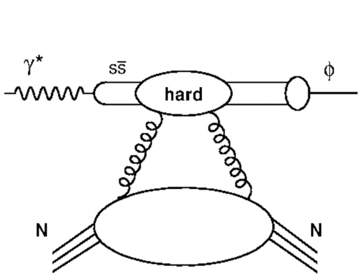
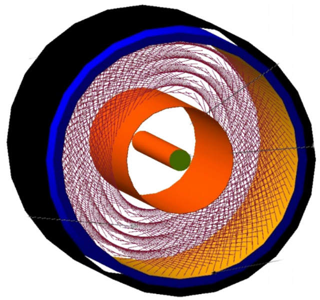
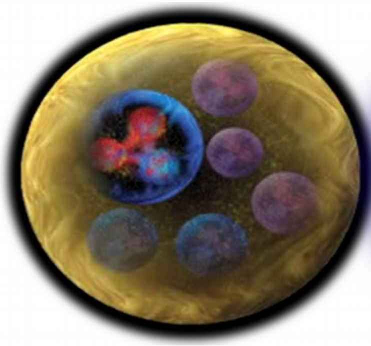
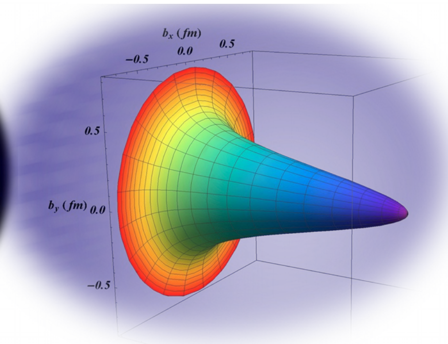
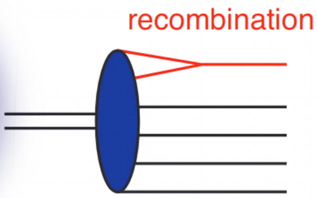
Lessons from Lepton-Nucleon and Lepton-Nuclei Interactions





Probing the structure of the atomic nucleus

Raphaël Dupré

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

université PARIS-SACLAY

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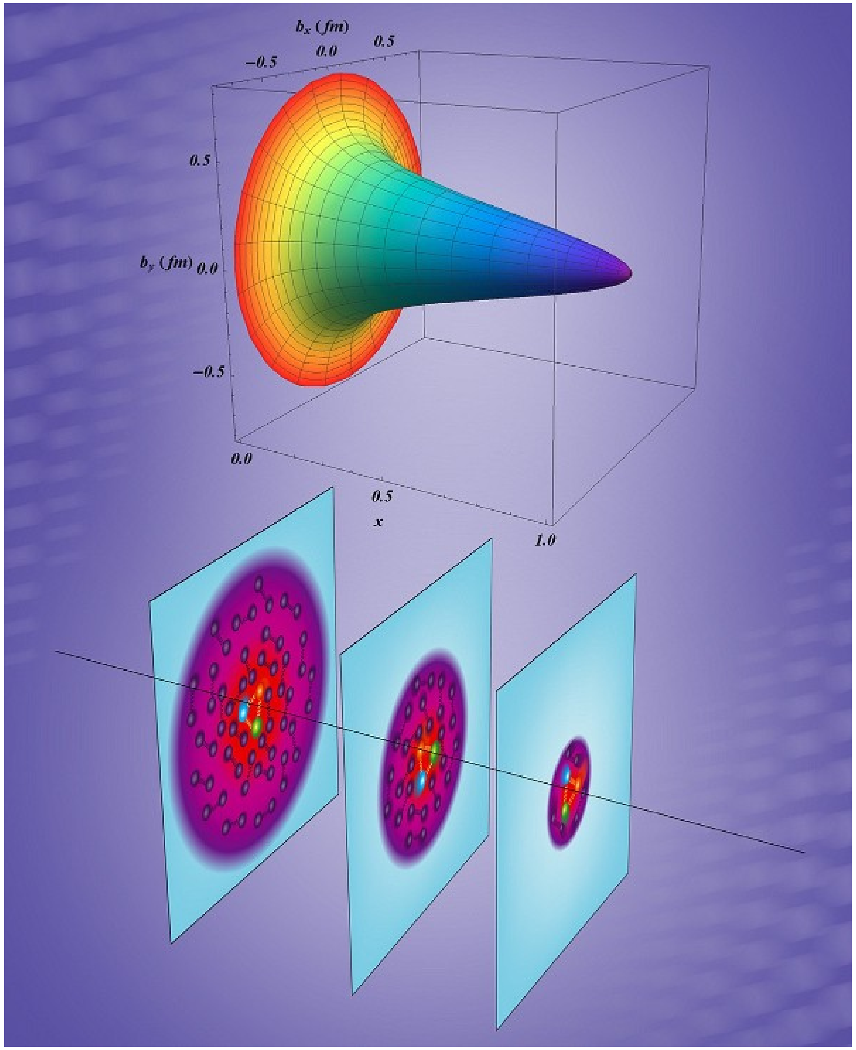
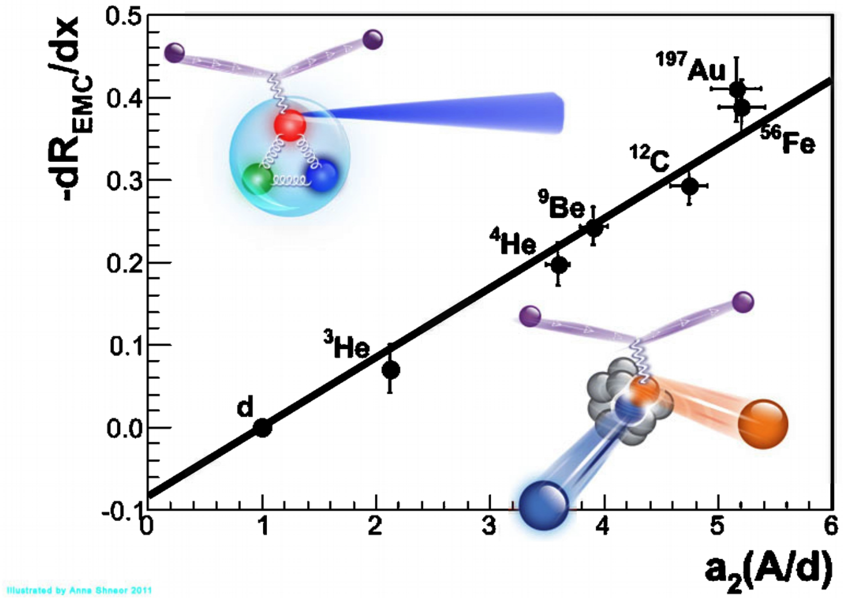
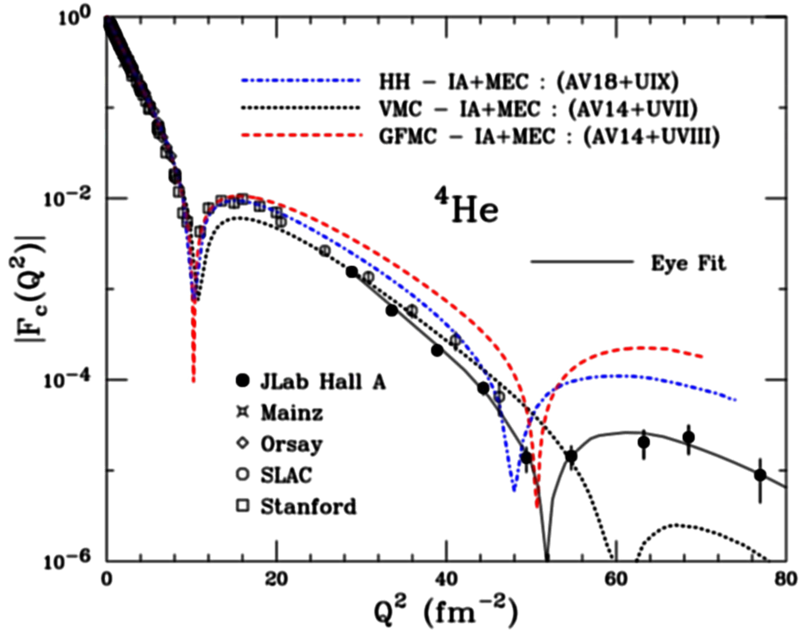
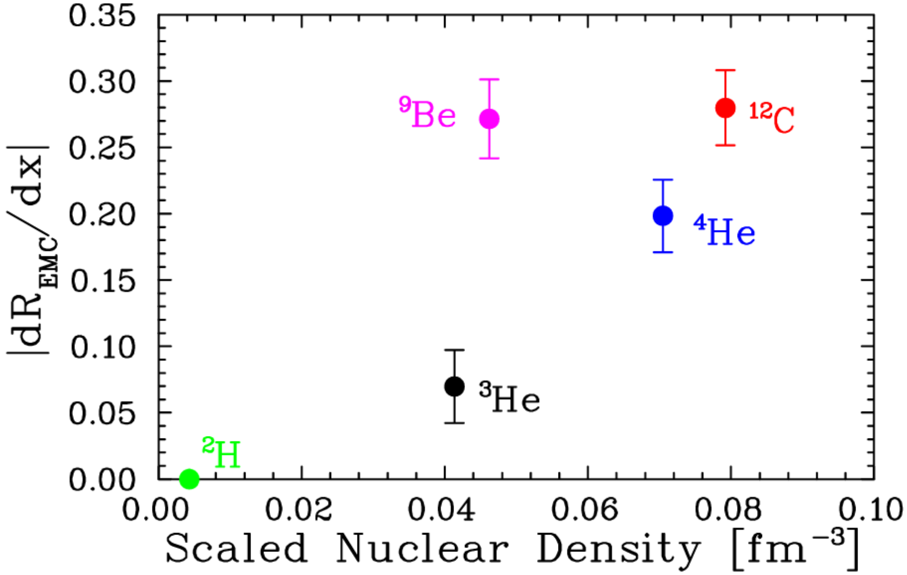
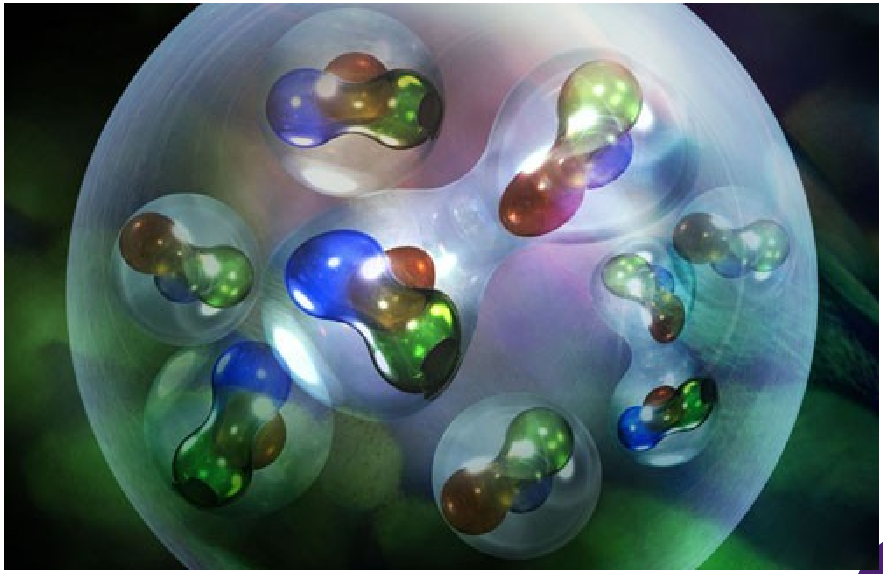


Part 2: Lepton-Nucleus









The nucleus in hadron physics

We have two coexisting pictures

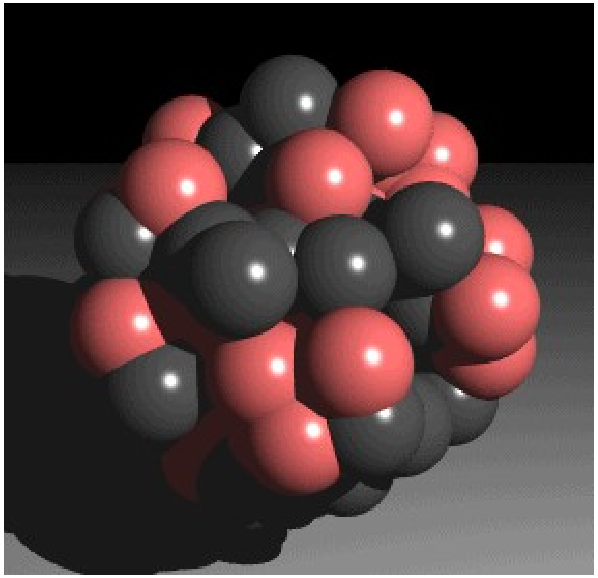
- A nucleus made of protons and neutrons
- A nucleus made of quarks and gluons somewhat bound into nucleons

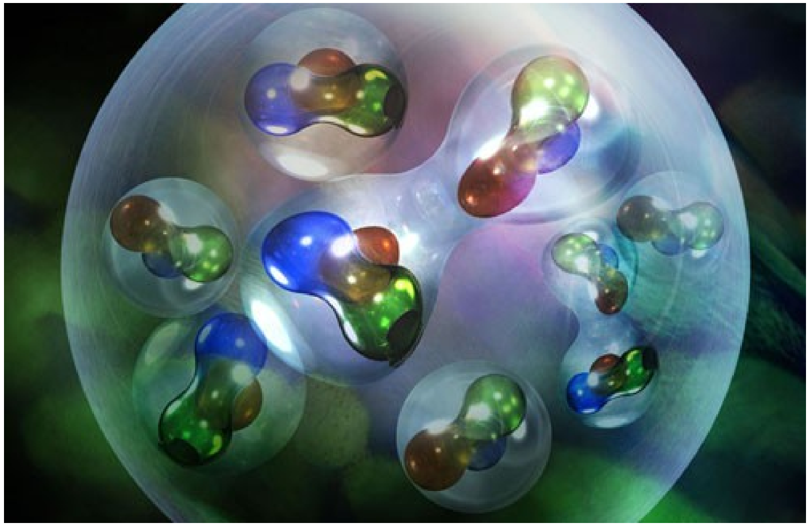
Main question:

- What are the right degrees of freedom?

Answer:

- It depends what you are trying to do





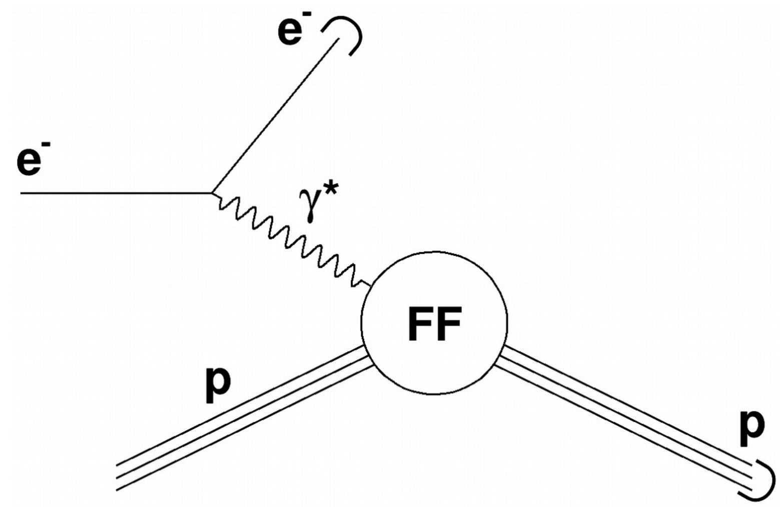
Nuclear Form Factors

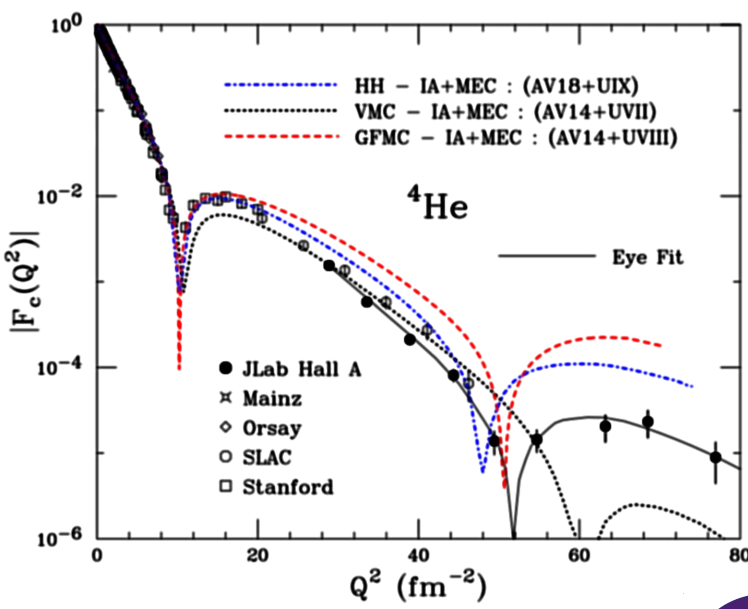
Very similarly to protons

- Elastic scattering on nuclei provides information on their size and charge distribution
- Large spins give access to non spherical components
- Mostly described in terms of classic protons and neutrons

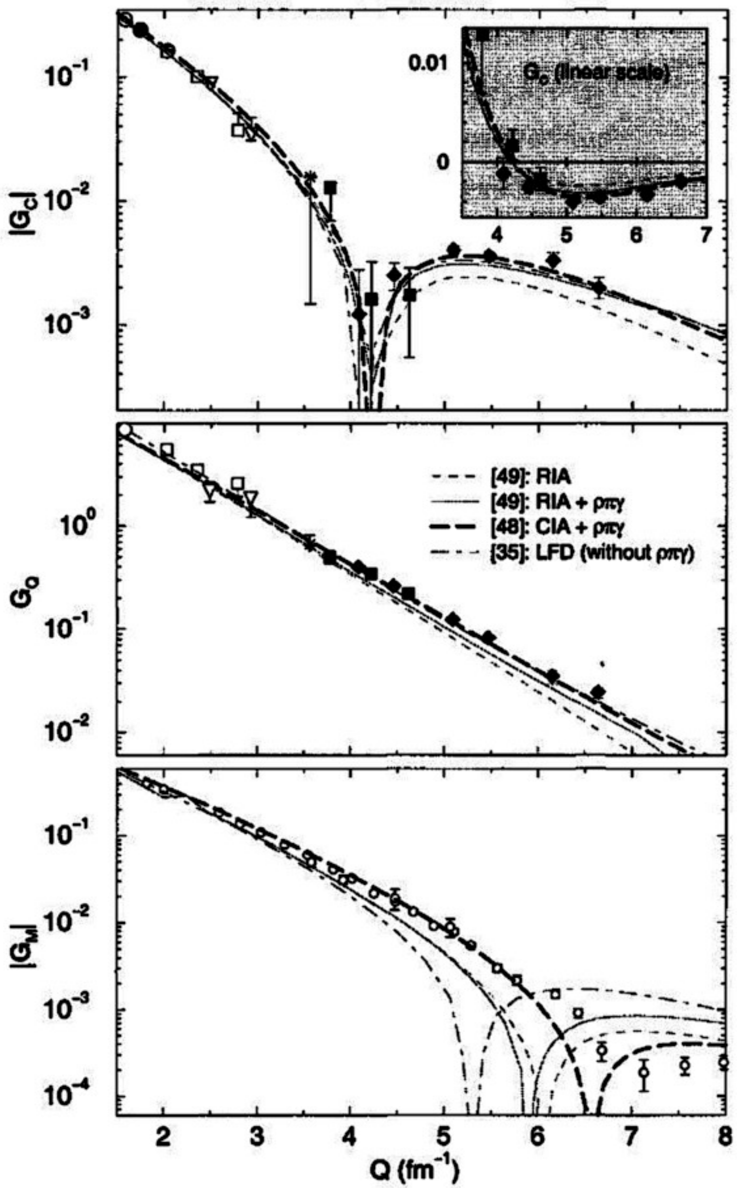
Large momentum transfer

- Give access to configurations where nucleons are close together
- Raise the question of nucleon overlap and its effect





Deuteron Form Factors



Deuterium has an extra form factor

- Allows to measure the quadrupole moment
- Gives access to the shape of deuterium

Very important measurement in nuclear physics

- Strong constraint on the N-N force
- Necessitate a relativistic treatment of the nucleus

Nuclear radius

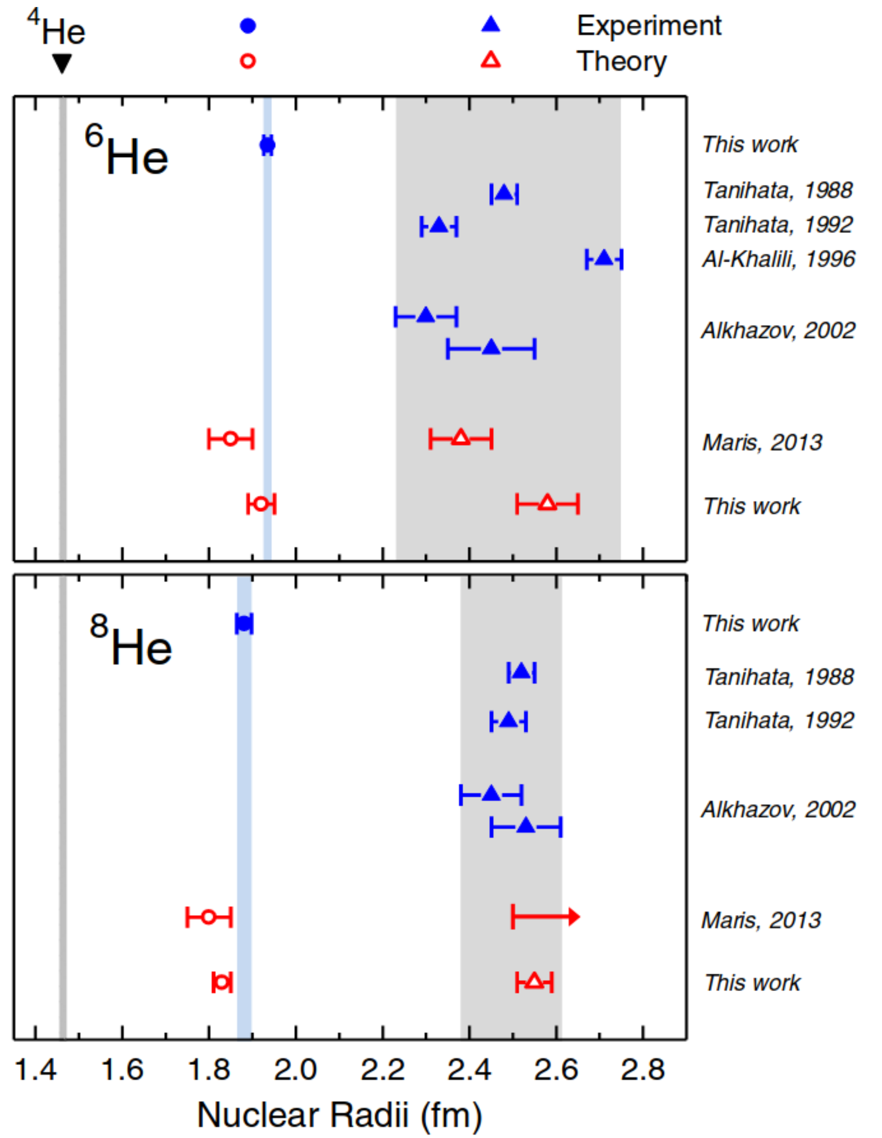
No puzzle here!

- Muonic atoms of light nuclei do not show any deviation from electronic ones

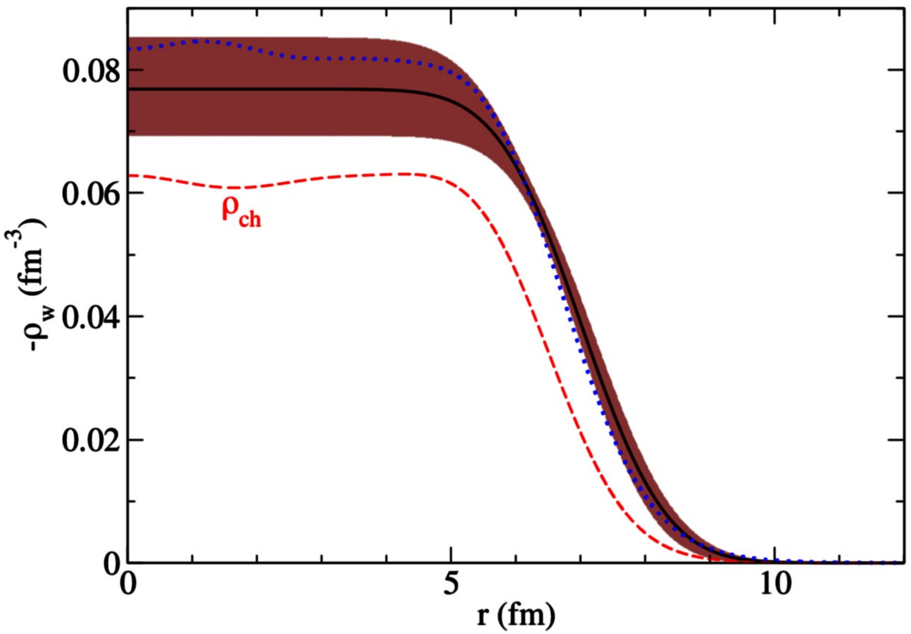
Radius of unstable nuclei

- Using laser traps and atomic physics measurements
- Combines they allow to measure precisely the radius of unstable nuclei

Z.-T. Lu et al. Rev.Mod.Phys. 85 (2013) 1383



Weak Charge FFs



Similar than for protons, we can look at nuclear weak charge with parity violating assymetries

- **In the nucleus, it highlights the contribution from neutrons**
- **Used to understand the neutron skin of nuclei of interest for low energy nuclear physics**

Can be of importance for other higher energy processes

- **Particularly when surface interactions are dominating**
  - *We will discuss some of them later!*

Quasi-elastic Scattering (QES)

What is it?

- Elastic scattering on a bound nucleon

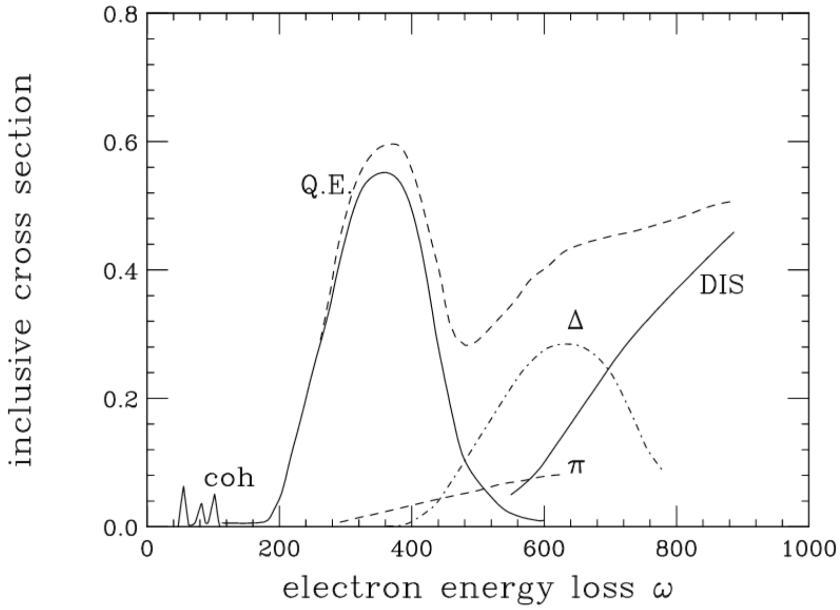
Are bound nucleons modified?

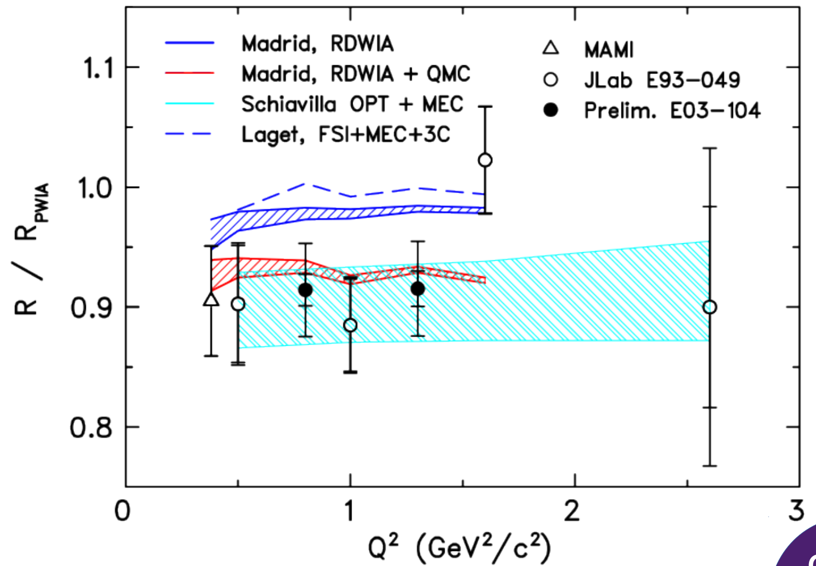
- It seems so, but there are many caveats
- Reinteractions with nuclear fragments are likely
  - *Final state interactions*
- Initial state nucleon are off their mass shell
  - *We actually measure transition form factors*

This remains an open question

- Much more to come on the topic

O. Benhar et al. Rev.Mod.Phys. 80 (2008) 189-224





Nuclear Dynamic

Nucleon kinematics can be inferred from QES

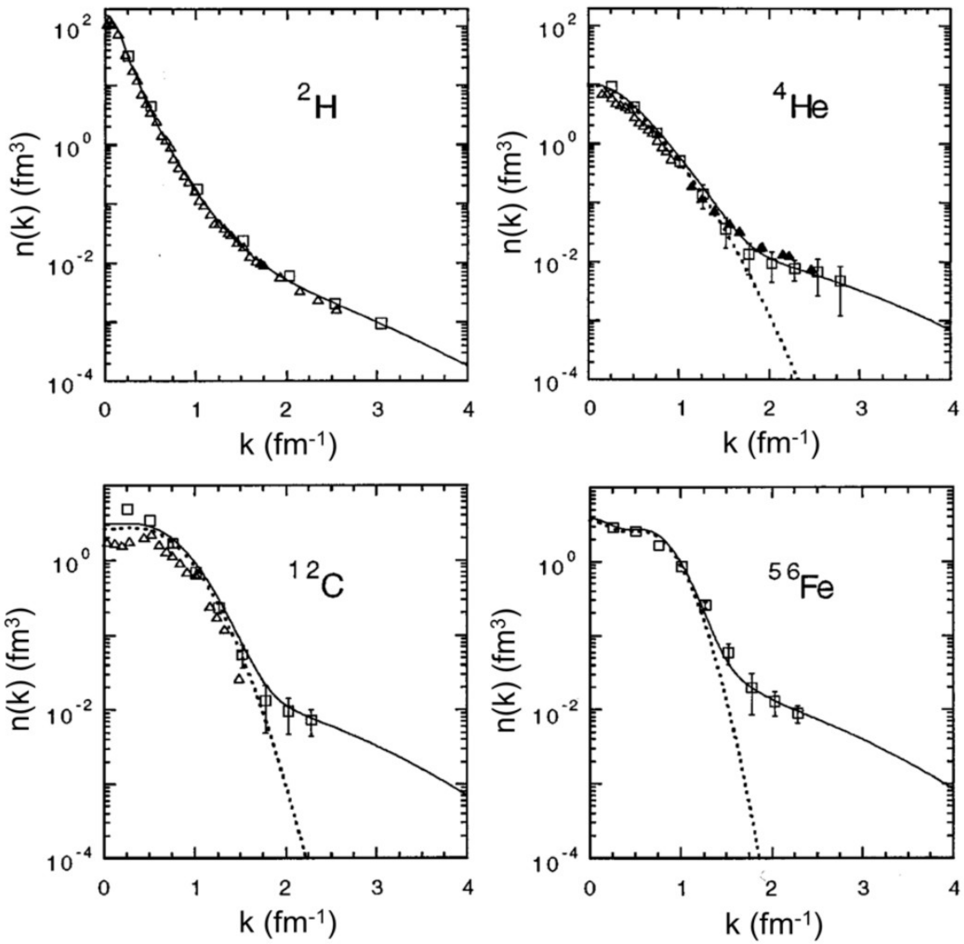
- Using the extra momentum of the reaction
- Similarly to previous discussion this is subject to corrections

We find two regions

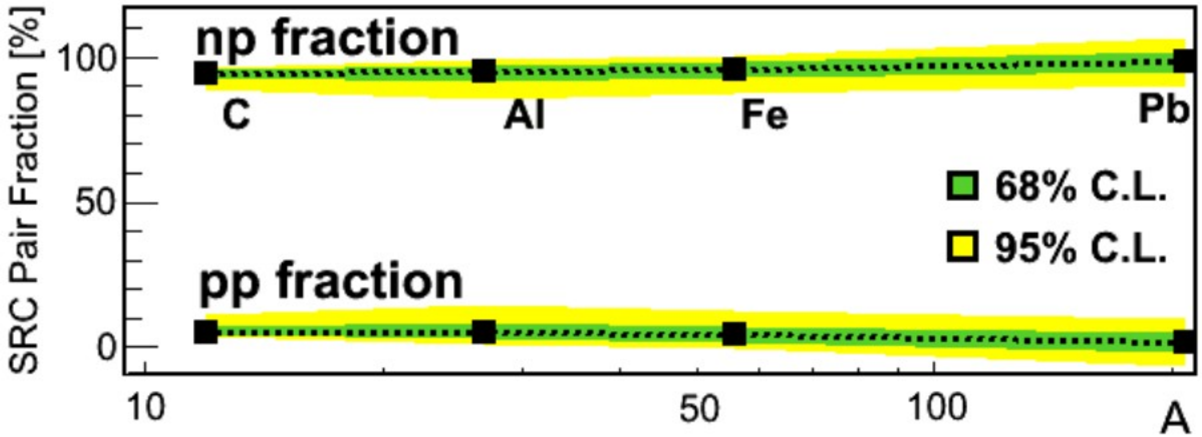
- Low momentum from Fermi motion
- High momentum contribution from short range correlated nucleon pairs (SRC)

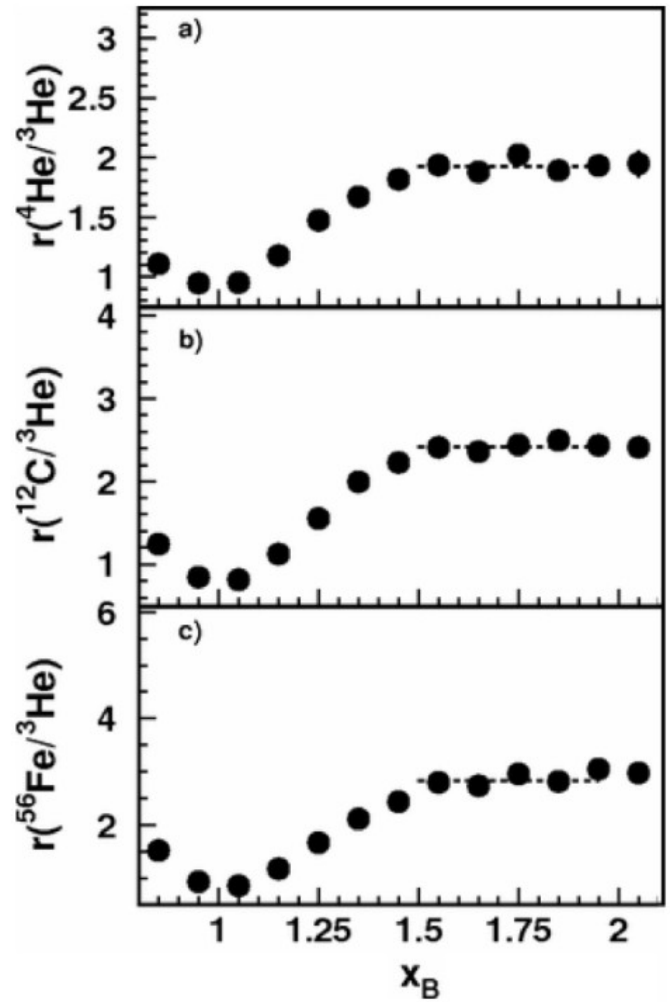
Past but coming back

- Recent calculations of nuclear dynamic are often beyond these methods
- Yet it is making a comeback to look into SRC pairs



Short Range Correlated Nucleons





Recent studies of SRC pairs

- **They have a universal behavior linked to the NN potential**
- **They are dominated by np pairs rather than pp or nn**
  - *This holds for neutron rich nuclei*
- **The tensor nuclear force dominates in this kinematic region**

Can they modify the nuclear structure ?

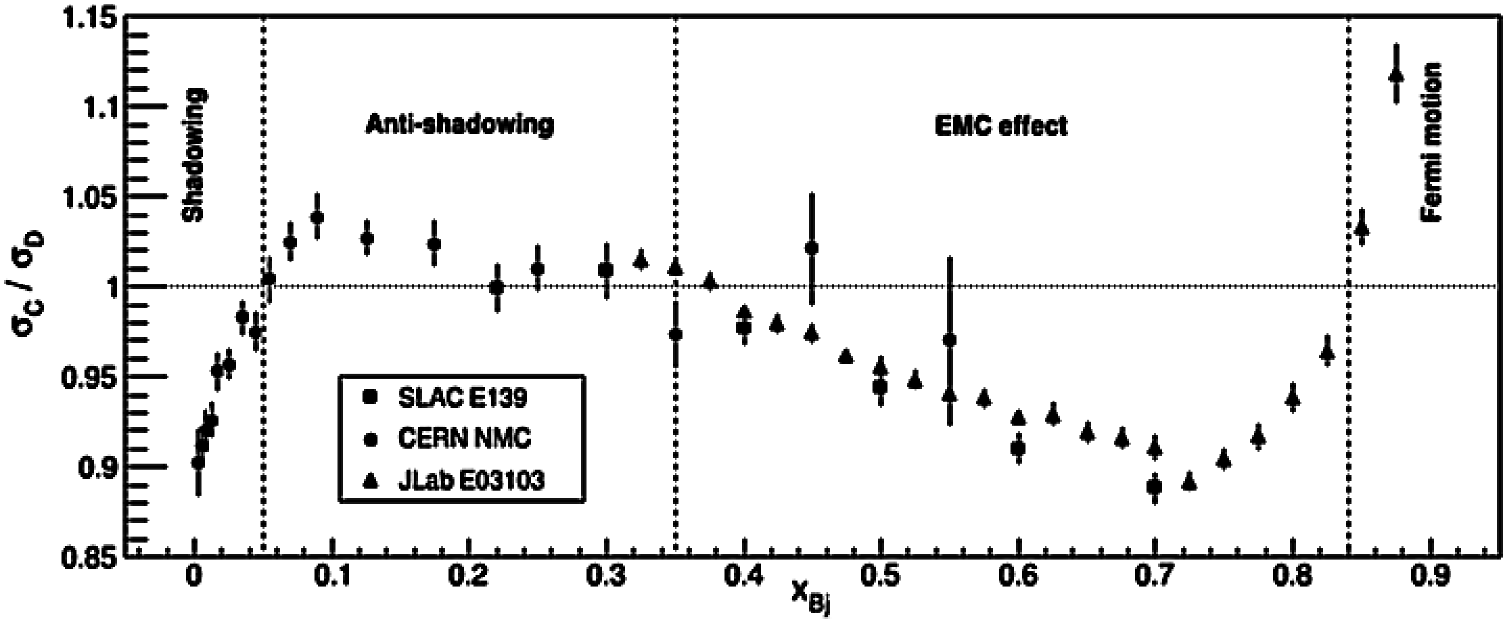
- **More on this later**

O. Hen et al. Rev.Mod.Phys. 89 (2017) no.4, 045002

C. Ciofi degli Atti, Physics Reports 590 (2015) 1–85

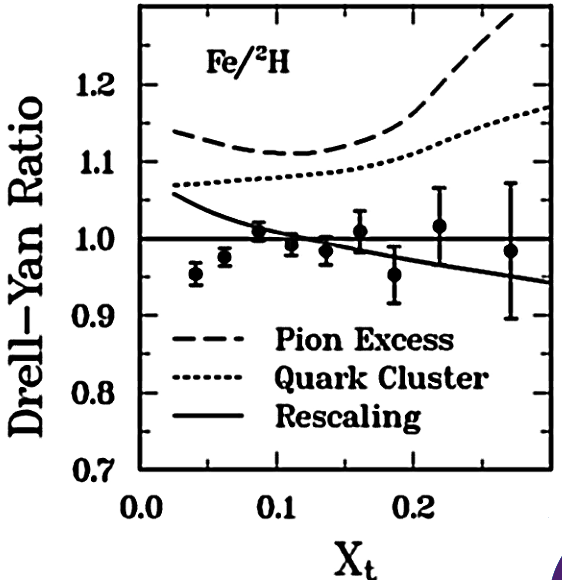
L. Frankfurt et al. Int.J.Mod.Phys. A23 (2008) 2991-3055

Nuclear PDFs



Measurement of nuclear PDFs was very surprising

- Shadowing
- Anti-shadowing
- EMC effect
- Fermi motion



Lot of theoretical activity

- Very little consensus

Nuclear PDFs

Similar issues than for the nucleon

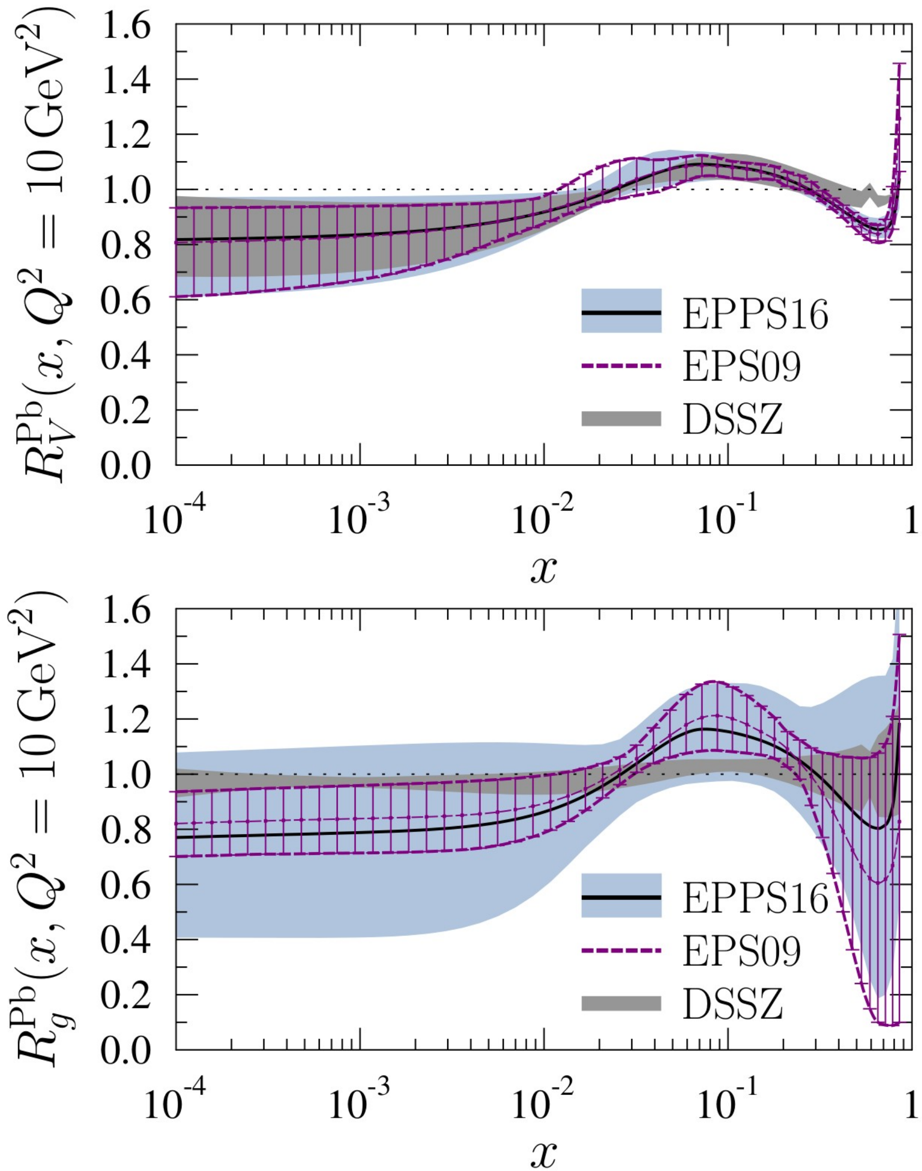
- **Made worst by additional complications**
- **Masses are large**
  - *Either make tighter cuts*
  - *Or apply corrections*

Amount of data is limited

- **No nuclei in A1 and Zeus**
  - *Hope for an EIC are high for this*
- **Leads to a reduced number of parameters i.e. model assumptions**

Summary

- **We observe the effects but with limited resolution**
- **Gluons, sea and even d are mostly unknown**



Shadowing

Linked to multiple scattering

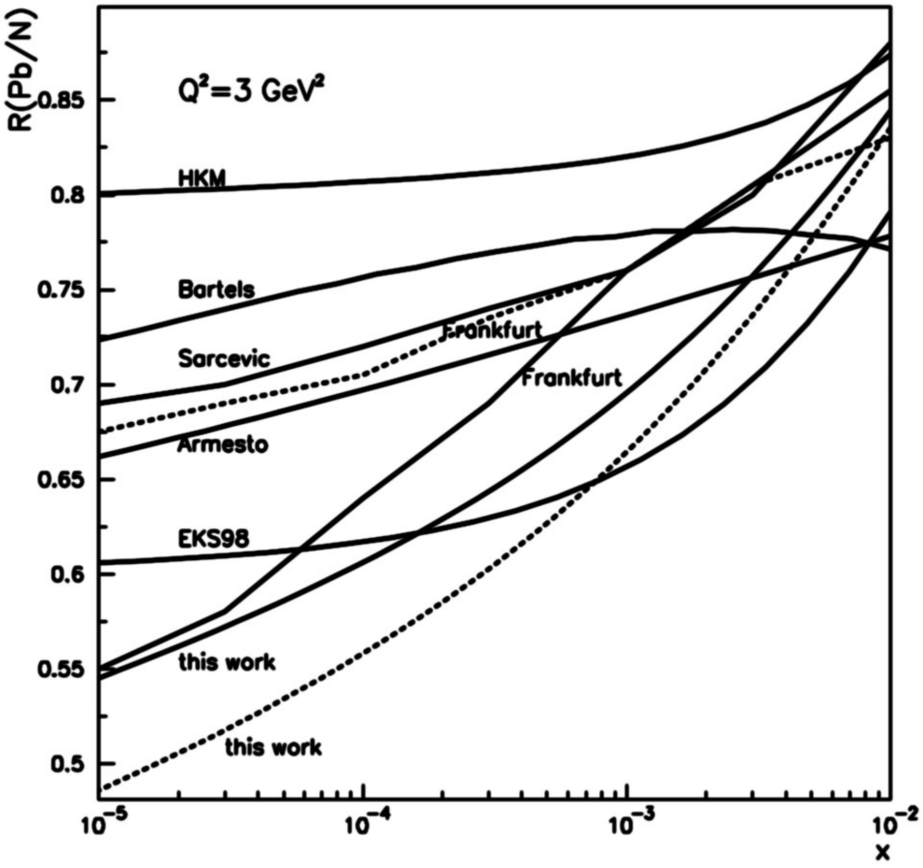
- Screening of some nucleons leads to reduced cross section
- Several calculation methods available
  - *Including CGC*
- They diverge largely at lower x

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

Anti-Shadowing

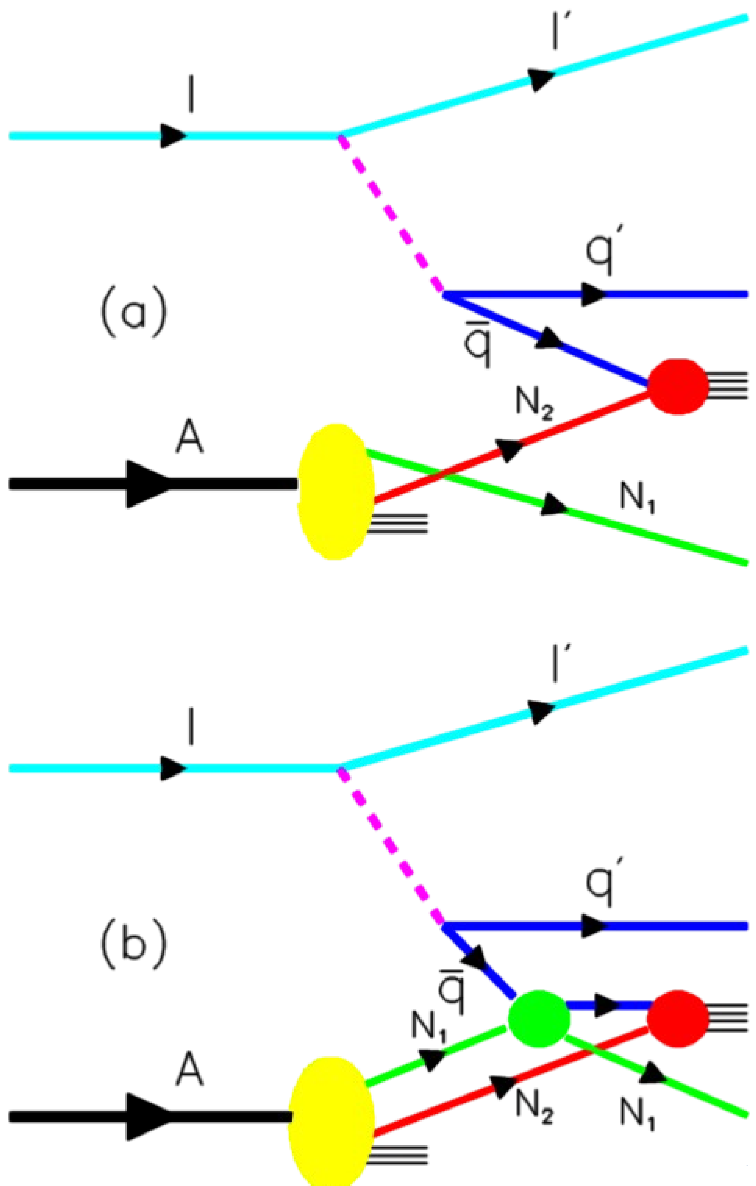
The least discussed nuclear effect

Mostly assumed to be there to satisfy sum rules

- **A very unsatisfactory explanation**

Few shadowing models have better integration of the effect

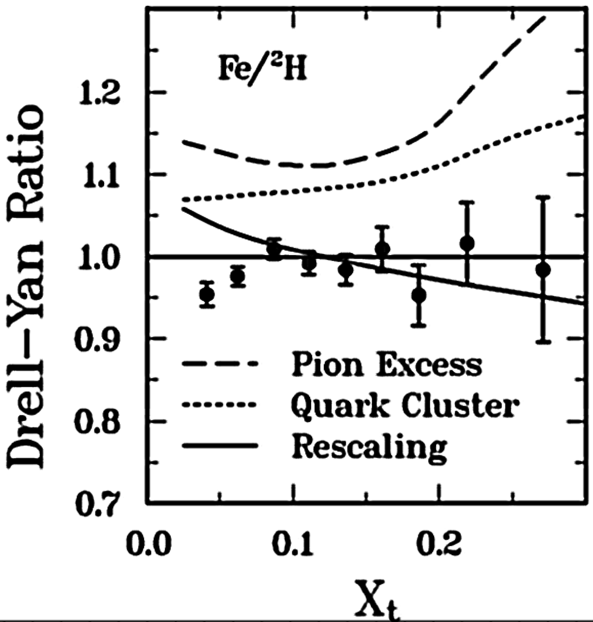
- **Anti shadowing being the constructive equivalent of the shadowing**
- **Leads to flavor behaviors still to be experimentally measured**
  - *As you will see, flavor dependent effects in nuclei are major issues*



EMC Effect

The most studied

- Much data from SLAC and JLab
- Now known at the percent level for many nuclei



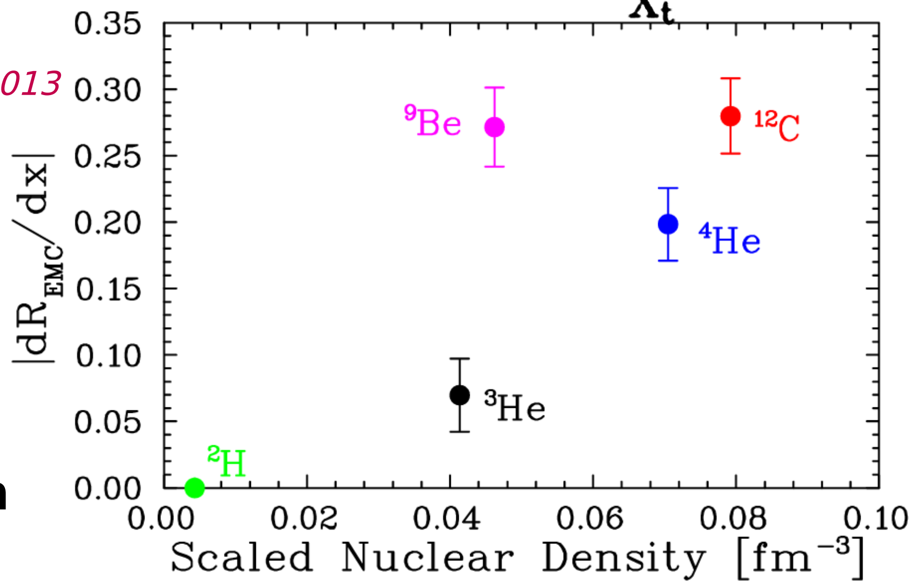
Easily described by models

- It is only a 1D effect
- Many, many models and lots of litterature:

O. Hen et al. Rev.Mod.Phys. 89 (2017) no.4, 045002

S. Malace et al. Int.J.Mod.Phys. E23 (2014) no.08, 1430013

P.R. Norton, Rept.Prog.Phys. 66 (2003) 1253-1297



First explanations eventually failed

- The most popular involved including pions in the nuclei
- Now the A dependence is often used to discriminate

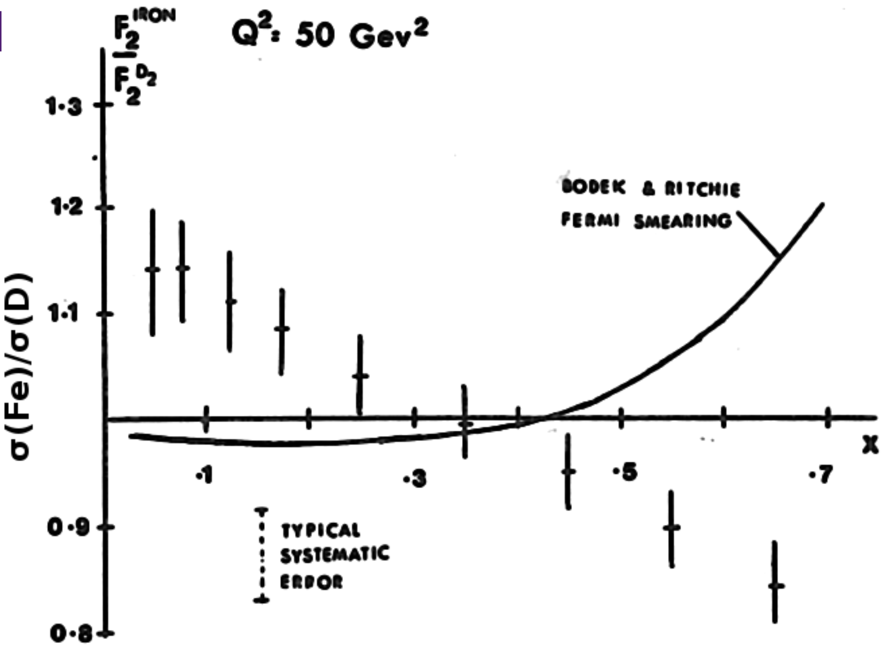
Fermi Motion

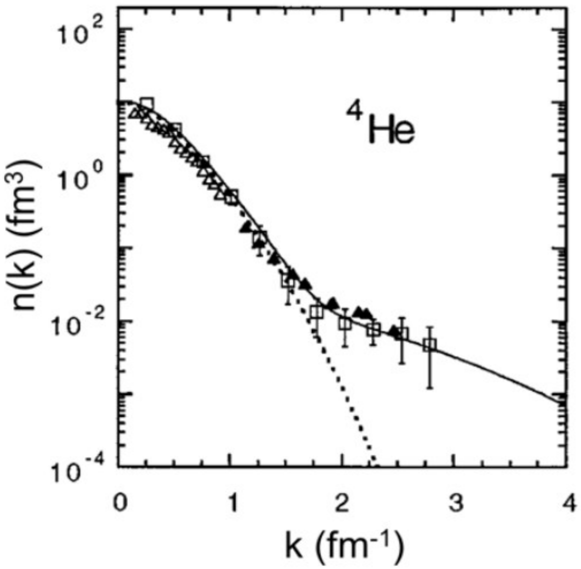
The only part that was expected

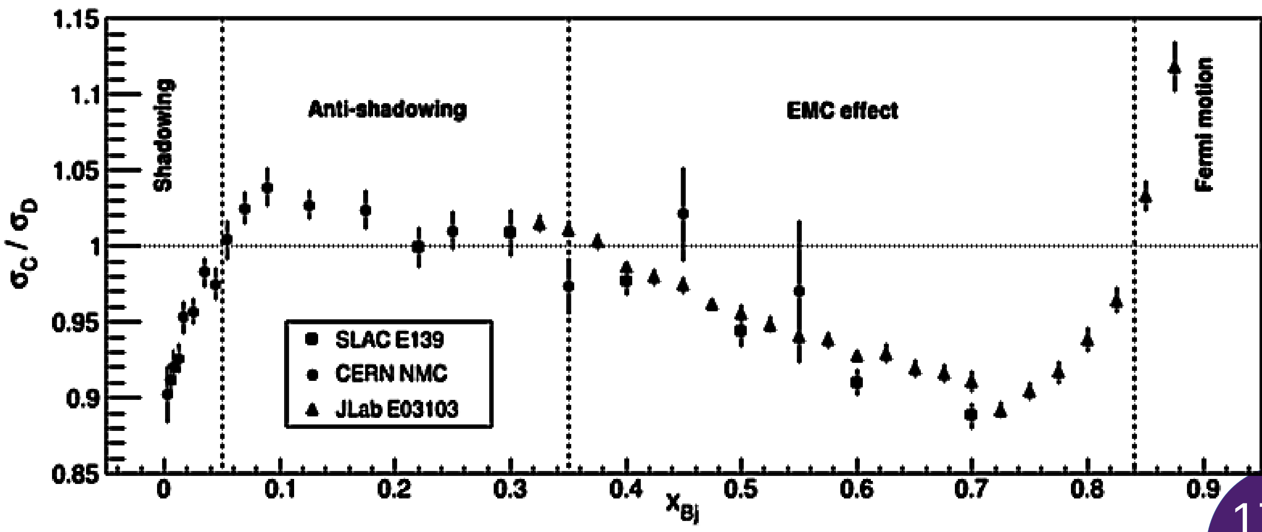
- In experiment however the effect is at higher x
- Meaning the EMC effect is that much stronger

Beware, this is not as straight forward as it might seem

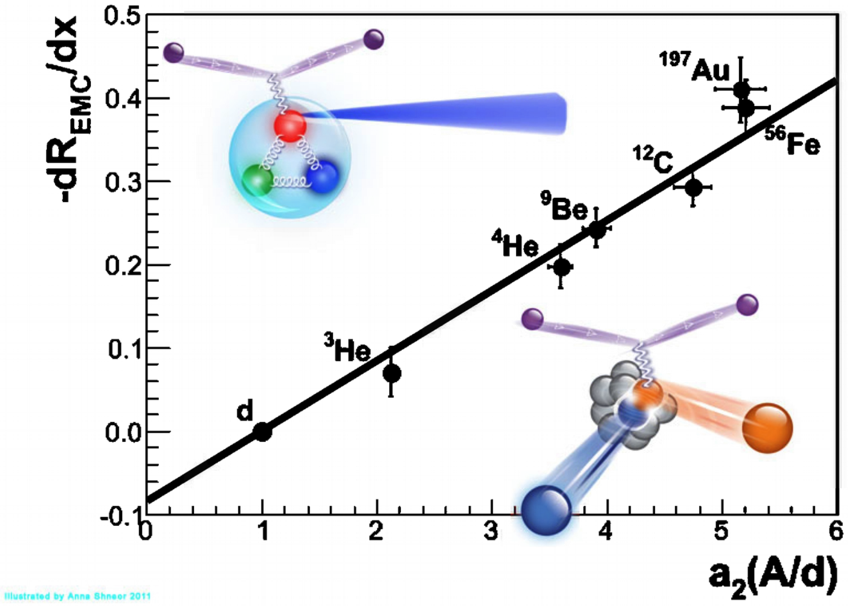
- The momentum distributions in nuclei are not simple
- Fast nucleons should be highly virtual







Describing the Nucleus



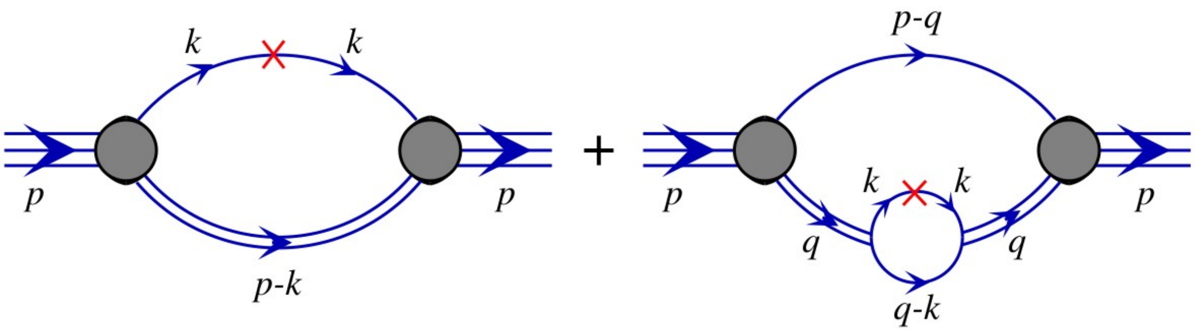
So why is it so difficult to describe the nucleus?

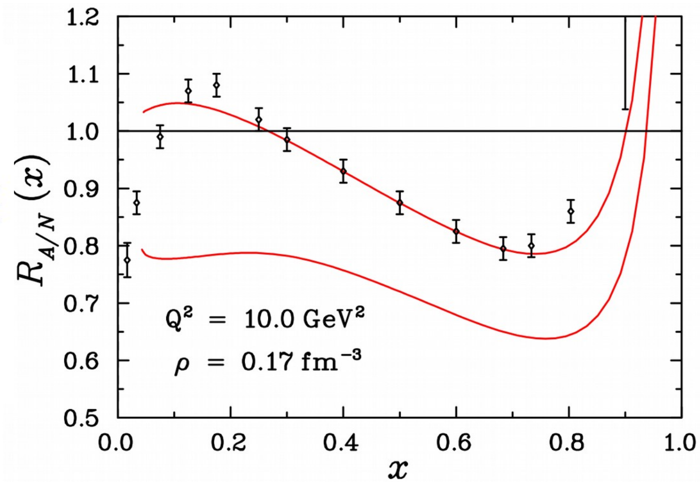
- **There is some overlap between nucleons**
  - *Which may or may not be significant*
- **No one knows what happens to virtual nucleons**
  - *Rescaling x or Q2 in nuclei can describe the EMC effect*
  - *They have completely different physics meaning*
- **There might be other objects in the nucleus**
  - *Is the nuclear force affecting the nucleon's structure?*
  - *Are close nucleons forming bound 6, 9 or even 12q bags?*

At the same time the nucleus is a complex object

- **We are starting to link the low energy nuclear aspects with hadron physics aspects**
  - *At the theoretical level with more and more advanced calculations*
  - *At the experimental level with short range correlation and soon tagging*

Mean Field Treatment





One can apply a mean field to nucleons

- **Necessitate a model of the nucleon**
- **Here the nucleon is modified by the scalar mean field**

The nucleon wave function gets modified

- **Hopefully you obtain a good description of the EMC effect**
- **Mean field treatment is unable to describe light nuclei**
  - *Which we know better in principle*
- **However they can make predictions for other observables**
  - *Polarized EMC effect here for example*

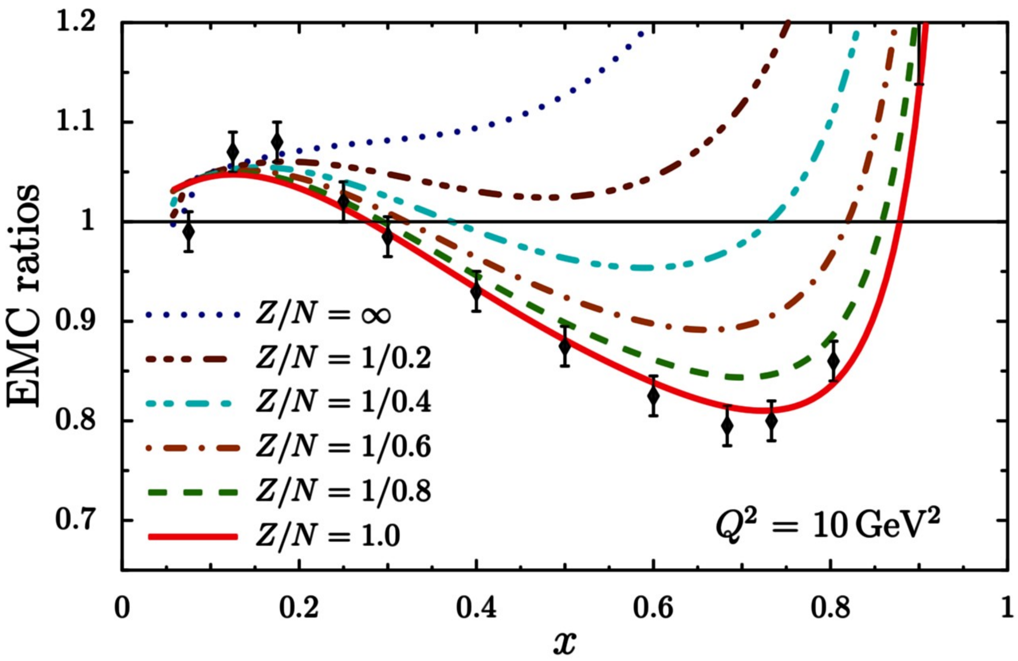
Model from I. Cloet et al. Phys.Rev.Lett. 95 (2005) 052302

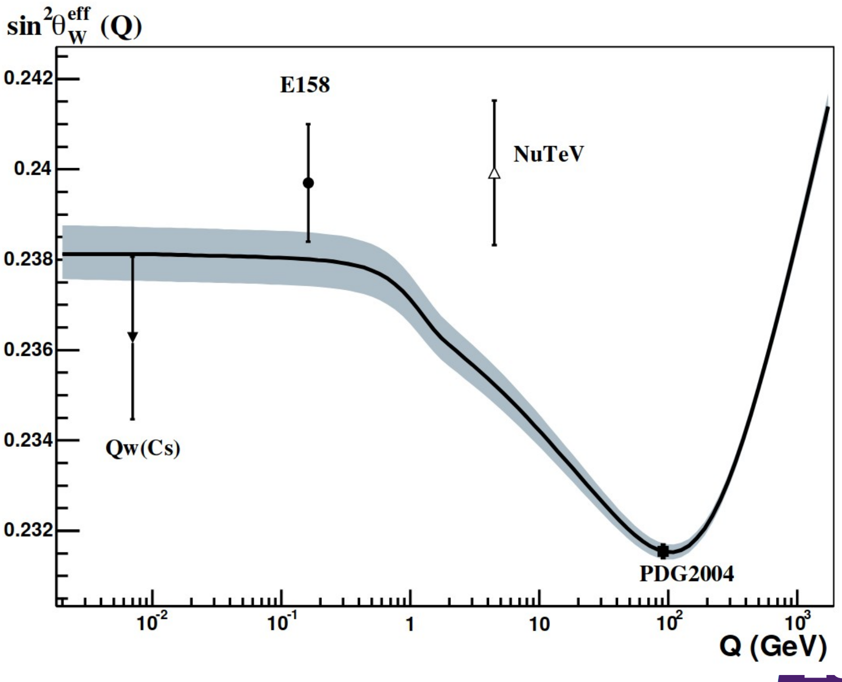
Nutev Anomaly

The same model predicts important flavor effects

- **These can have major impact on experiments**
- **The Nutev anomaly is a famous example**
  - *Nutev is a neutrino scattering experiment in Fermi Lab*
  - *They measured weak mixing angle and found a discrepancy*
  - *The problem appears to be that neutrino scattering experiments use nuclear targets, which flavor structure is unknown*

One could see Nutev as the first evidence of such flavor dependent nuclear effect





Rescaling

Rescaling models had a great deal of success

- They consist on shifting the bound nucleon PDFs
- Because of evolution, it can be done either for x or Q^2

Q^2 Rescaling → Nucleon size increased

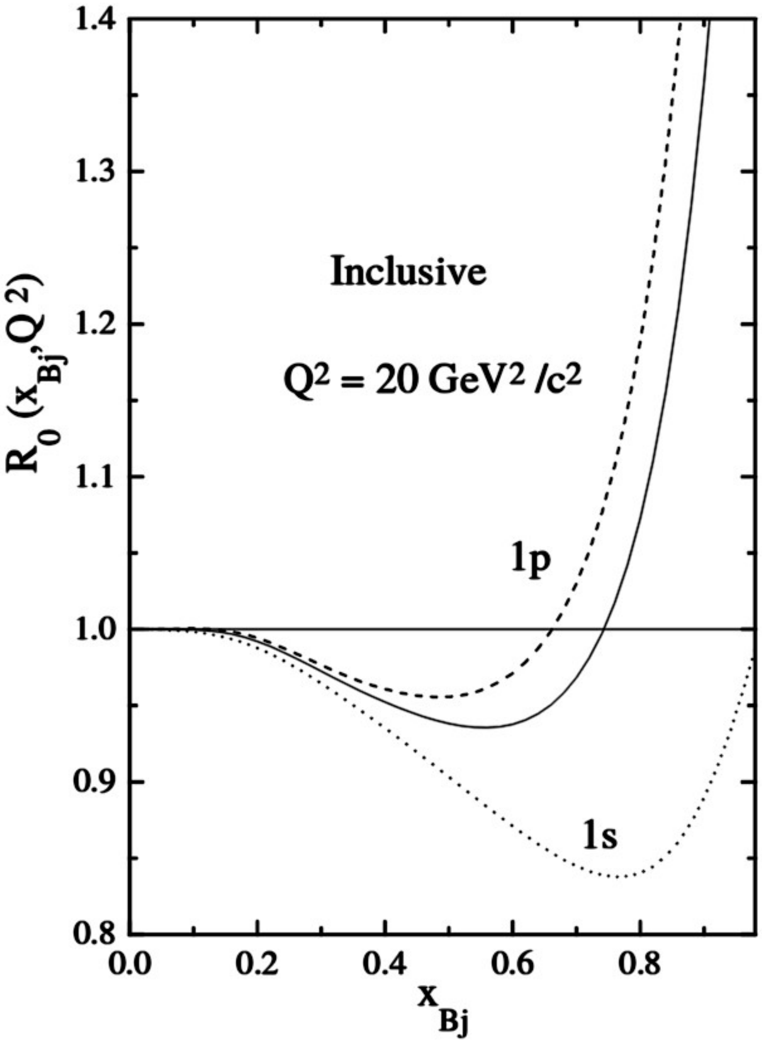
$$F_2^{N/A}(x,Q^2) = F_2^N(x,\xi_A(Q^2)Q^2)$$

x Rescaling → Binding reduce quark's momentum

$$F_2^{N/A}(x_A,Q^2,p_1^2) = F_2^{N/A}\left(\frac{x_{Bj}}{z_1^{(A)}},Q^2\right)$$

$$p_{10} = M_A - \sqrt{(M_{A-1}+E^*_{A-1})^2 + \vec{P}^2_{A-1}}$$

$$z_1^{(A)} = (p_{10} + |\vec{P}_{A-1}|\eta\cos\theta_{\widehat{\vec{P}_{A-1}\vec{q}}})/M$$



Future of Nuclear Exploration

Understand the nuclei and bound nucleons

- More measurements of the EMC effect are planned
- Most importantly, new observables are being measured

Polarized structure functions

- Highlights some important effects
- Complicated because they are diluted in large nucleus

Using 3D GPDs and TMDs on nuclei

- Experimental challenge taken over in the pas few years

R. Dupré and S. Scopetta, Eur.Phys.J. A52 (2016) no.6, 159

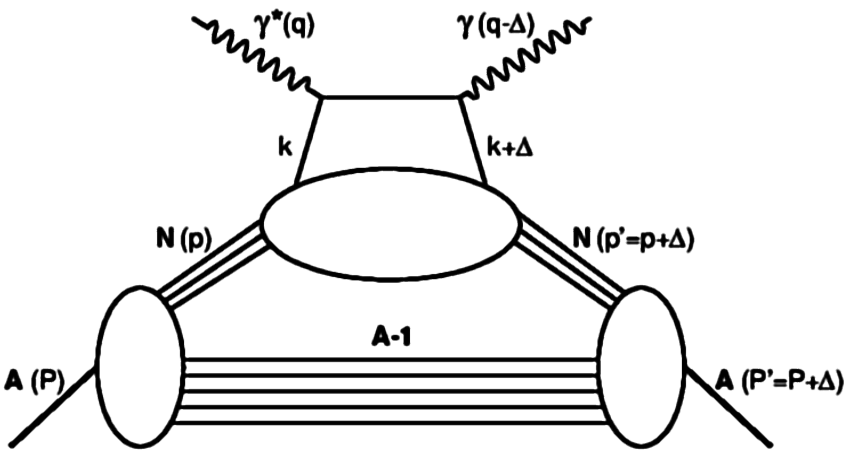
Correlating dynamic with PDFs

- The goal of new tagging measurements
- Detecting nuclear fragments at the same time as the hard scattered electron

GPDs & Nuclei

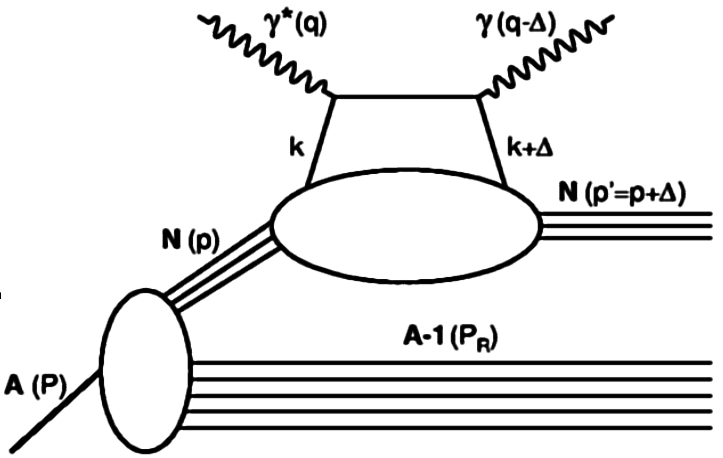
Nuclei give control over the spin

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



In the nucleus two processes

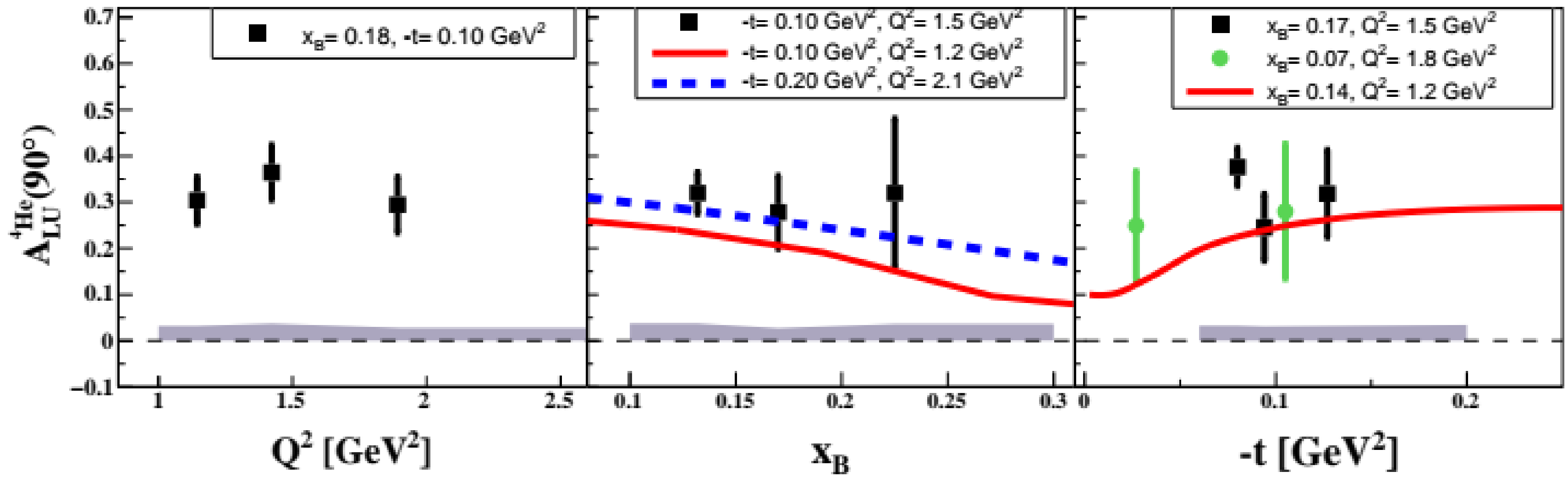
- Coherent and incoherent channels
  - *Similar to elastic and quasi-elastic*
- Give a global view and a probe of the components

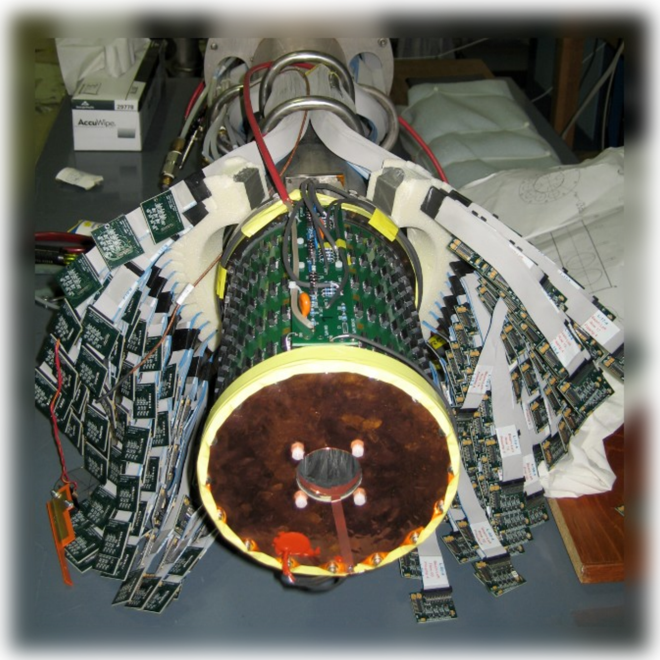


A perfect tool to study the EMC effect

- 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**
  - *Use recoil detector to ensure exclusivity*
- **Shows very strong 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**

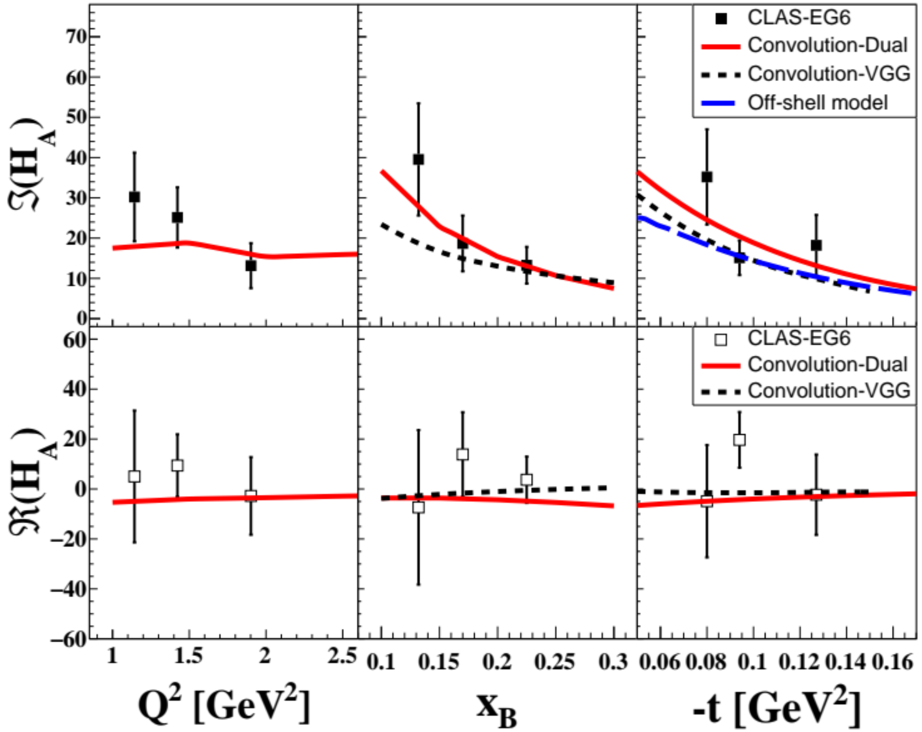
Extraction of the CFF

Helium allows for a simple extraction

- **Spin-0 → 1 GPD/CFF**

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

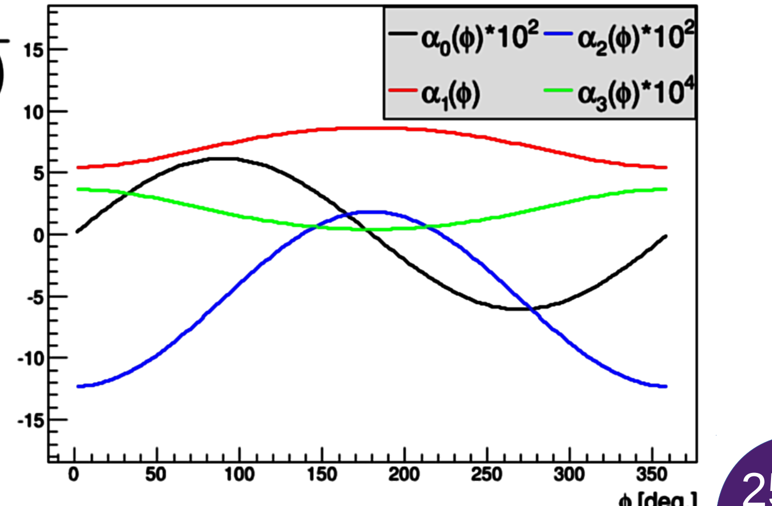
- **These are calculable within perturbative QCD**
- **Allows to separate their contributions**



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

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 again

- Proton bound in helium target

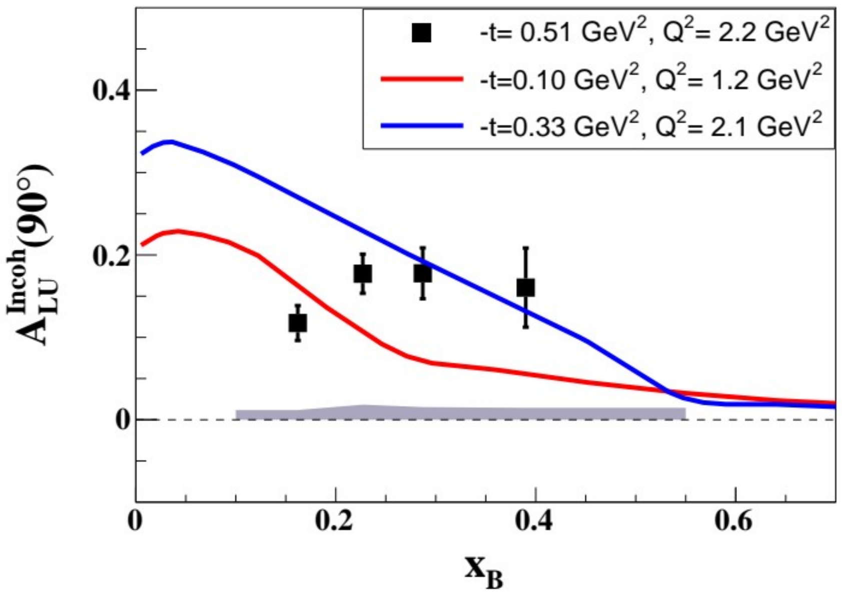
Gives a generalized EMC

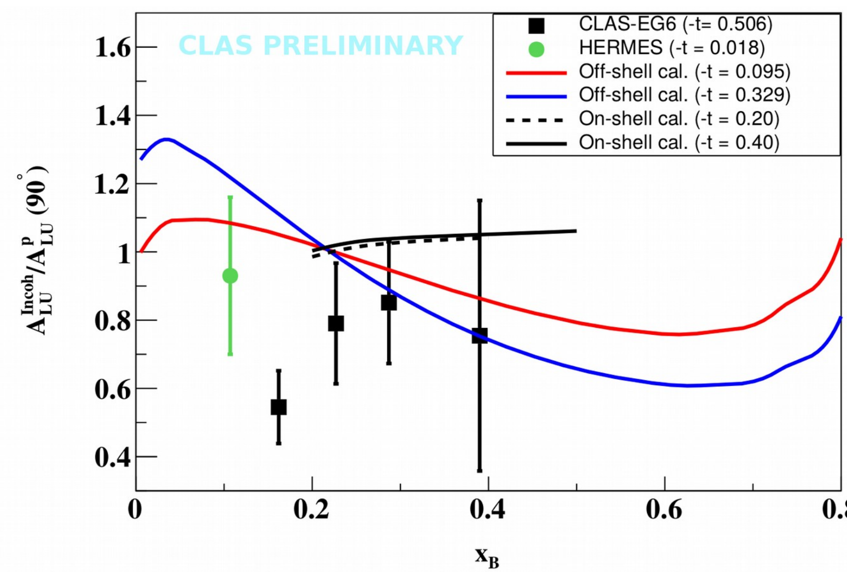
- Strongly suppressed in particular in the anti-shadowing region
- Strange behavior compared to the models

A New kind of EMC effect?

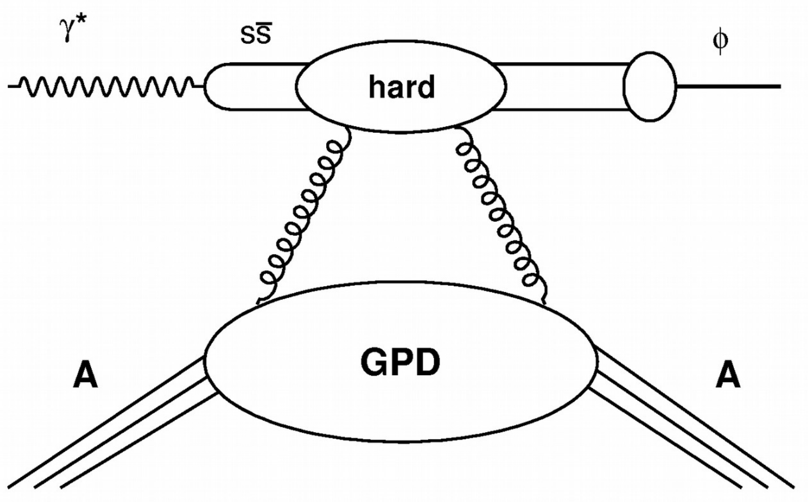
- It could be a nuclear effect
- Or it could be due to final state interactions
  - *Can be very complicated in DVCS*

Theoretical work still ongoing on these questions





Gluon GPDs



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

- Strange, or even better charm, composed
- Quark exchange is then highly suppressed
- Lead to a handbag diagram with gluons

This works can work for protons and nuclei

- Of special interest in nuclei as we know very little about gluons
- Are gluons subject to some nuclear modifications?

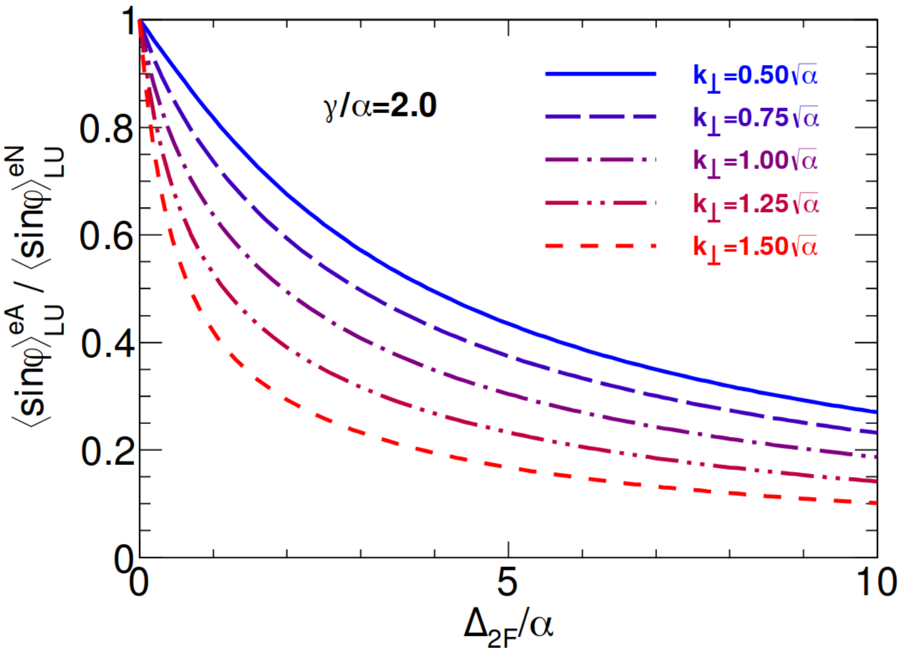
Nuclear TMD

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

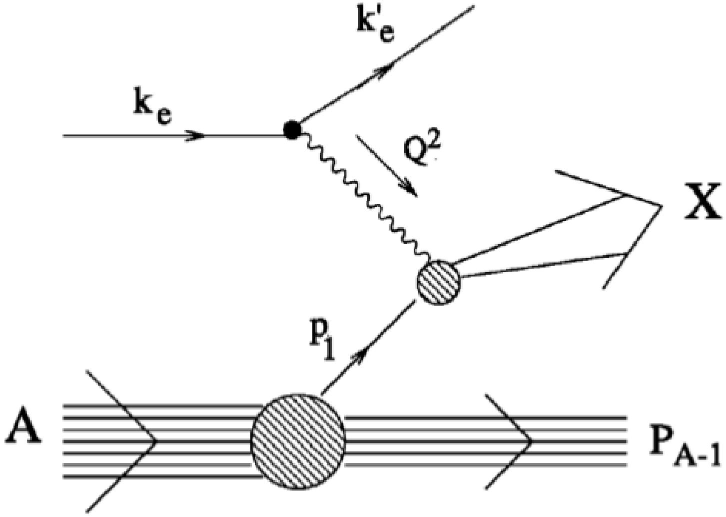
- Independent of final state effects

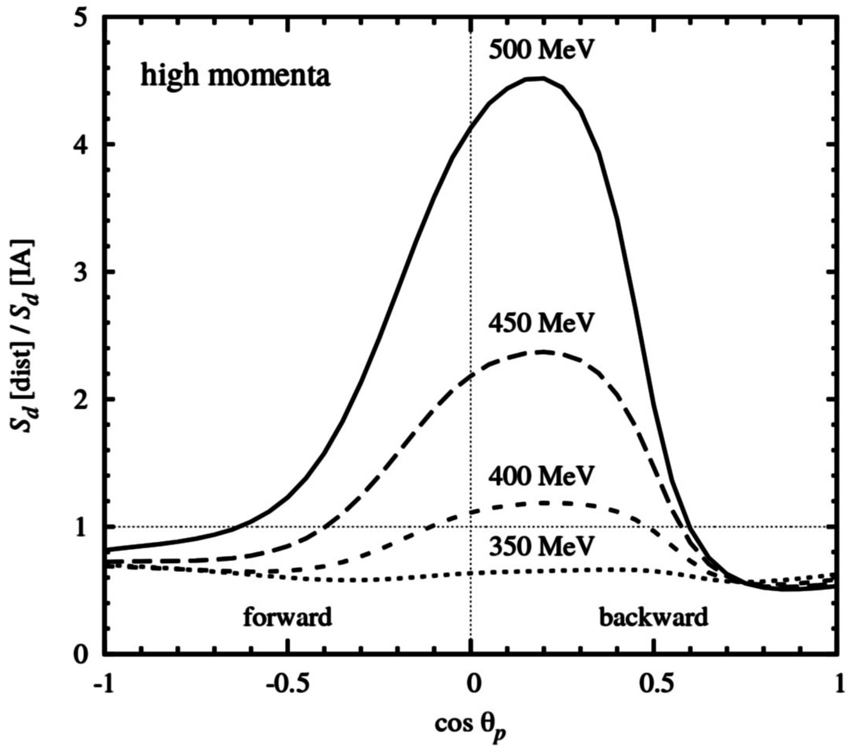


$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N)$$

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

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 to measure the neutron

First measurement performed at Jefferson Lab

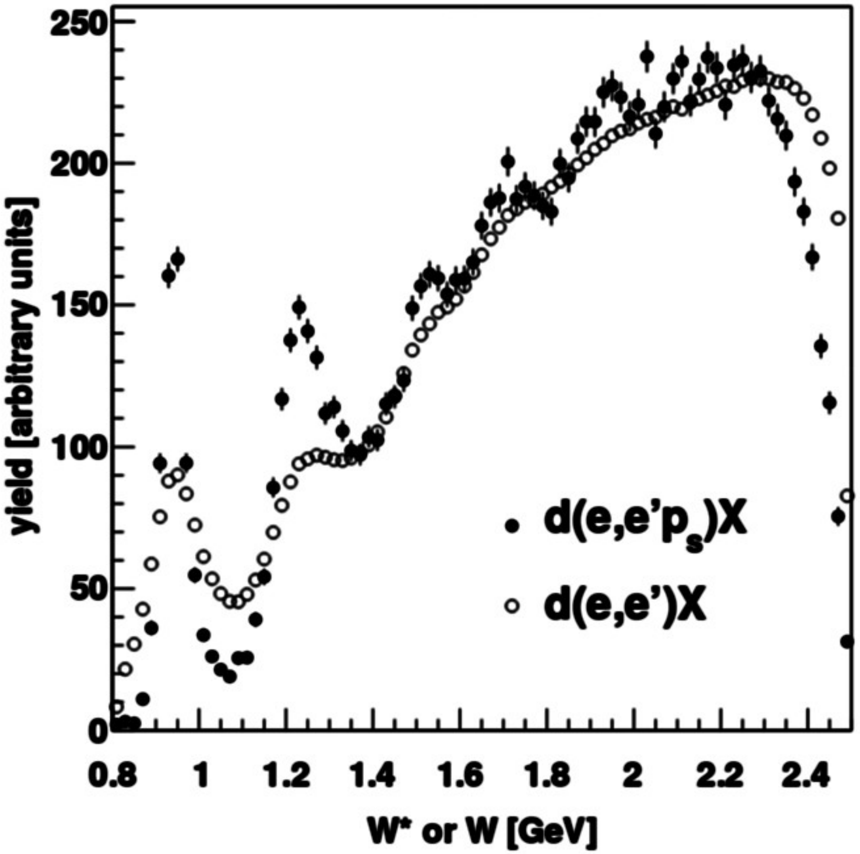
- Bonus experiment from CLAS
- Use deuterium target to access the neutron structure

We can observe a nice isolation of neutrons

- Neutron quasi-elastic and resonances are much sharper

So the tagging works! What can we do with it?

- Study the neutron structure
- Study nucleon structure as a function of its virtuality



The EMC effect through tagging

Projections for JLab

– **No data yet**

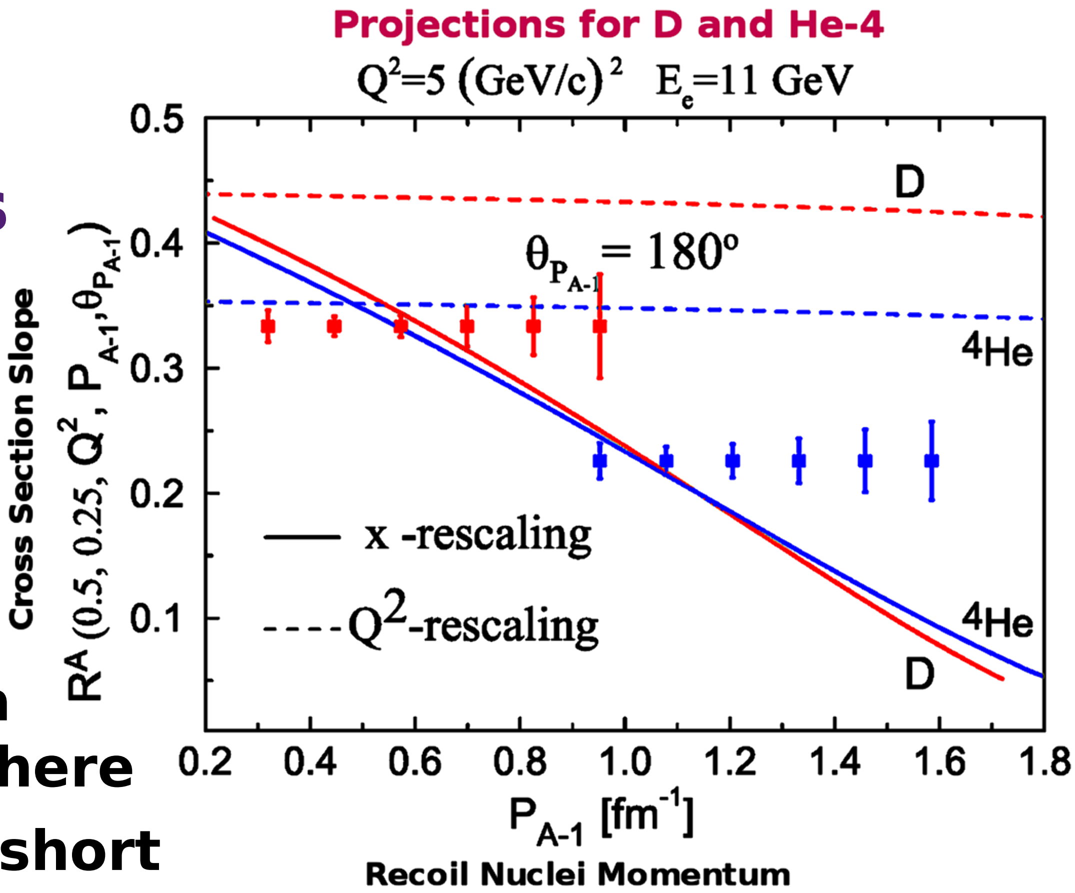
Tagging can help differentiate models

– **Q^2 and x rescaling give drastically different predictions**

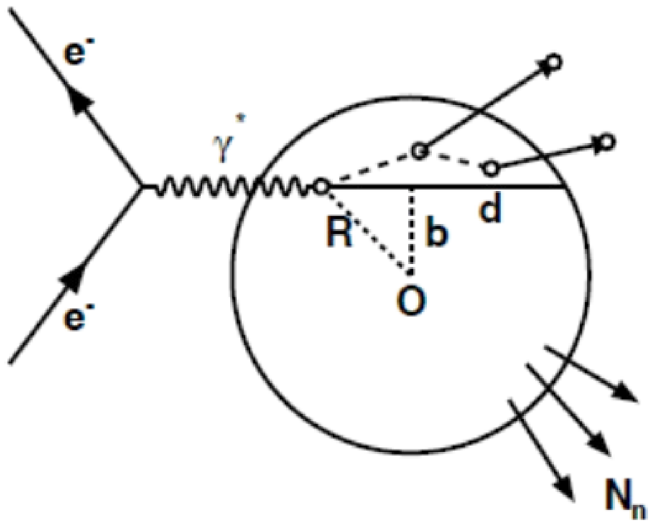
Some models have more trouble

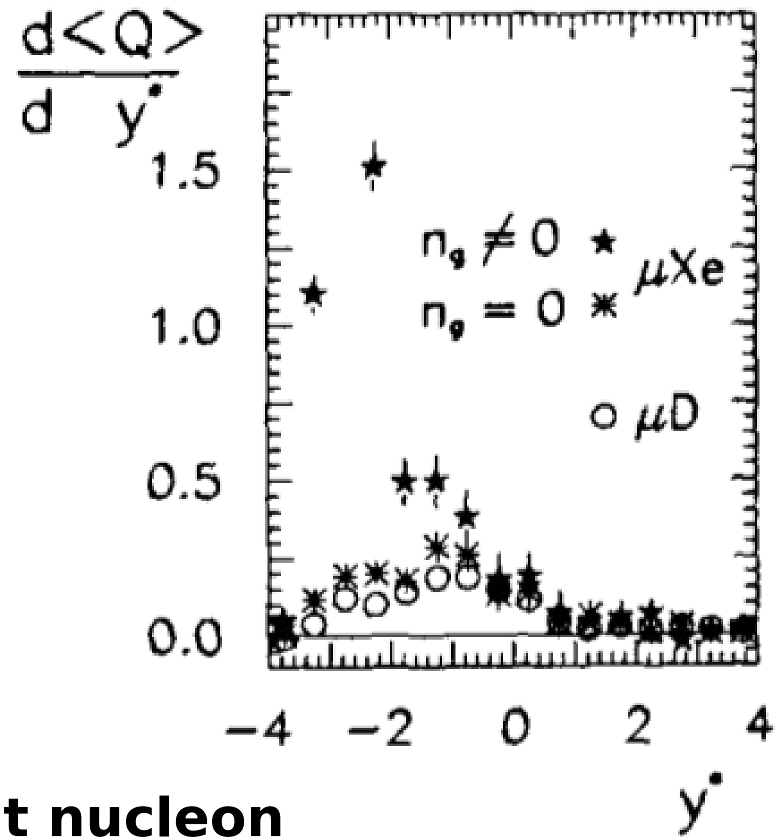
– **It is difficult to make a mean field prediction here**

– **If one wants to probe short range correlated nucleon pairs → Detect A-2 fragments**



Tagging the Centrality





Can we define something similar to centrality in eA scattering ?

- **Research in progress to look at nucleon emissions**
- **Some old data indicate interesting behaviors**

Research done with the EIC in mind

- **A perfect place to let T. Ullrich take over**

Summary

Lepton nucleus scattering

– **Helps to learn much about classic nuclear structure**
– **Opens a new avenue to look at the partons in nuclei**

We understand very little about partons in nuclei at this point

– **Nuclear structure in terms of quarks and gluons is a very active research domain**
– **Understanding the EMC effect is the principal goal**
– **The EIC will bring the nuclear targets to the nucleon level**

Beyond the scope of this lecture

– **Lepton nucleus interactions can be used to explore hadronization**

A. Accardi et al. Riv.Nuovo Cim. 32 (2010) 439-553

– **Important for neutrino interactions as well**

U. Mosel, Ann.Rev.Nucl.Part.Sci. 66 (2016) 171-195