Spectator Tagged DVCS at 22 GeV

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

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Argonne NATIONAL LABORATORY

Introduction

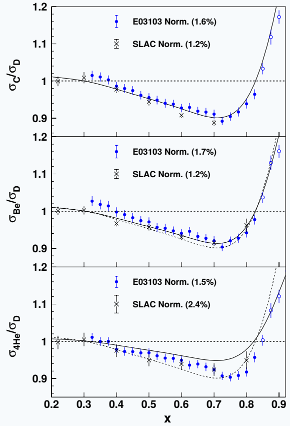
What questions are we trying to answer?

- What is the **origin of the EMC effect**
- What is the partonic structure of a bound nucleon?
- How is the **nucleon modified** in nuclear medium?
- How are **hadrons modified** in nuclear medium?

And how does 22 GeV help?

Nuclear Medium Effects

EMC Effect in DIS

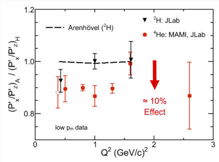


J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

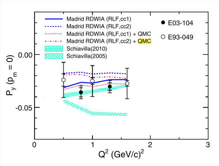
Is structure function modified?
Significant even in ^{4}He!
Origin of effect remains unclear

Polarization Transfer

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E+E')}{2M}\tan\theta/2$$



P_y is a measure of FSI

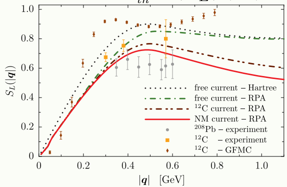


Quasi-elastic knockout possibly observing medium modified form factors

^{2}H: B. Hu et al., PRC 73, 064004 (2006). ^{4} He: S. Dieterich et al., PLB 500, 47 (2001); S. S., et al., PRL 91, 052301 (2003); M. Paolone, et al., PRL 105, 0722001 (2010); S. Malace et al., PRL 106, 052501 (2011)

Coulomb Sum Rule

$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}^+}^{\infty} d\omega\,\frac{R_L(q,\omega)}{|G_E^p|^2(Q^2)}$$



Cloet, et.al., Phys.Rev.Lett. 116 (2016)032701
Lovato, et.al., Phys.Rev.Lett. 111 (2013)092501

Observations of quenching the CSR remain contested.

New theory predictions will be put to the test with soon to be completed JLab experiment.

But nuclear effects persist in the form of corrections and possibly cloud conclusions.

The Challenge of Nuclear Effects

And attempts to overcome them

EMC Effect in DIS

Control initial state via **Spectator tagging** – separate mean field and SRC nucleons
FSI introduce model dependence

Partonic interpretation

Polarization Transfer

Induced polarization (P_y) provides feedback to FSI model FSIs

But only a **Nucleonic Observable**: What is going on with the quarks and gluons?

Coulomb Sum Rule

Observations of quenching complicated by model dependent nuclear corrections

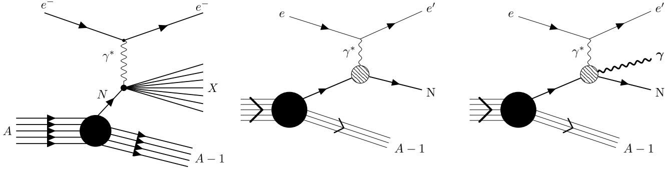
Nucleonic Interpretation

Model dependent corrections and FSIs are significant barrier to **unambiguously identifying any modification at the partonic level**.

Can we connect the **Partonic and Nucleonic** interpretations while systematically controlling final-state interactions and other model dependence?

Spectator-Tagged DVCS

Incoherent DVCS on bound nucleon with the spectator system (A-1) *tagged* with low energy recoil detector

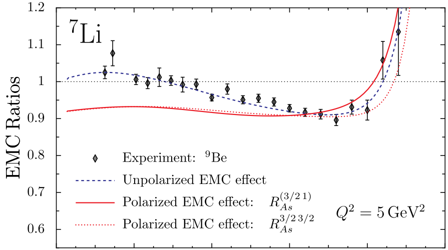


A clean link between the Partonic and Nucleonic

- Combines some good features of **DIS and QE** scattering
- DVCS $\rightarrow$ **parton level interpretation**
- Tagging spectator $\rightarrow$ identify struck nucleon and its initial momentum
- **separate mean field** from high momentum nucleons
- **Fully exclusive** measurement $\rightarrow$ unique handle to study and minimize FSIs

Neutron DVCS: A sensitive probe for medium modifications

$$\frac{\alpha_n^*}{\alpha_n} = \frac{\text{bound } n}{\text{quasi-free } n} = \frac{A_{LU}^{\sin\phi}(^4He)}{A_{LU}^{\sin\phi}(^2H)} \sim \frac{\mathrm{Im}\left(\frac{-t}{4M^2}F_2^{n^*}\mathcal{E}^{n^*} + x_B G_M^{n^*}\tilde{\mathcal{H}}^{n^*}\right)}{\mathrm{Im}\left(\frac{-t}{4M^2}F_2^{n}\mathcal{E}^{n} + x_B G_M^{n}\tilde{\mathcal{H}}^{n}\right)}$$



Cloët, Bentz, Thomas. Phys.Lett. B642 (2006) 210-217

The ratio in the forward limit looks like

$$\frac{\alpha_n^*}{\alpha_n} = \frac{\text{bound } n}{\text{quasi-free } n} \longrightarrow \frac{\mu_{n^*}}{\mu_n}\,\frac{g_1^{n^*}(x)}{g_1^{n}(x)},$$

$\mu_{n^*} \rightarrow$ nucleonic modification

$g_1^{n^*} \rightarrow$‘ partonic modification

Polarized EMC Effect and Medium Modified Form Factors

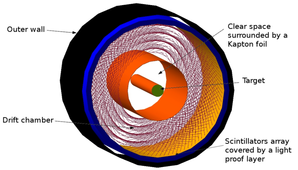
DVCS on a **bound neutron** is a **uniquely sensitive** probe of medium modifications

The ALERT Experiments

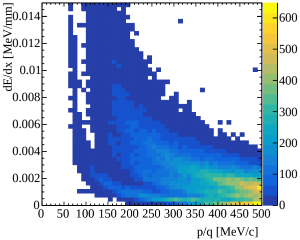
A comprehensive program to study nuclear effects

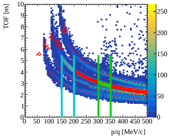
ALERT Requirements

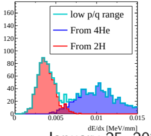
- Identify light ions: H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Detect the **lowest momentum** possible (close to beamline)
- Handle **high rates**
- Survive high radiation environment
  $\rightarrow$ **high luminosity**



- TOF is degenerate for ^{2}H and ^{4}He.
- dE/dx can separate these.
- At higher p, scintillator topology can also be used to separate.







Incoherent DVCS on ^{4}He and ^{2}H

- $^4\text{He}(e, e'\gamma\, p + {}^3\text{H})$
- $^4\text{He}(e, e'\gamma + {}^3\text{He})n$
- $^2\text{H}(e, e'\gamma\ + p)n$

Identify medium modified nucleons

Coherent Processes on ^{4}He

- $^4\text{He}(e, e'\ {}^4\text{He}\ \gamma)$
- $^4\text{He}(e, e'\ {}^4\text{He}\ \phi)$

Explore the partonic structure of ^{4}He

Tagged EMC Effect

- $^4\text{He}(e, e' + {}^3\text{H})X$
- $^4\text{He}(e, e' + {}^3\text{He})X$
- $^2\text{H}(e, e' + p)X$

Test FSI and rescaling models

PWIA and FSIs

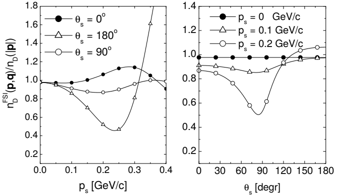
Plane-Wave Impulse Approximation

1. Virtual photon is absorbed by a single nucleon
2. This struck nucleon is the detected nucleon
3. It leaves the nucleus without interacting with the A-1 spectator system $\vec{p}_1 = -\vec{P}_{A-1}$

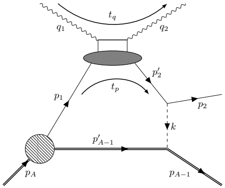
- Incoherent scattering means the lab frame is not the target nucleon rest frame.
  $\rightarrow$ The nucleus turns the system into a lousy collider configuration. $\sqrt{\delta s}$ up to 1 GeV for ^{4}He
- CM energy decreases in typical "low FSI" configurations, ie, backwards.
- **A 22 GeV beam helps to mitigate this loss of kinematic reach for incoherent processes.**

PWIA is the **reference** model for studying FSIs

- The PWIA is arguably the simplest model for FSIs (there are none!)
- All kinematics are computed within this reference model
- Deviations from the PWIA provide information about the nature of FSIs
- All IA models that leave an off-shell spectator require FSIs



EPJ, A19, 145-151, 2004

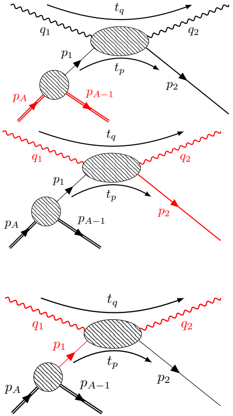


Fully Exclusive Incoherent DVCS

Detect all final state particles

Theoretical help needed!

- ^{4}He$(e, e'\gamma +^3$ H$p)$
  - Proton DVCS on ^4He
    $\rightarrow$ Measure full final state with ALERT
  - Study FSIs with proton
    $\rightarrow$ apply to neutron channels.
  - 22 GeV ALERT experiment helps understand FSIs
- ^{4}He$(e, e'\gamma +^3$ He$)n$
- ^{2}H$(e, e'\gamma + p)n$

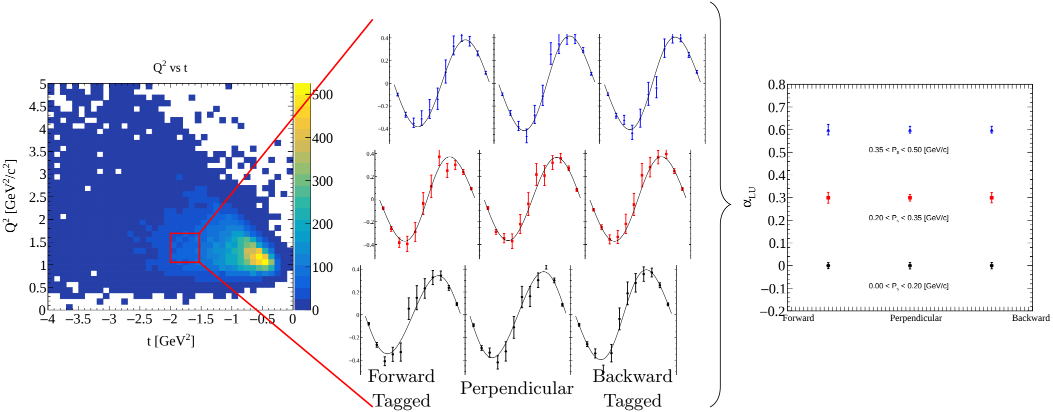


Looking to future

- Theory development moving closer to fully exclusive tagged incoherent DVCS on ^4He.
- Need help working out best way to leverage kinematic redundancy to study FSIs.

Tagged DVCS: Off-forward EMC Ratio

The plot below is for 12 GeV configuration. At 22 GeV, higher Q^2 possible.
Forward detector kinematics similar to DVCS on the nucleon (see WG4 session on Tuesday)

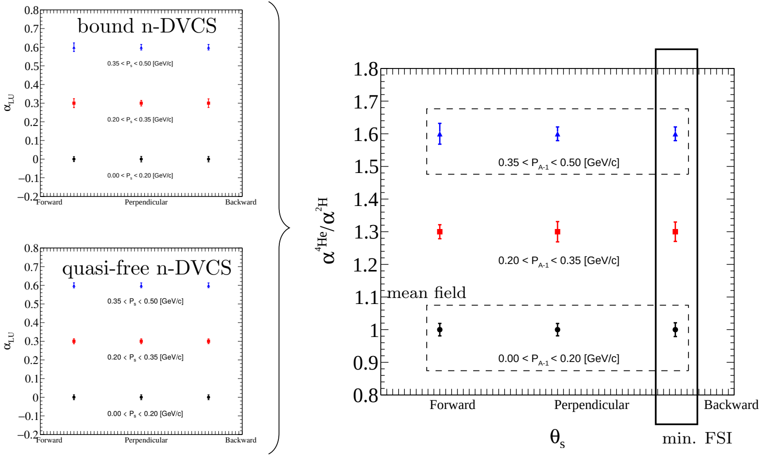


- 6 dimension binning (7 with helicity)
- Reduced to 5 after obtaining ‘$\sin\phi$‘ harmonic
- $\alpha_{LU} = \int A_{LU} \sin\phi \, d\phi$

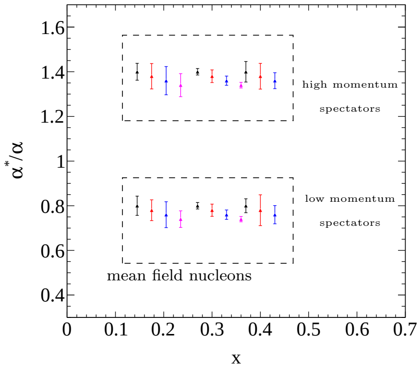
Off-forward EMC Ratio

$$^4\text{He}(e, e'\gamma +^3 \text{He})n$$

$$^2\text{H}(e, e'\gamma + p)n$$



Off-forward EMC Ratio



Colors indicate the different t bins which are shifted horizontally for clarity

- Separated mean field nucleon Off-forward EMC Effect and high momentum nucleon Off-forward EMC Effect
- **With FSIs systematically controlled**, observed deviations from unity indicate nuclear medium modifications of nucleons at the partonic level

$$^4\text{He} + \gamma^* \rightarrow \gamma + (n) + {}^3\text{He}$$

$$^2\text{H} + \gamma^* \rightarrow \gamma + (n) + p$$

$$^4\text{He} + \gamma^* \rightarrow \gamma + p + {}^3\text{H}$$

Summary

- Tagged DVCS will bridge the gap between **Partonic and Nucleonic interpretations** of medium modifications.
- Unique opportunity to cleanly connect the partonic structure of a "free nucleon" to its in-medium **partonic structure**
- This first-of-its-kind measurement with ALERT is complementary to a wide variety of existing and proposed experiments
- Full exclusivity provides ability to systematically study and control FSIs
- 22 GeV will give more of a lever arm on FSIs
- **Attn Theorists:** Predictions/model calculations needed for fully exclusive reaction $^{4}\text{He}(e, e'\gamma\, p + {}^{3}\text{H})$

Thank you!

Backup

Toy model of Kinematics with FSIs

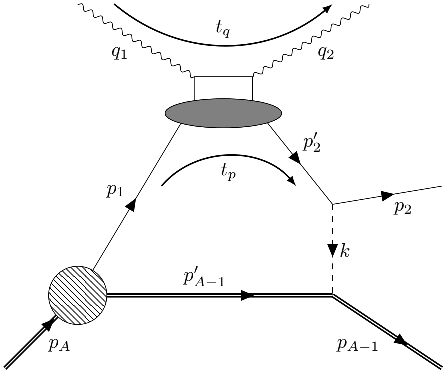
The power of exclusivity

For simplicity, fix virtual photon momentum:

$$\nu_1 = 9 \text{ GeV}, \qquad Q^2 = 2.65 \text{ GeV}^2,$$

Sample ^{4}He momentum distribution and sample uniformly the LIPS for proton and photon final state. Then generate a massless momentum exchange between the final state proton and spectator

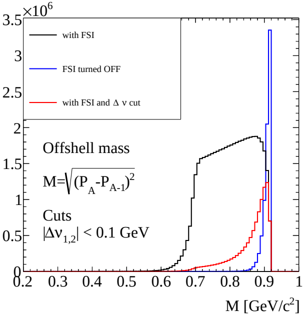
$$0 < |\vec{k}| < 200\text{MeV/c}$$

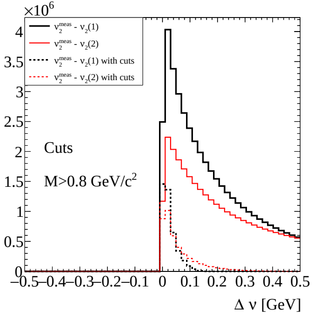


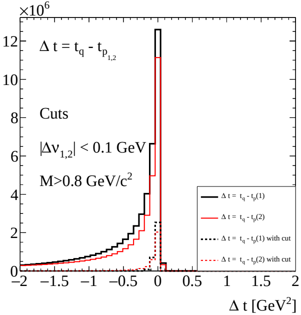
Goal

Demonstrate that with a fully detected final state we can identify events with **significant FSI** which have **kinematics inconsistent with the PWIA**

FSI Toy Model

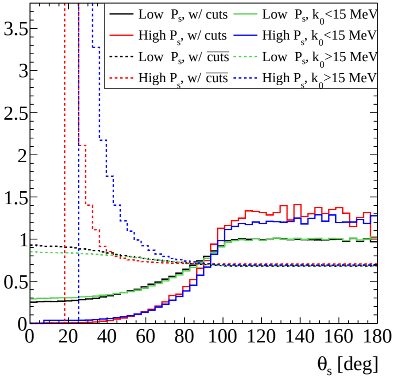


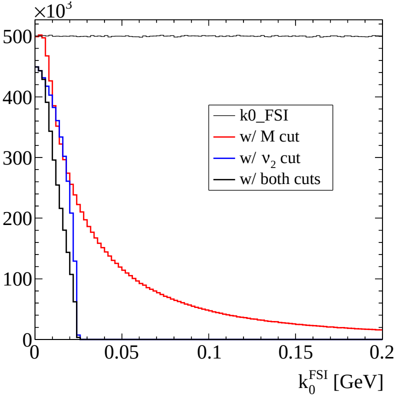




Select near on-shell mass and consistently reconstructed/measured photon energy.

FSI Toy Model





$$R = A\frac{N(x,Q^2,t,P_s|\text{FSI cut})}{N(x,Q^2,t,P_s)}$$

Useful tool for demonstrating idea but

We need theoretical help to realistically model FSI and test effectiveness.

Neutron DVCS: A sensitive probe for medium modifications

$$A_{LU,n}^{\sin\phi} \propto \mathrm{Im}\left(F_1^n \mathcal{H}^n - \frac{t}{4M^2} F_2^n \mathcal{E}^n + \frac{x_B}{2}(F_1^n + F_2^n)\tilde{\mathcal{H}}^n\right)$$

Term by term breakdown:

1. Suppressed by neutron Dirac FF
2. Connected to Ji's sum rule and quark OAM through GPD
3. Related to Polarized EMC effect and Modified Form Factors

Connection to Spin Structure Functions and Modified Form Factors:

The third term above is

$$\mathrm{Im}\left((F_1 + F_2)\tilde{\mathcal{H}}\right) = G_M(t) Im(\tilde{\mathcal{H}}(\xi,\xi,t))$$

Forward Limit (at leading order):

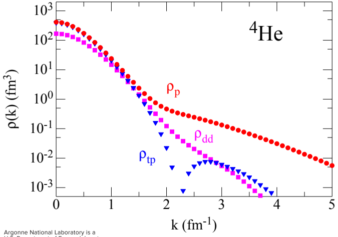
$$Im(\tilde{\mathcal{H}}(x,\xi,t)) \to \tilde{H}(x,0,0) = g_1(x)$$

$$G_M(t) \to \mu$$

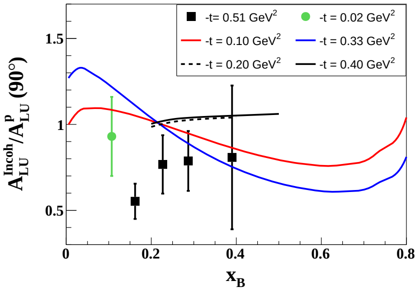
CLAS eg6 (E08-024)

Incoherent DVCS

- Unconstrained initial state: virtual photon-nucleon CM energy unknown due to Fermi motion
- Off-forward EMC Effect calculated using denominator from different experiment introduces extra systematics
- Interesting results, but, inconclusive interpretation: similar to untagged EMC Effect



$^4He(e, e' \gamma p)$

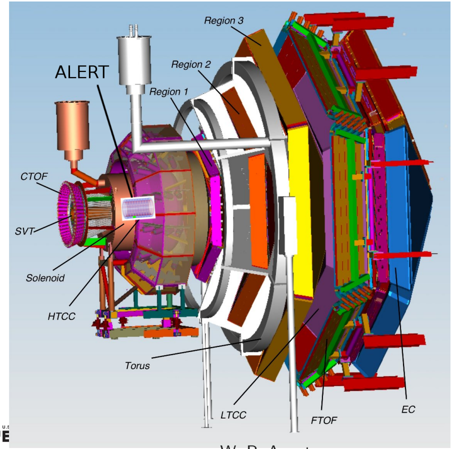


M. Hattawy, *et al.* PRL 123 (2019).

Interesting results but inconclusive (similar to regular EMC effect).

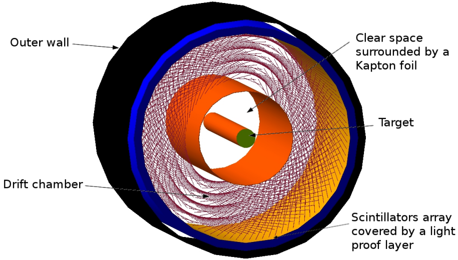
Experiment Setup: CLAS12 + ALERT

- Use CLAS12 to detect scattered electron, e', and forward scattered hadrons.
- A low energy recoil tracker (ALERT) will detect the spectator recoil or coherently scattered nucleus



ALERT Requirements

- Identify light ions: H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Detect the **lowest momentum** possible (close to beamline)
- Handle **high rates**
- Survive high radiation environment $\rightarrow$ **high luminosity**
- Provide **independent trigger** or high luminosity thresholds



ALERT PID

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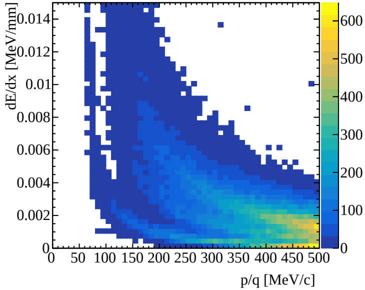

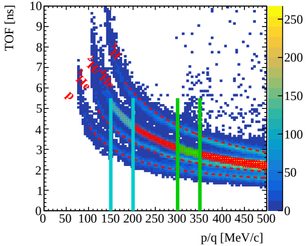

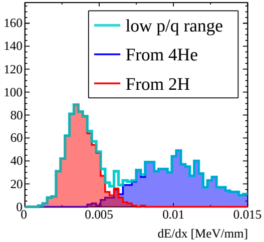

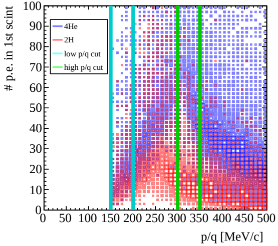

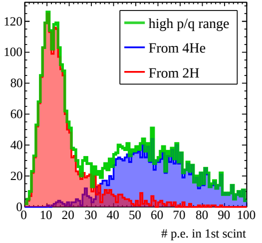

Ultrafast x ray pump-probe

- Breakdown of Born-Oppenheimer Approximation
- Initial state is modeled
- Final state after long time is known
- Studying the response for different parameters (Δt, λ, etc...) allows the model of dynamics to be better understood.
- Requires **high intensity** to resolve diffractive pattern

Incoherent Tagged DVCS

- Breakdown of PWIA
- Initial state is modeled
- Final state is fully measured (γ, p, A-1)
- Studying the response for different paramters (P_s, θ_s, ϕ_s, x, Q^2, t, ϕ...) allthe model of the nuclear dynamics to be refined
- Requires **high luminosity** to resolve multidimensional FSI pattern