Role of DCSB in the Pion & Nucleon

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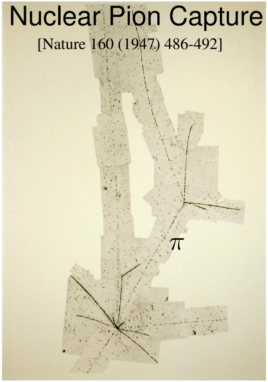
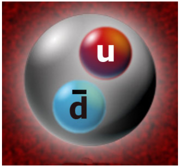
The Pion – Nature's strong messenger

- 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



- 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.:

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

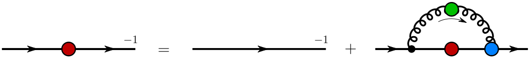
- The pion is unusually light, the key is dynamical chiral symmetry breaking
  - in coming to understand the pion's lepton-like mass, DCSB (and confinement) has been exposed as the origin of more than 98% of the mass in the visible Universe

- A unifying challenge of Hadron Physics is to:
  - discover the nature of *confinement* and its relation to *dynamical chiral symmetry breaking*

- *Computation is critical – as data alone can only reveal limited aspects about the theory underlying the strong interaction*

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

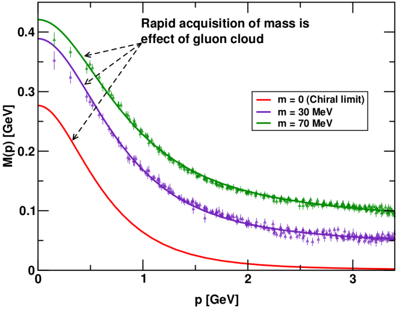


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

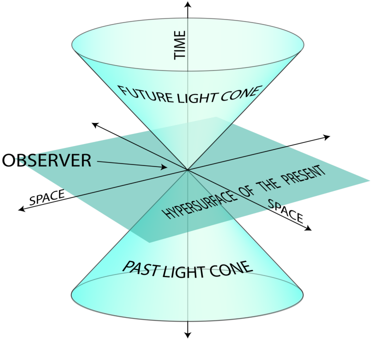
- $S(p)$ has correct perturbative limit
- mass function, $M(p^2)$, exhibits dynamical mass generation
- complex conjugate poles
  - no real mass shell $\Longrightarrow$ confinement

[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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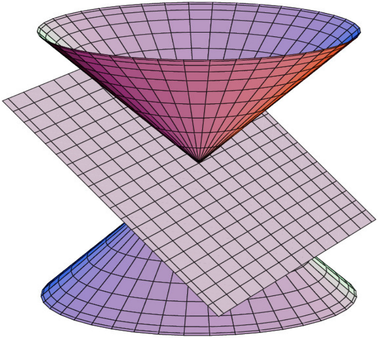

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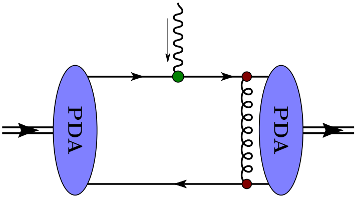
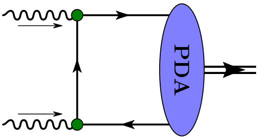
Pion's Parton Distribution Amplitude

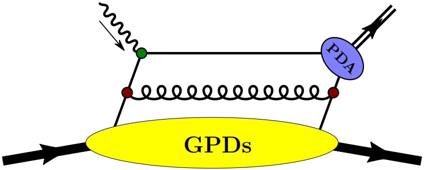
- pion's PDA – $\varphi_\pi(x)$: *is a probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*
  - it's a function of the light-cone momentum fraction $x = \frac{k^+}{p^+}$ and the scale Q^2

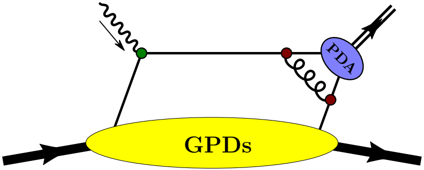


$$Q^2\, F_\pi(Q^2) \to 16\pi\, f_\pi^2\, \alpha_s(Q^2)$$



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





- PDAs enter numerous hard exclusive scattering processes

Pion's Parton Distribution Amplitude

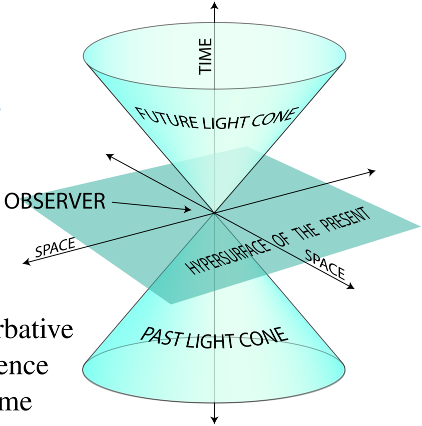
- The pion's PDA is defined by

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

- $S(k)\,\Gamma_\pi(k,p)\,S(k-p)$ 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

- Pion PDA is a *scale dependent* non-perturbative quantity, which e.g., alters the Q^2 dependence of pion form factor in the asymptotic regime



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

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

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

  - $\alpha = 3/2$ 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 $SL(2;\mathbb{R})$

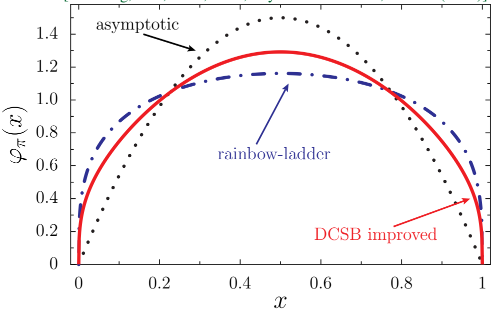
- The coefficients of the Gegenbauer polynomials, $a_n^{3/2}(Q^2)$, evolve logarithmically to zero as $Q^2 \to \infty$: $\varphi_\pi(x) \to \varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$

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

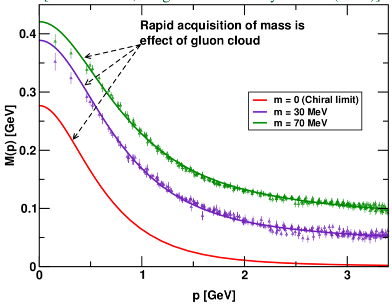
- E.g., AdS/QCD find $\varphi_\pi(x) \sim x^{1/2}\,(1-x)^{1/2}$ at $Q^2 = 1\,\text{GeV}^2$; expansion in terms of $C_n^{3/2}(2x-1)$ convergences slowly: $a_{32}^{3/2} / \, a_2^{3/2} \sim 10\,\%$

Pion PDA from the DSEs

[L. Chang, ICC, CDR, *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 $\xi = 2\,\text{GeV}$
- A realization of DCSB on the light-front
- *ERBL evolution demonstrates that the pion's PDA remains broad & concave for all accessible scales in current and conceivable experiments*
- Broading of PDA influences the Q^2 evolution of the pion's EM form factor

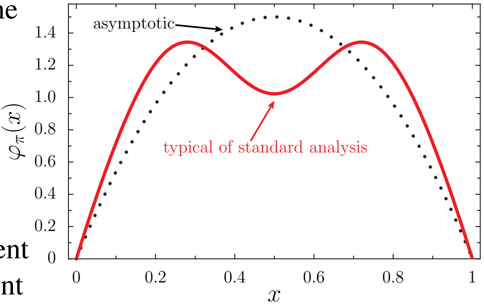
Pion PDA from Lattice QCD

- Currently, lattice QCD can determine only one non-trivial moment, e.g.:

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

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

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



- 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 $Q^2 \to \infty$
  - method results in a *double-humped* pion PDA – not supported by BSE WFs

- 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: $\alpha \sim 0.52$

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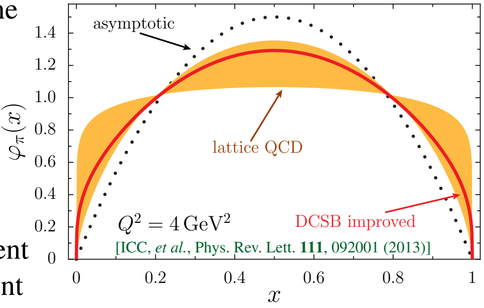

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- Most recent lattice QCD moment:

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

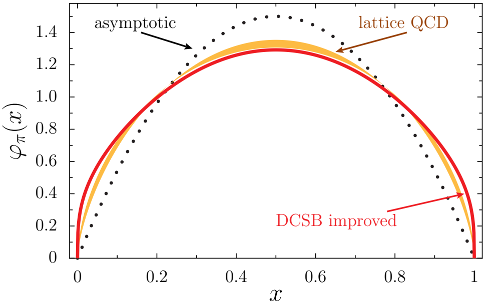
[V. M. Braun, *et al.*, Phys. Rev. D **92**, no. 1, 014504 (2015)]

- DSE prediction:

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

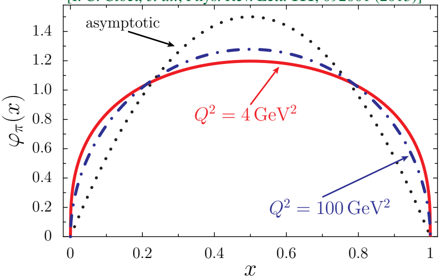
- *Near complete agreement between DSE prediction and latest lattice QCD result*

- Conclude that the pion PDA is a broad concave function
  - *double humped distributions are no longer tenable*

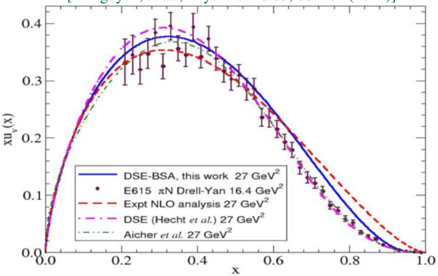


When is the Pion's PDA Asymptotic

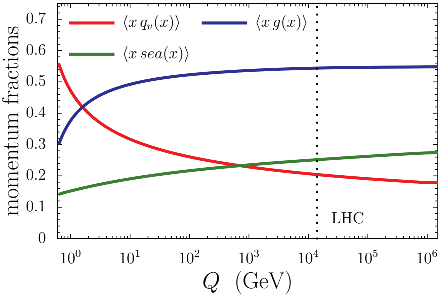
[I. C. Cloët, *et al.*, Phys. Rev. Lett. **111**, 092001 (2013)]

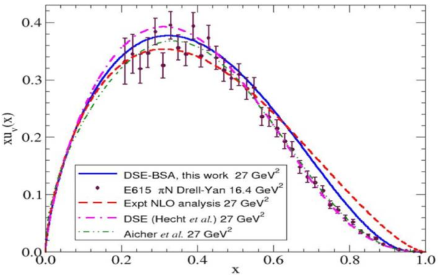


[T. Nguyen, *et al.*, Phys. Rev. C **83**, 062201 (2011)]



- 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





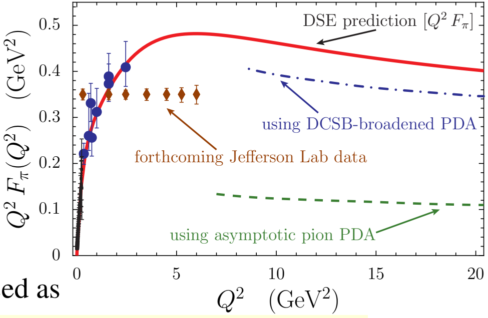
- LO QCD evolution of momentum fraction carried by valence quarks

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

  - 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

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



- 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
- The QCD prediction can be expressed as

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

- Find consistency between the *direct pion form factor calculation* and the QCD hard-scattering formula – if DSE pion PDA is used
  - 15% disagreement may be explained by higher order/higher-twist corrections
- *Predict that QCD power law behavior – with QCD's scaling law violations – sets in at* $Q^2 \sim 8\,\mathrm{GeV}^2$ *[Featured in 2015 NP Long Range Plan]*

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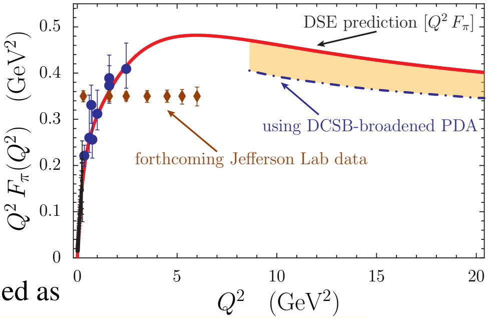

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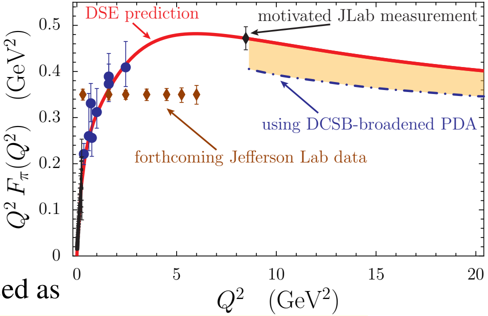

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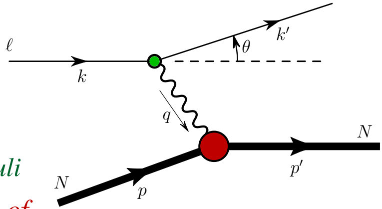
The Nucleon

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 hadrons and nuclei*
  - form factors also directly probe confinement at all energy scales

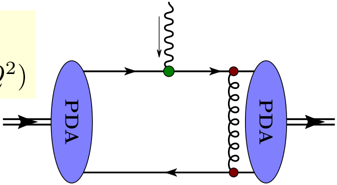
- Today accurate form factor measurements are creating a paradigm shift in our understanding of nucleon structure:
  - proton radius puzzle
  - $\mu_p \, G_{Ep}/G_{Mp}$ ratio and a possible zero-crossing
  - flavor decomposition and evidence for diquark correlations
  - meson-cloud effects
  - seeking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

Form Factors in Conformal Limit

- At asymptotic energies hadron form factors factorize into *parton distribution amplitudes* & a hard scattering kernel [Farrar, Jackson; Lepage, Brodsky; Radyushkin, Efremov]
  - only the valence Fock state ($\bar{q}q$ or qqq) can contribute as $Q^2 \to \infty$
  - both confinement and asymptotic freedom are important in this limit

- Most is known about $\bar{q}q$ bound states, e.g., for the pion:

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



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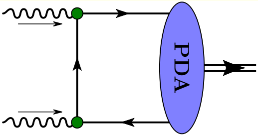
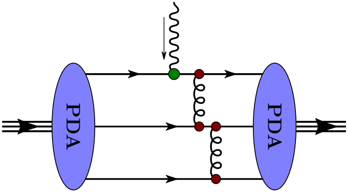


- For the nucleon, normalization is not known

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

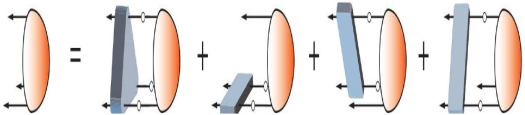
  - orbital angular momentum affects approach



- *Gluons play a critical role – formalism must reflect this & the DSEs do*

Diquarks & quark-sector form factors

- Nucleon wave function obtained from a Poincaré covariant Faddeev equation

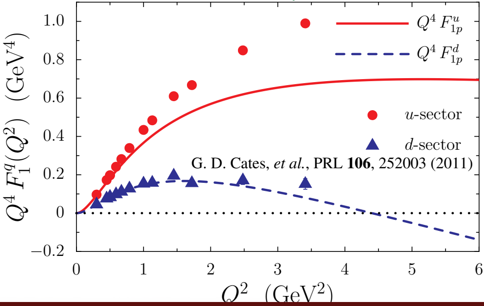


  - a *prediction* of these approaches is that owing to DCSB in QCD – strong *non-pointlike* diquark correlations exist within baryons
  - *scalar diquarks dominant for nucleon – has numerous empirical consequences*

- For example, consider the flavor separated proton form factors:

  u and d quark-sectors have very different scaling behavior

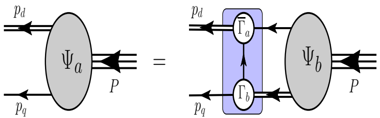
[I. C. Cloët, W. Bentz, A. W. Thomas, Phys. Rev. C **90**, 045202 (2014)]



- Prima facie a remarkable result, but naturally explained by dominance of scalar diquarks
  - in the proton (uud) the d quark is "bound" inside a scalar diquark $[ud]$ 70% of the time – therefore d-quark receives additional $1/Q^2$

Diquarks & quark-sector form factors

- Nucleon wave function obtained from a Poincaré covariant Faddeev equation



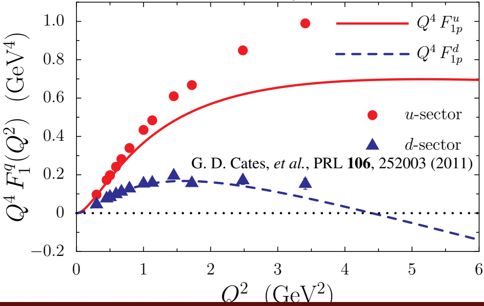
  - a *prediction* of these approaches is that owing to DCSB in QCD – strong *non-pointlike* diquark correlations exist within baryons
  - *scalar diquarks dominant for nucleon – has numerous empirical consequences*

- For example, consider the flavor separated proton form factors:

  u and d quark-sectors have very different scaling behavior

- Prima facie a remarkable result, but naturally explained by dominance of scalar diquarks
  - in the proton (uud) the d quark is "bound" inside a scalar diquark $[ud]$ 70% of the time – therefore d-quark receives additional $1/Q^2$

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



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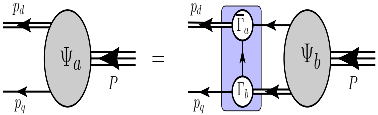

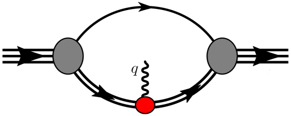

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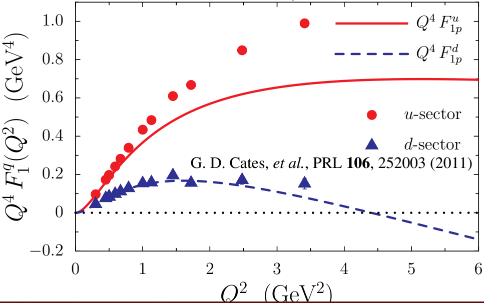
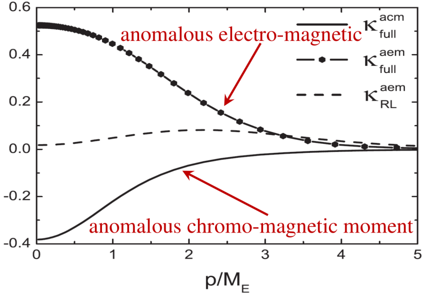
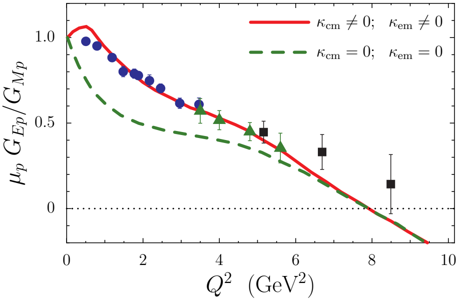


Proton G_E/G_M *Ratio*

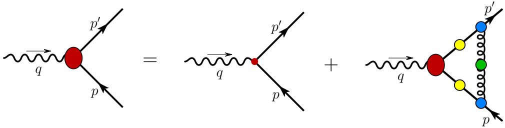
[L. Chang, Y. -X. Liu, CDR, Phys. Rev. Lett. **106**, 072001 (2011)]



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



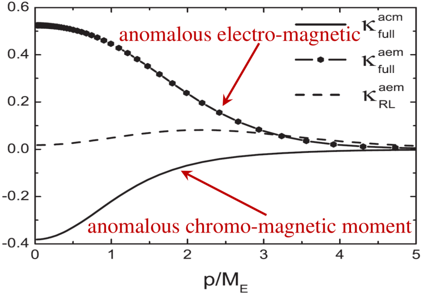
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
  - power law suppressed at large Q^2



- Feedback with EM *form factor measurements* helps constrain the *quark–photon vertex* and – via DSEs – the *quark–gluon vertex … current focus of much continuum and lattice analysis*
  - knowledge of quark–gluon vertex provides $\alpha_s(Q^2)$ within DSEs $\Leftrightarrow$ confinement

Neutron G_E/G_M Ratio

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



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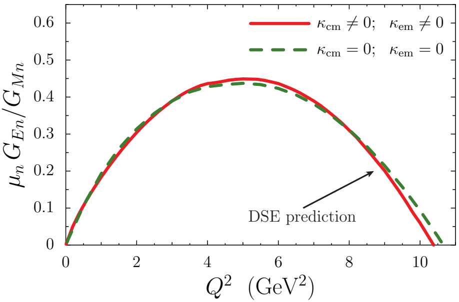

- Dressed quark anomalous chromo- ($\Longrightarrow$ electro-) magnetic moment has only a minor impact on neutron Sachs form factor ratio – *cancellations*
- The DSE *prediction* was confirmed on domain $1.5 \lesssim Q^2 \lesssim 3.5\,\mathrm{GeV}^2$
  - *shortcomings in other approaches have been exposed*
- Predict a zero-crossing in G_{En}/G_{Mn} at $Q^2 \sim 11\,\mathrm{GeV}^2$
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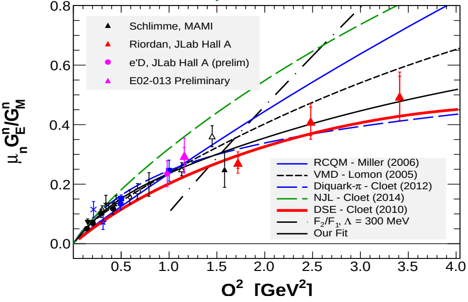
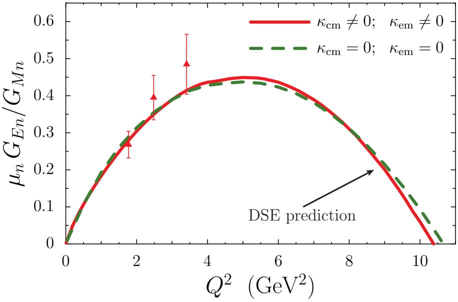
Neutron G_E/G_M Ratio

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



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



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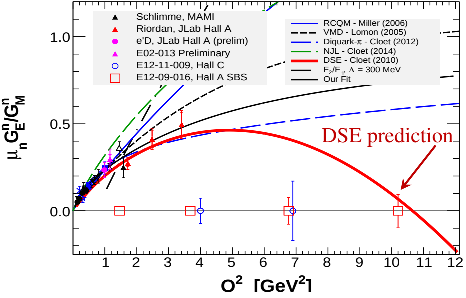

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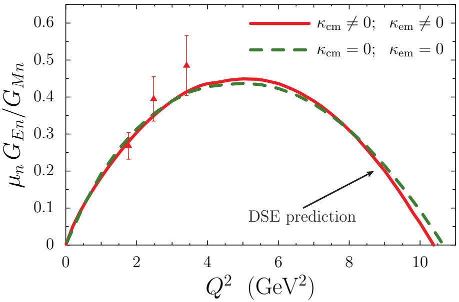

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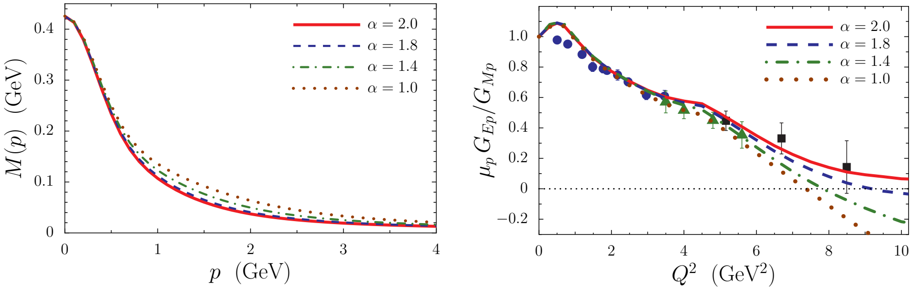
Proton G_E form factor & DCSB

[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 conformal limit*
  - the quicker the perturbative/conformal regime is reached the quicker $F_2 \to 0$

Conclusion

- Find that DCSB drives numerous effects in QCD, e.g.:
  - hadron masses & confinement
  - $Q^2\,F_\pi(Q^2)$ peaks at $6\,\mathrm{GeV}^2$
  - predict that QCD power law behaviour sets in at $Q^2 \sim 8\,\mathrm{GeV}^2$
  - dressed quarks have large anomalous chromo- & electro-magnetic moments
  - diquark correlations important for nucleon structure
  - e.g. location of zero's in form factors – G_{Ep}, F^d_{1p}, etc – provide tight constraints on QCD dynamics
- Research has stimulated numerous experiments, e.g.:
  - pion and kaon form factors
  - neutron form factors at large Q^2

Result featured in 2015 NP LRP

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