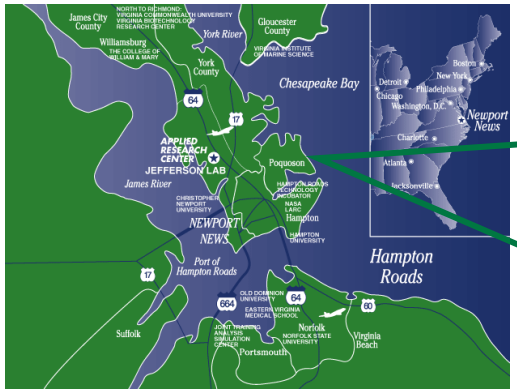
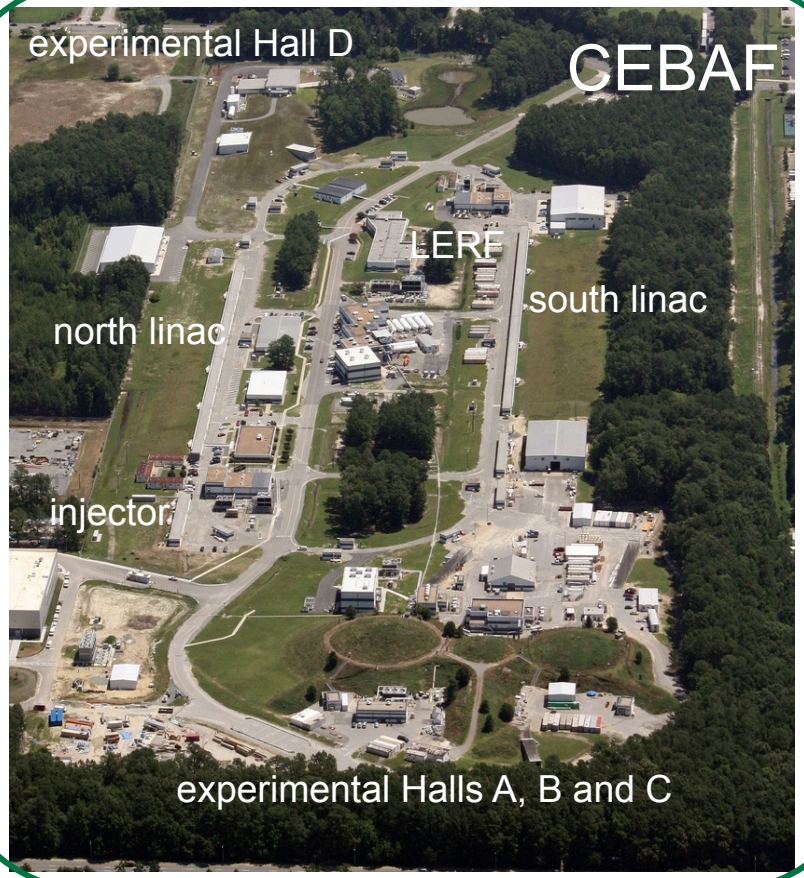
Nucleon and Nuclear structure studies in electroproduction with CLAS at Jefferson Lab

S. Stepanyan (JLAB) for the CLAS collaboration

22nd International Spin Symposium 2016
September 25-30, 2016, UIUC

Jefferson Lab

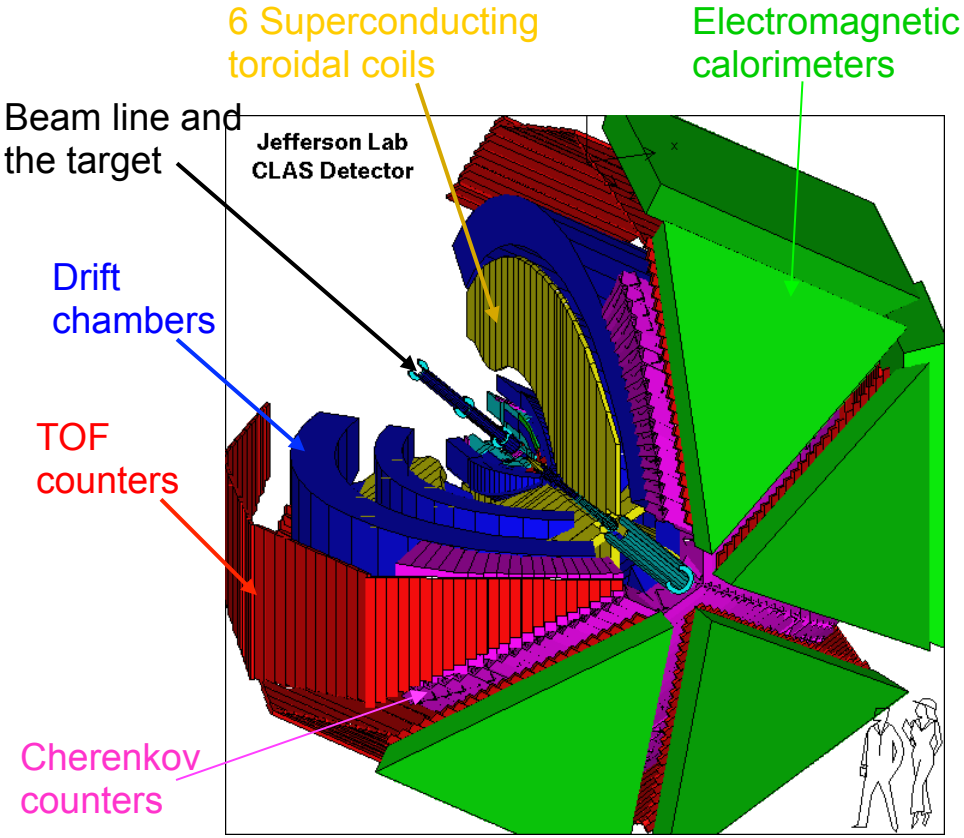




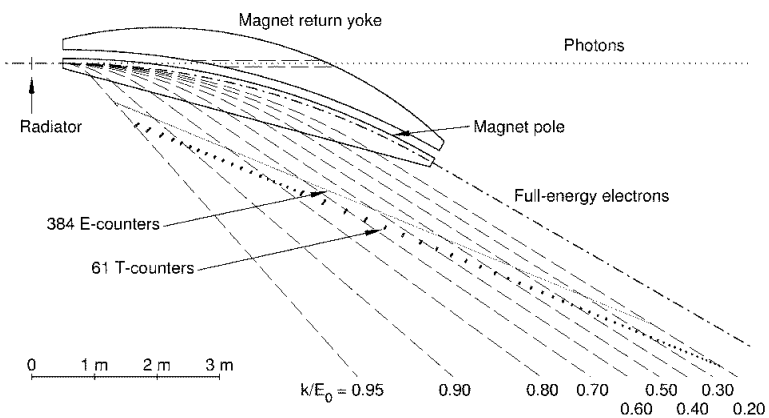
Parameter	1996 – 2012	2014 –
E_{max} (GeV)	6 (1.2/pass)	12 (2.2/pass)
I_{max} (μA)	200	100
Polarization	85%	85%
Simultaneous delivery of CW beam to	3 halls	3 halls (4@5th pass)

Hall B CLAS detector

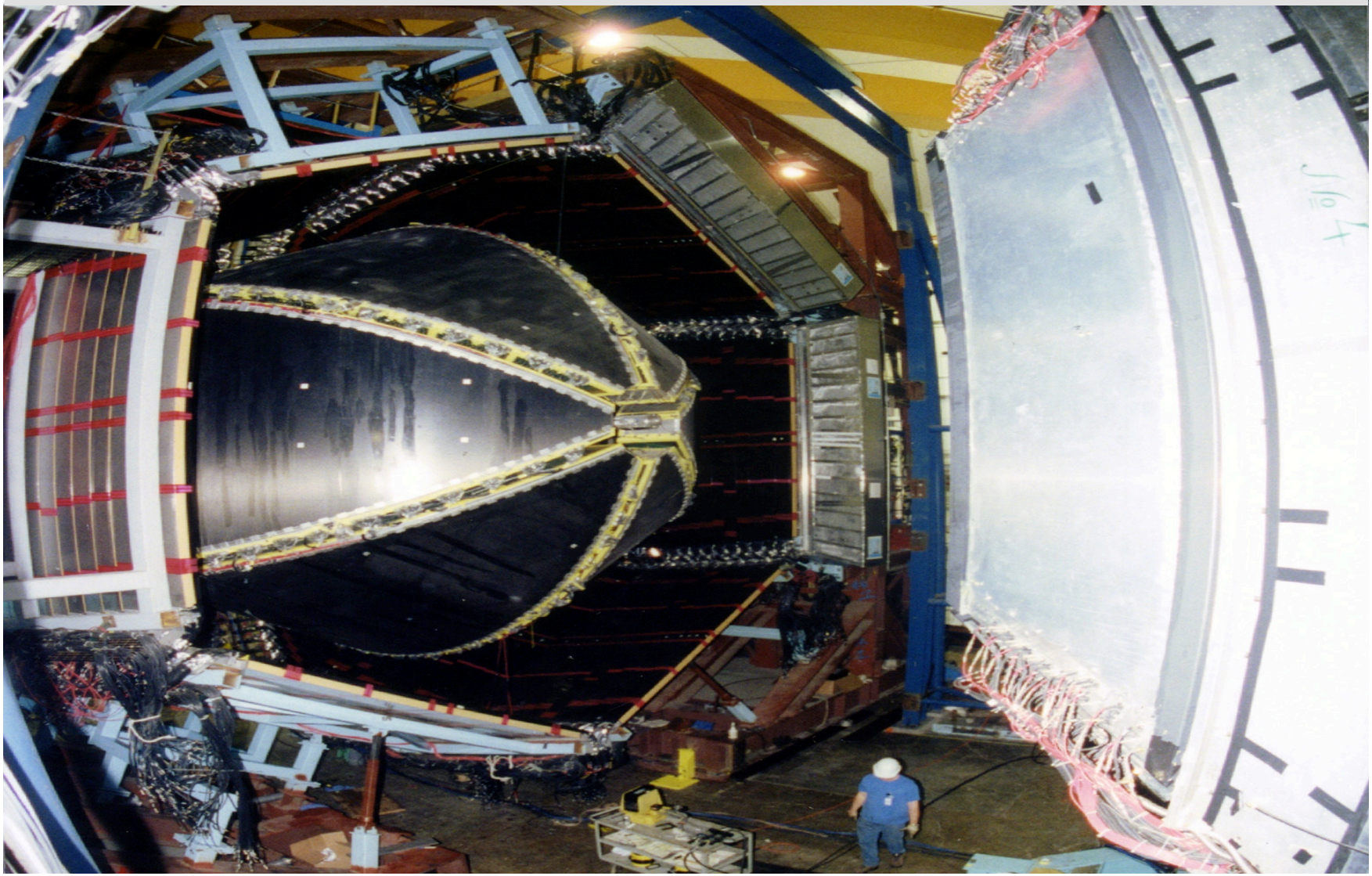
Experiments with [polarized] electron and photon beams using variety of cryogenic, solid and polarized targets



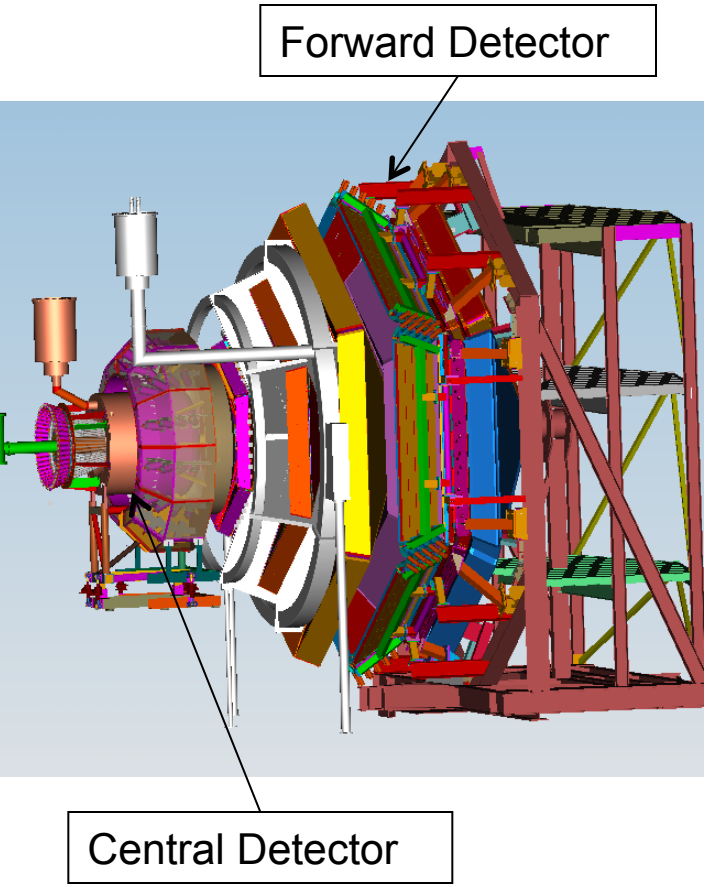
Bremsstrahlung tagged photon facility, photon energy resolution ~0.2%



Supported execution of a diverse physics program for 15 years



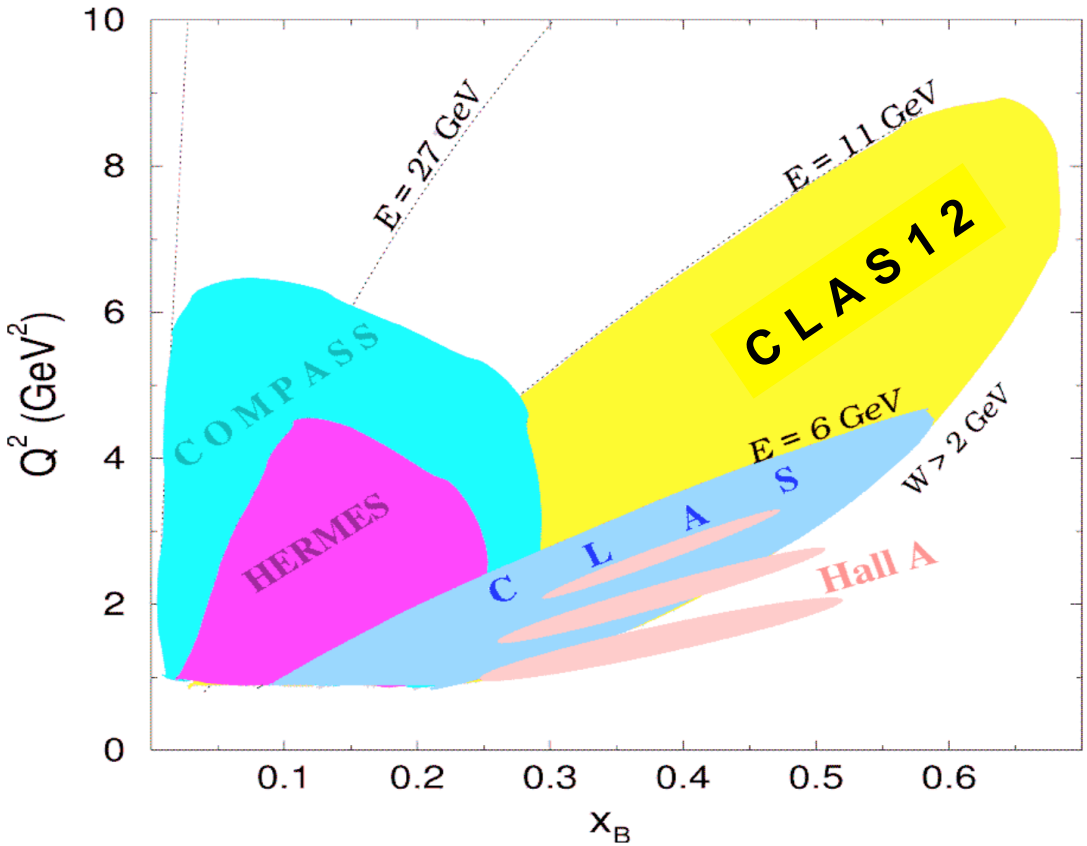
CLAS12 – Design Parameters



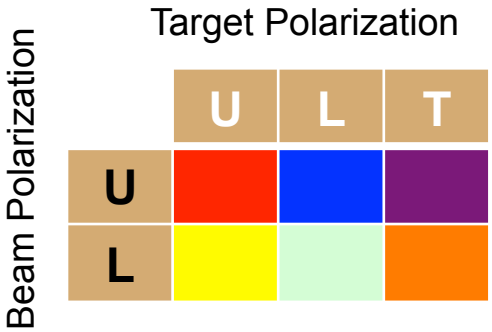
$$L = 10^{35} cm^{-2} s^{-1}$$

	FD	CD
Angular range		
Track	$5^0 – 40^0$	$35^0 – 125^0$
Photons	$2^0 – 40^0$	---
Resolution		
dp/p (%)	< 1 @ 5 GeV/c	< 5 @ 1.5 GeV/c
$d\theta$ (mr)	< 1	< 10 – 20
$\Delta\phi$ (mr)	< 3	< 5
Photon detection		
Energy (MeV)	>150	---
$\delta\theta$ (mr)	4 @ 1 GeV	---
Neutron detection	N_{eff}< 0.7	N_{eff}< 0.3
Particle ID		
e/π	Full range	---
π/p	< 5 GeV/c	< 1.25 GeV/c
π/K	< 2.6 GeV/c	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1.0 GeV/c
$\pi(\eta)\rightarrow\gamma\gamma$	Full range	---

JLAB kinematic and experimental reach



More than 1500 hours of beam time approved for CLAS12 experiments



Reaction	γ	$\pi^+/\pi^-/\pi^0$	η	ρ/ω/ϕ
Deeply exclusive (GPDs)				

Physics program of CLAS (CLAS12)

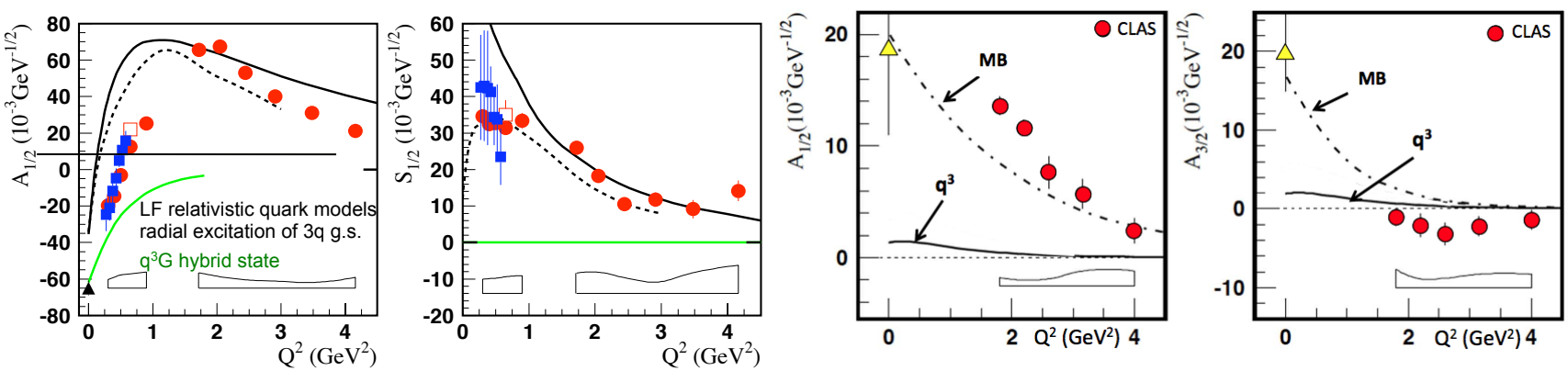
- Hadron spectroscopy
  - Spectrum of nucleon resonances
  - Exotics
- Nucleon structure (p & d targets)
  - Form Factors (FFs)
  - Parton Distribution Functions (PDFs)
  - Generalized Parton Distributions (GPDs)
  - Transverse Momentum Distributions (TMDs)
- Nuclear QCD
  - Nuclear GPDs
  - Quark propagation and hadronization in nuclei
  - Color transparency
  - Short-range correlations
  - Effects of binding on nucleon structure

Electroexcitation of nucleon resonances

- Over past decade, CLAS provided the lion's share of the world's data on meson photo- and electroproduction in the resonance excitation region.
- These data were not only important for in identifying new states (accommodated in CQM and LQCD) but also in revealing structure of known resonances
- Theoretical analyses of these results have revealed that there are two major contributions to the resonance structure:
  - an internal quark core
  - an external meson-baryon cloud

Helicity amplitudes for the

$\gamma^* p \rightarrow N(1440)P11$ and $\gamma^* p \rightarrow N(1675)5/2^-$



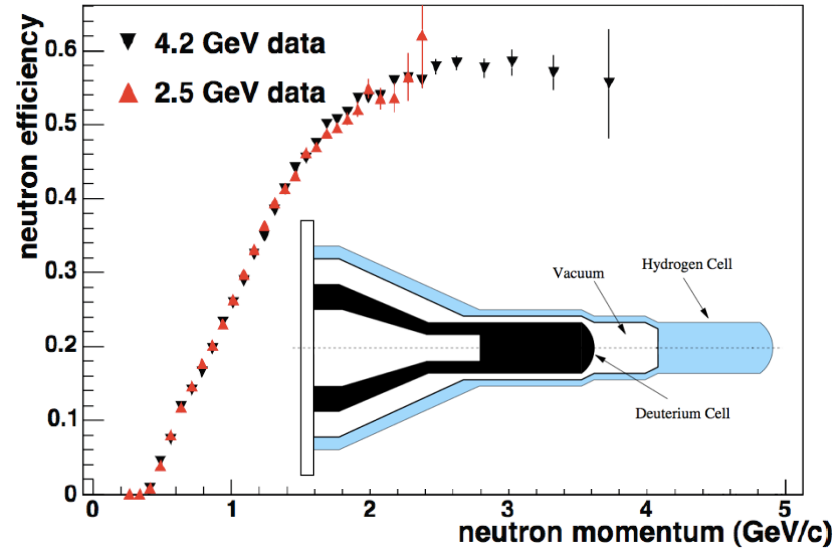
I. Aznauryan et al. (CLAS), PRC 80, 055203,2009

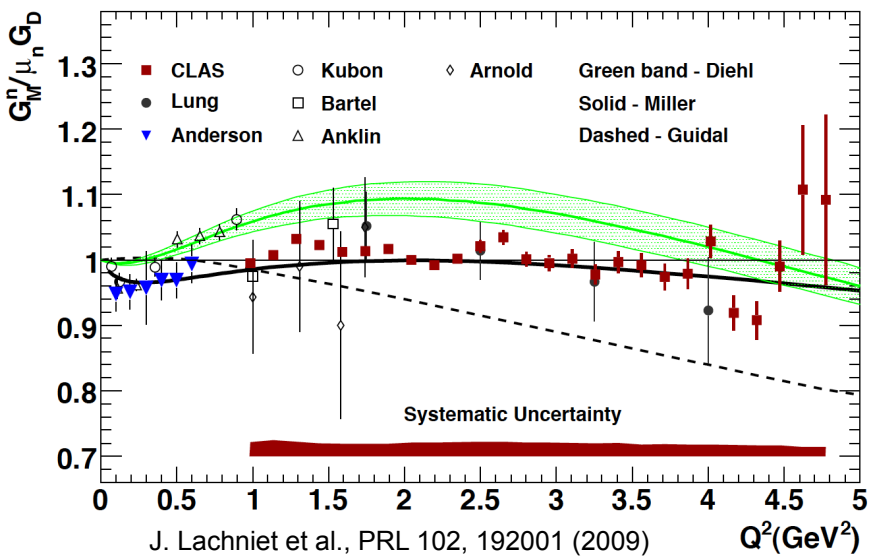
I.G. Aznauryan, V.D. Burkert, PR C92 (2015) 1, 015203 ; K. Park et al. (CLAS), PR C91 (2015) 045203

The neutron magnetic FF

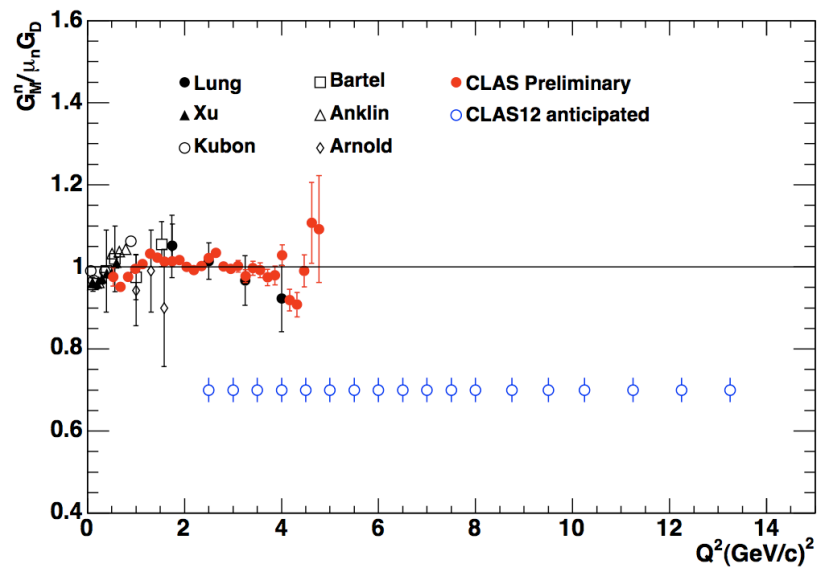
Dual-cell target containing LD_2 and LH_2 – need an accurate measurement of the neutron detection efficiency

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n)}{\frac{d\sigma}{d\Omega}(D(e,e'p)} \approx a(Q^2)\frac{\sigma^n_{mott}\left(G_E^{n\,2} + \frac{\tau_n}{\varepsilon_n}G_M^{n\,2}\right)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}\left(G_E^{p\,2} + \frac{\tau_p}{\varepsilon_p}G_M^{p\,2}\right)\left(\frac{1}{1+\tau_p}\right)}$$

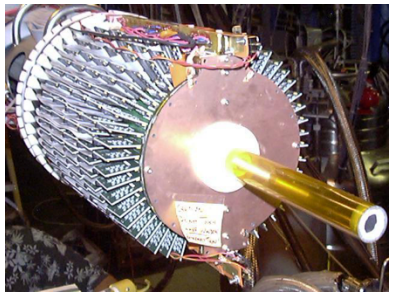


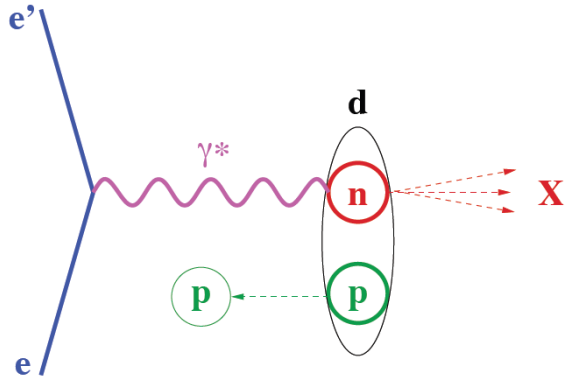


J. Lachniet et al., PRL 102, 192001 (2009)

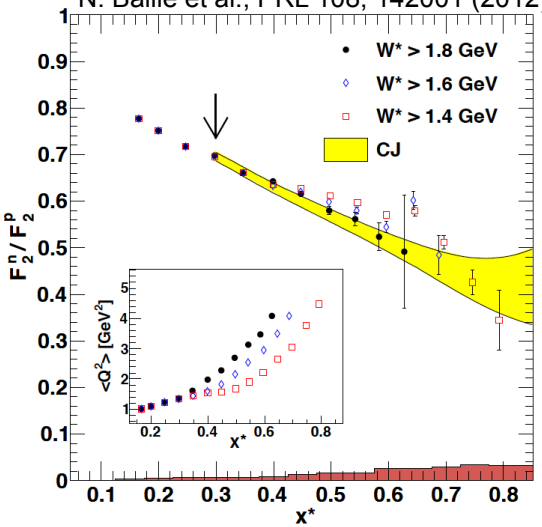


Structure of the Free Neutron at Large Bjorken x

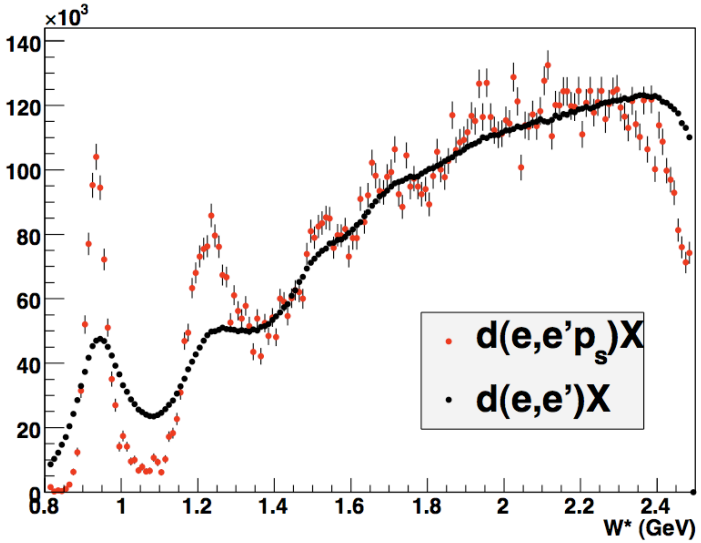




N. Bailie et al., PRL 108, 142001 (2012)

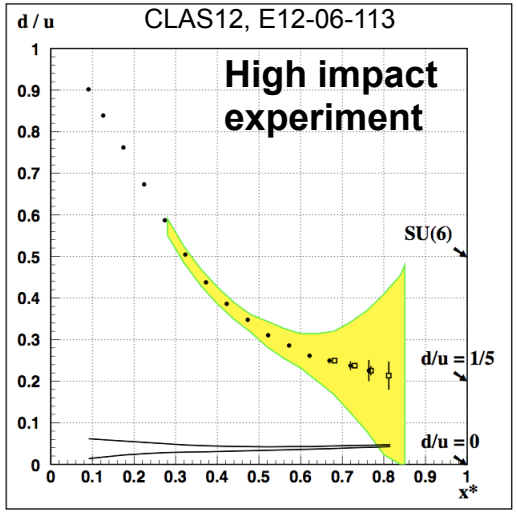


Radial TPC: 70 < p_s < 270 MeV/c

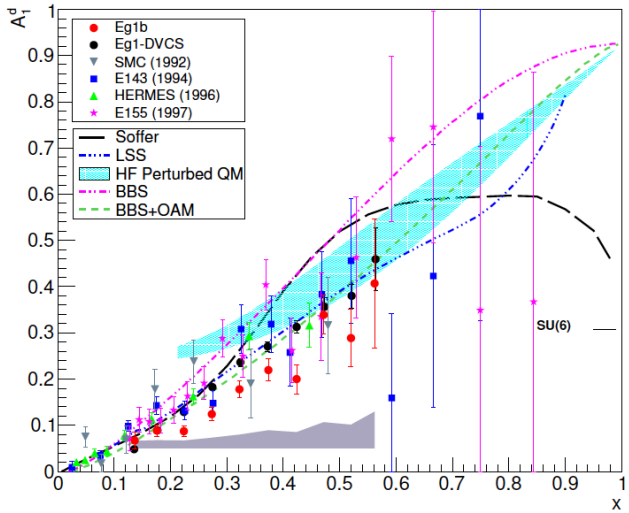


$$\frac{F_2^n}{F_2^p} = \left(\frac{F_2^n}{F_2^d}\right)\left(\frac{F_2^d}{F_2^p}\right)_{\text{model}}$$

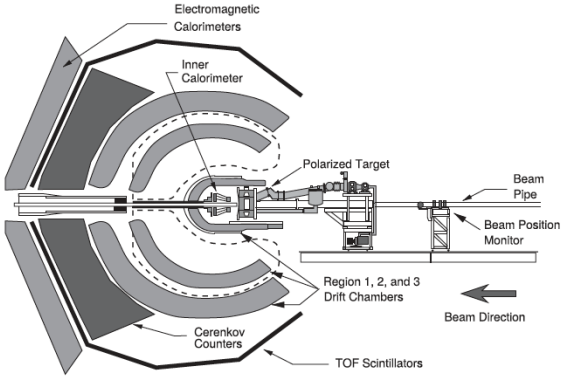
$$\frac{d(e,e'p_s)}{d(e,e')}$$



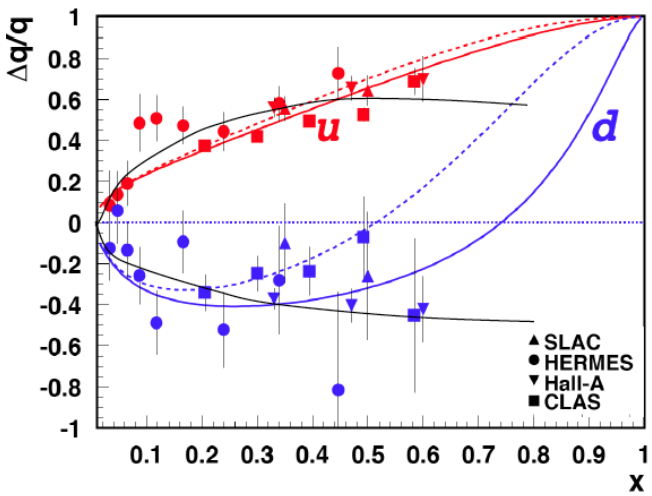
The Longitudinal Spin Structure of the Nucleon



- Dynamically polarized NH_3 and ND_3 targets
- Magnet provides natural Moller shielding



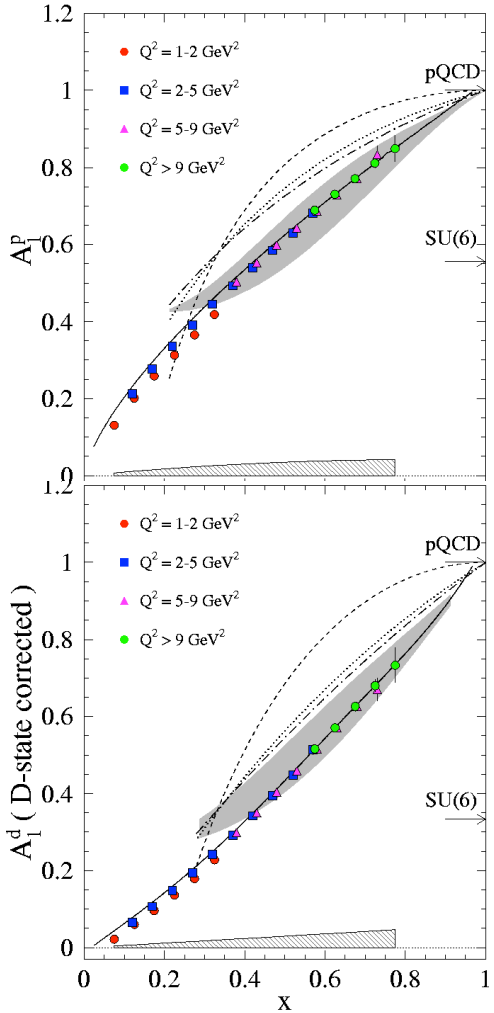
$$A_1(x) \approx \frac{g_1(x)}{F_1(x)} = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)}$$



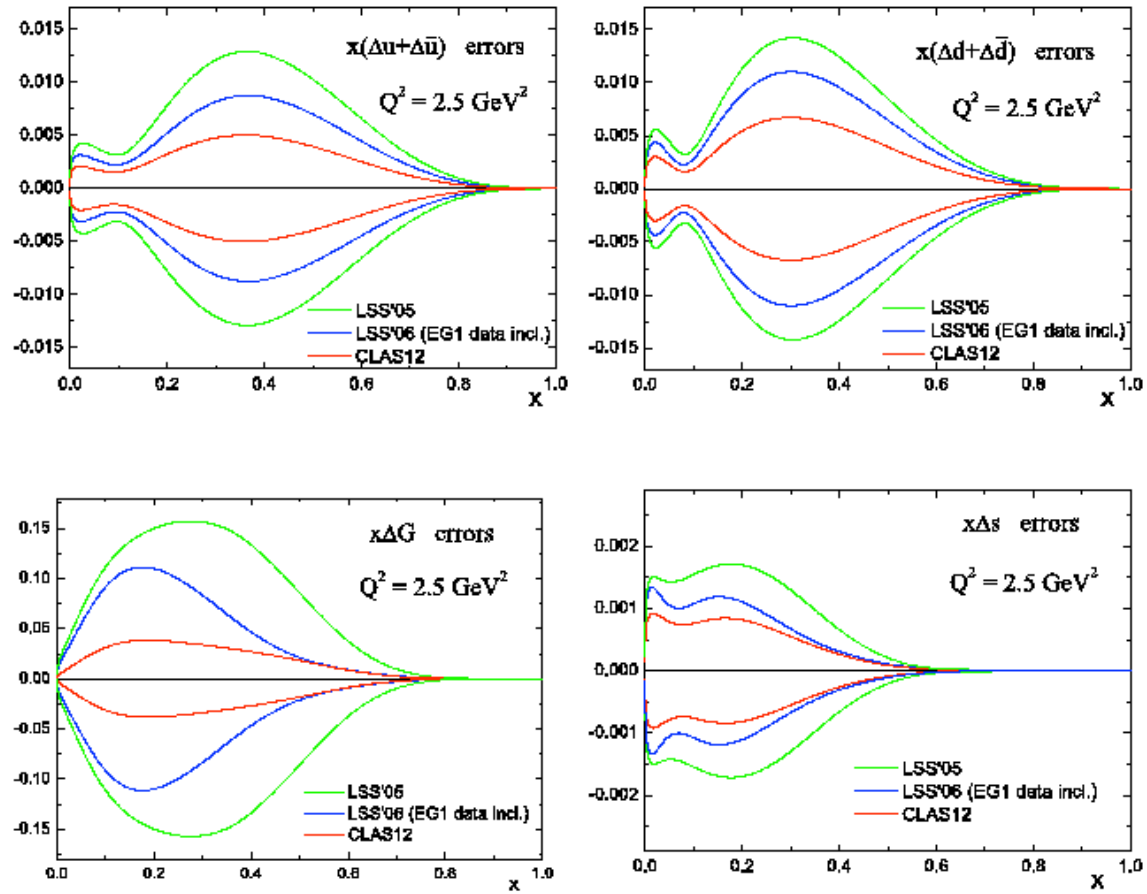
Model for x --> 1	A_1^p	A_1^n	d/u	Δu/u	Δd/d
SU(6)	5/9	0	1/2	2/3	-1/3
w/ hyperfine ($E_{S=0} < E_{S=1}$)	1	1	0	1	-1/3
One gluon exchange	1	1	0	1	-1/3
Suppressed symmetric WF	1	1	0	1	-1/3
S=1/2 dominance	1	1	1/14	1	1
$\sigma_{1/2}$ dominance	1	1	1/5	1	1
pQCD (conserved helicity)	1	1	1/5	1	1

No data are available at large x

Polarized structure functions at 11 GeV



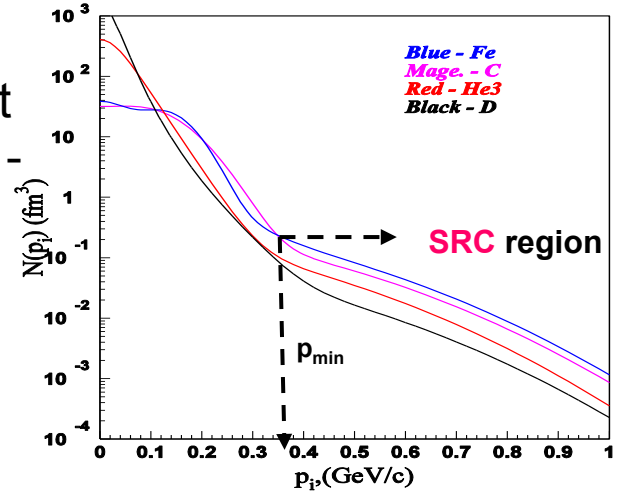
Expected uncertainties for Δu, Δd, ΔG and Δs from a NLO analysis

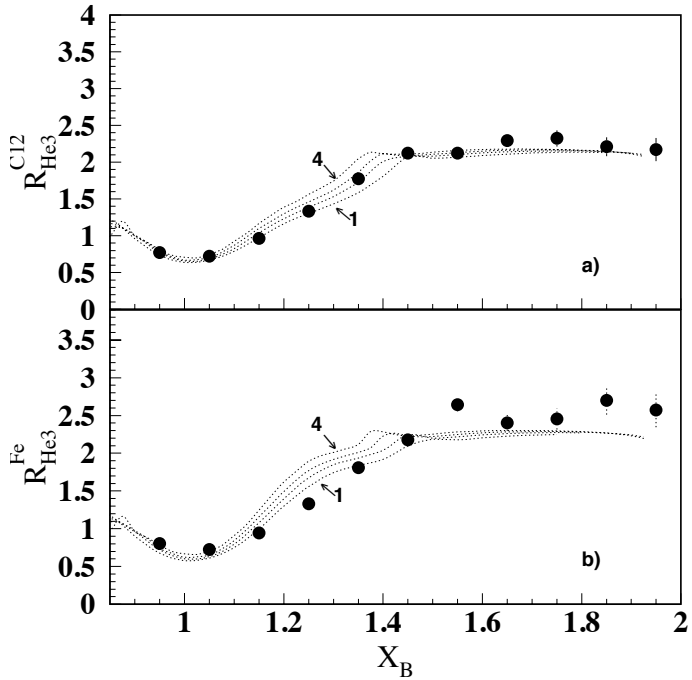


Short range correlations in nuclei

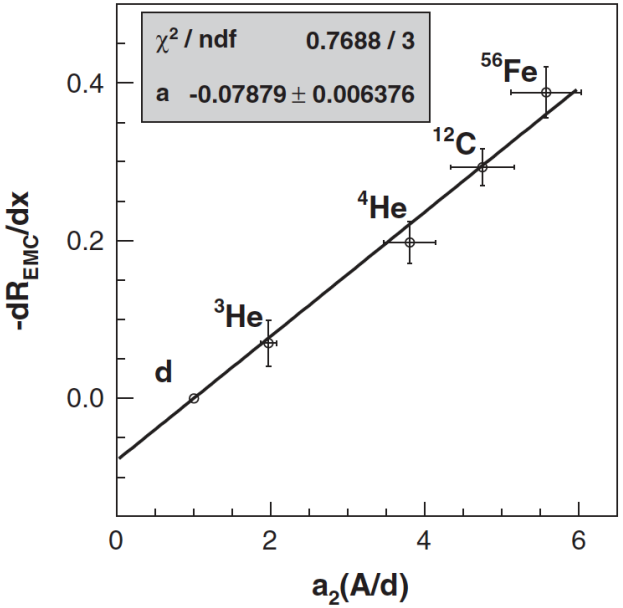
In the region of internal momentum where the NN short range correlations dominate the nuclear wave function -

- the form of the momentum distribution for different nuclei should be the same
- the ratios of quasi-elastic scattering cross sections for different nuclei should scale



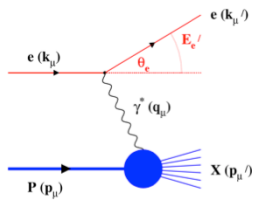


- a_2 is extracted using R(^{3}He/D) from model calculation
- The correlation between the slope of EMC ratio R_{EMC} in deep inelastic region and a_2 indicates that the EMC effect is result of local nuclear density

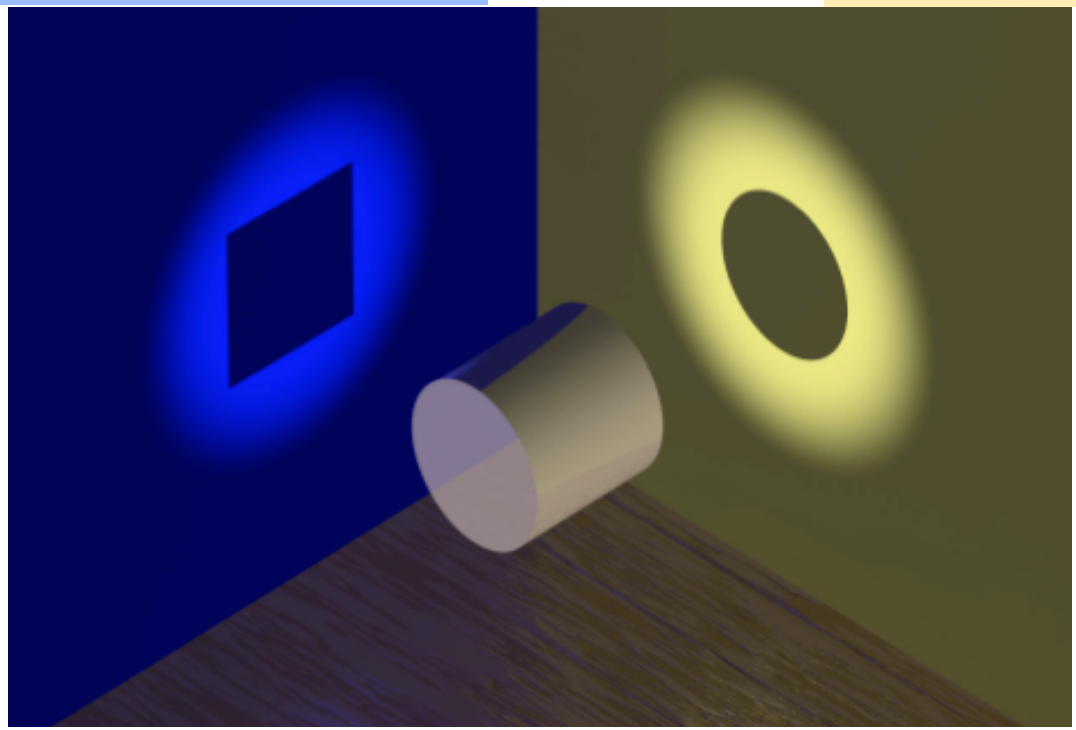


3-D Picture of the Nucleon

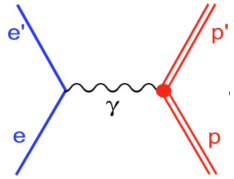
DIS Parton Distribution Functions



No information on the spatial location of the constituents



Elastic Form Factors



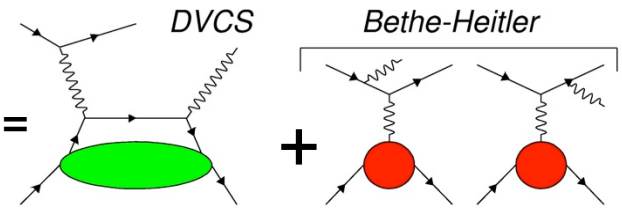
No information about the underlying dynamics of the system

Transverse Momentum Distributions & Generalized Parton Distributions

3-D imaging of the nucleon, the correlation of quark/antiquark transverse spatial and longitudinal momentum distributions, and on the quark angular momentum distribution

Accessing GPDs experimentally - DVCS

ep→epγ =

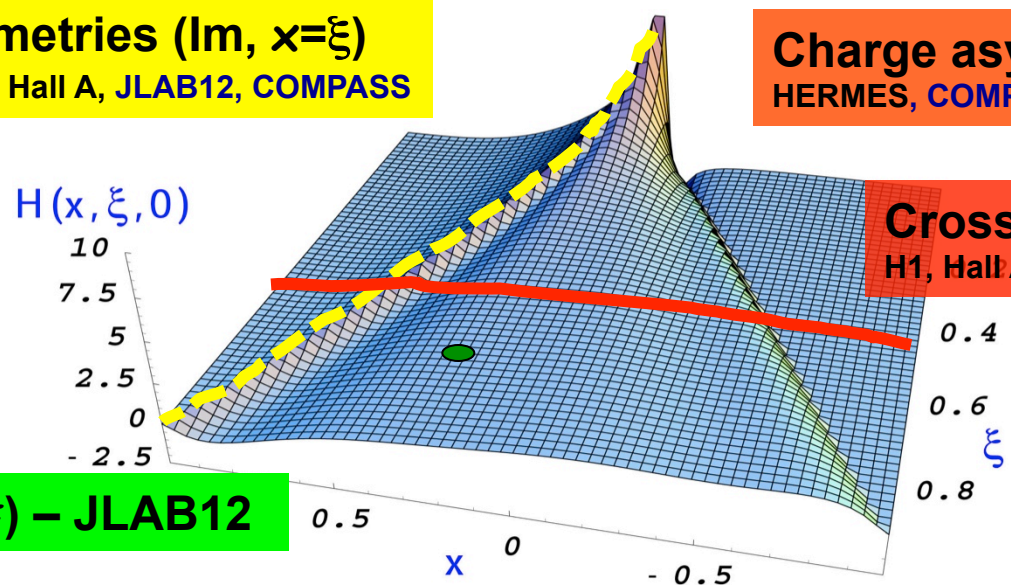


$$\mathcal{T}^2 = \left|\mathcal{T}_{BH}\right|^2 + \left|\mathcal{T}_{DVCS}\right|^2 + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

$$\mathcal{T}_{DVCS} \sim CFF \quad \mathcal{H}(\xi,t) = \underbrace{i\pi\left[H(\xi,\xi,t) - H(-\xi,\xi,t)\right]}_{Im} + \underbrace{P\int_{-1}^{+1} dx\left(\frac{1}{\xi - x} \pm \frac{1}{\xi + x}\right)\left[H(x,\xi,t) \mp H(-x,\xi,t)\right]}_{Re}$$

Spin asymmetries (Im, x=ξ)
HERMES, CLAS, Hall A, JLAB12, COMPASS

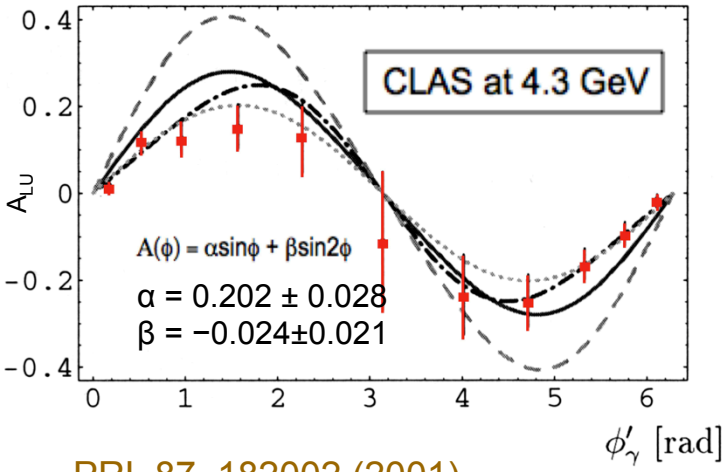
Charge asymmetry (|Re|)
HERMES, COMPASS



Cross sections (|Re|²)
H1, Hall A, JLAB12, COMPASS

DDVCS ($x \neq \xi$) – JLAB12

First DVCS measurements

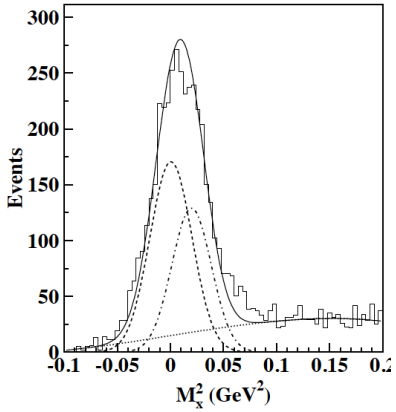


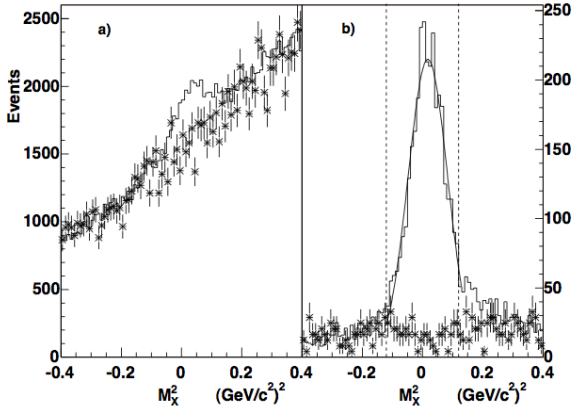
PRL 87, 182002 (2001)

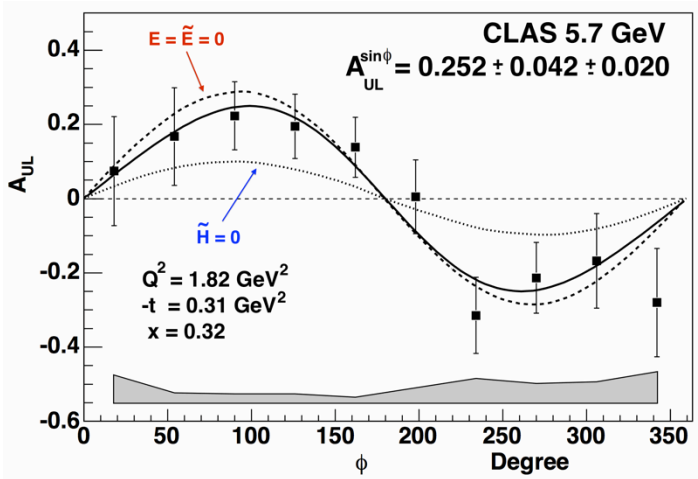
Analysis of existing CLAS data

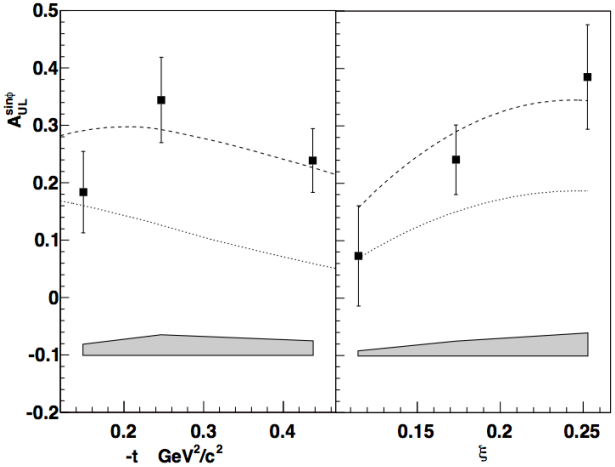
Reaction: $ep \rightarrow e'p'X$

Missing momentum analysis $X \approx \gamma$





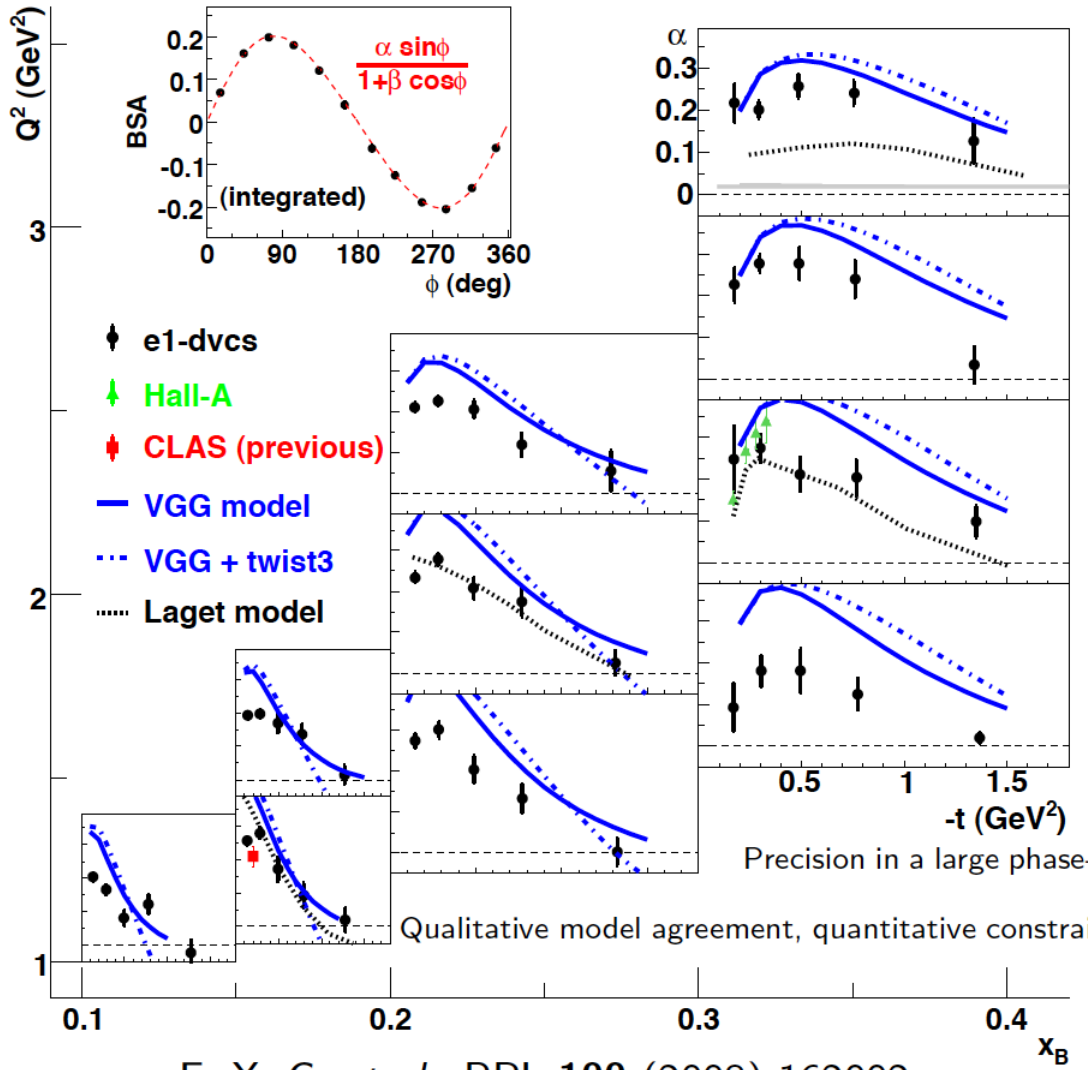




$$A_{UL}(\phi) = \frac{N^{\Uparrow}(\phi) - N^{\Downarrow}(\phi)}{f(P_t^{\Downarrow} N^{\Uparrow}(\phi) + P_t^{\Uparrow} N^{\Downarrow}(\phi))}$$

PRL 97, 072002 (2006)

CLAS DVCS beam spin asymmetry



Precision in a large phase-space (x_B, Q^2, t)

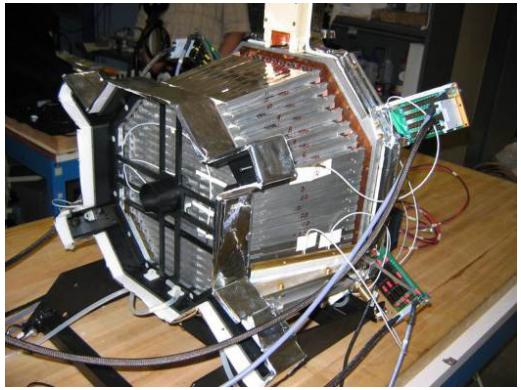
Qualitative model agreement, quantitative constraints on parameters

F.-X. G. *et al.*, PRL **100** (2008) 162002

The first most extensive set of DVCS data with CLAS

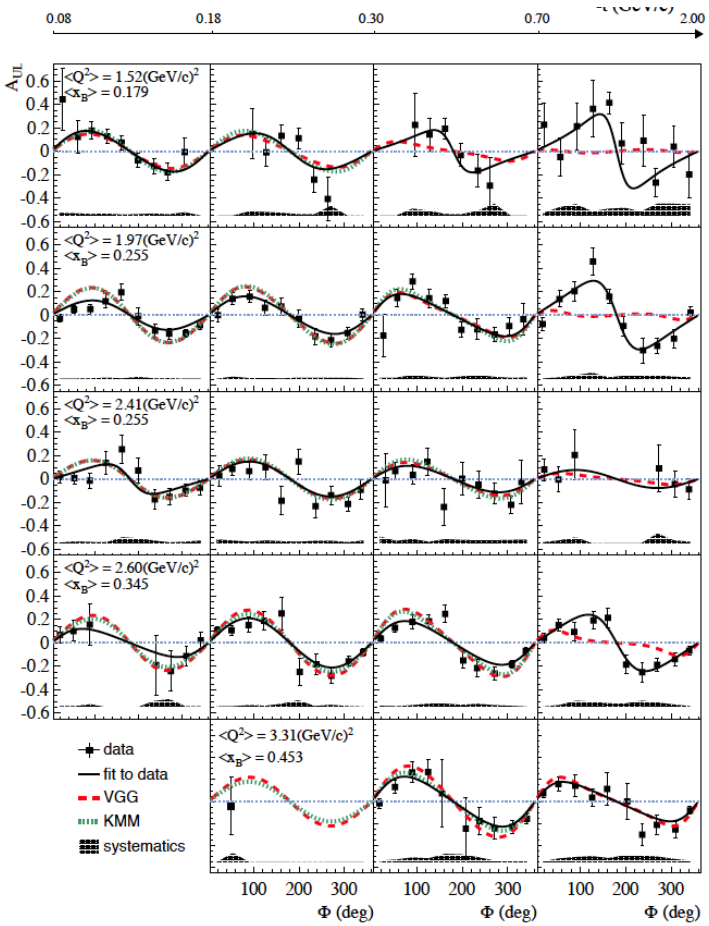
Fully excusive final state

$$ep \rightarrow e'p'\gamma$$

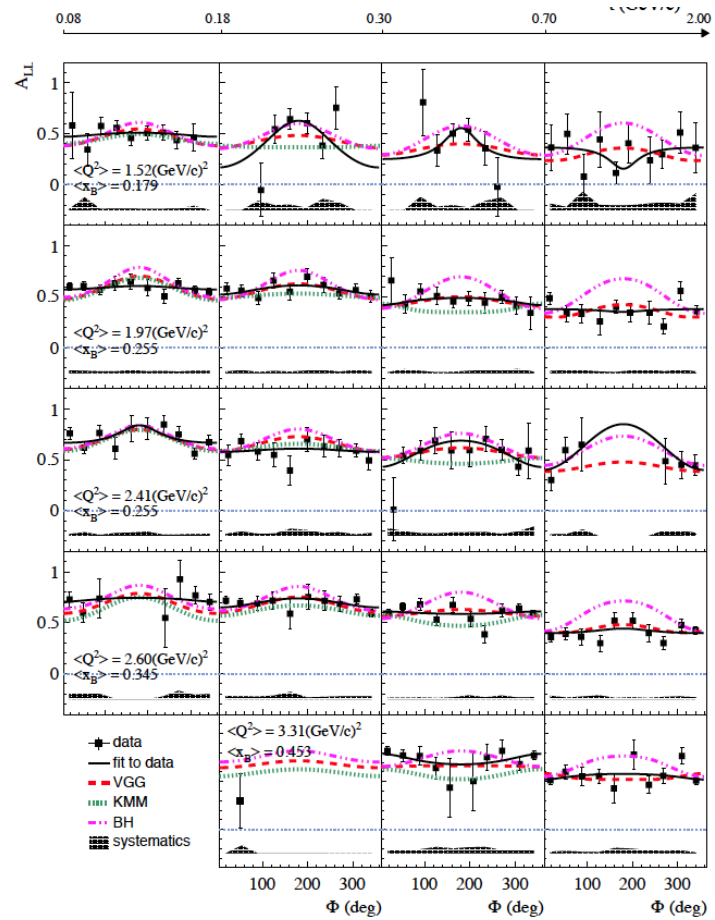


CLAS target and double spin asymmetry

$A_{UL} \propto F_1 \mathcal{I}m\,\tilde{\mathcal{H}}$



$A_{LL} \propto F_1 \mathcal{R}e\,\tilde{\mathcal{H}}$



E. Seder et al., Phys. Rev. Lett. 114, 032001 (2015)

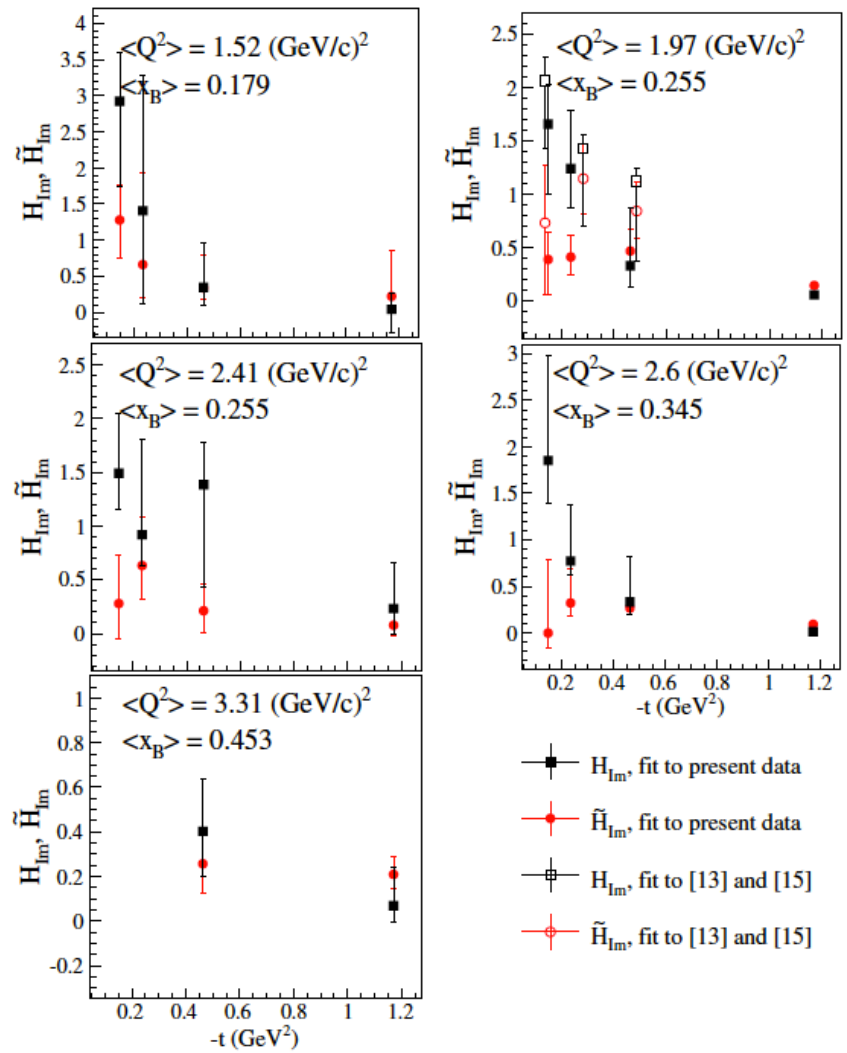
S. Pisano et al., Phys. Rev. D 91, 052014

Compton form factors from BSA, TSA and DSA

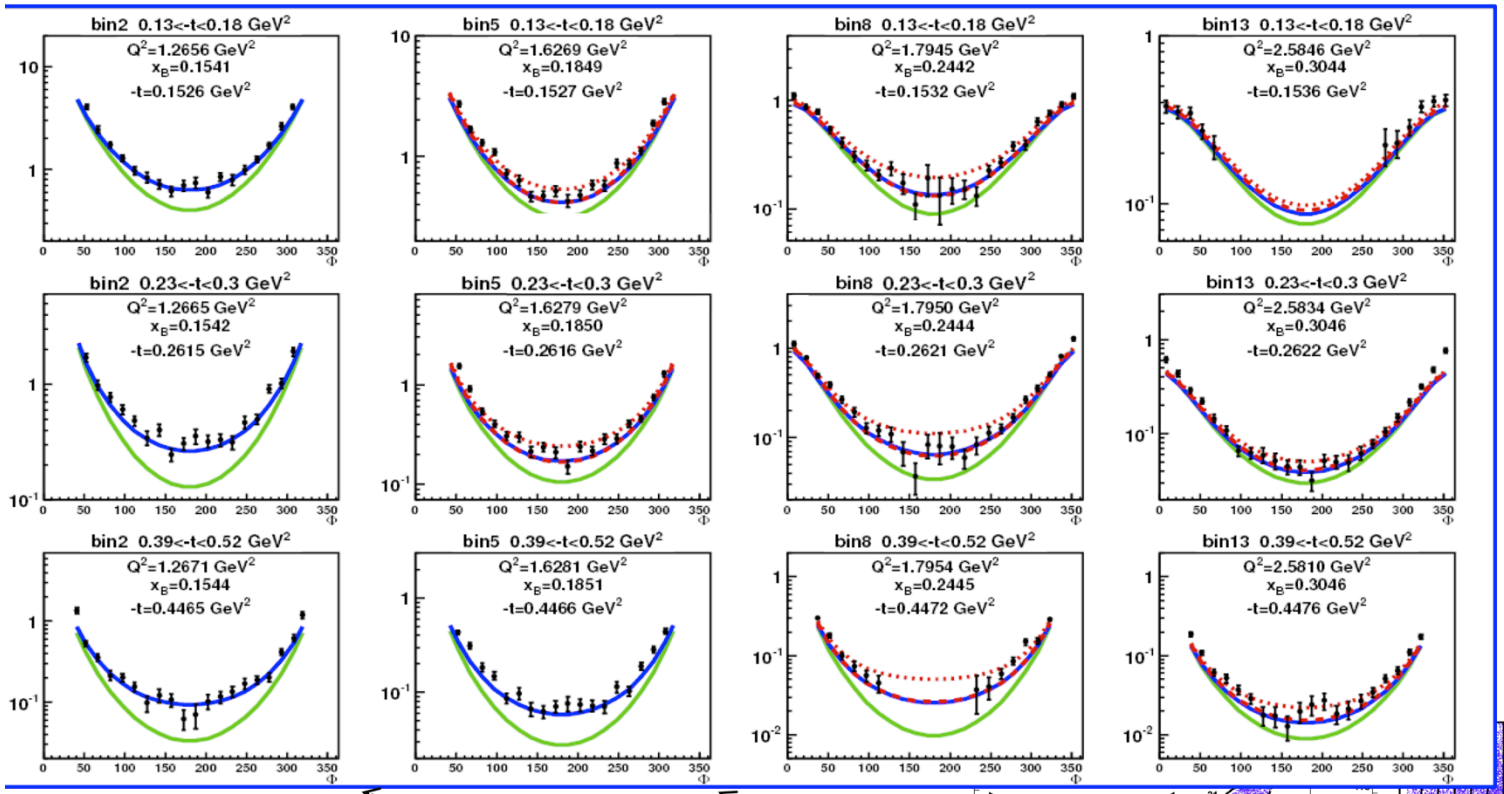
Using a local-fitting method at each given experimental (Q^2; x_B;−t) kinematic point and setting $\tilde{E}_{Im} = 0$, seven out of eight real and imaginary parts of CFF were left as free parameters

The better constrained CFF with these data are H_{Im} and $\tilde{H}_{Im}$

The t-slope of H_{Im} is much steeper than that of $\tilde{H}_{Im}$, hinting at the fact that the axial charge (linked to $\tilde{H}_{Im}$) might be more "concentrated" in the center of the nucleon than the electric charge (linked to H_{Im}).



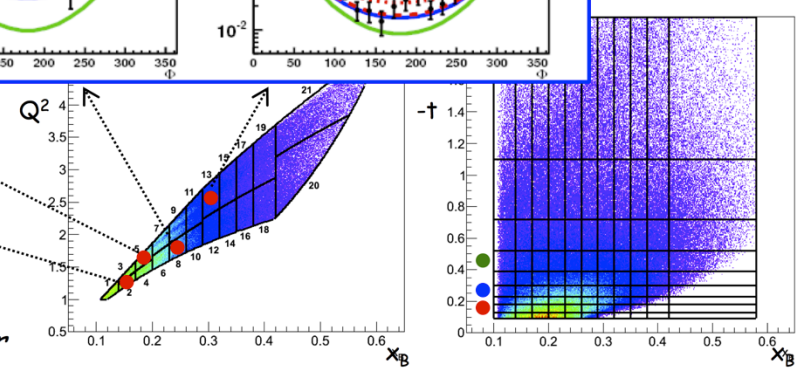
CLAS DVCS cross sections



$$\bullet \quad \frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} (nb/GeV^4)$$

BH — VGG (H only)

KM10 - - - KM10a



VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

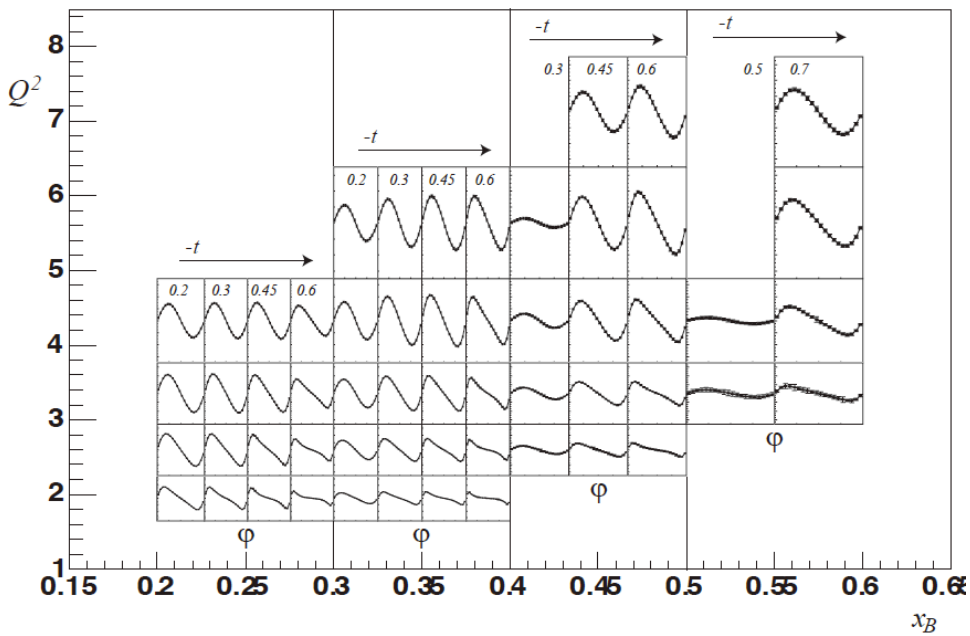
CLAS12 DVCS - longitudinally polarized beam

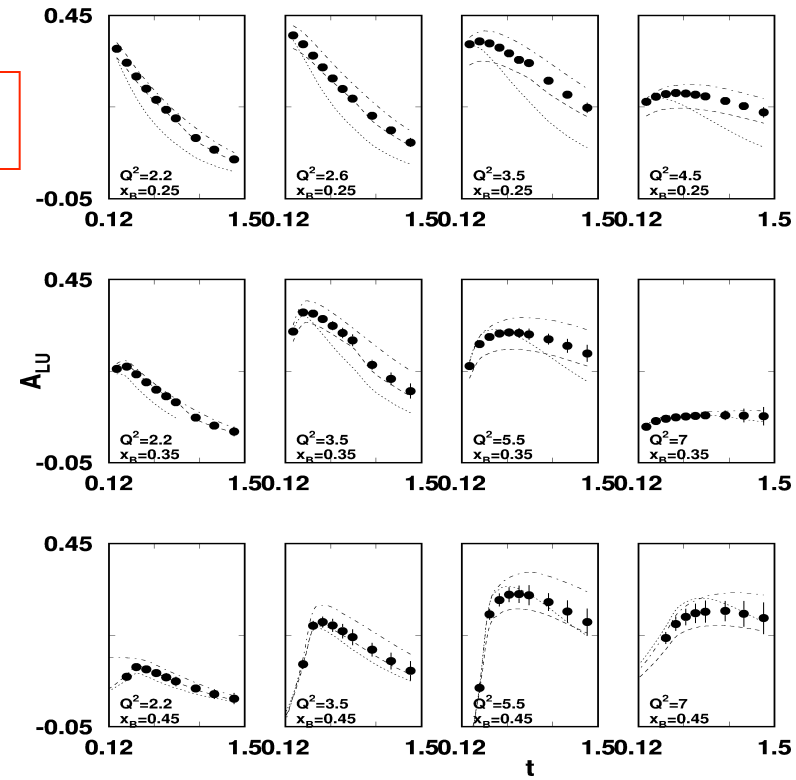
$$\vec{e}\, p \rightarrow ep\gamma$$

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Extract $H(\xi,t)$

$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + ..\} d\phi$



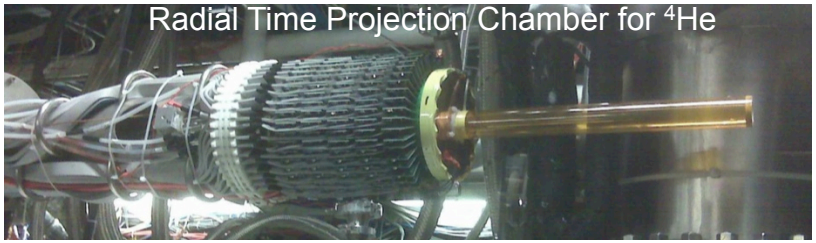


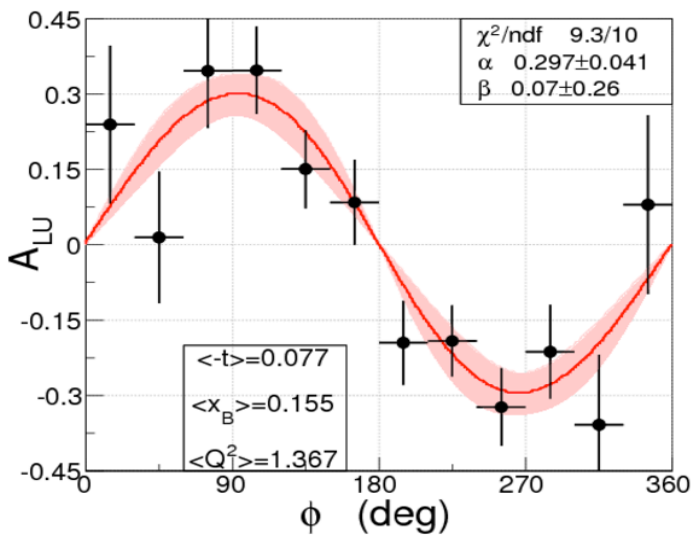
Large coverage in x_B, Q^2, and t with high statistical precision

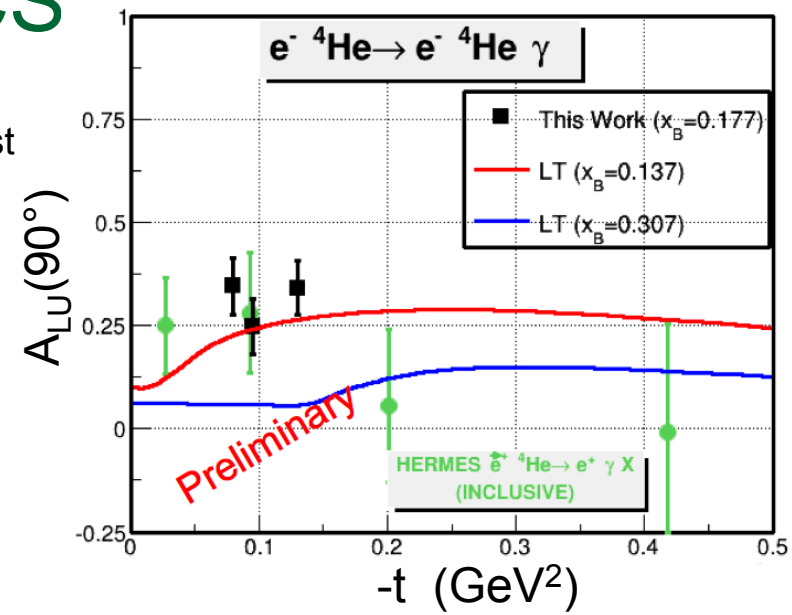
Nuclear GPDs - ^{4}He DVCS

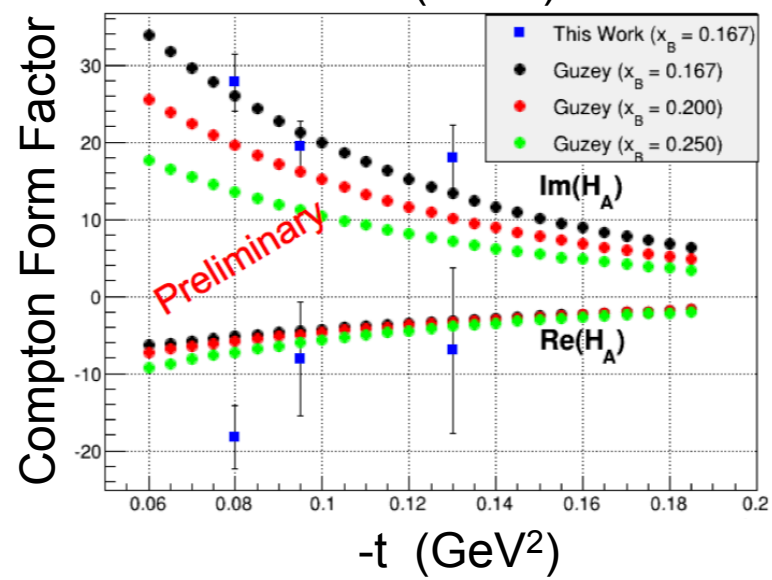
- 1st Exclusive Measurement of Coherent ^{4}He DVCS
- Spin-0 Nucleus → only 1 chiral-even GPD at leading twist

$$A_{LU} = \frac{\alpha_0(\phi)\mathcal{I}_A}{\alpha_1(\phi) + \alpha_2(\phi)\mathcal{R}_A + \alpha_3(\phi)(\mathcal{R}_A^2 + \mathcal{I}_A^2)}$$







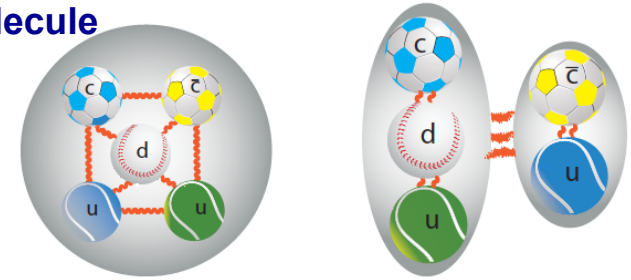


Hidden charmed pentaquarks and *gluonic structure* of the nucleon with CLAS12

What is the exact nature of *charmed pentaquark* states discovered by LHCb collaboration at CERN

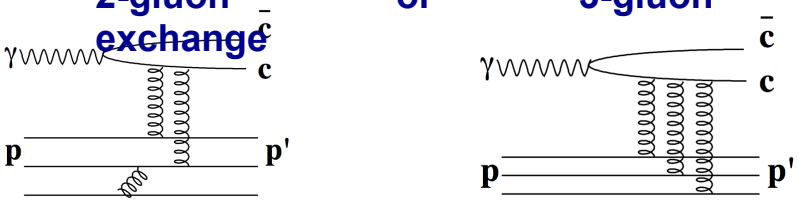
$$P_c \Rightarrow J/\psi\, p$$

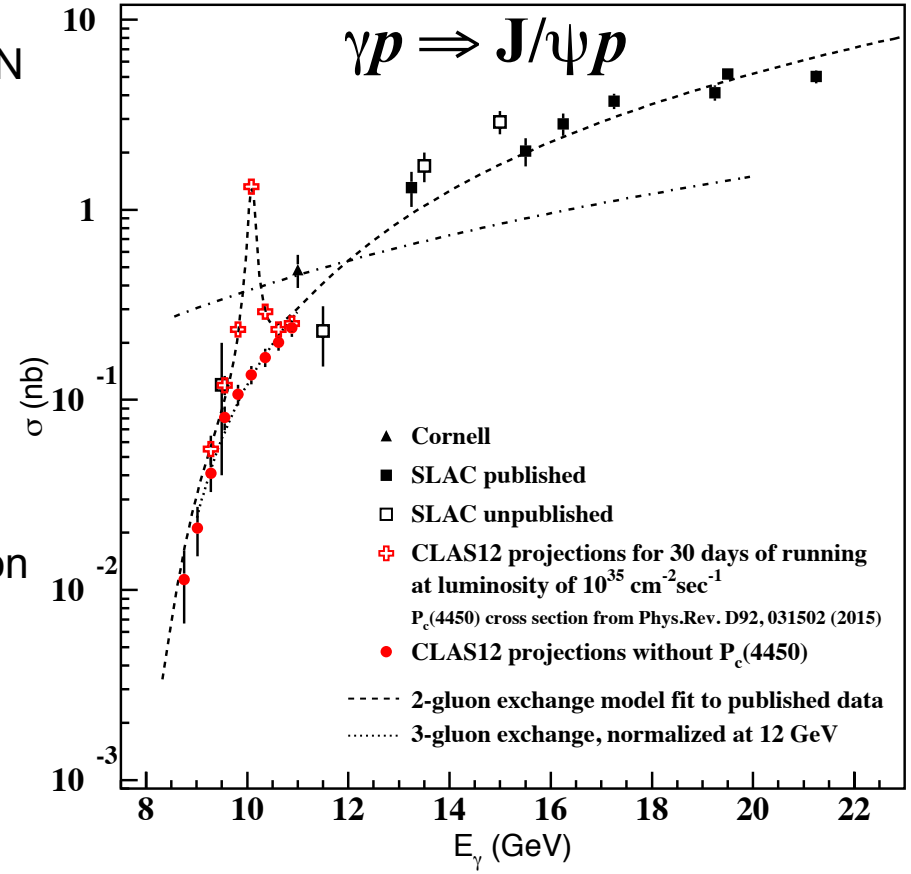
5-quark bound state **or** **Hadronic molecule**



What is the mechanism of charmonium production at the threshold

2-gluon exchange **or** **3-gluon**





Experiment E12-12-001 measures *J*/ψ production on the proton near threshold – will verify existence of the ***charmed pentaquarks*** and will study ***the gluon field of the nucleon***

Summary

- The Hall-B CLAS detector at Jefferson lab run successfully for about 15 years, supporting a diverse physics program
- CLAS physics program included experiments with [polarized] electron and photon beams, and variety of cryogenic, solid, and polarized targets
- The physics program of CLAS, the large part of which will continue with CLAS12, covers studies of nucleon and nuclear structure using inclusive and exclusive electroproduciton reactions, and hadron spectroscopy
- There is already more than 1500 hours of beam time approved for CLAS12 experiments
- The 12 GeV Upgrade greatly enhances the scientific “reach” of JLAB facility. Detectors in experimental halls are well suited to carry out vigorous physics program