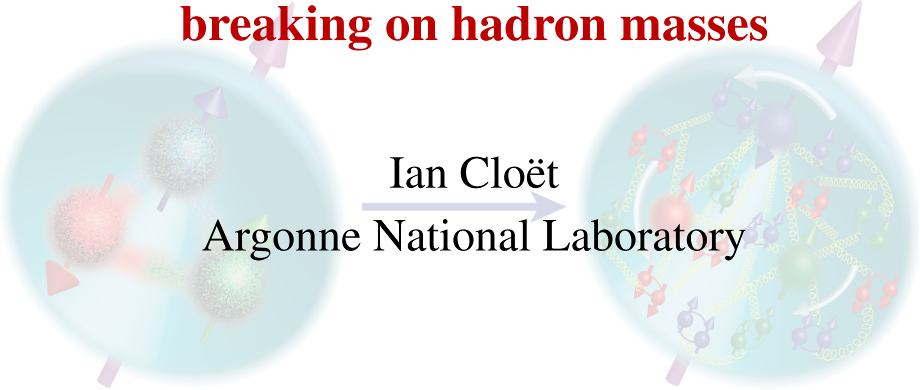
Impacts of dynamical chiral symmetry breaking on hadron masses



Ian Cloët

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The Proton Mass: At the Heart of Most Visible Matter

ECT*, 3–7 April 2017

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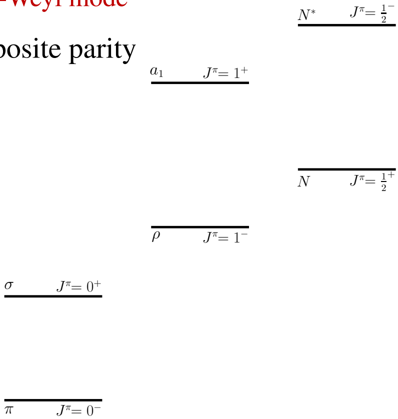
DCSB Refresher

- $\mathcal{L}_{\rm QCD}$ invariant under: $SU(N_f)_L \otimes SU(N_f)_R \Longleftrightarrow SU(N_f)_V \otimes SU(N_f)_A$
- For $N_f = 2$, $SU(N_f)_V$ transformations correspond to the isospin
  - hadron mass spectrum tells us nature largely respects isospin symmetry
  - $m_{\pi^-} \simeq m_{\pi^0} \simeq m_{\pi^+}, \;\; m_p \simeq m_n, \;\; m_{\Sigma^-} \simeq m_{\Sigma^0} \simeq m_{\Sigma^+}$
  - therefore $SU(N_f)_V$ is realized in the Wigner-Weyl mode
- $SU(N_f)_A$ transformations mix states of opposite parity
  - expect hadron mass spectrum to exhibit parity degeneracy

    $m_{a_1} - m_\rho; \; m_N - m_{N^*} \sim 500\,\mathrm{MeV}$
  - $m_u \simeq m_d \simeq 5\,\mathrm{MeV}$, cannot produce such large mass splittings
  - therefore $SU(N_f)_A$ must be realized in the Nambu-Goldstone mode
- Chiral symmetry is broken dynamically;

  $\Longrightarrow$ massless Goldstone bosons = pions



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N^* $J^\pi = \frac{1}{2}^-$

The hadronic matrix element of the energy-momentum tensor $\theta^{\mu\nu}$, at zero momentum transfer, is given by

$$\langle P\,|\theta^{\mu\nu}|\,P\rangle = 2\,P^\mu P^\nu$$

In chiral limit therefore have

$$\left\langle \pi\,\middle|\theta^\mu_\mu\middle|\,\pi\right\rangle = 2\,m_\pi^2 \to 0, \qquad \left\langle p\,\middle|\theta^\mu_\mu\middle|\,p\right\rangle = 2\,m_p^2$$

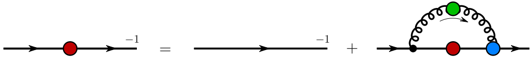
To properly address the original of the proton mass need a framework that encapsulates DCSB.

$\frac{1}{2}^+$

π $J^\pi = 0^-$

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

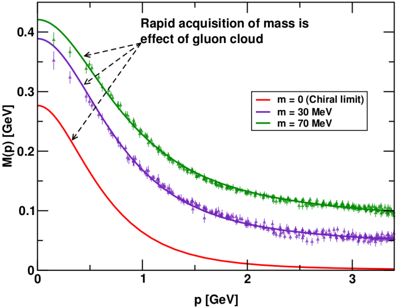


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

- $S(p)$ 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)]



QCDs Dyson-Schwinger Equations

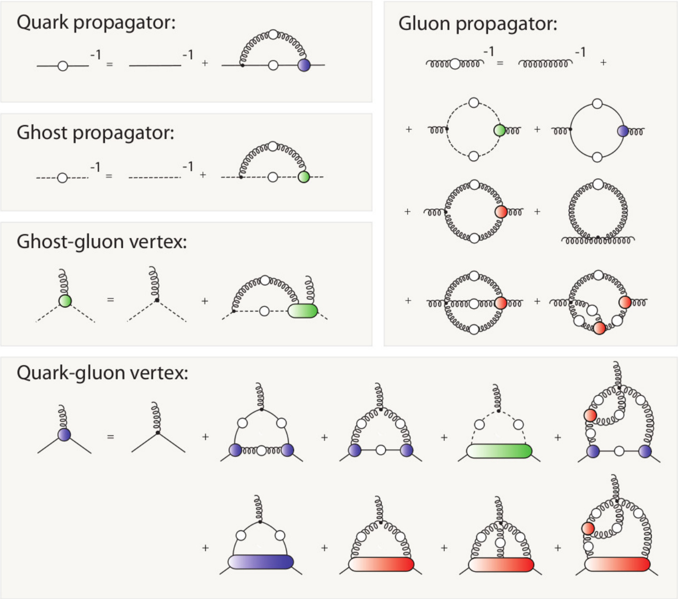
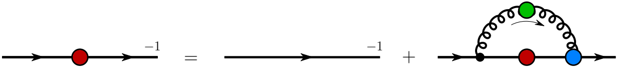


Image courtesy of Gernot Eichmann

ETC!

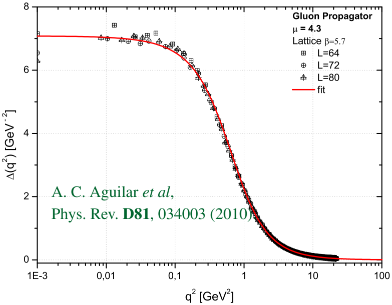
DSEs – A closer look



- Not possible to solve tower of equations – start with gap equation
  - need ansatz for *dressed gluon propagator* × *dressed quark-gluon vertex*
  - truncation must preserve symmetries, e.g., electromagnetic current, chiral

$$D^{\mu\nu}(p) = \left(\delta^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)\Delta(q^2) + \xi\,\frac{q^\mu q^\nu}{q^4}$$

$$\Gamma^{a,\mu}_{gqq}(p',p) = \frac{\lambda^a}{2}\sum_{i=1}^{12}\Lambda_i^\mu\; f_i(p'^2,p^2,q^2) = \frac{\lambda^a}{2}\left[\Gamma_L^\mu(p',p) + \Gamma_T^\mu(p',p)\right]$$



- usually choose Landau gauge $\xi = 0$

- Therefore both gluons and quarks posses dynamically generated masses
  - *QCD dynamically generates its own infrared cutoffs*

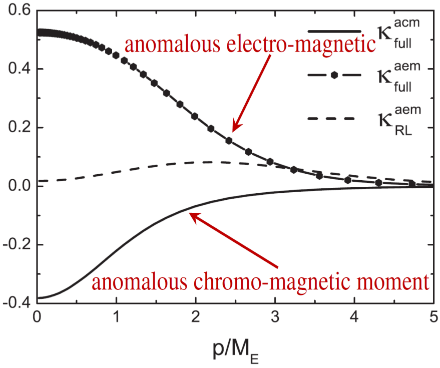
Beyond Rainbow Ladder Truncation

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

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

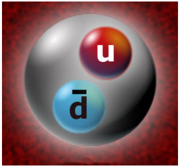
- In chiral limit *anomalous chromomagnetic* term can only appear through DCSB – since it is not chirally symmetric
- Expect strong gluon dressing to produce non-trivial structure for a dressed quark
  - recall dressing produces – from massless quark – a $M \sim 400\,\text{MeV}$ dressed quark
  - dressed quarks likely contain large amounts of orbital angular momentum
- 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)]



Pion Structure

The Pion in QCD

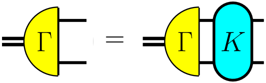


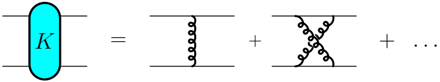
- Today the pion is understood as both a bound state of a *dressed-quark* and a *dressed-antiquark* in QFT and the Goldstone mode associated with DCSB in QCD
- This dichotomous nature has numerous ramifications, e.g.:

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

  - pion is unusually light, the key is *dynamical chiral symmetry breaking* (DCSB)

- In QFT a two-body bound state (e.g. a pion or rho) is described by the Bethe-Salpeter equation (BSE):





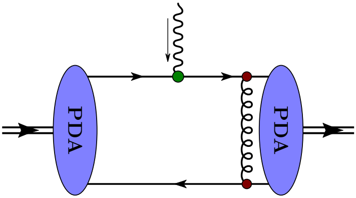
  - the kernel must yield a solution that encapsulates the consequences of DCSB, e.g., in chiral limit $m_\pi = 0$ & $m_\pi^2 \propto m_u + m_d$

- BSE wave function $\Longrightarrow$ *light-front wave function* (LFWF) $\Longrightarrow$ PDA

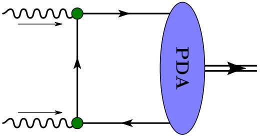
$$\psi(x, \boldsymbol{k}_T) = \int dk^- \; \chi_{\mathrm{BSE}}(p, k), \qquad \varphi(x) = \int d\boldsymbol{k}_T \; \psi(x, \boldsymbol{k}_T)$$

Pion's Parton Distribution Amplitude

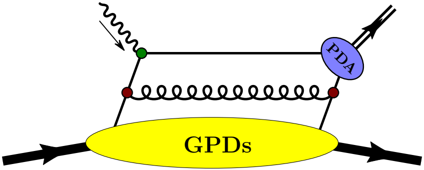
- pion's PDA – $\varphi_\pi(x)$: *is a probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*
  - it's a function of the light-cone momentum fraction $x = \frac{k^+}{p^+}$ and the scale Q^2

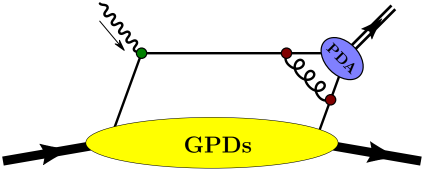


$$Q^2\, F_\pi(Q^2) \to 16\pi\, f_\pi^2\, \alpha_s(Q^2)$$



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





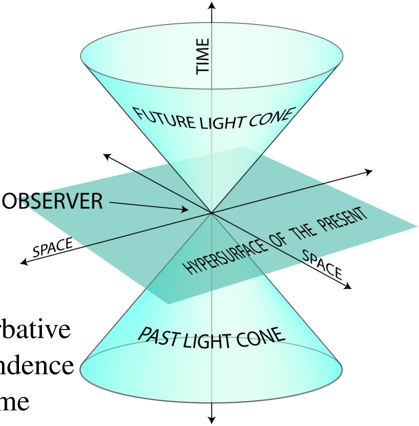
- PDAs enter numerous hard exclusive scattering processes

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

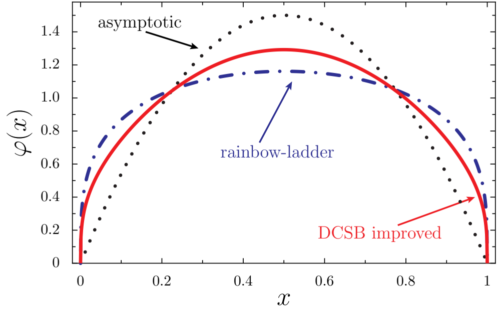


- Pion PDA is a *scale dependent* non-perturbative quantity, which e.g., governs the Q^2 dependence of pion form factor in the asymptotic regime

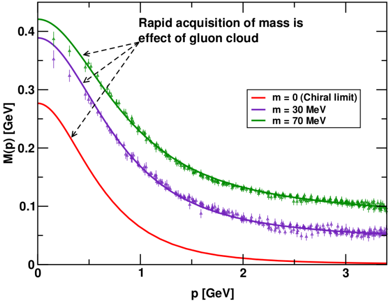
$$Q^2\, F_\pi(Q^2) \overset{Q^2\to\infty}{\longrightarrow} 16\,\pi\, f_\pi^2\, \alpha_s(Q^2) \qquad \Longleftrightarrow \qquad \varphi_\pi^{\text{asy}}(x) = 6\, x\,(1-x)$$

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

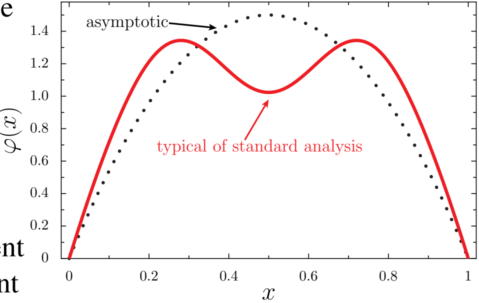
Pion PDA from Lattice QCD

- 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

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

  - 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*

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

- 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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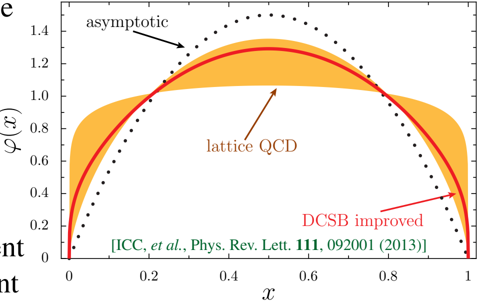

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Pion PDA from Lattice QCD – updated

- Most recent lattice QCD moment:

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

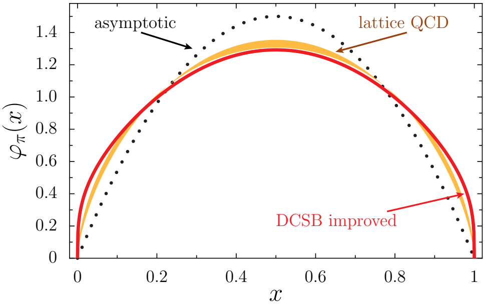
[V. M. Braun, *et al.*, Phys. Rev. D **92**, no. 1, 014504 (2015)]

- 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*

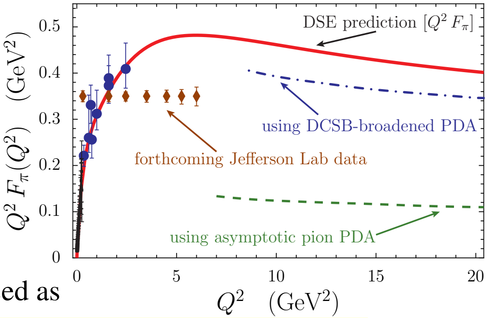
- Conclude that the pion PDA is a broad concave function
  - *double humped distributions are very likely for the pion*



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, CDR, *et al.*, Phys. Rev. Lett. **111**, 141802 (2013)]



- The QCD prediction can be expressed as

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

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

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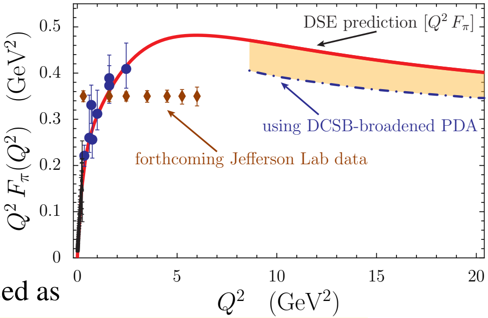

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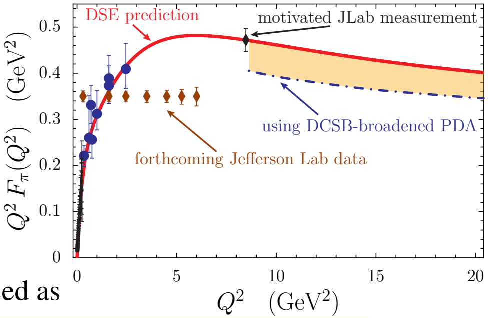

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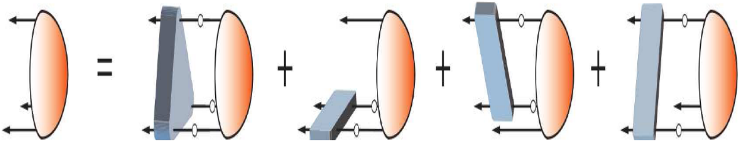
Nucleon Structure

Baryons in QFT

- 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 color-singlet mesons also generates *non-pointlike* diquark correlations in the color-$\bar{3}$ channel
  - where *scalar* (0^+) *& axial-vector* (1^+) *diquarks* most important for the nucleon

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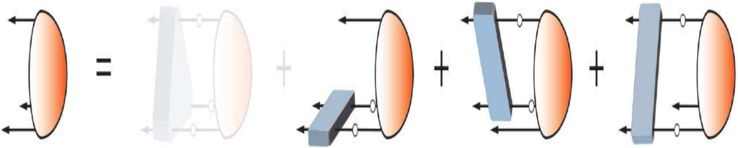

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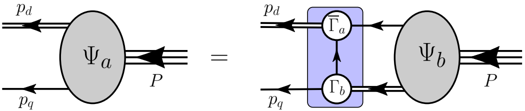
Diquarks

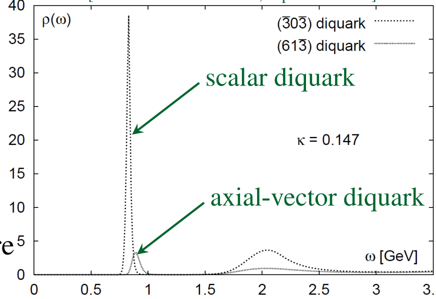
- Diquarks are dynamically generated correlations between quarks inside baryons



  - 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 $(1^+) \sim 30\%$

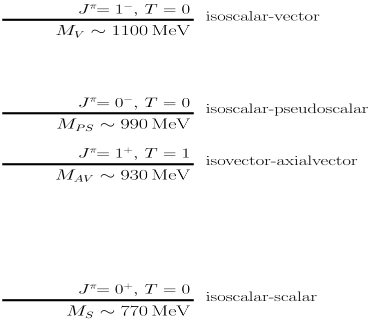
[I. Wetzorke and F. Karsch, hep-lat/0008008]



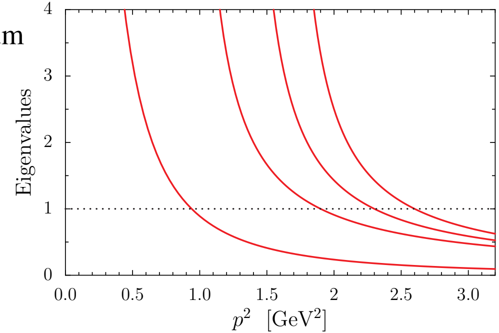
- *Faddeev equation spectrum has significant overlap with constituent quark model and limited relation to Lichtenberg's quark+diquark model*

- Mounting evidence from hadron structure (e.g. PDFs, form factors) and lattice

Diquark Spectrum



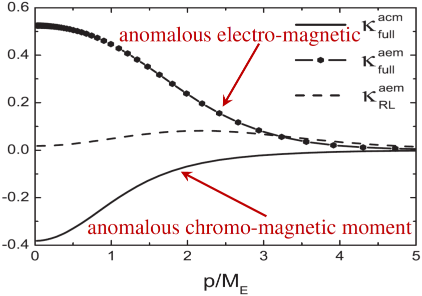
- DCSB results in a mass spectrum for the diquarks
- For nucleon – *in non-relativitic limit* – parity dictates that D_S and D_{AV} are in s-wave, and D_P and D_V in p-wave
  – opposite is true for $N^*(1535)$
- This interplay and DCSB produce bulk features of the baryon spectrum below $\sim$2 GeV
- Spectrum is given by values of p^2 with eigenvalue one
  - with parity $+1$ ground state is nucleon, parity -1 ground state is $N^*(1535)$, etc

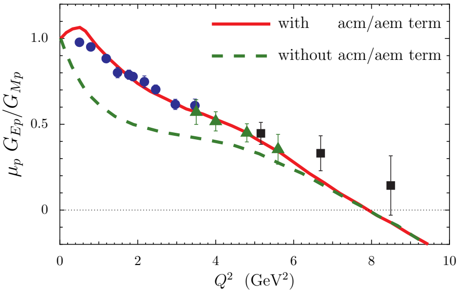


Proton G_E/G_M Ratio

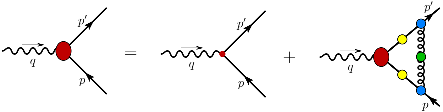
[L. Chang, Y. -X. Liu, *et al.*, Phys. Rev. Lett. **106**, 072001 (2011)]

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





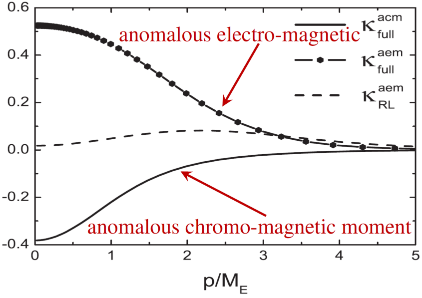
- Large chromo-magnetic moment is driven by DCSB
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
  - power law suppressed at large Q^2



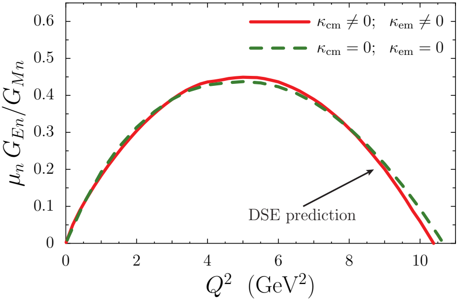
- Form factor measurements provide information on *quark– photon vertex* and by using the DSEs the *quark–gluon vertex*
  - knowledge of quark–gluon vertex provides $\alpha_s(Q^2)$ within DSEs $\Leftrightarrow$ confinement

Neutron G_E/G_M Ratio

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



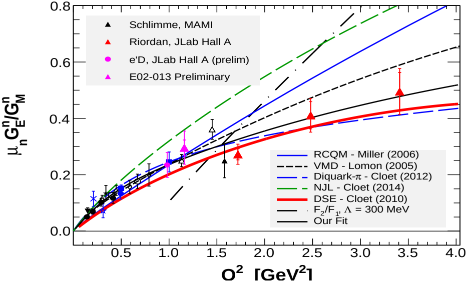
[I. C. Cloët, C. D. Roberts, Prog. Part. Nucl. Phys. **77**, 1 (2014)]



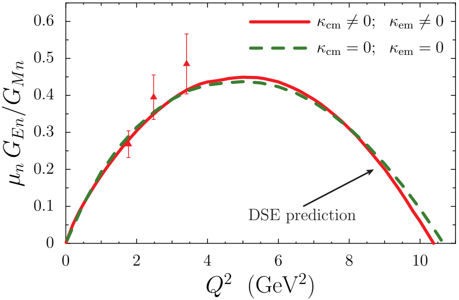
- Dressed quark anomalous chromo- ($\Longrightarrow$ electro-) magnetic moment has only a minor impact on neutron Sachs form factor ratio – *cancellations*
- The DSE *prediction* was confirmed on domain $1.5 \lesssim Q^2 \lesssim 3.5\,\mathrm{GeV}^2$
  - *shortcomings in other approaches have been exposed*
- Predict a zero-crossing in G_{En}/G_{Mn} at $Q^2 \sim 11\,\mathrm{GeV}^2$
  - zero-crossing driven by correlations in nucleon wave function
- *Turn over in G_{En}/G_{Mn} can be tested at the Jefferson Lab*

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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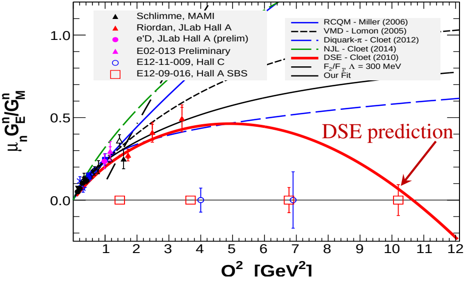

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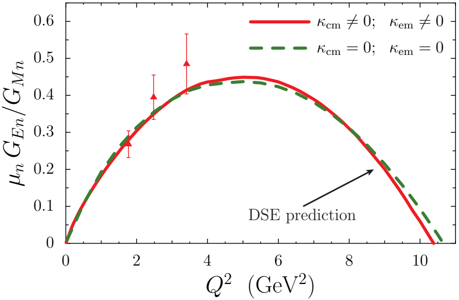

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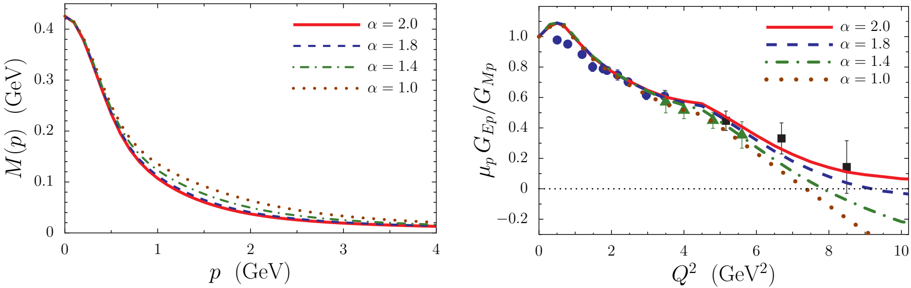
Proton G_E form factor & DCSB

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

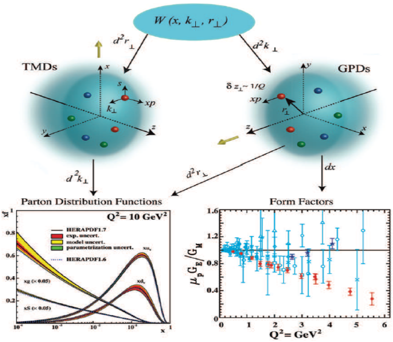


- Find that slight changes in $M(p^2)$ on the domain $1 \lesssim p \lesssim 3\,\mathrm{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
  - *strong indication that position of a zero is very sensitive to underlying dynamics and the nature of the transition from nonperturbative to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

Pion & Nucleon TMDs

Probing Transverse Momentum

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



- The new frontier in hadron physics is the 3D imaging of the quarks & gluons inside hadrons and nuclei – TMDs and GPDs
  - *parametrization of these functions is not sufficient – must calculate within a QCD-connected framework*
- Fragmentation functions – which appear in e.g. SIDIS – are also particularly important; they are challenging & interesting
  - *potentially fragmentation functions can shed the most light on confinement and DCSB – because they describe how a fast moving (massless) quark becomes a tower of hadrons*

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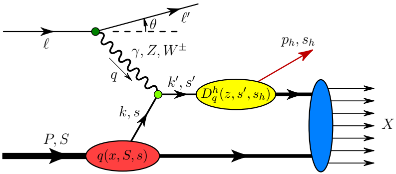

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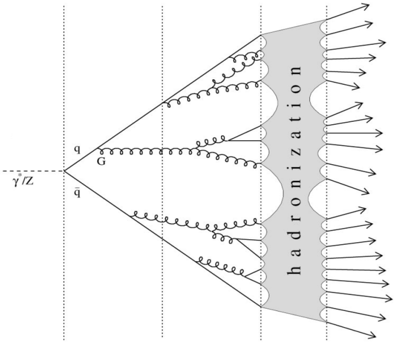

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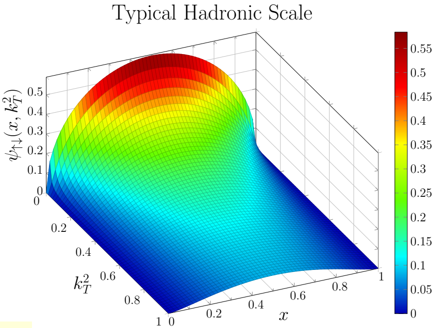
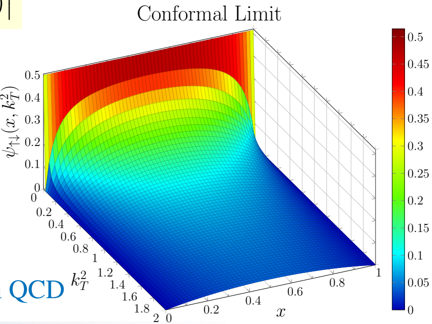
Pion TMD from its LFWFs

- DCSB results in broad pion LFWFs at hadronic scales
  - dramatic changes in curvature in conformal limit result
- Using pion's LFWFs straightforward to make predictions for pion GPDs, TMDs, etc; For TMDs:

$$f(x, \boldsymbol{k}_T^2) \propto \left|\psi_{\uparrow\downarrow}(x, \boldsymbol{k}_T^2)\right| + \boldsymbol{k}_T^2 \left|\psi_{\uparrow\uparrow}(x, \boldsymbol{k}_T^2)\right|$$

- Our result compared with Pasquini & Schweitzer [PRD **90** 014050 (2014)]
  - each result gives similar PDF but very different TMD
  - illustration of the potential for TMDs to differentiate between different frameworks & thereby expose quark-gluon dynamics in QCD





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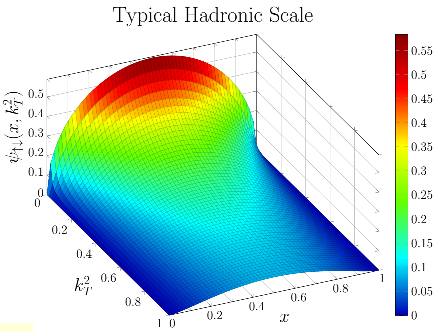

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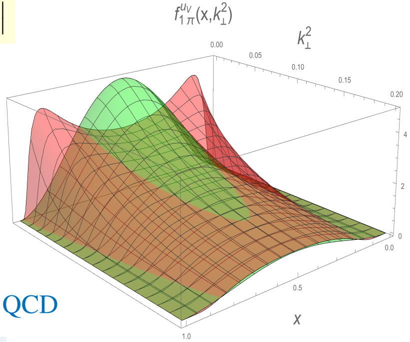
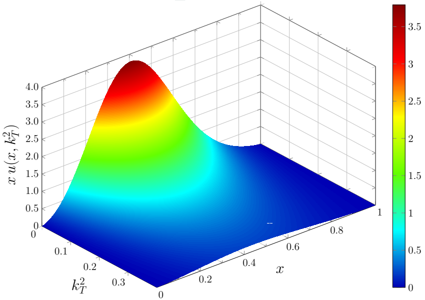
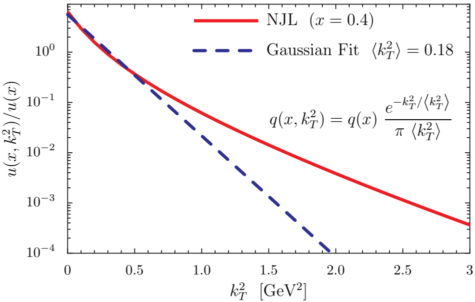
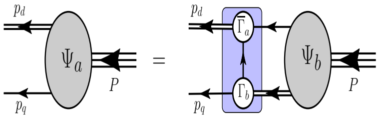


TMDs, Diquarks & Flavor Dependence



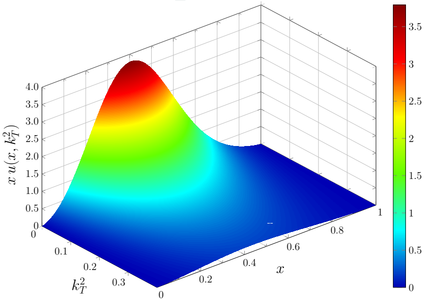


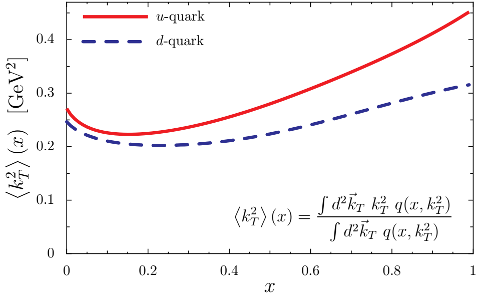
- Rigorously included transverse momentum of diquark correlations in TMDs



- This has numerous consequences:
  - scalar diquark correlations greatly increase $\langle k_T^2 \rangle$
  - find deviation from Gaussian anzatz and that TMDs do not factorize in x & k_T^2
  - diquark correlations introduce a significant flavor dependence in the average $\langle k_T^2 \rangle$ [analogous to the quark-sector electromagnetic form factors]
- Work is also underway for nucleon GPDs, and nuclear TMDs & GPDs

TMDs, Diquarks & Flavor Dependence





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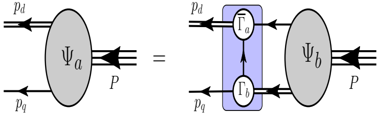

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Targets with Spin-1

Probing Transverse Momentum

leading twist		quark operator		
		unpolarized [U]	longitudinal [L]	transverse [T]
target polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ − Boer-Mulders
	L		$g_1 =$ − helicity	$h_{1L}^\perp =$ − worm gear 1
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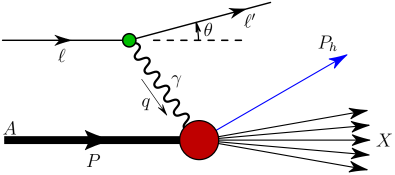
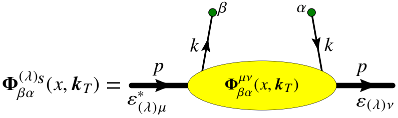
	TENSOR	$\theta_{LL}(x, \boldsymbol{k}_T^2)$ $\theta_{TT}(x, \boldsymbol{k}_T^2)$ $\theta_{LT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1TT}^\perp(x, \boldsymbol{k}_T^2)$ $h'_{1TT}, \quad h_{1TT}^\perp$ $h'_{1LT}, \quad h_{1LT}^\perp$



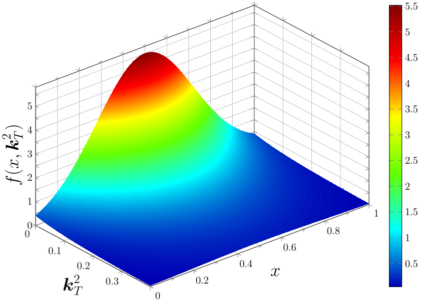


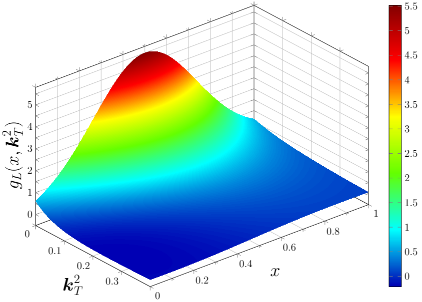
- A spin-1 target can have tensor polarization – 3 new T-even and 7 new T-odd TMDs compared to nucleon

- For DIS on spin-1 target there is one extra quark distribution:

$$b_1^q(x) = \int d^2\boldsymbol{k}_T \; \theta_{LL}^q(x, \boldsymbol{k}_T^2) - \frac{\boldsymbol{k}_T^2}{2\,M^2}\, \theta_{TT}^q(x, \boldsymbol{k}_T^2)$$

TMDs for a Rho Meson





- Are spin-one TMDs interesting – do they contain new information?
  - important question for the EIC – Jefferson Lab figure-eight design particularly suited to maintaining deuteron polarization
- Find that the six T-even spin-one TMDs that have a nucleon analogy contain few surprises
- Note, the simplest spin-one target is the deuteron ($J^\pi = 1^+$) and with only 2.2 MeV binding the helicity and transversity TMDs are likely much smaller

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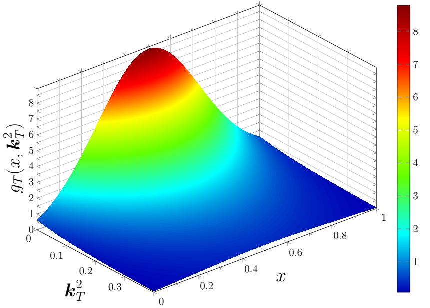

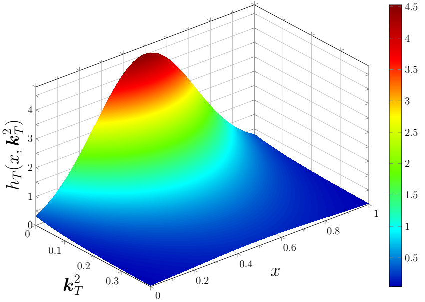

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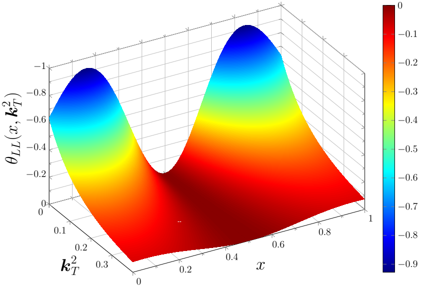
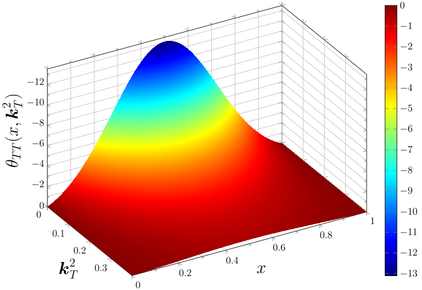
TMDs for a Rho Meson – Tensor Polarization





- The spin-one TMDs associated with a tensor polarized target have a number of surprising features
- The TMD $\theta_{LL}(x\,\boldsymbol{k}_T^2)$ vanishes when $x = 1/2$ for all $\boldsymbol{k}_T^2$
  - $x = 1/2$ corresponds to zero relative momentum between constituents, that is, s-wave contributions
  - therefore $\theta_{LL}(x\,\boldsymbol{k}_T^2)$ only receives contributions from $L \geqslant 1$ components of the wave function – *sensitive measure of orbital angular momentum*
- Features hard to determine from a few moments – difficult for lattice QCD

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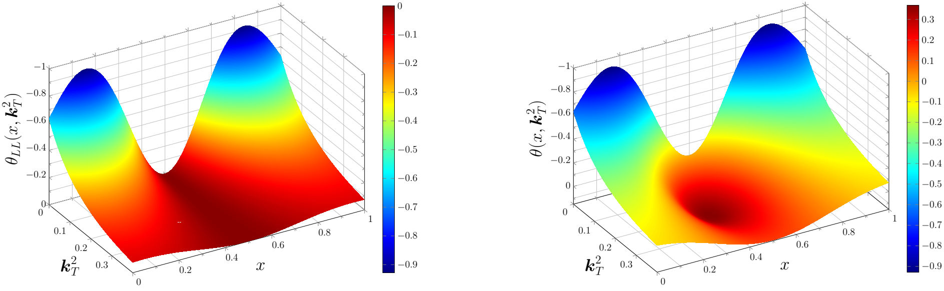

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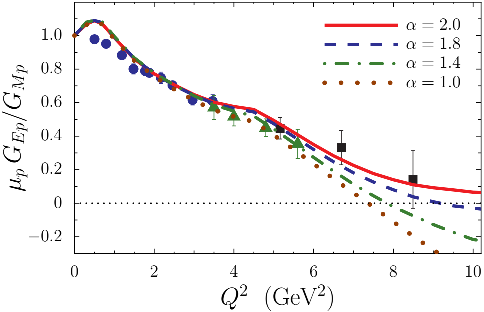
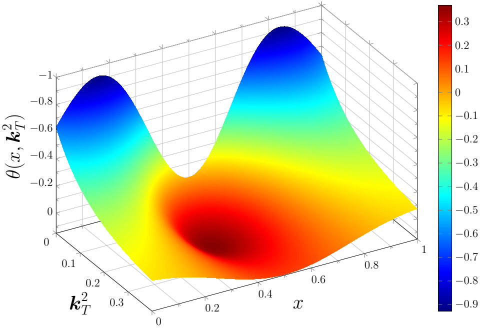
Conclusion

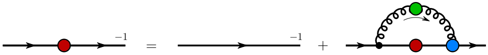
- To understand hadron masses must understand the role of DCSB
- Using DSEs find that DCSB drives numerous effects in QCD, e.g., hadron masses, confinement and many aspects of hadron structure
  - broading of pion PDA, maximum of $Q^2\,F_\pi(Q^2)$, etc
  - location of zero's in form factors – G_{Ep}, F_{1p}^d, etc – provide tight constraints on QCD dynamics
  - predict zero in G_{En}/G_{Mn} independent rate of change of DCSB
- Tensor polarized spin-one targets contain interesting new information about hadron and nuclear structure

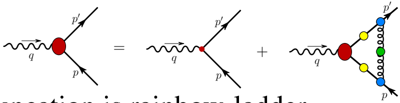




Backup Slides

Rainbow Ladder Truncation





- The most common symmetry preserving truncation is rainbow-ladder

$$\tfrac{1}{4\pi}\, g^2\, D_{\mu\nu}(p-k)\,\Gamma_\nu(p,k) \quad \longrightarrow \quad \alpha_{\text{eff}}(p-k)\, D^{\text{free}}_{\mu\nu}(p-k)\,\gamma_\nu$$

- Need model for $\alpha_{\text{eff}}(k^2)$ – must agree with perturbative QCD for large k^2
  - Maris–Tandy model is historically the most successful example [PRC 60, 055214 (1999)]

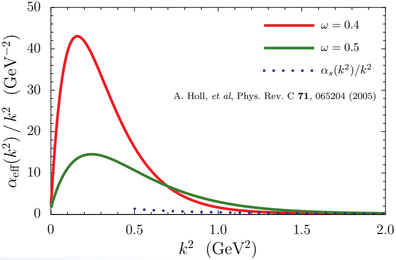
$$\alpha_{\text{eff}}(k^2) = \frac{\pi\, D}{\omega^6}\, k^4\, e^{-k^2/\omega^2} + \frac{24\,\pi}{25}\left(1 - e^{-k^2/\mu^2}\right) \ln^{-1}\!\left[e^2 - 1 + \left(1 + k^2/\Lambda^2_{\text{QCD}}\right)^2\right]$$

- Satisfies vector & axial-vector WTIs

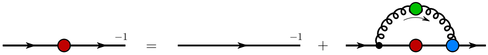
$$q_\mu\, \Gamma^\mu_{\gamma qq}(p',p) = \hat{Q}_q\left[S_q^{-1}(p') - S_q^{-1}(p)\right]$$

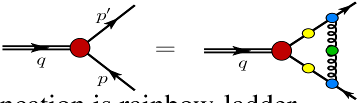
[em current conservation]

$$q_\mu\, \Gamma_5^{\mu,i}(p',p) = S^{-1}(p')\,\gamma_5\, t_i + t_i\,\gamma_5\, S^{-1}(p) + 2\,m\,\Gamma^i_\pi(p',p) \qquad \text{[DCSB]}$$



Rainbow Ladder Truncation





- The most common symmetry preserving truncation is rainbow-ladder

$$\frac{1}{4\pi}\, g^2\, D_{\mu\nu}(p-k)\, \Gamma_\nu(p,k) \quad\longrightarrow\quad \alpha_{\text{eff}}(p-k)\, D^{\text{free}}_{\mu\nu}(p-k)\, \gamma_\nu$$

- Need model for $\alpha_{\text{eff}}(k^2)$ – must agree with perturbative QCD for large k^2
  - Qin–Chang model is a modern update [PRC 84, 042202 (2011)]

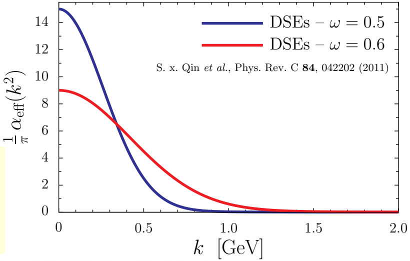
$$\alpha_{\text{eff}}(k^2) = \frac{\pi\, D}{\omega^4}\, k^2\, e^{-k^2/\omega^2} + \frac{24\,\pi}{25}\left(1 - e^{-k^2/\mu^2}\right) \ln^{-1}\!\left[e^2 - 1 + \left(1 + k^2/\Lambda^2_{\text{QCD}}\right)^2\right]$$

- Satisfies vector & axial-vector WTIs

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

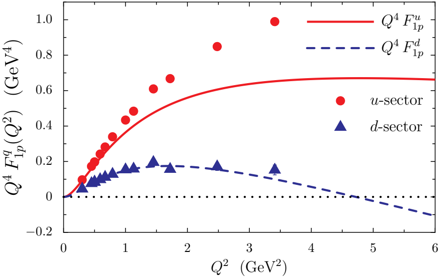
[em current conservation]

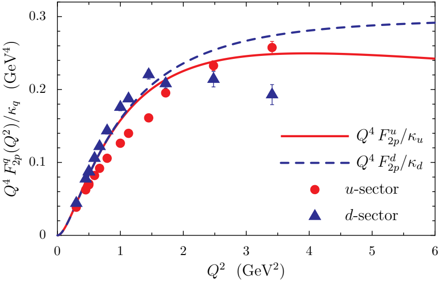
$$q_\mu\, \Gamma_5^{\mu,i}(p',p) = S^{-1}(p')\,\gamma_5\, t_i + t_i\,\gamma_5\, S^{-1}(p) + 2\,m\,\Gamma^i_\pi(p',p) \qquad \text{[DCSB]}$$



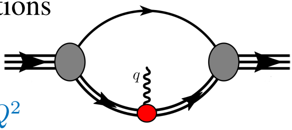
Flavor separated proton form factors

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





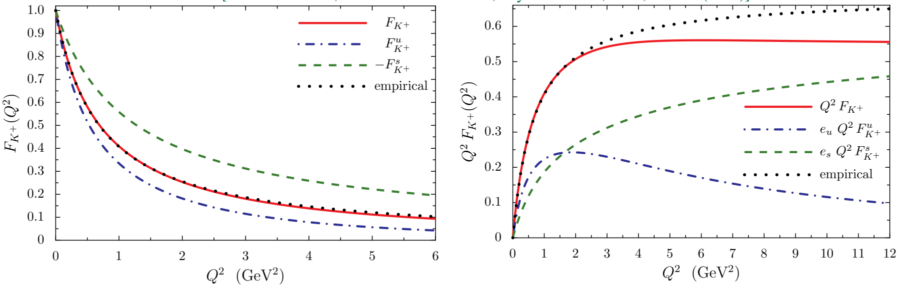
- Prima facie, these experimental results are remarkable
  - u and d quark sector form factors have very different scaling behaviour
- However, when viewed in context of diquark correlations results are straightforward to understand
  - in proton (uud) the d quark is "bound" inside a scalar diquark $[ud]$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



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

Form Factors and Confinement

[P. T. P. Hutauruk, ICC and A. W. Thomas, Phys. Rev. C **94**, no. 3, 035201 (2016)]



- Form factors must be a sensitive measure of confinement in QCD
  - but what are they telling us?
  - consider quark-sector kaon form factors
- Perturbative QCD provides: $F_{K^+}(Q^2)/F_{\pi^+}(Q^2) \overset{Q^2 \gg \Lambda_{\rm QCD}}{\longrightarrow} f_K^2/f_\pi^2$
- Using NJL model find remarkable flavor dependence of K form factors
  - s-quark much harder than the u/d-quark
  - confinement? If probe strikes a light u-quark it is much harder for the hadron to remain intact – compared to when an s quark is struck