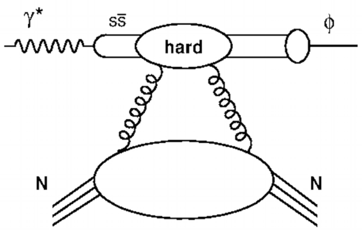
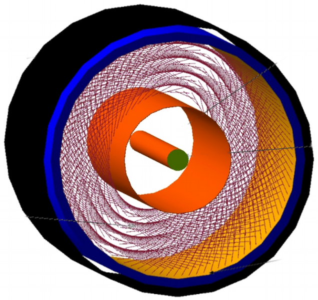
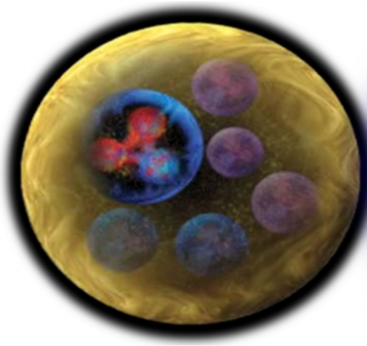
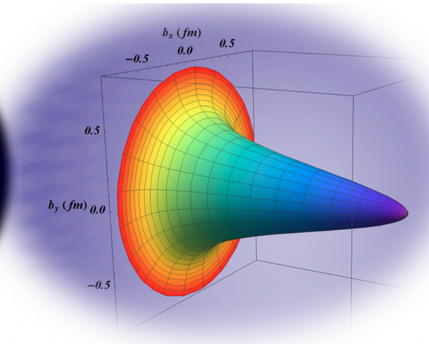
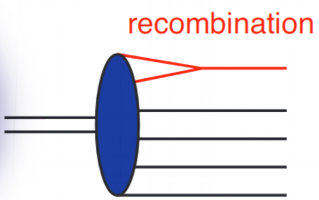
Understanding the Nucleus in 3D





Mapping the nuclear effects in three dimensions

Raphaël Dupré

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université PARIS-SACLAY

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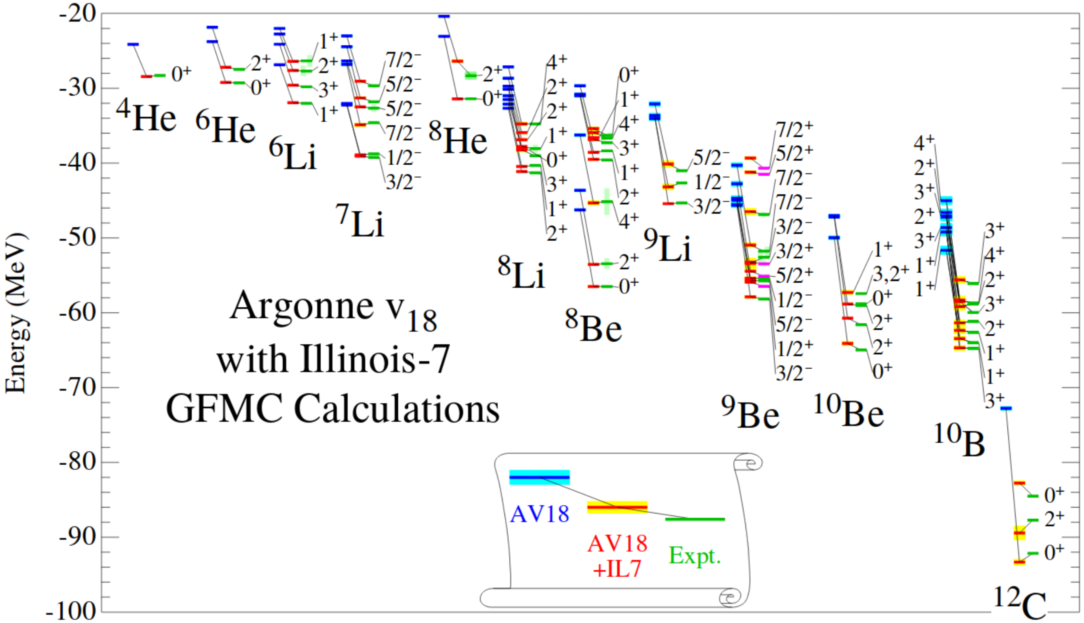
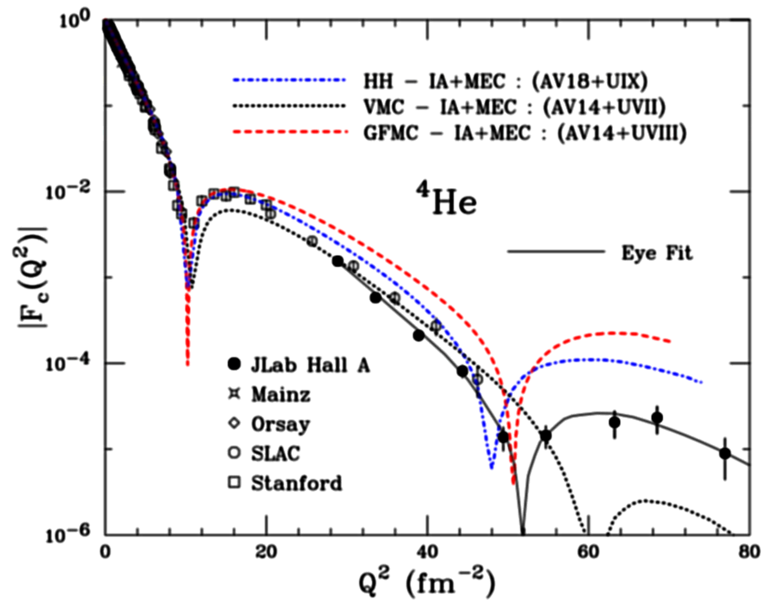
The Classic Nuclei





Nuclei described as a sum of protons and neutrons

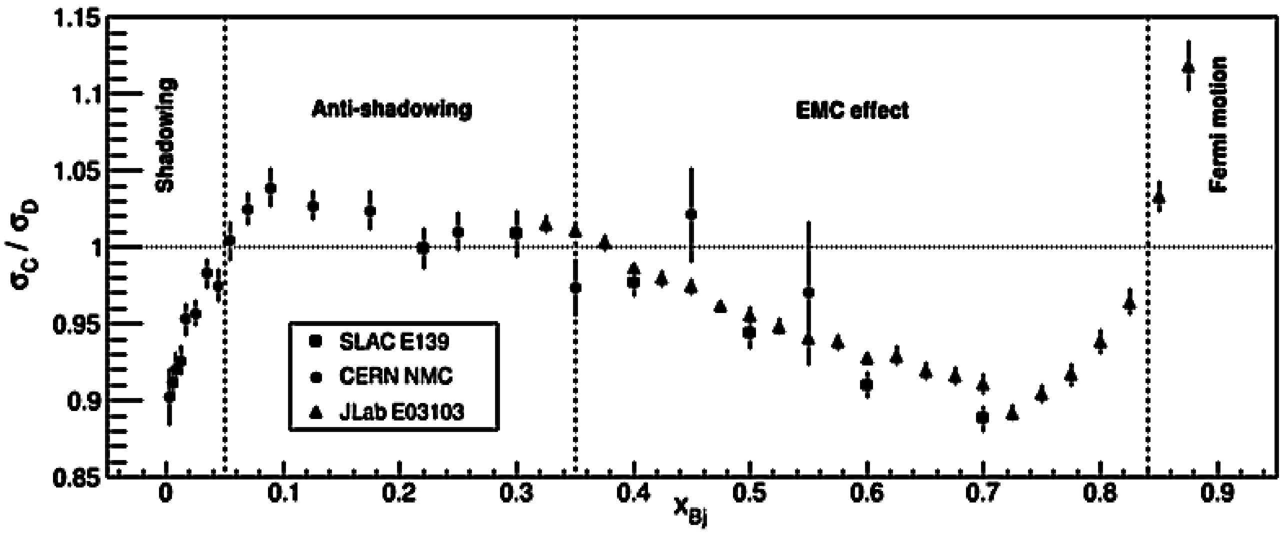
- Bound together by two and three body forces
- Can explain exactly the light nuclei spectrum

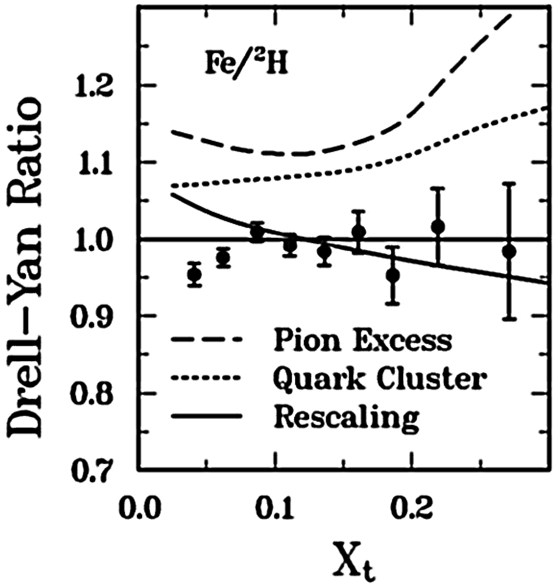
Can be related to electron scattering measurements

- Elastic form factors and quasi-elastic scattering
- Nucleon momentum spectrum matches

All seems well and working, until…

The EMC Effect





We discovered nuclear effects at the quark level

- Shadowing, anti-shadowing and EMC effect

The EMC effect remains a mystery to this day

- Meson content induced by NN interaction
- 6, 9, 12-quark clusters
  - *Both are excluded by Drell-Yan measurements*
- Nucleon size might change → bound FF
  - *Difficult to prove due to FSI effects*
- Q^2- or x-rescaling with widely different physical meaning

Shadowing

Linked to multiple scattering

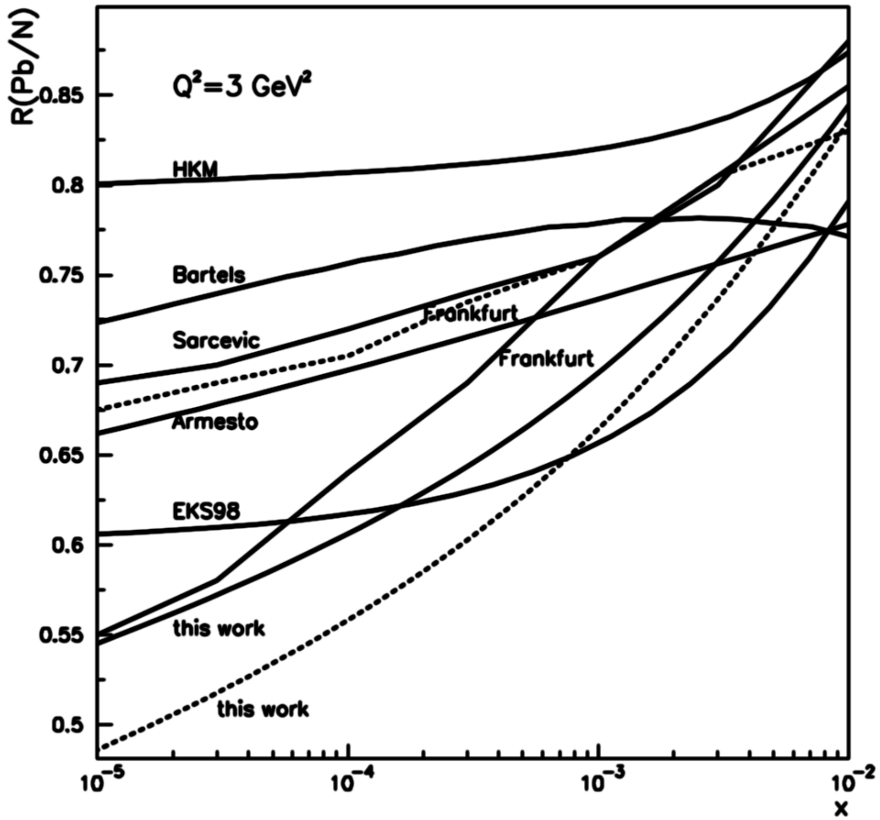
- Screening of some nucleons leads to reduced cross section
- Several calculation methods available
- They diverge largely at lower x

Data is very limited

- Low x coincide with low Q^2
- Below 10^{-2} is barely explored

Strong impact on LHC

- Relevant x range for PbPb collisions at LHC
- Very important phenomena to understand initial state in HIC



N. Armesto, J.Phys. G32 (2006) R367-R394

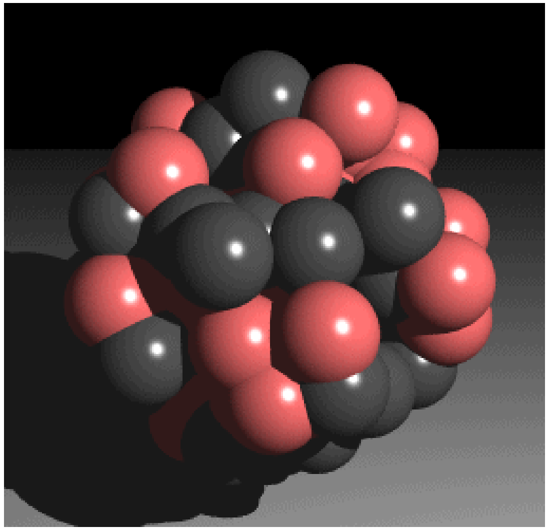
Reconciling Two Points of View

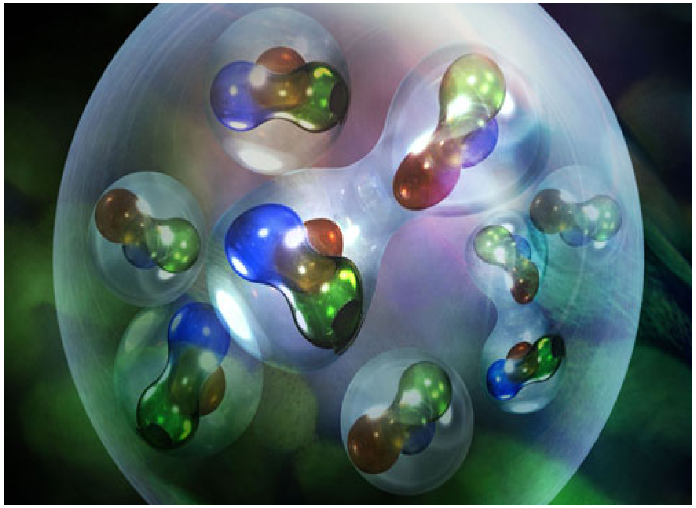
So where do we stand?

- New models are still coming up
- Yet they give similar predictions for traditional effects

How do we resolve this?

- Using new observables!
  - *There are many options, I will focus on GPDs and TMDs today*
- Mapping the nucleus in 3D will provide a much needed new stream on information on the nucleus

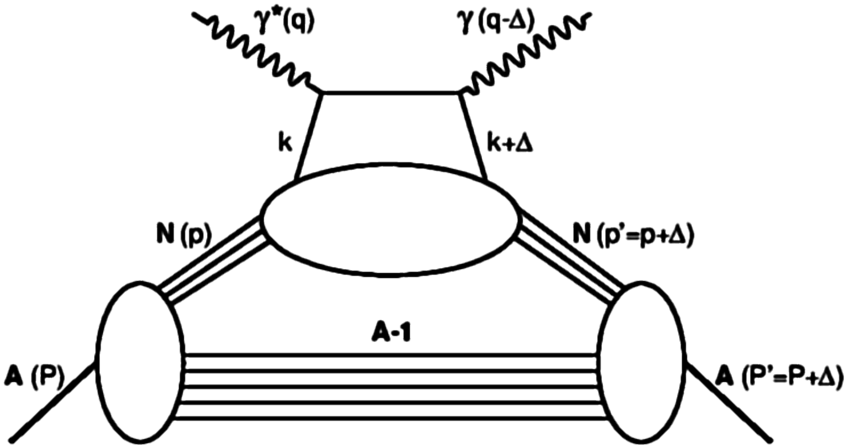




GPDs & Nuclei

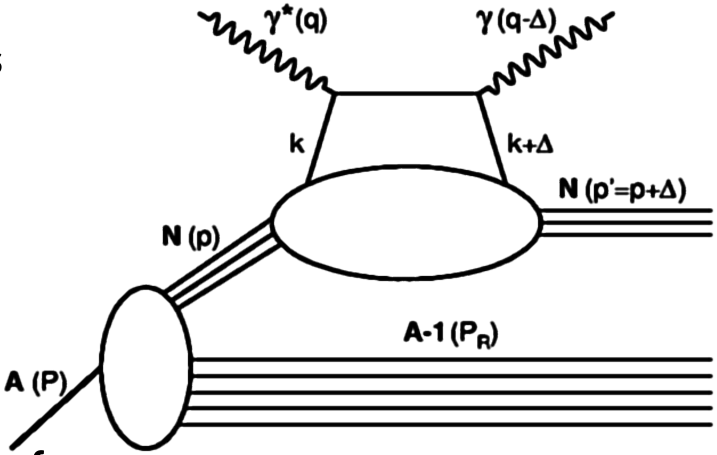
Nuclei give control over the spin

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



In the nucleus two processes

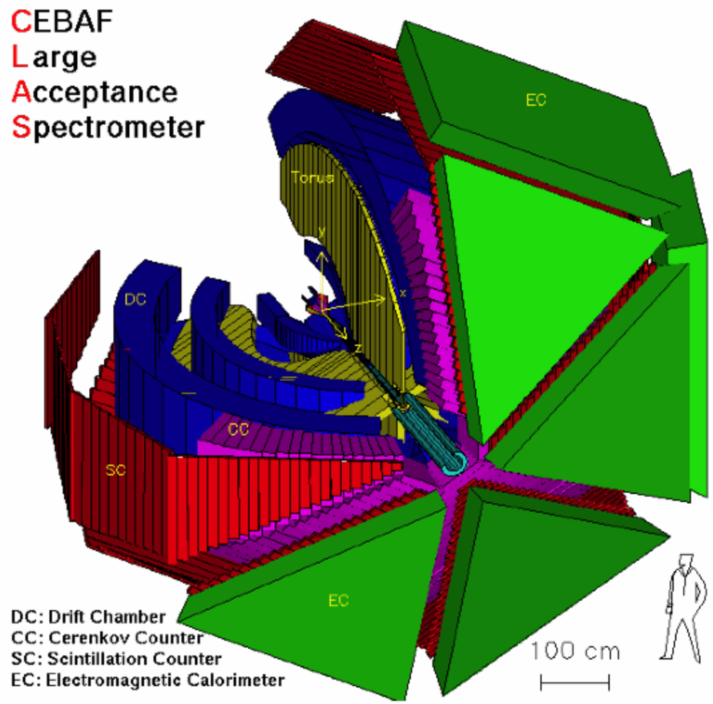
- Coherent and incoherent channels
  - *Similar to elastic and quasi-elastic*
- Give a global view and a probe of the components

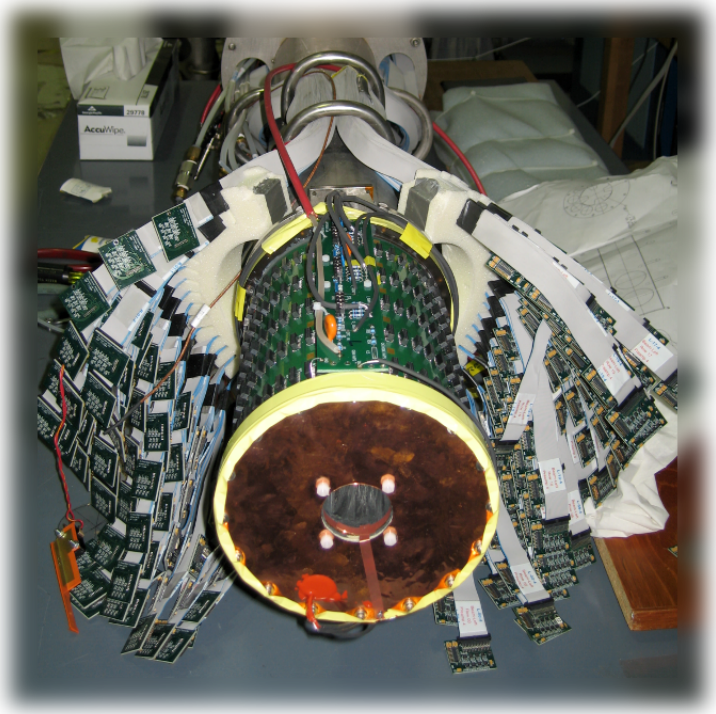


A perfect tool to study nuclear effects

- 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

Experimental Apparatus





Experimental challenges

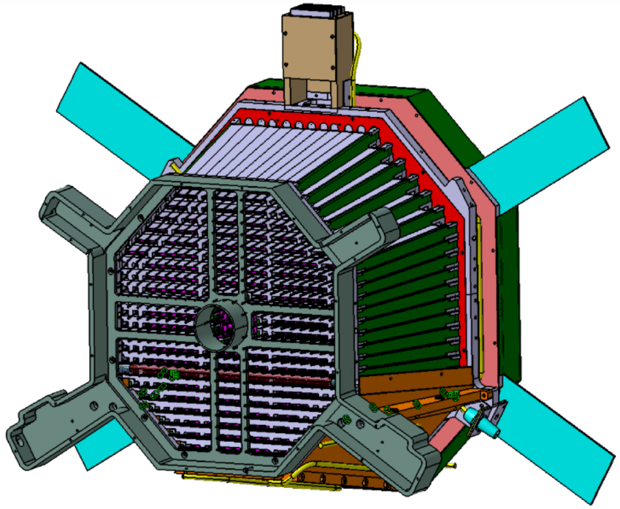
- Detecting very forward photons
- Detecting very low energy alphas (7 MeV)

Radial Time Projection Chamber

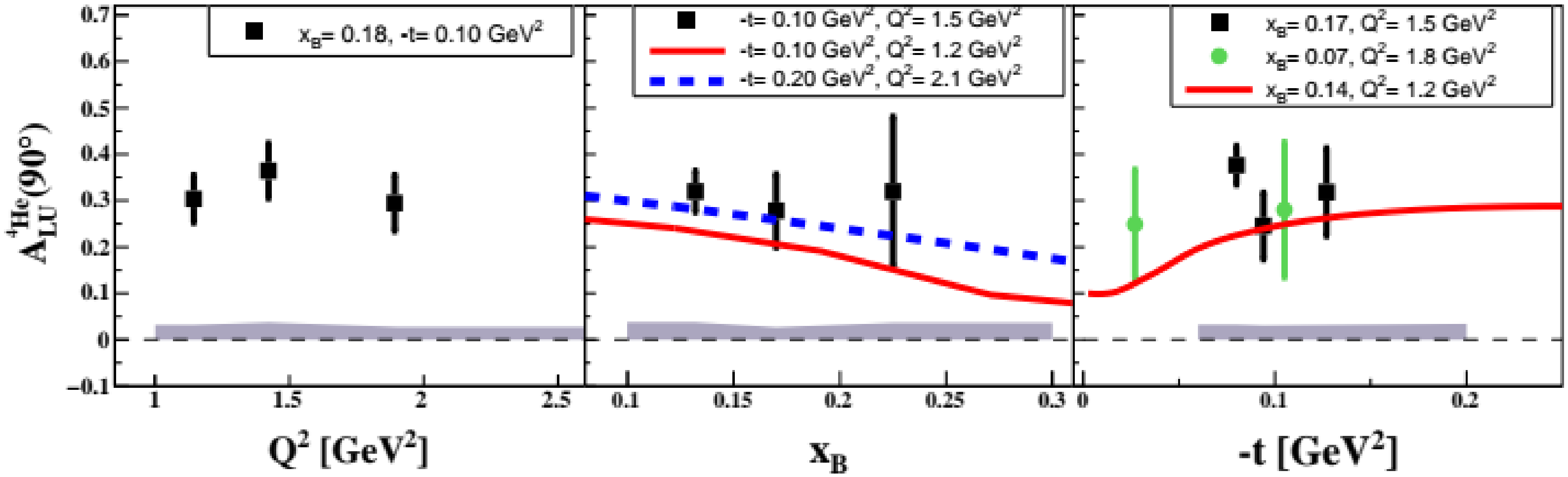
- Small TPC placed around the target

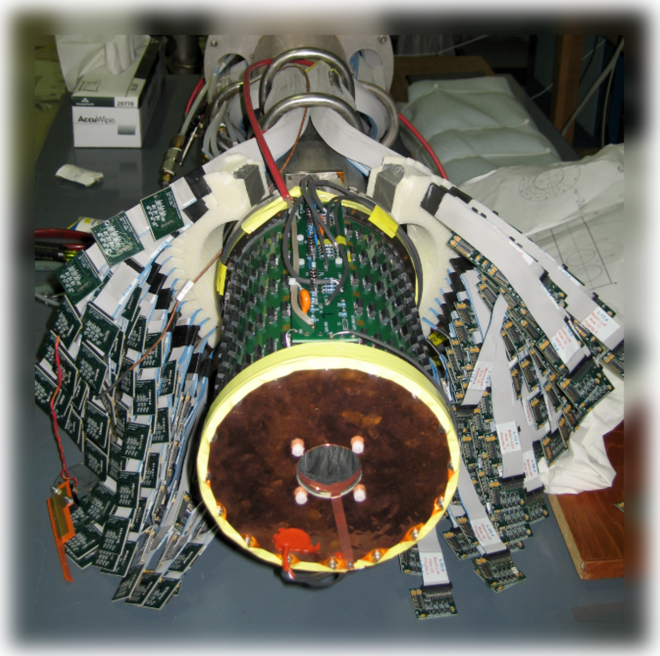
Inner Calorimeter

- Very forward electromagnetic calorimeter



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**

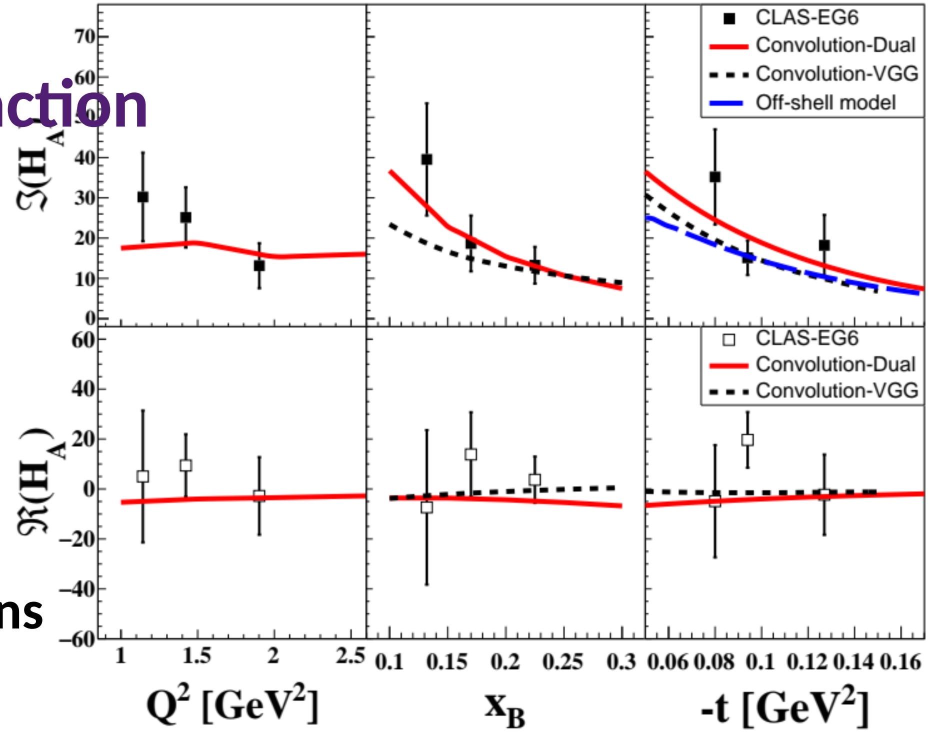
Interpretation

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

Easy direct GPD extraction

- **Helium has a single GPD**

Extraction of the CFF



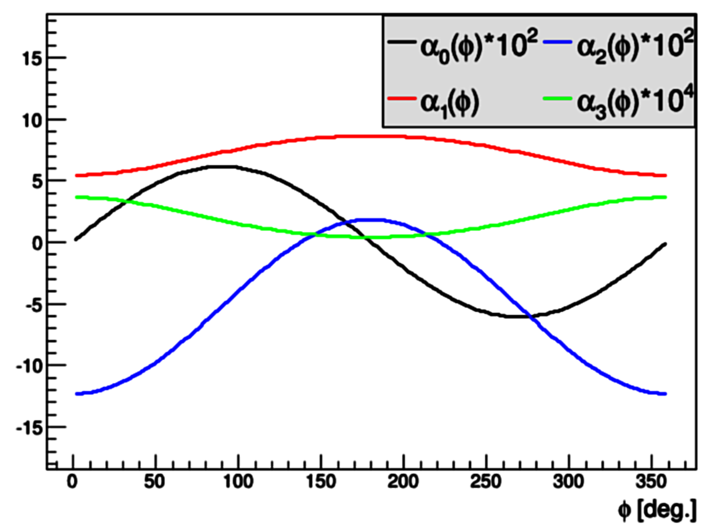
Helium allows for a simple extraction

- 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

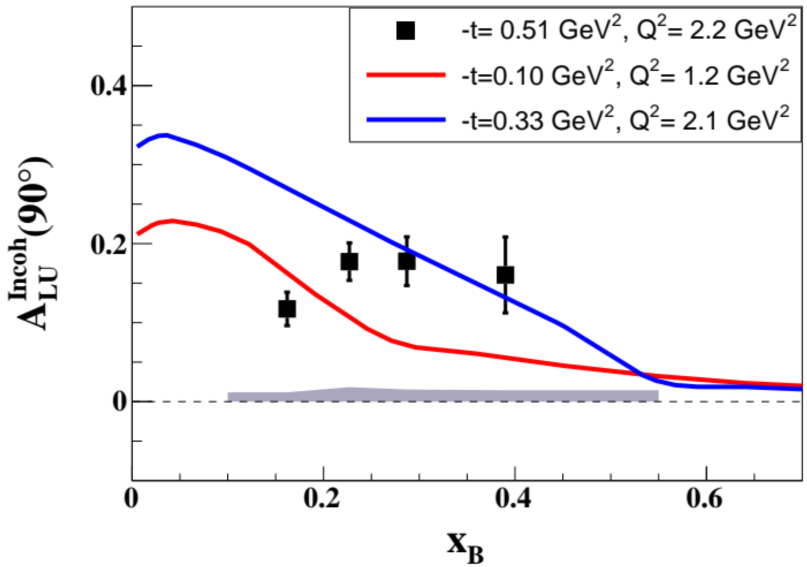
- Proton bound in helium target

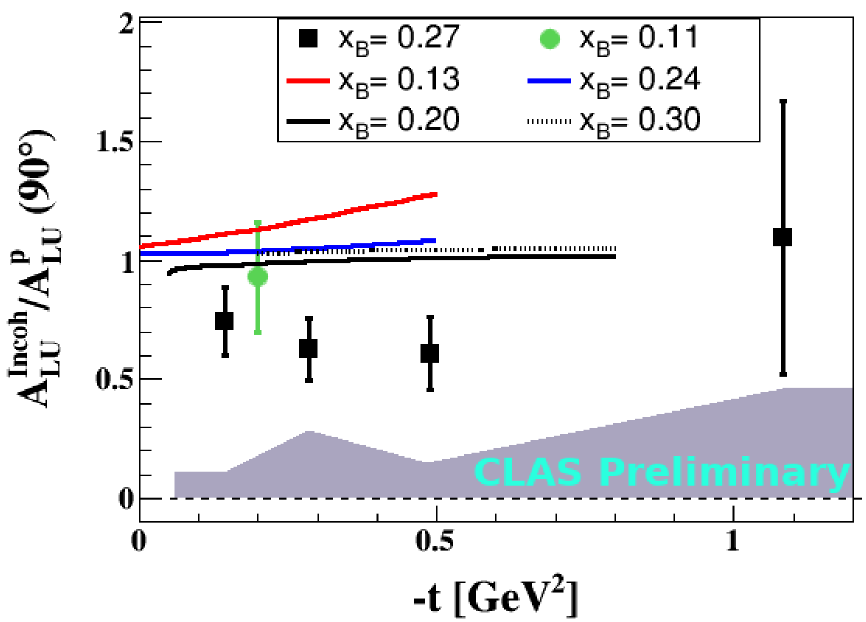
Gives a generalized EMC

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

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





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

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

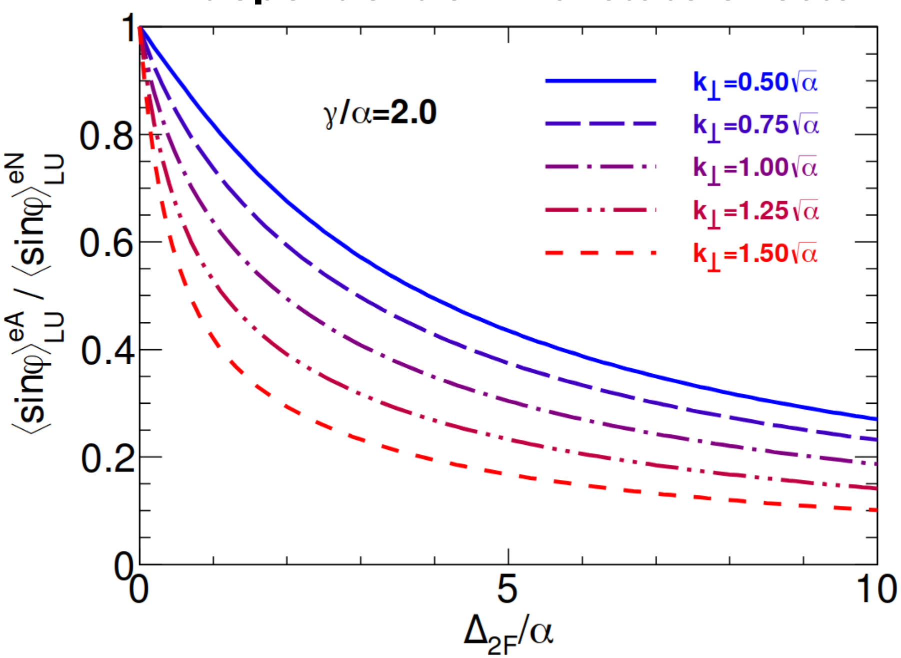
Nuclear TMD

Theory only, no experimental data

- But an important prospect
- Similarly to GPDs can offer an insight in nucleon modifications in medium
- Offers a view into the transport coefficient of the nuclear matter
  - *A controversial question with variations of an order of magnitude between theoretical extractions from data*

Asymmetries generated at the partonic level

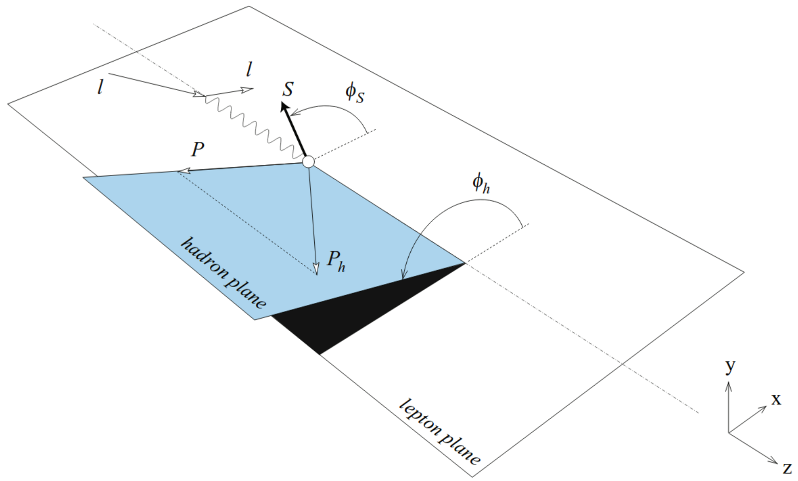
- Independent of final state effects

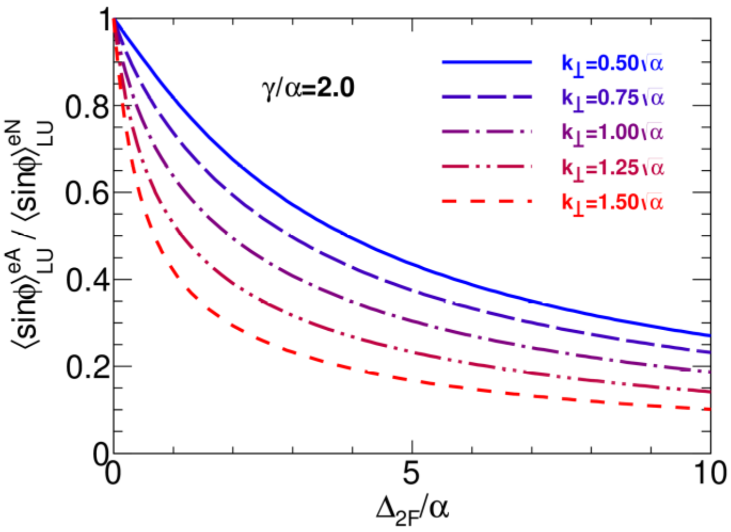


$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N)$$

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

Using TMDs for Hadronization





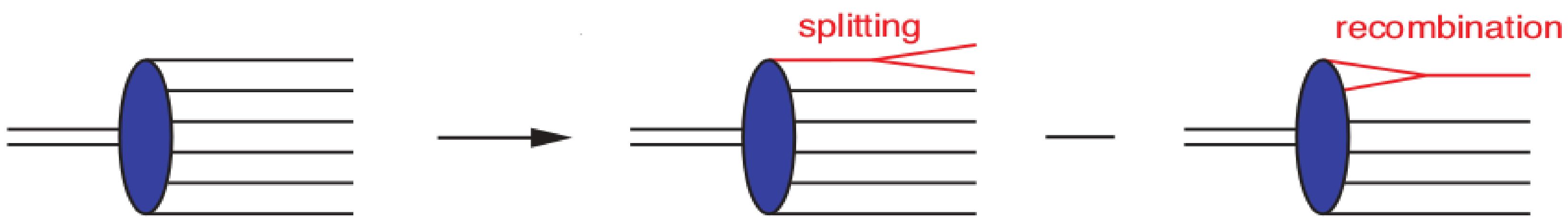
Usual hadronization measurements use outdated methods

- We should use the TMD framework to study semi-inclusive DIS on nuclei
- The sin and cos moments give direct parton level sensitivity to the transport coefficient

Offers two extra independent $\hat{q}$ measurements

- To be compared with the absorption and the transverse momentum broadening

From Hadronization to Saturation



Saturation is one of the key topics of EIC

- We want to look at the saturation scale in nuclei
- Transport coefficient and gluon saturation scale are the same thing

The hadronization studies will provide an independent result for this

- It can be measured for several nuclei
- Possibility to test the A dependence of the saturation scale

Future of Nuclear 3D Mapping

Short term @ JLab

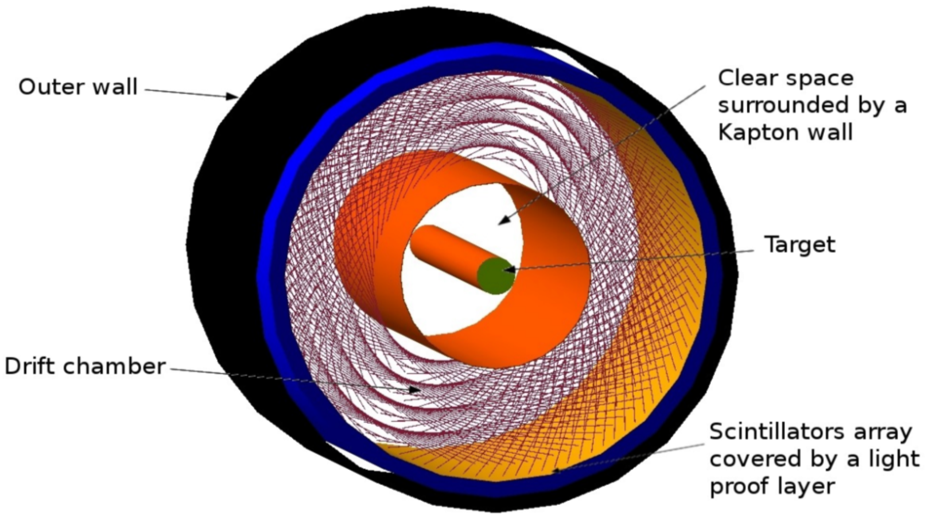
- The ALERT run group
  - *A Low Energy Recoil Tracker*
  - *Measure nuclear DVCS*
- What about nTMDs?
  - *Doable in CLAS12*

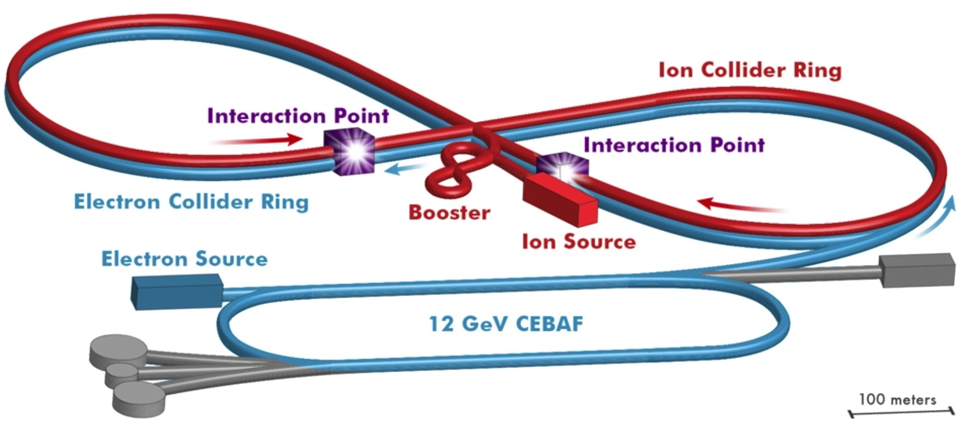
Long term @ EIC

- Collider kinematics
  - *Simplify low angle detection*
  - *Increase the phase space available*
- Polarized light nuclei
  - *Gives access to new observables*
- Higher energy
  - *Cleaner interpretation*

What Nuclei?

- Helium-3 for neutron
- Helium-4 for simplicity
- Deuterium for complex spin effects





Summary

We have a direct conflict between traditional nuclear physics and hadron physics measurements

- We need new observables to resolve it

We have now access to nuclear GPDs

- We are able to measure coherent and incoherent nuclear DVCS

Coherent DVCS has its expected large asymmetries

- We can extract CFFs in a fully model independent way
- Need much less data than for protons to get a result

Incoherent DVCS has surprisingly small asymmetries

- An EMC equivalent effect or another nuclear effect?

TMDs in Nuclei can be measured as well

- They offer a unique access to the property of the medium
- Can help measure the transport coefficient in new ways

The EIC and the 3D structure of nuclei

- Shadowing region, polarized light nuclei, gluons, parton energy loss comparable to RHIC & LHC…