The Jefferson Lab contribution to the QCD spin structure of the nucleon

From inclusive, **eN → e' + X**

to semi-inclusive **eN → e' π/K + X**

and exclusive **eN → e' N γ/ρ/ω/φ/π**

(polarized) deep inelastic scattering

for the determination of

Polarized parton distributions – helicity and transversity –

and

generalized parton distributions

of quarks in the nucleon

(with a look at quark-gluon correlations & SSA)

addressing the questions of

Intrinsic spin and orbital angular momentum of quarks

Michel Garçon – SPhN/Saclay – SPIN2004 Conference (Trieste, October 2004)

Nucleon spin structure at JLab (mostly W > 2 GeV)

	Hall A	*Hall B*	*Hall C*
Polarized p.d.f. (helicity) *from inclusive and semi-inclusive DIS*	^{3}He → n		
g_2 *and* **quark-gluon correlations**	^{3}He → n		
Transversity (and SSA)			
G.P.D. *from DVCS and (possibly) DVMP*		p @ 4.2 GeV	

Published results

Nucleon spin structure at JLab (mostly W > 2 GeV)

	Hall A	*Hall B*	*Hall C*
Polarized p.d.f. (helicity) *from inclusive* *and semi-inclusive DIS*	$^{3}He \rightarrow n$	p/d (tests of factorization)	
g_2 *and* **quark-gluon correlations**	$^{3}He \rightarrow n$		
Transversity **(and SSA)**		p (tests of factorization)	
G.P.D. *from DVCS* *and (possibly) DVMP*		p @ 4.2 GeV p @ 4.8-5.7 GeV ρ, ω, φ	

Published results .... Preliminary results

Nucleon spin structure at JLab (mostly W > 2 GeV)

	Hall A	*Hall B*	*Hall C*
Polarized p.d.f. (helicity) *from inclusive* *and semi-inclusive DIS*	$^3He \rightarrow n$	p/d (tests of factorization)	p/d SANE Semi-SANE
g_2 *and* **quark-gluon correlations**	$^3He \rightarrow n$		
Transversity **(and SSA)**	$^3He \rightarrow n$	p (tests of factorization)	Semi-SANE
G.P.D. *from DVCS* *and (possibly) DVMP*	p/n @ 6 GeV	p @ 4.2 GeV p @ 4.8-5.7 GeV p (and d?) @ 6 GeV ρ, ω, φ	π

+ 12 GeV upgrade

on

Nucleon spin structure at JLab (mostly W < 2 GeV)

See **Raffaella De Vita**'s talk for a related discussion of

Polarized structure functions in the resonance region

Generalized GDH sum rule

Higher twists

Duality

……

also addressing

the JLab contribution to the QCD spin structure of the nucleon

(See also A. Deur's talk on Friday afternoon, session 5)

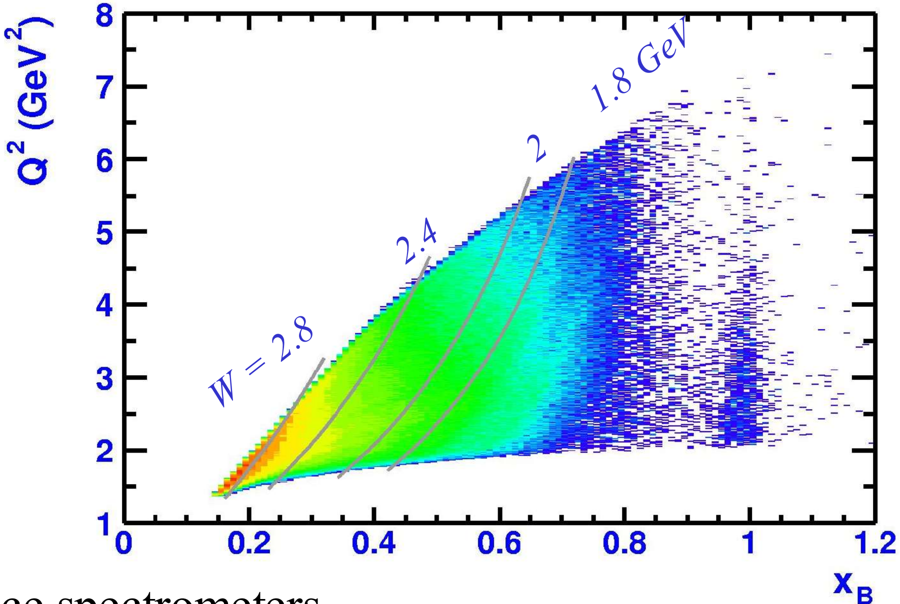
The specificities of JLab

♠ High luminosity

compensates relatively low energy
(for example, for exclusive measurements,
same Q^2 as high energy machines are achieved)

♥ Large *x* range (.15 - .75)

and from resonance region to DIS



♦ High resolution

truly exclusive measurements

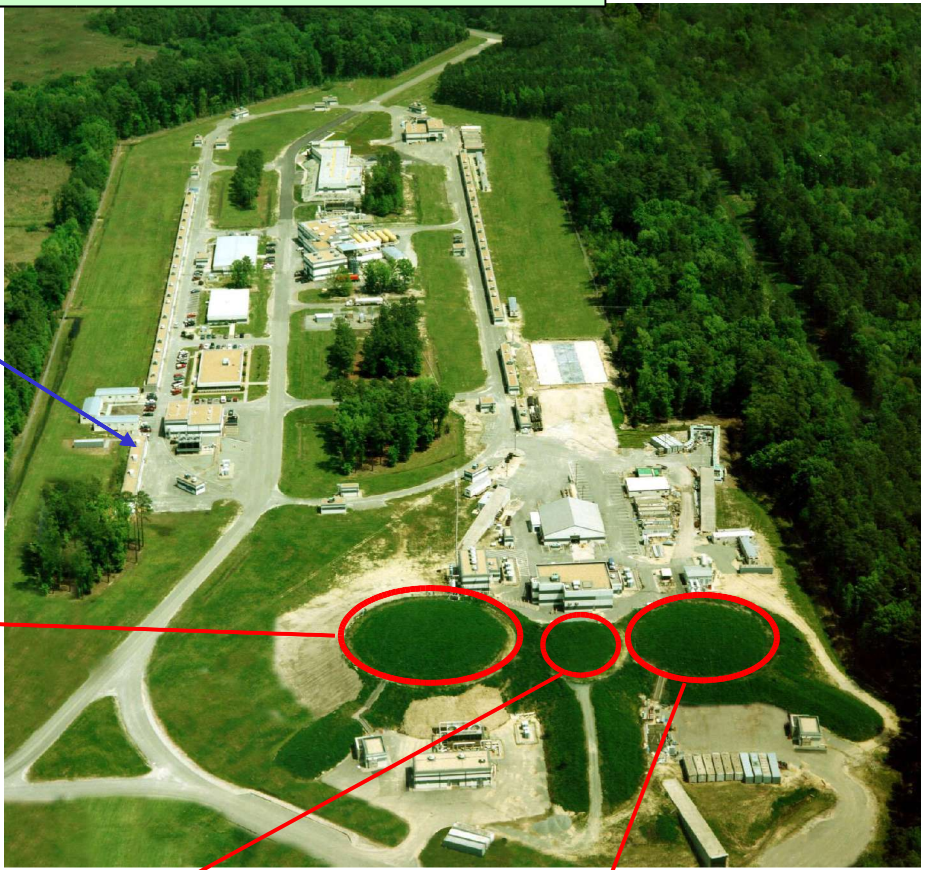
♣ Experimental equipment

from high resolution to large acceptance spectrometers,
polarized targets, and in particular unique ^{3}He for neutron spin,
highly polarized electron beam (80%)

☺ *All this enhanced in the planned 12 GeV upgrade*

CEBAF @ Jefferson Lab

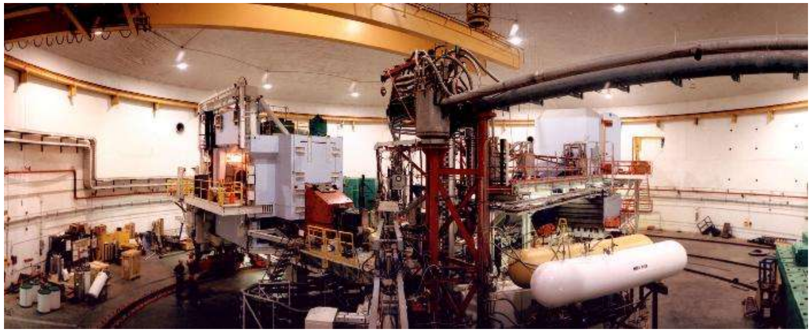
Polarized source



Hall A

Hall B

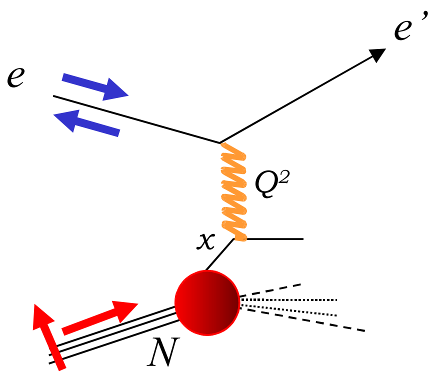
Hall C



Experimental equipment

	A	*B*	*C*
Standard	HRS	CLAS	HMS
Polarized targets	^{3}He	NH_3/ND_3 (longitudinal)	NH_3/ND_3 (long.+transverse)
New or short term development	DVCS (calo+recoil) BigBite	DVCS (calo+sol)	(LiD) BETA

Quark helicity distributions Δq



Using
longitudinally polarized electron beam
onto
longitudinally (//) or transversely (⊥) polarized target,
measure asymmetries with respect to the beam helicity
for inclusive scattering $eN \rightarrow e'X$

Asymmetries with respect to beam direction		*Asymmetries with respect to virtual photon direction*		*Polarized structure functions*
$\begin{pmatrix} A_{//} \\ A_{\perp} \end{pmatrix}$	$\longleftrightarrow$	$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix}$	$\longleftrightarrow$	$\begin{pmatrix} g_1(x,Q^2) \\ g_2(x,Q^2) \end{pmatrix}$

In the quark parton model $\quad g_1(x) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \left[q^{\uparrow}(x) - q^{\downarrow}(x)\right] = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \Delta q(x)$

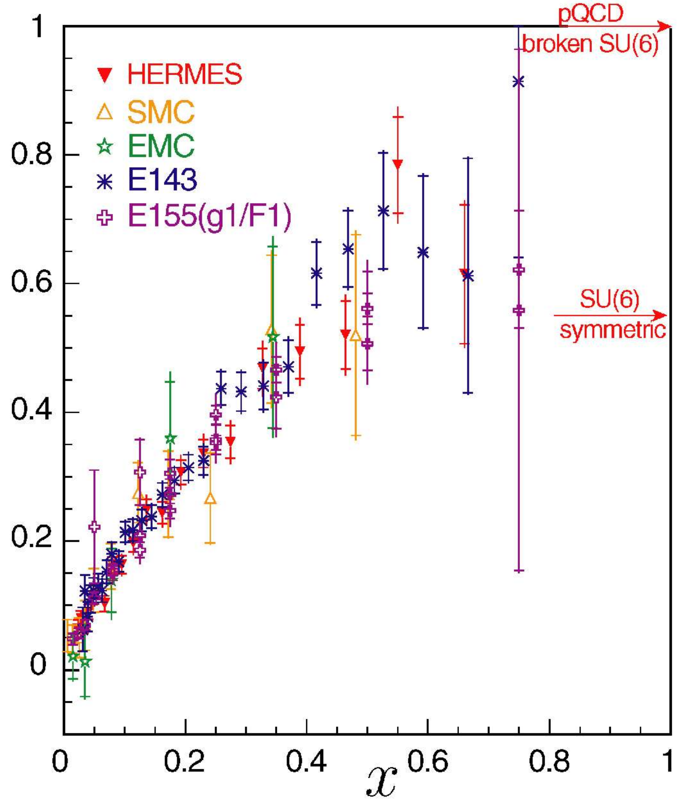
→ how does the quark spin contribute to the nucleon spin ?

g_2 represents interactions beyond the quark parton model

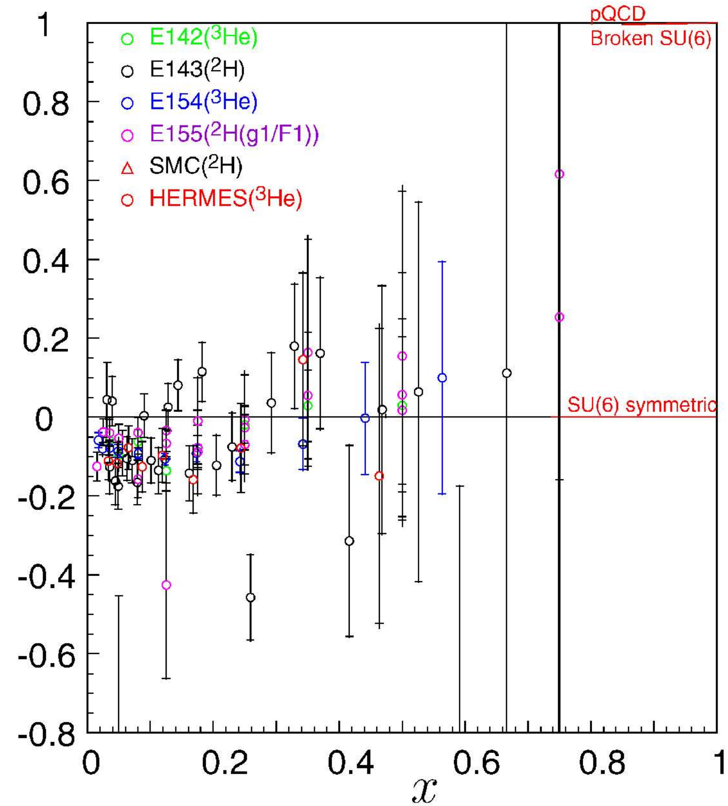
→ a tool to study higher twist effects, sensitive to quark-gluon correlations.

World data on A_1 and the high-x region

Proton



Neutron



High-x region hardly explored:

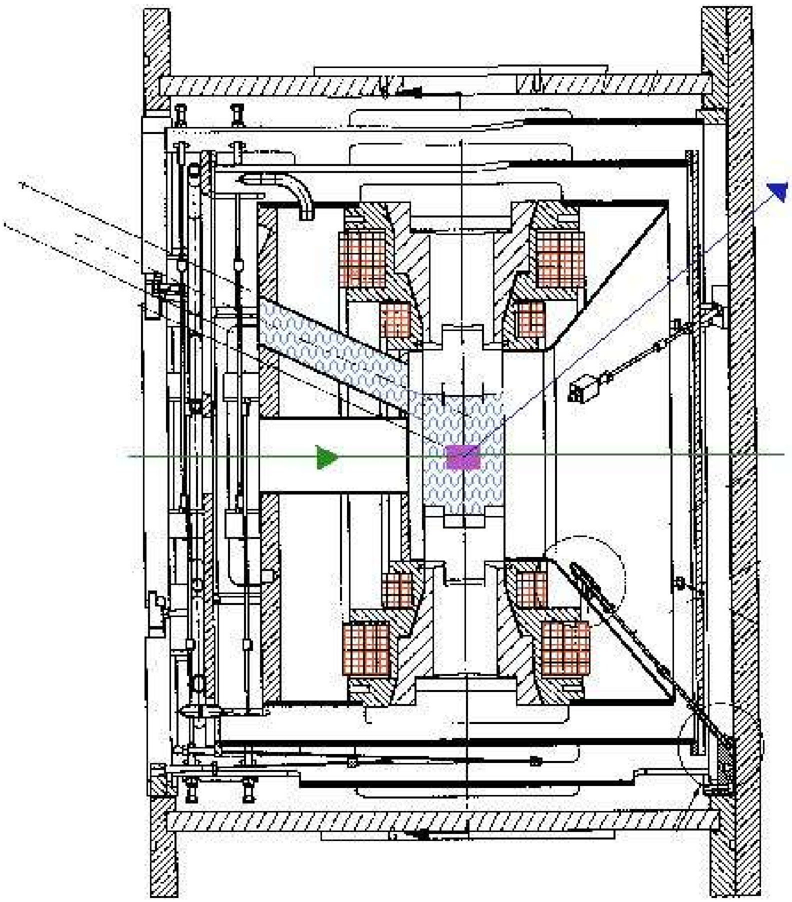
- constraints on the valence quark distributions,
- moments to be compared with lattice QCD calculations
- standard QCD factorization/evolution may break down (Ji, Vogelsang, …)

Experimental challenges: both the Mott cross section and $q(x)$ decrease as x increases

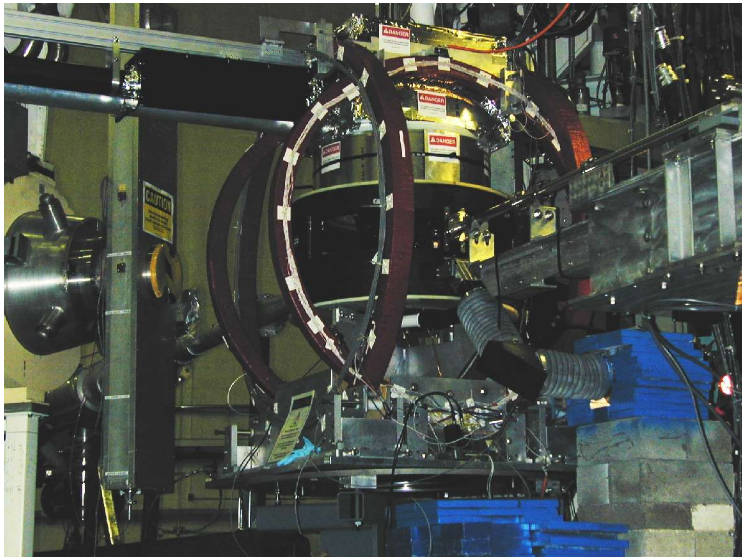
→ need high luminosity × acceptance

Polarized targets

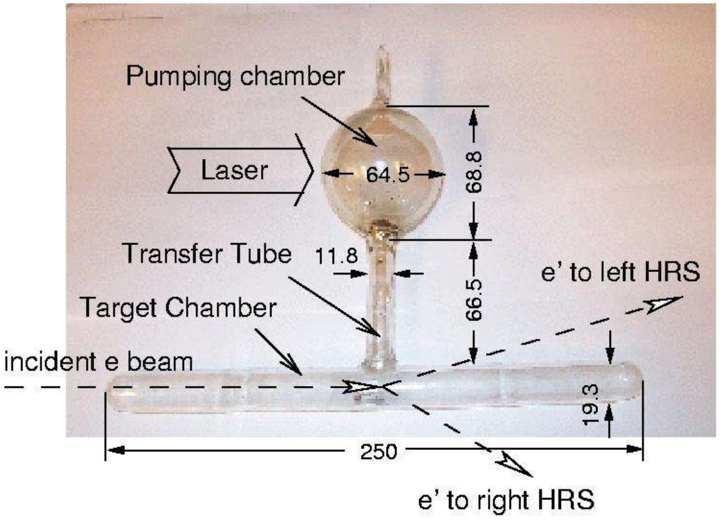
NH_3 / ND_3 (here for Hall B)



^{3}He in Hall A

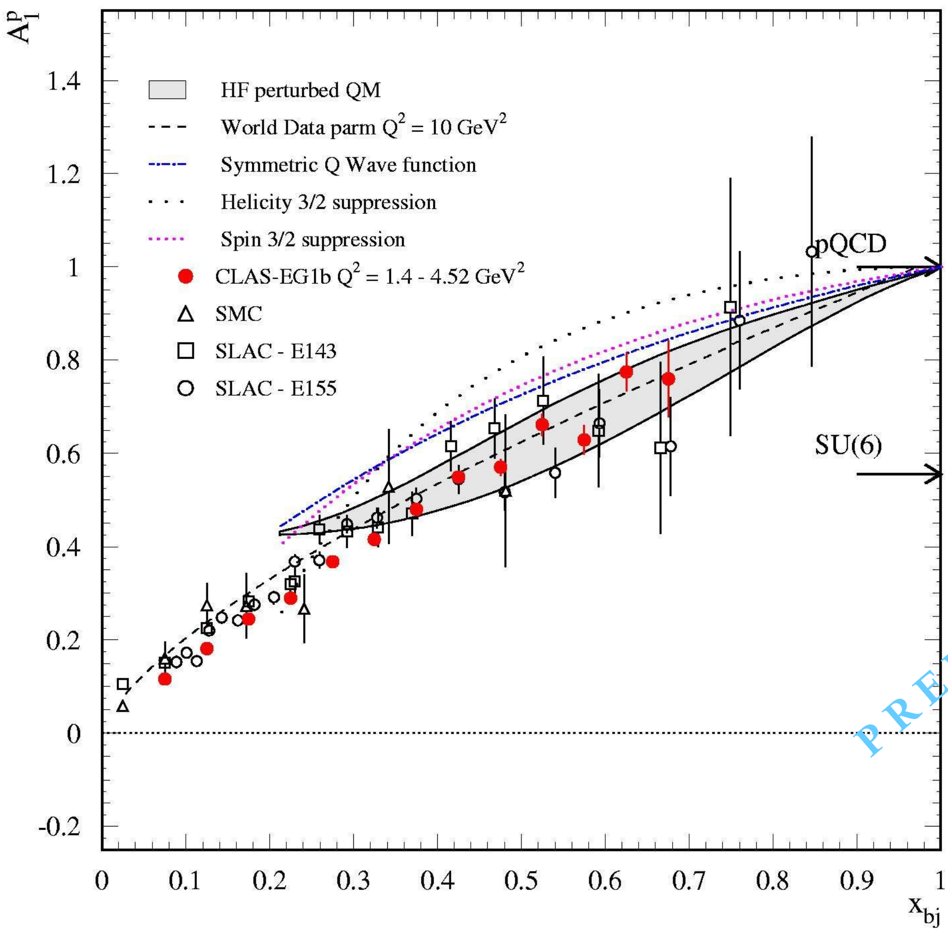


Optical pumping on Rb + spin exchange

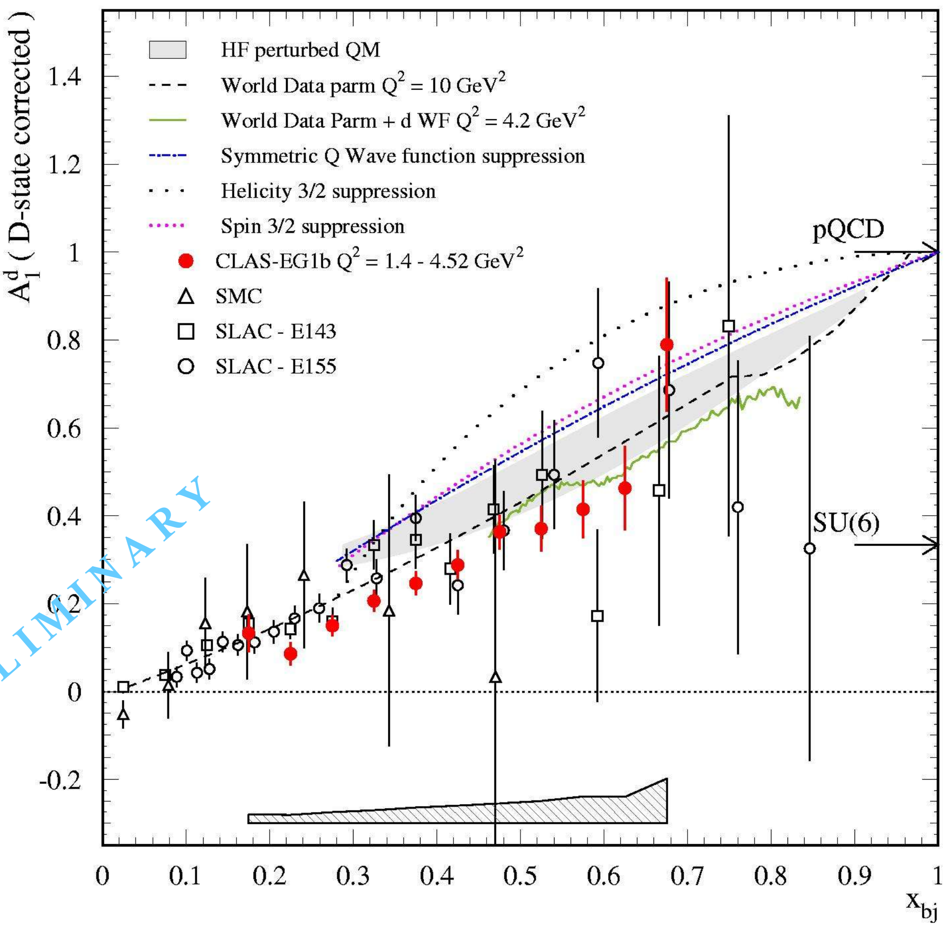


Preliminary results for p, d (CLAS/ Hall B)

Proton

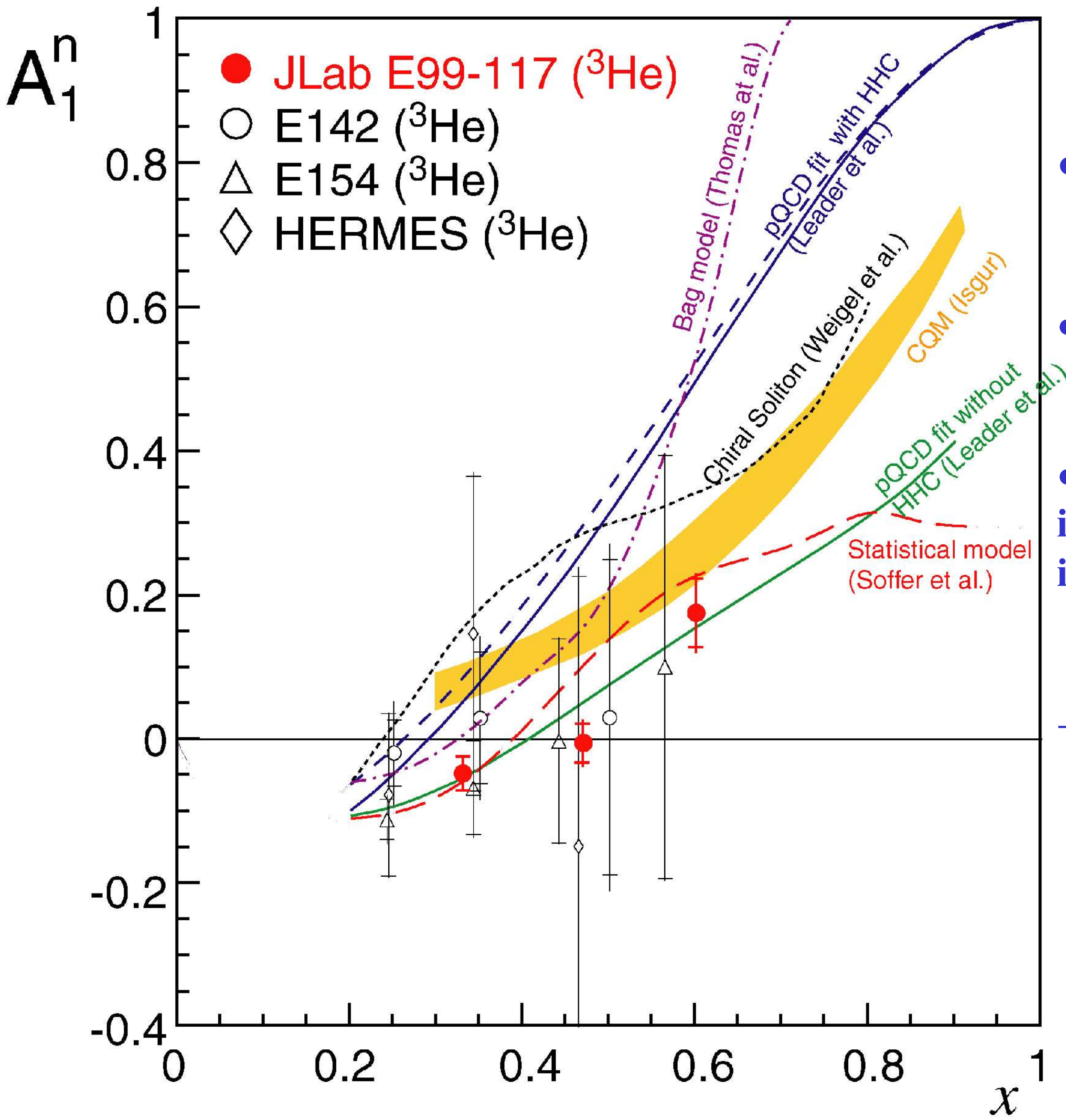


Deuteron



eg1b run, G. Dodge, S. Kuhn, M. Taiuti et al.

Results for n (Hall A/ He3)



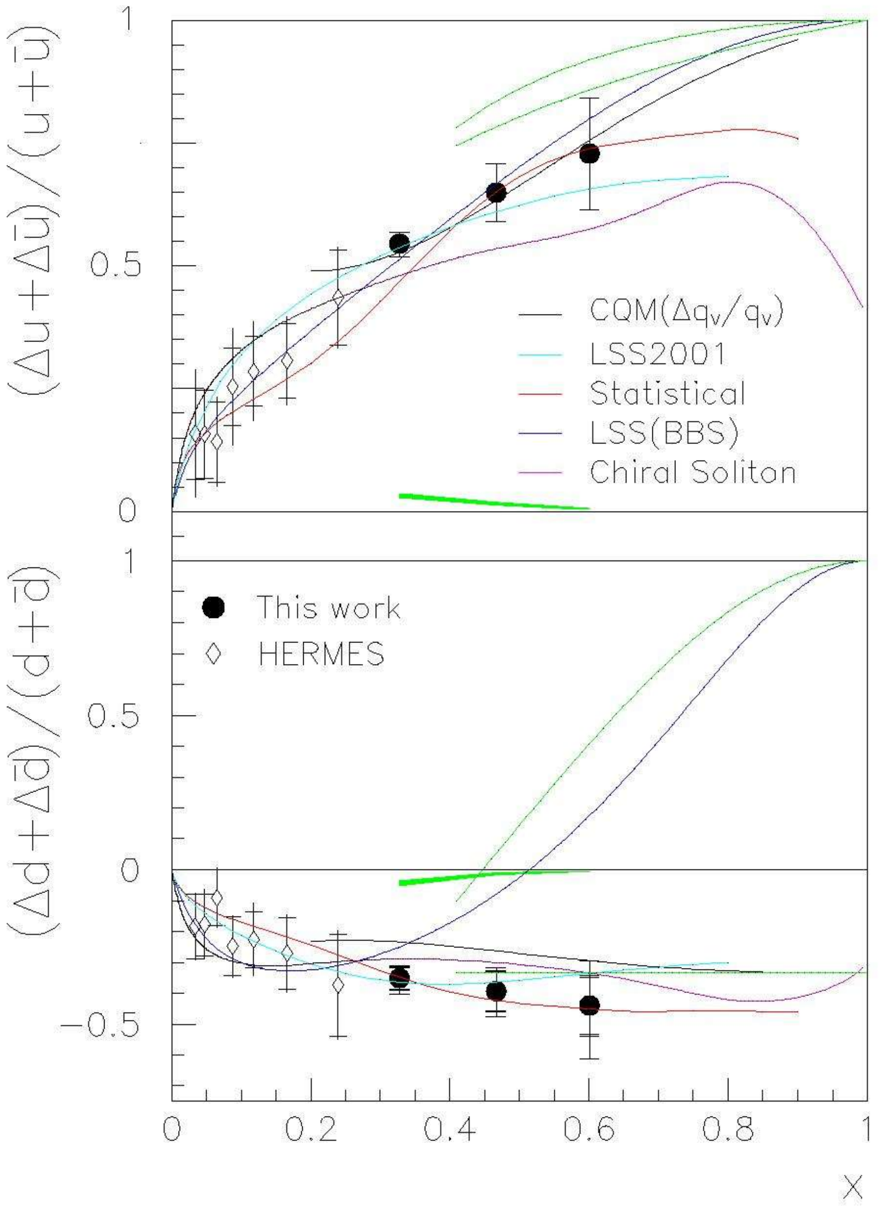
- **First clear signature of $A_1^n > 0$**
- **PQCD-based HHC may be ruled out**
- **(Rel.) constituent quark model introduces SU(6)-breaking hyperfine interaction**

→ *quark orbital angular momentum*

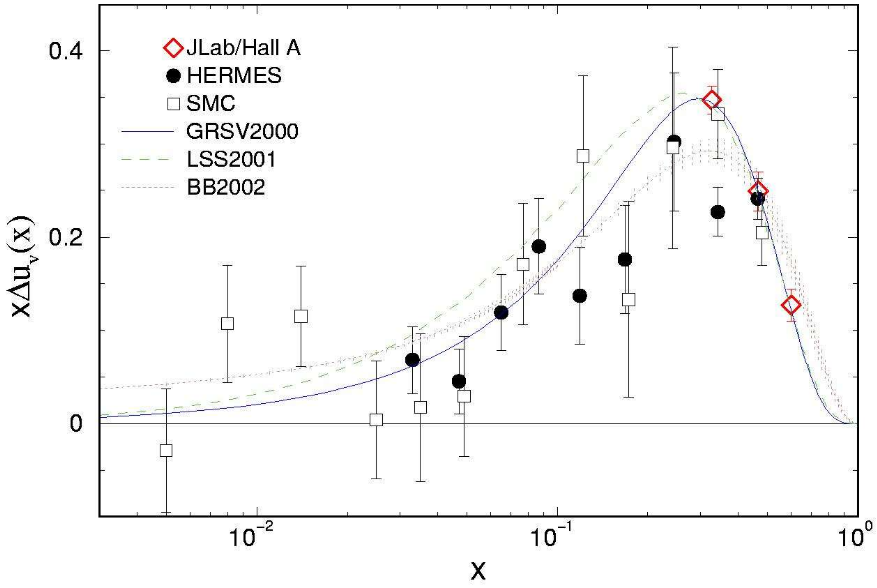
X. Zheng et al., PRL 92, 012004 and nucl-ex/0405005

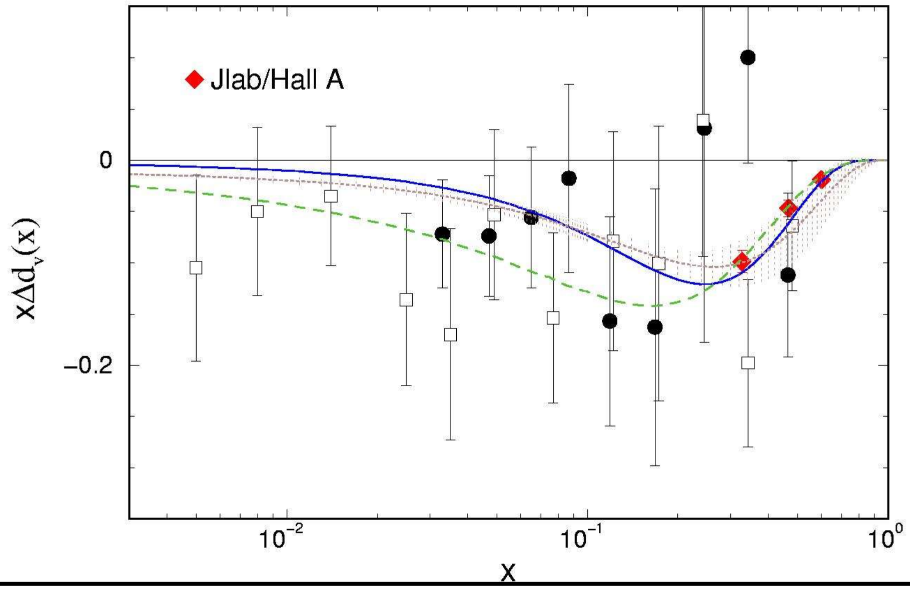
Flavour decomposition from p/n (1)

Using parameterizations of unpolarized structure functions and world data for g_1^p/F_1^p, neglecting strangeness at high x, extract from A_1^n :



Flavour decomposition from p/n (2)





Since the difference

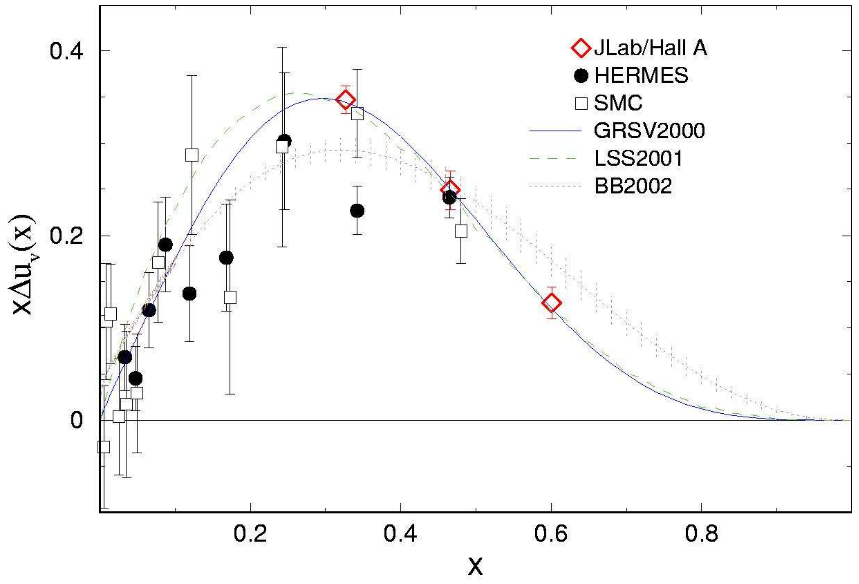
$$\frac{\Delta q + \Delta \bar{q}}{q + \bar{q}} - \frac{\Delta q_v}{q_v}$$

is smaller than experimental uncertainties,

extract

<u>polarized valence quark distributions</u>

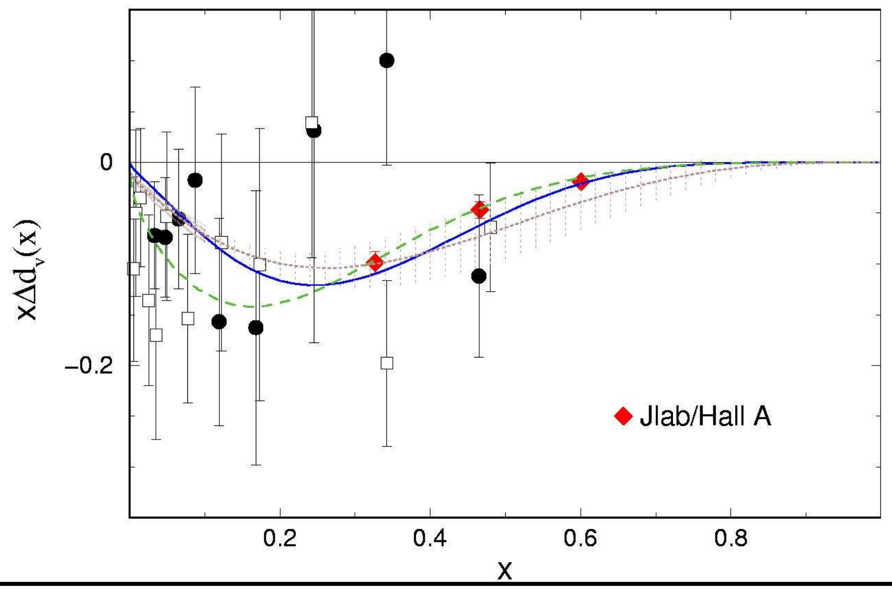
Flavour decomposition from p/ n (3)



Polarized valence quark distributions

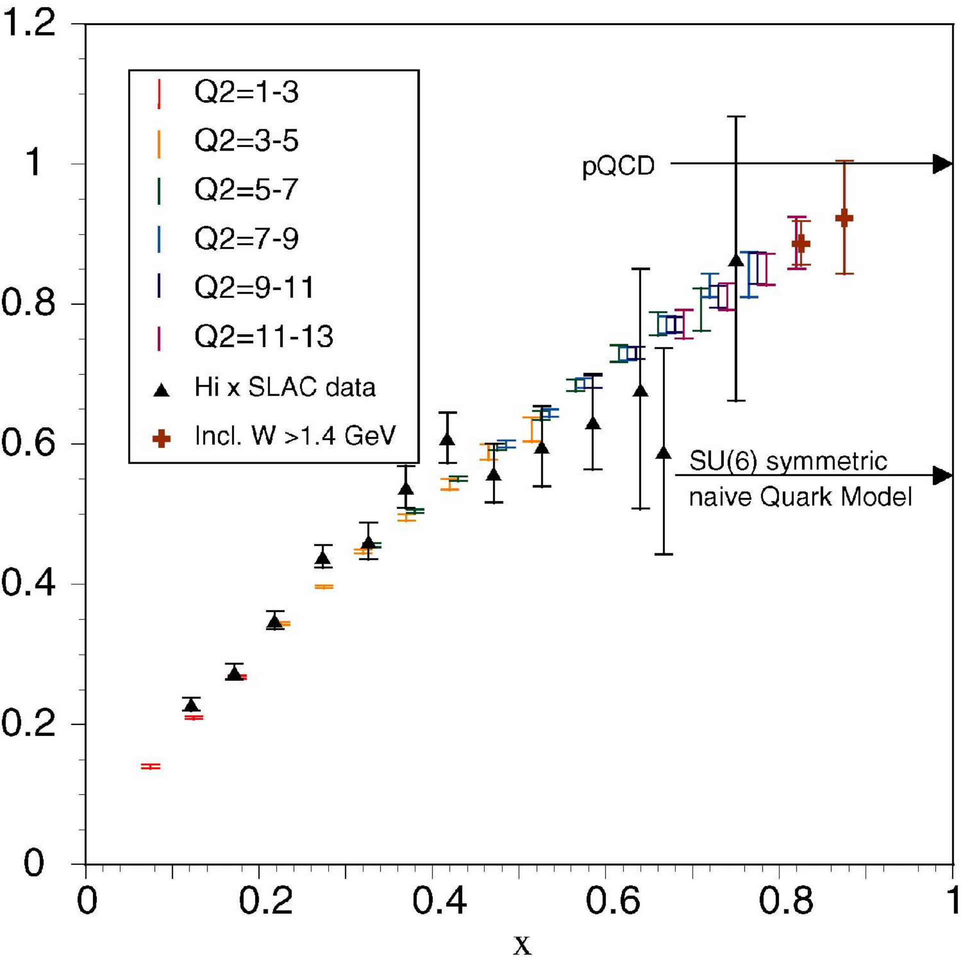
(linear *x*-scale)

using the results of X. Zheng et al.

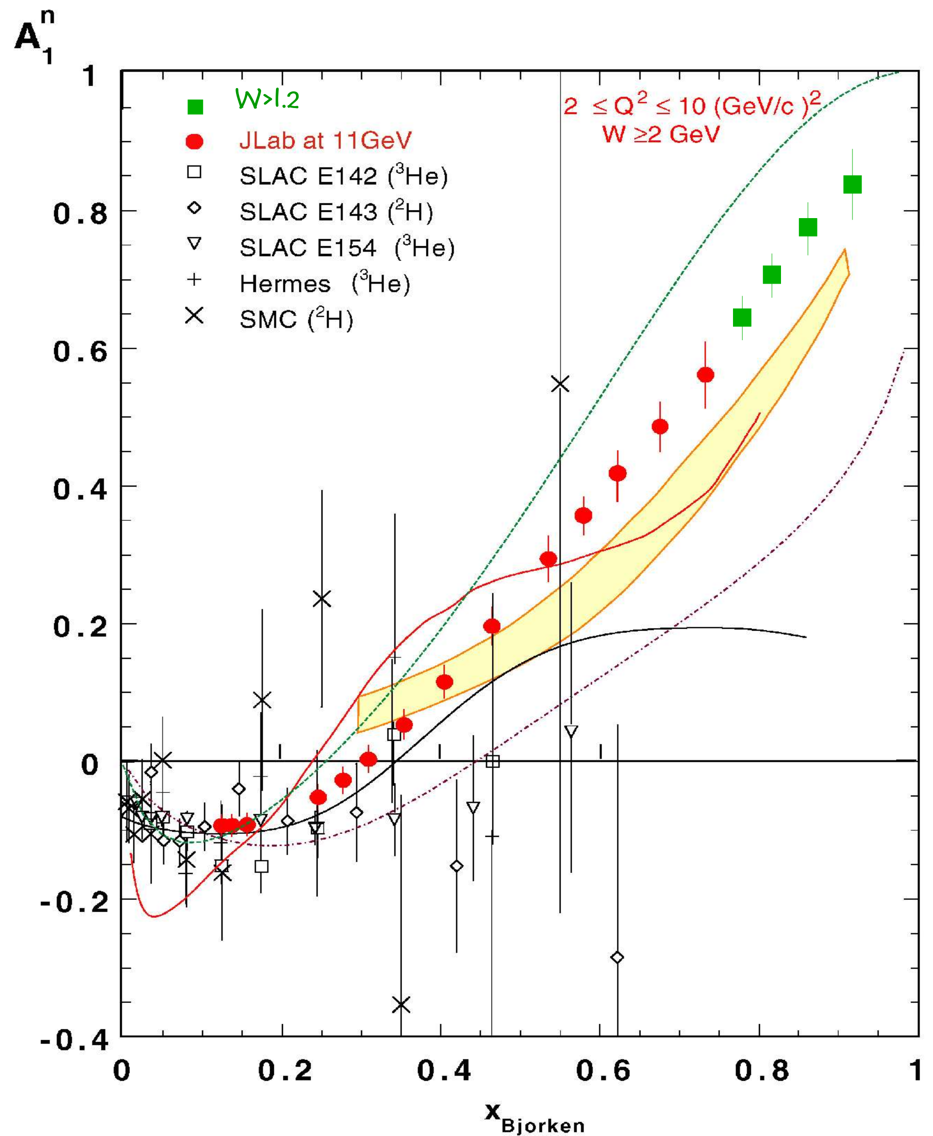


Projections for CEBAF@11GeV

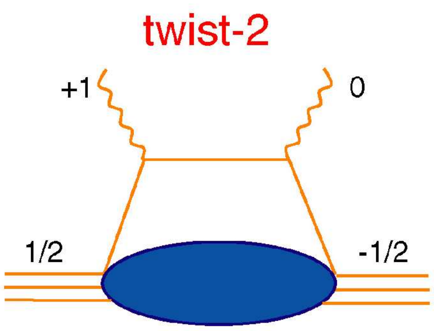
A_1^p at 11 GeV with CLAS++



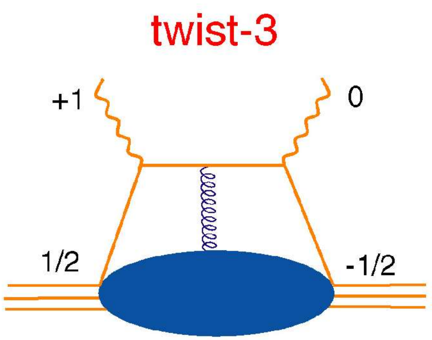
A_1^n at 11 GeV with MAD



g_2 and quark-gluon correlations



Carry one unit of orbital angular momentum



Couple to a gluon

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- a twist-2 term (Wandzura & Wilczek, 1977):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_0^1 g_1(y,Q^2)\frac{dy}{y}$$

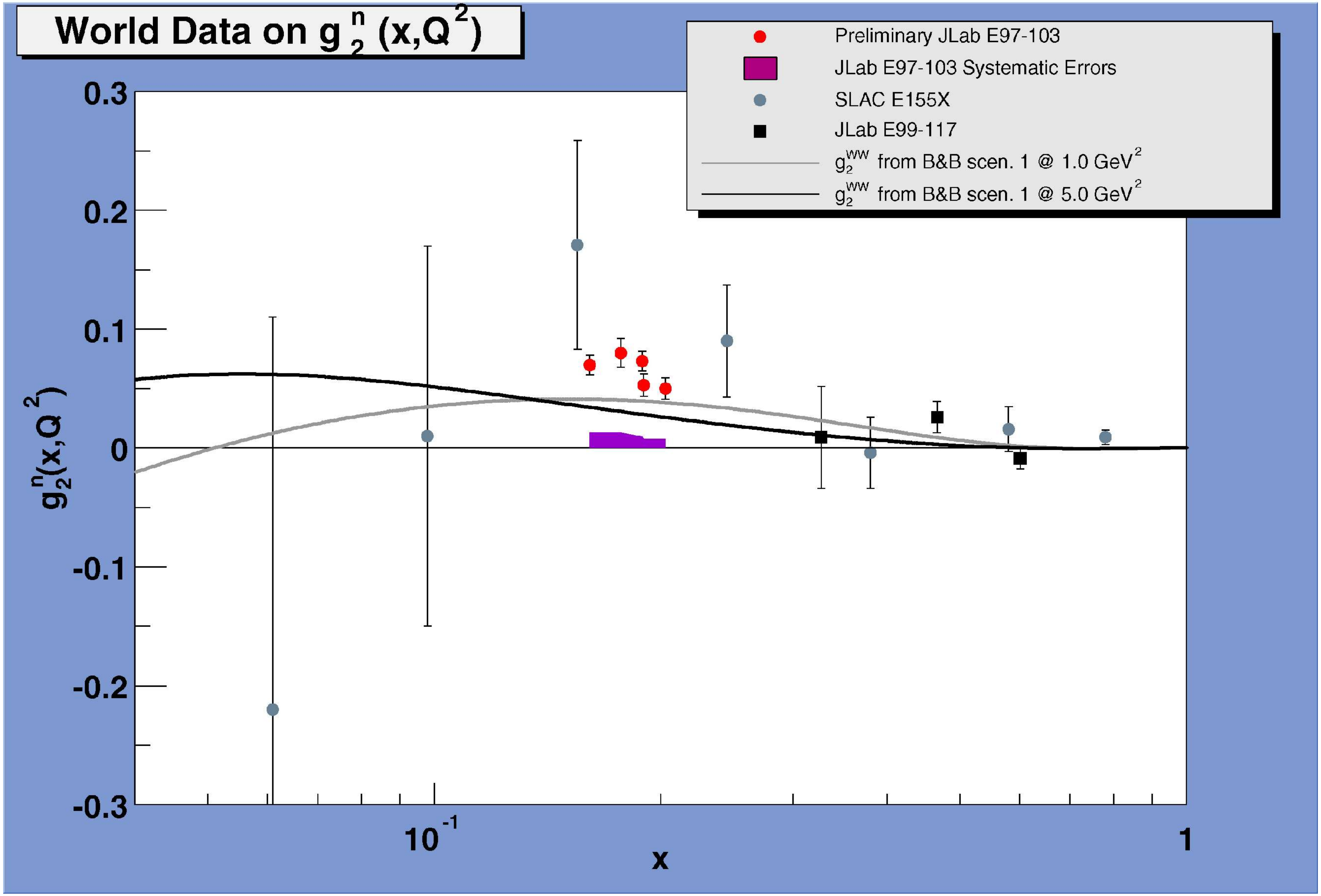
- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

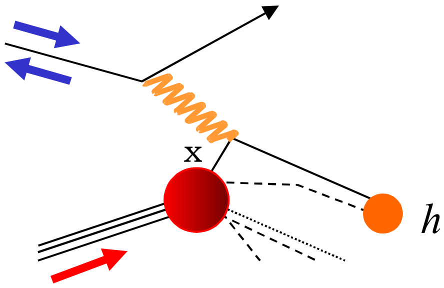
transversity (h_T)

quark-gluon correlation (ξ)

g_2 and quark-gluon correlations



SIDIS Spin Asymmetries



$z = \frac{E_h}{\nu}$

Detect the hadron from the current fragmentation and measure the **double spin asymmetry** $A_{//}^{h}$ in the semi-inclusive process eN → e h X

Assuming leading order (naïve) *x-z* factorization, get for each species *h:*

$$A_{1N}^{h}(x,Q^2,z) \equiv \frac{\Delta\sigma^{h}(x,Q^2,z)}{\sigma^{h}(x,Q^2,z)} = \frac{\sum_q e_q^2\,\Delta q(x,Q^2)\cdot D_q^h(z,Q^2)}{\sum_q e_q^2\,q(x,Q^2)\cdot D_q^h(z,Q^2)}$$

(Semi)-SANE program is to measure **10 double-spin asymmetries**

Semi-inclusive: $h = \pi^+, \pi^-, K^+, K^-$

Inclusive A_1

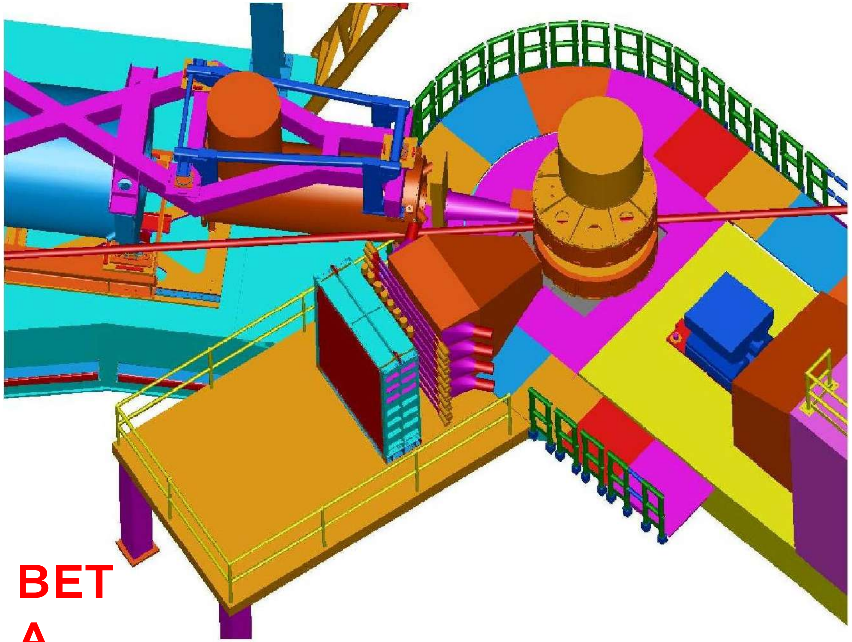
for both proton and deuteron (NH_3 and LiD polarized targets) in Hall C

and extract **5 polarized quark distribution functions**

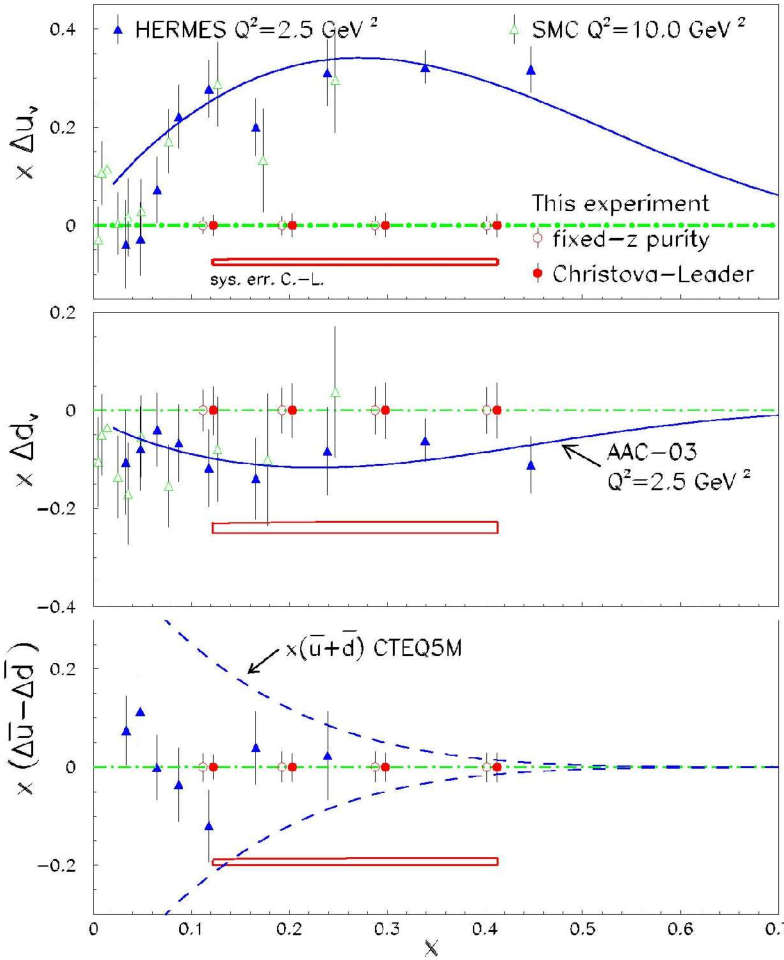
$$\Delta u,\ \Delta d,\ \Delta\bar{u},\ \Delta\bar{d},\ \Delta s$$

(Semi)-SANE apparatus in Hall C

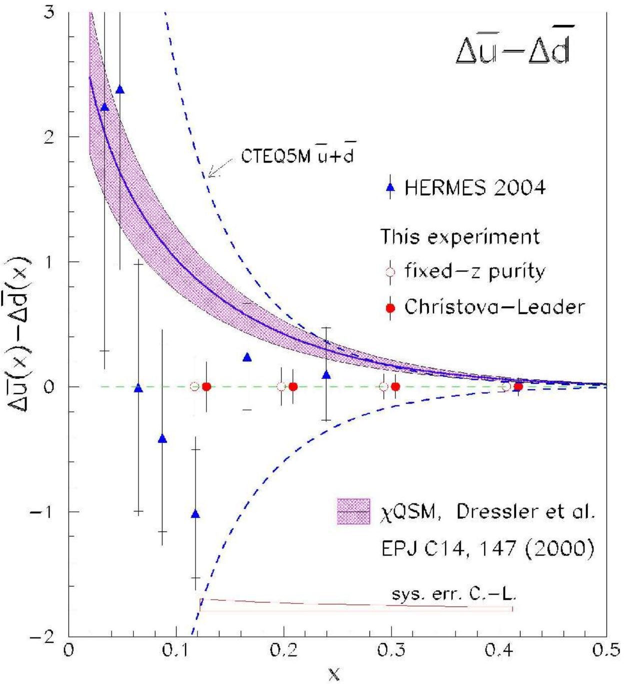
- NH_3 and LiD polarized targets
- Big Electron Telescope Array (BETA) in direct view of target – *under construction*
    - Lead glass calorimeter (1744 blocks, 194 msr)
    - Gas Cerenkov (1000:1 π/e rejection factor)
    - Lucite hodoscope array (tracking and redundant particle id.)
- *h*-arm: HMS + gas Cerenkov + aerogel for π/K identification
- Luminosity ~ 10^{35} $cm^{-2}s^{-1}$.



Anticipated results on spin-flavor decomposition



● Expectations from Semi-SANE



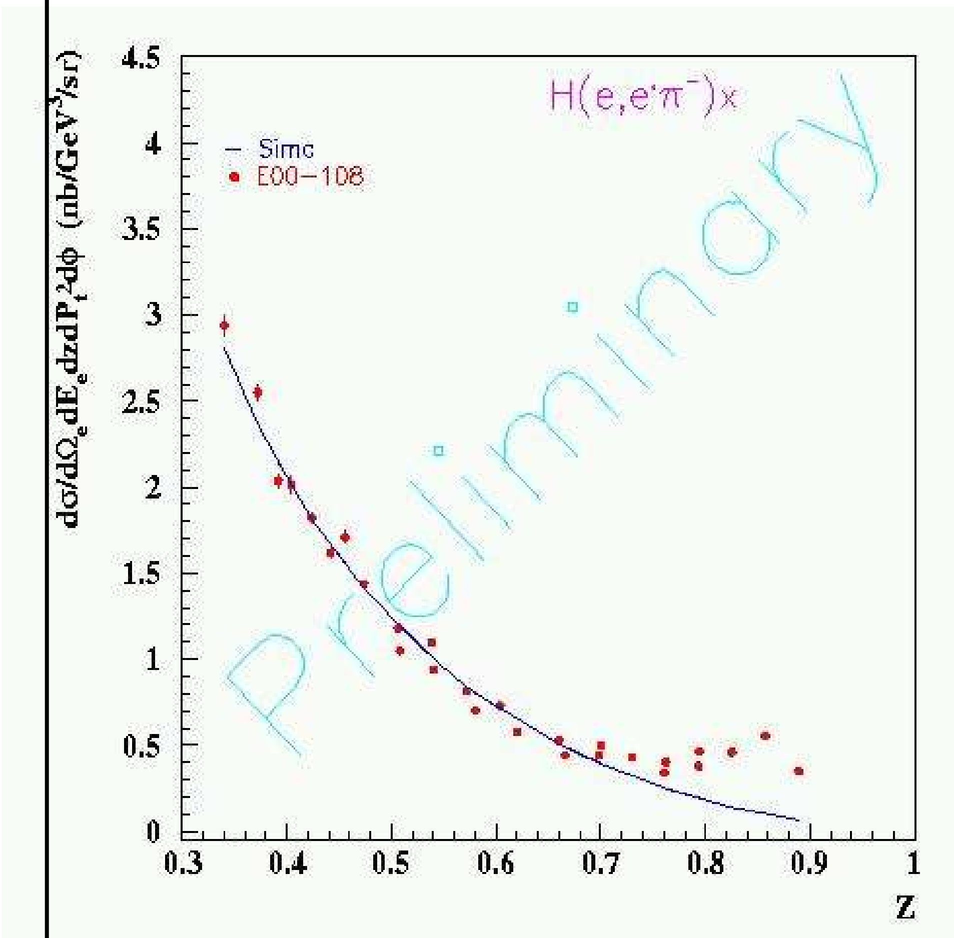
With many checks for systematic uncertainties (*x-z* factorization,..)

By-products: most accurate data on A_1^p ***and*** A_1^d.

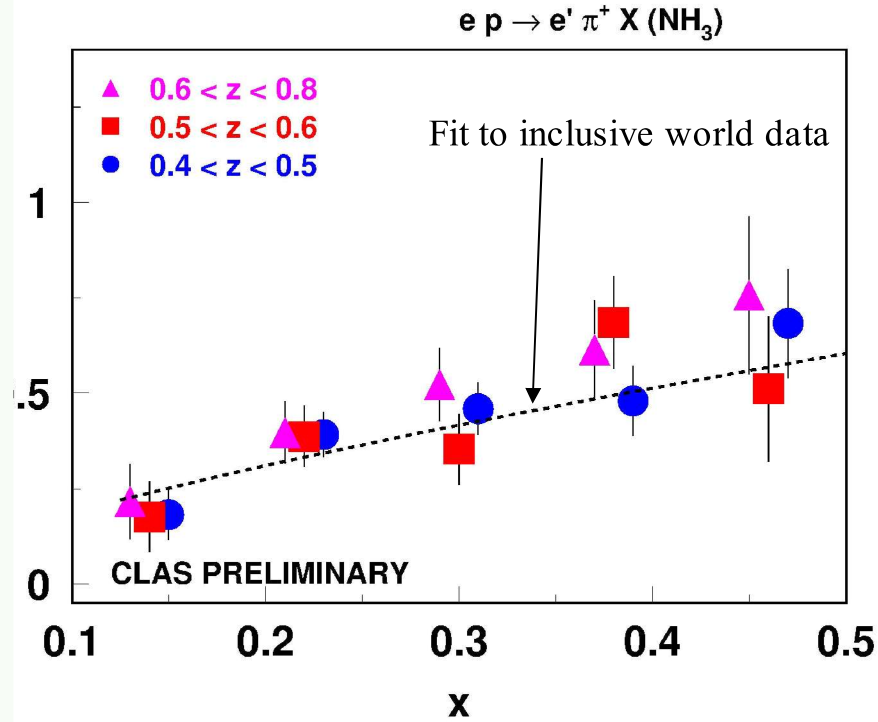
(the latter puts a strong constraint on the global fit of ΔG)

(See X. Jiang's talk on Friday afternoon, session 2)

Tests of x-z factorization



Cross section reproduced by Monte-Carlo based on LO *x-z* factorization (Hall C).

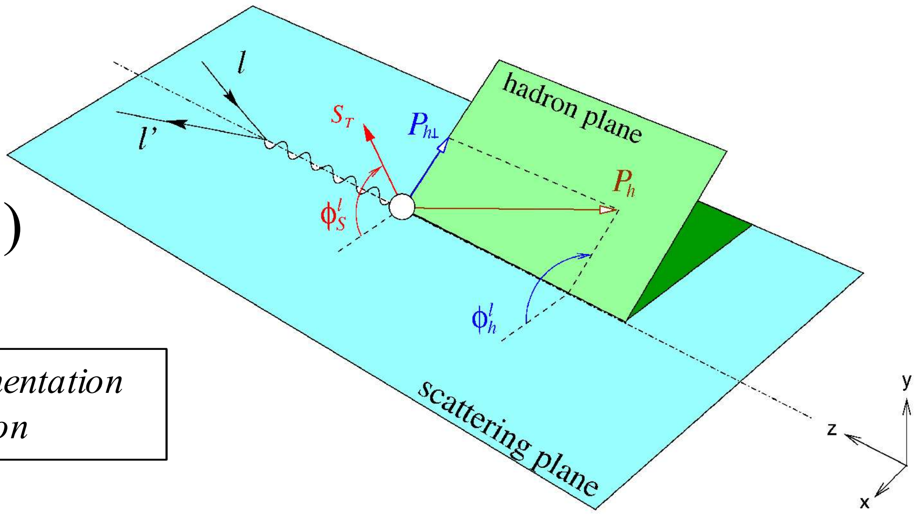


Semi-inclusive asymmetry $A_1^p(\pi^+)$ agrees with HERMES, SMC, falls on the same curve as inclusive A_1^p; no *z*-dependence observed (within errors)

LO x-z factorization is not (much) violated at 6 GeV

Transversity

In semi-inclusive d.i.s., at leading order, one can define 8 response functions (see Mulders).
With a transversely polarized target (S_T), 2 of the 3 contributions should be measurable:



$$\sin(\phi_h^l - \phi_S^l) \times \sum_{q,\bar{q}} e_q^2 \, f_{1T}^{\perp(1)q}(x) \cdot D_1^q(z, P_{h\perp}^2)$$

Asymmetric distribution of $k_\perp$ in a polarized nucleon

Usual fragmentation function

$$\sin(\phi_h^l + \phi_S^l) \times \sum_{q,\bar{q}} e_q^2 \, h_1^q(x) \cdot H_1^{\perp q}(z, P_{h\perp}^2)$$

*"**Transversity**" distribution: quark transverse polarization in a transversely polarized nucleon*

Fragmentation function which describes the correlation of $P_{h\perp}$ with the quark transverse polarization (Collins function)

Transversity (2)

(V. Barone's talk yesterday)

After $q(x)$ and $\Delta q(x)$,

$\boldsymbol{h_1}$ (or $\boldsymbol{\delta q(x)}$ or $\boldsymbol{\Delta_\perp q(x)}$)

is the third $k_\perp$-independent twist-2 quark distribution function

It measures the probability of having quarks with momentum fraction x

and

with transverse polarization in the same direction as the transversely polarized target.

Some characteristics :

$h_1(x) = \Delta q(x)$ for non relativistic quarks

$h_1(x)$ does not mix with gluon distributions in its evolution

$h_1(x)$ suppressed at low x with respect to Δq

Its first moment yields the tensor charge δq calculable in lattice QCD

Transversity (3)

Key experimental issue:

Transverse nucleon polarization

Induces transverse quark polarization

Affects quark transverse momentum distribution

Collins

Sivers

Both effects visible in transverse momentum distribution of hadron from fragmentation

E03-004 (X. Jiang, J.P. Chen, J.C. Peng), *using the polarized ^3He target and BigBite in Hall A*, will

- disentangle these two effects,

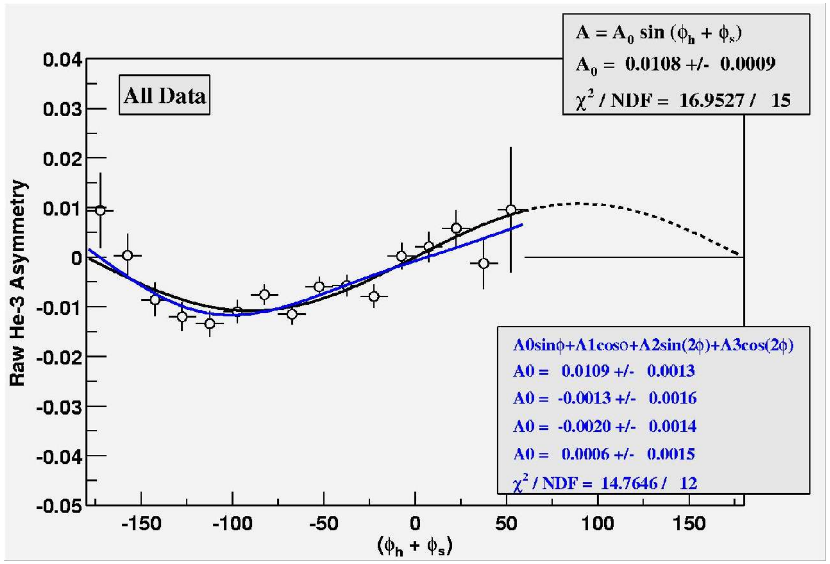
- measure the neutron transversity (sensitive to δd),

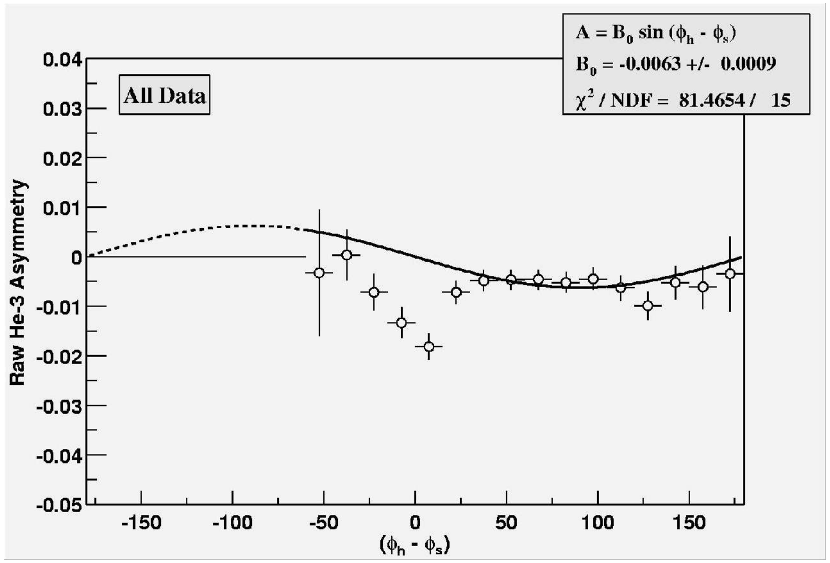
- probe other $k_\perp$ dependent distribution functions

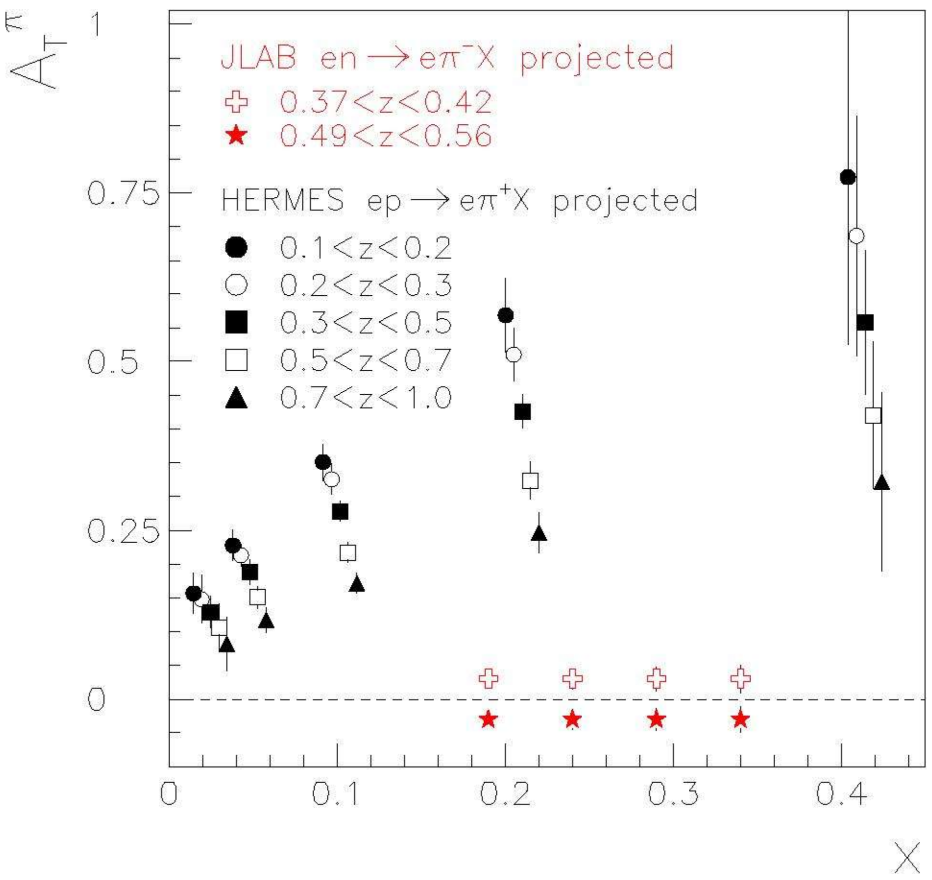
Single Spin Asymmetry measurements using transversely polarized ^3He target are complementary to HERMES and COMPASS

Transversity : expected results from E03-004

Data simulated with pure **sin(Φ_h+Φ_S)** dependence



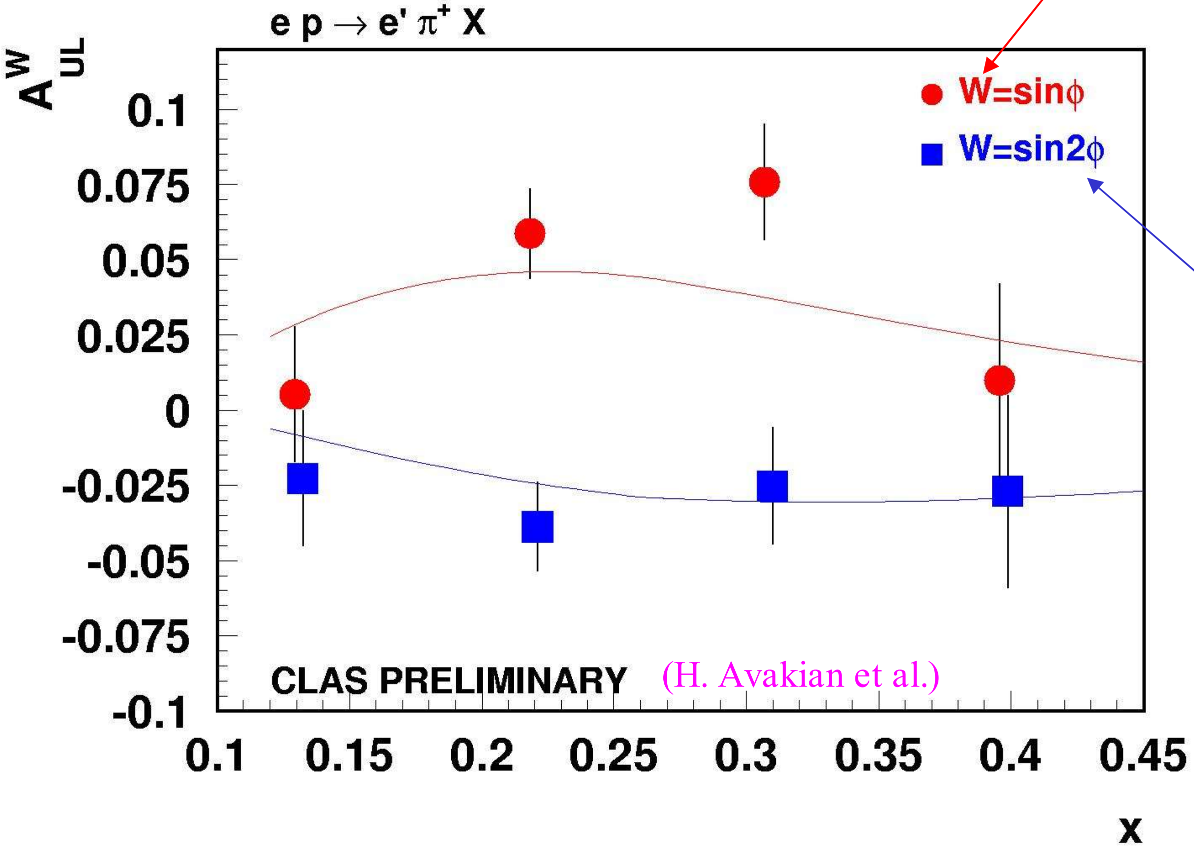




(See recent HERMES results hep-ex/0408013)

Target single spin asymmetry in SIDIS

Combination of Sivers and Collins effects (from S_T) and of higher-twist distributions (from S_L)



First indication of a non-zero sin2Φ moment (Kotzinian-Mulders asymmetry), clean source of Collins SSA.

HERMES result (PRD 64, 097101) compatible with 0

Both HERMES and CLAS results consistent with predictions (Efremov et al., PRD 67, 114014)

* Definitive conclusions require more data & higher accuracy

* Other SSA (A_{LU}) published (PRD 69, 112004) or under investigation from the high statistics CLAS/e1-6 run

Single spin asymmetry in SIDIS

- **Rich phenomenology associated with various SSA**

see e.g. Efremov, *M. Wakamatsu 's talk on Friday afternoon, session 2*, on distribution $e^a(x)$

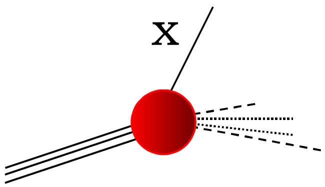
and consistency of HERMES/CLAS A_{UL}/A_{LU} measurements

(another indication that factorization is at work)

- **SSA linked to transverse momentum distributions of partons**

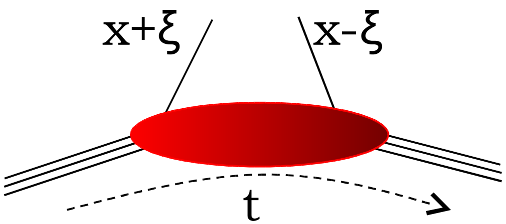
- **SSA ↔ orbital angular momentum ↔ GPD *E*, Pauli form factor F_2**

Generalized Parton Distributions



Probability $|\psi(x)|^2$ that a quark carries a fraction x of the proton momentum

→ "Ordinary" distributions of partons **q(x), Δq(x)** measured in inclusive reactions (D.I.S.)



Coherence $\psi^*(x+\xi)\cdot\psi(x-\xi)$, or interference,

between the initial state

where a quark carries a fraction x+ξ of momentum

and the final state

where it carries a fraction x-ξ

(and t-dependence related to transverse distributions)

→ **Generalized parton distributions (GPD)**

$H, \tilde{H}, E, \tilde{E}\ (x,\xi,t)$

measured in exclusive reactions (D.E.S.)

Generalized Parton Distributions

Very schematically, for 3q configurations represented by a wave function $\psi(x_1,k_1,x_2,k_2,x_3,k_3)$

Ordinary parton distributions integrate over "spectator" quarks and over all transverse momenta:

$$q(x) \sim \int \left|\psi(x,k_1,x_2,k_2,x_3,k_3)\right|^2 [dX]$$

While GPD's contain correlations

- between states of different longitudinal momenta

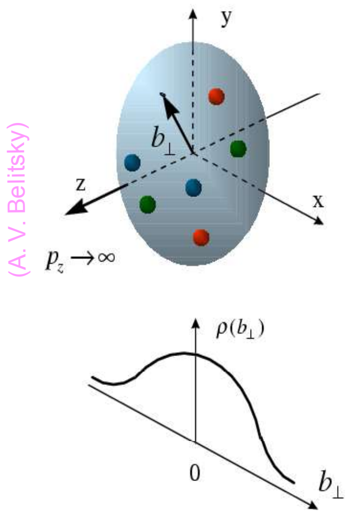
- between longitudinal momentum and transverse position :

$$H(x,\xi,t) \sim \int \psi^*(x-\xi,k_1+\Delta_\perp,\ldots)\cdot\psi(x+\xi,k_1,\ldots)[dX]$$

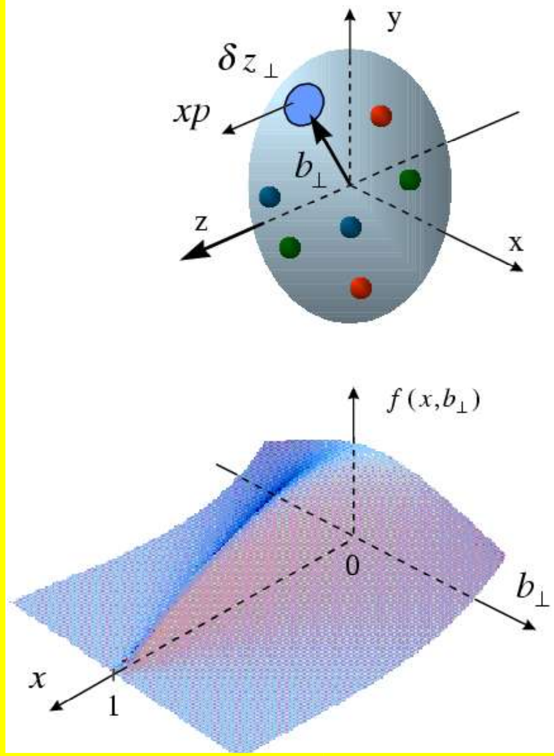
$$[dX] = \delta(x+x_2+x_3-1)\delta^{(2)}(k_1+k_2+k_3)dx_2dx_3dk_1dk_2dk_3$$

x and t dependence of GPDs: a femto-photography of the nucleon

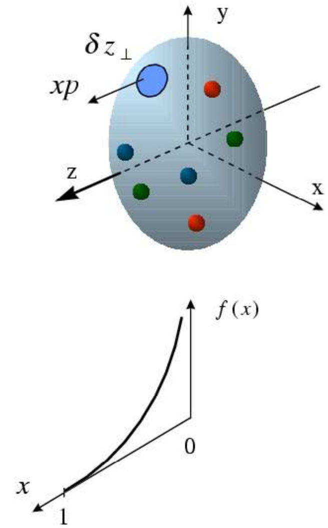
ℱ {Form factor F(t)}



ℱ {GPD (x,0,t)}



Quark distribution q(x)



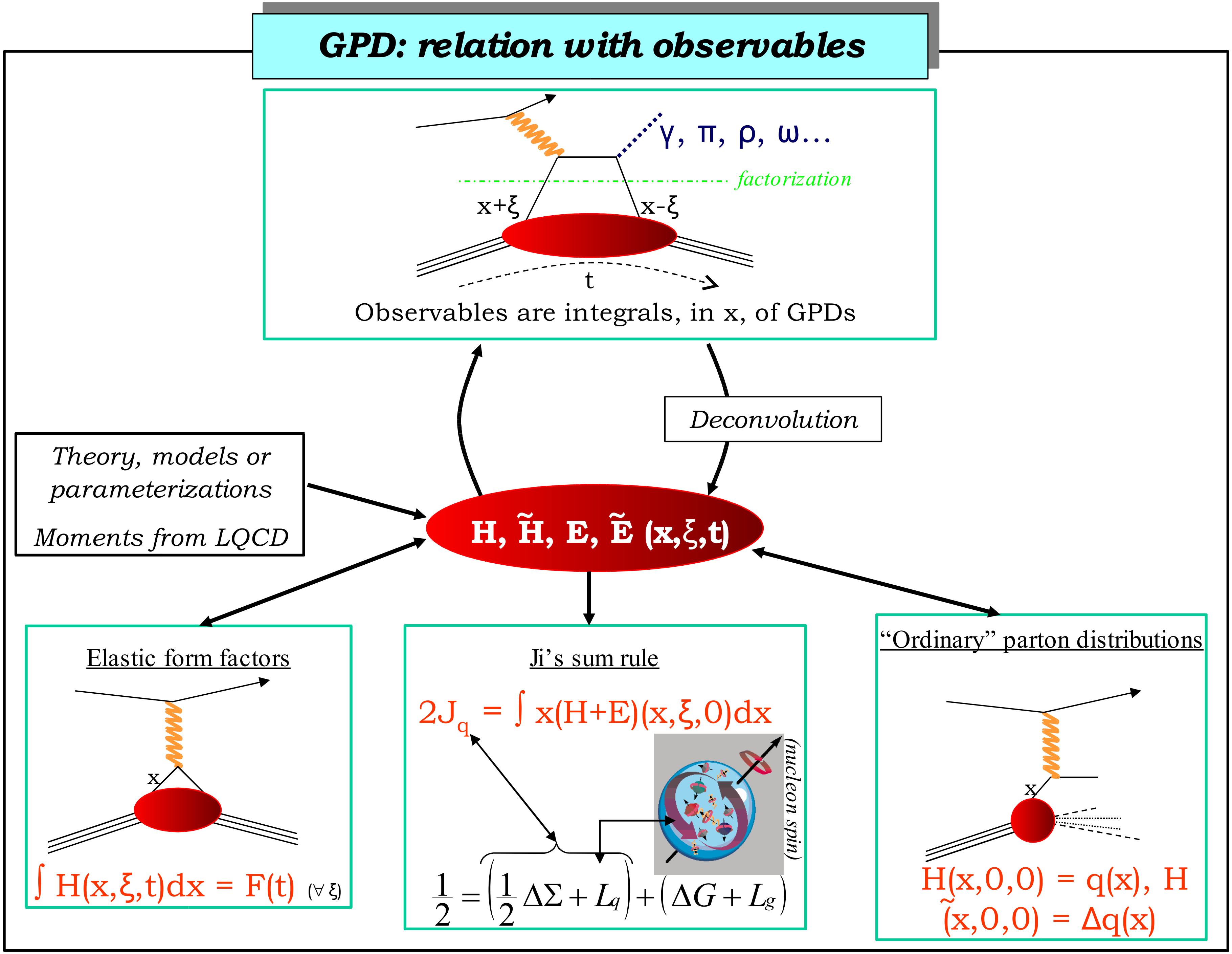
r

p

GPDs connect the form factors and parton distributions

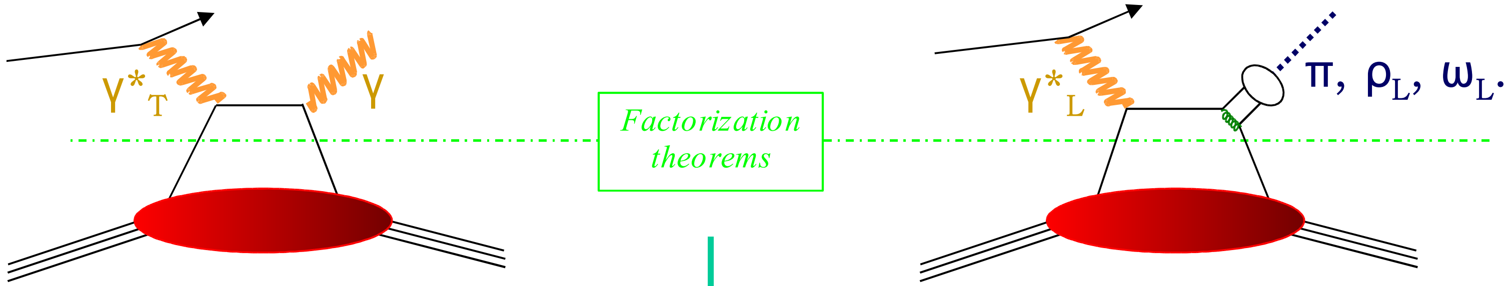
$r \wedge p$

and thus have a direct link with orbital angular momentum



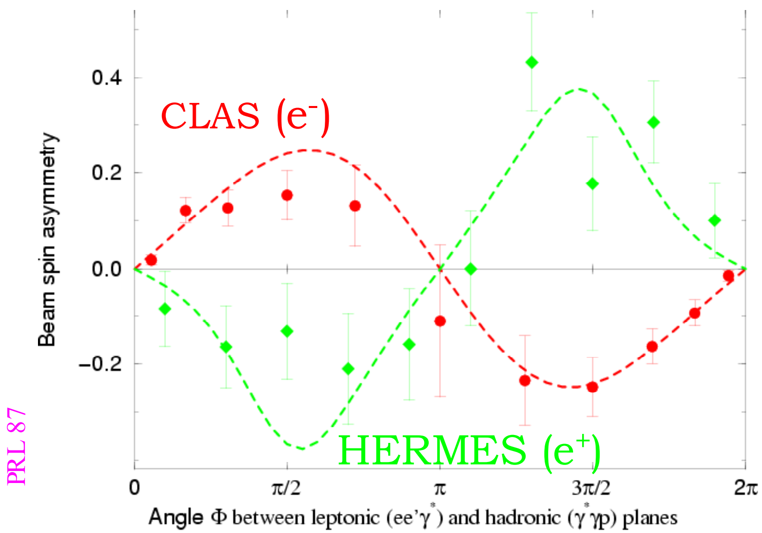
GPD: relation with observables
γ, π, ρ, ω…
factorization
x+ξ
x-ξ
t
Observables are integrals, in x, of GPDs
Deconvolution
Theory, models or parameterizations
Moments from LQCD
H, H̃, E, Ẽ (x,ξ,t)
Elastic form factors
x
∫ H(x,ξ,t)dx = F(t) (∀ ξ)
Ji's sum rule
$2J_q = \int x(H+E)(x,\xi,0)dx$
(nucleon spin)
$\frac{1}{2} = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$
"Ordinary" parton distributions
x
H(x,0,0) = q(x), H̃(x,0,0) = Δq(x)

Deeply virtual exclusive reactions (DES)



DVCS
(Virtual Compton)

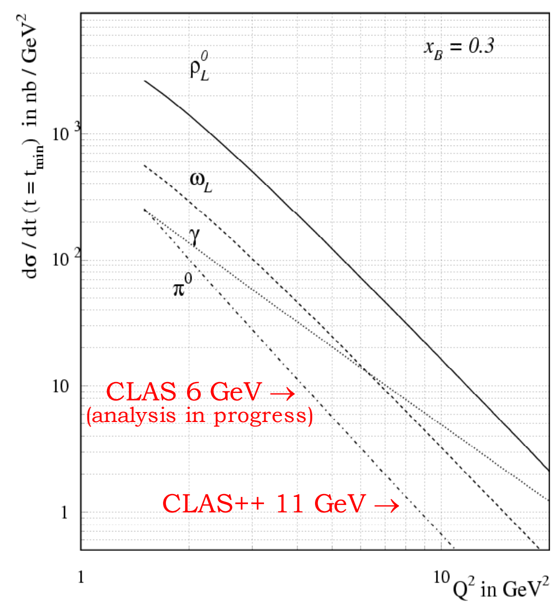
- Leading order/twist accessible at moderate Q^2,
- Interference with Bethe-Heitler process,
- First publications from H1, ZEUS (gluons) and:



(The sinusoidal behaviour is characteristic of the interference BH-DVCS)

DVMP
(Meson production)

- Allows a separation (H,E) ↔ ($\tilde{H}$,$\tilde{E}$) and according to quark flavors.
- Necessary to extract σ_L



DES: finite Q^2 corrections
(real world ≠ Bjorken limit)

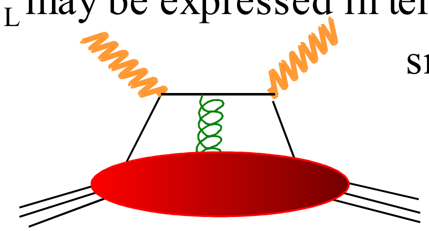
GPD evolution

Dependence on factorization scale μ :

$$\mu \frac{\partial}{\partial \mu} H(x,\xi,t;\mu) = \int \underbrace{K(x,y,\xi;\alpha_S(\mu))}_{\text{Kernel known to NLO}} H(y,\xi,t;\mu)\,dy$$

Evolution of DES amplitude

O (1/Q) *(here for DVCS)*

- Gauge fixing term
- Twist-3: contribution from γ^*_L may be expressed in terms of derivatives of (twist-2) GPDs.
- Other contributions such as  small (but measureable effect).

O ($1/Q^2$)

- "Trivial" kinematical corrections, of order $\frac{t}{Q^2}, \frac{M^2}{Q^2}, \frac{m^2}{Q^2}$
- Quark transverse momentum effects (modification of quark propagator)

$$\frac{1}{x+\xi-i\varepsilon} \rightarrow \frac{1}{x+\xi+k_\perp^2/Q^2-i\varepsilon}$$

- Other twist-4 ……

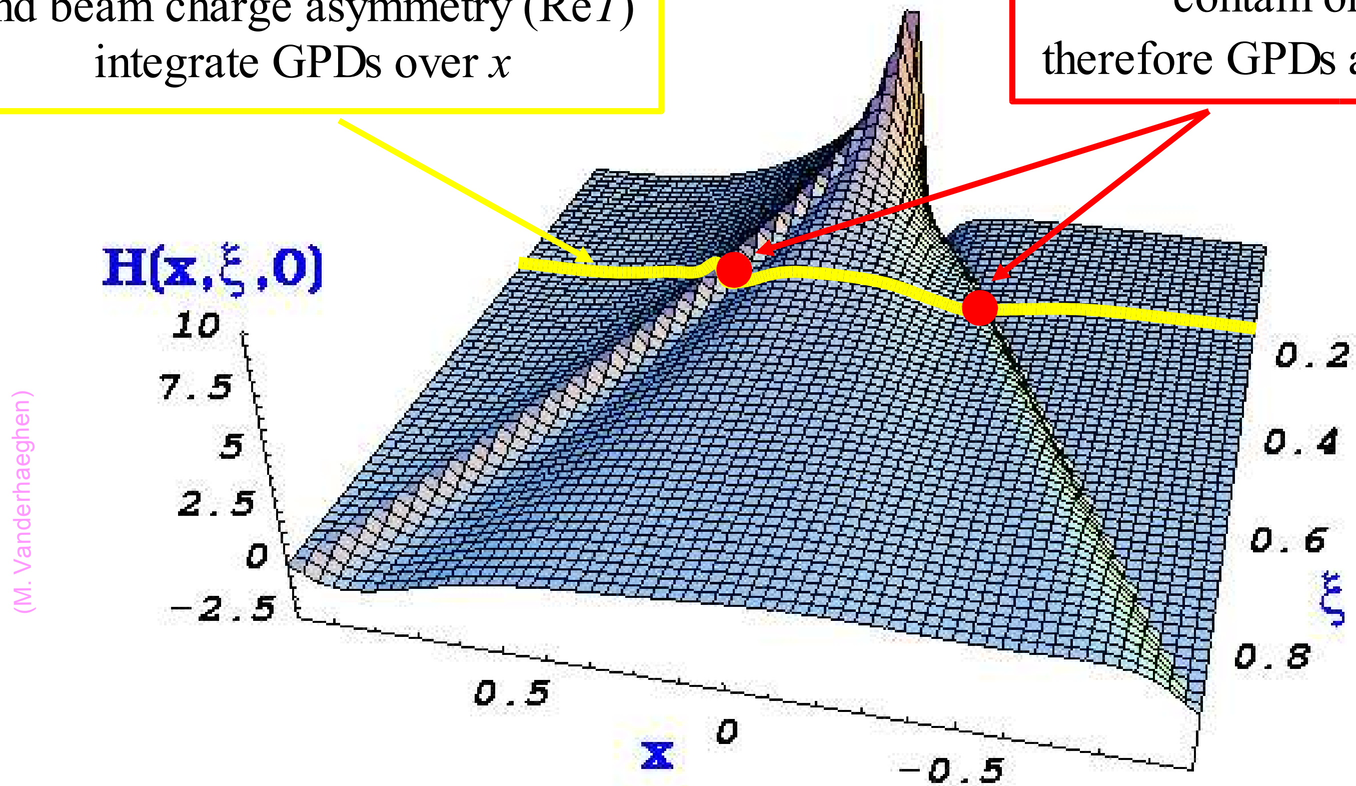
GPD and DVCS

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section measurement and beam charge asymmetry (ReT) integrate GPDs over x

Beam or target spin asymmetry contain only ImT, therefore GPDs at $x = \xi$ and $-\xi$



DVCS and GPDs : Beam and target spin asymmetries

DVCS-BH interference generates a
beam spin cross section difference: $\sigma^+ - \sigma^- = \Gamma \cdot [A \sin\Phi + \ldots]$

$$A = F_1(t) \cdot \mathrm{H} + \frac{x_B}{2 - x_B}[F_1(t) + F_2(t)] \cdot \widetilde{\mathrm{H}} - \frac{t}{4M^2} F_2(t) \cdot \mathrm{E}$$

and a
target spin cross section difference: $\sigma^+ - \sigma^- = \Gamma \cdot [A' \sin\Phi + \ldots]$

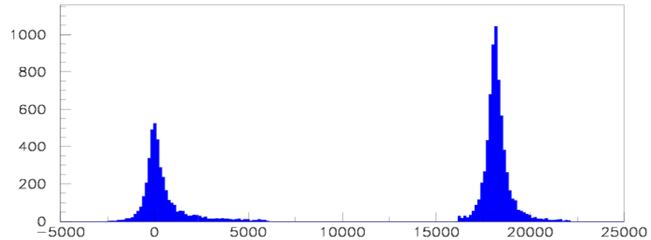
$$A' = F_1 \cdot \widetilde{\mathrm{H}} + \frac{x_B}{2 - x_B}[F_1 + F_2] \cdot \mathrm{H} + \frac{x_B}{2 - x_B}\left[\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2\right] \cdot \mathrm{E}$$

$$(\mathrm{H}, \widetilde{\mathrm{H}}, \mathrm{E}) = \pi \sum_q e_q^2 [GPD^q(\xi, \xi, t) \pm GPD^q(-\xi, \xi, t)]$$

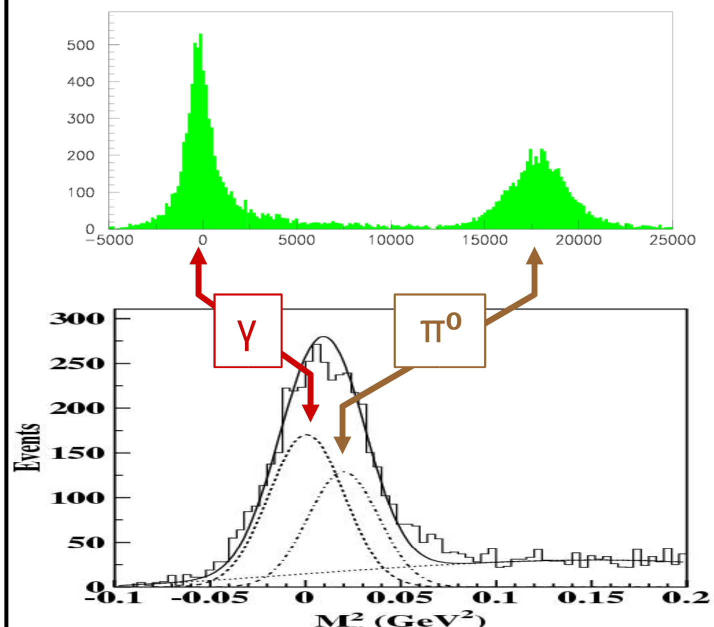
Spin asymmetries: $BSA / TSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

D.E.S.: an experimental challenge

Missing mass M_X^2

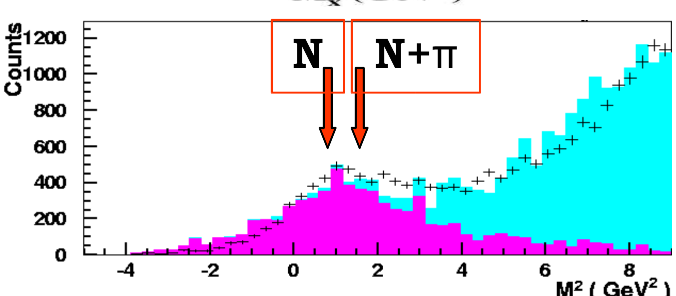


ep → epX
MAMI 850 MeV



ep → epX
Hall A
4 GeV

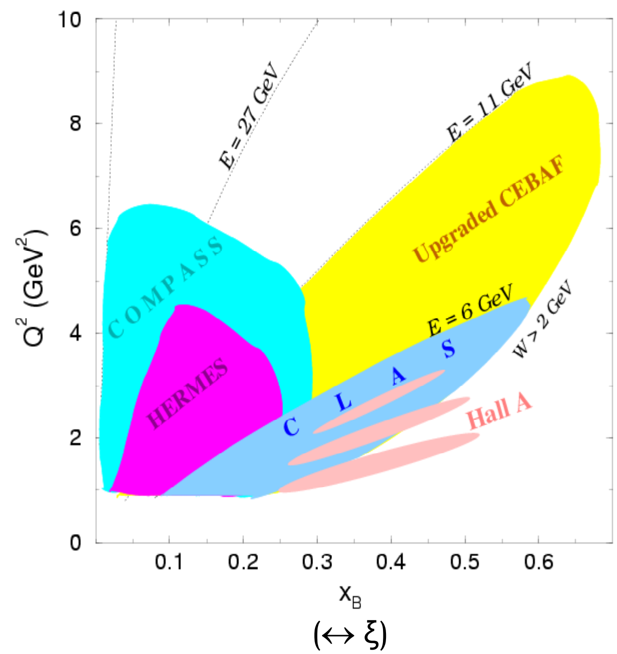
ep → epX
CLAS
4.2 GeV



ep → eγX
HERMES
28 GeV

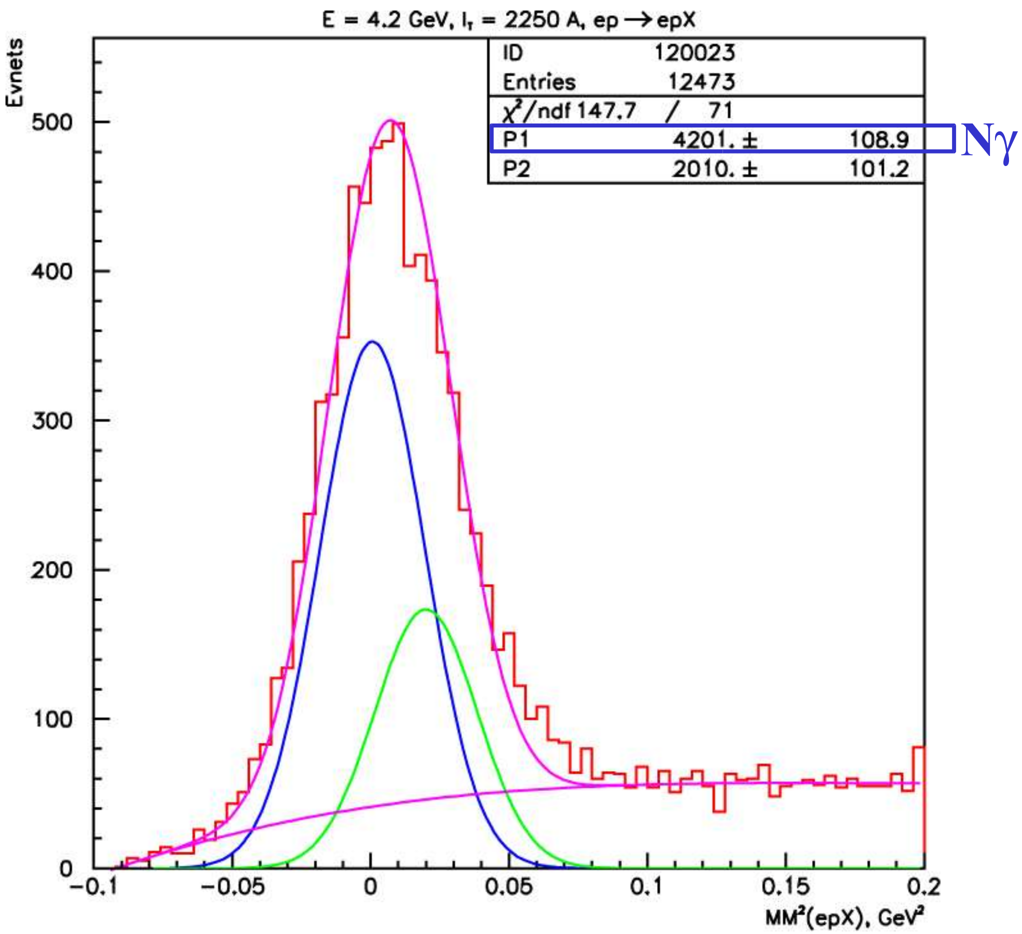
- Resolution
- Exclusivity
- Luminosity
- High transfers

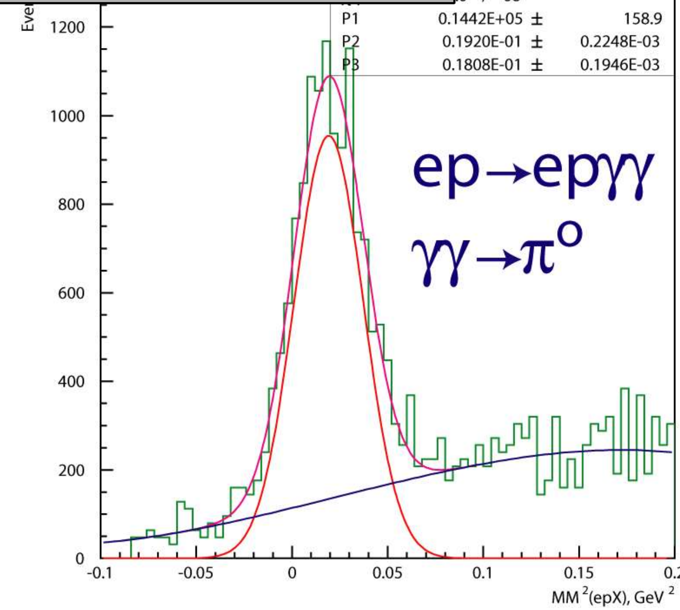
Accessible kinematical domain

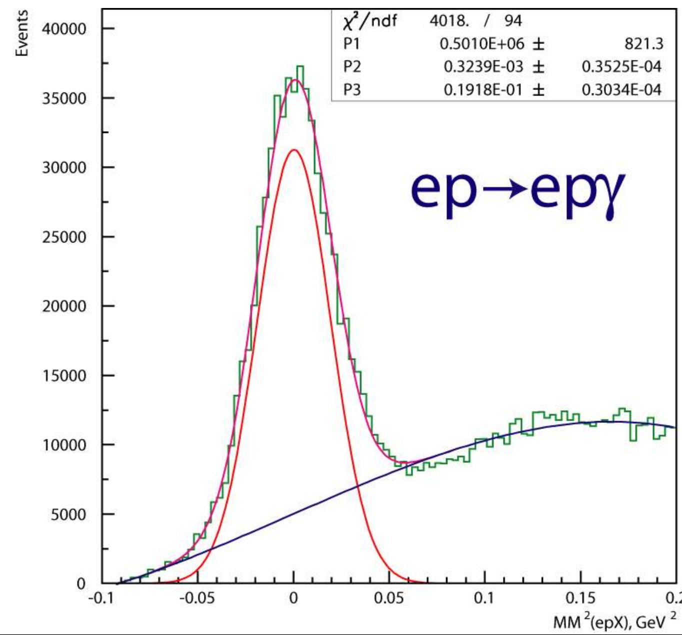


ep→epX (CLAS at 4.2 GeV) : X = γ or π⁰ ?

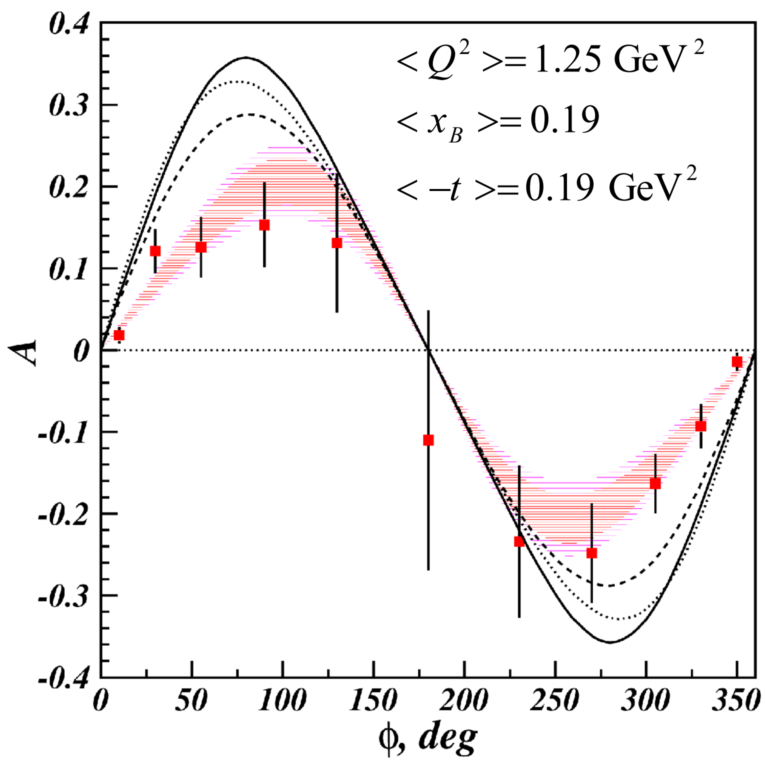
Only 2-parameter fit: N_γ and N_{π^0}





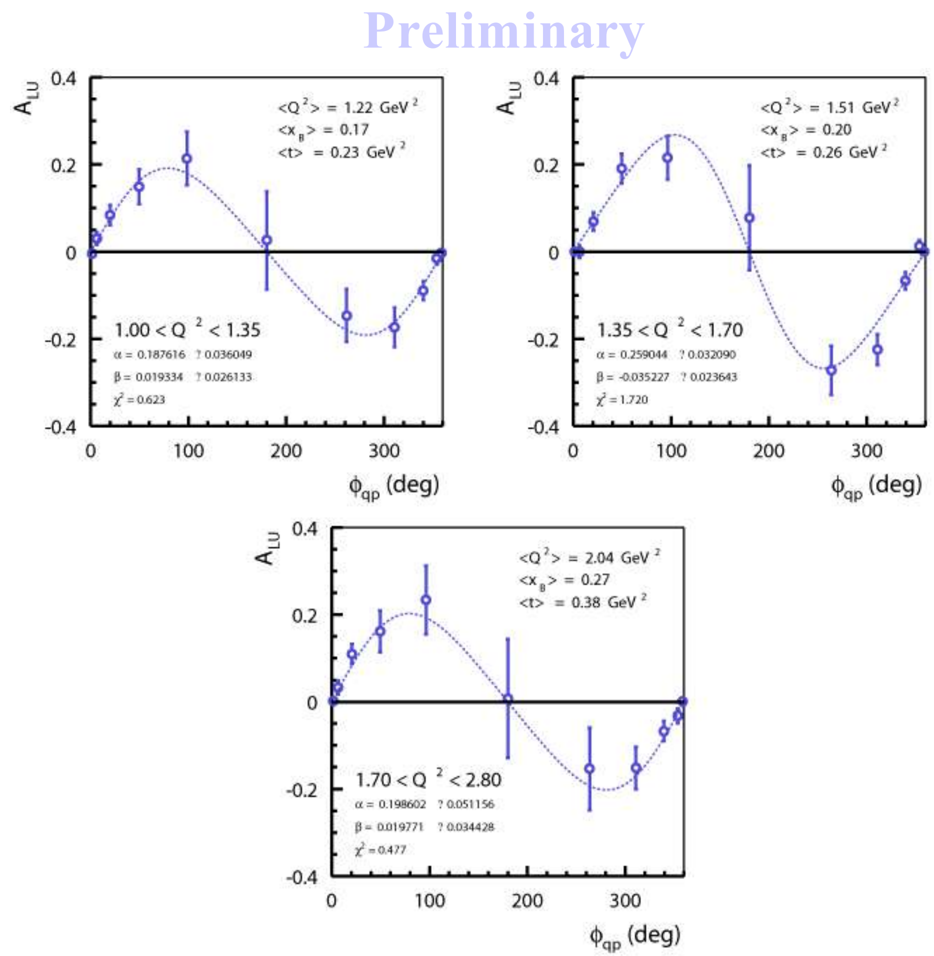


CLAS/ DVCS at 4.2 and 4.8 GeV



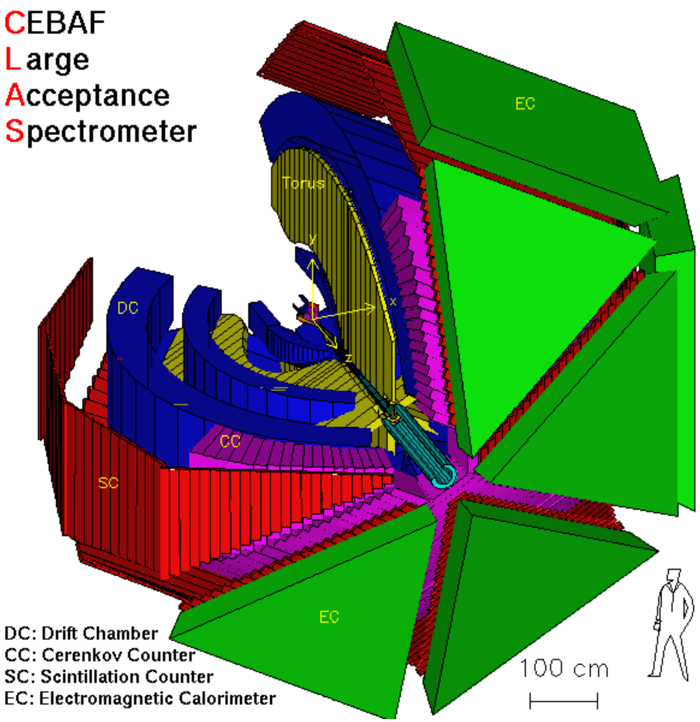
Published measurement at 4.2 GeV

Phys.Rev.Lett.87:182002,2001



Preliminary CLAS analysis
with 4.8 GeV data (G. Gavalian)

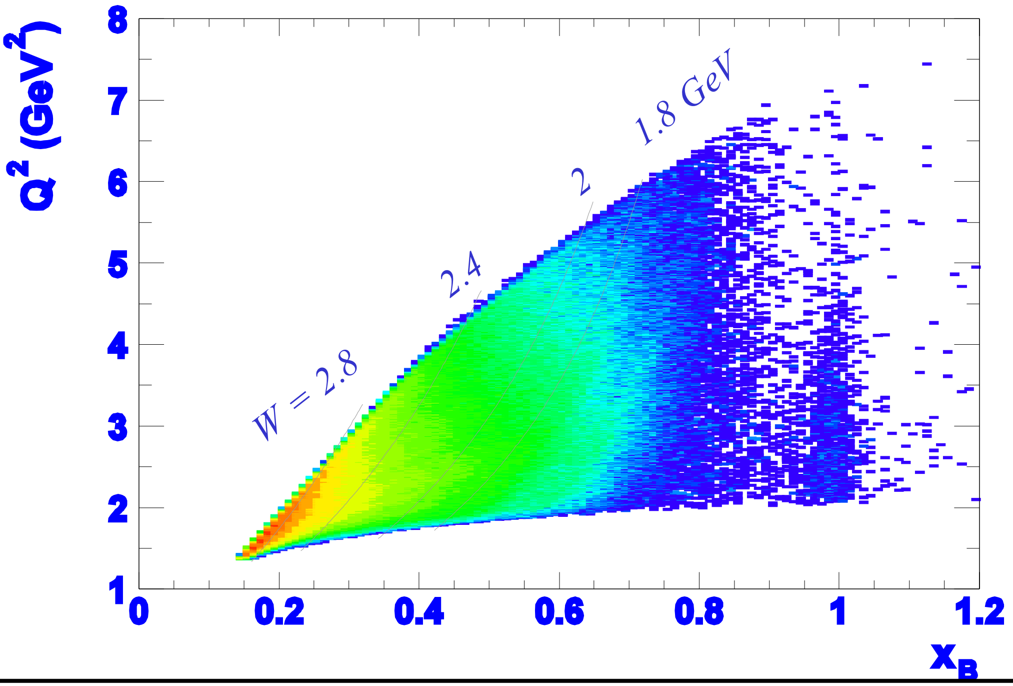
CLAS: high luminosity run at 5.75 GeV



First JLab experiment with GPDs in mind

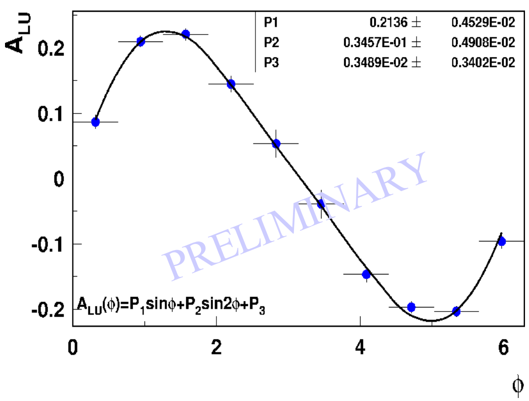
(october 2001 – january 2002)

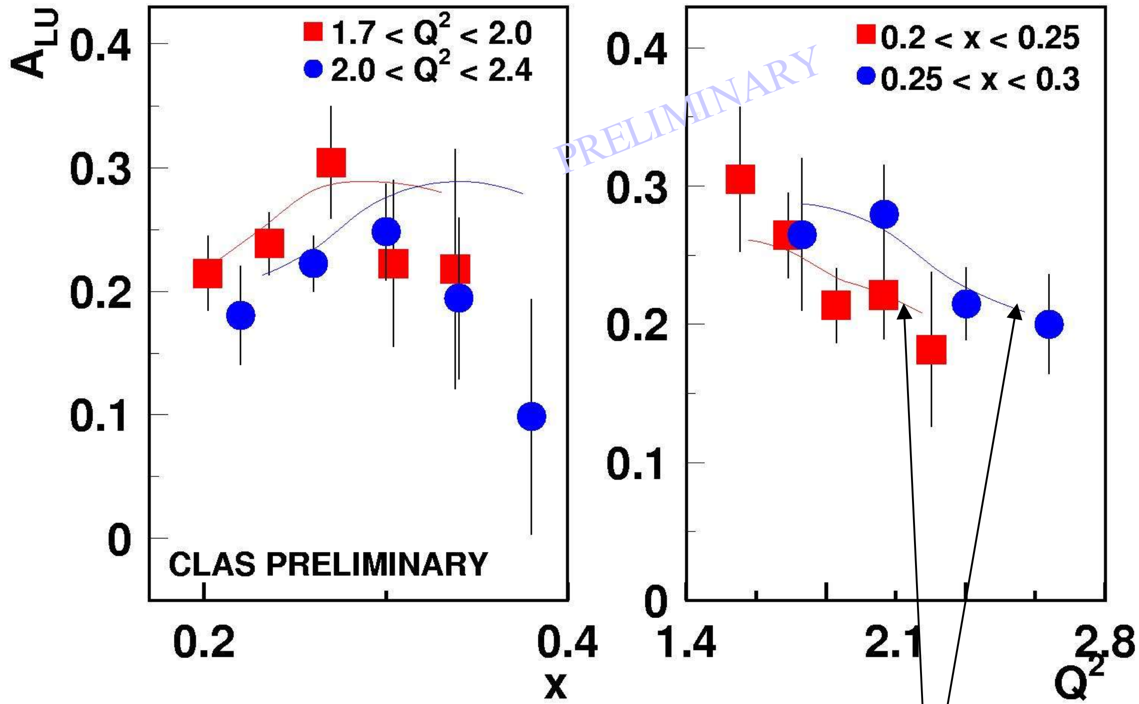
- polarized electrons, E = 5.75 GeV
- **Q^2 up to 5.5 GeV^2,**
- **Integrated luminosity: 30 fb^{-1}**
- **W up to 2.8 GeV**



CLAS/ DVCS (ep → epX) at 5.75 GeV

H. Avakian & L. Elouadrhiri





$0.15 < x_B < 0.4$

$1.50 < Q^2 < 4.5$ GeV^2

$-t < 0.5$ GeV^2

π^0 are « suppressed » due to analysis cuts (**only low *t***), but no subtraction or correction were done

GPD based predictions (Vanderhaeghen)

Once again, exclusivity, high statistics and precision data is the key !

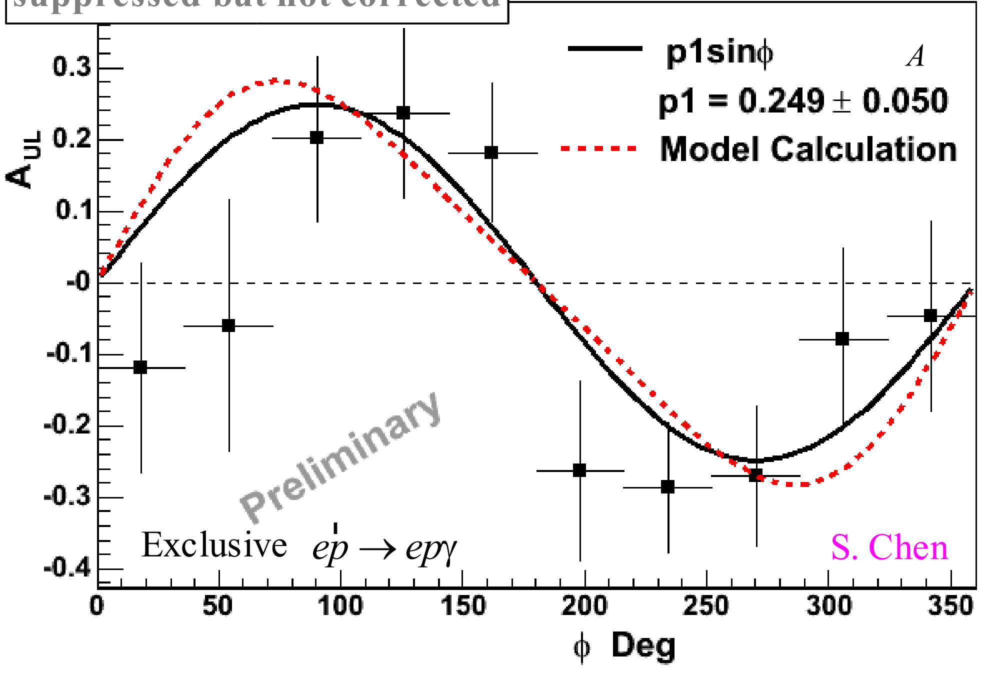
DVCS with a polarized target in CLAS

5.65 GeV run with **NH_3** longitudinally polarized target, Q^2 up to 4.5 GeV^2

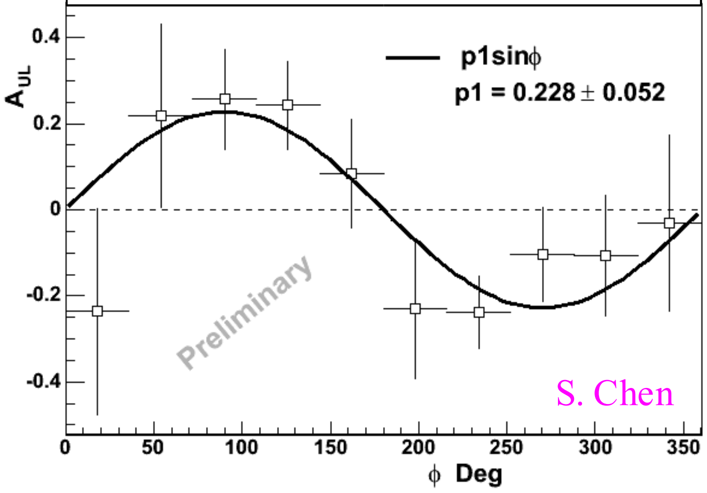
* **Detect all 3 particles** in the final state (e,p,γ) to eliminate contribution from N (but calorimeter is at too large angles) ,

* Apply kinematical cuts to suppress $ep \rightarrow ep\pi^0$ contribution.

π^0 contamination suppressed but not corrected



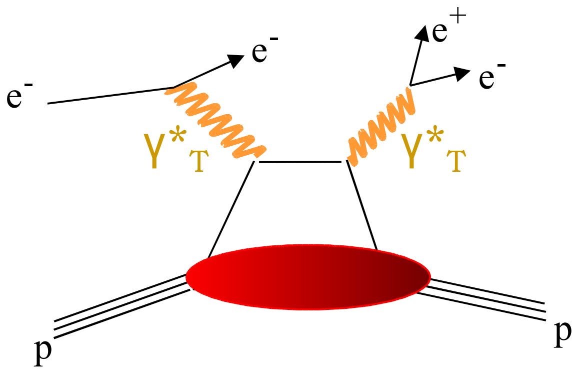
π^0 asymmetry (two photons required)

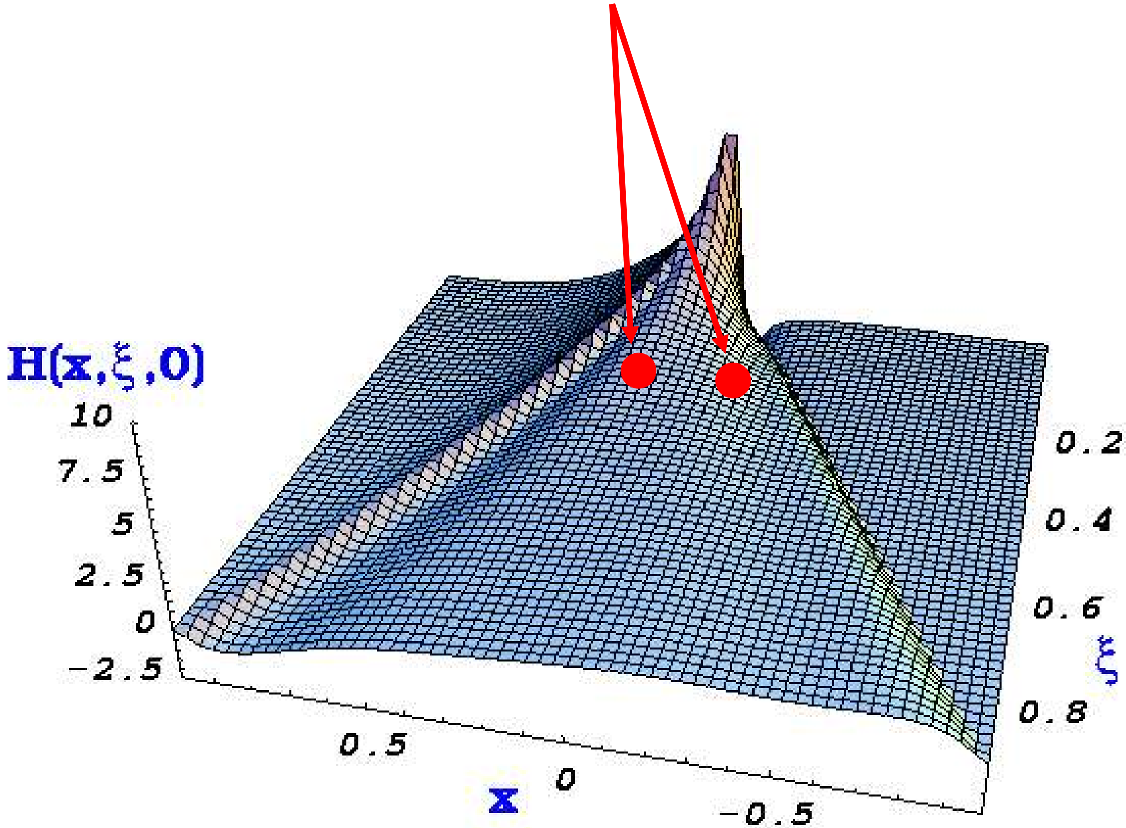


DDVCS
(Double Deeply Virtual Compton Scattering)

DDVCS-BH interference generates a **beam spin asymmetry** sensitive to

$$\operatorname{Im} T^{DDVCS} \sim H(\pm x(\xi, q'), \xi, t) + \ldots$$





The (continuously varying) virtuality of the outgoing photon allows to "tune" the kinematical point (x,ξ,t) at which the GPDs are sampled (with |**x** | < ξ).

M. Guidal & M. Vanderhaeghen, PRL 90
A. V. Belitsky & D. Müller, PRL 90

DDVCS: first observation of $ep \rightarrow epe^+e^-$

* **<u>Positrons identified</u>** among large background of positive pions

* **<u>$ep \rightarrow epe^+e^-$ cleanly selected</u>** (mostly) through missing mass $ep \rightarrow epe^+X$

* Φ distribution of outgoing γ^* and <u>beam spin asymmetry</u> extracted (integrated over γ^* virtuality)

but…

<u>A problem for both experiment and theory</u>:

* 2 electrons in the final state → *antisymmetrisation* was not included in calculations,

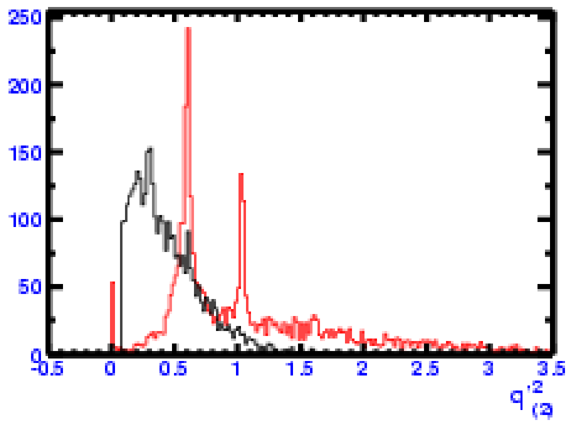
→ define domain of validity for *exchange diagram*.

* data analysis was performed assuming two different hypotheses

either detected electron = scattered electron

or detected electron belongs to lepton pair from γ^*

Lepton pair squared invariant mass

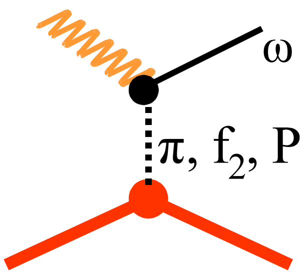


Hyp. 2 seems the most valid

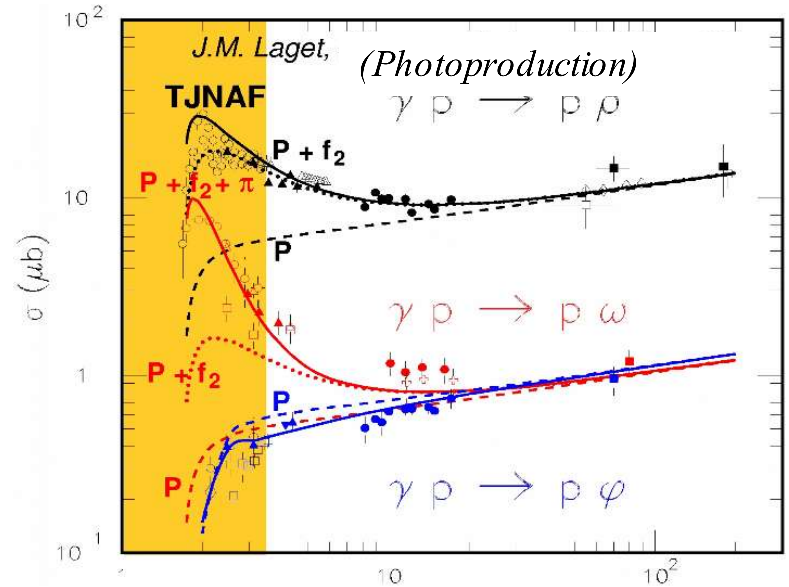
→ **quasi-real photoproduction of vector mesons**

Deeply virtual meson production

Meson and Pomeron (or two-gluon) exchange …



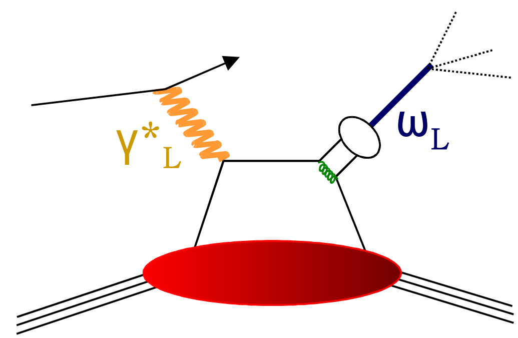
ρ^0	(σ), f_2, P
ω	π, f_2, P
Φ	P



… or scattering at the quark level ?

Flavor sensitivity of DVMP on the proton:

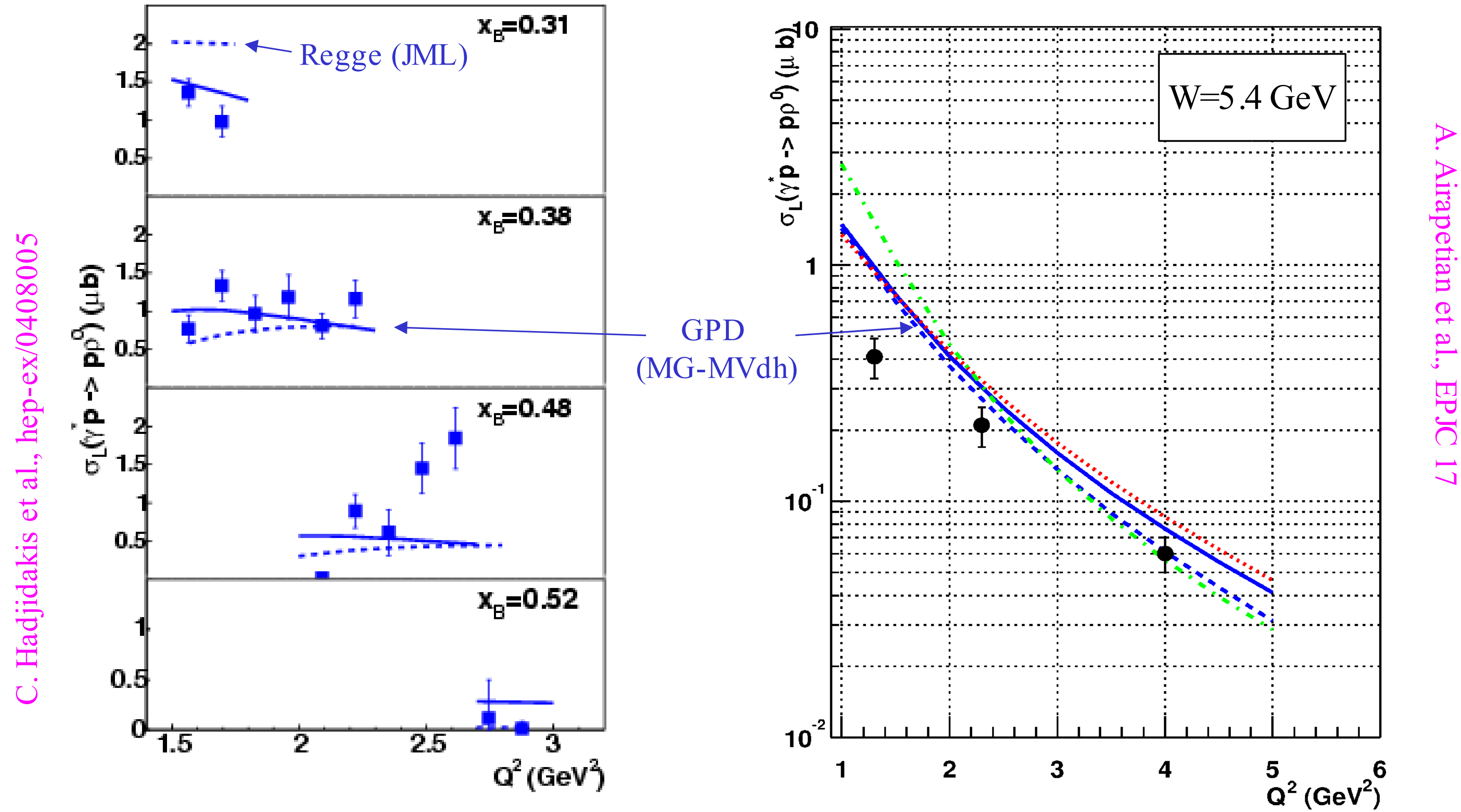
ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4
Φ	s, g
ρ^+	u-d



$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4}\left[\frac{\alpha_S}{Q}\sum\iint \frac{\psi_M(z)}{z}\,\frac{1}{x\pm\xi \mp i\varepsilon}(aH+bE)(x,\xi,t)\,dx\,dz\right]^2 \propto \frac{f(\xi,t)}{Q^6}$$

***Exclusive* ρ *meson production: ep* → *ep*ρ**

CLAS (4.2 GeV) HERMES (27 GeV)

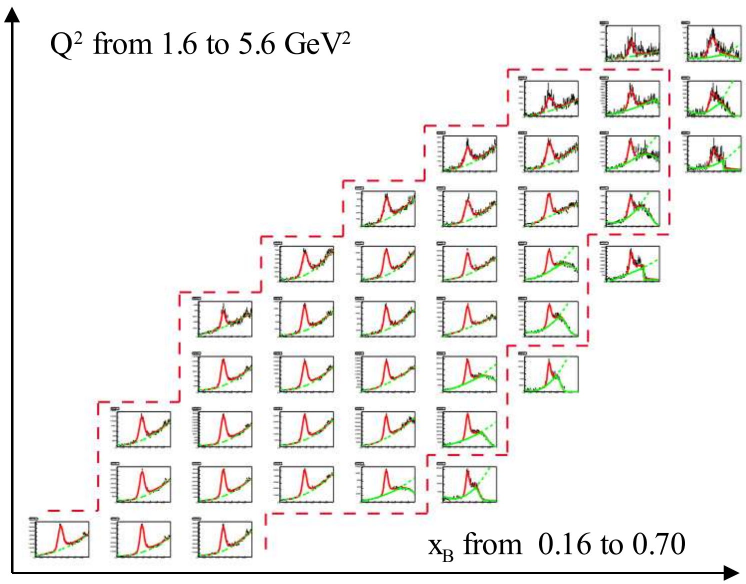


GPD formalism (beyond leading order) describes approximately data for x_B<0.4, Q^2 >1.5 GeV^2

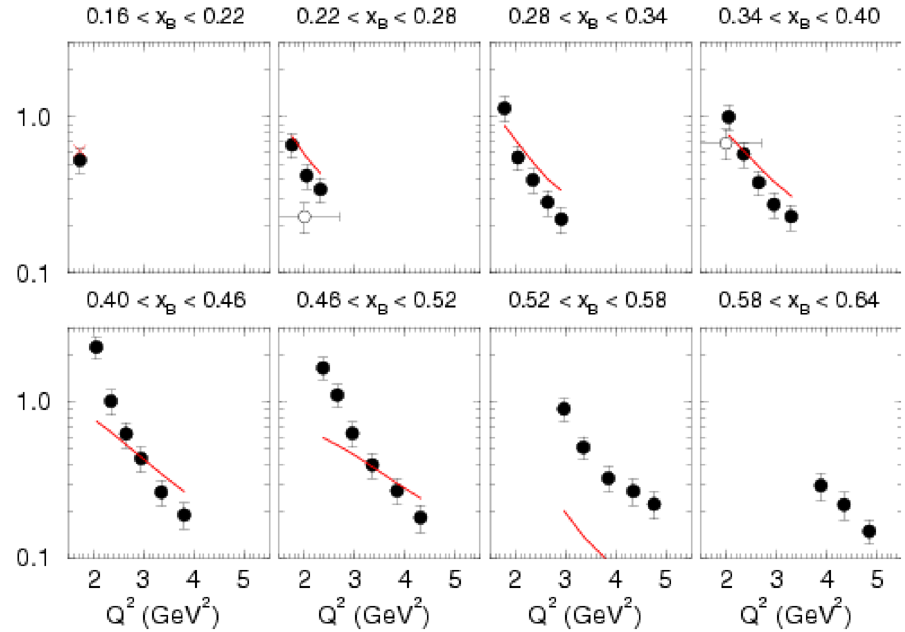
(See also P. Bosted's talk on Friday afternoon, session 5: double spin asymmetries in ep → epρ)

Deeply virtual* ω *production at 5.75 GeV

*Analysis of **cross sections** from for ep → epπ⁺X configurations*



ω peak in MM[epX] for (Q^2,x_B) bins



Ludyvine Morand's thesis, publication in preparation

*Analysis of **ω polarization** from ep → epπ⁺π⁻X configurations*

(for the first time for this channel above $Q^2 \sim 1$ GeV²)

- Cross sections larger than anticipated at high t (see J.-M. Laget, PRD 70, 054023)
- SCHC does not seem to hold → not possible to extract σ_L

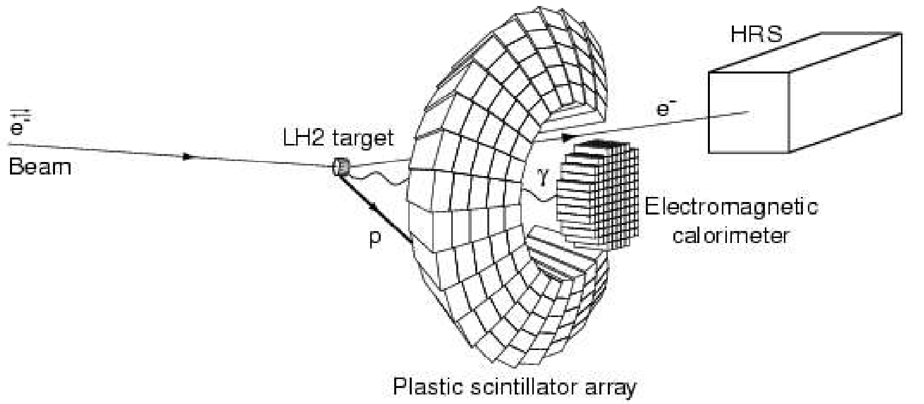
  handbag diagram estimated to contribute only about 1/5 of measured cross sections

→ **ω most challenging/difficult channel to access GPD**

- Evidence for unnatural parity exchange → π^0 exchange very probable even at high Q^2

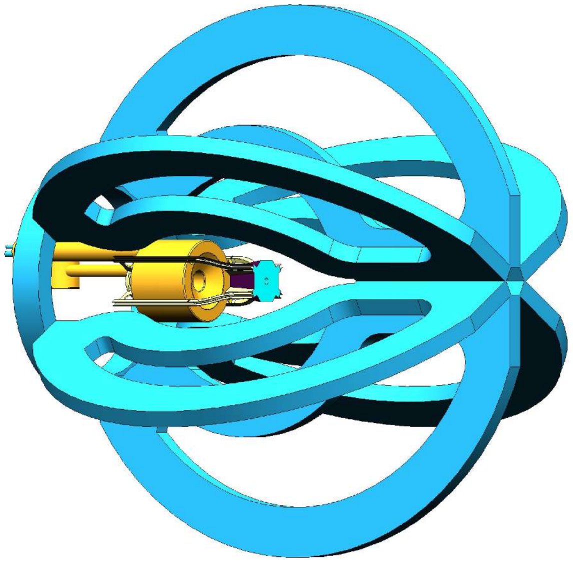
JLab dedicated DVCS experiments in 2004 - 2005

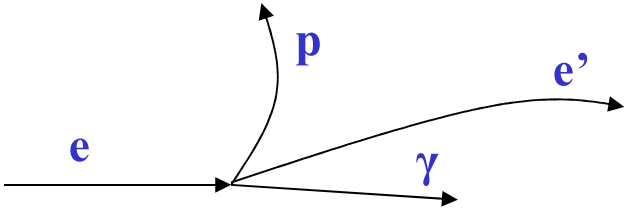
JLab/Hall A



JLab/CLAS

Calorimetrer and supraconducting magnet within CLAS torus





<u>Dedicated, high statistics, DVCS experiments</u>

→ Virtual Compton scattering at the quark level

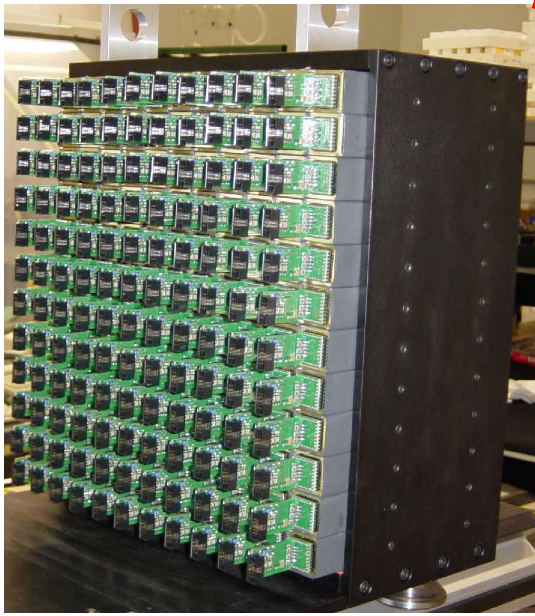
→ If scaling laws are observed (up to $Q^2 \sim 5$ GeV^2), or deviations thereof understood, first significant measurement of GPDs.

→ Large kinematical coverage in x_B and t leads to 3D-picture of the nucleon

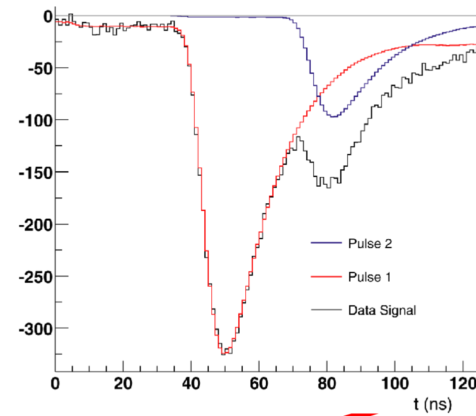
→ Opens the way for an ambitious program with JLab@12GeV (CLAS++ and other)

Experiment started mid-September

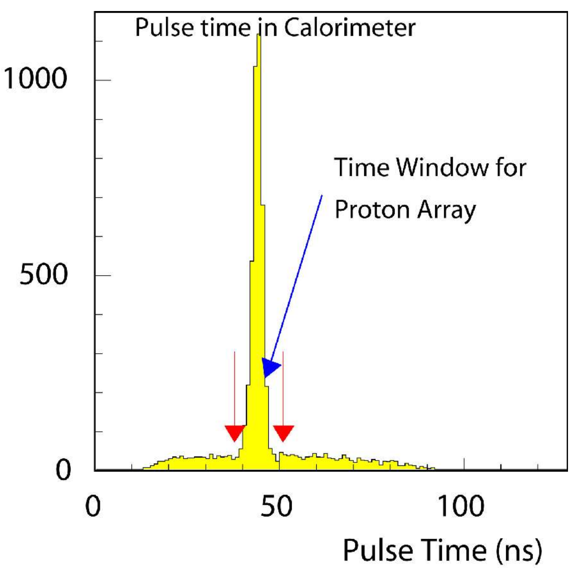
PbF_2 electromagnetic calorimeter



Fast-digitizing electronics
→ analysis of double pulses (pile-up)



Scintillator array for proton detection



HMS•calo ←

First

double

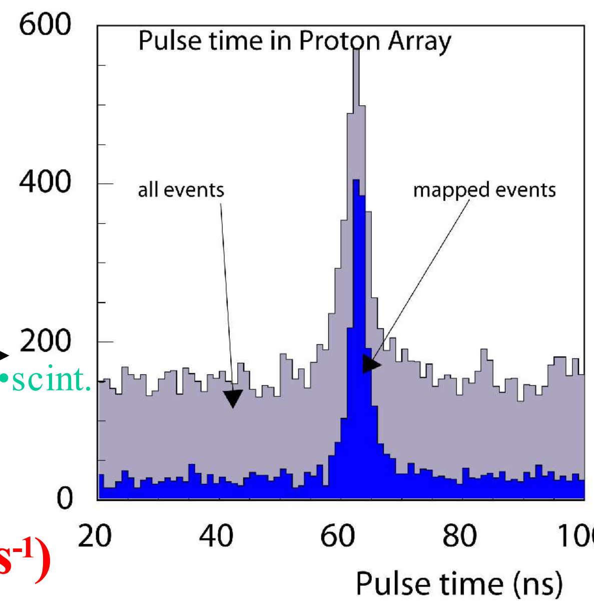
and

triple

→ HMS•calo•scint.

coincidences !

(luminosity = 10^{37} cm^{-2}s^{-1})



Hall A DVCS at 6 GeV – Projected results

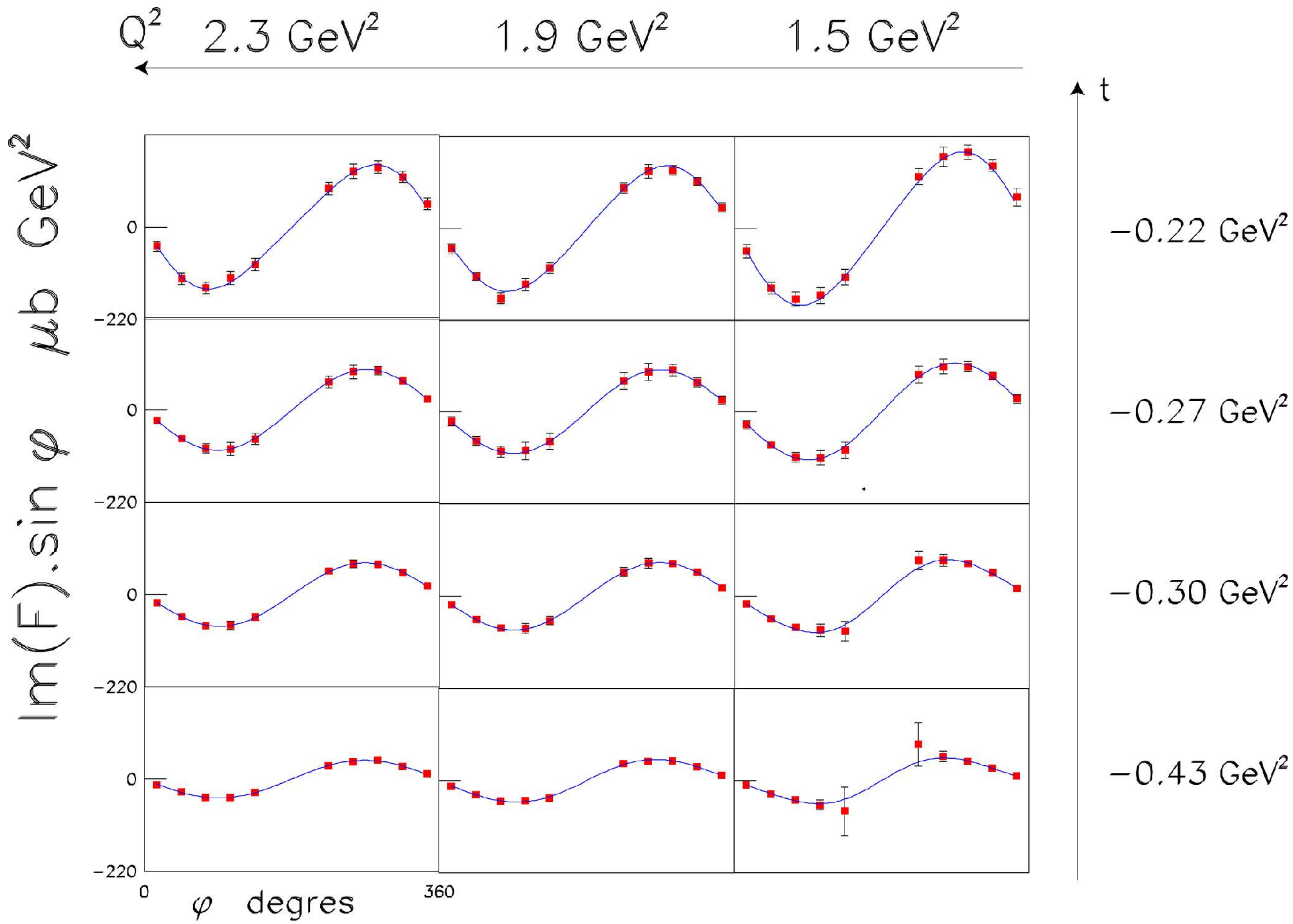
Unique characteristics:

- Very high luminosity (10^{37} cm^{-2}s^{-1})
- Well defined kinematics (high resolution)

➡ High precision for Q^2 up to 2.5 GeV^2 at fixed $x_B = 0.35$

Method:

Measure *cross-section differences* ("purer" than asymmetries) as function of φ angle. Deduce Q^2 dependence and relative importance of twist-2 and higher twists.



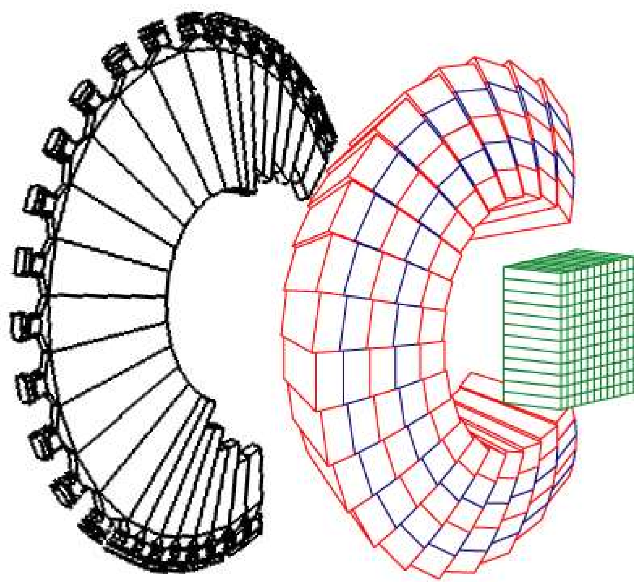
Goals:

- Test factorization of DVCS
- Measure linear combinations of GPD's

DVCS on the neutron

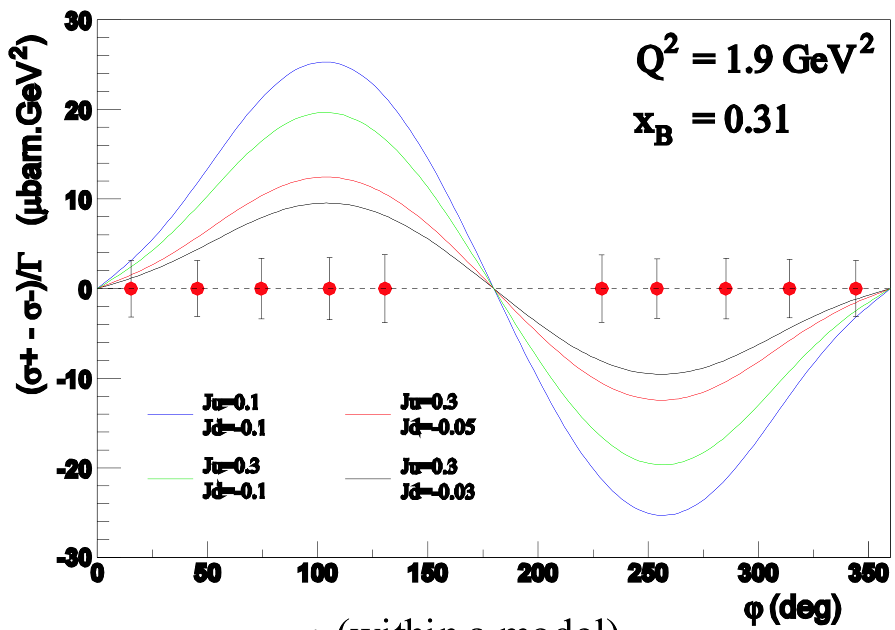
DVCS-BH interference generates
a **beam spin cross section difference** $\sigma^+ - \sigma^- = \Gamma \cdot [A \sin\Phi + \ldots]$

$$A = \underbrace{F_1(t)\cdot \mathrm{H}}_{\text{Main contribution for the proton}} + \frac{x_B}{2 - x_B}\left[F_1(t) + F_2(t)\right]\cdot \widetilde{\mathrm{H}} - \underbrace{\frac{t}{4M^2} F_2(t)\cdot \mathrm{E}}_{\text{Main contribution for the neutron}}$$



Veto detector added to the p-DVCS set-up

Run in November 2004

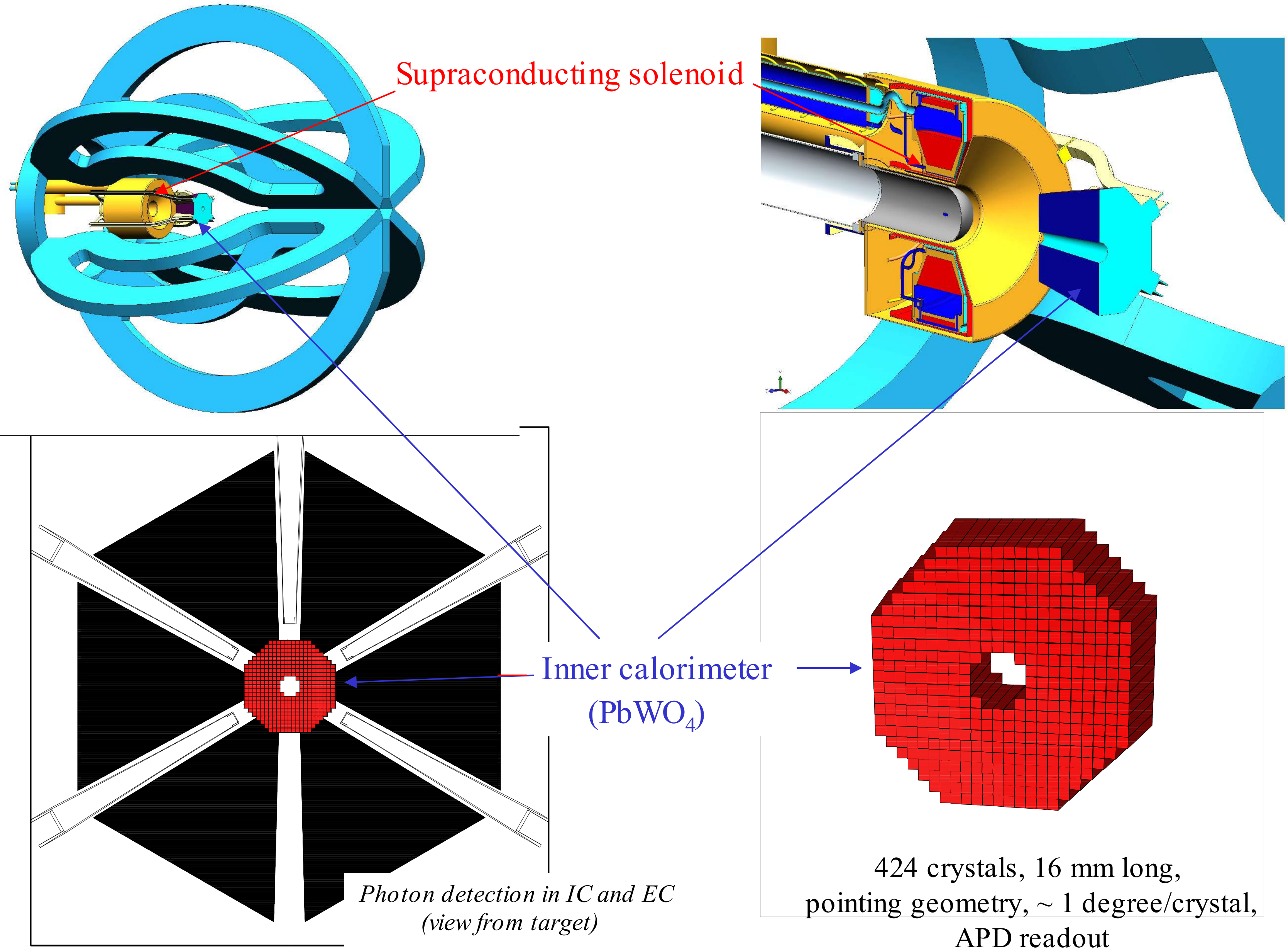


→ (within a model)

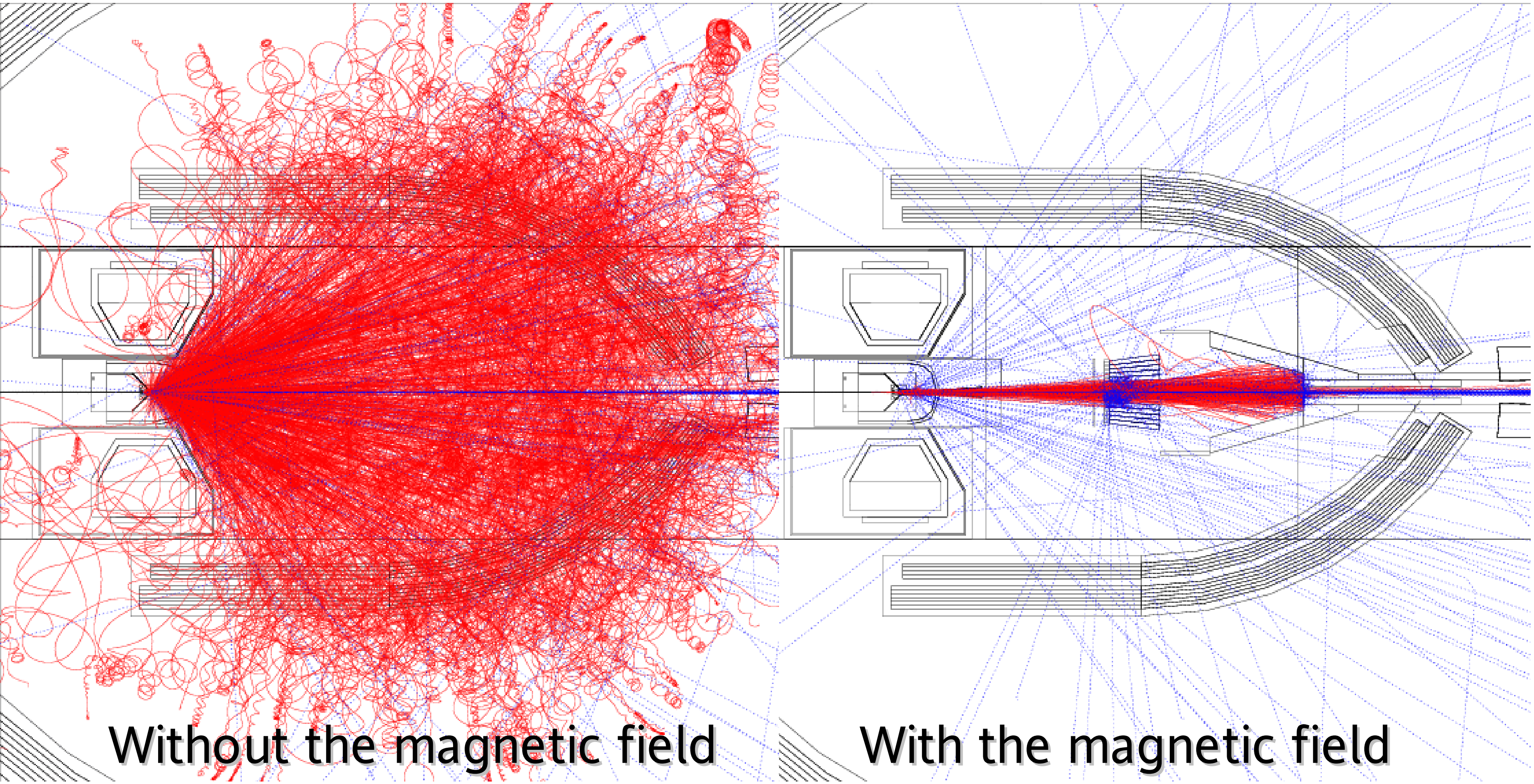
Sensitivity to quark angular momentum J

(P. Bertin, C.E. Hyde-Wright, F. Sabatié, E. Voutier et al. CEBAF/E-03-106)

CLAS/ DVCS

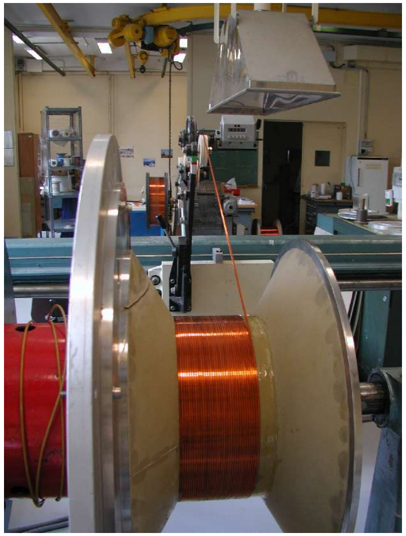

Supraconducting solenoid
Inner calorimeter
($PbWO_4$)
Photon detection in IC and EC
(view from target)
424 crystals, 16 mm long,
pointing geometry, ~ 1 degree/crystal,
APD readout

Møller electrons active magnetic shielding



CLAS/ DVCS

Magnet components



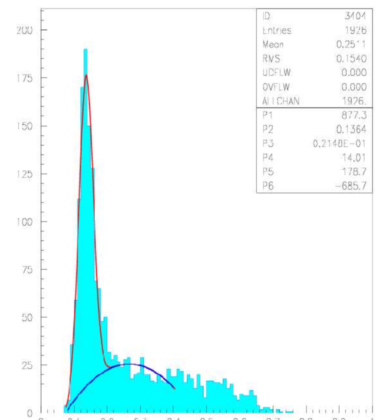
Main (trapezoidal) coil: from first to last (64th) layer

80K heat shield and mandrel holding legs

100 crystals prototype test at the end of 2003

$$\frac{\sigma}{E} \approx \frac{0.045}{\sqrt{E}} \oplus \frac{0.04}{E} \oplus 0.01$$

$$\sigma_x(\text{mm}) \approx \frac{1.8}{\sqrt{E}} \oplus 0.2$$

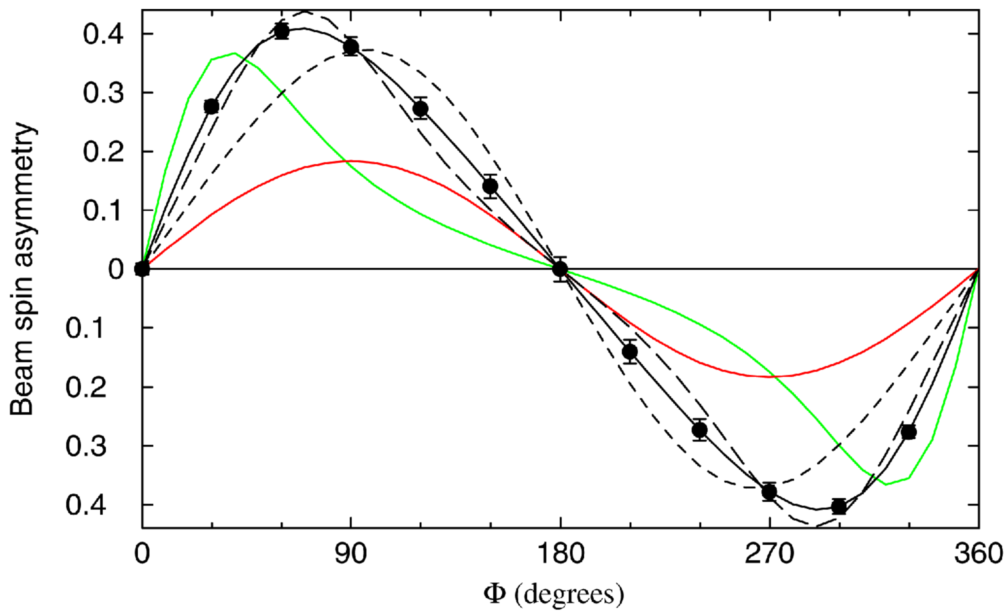


π^0 mass peak

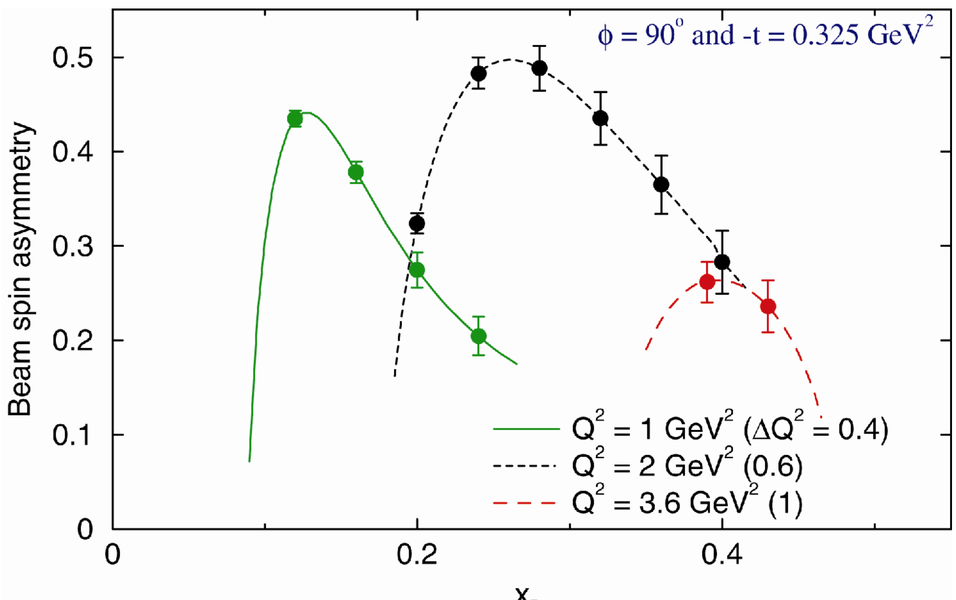
$\sigma \approx 21$ MeV

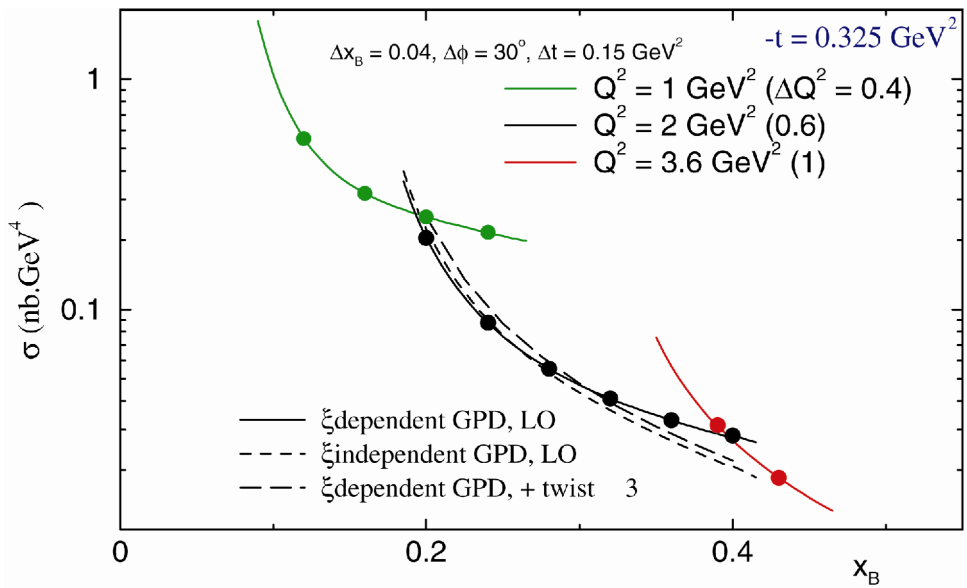
(with online calibration)

Projected results (sample)



Dependence of φ asymmetry and total cross-section as a function of x_B, t, Q^2, φ (372 bins)





E01-113 V. Burkert, L. Edouardrihi, M. Garçon, S. Stepanyan et al.

Run March-May 2005

DVCS on the deuteron

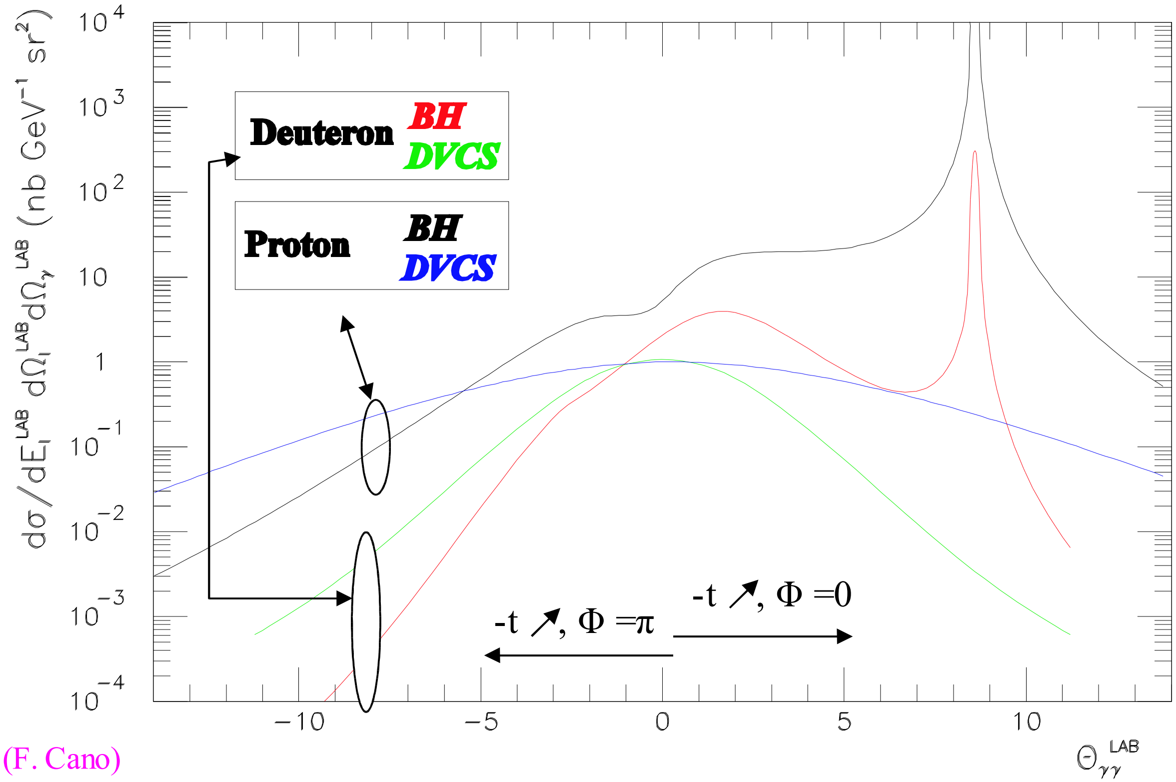
• **The deuteron as a neutron target** $e\, d \rightarrow e\, p_{sp}\, n\, \gamma$ (see above Hall A experiment in 2004)

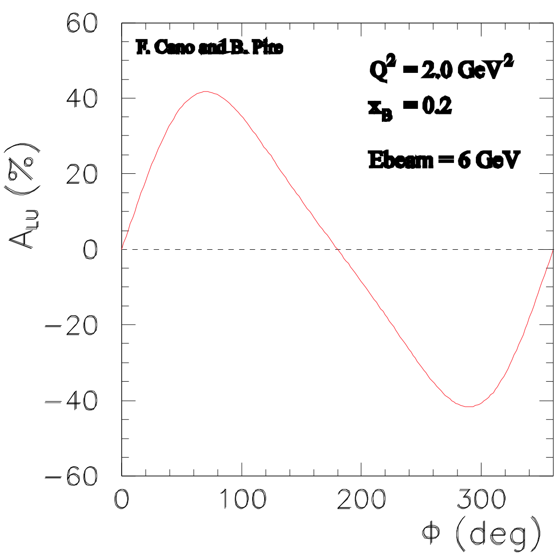
• **Coherent DVCS** $e\, d \rightarrow e\, d\, \gamma$ (feasible in CLAS and HERMES)

General formalism worked out (E.R. Berger et al.)

First model calculations (F. Cano & B. Pire)

Up to heavy nuclei (M.V. Polyakov PL B555, A. Kirchner & D. Müller, A. Freund & M. Strikman) : HERMES prel. data

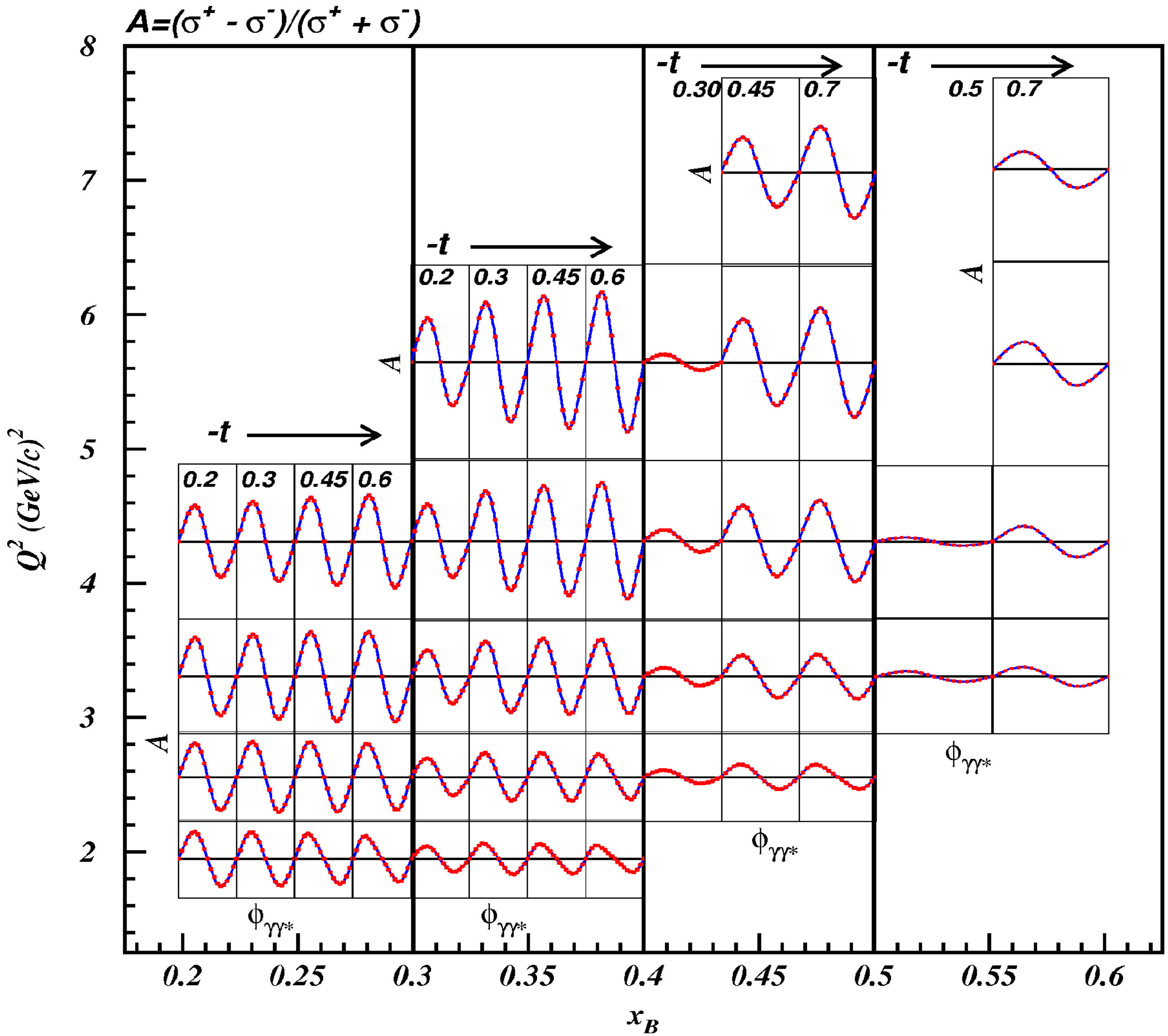




(F. Cano)

CLAS analysis in progress (F. Sabatié) + test run following CLAS/DVCS experiment ?

DVCS/BH projected for CLAS^{++} at 11 GeV



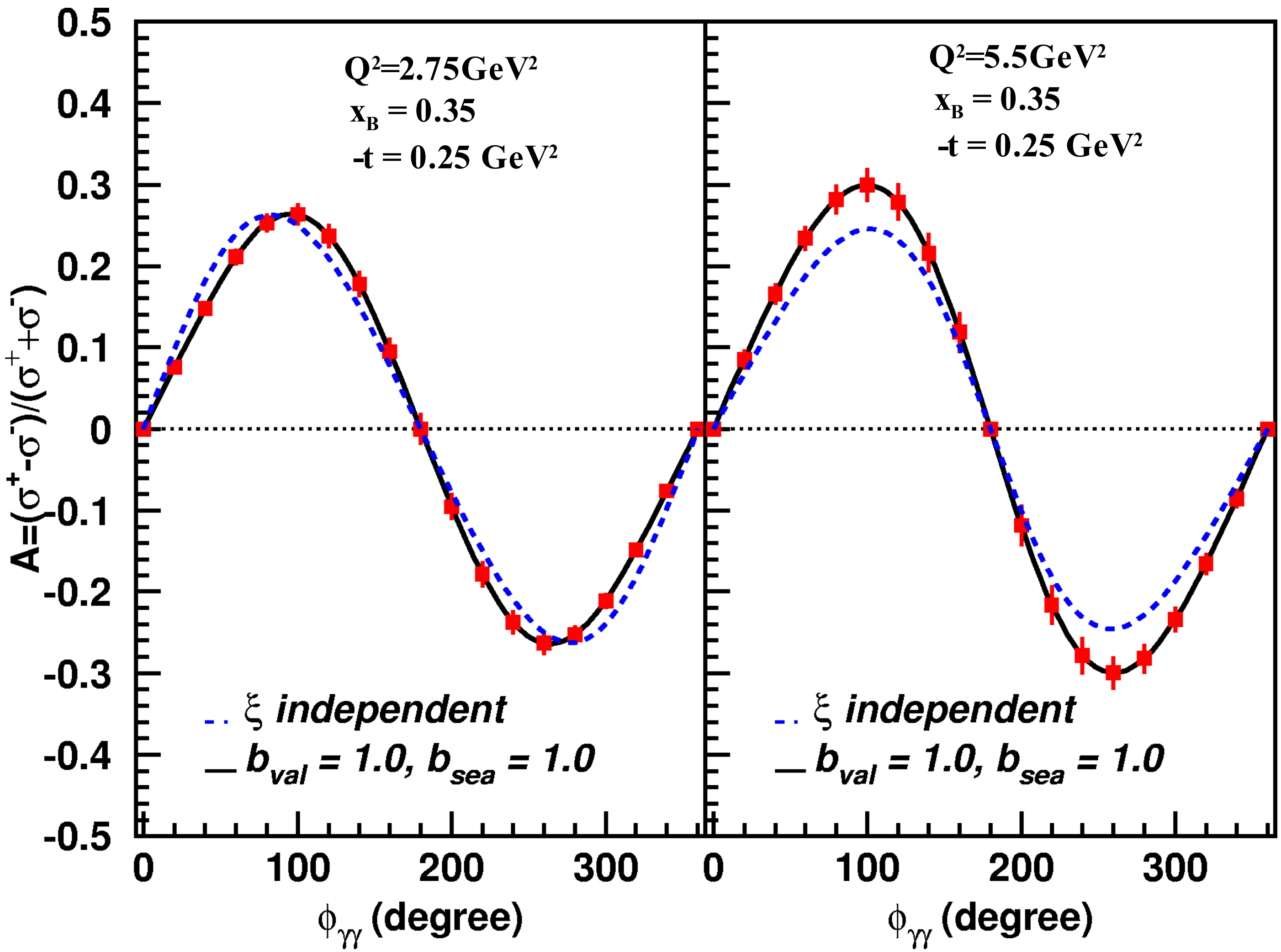
972 data points measured simultaneously

Q^2, x_B, t ranges measured simultaneously.

$A(Q^2,x_B,t)$
$\Delta\sigma\ (Q^2,x_B,t)$
$\sigma\ (Q^2,x_B,t)$

DVCS with CLAS^{++} at 11 GeV

2% of all data points that are measured simultaneously.



Conclusions and outlook

DIS/SIDIS (scattering at the quark level) **is being understood at moderate Q^2.**
Factorization is shown to work at lower energies than previously thought.

Jefferson Lab,
with the CEBAF beam energy nearing 6 GeV for the past two years,
and with its first data above the resonance region,
contributes and will contribute fully to the determination of polarized quark distributions (helicity and transversity).

Rich phenomenology in SSA, being explored experimentally

GPDs have emerged as an <u>attractive</u> and <u>unifying</u> concept for the nucleon structure

Jefferson Lab
is playing a leading role in providing the experimental basis of this concept.
Once proper scaling laws are verified in DVCS (and possibly DVMP),
first significant constraints on GPD models from dedicated experiments
A complete mapping and measurement of GPDs will probably have to await the 12 GeV upgrade.