Generalized Parton Distributions: an experimenter's approach

Some introductory remarks:

Is this the seven-year itch ?

Plan :

♠ Nucleon structure

♥ GPD – physical content

♦ GPD + deep exclusive reactions

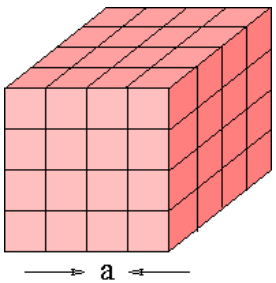
♣ Emerging data

☺ Next year and beyond

Theory of nucleon structure

QCD

Lattice calculations



- Continuum limit $a \to 0$,
- Thermodynamical limit $V \to \infty$,
- "Quenched" approximation
- Extrapolation $m_\pi \to 140$ MeV

Effective theory
(chiral perturbation)

Models

Quarks from QCD
($m \sim 0$)

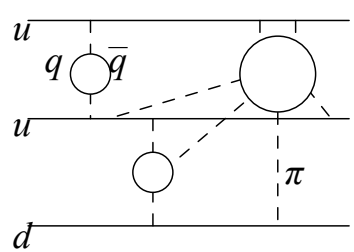
$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$

Constituent quarks
($m \sim M/3$)

$|p\rangle = |u_c u_c d_c\rangle$

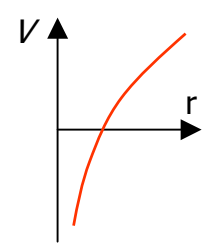
Quark-diquark

Chiral quark-soliton



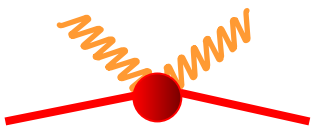
MIT bag model

Cloudy bag model



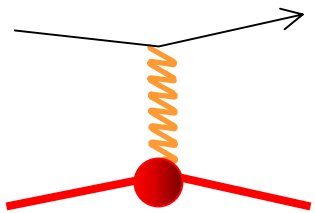
Nucleon structure: means of investigation

Compton scattering
($\gamma^{(*)}N \rightarrow \gamma N$)



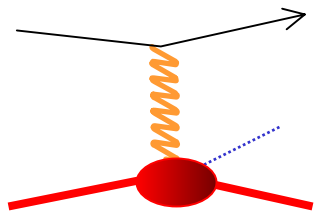
Polarisabilities

Lepton elastic
scattering



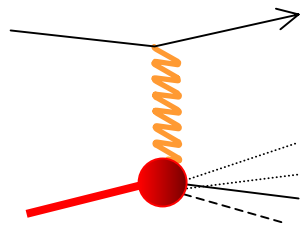
Form factors

Inelastic scattering
(γN, eN, πN…)



**Excited states
(résonances)**

Deeply inelastic
scattering

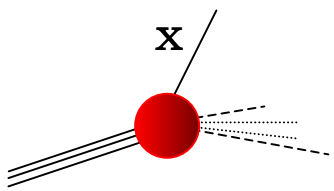


Structure functions

Distributions of charge and magnetization
in a nucleon at rest

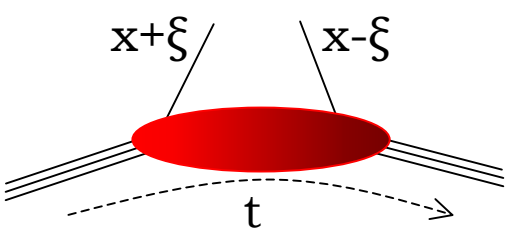
Distributions of partons:
momentum, spin,
carried by a quark or a gluon
in a fast moving nucleon

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

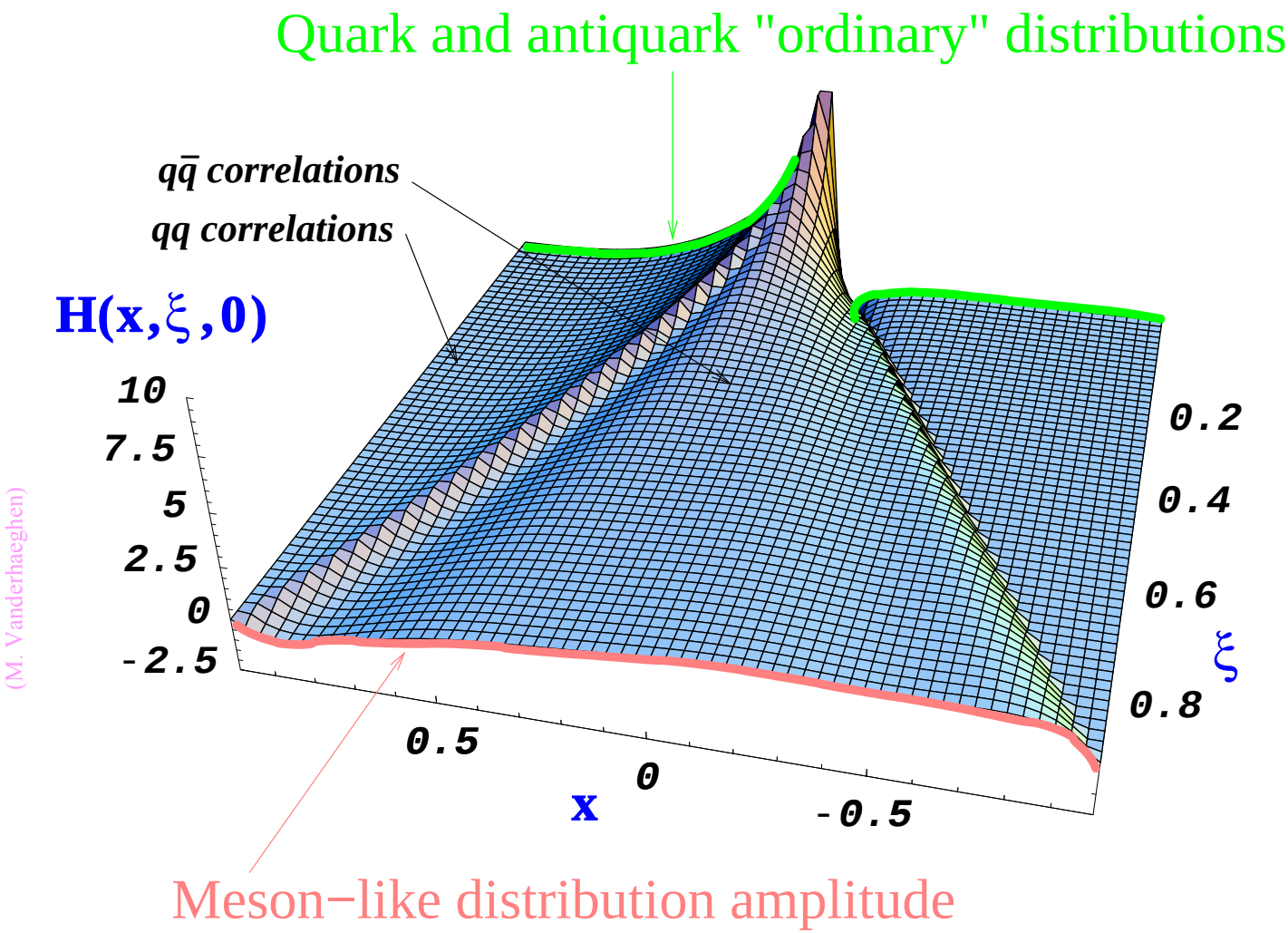
(et dependence on t related to transverse distributions)

→ Generalized parton distributions (GPD)

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

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

x and ξ – dependence of GPDs: a femto-tomography of the nucleon

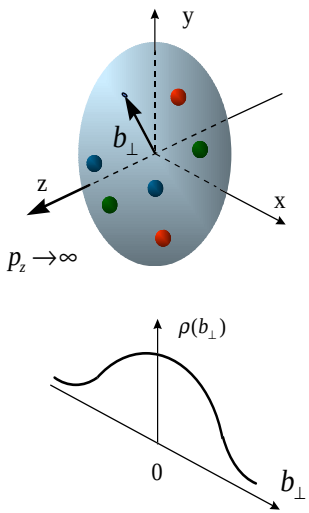


(M. Vanderhaeghen)

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

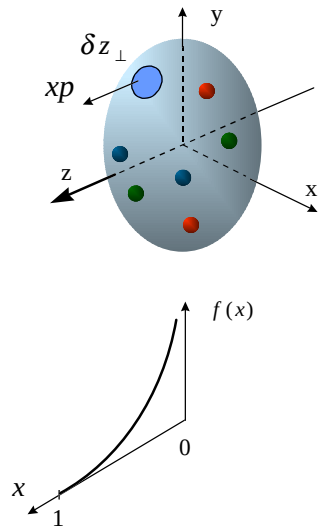
- Form factor

F{Form factor F(t)}



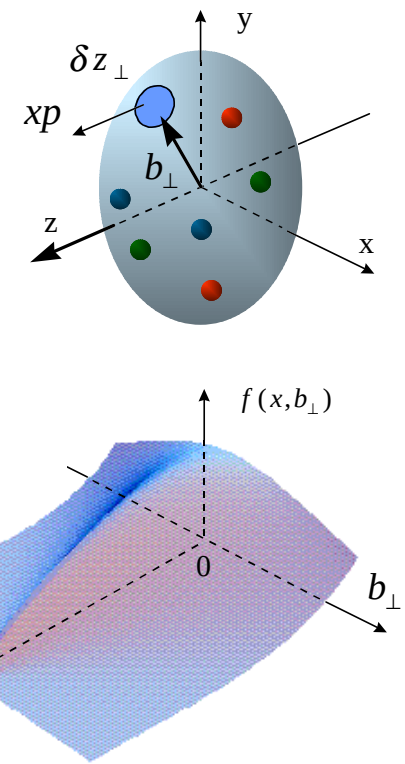
- Parton density

Quark distribution q(x)



$$q(x) \sim \int |\psi(x, \vec{k}_1, x_2, \vec{k}_2, x_3, \vec{k}_3)|^2 \; [dX]$$

GPD (x,0,t)



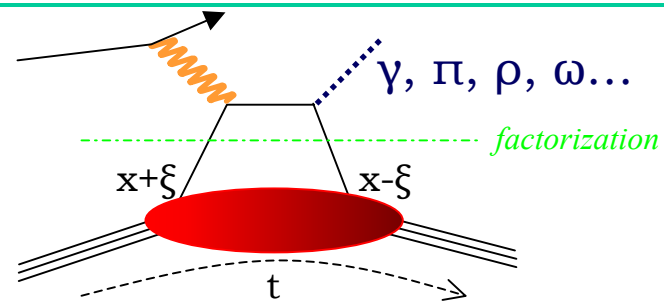
(A. V. Belitsky)

Simultaneous determination of longitudinal momentum and transverse position of quarks

$$H(x,\xi,t) \sim \int \psi^*(x-\xi, \vec{k}_1 + \vec{\Delta}_\perp, \ldots) \cdot \psi(x+\xi, \vec{k}_1, \ldots)[dX]$$

$$[dX] = \delta(x + x_2 + x_3 - 1)\delta^{(2)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) dx_2 dx_3 d^2\vec{k}_1 d^2\vec{k}_2 d^2\vec{k}_3$$

GPD: relation with observables



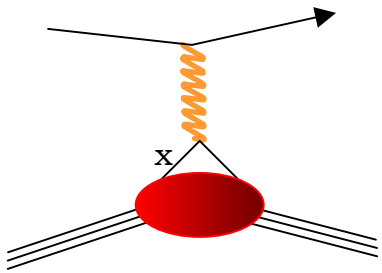
Observables are integrales, in x, of GPDs

Deconvolution

Theory, models or parameterizations

H, H̃, E, Ẽ (x,ξ,t)

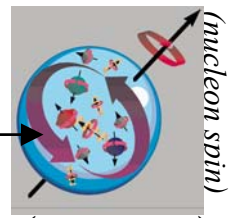
Elastic form factors



$\int H(x,\xi,t)dx = F(t)$ (∀ ξ)

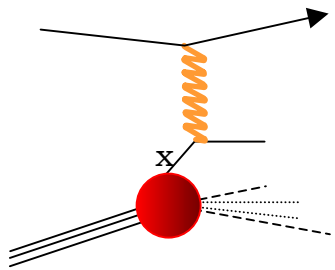
Ji's sum rule

$2J_q = \int x(H+E)(x,\xi,0)dx$



$$\frac{1}{2} = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$

"Ordinary" parton distributions

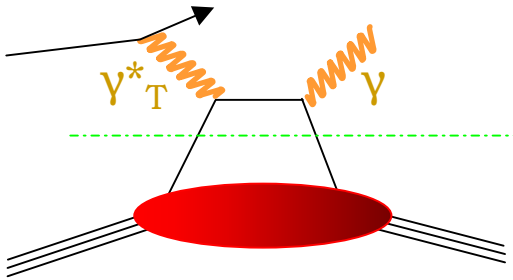


$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$

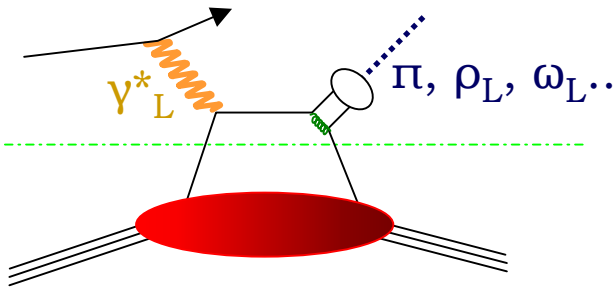
Classification of GPDs

Legend: GPD / Forward limit / Operator at nucleon level / Corresponding form factor		Operator at quark level
$q(x)$ **H** *Vector* $F_1(t)$	– **E** *Tensor* $F_2(t)$	*Vector* $\gamma^-_{\alpha\beta}$ **Quark helicity independent (or « unpolarized ») GPDs**
$\Delta q(x)$ $\tilde{\mathbf{H}}$ *Pseudo-vector* $g_A(t)$	– $\tilde{\mathbf{E}}$ *Pseudo-scalar* $h_A(t)$	*Axial vector* $\gamma^5 \gamma^-_{\alpha\beta}$ **Quark helicity dependent (or « polarized ») GPDs**

Deeply virtual exclusive reactions (DES)

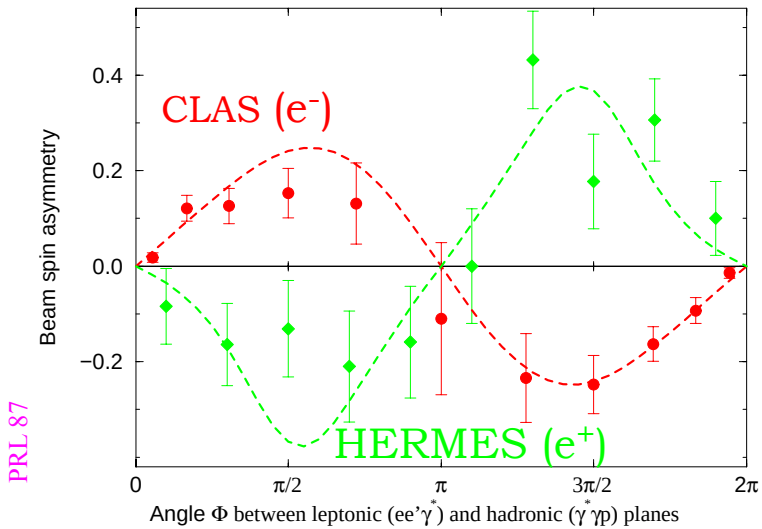


Factorization theorems



DVCS (Virtual Compton)

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

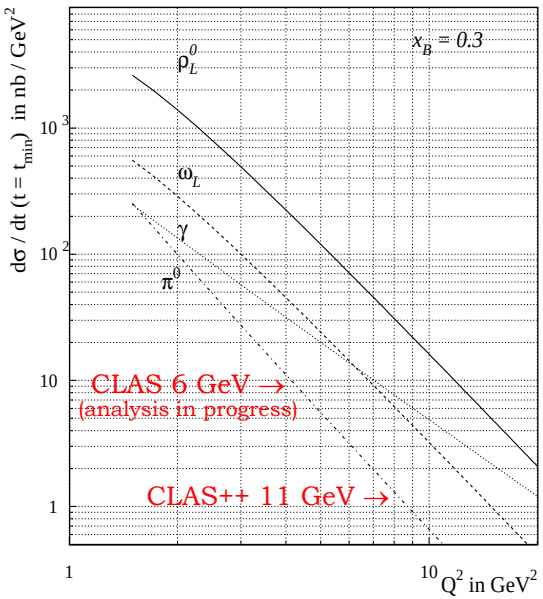


PRL 87

(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 $\gamma^* + p \rightarrow M + p : (M = \rho^0_L, \omega_L, \Phi_L, \pi^0, \gamma)$



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

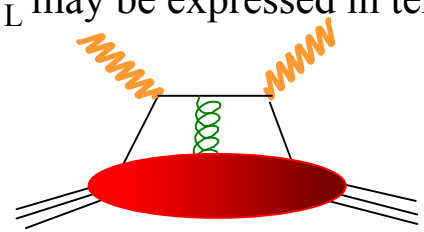
GPD evolution

Dependence on factorization scale μ :

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

$O(1/Q)$

(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 $\mathcal{O}(\frac{t}{Q^2}, \frac{M^2}{Q^2}, \frac{m^2}{Q^2})$ corrections

- Quark transverse momentum effects (modification of quark propagator)

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

- Other twist-4 ……

DES: the experiments

HERMES *27 GeV*	CLAS *4.2 GeV*	CLAS *4.8 GeV*	CLAS *5.75 GeV*	Hall A *6 GeV*	CLAS *6 GeV*	Hall C *6 GeV*
DVCS – SSA + CA + nuclei	DVCS - SSA (published)	DVCS	DVCS DDVCS ΔDVCS	DVCS proton neutron ?	DVCS proton deuteron ?	
$ep \to ep\rho$ σ_L + DSA	$ep \to ep\rho_L$		$ep \to ep\rho_L$ $ep \to ep\omega_L$			
			$ep \to ep\pi^0/\eta$	$ep \to ep\pi^0$	$ep \to ep\pi^0/\eta$	
$ep \to en\pi+$			$ep \to en\pi^+$			$ep \to en\pi^+$? σ_L
+ ….			$ep \to ep\Phi$			

GPD and DVCS

(at leading order)

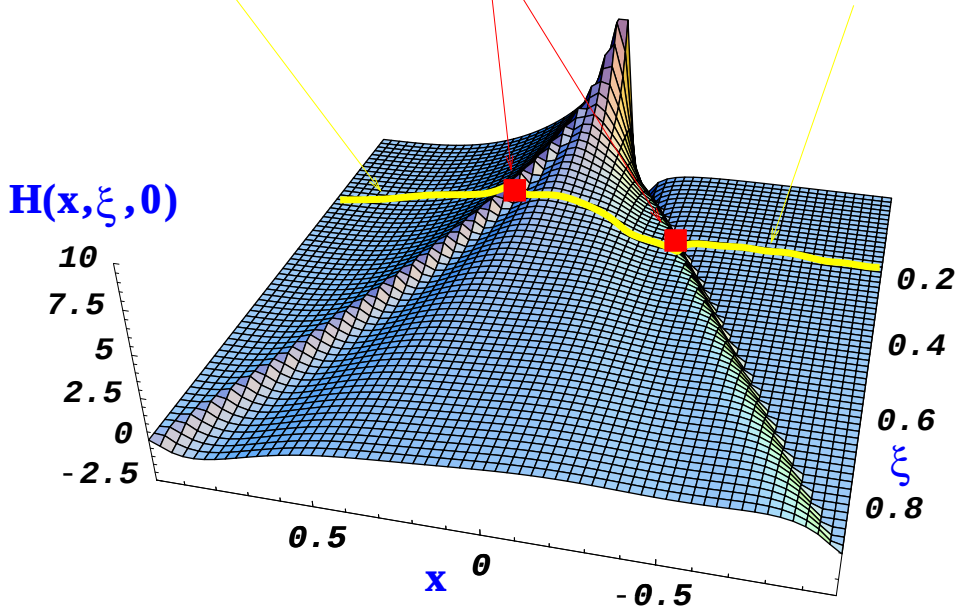
$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi+i\varepsilon}\, dx \quad + \; \ldots\ldots$$

$$\sim \; P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi} \quad - \quad i\,\pi \boxed{H(\xi,\xi,t)} \quad + \; ..$$

Real part through
Beam charge asymmetry

Imaginary part through
Beam spin asymmetry

Cross section measurement



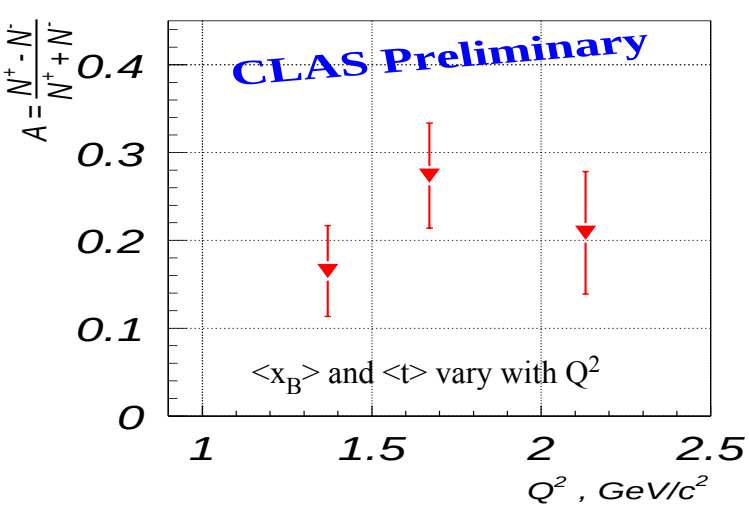
DVCS and GPDs

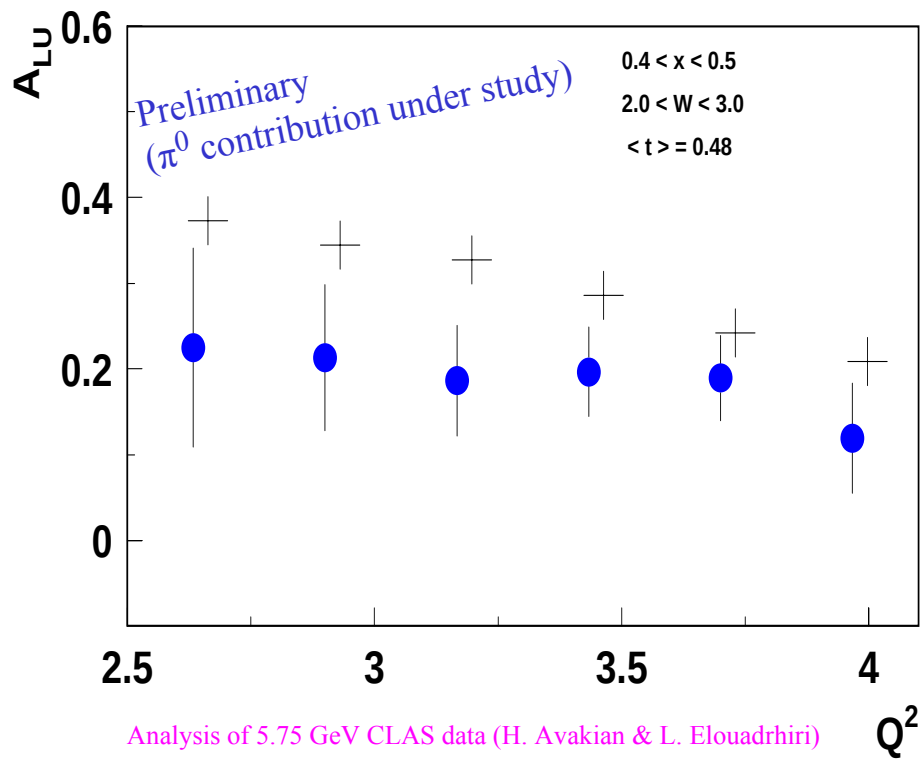
DVCS-BH interference generates
a **beam spin asymmetry**

$$\sigma^+ - \sigma^- = \Gamma \cdot [\mathcal{A} \sin\Phi \quad \cdots]$$

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

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

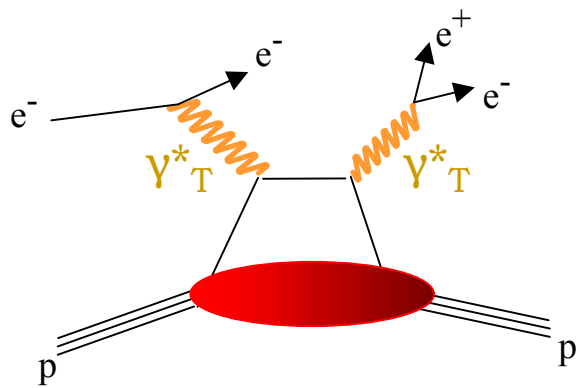




Analysis of 4.8 GeV CLAS data (G. Gavalian & S. Stepanyan)

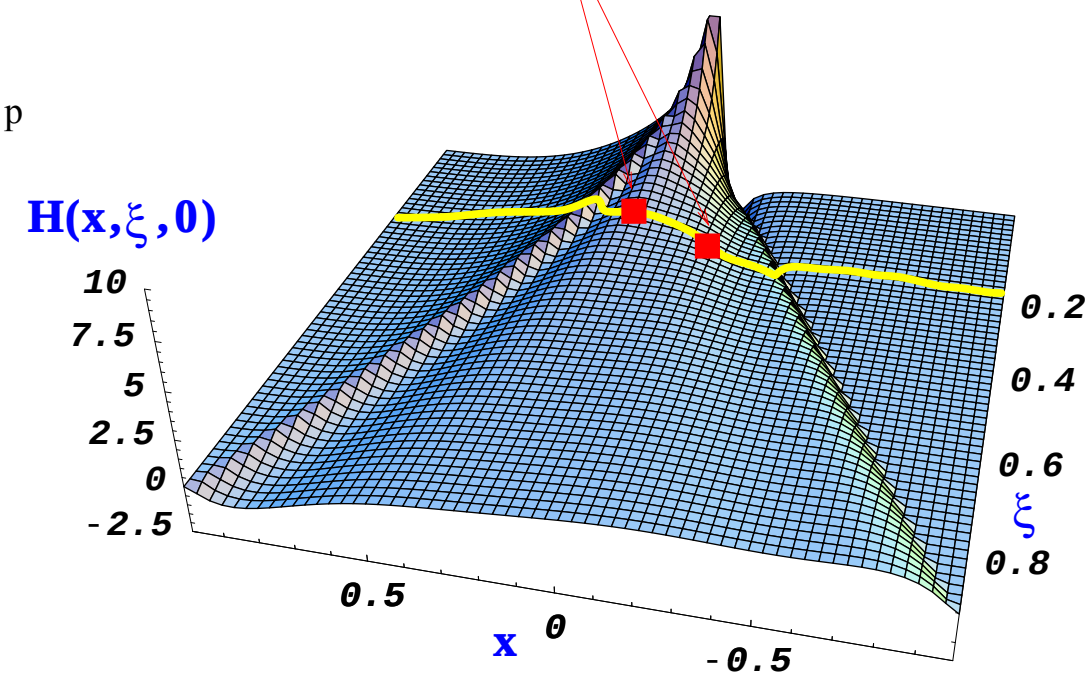
Analysis of 5.75 GeV CLAS data (H. Avakian & L. Elouadrhiri)

DDVCS
(Double Deeply Virtual Compton Scattering)



$$Im\,T^{DDVCS} \sim \quad H(x(\xi,q'),\,\xi,t) \quad + \quad ..$$

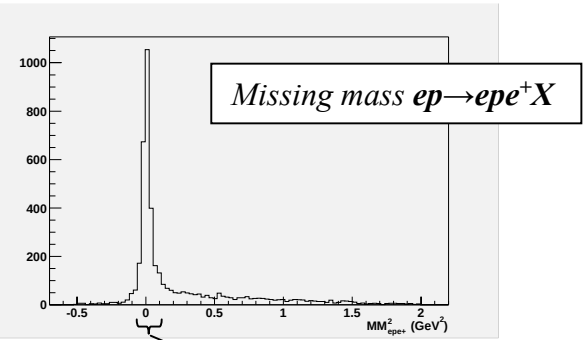
Beam spin asymmetry

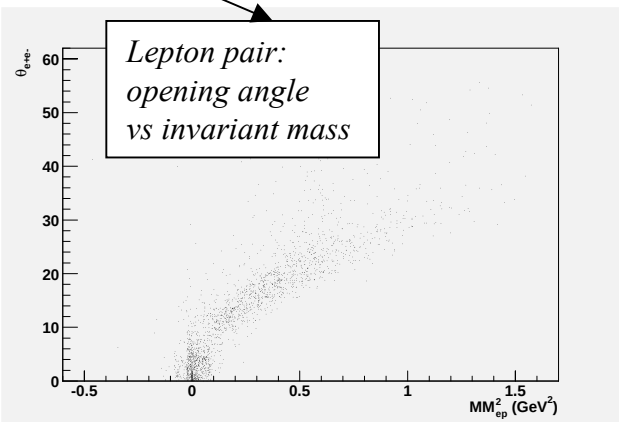


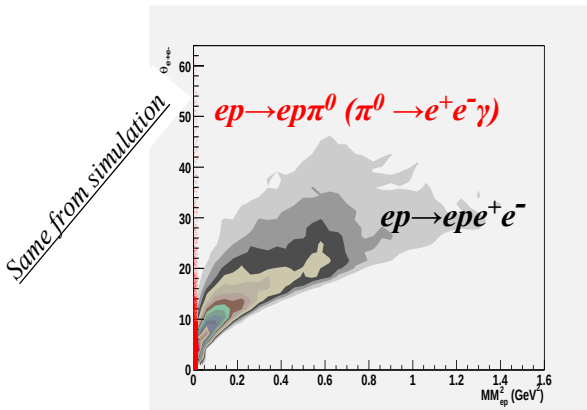
The (continuously varying) virtuality of the outgoing photon allows to "tune" the kinematical point (x,ξ,t) at which the GPDs are sampled (with |x | < ξ).

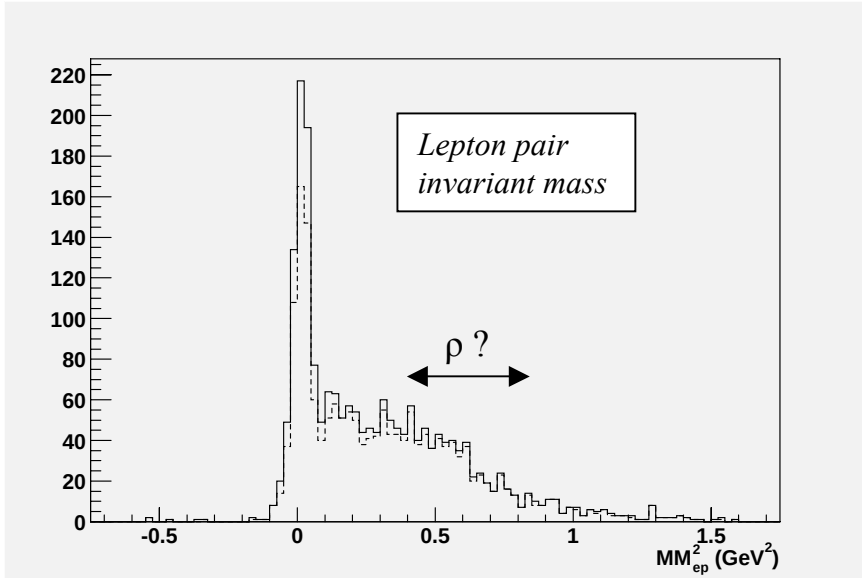
M. Guidal & M. Vanderhaeghen, PRL 90
A. V. Belitsky & D. Müller, PRL 90

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

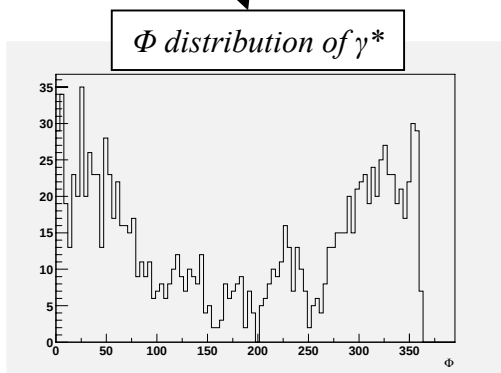








Distributions of counts
(not corrected from acceptance)



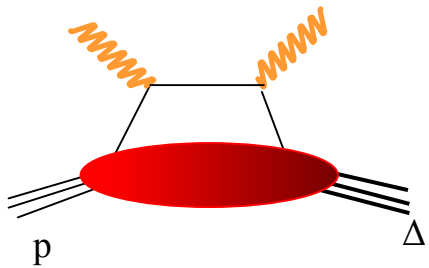
Next step: extract
beam polarization asymmetry

Analysis of 5.75 GeV CLAS data (S. Morrow + Saclay group)

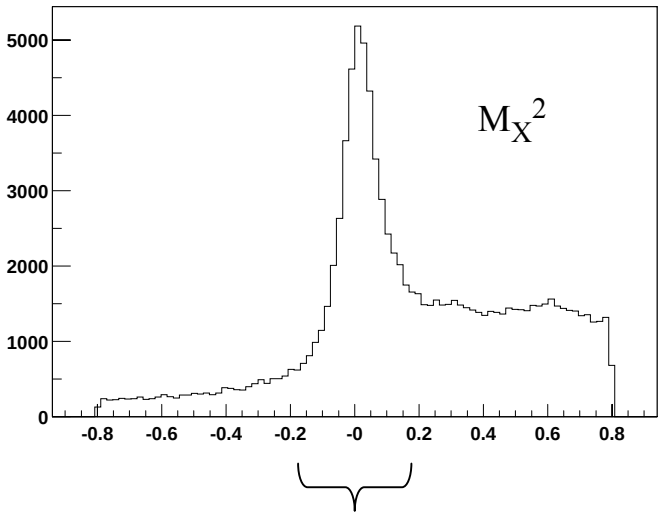
Transition GPDs and Δ-DVCS

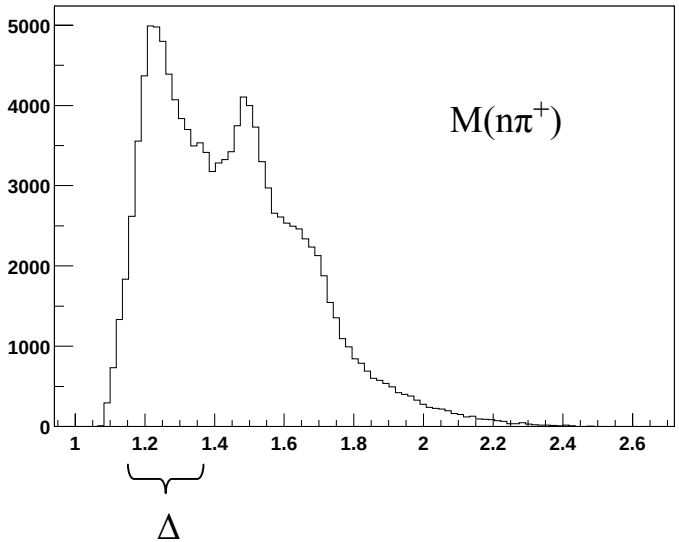
Transition GPDs are likewise defined to describe the process:

In the large N_c limit, they are related to the nucleon GPDs.



$$e\,p \rightarrow e\,n\,\pi^+\,X$$

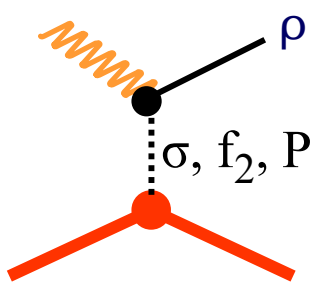


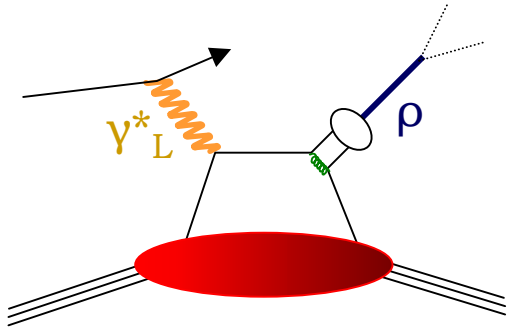


$$e\,p \rightarrow e\,\Delta\,\gamma\,/\,\pi^0$$

Analysis of 5.75 GeV CLAS data (S Bouchigny & Orsay group)

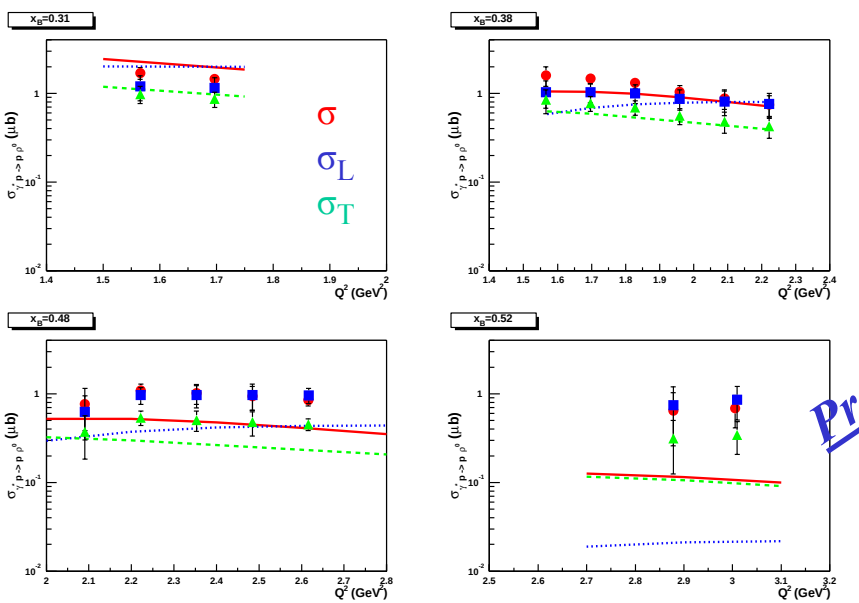
Deeply virtual ρ production at 4.2 GeV



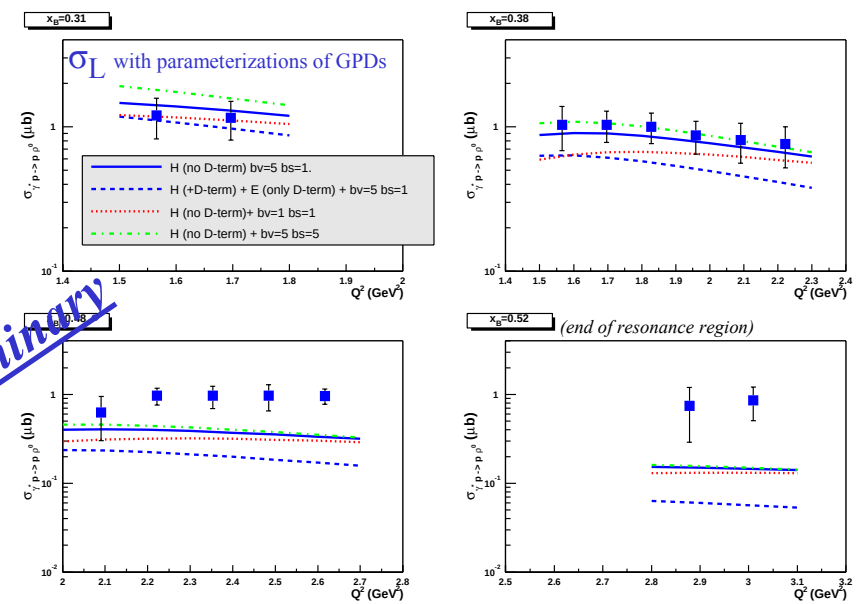


With determination of $R = \frac{\sigma_L}{\sigma_T}$

Regge model (Cano & Laget)



GPD model (Guidal & Vanderhaeghen)



Preliminary

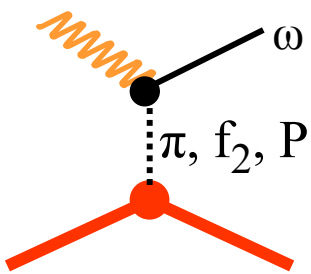
σ_L has too strong x (W) dependence, σ_T OK

Handbag diagram, + sizeable corrections, can account for JLab and HERMES data on σ_L

Analysis of 4.2 GeV CLAS data (C. Hadjidakis + Orsay group) - see also HERMES data EPJC 17,18

Deeply virtual ω production at 5.75 GeV

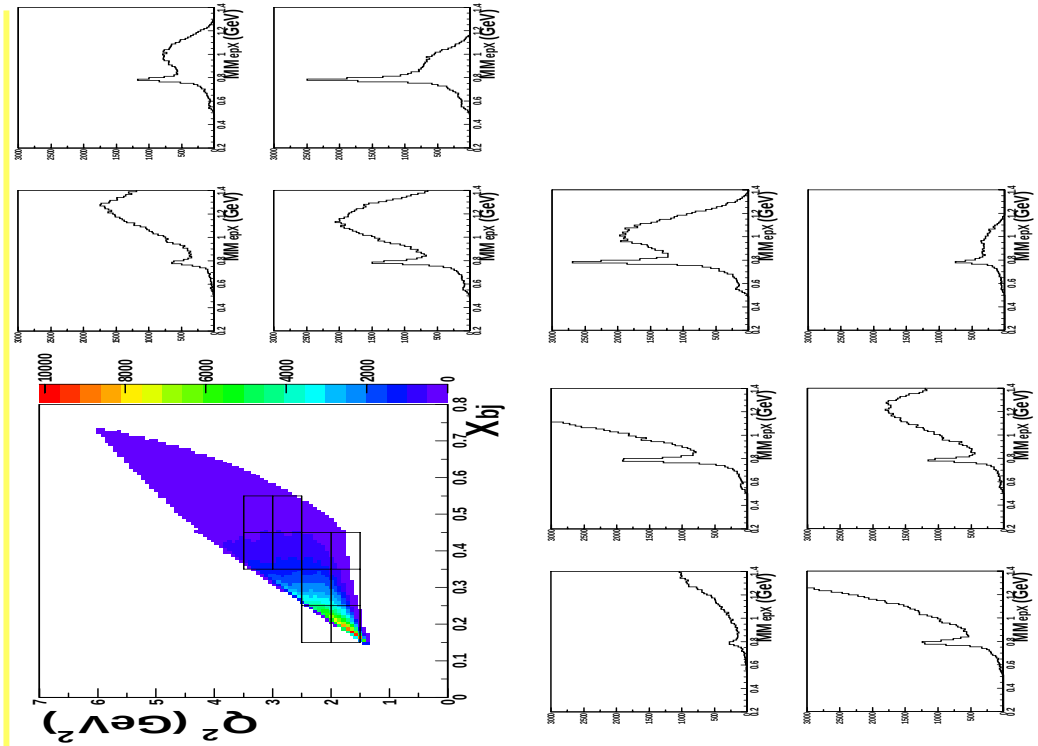
Meson and Pomeron exchange



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



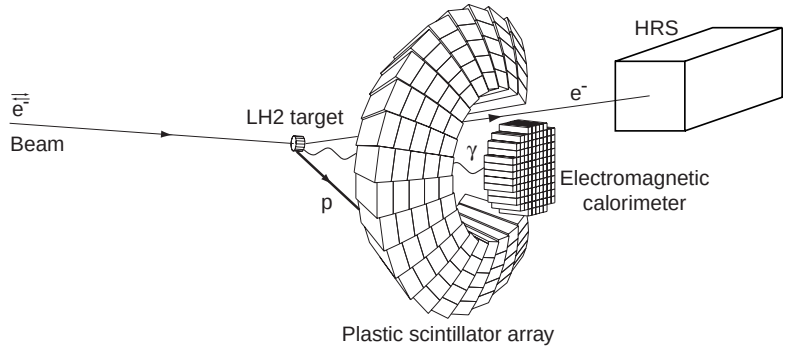
Counts distributions for ep → epπ^+X configurations
(with M_X>0.3 GeV)

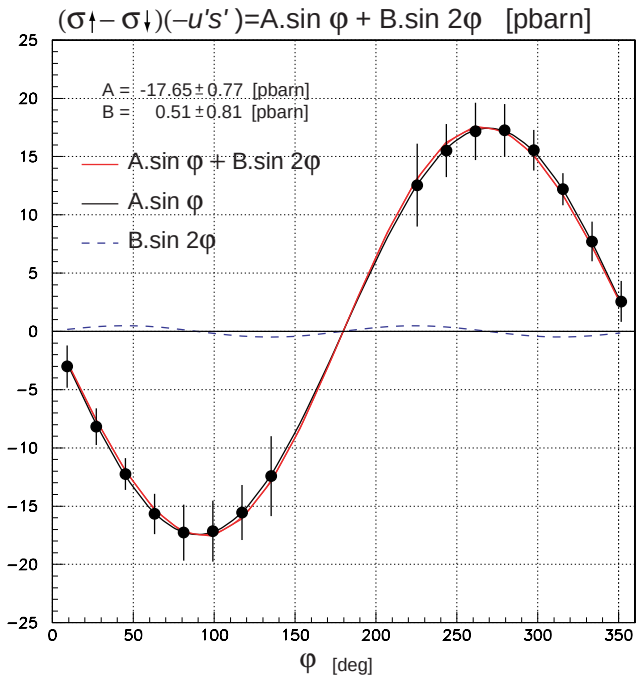
$R = \frac{\sigma_L}{\sigma_T}$ to be extracted from ep → ep$\pi^+\pi^-$X configurations
(for the first time for this channel above $Q^2 \sim 1$ GeV^2)

Analysis of 5.75 GeV CLAS data (L. Morand + Saclay group)

DVCS experiments in 2004

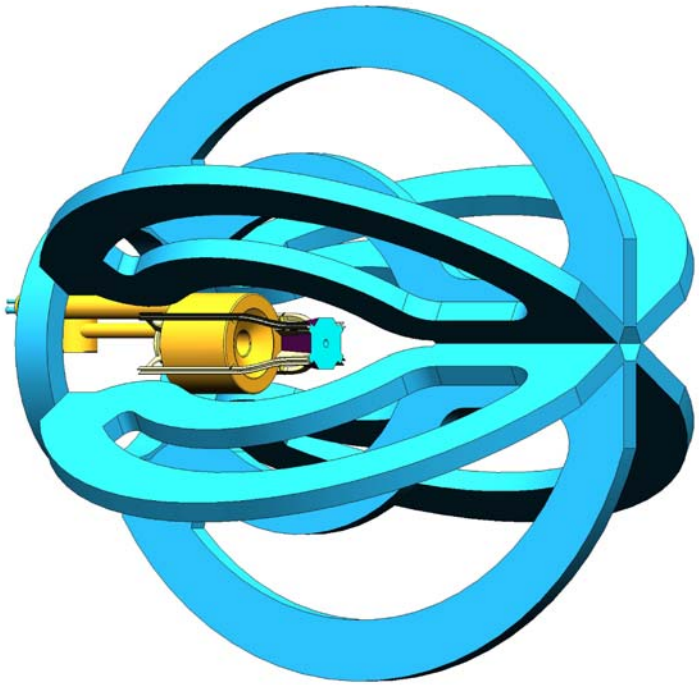
JLab/Hall A





JLab/CLAS

Calorimetrer and supraconducting magnet within CLAS torus



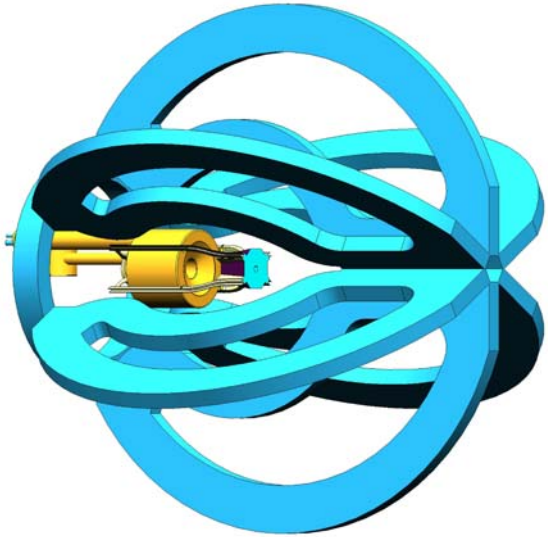
First precise experiments

Detection of 3 particles in the final state

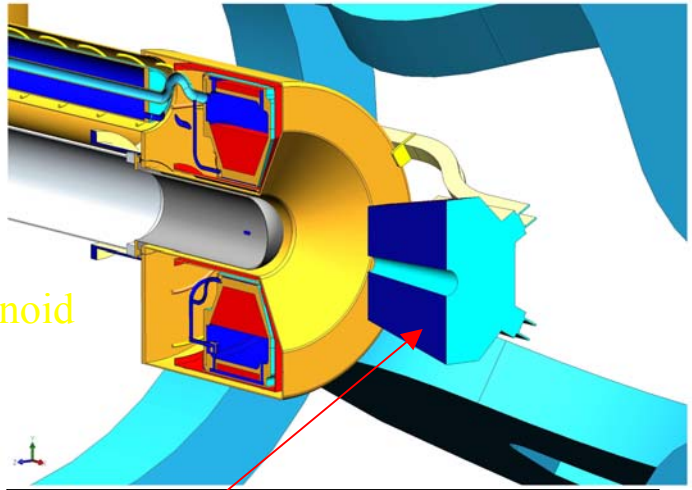
→ Scaling laws (Q^2 dependence)

→ If OK, significant tests of GPDs

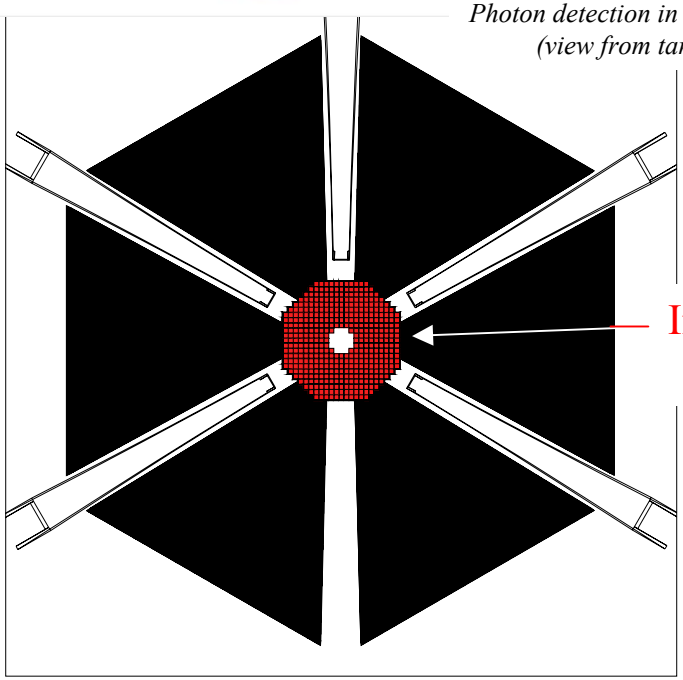
CLAS/DVCS



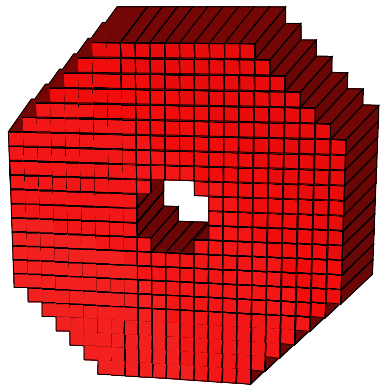
Supraconducting solenoid



Photon detection in IC and EC
(view from target)



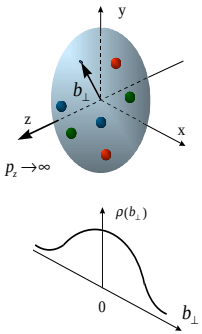
Inner calorimeter
($PbWO_4$)



424 crystals, 16 mm long,
pointing geometry, ~ 1 degree/crystal,
APD readout

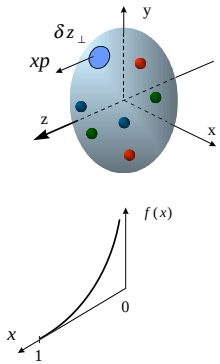
DVCS and nucleon femto-photography

- Form factor



x

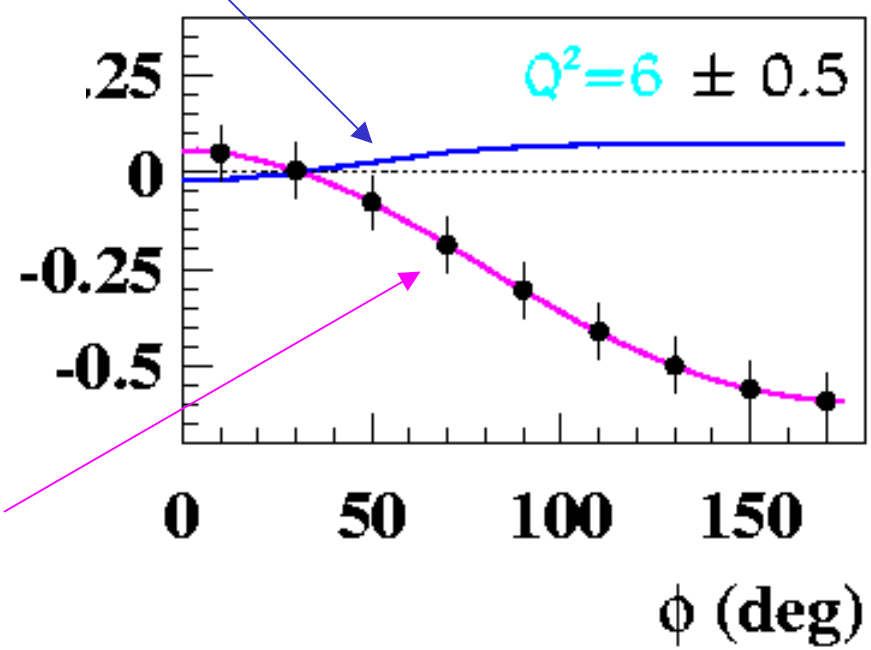
- Parton density



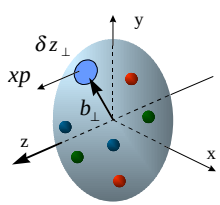
$\rightarrow$ q(x)F(t)

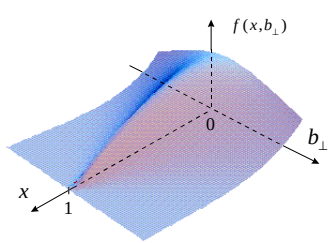
$$\frac{\sigma_{\mu+} - \sigma_{\mu-}}{\sigma_{\mu+} + \sigma_{\mu-}}$$

(estimation COMPASS)



- Generalized parton distribution at η=0





$\rightarrow$ H(x,ξ,t)

DVCS on the deuteron

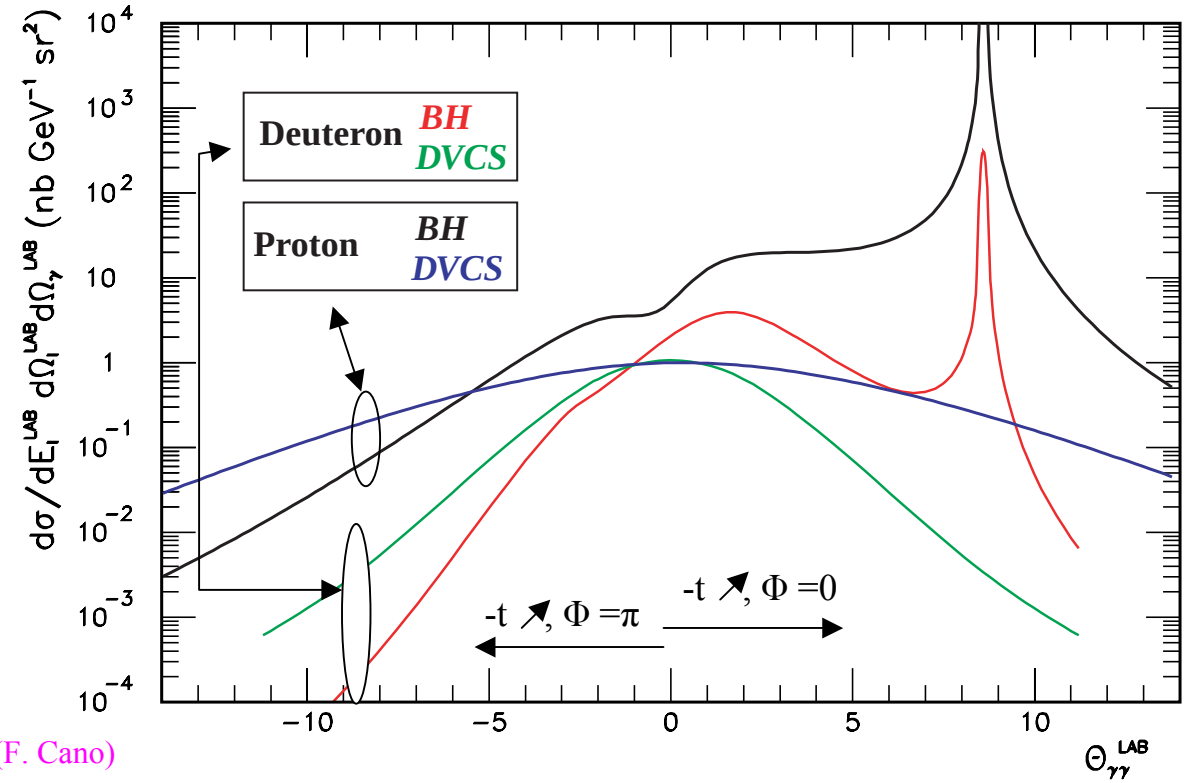
- **The deuteron as a neutron target** $e\,d \rightarrow e\,p_{sp}\,n\,\gamma$ (new initiative in Hall A)

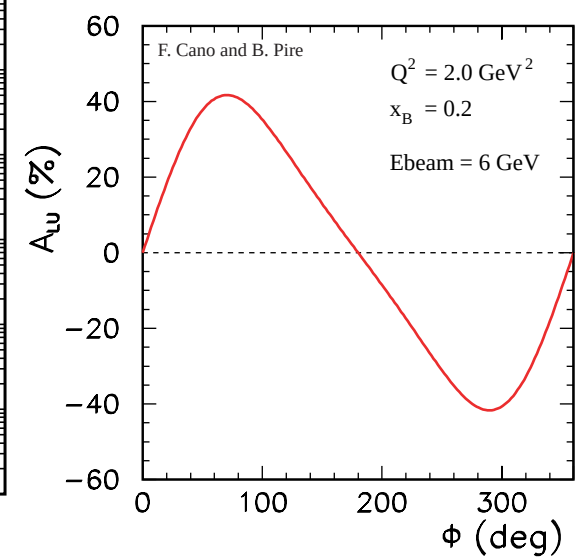
- **Coherent DVCS** $e\,d \rightarrow e\,d\,\gamma$ (feasible in CLAS and HERMES)

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) : HERMES preliminary data





(F. Cano)

DVCS on the neutron

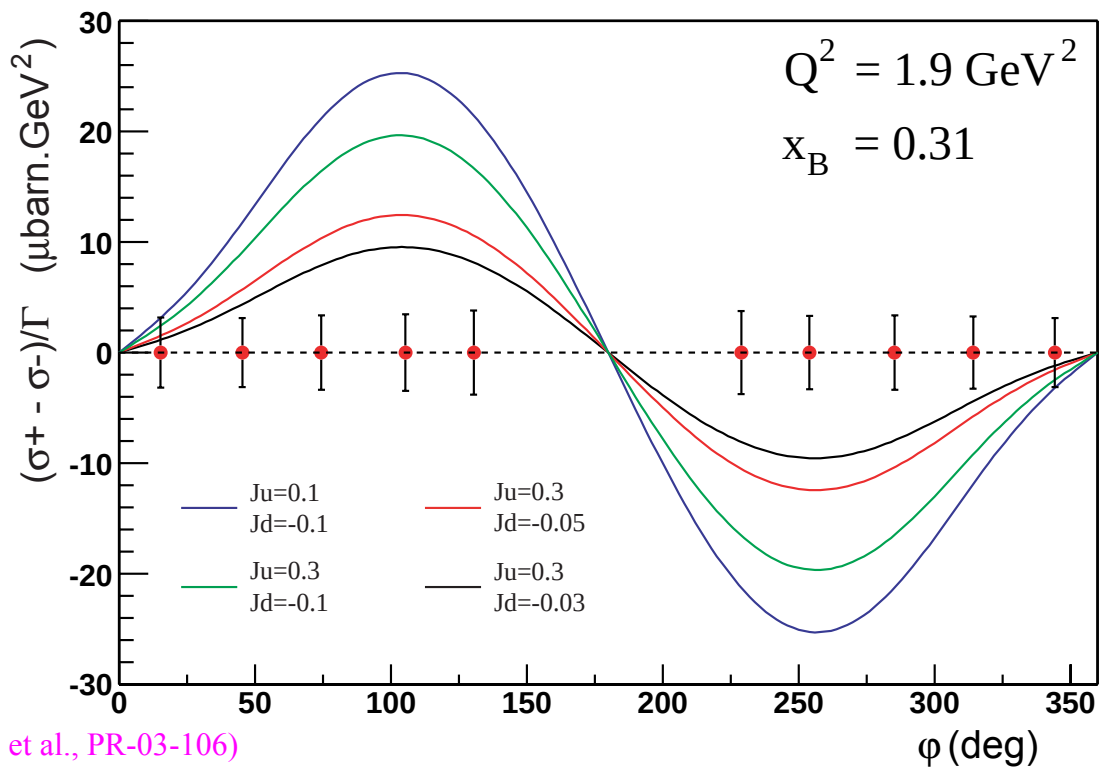
DVCS-BH interference generates
a **beam spin asymmetry**

$$\sigma^+ - \sigma^- = \Gamma \cdot [\mathcal{A} \sin\Phi \quad \cdots]$$

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

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

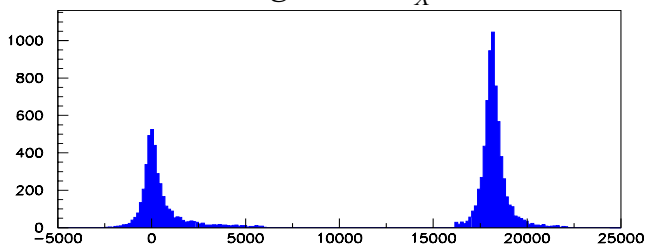
DVCS/SSA on the neutron shows (within a model) **sensitivity to quark angular momentum J**



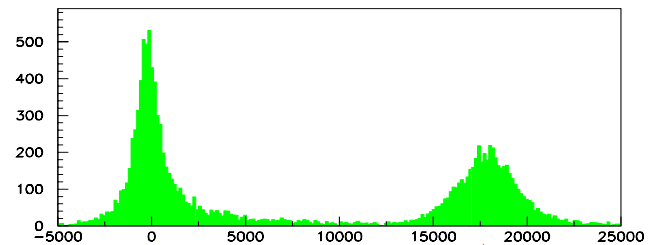
(F. Sabatié et al., PR-03-106)

D.E.S.: an experimental challenge

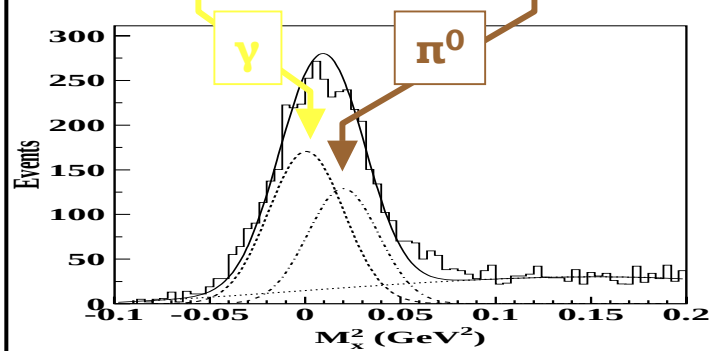
Missing mass M_X^2



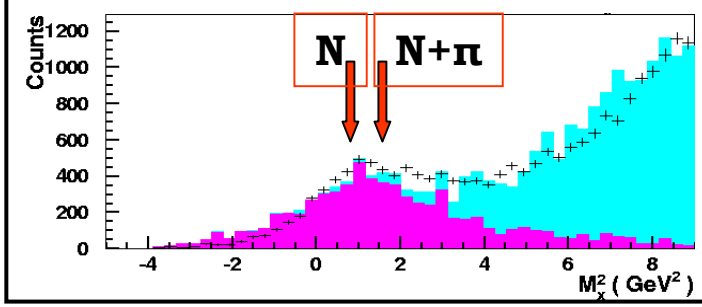
ep → epX
MAMI 850
MeV



ep → epX
Hall A
4 GeV



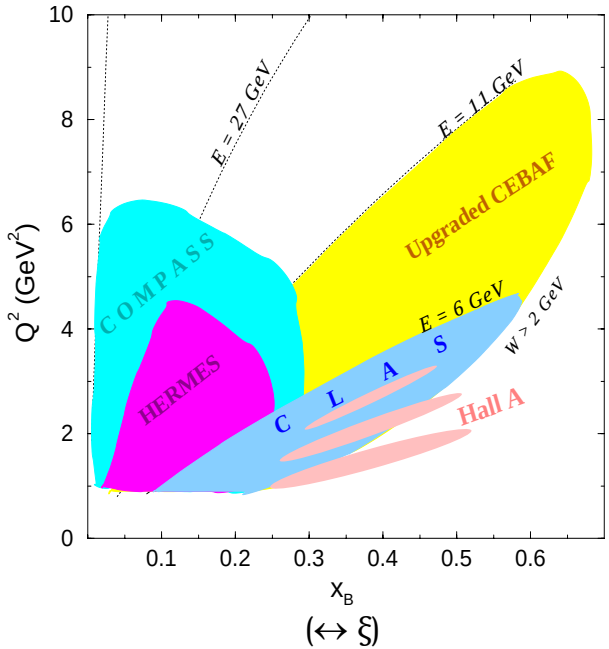
ep → epX
CLAS
4,2 GeV



ep → eγX
HERMES
28 GeV

- Resolution
- Exclusivity
- Luminosity
- High transfers

Accessible kinematical domain

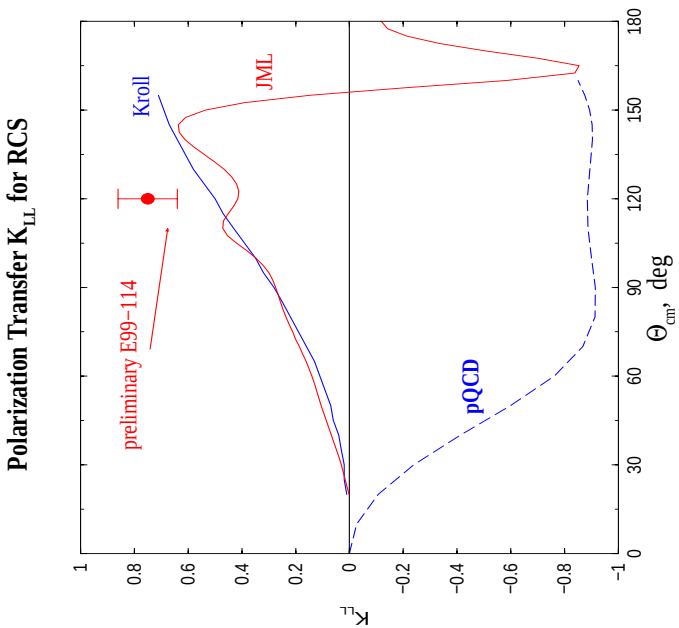


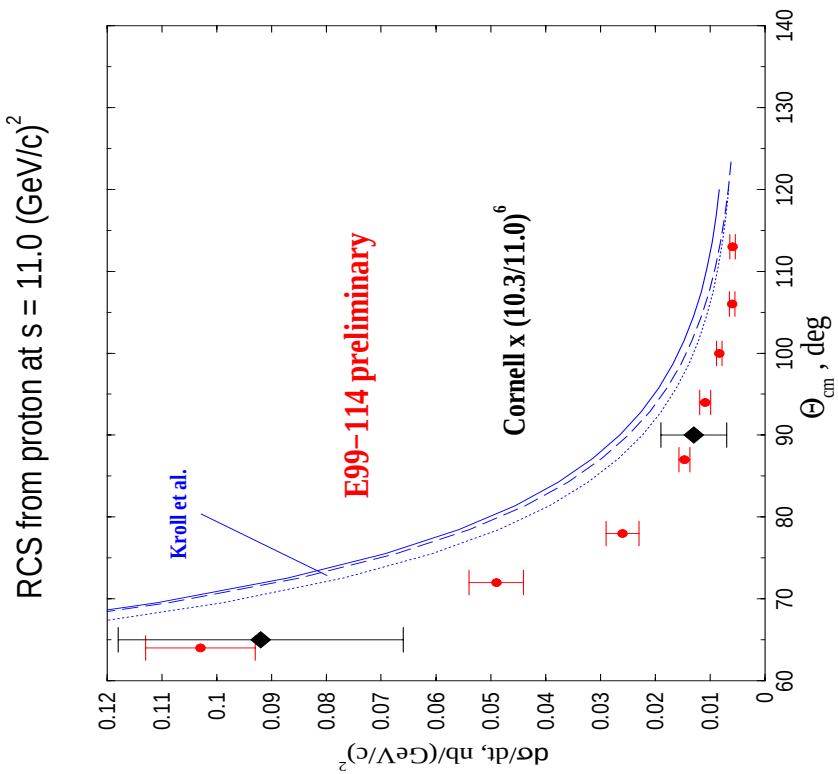
High t processes and GPDs

Factorization of DES amplitudes (handbag diagram) as presented so far applies for –t « M^2 and Q^2.

However, in $\gamma\, p \rightarrow \gamma\, p$ - RCS - (and in $\gamma^*_{L/T}\, p \rightarrow p\, \rho_L/\omega_L/\pi^0/\eta$) at high values of *–t*,
the amplitudes of the "soft overlap" contribution may be factorized into handbag diagrams,
and the corresponding form factors shown to represent *1/x* – moments of GPDs

(Kroll et al., Radyushkin).





Hall A RCS experiment

Conclusions and outlook

Theory :

- GPDs have emerged as a powerful, attractive and unifying concept for the nucleon structure,
- Interpretation and significance of GPDs under intense study,
- First lattice calculations just published,
- Q^2 evolution worked out to NLO,
  Twist-3 contributions to DVCS estimated,
- Deconvolution problem (from experiment to GPDs) only touched upon.

Experiment :

- We are in the prehistoric era :
  indications that the handbag diagram is at work in DVCS,
- Between now and 2005 :
  establish on firm grounds the validity of the approach,
  tests of scaling, factorization for different reactions,
  DVES on the neutron, on the deuteron ….,
- Beyond :
  systematic measurements of GPDs …
  CEBAF@12 GeV (and more) !

The actors

DESY	
HERMES	***ZEUS/H1***
Vector mesons DVCS	

JLab		
Hall A	***Hall B***	***Hall C***
p-DVCS n-DVCS ?	Vector mesons p-DVCS d-DVCS ??	Pseudoscalar mesons ??

CERN
COMPASS
Vector mesons DVCS ??

+ theory	(almost) everywhere