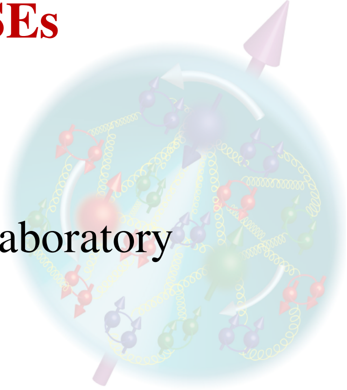
Hadron and Nuclear Structure from the DSEs



Ian Cloët

Argonne National Laboratory

Joint Hall A & C Summer Collaboration Meeting

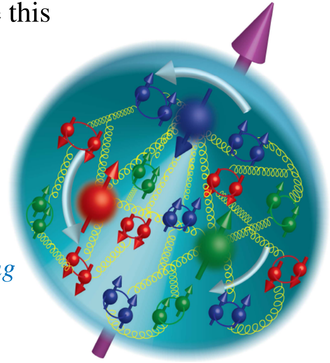
Jefferson Lab, 23–24 June 2016

U.S. DEPARTMENT OF ENERGY | Office of Science

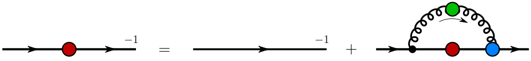
Argonne NATIONAL LABORATORY

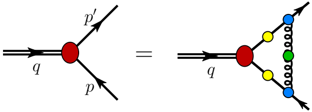
QCD: The Unifying Challenge

- Understanding QCD means to chart and compute this distribution of matter and energy within hadrons and nuclei – together with the complementary process of fragmentation functions
  - *a priori* have no idea what QCD can produce – but gives raise to ∼98% of mass in the visible universe
  - must understand the emergent phenomena of *confinement* and *dynamical chiral symmetry breaking*
  - *best promise for progress is a strong interplay between experiment and theory*



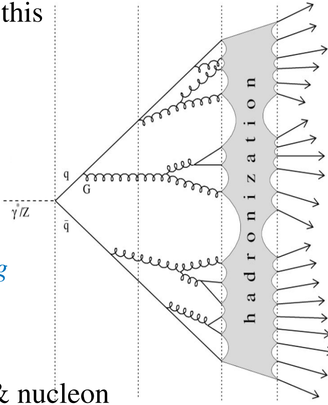
- Key pathways are provided by new data on pion & nucleon elastic form factors, TMDs, etc $\Longrightarrow$ diquarks, OAM, etc
- *In the DSEs an understanding of QCD is gained by exposing the properties of its dressed propagators, dressed vertices and interaction kernels – and the relations between them*



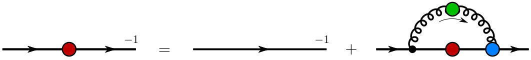


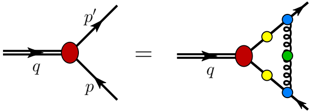
QCD: The Unifying Challenge

- Understanding QCD means to chart and compute this distribution of matter and energy within hadrons and nuclei – together with the complementary process of fragmentation functions
  - *a priori* have no idea what QCD can produce – but gives raise to ∼98% of mass in the visible universe
  - must understand the emergent phenomena of *confinement* and *dynamical chiral symmetry breaking*
  - *best promise for progress is a strong interplay between experiment and theory*



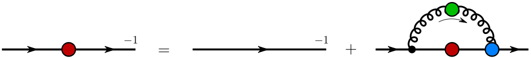
- Key pathways are provided by new data on pion & nucleon elastic form factors, TMDs, etc $\Longrightarrow$ diquarks, OAM, etc
- *In the DSEs an understanding of QCD is gained by exposing the properties of its dressed propagators, dressed vertices and interaction kernels – and the relations between them*





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

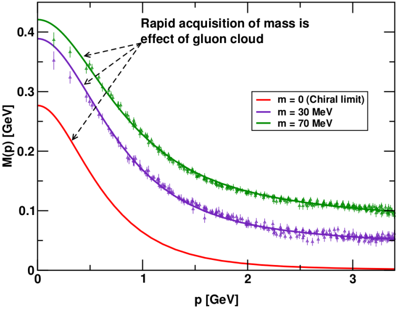


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

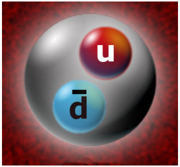
- $S(p)$ has correct perturbative limit
- mass function, $M(p^2)$, exhibits dynamical mass generation
- complex conjugate poles
  - no real mass shell $\Longrightarrow$ confinement

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

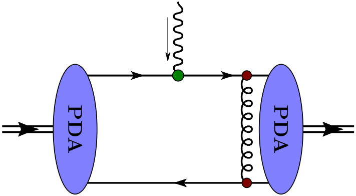


The Pion

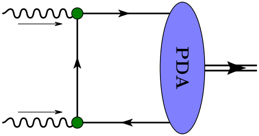
The Pion in QCD



- 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
- In QFT the pion's wave function is given by the solution to a Bethe-Salpeter equation
- A related quantity is the pion's parton distribution amplitude
  - $\varphi_\pi(x,\xi)$: *is a light-front probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*



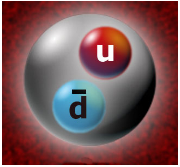
$$Q^2\,F_\pi(Q^2) \to 16\pi\,f_\pi^2\,\alpha_s(Q^2)$$



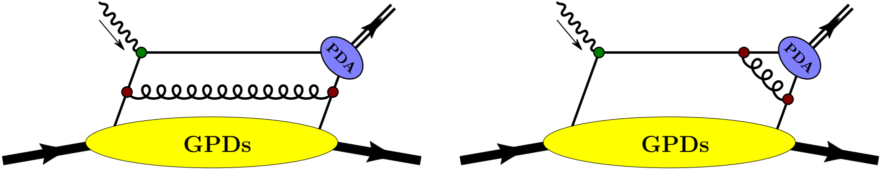
$$Q^2\,F_{\gamma^*\gamma\pi}(Q^2) \to 2\,f_\pi$$

- PDAs enter numerous hard exclusive scattering processes

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
- In QFT the pion's wave function is given by the solution to a Bethe-Salpeter equation
- A related quantity is the pion's parton distribution amplitude
  - $\varphi_\pi(x,\xi)$: *is a light-front probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*



- PDAs enter numerous hard exclusive scattering processes

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
- The pion's PDA is defined by

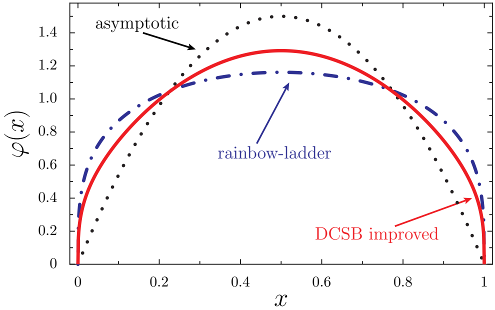
$$f_\pi \, \varphi_\pi(x) = Z_2 \int \frac{d^4k}{(2\pi)^2} \, \delta\left(k^+ - x\, p^+\right) \mathrm{Tr}\left[\gamma^+ \gamma_5 \, S(k)\, \Gamma_\pi(k,p)\, S(k-p)\right]$$

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

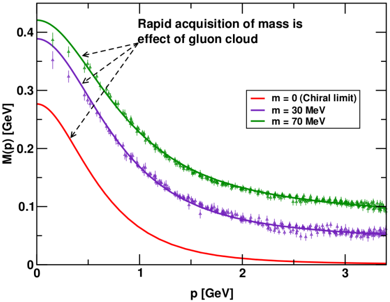
$$Q^2\, F_\pi(Q^2) \overset{Q^2\to\infty}{\longrightarrow} 16\,\pi\, f_\pi^2\, \alpha_s(Q^2) \qquad \Longleftrightarrow \qquad \varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$$

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

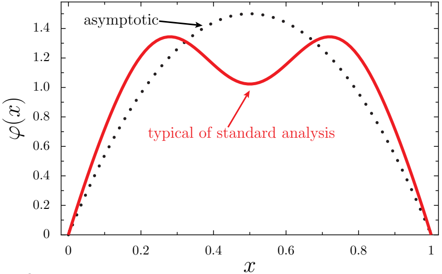
- As we shall see the dilation of pion's PDA will influence the Q^2 evolution of the pion's electromagnetic form factor

- 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: $\alpha \sim 0.52$

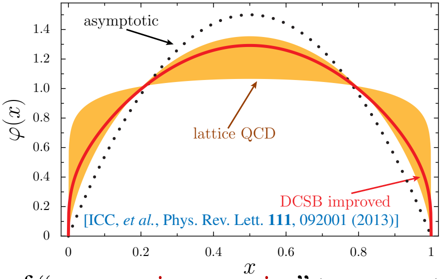
Pion PDA from lattice QCD

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



- 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 $Q^2 \to \infty$
  - this procedure results in a *double-humped* pion PDA

- Advocate using a *generalized expansion*

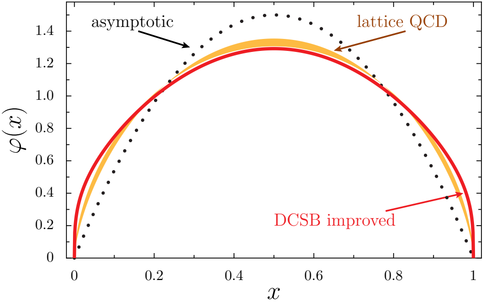
$$\varphi_\pi(x,Q^2) = N_\alpha\,x^\alpha(1-x)^\alpha\left[1+\sum_{n=2,\,4,\ldots} a_n^{\alpha+1/2}(Q^2)\,C_n^{\alpha+1/2}(2x-1)\right]$$

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

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]]

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

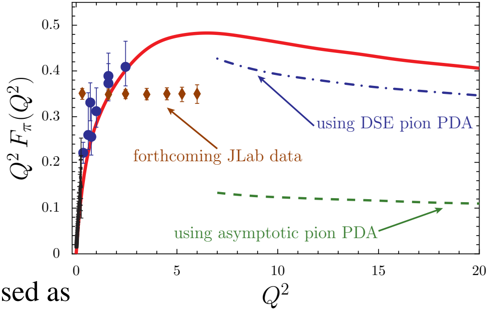
- DSE prediction:

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

Pion Elastic Form Factor

- Direct, symmetry-preserving computation of pion form factor predicts maximum in $Q^2 F_\pi(Q^2)$ at $Q^2 \approx 6\,\text{GeV}^2$
  - 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

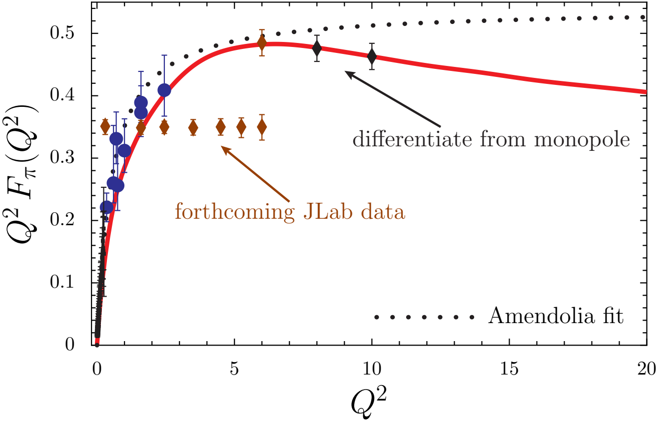
$$Q^2 F_\pi(Q^2) \overset{Q^2 \gg \Lambda^2_{\rm QCD}}{\sim} 16\,\pi\, f_\pi^2\, \alpha_s(Q^2)\, w_\pi^2; \qquad w_\pi = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\, \varphi_\pi(x)$$

- 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* $Q^2 \sim 8\,\text{GeV}^2$

Measuring onset of Perturbative scaling

Argonne NATIONAL LABORATORY



- To observe onset of perturbative power law behaviour – *to differentiate from a monopole* – optimistically need data at $8\,\mathrm{GeV}^2$ but likely also at $10\,\mathrm{GeV}^2$
  - 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

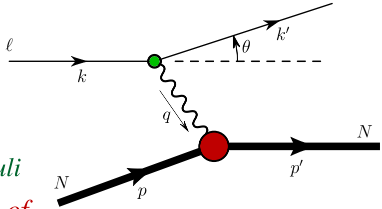
The Nucleon

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*

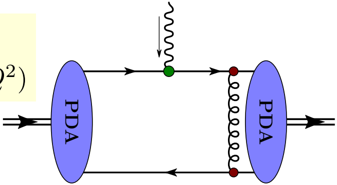


- *Provide vital information on the distribution of charge and magnetization within hadrons and nuclei*
  - form factors also directly probe confinement at all energy scales
- Today accurate form factor measurements are creating a paradigm shift in our understanding of nucleon structure:
  - proton radius puzzle
  - $\mu_p \, G_{Ep}/G_{Mp}$ ratio and a possible zero-crossing
  - flavour decomposition and evidence for diquark correlations
  - meson-cloud effects
  - seeking verification of perturbative QCD scaling predictions & scaling violations

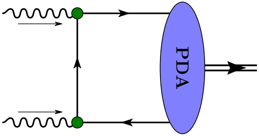
Form Factors in Conformal Limit ($Q^2 \to \infty$)

- 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:

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



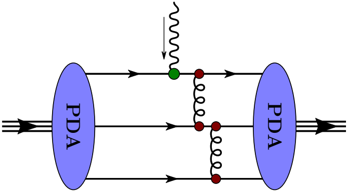
$$Q^2\, F_{\gamma^*\gamma\pi}(Q^2) \to 2\, f_\pi$$



- For the nucleon, normalization is not known

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

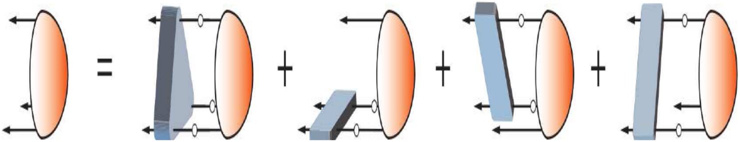
  - orbital angular momentum effects approach



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

- 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

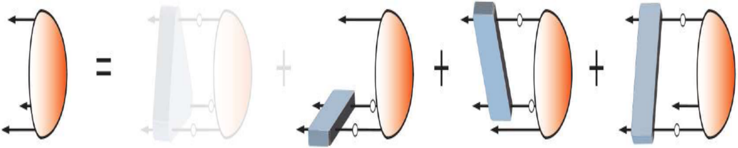


  - sums all possible interactions between three dressed-quarks
  - much of 3-body interaction can be absorbed into effecive 2-body interactions
  - *Faddeev eq. has solutions at discrete values of* $p^2 \ (= M^2) \implies$ *baryon spectrum*
- A *prediction* of these approaches is that owing to DCSB in 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

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

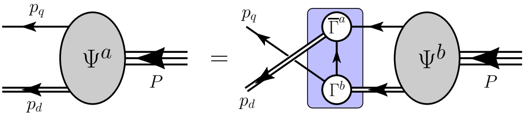
image from
Gernot Eichmann



  - sums all possible interactions between three dressed-quarks
  - much of 3-body interaction can be absorbed into effecive 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

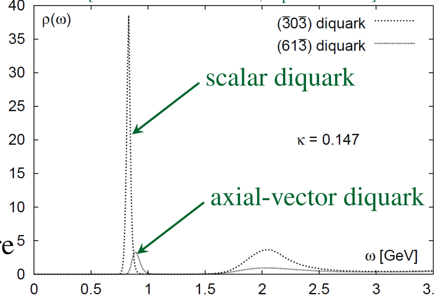
Diquarks

- 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]

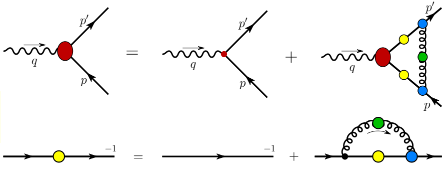


Nucleon EM Form Factors from DSEs

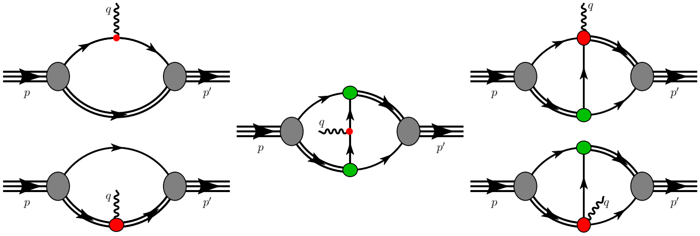
- A robust description of form factors is only possible if *electromagnetic gauge invariance* is respected; equivalently all relevant *Ward-Takahashi identities* (WTIs) must be satisfied
- For quark-photon vertex WTI implies:

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

  - transverse structure unconstrained



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



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

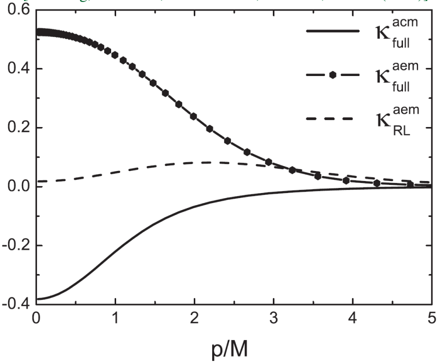
Beyond Rainbow Ladder Truncation

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

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

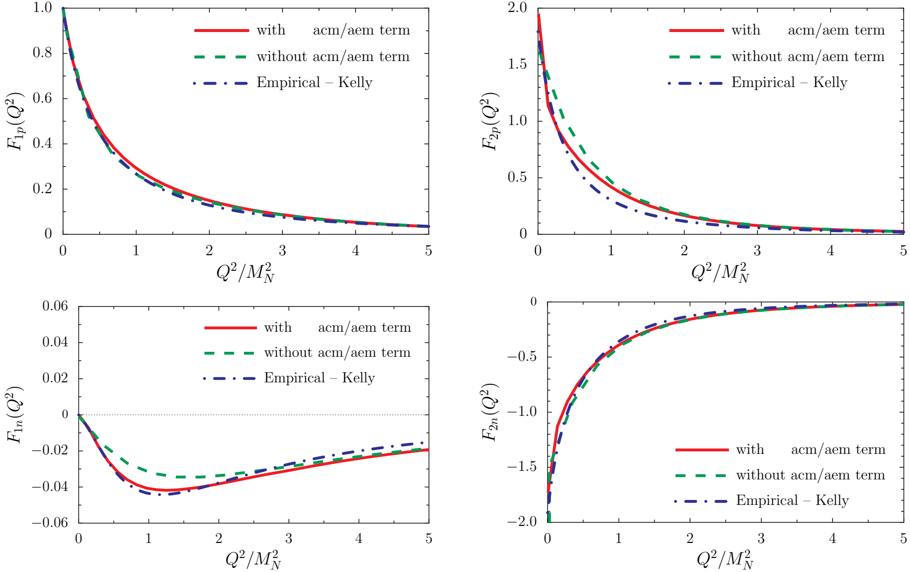
- In chiral limit *anomalous chromomagnetic* term can only appear through DCSB – not chirally symmetric and flips quark helicity
- EM properties of a spin-$\frac{1}{2}$ point particle are characterized by two quantities:
  - charge: e & magnetic moment: μ
- Expect strong gluon dressing to produce non-trivial 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)]



Nucleon Dirac & Pauli form factors

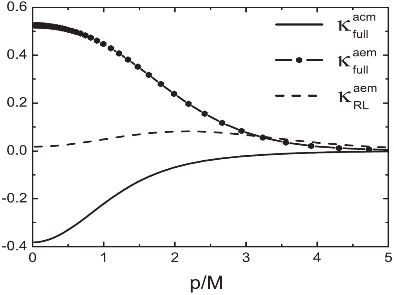
[ICC, G. Eichmann, B. El-Bennich, T. Klahn and C. D. Roberts,, Few Body Syst. **46**, 1 (2009)]



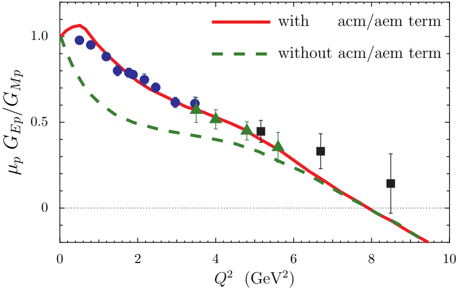
- quark aem term has important influence on Pauli form factors at low Q^2

Proton G_E/G_M Ratio

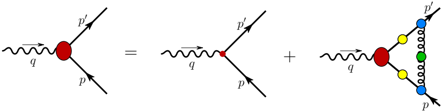
[L. Chang, Y. -X. Liu, C. D. Roberts, Phys. Rev. Lett. **106**, 072001 (2011)]



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



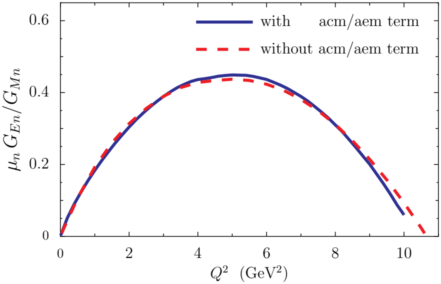
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
  - power law suppressed at large Q^2



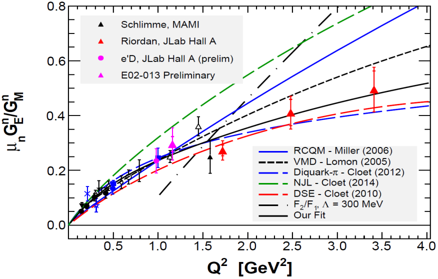
- Illustrates how feedback with EM *form factor measurements* can help constrain the *quark–photon vertex* and therefore the *quark–gluon vertex* within the DSE framework
  - knowledge of quark–gluon vertex provides $\alpha_s(Q^2)$ within DSEs $\Leftrightarrow$ confinement

Neutron G_E/G_M Ratio

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



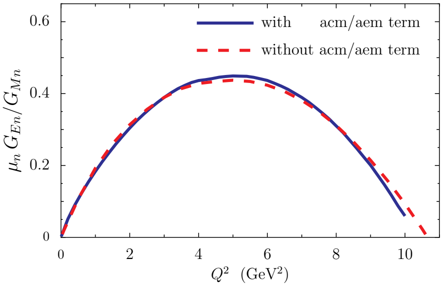
[S. Riordan *et al.*, Phys. Rev. Lett. **105**, 262302 (2010)]



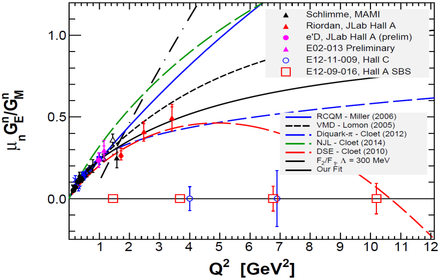
- Quark anomalous chromomagnetic moment – which drives the large anomalous electromagnetic moment – has only a minor impact on neutron Sachs form factor ratio
- Predict a zero-crossing in G_{En}/G_{Mn} at $Q^2 \sim 11\,\text{GeV}^2$
- Turn over in G_{En}/G_{Mn} will be tested at Jefferson Lab
- DSE *predictions*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

Neutron G_E/G_M Ratio

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



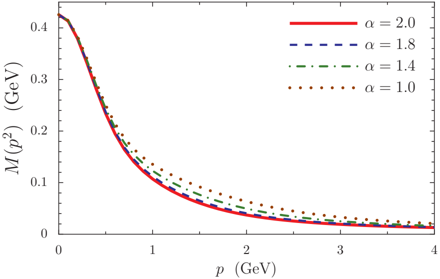
[S. Riordan *et al.*, Phys. Rev. Lett. **105**, 262302 (2010)]

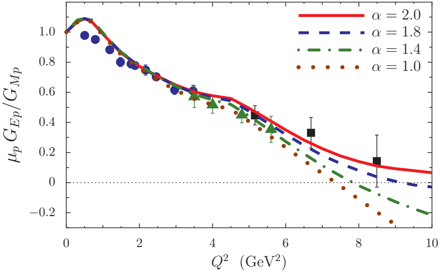


- Quark anomalous chromomagnetic moment – which drives the large anomalous electromagnetic moment – has only a minor impact on neutron Sachs form factor ratio
- Predict a zero-crossing in G_{En}/G_{Mn} at $Q^2 \sim 11\,\text{GeV}^2$
- Turn over in G_{En}/G_{Mn} will be tested at Jefferson Lab
- DSE *predictions*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

Proton G_E form factor and DCSB

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

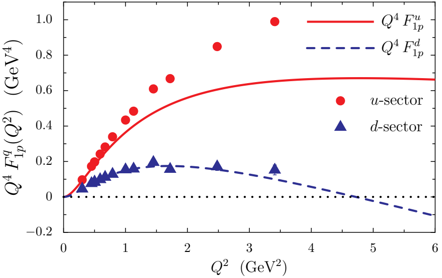


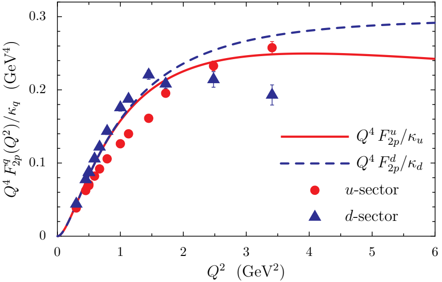


- Find that slight changes in $M(p^2)$ on the domain $1 \lesssim p \lesssim 3\,\text{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
  - *strong indication that position of a zero is very sensitive to underlying dynamics and the nature of the transition from nonperturbative to perturbative 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 $F_2 \to 0$

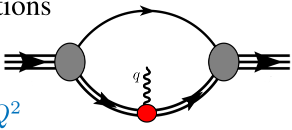
Flavour separated proton form factors

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





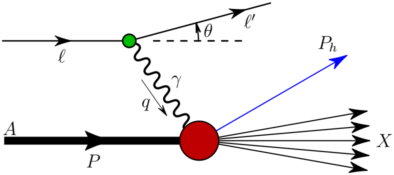
- Prima facie, these experimental results are remarkable
  - u and d quark sector form factors have very different scaling behaviour
- However, when viewed in context of diquark correlations results are straightforward to understand
  - in proton (uud) the d quark is "bound" inside a scalar diquark $[ud]$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



- 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 $x \to 1$

Probing Transverse Momentum with SIDIS

leading twist		quark polarization		
		unpolarized [U]	longitudinal [L]	transverse [T]
nucleon polarization	U	$f_1 =$ unpolarized		$h_1^\perp = \; - \;$ Boer-Mulders
	L		$g_1 = \; - \;$ helicity	$h_{1L}^\perp = \; - \;$ worm gear 1
	T	$f_{1T}^\perp = \; - \;$ Sivers	$g_{1T}^\perp = \; - \;$ worm gear 2	$h_{1T} = \; - \;$ transversity $h_{1T}^\perp = \; - \;$ pretzelosity



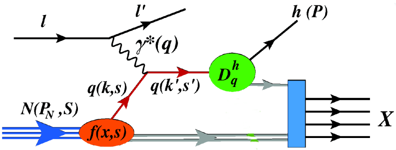
- The new frontier in hadron physics is the 3D imaging of the quarks & gluons
- SIDIS cross-section on nucleon has 18 structure functions – factorize as:

$$F(x, z, P_{h\perp}^2, Q^2) \propto \sum f^q(x, k_T^2) \otimes D_q^h(z, p_T^2) \otimes H(Q^2)$$

  - reveals correlations between parton transverse momentum, its spin & nucleon spin
- *Parametrization of these functions is not sufficient – must calculate in a framework with a well defined connection to QCD*
- Fragmentation functions are particularly challenging & therefore interesting

Probing Transverse Momentum with SIDIS

leading twist		quark polarization		
		unpolarized [U]	longitudinal [L]	transverse [T]
nucleon polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ — Boer-Mulders
	L		$g_1 =$ — helicity	$h_{1L}^\perp =$ — worm gear 1
	T	$f_{1T}^\perp =$ — Sivers	$g_{1T}^\perp =$ — worm gear 2	$h_{1T} =$ — transversity $h_{1T}^\perp =$ — pretzelosity



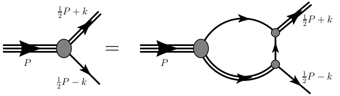
- The new frontier in hadron physics is the 3D imaging of the quarks & gluons
- SIDIS cross-section on nucleon has 18 structure functions – factorize as:

$$F(x, z, P_{h\perp}^2, Q^2) \propto \sum f^q(x, k_T^2) \otimes D_q^h(z, p_T^2) \otimes H(Q^2)$$

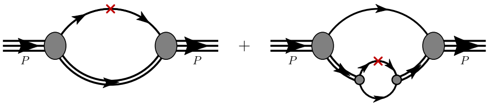
  - reveals correlations between parton transverse momentum, its spin & nucleon spin
- *Parametrization of these functions is not sufficient – must calculate in a framework with a well defined connection to QCD*
- Fragmentation functions are particularly challenging & therefore interesting

Nucleon quark distributions

- Nucleon = quark+diquark

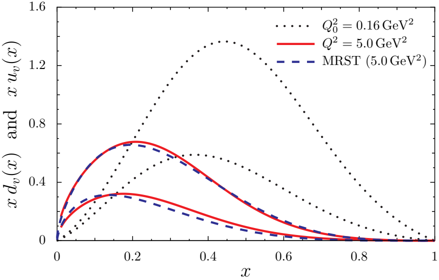


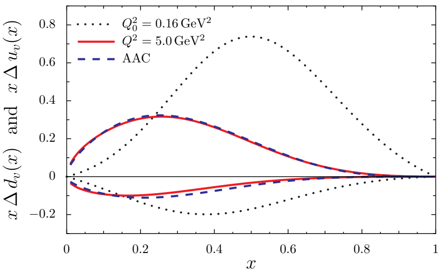
- PDFs given by Feynman diagrams: $\langle\gamma^{+}\rangle$



- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

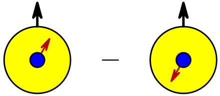
$$\langle q(x)-\bar{q}(x)\rangle = N_q, \quad \langle x\,u(x)+x\,d(x)+\ldots\rangle = 1, \quad |\Delta q(x)|\,,\ |\Delta_T q(x)| \leqslant q(x)$$





[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

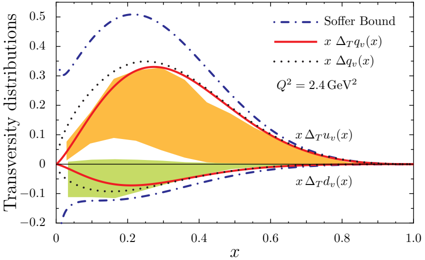
Nucleon transversity quark distributions

$\Delta_T q(x) =$ 

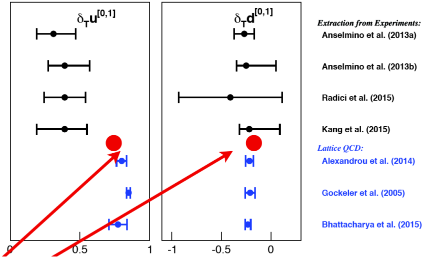
- Tensor charge given by

$$g_T = \int dx\, [\Delta_T u(x) - \Delta_T d(x)]$$

- quarks in eigenstates of $\gamma^\perp \gamma_5$
- Non-relativistically: $\Delta_T q(x) = \Delta q(x)$ – a measure of relativistic effects
- Helicity conservation: no mixing bet'n $\Delta_T q$ & $\Delta_T g$: $J \leqslant \frac{1}{2} \Rightarrow \Delta_T g(x) = 0$
- Therefore for the nucleon $\Delta_T q(x)$ is valence quark dominated
- At model scale we find: $g_T = 1.28$ *compare* $g_A = 1.267$ (input)

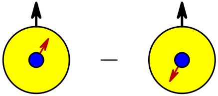


[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **659**, 214 (2008)]



[Gao *et al.*, The Universe, vol. 3, n. 2, April 2015]

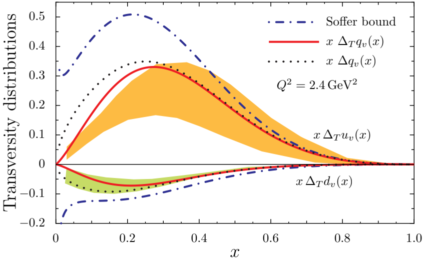
Nucleon transversity quark distributions

$\Delta_T q(x) =$ 

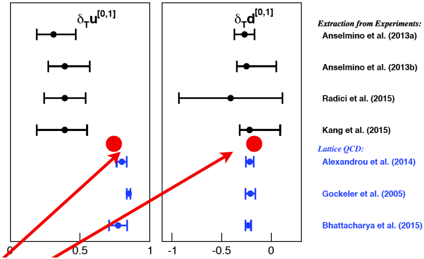
- Tensor charge given by

$$g_T = \int dx \left[\Delta_T u(x) - \Delta_T d(x)\right]$$

- quarks in eigenstates of $\gamma^{\perp}\,\gamma_5$
- Non-relativistically: $\Delta_T q(x) = \Delta q(x)$ – a measure of relativistic effects
- Helicity conservation: no mixing bet'n $\Delta_T q$ & $\Delta_T g$: $J \leqslant \frac{1}{2} \Rightarrow \Delta_T g(x) = 0$
- Therefore for the nucleon $\Delta_T q(x)$ is valence quark dominated
- At model scale we find: $g_T = 1.28$ *compare* $g_A = 1.267$ (input)

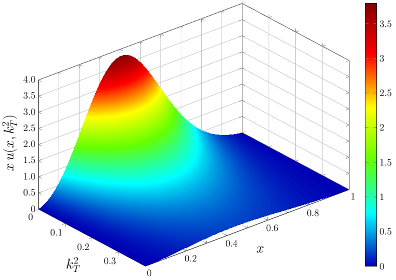


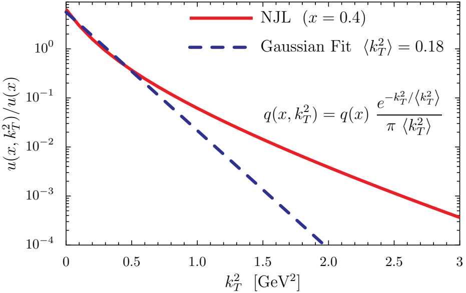
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **659**, 214 (2008)]



[Gao *et al.*, The Universe, vol. 3, n. 2, April 2015]

Transverse Momentum Dependent PDFs



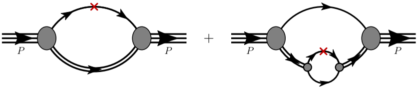


- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
- Rigorously included transverse momentum of diquark correlations in TMDs

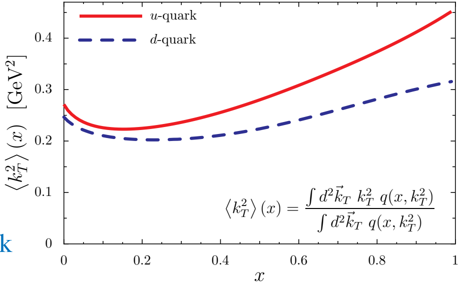
$$q_{D/N}(x, k_T^2) = \int_0^1 dy \int_0^1 dz \int d^2\vec{q}_\perp \int d^2\vec{\ell}_\perp$$
$$\delta(x - yz)\ \delta(\vec{\ell}_\perp - \vec{k}_\perp - z\vec{q}_\perp)\ f_{D/N}(y, \vec{q}_\perp)\ f_{q/D}(z, \vec{\ell}_\perp)$$

- Scalar diquark correlations greatly increase $\langle k_T^2 \rangle$

$$\langle k_T^2 \rangle_u^{Q^2=Q_0^2} = 0.43\,\mathrm{GeV}^2 \qquad \langle k_T^2 \rangle = 0.31\,\mathrm{GeV}^2\ _{\text{[HERMES]}},\quad 0.41\,\mathrm{GeV}^2\ _{\text{[EMC]}}$$

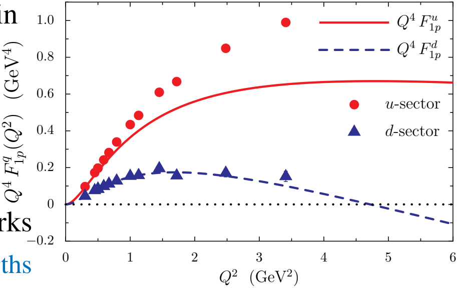


- Scalar diquark correlations give sizable flavour dependence in $\langle k_T^2 \rangle$
  - 70% of proton (uud) WF contains a scalar diquark $[ud]$; $M_s \simeq 650\,\text{MeV}$, with $M \simeq 400\,\text{MeV}$ difficult for d-quark to be at large x



- Scalar diquark correlations also explain the very different scaling behaviour of the quark sector form factors
  - $u[ud]$ diquark $\Longrightarrow$ extra $1/Q^2$ for d

- 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 $x \to 1$

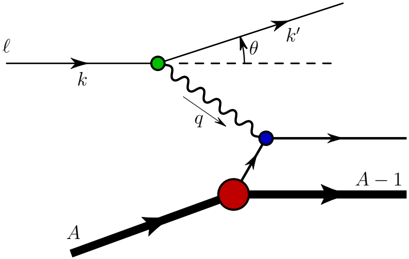


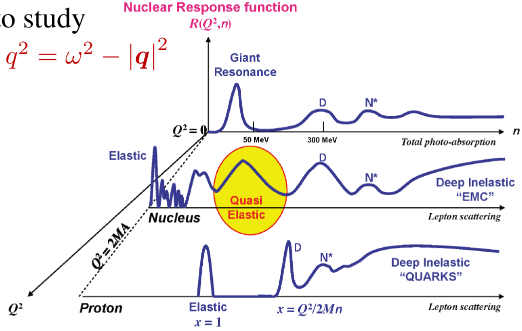
[ICC, Bentz, Thomas, PRC **90**, 045202 (2014)]

Nucleon in Medium

Quasi-elastic scattering

- Quasi-elastic scattering is used to study nucleon properties in a nucleus: $q^2 = \omega^2 - |\boldsymbol{q}|^2$





- The cross-section for this process reads

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2\,|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

  - response functions are accessed via Rosenbluth separation

- In the DIS regime – $Q^2, \omega \to \infty \quad x = Q^2/(2\,M_N\,\omega) = \text{constant}$ – response functions are proportional to the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

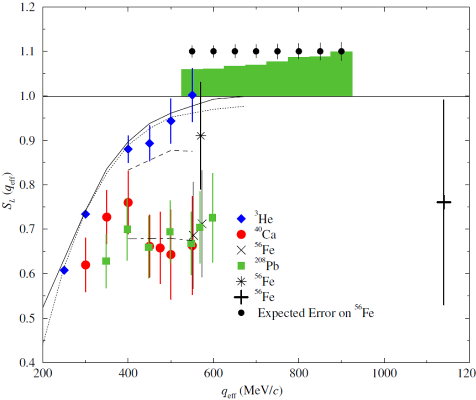
Coulomb Sum Rule

- The "Coulomb Sum Rule" reads

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}$$

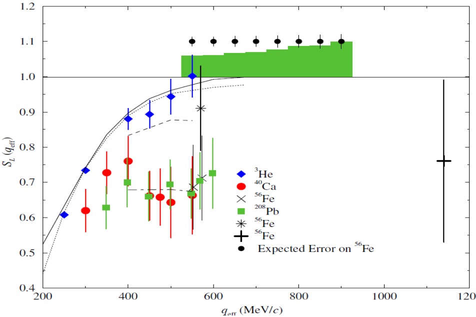
$$\tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$

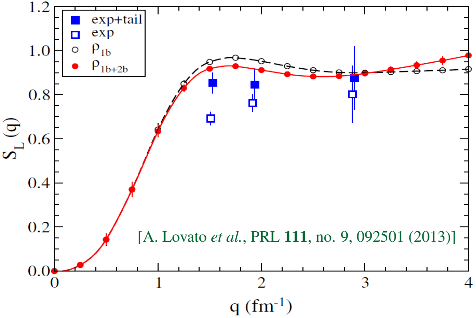
- Non-relativistic expectation – as $|\boldsymbol{q}|$ becomes large – $S_L(|\boldsymbol{q}| \gg p_F) \to 1$
  - CSR counts number of charge carriers
- The CSR was first measured at MIT Bates in 1980 then at Saclay in 1984
  - both experiments observed significant *quenching* of the CSR
- Two plausible explanations: 1) *nucleon structure is modified in the nuclear medium;* 2) *experiment/analysis is flawed e.g. Coulomb corrections*
- A number of influential physicists have argued very strongly for the latter



Coulomb Sum Rule Today

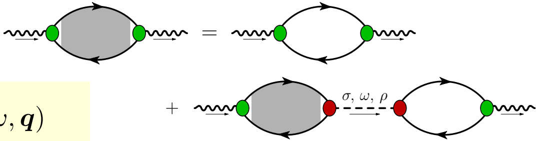
- No new data on the CSR since SLAC data from early 1990s
- The *quenching* of the CSR has become one of the most contentious observations in all of nuclear physics
- Experiment E05-110 was performed at Jefferson Lab in 2005 – should settle controversy of CSR *quenching* once and for all
  - publication of results expected soon
- State-of-the-art traditional nuclear physics (GFMC) calculations find no quenching in ^{12}C





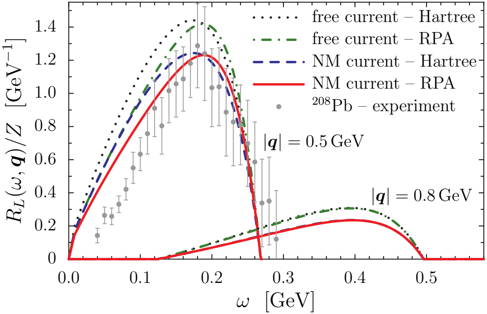
Longitudinal Response Function

- In nuclear matter response function given by



$$R_L(\omega,\boldsymbol{q}) = -\frac{2\,Z}{\pi\,\rho_B}\,\mathrm{Im}\,\Pi_L\,(\omega,\boldsymbol{q})$$

- Longitudinal polarization – Π_L – is obtained by solving a Dyson equation
- We consider two cases: (1) *the electromagnetic current is that if a free nucleon;* (2) *the current is modified by the nuclear medium*
- The *in-medium* nucleon current causes a sizeable quenching of the longitudinal response
  - driver of this effect is modification of the proton Dirac form factor
- Nucleon RPA correlations play almost no role for $|\boldsymbol{q}| \gtrsim 0.7\,\mathrm{GeV}$

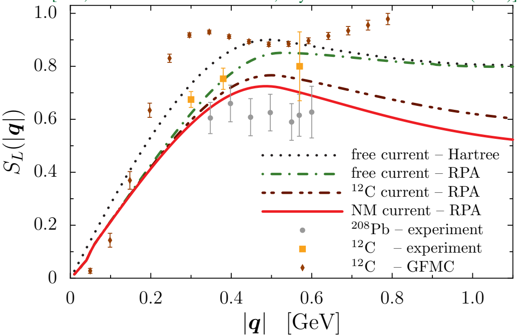


Coulomb Sum Rule

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{\tilde{G}_E^2(Q^2)}$$

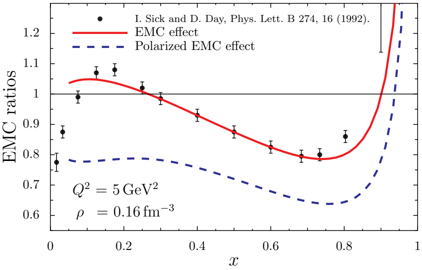
$$\tilde{G}_E^2 = Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)$$

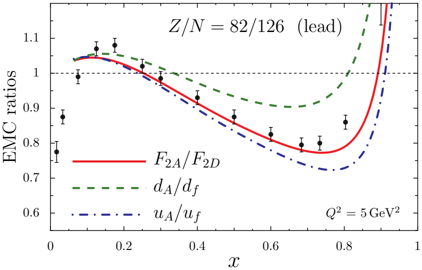
[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **116** 032701 (2016)]



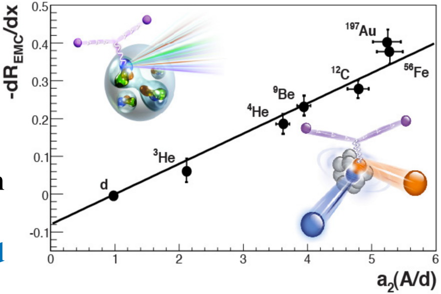
- Recall that the non-relativistic expectation is unity for $|\boldsymbol{q}| \gg p_F$
- GFMC ^{12}C results are consistent with this expectation
- For a *free nucleon current* find relativistic corrections of 20% at $|\boldsymbol{q}| \simeq 1\,\text{GeV}$
  - in the non-relativistic limit our CSR result does saturate at unity
- An *in-medium nucleon current* induces a further 20% correction to the CSR
  - good agreement with exisiting ^{208}Pb data – although this data is contested
- Our ^{12}C result is in stark contrast to the corresponding GFMC prediction
  - forthcoming Jefferson Lab should break this impasse

Understanding the EMC effect





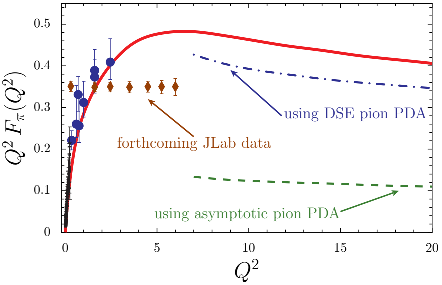
- *Puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs

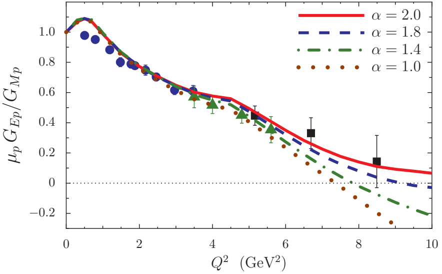


- Examples: Polarized and flavour dependence, spectator tagging, etc

Conclusion

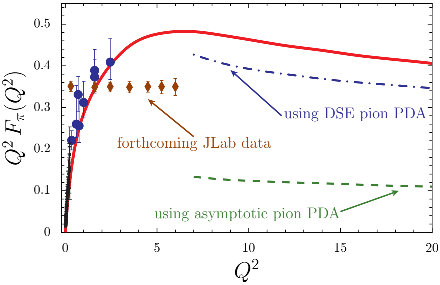
- Using the DSEs we find that DCSB drives numerous effects in QCD, e.g., hadron masses, confinement and many aspects of hadron structure
  - $Q^2\,F_\pi(Q^2)$ peaks at $6\,\mathrm{GeV}^2$
  - predict that QCD power law behaviour sets in at $Q^2 \sim 8\,\mathrm{GeV}^2$
  - e.g. location of zero's in form factors – G_{Ep}, F_{1p}^d, etc – provide tight constraints on QCD dynamics
  - predict zero in G_{En}/G_{Mn} independent rate of change of DCSB with scale
- Progress toward nucleon TMD results
  - diquark correlations result in a dramatic increase in $\langle k_T^2 \rangle$ and a significant flavour dependence

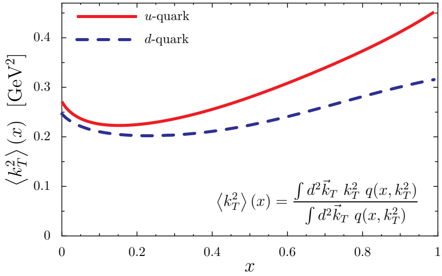




Conclusion

- Using the DSEs we find that DCSB drives numerous effects in QCD, e.g., hadron masses, confinement and many aspects of hadron structure
  - $Q^2\, F_\pi(Q^2)$ peaks at 6 GeV^2
  - predict that QCD power law behaviour sets in at $Q^2 \sim 8\,\text{GeV}^2$
  - e.g. location of zero's in form factors – G_{Ep}, F_{1p}^d, etc – provide tight constraints on QCD dynamics
  - predict zero in G_{En}/G_{Mn} independent rate of change of DCSB with scale
- Progress toward nucleon TMD results
  - diquark correlations result in a dramatic increase in $\langle k_T^2 \rangle$ and a significant flavour dependence

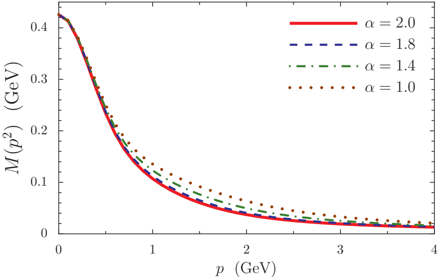


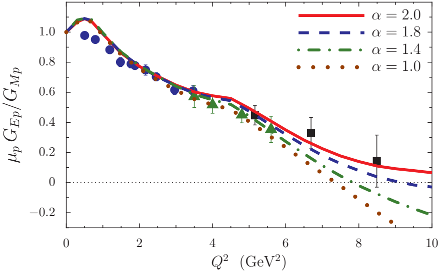


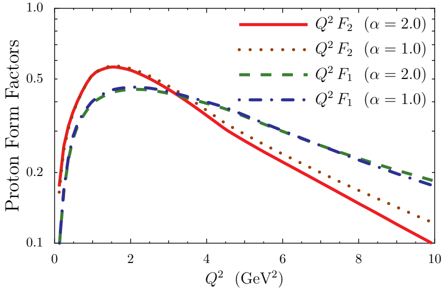
Backup Slides

Proton G_E form factor and DCSB

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

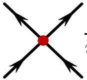




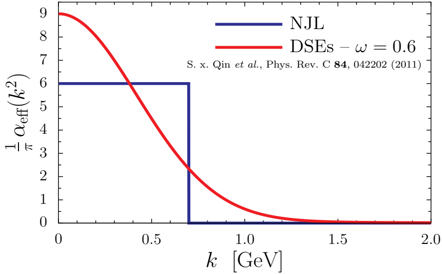


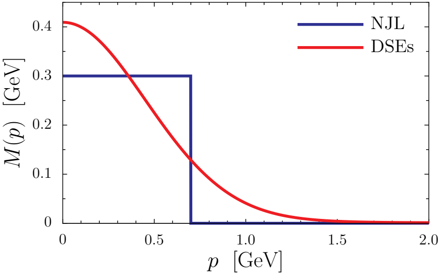
- Recall: $G_E = F_1 - \frac{Q^2}{4\,M_N^2}\,F_2$
- Only G_E is senitive to these small changes in the mass function
- *Accurate determination of zero crossing would put important contraints on quark-gluon dynamics within DSE framework*

Nambu–Jona-Lasinio model

Continuum QCD *"integrate out gluons"*  $\frac{1}{m_G^2}\ \Theta(\Lambda^2 - k^2)$

- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT which exhibits dynamical chiral symmetry breaking & it elements can be QCD motivated via the DSEs





- The NJL model is very successful - provides a good description of numerous hadron properties: form factors, PDFs, in-medium properties, etc
  - however the NJL model has no direct link to QCD
  - in general NJL has no confinement – but can be implemented with proper-time RS