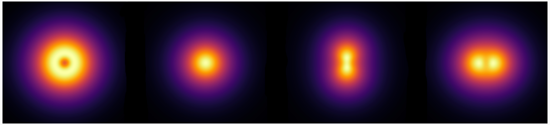
Revealing quarks and gluons in nuclei at Hall A



Ian Cloët

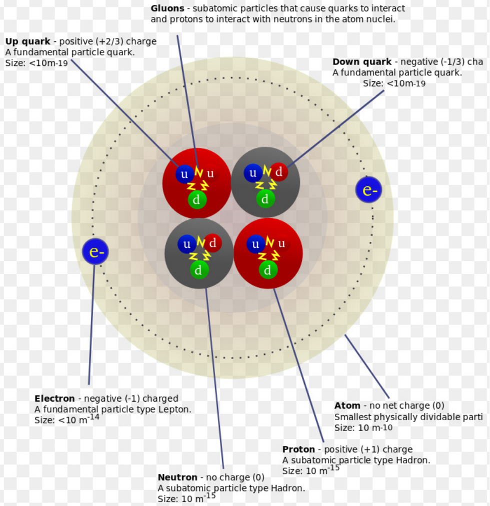
Argonne National Laboratory

Hall A Collaboration Winter Meeting

15-16 January 2025, Jefferson Lab

QCD and Nuclei @ Jefferson Lab

- There is a gap—perhaps a big gap—between traditional picture of a nucleus and a QCD picture
  - this gap manifests in the valence region — EMC effect
- Where to start? ^{4}He can be consider the lightest *"real"* nucleus $\left[{}^4\mathrm{He}_{\mathrm{BE}} = 7.1\,\mathrm{MeV/A}\right]$ and EMC effect is fully manifest $\left[{}^{208}\mathrm{Pb}_{\mathrm{BE}} = 7.9\,,\ {}^3\mathrm{He}_{\mathrm{BE}} = 2.6\,, {}^3\mathrm{H}_{\mathrm{BE}} = 2.8\,\mathrm{MeV/A}\right]$
- ^{4}He is a key constituent of nuclei — α clustering
  - "standard candle" for QCD and nuclei
- Many foundational QCD questions to address
  - Are the quarks and gluons confined to nucleon-like objects? Does this depend on, e.g., the momentum filter x?
  - What are the quark and gluon mass radii for ^{4}He and how does this contrast with the nucleon?
  - What are the pressure and shear forces in ^{4}He?
- Jefferson Lab is unique in its ability to bridge this gap



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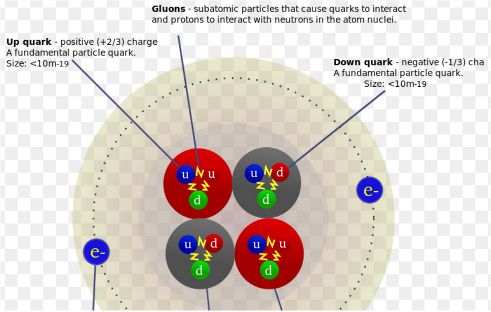

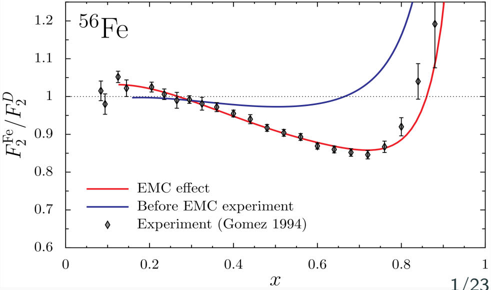

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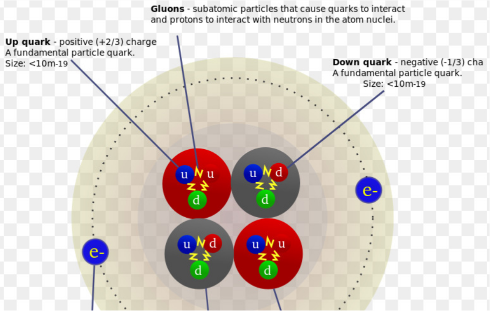

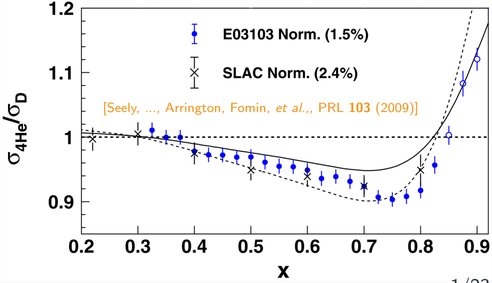

[Seely, ..., Arrington, Fomin, *et al.*,, PRL **103** (2009)]

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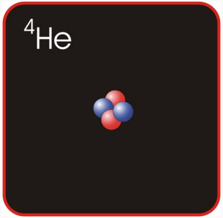
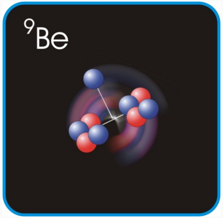
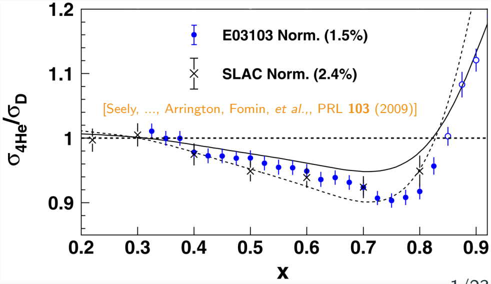
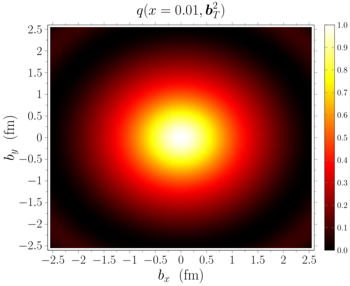


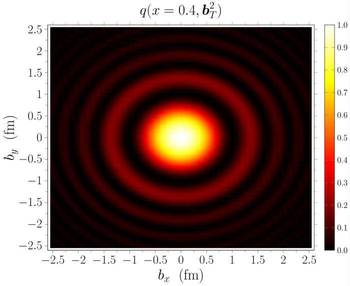


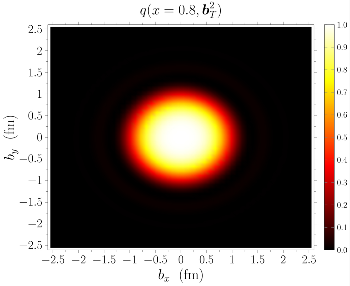


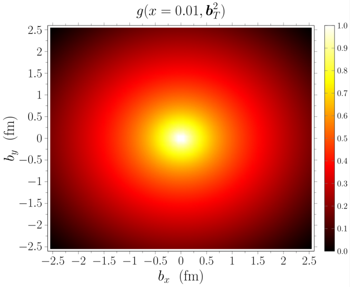
[Seely, ..., Arrington, Fomin, *et al.*,, PRL **103** (2009)]

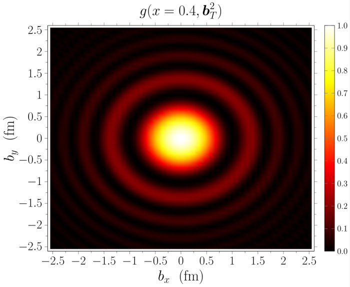
A More Realistic Impression of ^{4}He — Spatial Tomography


$q(x = 0.01, \boldsymbol{b}_T^2)$


$q(x = 0.4, \boldsymbol{b}_T^2)$


$q(x = 0.8, \boldsymbol{b}_T^2)$


$g(x = 0.01, \boldsymbol{b}_T^2)$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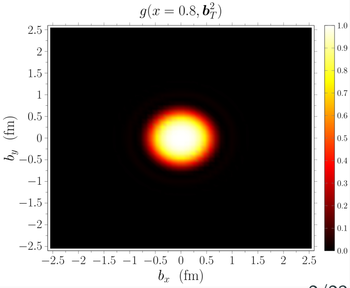
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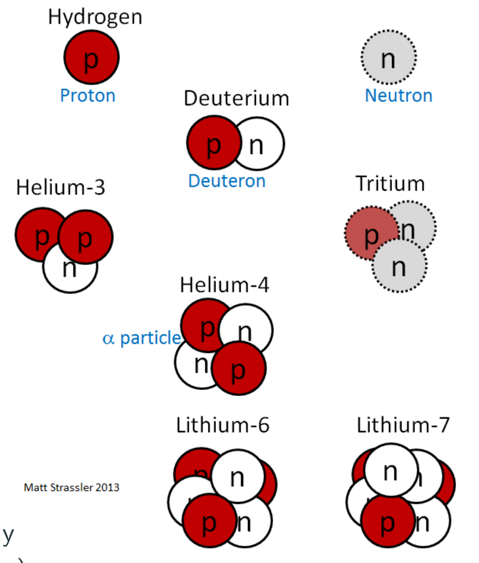
QCD and Imaging of Light Nuclei

- Nuclei provide a QCD laboratory with characteristics not avaliable from protons alone
- Program build around imaging of light nuclei would have tremedous impact and reveal many novel aspects of QCD
  - How is gluon dynamics modified by the nuclear medium?
  - $J \geqslant 1$ targets $\Rightarrow$ new PDFs, form factors, TMDs, GPDs, etc.
  - Exotic gluonic components from gluon transversity PDFs
  - Color transparency, hidden color, NN correlations, fast quarks
  - Isospin & baryon density effects, e.g., partial restoration of chiral symmetry and possible changes in confinement length scales between quarks and gluons
- Key question: *How does the nucleon-nucleon interaction arise from QCD?*
- Jefferson Lab's unique capabilities for proton structure apply equally to nuclei (e.g., luminousity frontier, polarization, etc.)



Matt Strassler 2013

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> *"No story of modern physics is more intriguing than the history of the theory of nuclear forces."*
> Ruprecht Machleidt, Weinberg's proposal of 1990: A very personal view

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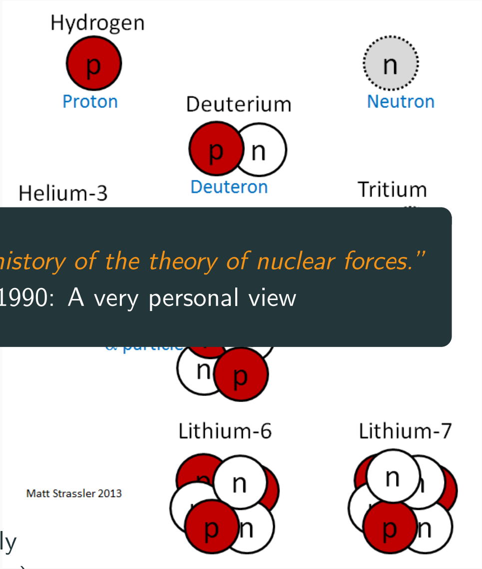

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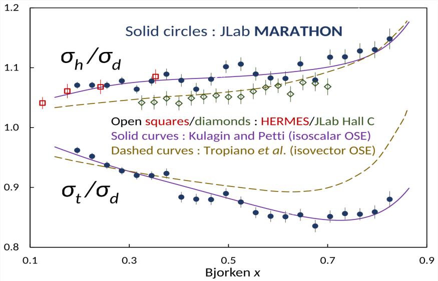
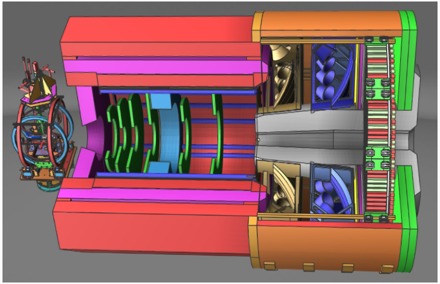
Nuclei & Hall A

- Significant nuclear (adjacent) program in Hall A: Marathon, SIDIS, J/Ψ production, SRCs, Tagged processes, SoLID, etc.
  - E12-10-007: PVDIS (Souder)
  - E12-09-018: Semi-Inclusive pion and kaon electro-production (Wojtsekhowski)
  - E12-10-006: Spin Asymmetry in SIDIS Transversely Polarized 3He (Gao)
  - E12-11-007: SIDIS of Charged Pion (Chen)
  - E12-11-112: Isospin dependence in the 2N and 3N SRCs (Arrington)
  - E12-12-006: Near Threshold J/Ψ at 11 GeV (Meziani)
  - C12-15-006A: Kaon Structure Function through Tagged DIS (Montgomery)
- Would be interesting to consider extensions of many of these experiments to include (other) nuclear targets, e.g., ^{4}He, ^{6}Li, and ^{7}Li



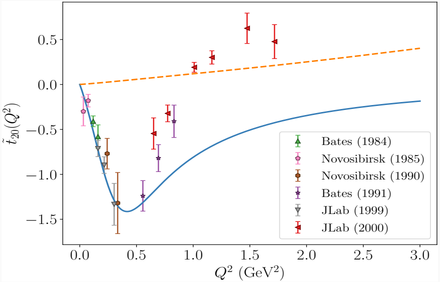


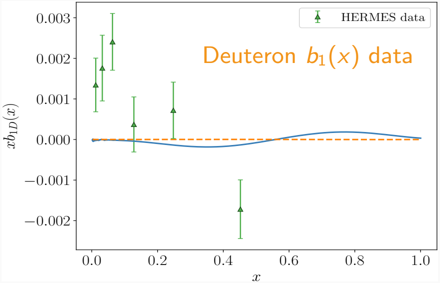
The Deuteron

- The deuteron is the simplest nucleus – naively consisting of a proton + neutron with 2.2 MeV binding
  - however deuteron is greater than sum of its parts, having many properties not found in either of its primary constituents
  - deuteron is also finally tuned — making it an interesting target to isolate QCD effects
- Unique properties of deuteron:
  - a quadrupole moment and gluon transversity PDF
  - many TMDs and GPDs associated with tensor polarization
- Additional spin-independent leading-twist PDF called $b_1^q(x)$

$$b_1(x) = e_q^2 \left[b_1^q(x) + b_1^{\bar{q}}(x)\right], \quad \int_0^1 dx \left[b_1^q(x) - b_1^{\bar{q}}(x)\right] = 0$$

- Need tensor polarized target to measure $b_1(x)$ – (HERMES)
  - impossible to explain HERMES data with only bound nucleon degrees of freedom — need exotic QCD states, 6q bags, etc.
  - Hall C proposal exists but not approved (J.-P. Chen, *et al.*)



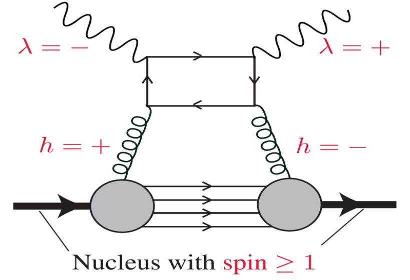


Gluon Transversity PDF

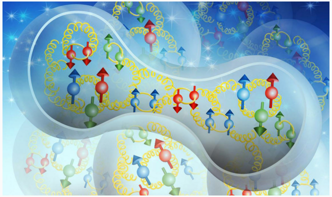
- Transversity PDFs are associated with double-helicity flip:

$$\Delta_T g(x) \simeq \mathcal{A}_{+-,-+} + \mathcal{A}_{-+,+-}$$

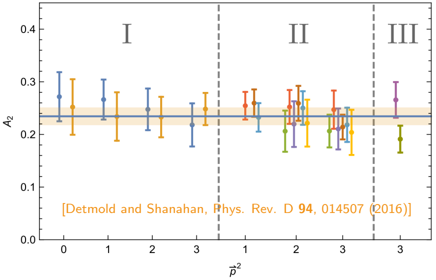
  - helicity conservation forbids this helicity amplitude for a gluon in a nucleon — no gluon transversity PDF in nucleon
  - need $J \geqslant 1$, so targets such as deuteron, ^{6}Li, . . .
  - Jaffe & Manohar, *“Nuclear Gluonometry”*, PLB **223**, 218 (1989)
  - LoI at JLab: J. Maxwell, *et al.* [arXiv:1803.11206 [nucl-ex]]



- Observation of a gluon transversity distribution in deuteron would be first direct evidence for non-nucleonic components in nuclei
  - exotic glue, $\Delta\Delta$ component, etc.



- Lattice calculations find significant gluon transversity in ϕ meson

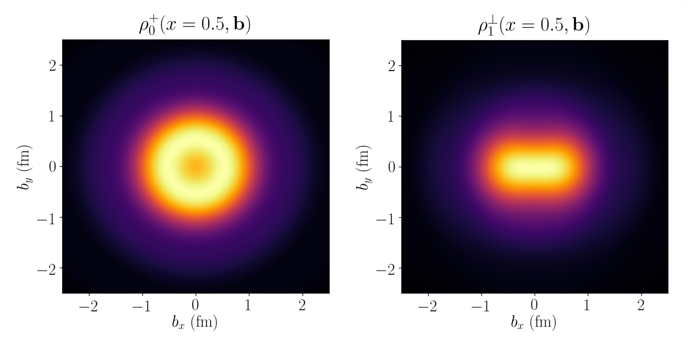


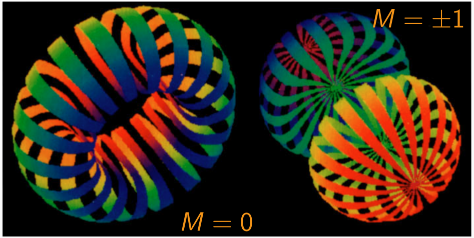
[Detmold and Shanahan, Phys. Rev. D **94**, 014507 (2016)]

Deuteron GPDs

- The deuteron has a rich GPD structure
- The impact parameter PDFs provide a spatial tomography for various x slices
  - tensor polarized along z-axis — clear donut shape
  - longitudinally polarized along x-axis — clear dumbbell shape
- These quantities provide an interesting connection to traditional nuclear physics results for the deuteron
  - nuclear spatial densities have donut and dumbbell shapes
- Does the gluon donut align with the quark donut – does this change with x? Incredible insight into NN interaction possible

[A. Freese, W. Bentz, and ICC, *to appear 2025*]



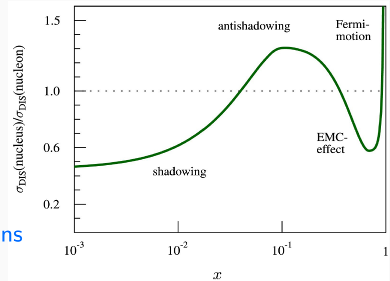


J. Carlson, R. Schiavalla, Rev. Mod. Phys. **70** 743 (1998)

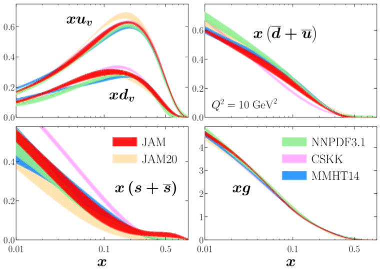
J. L. Forrest *et al.* Phys. Rev. **C54** 646 (1996)

Nuclear Structure Functions

- Nuclear structure functions have four distinct features relative to the nucleon — some easy to understand and others that continue to challenge physicists 40 years after discovery
  - **Fermi motion:** standard nuclear effect caused by NN interactions
  - **Shadowing:** caused by multi-nucleon interference effects
  - **EMC Effect:** no universally accepted explanation, common explanations are medium modification caused by mean-fields and/or SRCs
  - **Anti-Shadowing:** less studied, perhaps caused by flavor-dependent Reggeon exchange or a coherent effect from other mechanisms
- Anti-Shadowing region ($0.1 \lesssim x \lesssim 0.3$) is roughly equally dominated by valence quarks, sea-quarks, and gluons
  - precision measurements in this region would shed important light on, e.g., nuclear gluons, anti-quarks in nuclei, and flavor dependent effects



[JAM Collaboration]



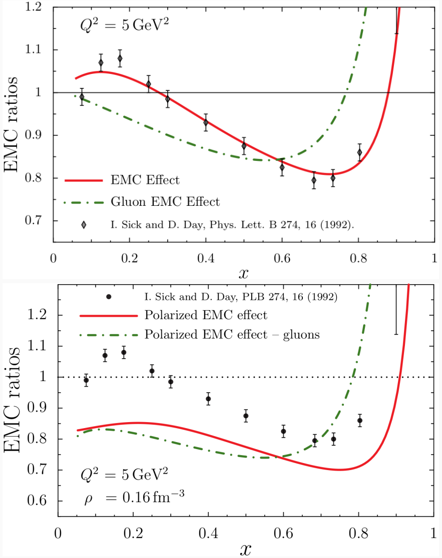
Spin and Gluon EMC Effects

- To solve puzzle of EMC effect need new observables, e.g., gluon and spin EMC effects
  - Can help distinguish between different explanations of the EMC effect
  - Mean-field and SRC make different predictions for spin EMC effect
- The gluon EMC effect can be defined as

$$R_g(x) = \frac{g_A(x)}{Z\, g_p(x) + N\, g_n(x)}$$

  - Analogous definition for gluon spin EMC effect, with, $Z \to P_p$ and $N \to P_n$
- Results obtained in mean-field model that describes the EMC effect and predicts spin EMC effect
  - Gluons are generated purely perturbatively
  - Provides a baseline for comparison and understanding of future measurements

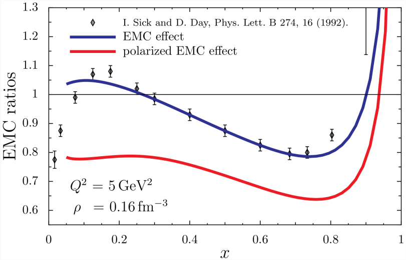
[X. G. Wang, W. Bentz, ICC, and A. W. Thomas, J. Phys. G **49**, (2022)]



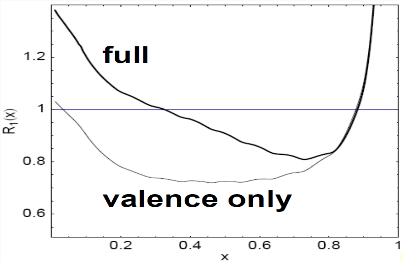
Mean-Field Calculations of Polarized Nuclear PDFs

- Several relativistic mean-field calculations of polarized Nuclear PDFs
  - all calculations find polarized EMC same size or larger than EMC effect
  - effects are as large or larger in anti-shadowing region
- Large effects in polarized nuclear PDFs results because in-medium quarks are more relativistic ($M^* < M$)
  - in-medium we find that quark spin is converted to orbital angular momentum

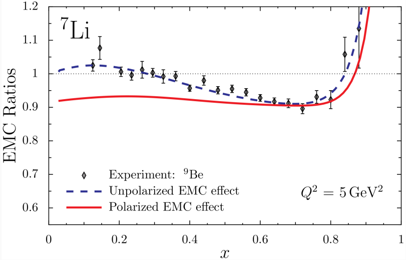
[ICC, W. Bentz and A. W. Thomas, PRL **95**, 052302 (2005)]



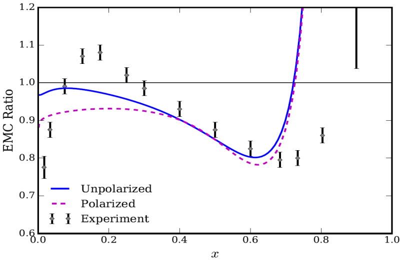
[J. R. Smith and G. A. Miller, Phys. Rev. C **72**, 022203(R) (2005)]



[ICC, W. Bentz and A. W. Thomas, PLB 642, 210 (2006)]



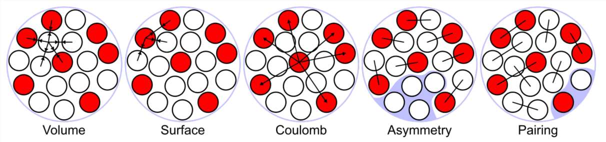
[Tronchin, Matevosyan and Thomas, PLB **783**, 247-252 (2018)]



Flavor Dependent/Isovector EMC Effect?

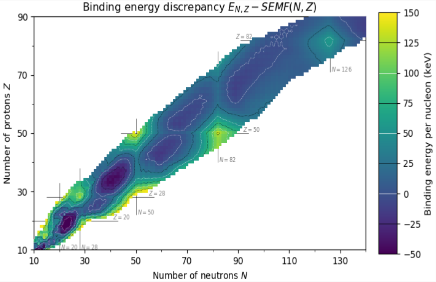
- Why should we expect a (large) isovector EMC effect?
- Consider the Bethe–Weizsäcker mass formula

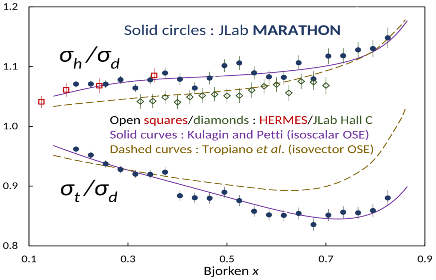
$$E_B = a_V\,A - a_S\,A^{2/3} - a_C\,\frac{Z^2}{A^{1/3}} - a_A\,\frac{(A-2\,Z)^2}{A} \pm \delta(A,Z)$$



$$a_V = 15.75 \quad a_S = 17.8 \quad a_C = 0.711 \quad a_A = 23.7 \quad a_P = 11.8$$

- *“MARATHON data ... do not provide evidence for a sizable isovector EMC effect”* [D. Adams, *et al.*, arXiv:2410.12099 [nucl-ex]]
- New data from DIS on ^{40}Ca and ^{48}Ca [Hall C]?



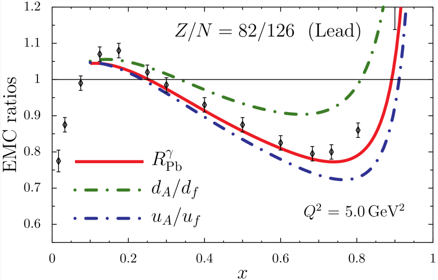


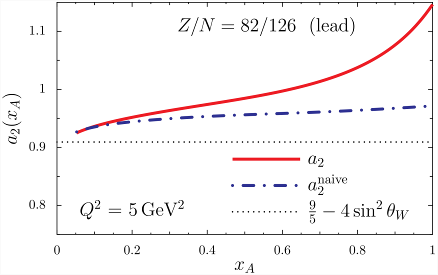
Flavor Dependence Nuclear PDFs

- In mean-field model with isovector forces find a flavor dependence to the EMC effect
  - for $N > Z$ nuclei, d-quarks feel more repulsion than u-quarks and therefore u quarks are more bound than d quarks
  - can explain large fraction of NuTeV anomaly
- Parity-violating DIS is particularly sensitive to isovector effects

$$a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\sim Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\,\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

  - momentum is shifted from u to d quarks and flavor dependence effect largest in EMC region
- Isovector EMC effect observed by JAM in analysis of MARATHON data
  - has same sign as mean-field predictions
- PVDIS and DIS together is the best way to access isovector EMC effect because full flavor separation is possible


[ICC, Bentz and Thomas, PRL **109**, 182301 (2012)]



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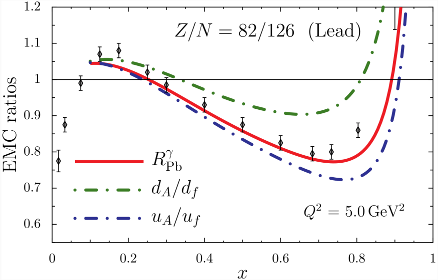
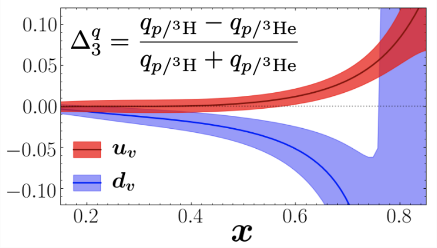
$$a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \overset{N\simeq Z}{=} \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)}$$

  - momentum is shifted from u to d quarks and flavor dependence effect largest in EMC region
- Isovector EMC effect observed by JAM in analysis of MARATHON data
  - has same sign as mean-field predictions
- PVDIS and DIS together is the best way to access isovector EMC effect because full flavor separation is possible

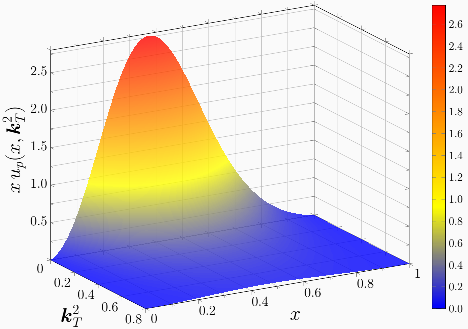
[ICC, Bentz and Thomas, PRL **109**, 182301 (2012)]

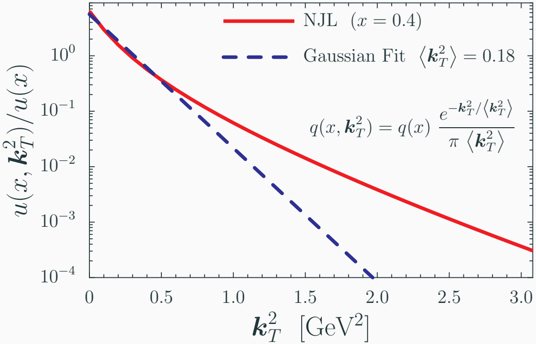


[Cocuzza *et al.*, PRL **127**, 242001 (2021)]



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 $\langle \boldsymbol{k}_T^2 \rangle (x)$

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

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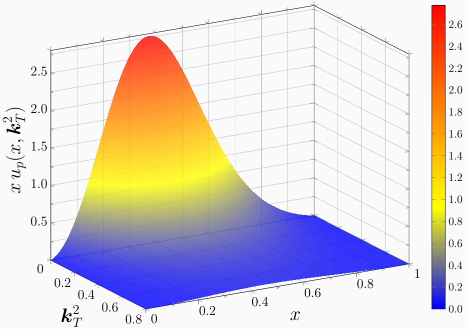

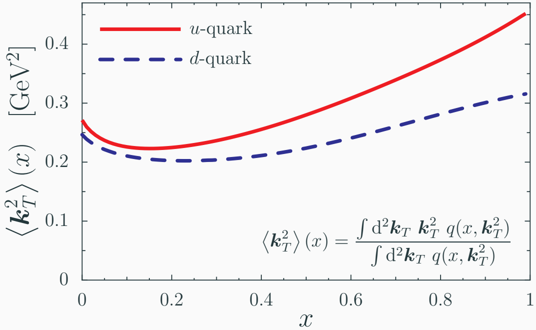

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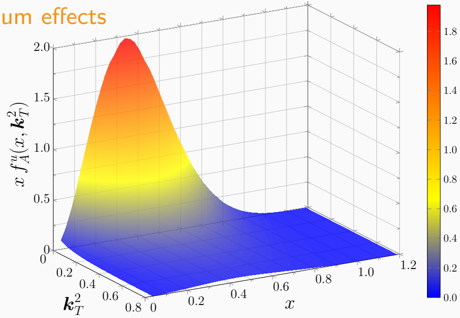
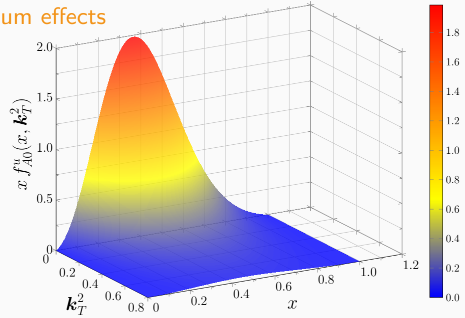
TMDs in Isoscalar Nuclear Matter

medium effects



no medium effects

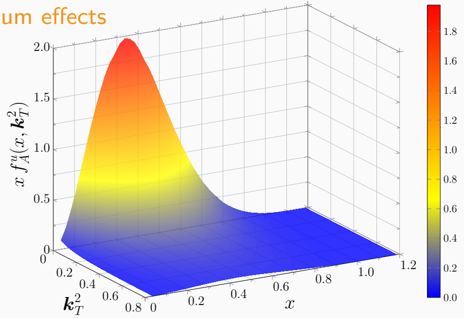


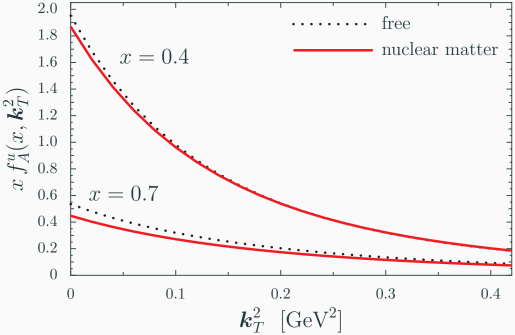
- So far only considered the simplest spin-averaged TMDs – $q(x, k_T^2)$
  - Integral of these TMDs over $\boldsymbol{k}_T$ gives the PDFs and reproduces the EMC effect

- 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 $\boldsymbol{k}_T^2$

TMDs in Isoscalar Nuclear Matter

medium effects





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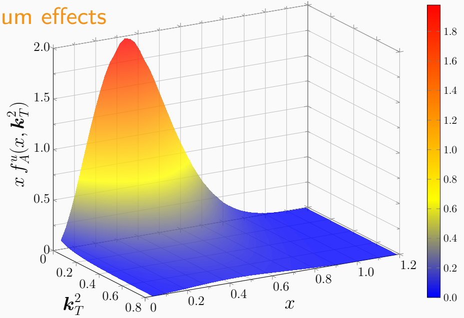

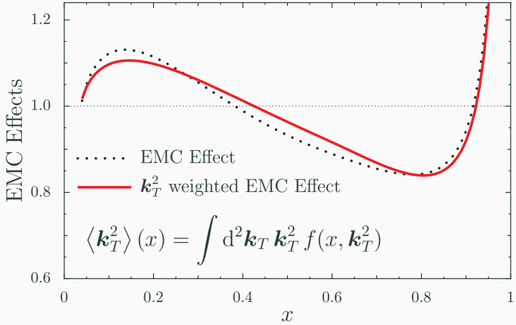

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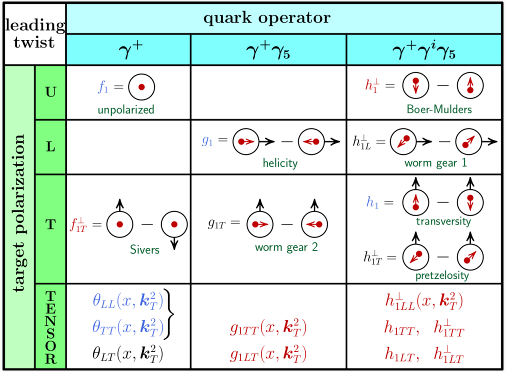
TMDs of Spin-1 Targets

- A spin-1 target can have tensor polarization $[\lambda = 0]$
  - 3 additional T-even and 7 additional T-odd quark TMDs compared to nucleon
- Analogous situation for gluon TMDs
  - to fully expose role of quarks and gluons in nuclei need polarized nuclear targets (transverse and longitudinal) with all spin projections, e.g., for $J = 1$: ^{2}H, ^{6}Li
- Spin 4-vector of a spin-one particle moving in z-direction, with spin quantization axis $\boldsymbol{S} = (\boldsymbol{S}_T, S_L)$, reads: $S^\mu(p) = \left(\frac{p_z}{m_h} S_L, \boldsymbol{S}_T, \frac{p_0}{m_h} S_L\right)$
  - for given direction $\boldsymbol{S}$ the particle has the three possible spin projections $\lambda = \pm 1, 0$
  - longitudinal polarization $\Longrightarrow$ $\boldsymbol{S}_T = 0, S_L = 1$; transverse $\Longrightarrow$ $|\boldsymbol{S}_T| = 1, S_L = 0$
- Associated quark correlation function:

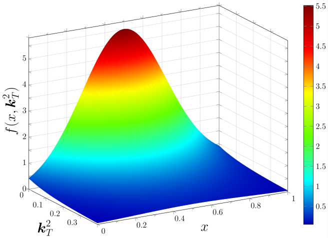
$$\langle\gamma^+\rangle_{\boldsymbol{S}}^{(\lambda)}(x, \boldsymbol{k}_T) \equiv f(x, \boldsymbol{k}_T^2) - \frac{3\lambda^2 - 2}{2}\left[\left(S_L^2 - \frac{1}{3}\right)\theta_{LL}(x, \boldsymbol{k}_T^2) + \frac{(\boldsymbol{k}_T \cdot \boldsymbol{S}_T)^2 - \frac{1}{3}\boldsymbol{k}_T^2}{m_h^2}\theta_{TT}(x, \boldsymbol{k}_T^2) + S_L \frac{\boldsymbol{k}_T \cdot \boldsymbol{S}_T}{m_h}\theta_{LT}(x, \boldsymbol{k}_T^2)\right]$$



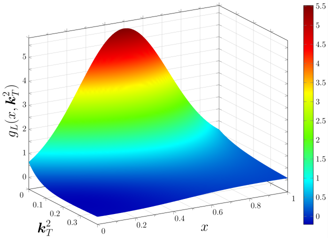
leading twist		quark operator		
		γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^i\gamma_5$
target polarization	**U**	$f_1 =$ unpolarized		$h_1^\perp =$ − Boer-Mulders
	L		$g_1 =$ − helicity	$h_{1L}^\perp =$ − worm gear 1
	T	$f_{1T}^\perp =$ − Sivers	$g_{1T} =$ − worm gear 2	$h_1 =$ − transversity $h_{1T}^\perp =$ − pretzelosity
	TENSOR	$\left.\begin{matrix}\theta_{LL}(x, \boldsymbol{k}_T^2)\\ \theta_{TT}(x, \boldsymbol{k}_T^2)\end{matrix}\right\}$ $\theta_{LT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ h_{1TT}, $h_{1TT}^\perp$ h_{1LT}, $h_{1LT}^\perp$

Spin-1 Target TMDs – with Nucleon Analogs

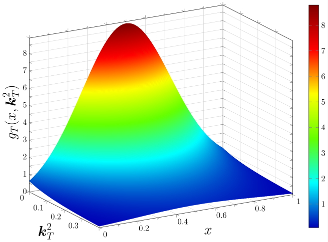
unpolarized



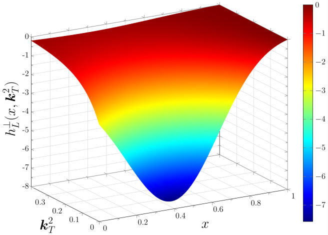
helicity



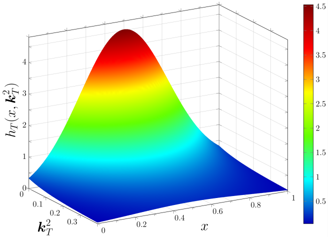
worm gear 2



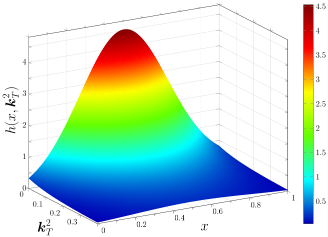
worm gear 1



pretzelosity



transversity



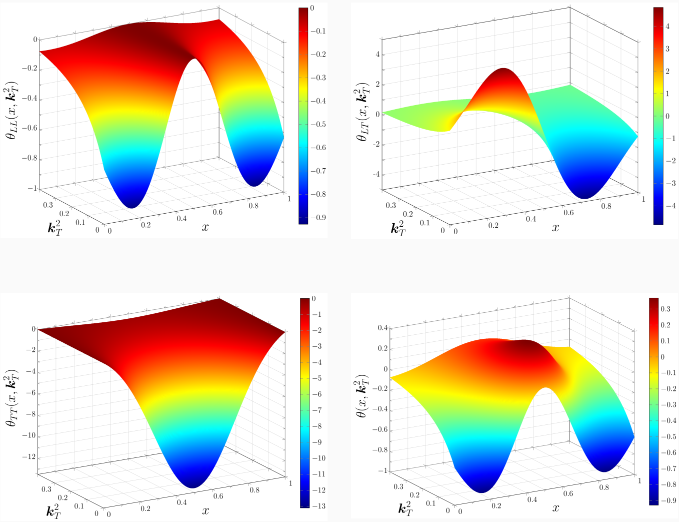
[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Spin-1 Target TMDs – Tensor Polarization

- Calculations assume point-like nucleons but nevertheless show tensor polarized TMDs have some surprising features

- TMDs $\theta_{LL}(x\,\boldsymbol{k}_T^2)$ & $\theta_{LT}(x\,\boldsymbol{k}_T^2)$ identically vanish at $x = 1/2$ for all $\boldsymbol{k}_T^2$
  - $x = 1/2$ corresponds to zero relative momentum between (the two) constituents, that is, *s*-wave contributions
  - therefore θ_{LL} & θ_{LT} primarily receive contributions from $L \geqslant 1$ components of the wave function – *sensitive to orbital angular momentum*

- Features hard to determine from a few moments — challenge for traditional lattice QCD methods



[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

Gravitational Structure of Nucleons and Nuclear Matter

- The nucleon has 3 gravitational form factors

$$\langle p' \,|\, T^{\mu\nu} \,|\, p \rangle = \bar{u}(p') \left[A(t)\, \frac{P^\mu P^\nu}{M} + D(t)\, \frac{\Delta^\mu \Delta^\nu - \Delta^2 g^{\mu\nu}}{4\,M} + J(t)\, \frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{2\,M} \right] u(p)$$

  - related to mass and angular momentum distributions $J(t) = \frac{1}{2}\left[A(t) + B(t)\right]$, and pressure and shear forces

- Gravitational form factors are related to GPDs

$$\sum_{i=q,g} \int_{-1}^{1} \mathrm{d}x\, x\, \left[H_i(x,\xi,t), E_i(x,\xi,t)\right] = \left[A(t) + \xi^2 D(t),\ B(t) - \xi^2 D(t)\right]$$

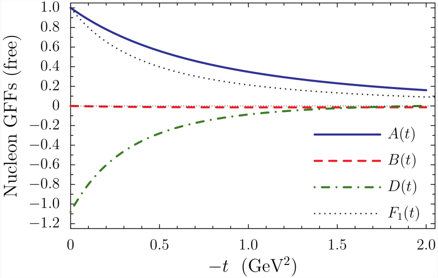
- We find (light front) charge and mass radii of:

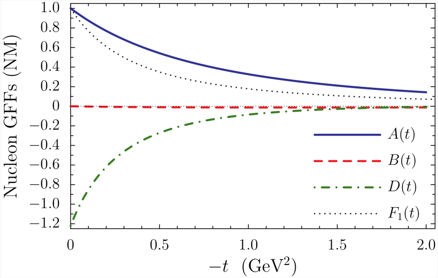
free $\quad \langle r^2 \rangle_C = (0.61\,\mathrm{fm})^2, \quad \langle r^2 \rangle_A = (0.45\,\mathrm{fm})^2, \quad D(0) = -1.08$

NM $\quad \langle r^2 \rangle_C = (0.66\,\mathrm{fm})^2, \quad \langle r^2 \rangle_A = (0.46\,\mathrm{fm})^2, \quad D(0) = -1.21$

  - mass radius changes much less than the charge radius
  - pressure and shear forces on the nucleon increase by around 10%
  - small mass radius may help explain success of traditional NP

[Adam Freese, ICC, Brean Maynard *to appear* (2025)]





Quasi-Elastic Scattering

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

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

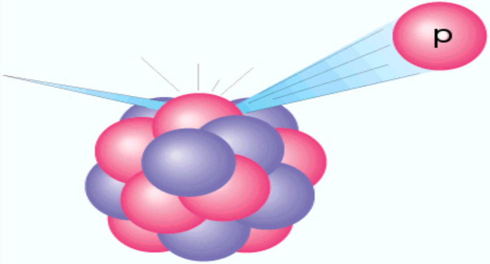
  - measurements at MIT Bates in 1980 on Fe — later confirmed at Saclay in 1984

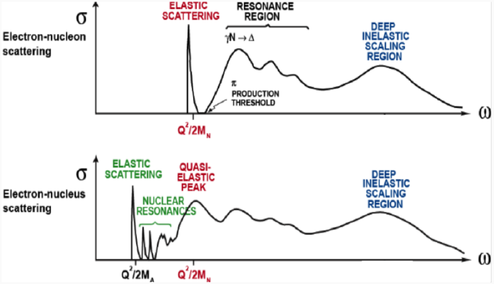
- These experiments, and *most* others following, observed a *quenching* of the Coulomb Sum Rule (CSR):

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

  - 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





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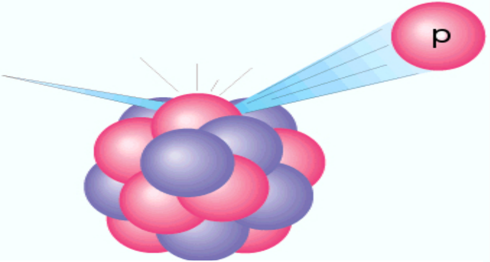
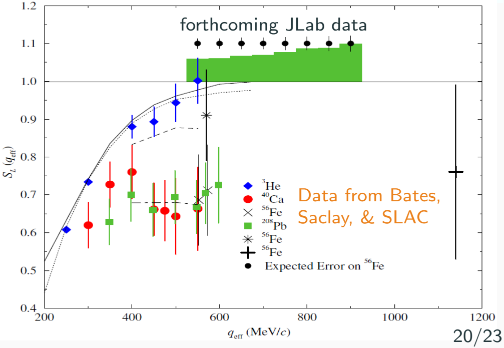




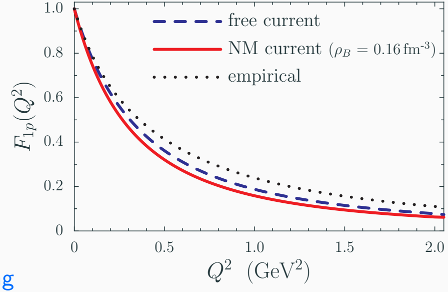
Coulomb Sum Rule

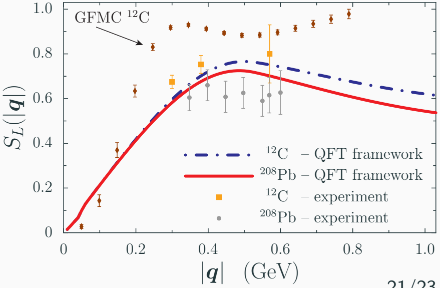
- QE scattering is sensitive to internal structural properties of bound nucleons
  - quenching of the CSR can be naturally explained by slight modification of bound nucleon EM form factors
  - natural consequence of QCD models

- 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 will hopefully be resolved as some point
  - *confirmation of either result will be an important milestone in QCD nuclear physics*

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





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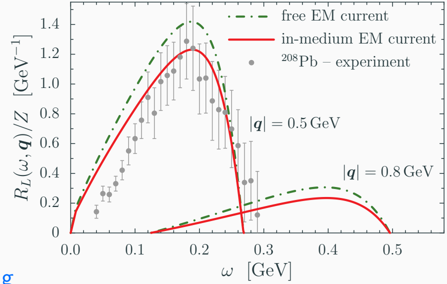
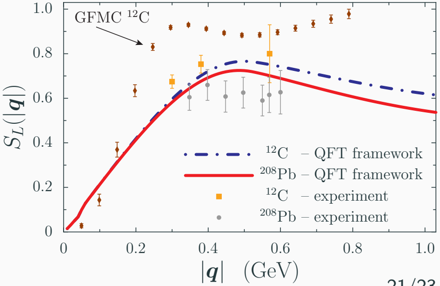
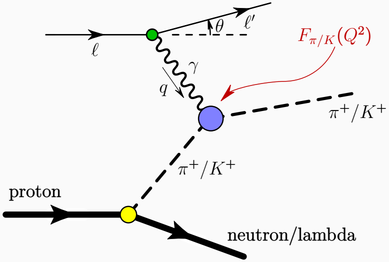
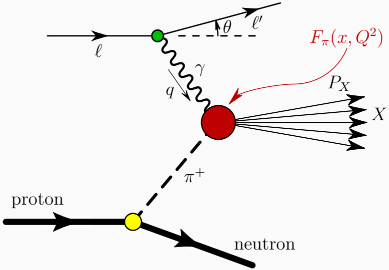


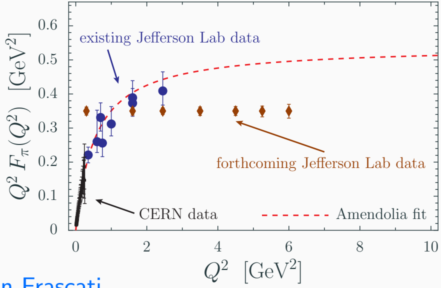


Sullivan Processes and Nuclei





- At Jefferson Lab pion and kaon structure can be accessed via Sullivan processes
  - initial pion/kaon is off mass-shell – need extrapolation to pole
  - proven results for pion form factors (Hall C)
- Can the Sullivan process be used to access quark and gluon nuclear effects?
  - Comparison between $e + p \to e' + \pi^+ + n$ with say $e + {}^3\mathrm{He} \to e' + \pi^+ + {}^3\mathrm{H}$ would be interesting
  - Suggestion/Question from Garth Huber at JLab 22 GeV Meeting in Frascati



Conclusion and Outlook

- Tremendous opportunity for Jefferson Lab to transform understanding of QCD in nuclei
  - GPDs and TMDs of light nuclei
  - medium effects on gluon structure via J/ψ production
  - Anti-shadowing region and its A dependence
  - $b_1(x)$ and gluon transversity in deuteron and ^{6}Li
- Key physics questions: How does the *NN* interaction arise from QCD? How do quark/gluon confinement length scales change in medium?
- Can explore these questions by imaging light nuclei and comparing quarks and gluons for slices in x, $\boldsymbol{k}_T^2$, and $\boldsymbol{b}_T^2$
  - correlations between quarks and gluons in nuclei provide insights into color confinement