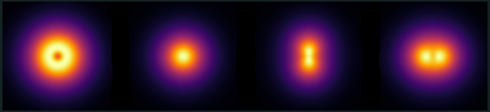
Science of light and heavy ions

Ian Cloët

Argonne National Laboratory



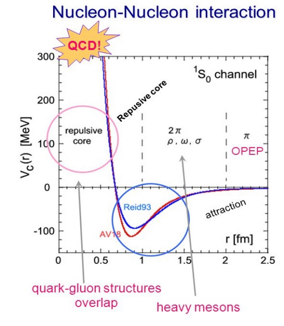
IR2@EIC: Science and Instrumentation of the 2nd IR for the EIC

17-19 March 2021, Argonne and CFNS Joint Workshop

Argonne NATIONAL LABORATORY

Why Nuclei?

- Nuclei give access to numerous aspects of QCD not found in a single proton
  - neutron target via deuteron or ^{3}He, mirror nuclei
  - only targets with $J \geqslant 1$, new PDFs, form factors, TMDs, GPDs, etc.
  - color transparency, hidden color, correlations
  - isospin & baryon density effects, e.g., partial chiral symmetry restoration and possible changes in confinement length scales
  - enhance numerous Standard Model effects: gluon saturation, QED, neutrino cross-sections, etc.

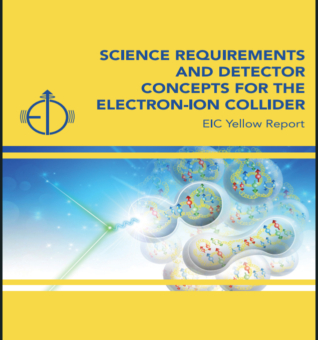


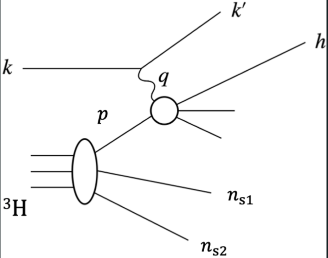
- At a fundamental level nuclear tomography (deuteron, ^{3}H, ^{3}He, ^{4}He, ^{7}Li, ...) can help address the key question: *How does the nucleon-nucleon interaction arise from QCD?*

> *"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

Nuclei in the Yellow Report

- Nuclei feature prominently in the Yellow Report
  - Abstract: *"The EIC … providing access to those regions in the nucleon and nuclei where their structure is dominated by gluons."*
  - The EIC Physics Case presents four major themes, including:
    7.2 Multi-dimensional imaging of nucleons, nuclei and mesons;
    7.3 The nucleus: a laboratory for QCD; and 7.4 Understanding hadronization
- Numerous novel physics processes discussed:





Double Spectator Nucleon Tagging

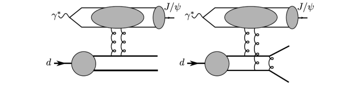


Figure 7.109: Diagrams for two mechanisms in exclusive quarkonium production on the deuteron with diffractive breakup. The virtual photon fluctuates into a color dipole and exchanges two gluons with the deuteron. Left: Two gluons attach to the same nucleon (color-singlet SRC). Right: Two gluons attach to different nucleons (color-octet SRC).

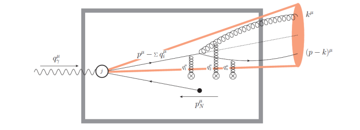
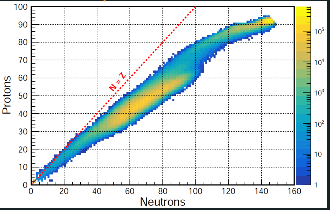


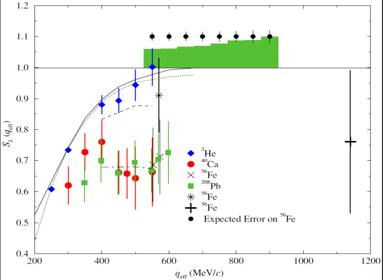
Figure 7.70: Illustration of the indicated jet kinematics for SIDIS in the Breit frame. The dark box represents the medium (nucleus) and the red cone represents the jet.

Nuclei produced from ^{238}U

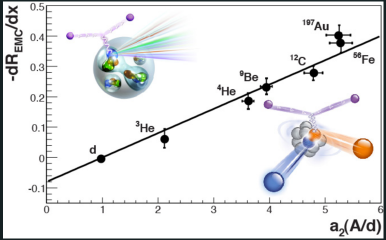


QCD and Nuclei – The Beginnings

- How the nuclear medium impacts quarks and gluons in nuclei (nuclear structure) is a longstanding mystery
- The first signs of *QCD effects in nuclei* came from quasi-elastic scattering experiments in the 1980s (e.g., MIT Bates, Saclay) and the observed quenching of the Coulomb Sum Rule
- The existence of QCD effects in nuclei is now established by the 1982 measurement from CERN of the EMC effect
  - valence quarks in nucleus carry less momentum than in a nucleon
  - 30+ years after discovery a broad consensus on explanation is lacking, current thinking is a combination of mean-field and SRC effects
- Understanding the origin is EMC effect is critical for a QCD based description of nuclei – the EIC provide many new opportunities
  - gluons in nuclei
  - comprehensive quark and gluon tomography of (polarized) light nuclei
  - using heavier nuclei and tagging to amplify and isolate effects



SRCs – Weinstein *et al.*, PRL 2011



QCD and Nuclei – The Beginnings

- How the nuclear medium impacts quarks and gluons in nuclei (nuclear structure) is a longstanding mystery
- The first signs of *QCD effects in nuclei* came from quasi-elastic scattering experiments in the 1980s (e.g., MIT Bates, Saclay) and the observed quenching of the Coulomb Sum Rule
- The existence of QCD effects in nuclei is now established by the 1982 measurement from CERN of the EMC effect
  - valence quarks in nucleus carry less momentum than in a nucleon
  - 30+ years after discovery a broad consensus on explanation is lacking, current thinking is a combination of mean-field and SRC effects
- Understanding the origin is EMC effect is critical for a QCD based description of nuclei – the EIC provide many new opportunities
  - gluons in nuclei
  - comprehensive quark and gluon tomography of (polarized) light nuclei
  - using heavier nuclei and tagging to amplify and isolate effects

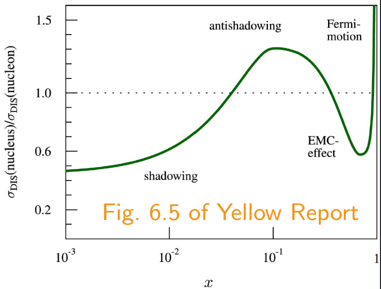
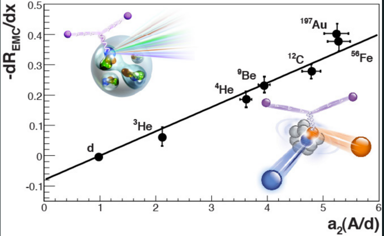


Fig. 6.5 of Yellow Report

SRCs – Weinstein *et al.*, PRL 2011

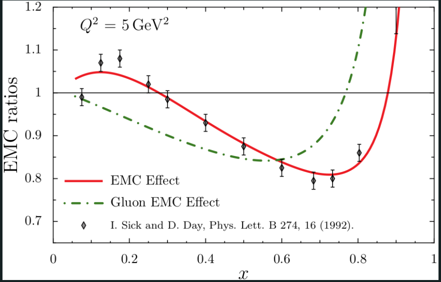


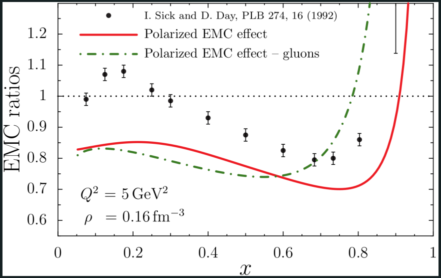
Gluon and Spin EMC Effects

- 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 (Everyone's Model is Cool – Jerry Miller)
  - 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 opposite 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 EIC measurements





DIS on Nuclear Targets ($J \geqslant 1$)

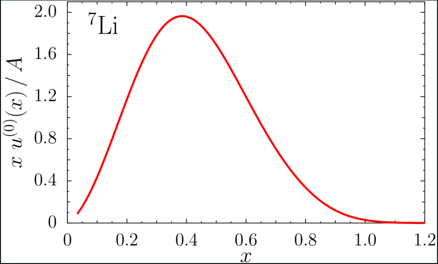
- In the Bjorken limit there are $2J+1$ *DIS structure functions* assuming Callen-Gross-like relations ($F_2 = 2x\,F_1$) [e.g. b_1]
  - can be labelled by target helicity $F_2^H = F_2^{-H}$ & $g_1^H = -g_1^{-H}$
  - measurement of F_2^H requires a polarized target, whereas g_1^H also needs a polarized beam
- New sum rules for associated multipole PDFs

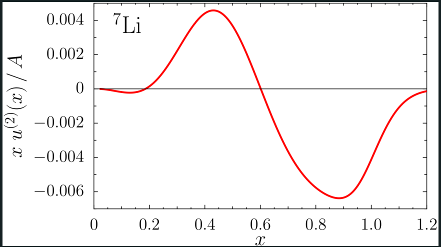
$$\int dx\, x^{n-1}\, q^{(K)}(x) = 0 \qquad K,\, n \text{ even } \; 2 \leqslant n < K$$

$$\int dx\, x^{n-1}\, \Delta q^{(K)}(x) = 0 \qquad K,\, n \text{ odd } \; 1 \leqslant n < K$$

Jaffe and Manohar, Nucl. Phys. B **321**, 343 (1989)

  - higher multipoles encapsulate differences between helicities
- Large $K > 1$ multipole PDFs would be surprising, may imply: non-nucleon components, large off-shell effects like SRC, etc.
  - effects can be explored in light nuclei, e.g., deuteron



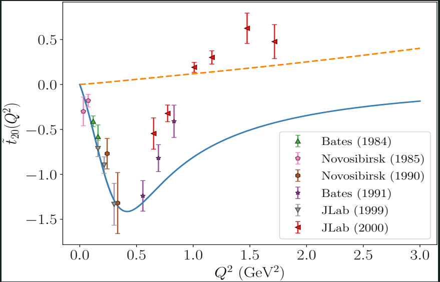


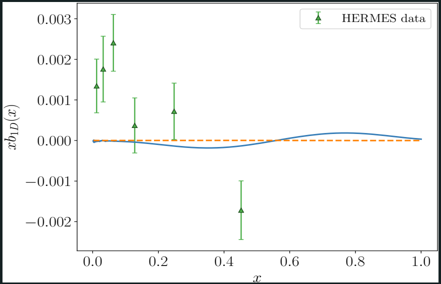
The Deuteron

- The deuteron is the simplest nucleus – consisting primarily of a proton + neutron with 2.2 MeV binding
  - however the deuteron is greater than the sum of its parts, having many properties not found in either of its primary constituents
  - the 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.





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 $\Longrightarrow |\boldsymbol{S}_T| = 1, S_L = 0$

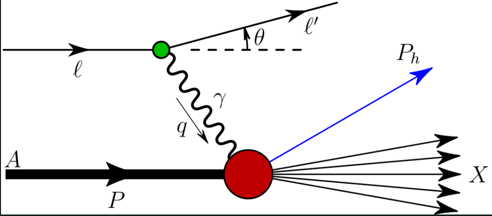
leading twist		quark operator: γ^+	quark operator: $\gamma^+\gamma_5$	quark operator: $\gamma^+\gamma^i\gamma_5$
target polarization	U	$f_1 =$ unpolarized		$h_1^\perp =$ Boer-Mulders
target polarization	L		$g_1 =$ helicity	$h_{1L}^\perp =$ worm gear 1
target polarization	T	$f_{1T}^\perp =$ Sivers	$g_{1T}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

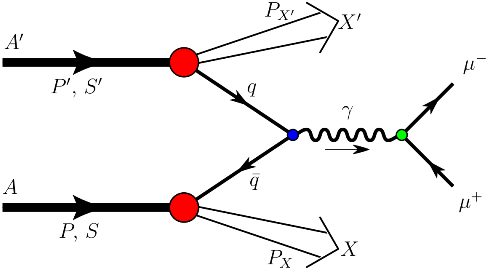
- Associated quark correlation function:

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

Measuring TMDs of Spin-1 Targets

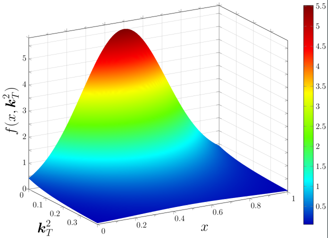
- Need longitudinal and tensor polarized spin-1 targets, e.g., deuteron and ^{6}Li
- For SIDIS there are 41 structure functions; 18 for U+L which also appear for spin-half and 23 associated with tensor polarization
  [W. Cosyn, M. Sargsian and C. Weiss, PoS DIS **2016**, 210 (2016)]
- For proton + deuteron Drell-Yan there are 108 structure functions; 60 associated with tensor structure of deuteron
  [S. Kumano, J. Phys. Conf. Ser. **543**, no. 1, 012001 (2014)]
- Challenging experimentally
  - need solid physics motivation and an EIC



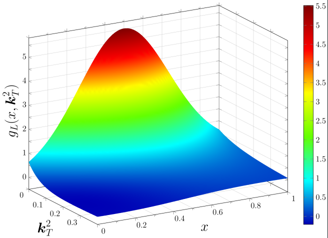


Spin-1 Target TMDs

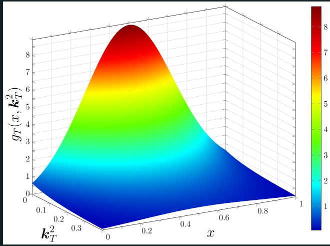
unpolarized



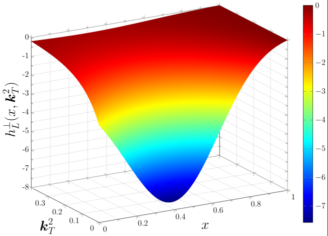
helicity



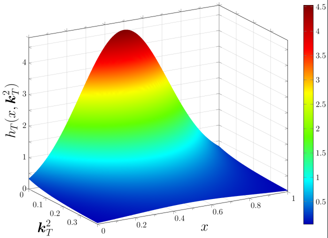
worm gear 2



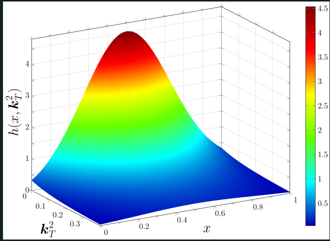
worm gear 1



pretzelosity



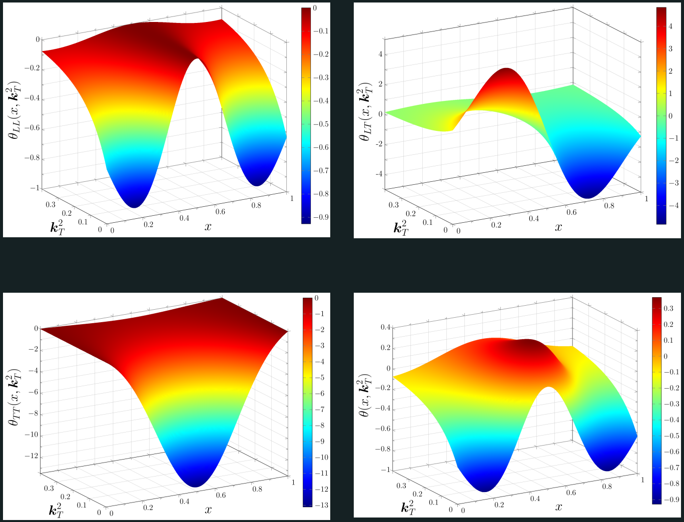
transversity



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

Spin-1 Target TMDs – Tensor Polarization

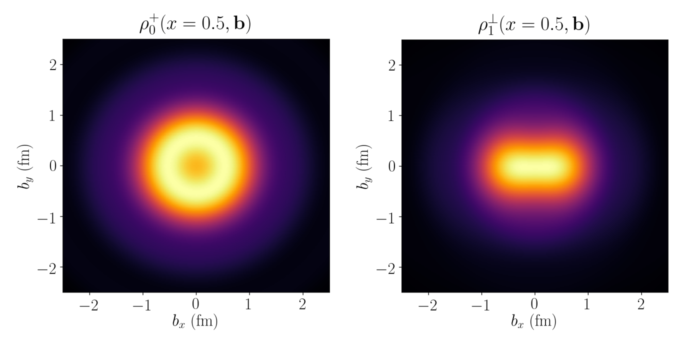
- Calculations assume point-like nucleon but nevertheless show tensor polarized TMDs have many surprising features
- TMDs $\theta_{LL}(x\,\boldsymbol{k}_T^2)$ & $\theta_{LT}(x\,\boldsymbol{k}_T^2)$ identically vanish at $x = 1/2$ for all $\boldsymbol{k}_T^2$
  - $x = 1/2$ corresponds to zero relative 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 – difficult for traditional lattice QCD methods

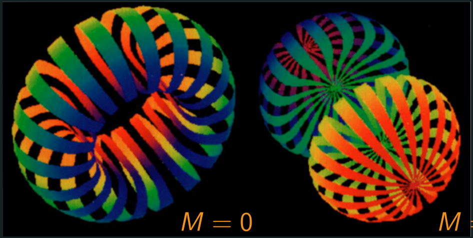


[Yu Ninomiya, ICC and Wolfgang Bentz, Phys. Rev. C **96**, no.4, 045206 (2017)]

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
    – donut shape is clear
  - longitudinally polarized along x-axis
    – dumbbell shape is clear
- 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 at an EIC





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

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

Results for Deuteron GPDs

- Nuclear GPDs given by convolution between quark/gluon GPDs in nucleon & nucleon GPDs nuclei

$$H_A(x_A, \xi_A, t) = h_A(y_A, \xi_y, t) \otimes H_N(z, \xi_z, t)$$

Electroweak Processes and NuTeV Anomaly

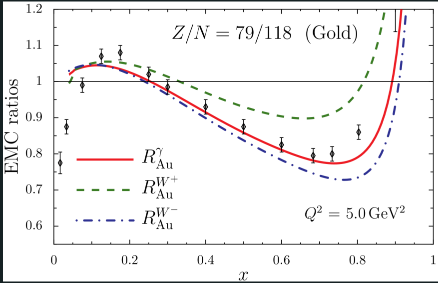
- Yellow Report: "7.5.1 Electroweak and BSM physics" and "7.5.2 Neutrino physics"

- Weak charged and neutral currents provide several important opportunities for the science of nuclei – a key example is flavor separation

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

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

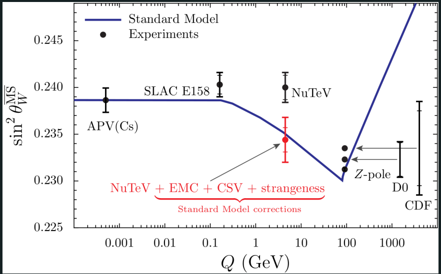
  - access flavor dependence of EMC effect



- Can impact NuTeV measurement of $\sin^2\theta_W$ (NuTeV Anomaly) using Paschos-Wolfenstein relation

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

  - at EIC can study analogous relations for many nuclei and test impact on NuTeV anomaly



Electroweak Processes and NuTeV Anomaly

- Yellow Report: “7.5.1 Electroweak and BSM physics” and “7.5.2 Neutrino physics”

- Weak charged and neutral currents provide several important opportunities for the science of nuclei – a key example is flavor separation

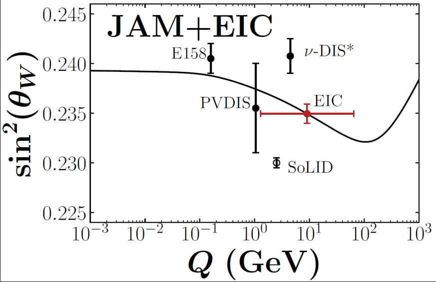
$$F_1^{W^+} = \bar{u} + d + s + \bar{c} \qquad F_3^{W^+} = -\bar{u} + d + s - \bar{c}$$
$$F_1^{W^-} = u + \bar{d} + \bar{s} + c \qquad F_3^{W^-} = u - \bar{d} - \bar{s} + c$$

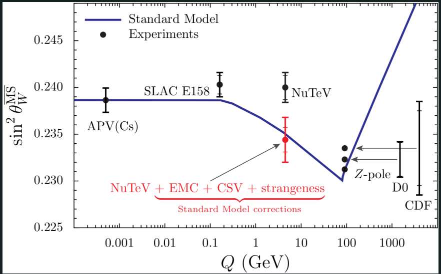
  - access flavor dependence of EMC effect

- Can impact NuTeV measurement of $\sin^2\theta_W$ (NuTeV Anomaly) using Paschos-Wolfenstein relation

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

  - at EIC can study analogous relations for many nuclei and test impact on NuTeV anomaly





Conclusion and Outlook

- Tremendous opportunity for the EIC to transform our understanding of QCD and nuclei
  - quark & gluon GPDs and TMDs of: proton, deuteron, triton, ^{3}He, ^{4}He, . . .
  - quark & gluon PDFs of ^{7}Li, ^{11}B, ^{56}Fe, . . .
  - flavor separation, e.g., s-quarks
- Key physics question: How does the NN interaction arise from QCD?
- Can explore this question by imaging 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 connected to color confinement
  - could impact physics as far afield as neutron star equation of state (e.g. hyperon puzzle)