Transverse Motion of Quarks in Nuclei

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Argonne National Laboratory

Short-range Nuclear Correlations at an Electron-Ion Collider

Center for Frontiers in Nuclear Science, 5–7 September 2018

U.S. DEPARTMENT OF ENERGY | Office of Science

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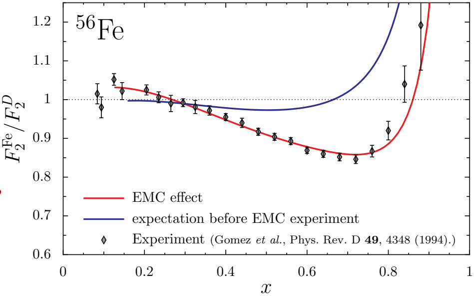
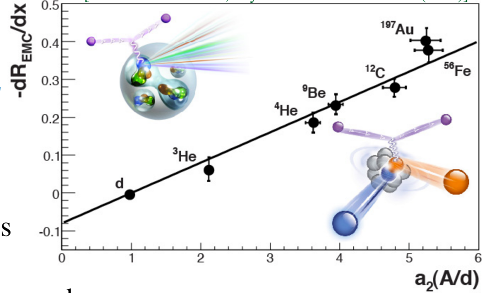
QCD and Nuclei

- Understanding origin of the EMC effect is critical for a QCD based description of nuclei
- Important question: *In what processes, and at what energy scales, do quarks and gluons become the effective degrees of freedom?*
- Modern explanations based around medium modification of the bound nucleons
  - is modification caused by *mean-fields* which modify all nucleons all of the time or by *SRCs* which modify some nucleons some of the time?
- Microscopic calculations/predictions that describe nucleon and nuclear structure only exist in mean-field approach

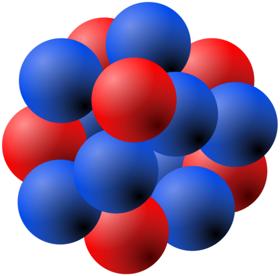


[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]

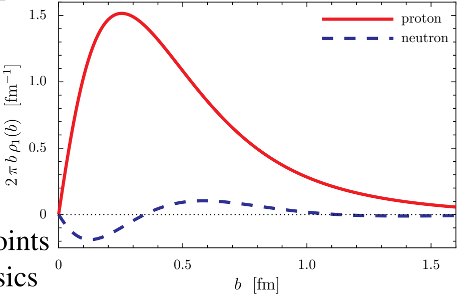


Nucleons in Nuclei

- Nuclei are extremely dense:
  - proton rms radius is $r_p \simeq 0.85\,\text{fm}$, corresponds hard sphere $r_p \simeq 1.10\,\text{fm}$
  - ideal packing gives $\rho \simeq 0.13\,\text{fm}^{-3}$; nuclear matter density is $\rho \simeq 0.16\,\text{fm}^{-3}$
  - 20% of nucleon volume inside other nucleons – nucleon centers $\sim 2\,\text{fm}$ apart



- For realistic charge distribution 25% of proton charge at distances $r > 1\,\text{fm}$
- *Natural to expect that nucleon properties are modified by nuclear medium – even at the mean-field level*
  - in contrast to traditional nuclear physics



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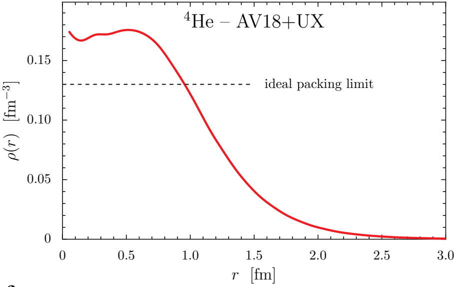

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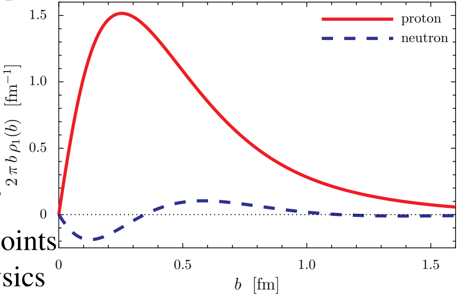

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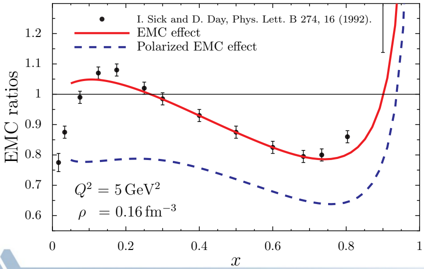
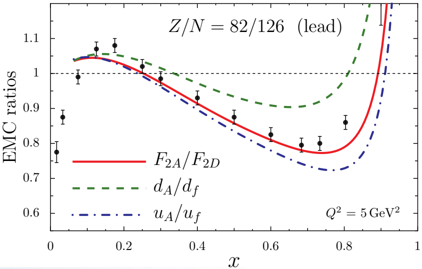
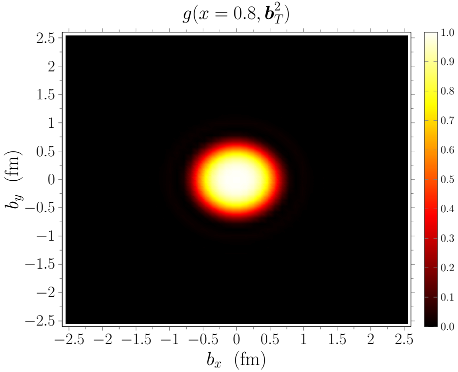
Understanding the EMC effect

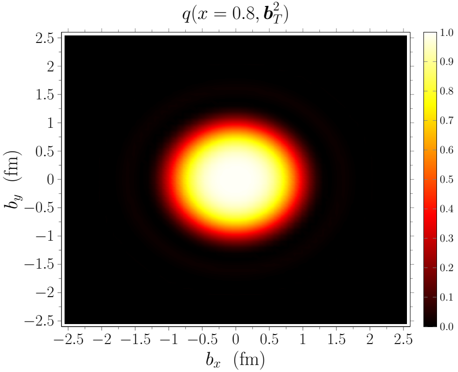
- *The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect*
- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs
- Important examples are measurements of the *EMC effect in polarized structure functions* & the *flavor dependence of EMC effect*
- A JLab experiment has been approved to measure the spin structure of ^{7}Li
- Flavor dependence will be accessed via JLab DIS experiments on ^{40}Ca & ^{48}Ca – *but parity violating DIS stands to play the pivotal role (maybe at EIC)*





Imaging of Nuclei *[see Adam's talk tomorrow]*





- Next step is the quark and gluon imaging/tomography of nuclei [JLab, EIC, Fermilab, . . .]
- Key example is nuclear GPDs – provides a spatial tomography of nuclei
  - spatial location of the quarks and gluons, their variation with x, and radii
- Most directly addresses the question:
  How does the nucleon-nucleon interaction arise from QCD?

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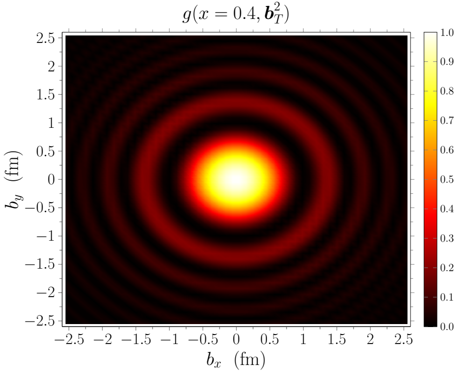

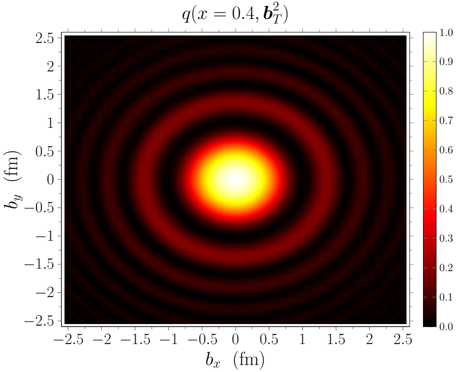

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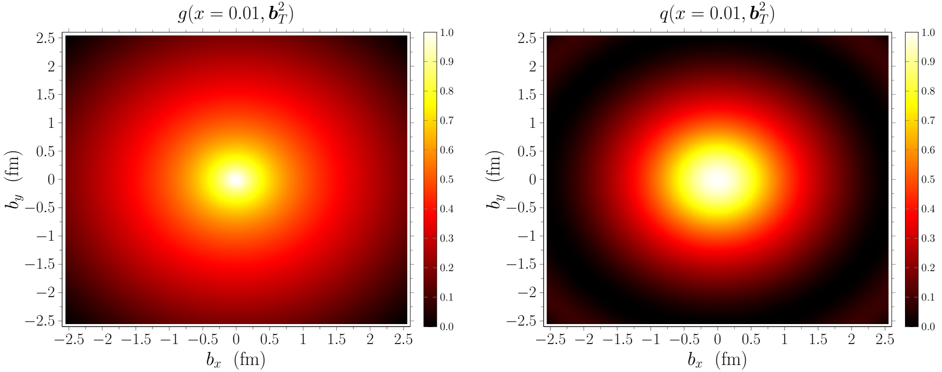

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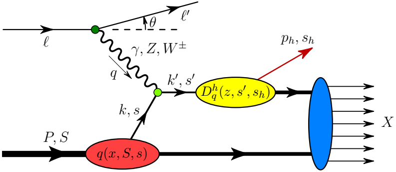
Probing Transverse Momentum

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



- SIDIS cross-section on nucleon has 18 structure functions – factorize as:

$$F(x, z, P_{h\perp}^2, Q^2) \propto \sum f^q(x, \boldsymbol{k}_T^2) \otimes D_q^h(z, \boldsymbol{p}_T^2) \otimes H(Q^2)$$

  - reveals correlations between parton transverse momentum, its spin & target spin

- Fragmentation functions are particularly important, but also challenging
  - *potentially fragmentation functions can shed the most light on confinement and DCSB – because they describe how a fast moving (massless) quark or gluon becomes a tower of hadrons*

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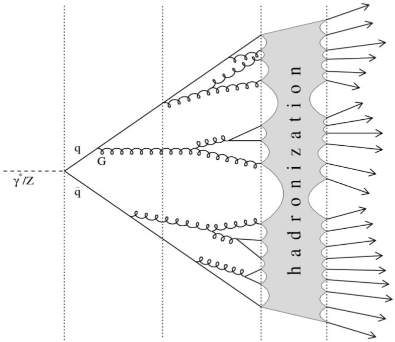

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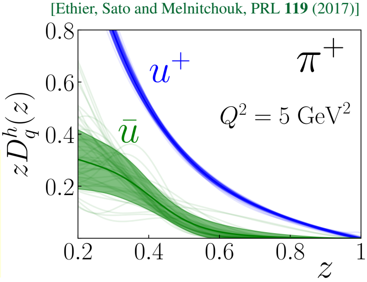
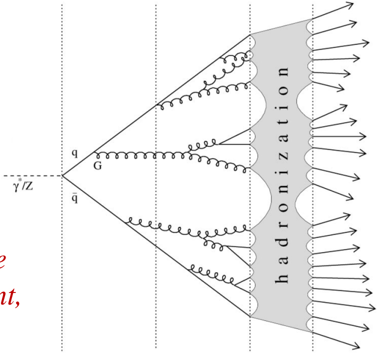
Fragmentation Functions



- Fragmentation functions describe how a fast moving quark or gluon fragments to form hadrons (hadronization); *spin-independent:*

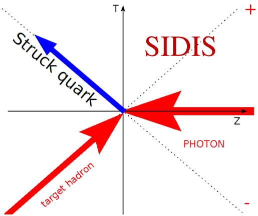
$$D_q^h(z) = \frac{z}{12} \hat{\sum_n} \int \frac{d\xi^-}{2\pi}\, e^{ip^+\xi^-/z} \times \langle p(h), p_n \,|\bar{\psi}(0)|\, 0\rangle\, \gamma^+ \,\langle 0\,|\psi(\xi^-)|\, p(h), p_n\rangle$$

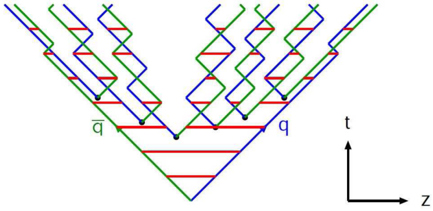
- Physical interpretation *(on the light-front)*: *the number density for a hadron h in a dressed-quark q to have a fraction z of the quark light-cone momentum ($p^+ = z\, k^+$)*



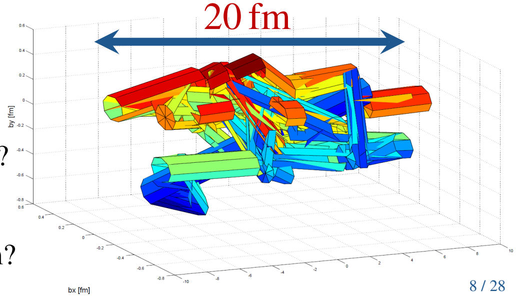
- *Characteristics of fragmentation processes must be dramatically influenced by structure of quark and gluon propagators, confinement, and DCSB.*

Current Treatments of Fragmentation Functions





- Current state-of-the-art treatments of fragmentation functions are usually, in part, semi-classical – e.g. PYTHIA and LUND model
- Implementation and interpretation relies heavily on the concepts of flux tubes or strings
- *Difficult to gain insight into QCD with this framework*
- Are 20 fm flux tubes conceivable?
  - What about confinement?
- How does this change in-medium?



Theory approaches to EMC effect

- To address the like EMC effects must determine e.g. nuclear PDFs, TMDs:

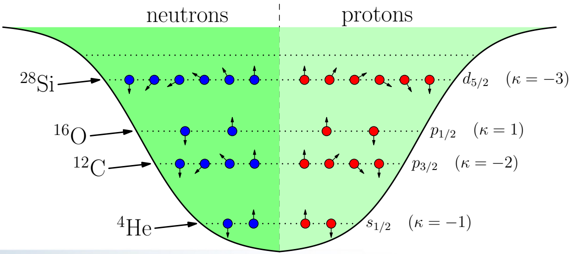
$$q_A\left(x_A\right) = \frac{P^+}{A} \int \frac{d\xi^- \boldsymbol{\xi}_T}{2\pi} e^{i x_A\, P\cdot\xi/A} \langle A, P|\overline{\psi}_q(0)\, \gamma^+\, \psi_q(\xi^-, \boldsymbol{\xi}_T)|A, P\rangle\Big|_{\xi^+=0}$$

- Common to approximate using convolution formalism

$$q_A(x_A, \boldsymbol{k}_T^2) = \sum_\alpha \int_0^A dy_A \int_0^1 dz\, \delta(x_A - y_A z) \int d^2\boldsymbol{q}_T \int d^2\boldsymbol{\ell}_T \\ \delta(\boldsymbol{\ell}_T - \boldsymbol{k}_T + z\,\boldsymbol{q}_T)\, f_A^\alpha(y_A, \boldsymbol{q}_T^2)\, q_\alpha(z, \boldsymbol{\ell}_T^2)$$

  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .

For TMDs must Lorentz transform nucleon to the frame where the nucleus has zero transverse momentum



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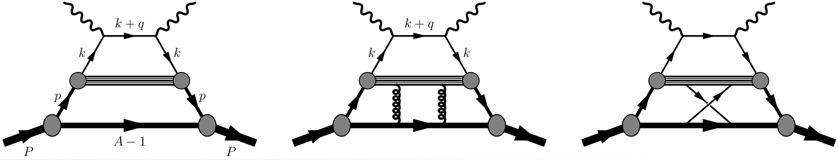
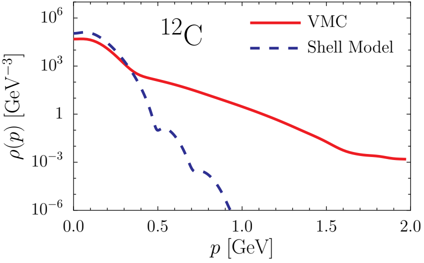
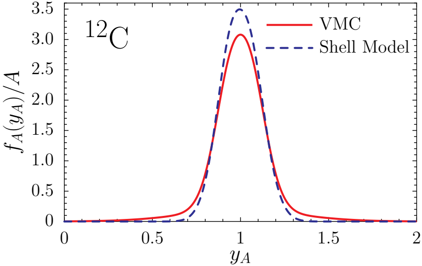
  - $\alpha =$ (bound) protons, neutrons, pions, deltas. . . .
  - $q_\alpha\left(z, \boldsymbol{\ell}_T^2\right)$ TMDs of quarks q in bound hadron α
  - $f_\alpha\left(y_A, \boldsymbol{q}_T^2\right)$ TMDs of hadron in nucleus



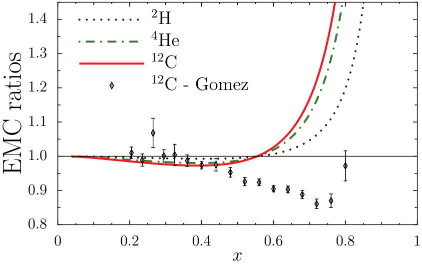
Nucleon Momentum Distributions in Nuclei





- Modern GFMC or VMC nucleon momentum distributions have significant high momentum tails
  - indicates momentum distributions contain SRCs: ∼20% for ^{12}C
- Light-cone momentum distribution:

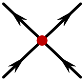
$$f(y_A) = \int \frac{d^3\vec{p}}{(2\pi)^3}\, \delta\left(y_A - \frac{p^+}{P^+}\right)\, \rho(p)$$



- *Naive SRCs introduce effect of opposite sign to EMC effect*

Quarks, Nuclei, and the NJL model

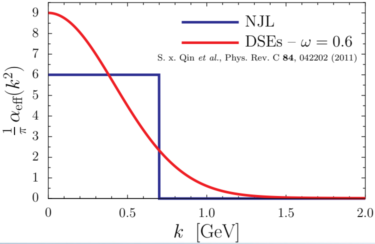
QCD "*integrate out gluons*" →

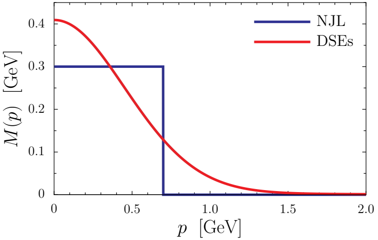


$\frac{1}{m_g^2}\ \Theta(\Lambda^2 - k^2)$

- 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

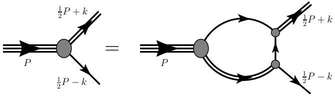
- Quark confinement is implemented via proper-time regularization
  - quark propagator: $[\not{p} - m + i\varepsilon]^{-1} \quad \rightarrow \quad Z(p^2)[\not{p} - M + i\varepsilon]^{-1}$
  - wave function renormalization vanishes at quark mass-shell: $Z(p^2 = M^2) = 0$
  - *confinement is critical for our description of nuclei and nuclear matter*

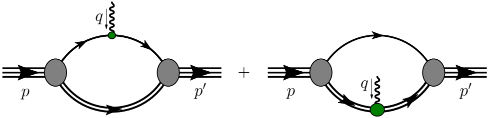




Nucleon Electromagnetic Form Factors

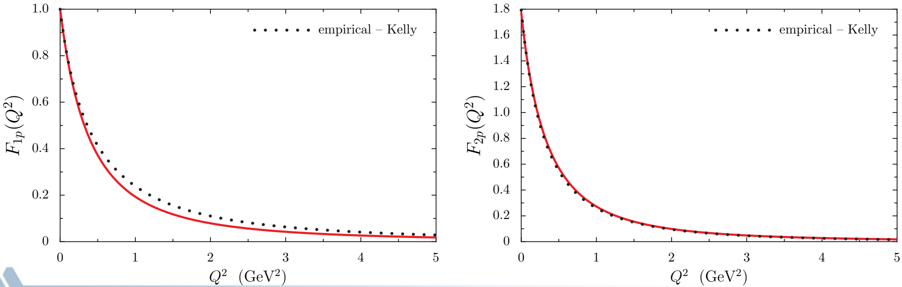
- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:





- Calculation satisfies electromagnetic gauge invariance; includes
  - dressed quark–photon vertex with ρ and ω contributions
  - contributions from a pion cloud

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



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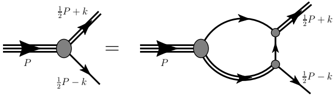

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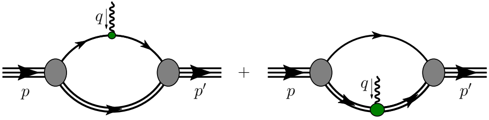

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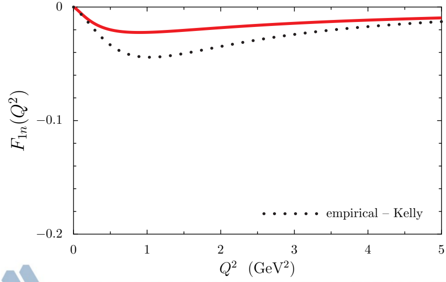
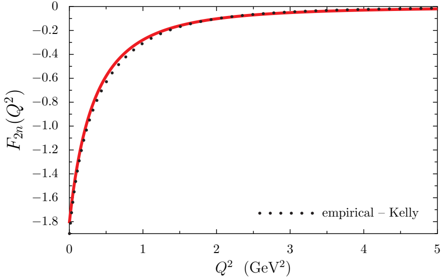
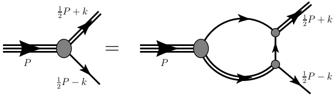
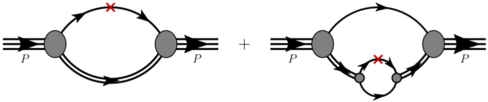




Nucleon quark distributions

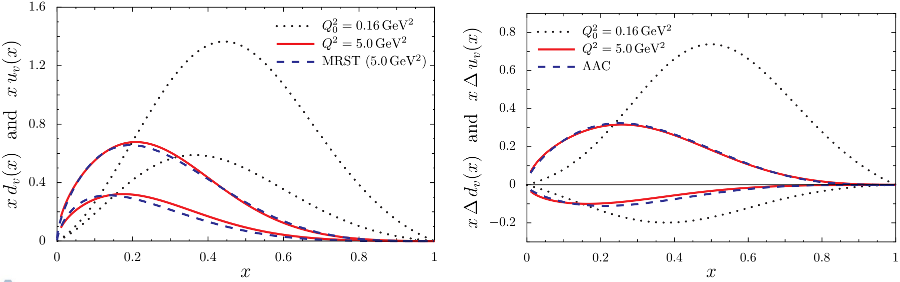
- Nucleon = quark+diquark
- PDFs given by Feynman diagrams: $\langle\gamma^+\rangle$





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

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



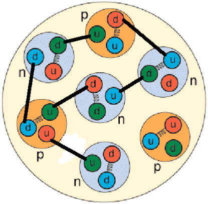
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **621**, 246 (2005)]

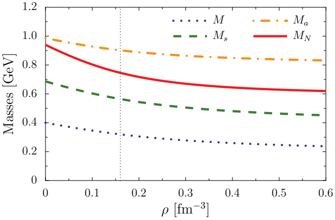
NJL at Finite Density

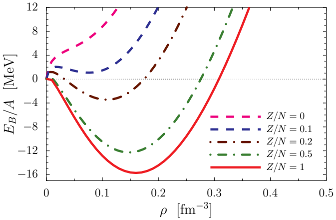
- Finite density (mean-field) Lagrangian: $\bar{q}q$ interaction in $\sigma,\ \omega,\ \rho$ channels

$$\mathcal{L} = \overline{\psi}_q \left(i \not{\partial} - M^* - \not{V}_q\right) \psi_q + \mathcal{L}'_I$$

- *Fundamental physics – mean fields couple to the quarks in nucleons*







- Quark propagator:

$$S(k)^{-1} = \not{k} - M + i\varepsilon \longrightarrow S_q(k)^{-1} = \not{k} - M^* - \not{V}_q + i\varepsilon$$

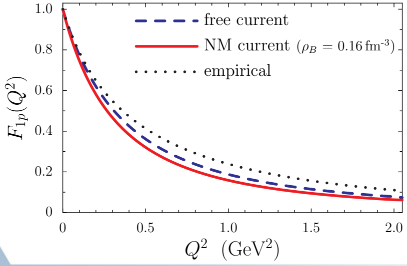
- Hadronization + mean–field $\Longrightarrow$ effective potential (solve self-consistently)

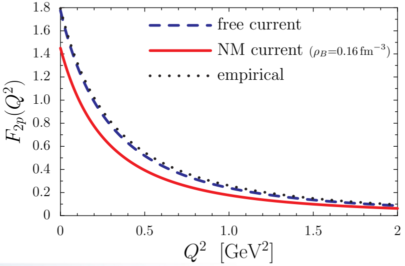
$$V_{u(d)} = \omega_0 \pm \rho_0, \qquad \omega_0 = 6\, G_\omega \left(\rho_p + \rho_n\right), \qquad \rho_0 = 2\, G_\rho \left(\rho_p - \rho_n\right)$$

  - $G_\omega \Longleftrightarrow Z = N$ saturation & $G_\rho \Longleftrightarrow$ symmetry energy

Nucleons in the Nuclear Medium

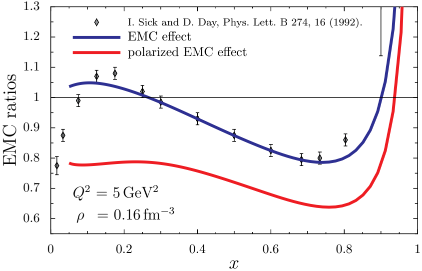
- For nuclear matter find that quarks bind together into color singlet nucleons
  - however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment
  - *as a consequence bound nucleons are modified by the nuclear medium*
- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure
- For a proton in nuclear matter find
  - Dirac & charge radii each increase by about 8%; Pauli & magnetic radii by 4%
  - $F_{2p}(0)$ decreases; however $F_{2p}/2M_N$ almost constant – μ_p almost constant



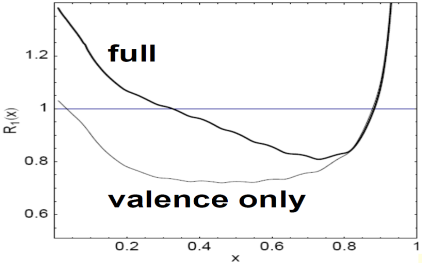


EMC and Polarized EMC effects

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **95**, 052302 (2005)]



[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



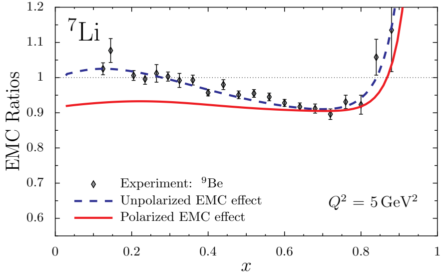
- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

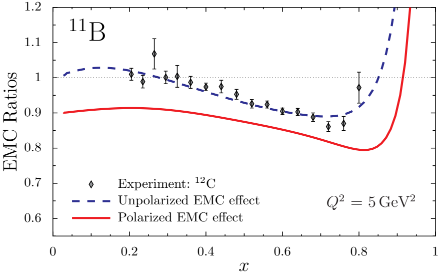
$$\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$$

- Large polarized EMC effect results because in-medium quarks are more relativistic ($M^* < M$)
  - lower components of quark wave functions are enhanced and these usually have larger orbital angular momentum
  - *in-medium we find that quark spin is converted to orbital angular momentum*
- A large polarized EMC effect would be difficult to accommodate within traditional nuclear physics and many other explanations of the EMC effect

EMC effects in Finite Nuclei

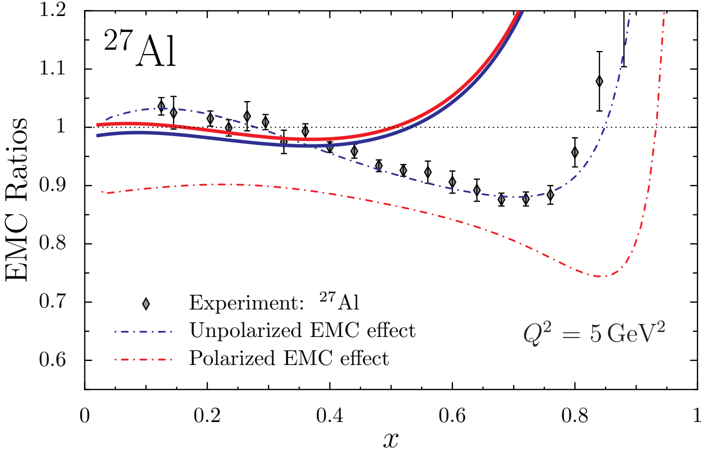
[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]





- Spin-dependent cross-section is suppressed by $1/A$
  - should choose light nucleus with spin carried by proton e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, ...
- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*

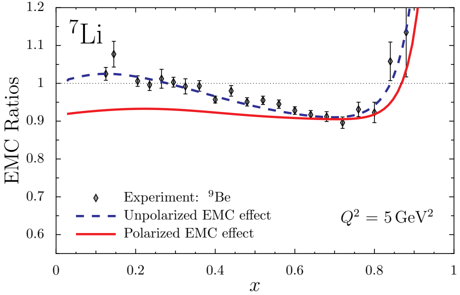
Turning off Medium Modification



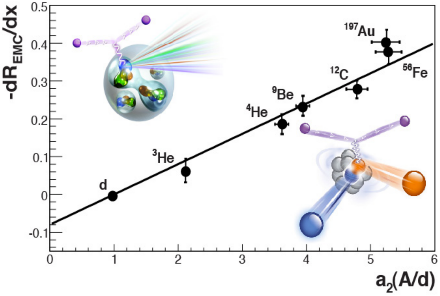
- Without medium modification both EMC & polarized EMC effects disappear
- Polarized EMC effect is smaller than the EMC effect – this is natural within standard nuclear theory and also from SRC perspective
- Large splitting very difficult without *mean-field* medium modification

Mean-field vs SRC induced Medium Modification

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



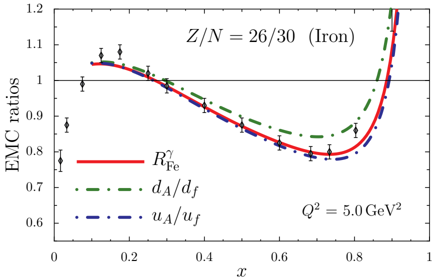
[L. B. Weinstein *et al.*, Phys. Rev. Lett. **106** 052301 (2011)]

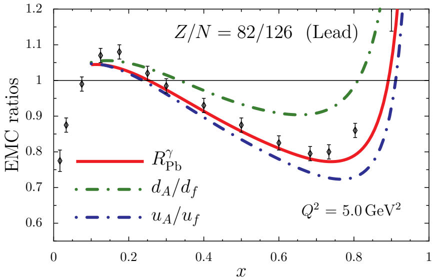


- Explanations of EMC effect using SRCs also invoke medium modification
  - since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models
- For polarized EMC effect only 2–3% of nucleons are involved in SRCs
  - it would therefore be natural for SRCs to produce a smaller polarized EMC effect
- Observation of a large polarized EMC effect would imply that SRCs are less likely to be the mechanism responsible for the EMC effect

Flavor dependence of EMC effect

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)]





- Measured in e.g. parity-violating DIS, ν, charged current reactions, ...
- Find that EMC effect is basically a result of binding at the quark level
  - for $N > Z$ nuclei, d-quarks feel more repulsion than u-quarks: $V_d > V_u$
  - therefore u quarks are more bound than d quarks
- Find isovector mean-field shifts momentum *from* u-quarks *to* d-quarks

$$q(x) = \frac{p^+}{p^+ - V^+}\, q_0\left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+}\right)$$

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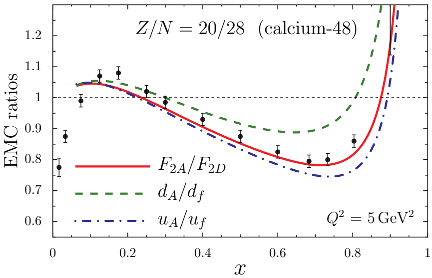

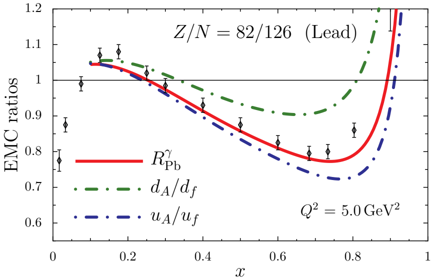

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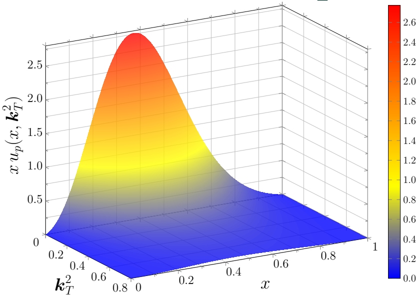
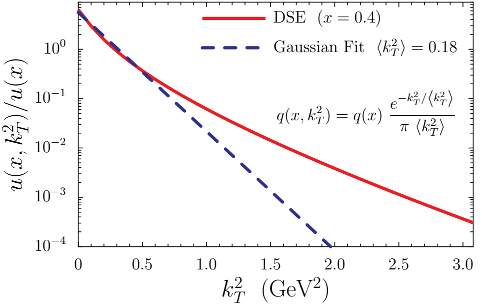
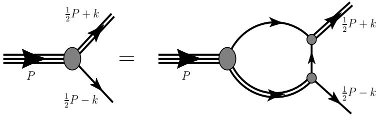
Momentum Imaging of Nuclei

Nucleon TMDs, Diquarks & Flavor Dependence



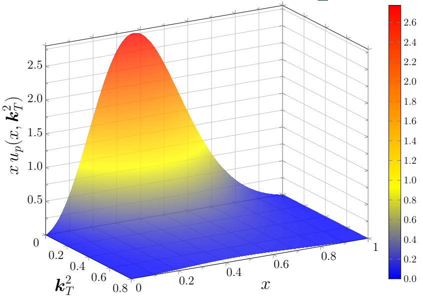


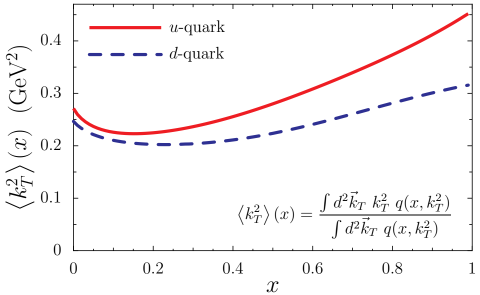
- Rigorously included transverse momentum of diquark correlations in TMDs
- This has numerous consequences:
  - scalar diquark correlations greatly increase $\langle \boldsymbol{k}_T^2 \rangle$
  - find deviation from Gaussian anzatz and that TMDs do not factorize in x & $\boldsymbol{k}_T^2$
  - diquark correlations introduce a significant flavor dependence in $\langle \boldsymbol{k}_T^2 \rangle (x)$



$$\langle \boldsymbol{k}_T^2 \rangle^{\mu_0^2} = 0.47^2\,\text{GeV}^2 \qquad \langle \boldsymbol{k}_T^2 \rangle = 0.56^2\,\text{GeV}^2\ \text{[HERMES]},\ \ 0.64^2\,\text{GeV}^2\ \text{[EMC]}$$

Nucleon TMDs, Diquarks & Flavor Dependence





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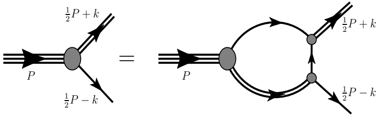

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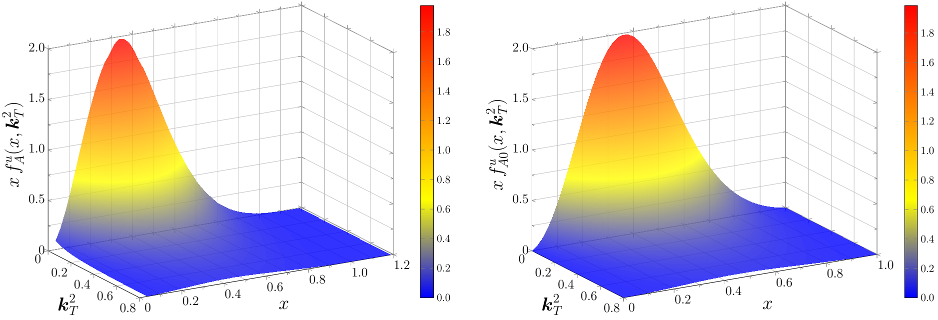
Isoscalar Nuclei (NM) TMDs



- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect
- Medium effects have only a minor impact on $\boldsymbol{k}_T^2$ dependence of TMD
  - scalar field causes $M^* < M$ but also $r_N^* > r_N$, net effect $\langle \boldsymbol{k}_T^2 \rangle$ slightly decreases
  - fermi motion has a minor impact – analogous to x-dependence in EMC effect
  - vector field only has zeroth component, no direct effect on $\boldsymbol{k}_T^2$

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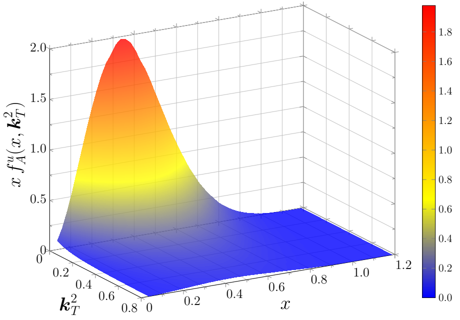

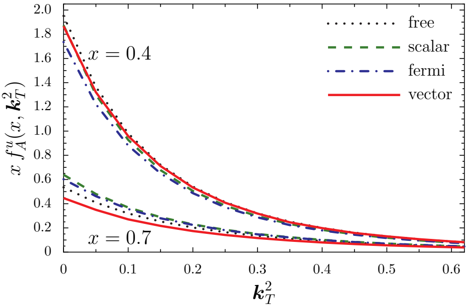

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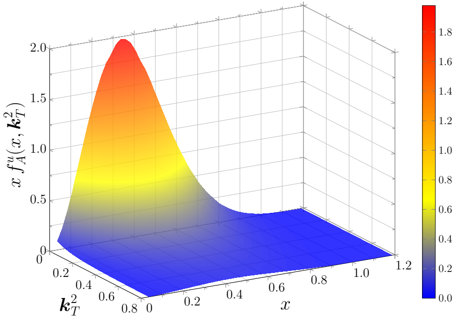

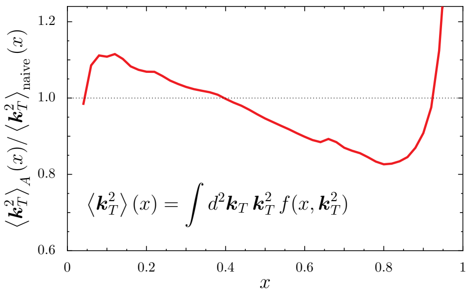

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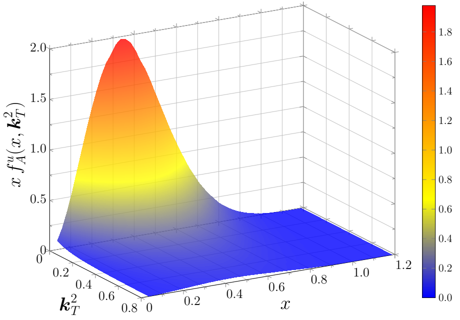

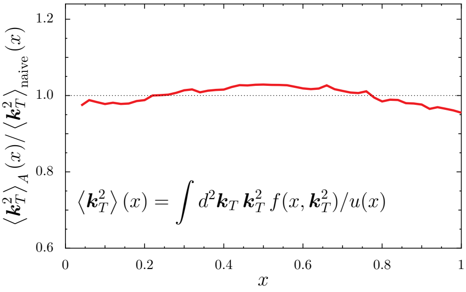

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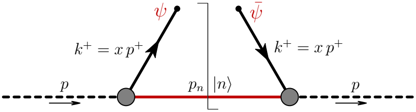
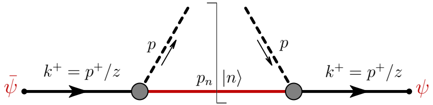
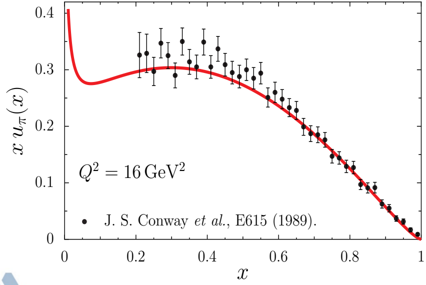
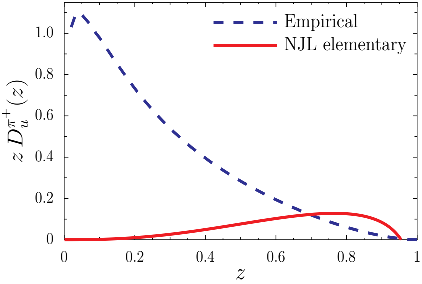
Pion PDF and Fragmentation Functions in NJL





- Truncate the spectator state $|n\rangle$ to a single dressed quark
- Ingredients: $S^{-1}(p) = \not{p} - M + i\varepsilon; \qquad \Gamma_\pi = \sqrt{Z_\pi}\,\gamma_5\,\tau_\pi$
- Excellent result for the pion PDF – however FF results are disastrous!
  - momentum sum rule for fragmentation functions not satisfied: $\langle z \rangle \simeq 0.1$

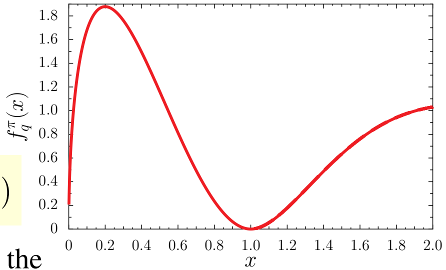




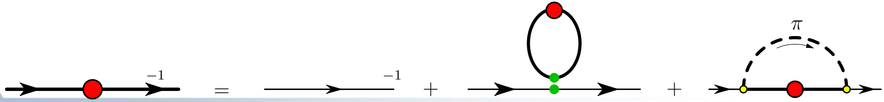
Drell–Levy–Yan Relation

- A formal relation between PDFs at $x > 1$ and FFs can be obtained using crossing symmetry – Drell–Levy–Yan (DLY) relation:

$$D_q^h(z) = (-1)^{2(s_q+s_h)+1}\,\frac{z}{6}\,f_q^h\left(x = z^{-1}\right)$$

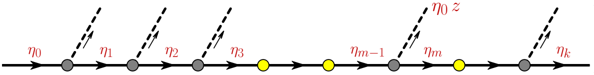


- In NJL the DLY relation is satisfied for the elementary process: $\pi \to \bar{q}q$ & $q \to q\,\pi$; *poor agreement with data for FFs!*
- *Is the DLY relation flawed? Or are certain approximations very good for PDFs but completely inadequate for FFs*
- For example a high-energy quark can radiate a large number of pions and we must sum up the momenta of all pions!
- To maintain DLY and get good argeement for FFs may need to solve:



NJL-Jet Model

$$D_q^\pi(z) = \sum_{k=1}^{N} P(N,k) \left(\sum_{m=1}^{k} \right.$$

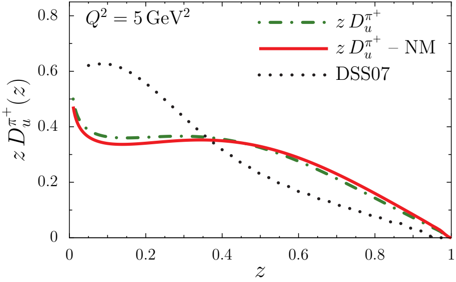


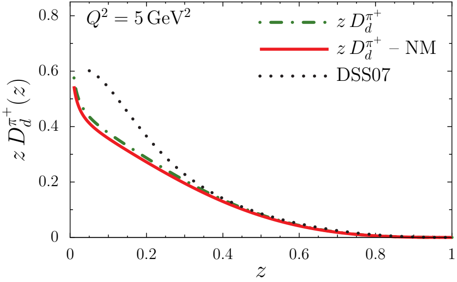
- Replace elementary pion fragmentation with a cascade of emitted pions
  - $P(N,k)$ is the probability that k pions are emitted
  - as $N \to \infty$, $P(N,k)$ becomes a Gaussian distribution and the sum rules are satisfied exactly
- The fragmentation functions can then be represented by an integral equation:

$$D_q^\pi(z) = \hat{d}_q^h(z) + \sum\nolimits_Q \left[\hat{F}_q^Q \otimes D_Q^\pi\right](z)$$

  - $F_q^Q(z)$ is the number density for a meson emitted from the quark q leaving the momentum fraction z to the remaining quark Q
- Similar idea to Field and Feynman (1977) and can be applied to any framework where the elementary FFs can be calculated, e.g., DSEs

Fragmentation Function Results



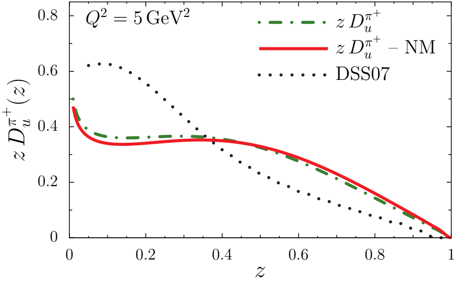


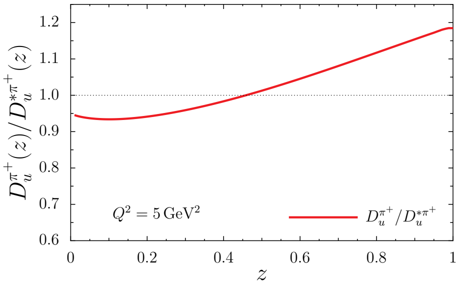
- Cascade-like processes enhance the fragmentation functions tremendously!
- Momentum and isospin spin rules are satisfied exactly:

$$\sum_h \int dz\; z\; D_q^h(z) = 1 \qquad \& \qquad \sum_h \int dz\; t_h\; D_q^h(z) = t_q$$

- Medium effects causes support of FFs to shift to larger z
  - scalar field causes $M^* < M$ so easier for emitted pion to remove momentum
  - medium effects similar in size to EMC effect at large z
- Creating full model for cross-section to study e.g. p_T-broadening

Fragmentation Function Results





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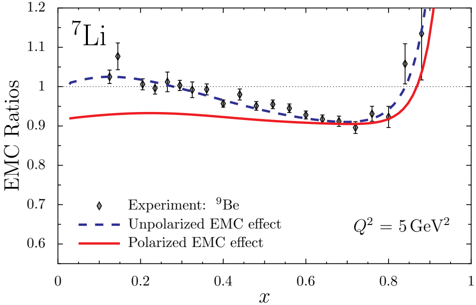
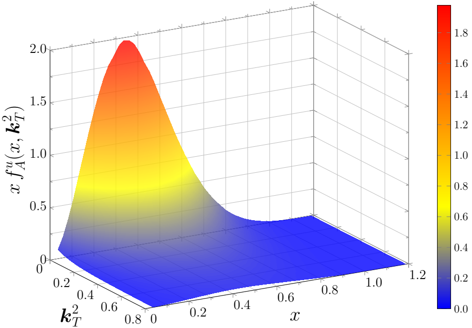
Conclusion

- Understanding the EMC effect is a critical step towards a QCD based description of nuclei
  - understanding spin and flavor dependence of EMC effect is an important near-term goal



- EIC would be transformational for understanding QCD and nuclei
  - quark and gluon GPDs and TMDs of: proton, deuteron, triton, ^{3}He, ^{4}He
  - quark & gluon PDFs of ^{7}Li, ^{11}B, . . .
  - must have flavor separation



- Unprecedented opportunity to address the question:

How does the nucleon-nucleon interaction arise from QCD?

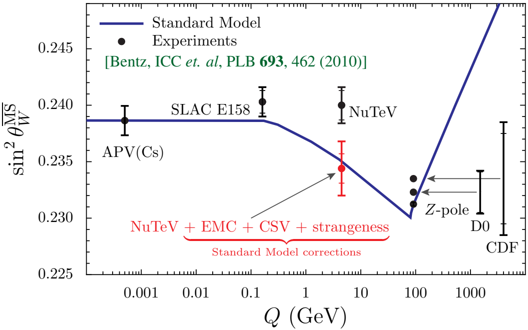
Backup Slides

Nuclear spin sum

Proton spin states	Δu	Δd	Σ	g_A
p	0.97	-0.30	0.67	1.267
^{7}Li	0.91	-0.29	0.62	1.19
^{11}B	0.88	-0.28	0.60	1.16
^{15}N	0.87	-0.28	0.59	1.15
^{27}Al	0.87	-0.28	0.59	1.15
Nuclear Matter	0.79	-0.26	0.53	1.05

- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
  - in medium $M^* < M$ and therefore quarks are more relativistic
  - lower components of quark wavefunctions are enhanced
  - quark lower components usually have larger angular momentum
  - $\Delta q(x)$ very sensitive to lower components
- Therefore, in-medium quark spin → orbital angular momentum

A Reassessment of the NuTeV anomaly



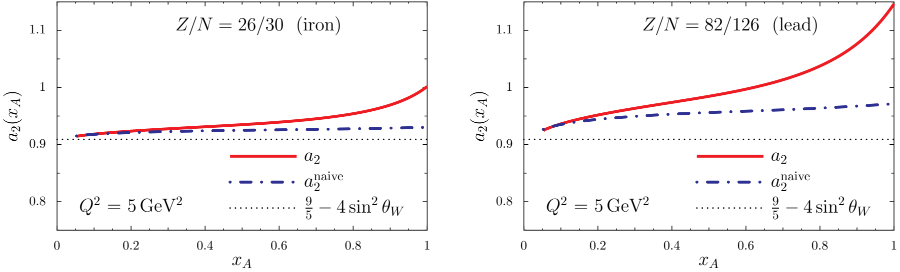
- Paschos-Wolfenstein ratio motivated NuTeV study:

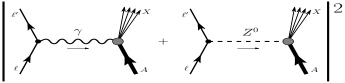
$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar\nu A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar\nu A}} \overset{N\sim Z}{=} \frac{1}{2} - \sin^2\theta_W + \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x\,u_A^- - x\,d_A^-\rangle}{\langle x\,u_A^- + x\,d_A^-\rangle}$$

- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004 \Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- Using NuTeV *functionals*: $\sin^2\theta_W = 0.2221 \pm 0.0013(\text{stat}) \pm 0.0020(\text{syst})$
- 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
  - consistent with mean-field expectation – momentum shifted *from u to d* quarks

Parity-Violating DIS

[ICC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **109**, 182301 (2012)]



- PV DIS – γZ interference: $\sum_X \Big|$  $\Big|^2$

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

- Deviation from naive expectation: momentum shifted *from u to d-quarks*
- $F_2^{\gamma Z}(x)$ has markedly different flavour dependence compared with $F_2^{\gamma}(x)$
  - a measurement of both enables an extraction of $u(x)$ and $d(x)$ separately
- Proposal to measure a_2 of ^{48}Ca was deferred – hopefully approved soon

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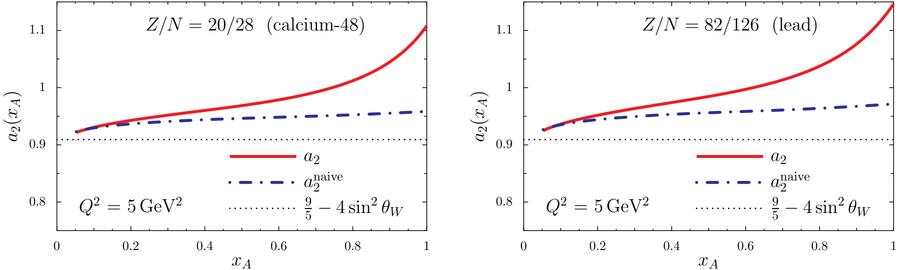
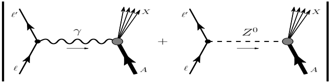


- PV DIS – $\gamma\, Z$ interference: $\sum_X \Big|$  $\Big|^2$

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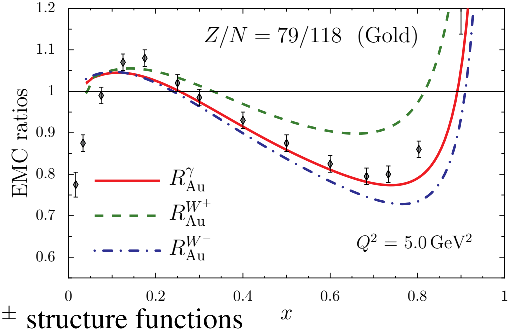
Charged Current Processes

- The reaction $e^{\mp}\, A \longrightarrow \nu\,(\bar{\nu})\, X$ has incredible promise for shedding new light on nucleon and nuclear PDFs
  - at EIC neutrino energy can be reconstructed from final state



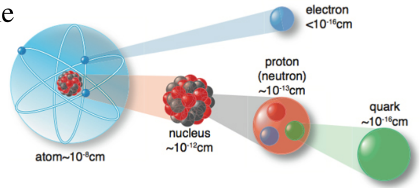
- Parton model expressions for $W^{\pm}$ structure functions

$$F_1^{W^+} = \bar{u} + d + s + \bar{c} \qquad F_3^{W^+} = -\bar{u} + d + s - \bar{c}$$
$$F_1^{W^-} = u + \bar{d} + \bar{s} + c \qquad F_3^{W^-} = u - \bar{d} - \bar{s} + c$$

- Would provide much needed data on flavour structure of both valence and sea quark distribution functions
- Flavor dependence can also be test using e.g. SIDIS, π^+/π^- Drell-Yan, PVDIS, ν-DIS & W-production at RHIC

Quasi-Elastic Scattering

- First hints for QCD effects in nuclei came from quasi-elastic electron scattering:



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

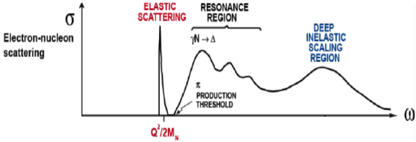
  - in measurements at MIT Bates in 1980 on Fe, which were later confirmed at Saclay in 1984

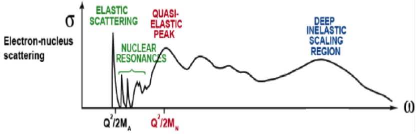
- These experiments, and *most* others following, observed a *quenching* of the Coulomb Sum Rule (CSR):

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

  - despite widespread expectation that the CSR should approach unity for $|\boldsymbol{q}| \gg k_F$

- Observation of quenching began one of the most controversial issues in nuclear physics – which remains to this day





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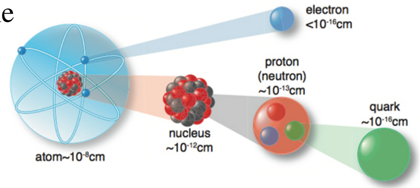

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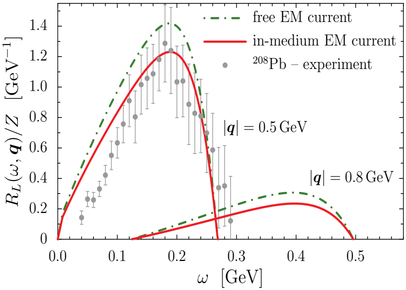

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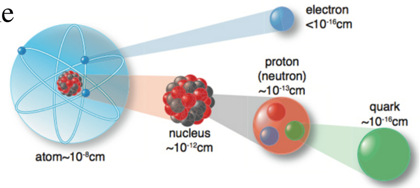

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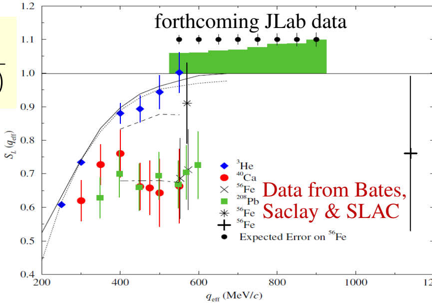
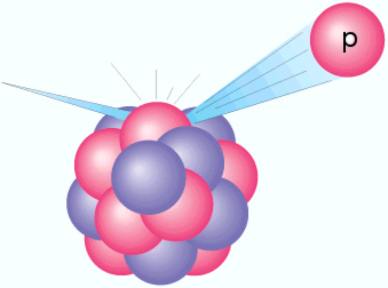
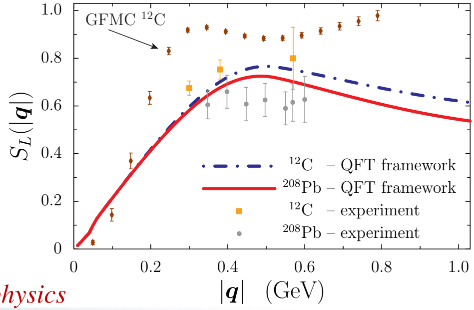


Coulomb Sum Rule

- QE scattering is sensitive to internal structural properties of bound nucleons
  - quenching of the CSR can be naturally explained by slight modification of bound nucleon EM form factors
  - natural consequence of QCD models
- Two state-of-the-art theory results exist, both from Argonne:
  - the GFMC result, with no explicit QCD effects, finds no quenching
  - QCD motivated framework finds a dramatic quenching; 50% relativistic effects & 50% medium modification
- Jefferson Lab has revisited QE scattering & this impasse stands to be resolved shortly
  - *confirmation of either result will be an important milestone in QCD nuclear physics*





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[I. C. Cloët, *et al.*, Phys. Rev. Lett. **116** 032701 (2016)]