Revealing the Quark and Gluon Structure of Hadrons and Nuclei

(*including charge symmetry breaking effects*)

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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 observables*

Meeting this Challenge – QCDs Dyson–Schwinger Eqns

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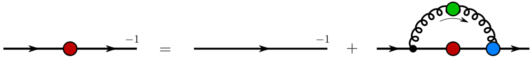
- The equations of motion of QCD $\Longleftrightarrow$ QCDs Dyson–Schwinger equations
  - an infinite tower of coupled integral equations
  - must implement a symmetry preserving truncation
- The most important DSE is QCDs gap equation $\Longrightarrow$ quark propagator

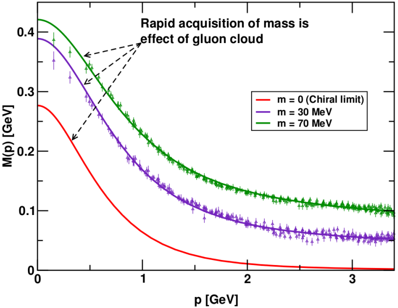


  - ingredients – dressed gluon propagator & dressed quark-gluon vertex

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

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

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



Light-Front Wave Functions

- In equal-time quantization the wave function for a hadron is a frame dependent concept
  - as it is defined by observations of different space points at a fixed time
  - boost operators are interaction dependent, i.e. are dynamical
- In high energy scattering experiments particles move at near speed of light
  - natural to quantize a theory at equal light-front time: $\tau = (t+z)/\sqrt{2}$
- Light-front wave functions, $\psi(x_i, \vec{k}_{\perp i})$, have many remarkable properties
  - provide a frame-independent representation of hadrons
  - have a probability interpretation – as close as QFT gets to QM
  - do not depend on the hadrons 4-momentum; only internal variables: x_i & $\vec{k}_{\perp i}$
  - boosts are kinematical – *not dynamical!!*
- Parton distribution amplitudes (PDAs) are (almost) obserables & are related to light-front wave functions

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

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 Bjorken scaling variable $x = \frac{k^+}{p^+}$ and the scale Q^2
- The pion's PDA is defined by

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

- $S(k)\, \Gamma_\pi(k,p)\, S(k-p)$ 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 [pseudo-scalar projection also non-zero]
- Pion PDA is interesting because it is calculable in perturbative QCD and, e.g., in this regime governs the Q^2 dependence of the pion form factor

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

QCD Evolution & asymptotic PDA

- Scale (Q^2) dependence of pion PDA [c.f. DGLAP equations for PDFs]

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

- This evolution equation has a solution of the form

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

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

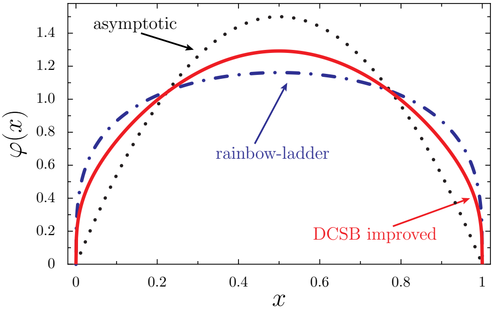
- The coefficients of the Gegenbauer polynomials, $a_n^{3/2}(Q^2)$, evolve logarithmically to zero as $Q^2 \to \infty$: $\varphi_\pi(x) \to \varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$

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

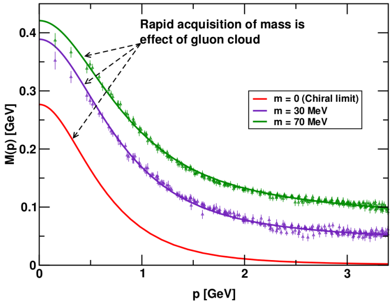
- E.g., AdS/QCD find $\varphi_\pi(x) \sim x^{1/2}\,(1-x)^{1/2}$ at $Q^2 = 1\,\text{GeV}^2$ expansion in terms of $C_n^{3/2}(2x-1)$ convergences slowly: $a_{32}^{3/2} / \, a_2^{3/2} \sim 10\,\%$

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

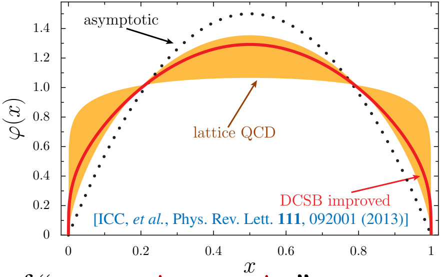
Pion PDA from lattice QCD

- Lattice QCD can only determine one non-trivial moment

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

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

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



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

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

  - 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*

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

- 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 PDA Asymptotic

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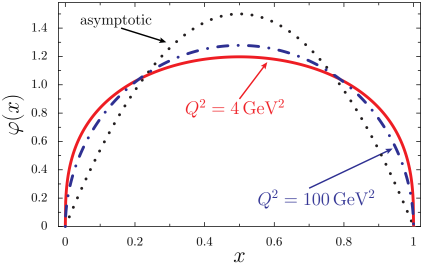
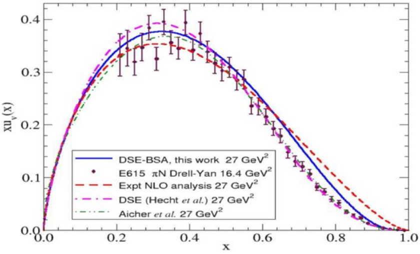
[I. C. Cloët, *et al.*, Phys. Rev. Lett. **111**, 092001 (2013)]

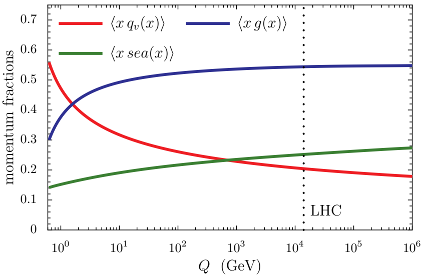


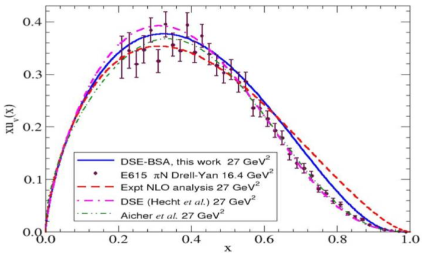
[T. Nguyen, *et al.*, Phys. Rev. C **83**, 062201 (2011)]



- Under leading order Q^2 evolution the pion PDA remains broad to well above $Q^2 > 100\,\mathrm{GeV}^2$, compared with $\varphi_\pi^{\rm asy}(x) = 6\,x\,(1-x)$
- *Consequently, the asymptotic form of the pion PDA is a poor approximation at all energy scales that are either currently accessible or foreseeable in experiments on pion elastic and transition form factors*
- Importantly, $\varphi_\pi^{\rm asy}(x)$ 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

When is the Pion's Valence PDF Asymptotic





- LO QCD evolution of momentum fraction carried by valence quarks

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

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

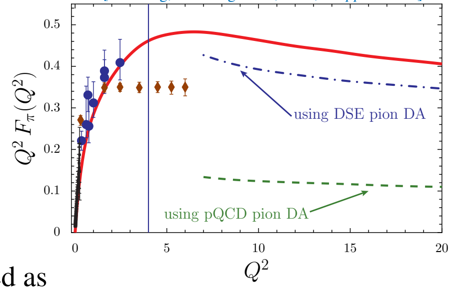
- At LHC energies valence quarks still carry 20% of pion momentum
  - we find that the gluon distribution saturates at $\langle x\, g(x)\rangle \sim 55\%$

- *Asymptotia is a long way away! Practically QCD is always non-perturbative*

Pion Elastic Form Factor

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

[L. Chang, including Cloët, *et al.*, *to appear* PRL]



- 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 PDA
  - 15% disagreement explained by higher order/higher-twist corrections
- *We prediction that QCD power law behaviour sets in at $Q^2 \sim 8\,GeV^2$*

Charge Symmetry and Charge Independence

- Charge symmetry is a particular type of isospin invariance
  - namely the invariance under an isospin rotation of 180° about the y-axis (with charge associated with the z-axis)
  - corresponds to the interchange of u and d quarks: $u \leftrightarrow d$, $\bar{u} \leftrightarrow \bar{d}$

$$P_{\text{cs}}\,|u\rangle = -\,|d\rangle\,, \qquad P_{\text{cs}}\,|d\rangle = |u\rangle\,, \qquad P_{\text{cs}} = e^{i\,\pi\,T_2}$$

- Charge symmetry does not imply *charge independence*, which is associated with invariance under arbitrary rotations in isospin space
- E.g.: pion masses break charge independence but respect charge symmetry

$$\left|\pi^+\right\rangle = \left|u\bar{d}\right\rangle \qquad m_{\pi^+} = 139.57\,\text{MeV}$$

$$\left|\pi^0\right\rangle = \frac{1}{\sqrt{2}}\left[|u\bar{u}\rangle - \left|d\bar{d}\right\rangle\right] \qquad m_{\pi^0} = 134.98\,\text{MeV}$$

$$\left|\pi^-\right\rangle = |d\bar{u}\rangle \qquad m_{\pi^-} = 139.57\,\text{MeV}$$

  - isospin breaking effects of the order: $\frac{m_{\pi^+} - m_{\pi^0}}{m_{\pi^+}} \sim 3 - 4\%$

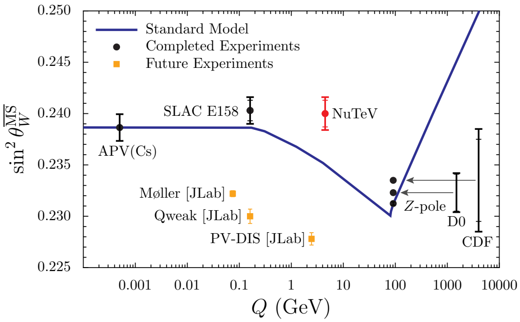
Charge Symmetry Breaking & $M_n - M_p$

- In Standard Model two main sources of charge symmetry breaking
  - quark mass differences: $\delta m = m_d - m_u \sim 4\,\mathrm{MeV}$
  - quark charges: $e_u = +2/3, \quad e_d = -1/3$
- The proton (uud) neutron (udd) mass difference, $\delta M_N = M_n - M_p = 1.29\,\mathrm{MeV}$, indicates charge symmetry breaking
  - charge symmetry breaking effects of the order: $\frac{M_n - M_p}{M_p} < 1\%$
- For $m_u = m_d$ electrostatic replusion implies $M_p > M_n$
  - recent analysis finds: $\delta M_N^{\mathrm{QED}} = -1.30(03)(47)\,\mathrm{MeV}$ [Walker-Loud *et al.* PRL **108**, 232301 (2012)]
- Therefore the proton-neutron mass splitting from $m_u \neq m_d$ alone is:

$$\delta M_N^{\mathrm{QCD}} = 2.60(03)(47)\,\mathrm{MeV}$$

- We will focus on charge symmetry breaking effects in nucleon PDFs
  - why is this interesting?

Weak mixing angle and the NuTeV anomaly



Fermilab press conference

"The predicted value was 0.2227. The value we found was 0.2277, a difference of 0.0050. It might not sound like much, but the room full of physicists fell silent when we first revealed the result"

"99.75% probability that the neutrinos are not behaving like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction"

- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$

[G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002)]

- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$ $\Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Huge amount of experimental & theoretical interest [500+ citations]
- Evidence for physics beyond the Standard Model?
- No universally accepted *complete* explanation

Paschos-Wolfenstein ratio

- Paschos-Wolfenstein ratio motivated the NuTeV study:

$$R_{PW} = \frac{\sigma^{\nu A}_{NC} - \sigma^{\bar{\nu} A}_{NC}}{\sigma^{\nu A}_{CC} - \sigma^{\bar{\nu} A}_{CC}} = \frac{\left(\frac{1}{6} - \frac{4}{9}\sin^2\theta_W\right)\langle x_A\, u^-_A\rangle + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)\langle x_A\, d^-_A + x_A\, s^-_A\rangle}{\langle x_A\, d^-_A + x_A\, s^-_A\rangle - \frac{1}{3}\langle x_A\, u^-_A\rangle}$$

  - $\langle x_A\, q^-_A\rangle$ fraction of target momentum carried by valence quarks of flavor q

- For an isoscalar target $u_A \simeq d_A$ and if $s_A \ll u_A + d_A$

$$R_{PW} = \frac{1}{2} - \sin^2\theta_W + \Delta R_{PW}; \quad \Delta R_{PW} = \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x_A\, u^-_A - x_A\, d^-_A - x_A\, s^-_A\rangle}{\langle x_A\, u^-_A + x_A\, d^-_A\rangle}$$

- ΔR_{PW} well constrained $\Longrightarrow$ excellent way to measure weak mixing angle
- NuTeV "result" for R_{PW} is smaller than Standard Model value
- Studies suggest that largest contributions to ΔR_{PW} maybe:
  - strange quarks
  - charge symmetry breaking (CSB) $\Longrightarrow u_p \neq d_n, \;\; d_p \neq u_n$
  - nuclear effects
- NuTeV target was 690 tons of steel $\overset{?}{\Longrightarrow}$ non-trivial nuclear corrections

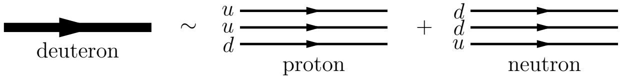
CSB Correction to NuTeV

- Two sources of charge symmetry breaking (CSB) corrections
  - quark mass differences: $\delta m = m_d - m_u \sim 4\,\mathrm{MeV}$
  - quark charge differences: $e_u^2 \neq e_d^2$ [QED splitting/QED evolution of PDFs]
- CSB correction to Paschos-Wolfenstein ratio:

$$\Delta R_{PW}^{CSB} \simeq \left(1 - \tfrac{7}{3}\sin^2\theta_W\right) \frac{\langle x\, u_A^- - x\, d_A^- \rangle}{\langle x\, u_A^- + x\, d_A^- \rangle} \longrightarrow \tfrac{1}{2}\left(1 - \tfrac{7}{3}\sin^2\theta_W\right) \frac{\langle x\, \delta u^- - x\, \delta d^- \rangle}{\langle x\, u_p^- + x\, d_p^- \rangle}$$

$$\delta d^-(x) = d_p^-(x) - u_n^-(x) \qquad \delta u^-(x) = u_p^-(x) - d_n^-(x)$$

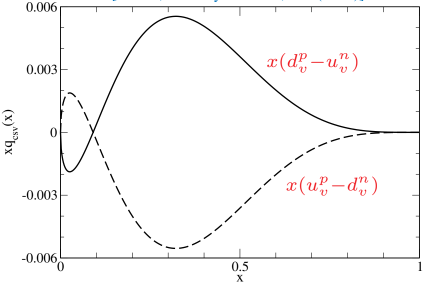
- Mass differences – what do we expect? Consider deuteron:



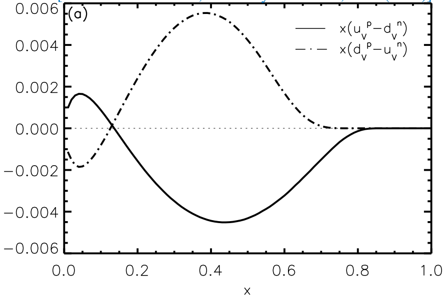
  - therefore since: $m_u < m_d \implies \langle x\, u_A^- \rangle < \langle x\, d_A^- \rangle$
- $e_u^2 > e_d^2 \implies$ u-quarks lose momentum faster than d-quarks to γ-field
- Expect CSB corrections reduce NuTeV discrepancy with Standard Model

CSB – experiment & theory

[MRST, Eur. Phys. J. C **35**, 325 (2004)]



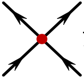
[E. N. Rodionov *et al.*, Mod. Phys. Lett. A **9**, 1799 (1994)]



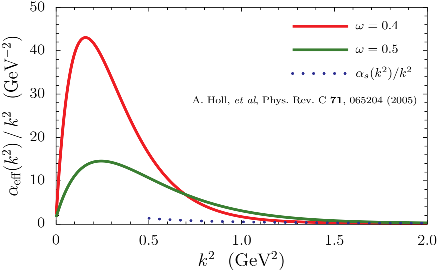
- MRST has done two studies of CSB in PDFs (includes all CSB sources)
  - $\Delta R_{PW}^{CSB} = -0.002$ or 90% confidence of $-0.007 < \Delta R_{PW}^{CSB} < 0.007$
- Theory [Rodionov *et al.*] and MRST in excellent agreement
- Londergan & Thomas [PRD 2003]: $\langle x\,\delta u^- - x\,\delta d^- \rangle \simeq \frac{\delta m}{M_N}$
- The correction to NuTeV is (explains ∼30% of anomaly):

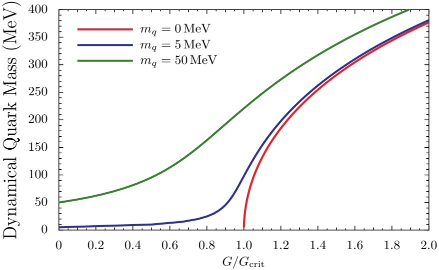
$$\Delta R_{PW}^{\delta m} \equiv \Delta^{\delta m} \sin^2\theta_W = -0.0020$$

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, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be QCD motivated via the DSEs

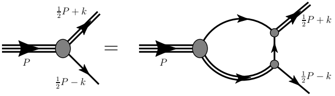


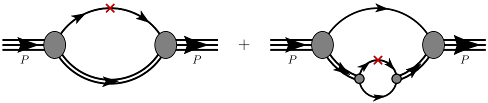


- Proper-time regularization: Λ_{IR} & Λ_{UV} $\Longrightarrow$ Confinement
- Quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \;\rightarrow\; Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - on mass-shell: $Z(p^2 = M^2) = 0$

Nucleon quark distributions

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

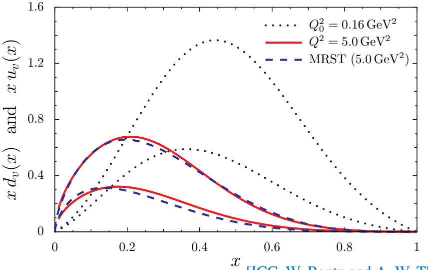


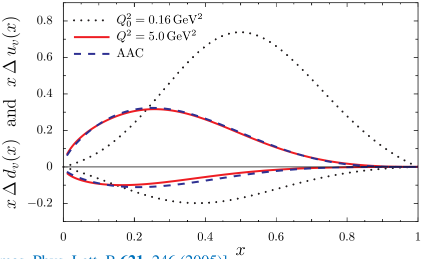


- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

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

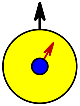
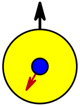
- $q(x)$: probability strike quark of favor q with momentum fraction x of target





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

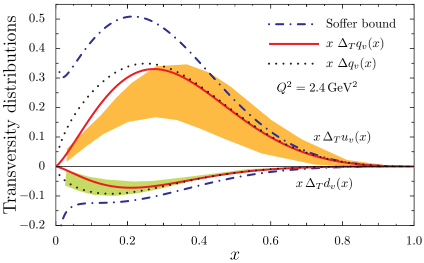
Nucleon transversity quark distributions

$\Delta_T q(x) =$  $-$ 

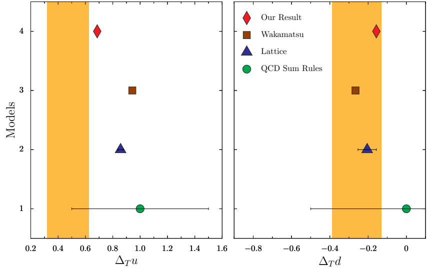
- Sum rule gives tensor charge

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

- 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)



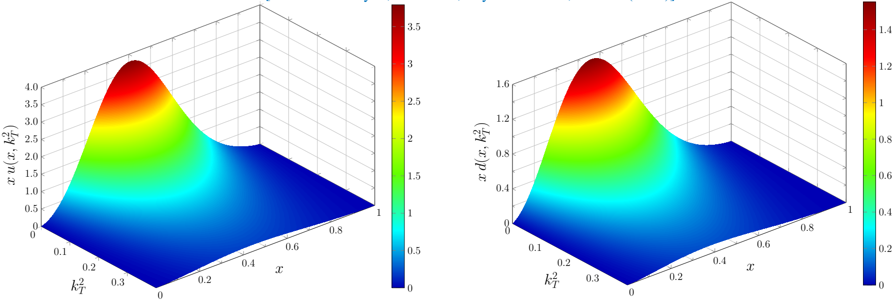
[ICC *et al.*, Phys. Lett. B **659**, 214 (2008)]



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

Transverse Momentum Dependent PDFs

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



- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
- In phenomenology common to work with parametrization of the form:

$$q(x, k_T^2) = q(x)\;\frac{e^{-k_T^2/\langle k_T^2\rangle_0}}{\pi\;\langle k_T^2\rangle_0}$$

$$\langle k_T^2\rangle^{Q^2=Q_0^2} = 0.36^2\,\text{GeV}^2 \sim M^2$$

$$\langle k_T^2\rangle = 0.56^2\,\text{GeV}^2\ \text{[HERMES]},\quad 0.64^2\,\text{GeV}^2\ \text{[EMC]}$$

- Gaussian ansatz fits our results well
  - argeement with experiment reasonable as $\langle k_T^2\rangle$ grows with Q^2

Charge Symmetry Breaking Results

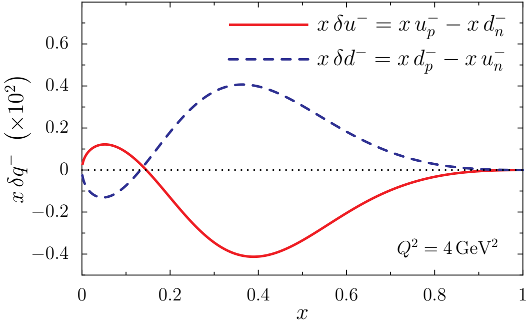
- Our dressed quark mass is $M_0 = 400\,\text{MeV}$ in the charge symmetry limit
  - define: $M_u = M_0 - \delta_M$ & $M_d = M_0 + \delta_M$; $\delta_M \mid M_n - M_p = 3\,\text{MeV}$

$$M_u = 397\,\text{MeV} \;\;\&\;\; M_d = 403\,\text{MeV} \implies \frac{M_d - M_u}{M_d} \simeq 1.5\%; \quad \frac{m_u}{m_d} = 0.58$$

- For the CSB PDFs we find, at $Q^2 = 4\,\text{GeV}^2$:

$$\langle x\,\delta u^- \rangle = -0.0019 \qquad \langle x\,\delta d^- \rangle = \;\; 0.0019$$

  - therefore a small amount of momentum is shifted from the u to the d quarks



- Recent lattice QCD analysis at $Q^2 = 4\,\text{GeV}^2$ find:

[R. Horsley *et al.*, PRD **83**, 051501 (2011)]

$$\langle x\,\delta u \rangle = -0.0023(6)$$
$$\langle x\,\delta d \rangle = \;\; 0.0020(3)$$

- Therefore our results are consistent with Lattice

QED splitting & total CSB correction to NuTeV

- QED evolution of PDFs – compare DGLAP evolution in QCD

$$\frac{d}{d\ln Q^2}\, q^-(x,Q^2) = \frac{\alpha_e}{4\pi}\, e_q^2\, P_{q\gamma}(z) \otimes q^-(x,Q^2)$$

  - contributes even if $m_u = m_d$
  - $e_u^2 > e_d^2 \implies u$-quarks lose momentum faster than d-quarks to γ-field

- Model independent – however where to start &/or stop Q^2 evolution?

- QED splitting: M. Glück *et al.*, PRL **95**, 022002 (2005) – assign 100% error

$$\Delta R^{QED} = -0.011 \pm 0.011$$

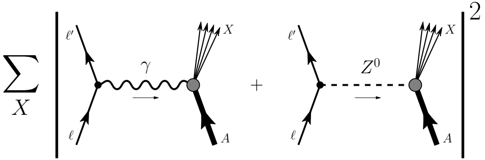
  - QED evolution started at $Q^2 \sim m_q^2$

- Total CSB correction to NuTeV $\sin^2\theta_W$ measurement

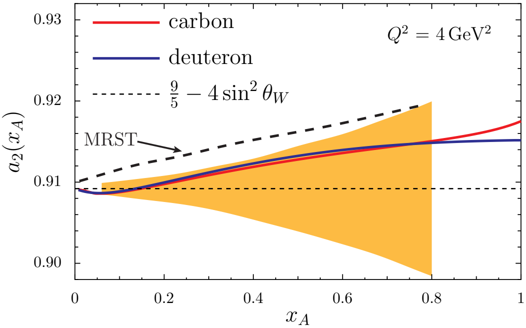
$$\Delta R^{CSB} = \Delta R^{\delta m} + \Delta R^{QED} \equiv \Delta^{CSB}\sin^2\theta_W = -0.0024 \pm 0.0012$$

Measuring CSB – Parity Violating DIS

- Leading contribution to PV-DIS
  - $\gamma\, Z$ interference
- Construct asymmetry:



$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2 g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u^+(x) - d^+(x)}{u^+(x) + d^+(x)}$$



- For CSB, correction term has the form

$$\Delta a_2 = -\frac{6}{25}\frac{\delta u^+(x) - \delta d^+(x)}{\delta u^+(x) + \delta d^+(x)}$$

- Our result too small to be measured in proposed JLab 12 GeV experiment
  - however, still need to include QED splitting – CSB increases

Conclusion

- QCD and therefore Hadron Physics is unique:
  - must confront a fundamental theory in which the elementary degrees-of-freedom are intangible (confined) and only composites (hadrons) reach detectors
- QCD will only be solved by deploying a diverse array of experimental and theoretical methods:
  - must define and solve the problems of confinement and its relationship with DCSB
- These are two of the most important challenges in fundamental Science
- At experimental energies pion PDA & PDF are a long way from asymptotia
  - DCSB $\Leftrightarrow$ valence quarks – remains importance to well beyond LHC energies
- Presented state-of-the-art results for the x dependence of CSB effects in PDFs
  - CSB effects will be measured in PV-DIS experiments at JLab but experimental errors may still be too large see CSB effects
- Highlight the importance of understanding the EMC effect as a critical step towards a QCD based description of nuclei

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