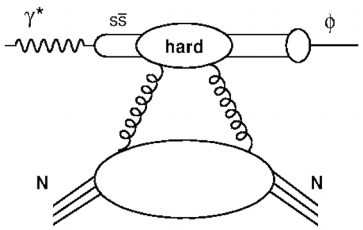
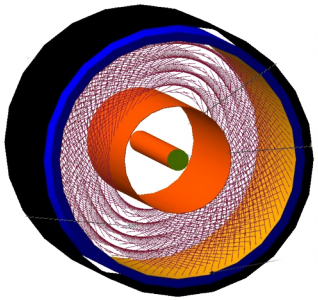
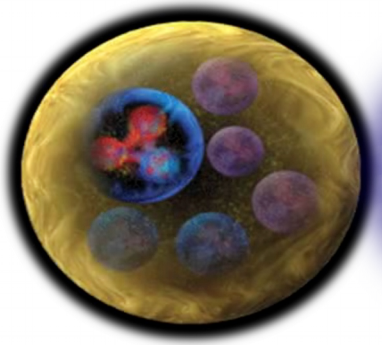
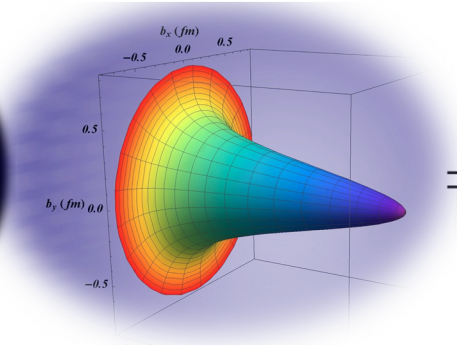
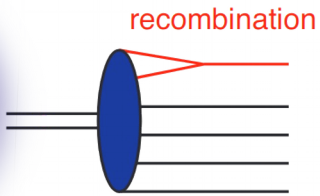
The Foundations of EIC Physics at JLab 6 and 12 GeV











We are starting now at JLab
much of the science program of EIC

Raphaël Dupré

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université PARIS-SACLAY

erc European Research Council
Established by the European Commission

Disclaimer

This can only be a selection

- I made this presentation as a parallel to the EIC white paper

The Next QCD Frontier : Understanding the glue that binds us all
Accardi et al. Eur. Phys. J. A52 (2016) no.9, 268

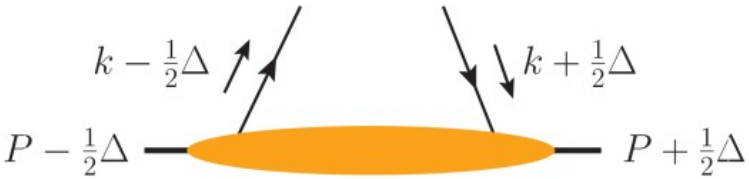
- Skipped many other topics in JLab program that are interesting in EIC perspective

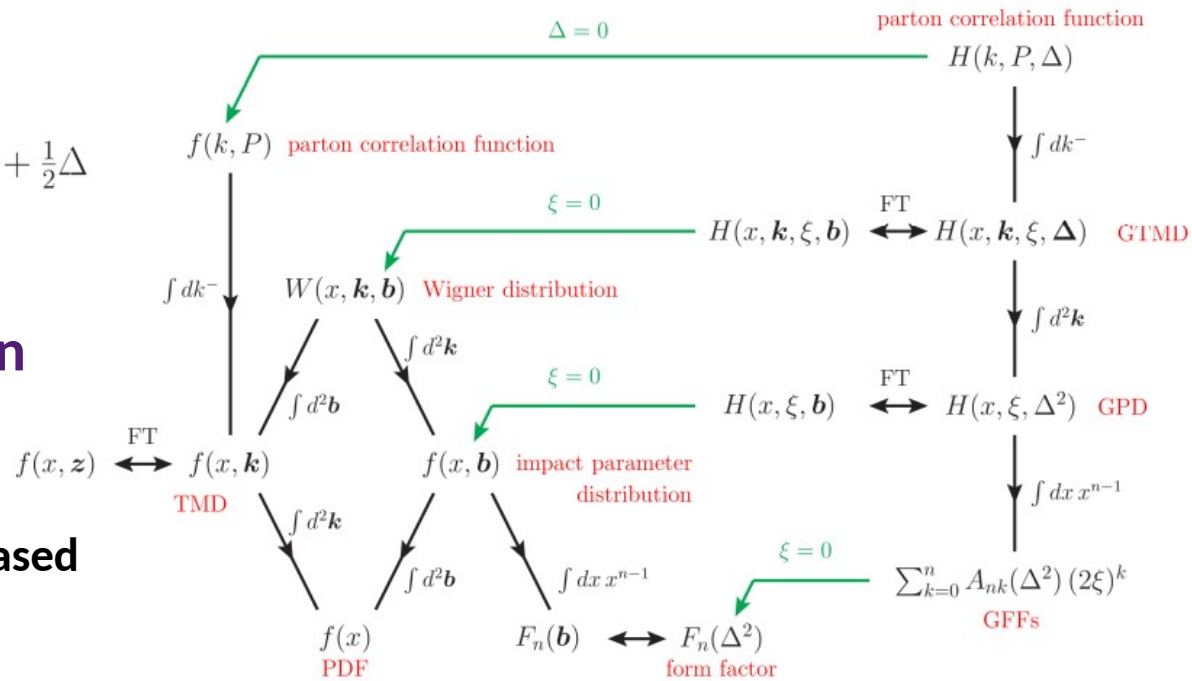
Interestingly, this is not a one way road

- Many aspects of the EIC program are inspired from JLab
- In some occasions the opposite is true as well

Anyway, there is a lot to cover...

Nucleon Structure





Many functions to parameterize the unknown

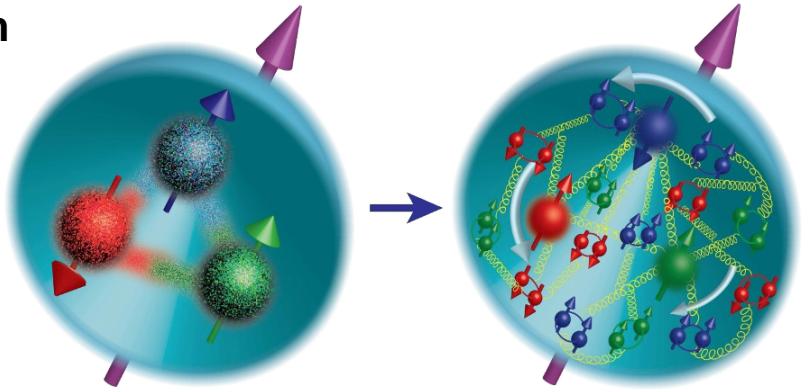
- **In QCD we have very little direct information on them**
- **Their knowledge is mostly based on experiment**

They are carefully defined

- **To understand the structure of the target hadron**
- **They are universal, i.e. not process dependent**

A Key element of the EIC program

- **Study of the 3D functions (GPDs and TMDs)**
  - *Focused on low x and the glue*
- **Hope for extensions up to Wigner functions (5D)**



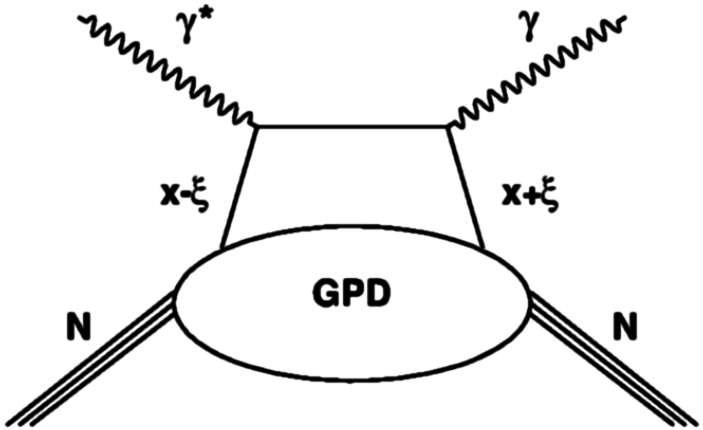
Generalized Parton Distributions

Generalizing the parton distributions

- Three dimensional (x, ξ and t) structure functions
- Accessible through exclusive processes
  - *DVCS, DVMP, TCS, DDVCS…*

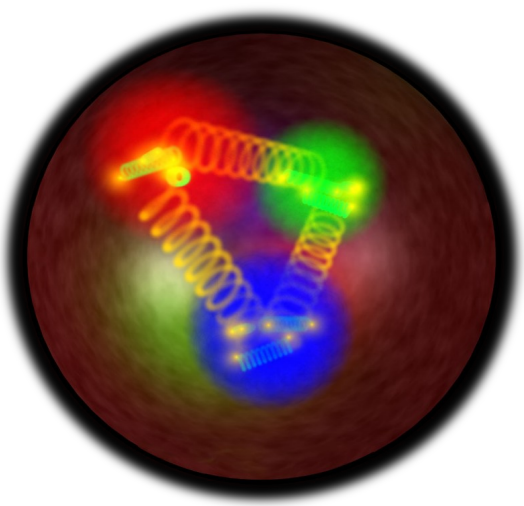
Deeply virtual Compton scattering

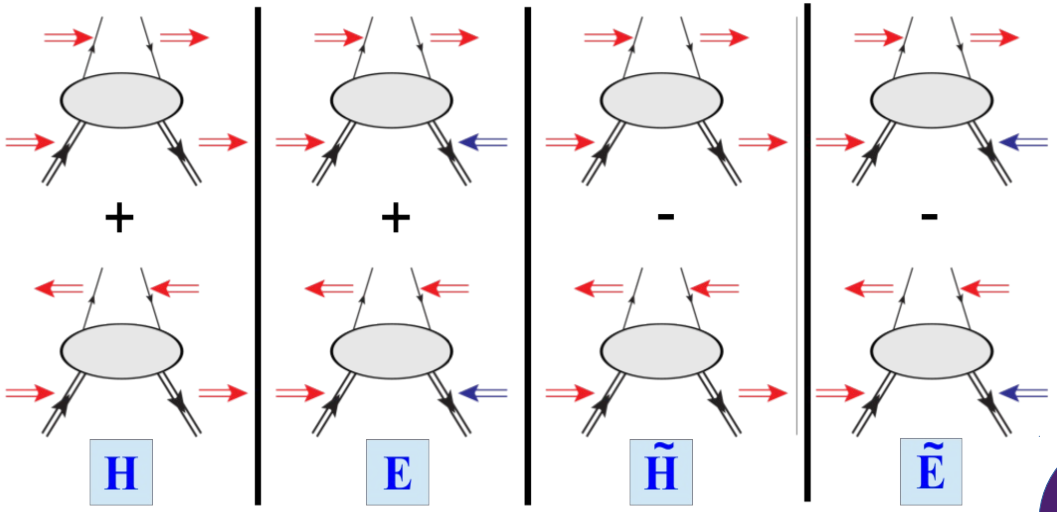
- The exclusive electro-production of a photon
  - *The simplest access to GPDs*
- x is not directly measurable
- We access the Compton Form Factors (CFF)



$$F_{Re}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left[\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right] F(x,\xi,t),$$

$$F_{Im}(\xi,t) = F(\xi,\xi,t) \mp F(-\xi,\xi,t).$$





Measuring DVCS

DVCS is not the only process to produce photons exclusively

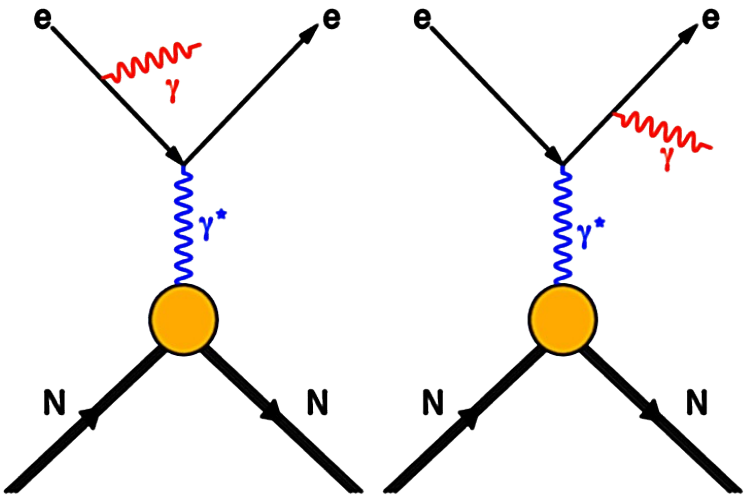
- Photons can be emitted by the lepton (Bethe-Heitler)
- Generates asymmetries through its interference with DVCS

Gives many interesting observables

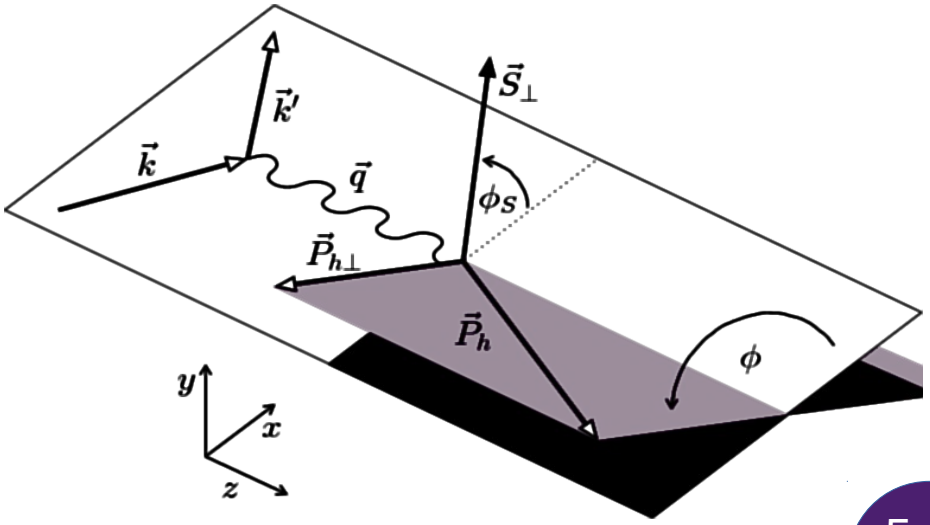
- Absolute cross sections
- Spin asymmetries (beam and target)
- Charge asymmetries

Allows to extract the complex CFFs

- A complete set of measurement is possible
- But only achieved by HERMES



$$d\sigma \propto |\tau_{BH}|^2 + \underbrace{(\tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS})}_{\mathcal{I}} + |\tau_{DVCS}|^2$$



GPDs at JLab 6 GeV

Jefferson Lab has a key role for GPDs

- **It is the main provider of DVCS data**

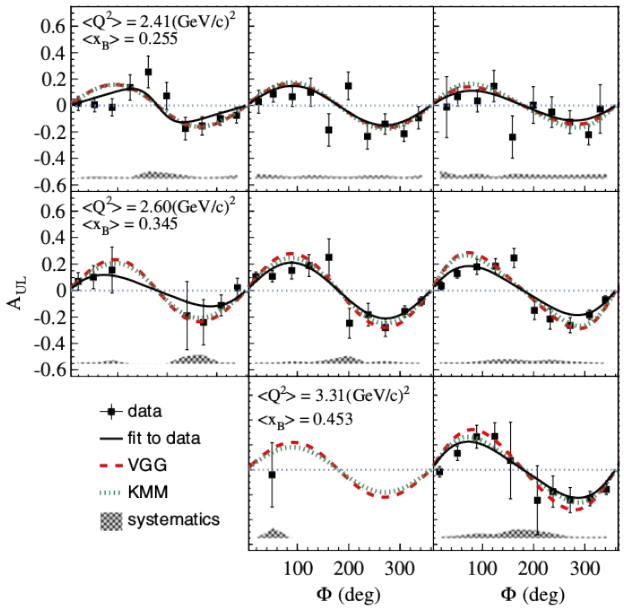
JLab Hall A Collaboration (Defurne, M. et al.) Phys.Rev. C92 (2015) no.5, 055202

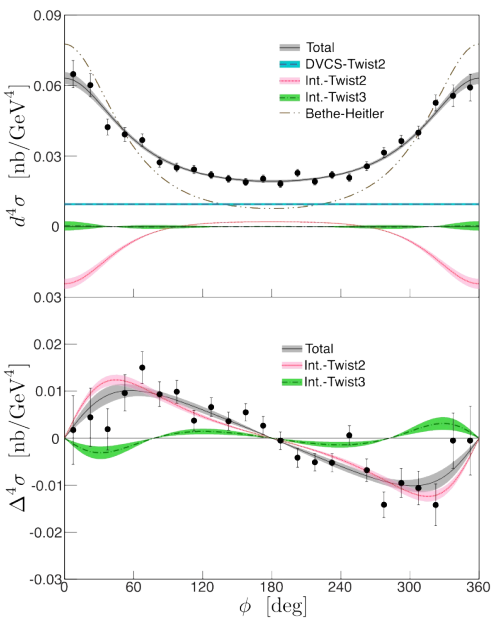
CLAS Collaboration (Jo, H.S. et al.) Phys.Rev.Lett. 115 (2015) no.21, 212003

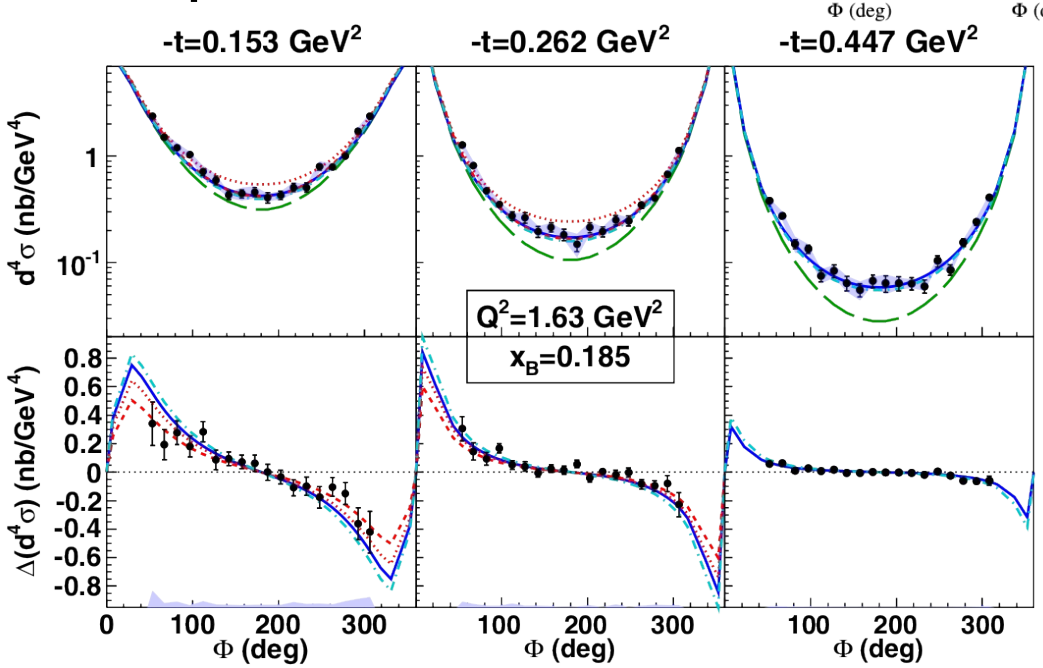
CLAS Collaboration (Pisano, S. et al.) Phys.Rev. D91 (2015) no.5, 052014

CLAS Collaboration (Seder, E. et al.) Phys.Rev.Lett. 114 (2015) no.3, 032001

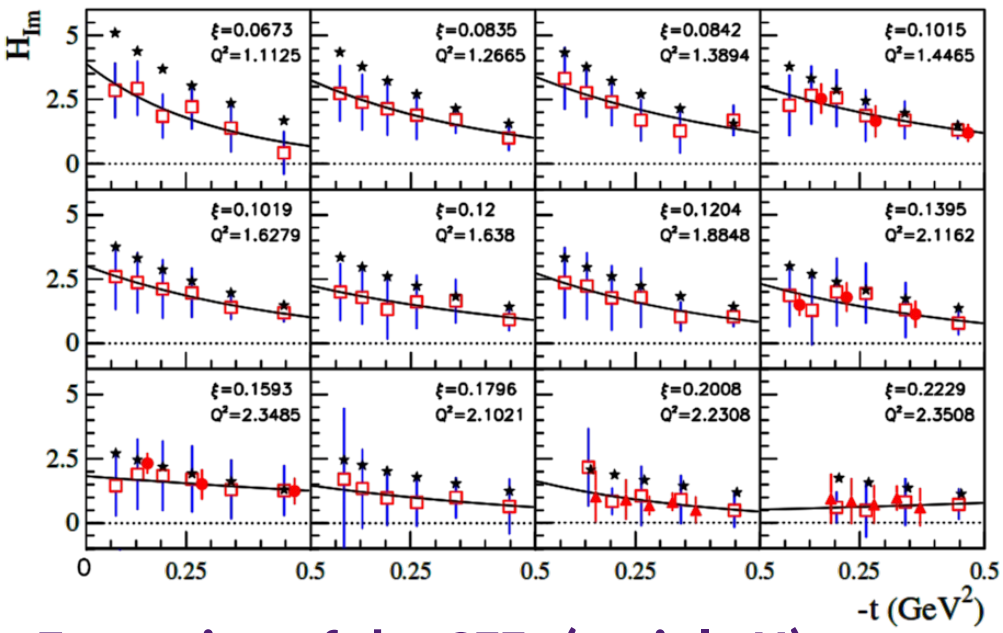
- **Much data over a large phase space**
  - *Allows already GPD extractions and tomography*
- **Also a key facility in exclusive meson production**

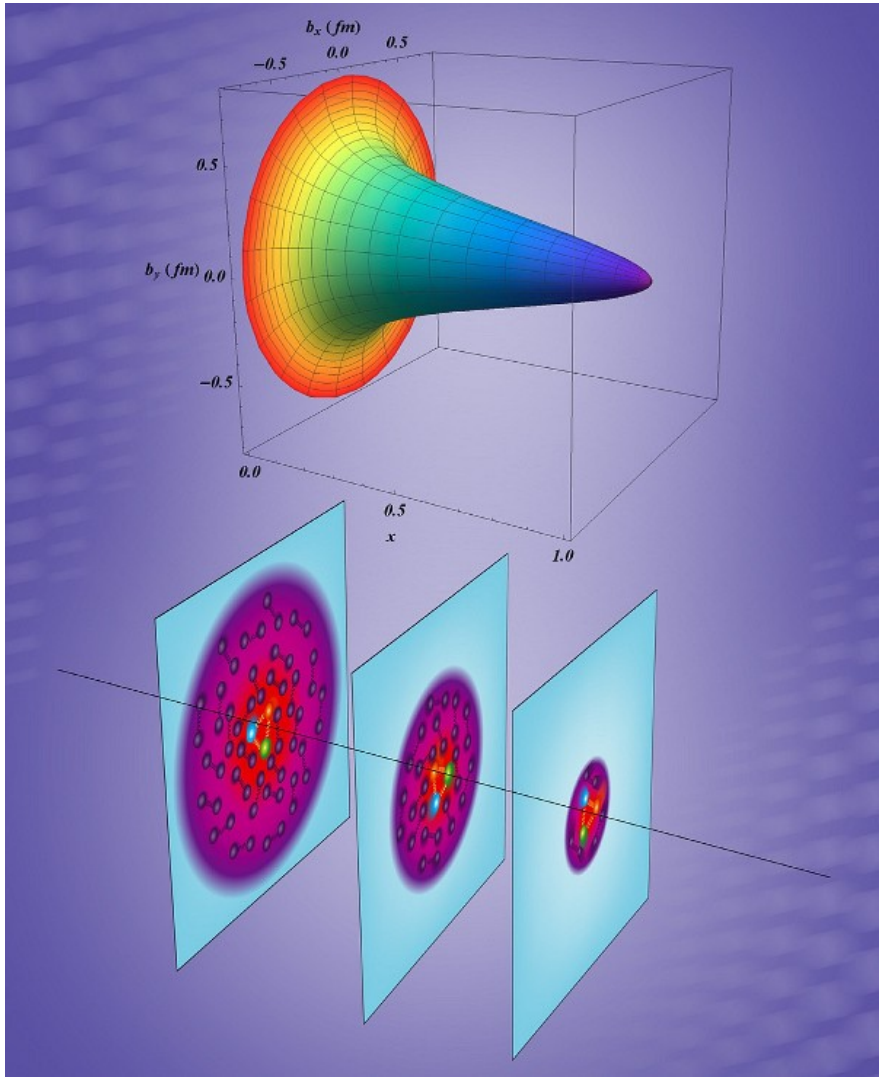






Proton Tomography





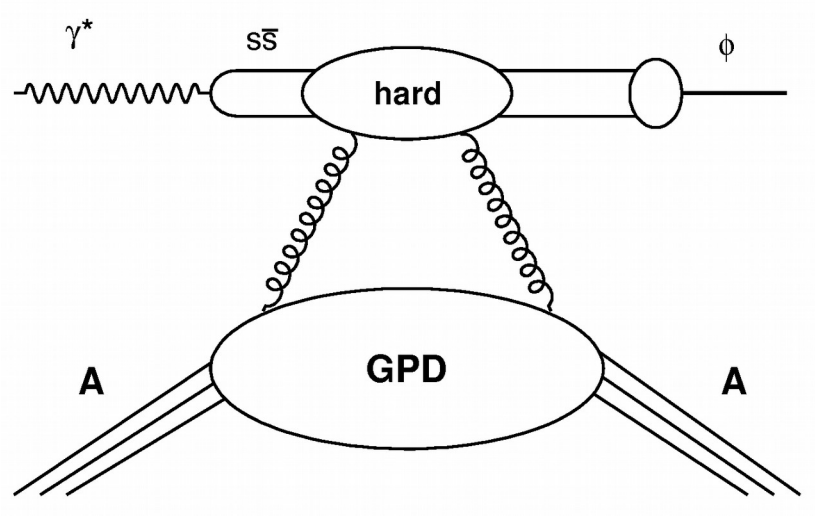
Extraction of the CFFs (mainly H)

- Directly linked to the tomography of the proton
- Allows to extract the mean square charge radius of the proton for slices of x

The nucleon size clearly shrinking with x

- Also possible for axial charge in the future
- Another goal, measuring the Ji sum rule
  - *Linked to the orbital angular momentum*

Gluon GPDs to adapt to nucleon



Can we measure the gluon GPDs?

- Possible through the exclusive production of vector mesons
- These are directly produced from the photon

If the vector meson is heavy enough

- EIC plans to do this with J/Ψ the ideal probe for this reaction
- Quark exchange is then highly suppressed and we have a leading handbag diagram with gluons

This has been proposed in JLab with the ϕ

- CLAS experiment part of run group A of Hall-B

The neutron GPDs

Why the neutron?

- Gives access to flavor decomposition of the GPDs
- GPD H is suppressed giving a better access to the GPD E

Important GPD for the Ji sum rule

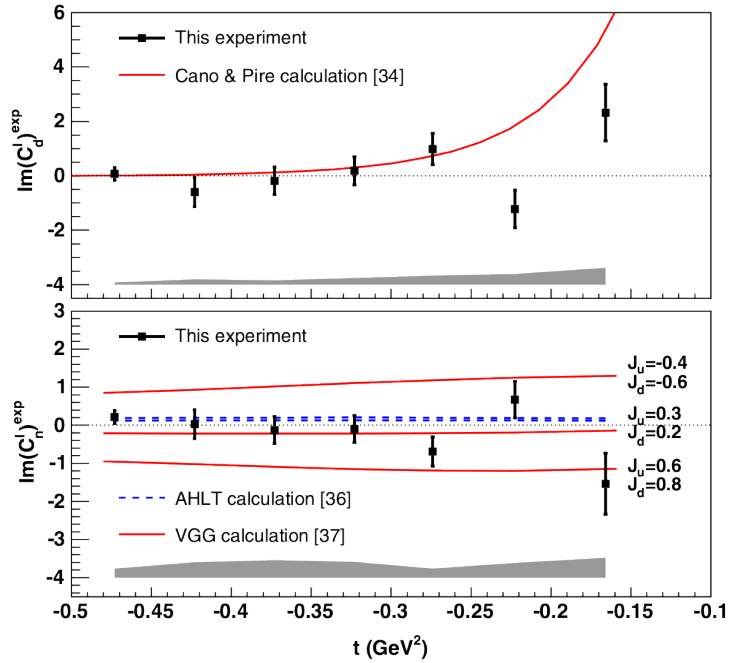
- Hall A results performed by subtracting proton to the deuterium
- Asymmetries are found to be in line with expectations
- But they are small and the subtraction is tricky

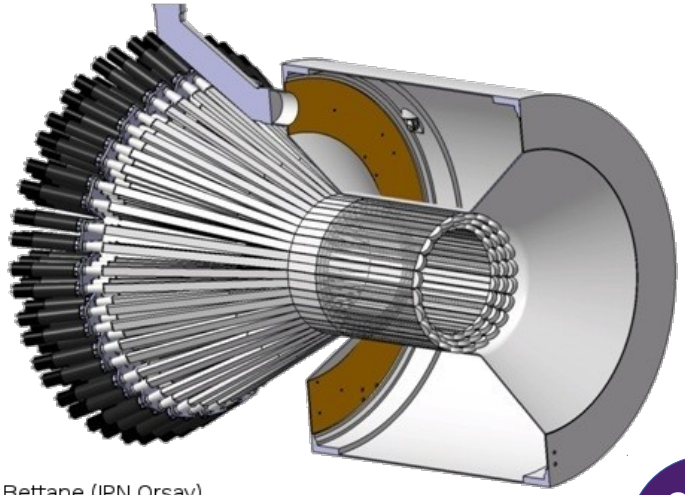
M. Mazouz et al. Phys.Rev.Lett. 99 (2007) 242501

New results presented yesterday by C. Munoz-Camacho

CLAS12 perspectives

- Experiment to solve this issue with the use of a neutron detector
- New experiment proposed at this PAC (M. Hattawy et al.) using tagging
  - *Tag the spectator proton with Bonus12*





J. Bettane (IPN Orsay)

Extracting Signal of the TMDs

TMD extraction is simple, in principle

- Each function has a different modulation
- Experimentally, it is a bit more complicated

Experimental needs

- Polarized targets
  - *Preferably long. and tr.*
- High acceptance
- High resolution

$$
\begin{aligned}
\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} &= \frac{\alpha^2}{x_B y\,Q^2}\,\frac{y^2}{2(1-\varepsilon)} \\
&\times \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+ \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+ S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&+ S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+ |S_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+ |S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}.
\end{aligned}
$$

TMD data from JLab 6 GeV

Many results from CLAS and Hall A

- **Provided many different hadrons for many spin configurations**
- **Large program carried on with polarized ^{3}He**
  - *Provides effective polarized neutron target*

CLAS Collaboration (H. Avakian et al.) Phys.Rev. D69 (2004) 112004

CLAS Collaboration (H. Avakian et al.) Phys.Rev.Lett. 105 (2010) 262002

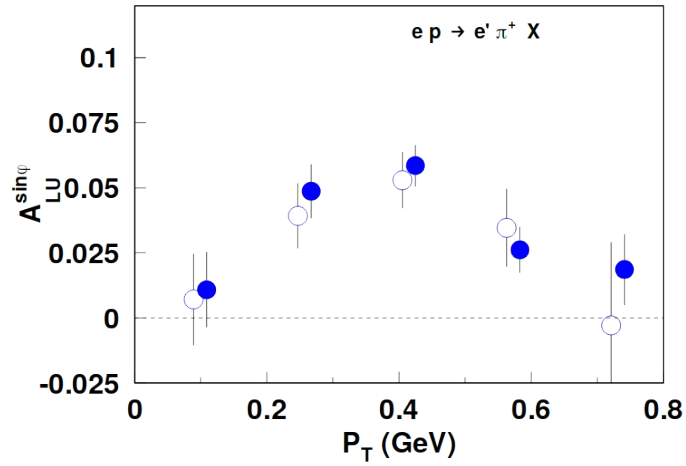
Hall A Collaboration (X. Qian et al.), Phys. Rev. Lett.107, 072003 (2011)

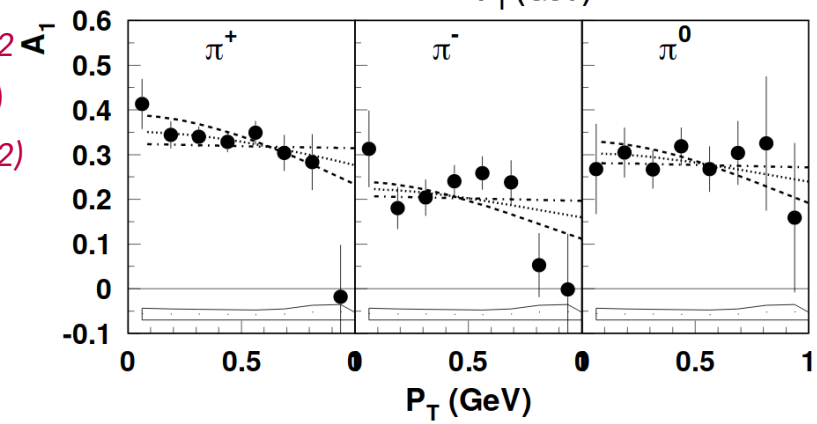
Hall A Collaboration (J. Huang et al.), Phys. Rev. Lett.108, 052001 (2012)

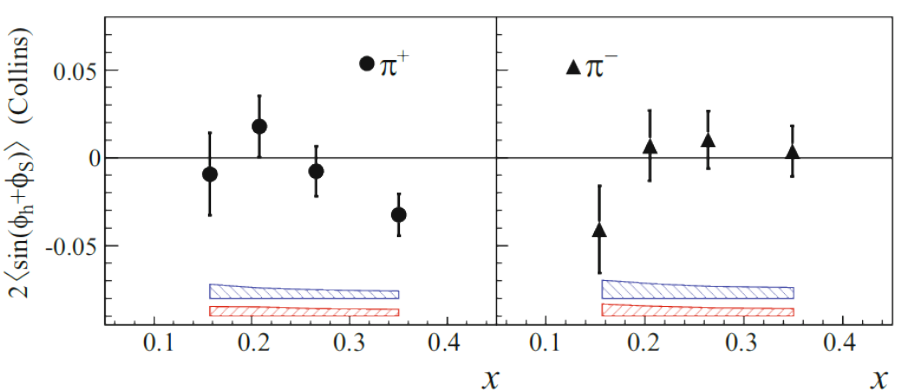
Hall A Collaboration (Y.X. Zhao et al.), Phys. Rev. C90, 055201 (2014)

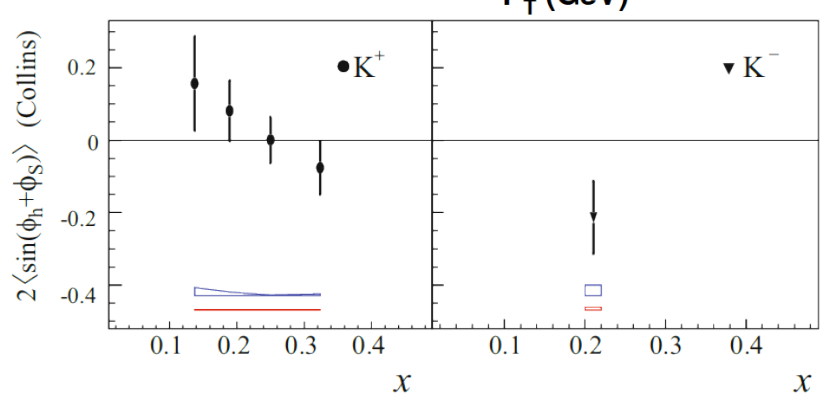
Hall A Collaboration (Y. Zhang et al.), Phys. Rev. C90,055209 (2014)

Hall A Collaboration (Y.X. Zhao et al.), Phys. Rev. C92, 015207 (2015)

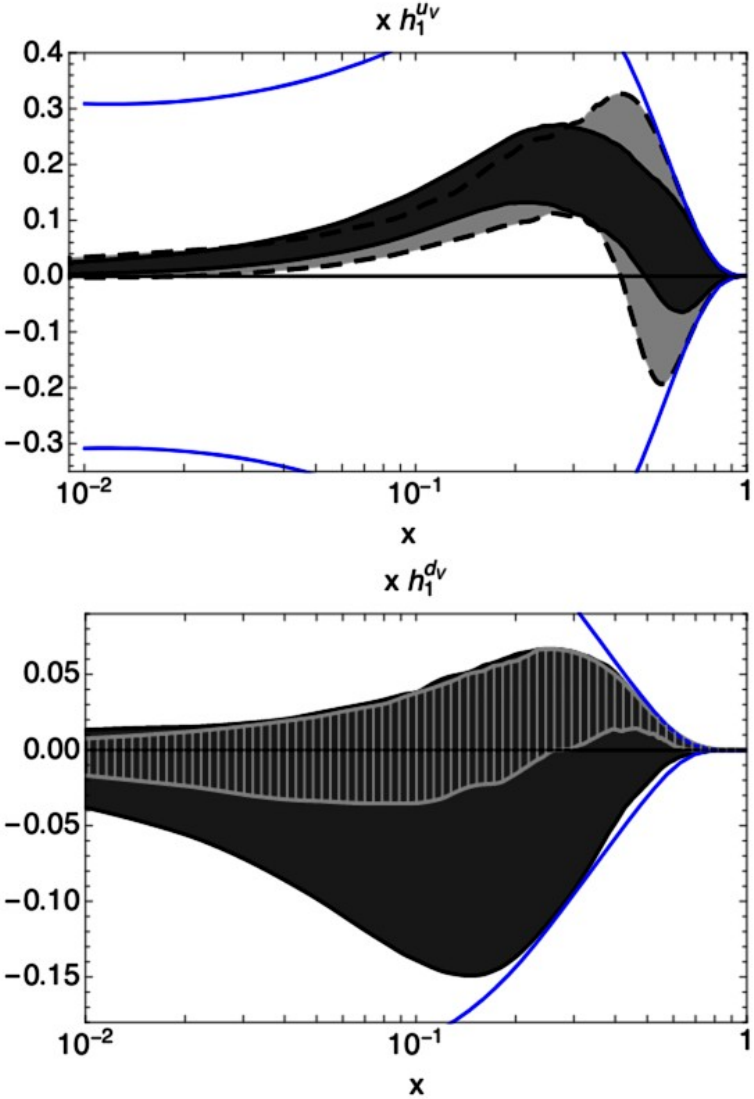








TMD Fits



Fits of TMDs are just starting

- **Includes lepton-lepton, lepton-proton and proton-proton**
- **Allows to separate various functions and flavor**

M. Radici, A. Bacchetta Phys.Rev.Lett. 120 (2018) no.19, 192001

A. Bacchetta et al. JHEP 1706 (2017) 081, Erratum: JHEP 1906 (2019) 051

These are in their infancy

- **They do not include JLab data**
- **Theoretical progress and 12 GeV will hopefully change that**

Summary on 3D nucleon structure

The three dimensional structure of the nucleon is where JLab and EIC program intersect the most

- **JLab provides the valence region (x > 0.1) data**
  - *Lots of promises in this field with numerous proposals approved on the topic*
  - *Aims toward fully constrained fits of the data by the end of the program*
- **But not only, it is the base to work on key problems**
  - *What observables are needed to extract the GPDs and TMDs?*
  - *Can we interpret vector meson production to understand the gluon structure of the nucleon?*

EIC will extend these programs but also leans on them

- **Extension at low x**
  - *How wide gets the nucleon at the lowest x ?*
- **Extension to gluons**
  - *Are there a significant difference between the transverse distribution and dynamics of quarks and gluons?*

Reconciling Two Points of View

Is the nucleus made of nucleons or quarks and gluons?

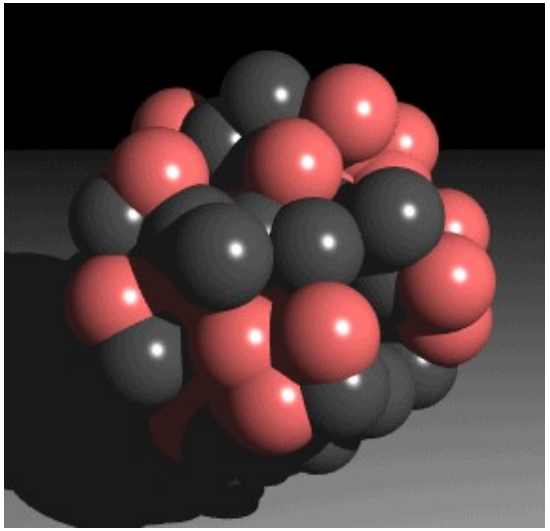
- Is the nucleon picture sufficient?

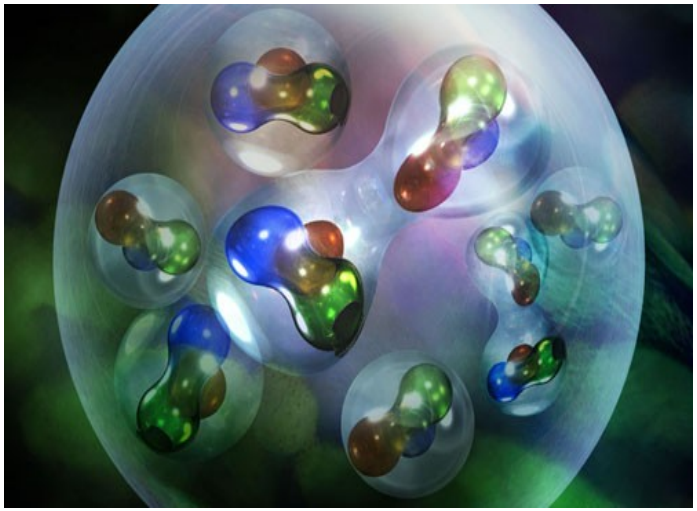
Where do we stand?

- New models are still coming up, with strong arguments as illustrated yesterday
- Yet, they give similar predictions for traditional effects, so how do we resolve this?

JLab and EIC scientific program

- Mostly separate between low-x shadowing and high-x EMC effect
- But we can find some common interests

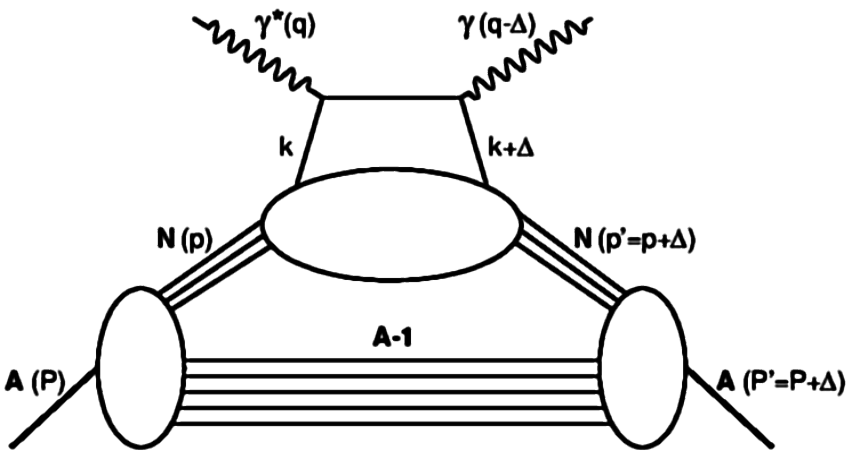




GPDs & Nuclei

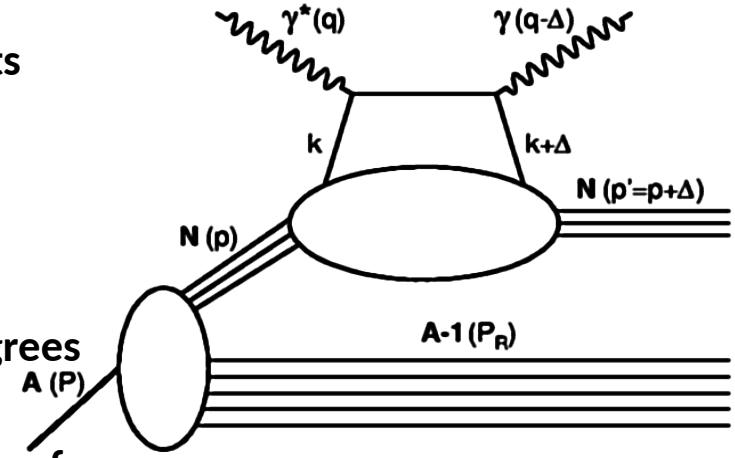
Nuclei give control over the spin

- Spin-0 → 2 GPDs
- Spin-1/2 → 8 GPDs
- Spin-1 → 18 GPDs
- Half only intervene in DVCS



In the nucleus two processes

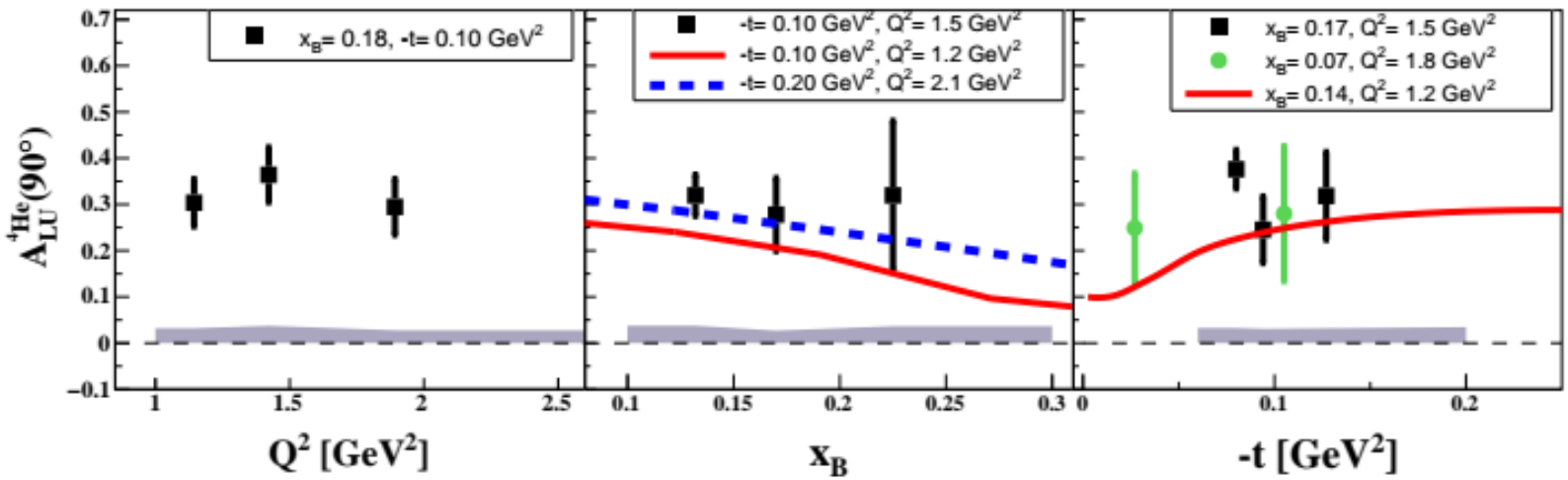
- Coherent and incoherent channels
  - *Similar to elastic and quasi-elastic*
- Give a global view and a probe of the components

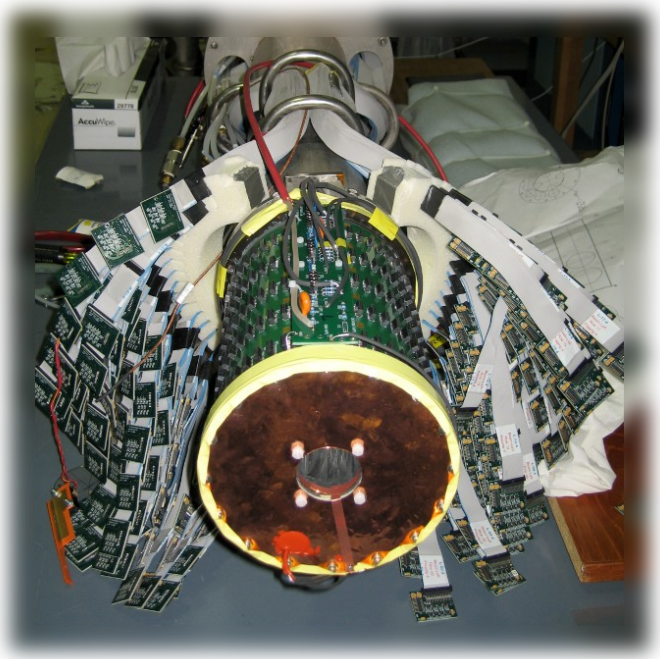


A perfect tool to study the EMC effect

- Offer localization with the *t* dependence
- Coherent DVCS gives access to non-nucleonic degrees of freedom
- Incoherent DVCS gives access to the modifications of the nucleon

CLAS Coherent DVCS





Coherent DVCS on helium

- **Measured at CLAS**
  - *Unlike HERMES previous measurement we use a recoil detector to ensure exclusivity*
- **We observe the expected larger beam spin asymmetry**

Interpretation

- **Very strong signal proves that we have the nuclei as a whole**

Easy direct GPD extraction

- **Helium has a single GPD**

CLAS Collaboration (M. Hattawy et al.) Phys.Rev.Lett. 119 (2017) no.20, 202004

Extraction of the CFF

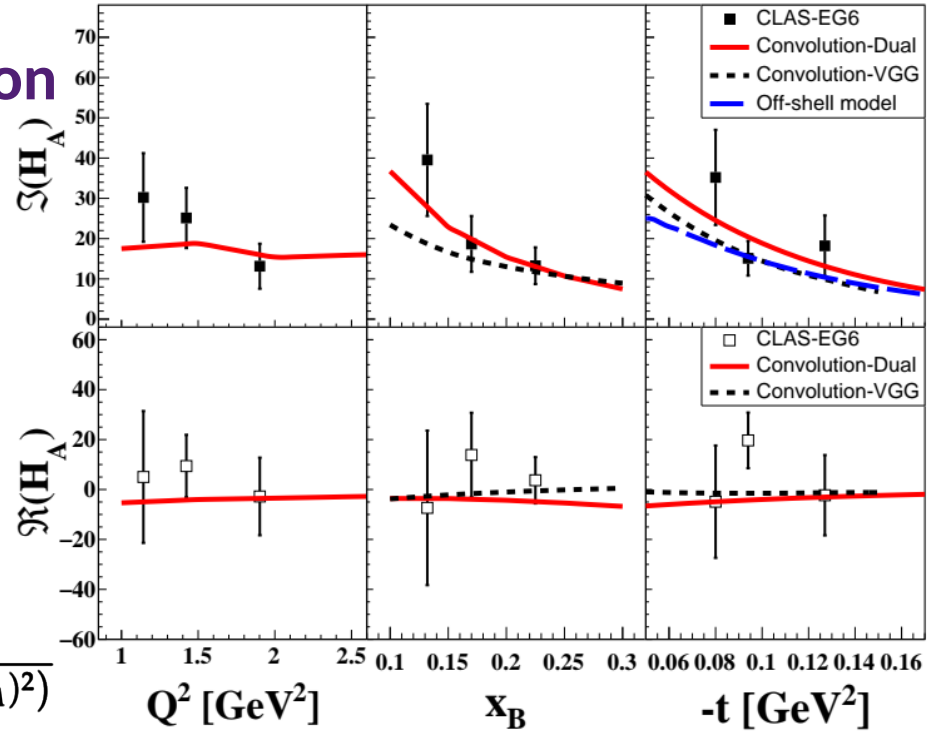
Helium allows for a simple extraction

- Spin-0 → 1 GPD/CFF

Different contributions from *Im* and *Re* in phi

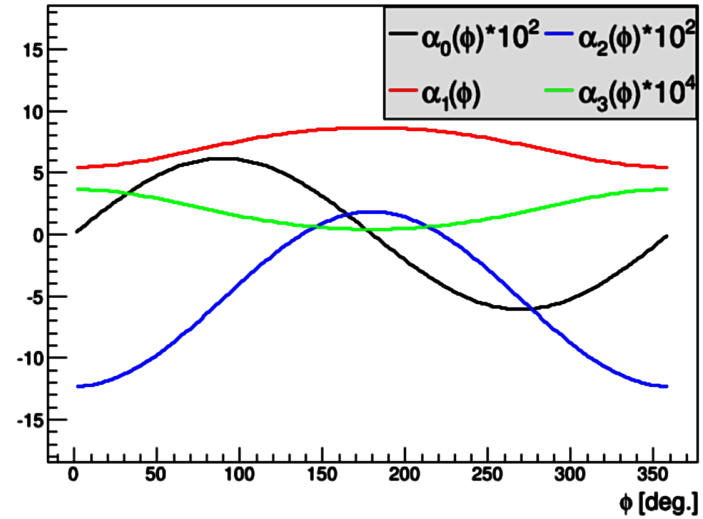
- These are calculable within perturbative QCD
- Allows to separate their contributions

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



Works very well

- We are mostly sensitive at the imaginary part
- More statistics will help with binning and the real part of H



CLAS Incoherent DVCS

Measurement of CLAS

- Proton bound in helium target

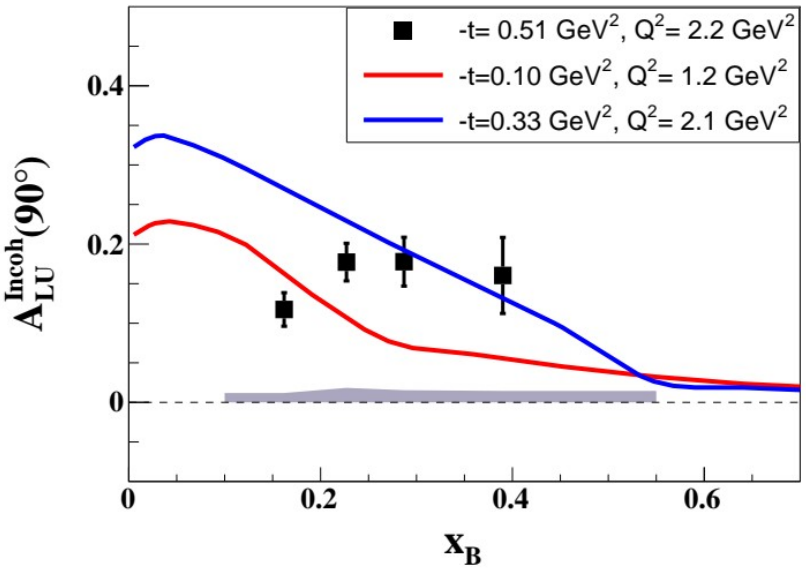
Gives a generalized EMC

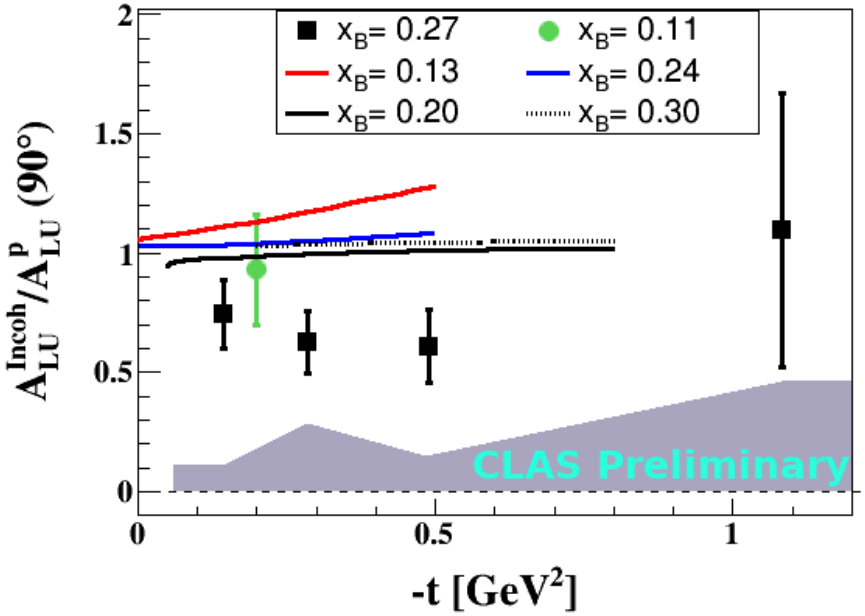
- Strongly suppressed in particular in the anti-shadowing region
- Strange behavior compared to the models

CLAS Collaboration (M. Hattawy et al.) accepted in PRL arXiv:1812.07628

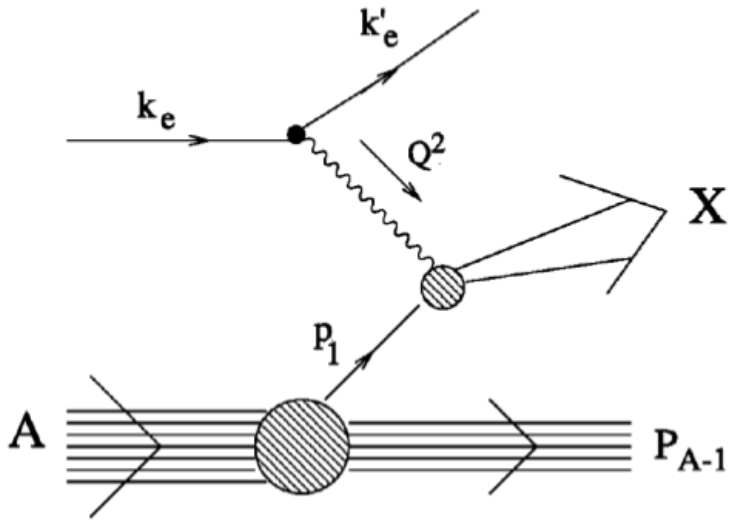
A New kind of EMC effect?

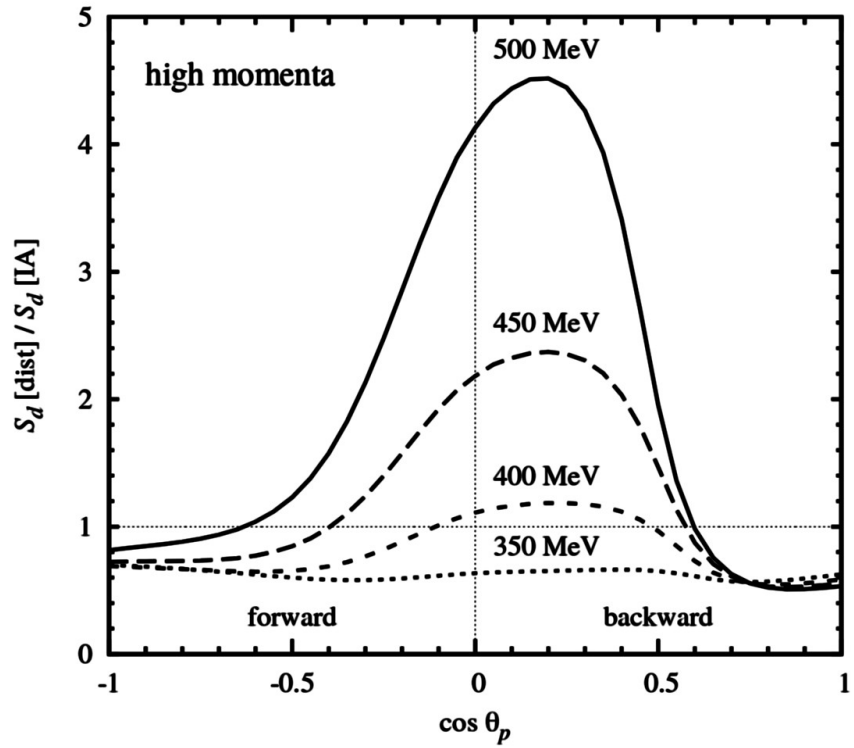
- It could be an initial state nuclear effect
- Or it could be due to final state interactions
  - *Can be very complicated in DVCS*
- Tagged measurements will help resolve this question → ALERT





Tagged Reactions





Detect the A-1 recoil

- Gives the initial nucleon kinematic
- Indicates the direction of the nuclear fragments

Allows to control the struck nucleon virtuality

$$v(|\mathbf{p}|, E) = \left(M_A - \sqrt{(M_A - m_N + E)^2 + \mathbf{p}^2}\right)^2 - \mathbf{p}^2 - m_N^2$$

Allows to control the amount of final state interactions

- Backward and lower momenta are best for reduced FSI

Tagging Nuclear Reactions

Tagged processes

- When we detect nuclear fragments in coincidence
- Mix classic nuclear physics with quark level observables

Why tagging?

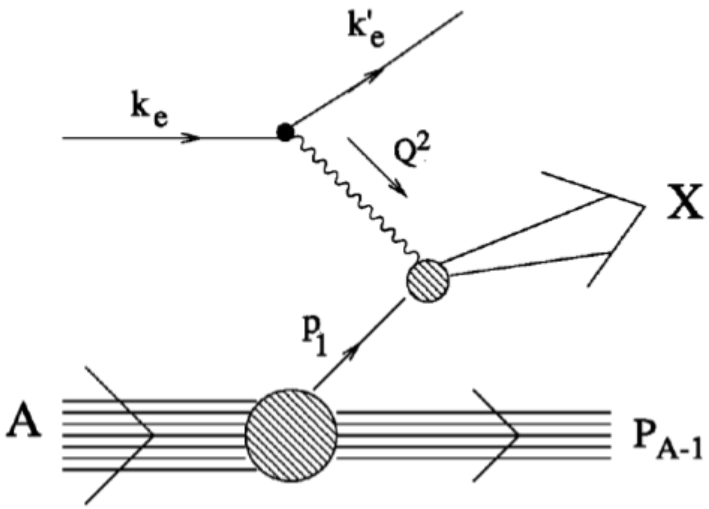
- To control final state interaction
- To control the initial state
  - *Access to the nucleon's virtuality*

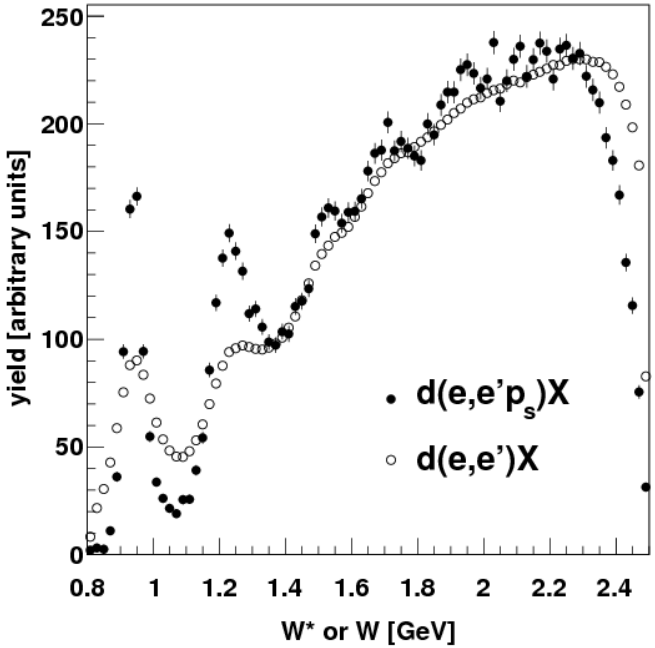
Can we do tagging?

- Done only for deuterium
  - *Bonus measurement from CLAS*
- Need a recoil detector (fixed target)

  → ALERT
- Or a forward detector (collider)

  → EIC





The EMC effect through tagging

Projections for JLab

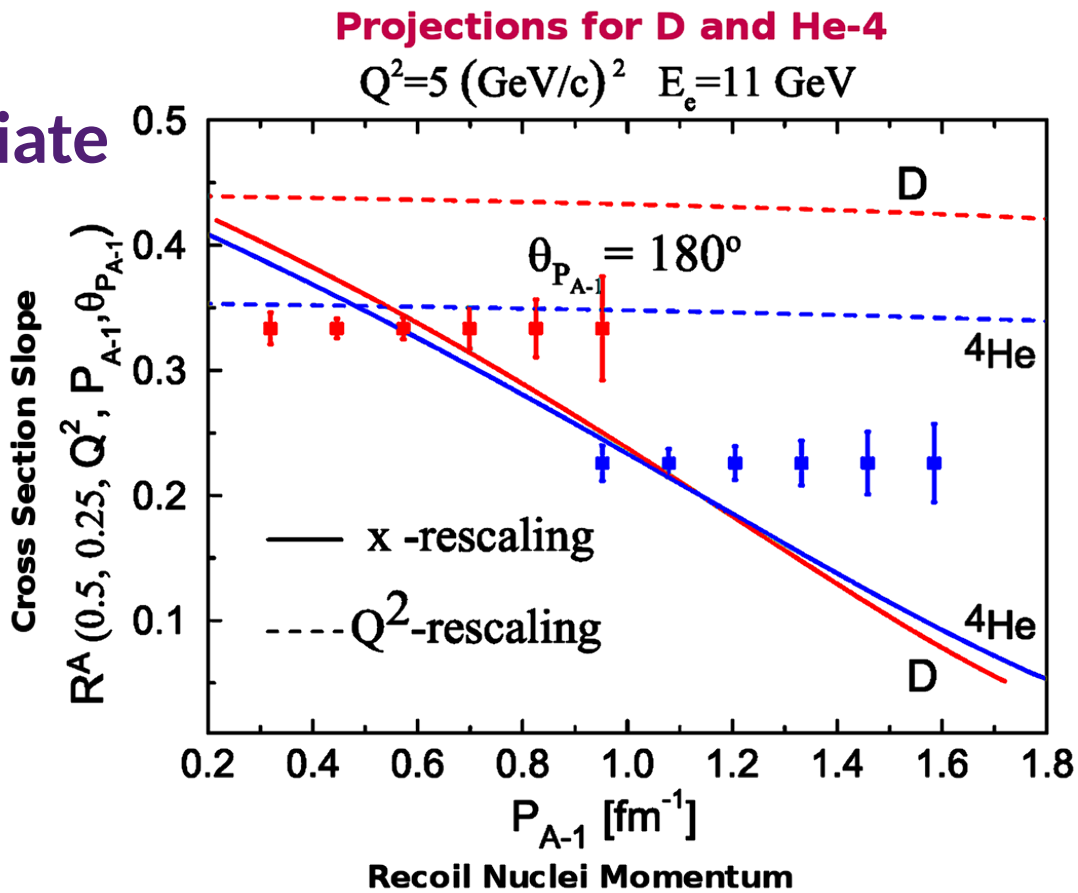
- No data yet

Tagging can help differentiate models

- Q^2 and x rescaling give drastically different predictions

Some models have more trouble

- It is difficult to make a mean field prediction here
- If one wants to probe short range correlated nucleon pairs → Detect A-2 fragments



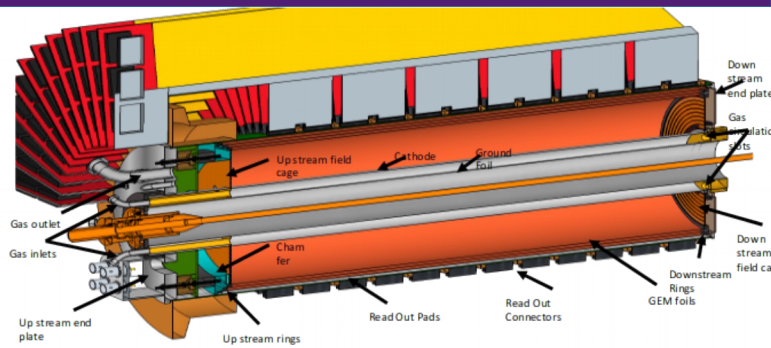
Tagging for neutron and meson structure

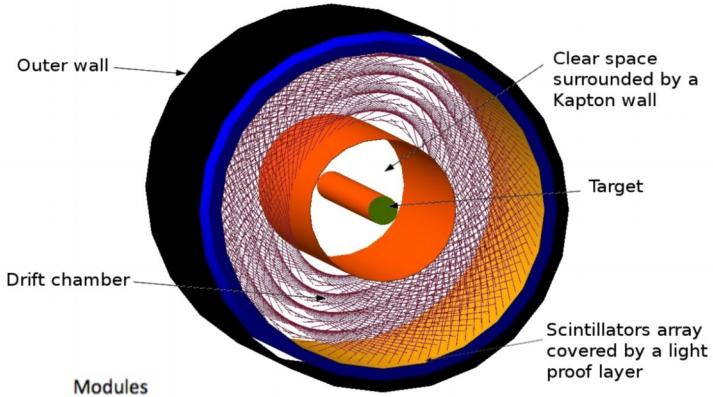
Because of the collider kinematic situation EIC will use tagging method thoroughly

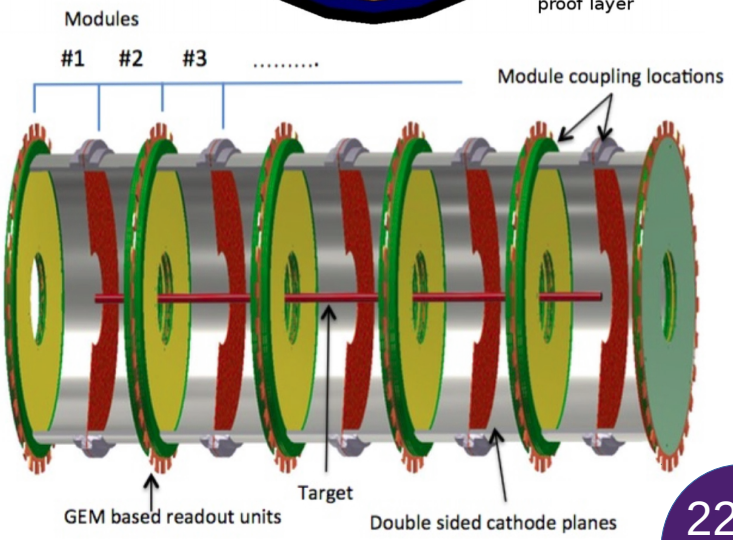
- **Yet, since the first Bonus experiment tagging is also an important part of the JLab program**

Three main detector projects are in progress at JLab

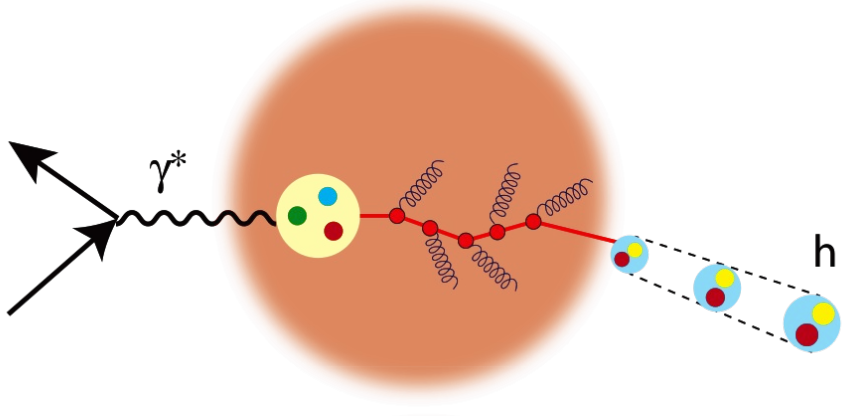
- **Bonus12 the natural extension of Bonus**
  - *Looking into neutron structure function and neutron GPDs*
- **ALERT an improved version for light nuclei tagging (up to alphas)**
  - *Will measure coherent and incoherent DVCS as well as tagged DIS to study the EMC effect*
- **TDIS experiment to access the pion structure**

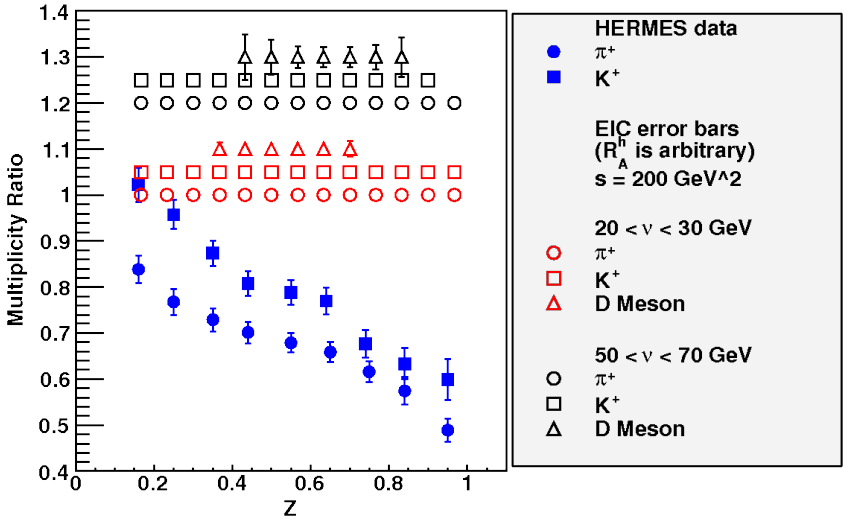






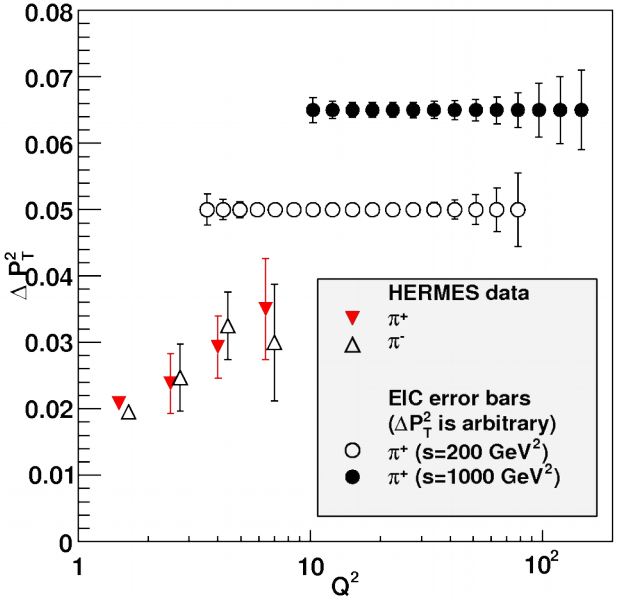
Hadronization





Dominated by parton energy loss at EIC

- Describe hadron suppression and transverse momentum broadening in nuclear material
- Gives access to the properties of the medium
  - *In particular gluon density*



At JLab energy a wider variety of theoretical treatments

- Yet, this is just the start of a larger program
- We have now the chance to start looking at these in terms of nuclear TMDs and modernize our tools

Nuclear TMD

Theory only, no experimental data

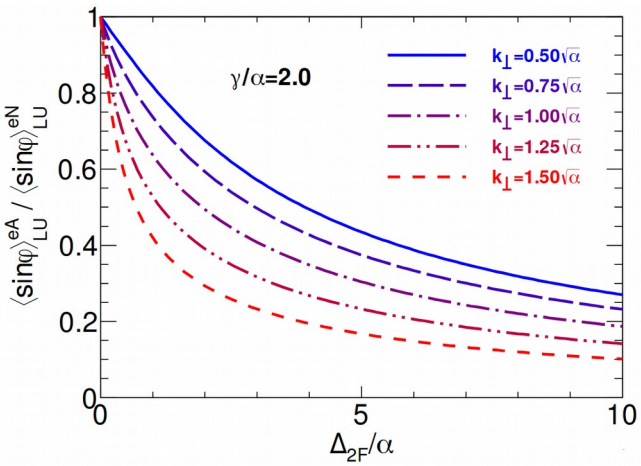
- But an important prospect
- Similarly to GPDs can offer an insight in nucleon modifications in medium

Asymmetries generated at the partonic level

- Final state effects can be separated in a more elegant manner than in traditional hadronization studies

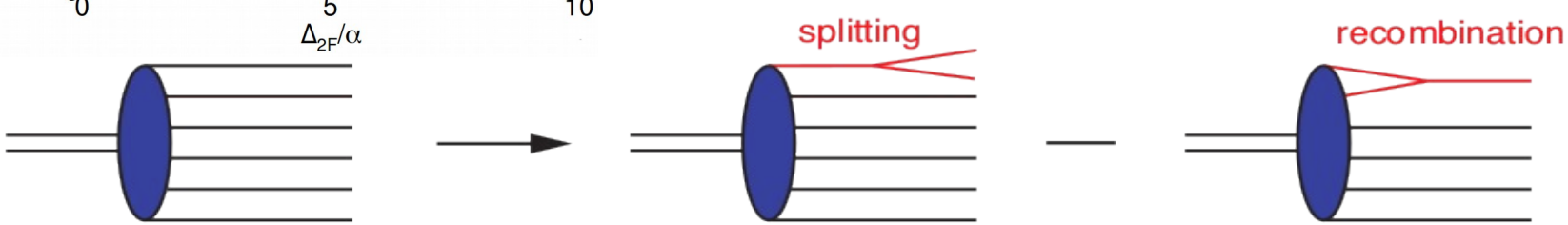
Offers a view into the transport coefficient of the nuclear matter

- A controversial question with variations of an order of magnitude between different theoretical extractions from data
- Directly linked to the saturation scale giving a direct insight into EIC physics



$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N)$$

$$\hat{q}_F(\xi_N) = \frac{2\pi^2 \alpha_s}{N_c} \rho_N^A(\xi_N)[x f_g^N(x)]_{x\to 0}$$



Summary

Electro-weak physics

- I skipped it, but it also offers opportunities to build on JLab experience in the field

The EIC physics program appears as a natural prolongation of JLab's

- Even if the x range will go down, the tools are often the same
- The experiments performed today in JLab are providing the ground work for many topics proposed in the EIC white paper

Interestingly all main topics of EIC can be studied in JLab

- The 3D structure of the nucleon
- The propagation of quarks in nuclear matter
- The nuclear structure at the low x limit

I should also remind that the EIC physics program is still very much in its construction phase

Tagging detector for nuclear physics: ALERT

Necessary for coherent processes

- **DVCS and DVMP on Helium-4**
  - *Compare quarks and gluons in a nuclei in the valence region*

Open the door to many tagging prospects

- **Light nuclei breackup**
- **Isolate interaction on quasi-free or bound nucleons**
  - *For DIS to understand the EMC effect*
  - *For DVCS to understand new effect highlighted before*

Beyond its initial proposals

- **Already one new proposal has been submitted using gold target**
- **A wealth of new observables are open to us with such detector**