Spectator-Tagged Exclusive Processes on Light Nuclei

INT Program INT-17-3
Spatial and Momentum Tomography of Hadrons and Nuclei

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Argonne National Laboratory

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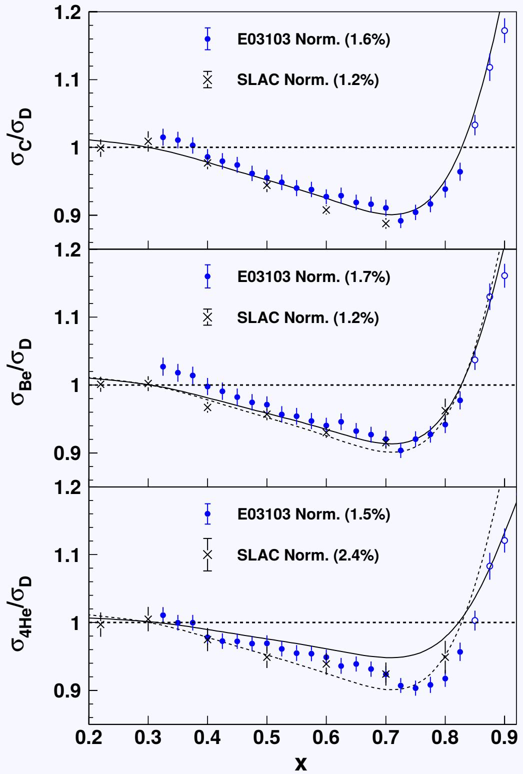
Introduction

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?

Nuclear Medium Effects

EMC Effect in DIS



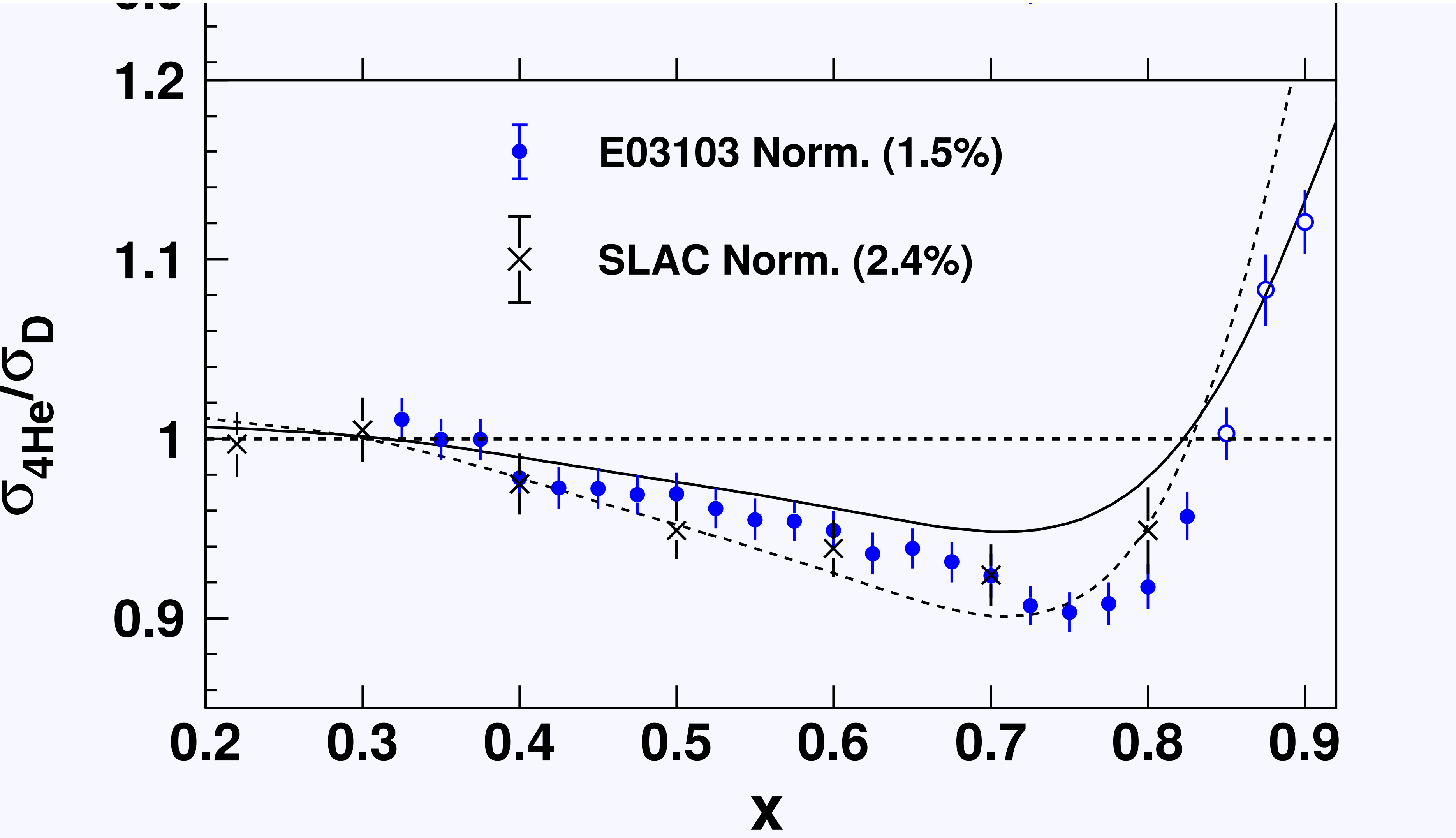
J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

Is structure function modified?

Significant even in ^{4}He!

Origin of effect remains unclear

Nuclear Medium Effects



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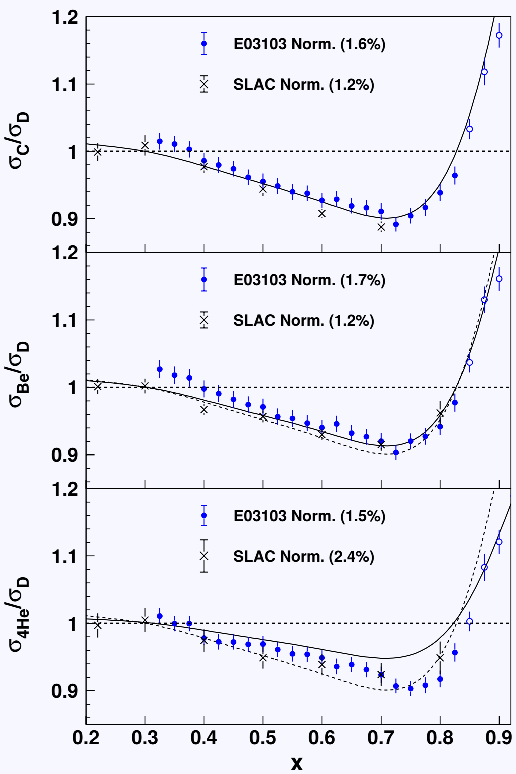

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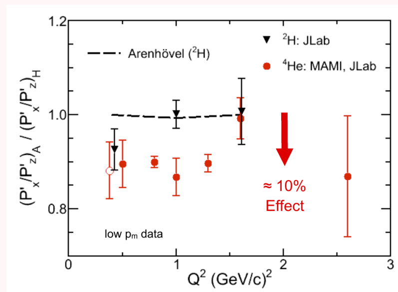
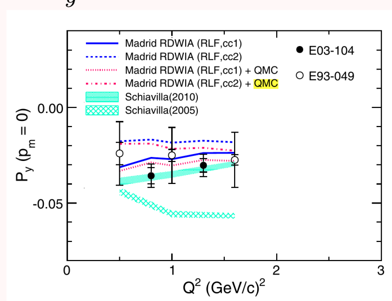


P_y is a measure of FSI



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)

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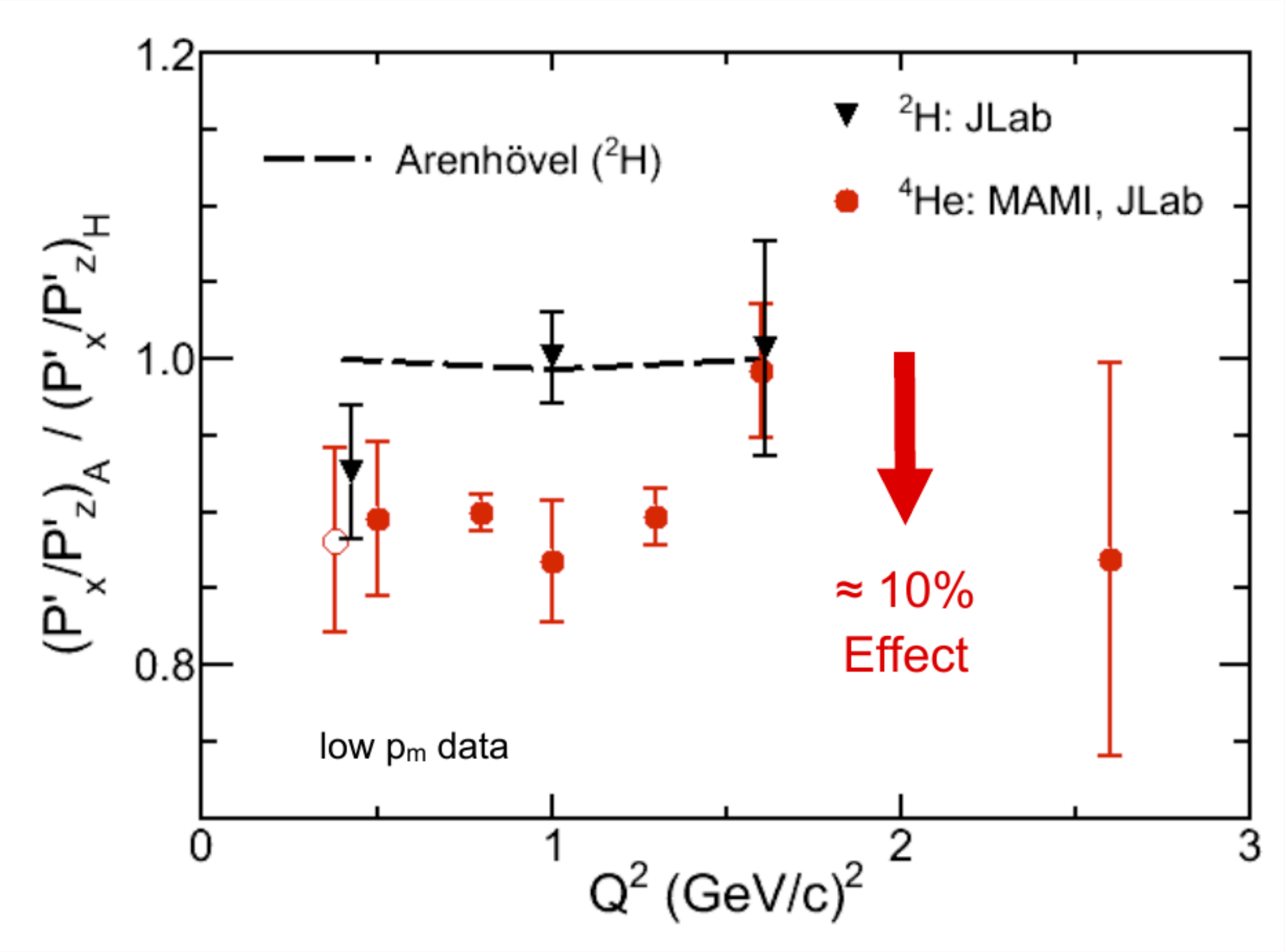

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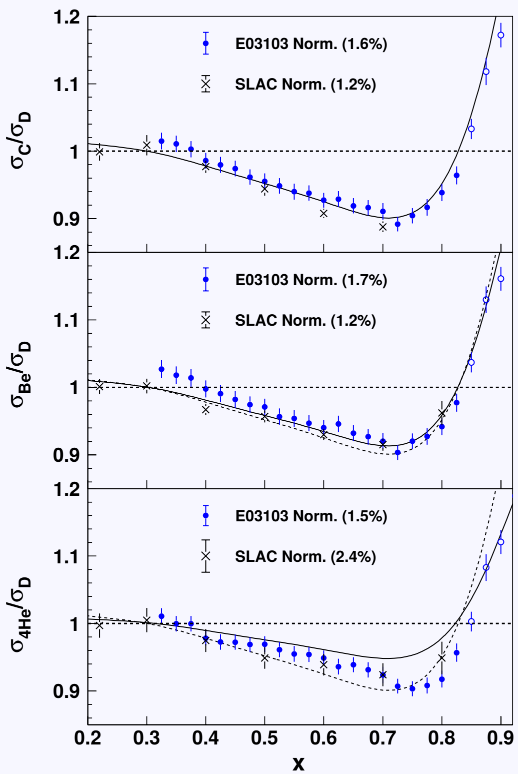

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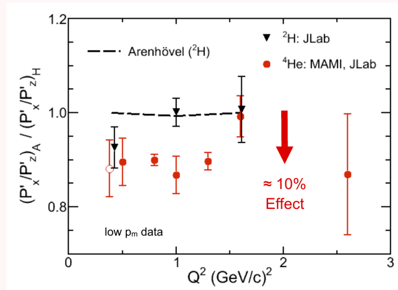

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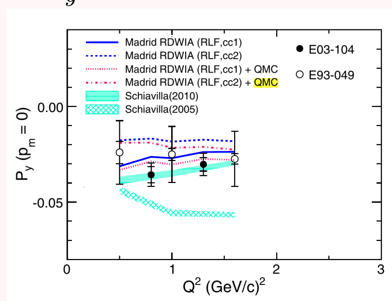

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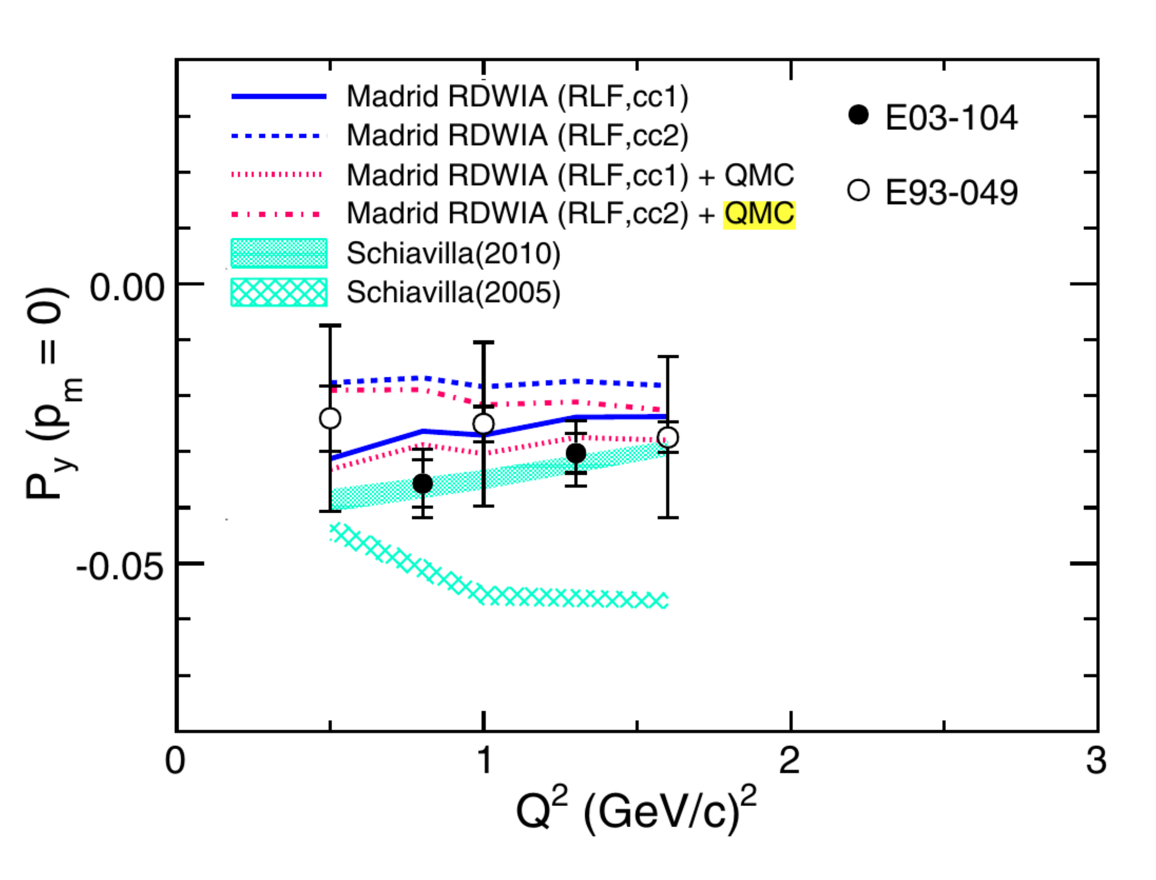

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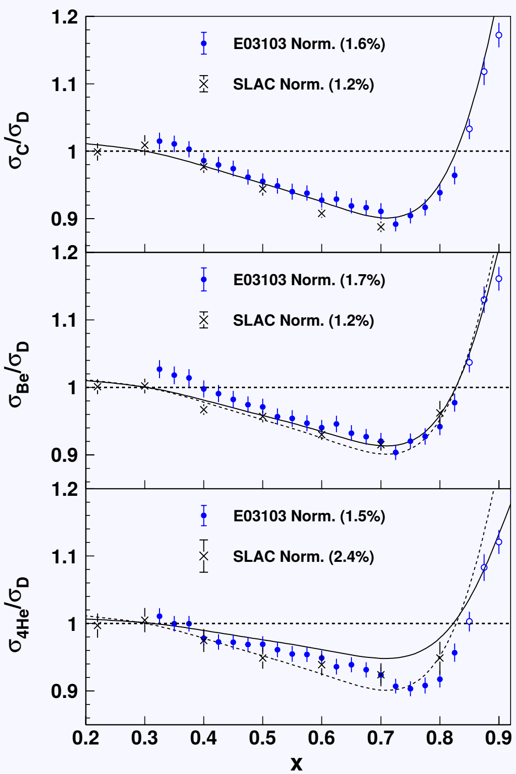

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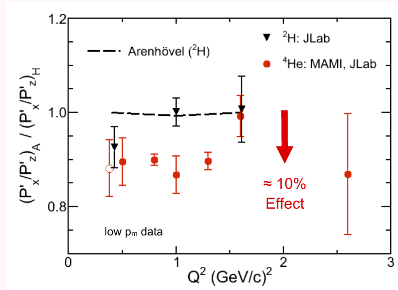

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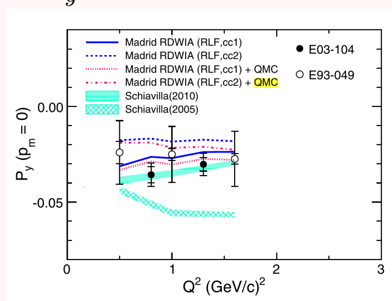

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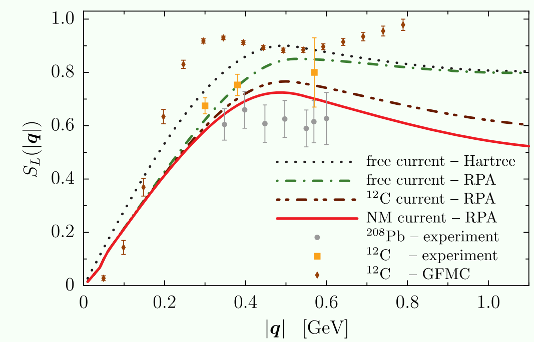
Coulomb Sum Rule

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



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

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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.

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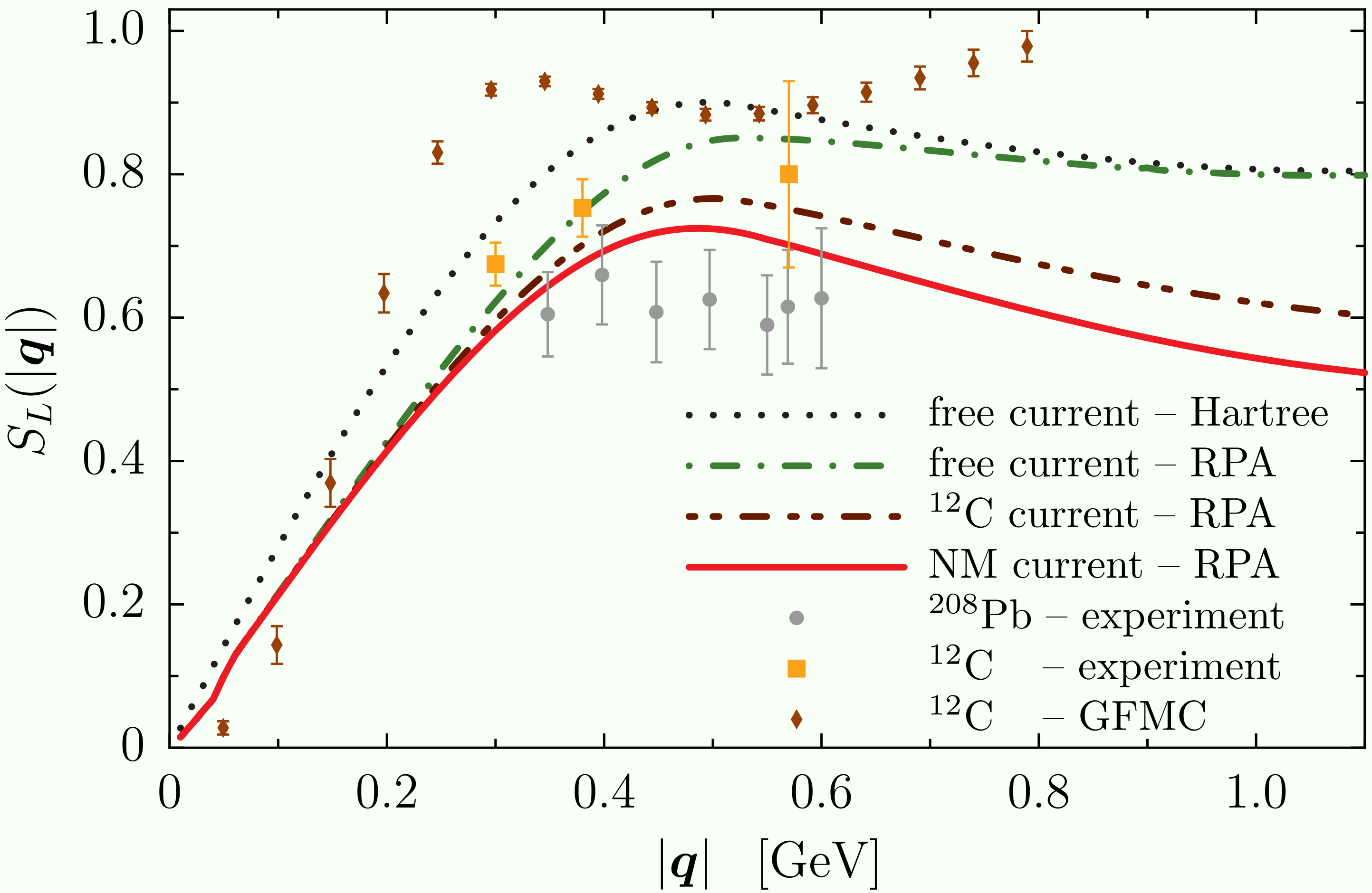

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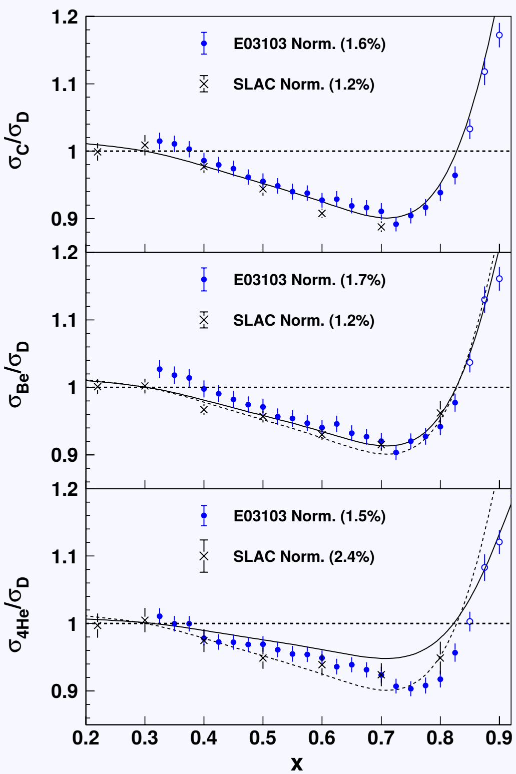

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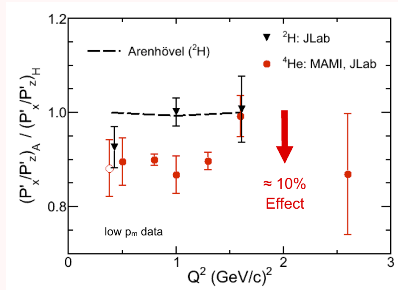

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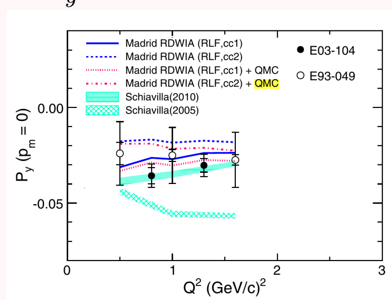

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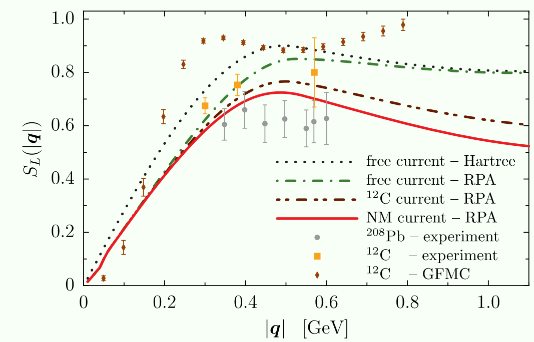

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The Challenges of Nuclear Effects

EMC Effect in DIS

Spectator tagging to control initial state and separate mean field from SRC nucleons FSI Model dependence

Partonic interpretation

Polarization Transfer

Induced polarization (P_y) provides an excellent lever arm on FSIs

but only a **Nucleonic Interpretation**: What is going on with the quarks and gluons?

Coloumb Sum Rule

Observations of quenching complicated by model dependent nuclear corrections

Nucleonic Interpretation

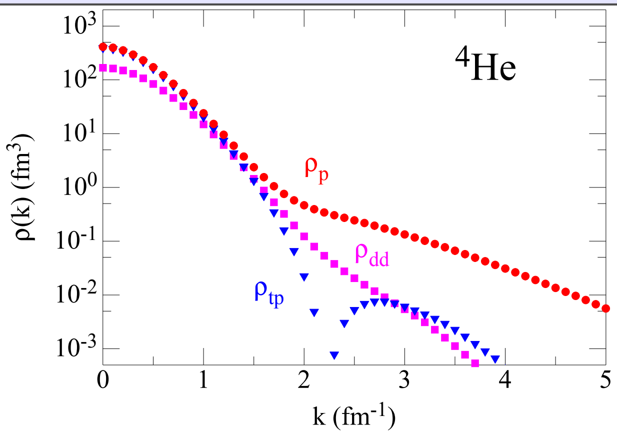
Nuclear effects present the major hurdle to **unambiguously identifying modified nucleons**.

How to connect the **Partonic and Nucleonic** interpretations while systematically controlling final-state interactions?

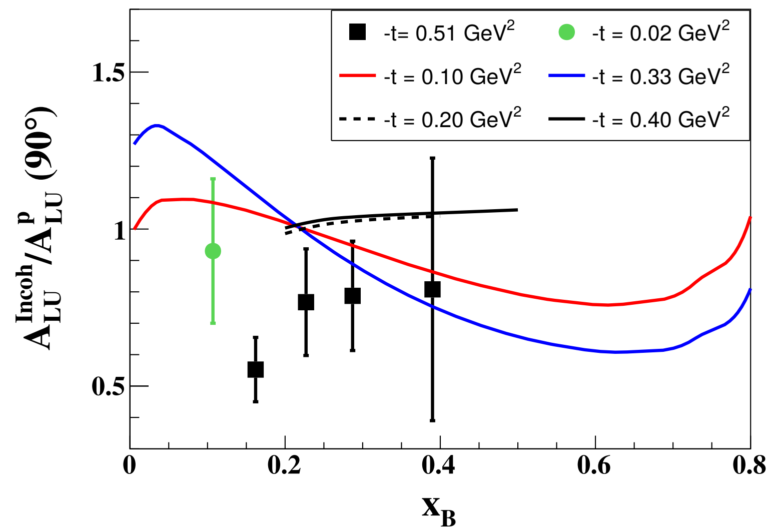
CLAS eg6 (E08-024)

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



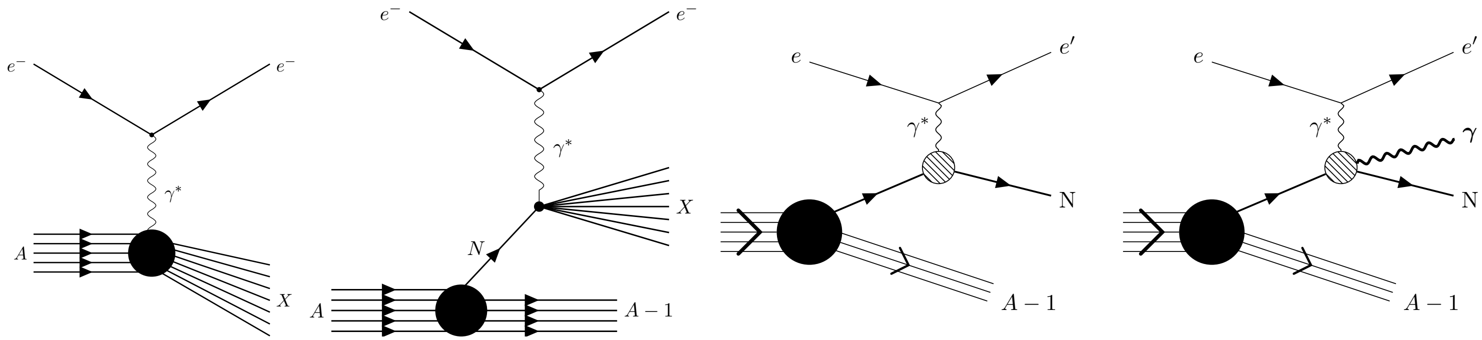
$^4He(e,e'\gamma p)$



Preliminary results courtesy of M. Hattawy.

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

Why Spectator-Tagged DVCS?



A new link between the Partonic and Nucleonic

- Combines the beneficial features of **DIS and QE** scattering
- Identify struck nucleon → **separate mean field** from high momentum nucleons
- DVCS → **parton level interpretation** and in-medium hadron tomography
- DVCS on Nuclear targets → **Off-forward EMC effect**
- **Fully exclusive** measurement → Unique opportunity to study and control FSIs
- Neutron's beam-spin asymmetry ratio → very sensitive to medium modifications

Neutron DVCS: A sensitive probe for medium modifications

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

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

The Connection to Spin Structure Functions and Modified Form Factors:

The third term above is

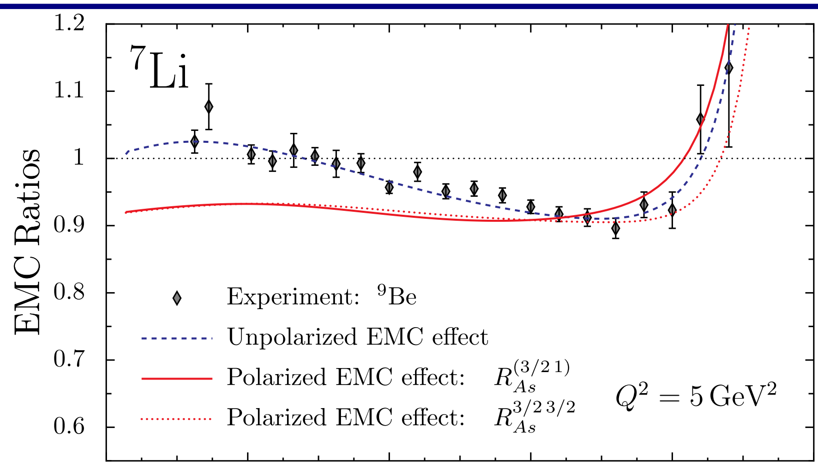
$$\text{Im}\left((F_1 + F_2)\tilde{\mathcal{H}}\right) = G_M(t) Im(\tilde{\mathcal{H}}(\xi,\xi,t))$$

Forward Limit (at leading order):

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

Neutron BSA Ratio

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



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

The ratio in the forward limit looks like

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

$\mu_{n^*} \rightarrow$ 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

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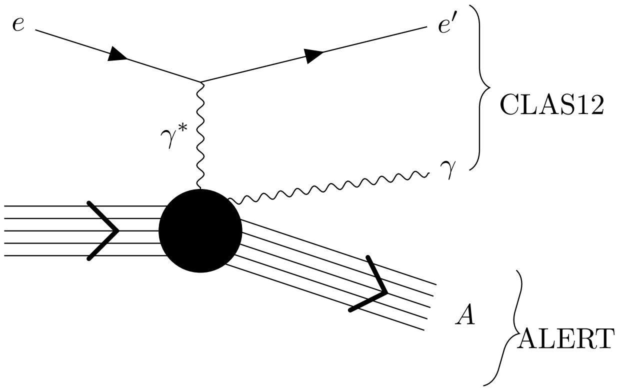
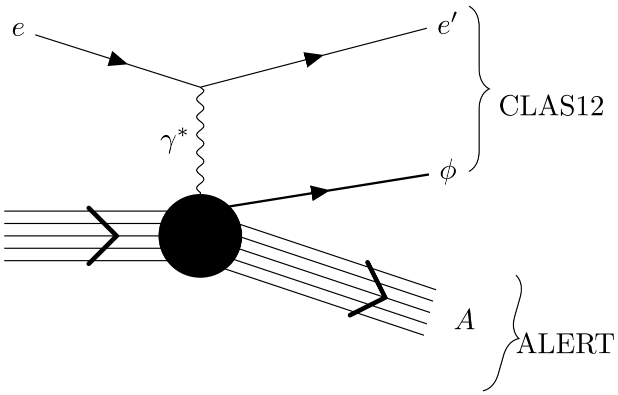
Coherent Processes on ^{4}He

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

Explores the partonic structure of ^{4}He





The ALERT Experiments

A comprehensive program to study nuclear effects

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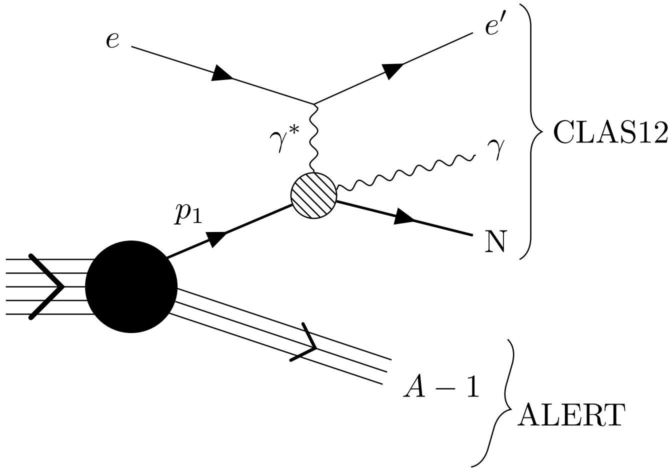
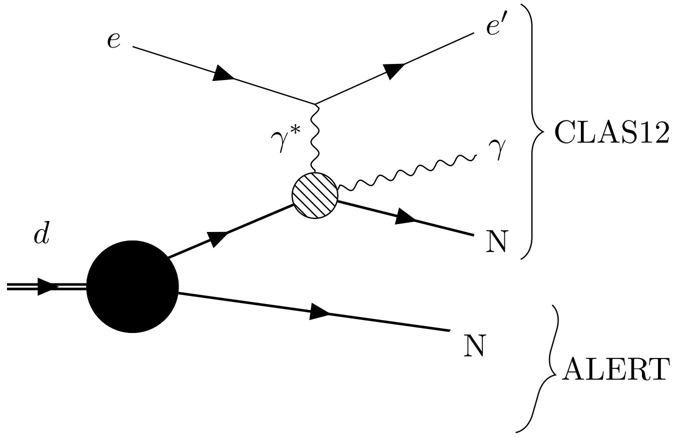
Explores the partonic structure of ^{4}He

Incoherent processes 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





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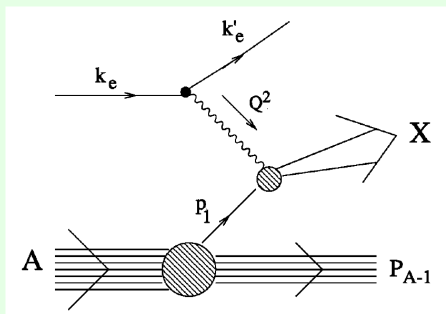
Identify medium modified nucleons

DIS on ^{4}He and ^{2}H : Tagged EMC Effect

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



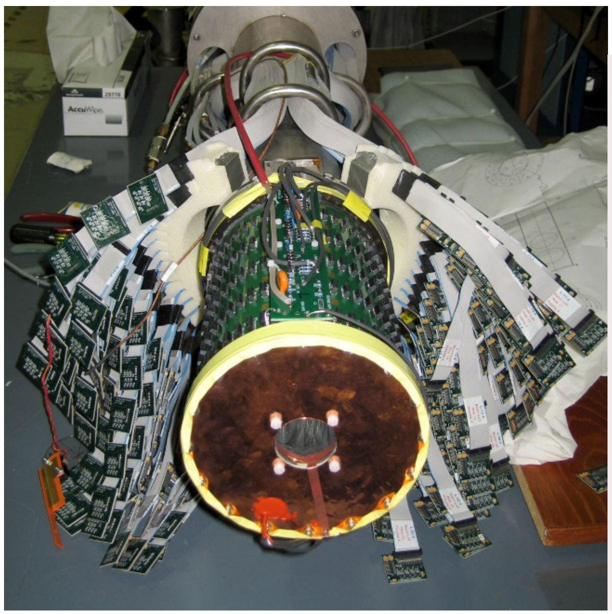
Test FSI and rescaling models

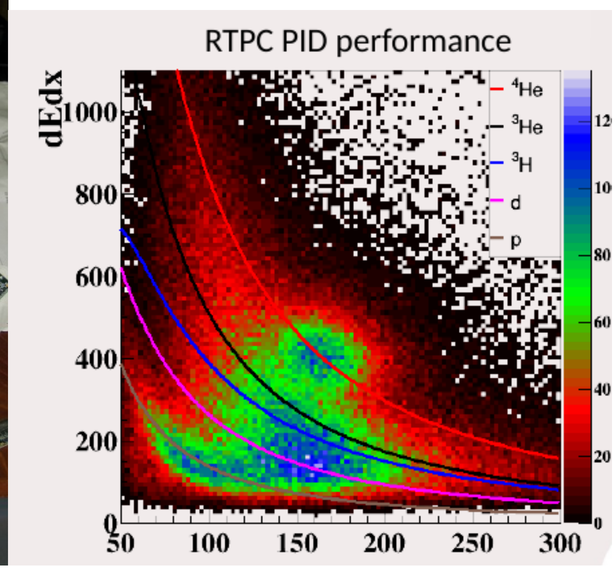
And many more channels for free

Why ALERT?

A new detector is needed

- Existing and proposed detectors (RTPCs) do not meet experimental needs

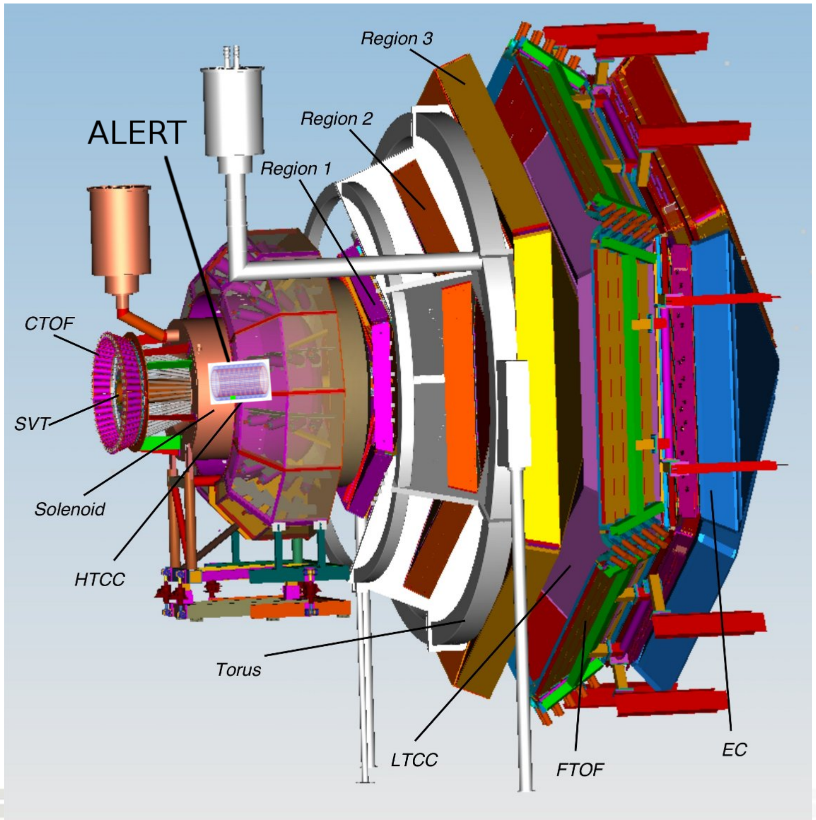




- Designed to operate in CLAS12 5 T field
- Runs at **CLAS12 luminosity limit** and **Hall-B beam current limit**
- PID of ions from protons to ^{4}He
- Independent trigger (can be adjusted to operate with higher luminosities).

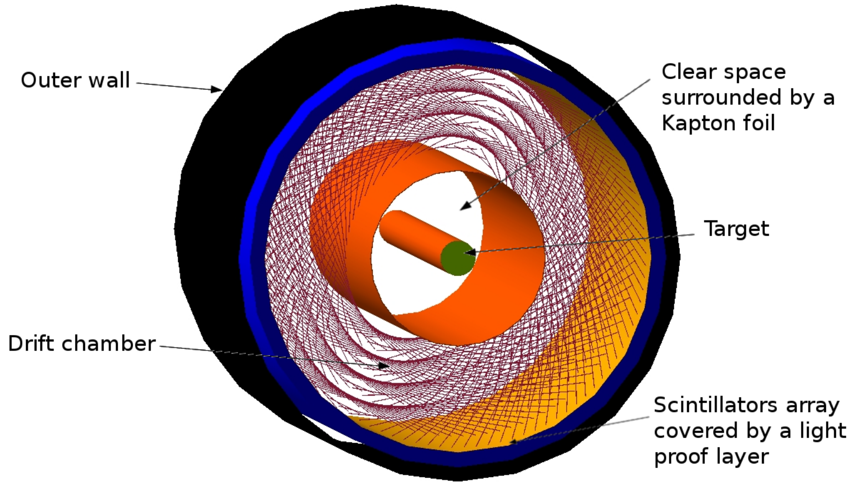
Proposed Setup: CLAS12 + ALERT

- 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



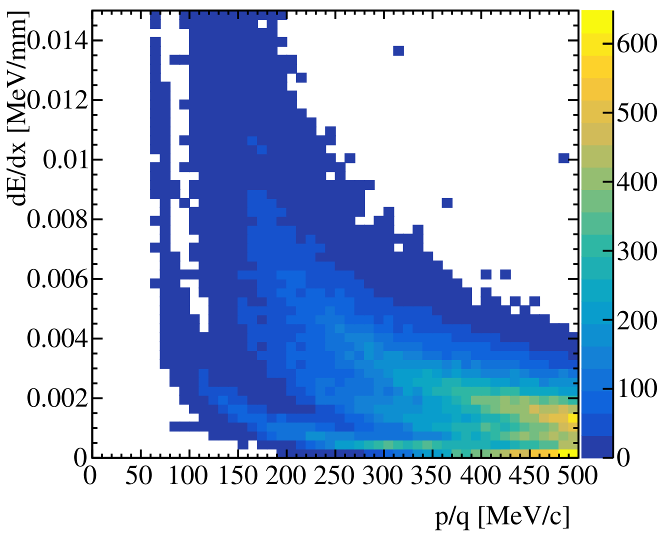
ALERT requirements

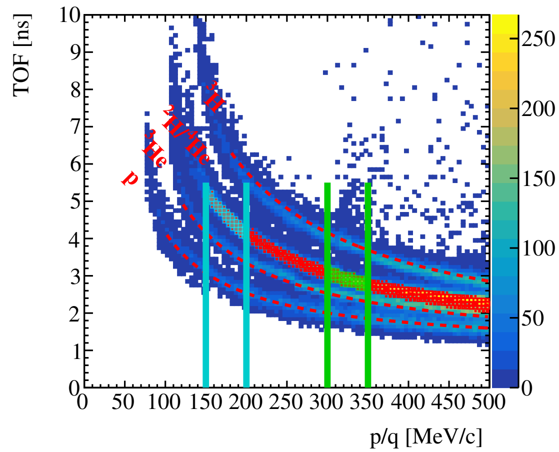
- Identify light ions: H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Detect the **lowest momentum** possible (close to beamline)
- Handle **high rates**
- Provide **independent trigger**
- Survive high radiation environment
  → **high luminosity**

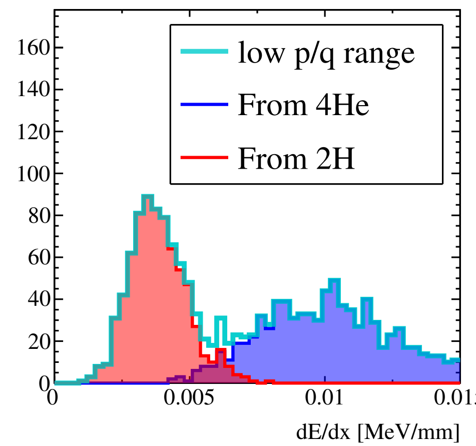


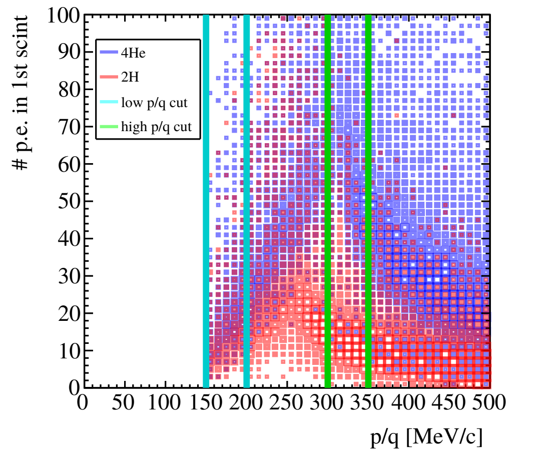
ALERT PID

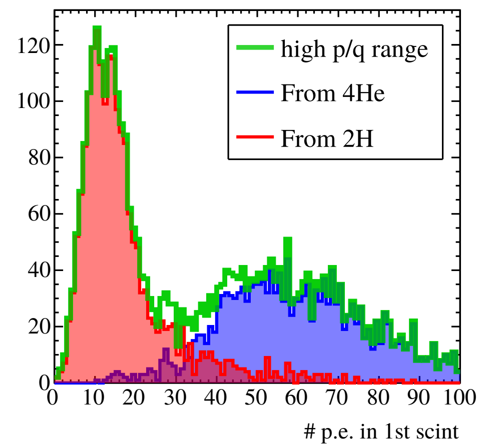
- TOF is degenerate for ^{2}H and ^{4}He.
- dE/dx can separate these.
- At higher p, scintillator topology can also be used to separate.







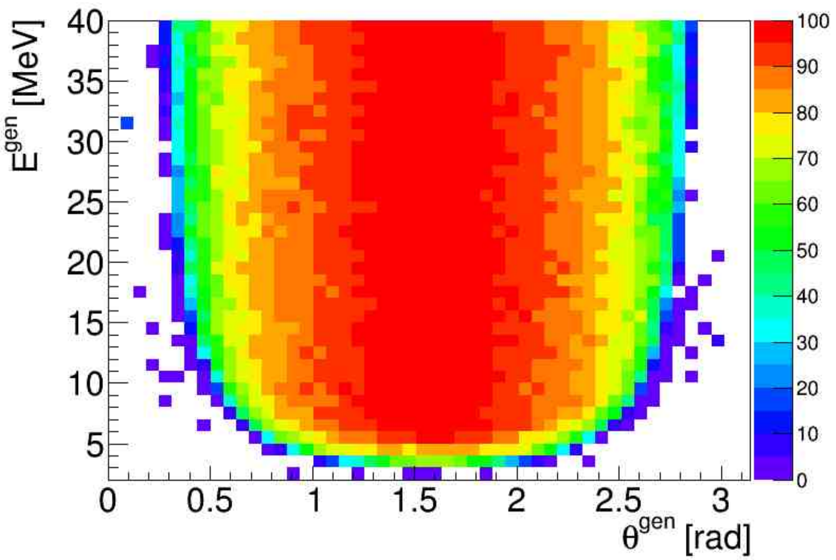


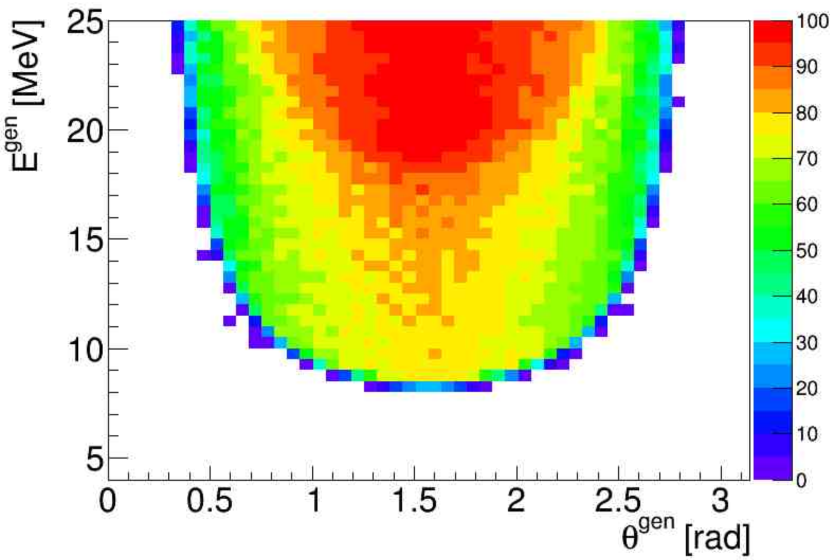


ALERT Simulation

Full Geant4 Simulation

- Acceptances minimum momenta: 70 MeV/c for protons, 240 MeV/c for ^{4}He





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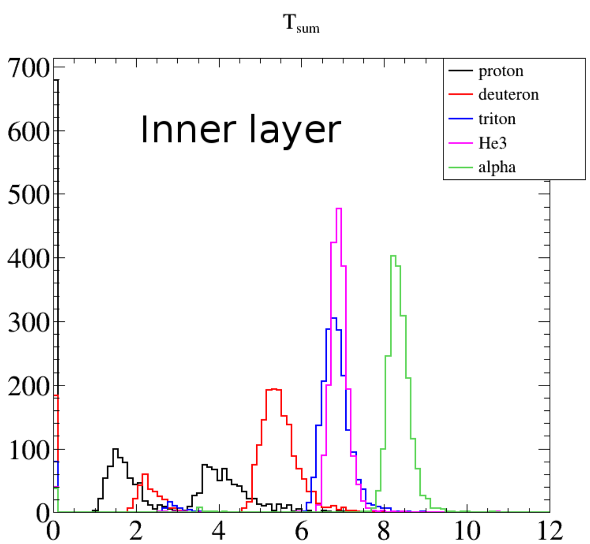
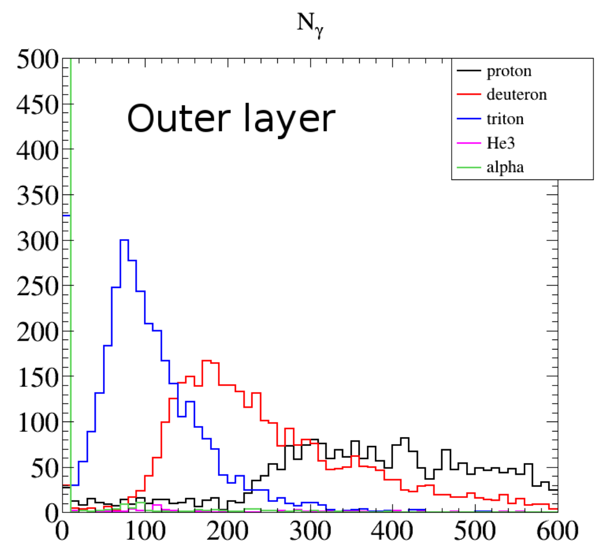
- Detailed scintillator photon yields and timing information → optimize geometry to provide the best PID





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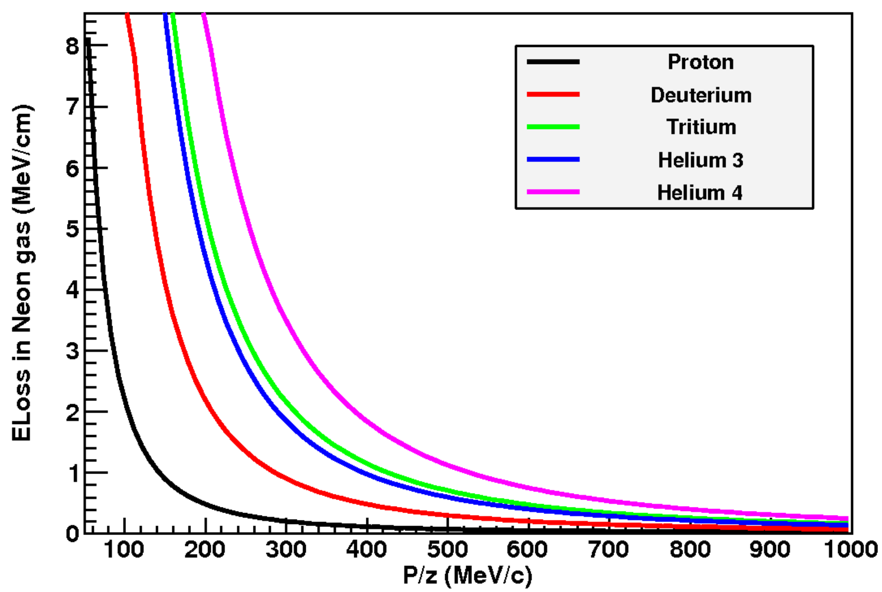

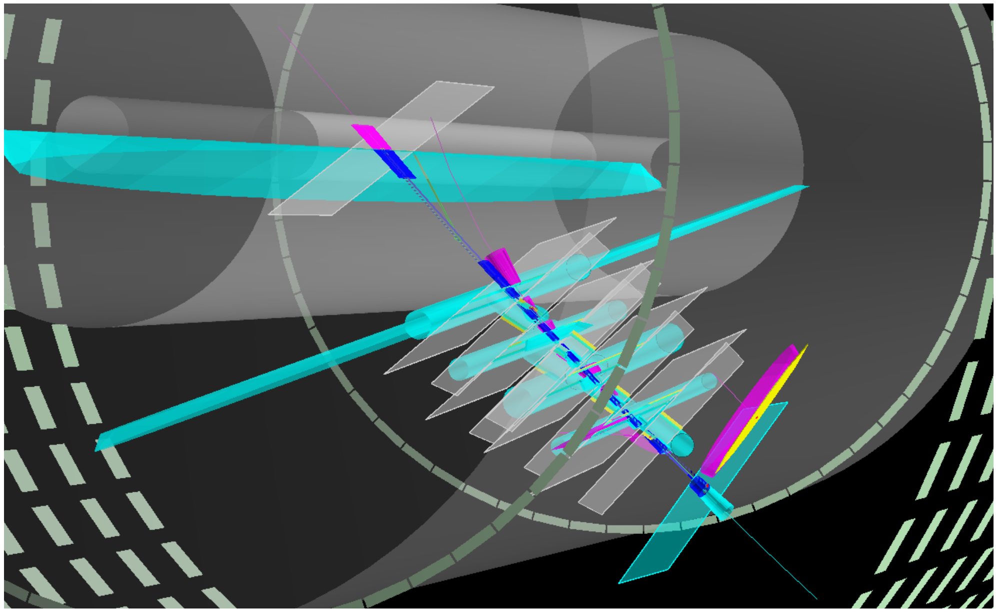

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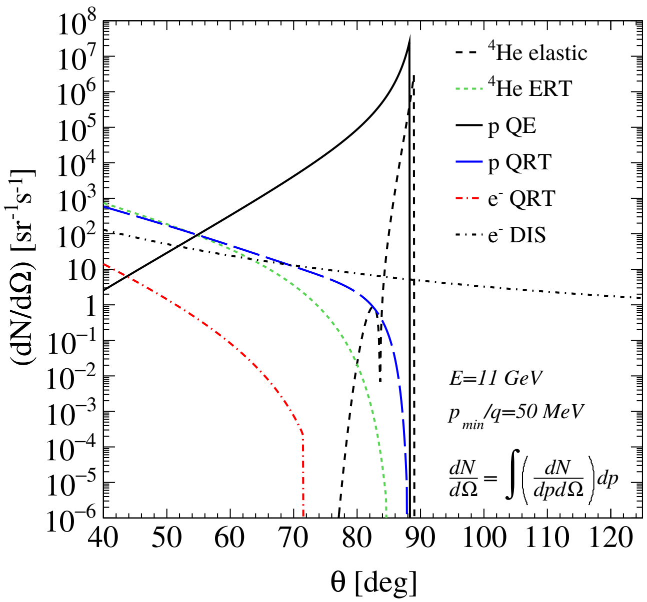
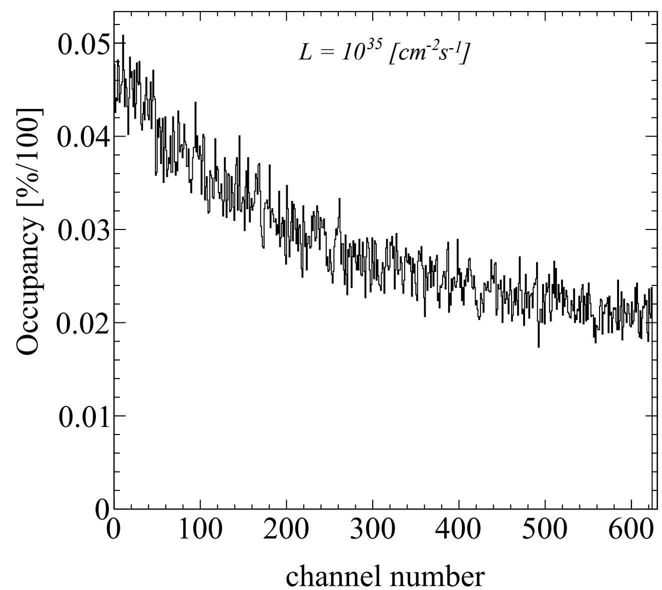
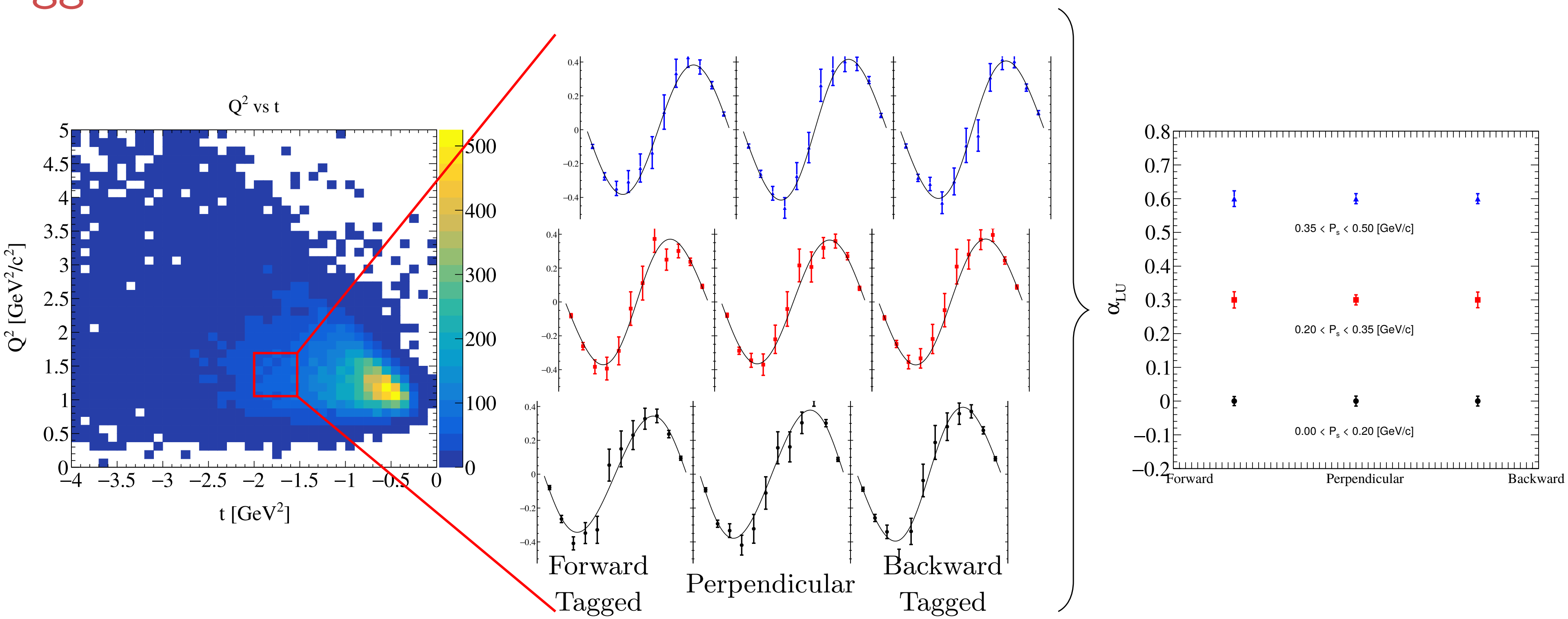
- Working on Kalman Filter based track reconstruction → optimize DC wire layout; Also get track dE/dx for PID
- DC hit occupancies simulated - can operate comfortably at nominal CLAS12 luminosity





Tagged DVCS: Off-forward EMC Ratio

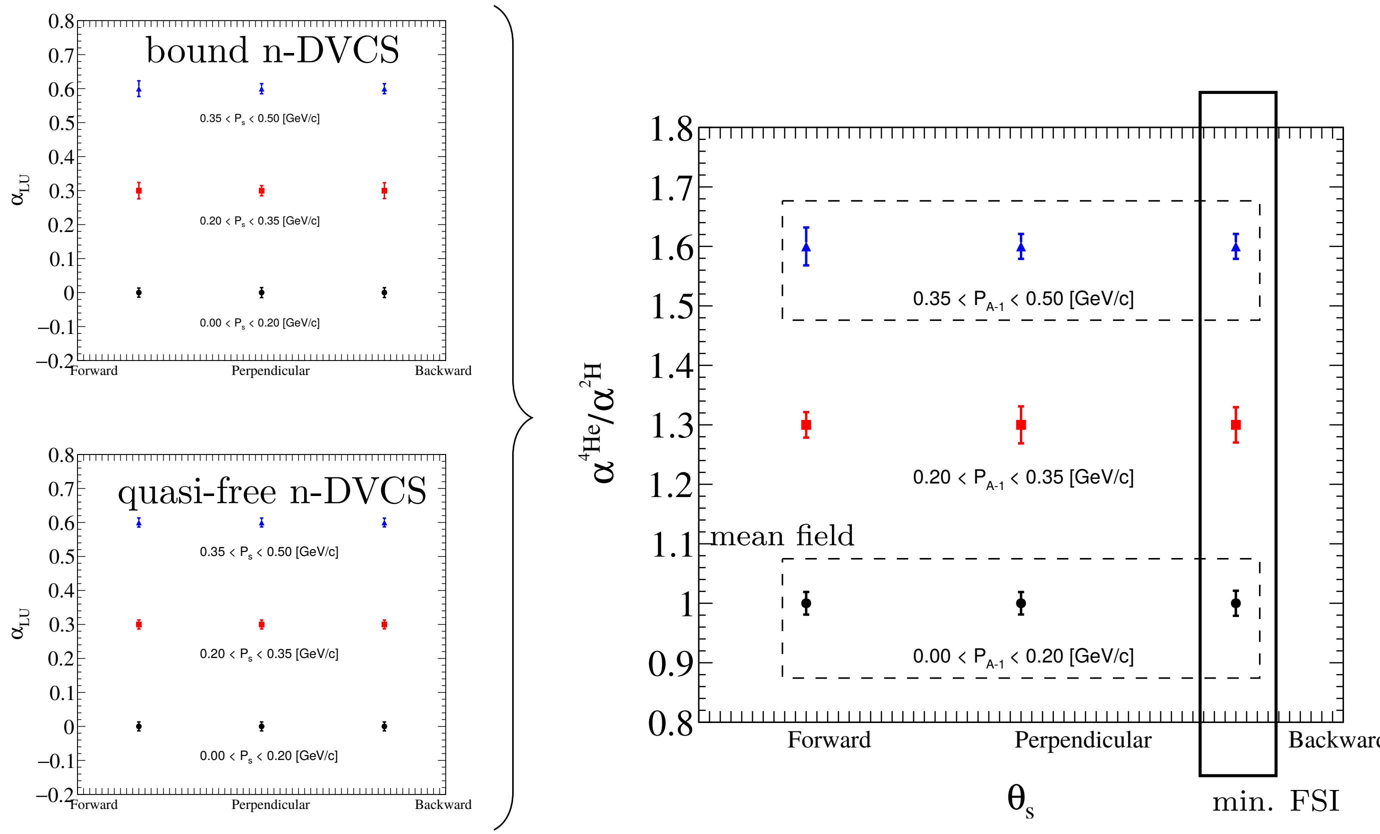


- 6 dimension binning (7 with helicity)
- Reduced to 5 after obtaining 'sin ϕ' harmonic
- $\alpha_{LU} = \int A_{LU} \sin\phi \, d\phi$

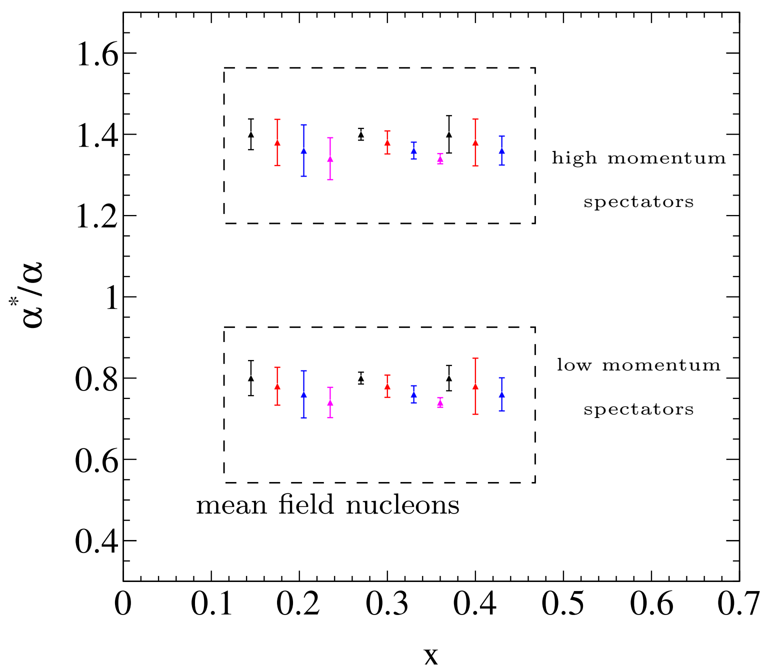
Off-forward EMC Ratio

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

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



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

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

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

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

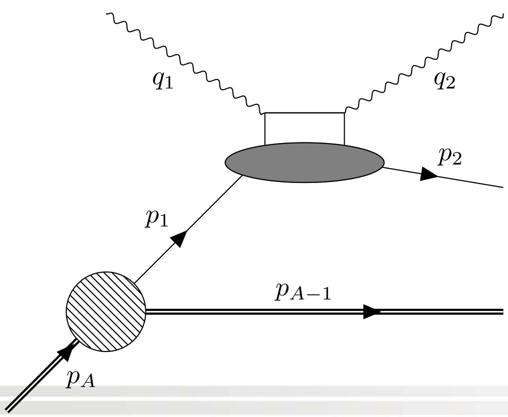
PWIA and FSIs

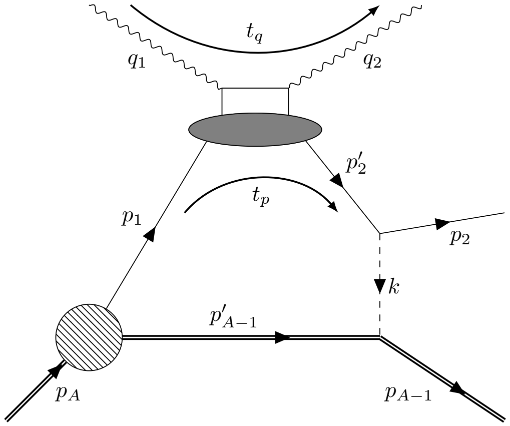
Plane-Wave Impulse Approximation

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 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





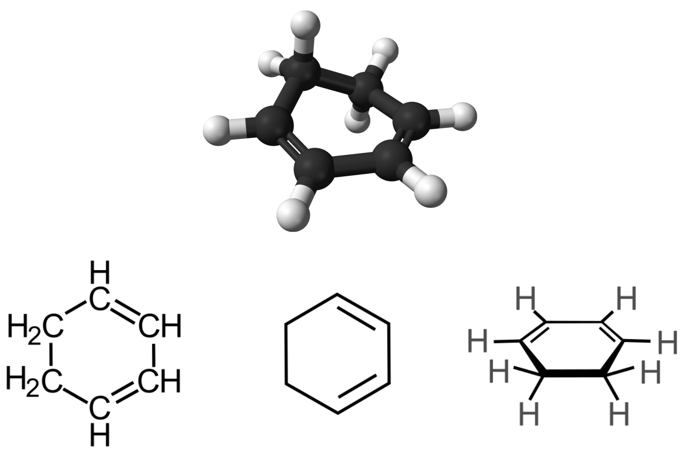
Ultrafast Pump-probe Spectroscopy

Molecular Dynamics

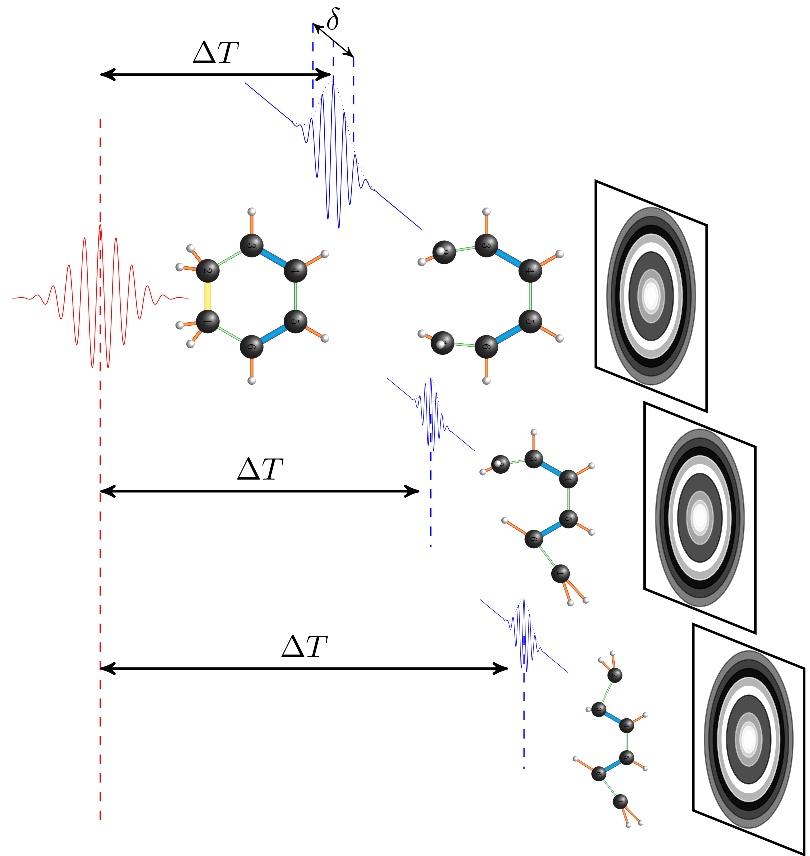
- Breakdown of Born-Oppenheimer approximation : Motion of atomic nuclei now matters
- The $\psi \neq \psi_e \times \psi_{\text{Nucleus}}$
- 1,3-cyclohexadiene molecular dynamics
- myoglobin“Protein Quakes”

Example: 1,3 Cyclohexadiene photo-disassociation

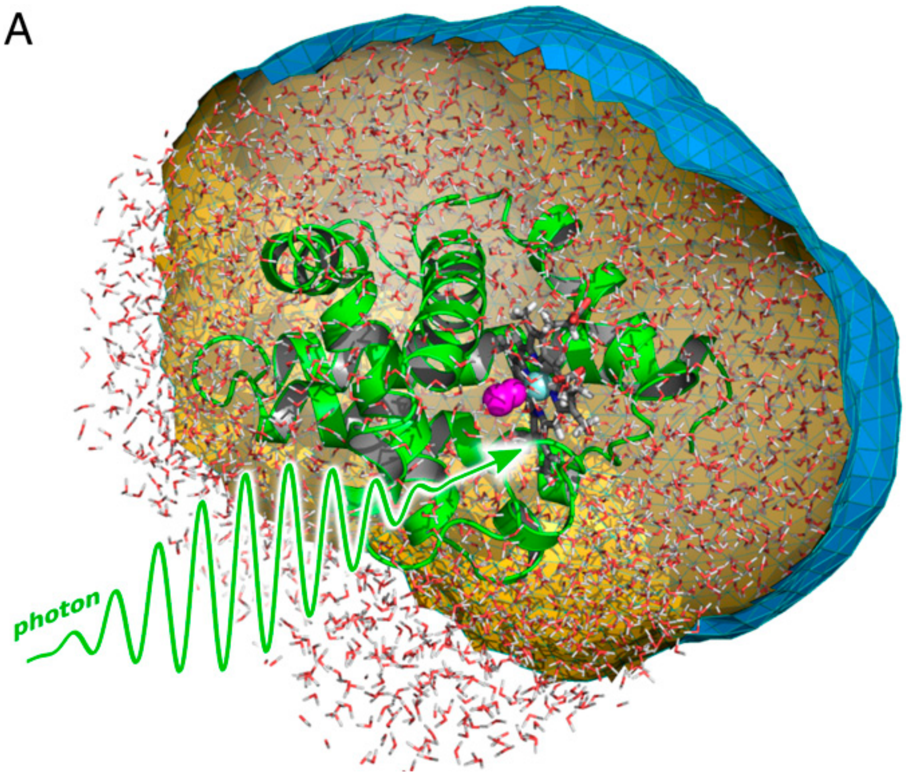
Molecular Movie

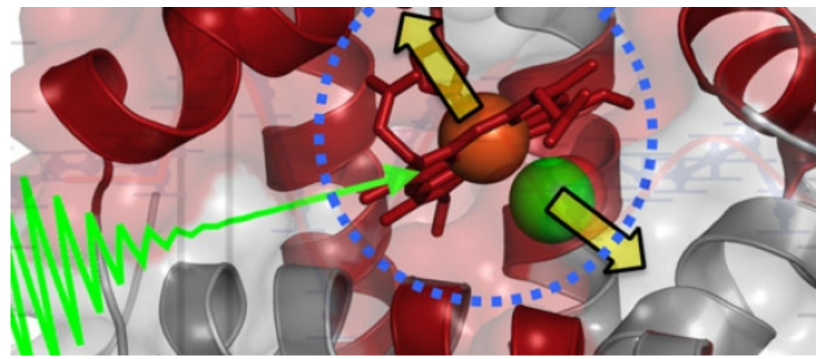


- Modeling the molecular dynamics and simulating diffractive patterns
- The initial state is modeled (i.e., when molecular bond broken)
- The final state is well known (since it is stable $\Delta t \to 0$)



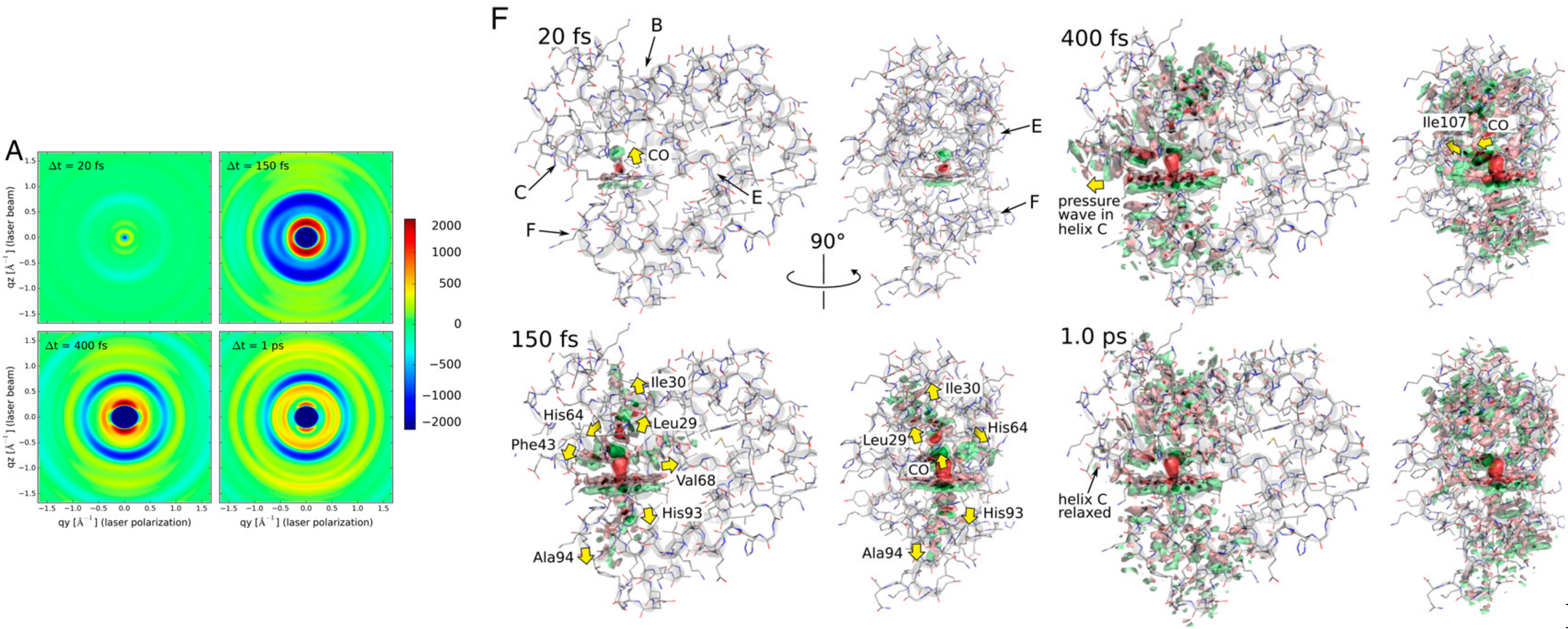
A more complicated example: Protein Quakes





Brinkmanna, et.al., PNAS vol. 113, 38 10565-10570

Structural Biology

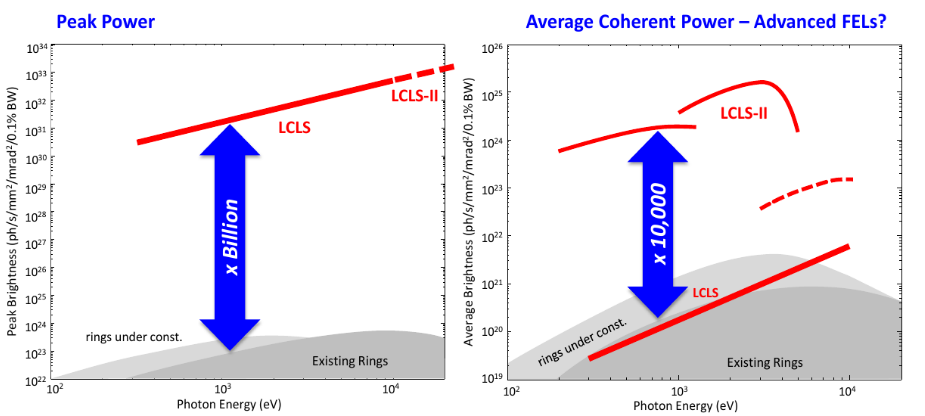


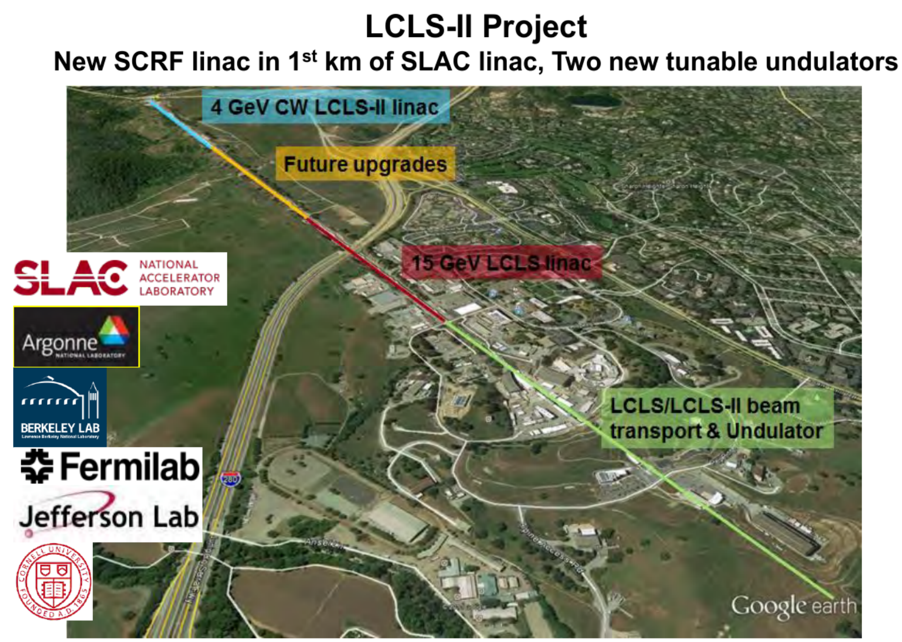
B et.al., PNAS vol. 113, 38 10565-10570

Light source facilities?

What are the key aspects to this technique?

- Ultrafast pulsed laser source (fs)
- **High Intensity** source (lots of photons)
- Variable photon wavelength





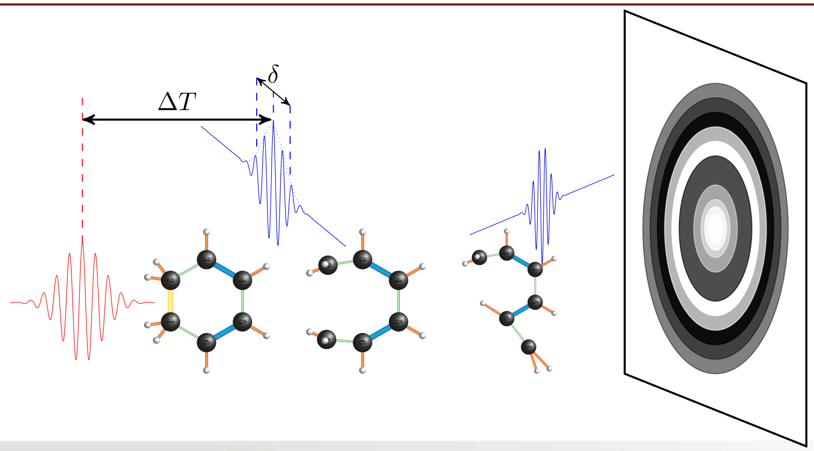
Taken from talk by Robert Schoenlein - July 2015

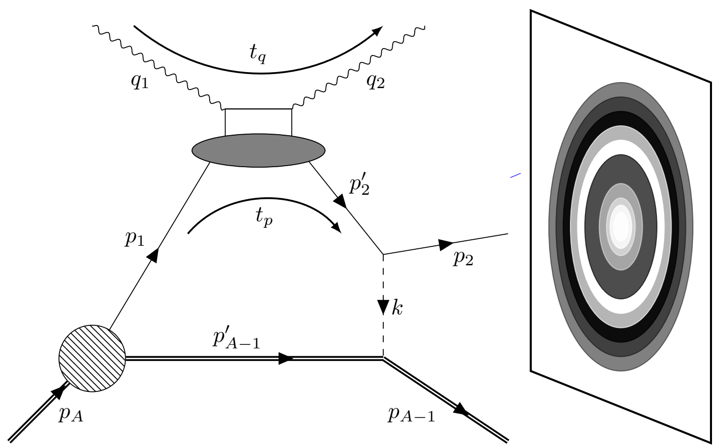
Ultrafast x ray pump-probe

- Breakdown of Born-Oppenheimer Approximation

Incoherent Spectator-Tagged DVCS

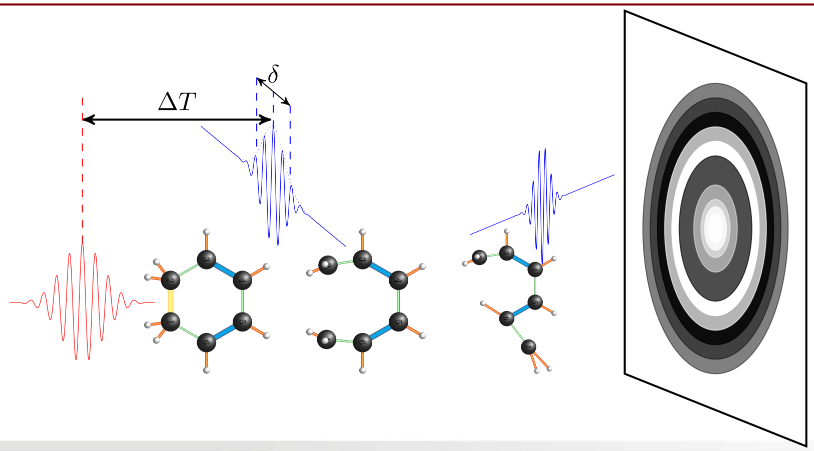
- Breakdown of PWIA





Ultrafast x ray pump-probe

- Breakdown of Born-Oppenheimer Approximation
- Initial state is modeled



Incoherent Spectator-Tagged DVCS

- Breakdown of PWIA
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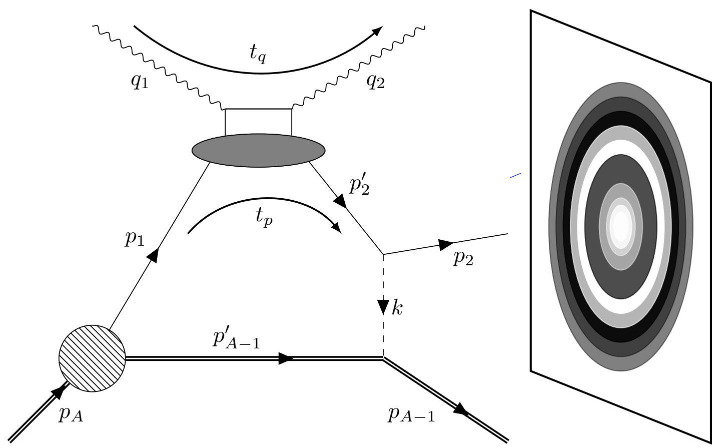
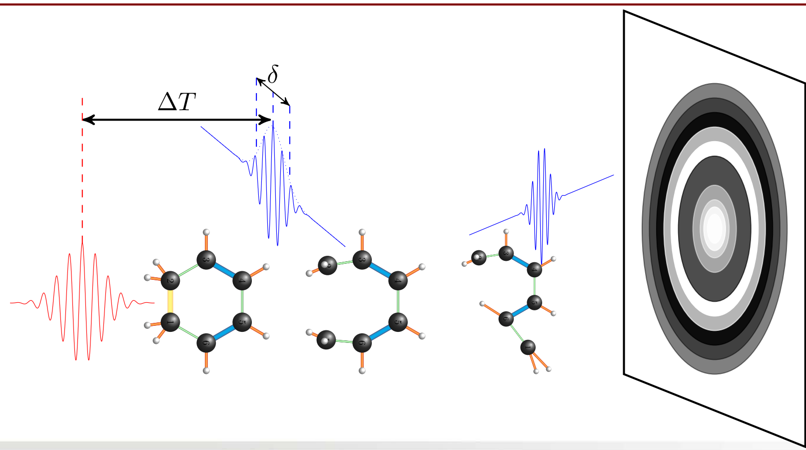


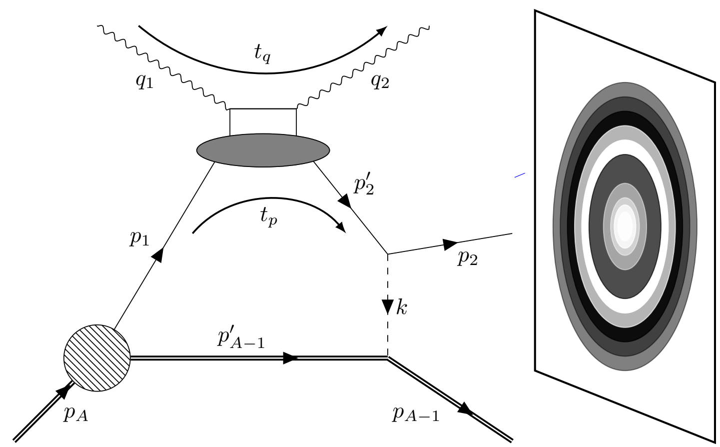
Ultrafast x ray pump-probe

- Breakdown of Born-Oppenheimer Approximation
- Initial state is modeled
- Final state after long time is known

Incoherent Spectator-Tagged DVCS

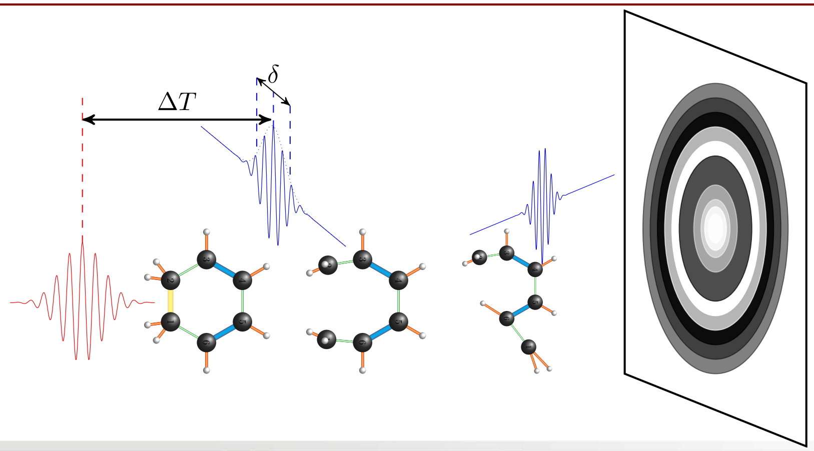
- Breakdown of PWIA
- Initial state is modeled
- Final state is well defined (γ, p, A-1)





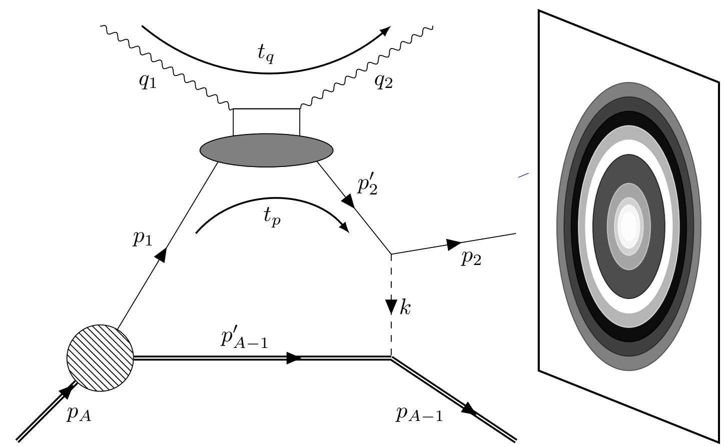
Ultrafast x ray pump-probe

- 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.



Incoherent Spectator-Tagged DVCS

- Breakdown of PWIA
- Initial state is modeled
- Final state is well defined (γ, p, A-1)
- Studying the response for different paramters (P_s, θ_s, ϕ_s, x, Q^2, t, ϕ...) allows the model of the nuclear dynamics to be refined

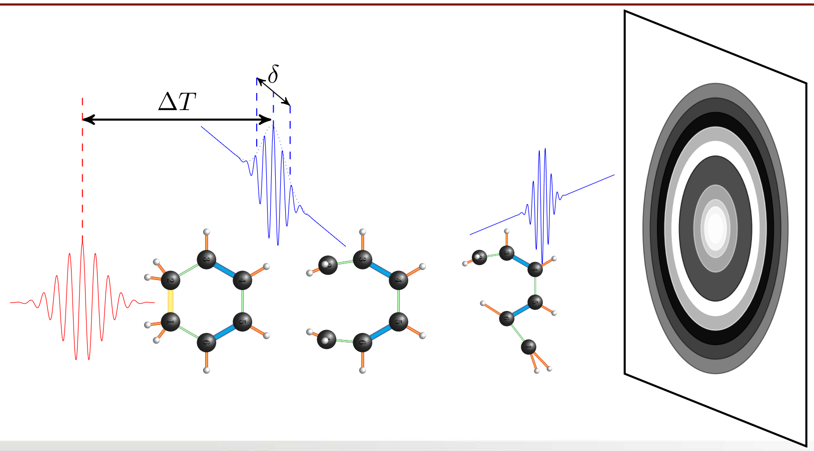


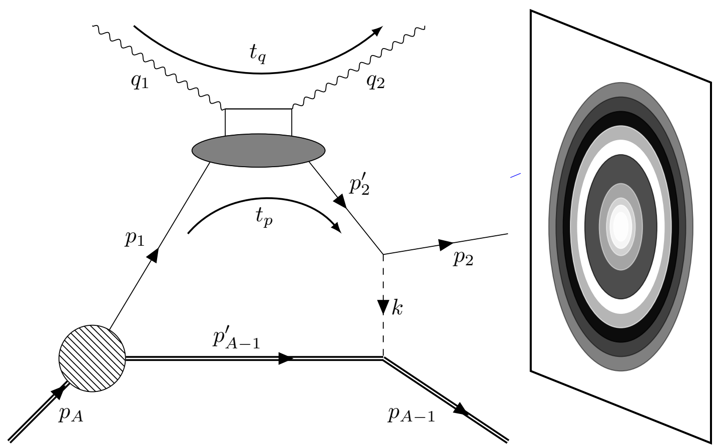
Ultrafast x ray pump-probe

- 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 Spectator-Tagged DVCS

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





Toy model of FSIs

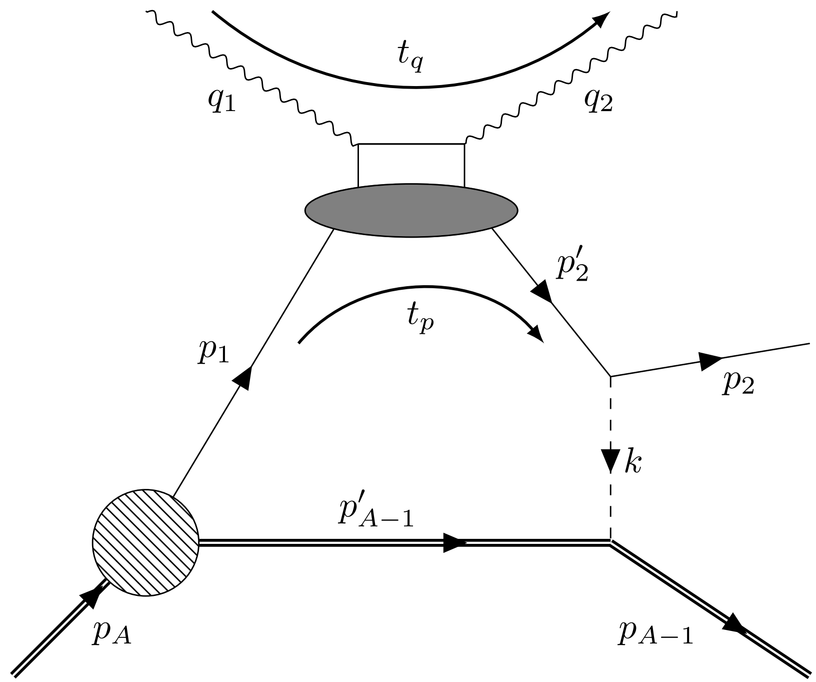
The power of exclusivity

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

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



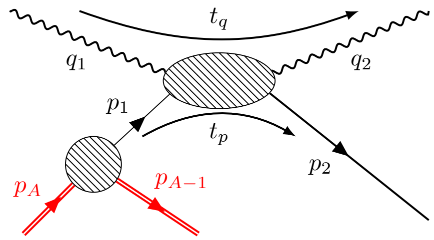
Goal

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

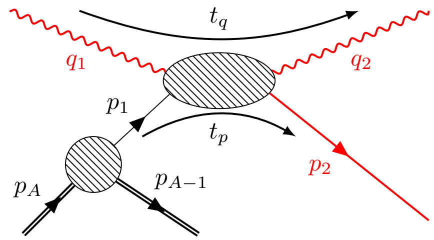
Over-determined Kinematics

Calculations using the PWIA

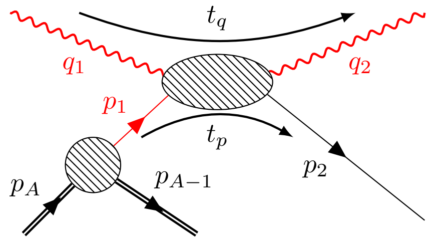
$$\bar{M}^2_{(0)}(p_A, p_{A-1}) = (p_A - p_{A-1})^2$$
$$= M_A^2 + M_{A-1}^2 - 2M_A E_{A-1}$$



$$\bar{M}^2_{(1)}(q_1, q_2, p_2) = M^2 - Q^2 + 2E_2(\nu_1 + \nu_2) + 2|\vec{p}_2||\vec{q}_1|\cos\theta_{p_2 q_1}$$
$$- 2\nu_2\left(\nu_1 + |\vec{p}_2|\cos\theta_{p_2 q_2} - |\vec{q}_1|\cos\theta_{q_1 q_2}\right)$$



$$\bar{M}^2_{(2)}(q_1, q_2, p_1) = \frac{1}{2(\nu_1 - \nu_2)}\sqrt{(a_+ + Q^2 + 2\vec{q}_1\cdot\vec{p}_1)(a_- + Q^2 + 2\vec{q}_1\cdot\vec{p}_1)}$$
$$a_\pm = 2\nu_1(\nu_2 \pm |\vec{p}_1|) - 2\nu_2|\vec{p}_1|(\cos\theta_{p_1 q_2} \pm 1 + \frac{|\vec{q}_1|}{|\vec{p}_1|}\cos\theta_{q_1 q_2})$$



Over-determined Kinematics

ν_2 also measured

$$\nu_2^{(1)} = \frac{(M^2 - \bar{M}^2_{(0)} + Q^2)/2 - \nu_1 E_1 + |\vec{q}_1|\,|\vec{p}_1| \cos\theta_{p_1 q_1}}{|\vec{q}_1| \cos\theta_{q_1 q_2} + |\vec{p}_1| \cos\theta_{p_1 q_2} - E_1 - \nu_1}$$

$$t_q^{(1)} = -Q^2 - 2(\nu_1 - |\vec{q}_1| \cos\theta_{q_1 q_2}) \frac{(M^2 \bar{M}^2_{(0)} + Q^2)/2 - \nu_1 E_1 + |\vec{q}_1|\,|\vec{p}_1| \cos\theta_{p_1 q_1}}{|\vec{q}_1| \cos\theta_{q_1 q_2} + |\vec{p}_1| \cos\theta_{p_1 q_2} - E_1 - \nu_1}$$

$$\nu_2^{(2)} = \frac{(\bar{M}^2_{(0)} - M^2 + Q^2)/2 + \nu_1 E_2 - |\vec{q}_1||\vec{p}_2| \cos\theta_{q_1 p_2}}{|\vec{q}_1| \cos\theta_{q_1 q_2} - |\vec{p}_2| \cos\theta_{p_2 q_2} - \nu_1 + E_2}$$

$$t_q^{(2)} = -Q^2 - 2(\nu_1 - |\vec{q}_1| \cos\theta_{q_1 q_2}) \left[\frac{(\bar{M}^2_{(0)} - M^2 + Q^2)/2 + \nu_1 E_2 - |\vec{q}_1||\vec{p}_2| \cos\theta_{q_1 p_2}}{|\vec{q}_1| \cos\theta_{q_1 q_2} - |\vec{p}_2| \cos\theta_{p_2 q_2} - \nu_1 + E_2} \right]$$

FSIs in Tagged DVCS

The power of exclusivity

$$\left[\bar{M}_{(1)}\right] \longrightarrow \quad \bar{M}^{\text{calc}} = \bar{M}_{(1)}(p_2, \hat{q}_2, \nu_2^{\text{exp}})$$

$$\left[\nu_2^{(1)}\right] \longrightarrow \quad \nu_2^{\text{calc}} = \nu_2^{(1)}(p_1, \hat{q}_2, \bar{M}_{(0)})$$

$$\left[\nu_2^{\text{calc}} \neq \nu_2^{\text{exp}}, \bar{M}^{\text{calc}} \neq \bar{M}_{(0)}\right] \Longrightarrow \quad \text{PWIA modified by FSI.}$$

$$\left[\bar{M}_{(2)}\right] \longrightarrow \quad \bar{M}^{\text{calc}} = \bar{M}_{(2)}(p_1, \hat{q}_2, \nu_2^{\text{exp}})$$

$$\left[\nu_2^{(2)}\right] \longrightarrow \quad \nu_2^{\text{calc}} = \nu_2^{(2)}(p_2, \hat{q}_2, \bar{M}_{(0)})$$

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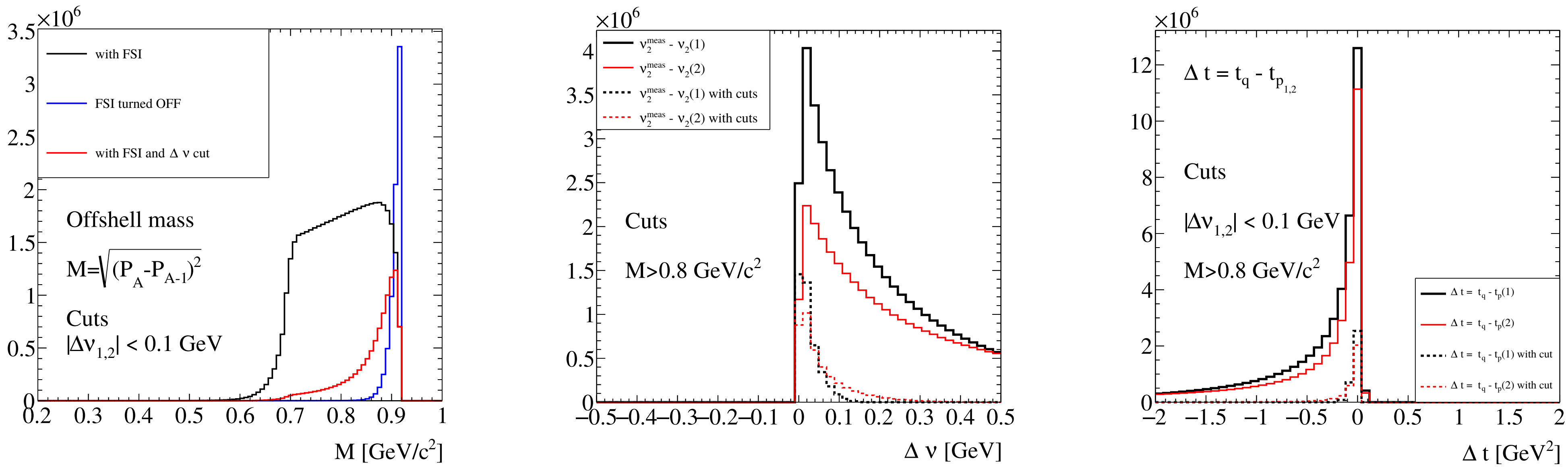
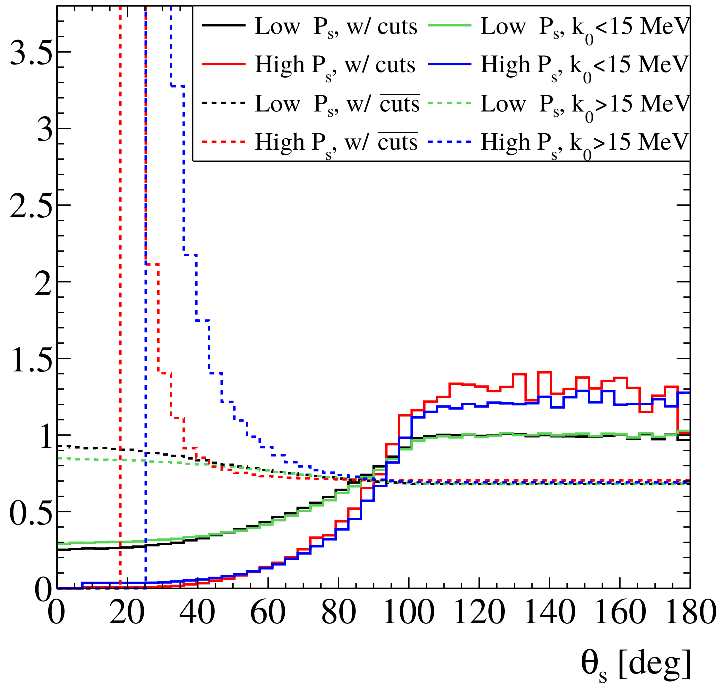
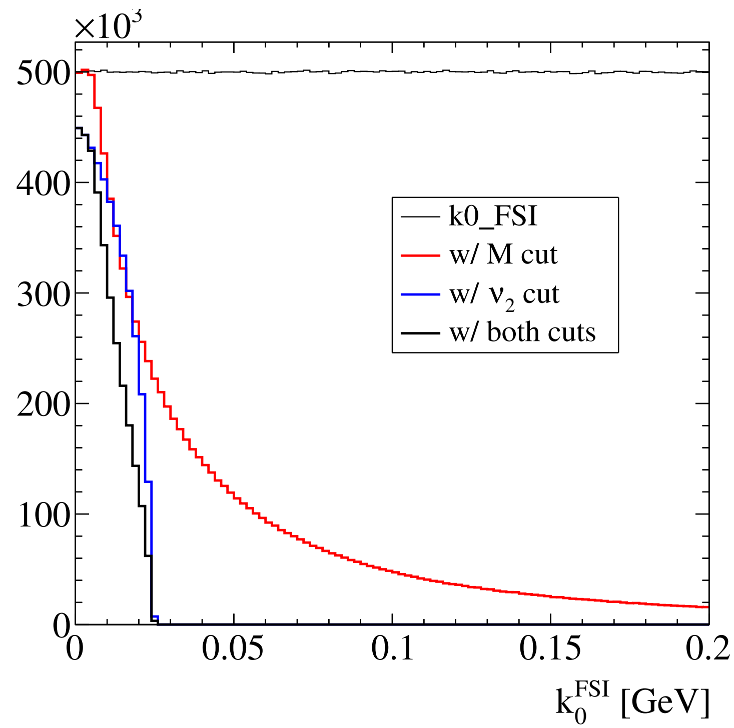
FSI Toy Model



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 modeling FSIs

With the FSIs systematically under control the origin of the EMC effect can be unambiguously identified as partonic in origin.

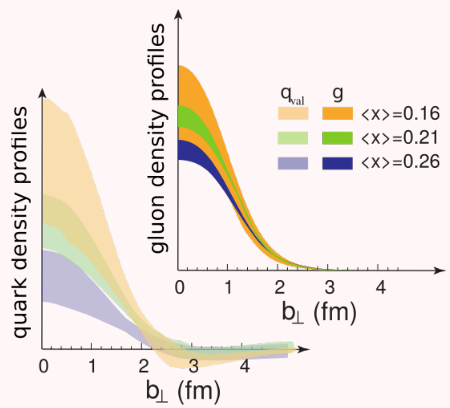
Extra Physics with ALERT (for free)

- With ALERT's **high luminosity and excellent PID capabilities**, the Spectator Tagged 3-Body Break-up (3BBU) through DVCS will also be extracted.
- **3BBU will isolate short-range correlated nucleons** by detecting both a spectator and a correlated nucleon in ALERT.
- ^{4}He$(e, e' \gamma + {}^2$H $+ p)n$
  For example the n-DVCS with a 2H spectator and recoiling SRC proton can provide the Off-forward ratio for the specific SRC configurations.
- ALERT can also reconstruct pair's relative momentum
- **Spectator-tagged DVCS with ALERT** can shed light on the **Partonic interpretation** of SRC nucleons and their contribution to the **Off-forward EMC Effect**

ALERT Run Group

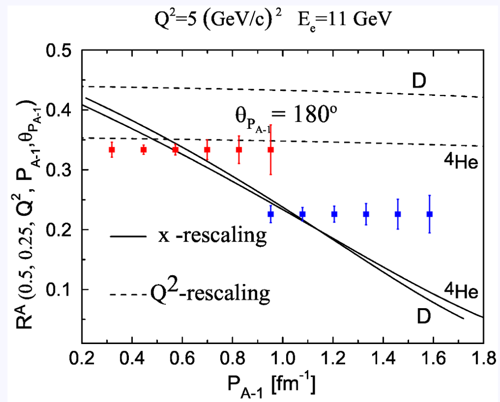
A Comprehensive Program to Study Nuclear Effects

Nuclear GPDs



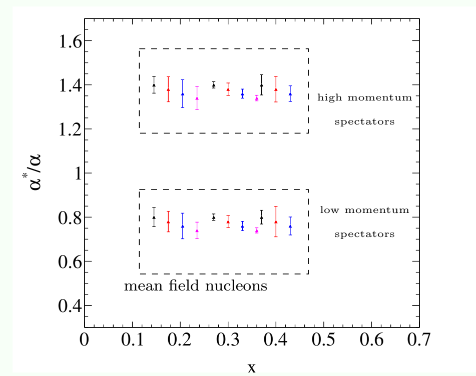
Directly compare quark and gluon radii

Tagged EMC



Address key questions about the EMC effect

Tagged DVCS



Connect partonic and nucleonic modification

ALERT is a bridge from JLab 12 GeV physics to the Electron Ion Collider

Nuclear Physics and the ~~Nucleon~~ α Particle

From the first textbook on Nuclear Physics

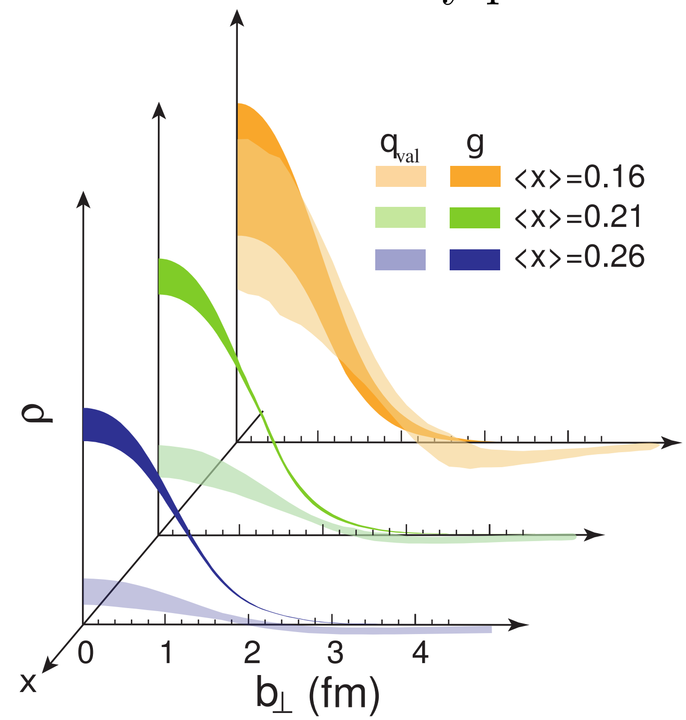
"The general evidence on nuclei strongly supports the view that **the α particle is of primary importance as a unit of the structure of nuclei** in general and particularly of the heavier elements. It seems very possible that the greater part of the mass of heavy nuclei is due to **α particles which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

ALERT Nuclear GPD projected results

Transverse density profiles

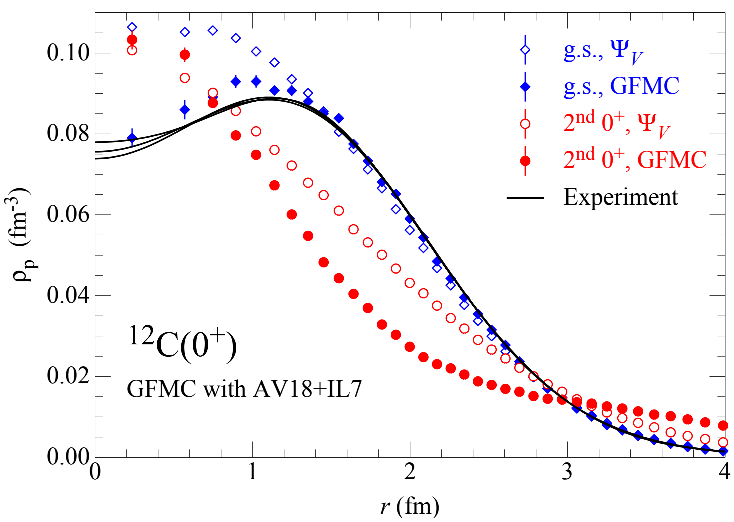


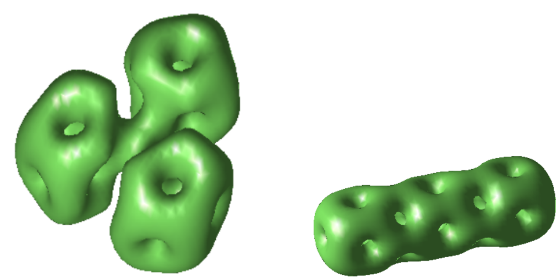
- Extract **quark and gluon radii!**
- Significant impact on EIC physics

Nuclear Physics ~~at~~ before an EIC

Looking to the near future

- Can we measure the transverse quark and gluon distributions in ^{12}C?
  - Detecting the recoil ^{12}C is very difficult! $\rightarrow$ new detector technology (early stages of R&D at Argonne)





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

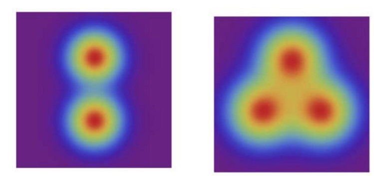


Figure 1 Charge density of ^{8}Be and ^{12}C in ACM.

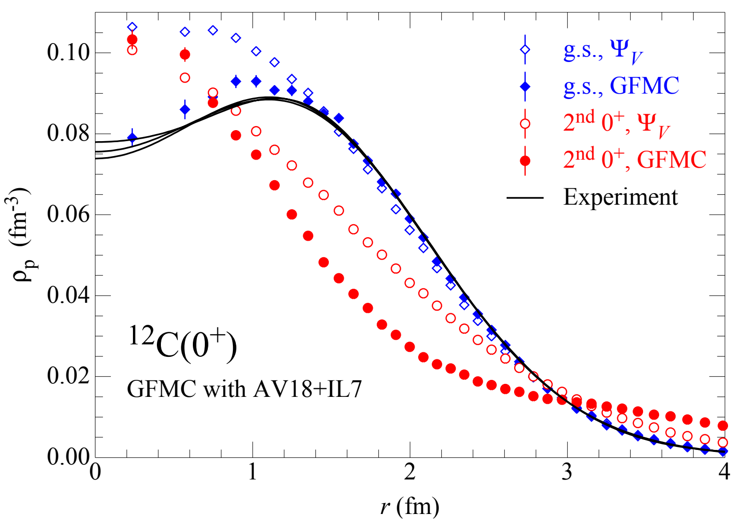
(Della Rocca, Iachello in progress)

Carlson, et.al., Rev.Mod.Phys. 87 (2015) 1067

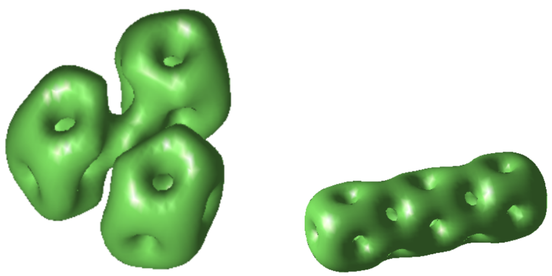
Nuclear Physics ~~at~~ before an EIC

Looking to the near future

- Can we measure the transverse quark and gluon distributions in ^{12}C?
  - Detecting the recoil ^{12}C is very difficult! → new detector technology (early stages of R&D at Argonne)
- Can we measure the **quark and gluon distributions of the α particles inside ^{12}C?**
  - Detecting the recoil α is slightly easier.
  - A new kind of nuclear EMC effect – αs are the new nucleons



Carlson, et.al., Rev.Mod.Phys. 87 (2015) 1067



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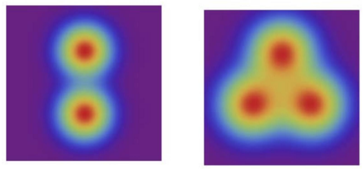

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Nuclear Physics ~~at~~ before an EIC

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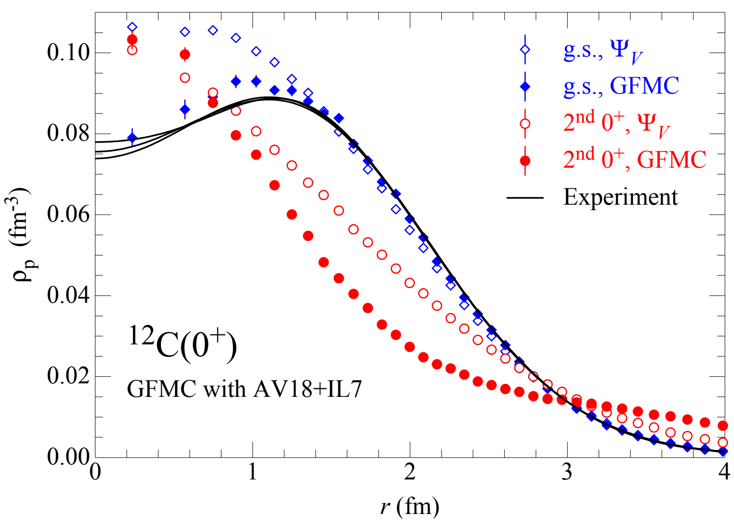
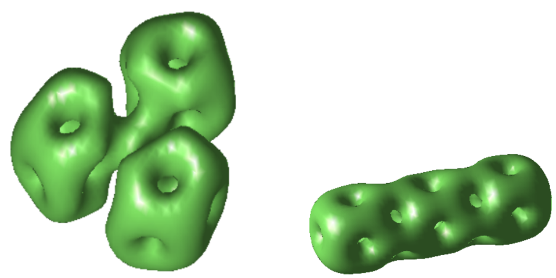
- Can we measure the **quark and gluon distributions of the α particles inside ^{12}C?**
    - Detecting the recoil α is slightly easier.
    - A new kind of nuclear EMC effect – αs are the new nucleons
- We can measure the coherent deuteron with ALERT. What about the coherent knockout of a deuteron in ^{4}He? (Non-nucleonic degrees of freedom, Hidden color)



Carlson, et.al., Rev.Mod.Phys. 87 (2015) 1067



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

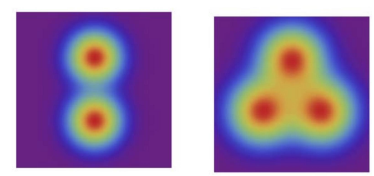


Figure 1 Charge density of ^{8}Be and ^{12}C in ACM.

(Della Rocca, Iachello in progress)

Summary

- Tagged DVCS will bridge the gap between **Partonic and Nucleonic interpretations** of medium modifications.
- Unique opportunity to connect the "free nucleon" modification in nuclear medium to its **partonic structure modification**
- This first-of-its-kind measurement is complementary to a wide variety of existing and proposed experiments
- Exclusivity provides a unique ability to systematically control nuclear effects and produce an unambiguous result
- Preliminary measurement for **in-medium hadron tomography program** at an Electron Ion Collider

Thank you!