Towards a 3D Landscape of Nucleons and Nuclei

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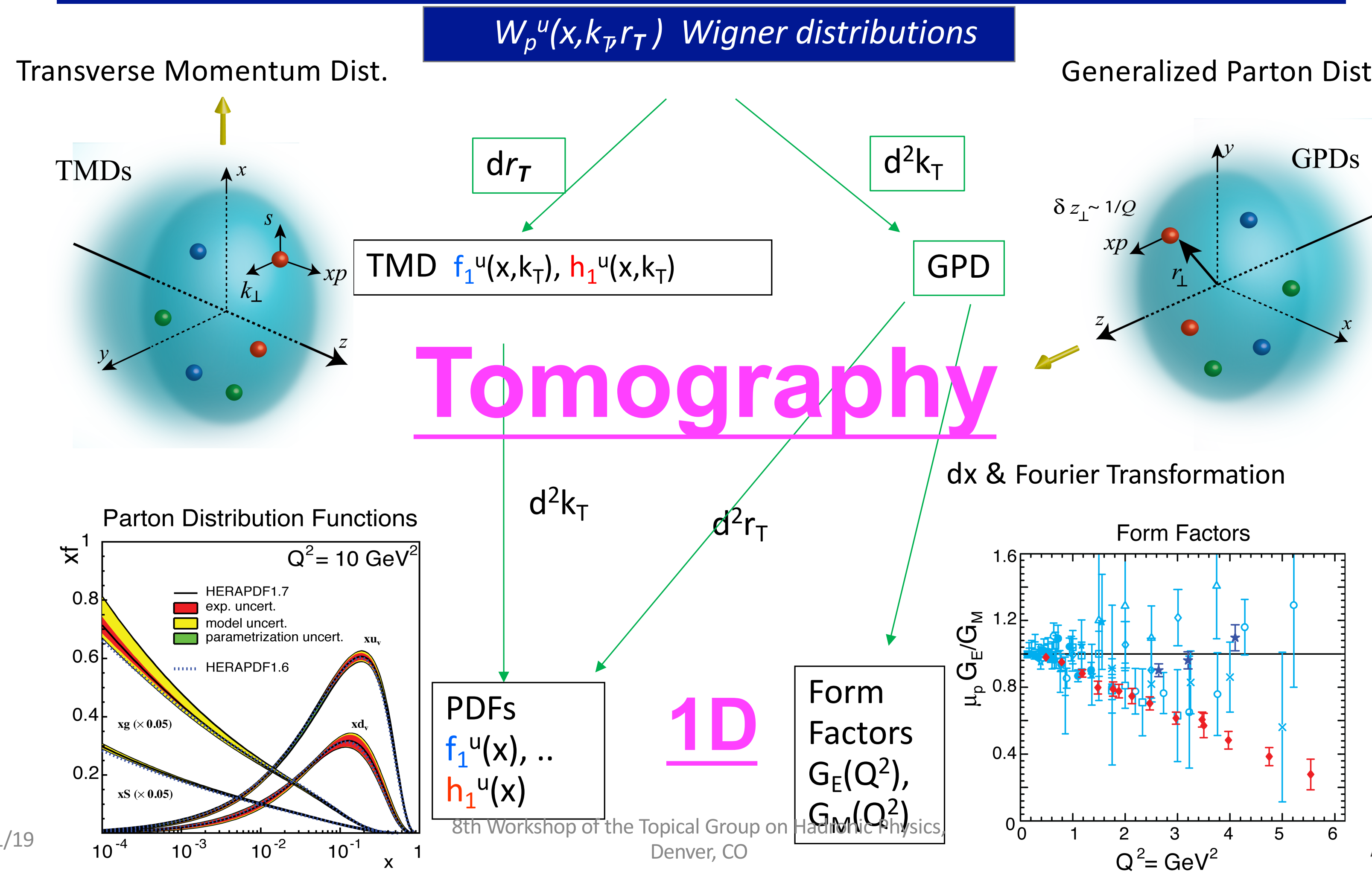
- Introduction
- Partonic imaging of the nucleon in position and momentum
- Partonic description of nuclei in position and momentum
- Summary

Unified View of Nucleon Structure



Science Goals

- Exploring our understanding of QCD
  - Factorization
  - Evolution, universality
- Distributions of confined partons
  - charge and matter distributions, pressure distribution and spin distribution.
- Dynamics of confined motion of partons
  - Orbital motion, spin-orbit correlations, phases
- Hadron formation, hadron propagation, coherence.

- Rest frame vs infinite momentum frame
- Models of the nucleon
- Lattice QCD
  - Moments of pdfs, quasi-pdfs….

Question in Nuclear Physics:

When does a nucleus behaves as one coherent collection of partons?

3D Imaging of Nucleons & Nuclei

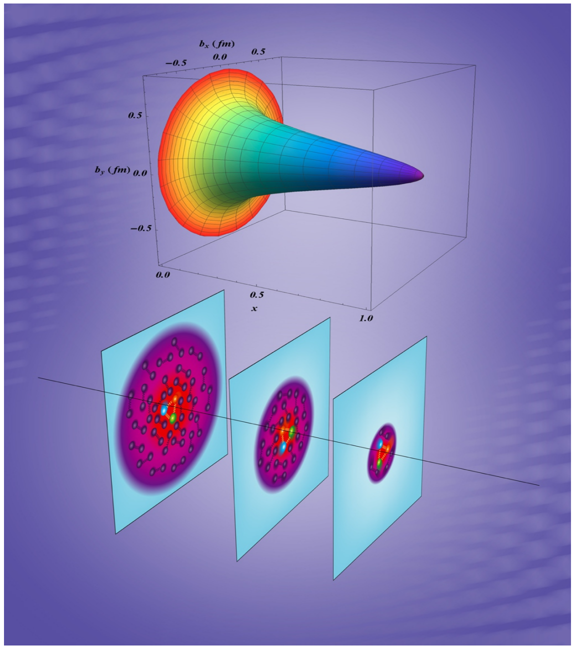
R. Dupré, M. Guidal, S. Niccolai and M. Vanderhaeghen
Eur. Phys. J. A **53,** no. 8, 171 (217)

- New theoretical framework within QCD
  - ✓ Non-local matrix elements linked to measurements
  - ✓ Wigner distribution for a unified picture
  - ✓ GPDs, TMDs: 3D images in space and momentum

- Valence Quarks: Proof of principle achieved using JLab 6 GeV data, 12 GeV data are forthcoming in the short term.
- Gluons and Sea quarks: EIC is the key facility

- 3D imaging is intimately linked to profound questions about intrinsic properties of the system in relation to its partonic constituents
  - Confinement size of charge and of matter, total mass, total spin

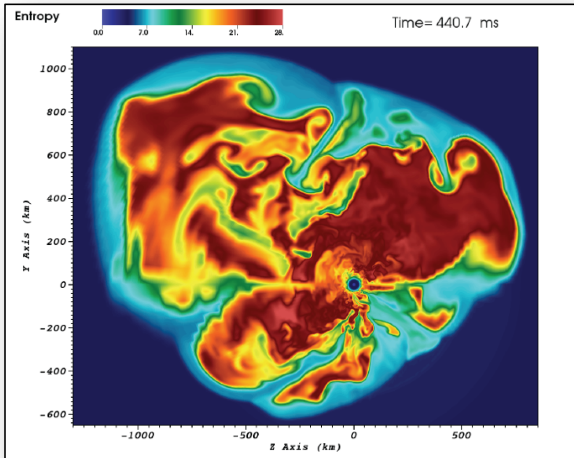
- The nucleus: a laboratory to study partons coherence, partons propagation, partons saturation, parton hadronization.



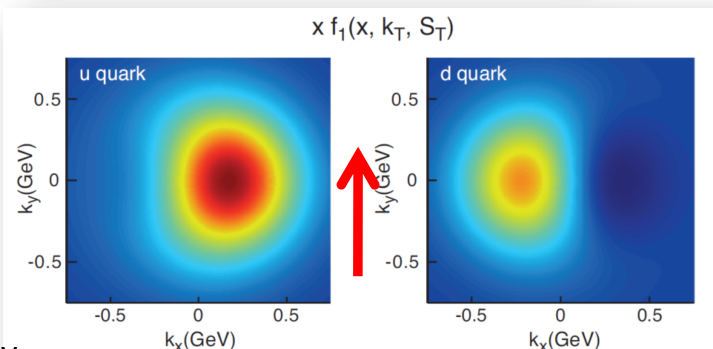
2D+1 quark spatial charge distribution in a proton accessible with JLab @ 12 GeV

Science in 3-Dimensions

3D simulation of $15M_{\odot}$ supernova (ORNL)

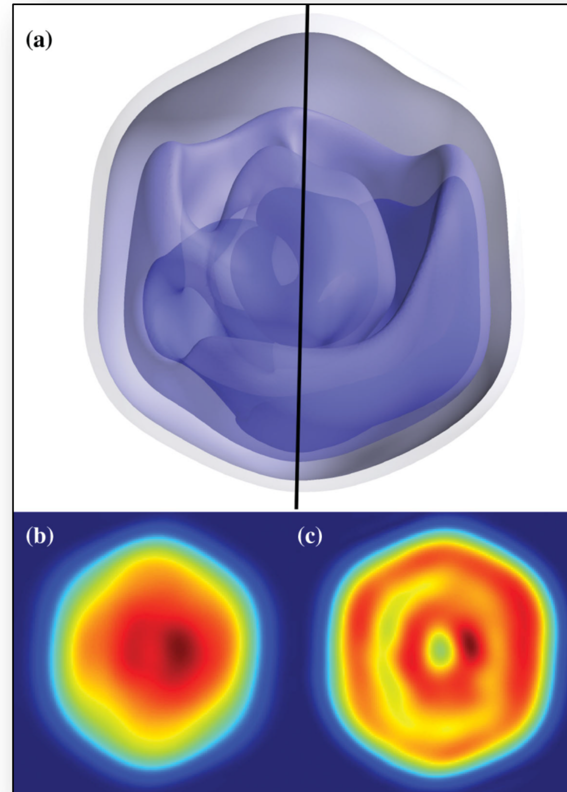


Predicted quark TMD for a polarized proton (accessible with JLab @ 12 GeV)



Prediction informed by
A global analysis of data from
HERMES, COMPASS and Jlab 6

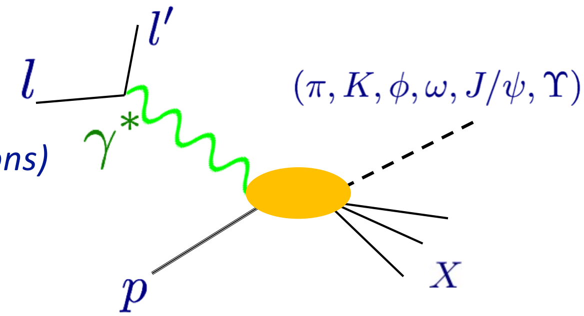
X=0.1



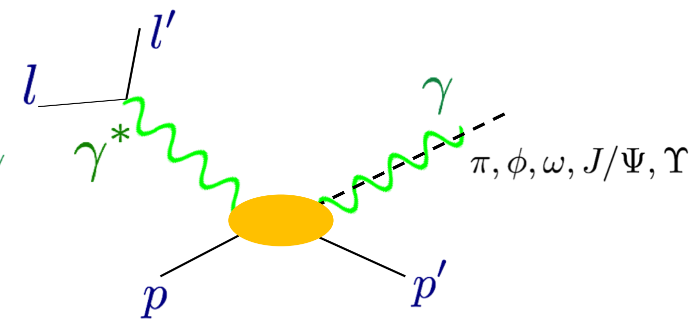
Mimivirus imaged at LCLS (SLAC)

Experimental tools to access GPDs & TMDs

- Semi-Inclusive reactions: *e+p/A → e'+h(π,K,…)+X*
  - *Detect scattered lepton in coincidence with identified hadrons (mesons)*
    Semi-Inclusive Deep Inelastic Scattering (SIDIS)
  - Challenge:
    - High polarized luminosity combined with large acceptance detectors
    - 5 key variables x,Q^2, z, p_T and angle between leptonic and hadronic plane
    - Fine binning needed

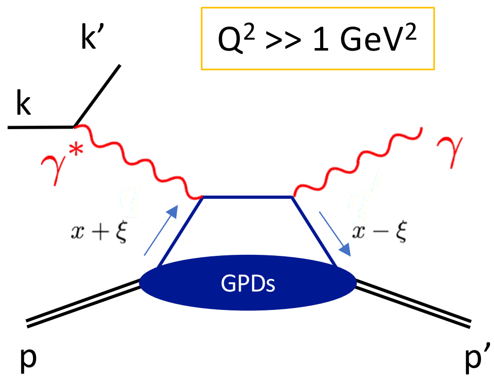


- Exclusive reactions: *e+p/A → e'+ p'/A'+ (γ,π,K,…)*
  - *Detect all final states including recoiling nucleon or nucleus*
    Deep Virtual Compton Scattering (DVCS) when detecting the real photon γ
    Deep Virtual Meson Production (DVMP) when detecting $\pi, \phi, \omega, J/\Psi, \Upsilon$
  - Challenge:
    - High polarized luminosity combined with large acceptance detectors
    - 4 key variables x,Q^2,t and angle between leptonic and production plane (ϕ)
    - Fine binning needed

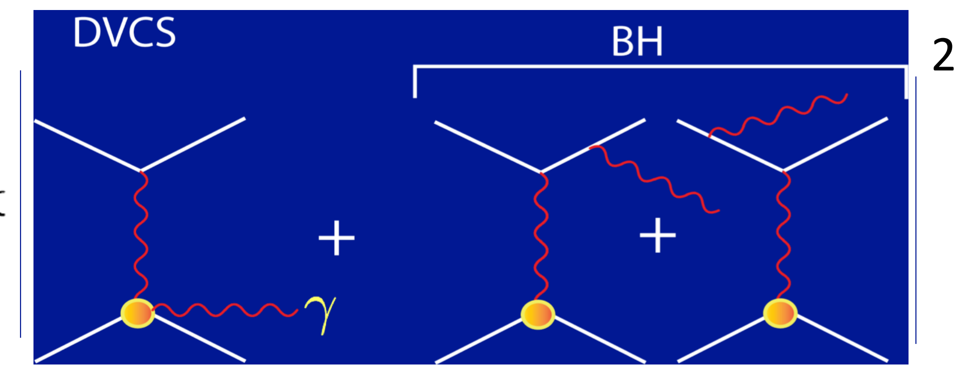


Deeply Virtual Compton Scattering

A clean probe of GPDs



$$\sigma(ep \longrightarrow ep\gamma) \propto \frac{d\sigma}{dx_B dQ^2 dt d\phi}$$



$$Q^2 = -q^2 = -(k - k')^2$$

$$t = (p' - p)^2$$

$$x_B = Q^2/2p \cdot q$$

$$t \ll Q^2 \quad , \xi \rightarrow \frac{x_B}{2 - x_B}$$

- At large Q^2: QCD factorization theorem
- At twist-2: 4 quark helicity conserving GPDs: $H_q(x, \xi, t, Q^2), E_q(x, \xi, t, Q^2), \ldots$
- Key: Q^2 leverage needed to test QCD scaling
- High statistics required for a clean extraction

Separating GPDs Through Polarization Measurements of Compton FF

$ep \longrightarrow ep\gamma$

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$

$k = -t/4M^2$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

⇒ $H, \tilde{H}, E$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H}+\xi(F_1+F_2)(H + \ldots\}d\phi$$

⇒ $H, \tilde{H}$

Unpolarized beam, transverse target:

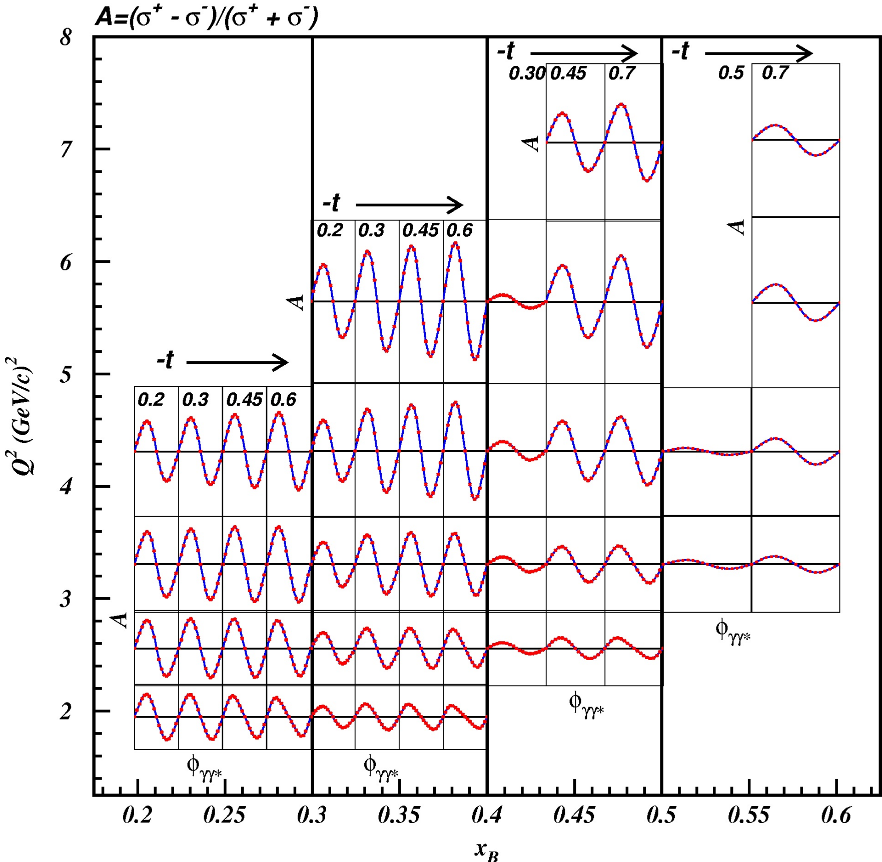
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \ldots..\}d\phi$$

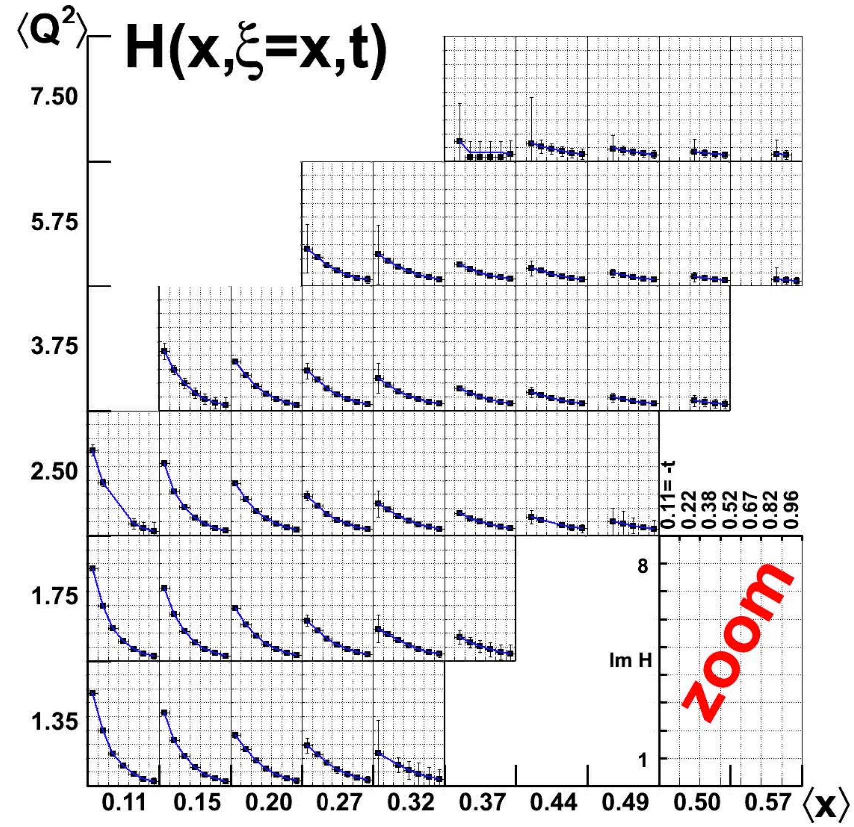
⇒ H, E

Global analysis of polarized and unpolarized data needed for GPDs separation

Proton Beam Spin Asymmetry A_{LU} (CLAS 12 projections)

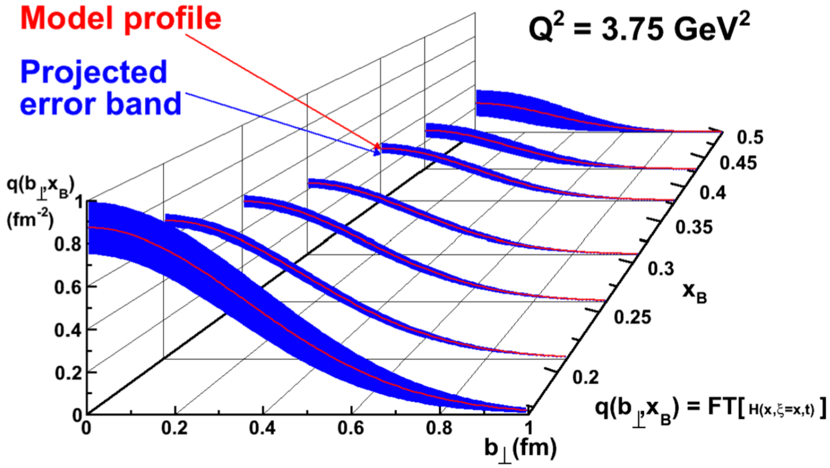
80 days @ 10^{35} cm^{-2}s^{-1} Polarized beam at 85% E12-06-009



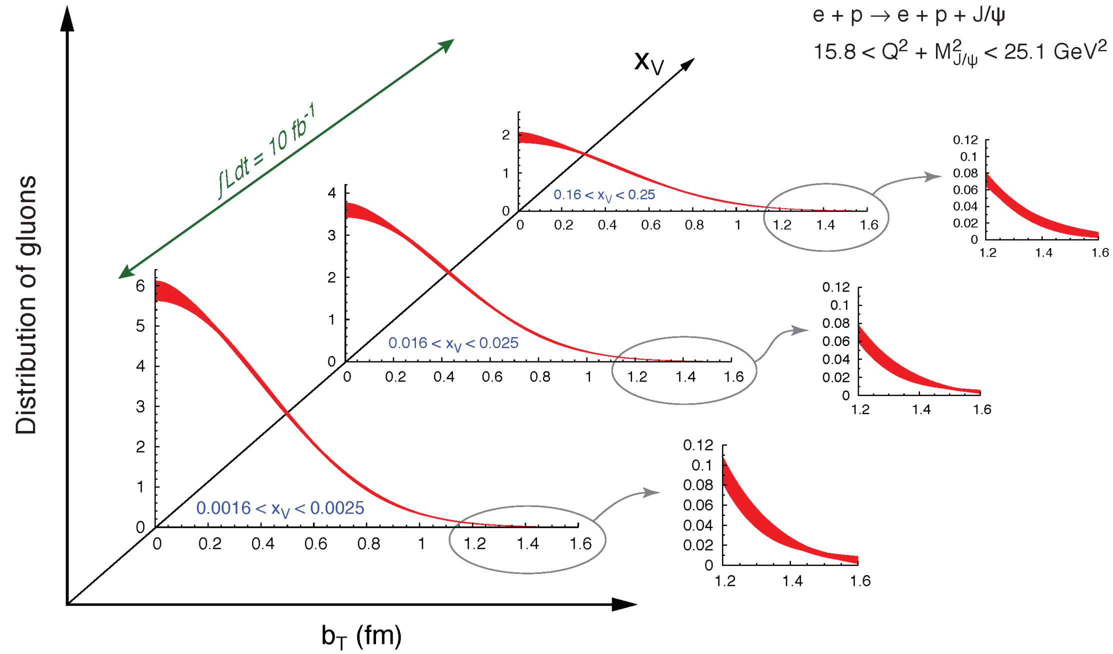


Projected Proton Transverse Profile for quarks and gluons

JLab with CLAS12
Valence quarks



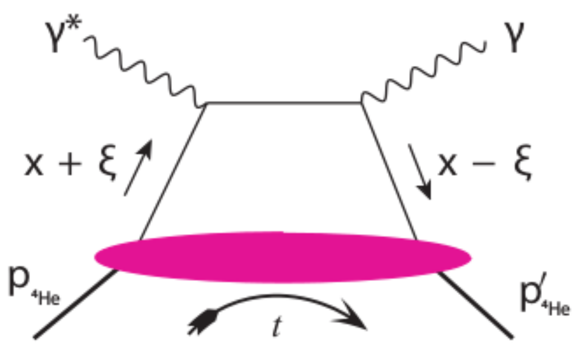
EIC
Gluons



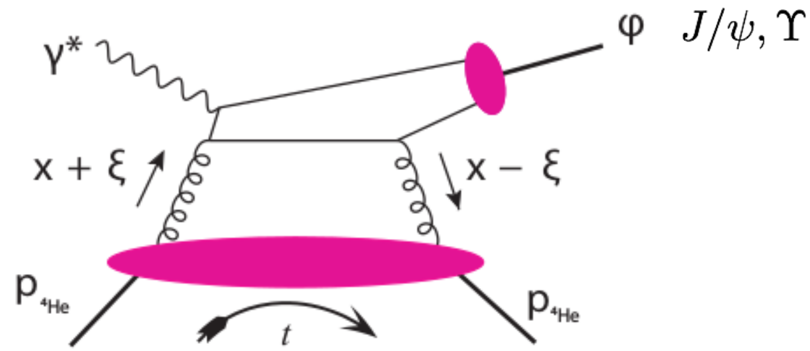
The Approved SIDIS Experiments in the 12 GeV Era at JLab

- **Hall A** (polarized ^{3}He and NH_3)
  - **Super Bigbite Spectrometer**
    - E12-09-018: SIDIS, 64d A-
  - **SoLID**
    - E12-11-108: *Target Single Spin Asymmetries in SIDIS (e,eπ±) Reaction on a Transversely Polarized Proton Target.* 120d A
    - E12-10-006: *Target Single Spin Asymmetries in SIDIS (e,eπ±) Reaction on a Transversely Polarized* ^{3}He target at 8.8 and 11 GeV 90d A
    - E12-11-007: *Asymmetries in SIDIS (e,eπ±) Reaction on a Londitudinally Polarized* ^{3}He target at 8.8 and 11 GeV ^{3}He, 35d A
- **Hall C** (unpolarized targets)
  - **SMS-SHMS**
    - E12-06-104: *Measurement of the ratio R= L/sigmaT in SIDIS,* 30d A
    - E12-13-007 *Measurement of Semi-Inclusive πº Production as Validation of Factorization,* 40d A-
- **Hall B** (unpolarized and polarized NH3, ND3, HD)
  - CLAS12
    - C12-11-111 *SIDIS on Tranversely Polarized Target (HDICE)*
    - *C12-12-009 Measurement of transversity with di-hadrons production in SIDIS with transversely polarized target (HDICE)*
    - E12-06-112 *Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV,* 38d A
    - E12-09-008 *Studies of the Boer-Mulders Asymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets,* 38d A-
    - E12-07-107 *Studies of Spin-Orbit Correlations with Longitudinally Polarized Target* 38d A-
    - E12-09-009 *Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with polarized hydrogen and deuterium* targets, 38d B+
    - E12-06-112A/E12-09-008A *Semi-Inclusive \Lambda electroproduction in the Target Fragmentation Region*
    - E12-06-112B/E12-09-008B *Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium.*

Nuclear Physics with Partons; A New Paradigm



Scanning quarks in ^{4}He



Scanning the gluons in ^{4}He

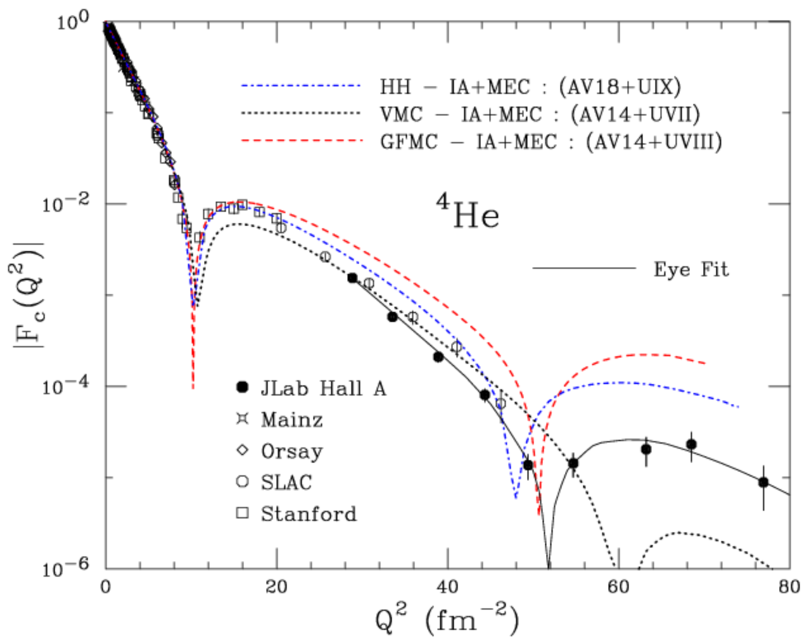
- Direct 3D partonic tomography using Coherent DVCS and DVMP on nuclei
- Investigate nuclei beyond the sum of nucleons
- Studying coherent phenomena at the partonic level
- Involving lattice to explore new phenomena at the partonic level
- Providing lattice data in the phase space that is not available

What do we know about ^{4}He?

A. Camsonne *et al.* PRL **112,** 132503 (2014)

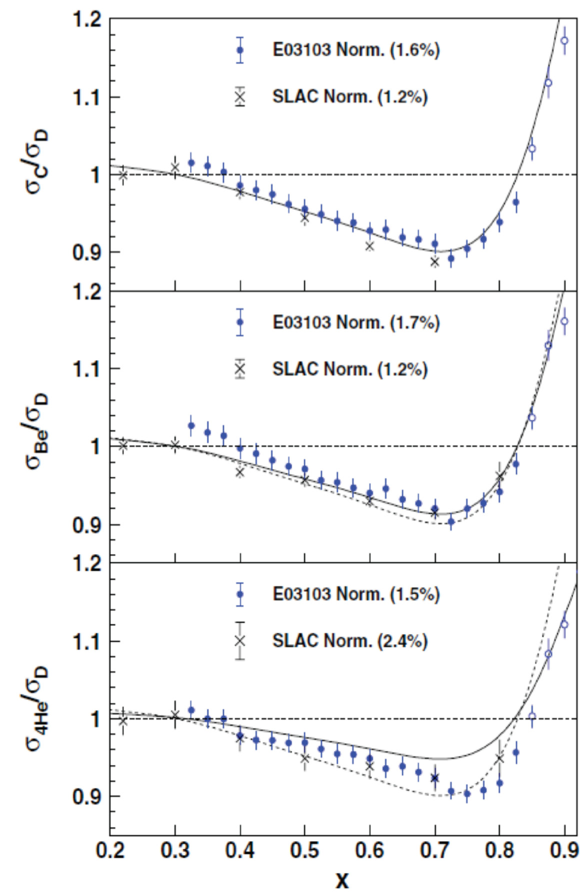
J. Seely et al., PRL **103**, 202301 (2009)

^{4}He Charge form factor



Nucleonic description

EMC effect



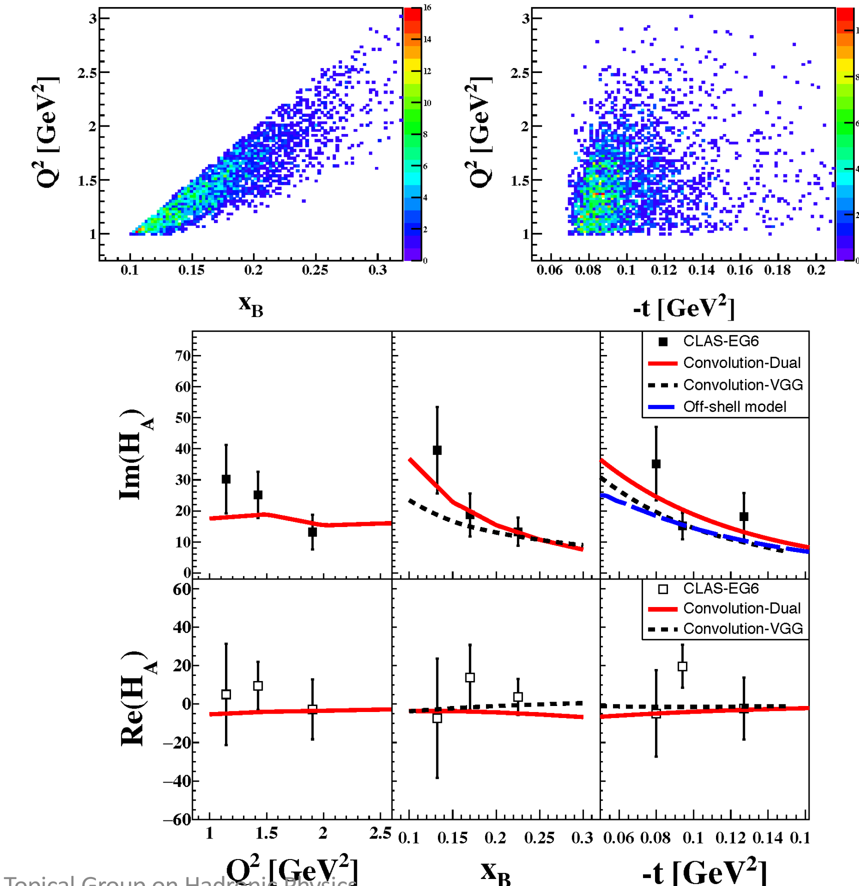
^{12}C

^{8}Be

^{4}He

DVCS on spin zero nuclei: ^{4}He; Proof of Principle Example

- A first DVCS experiment was performed at Jefferson Lab using a 6 GeV beam. It is JLab E08-024 performed with CLAS in Hall B.
- ^{4}He is a nucleus that can be described by one chiral-odd GPD $H_A(x, \xi, t)$
- Two channels are accessible with nuclear targets a coherent and incoherent channel; we consider the more potent being Coherent DVCS.
- The challenge: luminosity, exclusivity and small phase space at 6 GeV beam energy.



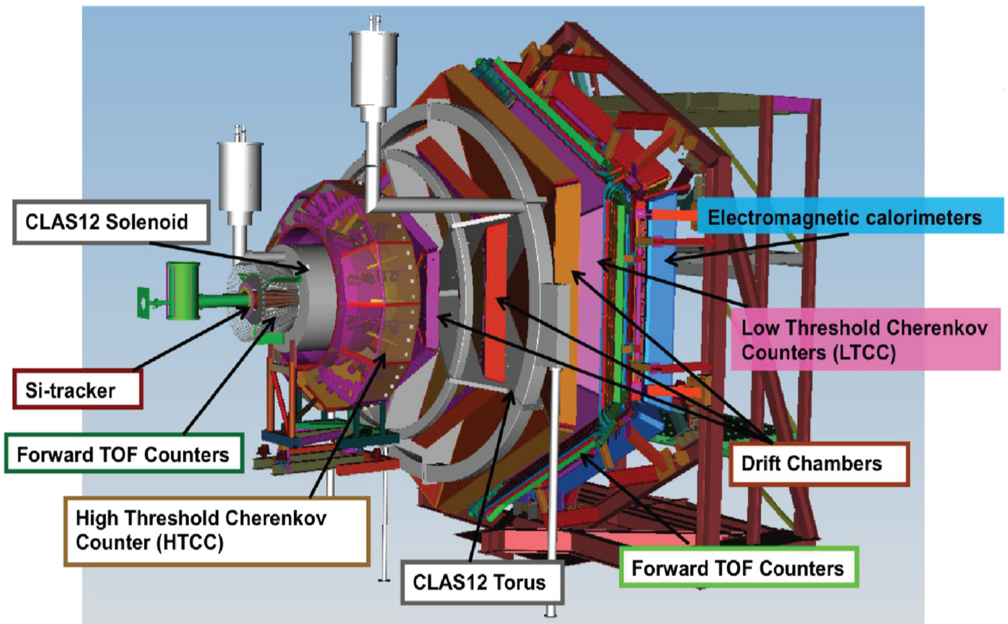
M. Hattawy *et al.* PRL **119** (2017) no.20, 202004

A follow-up JLab Proposal For CLAS 12

Partonic structure of nuclei, W. Armstrong *et al.,*
arXiv:1708.00888 [nucl-ex]. See also arXiv:1708.00891 [nucl-ex] and arXiv:1708.00835

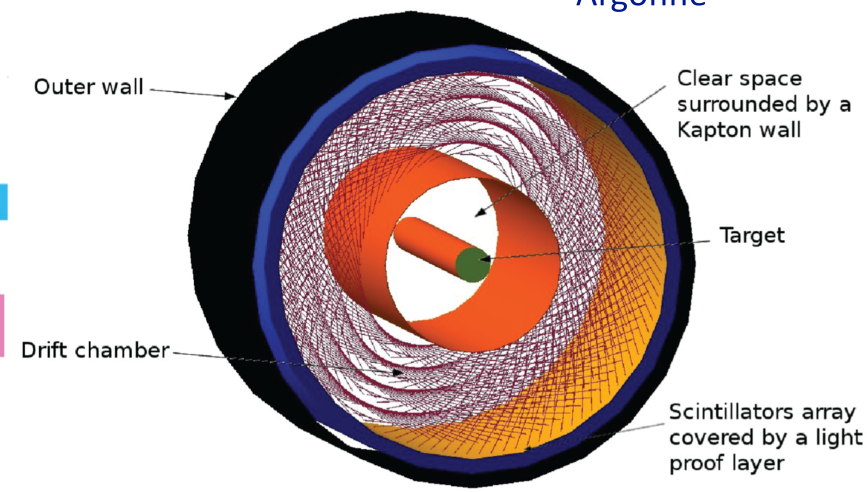
Spokespeople: W. Armstrong, N. Baltzell, R. Dupré, K. Hafidi, M. Hattawy, Z.-E. M(contact), M. Paolone

CLAS12 Detector



ALERT detector

IPN Orsay
Argonne



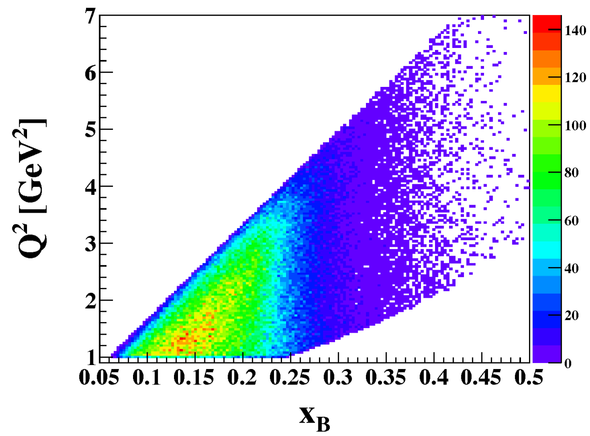
- 300 mm long
- 90 mm diameter

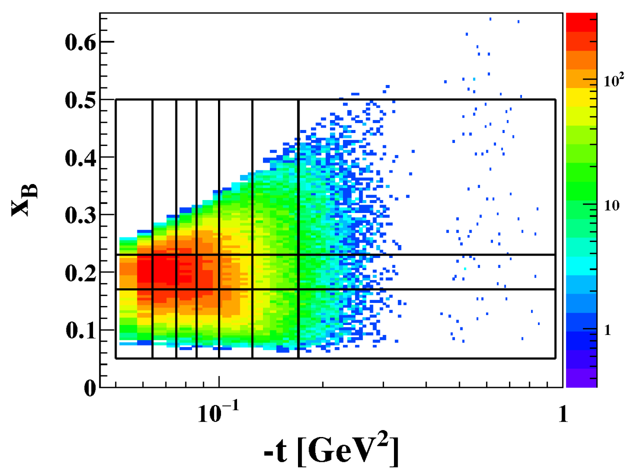
CLAS12 in combination with ALERT

- It is proposed to measure the partonic structure of ^{4}He, namely quarks and gluons GPDs using DVCS and DVMP (phi production)

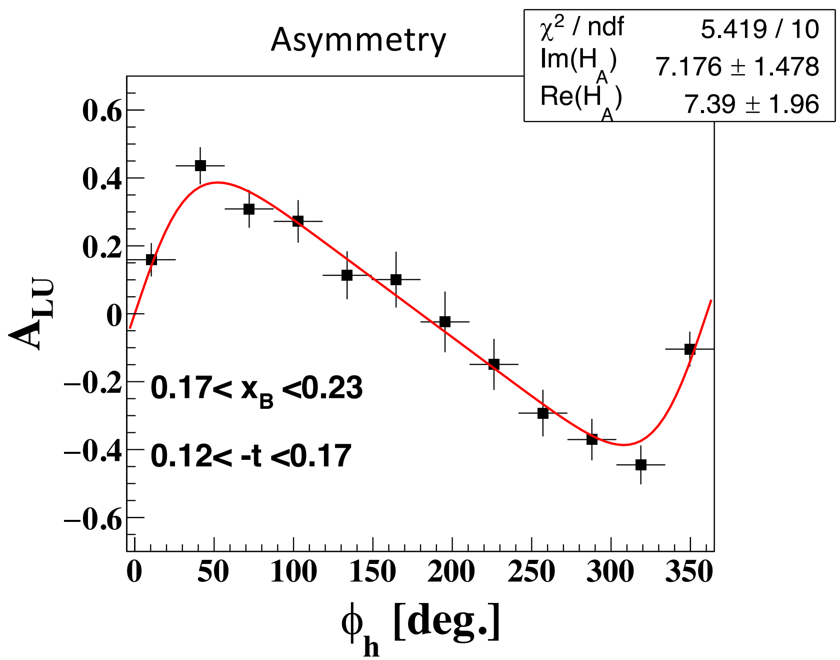
- For exclusivity CLAS12 detector will be used in combination with a new recoil detector known as ALERT

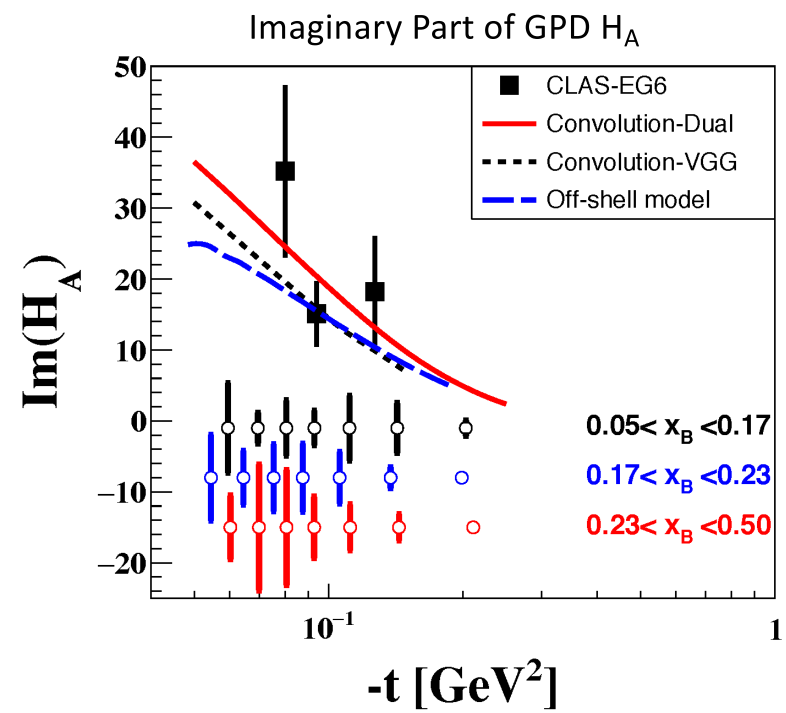
- Advantages:
  - Wider kinematic range
  - Higher statistics allowing 3D binning
  - More precise CFF extractions





Projected data with CLAS12 and ALERT: Valence Quarks

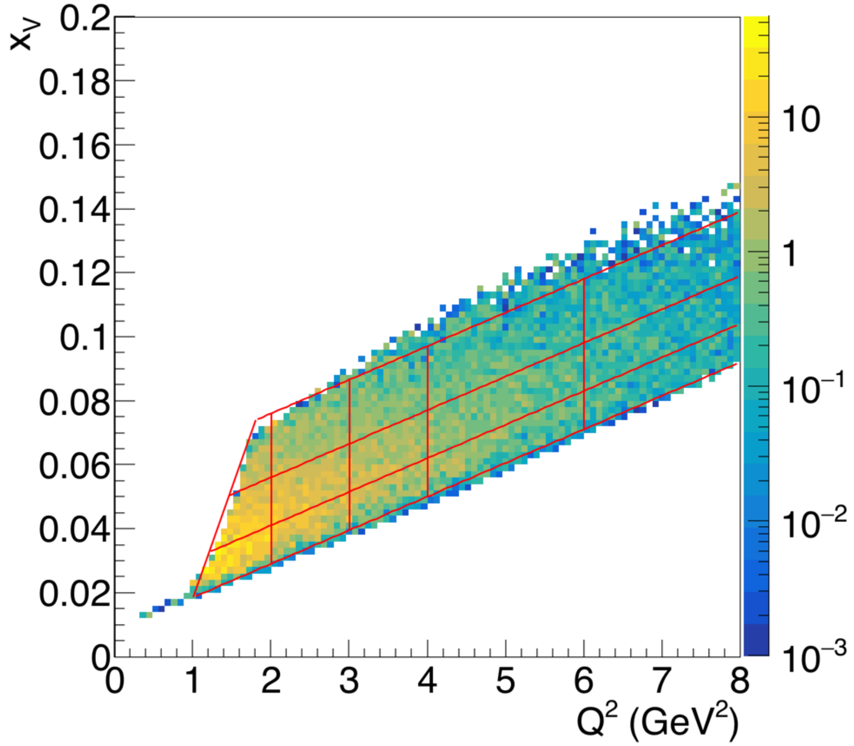


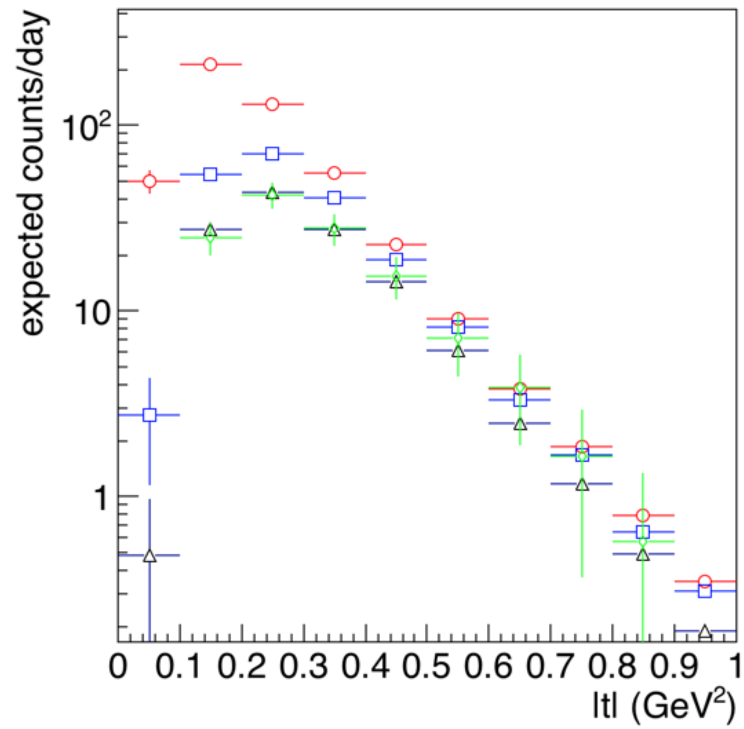


Valence Quarks

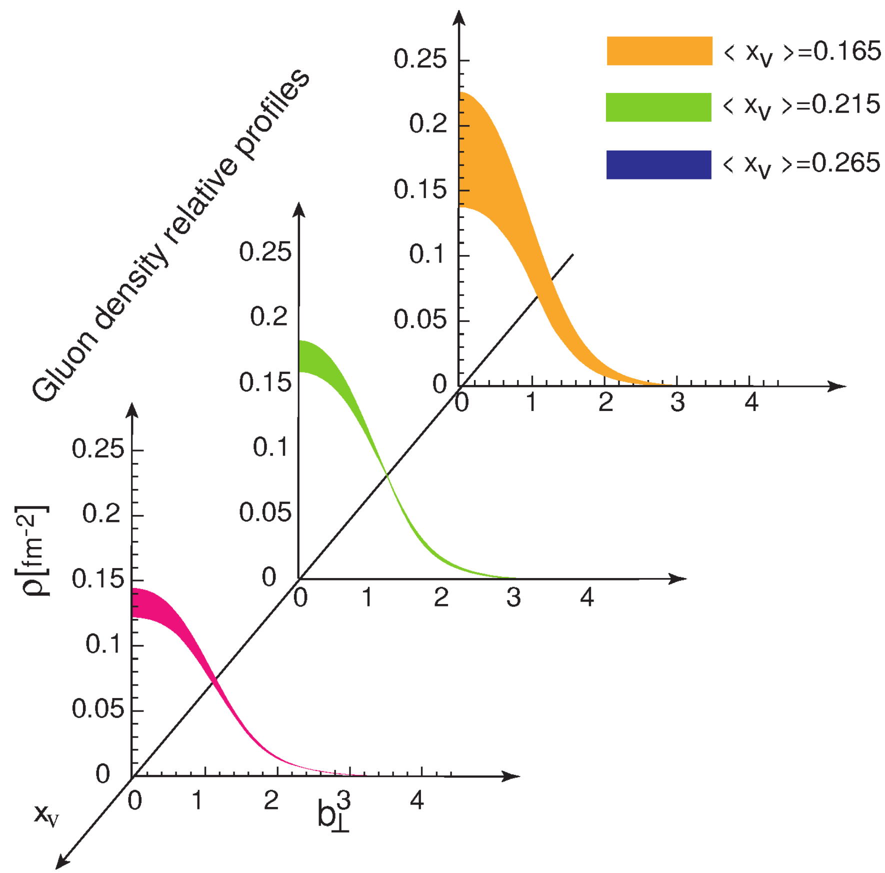
Projected data with CLAS12 and ALERT: Gluons

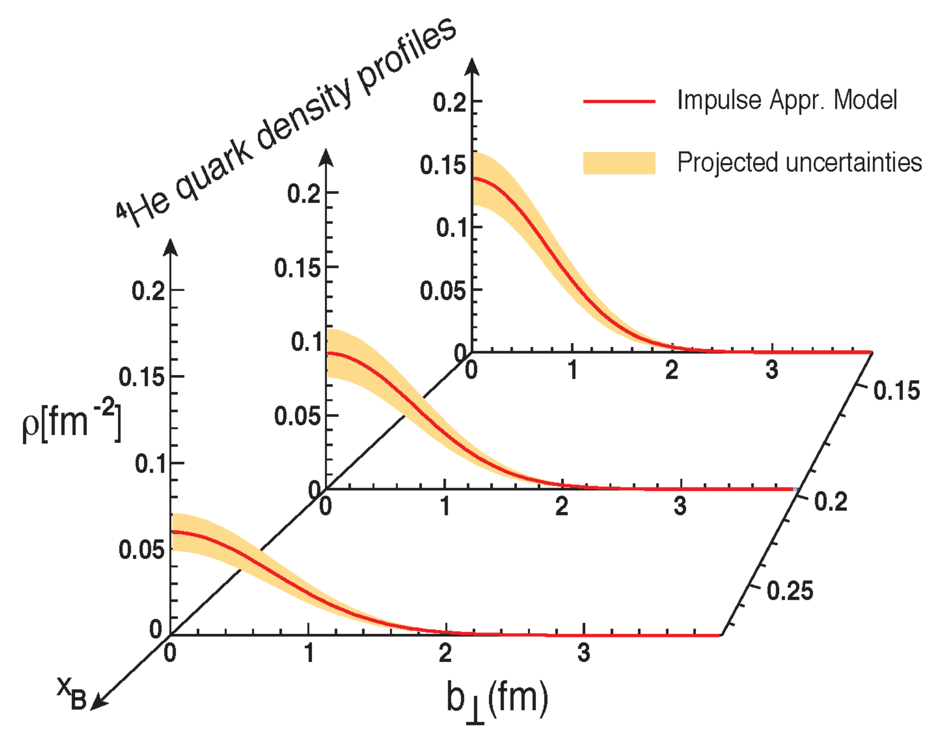
Deep Electroproduction of phi with subsequent phi decay into K^+K^-





Charge and matter density profiles in ^{4}He: Projected Results

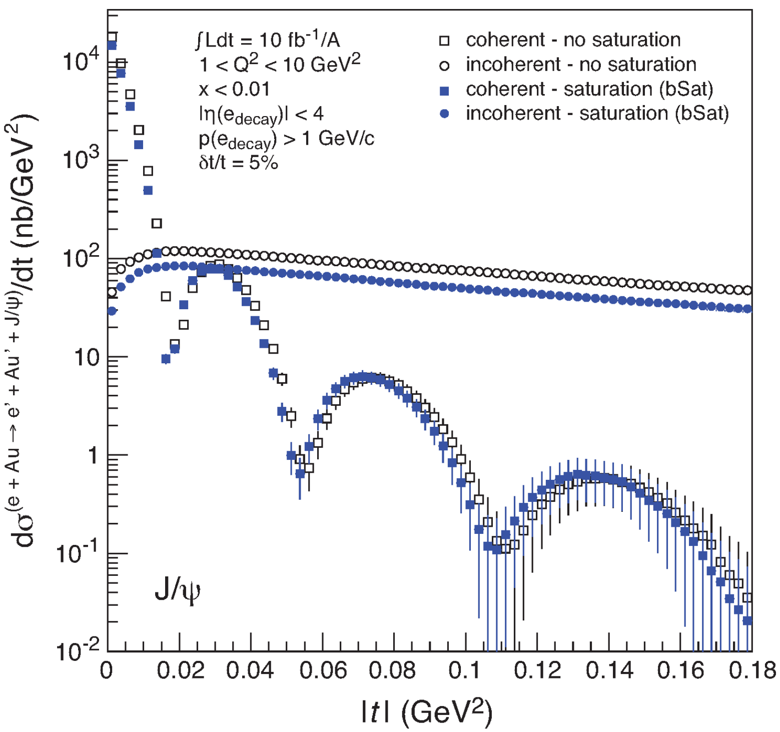




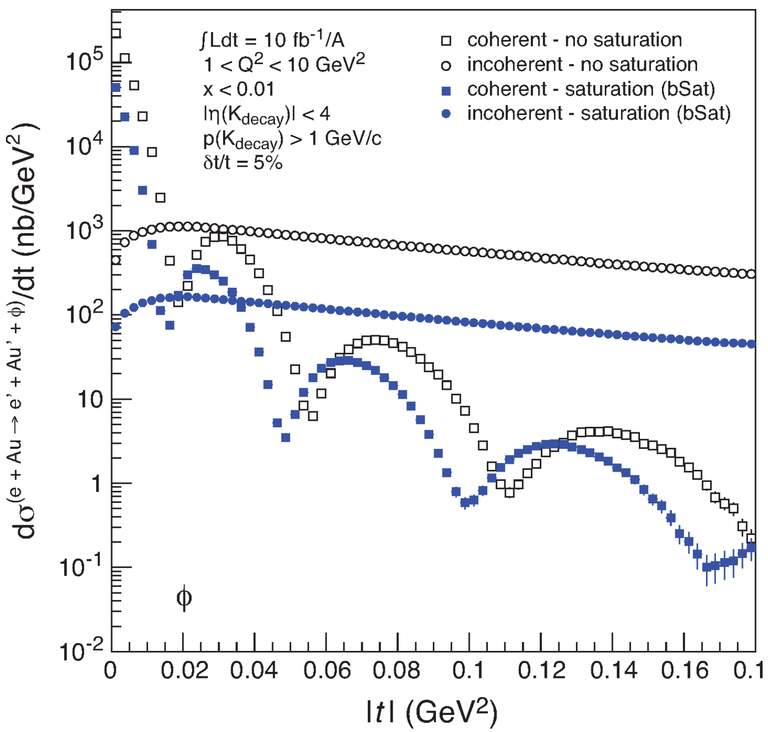
Coherent production at an EIC using $J/\psi, \phi$ Production

EIC White paper

J/ψ



ϕ



Challenges with Nuclei

- Jefferson Lab will provide information in the valence region
  - Coherent DVCS is safer, in terms of factorization, than coherent DVMP for the energy range involved.
  - The decrease in cross section due to the form factor requires CLAS12 high luminosity 10^{35} $cm^{-2}s^{-1}$ and higher.
  - Exclusivity requirement difficult for fixed heavy targets
  - The Q^2 should be large enough to insure factorization and the handbag diagram approach.
- EIC will provide information on the sea and gluon dominated region
  - Coherent DVCS and DVMP in a wide kinematic range will be accessible
  - DVMP with heavy quarkonia can provide more direct information on gluons
  - Recoiling nuclei will a little be easier to detect than in fixed target experiments
  - The luminosity is critical for the DVCS process for zero spin.

Confined Motion of Quarks and Gluons in ^4He

- One of the transverse momentum dependent distribution functions is known as the Boer-Mulders function
  - It corresponds to transversely polarized quarks in unpolarized nucleons.
  - The observable that contains the Boer-Mulders function is the angular modulation of the hadron plane with respect to the lepton plane.
  - It would be important to understand the EMC effect in the transverse momentum dependent distributions in comparison to the longitudinal case.
  - With the Boer-Mulders function there is no need to polarize the target and separate structure effect from spin effects.

- JLab 12 will start such a program using nuclear targets

- EIC will be the ultimate machine for such studies since it has wide kinematic flexibility to validate the global analysis of data.

- The challenge is having high luminosity and thus statistics to be able to provide bin in 5 –dimensions

$$x, Q^2, z, P_T, \phi - \phi_s$$

Summary

- The 3D landscape of nucleon and nuclei is challenging but not impossible.
- JLab 12 GeV is poised to make progress toward 3D imaging of the valence quark region of light nuclei
- An EIC with high polarized luminosity and variable energy with comprehensive recoil detection is key to probe the gluonic and sea quark landscape of nuclei

- Lattice calculations need to use the data for benchmark but should also guide the experiments in the corners of the phase space not accessible by experiment.

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Volume 56 Number 4 May 2016
“Polarized”
Luminosity is the key
THANK YOU
LHC
Run 2 restarts after the technical shutdown
p7
PROJECTS
The ILC programme maintains its high momentum
p16
THE HL-LHC IN FULL SWING
Successful tests for the first components p31