# Exploring the Partonic Structure of $^{4}$He through Exclusive Processes with Positrons

Positron Working Group Workshop

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# Introduction

**What questions are we trying to answer?**

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

**And how does a positron facility help?**

# Nuclear Physics and the ~~Nucleon~~ $\alpha$ Particle

**From the first textbook on Nuclear Physics**

"The general evidence on nuclei strongly supports the view that **the $\alpha$ particle is of primary importance as a unit of the structure of nuclei** in general and particularly of the heavier elements. It seems very possible that the greater part of the mass of heavy nuclei is due to $\alpha$ **particles which have an independent existence in the nuclear structure**."

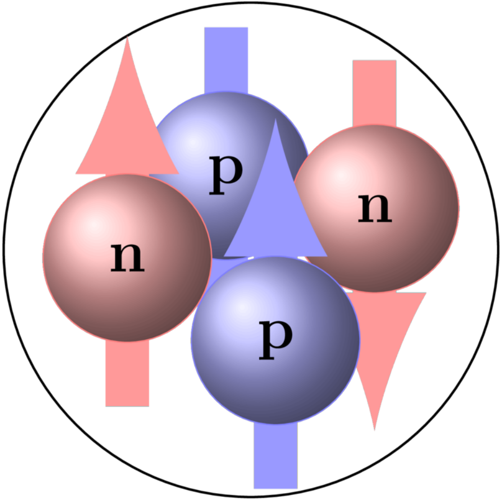
— Rutherford, Chadwick, and Ellis (1930)

Note: this is roughly 2 years before the discovery of the neutron.

- The charge distribution of $^{4}$He is well established
- Armed with QCD, take the 1930 view of the $\alpha$ as a nuclear building block of quarks and gluons...
- Do we discover the nucleonic degrees of freedom when we probe the partonic?

# The Partonic Structure of the alpha particle

## A cartoon




- Two goggles to view the nucleus...

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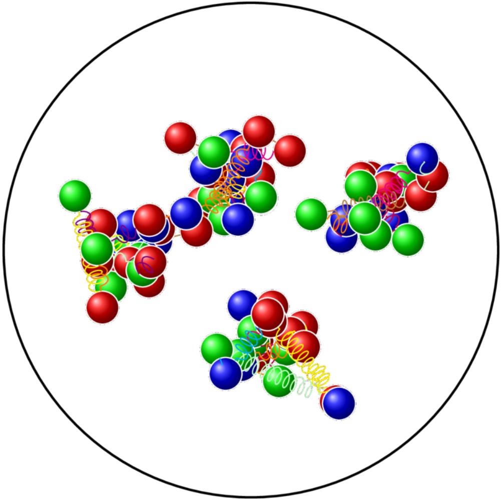

- Two goggles to view the nucleus...
- One for the charge (quark) content (Coherent DVCS)

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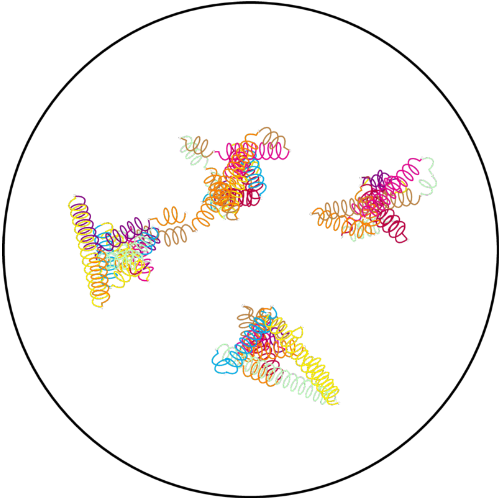

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- Another for the gluonic matter content (Coherent VM production)

# The Partonic Structure of the alpha particle

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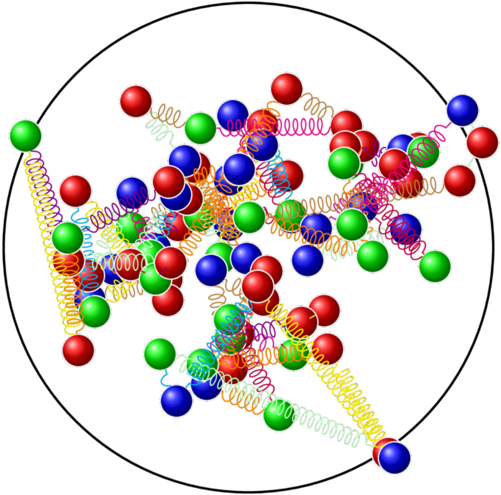


- Two goggles to view the nucleus...
- One for the charge (quark) content (Coherent DVCS)
- Another for the gluonic matter content (Coherent VM production)
- How do these compare?

# Coherent Photoproduction of phi on $^4$He

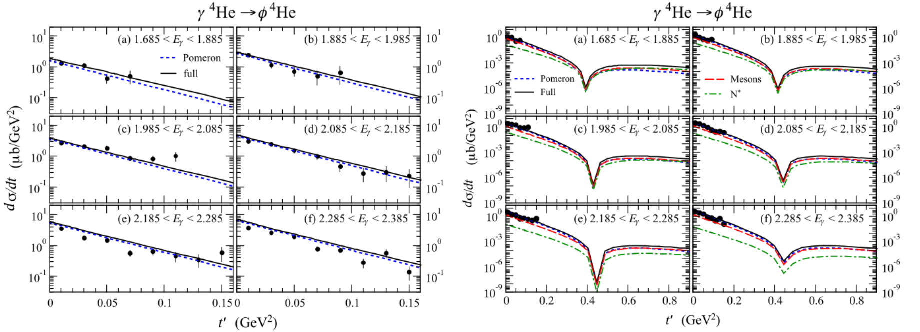



**Fig. 5** Differential cross sections $d\sigma/dt$ for $\gamma^4\text{He} \rightarrow \phi^4\text{He}$ are plotted as functions of $t' \equiv |t| - |t|_{\text{min}}$ at $1.685 < E_\gamma < 2.385$ GeV [11]. The LEPS data are from Ref. [14]

(Kim, Lee ,Nam, Oh Few-Body Syst (2024))

Data limited to low-t.

**What happens around the minimum in the $^4$He Form Factor?**

**Does the glue/matter follow the charge?**

# Gravitational Form Factors

## Mechanical properties

The GFFs parameterize the matrix element of the Energy Momentum Tensor.
For a spin-0 target we have:

$$\langle p'|T_{\mu\nu}|p\rangle = 2A(t)P_\mu P_\nu + \frac{D(t)}{2}(q_\mu q_\nu - \eta_{\mu\nu}q^2),$$

$$\langle r^2\rangle_m = 6\frac{dA(t)}{dt}\Big|_{t=0} - \frac{3D(0)}{2M^2}$$

$$\langle r^2\rangle_s = 6\frac{dA(t)}{dt}\Big|_{t=0} - \frac{9D(0)}{2M^2}$$

$$\langle r^2\rangle_t = 6\frac{dA(t)}{dt}\Big|_{t=0}$$

$$\langle r^2\rangle_{mech} = \frac{D(0)}{\int D(t)dt}$$

(Martin-Caro, Huidobro, Hatta PRD 108 (2023))

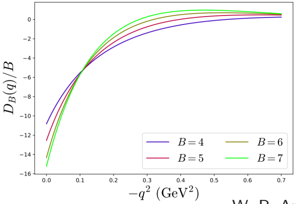
# Why focus on $^4$He?

Two Leading twist GPDs:
$H$ (chiral-even) and $H_T$ (chiral-odd)
Accessible in DVCS and DVMP
And 1 twist-3 GPD: $H_3$
(Tanaka PRD 98 (2018))

$$\int dx x H_3(x, \xi, t) = -\xi D(t)$$

Gravitation form factors for light nuclei:

- Skyrme Model: (Martin-Caro, Huidobro, Hatta PRD 108 (2023))
- Holographic QCD (Mamo and Zahed) PRD 104 (2021) 6, 066023
- (He and Zahed 2024: arXiv:2310.12315

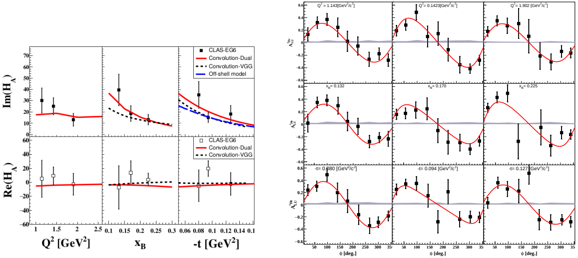


# Accessing the Quark GPD

## Coherent DVCS

- Complex-valued Compton form factor: $\mathcal{H}_A$.
  Neglecting anti-quarks: $H_A(\xi,\xi,t) = \Im m(\mathcal{H}_A)$.
- Compute Fourier coefficients for beam spin asymmetry
- Fit angular distribution to get harmonic parts of $A_{LU}$

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$




CLAS eg6 (Hattawy, et.al. PRL 2017)

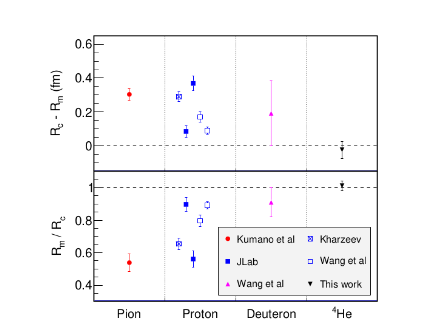
With **positrons and electrons** the beam charge asymmetry is sensitive to the real part of the CFF.

$$A_c = \frac{\sigma(e^+,\phi) - \sigma(e^-,\phi)}{\sigma(e^+,\phi) + \sigma(e^-,\phi)} \propto \Re e(\mathcal{H}_A)$$

# Renewed interest in $^4$He

- Potential discovery of nuclear excitation in X17 (See Eur.Phys.J.C 83 (2023) 3, 230) $\rightarrow$ QCD explanation includes new hidden color configuration unique to to $^4$He. *QCD hidden-color hexadiquark in the core of nuclei* – West, et.al.
- Near-threshold coherent photoproduction and electroproduction measurements of $\phi$ on $^4$He
- "We argue that it is a pioneering and pivotal approach to scrutinize the nuclear structure via the examination of the difference between the **charge and mass radii** of a nucleus." – Wang,et.al. PRC109 (2024)

## Wang,et.al. PRC109 (2024)

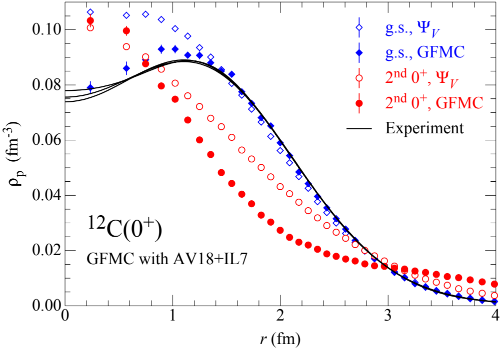


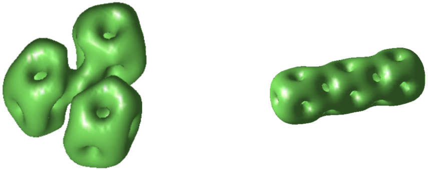

- fit $\phi$ photoproduction data to get $G(t)$
- $^4$He mass radius nearly same as charge radius
- Data needs to be extended to cover a wider range of $|t|$
- Surprising result?
- Why the mass radius of the proton smaller than its charge radius?
- Is $\langle r^2 \rangle_m^{4\mathrm{He}} \simeq \langle r^2 \rangle_{ch}^{4\mathrm{He}}$? If so, why?

# The $\alpha$ particle and the structure of light nuclei

The $\alpha$ is still a fundamental unit of nuclear structure!

| Hadron | $\langle r^2 \rangle^{1/2}$ |
|---|---|
| $\pi$ | 0.64 fm |
| p | 0.84087 ± 0.00039 fm |
| $^2$H | 2.130 ± 0.010 fm |
| $^3$H | 1.755 ± 0.087 fm |
| $^3$He | 1.959 ± 0.034 fm |
| $^4$He | 1.676 ± 0.008 fm |
| $^9$Be | 2.519 ± 0.012 fm |
| $^{12}$C | 2.472 ± 0.015 fm |
| $^{13}$C | 2.440 ± 0.025 fm |



Skyrme Model

W. R. Armstrong

Karliner, et al., J.Phys. G43 (2016) no.5, 055104

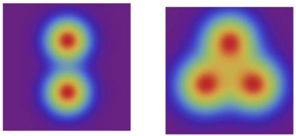


**Figure 1** Charge density of $^8$Be and $^{12}$C in ACM.

$\alpha$-cluster model

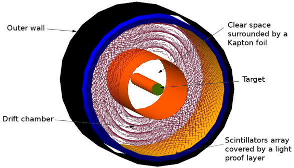
Della Rocca and Iachello, in progress

# The ALERT Experiments

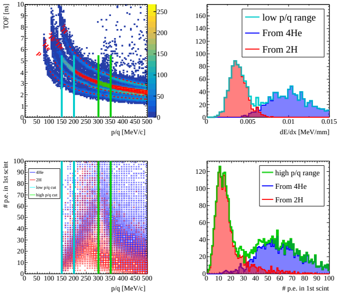
A comprehensive program to study nuclear effects

## 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

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

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

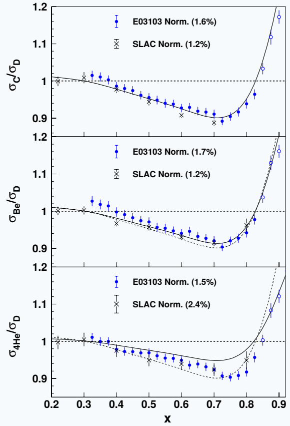
- $^{4}\text{He}(e, e'{+}^{3}\text{H})\text{X}$
- $^{4}\text{He}(e, e'{+}^{3}\text{He})\text{X}$
- $^{2}\text{H}(e, e' + p)\text{X}$

Test FSI and rescaling models

And many more channels for free

# Nuclear Medium Effects

## EMC Effect in DIS

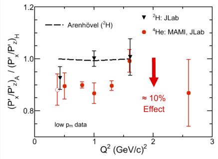



J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

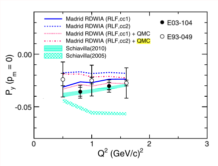
Is structure function modified?
Significant even in $^4$He!
Origin of effect remains unclear

## 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

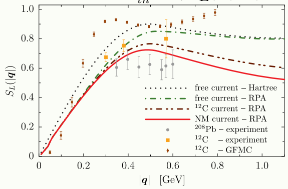



Quasi-elastic knockout possibly observing medium modified form factors

$^2$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

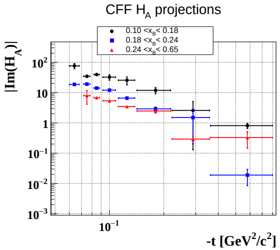
Observations of quenching the CSR remain contested.
New theory predictions will be put to the test with soon to be completed JLab experiment.
But nuclear effects persist in the form of corrections and possibly cloud conclusions.

# 4He Transverse Quark and Gluon Densities

## Coherent scattering on $^{4}$He

DVCS

**Charge profile**

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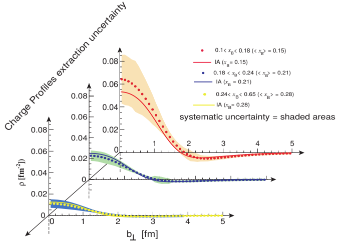
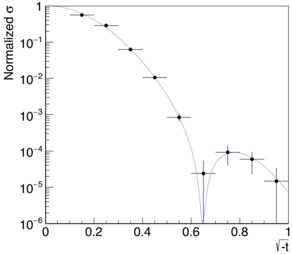



$\phi$ Production

**Gluon profile**

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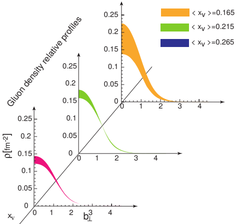


# The Challenge of Nuclear Effects

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

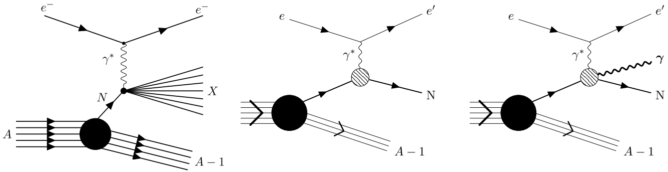
**Nucleonic Interpretation**

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

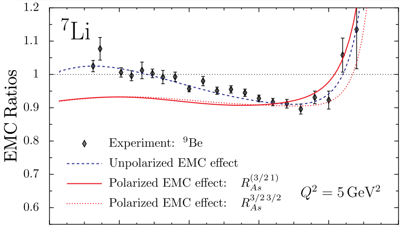



## A clean link between the Partonic and Nucleonic

- 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

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




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

The ratio in the forward limit looks like

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

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

$g_1^{n^*} \to$' partonic modification

## Polarized EMC Effect and Medium Modified Form Factors

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

## Use positron beam for **Ratio of Beam Charge Asymmetries**

$$\frac{A_c^{n^*\cos\phi}}{A_c^{n\,\cos\phi}} = \frac{\text{bound } n}{\text{quasi-free } n} = \frac{A_c^{\cos\phi}(^4He)}{A_c^{\cos\phi}(^2H)} \longrightarrow$$ Sensitive to real parts for ratio similar to above?

# PWIA and FSIs

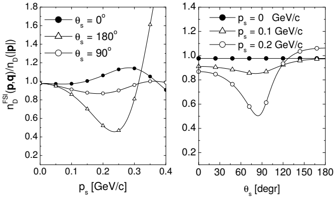
## Plane-Wave Impulse Approximation

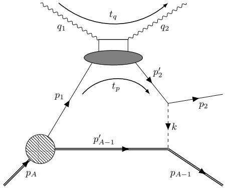
1. Virtual photon is absorbed by a single nucleon
2. This struck nucleon is the detected nucleon
3. It leaves the nucleus without interacting with the A-1 spectator system $\vec{p}_1 = -\vec{P}_{A-1}$

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

- The PWIA is arguably the **simplest model** of FSIs $\rightarrow$ there are none!
- All kinematics are computed within this reference model
- Identifiable deviations from PWIA provide information about the nature of FSIs
- All IA models that leave an off-shell spectator require FSIs

- 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.




EPJ, A19, 145-151, 2004

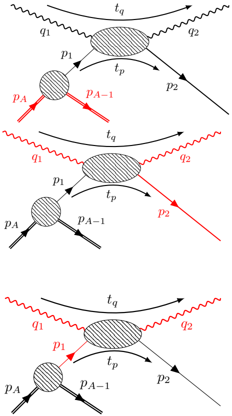
# Fully Exclusive Incoherent DVCS

Detect all final state particles

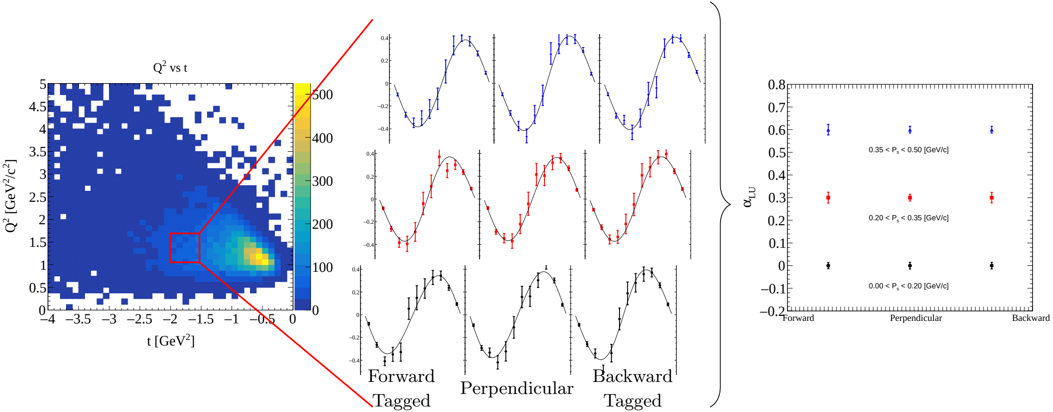
- $^4\text{He}(e, e'\gamma +^3 \text{H}p)$
  - Proton DVCS on $^4He$
    $\rightarrow$ Measure full final state with ALERT
  - Study FSIs with proton
    $\rightarrow$ use charge symmetry and apply to neutron channels.
- $^4\text{He}(e, e'\gamma +^3 \text{He})n$
- $^2\text{H}(e, e'\gamma + p)n$

**Looking to future**

- Theory development moving closer to **fully exclusive** tagged incoherent DVCS on $^4He$.
- Looking for theoretical support leveraging kinematic redundancy to study FSIs.



# Tagged DVCS: Off-forward EMC Ratio

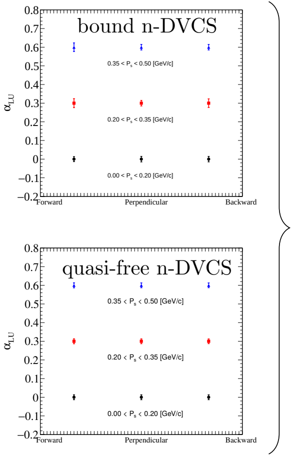


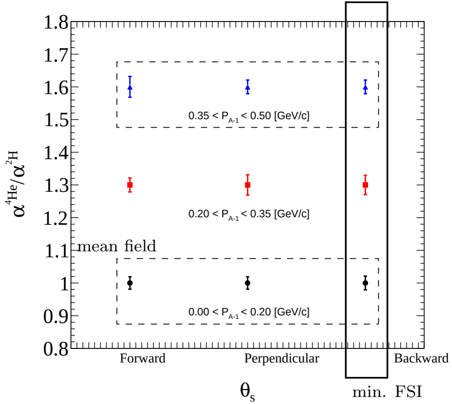

- 6 dimension binning (7 with helicity)
- Reduced to 5 after obtaining ‘$\sin\phi$‘ harmonic
- $\alpha_{LU} = \int A_{LU} \sin\phi \, d\phi$
- $\alpha_c = \int A_c \cos\phi \, d\phi$

# Off-forward EMC Ratio

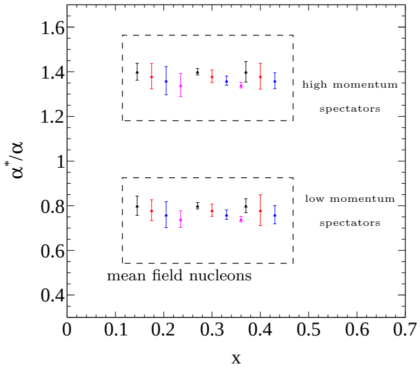
$^{4}\text{He}(e, e'\gamma + {}^{3}\text{He})n$

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



# 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

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

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

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

# Positrons in General

"Experimental facilities having electron and positron beams is an ideal place to disentangle and study GPDs..."
– Belitsky, Muller, Kirchner 2002

- Given the EIC program is centered around imaging, should more noise be made to get positrons at the EIC?

# 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
- A positron beam is an excellent opportunity to study nuclear effects from every angle
- Better access to Compton Form Factors through beam charge asymmetry $\rightarrow$ Better isolate Re/Im parts of CFF from higher-twist, finite-t and target/hadron mass power corrections. II

**Thank you!**

Backup

## 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 ($\Delta t$, $\lambda$, 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 ($\gamma$, $p$, A-1)
- Studying the response for different paramters ($P_s$, $\theta_s$, $\phi_s$, x, $Q^2$, $t$, $\phi$...) allthe model of the nuclear dynamics to be refined
- Requires **high luminosity** to resolve multidimensional FSI pattern