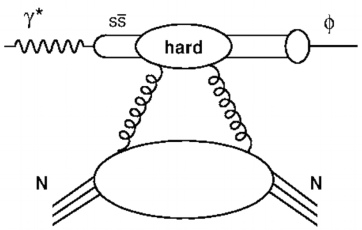
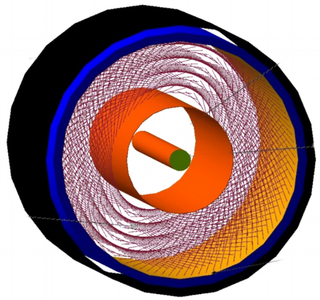
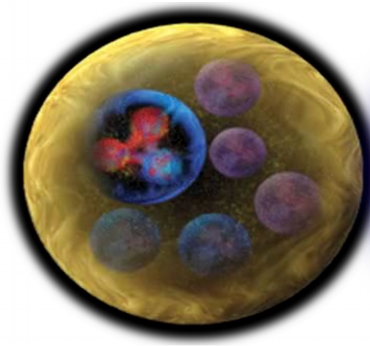
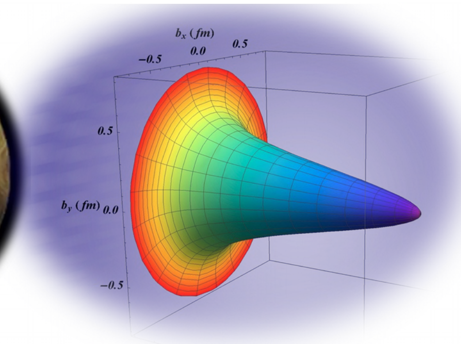
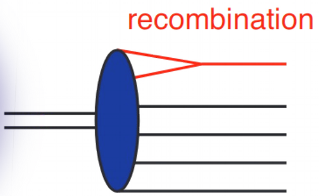
Exploring the Nucleus in 3D





Mapping the nuclear effects in three dimensions

Raphaël Dupré

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

université PARIS-SACLAY

European Research Council
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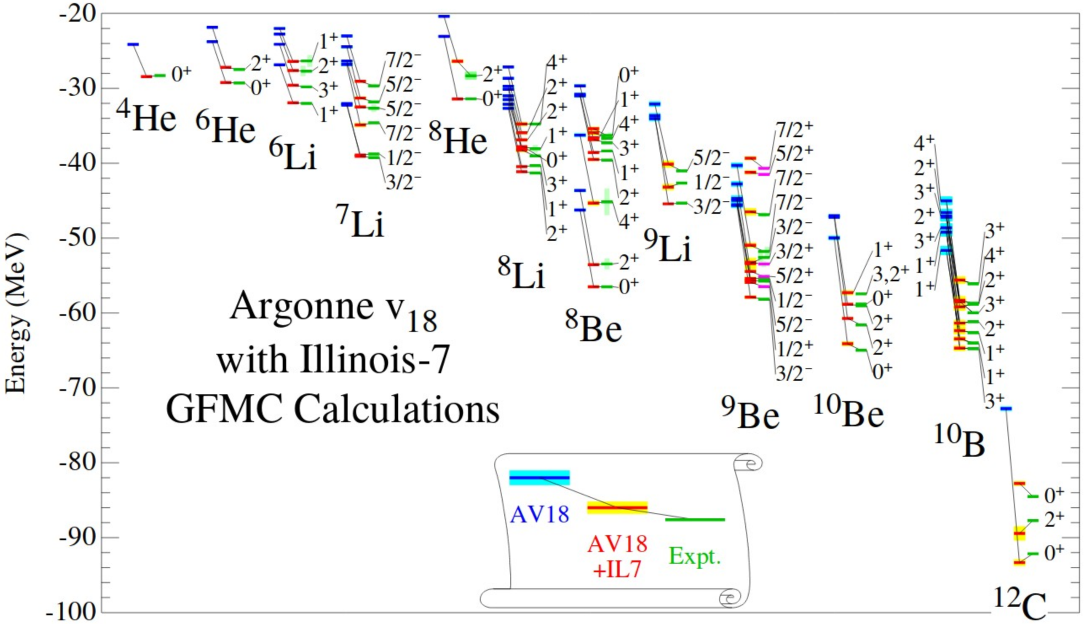
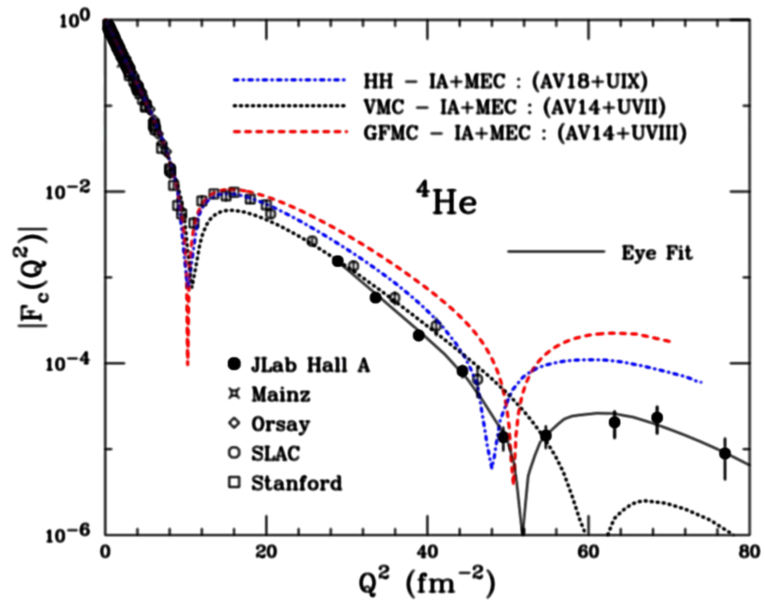
The Classic Nuclei





Nuclei described as a sum of protons and neutrons

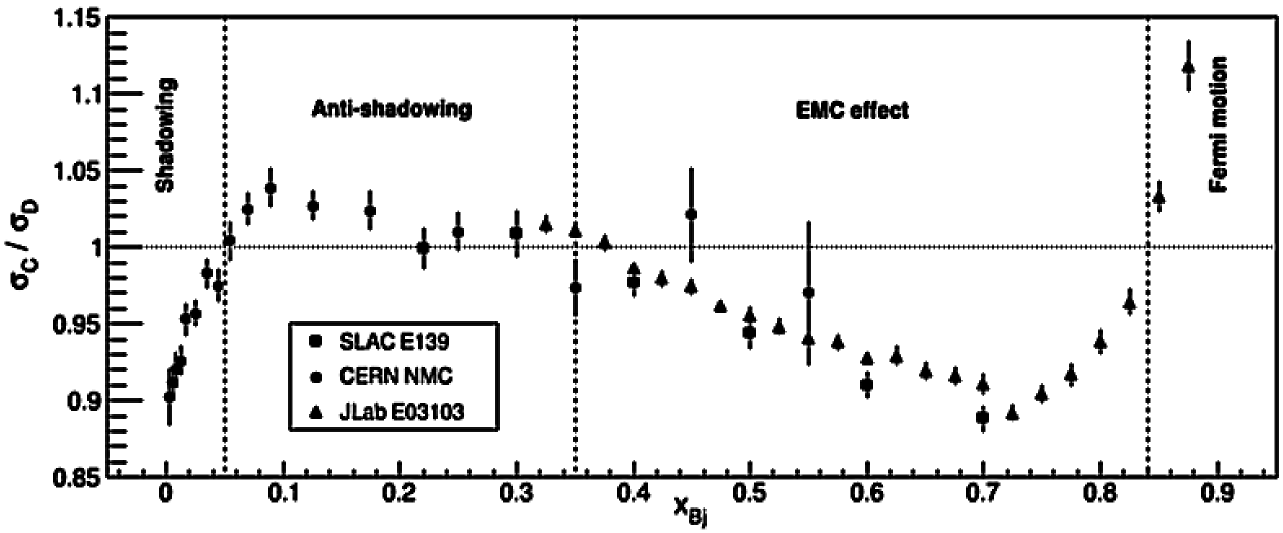
- Bound together by two and three body forces
- Can explain exactly the light nuclei spectrum

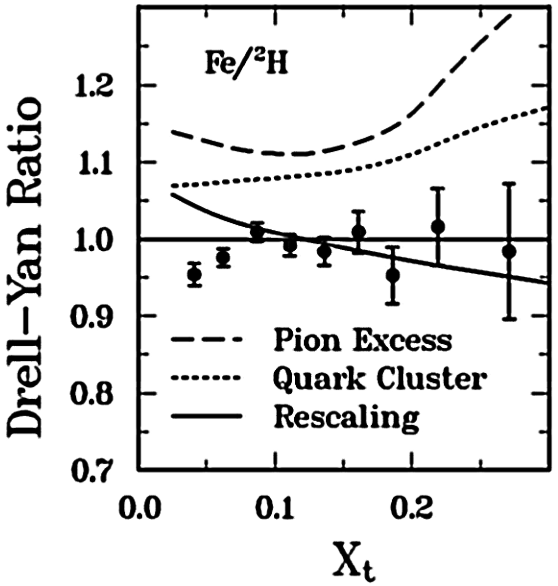
Can be related to electron scattering measurements

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

All seems well and working, until...

The Nuclear Effects





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

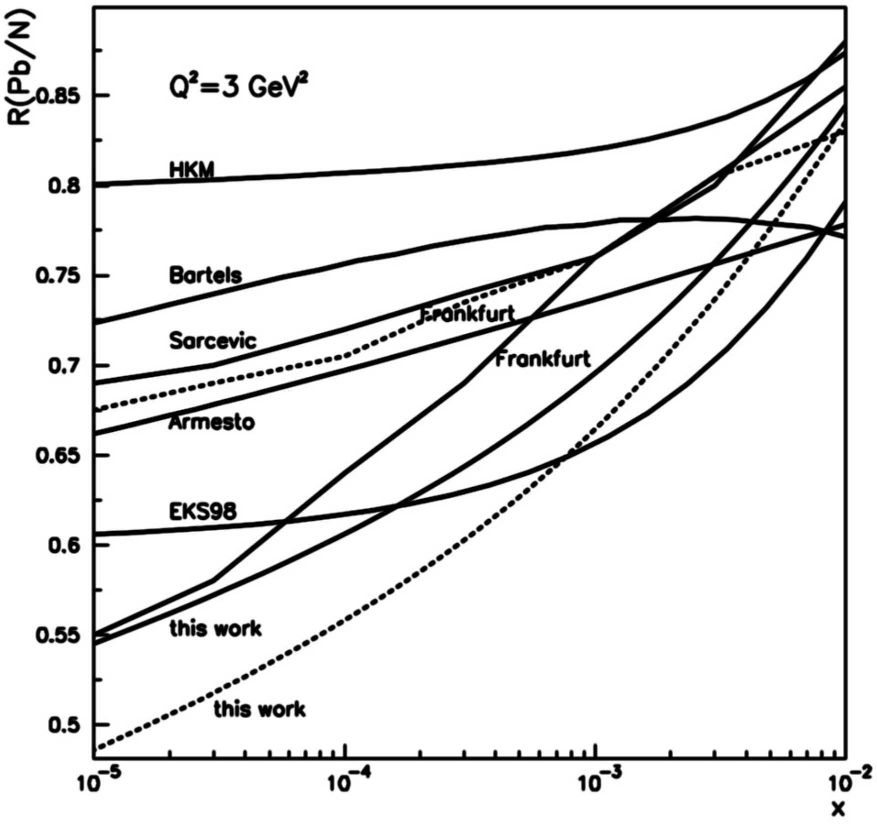
- Screening of some nucleons leads to reduced cross section
- Several calculation methods available
- They diverge largely at lower x

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

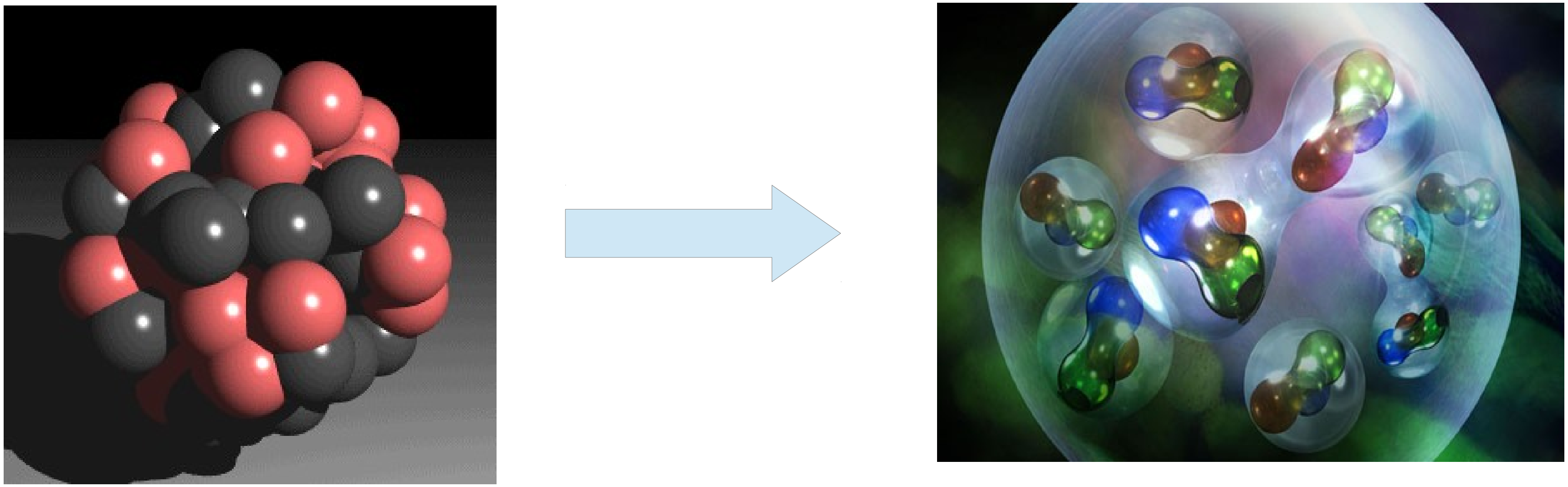
Reconciling Two Points of View

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!
- Mapping the nucleus in 3D will provide a much needed new stream on information on the nucleus



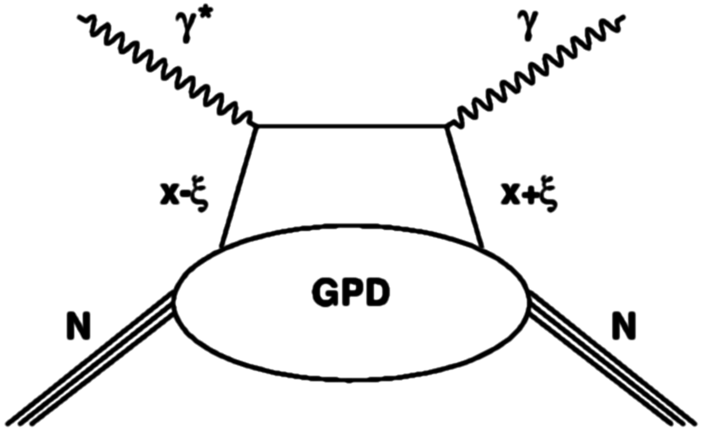
Generalized Parton Distributions

Generalizing the parton distributions

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

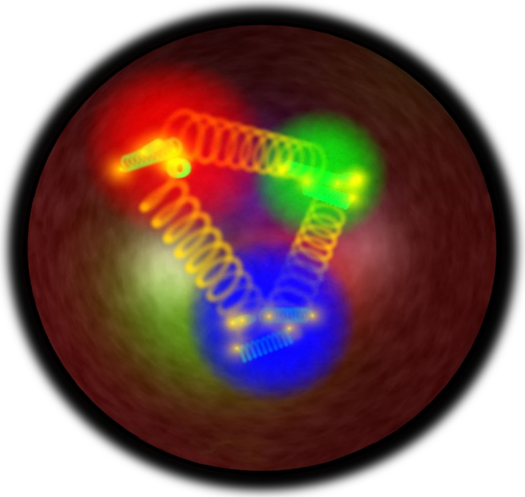
Deeply virtual Compton scattering

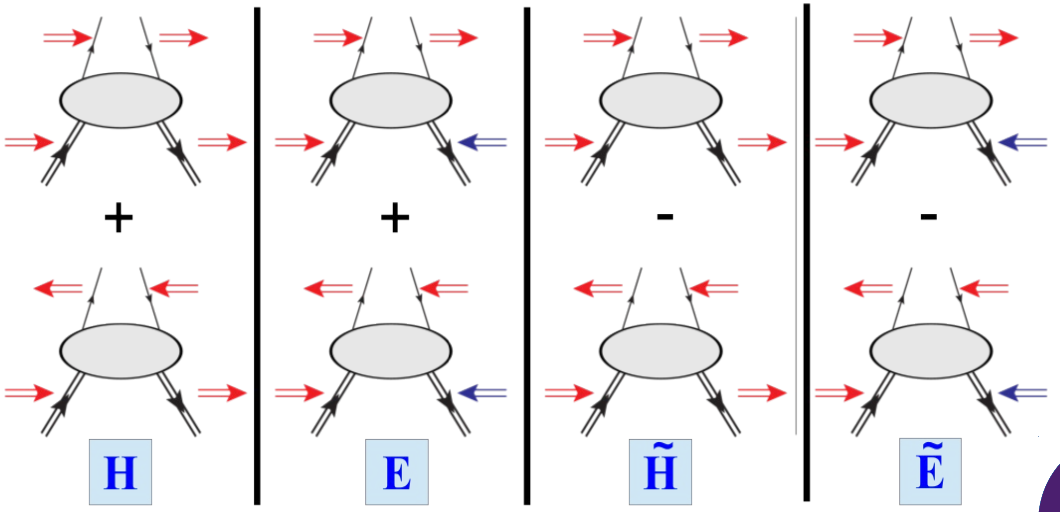
- **The exclusive electro-production of a photon**
  - *The simplest access to GPDs*
- **x is not directly measurable**
- **We access the Compton Form Factors (CFF)**



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

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





Measuring DVCS

DVCS is not the only process to produce photons exclusively

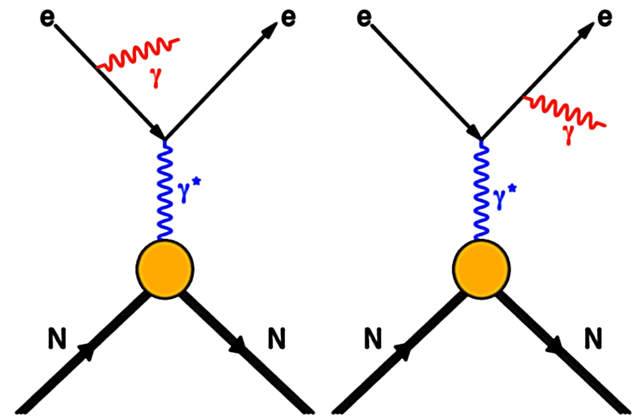
- Photons can be emitted by the lepton (Bethe-Heitler)
- Generates asymmetries through its interference with DVCS

Gives many interesting observables

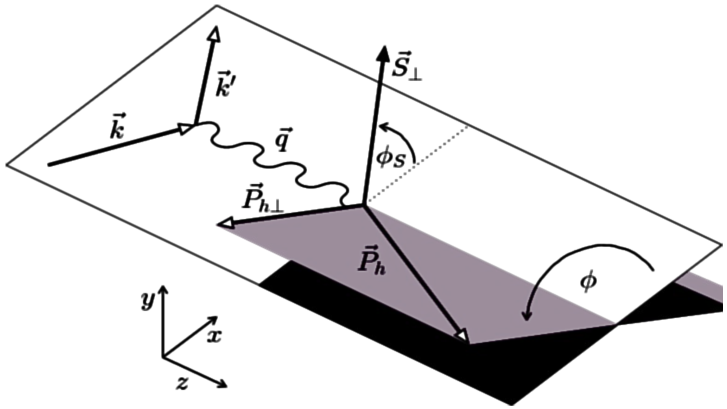
- Absolute cross sections
- Spin asymmetries (beam and target)
- Charge asymmetries

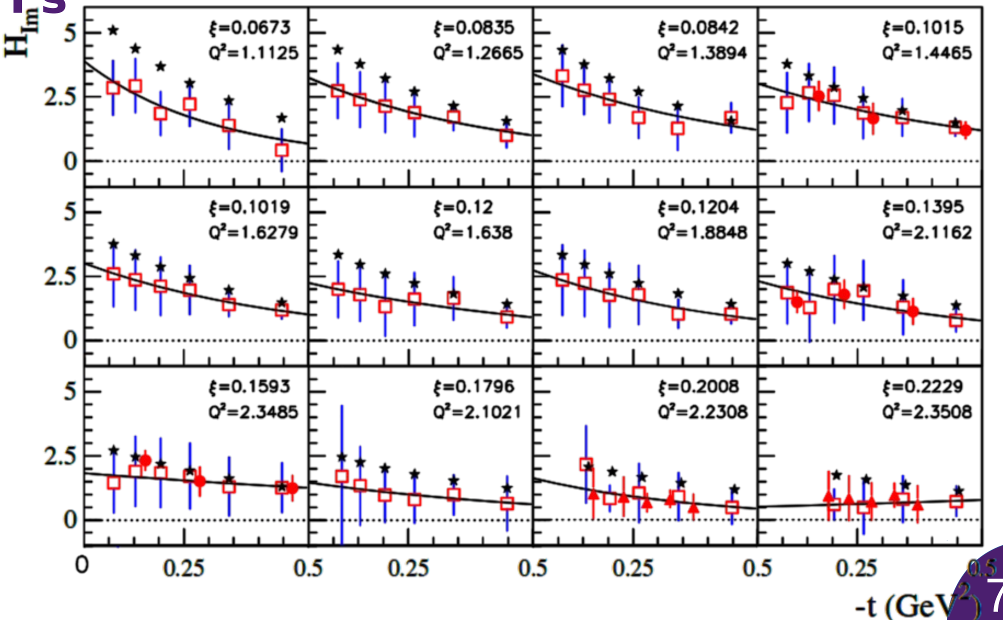
Allows to extract the complex CFFs

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

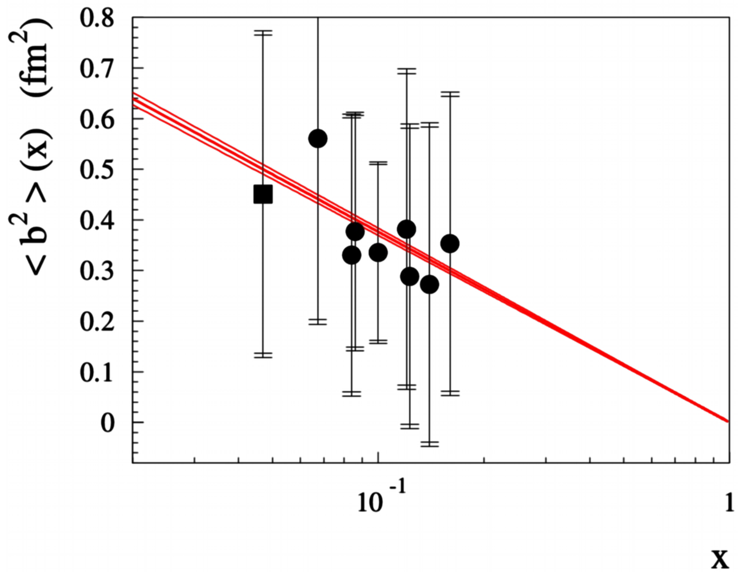


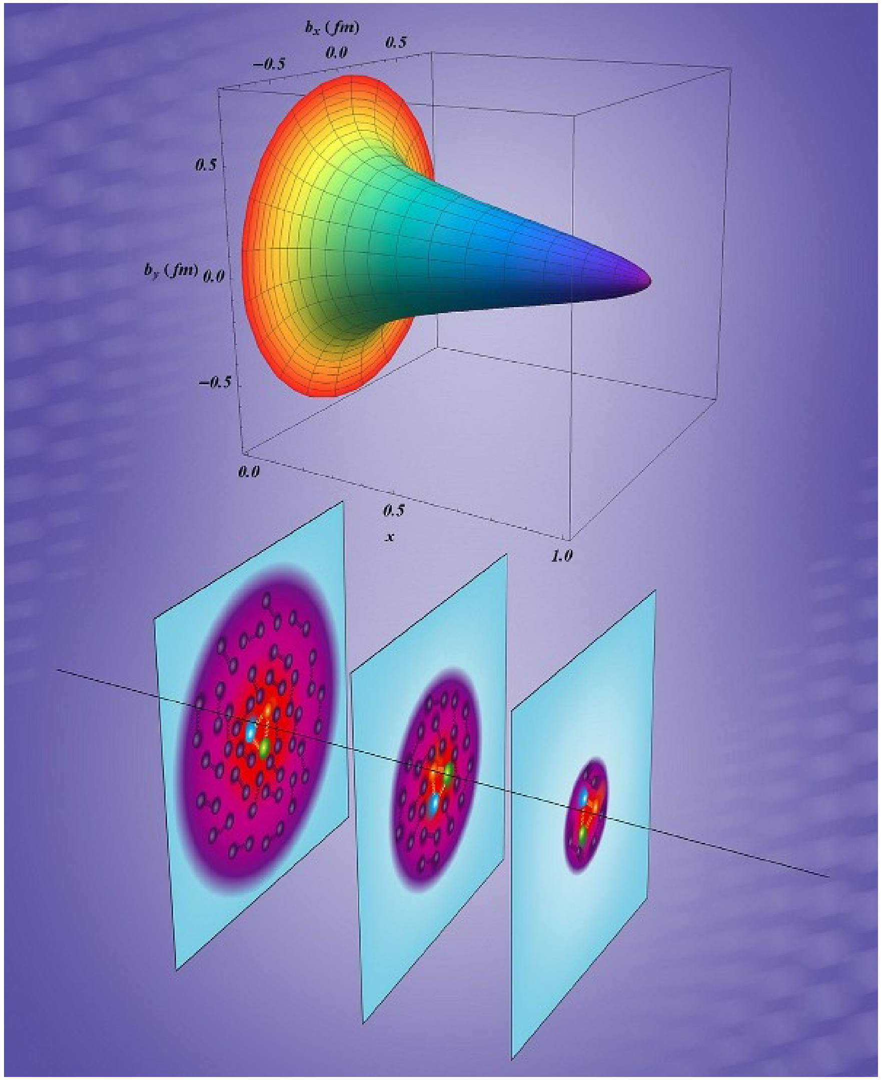
$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}})}_{\mathcal{I}} + |\tau_{\mathrm{DVCS}}|^2$$





Proton Tomography





CFFs are directly linked to the tomography of the proton

- The mean square charge radius of the proton for slices of x
- Error bars reflect a factor 5 of the model for unconstrained CFFs

We observe the nucleon size shrinking with x

- A proof that the framework holds

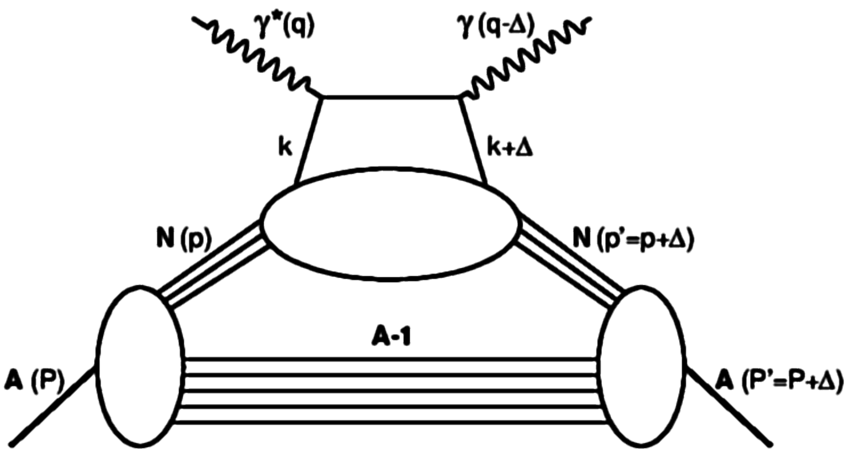
New observables are best to reduce the model errors

- Also important for the spin structure

GPDs & Nuclei

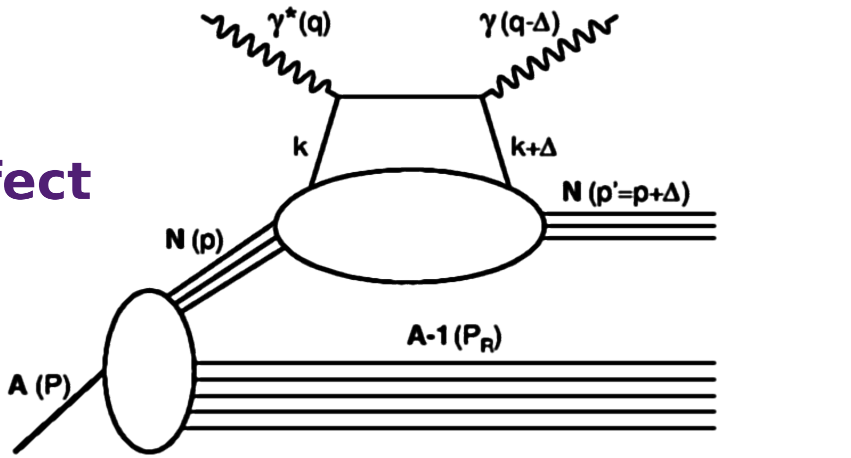
Nuclei give control over the spin

- 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**



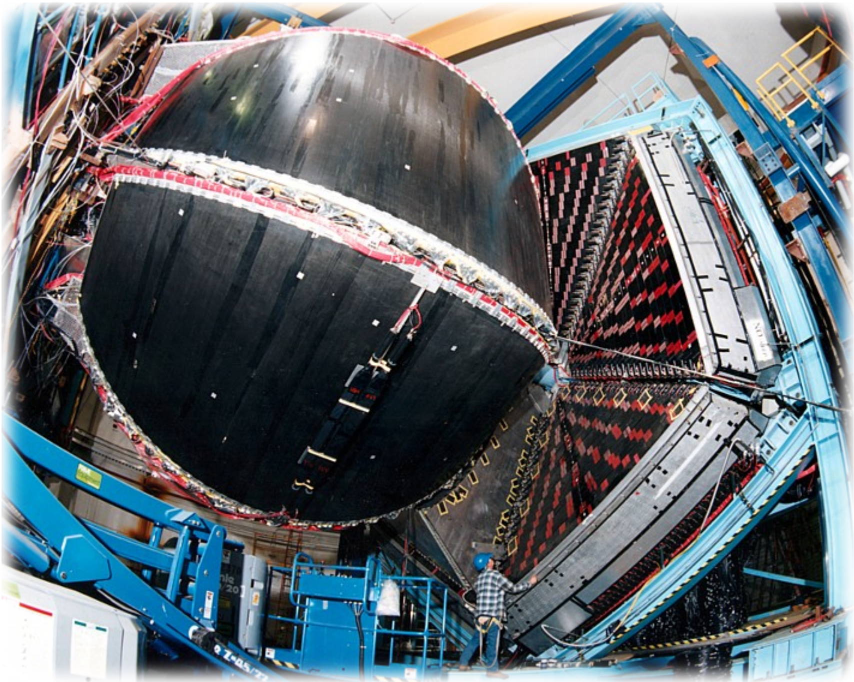
A perfect tool to study the EMC effect

- 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

Measuring DVCS on Helium

Jefferson Laboratory

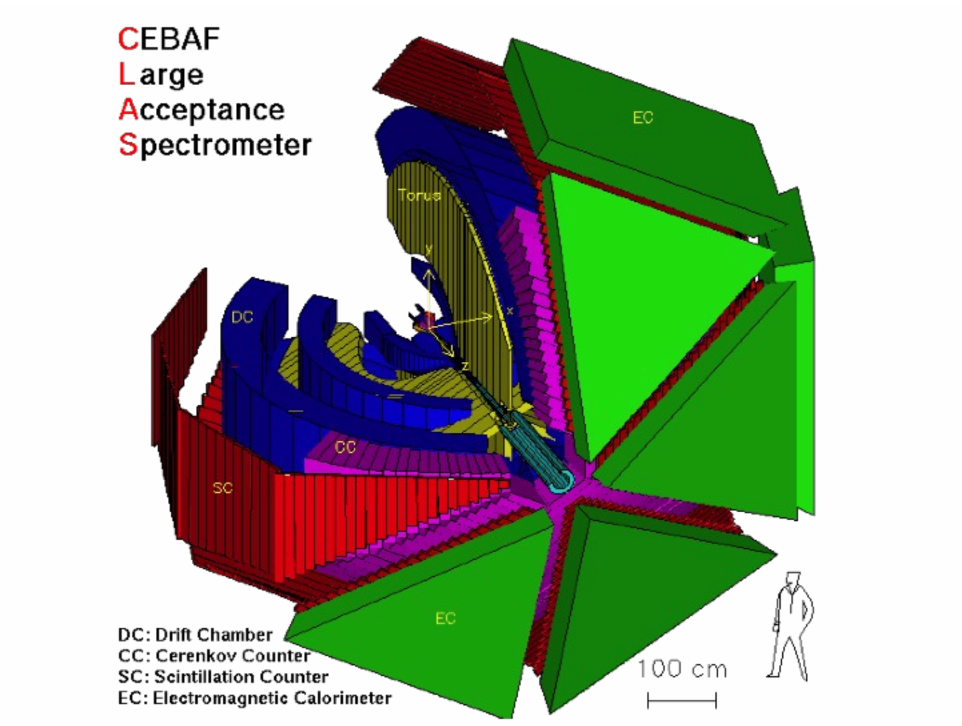
- Provides a 6 GeV electron beam (now up to 12 GeV)
- High quality beam
- 100% duty factor
- Beam 150 μm wide
- Intensity up to 100 μA

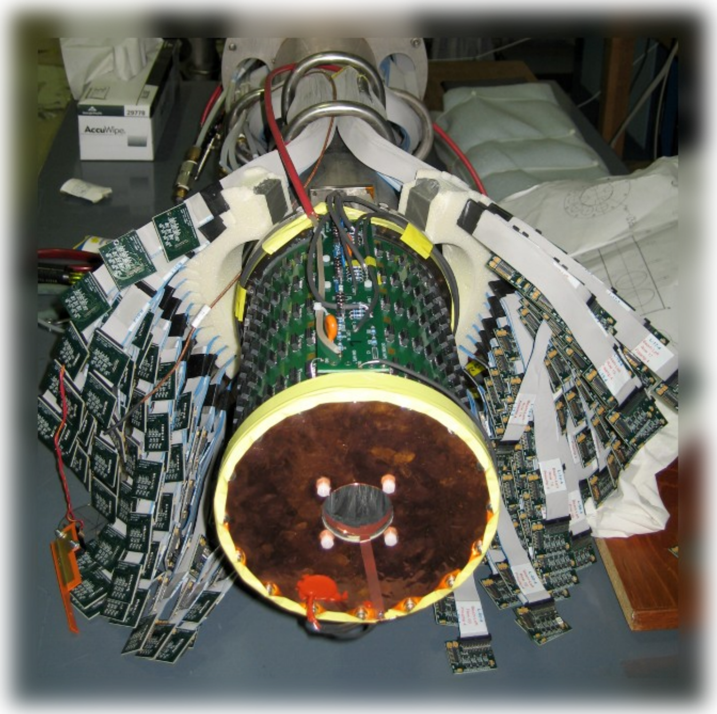


CEBAF Large Acceptance Spectrometer

- Nearly 4π
- Offers electron and proton identification for our experiment
- Recording rates up to 8 kHz

Experimental Apparatus





Experimental challenges

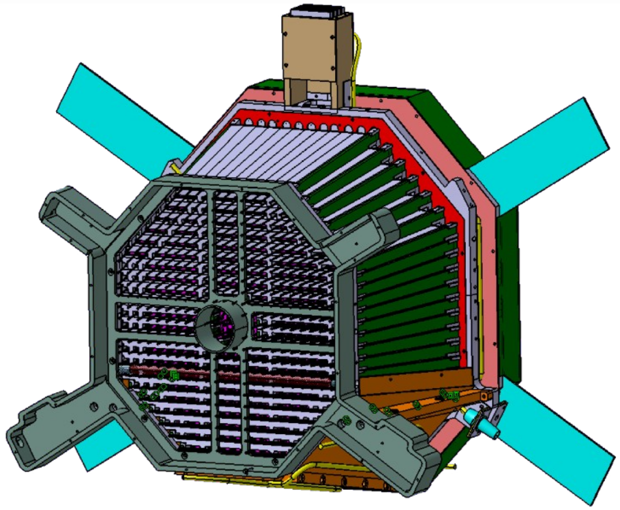
- Detecting very forward photons
- Detecting very low energy alphas (7 MeV)

Radial Time Projection Chamber

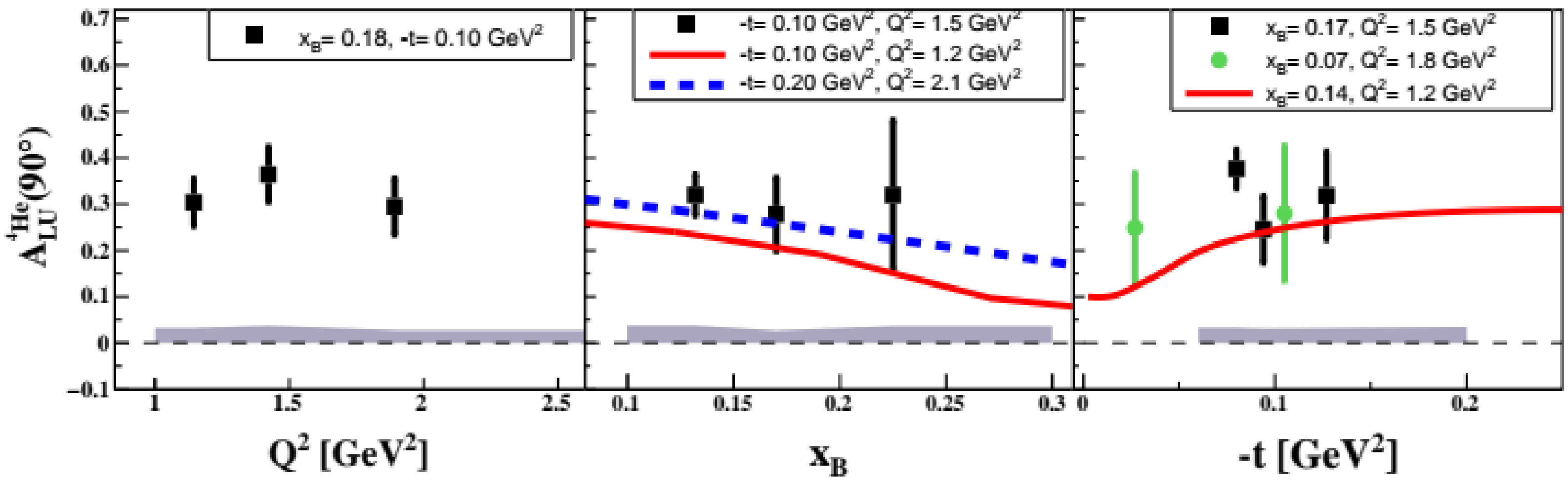
- Small TPC placed around the target

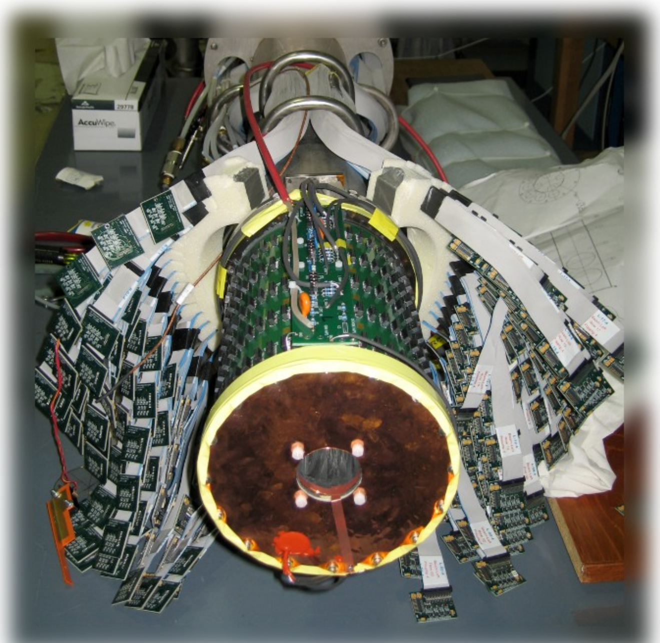
Inner Calorimeter

- 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**

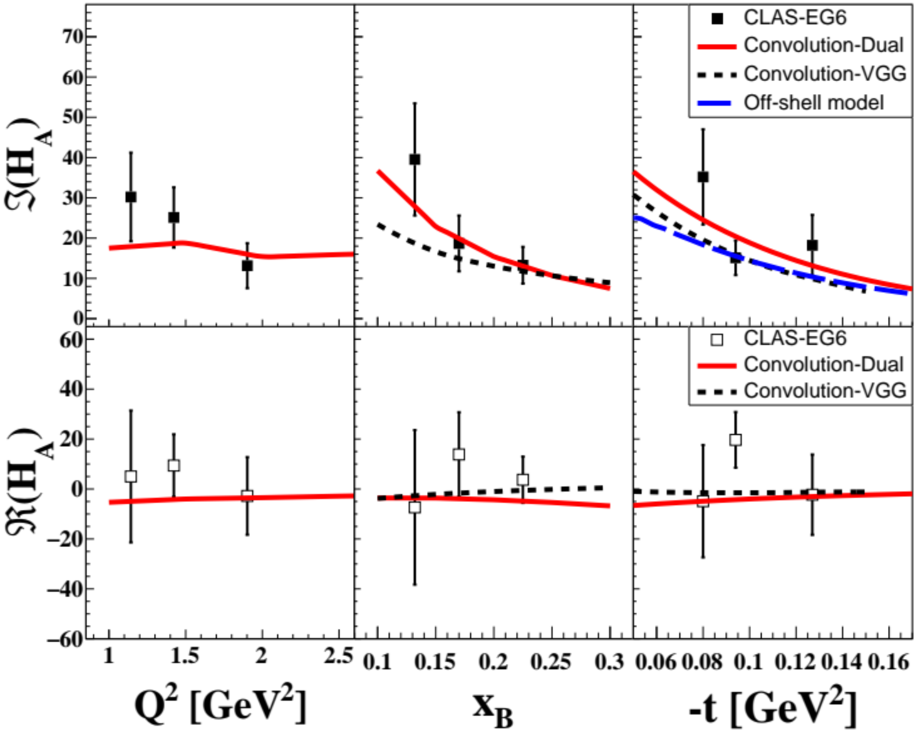
Extraction of the CFF

Helium allows for a simple extraction

- Spin-0 → 1 GPD/CFF

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

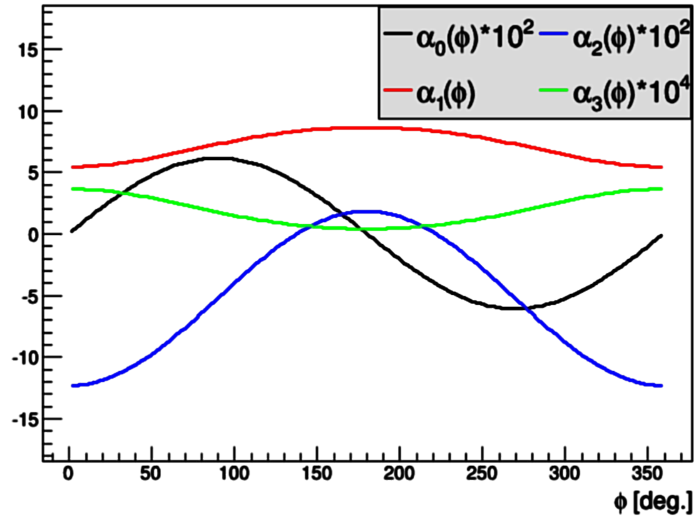
- These are calculable within perturbative QCD
- Allows to separate their contributions



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

Works very well

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



From DVCS to GPDs

Is this problem tractable?

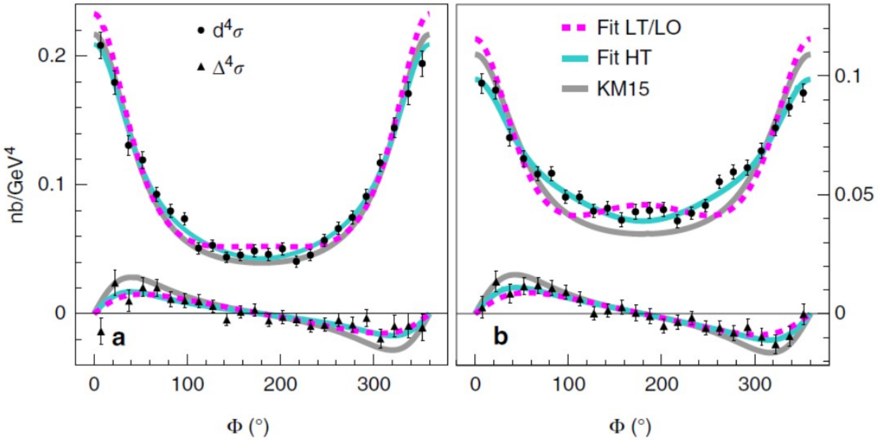
- It is actually not that clear
- We will need many observables
- We get only to the CFFs not GPDs

What about NLO and HT ?

- Hall A in JLab seems to point to HT effect
- Can we check these using nuclei?

Fit from Kumericki

LT/LO	$\mathbb{H}_{++}, \mathbb{E}_{++}$	✗ bad fit
HT	$\mathbb{H}_{++}, \mathbb{H}_{0+}$	✓ good fit
NLO	$\mathbb{H}_{++}, \mathbb{H}_{-+}$	✓ good fit



$$\Delta\sigma_{LU} \propto \sin\phi \;\; Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + ...\}$$

$$\Delta\sigma_{UL} \propto \sin\phi \;\; Im\left\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\tilde{\mathcal{H}} + \frac{x_B}{2}\mathcal{E}\right) - \xi kF_2\tilde{\mathcal{E}} + ...\right\}$$

$$\Delta\sigma_{LL} \propto (A + B\cos\phi) \;\; Re\left\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) + ...\right\}$$

$$\Delta\sigma_{Ux} \propto \sin\phi \;\; Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + ...\}$$

CLAS Incoherent DVCS

Measurement of CLAS

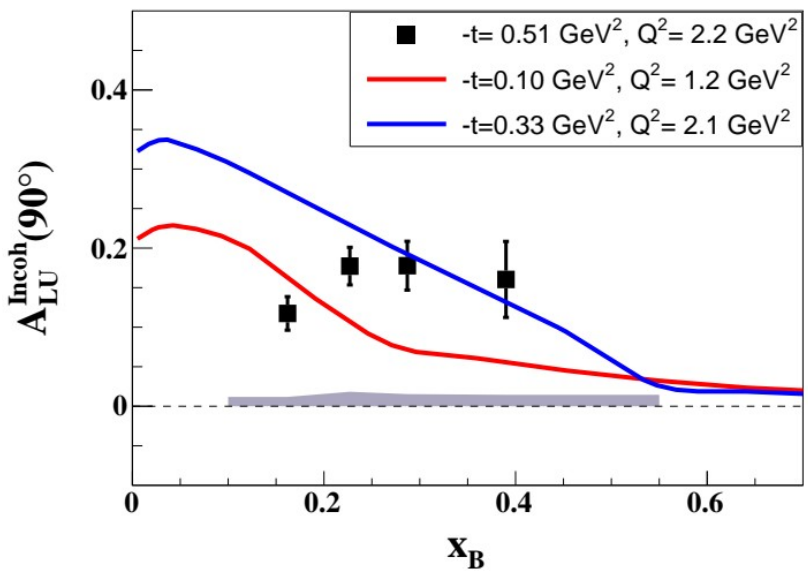
- **Proton bound in helium target**

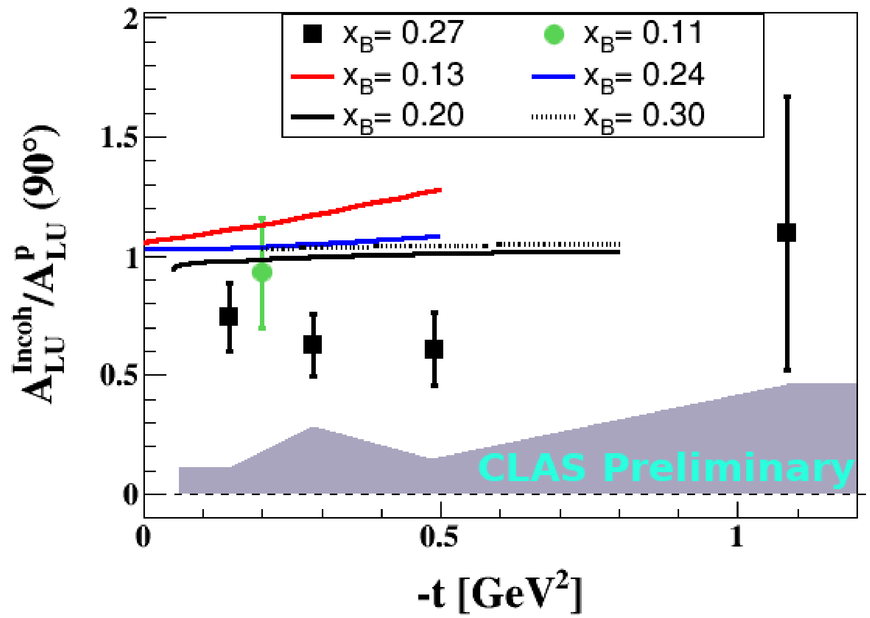
Gives a generalized EMC

- **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

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

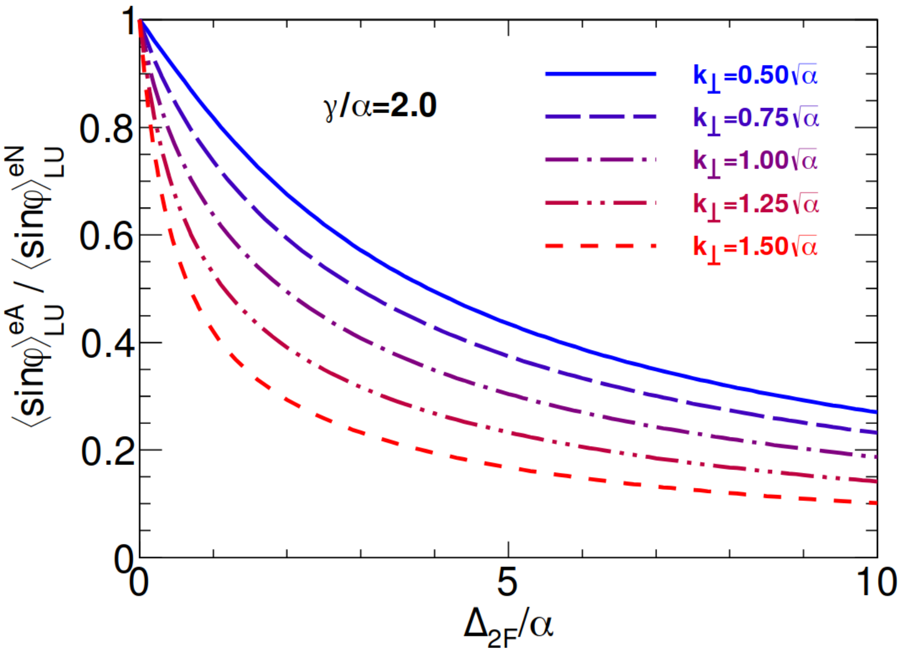
Nuclear TMD

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

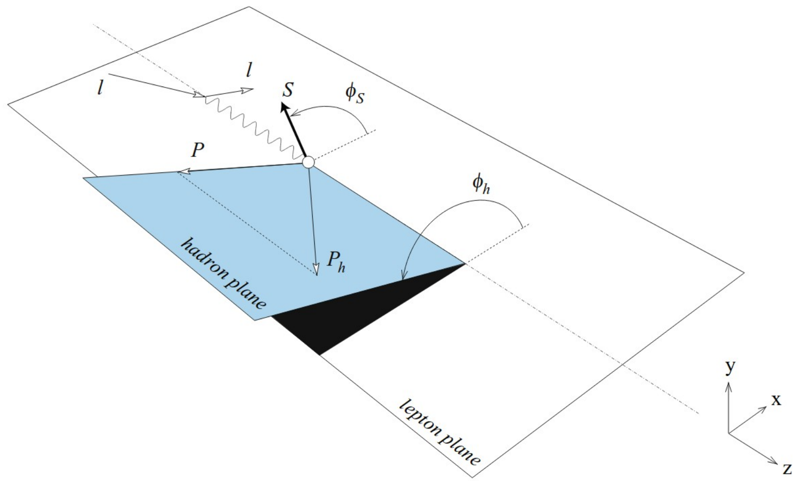
- Independent of final state effects

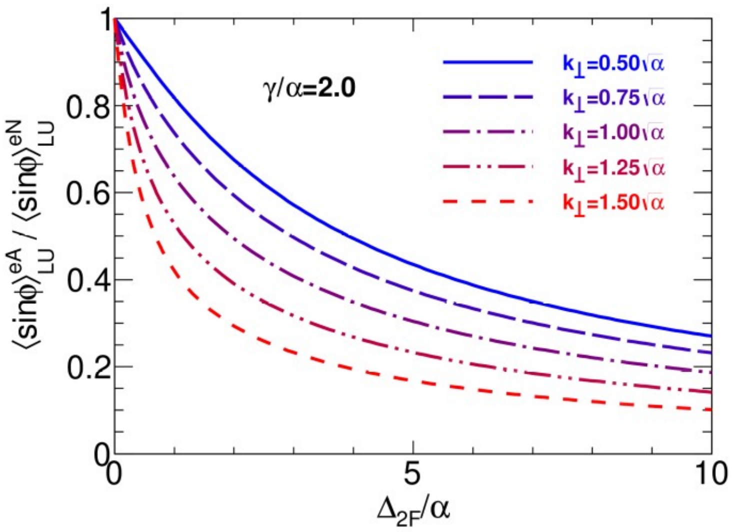


$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N)$$

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

Using TMDs for Hadronization





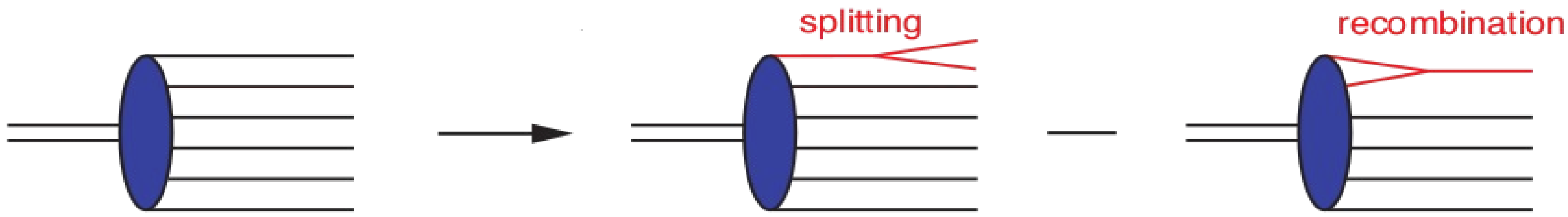
Usual hadronization measurements use outdated methods

- **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 $\hat{q}$**

Offers two extra independent 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

One Function to Unify Them All

Eventually, we would like to unify all of this

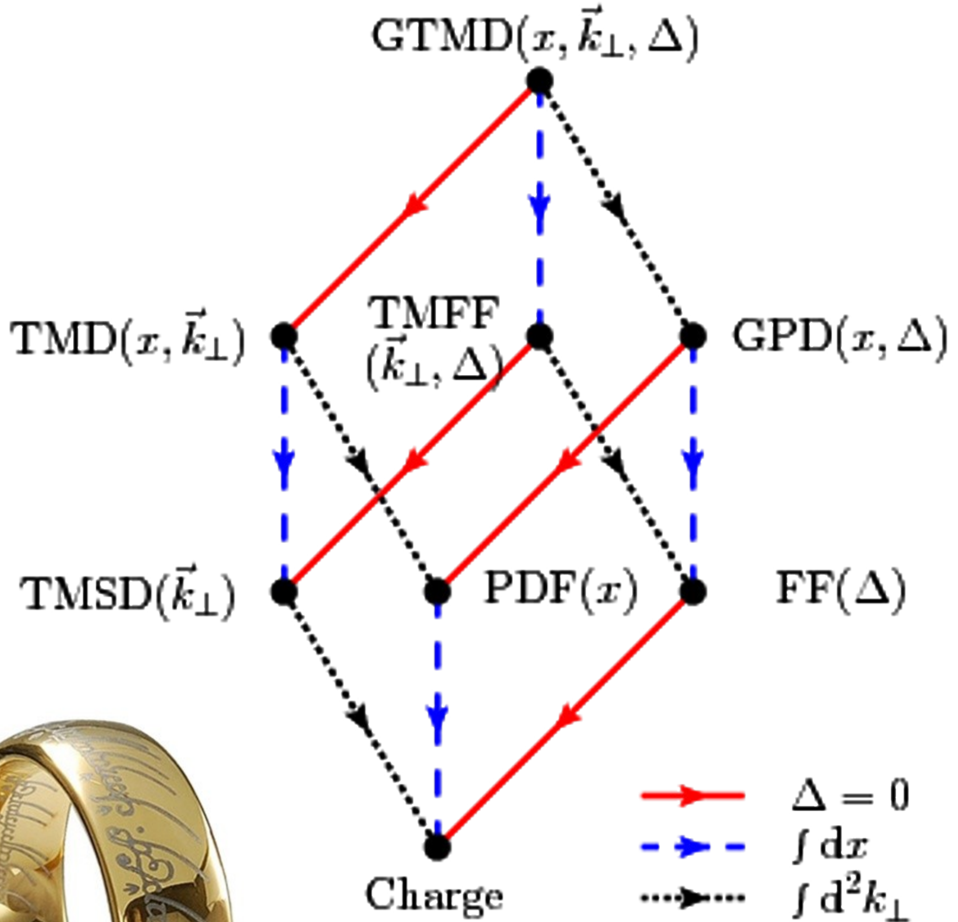
- **Wigner distributions are the tool of choice**

We would like to understand higher order and higher twist

- **Leads to a massive zoology of functions**
- **Becomes increasingly difficult to extract from data**

How to measure all this?

- **Ideas are proposed**
- **16 complex GTMDs for the proton**
- **What about the helium-4 though?**
  - *At first sight just a convolution of nucleons without spin exchange*



Future of Nuclear 3D Mapping

Short term @ JLab

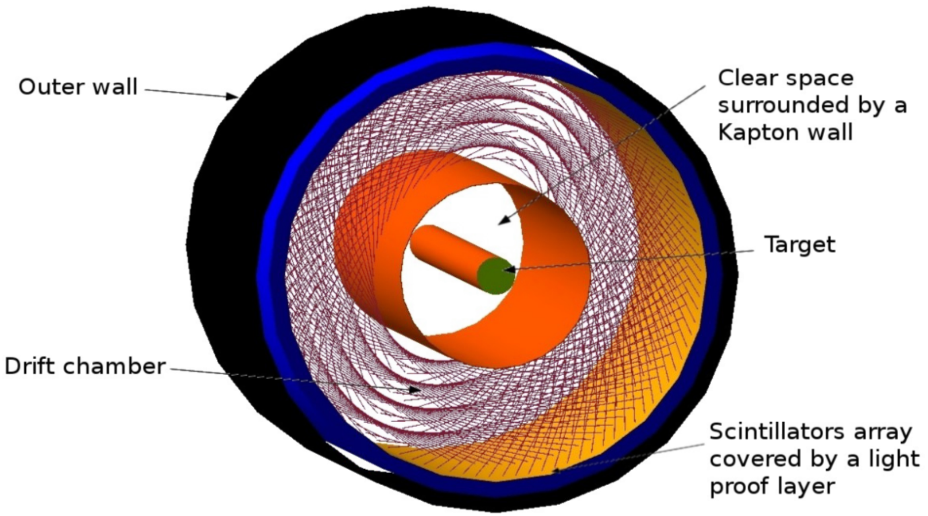
- **The ALERT run group**
  - *A Low Energy Recoil Tracker*
  - *Measure nuclear DVCS*
- **What about nTMDs?**
  - *Doable in CLAS12*

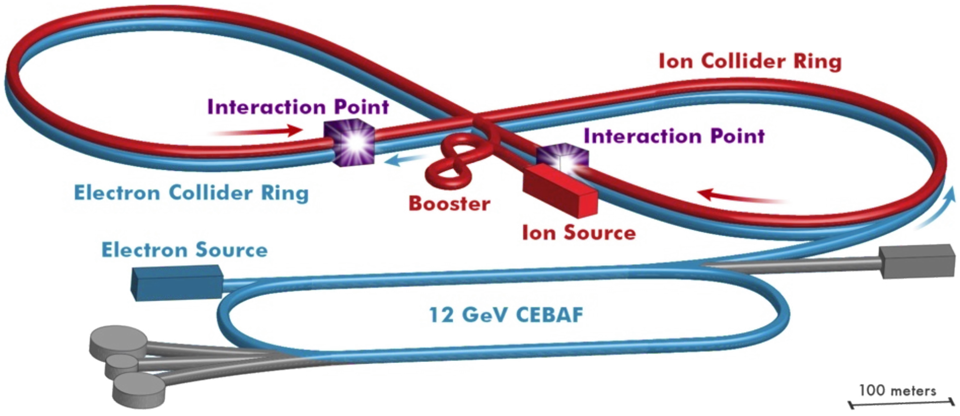
Long term @ EIC

- **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 complexity**





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 nuclear DVCS**

Coherent DVCS shows strong signal

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

Incoherent DVCS surprising result

- **Surprisingly small asymmetries**

TMDs in Nuclei

- **Offer a unique access to the property of the medium and the saturation scale**
- **Can help separate initial and final state effects**

EIC and 3D nuclei

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