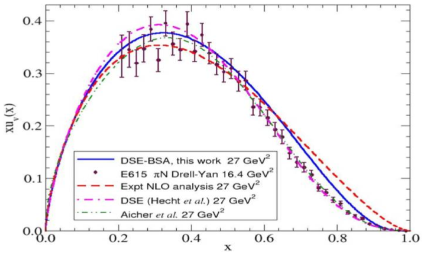
[T. Nguyen, *et al.*, Phys. Rev. C **83**, 062201 (2011)]



- Under leading order Q^2 evolution the pion PDA remains broad to well above $Q^2 > 100\,\mathrm{GeV}^2$, compared with $\varphi_\pi^{\mathrm{asy}}(x) = 6\,x\,(1-x)$
- *Consequently, the asymptotic form of the pion PDA is a poor approximation at all energy scales that are either currently accessible or foreseeable in experiments on pion elastic and transition form factors*
- Importantly, $\varphi_\pi^{\mathrm{asy}}(x)$ is only guaranteed be an accurate approximation to $\varphi_\pi(x)$ when pion valence quark PDF satisfies: $q_v^\pi(x) \sim \delta(x)$
- This is far from valid at forseeable energy scales

When is the Pion's Valence PDF Asymptotic





- LO QCD evolution of momentum fraction carried by valence quarks

$$\langle x\, q_v(x)\rangle (Q^2) = \left(\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}\right)^{\gamma_{qq}^{(0)2}/(2\beta_0)} \langle x\, q_v(x)\rangle (Q_0^2) \quad \text{where} \quad \frac{\gamma_{qq}^{(0)2}}{2\beta_0} > 0$$

  - therefore, as $Q^2 \to \infty$ we have $\langle x\, q_v(x)\rangle \to 0$ implies $q_v(x) \propto \delta(x)$

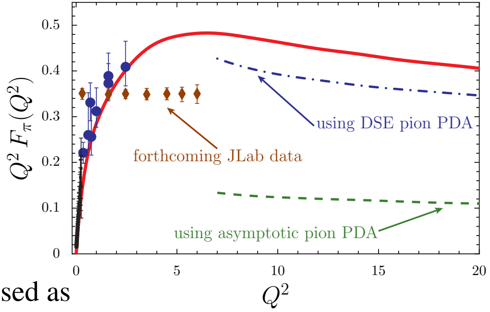
- At LHC energies valence quarks still carry 20% of pion momentum
  - the gluon distribution saturates at $\langle x\, g(x)\rangle \sim 55\%$

- *Asymptotia is a long way away!*

Pion Elastic Form Factor

- Direct, symmetry-preserving computation of pion form factor predicts maximum in $Q^2\,F_\pi(Q^2)$ at $Q^2 \approx 6\,\mathrm{GeV}^2$
  - magnitude of this product is determined by strength of DCSB at all accessible scales

[L. Chang, ICC, *et al.*, Phys. Rev. Lett. **111**, 141802 (2013)]



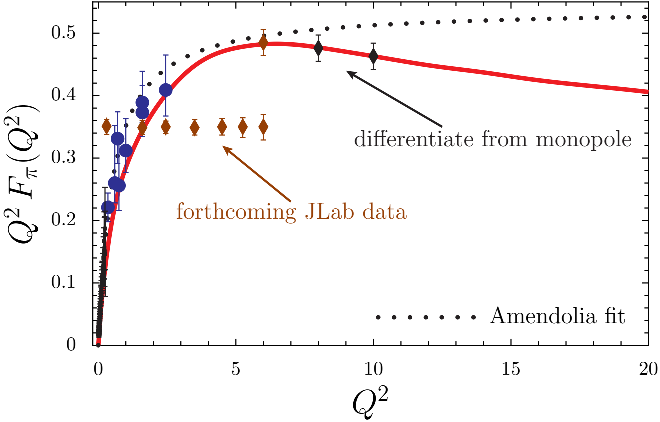
- The QCD prediction can be expressed as

$$Q^2 F_\pi(Q^2) \overset{Q^2\gg\Lambda^2_{\rm QCD}}{\sim} 16\,\pi\,f_\pi^2\,\alpha_s(Q^2)\,w_\pi^2; \qquad w_\pi = \frac{1}{3}\int_0^1 dx\,\frac{1}{x}\,\varphi_\pi(x)$$

- Within DSEs there is consistency between the direct pion form factor calculation and that obtained using the DSE pion PDA
  - 15% disagreement explained by higher order/higher-twist corrections

- *We predict that QCD power law behaviour – with QCD's scaling law violations – sets in at* $Q^2 \sim 8\,\mathrm{GeV}^2$

Measuring onset of Perturbative scaling



- To observe onset of perturbative power law behaviour – *to differentiate from a monopole* – optimistically need data at $8\,\text{GeV}^2$ but likely also at $10\,\text{GeV}^2$
  - this is a very challenging task experimentally
- Scaling predictions are valid for both spacelike and timelike momenta
  - timelike data show promise as the means of verifying modern predictions

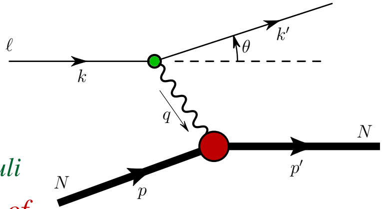
The Nucleon

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*

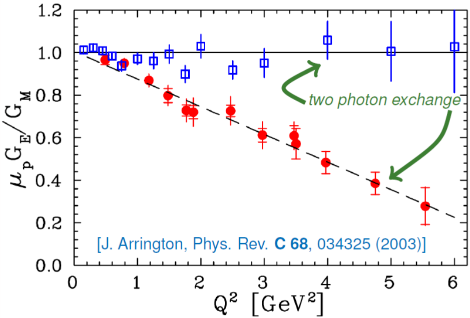


- *Provide vital information on the distribution of charge and magnetization within the most basic element of nuclear physics*
  - form factors also directly probe confinement at all energy scales

- 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 [7σ]

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

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

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

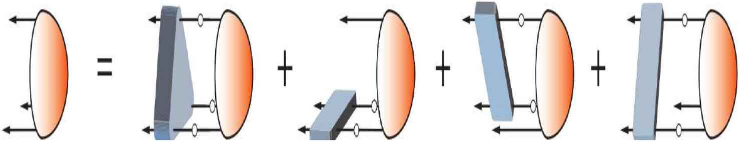
$r_{Ep} = 0.8775 \pm 0.0051$ fm

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

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

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



  - sums all possible interactions between three dressed-quarks
  - much of the three-body interaction can be absorbed into renormalized two-body interactions

- 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 and axial-vector diquarks* are most important for the nucleon

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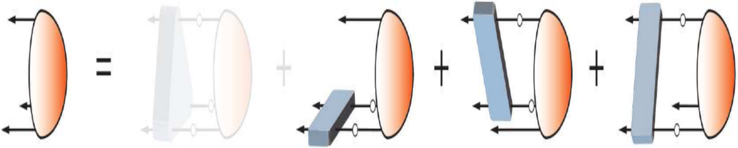

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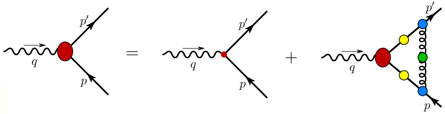
Nucleon EM Form Factors from DSEs

- 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

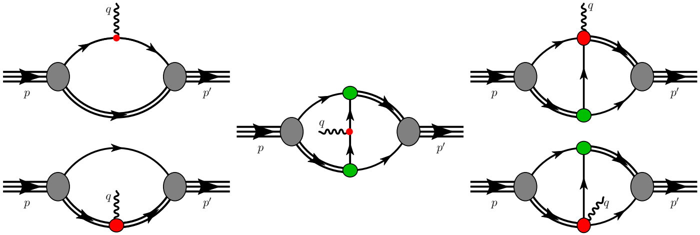
- For quark-photon vertex WTI implies:



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

  - 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

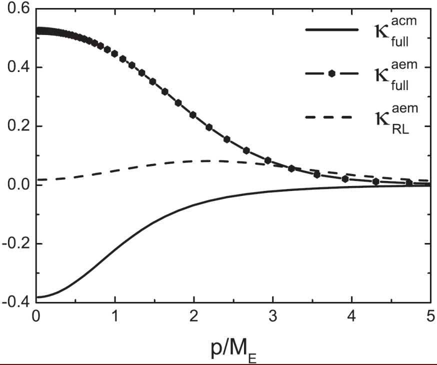
Beyond Rainbow Ladder Truncation

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

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

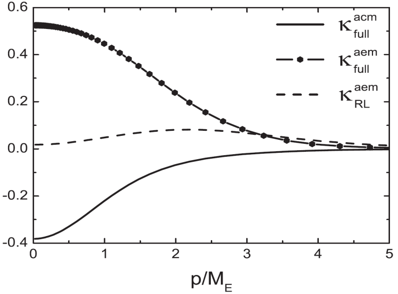
- In chiral limit *anomalous chromomagnetic* term can only appear through DCSB – since operator flips quark helicity
- EM properties of a spin-$\frac{1}{2}$ point particle are characterized by two quantities:
  - charge: e & magnetic moment: μ
- Expect strong gluon dressing to produce non-trivial electromagnetic 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)]

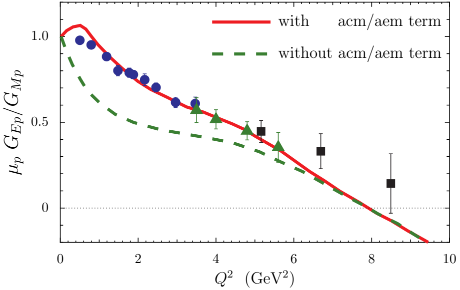


Proton G_E/G_M *Ratio*

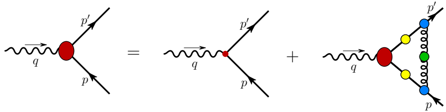
[L. Chang, Y. -X. Liu, C. D. Roberts, Phys. Rev. Lett. **106**, 072001 (2011)]



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



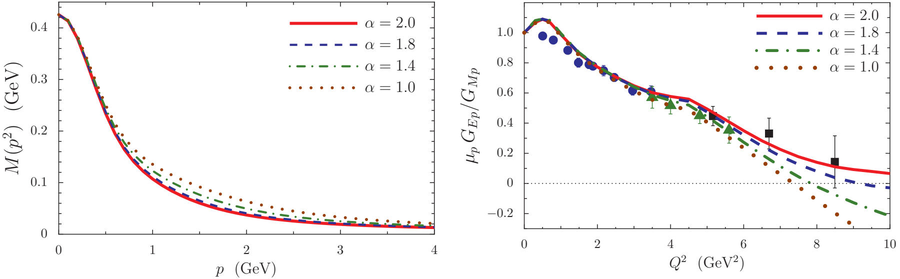
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
  - power law suppressed at large Q^2



- 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

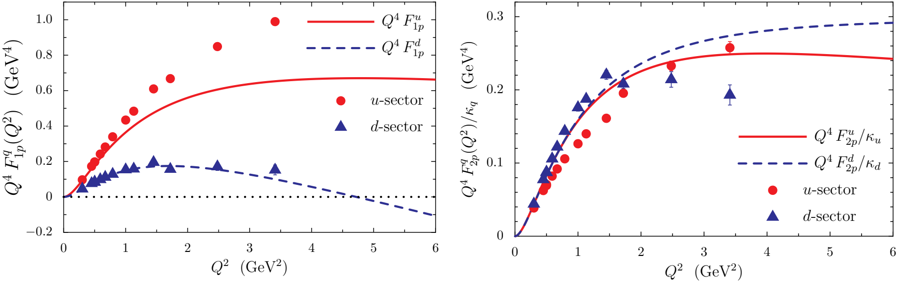
[I. C. Cloët, C. D. Roberts and A. W. Thomas, Phys. Rev. Lett. **111**, 101803 (2013)]



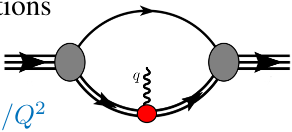
- Find that slight changes in $M(p^2)$ on the domain $1 \lesssim p \lesssim 3\,\text{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
  - *strong indication that position of a zero is very sensitive to underlying dynamics and the nature of the transition from nonperturbative to perturbative 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)]



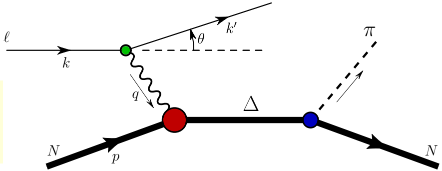
- Prima facie, these experimental results are remarkable
  - u and d quark sector form factors have very different scaling behaviour
- However, when viewed in context of diquark correlations results are straightforward to understand
  - in proton (uud) the d quark is much more likely to be in a scalar diquark $[ud]$ than a u quark; diquark $\Longrightarrow 1/Q^2$



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

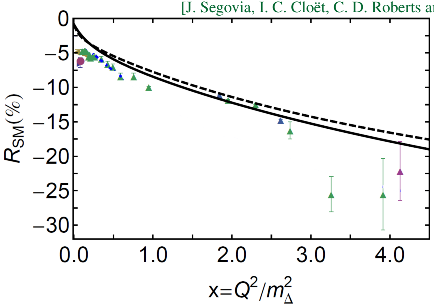
- Given the challenges posed by non-perturbative QCD it is insufficient to study hadron ground-states alone
- Nucleon transition form factors provide a critical extension to elastic form factors – providing more windows into and different perspectives on quark-gluon dynamics
  - e.g. nucleon resonances 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:

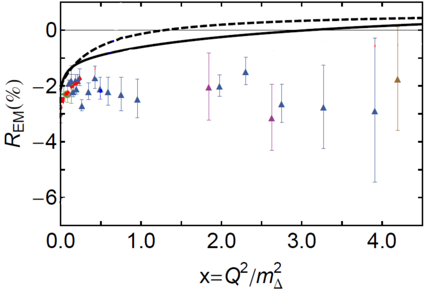
$$R_{EM} = -\frac{G_E^*}{G_M^*}, \qquad R_{SM} = -\frac{|\boldsymbol{q}|}{2\,M_\Delta}\,\frac{G_C^*}{G_M^*}$$



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

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

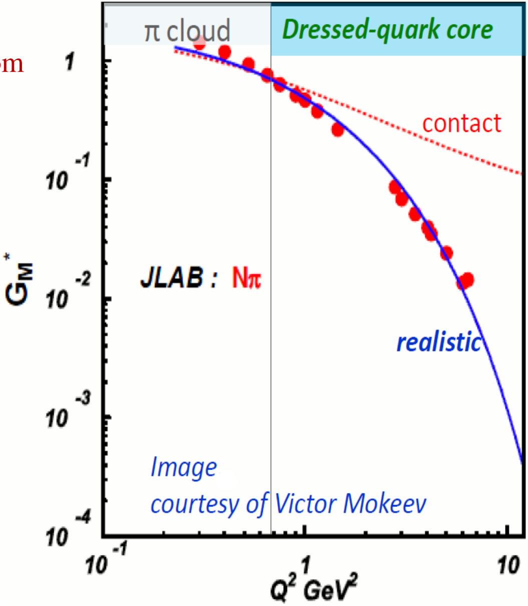




- For $R_{SM} = -\frac{|\boldsymbol{q}|}{2\,M_\Delta}\frac{G_C^*}{G_M^*}$ DSEs reproduces rapid fall off with Q^2
- Find that $R_{EM} = -\frac{G_E^*}{G_M^*}$ is a particular sensitive measure of *quark orbital angular momentum* within the nucleon and Δ
- At large Q^2 helicity conservation demands: $R_{SM} \to$ 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 suggest that the pion cloud is masking expected zero in R_{EM}

$N \to \Delta$ magnetic form factor

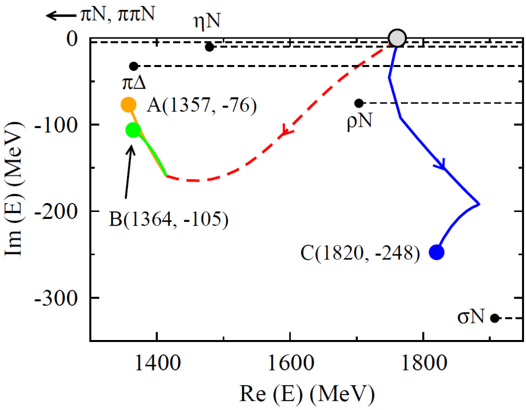
- Results are indistinguishable from data for $Q^2 \gtrsim 0.7\,\mathrm{GeV}^2$
- With same set of inputs provide a unified description of nucleon, Delta and $N \to \Delta$ form factors
- For example, same
  - quark propagators
  - diquark masses and amplitudes
  - Faddeev kernel
  - electromagnetic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

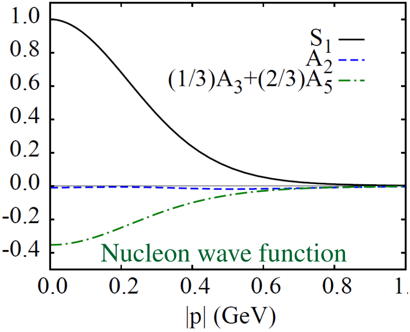


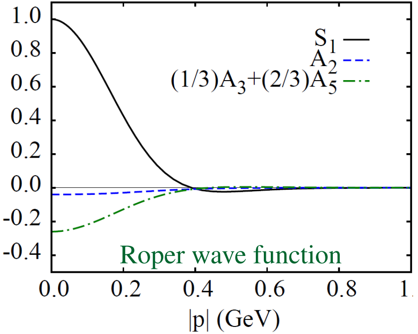
- The Excited Baryon Analysis Center (EBAC), resolved a fifty-year puzzle by demonstrating that the Roper resonance is the proton's first radial excitation
  - its lower-than-expected mass owes to a dressed-quark core shielded by a dense cloud of pions and other mesons

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

Roper Resonance from the DSEs

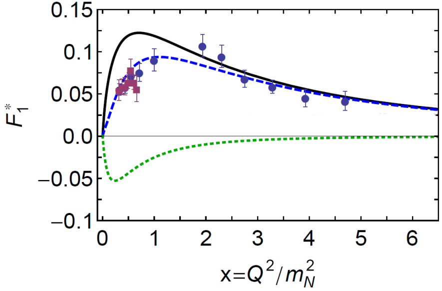
[J. Segovia, B. El-Bennich, E. Rojas, I. C. Cloët, C. D. Roberts, S. S. Xu and H. S. Zong, arXiv:1504.04386 [nucl-th]]

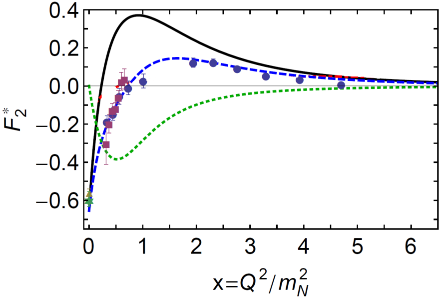




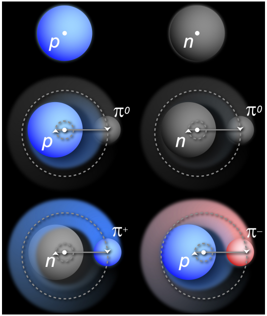
- The Faddeev equation that produces the nucleon also gives its excited states
  - amplitudes for the lightest excited state typically possess a zero
  - therefore lightest nucleon excited state is a radial excitation $\Longleftrightarrow$ Roper resonance
  - "quark core" mass: $M_R = 1.73\,\mathrm{GeV}$; c.f. Argonne-Osaka group $M_R = 1.76\,\mathrm{GeV}$
- 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

[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]]



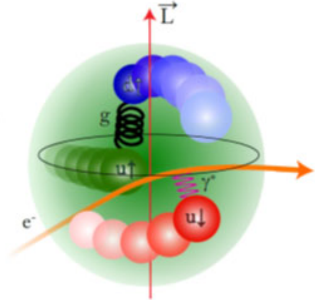


- Results agree well with data for $Q^2 \gtrsim 2\, m_N^2$ & at the real photon point
- However contemporary kernels just produce a hadron's *dressed-quark core*
  - pion cloud contributions are absent from our calculation, however these are inferred from the deviation with data
  - on domain $0 < Q^2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



Conclusion

- QCD and therefore hadron physics is unique:
  - must confront a fundamental theory in which the elementary degrees-of-freedom are confined and only hadrons reach detectors



- 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
- Determined the pion form factor for all spacelike momenta
  - $Q^2 F_\pi(Q^2)$ peaks at $6\,\text{GeV}^2$, with maximum directly related to DCSB
  - predict that QCD power law behaviour sets in at $Q^2 \sim 8\,\text{GeV}^2$
  - DSEs & lattice QCD agree pion PDA is much broader than asymptotic result
- Location of a zero in G_{Ep}/G_{Mp} is a sensitive measure of DCSB in QCD
- *Continuum-QCD approaches are essential; are at the forefront of guiding experiment & provide rapid feedback; building intuition & understanding*