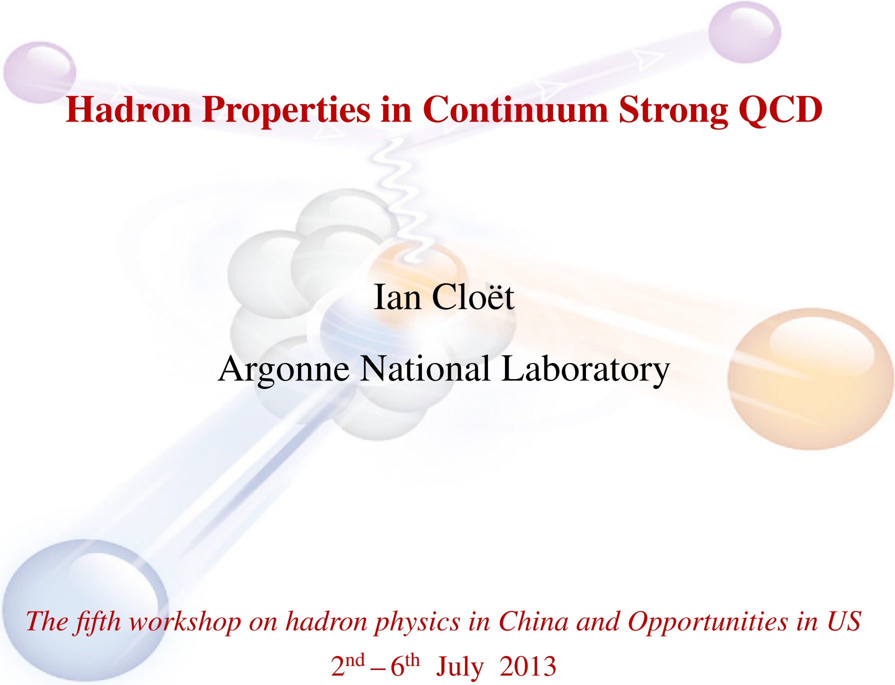

Hadron Properties in Continuum Strong QCD

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Argonne National Laboratory

The fifth workshop on hadron physics in China and Opportunities in US

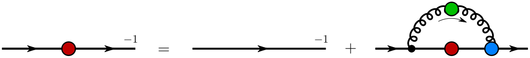
2nd – 6th July 2013

The Challenge of QCD

- QCD is the only known example in nature of a fundamental quantum field theory that is innately non-perturbative
  - *a priori* no idea what such a theory can produce
- Solving QCD will have profound implications for our understanding of the natural world
  - e.g. it will explain how massless gluons and light quarks bind together to form hadrons, and thereby explain the origin of $\sim$98% of the mass in the visible universe
  - *given QCDs complexity, the best promise for progress is a strong interplay between experiment and theory*
- QCD is characterized by two emergent phenomena:
  - confinement & dynamical chiral symmetry breaking (DCSB)
  - a world without DCSB would be profoundly different, e.g. $m_\pi \sim m_\rho$
- *Must discover the origin of confinement, its relationship to DCSB and understand how these phenomenon influence hadronic obserables*

Meeting this Challenge – QCDs Dyson–Schwinger Eqns

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

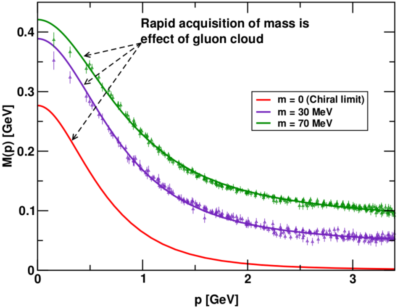


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

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

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



Pion's (valence quark) Distribution Amplitude

- pion's DA – $\varphi_\pi(x)$: *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 Bjorken scaling variable $x = \frac{k^+}{p^+}$ and the scale Q^2
- In QCD the pion's DA it is defined by

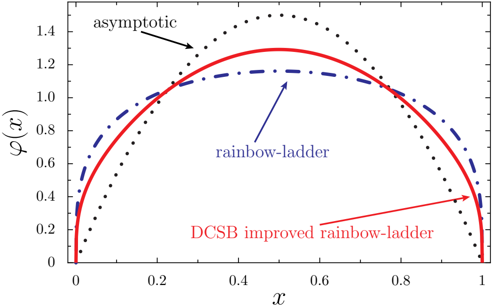
$$f_\pi \, \varphi_\pi(x) = Z_2 \int \frac{d^4k}{(2\pi)^2} \, \delta\left(k^+ - x\, p^+\right) \mathrm{Tr}\left[\gamma^+ \gamma_5 \, S(k) \, \Gamma_\pi(k,p) \, S(k-p)\right]$$

- $S(k)\,\Gamma_\pi(k,p)\,S(k-p)$ 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 light front
- PDA is interesting because it is calculable in perturbative QCD and, for example, in this regime governs the Q^2 dependence of the pion form factor

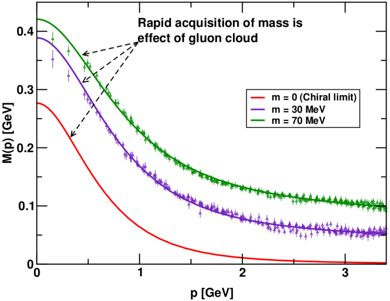
$$Q^2 \, F_\pi(Q^2) \overset{Q^2 \to \infty}{\longrightarrow} 16\,\pi\, f_\pi^2 \, \alpha_s(Q^2) \qquad \Longleftrightarrow \qquad \varphi_\pi^{\mathrm{asy}}(x) = 6\,x\,(1-x)$$

Pion DA in 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 DA
  - scale of calculation is given by renormalization point $\zeta = 2\,\text{GeV}$
- Broading of the pion's DA is directly linked to DCSB
  - if there is no DCSB, DSEs give $\varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$
- As we shall see the dilation of pion's DA will influence the Q^2 evolution of the pion's electromagnetic form factor, which is measurable at JLab

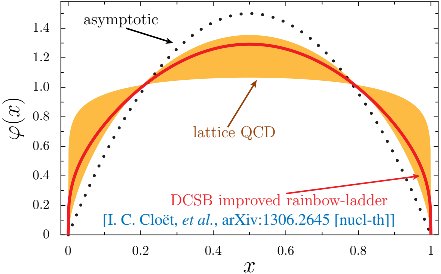
Pion DA from lattice QCD

- 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

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

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

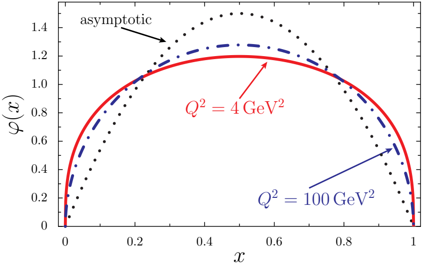
- Advocate using a *generalized expansion*

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

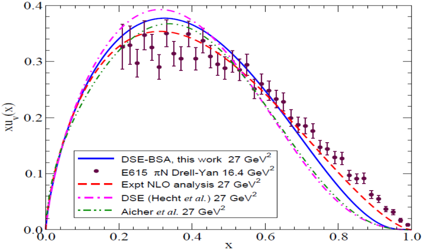
- Find $\varphi_\pi \simeq x^\alpha(1-x)^\alpha,\ \alpha = 0.35^{+0.32}_{-0.24}$; good agreement with DSE: $\alpha \simeq 0.30$

When is the Pion's DA Asymptotic

[I. C. Cloët, *et al.*, arXiv:1306.2645 [nucl-th]]



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

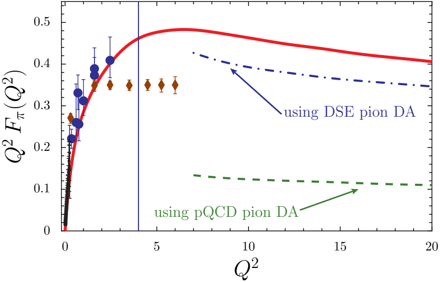


- Under leading order Q^2 evolution the pion DA remains broad to well above $Q^2 > 100\,\mathrm{GeV}^2$, compared with $\varphi_\pi^{\mathrm{asy}}(x) = 6\,x\,(1-x)$
- Consequently, the asymptotic form of the pion DA is a poor approximation at all energy scales that are either currently accessible or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

Pion Elastic Form Factor

- Extended the pre-experiment DSE prediction to $Q^2 > 4\,\mathrm{GeV}^2$
- Predict maximum at $Q^2 \approx 6\,\mathrm{GeV}^2$, lies within domain accessible at JLab12
- Comparison with perturbative QCD?

[L. Chang, *et al.*, arXiv:1307.0026 [nucl-th]]



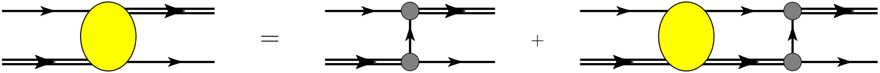
- The QCD prediction can be expressed as

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

- Using $\varphi_\pi^{\rm asy}(x)$ significantly underestimates experiment
- Within DSEs there is consistency between the direct pion form factor calculation and that obtained using the DSE pion DA
  - slight disagreement likely explained by a combination of higher order, higher-twist corrections and shortcomings of rainbow-ladder truncation

Structure of Baryons

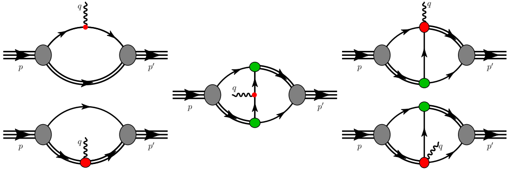
- In QFT baryons appear as poles in 6-point Green functions
- This scattering amplitude is the solution to a Poincaré covariant Faddeev equation, which sums all possible interactions between the three quarks
  - traceable solution via observation that an interaction which produces colour singlet mesons must also generate (nonpointlike) diquark correlations in colour $\bar{3}$ channel

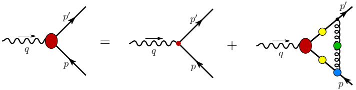


  - diquark correlations are not inserted by hand, such correlations are a dynamical consequence of strong coupling in QCD
  - they are also directly related to DCSB, as this single mechanism produces both the almost massless pion and strong scalar-diquark correlations
- For the nucleon the most important diquark correlations are in the scalar $(J^P = 0^+, T = 0)$ and axial-vector $(J^P = 1^+, T = 1)$ channels
  - in the rest frame the nucleon wave function contains s, p & d wave components
  - this has important implications for the nucleon spin sum

Nucleon Electromagnetic Form Factors

- Elastic form factors provide information on the *momentum space* distribution of charge and magnetization within the nucleon
- Accurate form factor measurements are creating a paradigm shift in our understanding of hadron structure; e.g.
  - proton radius puzzle, $\mu_p\, G_{Ep}/G_{Mp}$ ratio and a possible zero in G_{Ep}
  - flavour decomposition and diquark correlations
  - tests perturbation QCD scaling predictions
- In the DSEs the nucleon current is given by:





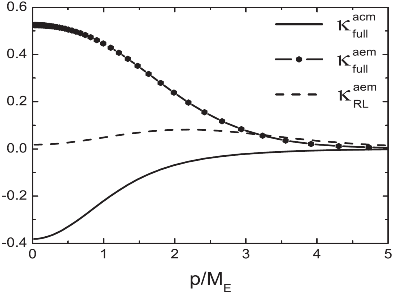
$$\Gamma^\mu = \Gamma^\mu_L + \Gamma^\mu_T; \quad q_\mu\, \Gamma^\mu_T = 0$$

$$q_\mu\, \Gamma^\mu_L = \hat{Q}\, \left[S^{-1}(p') - S^{-1}(p)\right]$$

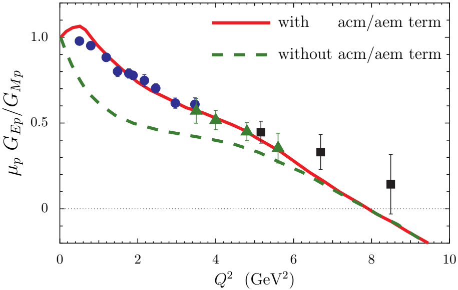
- Feedback with experiment can constrain DSE quark–gluon vertex
- Knowledge of quark–gluon vertex provides $\alpha_s(Q^2)$ within DSEs
  - also gives the β-function which may shed light on confinement

Proton form factors ratios

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



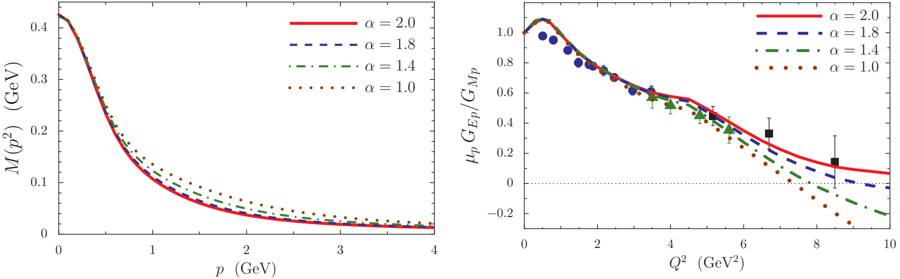
[ICC, C. D. Roberts, *et al.*, Few Body Syst. **46**, 1 (2009)]



- Latest results include effect from anomalous chromomagnetic moment term in the quark–gluon vertex
  - generates large anomalous electromagnetic term in quark–photon vertex
- Quark anomalous magnetic moment required for good agreement with data
  - important for low to moderate Q^2
- For massless quarks anomalous chromomagnetic moment is only possible via DSCB
- Discrepancy at low Q^2 is alleviated by including the ρ and ω contributions to quark-photon vertex

Proton G_E form factor and DCSB

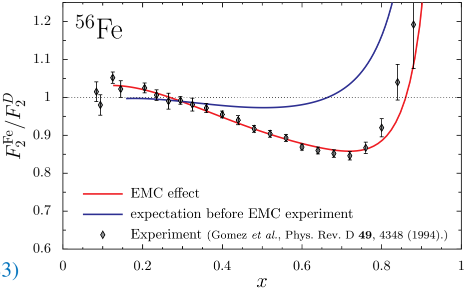
[I. C. Cloët, C. D. Roberts and A. W. Thomas, arXiv:1304.0855 [nucl-th]]



- Find that slight changes in $M(p)$ on the domain $1 \lesssim p \lesssim 3\,\text{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
  - position of zero, or lack thereof, in G_E is extremely sensitive to underlying quark-gluon dynamics
- 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 magnetic moment
  - the quicker the perturbative regime is reached the quicker $F_2 \to 0$

Quarks and Nuclei – The EMC effect

- An important motivation for this work remains the discovery of the *EMC effect* at CERN in 1983
- The European Muon Collaboration (EMC) conducted DIS experiments on an iron target
  - J. J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983)

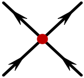


"The results are in complete disagreement with the calculations ... We are not aware of any published detailed prediction presently available which can explain behavior of these data."

- Measurement of the *EMC effect* destroyed a particle-physics paradigm regarding QCD and nuclear structure
  - more than 30 years after discovery broad consensus on explanation is lacking
  - what is certain: *valence quarks in nucleus carry less momentum than in a nucleon*
- One of the most important nuclear structure discoveries since advent of QCD
  - understanding its origin is critical for a QCD based description of nuclei

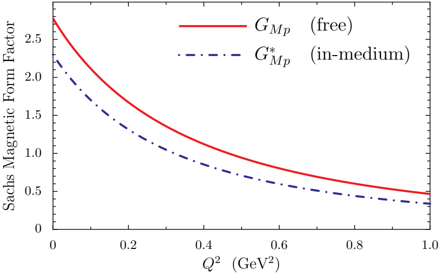
Quarks and Nuclei

Continuum QCD *"integrate out gluons"* →



$\frac{1}{m_G^2}\,\Theta(\Lambda^2-k^2)$

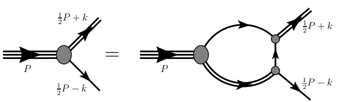
- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be related back to QCD via the DSEs

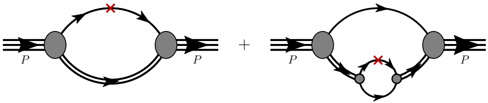


- For nuclei, we find that quarks bind together into color singlet nucleons
  - however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment
  - *as a consequence bound nucleons are modified by the nuclear medium*
- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure
- These studies provide a complementary approach to more traditional nuclear physics research (e.g. GFMC)

Nucleon quark distributions

- Nucleon = quark+diquark
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$

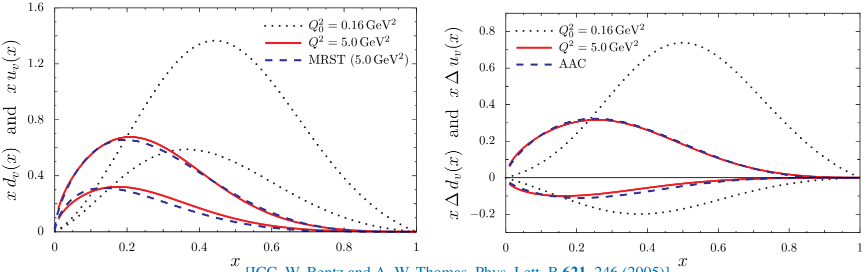




- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

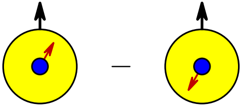
- $q(x)$: probability strike quark of favor q with momentum fraction x of target



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

Nucleon transversity quark distributions

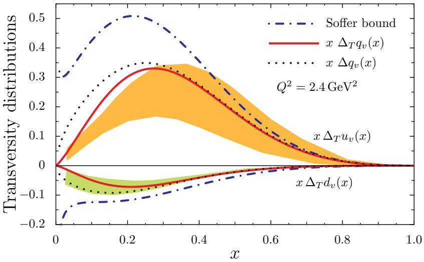
$\Delta_T q(x) =$



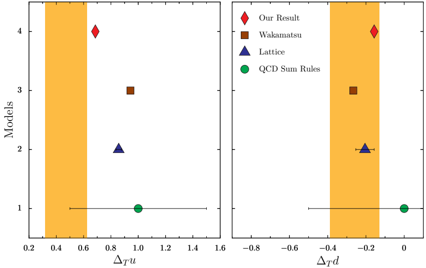
- Sum rule gives tensor charge

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

- 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)



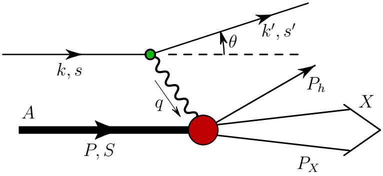
[ICC *et al.*, Phys. Lett. B **659**, 214 (2008)]



[M. Anselmino *et al*, Nucl. Phys. Proc. Suppl. **191**, 98 (2009)]

Transverse Momentum Dependent PDFs

- Measured in semi-inclusive DIS



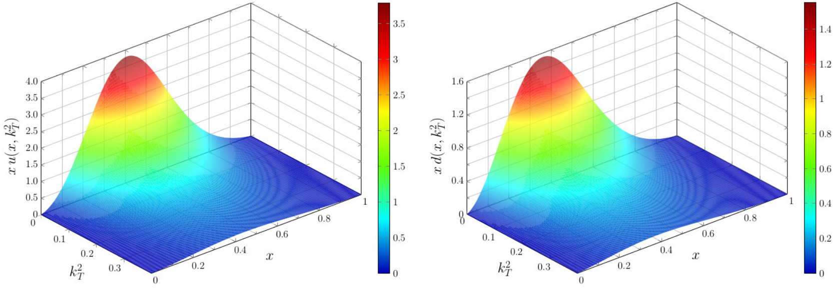
- Leading twist 6 T-even TMD PDFs

$$q(x, k_\perp^2), \quad \Delta q(x, k_\perp^2), \quad \Delta_T q(x, k_\perp^2)$$
$$g_{1T}^q(x, k_\perp^2), \quad h_{1L}^{\perp q}(x, k_\perp^2), \quad h_{1T}^{\perp q}(x, k_\perp^2)$$

- $$\langle p_T \rangle (x) \equiv \frac{\int d\vec{k}_\perp \, k_\perp \, q(x, k_\perp^2)}{\int d\vec{k}_\perp \, q(x, k_\perp^2)}$$

[H. Avakian, *et al.*, Phy. Rev. D81, 074035 (2010)]

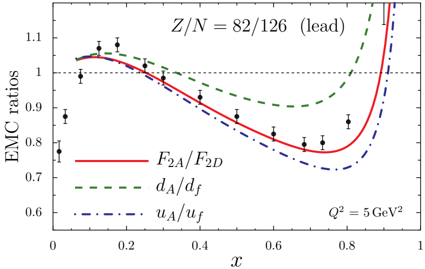
- $\langle p_T \rangle^{Q^2 = Q_0^2} = 0.36\,\text{GeV}$ c.f. $\langle p_T \rangle_{\text{Gauss}} = 0.56\,\text{GeV}$ [HERMES], $0.64\,\text{GeV}$ [EMC]



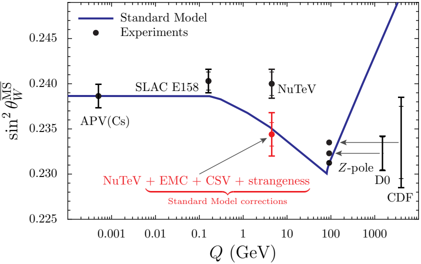
[H. H. Matevosyan, ICC *et al.*, Phys. Rev. D **85**, 014021 (2012)]

Isovector EMC effect & the NuTeV Anomaly

[I. C. Cloët *et. al*, Phys. Rev. Lett. **109**, 182301 (2012)]



[W. Bentz *et. al* [including Cloët], Phys. Lett. B **693**, 462 (2010)]



- Model provides a natural explanation of the EMC effect
- Predicts that isovector nuclear forces result in a large quark flavor dependence of the EMC effect
  - parity-violating DIS experiments at JLab are sensitive to this flavor dependence
- Evidence for a flavor dependence of the EMC effect may already exist from the NuTeV measurement of $\sin^2\theta_W$ (weak mixing angle) [iron target]
  - NuTeV result disagrees with the Standard Model by $3\,\sigma \iff$ NuTeV anomaly
- Corrections from the EMC effect ($\sim 1.5\,\sigma$) and charge symmetry violation ($\sim 1.5\,\sigma$) brings NuTeV result into agreement with the Standard Model

Conclusion

- Both DSEs and lattice QCD agree that the pion DA is significantly broader than the asymptotic result
  - using LO evolution find dilation remains significant for $Q^2 > 100\,\mathrm{GeV}^2$
  - strictly the asymptotic form of the pion DA is only valid when $q_v^\pi(x) \propto \delta(x)$
- Anomalous chromomagnetic moment generates large anomalous EM moment; essential for agreement with nucleon form factor data in DSEs
- An interplay between experiment and DSE theory, focusing on nucleon (transition) form factors, can shed further light on the quark–gluon vertex
- Highlight the importance of understanding the EMC effect as a critical step towards a QCD based description of nuclei
- EMC effect and NuTeV anomaly are interpreted as evidence for medium modification of the bound nucleon wavefunction
  - predictions will be tested using PV DIS
- Using $W^\pm$ exchange an EIC is an excellent tool to unravel the quark flavour sector contributions to nucleon and nuclear structure
  - provided, of course, it can make measurements in the valence quark region

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