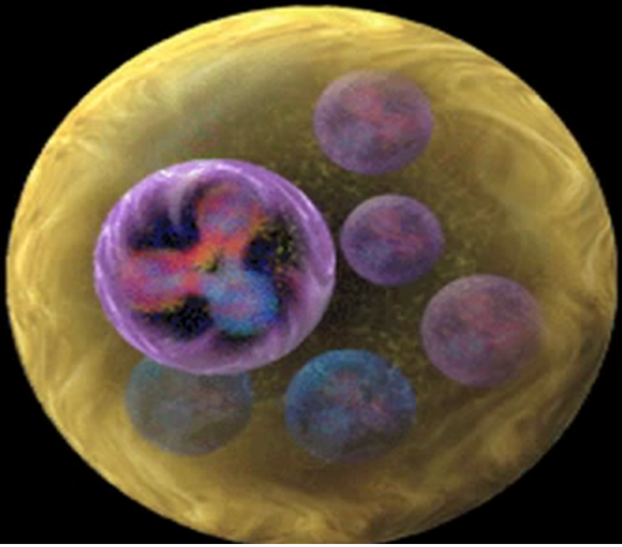
NEXT GENERATION NUCLEAR EXPERIMENTS:

TOWARD 3D TOMOGRAPHY OF NUCLEI



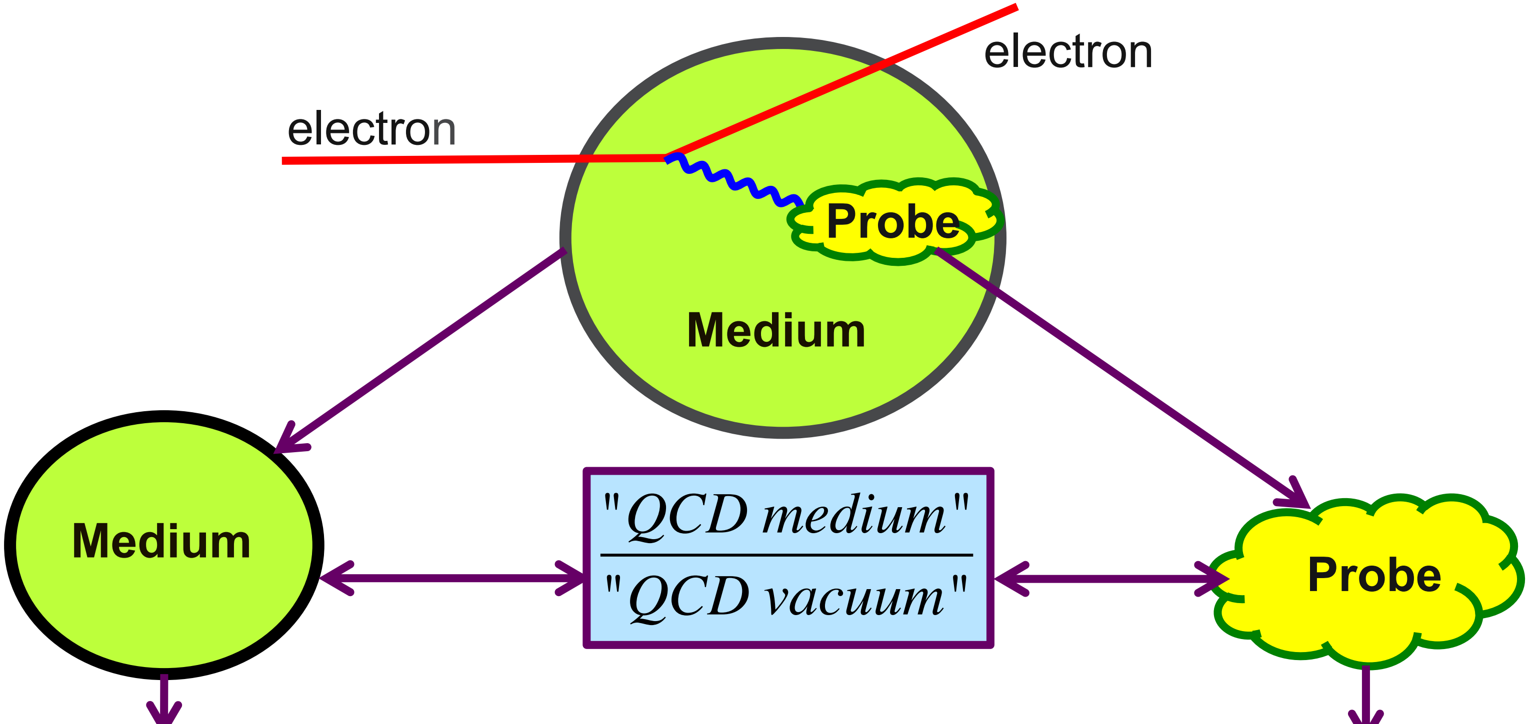
KAWTAR HAFIDI

Tuesday December 12, 2017 Transversity 2017 INFN Frascati National Laboratories

OUTLINE

- **The nucleus as a QCD laboratory**
  - Important questions to be addressed by current and future facilities
- **Partonic structure of nuclei - ^{4}He nucleus**
  - First measurements of exclusive Deep Virtual Compton Scattering (DVCS) off ^{4}He and model independent extraction of its Compton Form Factor (CFF)
- **EMC effect: Beyond inclusive measurements**
  - Generalized EMC effect
- **ALERT program at JLab: Next generation nuclear QCD measurements**
  - A first glimpse into gluon physics before the EIC
  - Tagged EMC and DVCS measurements
- **Summary and outlook**

THE NUCLEUS AS A QCD LABORATORY



- Studying the structure of the nucleus itself: 3D tomography, EMC, Short-range correlations

- Using the nucleus as a femtometer detector to study hadronization, Color Transparency,..

- **How are quarks and gluons distributed in space and momentum inside the nucleus?**
- **How are quarks and gluons distributions affected when they are embedded in nuclei compared to free nucleons?**

- How do an energetic quark interact with the nuclear medium and subsequently neutralize its color and become confined inside a hadron?

3D IMAGING

Boosted 3D Nucleon Structure

Momentum Space

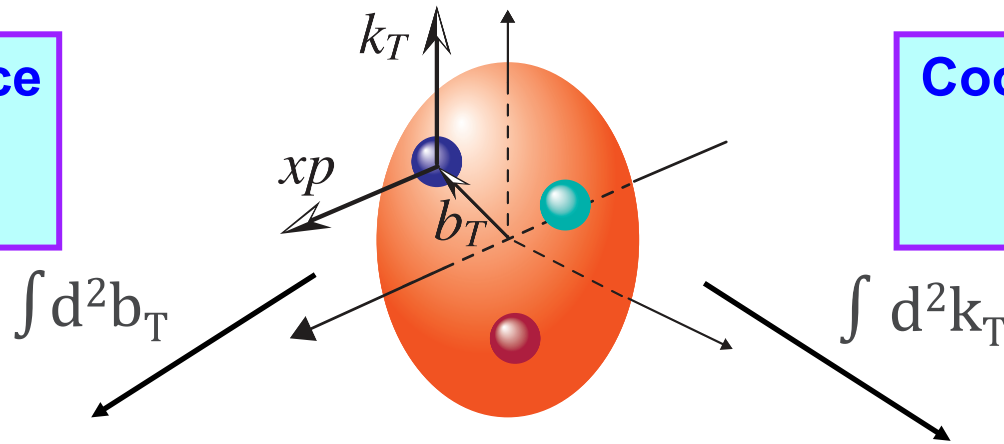
TMDs

Transverse momentum distributions

Coordinate Space

GPDs

Transverse spatial distribution

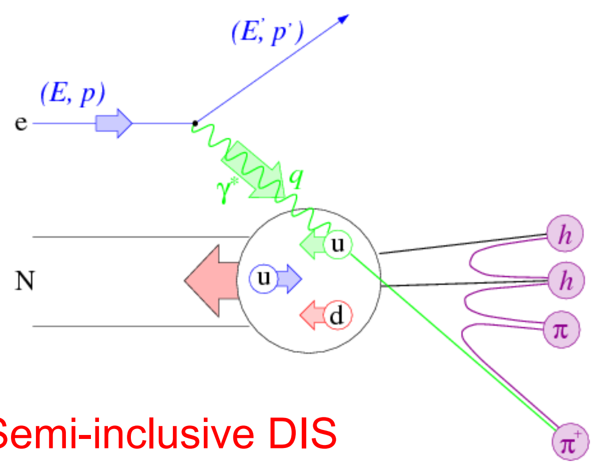


$f(x,k_T)$

Two-scales observables

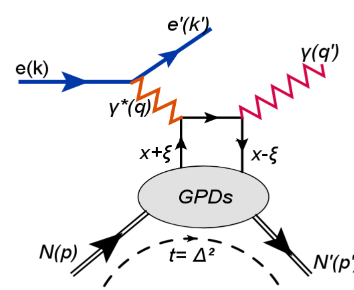
$f(x,b_T)$

3D momentum space images

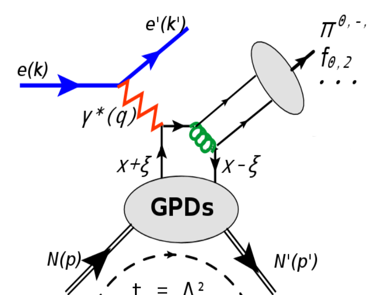


Semi-inclusive DIS

2+1D coordinate space images



Deeply Virtual Compton Scattering



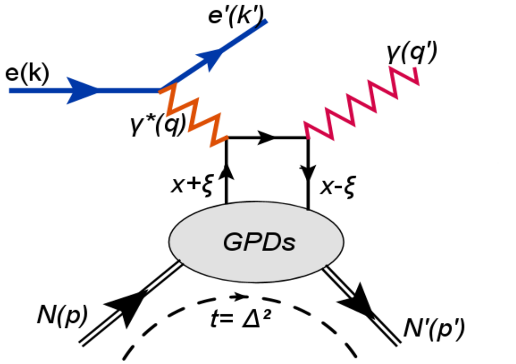
Deeply Virtual Meson Production

Exclusive DIS

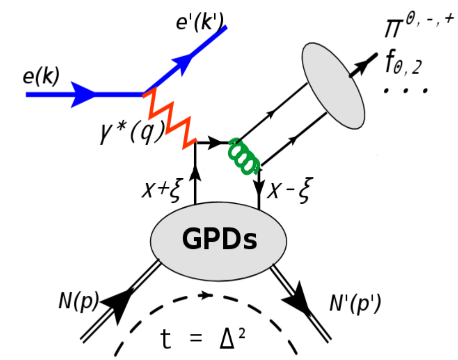
GENERALIZED PARTON DISTRIBUTIONS

D. Muller et al. Fortsch.Phys. 42 (1994) 101, X.-D. Ji Phys.Rev.Let. 78 (1997) 610, A. Radyushkin Phys.Let. B380 (1996) 417

- **GPDs encode the non perturbative structure of the nucleon**
  - $GPD(x, \xi, t)$ are three dimensional functions
  - Contains correlations between longitudinal momentum and transverse spatial position of partons
  - At leading twist, leading order DVCS is described by 1 GPD (spin=0), 4 GPDs (Spin=1⁄2) and 9 GPDs (spin=1)
  - GPDs can be translated into tomographic images of the nucleon



Deeply Virtual Compton Scattering



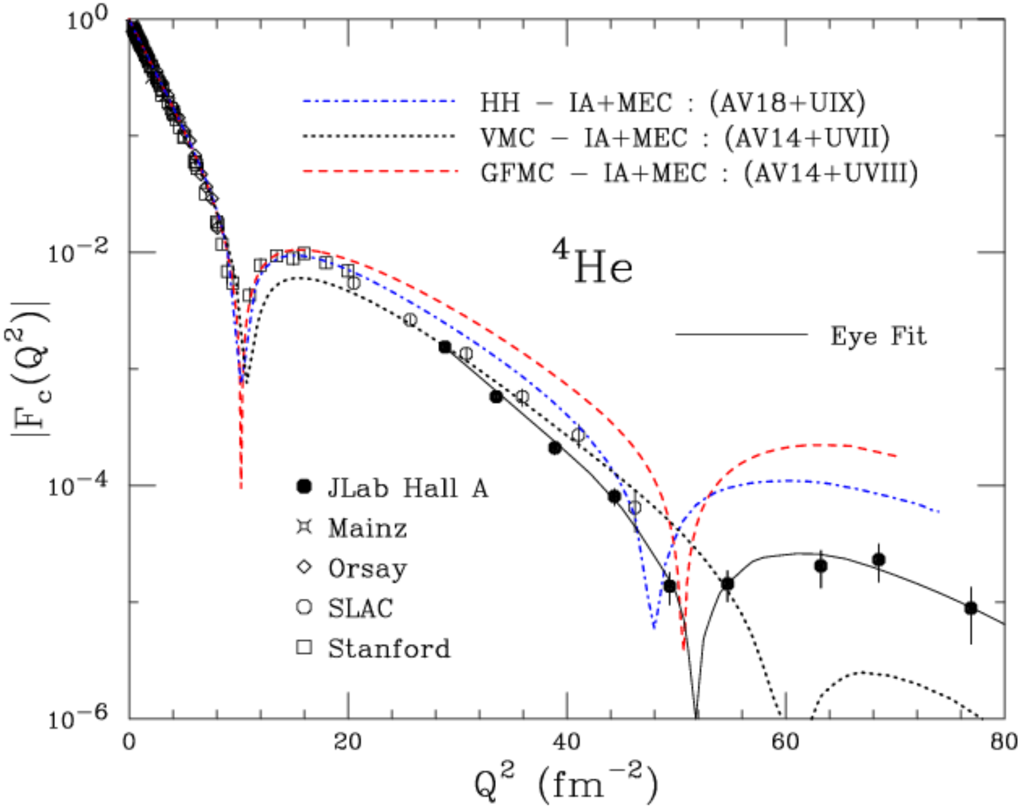
Deeply Virtual Meson Production

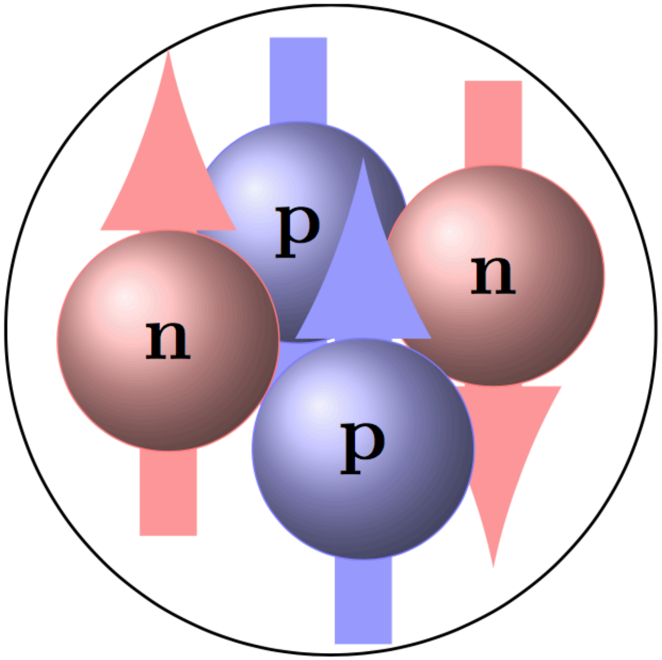
- **GPDs can be extracted from exclusive processes**
  - Using factorization gives access to GPDs
  - Only give access to Compton Form Factors (CFFs) since x (longitudinal momentum fraction of the active quark) is not accessible experimentally
  - CFFs are extracted from measurements of cross sections, beam/target/double spin asymmetries (BSA, TSA, DSA)

$$GPD(x, \xi, t)$$
$$\xi \simeq x_B/(2 - x_B)$$
$$x_B = Q^2/2\,p.q$$
$$t = (p - p')^2$$

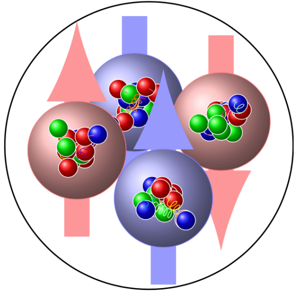
The Nucleonic Structure of the α Particle

Camsonne, et.al., PRL.112. 132503

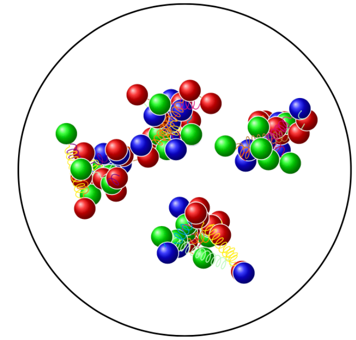




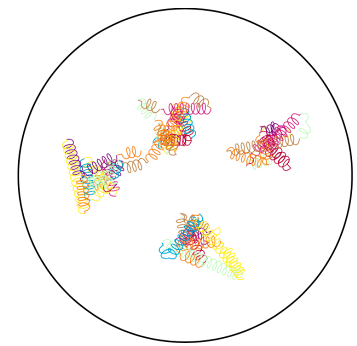
- Spin-0 → Only charge form factor
- Tightly bound system → smaller radius than ^3H and ^3He
- Diffractive Minimum → composite system of nucleons



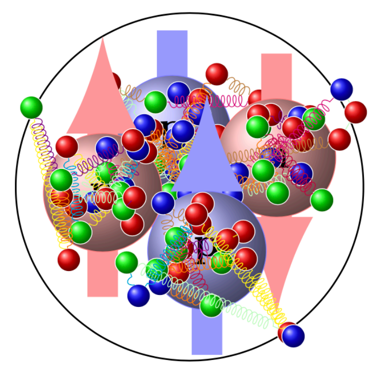
The Partonic Structure of the α Particle

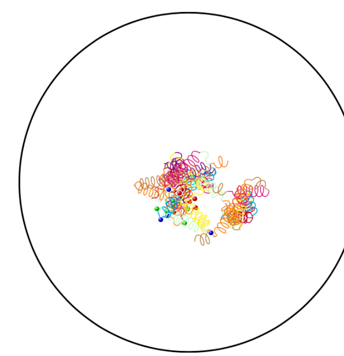


- Imagine we know nothing about nucleons and could only observe quarks...
- How would we "discover" the nucleon degrees of freedom?



- Is the quark radius of the nucleon the same as the gluon radius?
- Do they both swell?
- Do they fill the nuclear volume equally?
- Are quarks and/or gluons ever localized?





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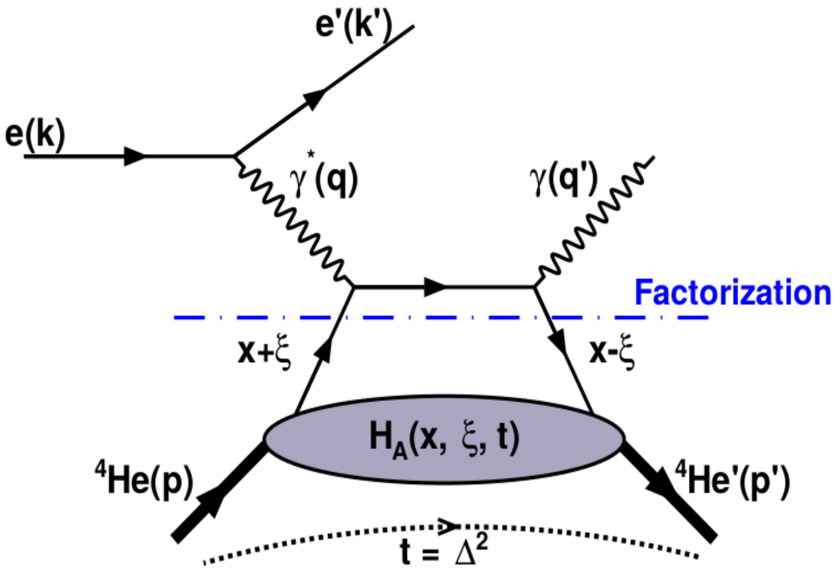
Deep Virtual Compton Scattering off ^{4}He

^{4}He is a golden nucleus

- **Simple:** exact calculations possible at the nucleon level
- **Dense:** amplifies possible nuclear modifications
- **^{4}He is spin zero** and therefore has only one chirally even GPD at leading twist



Coherent ^{4}He DVCS allows model-independent extraction of CFF

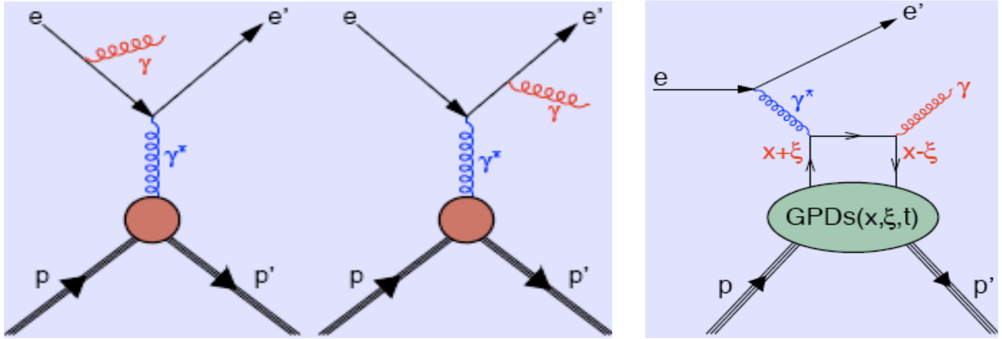
- Beam-Spin Asymmetry is sufficient to describe ^{4}He
- We detect all product of the reaction including the recoil
- Measured previously by HERMES without detection of the recoil ^{4}He

  → ambiguity over coherent/incoherent purity

Beam Spin Asymmetry and CFF

$$A_{LU}(\phi) = \frac{d\overrightarrow{\sigma}(\phi) - d\overleftarrow{\sigma}(\phi)}{d\overrightarrow{\sigma}(\phi) + d\overleftarrow{\sigma}(\phi)}$$

$$|\tau|^2 = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}^* \tau_{DVCS} + \tau_{DVCS}^* \tau_{BH}$$

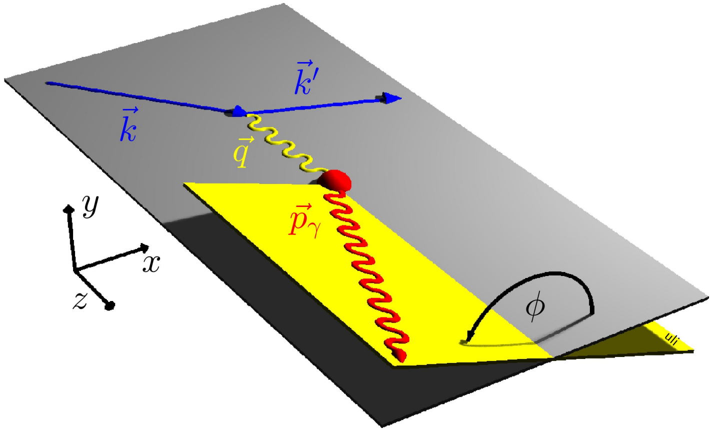


Leading order in α_s and neglecting DVCS and interference part in denominator

$$A_{LU}(\phi) \propto \Im m\{C^I\} \sin\phi$$

$$C^I = F_1 \mathcal{H} + \frac{x_B}{2 - x_B}(F_1 + F_2)\tilde{\mathcal{H}} - \frac{\Delta^2}{4M^2} F_2 \mathcal{E}$$ **nucleon**

$$C^I = \mathcal{H} \quad F$$ **^{4}He nucleus**



$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\, \Im}{\alpha_1(\phi) + \alpha_2(\phi)\, \Re + \alpha_3(\phi)(\Re^2 + \Im^2)}$$

$$\Im = \Im m\{\mathcal{H}_{^4He}\}$$

$$\Re = \Re e\{\mathcal{H}_{^4He}\}$$

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JLab E08-024 “Eg6” experiment

Exclusive coherent beam spin asymmetry

$$e + {}^4He \rightarrow e + {}^4He + \gamma$$

Electron beam polarization = 83%

Experimental challenges

- Detecting very forward photons
- Detecting low energy α

Radial Time Projection Chamber

- Small TPC around the target

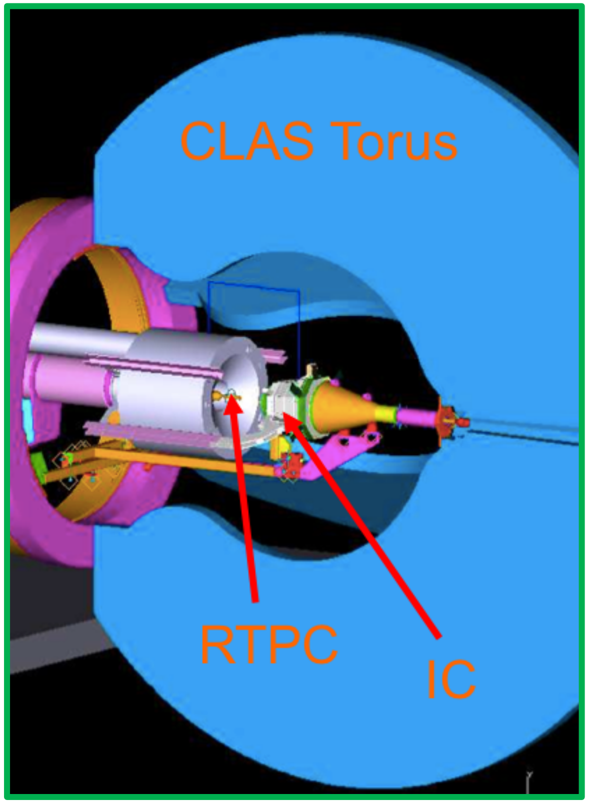
Inner Calorimeter

- Very forward electromagnetic calorimeter

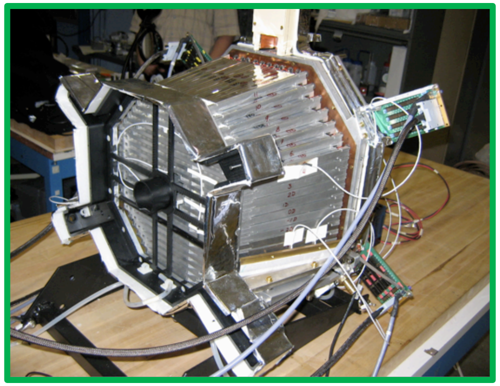
Solenoid

- Shields the detectors from Møller electrons
- Enables tracking in the RTPC

^{4}He gas target at 6 atm



Inner Calorimeter



Radial Time Projection Chamber (RTPC)

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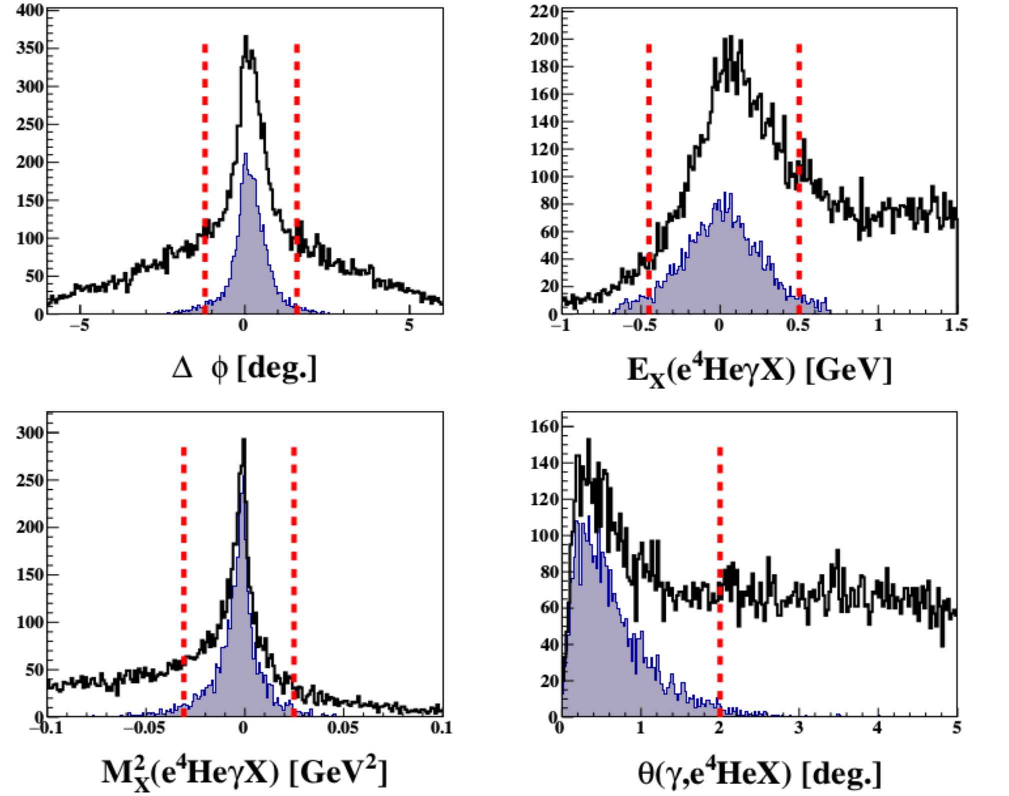
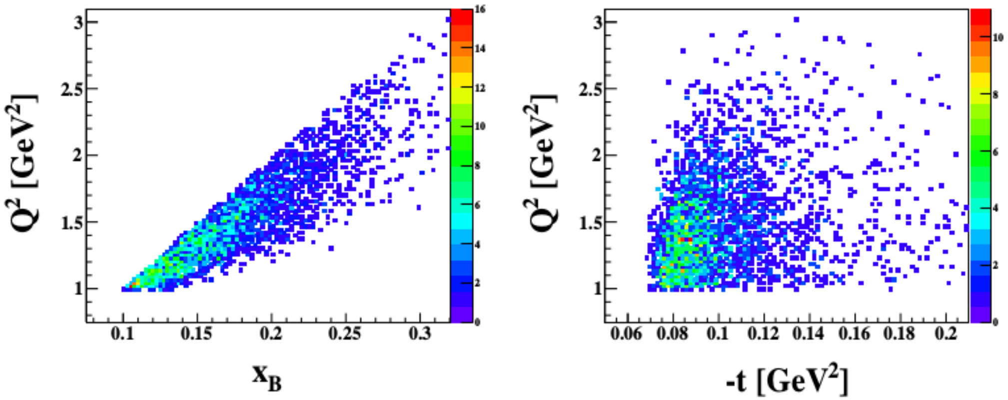
COHERENT DVCS SELECTION

We select coherent events with

- Only one good electron in CLAS
- At least one high-energy photon ($E\gamma > 2$ GeV) in IC
- Only one ^4He in RTPC with p ~ 250 - 400 MeV
- The interaction occurs at the partonic level and applicability of the factorization on the DVCS handbag diagram ($Q^2 > 1$ GeV^2)
- π^0 background subtraction based on data and simulation (2 - 4% contamination)

Coplanarity angle between the (γ,γ^*) and $(\gamma^*,{}^4He')$ planes



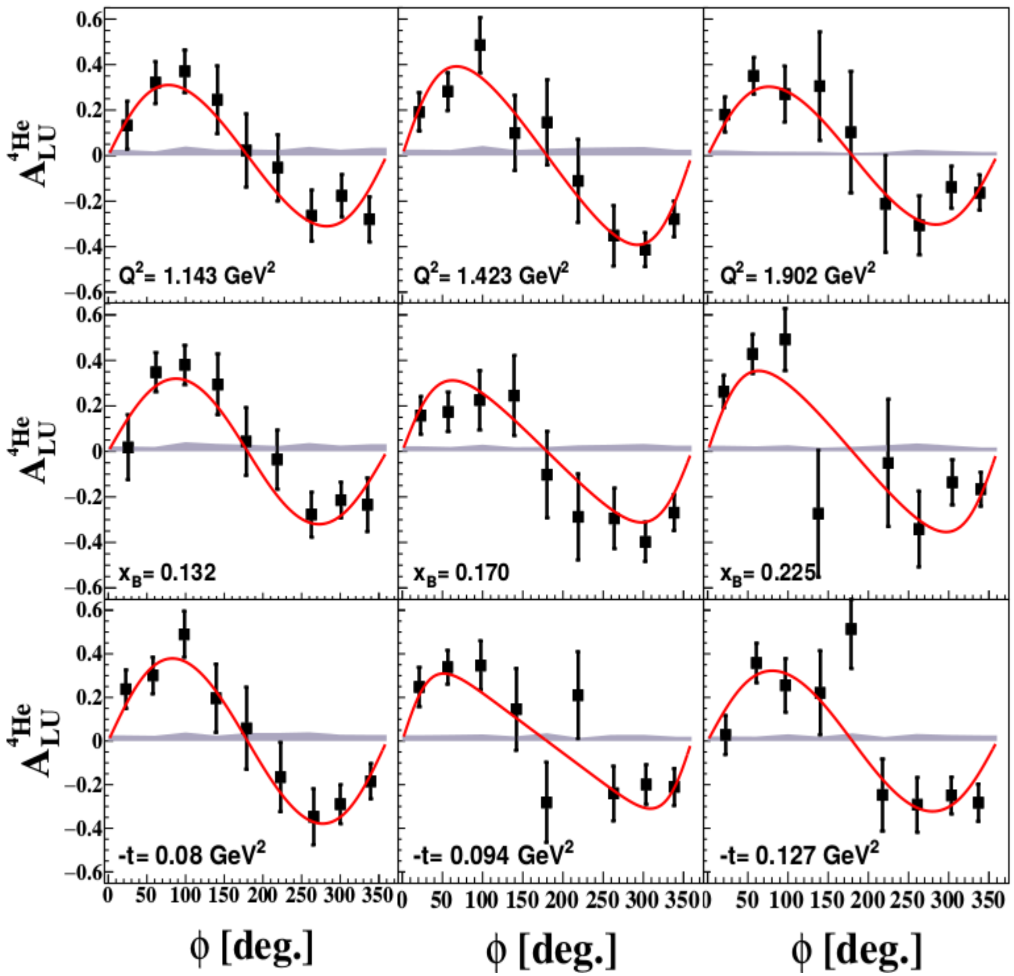


- In Black, coherent events before all exclusivity cuts
- In shaded gray, coherent DVCS events which pass all the other exclusivity cuts except the one plotted

EXTRACTION OF THE BEAM SPIN ASYMMETRY

$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

M. Hattawy et al. PRL 119 (2017) 202004

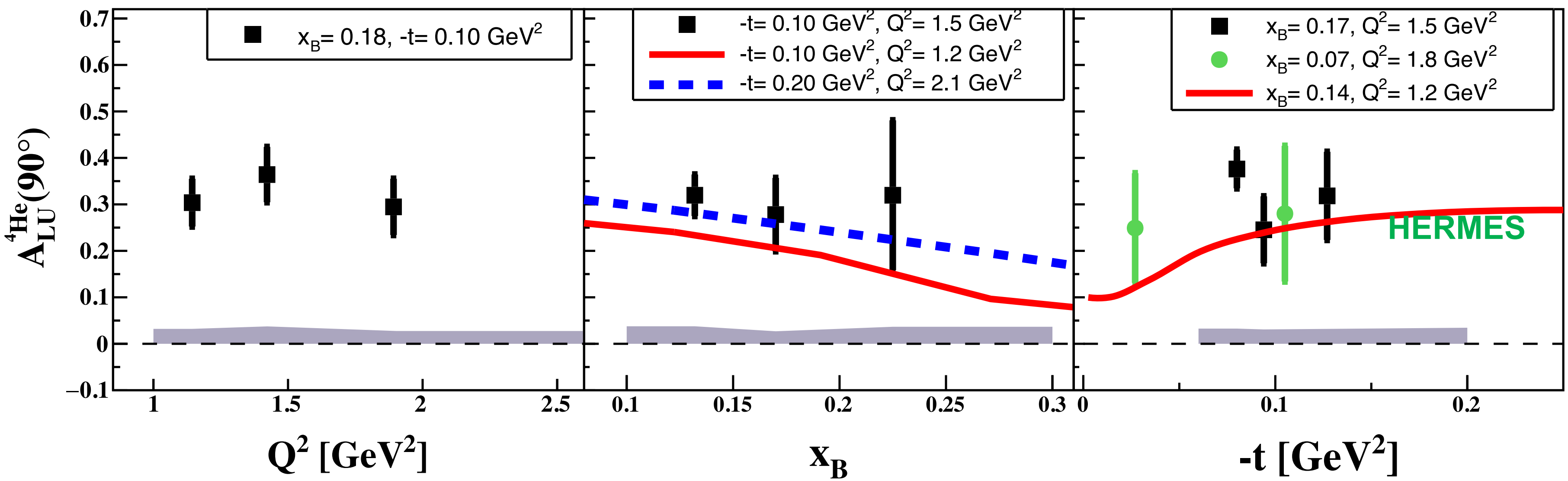


- Statistics dominate uncertainties
- Systematic uncertainties (~10%) is dominated by exclusivity cuts

EXTRACTION OF THE BEAM SPIN ASYMMETRY

S. Liuti and S. K. Taneja, PRC 72 (2005) 032201
HERMES: A. Airapetian, et al., PRC 81, 035202 (2010)

- Large asymmetries
- Limited statistics and kinematical coverage



The Liuti et al. model accounts for the effect of the nucleon virtuality (off-shellness) on the quark distribution

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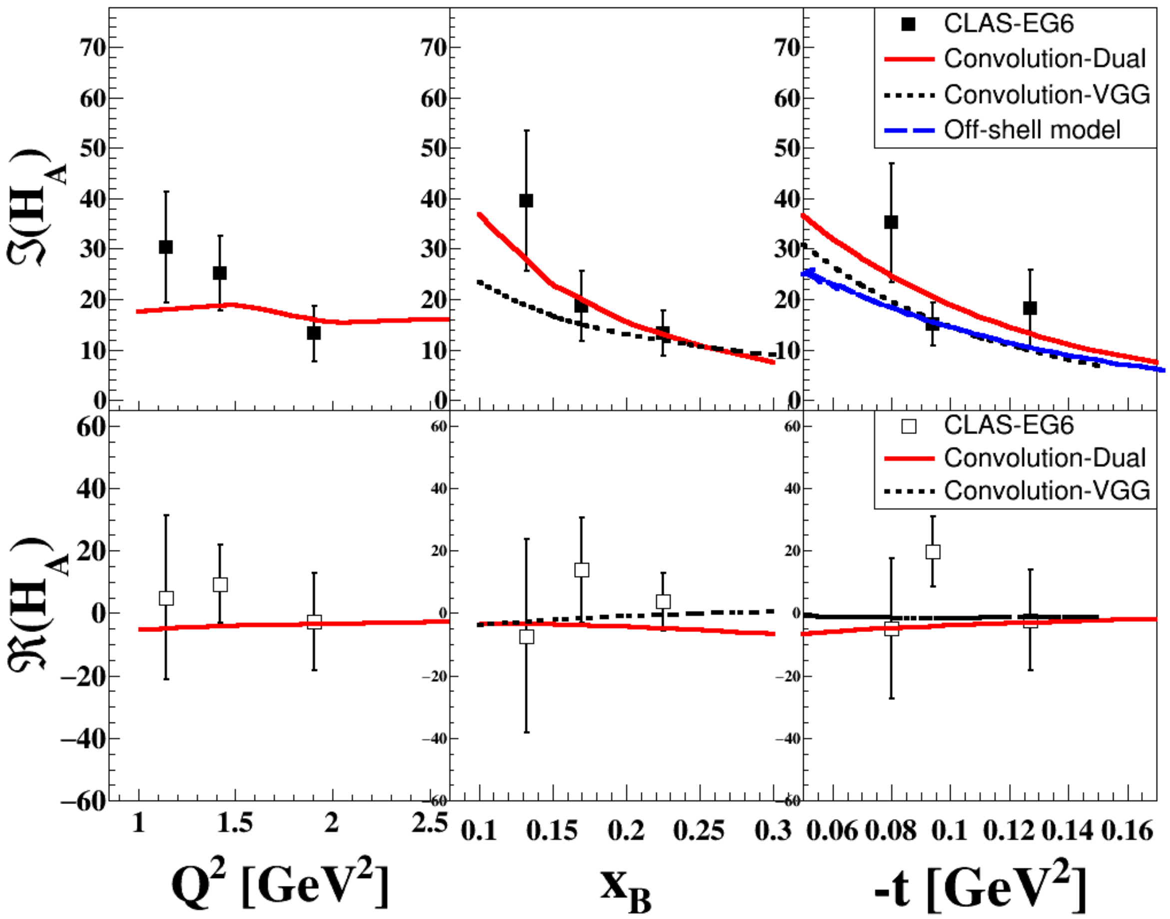
EXTRACTION OF THE COMPTON FORM FACTOR

First ever experimental extraction of the real and imaginary part of ^{4}He CFF

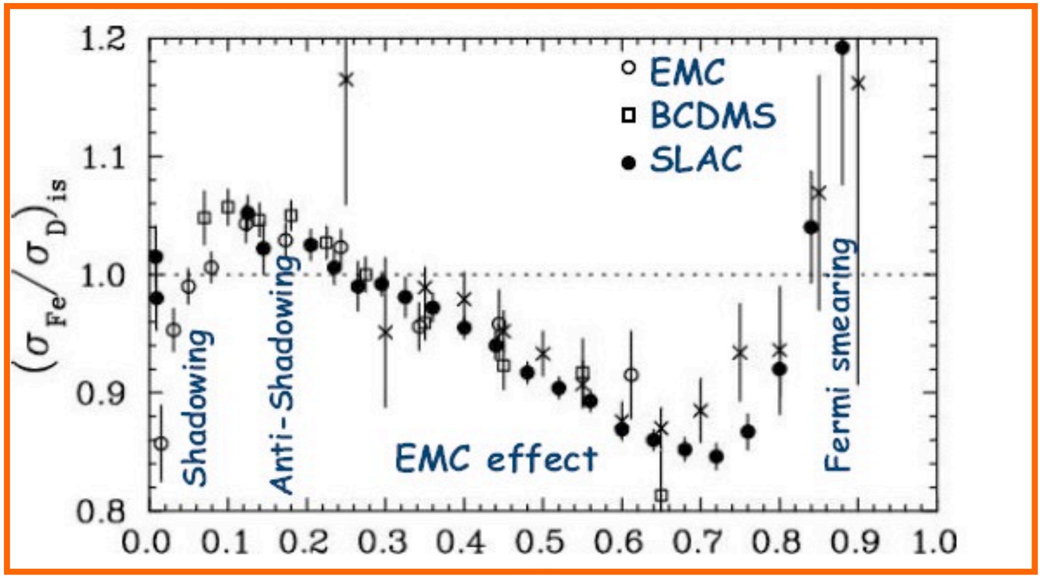


- **Convolution Dual:** V. Guzey, PRC 78, 025211 (2008)
- **Convolution-VGG**: M. Guidal, M. V. Polyakov, A. V. Radyushkin and M. Vanderhaeghen, PRD 72, 054013 (2005)
- **Off-shell model:** J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein and K. Kathuria, PRC 88, 065206 (2013)

EMC EFFECT:
BEYOND INCLUSIVE MEASUREMENTS

QUARK DISTRIBUTION IN NUCLEI

J.J. Aubert et al., Phys. Lett. B123, 275 (1983)



$$F_2(x) \sim \sum_f e_f^2 q_f(x) \quad f = u, d, s$$

Because
nuclear binding (MeV) << energy scale of the probe, nucleon excitations (GeV)

One expects that

$$F_2^A(x) \approx Z F_2^p(x) + N F_2^n(x)$$

is insensitive to the details of the nuclear structure beyond Fermi motion

- Quarks in nuclei behave differently and in a non trivial way than quarks in a free nucleon
- EMC effect fundamentally challenged our understanding of nuclei
- Specific origins of the modification are not clearly identified yet

MODELS OF THE EMC EFFECT

EMC - Everyone's Model is Cool - G. Miller

Nucleon Structure is modified in the nuclear QCD medium

- Nucleon "swelling"
- Dynamical rescaling
- Multiquark clusters (6q, 9q "bags")

Nucleon Structure is modified due to Hadronic effects

- More detailed binding calculations: Fermi motion + binding+ N-N correlations
- Nuclear pions

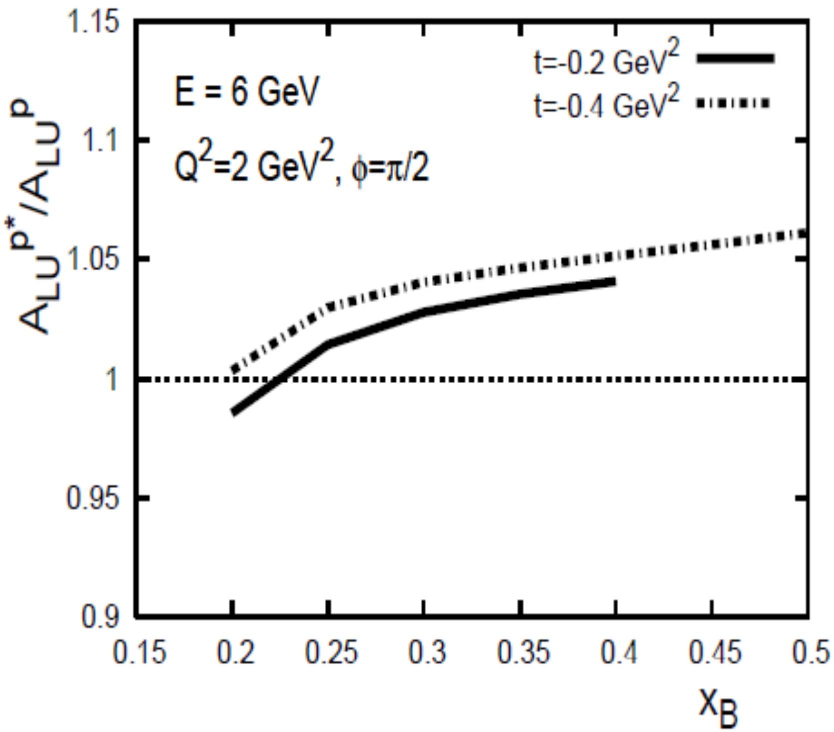
Use DVCS for in-medium hadron tomography

- DVCS on bound nucleons - Off forward EMC effect

Theoretical Prediction for Generalized EMC effect

On-shell calculations:

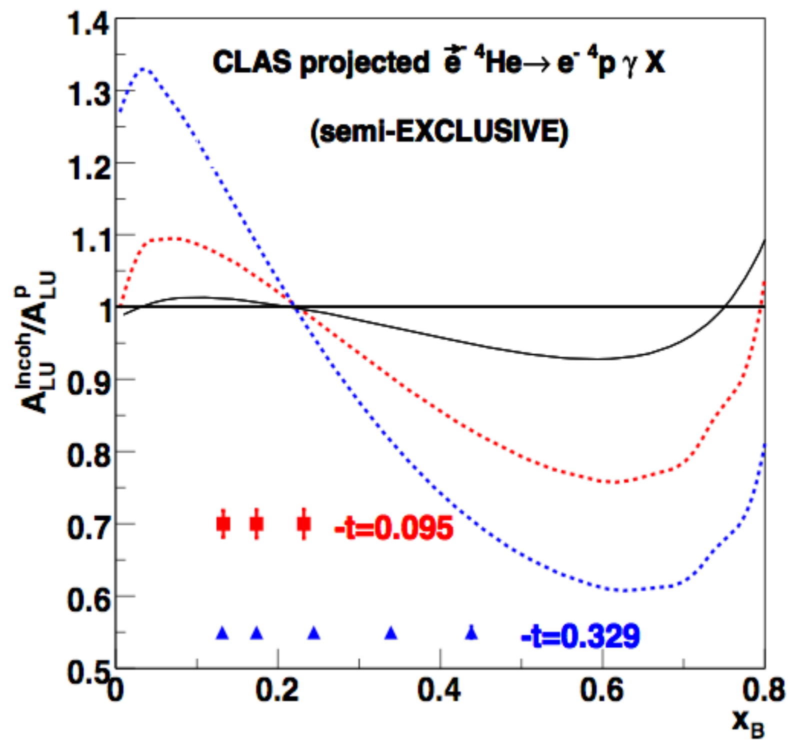
Impulse approximation and modified form factors



[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

Off-shell calculations:

Bound nucleons + nuclear binding effects



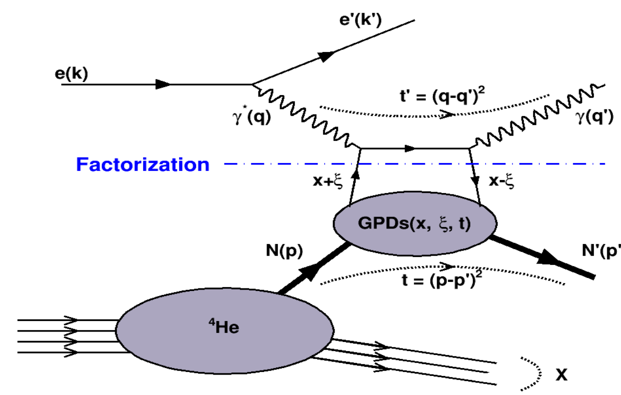
[S. Liuti, K.Taneja, PRC 72 (2005) 034902]

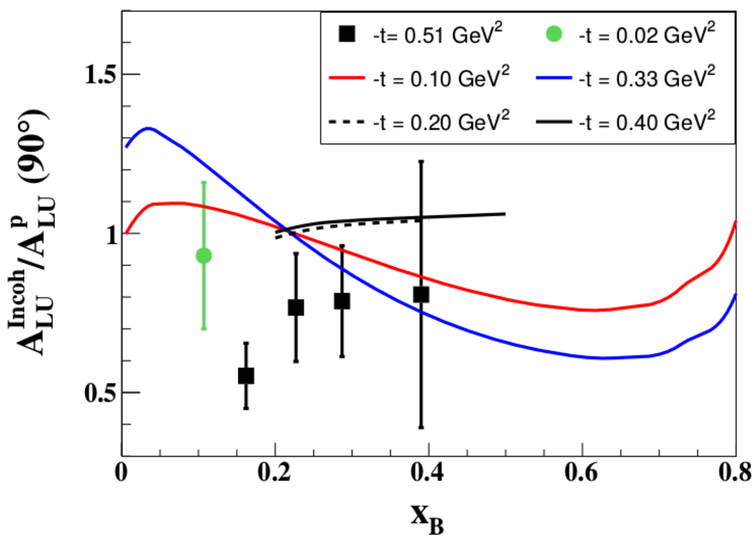
Incoherent DVCS off ^{4}He

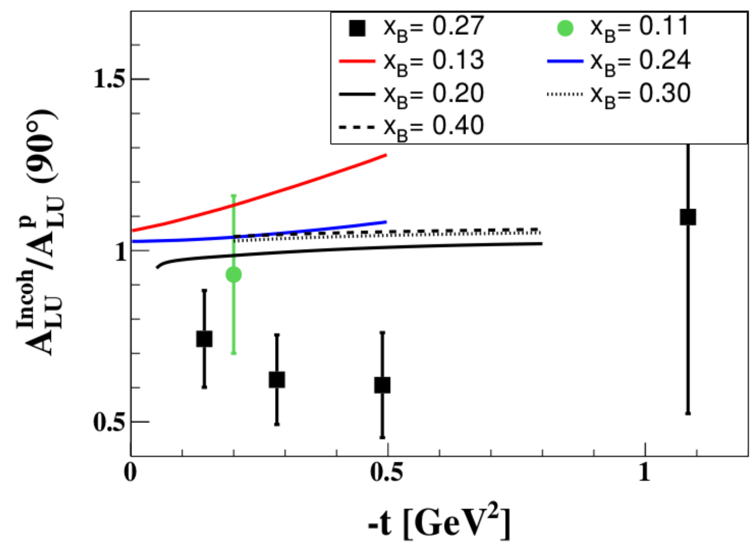
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

We select events with :

- Only one good electron in CLAS
- At least one high-energy photon (Eγ > 2 GeV)
- Only one proton in CLAS
- π^0 background subtraction based on data and simulation (8-11% contamination)





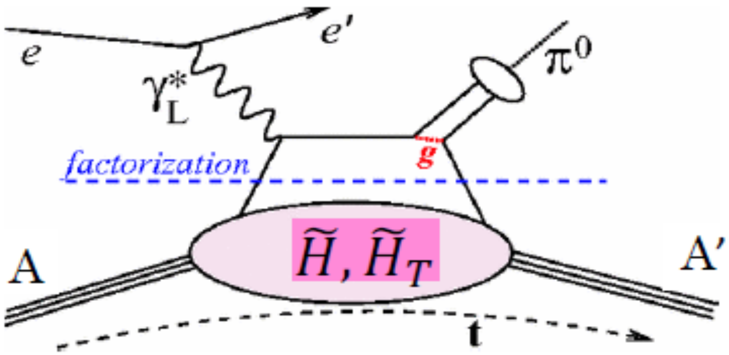


- Unconstrained initial state virtual photon-nucleon CM energy unknown due to Fermi motion
- Off-forward EMC Effect calculated using denominator from different experiment introduces extra systematics
- Interesting results, but, inconclusive interpretation due to possible final state interaction

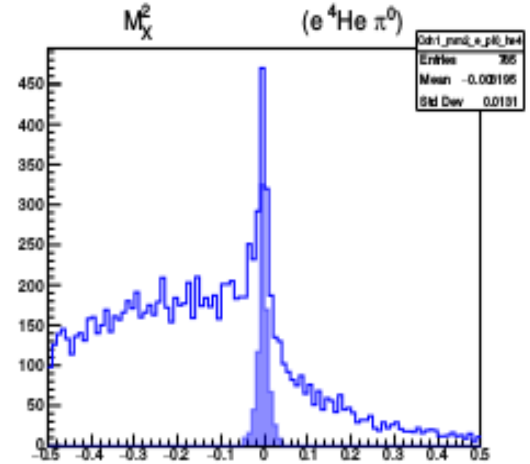
Ongoing coherent/incoherent π^0 production off ^{4}He

Grad students: Frank Cao and Bayram Torayev

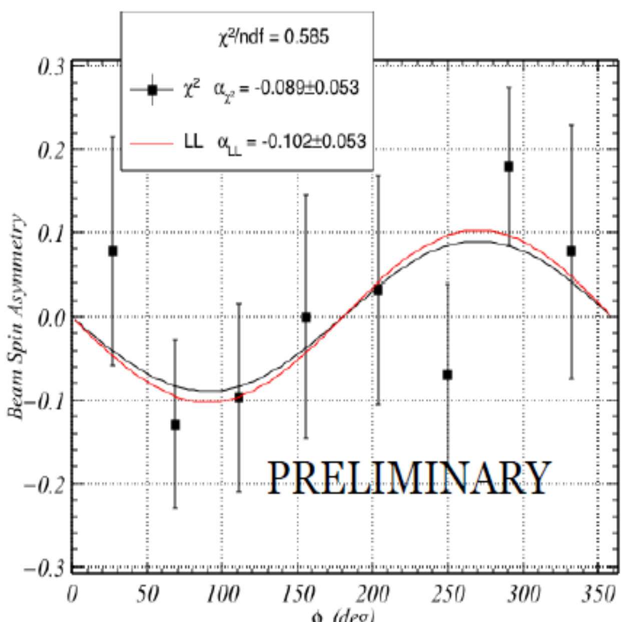
$$A_{LU} \sim \sigma_{LT'} \sim \widetilde{H} * \widetilde{H}_T$$



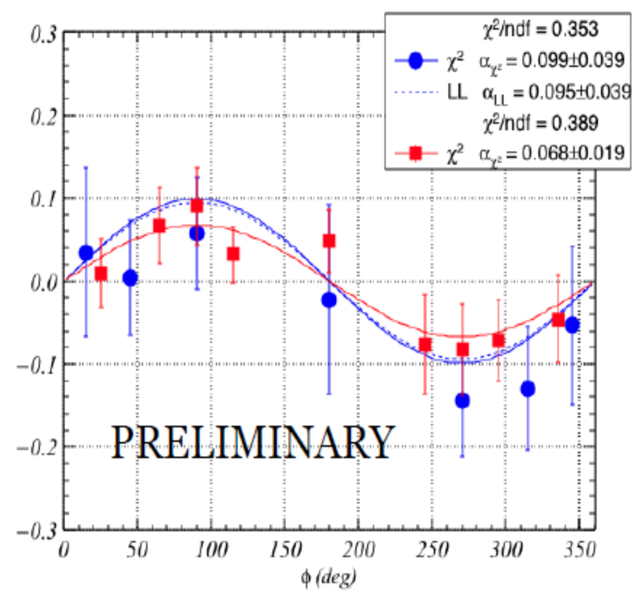
chiral-odd quark helicity-flip GPDs



$$\vec{e}\,{}^4He \rightarrow e'\,{}^4He'\pi^0$$



$$\vec{e}\,{}^4He \rightarrow e' N \pi^0 X$$



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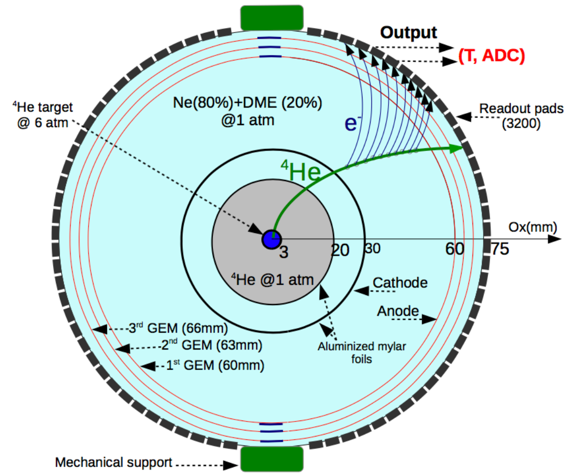
A LOW ENERGY RECOIL TRACKER

“ALERT” PROGRAM
AT JEFFERSON LAB 12 GEV

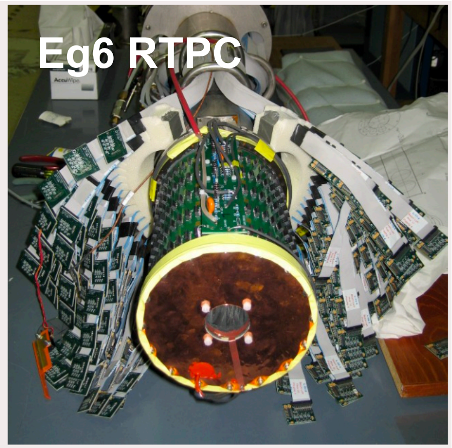
BETTER 3D TOMOGRAPHY AND EMC MEASUREMENTS

LIMITATIONS OF EG6 MEASUREMENTS

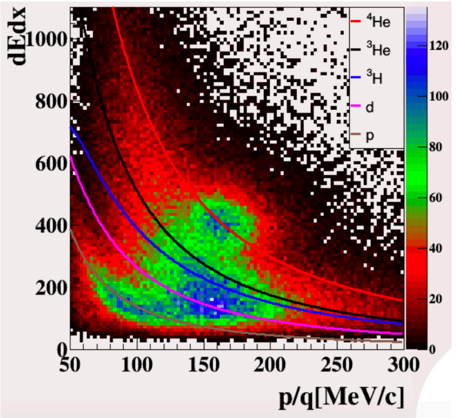


RTPC has great capabilities for slow recoil detection

- We built it and used it for ^{4}He coherent DVCS in CLAS - Dupre et al. NIM 2017
- However particle identification is limited
  - Even with improvements it cannot differentiate between ^{3}He and ^{3}H
- The data acquisition rate was the limiting factor for the luminosity of this experiment
- Because of pile-up, the time resolution (few hundreds ns) and long drift time (few µs) severely limit its performance at high luminosity



PID with RTPC



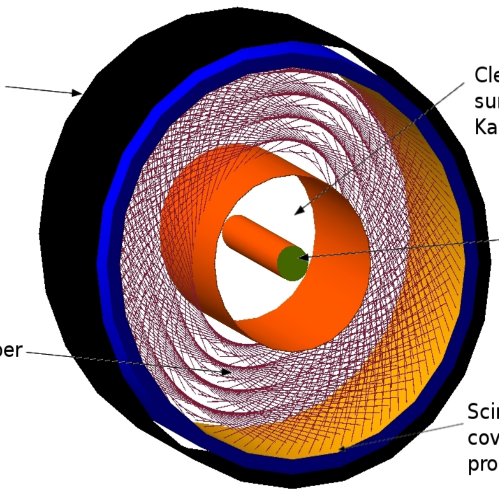
We came to the conclusion that we need another detector

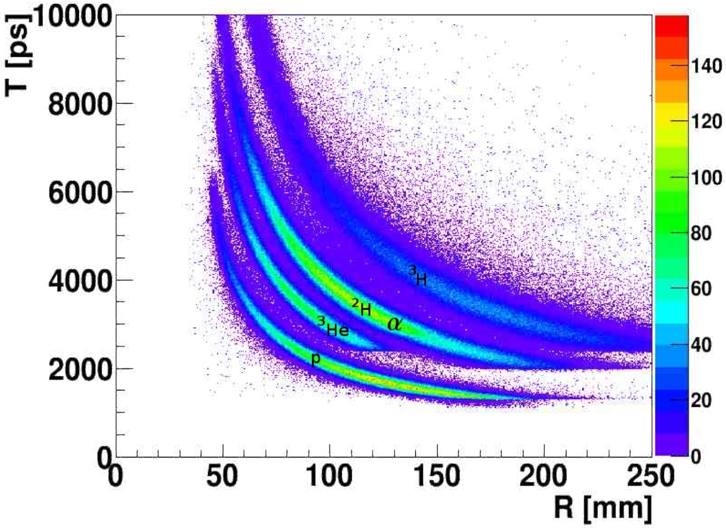
- To use fully CLAS12 luminosity capabilities
- To perform tagged measurements

ALERT - A LOW ENERGY RECOIL TRACKER

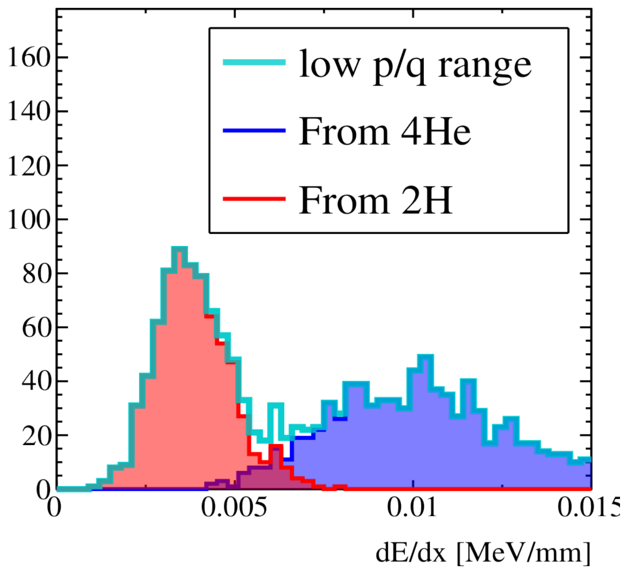
- Capabilities for very low momentum detection
  - As low as 70 MeV/c for protons and 240 MeV/c for ^{4}He
  - Forward and backward detections (25° from the beam)
- Capabilities to handle high rates
  - Small distance between wires leads to short drift time <250 ns (5 μs in a similar RTPC)
  - This translates into 20× less accidental hits
  - Will be integrated in the trigger for significantly reduced DAQ rate
- Improved PID
  - Like in the RTPC, we get dE/dx measurements
  - TOF information

Hyperbolic drift chamber
Stereo angles gives the z-axis resolution





Reconstructed radius in the drift chamber



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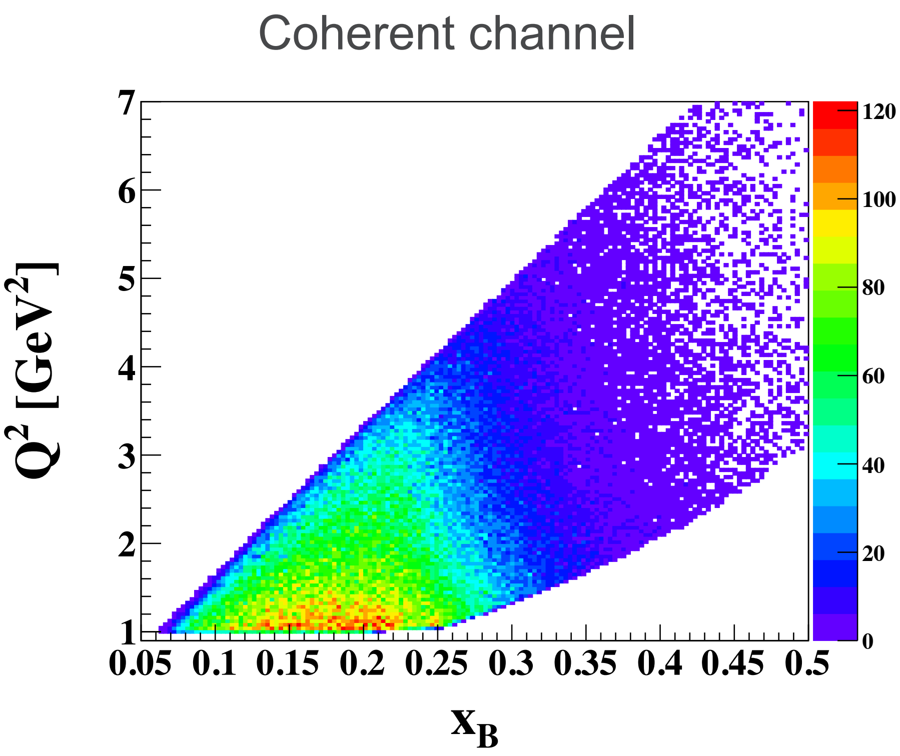
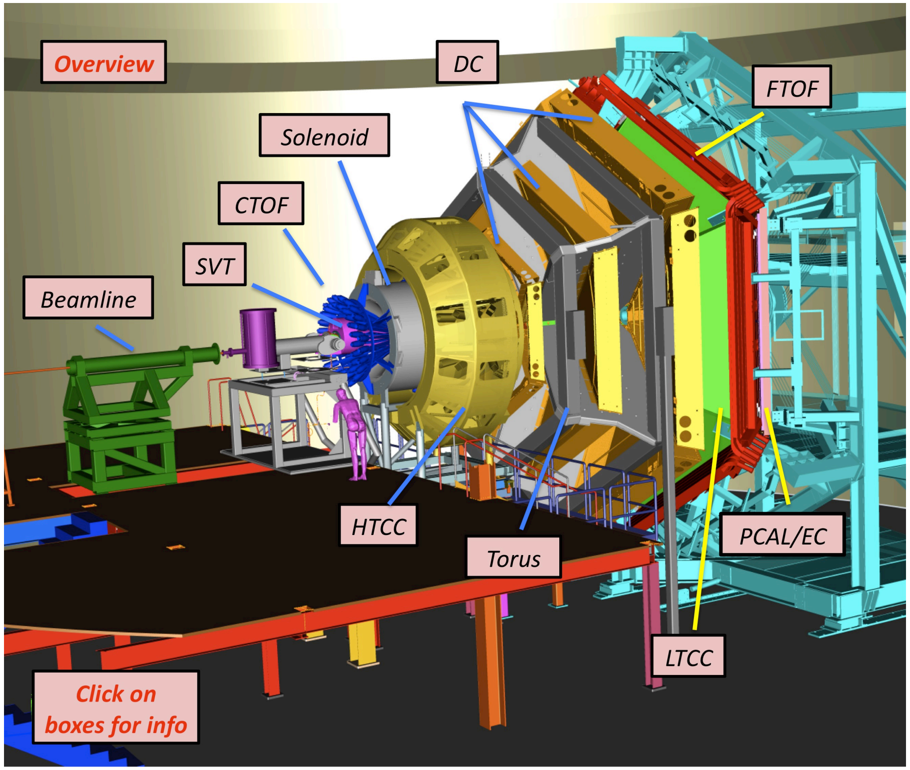
CLAS12



Coherent channel
120
100
80
60
40
20
0
7
6
5
4
3
2
1
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Q^2 [GeV^2]
x_B

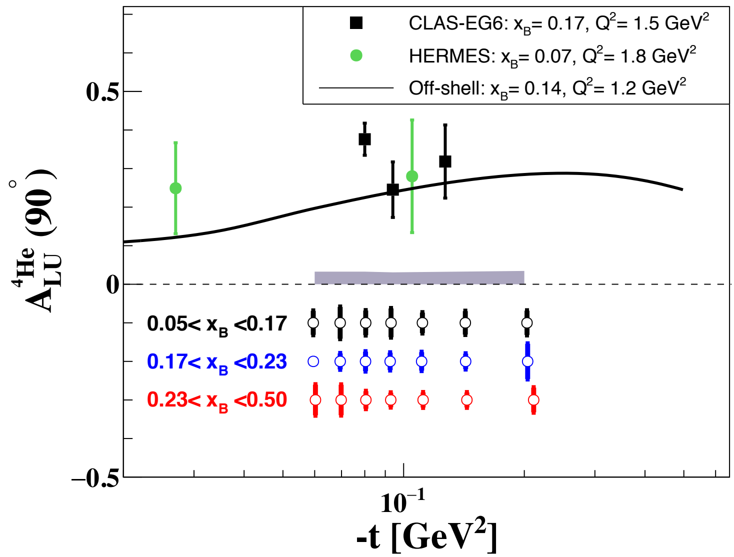


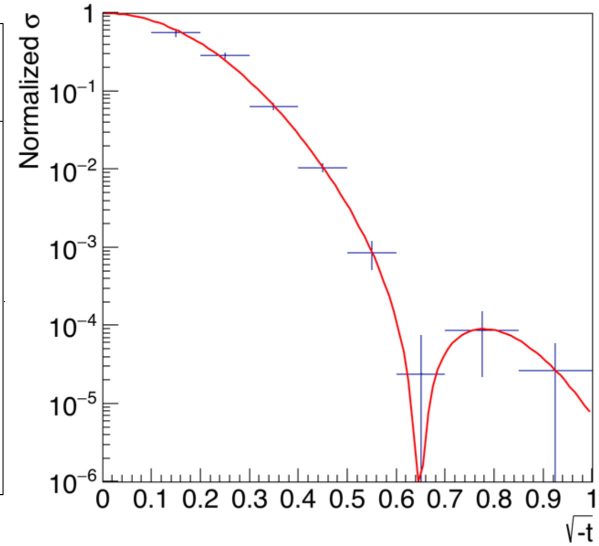
Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC
Click on boxes for info

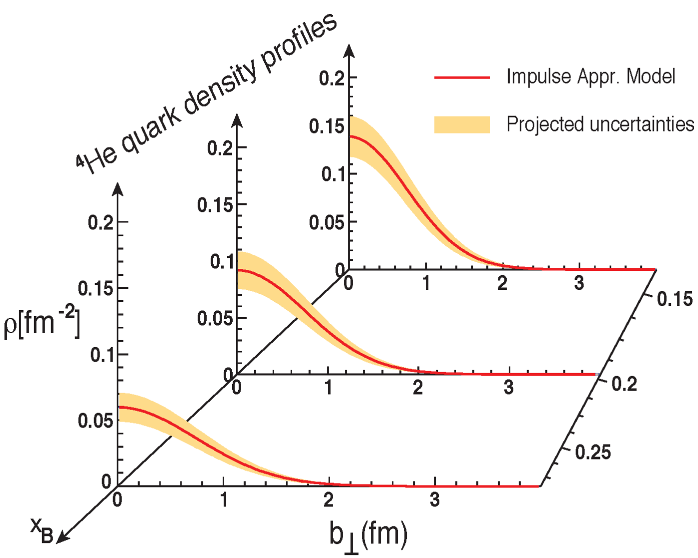
3D TOMOGRAPHY OF NUCLEI

Deep Virtual Phi production

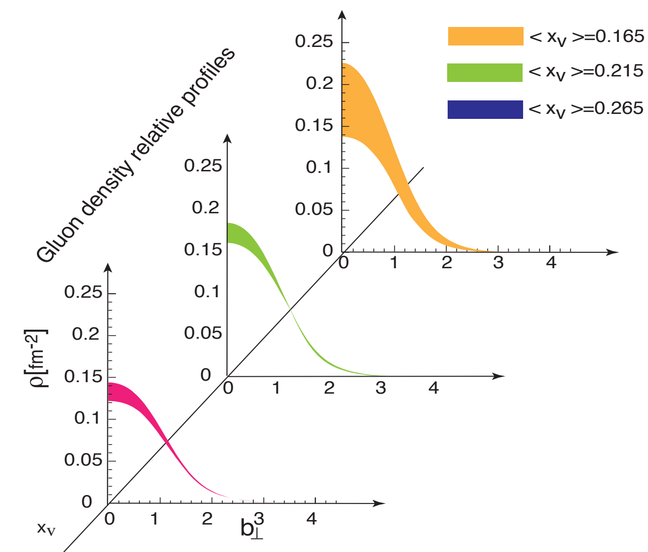
Deep Virtual Compton Scattering



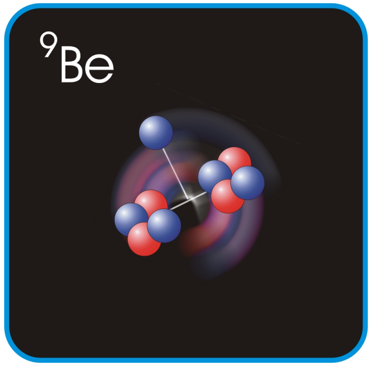




- Toward a complete tomography of ^{4}He
- Unique opportunity to compare gluon radius to charge radius in nuclei
- Provide a glimpse into gluon physics before the EIC

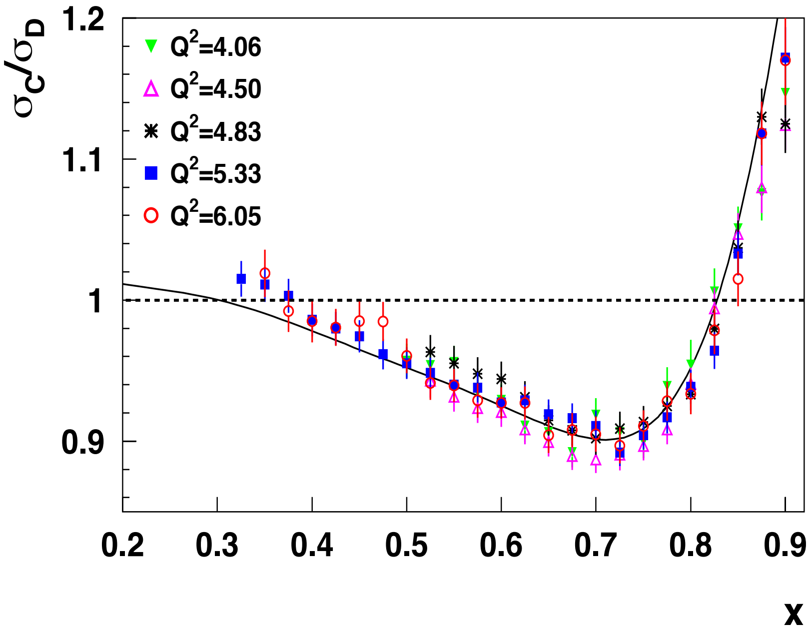


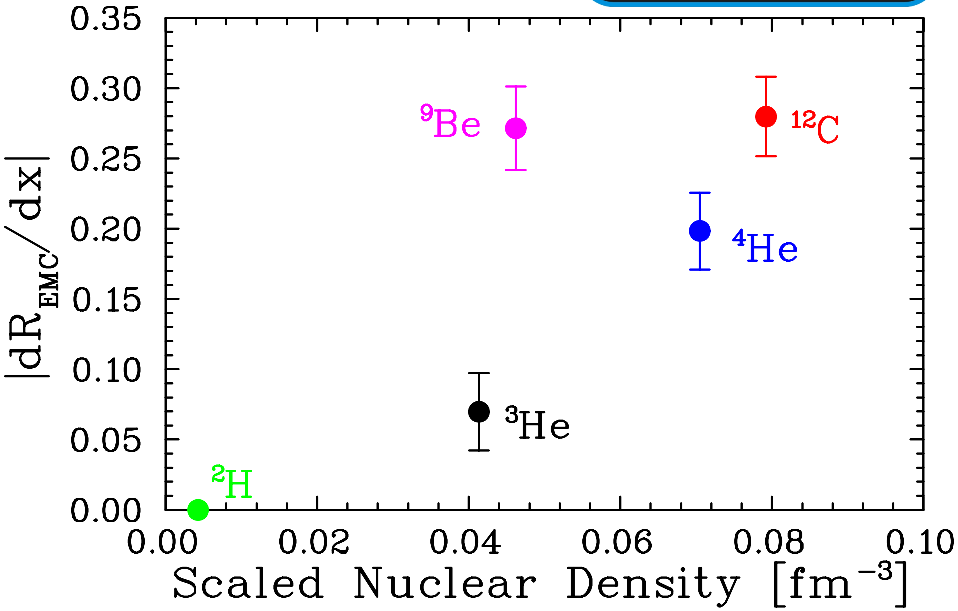
NEW INSIGHTS ON THE EMC EFFECT



J. Seely et al., PRL 2009

J. Arrington et al. PRC 2012

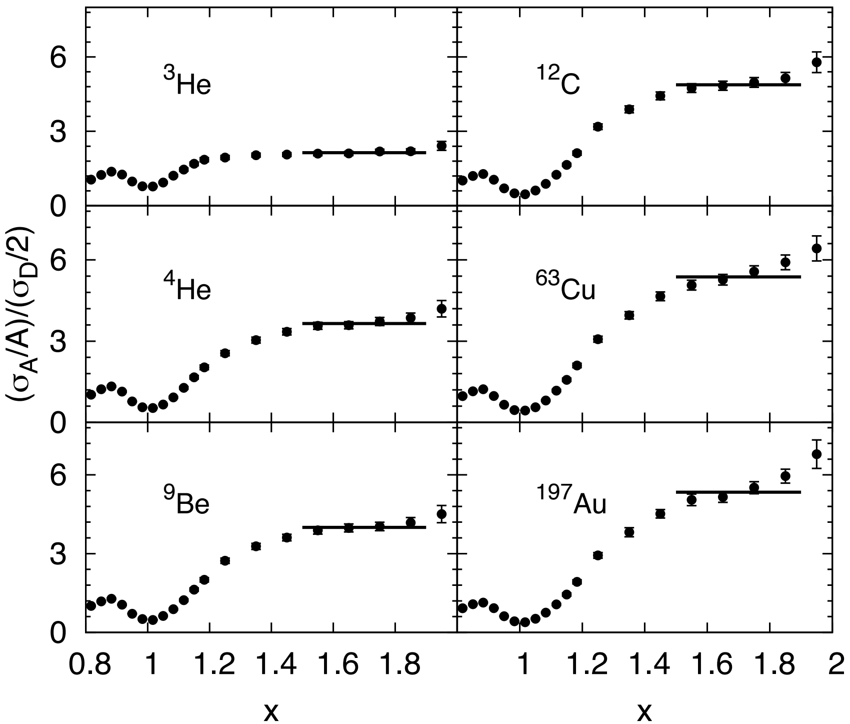




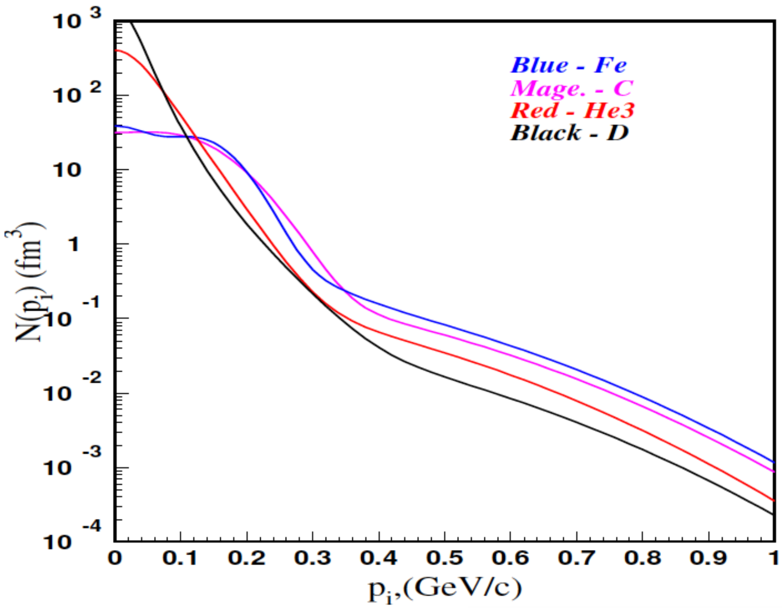
- Rules out previously-assumed scaling with $A^{-1/3}$ or average density
- Suggests ‘local density’ is important, two-body effects may generate the EMC effect

Short Range Correlations (SRC) via (e,e') ratios

N. Fomin et al., PRL. **108** (2012)



C. Atti and S. Simula, PRC 1996



- ❑ Magnitude of the plateaus proportional to the probability for finding pairs in the nucleus
- ❑ Consistent with the idea that the functional form of these pairs is the same in all nuclei

We know that

- ~25% of nucleons in medium nuclei have p > 300 MeV/c
- More than 90% of these nucleons have a correlated partner nucleon
- These NN Short Range Correlated (SRC) pairs are dominated by np pairs

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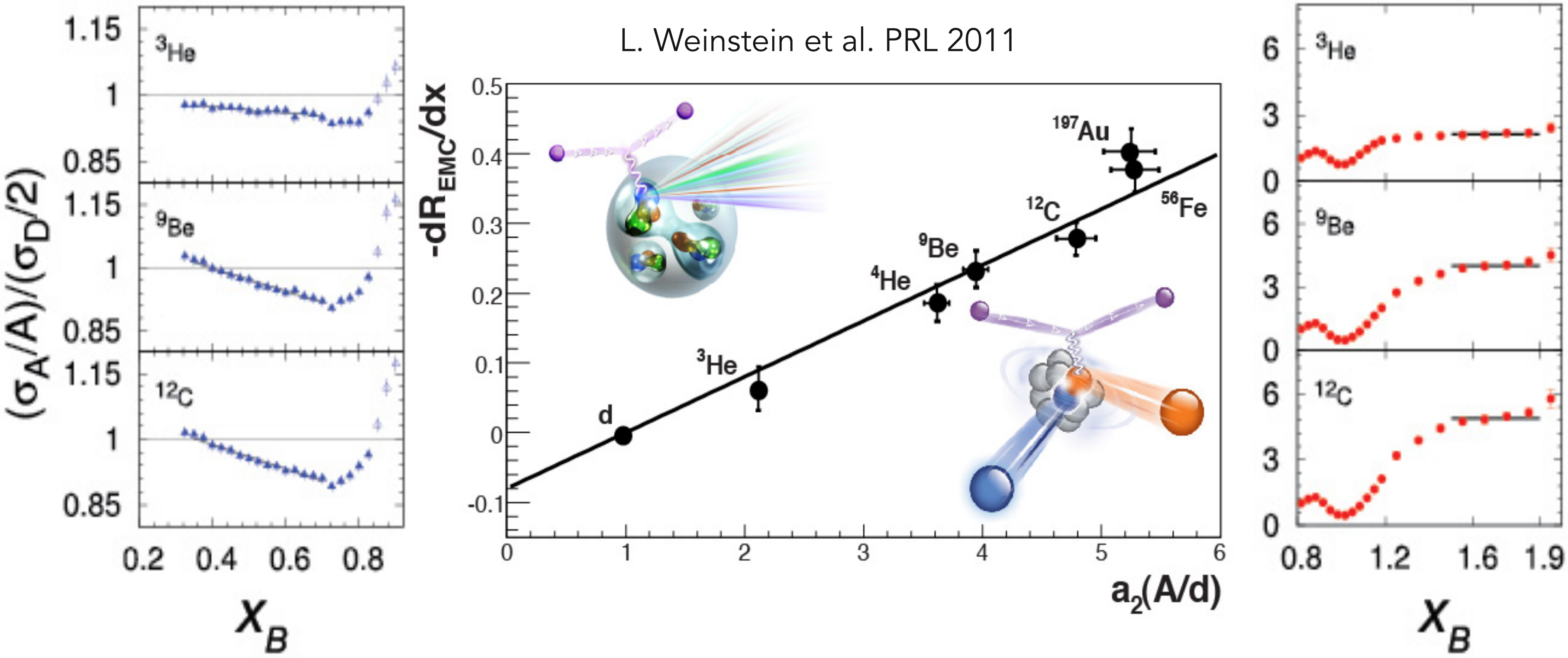
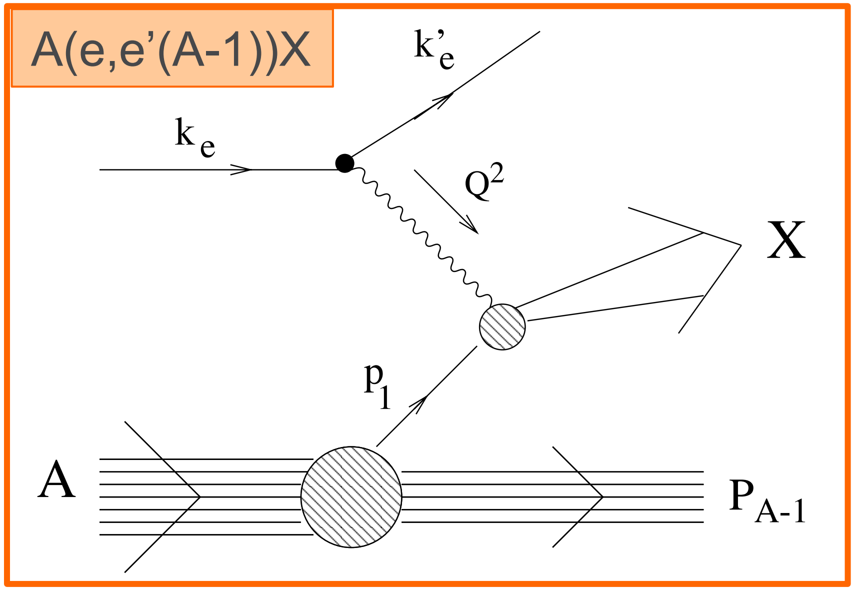
Experimental connection between EMC and SRC



- ❑ The data show that EMC effect slopes are proportional to the SRC plateaus
- ❑ EMC effect and SRCs might be both a consequence of the local QCD effects within the nucleus

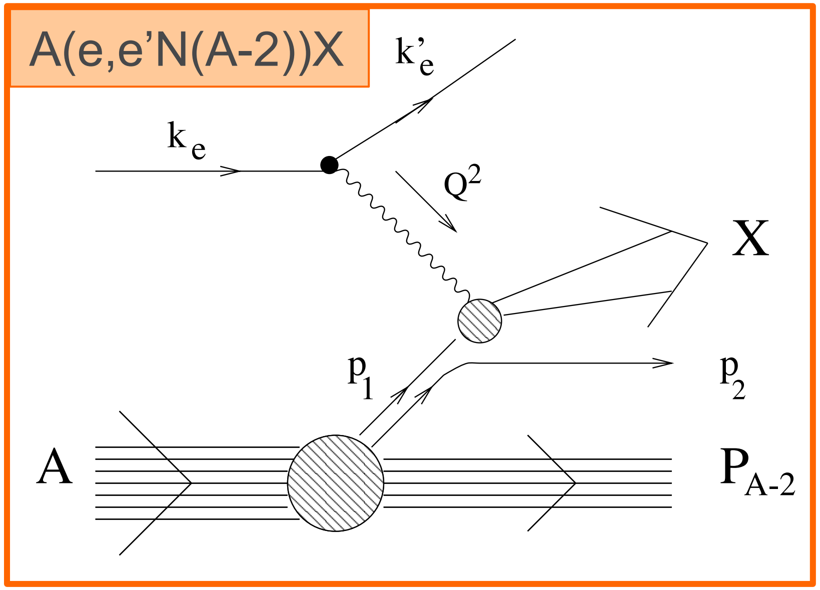
DO NUCLEONS WITH DIFFERENT BINDING ENERGIES CONTRIBUTE DIFFERENTLY TO THE EMC EFFECT?

DIS on weakly bound nucleons



- DIS on low momentum nucleon
- Detect scattered electron and low momentum, low excitation energy (A-1) nucleus

DIS on deeply bound nucleons



- DIS on high momentum nucleon
- Detect scattered electron, the high momentum nucleon from the pair and low momentum, low excitation energy (A-2) nucleus

WHY TAGGED MEASUREMENTS?

EMC effect remains a mystery

- To Solve it we need new observables

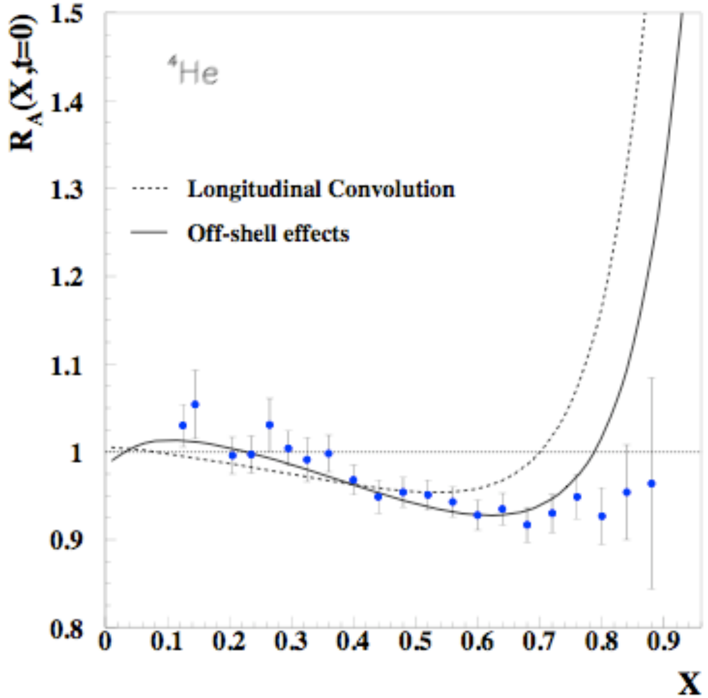
Tagged measurements give access to virtuality

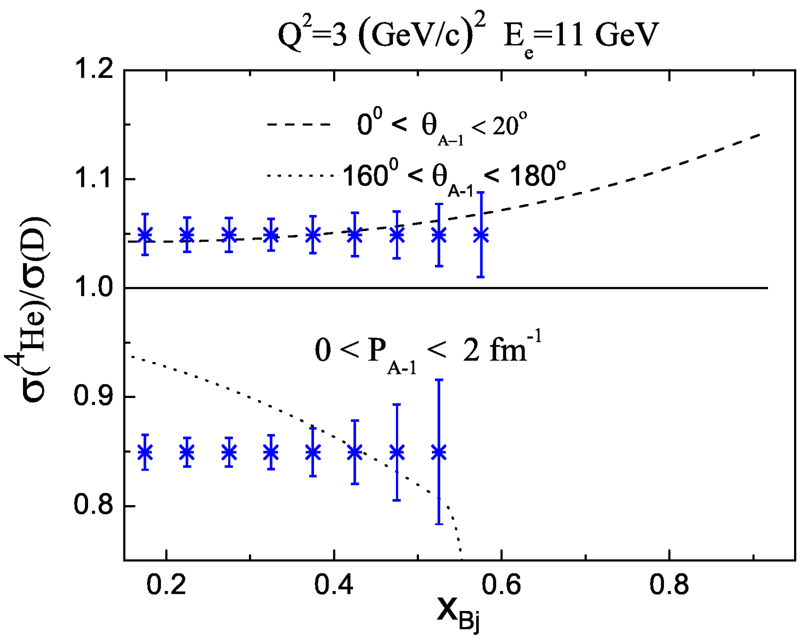
- The virtuality or off-shellness of the struck nucleon is linked to its momentum in the nucleus

Nuclear measurements are often affected by Final State Interaction effects

- Tagging of backward fragments is the safest measurement in this regard

MORE TESTS OF THE EMC EFFECT





Tagged DIS gives many other opportunities to test the EMC models

- In binding model, the EMC effect is due to the cancellation of much larger effects that can be separated with spectator detection
- Is EMC effect dependent of locality? mean field nucleons vs. Short-range correlated pairs

SPECTATOR - TAGGED DVCS

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

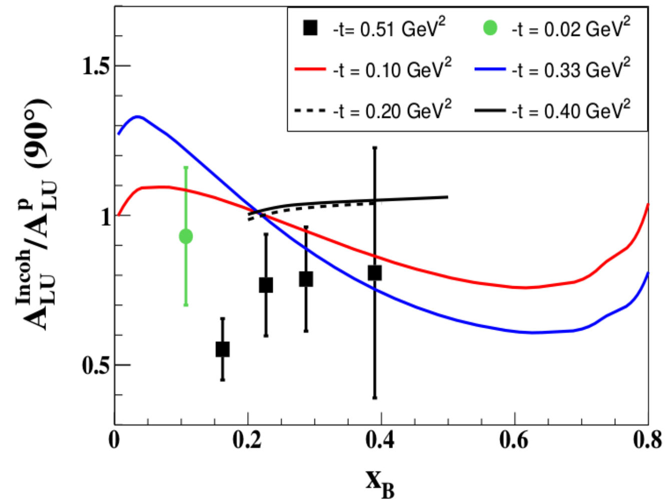
- Bound n-DVCS measurement
- Use isospin symmetry to relate FSIs

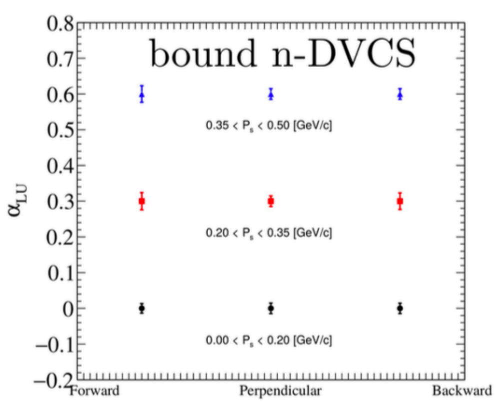
$^2\text{H} + \gamma^* \rightarrow \gamma + (n) + p$

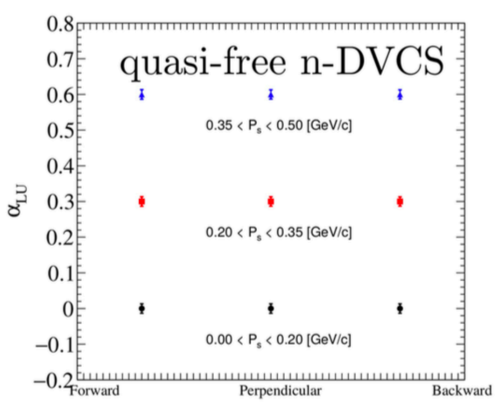
- Quasi-free n-DVCS measurement
- BSA ratio forming denominator of *Off-forward EMC Effect* Ratio

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

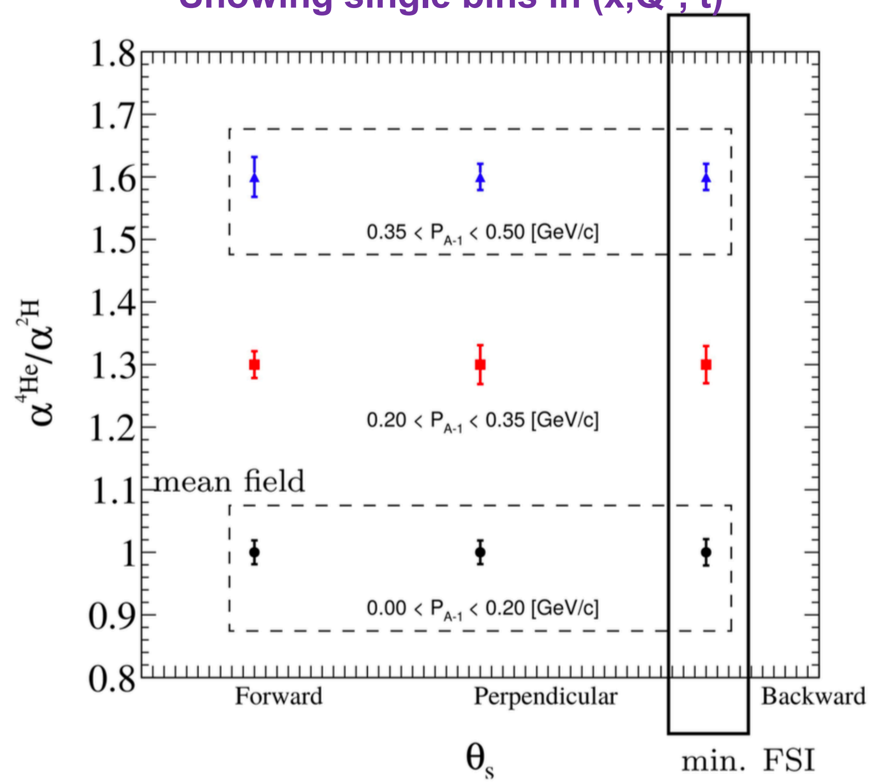
- Bound p-DVCS measurement
- Fully detected final state provides **unique opportunity to study FSIs**







Showing single bins in (x,Q^2, t)



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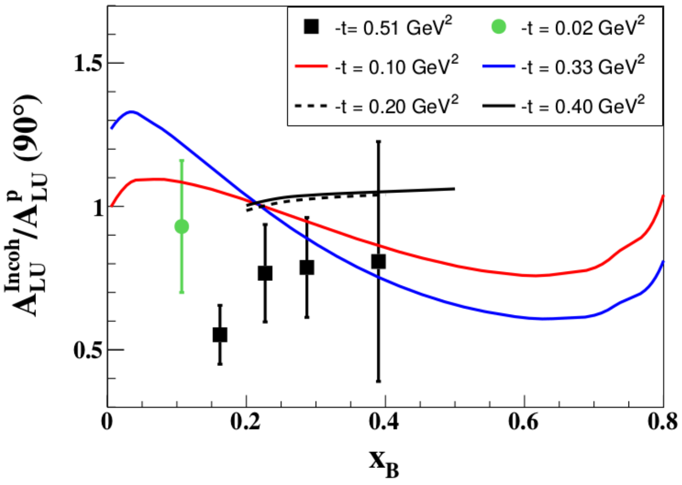
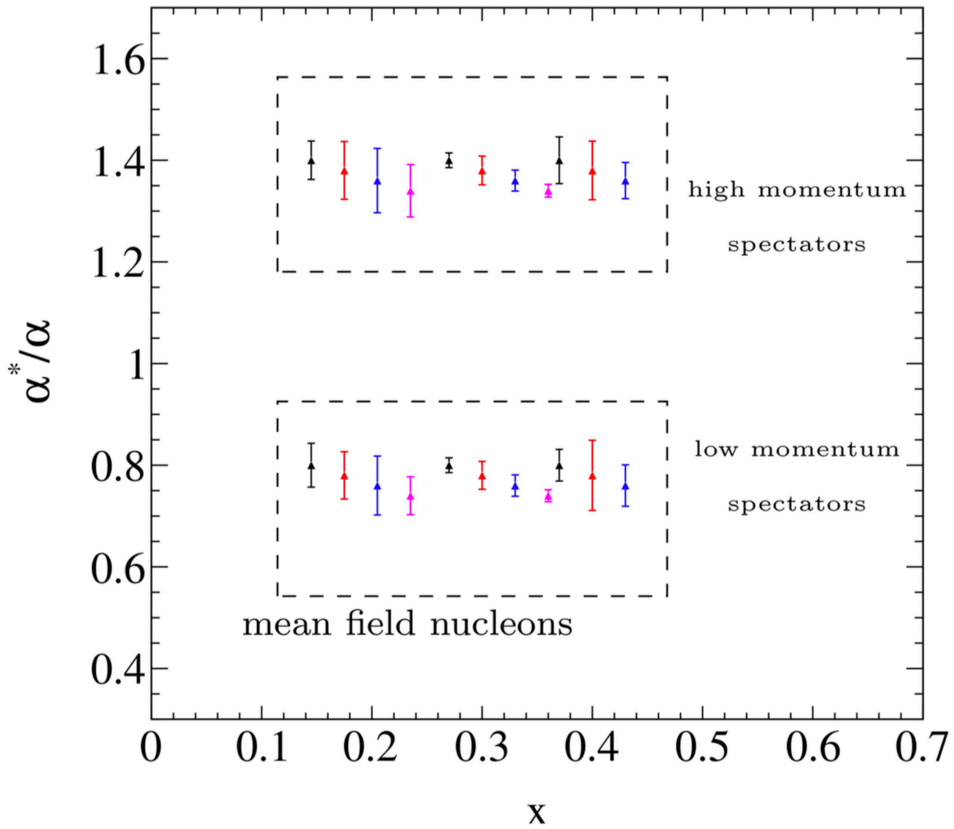
OFF-FORWARD EMC RATIO - PROJECTIONS





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

- 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**

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

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

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

Backward tagged spectator to minimize FSI

SUMMARY AND OUTLOOK

- First measurements of coherent/incoherent DVCS off ^{4}He at CLAS 6 GeV enabling model independent extraction of the ^{4}He Compton Form Factors
- Approved experimental program at JLab 12 GeV using a new low energy recoil tracker (ALERT) will allow the next generation nuclear QCD experiments
- DVCS and Phi production off ^{4}He will allow first attempt into 3D tomography of nuclei including comparing the quarks and gluons density profiles - EIC physics
- Tagged EMC and DVCS measurements will significantly advance our understanding of various nuclear effects including the EMC effect, the role of short range correlation and the in-medium hadron tomography

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CLAS Collaboration

THANK YOU!