The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1751 - 54

Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Physics with CLAS at JLab

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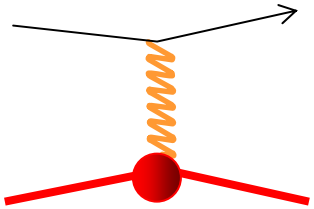
FRANCE

Physics with CLAS at JLab
(selected topics)

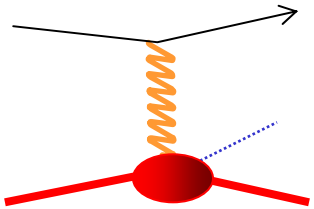
Hadron structure studies,

Electron elastic scattering



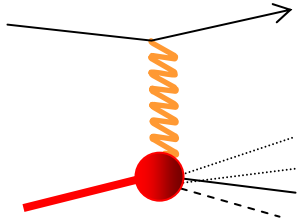
Form factors

Inelastic scattering
(γN, eN)



Excited states (resonances)

Deeply inelastic scattering



Parton distributions,
Transverse Momentum Distr.
Generalized Parton Distr.

… a word on Color Transparency

… and a blink into the future: CLAS12

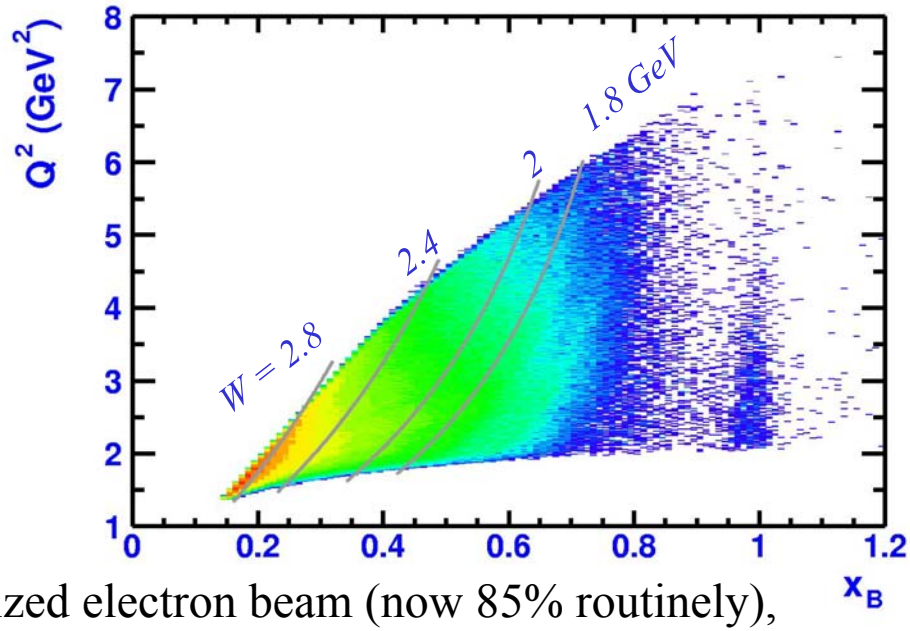
The specificities of CLAS

♠ High luminosity x acceptance

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

♥ Large *x* range

and from resonance region to DIS



♦ Good resolution

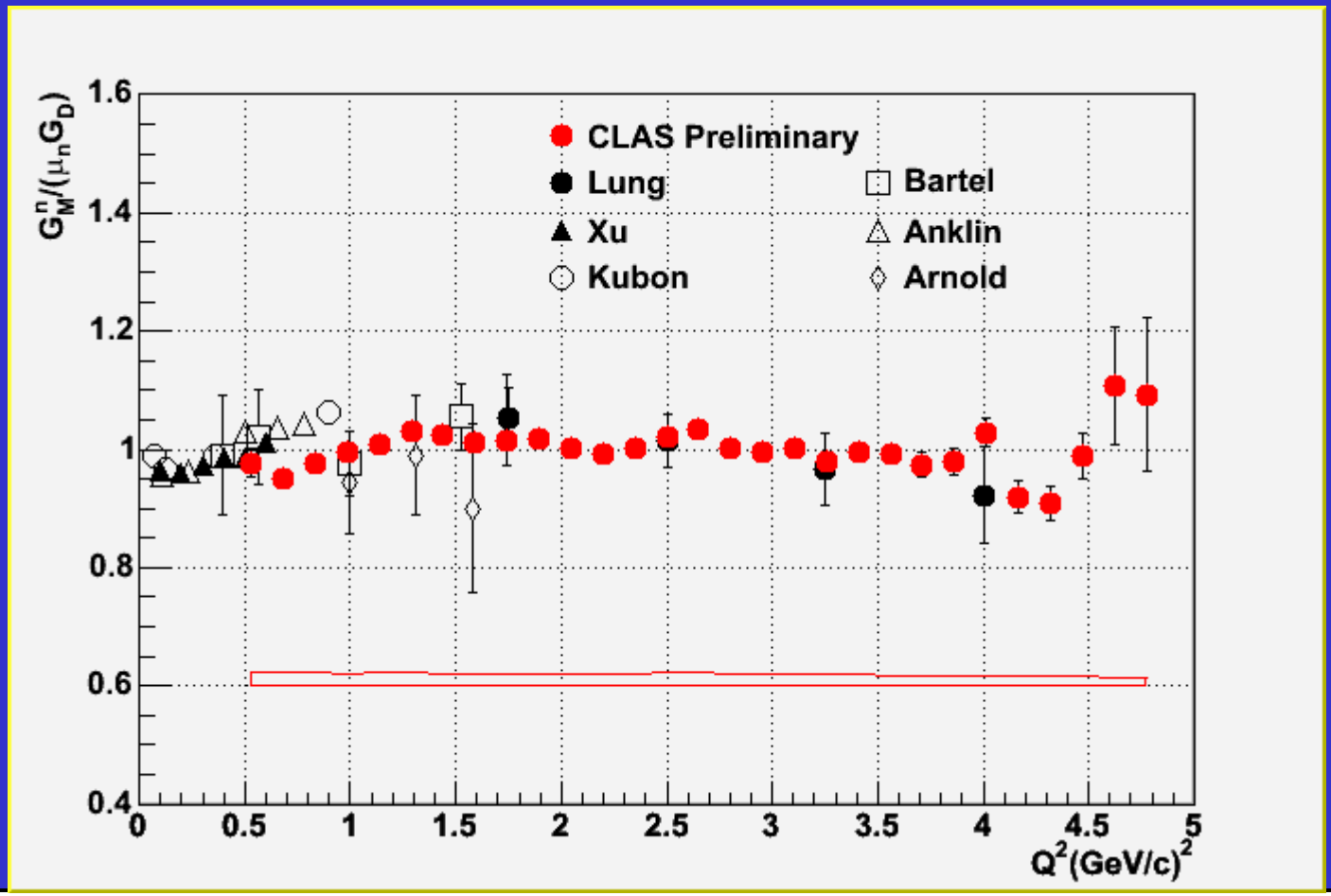
truly exclusive measurements

♣ Experimental equipment

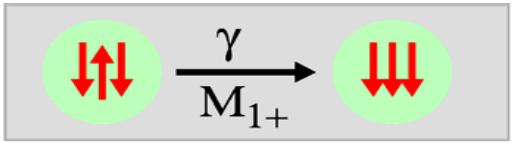
highly polarized electron beam (now 85% routinely),
tagged photon beam,
with new capability for linear polarization (> 90%)
longitudinally polarized target (+ new plans),
specific equipment for dedicated experiments
(GDH at low Q^2, DVCS, BoNuS, etc)

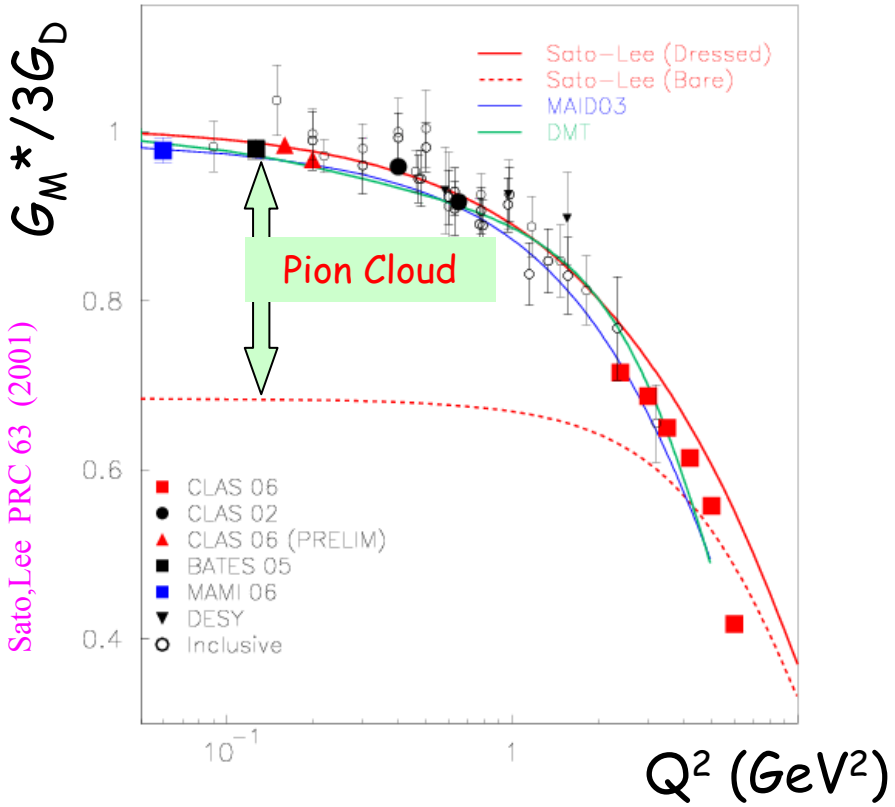
Neutron magnetic form factor

$$R = \frac{\frac{d\sigma}{d\Omega}\left(D(e,e'n)\right)}{\frac{d\sigma}{d\Omega}\left(D(e,e'p)\right)} = a(Q^2)\,\frac{\frac{G_{En}^2+\tau G_{Mn}^2}{1+\tau} + 2\tau G_{Mn}^2 \tan^2\left(\frac{\Theta}{2}\right)}{\frac{G_{Ep}^2+\tau G_{Mp}^2}{1+\tau} + 2\tau G_{Mp}^2 \tan^2\left(\frac{\Theta}{2}\right)}$$



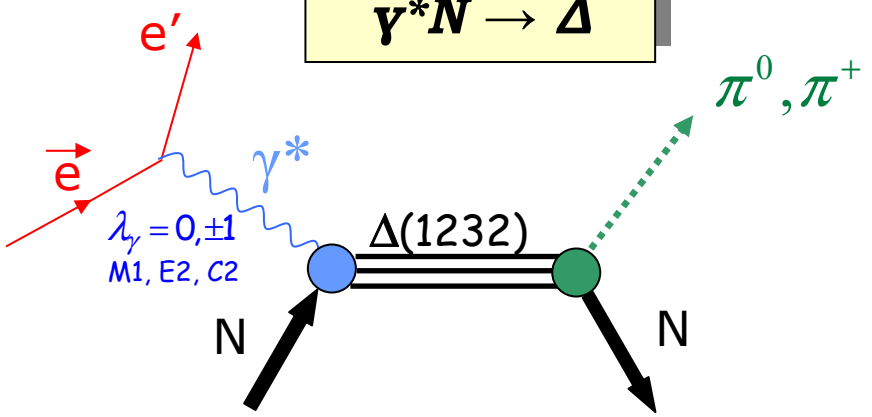
Dominant magnetic dipole transition and the pion cloud



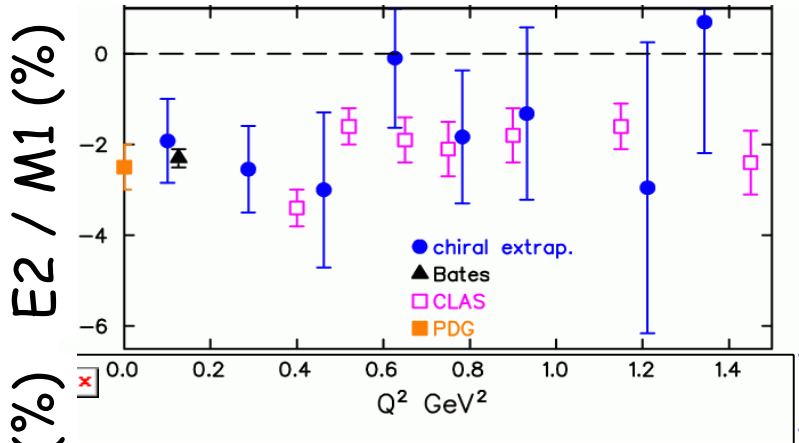


Fits of dynamical pion models to π photoproduction data suggest 30-50% of M1 photocoupling strength near $Q^2=0$ due to meson rescattering at EM vertex.

$\gamma^* N \rightarrow \Delta$



Small quadrupole transitions and lattice QCD



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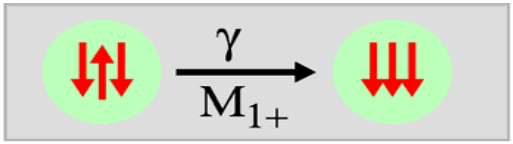

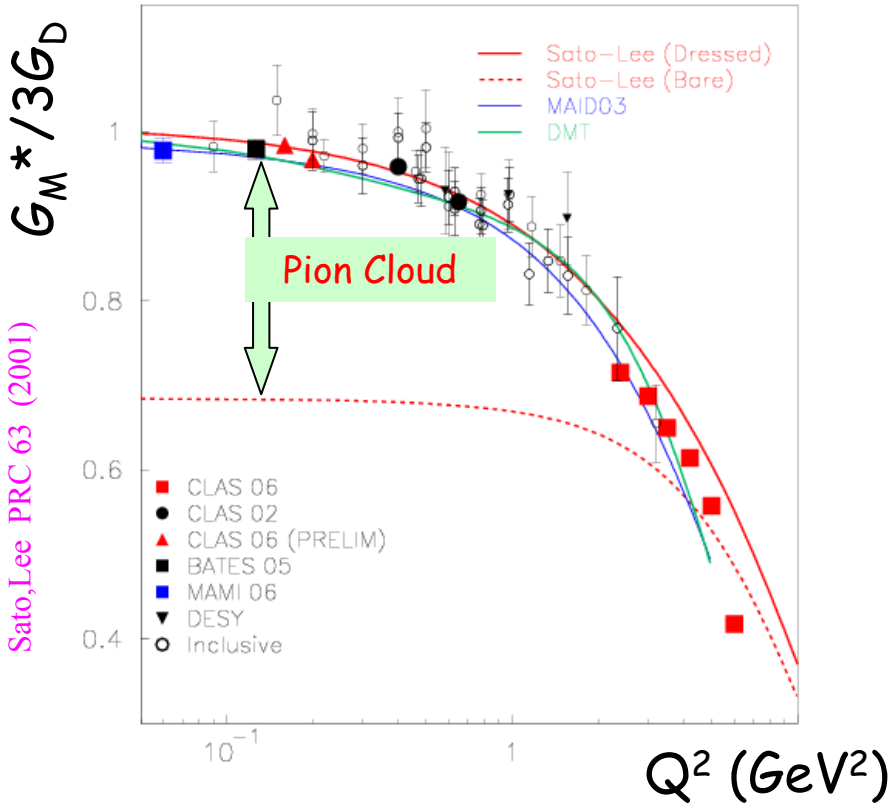

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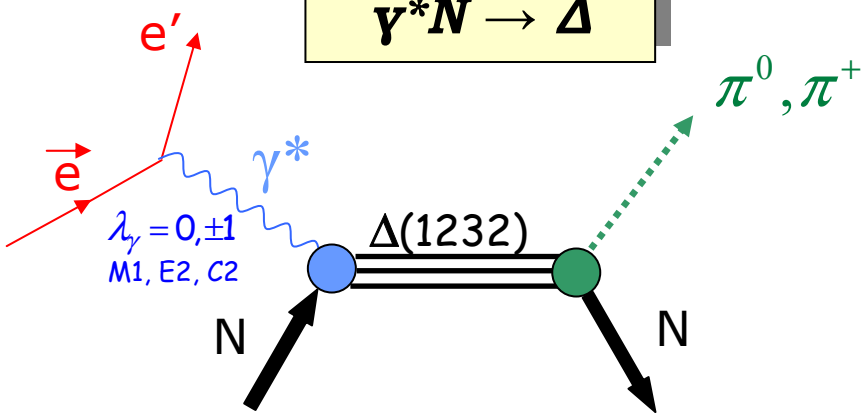
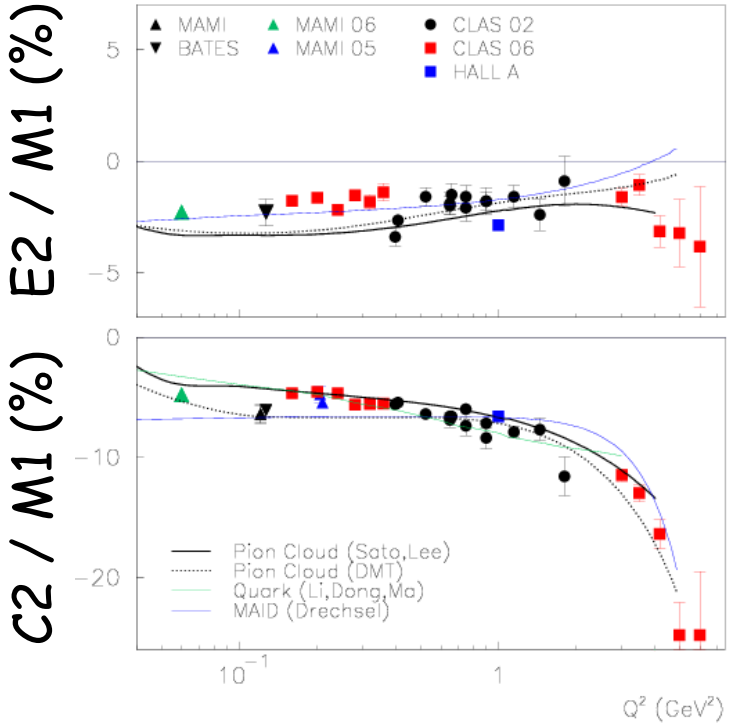
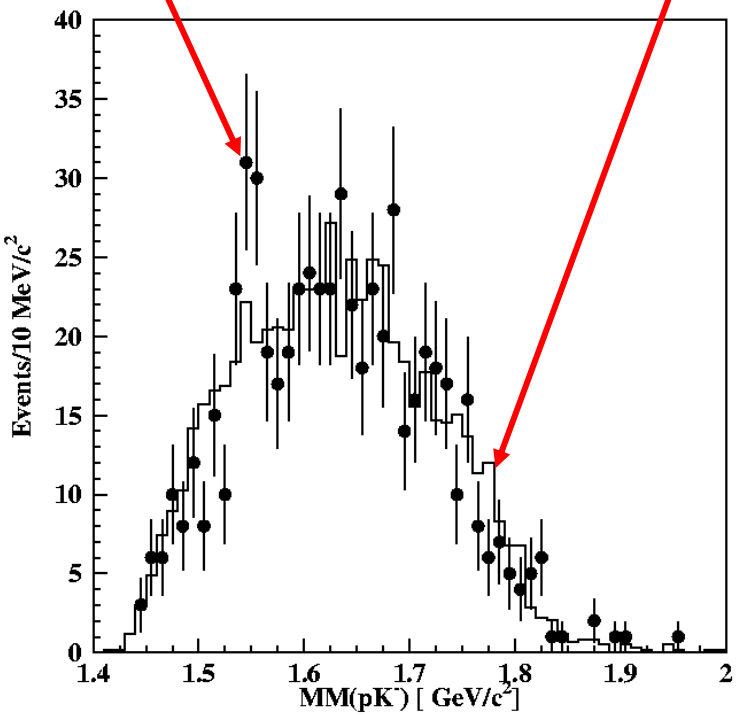


Small quadrupole transitions and new data



Pentaquark:
not declared dead, but in deep coma

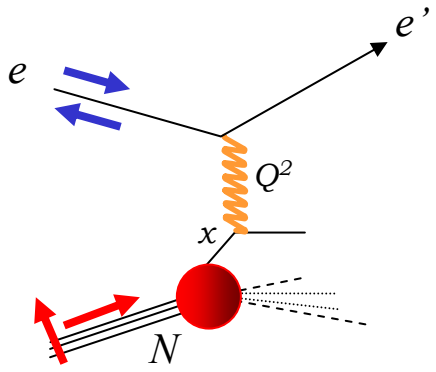
Reaction channel	*Non dedicated experiments*	*Dedicated experiments*
$\gamma d \to \underline{nK^+}K^- p$	Phys. Rev. Lett. **91** (2003)	hep-ex/0603028 (accepted in PRL)



Pentaquark: not declared dead, but in deep coma

Reaction channel	**Four new results (*and more to come*) from 2 dedicated high statistics runs put stringent limits on Θ^+ and Θ^{++} production**	*Dedicated experiments*
$\gamma d \to n K^+ K^- p$		hep-ex/0603028 (accepted in PRL)
$\gamma p \to \pi^+ K^- K^+ n$		Expt in 2007
$\gamma p \to \overline{K}^0 K^+ n$		Phys. Rev. Lett. **96** (2006) Supersedes SAPHIR obs.
$\gamma d \to \Lambda K^+ n$		hep-ex/0604047 (submitted to PRL)
$\gamma p \to p K^+ K^-$		hep-ex/0605001 (submitted to PRL)

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→e'X***

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

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

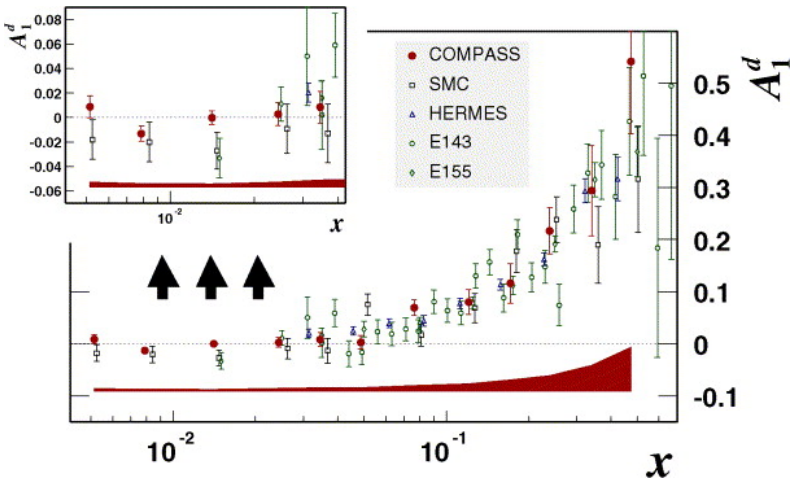
→ how does the quark spin contribute to the nucleon spin ?

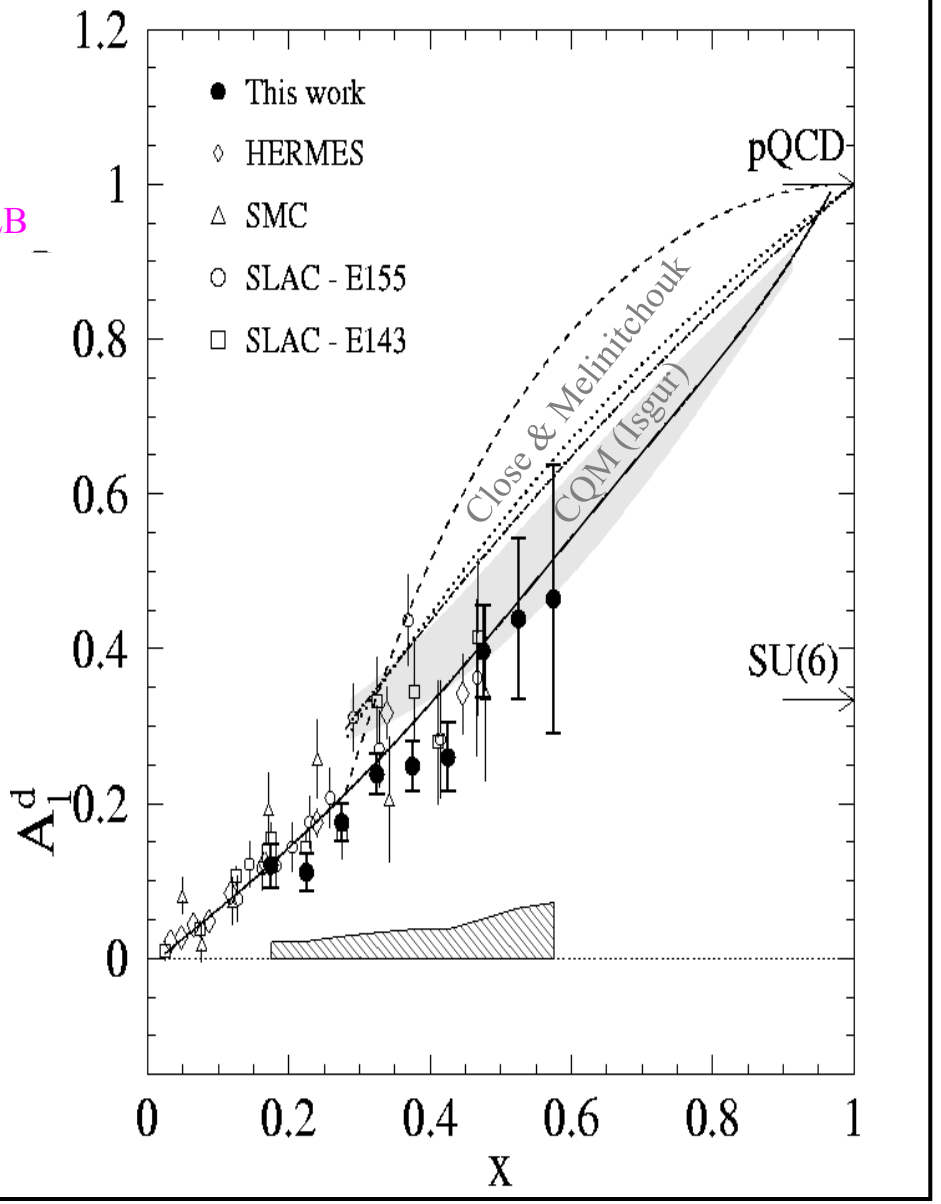
New results for A_1^d at high x

CLAS, nucl-ex/0605028, submitted to PLB
(M. Ripani's talk last Tuesday)

Nicely complement new results at low x

COMPASS, PLB 612 (2005)

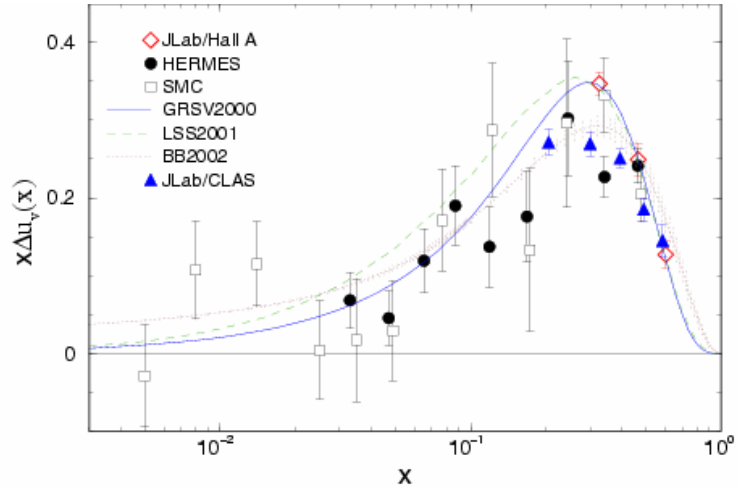


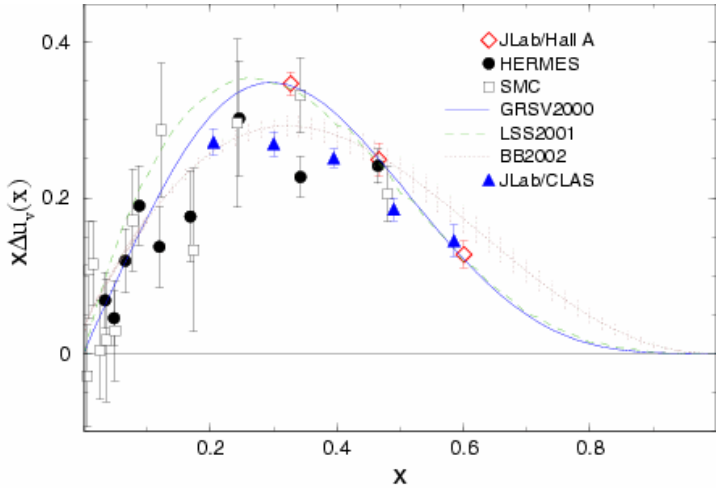


Flavour decomposition from p/n

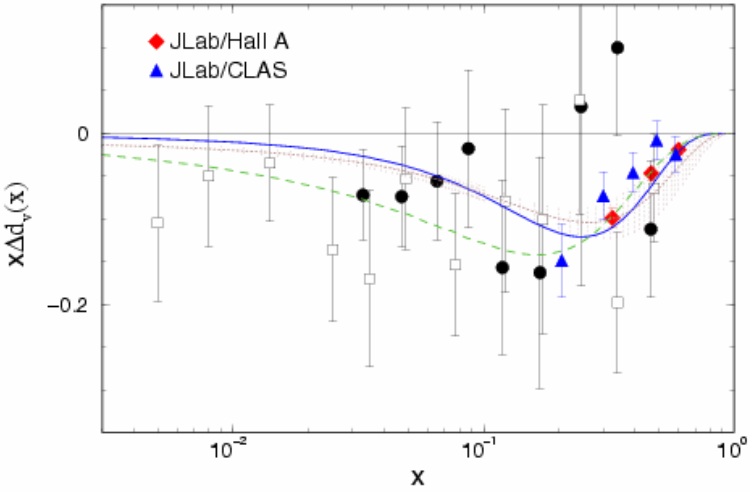
Since $\frac{\Delta q + \Delta \bar{q}}{q + \bar{q}} \approx \frac{\Delta q_v}{q_v}$ in our x-range, extract polarized valence quark distributions

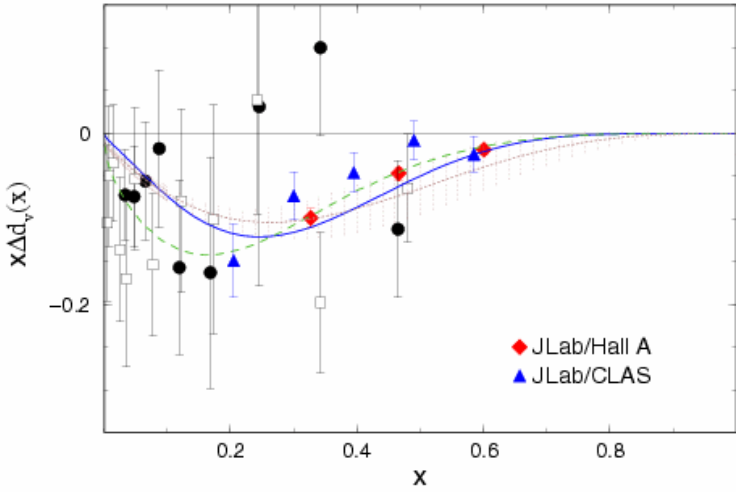
(at Q^2 = 2.5 GeV^2, using evolution only at LO for CLAS data)





(adapted from Review of Particle Properties, PLB **592**; Hall A & CLAS results calculated by MG – not official collaborations results)





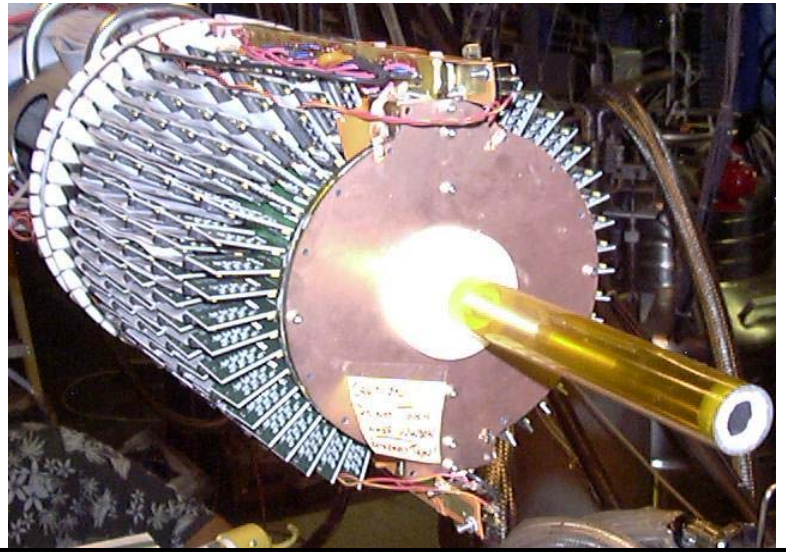
Bound Nucleon Structure (BoNuS - 2005)

Goal: Unpolarized structure function on loosely bound neutrons

from $e^- d \rightarrow e^- p_{back} X$ → determination of d(x)/u(x))

Method: Detection of backward protons
of momenta as low as 70 MeV/c (spectators),
with Radial Time Projection Chamber
(RTPC, built around thin D_2 (H_2) target, placed inside solenoid
for Møller background suppression and momentum analysis)

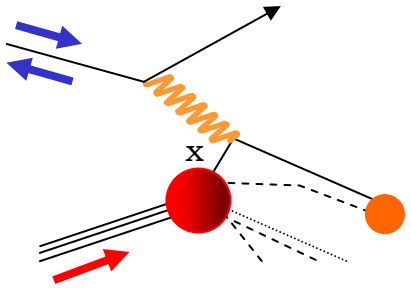
Run: Fall 2005



See also, with standard CLAS setup,
PRC **73**, 035212 (2006)

(p-spectator > 280 MeV/c)

SIDIS Double 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*:

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

SMC PLB 420 (1998), **HERMES** PRD 71 (2005) + **JLab/Hall C** exp.ᵗ in preparation

SIDIS Single Spin Asymmetries

Beam or Target **single spin asymmetries** (A_{LU}/A_{UL}) can also be expressed in terms of

quark distributions x fragmentation functions

(P. Bosted's talk last Tuesday)

Single spin asymmetries in SIDIS

- **Several studies (at CLAS and in other JLab expts) show that**

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

- **Rich phenomenology associated with various SSA**

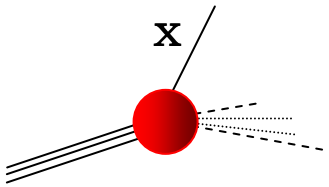
- **SSA linked to transverse momentum distributions (TMD) of partons in the nucleon**

- **SSA ↔ orbital angular momentum**

  ↔ GPD *E*, Pauli form factor F_2

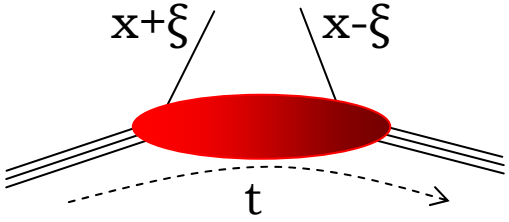
CLAS, PRD **69** (2004)
+ P. Bosted's talk last Tuesday

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 $\psi^*(x+\xi)\bullet\psi(x-\xi)$, or interference, between states of different longitudinal momenta, + t-dependence related to transverse distributions

→ **Generalized parton distributions (GPD)**

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

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

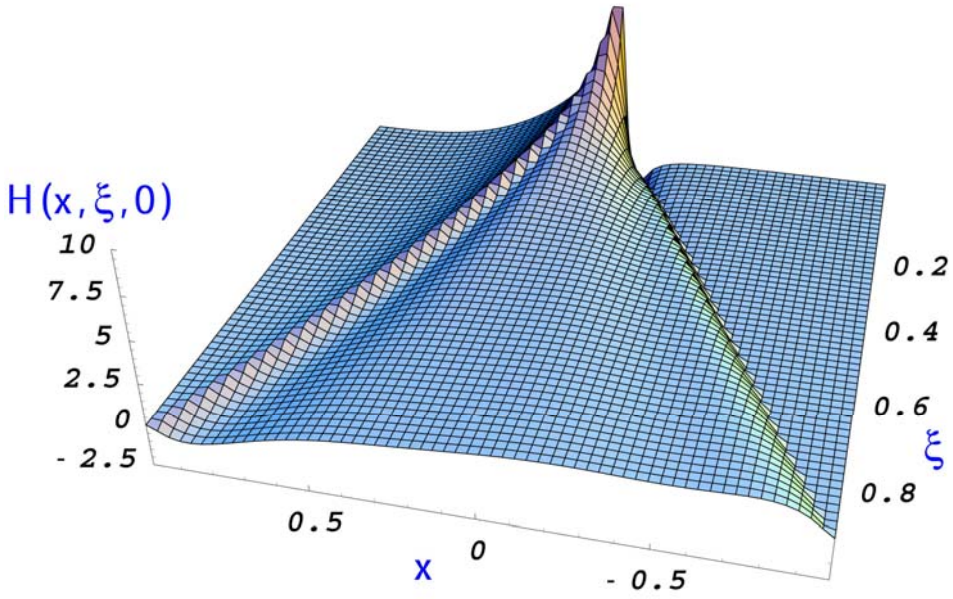
Generalized Parton Distributions: a richer concept of nucleon structure

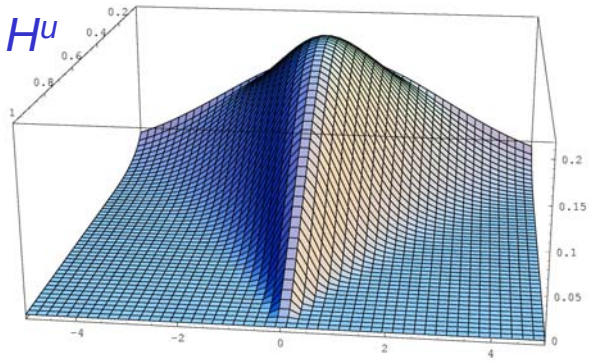
$H, \tilde{H}, E, \tilde{E}\ (x,\xi,t)$

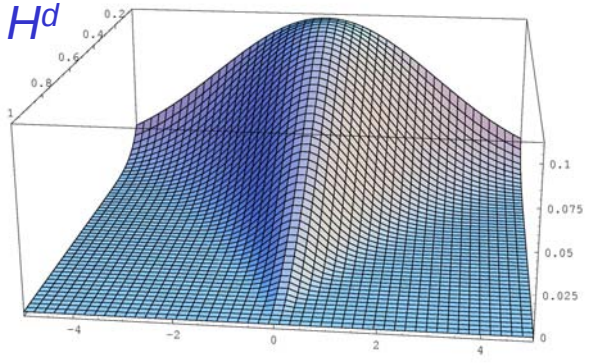
$x-\xi$ correlations

$x-t$ correlations

$\mathcal{F}\{H(x,0,t)\}$

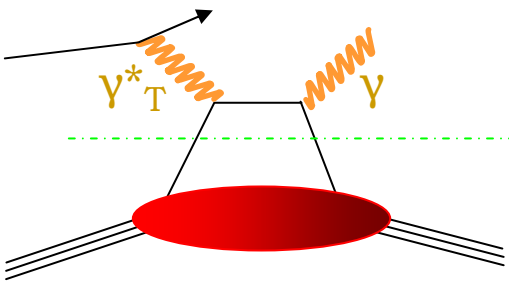




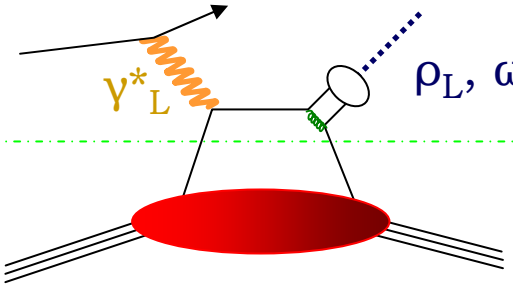


(M. Vanderhaeghen)

Deeply virtual exclusive reactions (DES)



Factorization theorems

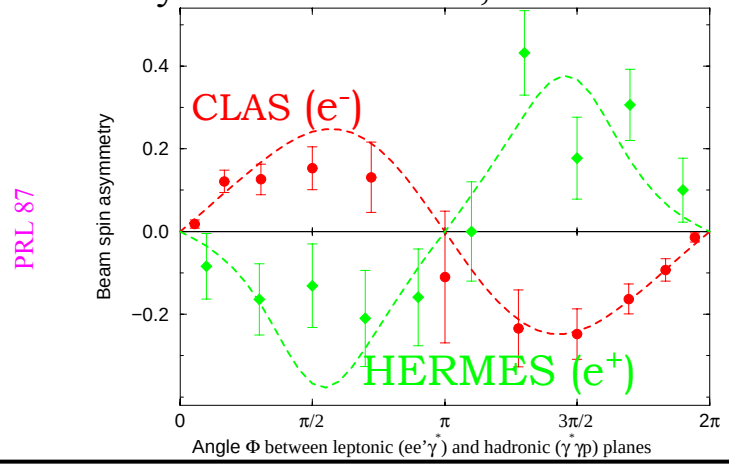


DVCS (Virtual Compton)

- Leading order/twist accessible at moderate Q^2,

- Interference with Bethe-Heitler process,

- Different observables have different sensitivity to the four GPDs,



DVMP (Meson production)

- Handbag diagram dominance expected to be reached at higher Q^2
(but asymmetry ratios may be less sensitive to higher twist contributions)

- Allows a separation (H,E) ↔ $(\widetilde{H},\widetilde{E})$ and according to quark flavors,

- Necessary to extract longitudinal contribution to observables (σ_L, …).

DVCS beam spin asymmetry from high-statistics ep→epX

$$BSA \propto F_1(t)\cdot \mathrm{H} + \frac{x_B}{2-x_B}\left[F_1(t)+F_2(t)\right]\cdot \tilde{\mathrm{H}} - \frac{t}{4M^2}F_2(t)\cdot \mathrm{E}$$

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

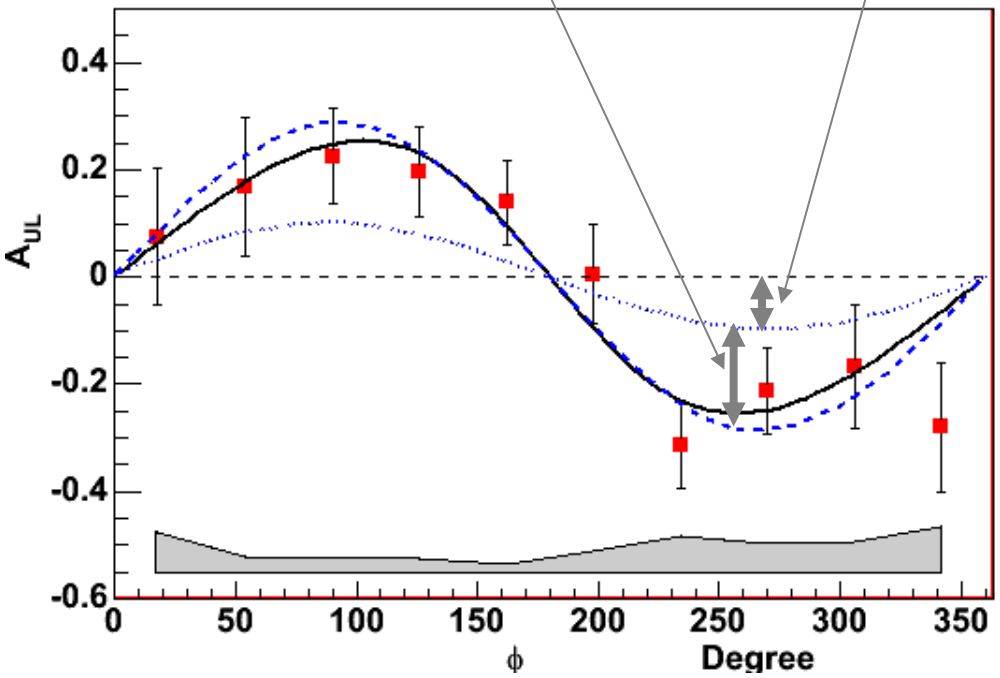
$0.15 < x_B < 0.4$
$1.50 < Q^2 < 4.5$ GeV^2
$-t < 0.5$ GeV^2

GPD based predictions
(Vanderhaeghen)

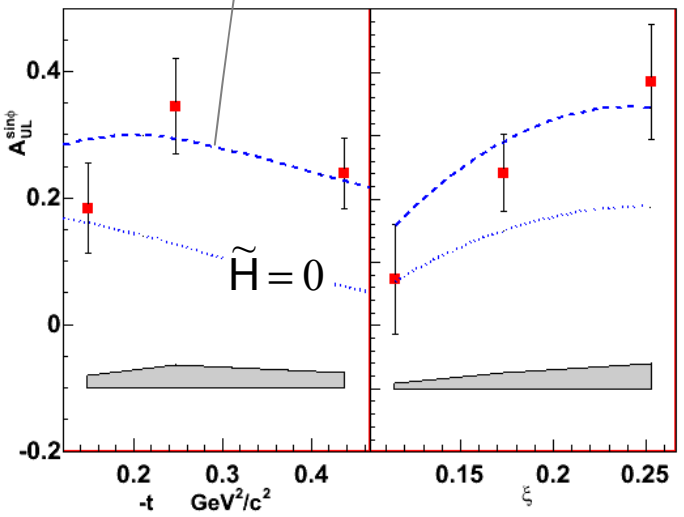
π^0 are suppressed due to analysis cuts (**only low *t***),
residual contribution ($\pi/\gamma \sim$ 5-15%) estimated from MC

DVCS Target Spin Asymmetry (NEW!)

$$TSA \propto F_1 \cdot \tilde{\mathrm{H}} + \frac{x_B}{2-x_B}\left[F_1 + F_2\right]\cdot \mathrm{H} + \frac{x_B}{2-x_B}\left[\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right]\cdot \mathrm{E}$$



Full GPD model,
(VGG, PRD **60** (1999))



ep → epγ on longitudinally polarized NH_3 target

(S. Chen *et al.*, hep-ex/0605012, submitted to PRL)

JLab experiments dedicated to the study of GPDs

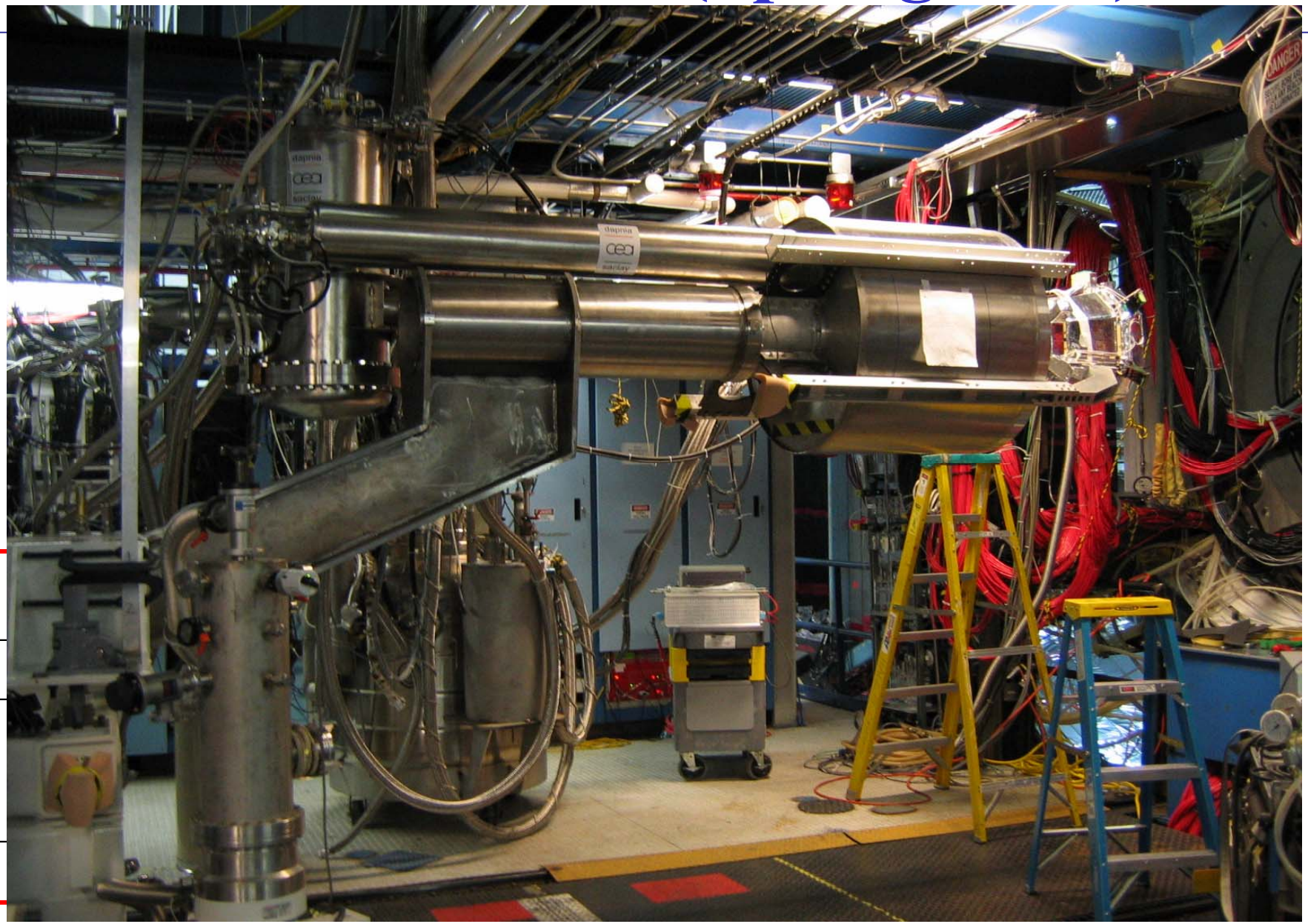
GPD	Reaction	Obs.	Hall	E	Expt#	Status
$H(\pm\xi,\xi,t)$	**ep→epγ**	$\Delta\sigma$, σ	Hall A	5.75 GeV	E-00-110	Fall 04
		BSA A_{LU}	CLAS		E-01-113	Spring 05
					6-003	2007
$H+\widetilde{H}(\pm\xi,\xi,t)$	**ep→epγ**				5-114	2008
$E(\pm\xi,\xi,t)$	**e(n)→enγ**				-106	Fall 04
$\int_x H,E \quad (2u+d)$	**ep→epρ**	σ_L	CLAS	5.75 GeV	E-99-105	Winter 02
$\int_x H,E \quad (2u-d)$	**ep→epω**		CLAS	5.75 GeV	E-99-105	Winter 02
	+ other m				r analyses in the three Halls.	

New results demonstrate that scaling regime is reached in DVCS around 2 GeV² ! (M. Mazouz' talk on Tuesday)

Preliminary results (+ HERMES) in qualitative agreement with GPD-based calculation

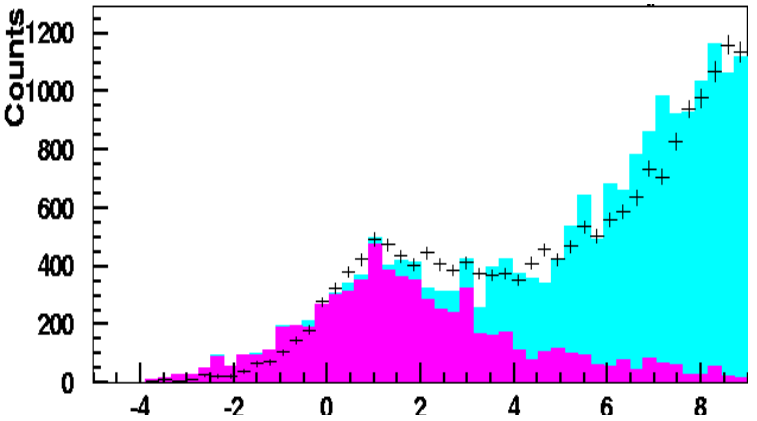
Published results demonstrate that scaling regime is NOT reached in ω production

CLAS / DVCS (Spring 2005)

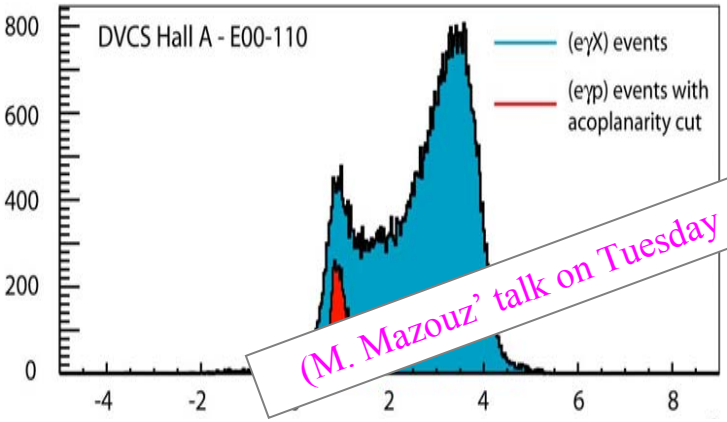


D.E.S.: an experimental challenge

ep → eγX
HERMES
28 GeV

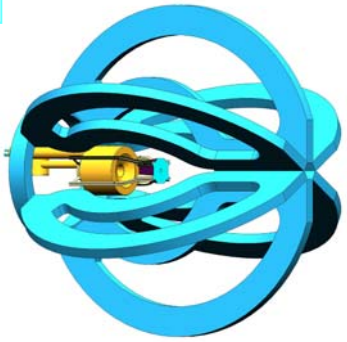


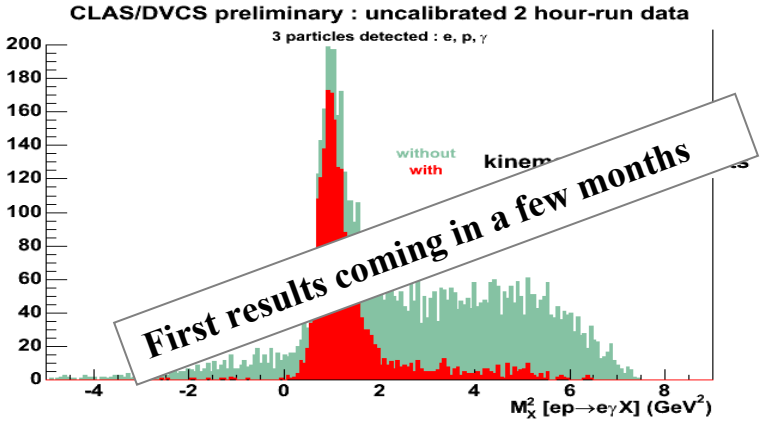
Exclusivity
→ resolution
→ redundant constraints
High Q^2
→ luminosity × acceptance



(M. Mazouz' talk on Tuesday

ep → epγ
Hall A & CLAS
5.75 GeV

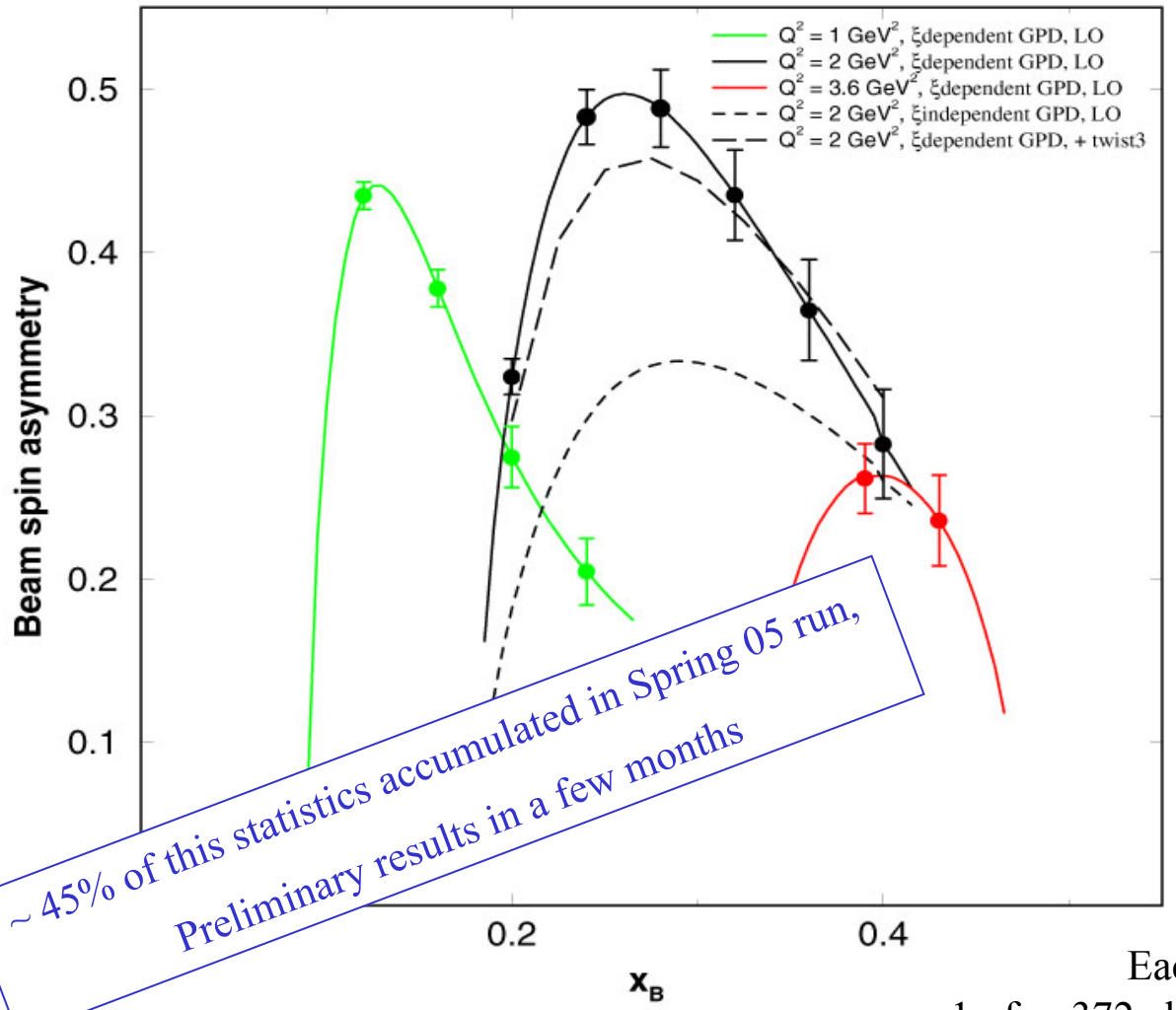




First results coming in a few months

A_{LU} : *Expected results from CLAS*

Equivalent 60 full days of beam time at $L = 2 \times 10^{34}$ cm^{-2} sec^{-1} and $P_e = 0.8$



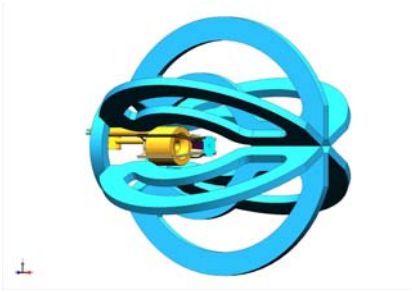
~ 45% of this statistics accumulated in Spring 05 run,
Preliminary results in a few months

x_B dependence at

$\phi = 90^o$,

$t = -0.325\ \text{GeV}^2$

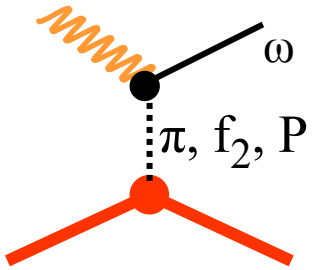
and 3 values of Q^2



Each point in this graph corresponds to
1 of ~ 372 elementary bins in (Q^2, x_B, t, Φ) space

Deeply virtual meson production

Meson and Pomeron (or two-gluon) exchange …

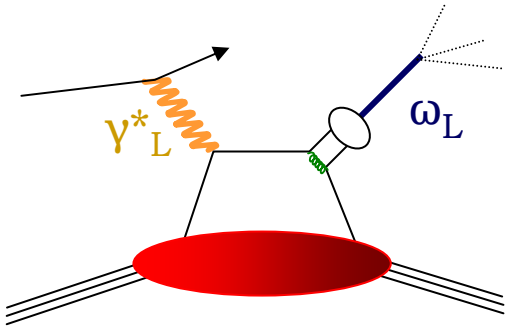


ρ^0	(σ), f_2, P
ω	π, f_2, P
Φ	P

… or scattering at the quark level ?

Flavor sensitivity of DVMP on the proton:

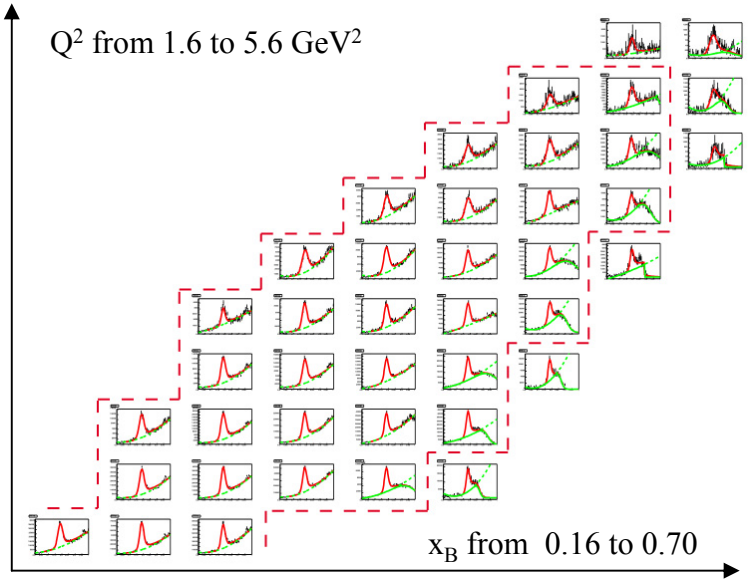
ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4
Φ	s, g
ρ^+	u-d



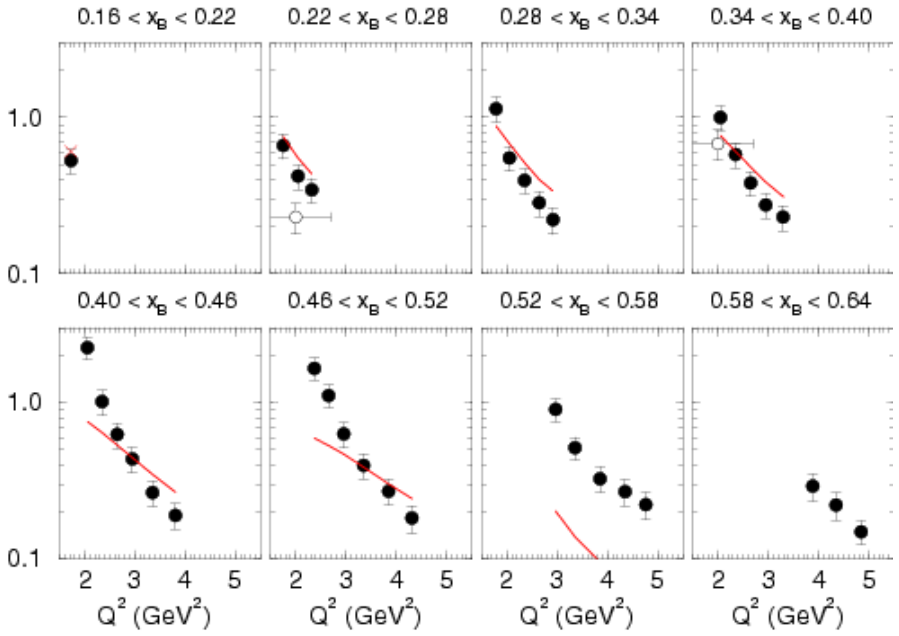
$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4}\left[\frac{\alpha_S}{Q}\sum\iint\frac{\psi_M(z)}{z}\frac{1}{x\pm\xi\mp i\varepsilon}(aH+bE)(x,\xi,t)dxdz\right]^2 \propto \frac{f(\xi,t)}{Q^6}$$

Deeply virtual ω production at 5.75 GeV

*Analysis of **cross sections** from for $ep \rightarrow ep\pi^+X$ configurations*



ω peak in MM[epX] for (Q^2,x_B) bins



CLAS, EPJA **24** (2005)

*Analysis of **ω polarization** from $ep \rightarrow ep\pi^+\pi^-X$ configurations*
(for the first time for this channel above $Q^2 \sim 1$ GeV^2)

- 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

Deeply virtual ρ production at 5.75 GeV

s-channel helicity conserved

$R = \sigma_L/\sigma_T$ measured

New results for σ_L

Red curve from GPD model (q)

Green curve from GPD model (g)

$\sigma_L(W)$ for various bins in Q^2

• PRELIMINARY
(not for circulation)

+ earlier results at 4.2 GeV

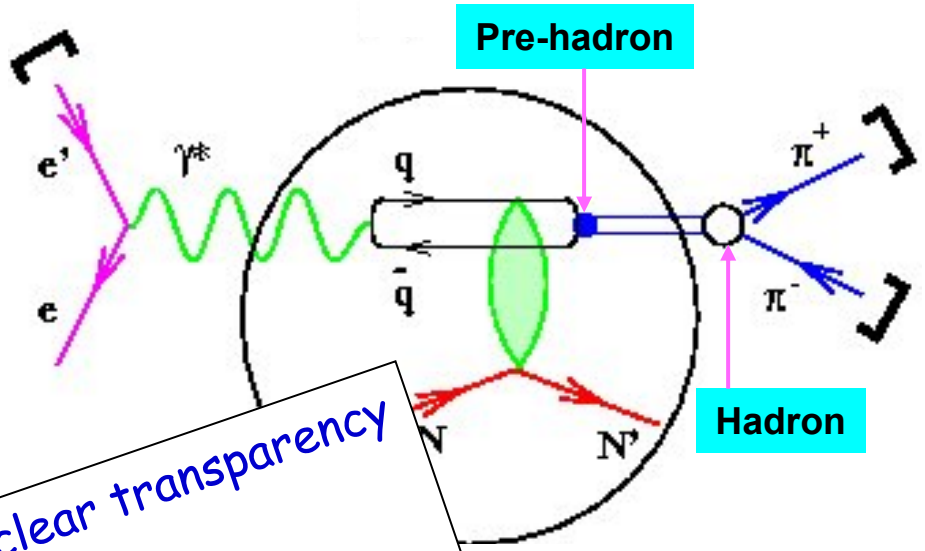
C. Hadjidakis *et al.*, PLB **605** (2005)

Color Transparency in ρ production

Study of

$e + N \rightarrow e' + N + \rho^0$

in the nuclear medium



The signature of CT is the rising of the nuclear transparency with increasing hardness of the reaction (for fixed coherence length)

$T(A,Q^2) = \sigma_A / A\sigma_N$

T

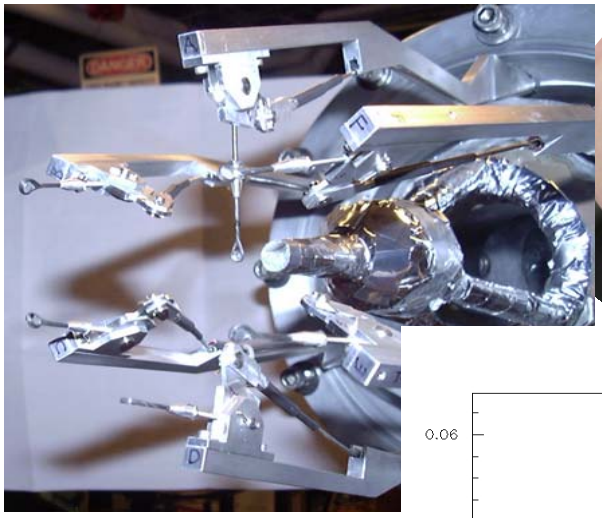
Complete transparency

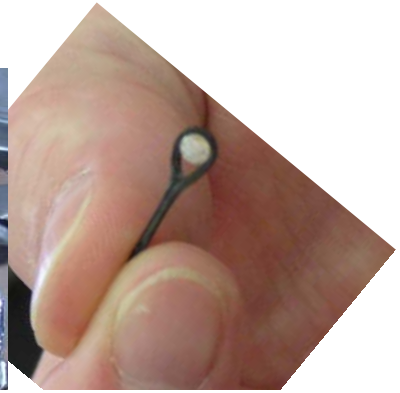
N. Bianchi's talk last Tuesday
B. Kopeliovich's talk last Wednesday

Q^2

Color Transparency in ρ production

Solid targets

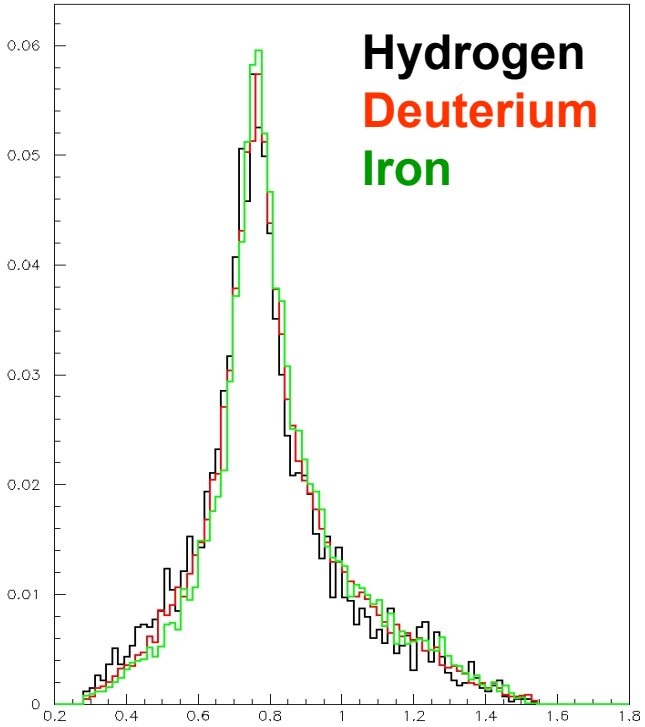




PRELIMINARY
(not for circulation)

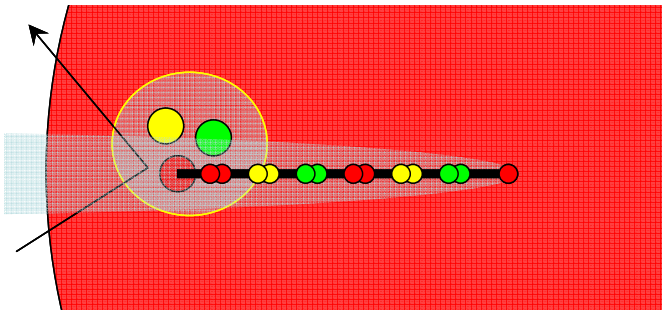
$\Delta E = \nu - E_\rho + t/2M_p$

W > 2 GeV
-0.5 < t < -0.1
|ΔE| < 0.1 GeV



(Analysis in progress)

Quark propagation through nuclei



Measure *attenuation*

and *transverse momentum broadening*

of hadrons (π, K)

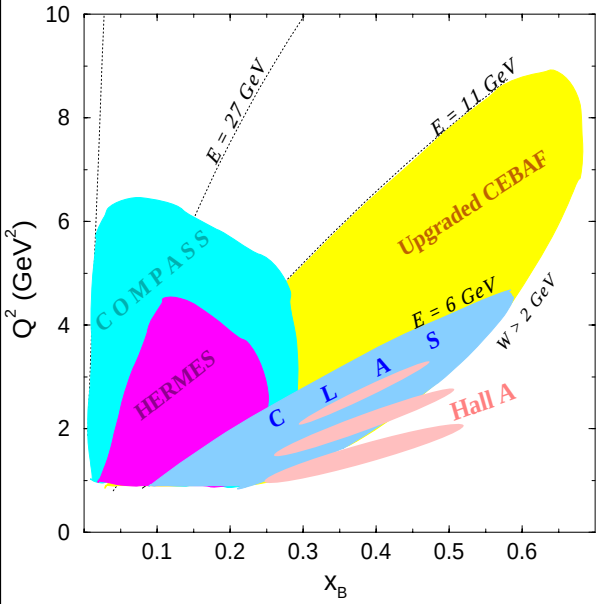
in DIS kinematics.

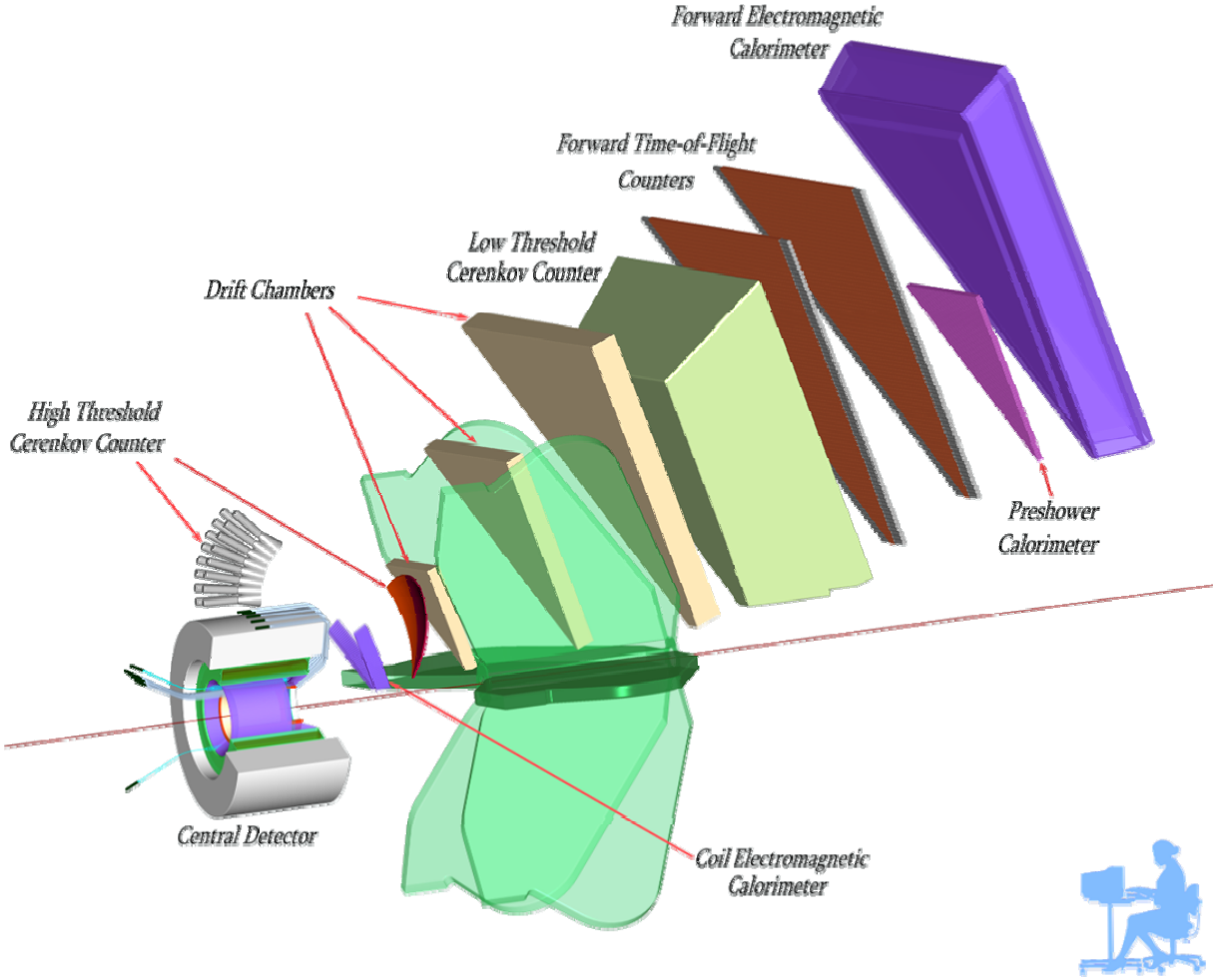
Compare absorption

in deuterium, carbon, iron, tin, and lead

Huge statistics accumulated

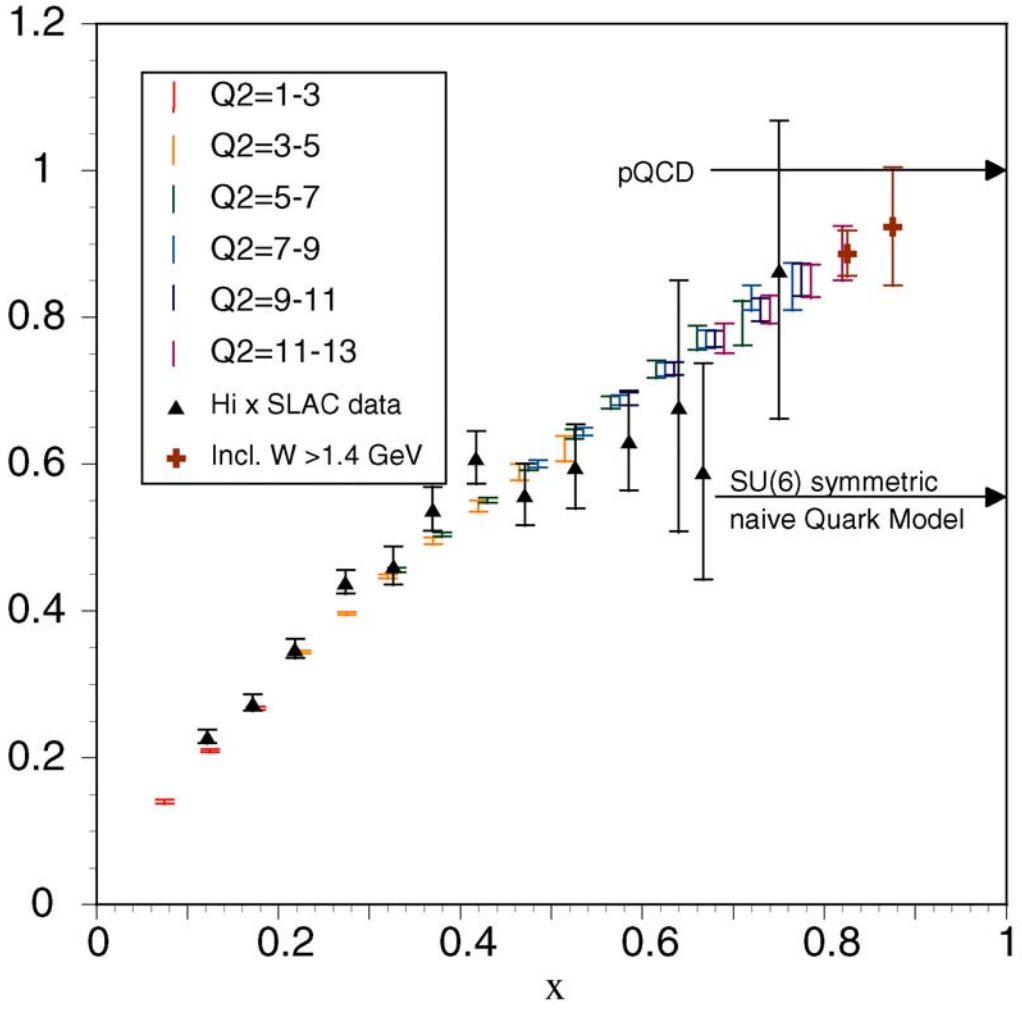
CEBAF@11GeV and CLAS12



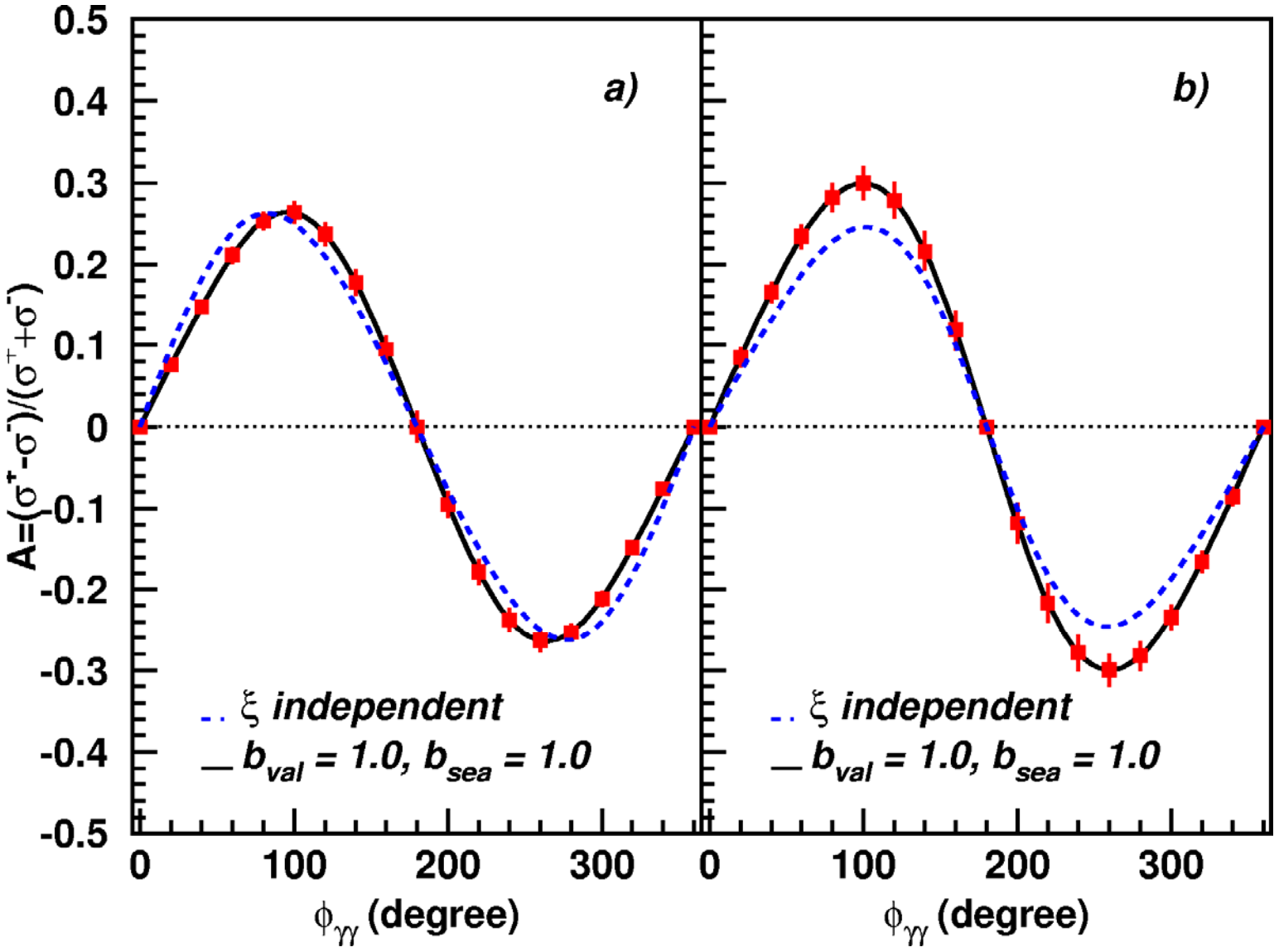


Projections for CLAS@11GeV

A_1^p at 11 GeV with CLAS12



DVCS/BH projected for CLAS12 at 11 GeV



972 data points measured simultaneously

Q^2, x_B, t ranges measured simultaneously.

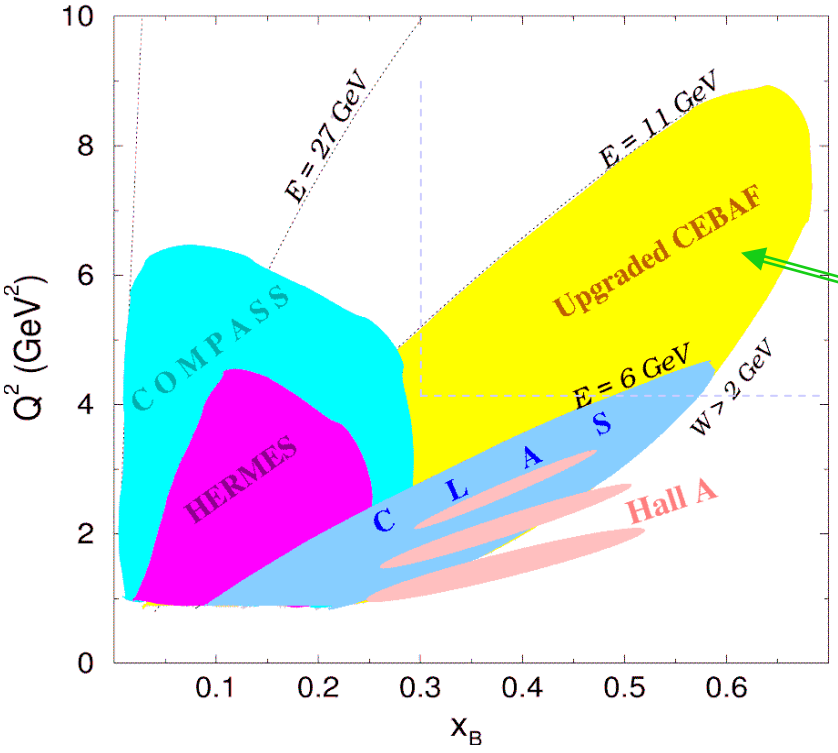
$A(Q^2,x_B,t)$
$\Delta\sigma\ (Q^2,x_B,t)$
$\sigma\ (Q^2,x_B,t)$

ρ^0/ω production with transverse polarized target

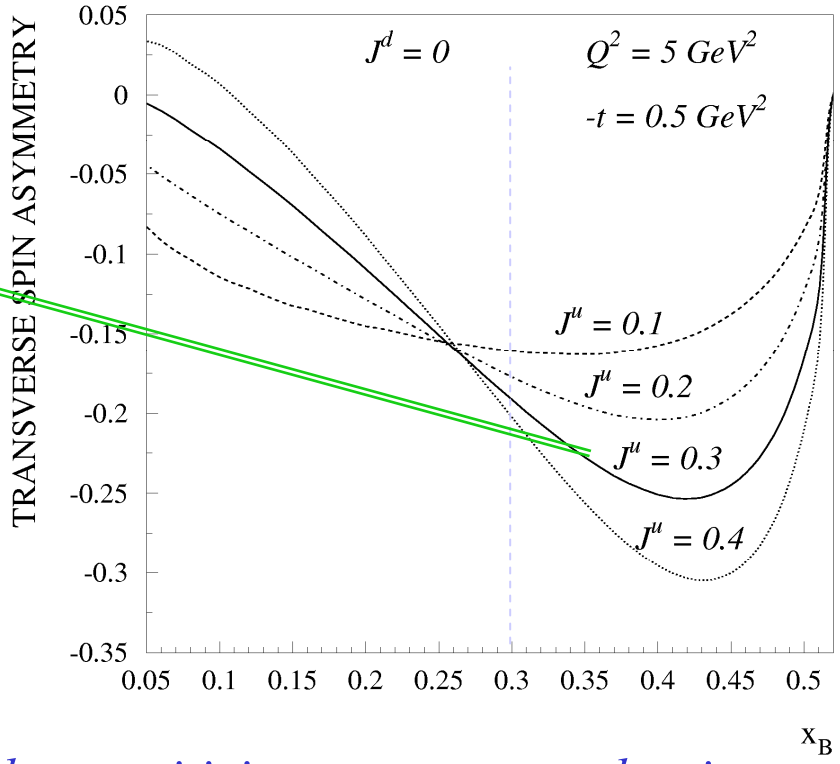
$$A_{UT} \propto \frac{\mathrm{Im}(\mathcal{H}^{*}\mathcal{E})}{|\mathcal{H}|^2(1-\xi^2) - |\tilde{\mathcal{H}}|^2(\xi^2 + t/4M^2) - 2\xi^2\,\mathrm{Re}(\mathcal{H}^{*}\tilde{\mathcal{E}})}$$

$$\mathcal{H}_\rho = \int_{-1}^{+1} \frac{dx}{\sqrt{2}} \left(e_u H^u - e_d H^d\right)\left[(x-\xi+i\varepsilon)^{-1} + (x+\xi-i\varepsilon)^{-1}\right]$$

Asymmetry depends linearly on the GPD *E*, which enters in Ji's sum rule. High x_B contribute significantly.



$\gamma_L^* + p \rightarrow \rho_L^0 + p$



ω_L has similar sensitivity to proton quark spin

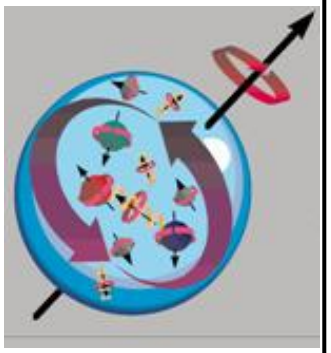
Conclusions and outlook (1)

Nucleon structure:

Precise and exciting new data coming now and in the near future:

Form factors, (polarized) parton distributions,

k_T-dependent parton distributions, GPD,…..



Baryon spectroscopy:

Signals for ***pentaquarks*** not present in dedicated high statistics experiments. Stringent upper limits on production in different channels.

Extensive set of data in ***photo- and electroproduction of resonances***. Excited Baryon Analysis Center (T.-S. H. Lee *et al.*) launched.

Conclusions and outlook (2)

Other research topics at CLAS

Transition from resonance to D.I.S. region,
higher-twist, duality.
Search for "missing" resonances
e.g. in 2π channels.
The nucleus as a QCD laboratory,
color transparency in ρ production,
quark propagation.
N-N correlations in nuclei.

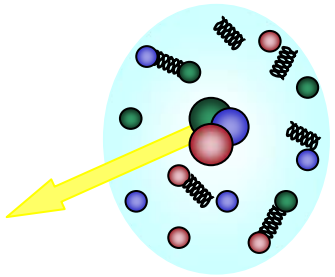
Experimental outlook:

New campaign of 6 GeV operation in 2007-2008
"Complete" experiments for baryon spectroscopy
(new frozen spin target for photon experiments)
12 GeV upgrade on tracks

Conclusions and outlook (3)

First 12 GeV proposals will be examined in August

CLAS (and other Halls at JLab) actively preparing such proposals:



- DVCS
- Deep exclusive π^0 & η production
- Azimutal moments in pion production in SIDIS
- A_1 / g_1 at high x
- DIS on the neutron (p spectator tagging)
- Study of nuclear transparency in exclusive ρ electroproduction
- Quark propagation and hadron formation in electroproduction of hadrons (including strange mesons and hyperons) from nuclei.
- Study of short-range properties of nucleons at $Q^2 < 12$ GeV^2 using D(e,e'p)n

CLAS12 detector being designed now

A good time to join !