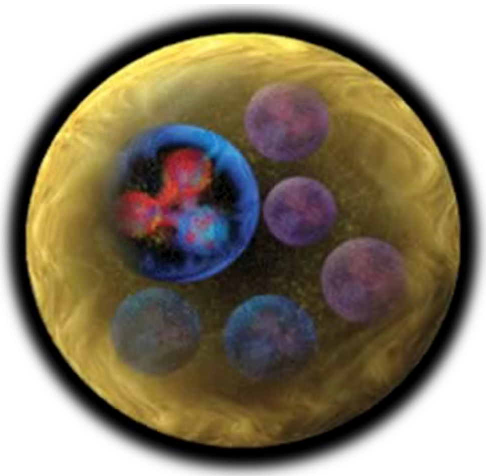
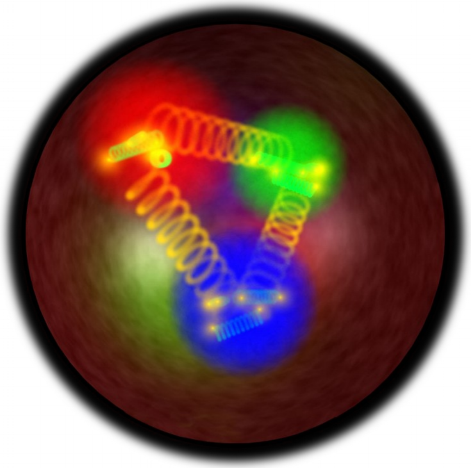
3D Partonic Structure of Light Nuclei

M. Hattawy

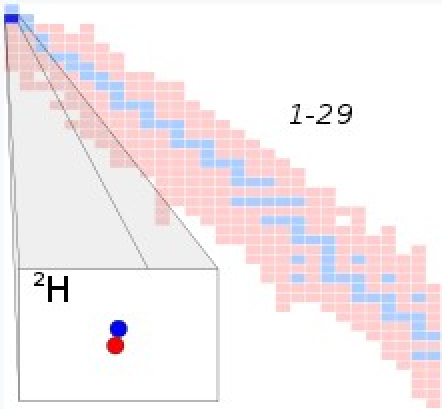


- Physics Motivations
- Recent Results.
- Future Measurements.



Simplest Nuclei

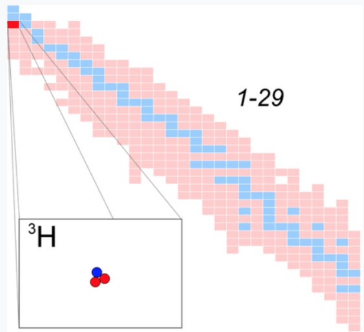
Deuterium, ^{2}H or D



General	
Name, symbol	Hydrogen-2, ^{2}H or D
Neutrons	1
Protons	1
Nuclide data	
Natural abundance	0.0115% (Earth) [1]
Isotope mass	2.01410178 u
Spin	1^+
Excess energy	13135.720± 0.001 keV
Binding energy	2224.52± 0.20 keV

Complete table of nuclides

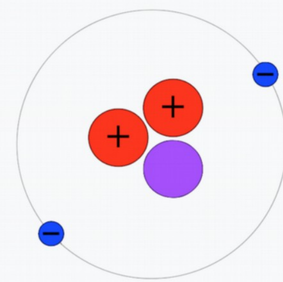
Tritium, ^{3}H



General	
Name, symbol	tritium, ^{3}H
Neutrons	2
Protons	1
Nuclide data	
Natural abundance	trace
Half-life	12.32 years
Decay products	^{3}He
Isotope mass	3.0160492 u
Spin	½
Excess energy	14,949.794± 0.001 keV
Binding energy	8,481.821± 0.004 keV
Decay modes	
Decay mode	Decay energy (MeV)
Beta emission	0.018590

Complete table of nuclides

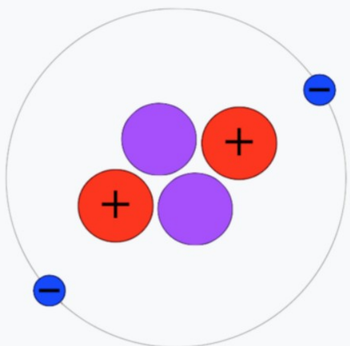
Helium-3, ^{3}He



General	
Name, symbol	Helium-3, He-3, ^{3}He
Neutrons	1
Protons	2
Nuclide data	
Natural abundance	0.000137% (% He on Earth)
Half-life	stable
Parent isotopes	^{3}H (beta decay of tritium)
Isotope mass	3.0160293 u
Spin	½

Note: Isospin doublet
Just like p and n

Helium-4, ^{4}He



General	
Name, symbol	Helium-4, He-4, ^{4}He
Neutrons	2
Protons	2
Nuclide data	
Natural abundance	99.999863%
Half-life	stable
Isotope mass	4.002602 u
Spin	0
Binding energy	28300.7 keV

* But how to describe Nuclei ??

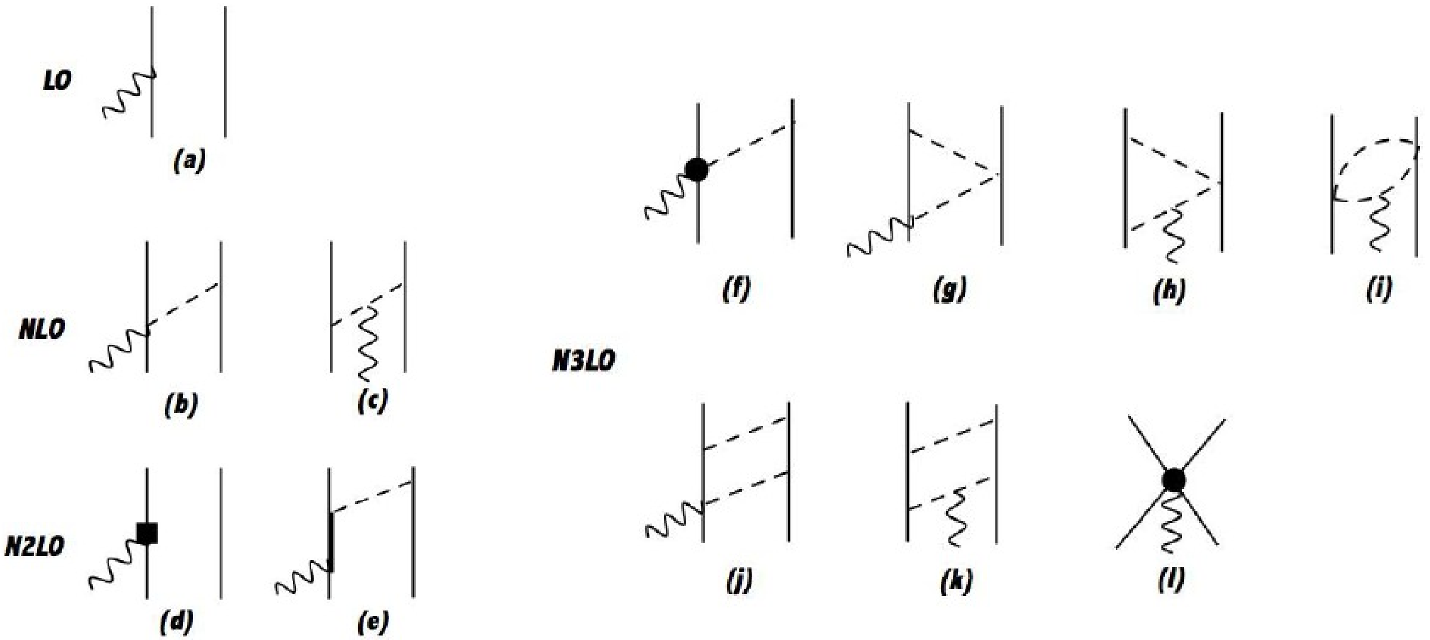
ODU

Local Chiral Effective Field Theory for N-N int.

- https://arxiv.org/pdf/1809.10180.pdf
- https://arxiv.org/pdf/1406.0454.pdf

Chiral EFT:

- describes low-energy hadronic interactions based on asymmetries in QCD
- the different contributions to nuclear forces are arranged according to their importance by emlpoing A power-counting scheme.
- Electromagnetic currents up to N3LO in the N-N interaction:



The contributions to the electromagnetic current up to N3LO. Nucleons, Delta-isobars, pions, and external elds are denoted by solid, thick-solid, dashed, and wavy lines, respectively. The square in panel (d) represents relativistic corrections to the LO current. Only a single time ordering is shown in panels (b), (c), and (e).

Nuclei Description

Nuclei are described as a sum of protons and neutrons

- Bound together by two and three body forces

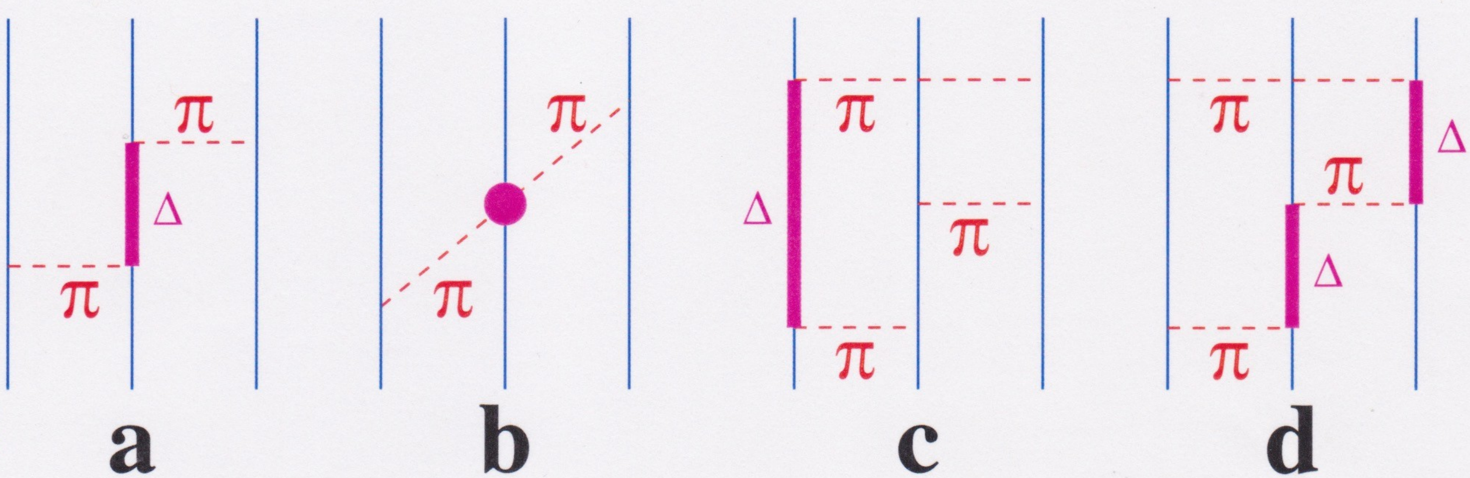
(More from Rev. Mod. Phys. 70, 1998)

N-body Hamiltonian $$H = \sum_i \sqrt{\mathbf{p}_i^2 + m^2} + \sum_{i<j} v_{ij}(\mathbf{r}_{ij};\mathbf{P}_{ij})$$ NN potential

May have to add 3-body force $$+ \sum_{i<j<k} V_{ijk}(\mathbf{r}_{ij},\mathbf{r}_{ik};\mathbf{P}_{ijk}), \quad (2.12)$$

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R}, \quad V_{ijk}^{R} = U_0 \sum_{\mathrm{cyc}} T_\pi^2(r_{ij}) T_\pi^2(r_{ik}).$$

Fig. 2 (Pieper, et al.)



Nuclei Description

Nuclei are described as a sum of protons and neutrons

- Bound together by two and three body forces
- How to sovle how to solve Schrödinger Eq.?

- **3-body: Fadeev approach:**

  * decomposes 3-body wave function in 3 2-body ones.

  * applies to both bound states and scattering

R.A. Malfliet, J.A. Tjon, Nuclear Physics A,Volume 127, Issue 1,1969,

ODU

Nuclei Description

Nuclei are described as a sum of protons and neutrons

- Bound together by two and three body forces
- How to sovle how to solve Schrödinger Eq.?

- **3-body: Fadeev approach**
- **3-4 body: Hyperspherical harmonics**

* expands the baryon wave function into hyperspherical harmonics

$$\Psi(\boldsymbol{\rho}, \boldsymbol{\lambda}) = \sum_{[L]} \frac{u_{[L]}(\xi)}{\xi^{5/2}} \mathcal{P}_{[L]}(\Omega_5) ,$$

J A Mignaco and I Roditi, Journal of Physics B: Atomic and Molecular Physics,1981.

* the Schrödinger equation HΨ = EΨ, whose expression in spherical coordinates reads

$$\left[\frac{1}{m\xi^{5/2}} \frac{d^2}{d\xi^2} \xi^{5/2} - \frac{1}{m} \frac{\mathcal{L}^2 + 15/4}{\xi^2} + E - V(\xi, \Omega_5)\right] \Psi = 0 ,$$

becomes equivalent to the infinite set of coupled radial equations

$$\frac{1}{m} u''_{[L]}(\xi) - \frac{(L+3/2)(L+5/2)}{m\xi^2} u_{[L]}(\xi) + \left[E - V_{[L],[L]}(\xi)\right] u_{[L]}(\xi) = \sum_{[L] \neq [L]'} V_{[L],[L]'}(\xi) u_{[L]'}(\xi) ,$$

$$V_{[L],[L]'}(\xi) = \int d\Omega_5 \mathcal{P}^*_{[L]}(\Omega_5) V(\xi, \Omega_5) \mathcal{P}_{[L]'}(\Omega_5) .$$

solving the three-body problem that way implies overcoming the following difficulties: listing the appropriate HH, computing the angular projections

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- **3-body: Fadeev approach**
- **3-4 body: Hyperspherical harmonics**
- **≥3: Monte Carlo methods:**

  - Green's function Monte Carlo:

    * uses stochastic integration over the particle coordinates
    * performs explicit summations in spin-isospin space
    * very accurate, but very costly
    * allows only nuclei with A ≤12

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  - Auxiliary-field diffusion Monte Carlo;

  * uses simpler variational wave functions rather than the GFMC.
  * using stochastic approach to the particle coordinate
  * evaluates the summations in spin-isospin space.

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Nuclei Description

Nuclei are described as a sum of protons and neutrons

- Bound together by two and three body forces
- How to sovle how to solve Schrödinger Eq.?
- Can explain exactly the light nuclei spectrum

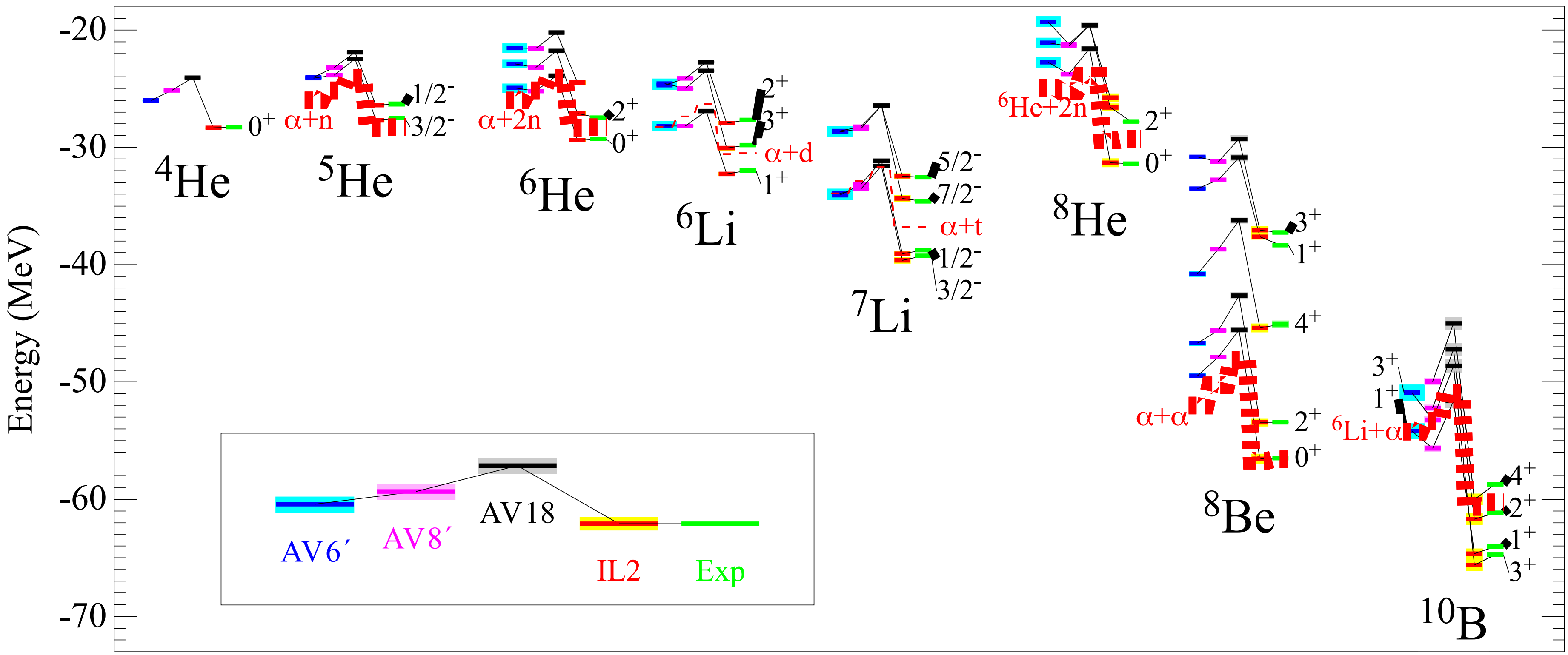
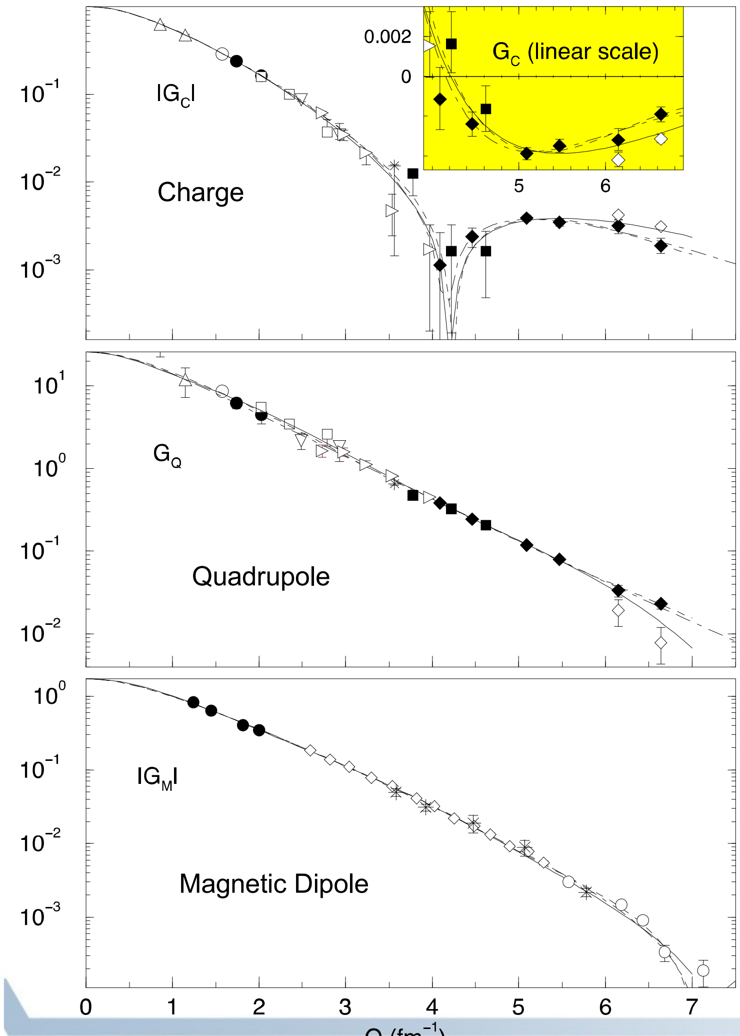


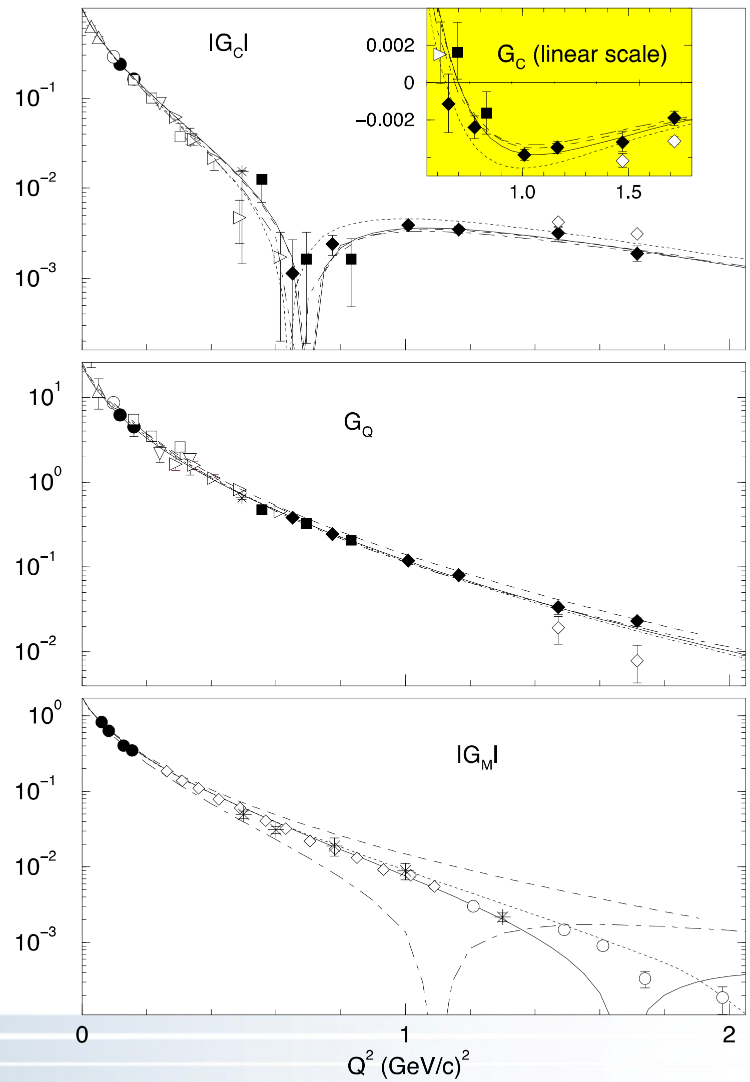
FIG. 2: Nuclear energy levels for the more realistic potential models; shading denotes Monte Carlo statistical errors.

Nuclei Description

Nuclei are described as a sum of protons and neutrons

- Bound together by two and three body forces
- How to sovle how to solve Schrödinger Eq.?
- Can explain exactly the light nuclei spectrum
- Can be related to electron scattering measurements and nucleon momentum spectrum





Left: non-relativistic potential model

Right: fully relativistic calculation

* Note different horizontal scale (Q vs Q^2, although same maximum)

More Form Factors

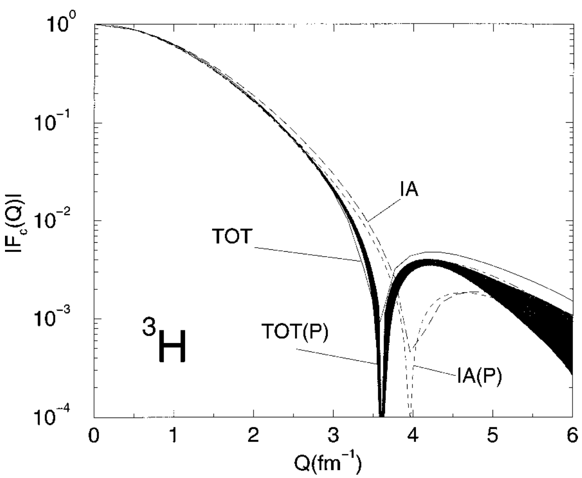


FIG. 27. The charge form factors of ^{3}H, obtained in the impulse approximation (IA) and with inclusion of two-body charge contributions and relativistic corrections (TOT), compared with data (shaded area) from Amround *et al.* (1994).

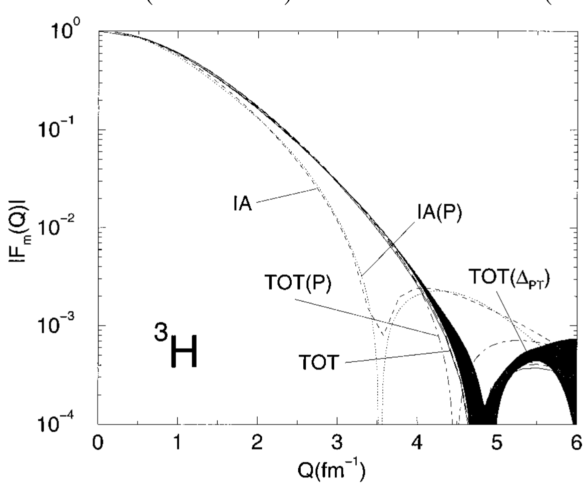


FIG. 25. The magnetic form factors of ^{3}H, obtained in the impulse approximation (IA) and with inclusion of two-body current contributions and Δ admixtures in the bound-state wave function (TOT), compared with data (shaded area) from Amroun *et al.* (1994). Theoretical results correspond to the

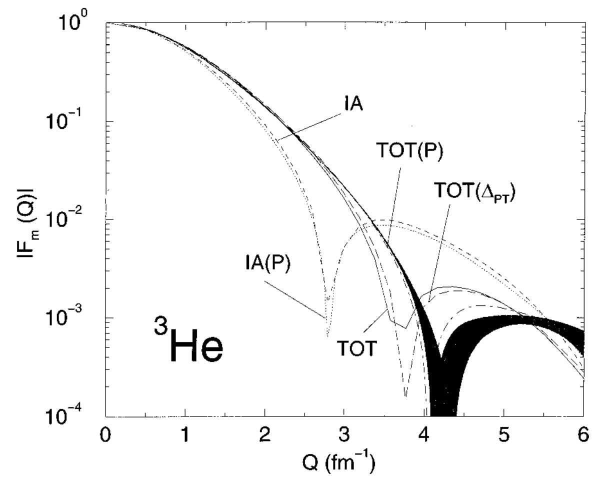


FIG. 26. Same as in Fig. 25, but for ^{3}He.

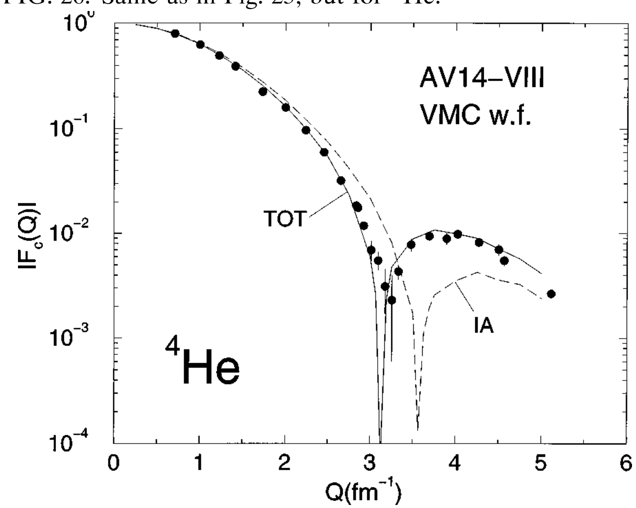
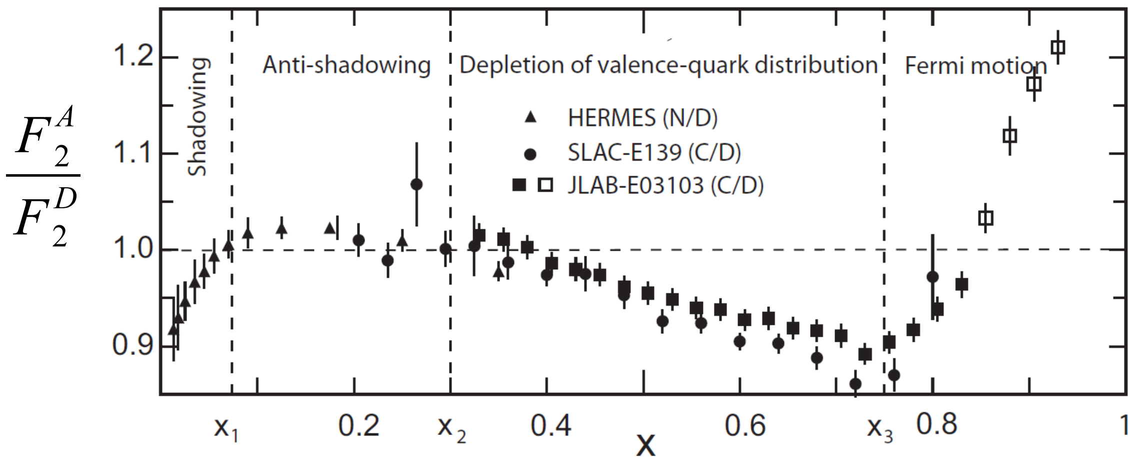


FIG. 29. The charge form factors of ^{4}He, obtained in the impulse approximation (IA) and with inclusion of two-body charge contributions and relativistic corrections (TOT), compared with data from Frosch *et al.* (1968) and Arnold *et al.*

All seems well and working, until ...

EMC Effect

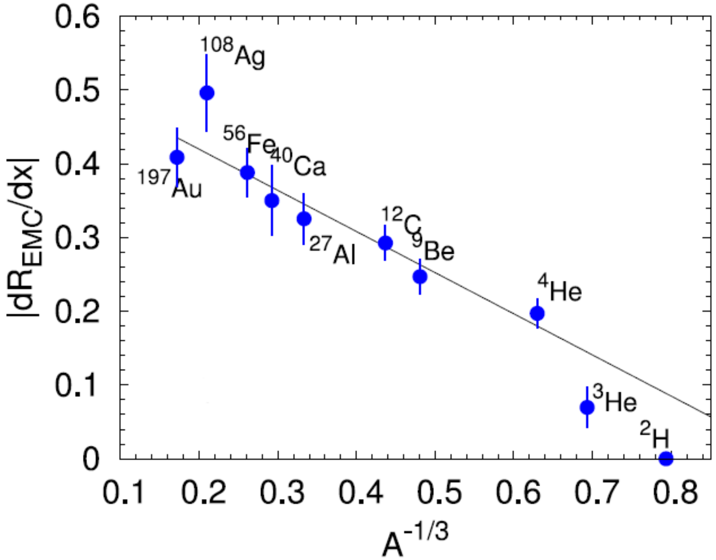


[K. Rith, arXiv:1402.5000 [hep-ph], 2014]

EMC effect: the modification of the PDF F_2 as a function of the longitudinal momentum fraction x [0.3, 0.75] carried by the parton.

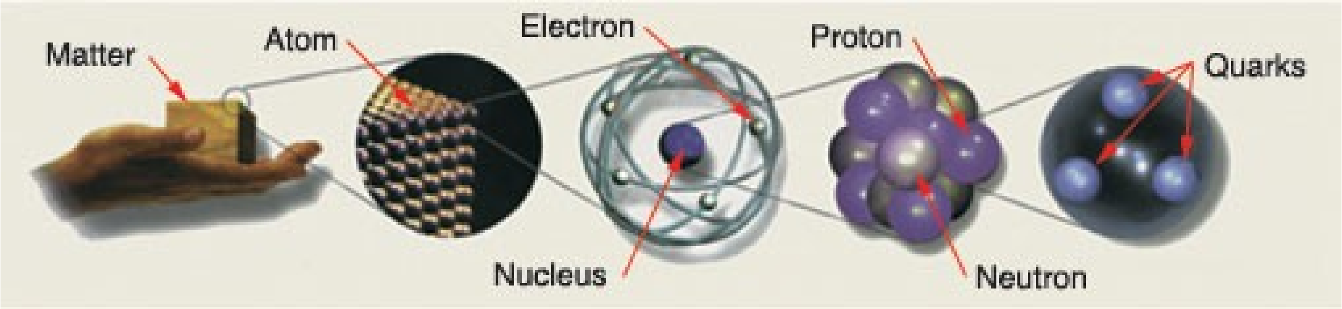
- Precise measurements at CERN, SLAC and JLab
  → Links with the nuclear properties, i.e. mass & density

- The origin of the EMC effect is still not fully understood, but possible explanations:
  → Modifications of the nucleons themselves
  → Effect of non-nucleonic degrees of freedom, e.g. pions exchange
  → Modifications from multi-nucleon effects (binding, N-N correlations, etc...)

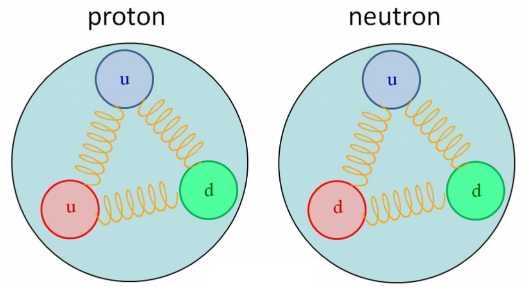


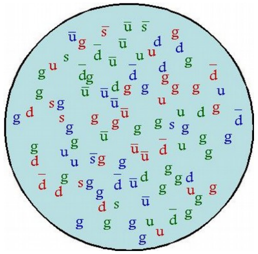
[J. Arrington et al., Phys. Rev. C 86 (2012) 065204]

Let's look back at the nucleons



◊ **Nucleon pictures:** → Valence region → Sea/Gluon region





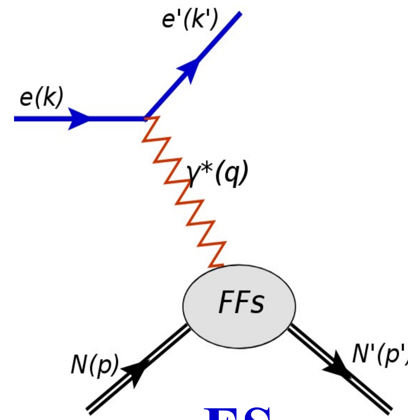
How the electromagnetic properties arise from its partons?

◊ **Nucleon has spin ½.**
How this spin build up from the polarization and the orbital angular momentum of the partons?

◊ **The partonic structure of free nucleons differs from that of the bound nucleons (EMC effect, 1983).** What is the exact nature of the strong forces?

Quick reminder about the Hadron Structure

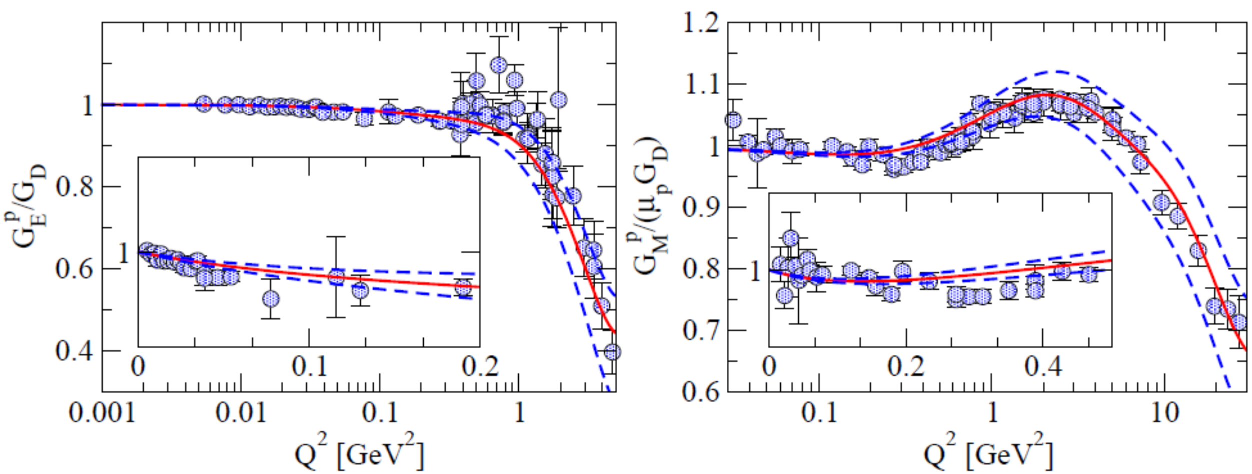
Most of what we know today about hadrons' structure has come from the electromagnetic probes which give access to measure structure functions that quantify the properties of partons in hadrons.

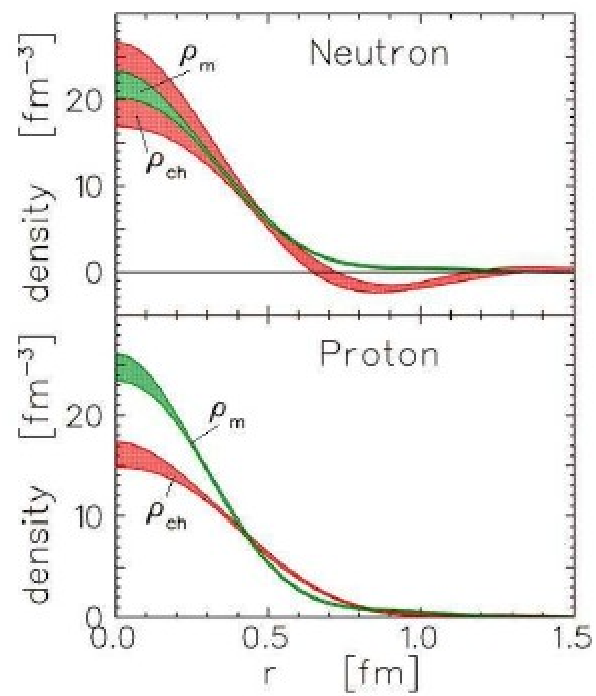


ES

- **Form Factors (FFs)**
  - → Provide the charge and magnetization distributions inside a hadron.
  - → Accessible via Elastic Scattering (ES).

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left(\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)\right)$$



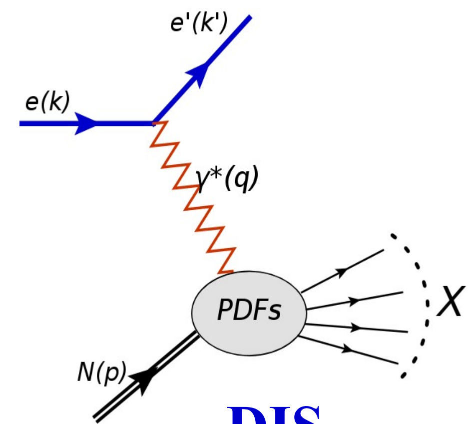


- C. F. Perdrisat, V. Punjabi and M. Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694-764 (2007)
- Kelly J. J., Phys. Rev. C 66, 065203 (2002)

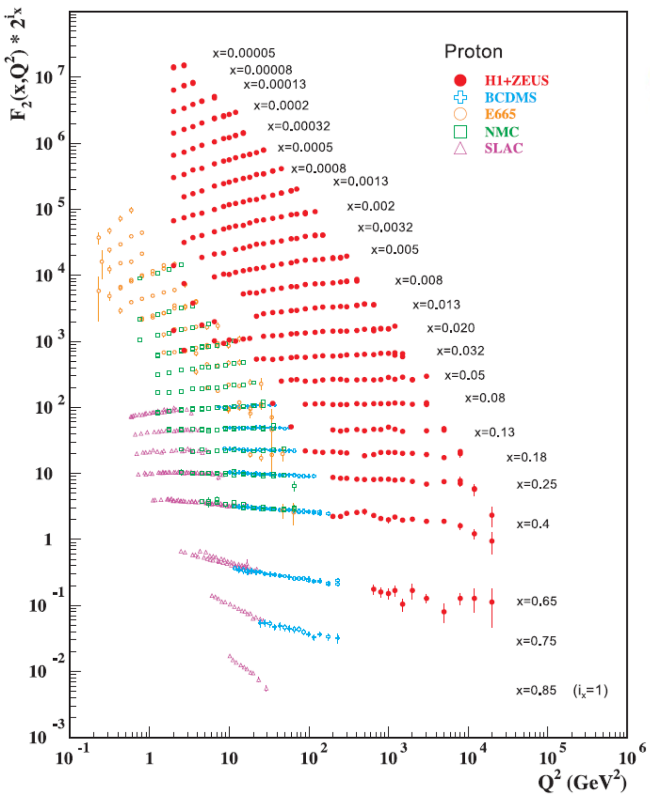
Quick reminder about the Hadron Structure

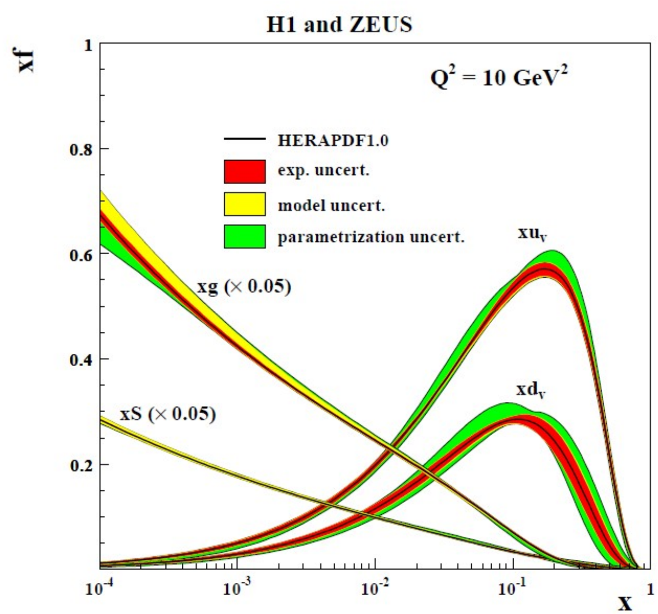
Structure functions that quantify the properties of the partons in a hadron:

- **Form Factors (FFs)**
- **Parton Distribution Functions (PDFs)**
  - → Provide partons longitudinal momentum distributions
  - → Measurable via Deep Inelastic Scattering (DIS).
    - \- For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with $\mathcal{F}_1(x) = \frac{1}{2}\sum_q e_q^2 f_q(x)$ and $\mathcal{F}_2(x) = x\sum_q e_q^2 f_q(x)$



DIS





Proton structure:

- → Large x, $u_v(x) \sim 2\, d_v(x)$
- → Low x, more gluons radiated and slpitting producing sea quarks

- J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001, page241, 2012.
- R. Placakyte et al. (H1 and ZEUS Collaborations), arXiv:1111.5452 [hep-ph], 2010.

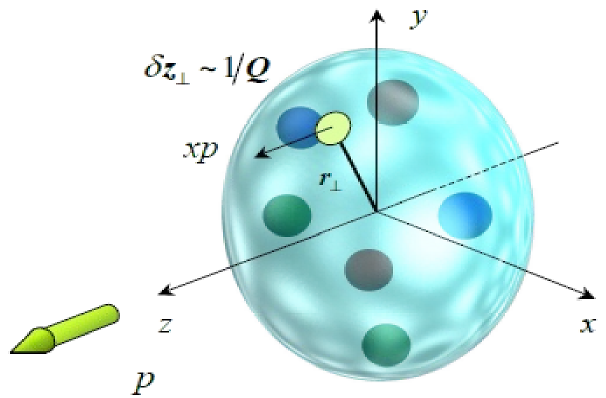
Where do we stand?

WE DO NOT HAVE FULL UNDERSTANDING OF THE NUCLEAR EFFECTS USING THE TRDITIONAL ONE-DIMENSION PICTURES OF HADRONS

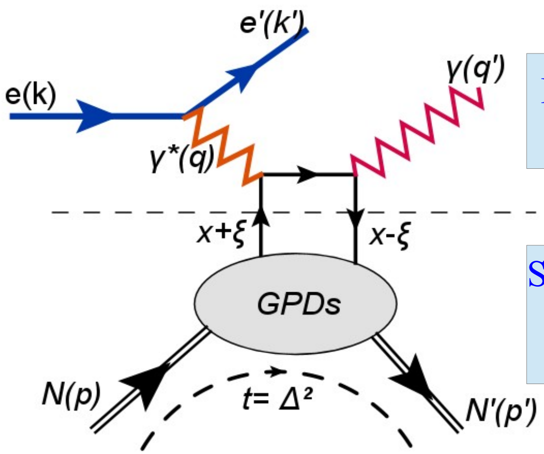
Clear explanations may arise from measuring the nuclear modifications via measuring the Generalized Parton Distributions.

Generalized Parton Distributions

- **Contain information on:**
  → Correlation between quarks and anti-quarks
  → Correlation between longitudinal momentum and transverse spatial position of partons



- **Can be accessed via hard exclusive processes such as deeply virtual Compton scattering (DVCS):**



Hard part (perturbative, calculable in PQED)

Soft part (non-perturbative, parameterized in terms of GPDs)

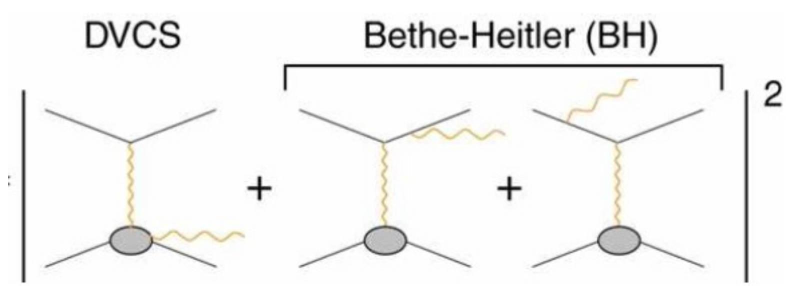
$$\xi \simeq x_B/(2-x_B) \qquad x_B = Q^2/2\text{p.q}$$

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

* At leading order in $1/Q^2$ (twist-2) and in the coupling constant of QCD (α_s).

- **Experimentally,** the measured photon-electroproduction cross section (ep → epγ) is:

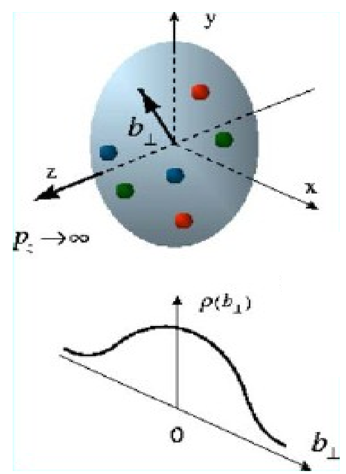
$$d\sigma \propto |\tau_{BH}|^2 + \underbrace{(\tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS})}_{\mathcal{I}} + |\tau_{DVCS}|^2$$

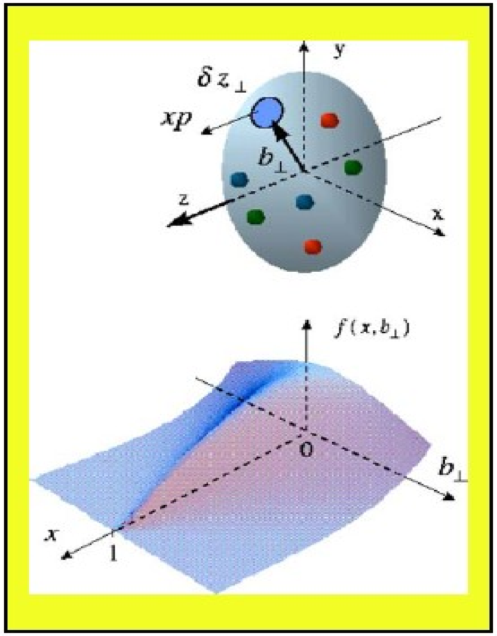


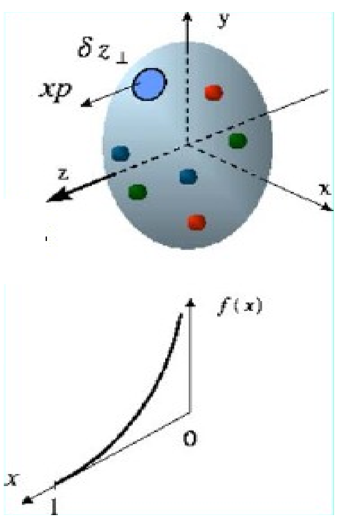
- The DVCS signal is enhanced by the interference with BH.

GPDs links to FFs and PDFs

GPDs: H, E, $\tilde{H}$, $\tilde{E}$
Fully correlated quark distributions in both coordinate and momentum space

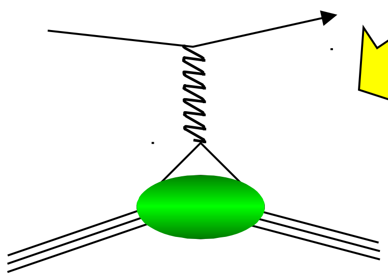


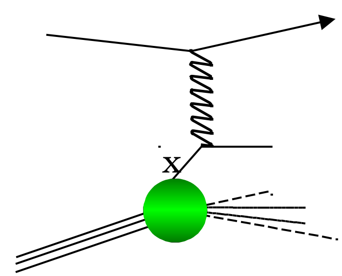




Form factors: **transverse quark distribution** in coordinate space

Parton distributions: **longitudinal quark distribution** in momentum space





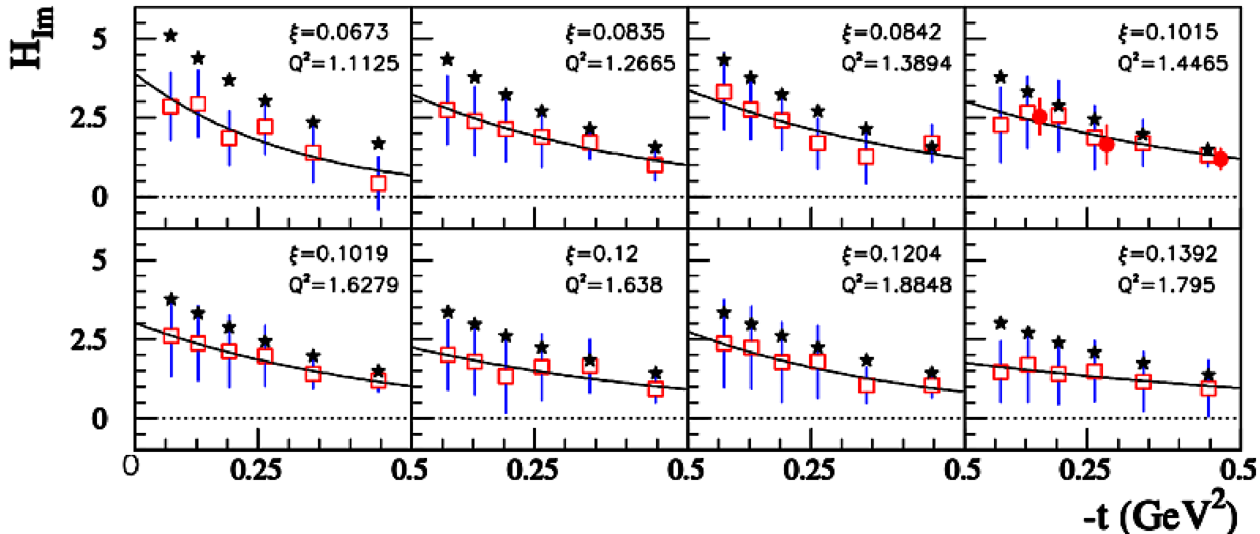
$\int H(x,\xi,t)dx = F_1(t)$ $(\forall\, \xi)$

$\int E(x,\xi,t)dx = F_2(t)$ $(\forall\, \xi)$

$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$

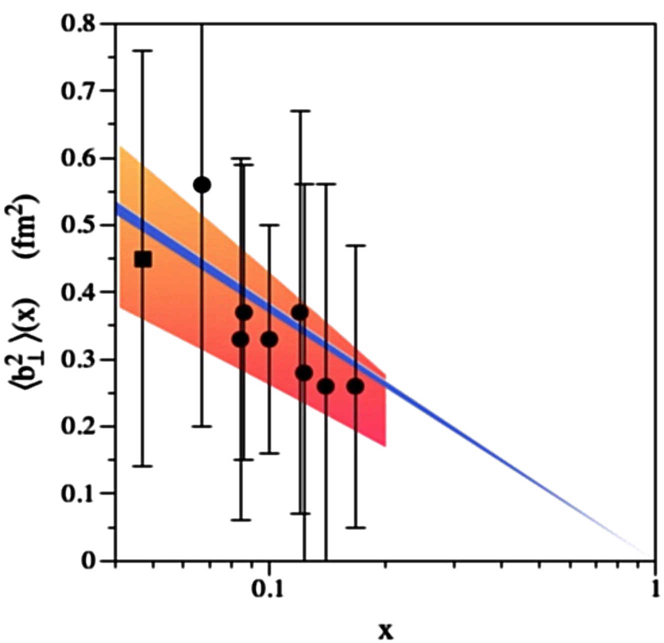
Proton Tomography via DVCS

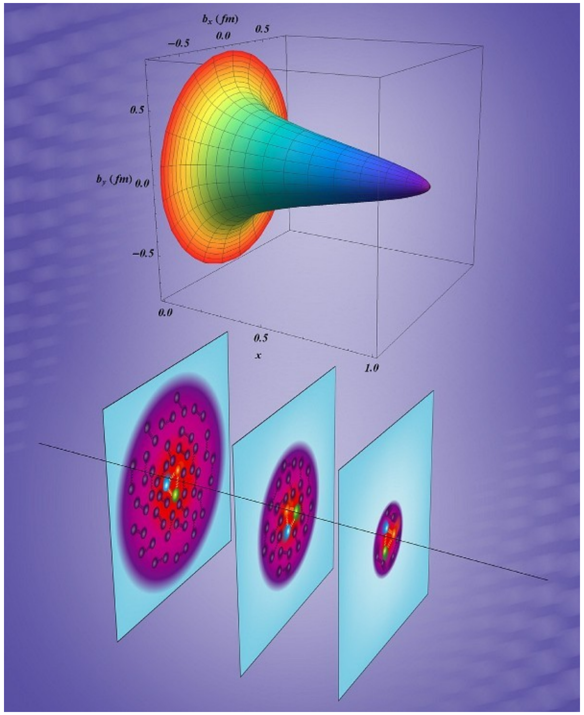
- Local fit of all the JLab data
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)



- Enough coverage to explore the t and x_B (→ξ) dependence of H_{Im}.

- Obtaining the tomography of the proton
  - Represented is the mean square charge radius of the proton for slices of x.





- The nucleon size is shrinking with x.

[R. Dupré et al. Phys.Rev. D95 (2017) no.1, 011501]

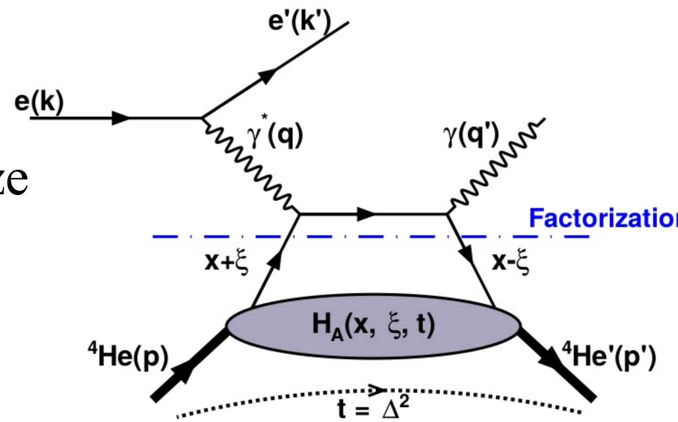
DVCS off Nuclei

Two DVCS channels are accessible with nuclear targets:

◊ **Coherent DVCS: $e^- A \rightarrow e^- A\ \gamma$**

→ Study the partonic structure of the nucleus.

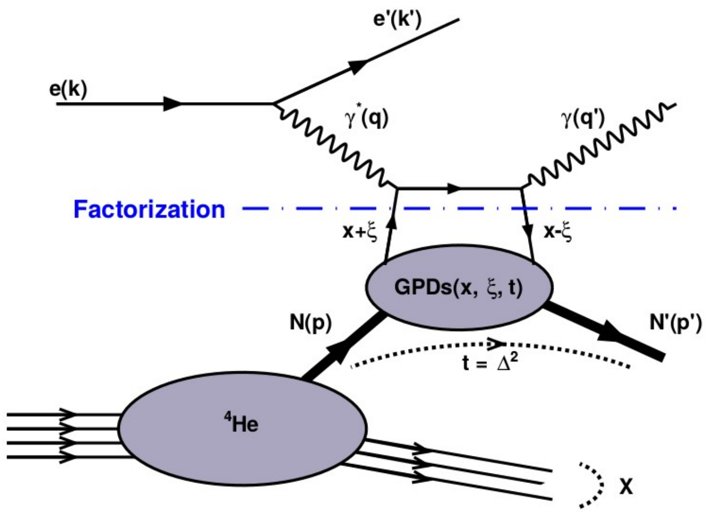
→ One chiral-even GPD ($H_A(x,\xi,t)$) is needed to parametrize the structure of the spinless nuclei (^{4}He, ^{12}C, ^{16}O, ...).

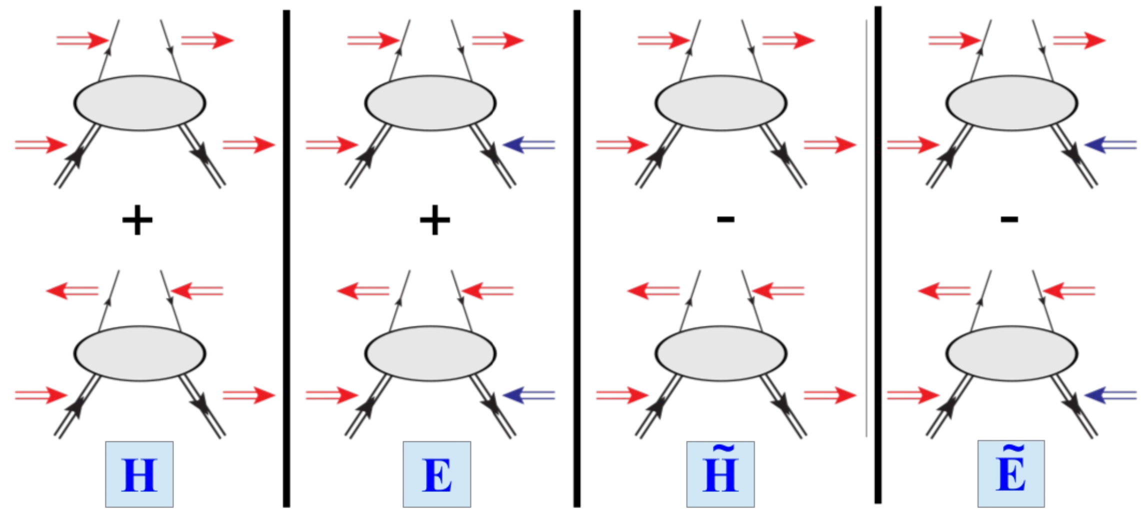


◊ **Incoherent DVCS: $e^- A \rightarrow e^- N\ \gamma\ \ X$**

→ The nucleus breaks and the DVCS takes place on a nucleon.

→ Study the partonic structure of the bound nucleons (4 chiral-even GPDs are needed to parametrize their structure).





Nuclear Spin-Zero DVCS Observables

The GPD H_A parametrizes the structure of the spinless nuclei (^{4}He, ^{12}C, …)

$$\mathcal{H}_A(\xi,t) = Re(\mathcal{H}_A(\xi,t)) - i\pi Im(\mathcal{H}_A(\xi,t))$$

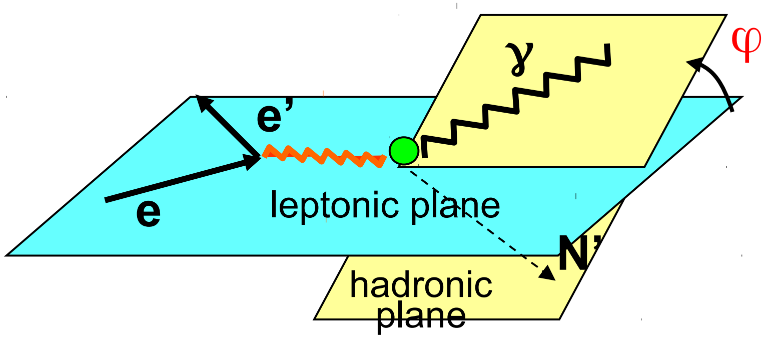
$$Im(\mathcal{H}_A(\xi,t)) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t)$$

$$Re(\mathcal{H}_A(\xi,t)) = \mathcal{P}\int_0^1 dx[H_A(x,\xi,t) - H_A(-x,\xi,t)]C^+(x,\xi)$$

Quark propagator

$$C^+(x,\xi) = \frac{1}{x-\xi} + \frac{1}{x+\xi}$$

→ Beam-spin asymmetry ($A_{LU}(\varphi)$) : (+/- beam helicity)



$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

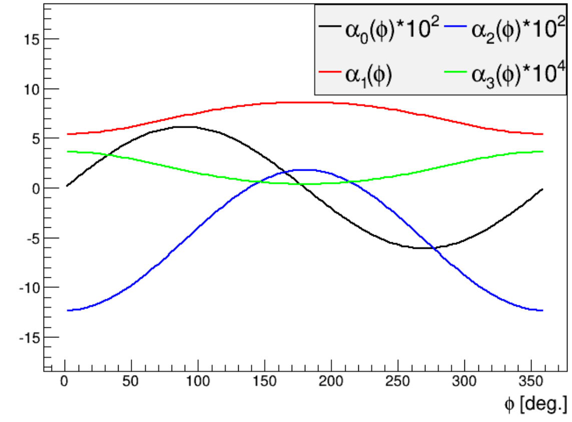
$$= \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

$$\alpha_0(\phi) = \frac{x_A(1+\varepsilon^2)^2}{y}S_{++}(1)\sin(\phi)$$

$$\alpha_1(\phi) = c_0^{BH} + c_1^{BH}\cos(\phi) + c_2^{BH}\cos(2\phi)$$

$$\alpha_2(\phi) = \frac{x_A(1+\varepsilon^2)^2}{y}(C_{++}(0) + C_{++}(1)cos(\phi))$$

$$\alpha_3(\phi) = \frac{x_A^2 t(1+\varepsilon^2)^2}{y}\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\cdot 2\frac{2-2y+y^2+\frac{\varepsilon^2}{2}y^2}{1+\varepsilon^2}$$



Theoretical Predictions of the EMC in ^{4}He

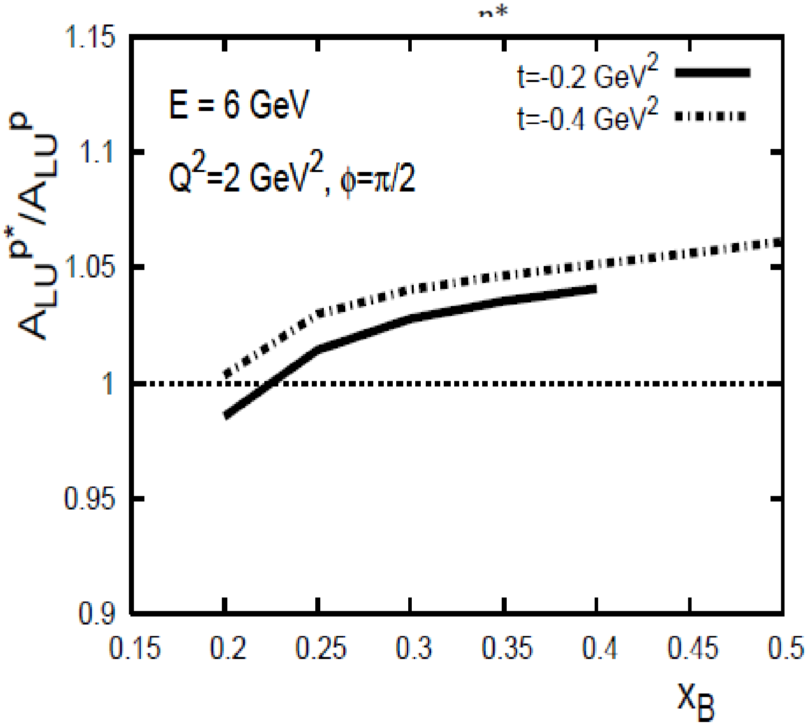
On-shell calculations:

(1) Impulse approximation

$GPD^{4He}(x,\xi,t) = \Sigma$ (free p and n GPDs)*$F_{4He}(t)$

(2) Medium modifications:

$$H^{q/p^*}(x,\xi,t,Q^2) = \frac{F_1^{p^*}(t)}{F_1^p(t)} H^q(x,\xi,t,Q^2),$$



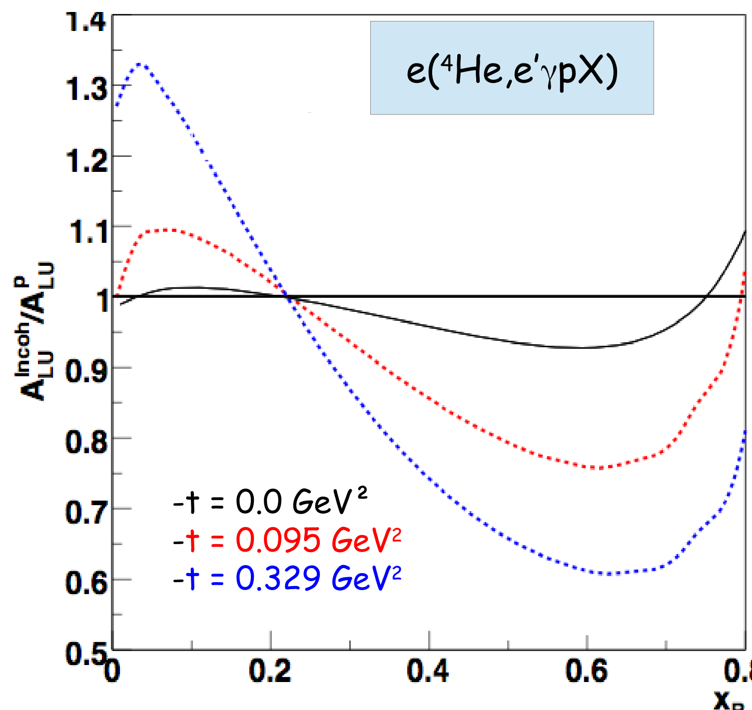
[V. Guzey, A. W. Thomas, K. Tsushima, PRC 79 (2009) 055205]

Off-shell calculations:

Nucleus = bound nucleons + nuclear binding effects

$$H^A(x,\xi,t) = \sum_N \int \frac{d^2P_\perp dY}{2(2\pi)^3} \frac{1}{A-Y} \mathcal{A}\rho^A(P^2,P'^2) \times \sqrt{\frac{Y-\xi}{Y}} \left[H^N_{OFF}\left(\frac{x}{Y},\frac{\xi}{Y},P^2,t\right) - \frac{1}{4}\frac{(\xi/Y)^2}{1-\xi/Y} E^N_{OFF}\left(\frac{x}{Y},\frac{\xi}{Y},P^2,t\right) \right]$$

Nuclear spectral function



[S. Liuti, K.Taneja, PRC 72 (2005) 034902]

New ^{4}He GPDs calculation is coming

Nuclear DVCS Measurements: HERMES

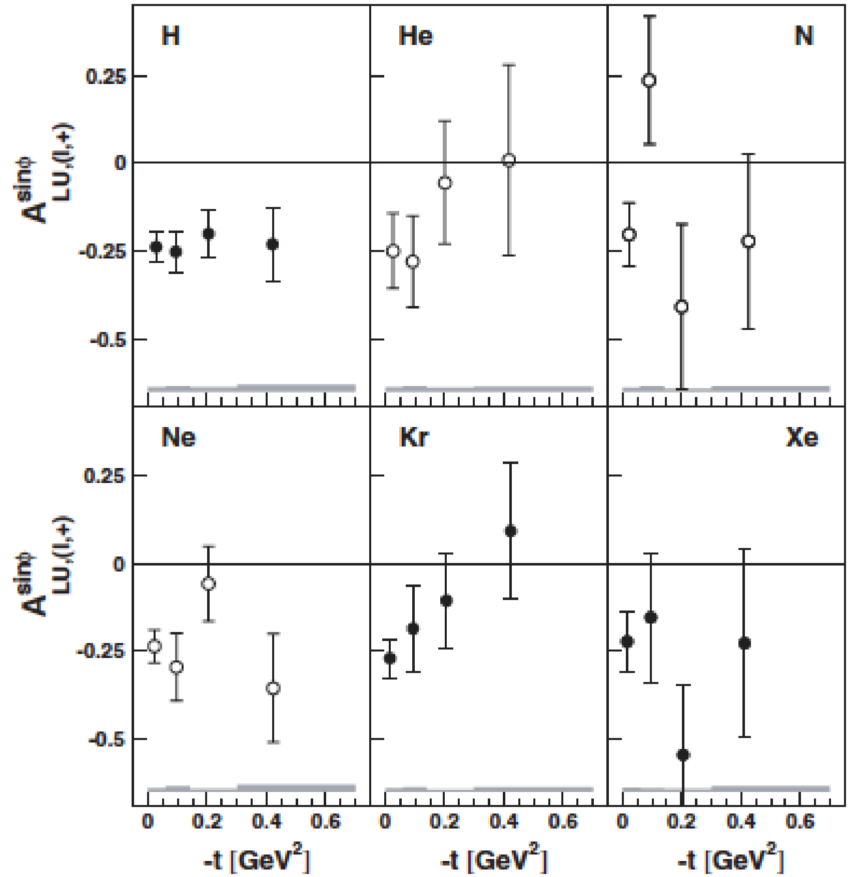
- The exclusivity is ensured via cut on the missing mass of eγX final state configuration.

- Coherent and incoherent separation depending on -t, i.e. coherent rich at small -t.

- Conclusions from HERMES:
  No nuclear-mass dependence has been observed.

In CLAS - E08-024, we measured EXCLUSIVELY the coherent and incoherent DVCS channels off ^{4}He

$$A_{LU}^{sin} = \frac{1}{\pi} \int_0^{2\pi} d\phi \, \sin\phi \, A_{LU}(\phi)$$



[A. Airapetian, et al., Phys Rev. C 81 (2010) 035202]

CLAS - E08-024 Experimental Setup

$e^- \, {}^4He \rightarrow e^- \, ({}^4He/pX) \, \gamma$

6 GeV,
L. polarized

Beam polarization (P_B) = 83%

- CLAS:
- → Superconducting Torus magnet.
- → 6 independent sectors:
  - → DCs track charged particles.
  - → CCs separate e^-/π^-.
  - → TOF Counters identify hadrons.
  - → ECs detect γ, e^- and n [8º,45º].

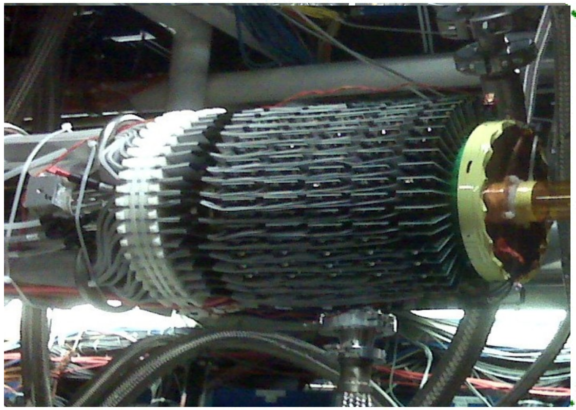
- IC: Improves γ detection acceptance [4º,14º].

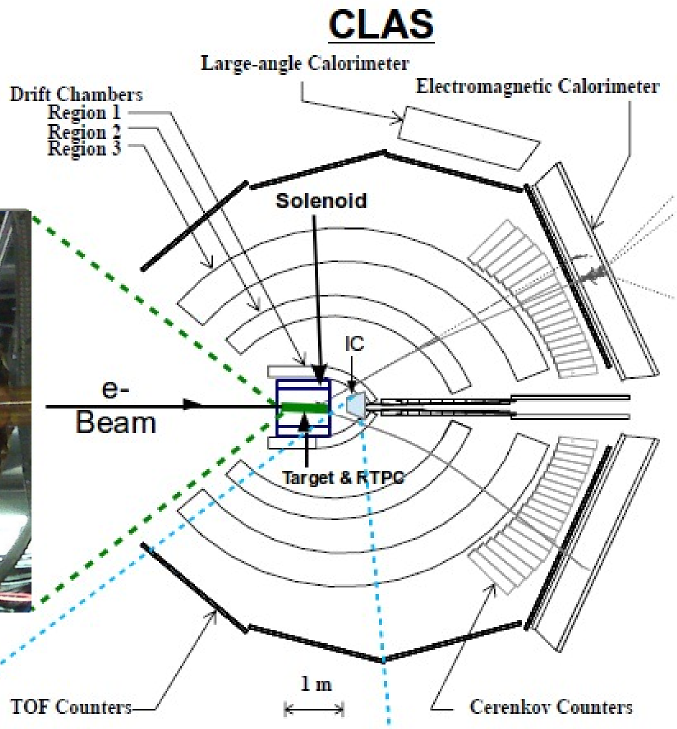
- RTPC: Detects low energy nuclear recoils.

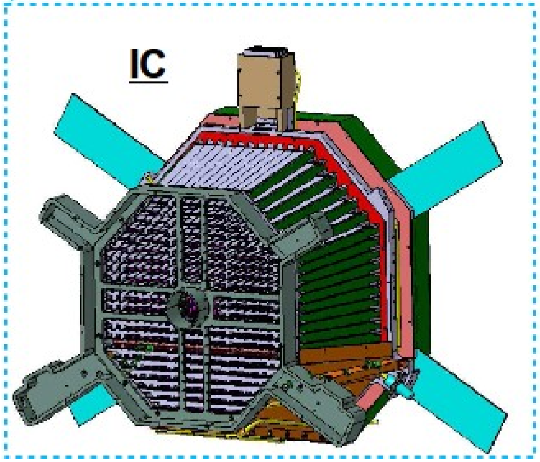
- Solenoid: - Shields the detectors from Møller electrons.
- Enables tracking in the RTPC.

- Target: ^{4}He gas @ 6 atm, 293 K

RTPC







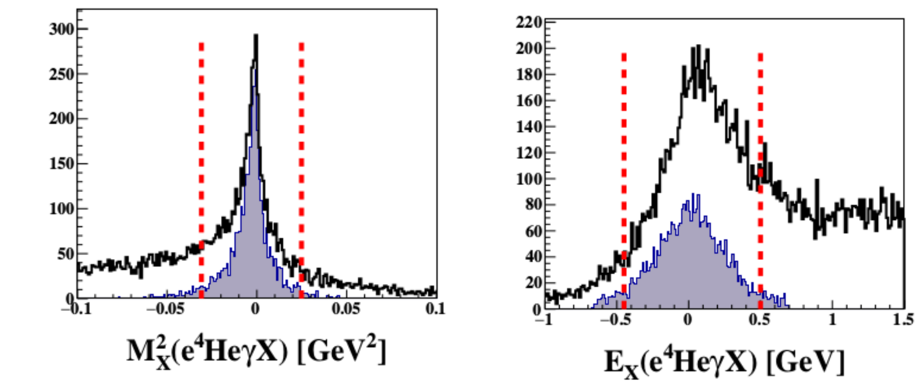
Coherent DVCS Selection & Asymmetries

1. We select COHERENT events which have:

◊ Events with :
- Only one good electron in CLAS
- At least one high-energy photon (Eγ > 2 GeV)
- Only one ^{4}He in RTPC (p ~ 250-400 MeV).

◊ $Q^2 > 1$ GeV^2.

◊ Exclusivity cuts.

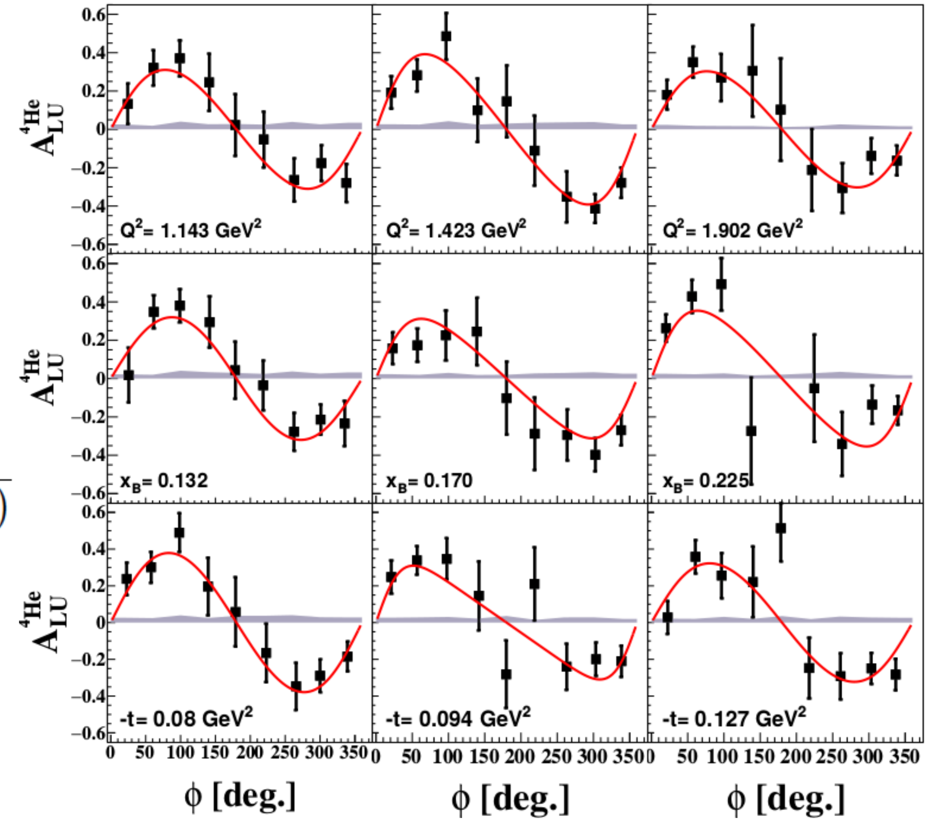


2. π^0 background subtraction based on data and simulation (cont. ~ 2 – 4%)

3. Beam-spin asymmetry:

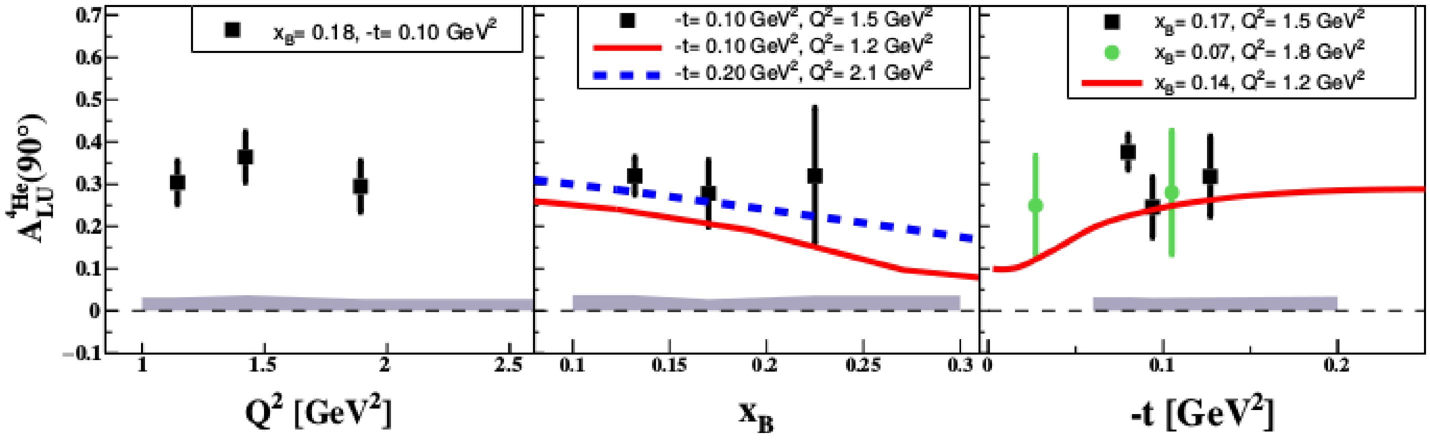
$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

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



- 2D bins due to limited statistics
- Uncertainities dominated by statictics
- Systematic uncertainities (~ 10 %)
- dominated by exclusivity cuts (~8 %) and large phi bining (~5 %)

Coherent A_{LU} and CFFs



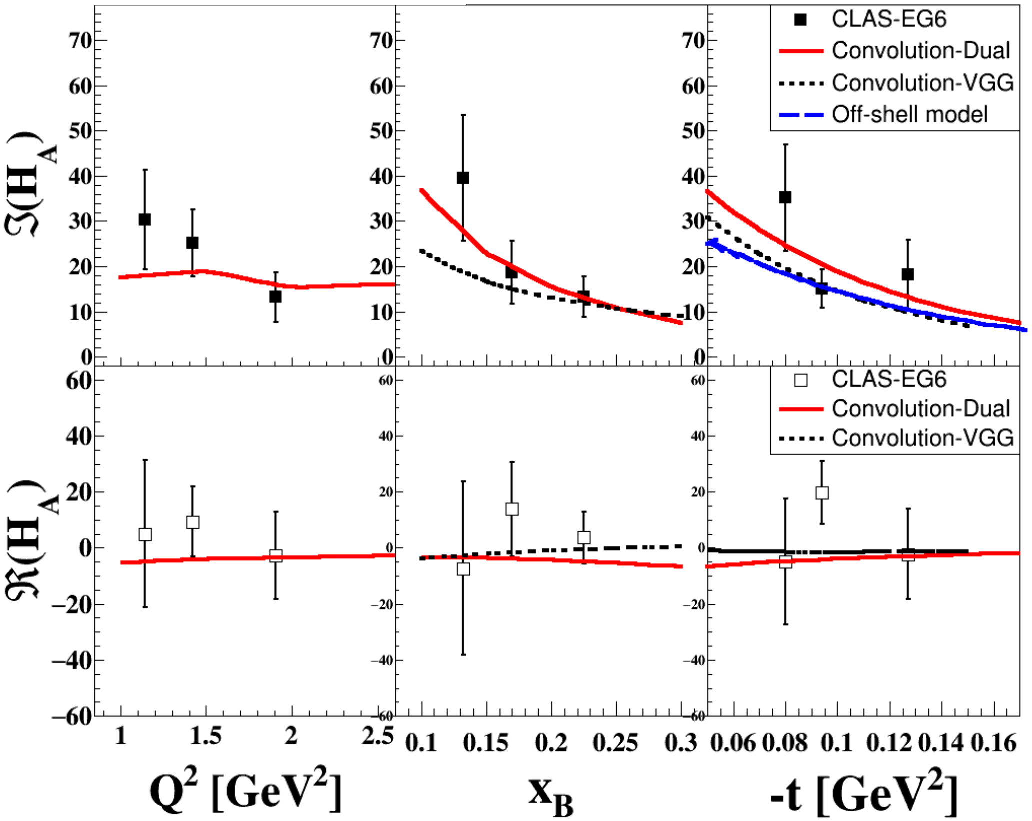
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[HERMES: A. Airapetian, et al., PRC 81, 035202 (2010)]

→Same A_{LU} sign as HERMES.

→Asymmetries are in agreement with the available models.

→The first ever experimental extraction of the real and the imaginary parts of the ^{4}He CFF. Compatible with the calculations.

→More precise extraction of Im(H_A).



CLAS-EG6: M. Hattawy et al., Phys. Rev. Lett. 119, 202004 (2017)
Convolution-Dual: V. Guzey, PRC 78, 025211 (2008).
Convolution-VGG: M. Guidal, M. V. Polyakov, A. V. Radyushkin and M. Vanderhaeghen, PRD 72, 054013 (2005).
Off-shell model: J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein and K. Kathuria, PRC 88, no. 6, 065206 (2013)

Incoherent DVCS Selection & Asymmetries

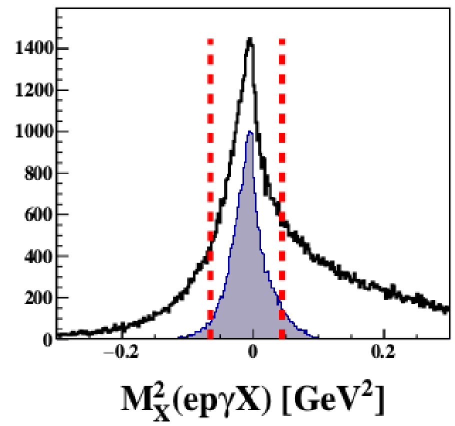
1. We select events which have:

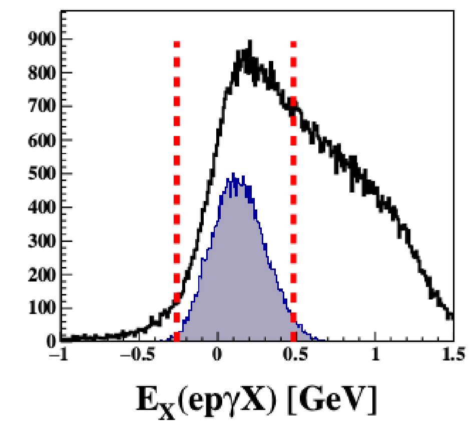
◊ Events with :

- Only one good electron in CLAS
- At least one high-energy photon (Eγ > 2 GeV)
- Only one proton in CLAS.

◊ $Q^2 > 1$ GeV² and W> 2 GeV/c²

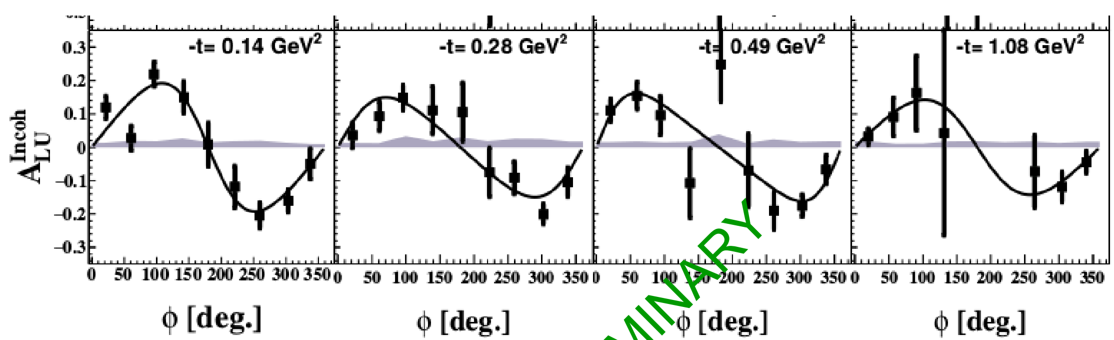
◊ Exclusivity cuts (3 sigmas).





2. π^0 background subtraction (contaminations ~ 8 - 11%)

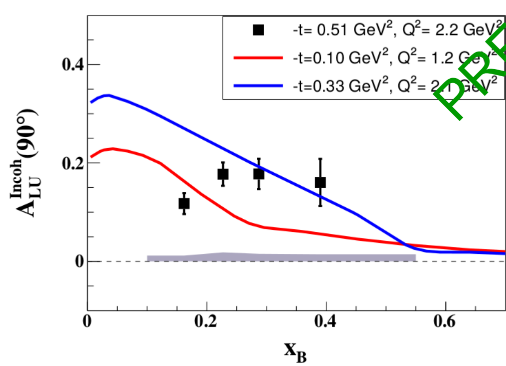
3. Beam-spin asymmetry:

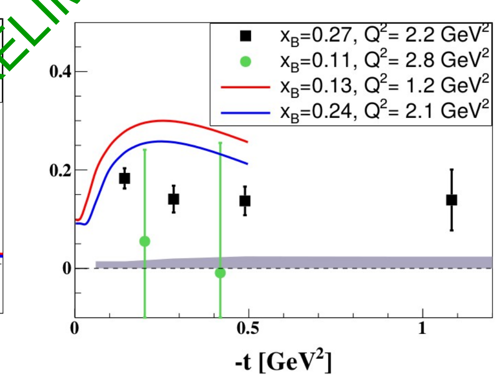


$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{LU} \propto \alpha(\phi)\{F_1 H + \xi(F_1 + F_2)\widetilde{H} + \kappa F_2 E\}$$

- 2D bins due to limited statistics
- Fits in the form: $\dfrac{\alpha * \sin(\phi)}{(1+\beta*\cos(\phi))}$





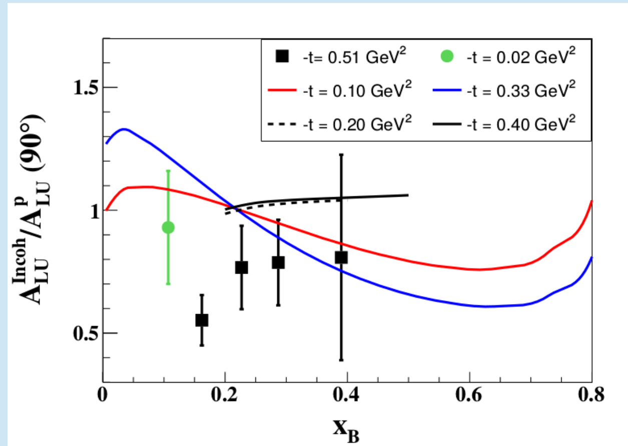
[S. Liuti and K. Taneja. PRC 72 (2005) 032201]

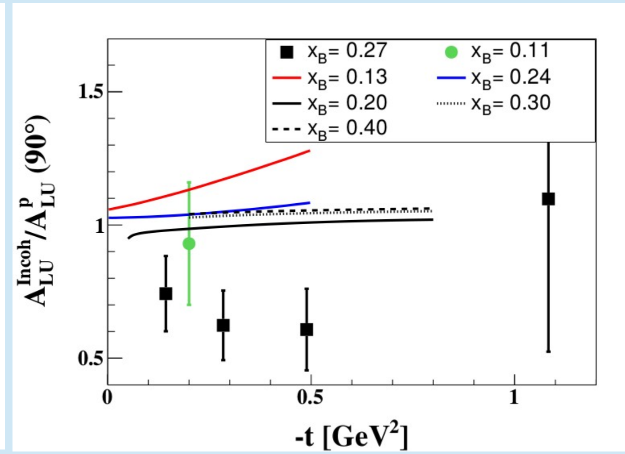
* A PRL presenting the incoherent results is under progress.

Generalized EMC Ratio

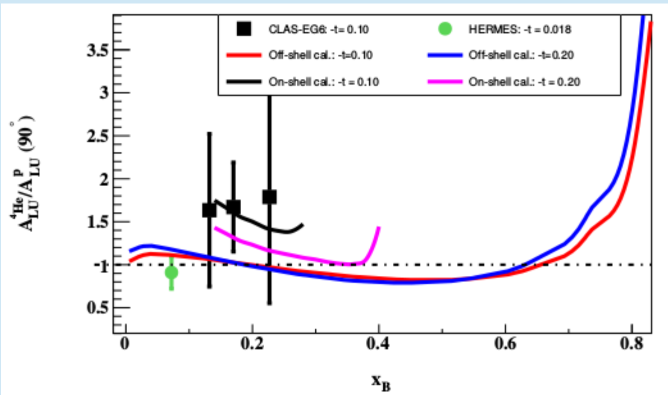
◊ We comparing our measured coherent/incoherent asymmetries to the asymmetries measured in CLAS DVCS experiment on free proton

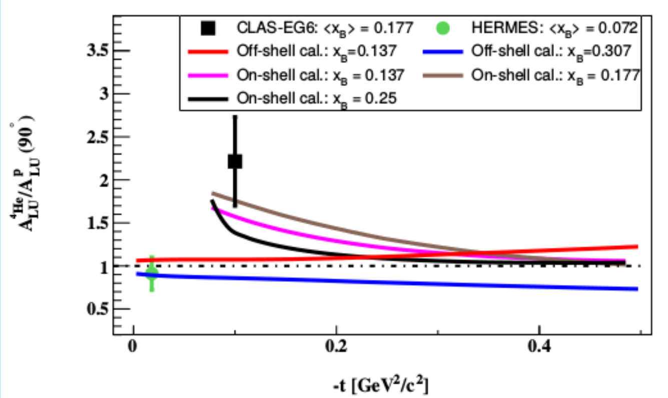
- Incoherent/proton:





- Coherent/proton:





→ **Coherent/proton** is:

- Consistent with the enhancement predicted by the Impulse approximation model [V. Guezy et al., PRC 78 (2008) 025211]
- Does not match the inclusive measurement of HERMES.

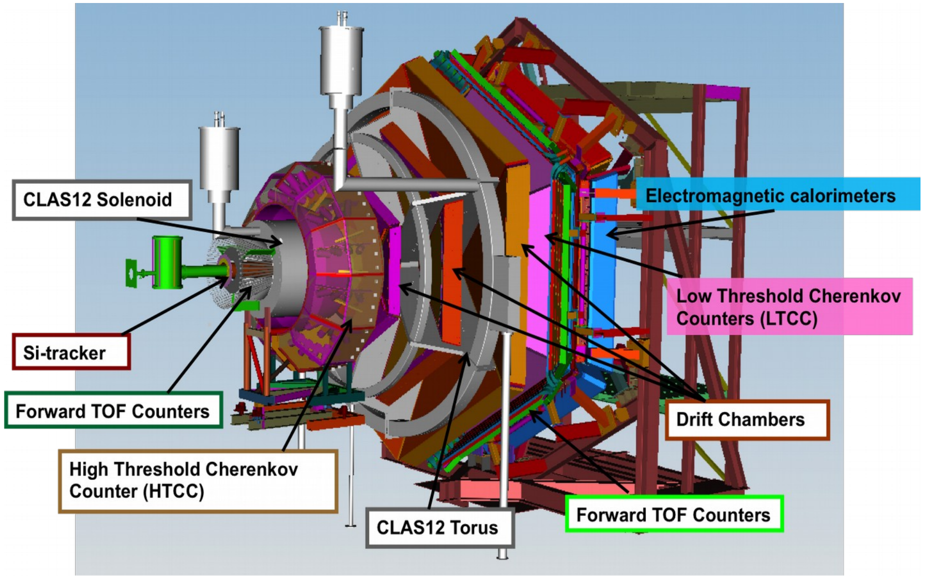
[A. Airapetian, et al., Phys. Rev. C 81, 035202 (2010)]

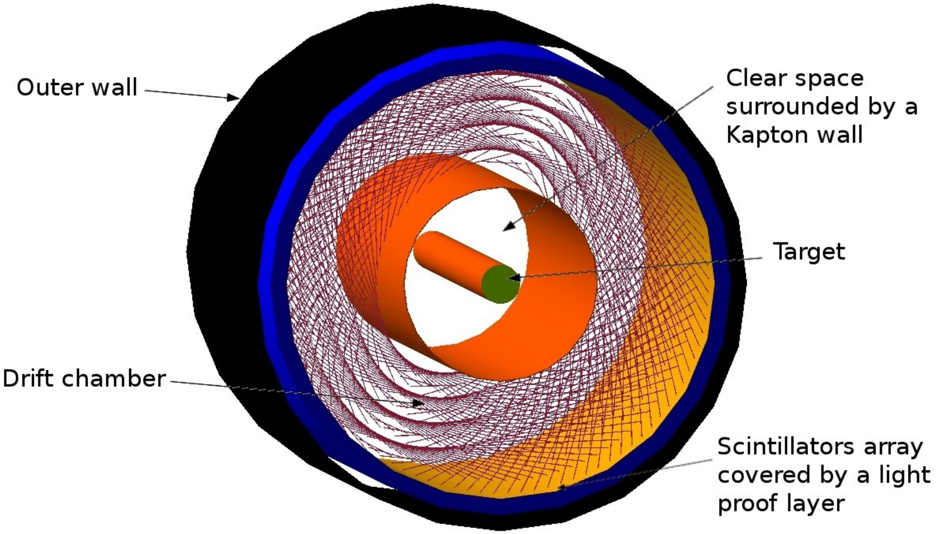
→ **Incoherent/proton** is supressed compared to both the PWIA and the nuclear spectral function calculations.

[S. Liuti and K. Taneja. PRC 72 (2005) 032201]
[V. Guezy et al., PRC 78 (2008) 025211]

CLAS12-ALERT Program

- CLAS–E08-024 experiment:
  - 2D binning due to limited statistics
  - Limited phase-space.
- CLAS12 experimental apparatus:
  - High luminosity & large acceptance.
  - Measurements of deeply virtual exclusive, semi-inclusive, and inclusive processes.
- We proposed to measure with CLAS12:
  - Partonic Structure of Light Nuclei.
  - Tagged EMC Measurements on Light Nuclei.
  - Spectator-Tagged DVCS Off Light Nuclei.
  - Other Physics Opportunities.
- The momentum threshold of the CLAS12 inner tracker is too high to be used for our measurements.
- Proposed experimental setup:
  - CLAS12 forward detectors.
  - A Low Eenergy Recoil Tracker (ALERT) in place of CLAS12 Central detector (SVT & MVT).
- CLAS12-ALERT setup will allow higher statistics and wider kinematical coverage.





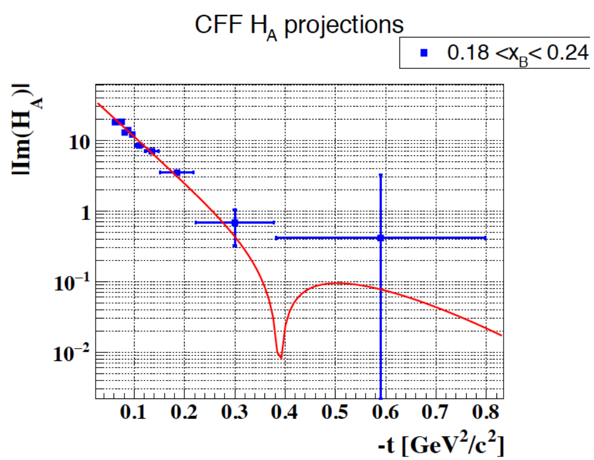
Partonic Structure of Light Nuclei (PR12-17-012)

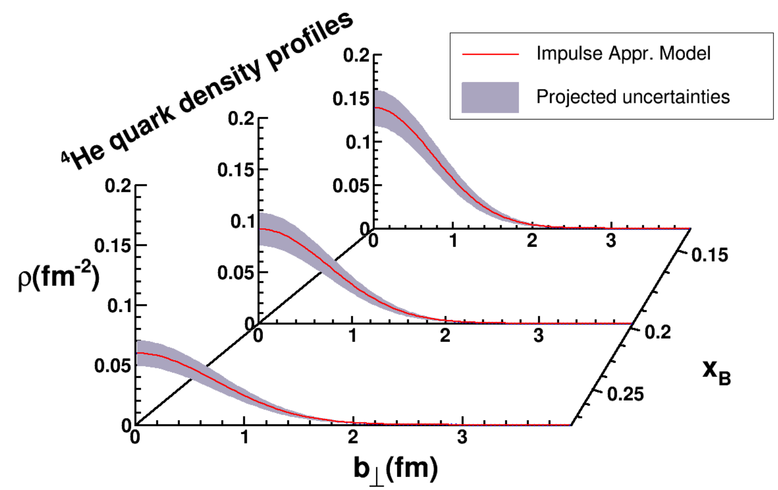
- Map the fundamental structure of nuclei within the GPD framework
- Compare the quark and gluon 3D structure of the Helium nucleus

e ^{4}He→e` $^4$He`γ:

- Fully model independent extracion of H_A CFF from fitting the BSA.
- Fourier transform of Im(H_A) at ξ=0 gives probability densitiy of quarks as function of x and impact parameter.

$$\rho(x,0,b_\perp) = \int_0^\infty J_0(b\sqrt{t})H^A(x,0,t)\frac{\sqrt{t}}{2\pi}d\sqrt{t}$$

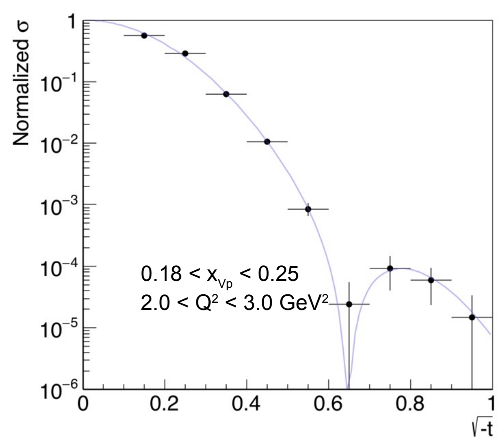


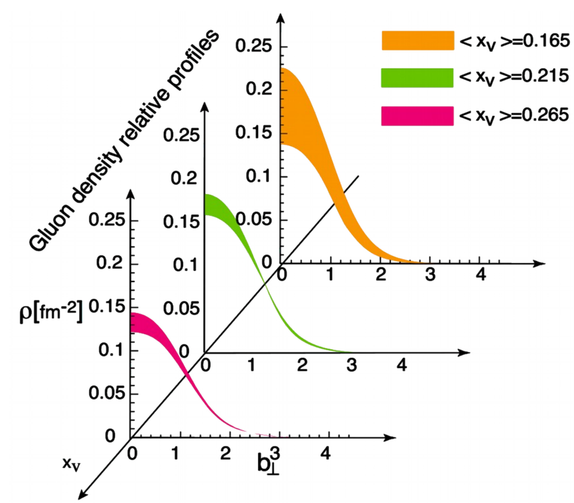


e ^{4}He→e` $^4$He`φ:

- Detect recoil ^{4}He, e, and K$^+$ (missing K$^-$)
- The longitudinal cross-section will be extracted from the angular distribution of the kaon decay in the phi helicity frame.
- Gluon density extraction:

$$\rho_g(x,0,b_\perp) \rightarrow \int_0^\infty J_0(b\sqrt{t})\sqrt{\frac{d\sigma_L}{dt}}\frac{\sqrt{t}}{2\pi}d\sqrt{t}$$

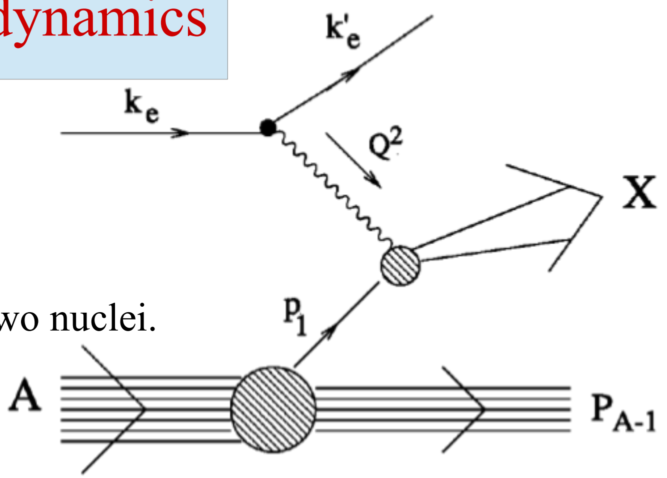




Requested PAC days: 20 days at 3x10^{34} cm^{-2}s^{-1} + 10 days at 6x10^{34} cm^{-2}s^{-1} + (5 Com.)

Tagged EMC Measurements (PR12-17-012A)

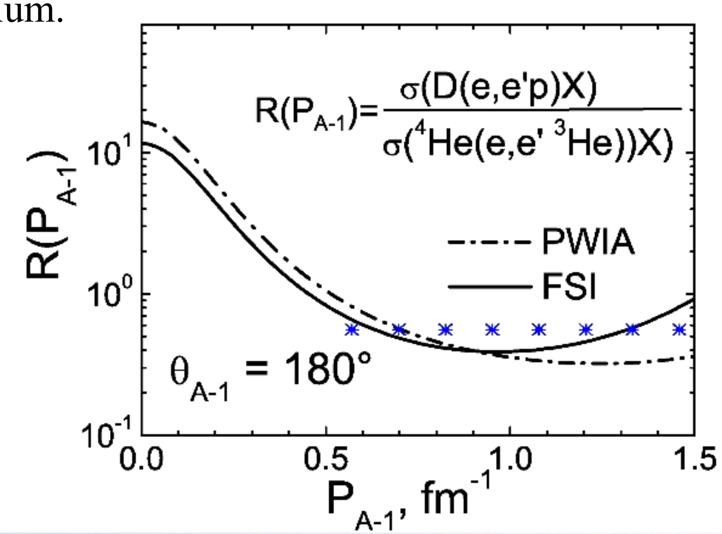
DIS, with tagged spectator, provides access to new variables and explore links between EMC effect and intranuclear dynamics

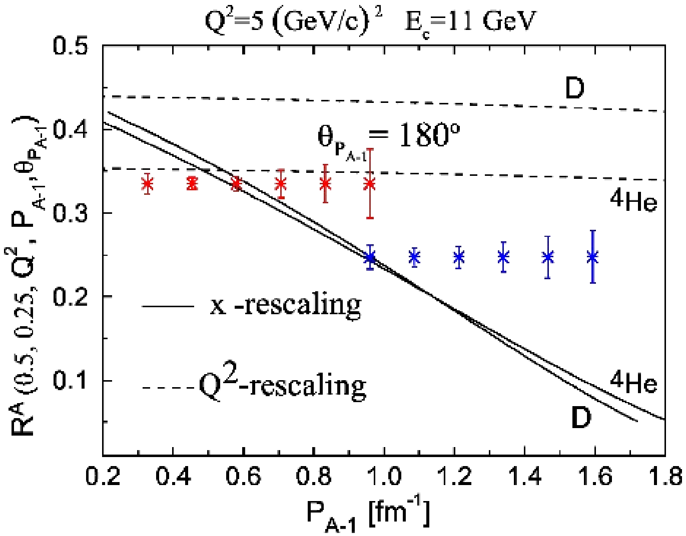


- Comparing D to ^4He is particularly interesting:
  - It conserves the nucleus isospin symmetry.
  - ^4He is a light nuclei with a sizable EMC effect.
  - The two rescaling effects are cleanly separated by the comparison between the two nuclei.
  - They complement each other in spectator momentum coverage.

- Tagged DIS provides test for:
  - FSI models over wide momentum and angle ranges.
  - EMC effect models: x/Q^2 scaling.
  - d/u ratio changes in nuclear medium.

- 40 (+5) PAC days
  - 20 on ^4He ($3x10^{34}$ $cm^{-2}s^{-1}$).
  - 20 on D $3x10^{34}$ $cm^{-2}s^{-1}$).

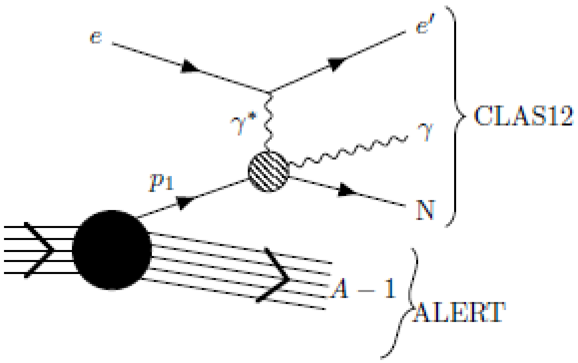


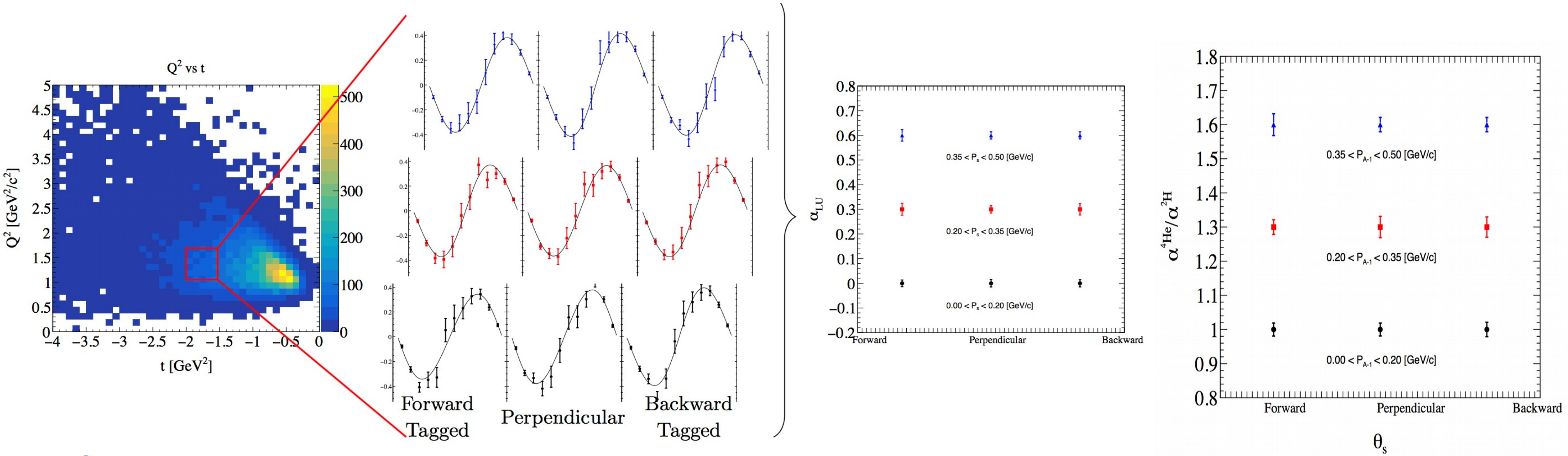


Spectator-Tagged DVCS On Light Nuclei (PR12-17-012B)

- Probe connection between partonic and nucleonic interpretations via DVCS
- Partonic interpretation and in-medium hadron tomography of nucleons
- Study of Off-Forward EMC effect in incoherent DVCS

- Bound-p DVCS:
  - Fully detected ep^{3}H final state, provides unique opportunity to study FSI, test PWIA, identify kinematics with small/large FSI.
- Bound neutron in ^{4}He/quasi-free in ^{2}H:
  - e ^{3}He(n) / ep(n) final states (p detection down to ~70 MeV, ^{3}He to ~120 MeV).
  - Six-dimensional binning (Q^2, x_B, t, φ, p_s, θ_s).
- No additional PAC days





Other Physics Opportunities (PR12-17-012C)

The three main proposals of the ALERT run group is only a fraction of the physics that can be achieved by successfully analyzing the ALERT run group data

- π^0 production off ^{4}He
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.
- Coherent DVCS off D
  - Access to new GPDs, H_3 , with relationships to dueteron charge form factors.
- Coherent DVMP off D
  - π^0 , φ, ω and ρ mesons.
- Semi-inclusive reaction p(e,e`p)X
  - Study the π^0 cloud of the proton.
- D(e, e`pp$_S$)X
  - Study the π^- cloud of the neutron.
- More Physics:
  - Helium GPDs beyond the DVCS at leading order and leading twist.
  - Tagged nuclear form factors measurements.
  - The role of Δs in short-range correlations.
  - The role of the final state interaction in hadronization and medium modified fragmentation functions.
  - The medium modification of the transverse momentum dependent parton distributions.
  - ... and more

Conclusions & Perspectives

◊ **Several decades of elastic and DIS experiments on hadrons** have provided one-dimensional views of hadrons' structure.

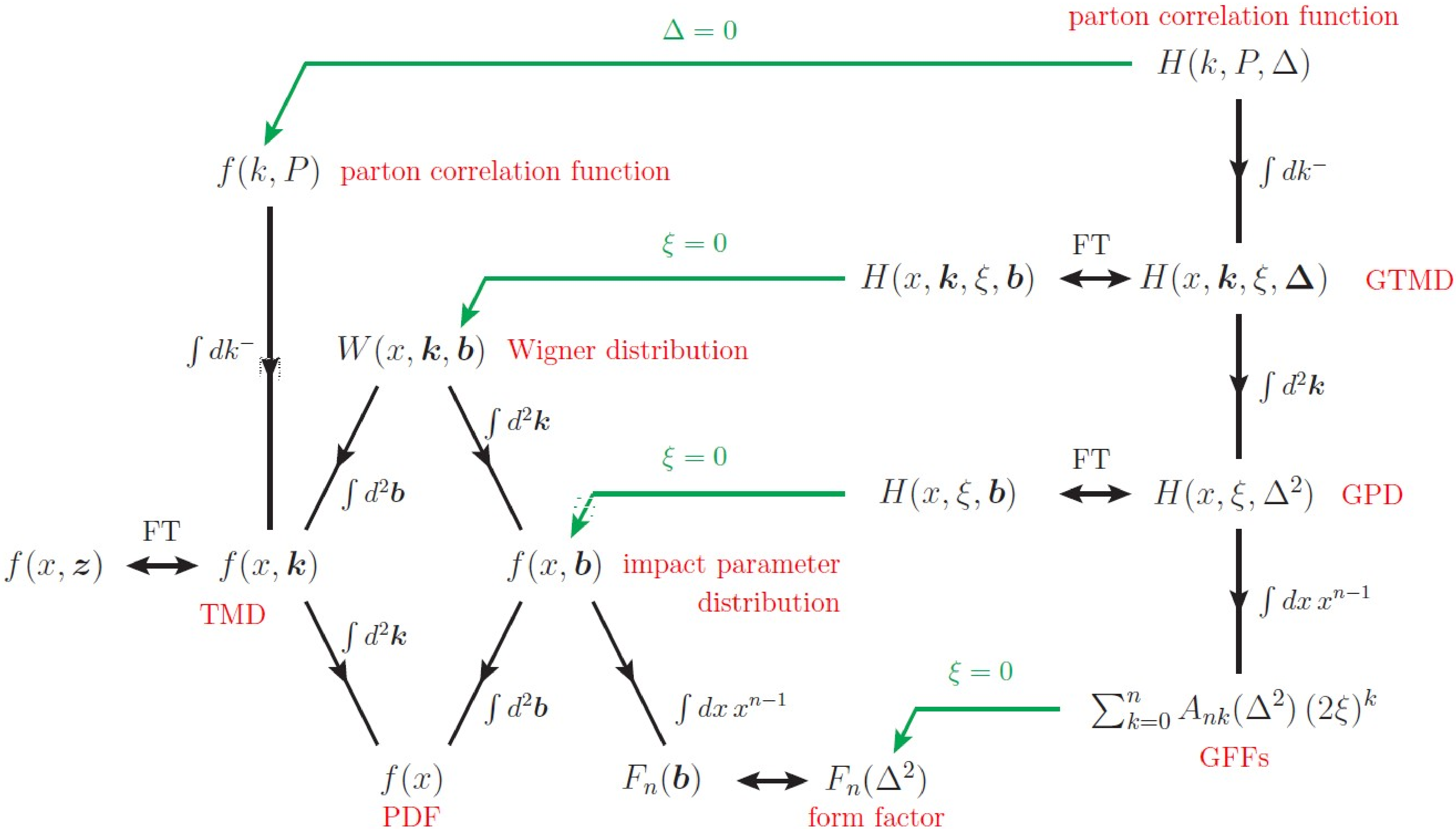
◊ **We are now exploring the 3D structure of nucleons within the GPD framework**
→ Fifteen years of successful experiments at JLab.
→ Accumulated a wide array of proton data.
→ The first tomography was extracted.

◊ **The first exclusive measurement of DVCS off ^{4}He:**
→ The coherent DVCS shows a stronger asymmetry than the free proton as was expected from theory.
→ We performed the first ever model independent extraction of the ^{4}He CFF.
→ We extracted EMC ratios and compared them to theoretical predictions.
→ The bound proton has shown a different trend compared to the free one indicating the medium modifications of the GPDs and opening up new opportunities to study the EMC effect.

◊ **CLAS12-ALERT** will provide wider kinematical coverage and better statistics that will:
→ Allow performing ^{4}He tomography in terms of quarks and gluons.
→ Allow comparing the gluon radius to the charge radius.
→ Use tagging methods to study EMC effect via DIS measurements.
→ Use Tagged-DVCS techniques to study in-medium nucleon interpretations.
→ Reinforce EIC physics program by proving their usefulness in the valence region.

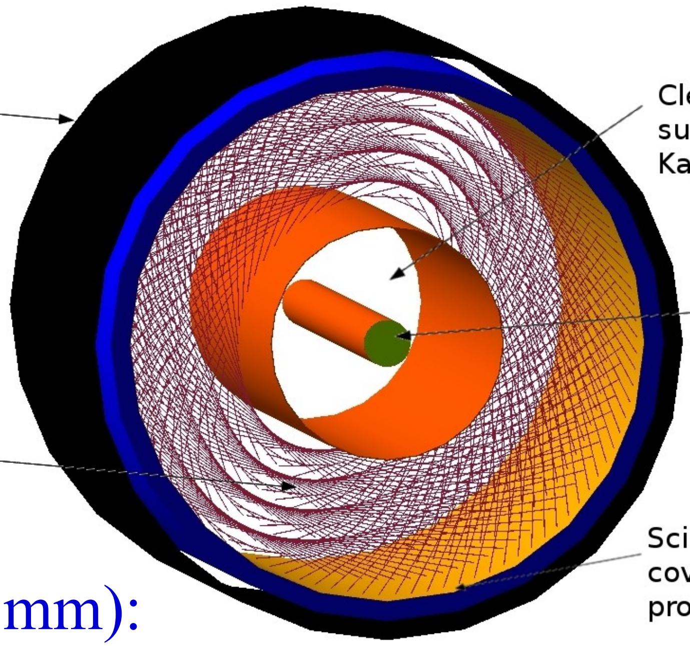
Hadronic Structure Functions

Structure functions that quantify the properties of the partons in a hadron:



[M. Diehl, arXiv:1512.01328v2 [hep-ph]]

ALERT Detector



- **Cylindrical target:**
  - 30 cm long
  - 6 mm outer radius.
  - Target at 3 atm pressure.
  - 25μm target wall (Kapton).

- **A clear space filled with helium**

  to reduce secondary scattering from the high rate Moller electrons (R_{out} = 30 mm).

- **Hyperbolic drift chamber (32 mm< R< 85 mm):**

  →Will detect the trajectory of the low energy nuclear recoils.
  - 8 circular layers of 2mm hexagonal cells.
  - 10° stereo-angle to give z-resoluation.
  - Total of 2600 wires, < 600 kg tension.
  - Maximum drift time ~ 250 ns, will be included in the trigger.

- **Two rings of plastic scintillators (**Total thickness of 20 mm, SIPMs directly attached**):**

  → TOF (< 150 ps resolution) and deposited energy measurements.

→ Separate protons, deuterium, tritium, alpha, ^{3}He

ALERT Expected Performance

- **Capabilities for very low momentum detection**
  - As low as 70 MeV/c for protons and 240 MeV/c for ^{4}He
  - Forward and backward detections (25° from the beam).
- **Capabilities to handle high rates**
  - Small distance between wires leads to short drift time <250 ns (5 μs in a similar RTPC)
  - This translates into 20× less accidental hits
  - Will be integrated in the trigger for significantly reduced DAQ rate
- **Improved PID**
  - Like in the RTPC, we get dE/dx measurment
  - We have more resolution on the curvature due to the large pad size in previous RTPCs
  - TOF information