# Deeply Virtual Compton Scattering with CLAS

## first results from the e1dvcs experiment

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JLab
April 27$^{th}$, 2007

# Outline

# Wigner distributions

## What are they ?

E.P. Wigner, Phys. Rev. 40 (1932) 749

$$W(\vec{r},\vec{p}) = \int \frac{d^3\vec{R}}{(2\pi\hbar)^3} e^{-\imath\vec{p}\cdot\vec{R}/\hbar}\psi^*(\vec{r}-\vec{R}/2)\psi(\vec{r}+\vec{R}/2)$$

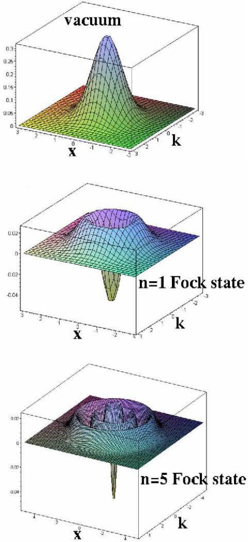
$\Longleftrightarrow$ wave function/density matrix

$\overset{\hbar\to 0}{\Leftrightarrow}$ classical distribution in phase space (if it exists)

$$|\psi(\vec{r})|^2 = \int d^3\vec{p}\, W(\vec{r},\vec{p})$$

$$|\psi(\vec{p})|^2 = \int \frac{d^3\vec{r}}{(2\pi\hbar)^3} W(\vec{r},\vec{p})$$

$$\langle\mathcal{O}\rangle = \int d^3\vec{p}\, d^3\vec{r}\, \mathcal{O}_{\text{Weyl}}(\vec{r},\vec{p}) W(\vec{r},\vec{p})$$



# Wigner distributions and GPDs

What do we wish we knew ? What can we know ?

Wigner distributions $W^q_\Gamma(\vec{r}, \vec{k})$

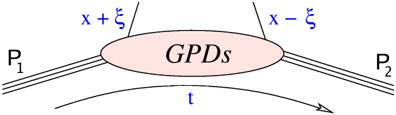
$$\Downarrow \int \mathrm{d}^2\vec{k}_\perp + \mathcal{FT}$$

Generalized Parton Distributions (GPDs)

4 chiral even GPDs

$$F^q_{\gamma^+}(x,\xi,t) = \bar{U}(P_2)\left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)\frac{\imath\sigma^{+i}q_i}{2M}\right]U(P_1)$$

$$F^q_{\gamma^+\gamma_5}(x,\xi,t) = \bar{U}(P_2)\left[\tilde{H}^q(x,\xi,t)\gamma^+\gamma_5 + \tilde{E}^q(x,\xi,t)\frac{\gamma_5 q^+}{2M}\right]U(P_1)$$



# Known quantities from novel ones

What do we wish we knew ? What can we know ? What do we know ?

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$\swarrow$ $\searrow$

Parton distribution functions (PDFs)

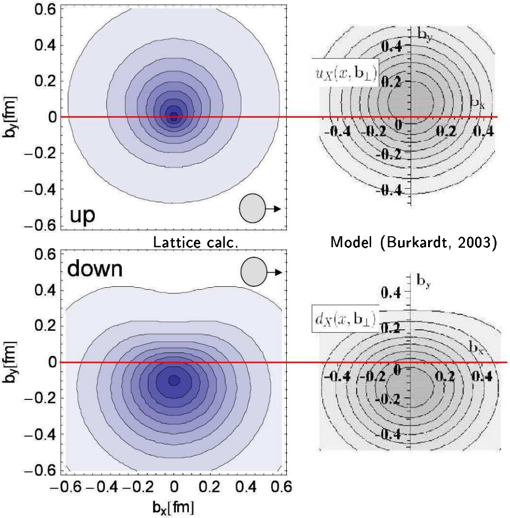
$$H^q(x,0,0) = q(x)$$

Form factors (FFs)

$$\int_{-1}^{1} \mathrm{d}x\, H^q(x,\xi,t) = F_1^q(t)$$

Universal functions constrained by specific processes

# Physical content of GPDs : Momentum distributions in the transverse plane




$$q(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} H(x, 0, t) e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$

$$- \frac{1}{2M} \frac{\partial}{\partial b_y} \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} E(x, 0, t) e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$

M. Burkardt, Int. J. Mod. Phys. **A18**, (2003) 173.
Distributions at $x_B \sim 0.3$

Lattice : QCDSF-UKQCD collaboration
Nucl. Phys. Proc. Suppl. **153** (2006) 146.
$n = 1$ Mellin moment w.r.t. x of distributions

$u$ and $d$ quarks have opposite orbital motions in a transversly polarized proton

# Physical content of GPDs : Energy-momentum tensor of $q$ flavored quarks

$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{\imath(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

How to measure gravitational FFs ?
Through graviton scattering...
or through the GPDs identities :

$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)] \quad , \quad M_2^q(t) + \frac{4}{5}d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1}\mathrm{d}x\, x H^q(x,\xi,t)$$

(Ji's sum rule)

Few physical results obtained in the $\chi$QSM,
P. Schweitzer, *GPD2006 Workshop, Trento*

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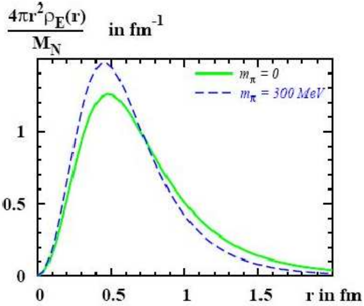
$M_2(t) \longleftrightarrow T_{00}$ : mass distributions inside the hadron

$J(t) \longleftrightarrow T_{0i}$ : angular momentum distributions

$d_1(t) \longleftrightarrow T_{ij}$ : forces and pressure distributions




Mass/energy distributions similar to electric charge (same dipole mass)

Nucleon "grows" as $m_\pi \to 0$

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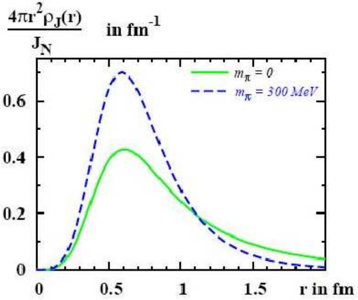


$\langle r_J^2\rangle$ about twice larger than $\langle r_E^2\rangle$ or $\langle r^2_{\text{e.m.}}\rangle$

$\rho_J(r) \propto r^2$ at small $r$

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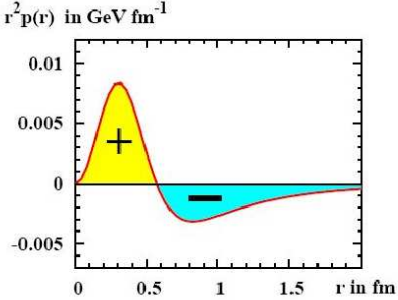


Stability $\Rightarrow \int_0^\infty \mathrm{d}r\, r^2 p(r) = 0$

$r < 0.57$ fm $\Rightarrow p(r) > 0 \leftrightarrow$ repulsion (quark core)

$r > 0.57$ fm $\Rightarrow p(r) > 0 \leftrightarrow$ attraction (pion cloud)

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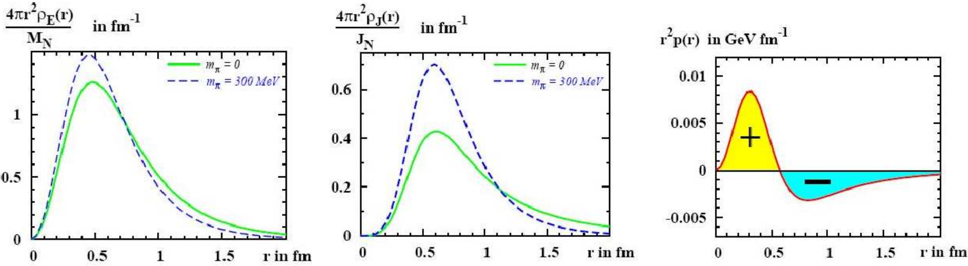
Ji's sum rule



# Access to GPDs : the DVCS process

## Observables in the Bjorken limit

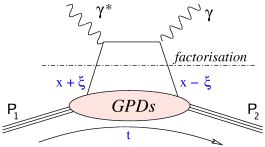
$$\gamma^* p \to \gamma p'$$

Bjorken regime :

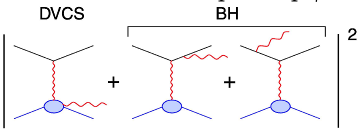
$Q^2 \to \infty$, $\nu \to \infty$ and

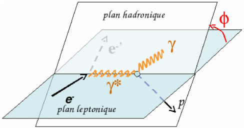
$x_B = Q^2/2M\nu$ fixed

$\left(\xi \to \frac{x_B}{2-x_B}\right)$




$$\vec{e}p \to ep\gamma$$




Diehl, Gousset, Pire, Ralston (1997)

Belitsky, Müller, Kirchner (2002)

$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

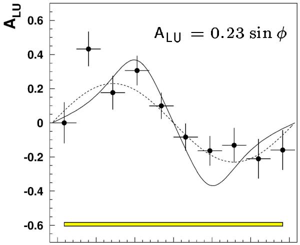
$$\alpha \propto \left(F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

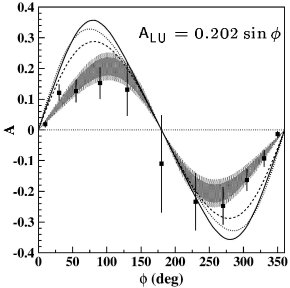
$$\mathcal{H}(\xi,t) = \pi\sum_q Q_q^2\left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$

# Non-dedicated DVCS observations

| Experiment | Observable |
|---|---|
| H1 | $\sigma$ |
| ZEUS | $\sigma$ |
| HERMES | BSA/$A_{LU}$<br>BCA<br>TSA/$A_{UL}$ & $A_{UT}$ |
| CLAS | BSA/$A_{LU}$<br>TSA/$A_{UL}$ |

HERMES and CLAS : first observations $A_{LU} \sim \sin\phi$



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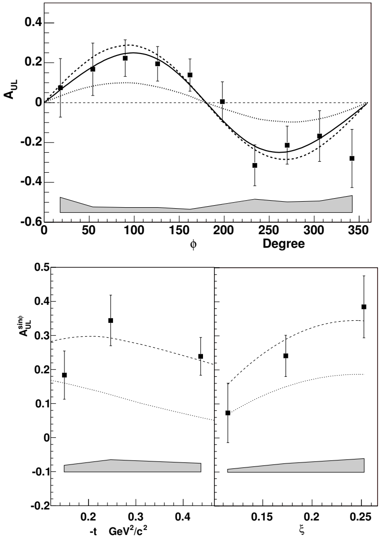
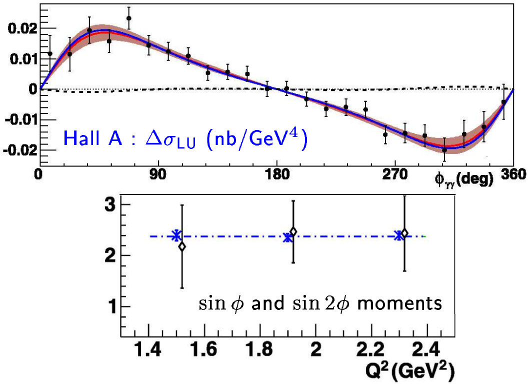
First publication of exclusive

$A_{UL} \sim \sin\phi$ for DVCS



# DVCS dedicated experiments

| Expérience | Observable |
|---|---|
| HERMES | BSA/$A_{LU}$ BCA |
| CLAS | BSA/$A_{LU}$ |
| Hall A | $\sigma$ & $\Delta\sigma_{LU}$ on the neutron |

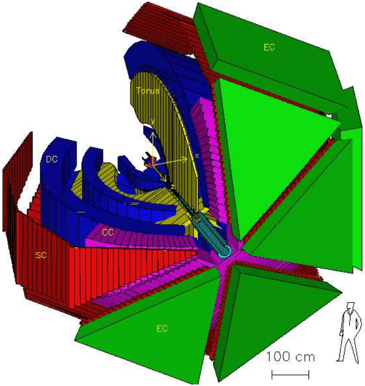



The $Q^2$ dependancy shows perturbative QCD scaling.

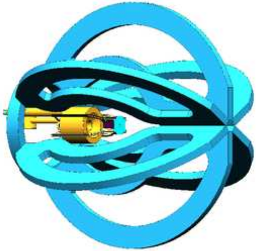
First solid evidence of twist-2 dominance.

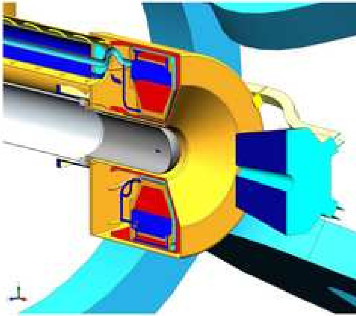
# The e1dvcs experiment with CLAS

- Began 02/01/2005
- 6 weeks of installation
- 1 week of commissioning
- 10 weeks of data taking
- $E = 5.8$ GeV
- Average beam polarisation 80%
- Average current 25 nA
- Target : l$H_2$ 2.5 cm
- $\mathcal{L}_{H_2} = 1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- $L_{H_2} = 45$ fb$^{-1}$
- $\approx$ 7 TBytes raw data



# CLAS upgrade



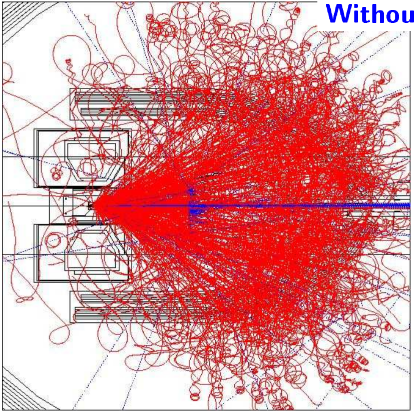


- Inner Calorimeter (IC) :
  424 $PbWO_4$ crystals
  ($16$ cm length, $1.3$ cm$^2$ to $1.6$ cm$^2$)
  $X_0 = 0.9$ cm, $R_M = 2.0$ cm
  Truncated pyramidal stacking
  Light collection : APDs
  $-2\%/^\circ \Rightarrow$ temperature stabilisation
  laser monitoring system
- Move target upstream w.r.t. nominal CLAS center
- Superconductor solenoidal magnet :
  Cu+Nb/Ti alloy at 4.3 K
  Original cryogenic system
  Additional coil compensate fringe field

  Average field at the level of the target 4.5 T at 534 A

# Illustrations

## The solenoidal field acts as a magnetic shield



**Without field**

Møller electrons energy of the order 1-10 MeV

# Illustrations

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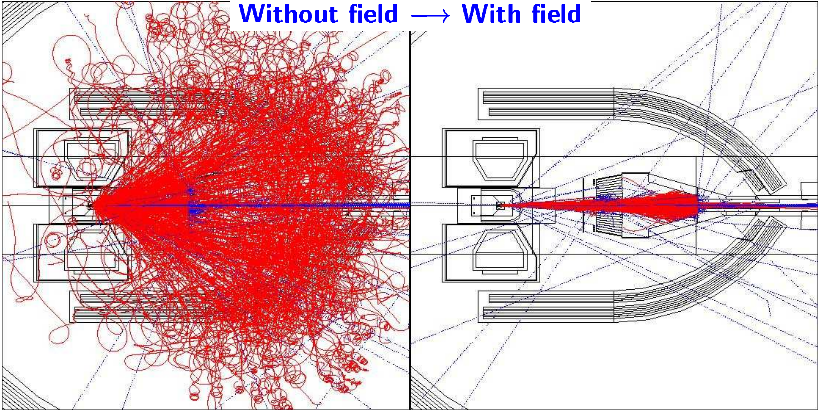
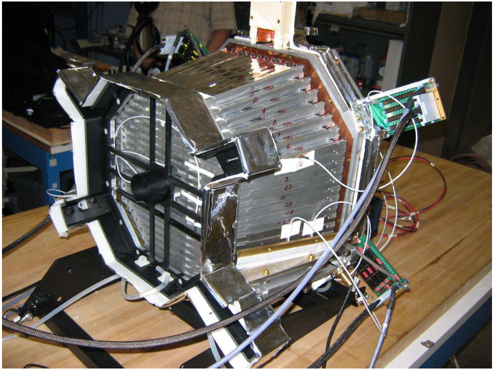
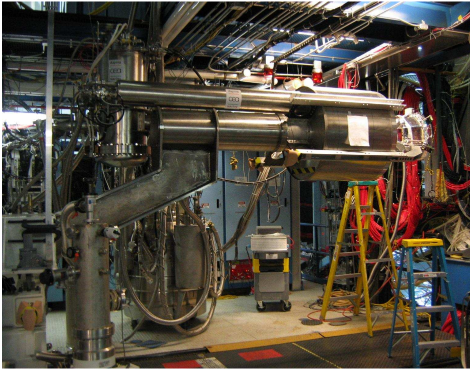



Møller electrons energy of the order 1-10 MeV

# Illustrations

## IC cabling and insertion in CLAS

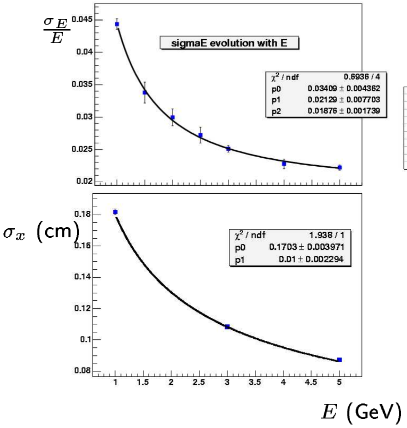


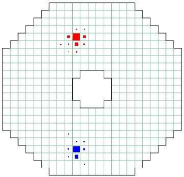


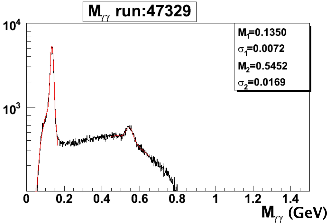
**Instrumentation from international collaboration CEA/IN2P3/ITEP(Moscow)/JLab**

# IC resolutions : Energy and Position

## Simulations and Data





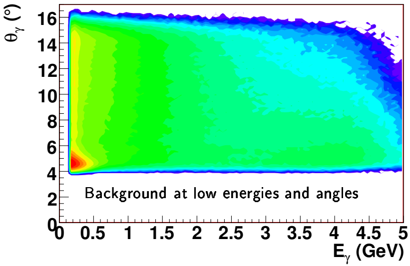

$$\frac{\sigma_E}{E} = \frac{0.02}{E} \oplus \frac{0.03}{\sqrt{E}} \oplus 0.024 \quad (E \text{ in GeV})$$

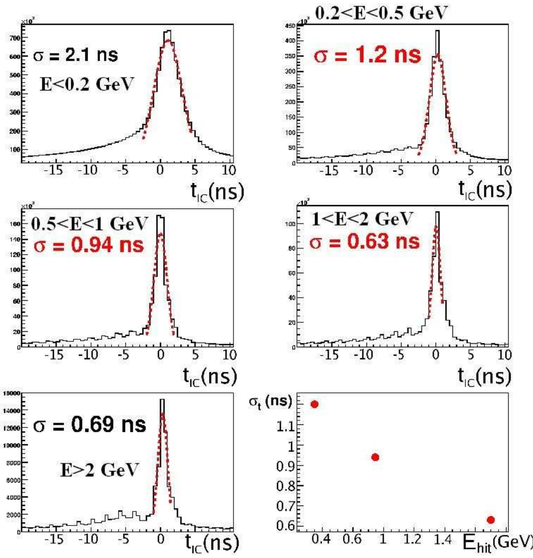
$$\sigma_x = \frac{0.2}{\sqrt{E}} \text{ (cm)}$$

# IC resolutions : Timing

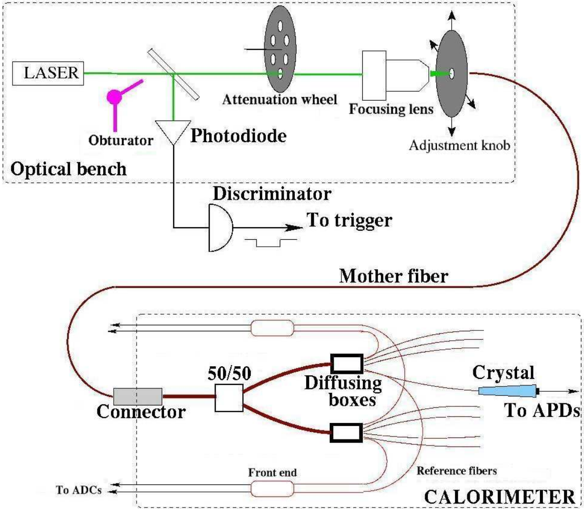
Data

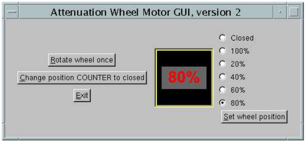
- Correction for time-walk
- Time spectra for several energies (all channels)
- CEBAF beam packet structure visible
- Very few accidentals with good electron trigger

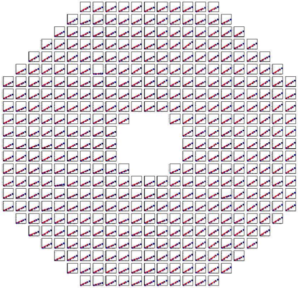


# Monitoring system



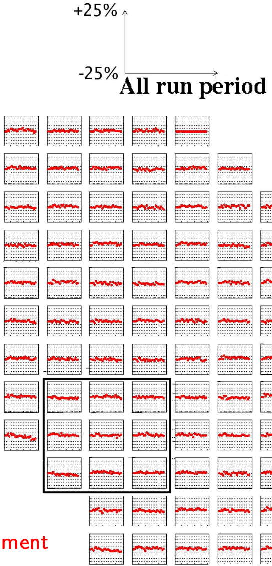
# Radiation doses in IC

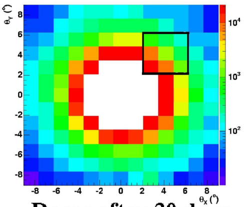
**Relative** gains measured with LASER

Doses evaluated with pedestals taken with beam on

Agreement with Møller electrons simulations

Transparency losses : compatible with expectations.



Doses after 30 days
(rad)

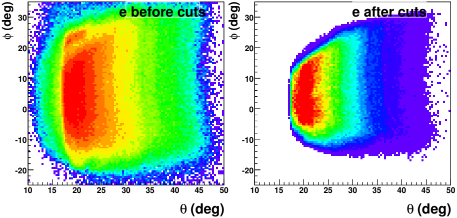
Succesful operation of the new equipment

# Electron trigger, Proton, Photon

- Electron :
  - Reconstruction in DC
  - $P > 800$ MeV/c
  - $\pi^-$ rejection : EC and CC
  - Fiducial cuts in DC and EC
- Proton :
  - Reconstruction in DC
  - Fiducial cuts DC
  - $\Delta\beta = \frac{l}{ct} - \frac{p}{\sqrt{p^2+M^2}}$
- Photon :
  - EC : fiducial cuts, $\beta_\gamma > 0.92$ (neutrons rejection)
  - IC : fiducial cuts

Fiducial cuts $(\theta, \phi)$ for the electron

before after



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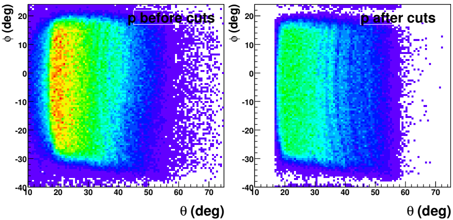
Fiducial cuts $(\theta, \phi)$ for the proton

before after



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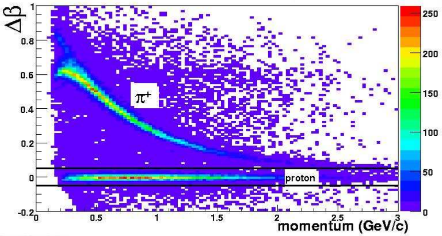
Proton : $\Delta\beta$ cut



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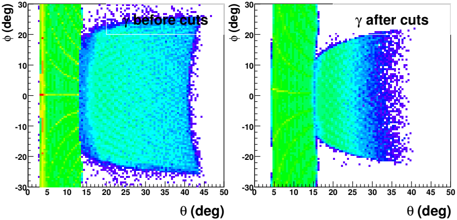
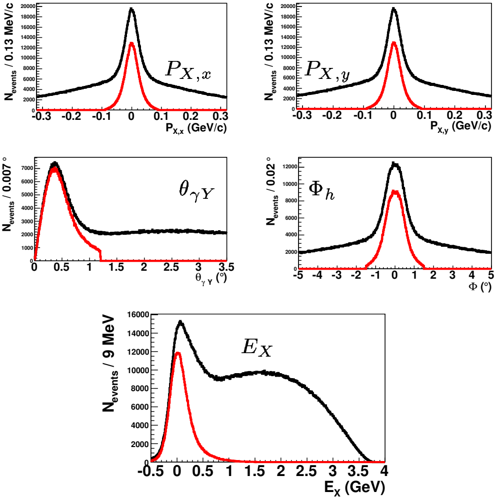
  - $\Delta\beta = \frac{l}{ct} - \frac{p}{\sqrt{p^2+M^2}}$
- Photon :
  - EC : fiducial cuts, $\beta_\gamma > 0.92$ (neutrons rejection)
  - IC : fiducial cuts

Fiducial cuts $(\theta, \phi)$ for the photon

before after



# Exclusivity cuts : IC

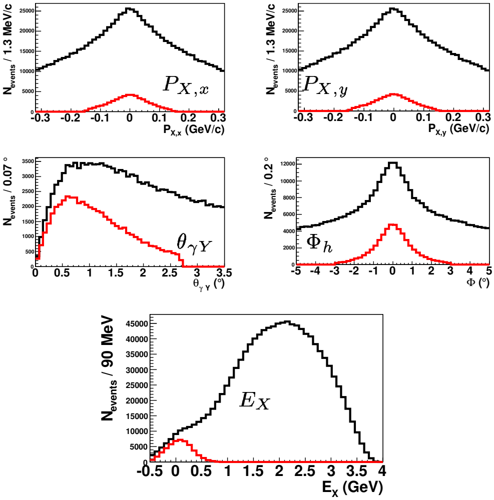



$e$, $p$ and $\gamma$ detected + exclusivity cuts

$ep \to ep\gamma X$
$ep \to epY$

- Missing transverse momentum : $|P_{X\perp}| < 90$ MeV/c
- Angle between photon and predicted photon $\theta_{\gamma Y} < 1.2°$
- Hadron coplanarity : $|\Phi_h| < 1.5°$
- Missing energy : $E_X < 300$ MeV

# Exclusivity cuts : EC

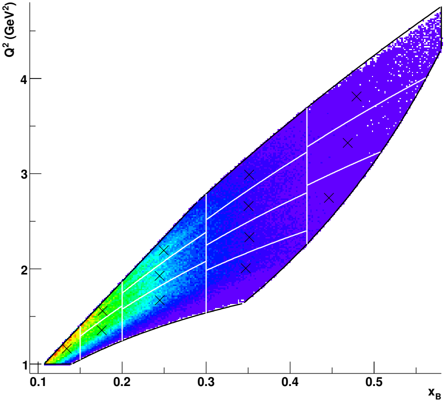



$e$, $p$ and $\gamma$ detected + exclusivity cuts

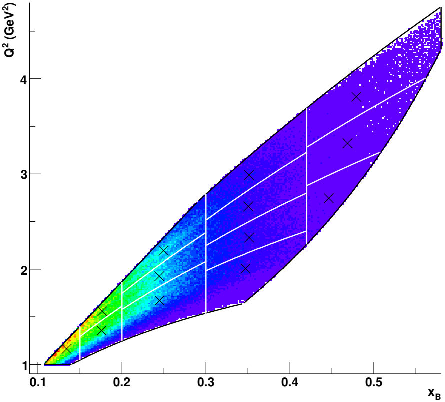
$ep \to ep\gamma X$
$ep \to epY$

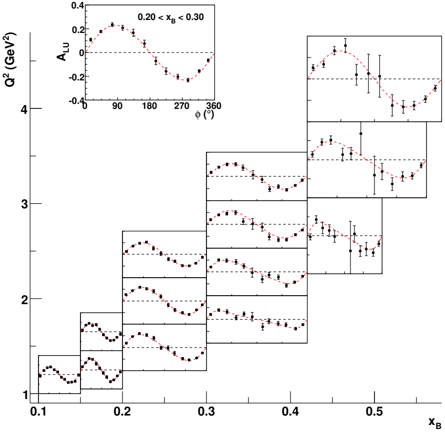
- Missing transverse momentum : $|P_{X\perp}| < 150$ MeV/c
- Angle between photon and predicted photon $\theta_{\gamma Y} < 2.7°$
- Hadron coplanarity : $|\Phi_h| < 3°$
- Missing energy : $E_X < 500$ MeV

# Kinematical coverage and binning



# Raw asymmetries as a function of $\phi$



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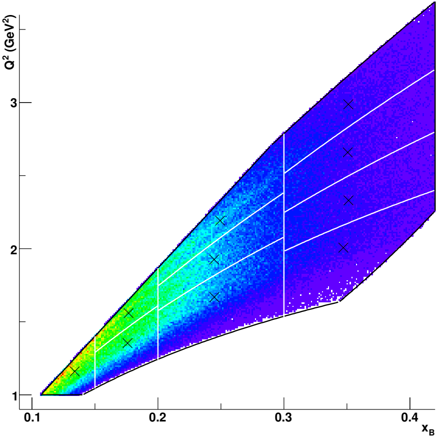


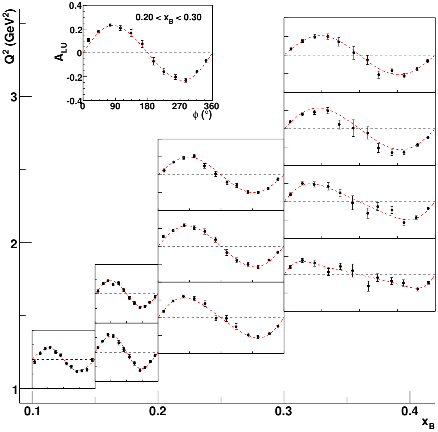

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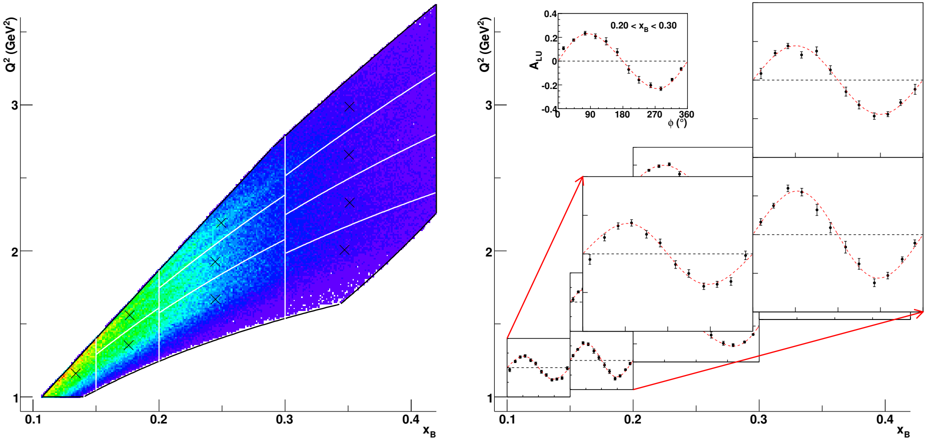


# $\pi^0$ subtraction

## Simulations : GSIM and Fast Monte-Carlo

**Principles :**

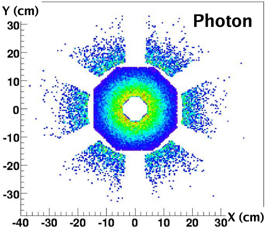
Evaluate contamination in :

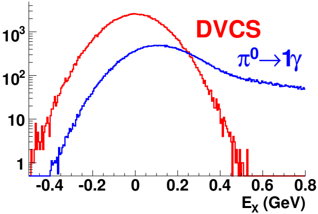
$$N_{ep\to ep\gamma X} = N_{ep\gamma} + N^{1\gamma}_{\pi^0}$$

in each elementary bin

$$\sigma_{ep\to ep\pi^0} \propto \frac{N^{2\gamma}_{\pi^0}}{\text{Acc}^{2\gamma}_{\pi^0}} = \frac{N^{1\gamma}_{\pi^0}}{\text{Acc}^{1\gamma}_{\pi^0}}$$

$$N^{1\gamma}_{\pi^0} = N^{2\gamma}_{\pi^0} \frac{N^{1\gamma}_{\pi^0\,\text{simu}}}{N^{2\gamma}_{\pi^0\,\text{simu}}}$$

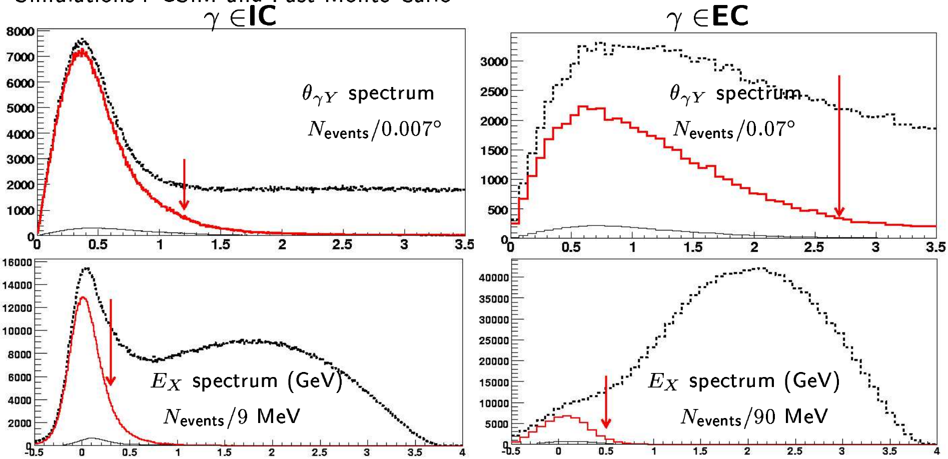


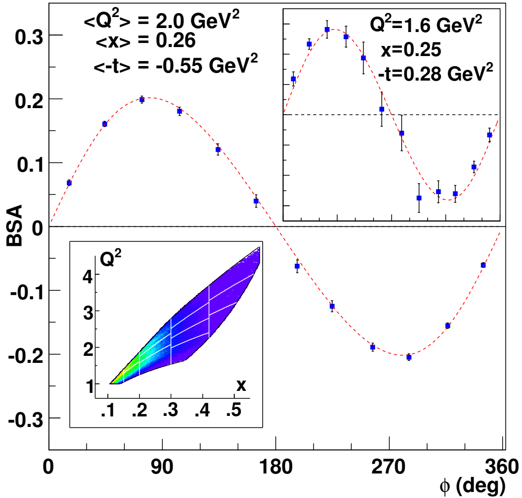

**Result :** $\frac{N^{1\gamma}_{\pi^0}}{N_{ep\to ep\gamma X}}$ rises slightly with $t$, between 5 and 15%

# $\pi^0$ subtraction

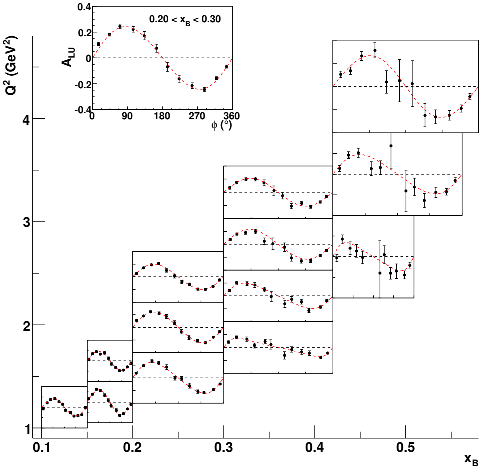
Simulations : GSIM and Fast Monte-Carlo



# Asymmetries as a function of $\phi$ integrated over $(x_B, Q^2, t)$



# Asymmetries as a function of $\phi$ integrated over $t$




$$A_{LU} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

Results integrated on all range
$0.09 < -t < 1.8$ GeV$^2$

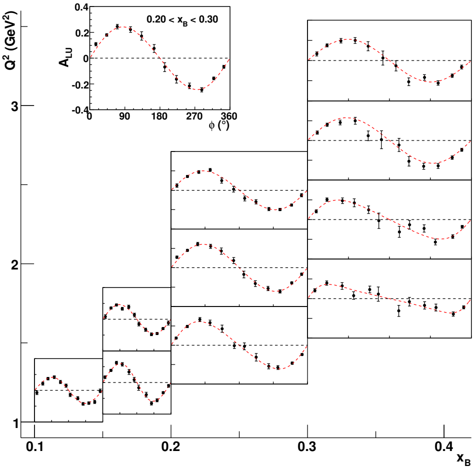
Fitted with parameterization :

$$A_{LU} = \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$

describing well the observed shapes

Errors dominated by statistics

# Asymmetries as a function of $\phi$ integrated over $t$

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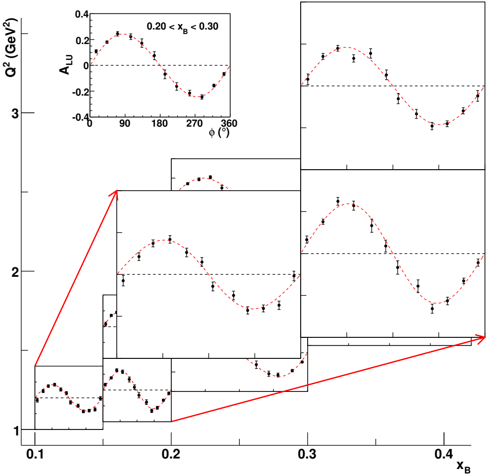


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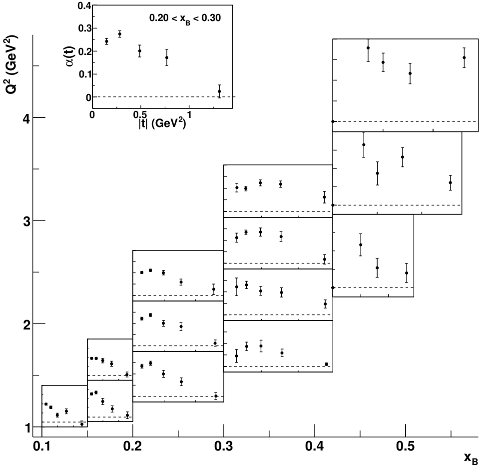
# Asymmetries at 90° as function of $t \Leftrightarrow \alpha(t)$




Slope $d\alpha/d|t|$ decreases with $x_B/Q^2$

First constraints
for a global fit of GPDs
on a wide kinematical domain

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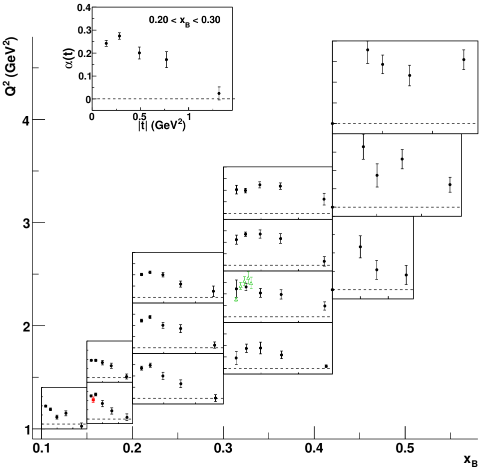


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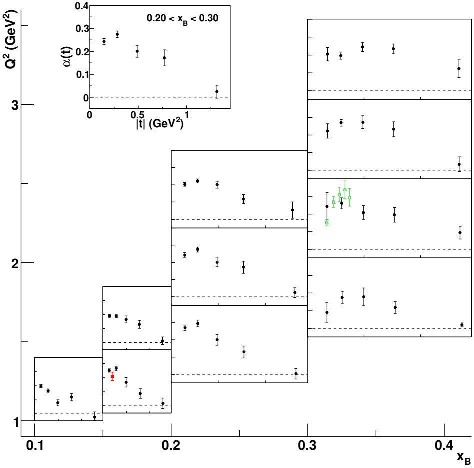


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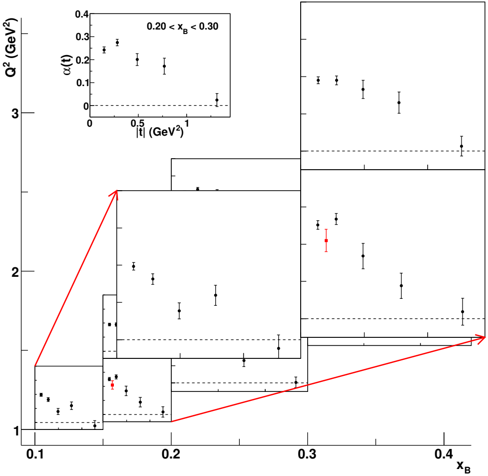


Slope $d\alpha/d|t|$ decreases with $x_B/Q^2$

First constraints
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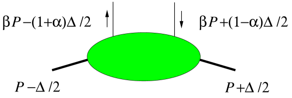
# Description : VGG model

## Doubles Distributions and Regge phenomenology




Analytical constraints automatically satisfied.

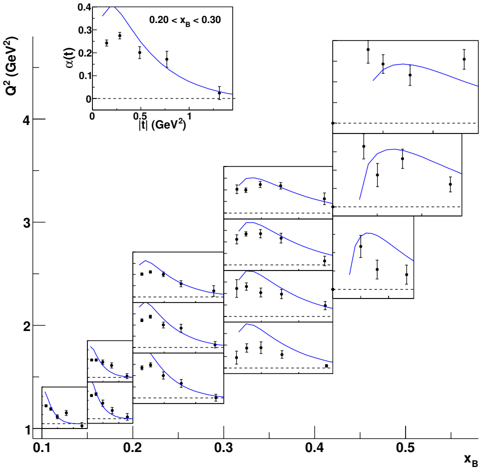
Phenomenological constraints (FFs & PDFs) naturally implemented.

$$H^q(x,\xi,t) = \int_{-1}^{1} \mathrm{d}\beta \int_{-1+|\beta|}^{1-|\beta|} \mathrm{d}\alpha\, \delta(x-\beta-\xi\alpha)\mathfrak{h}_V^q(\beta,\alpha,t) + \theta(1-\frac{x^2}{\xi^2}) D^q\left(\frac{x}{\xi},t\right)$$

$$\begin{aligned} \mathfrak{h}_V^q(\beta,\alpha,t=0) &= q(\beta)\pi_b(\beta,\alpha) \\ \mathfrak{h}_V^q(\beta,\alpha,t) &= \mathfrak{h}_V^q(\beta,\alpha,t=0)\beta^{-\alpha'_1(1-\beta)t} \\ D^q\left(\frac{x}{\xi},t\right) & \quad \text{Calculated in the } \chi\text{QSM model} \end{aligned}$$

# Confrontation with data

$t$ dependancy




Model with $D$-tern without GPD $E$

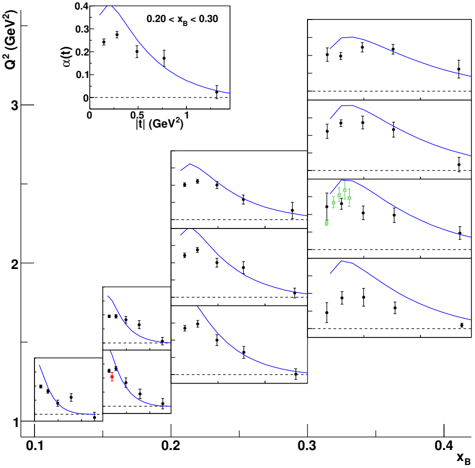
Excellent qualitative agreement

Good quantitative agreement

Overshoot at moderate $|t|$

# Confrontation with data

## $t$ dependancy

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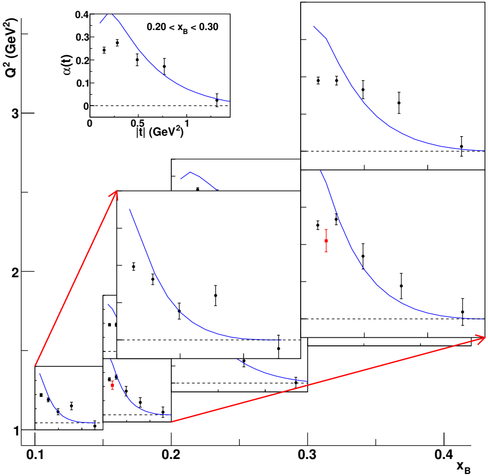


Model with $D$-tern without GPD $E$

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# Confrontation with data

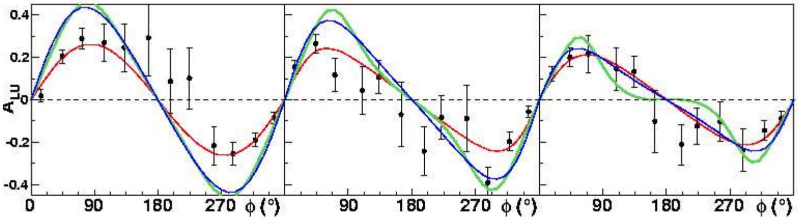
$\phi$ dependancy for twist-3 in WW "approximation"

$x_B = 0.35$ and $Q^2 = 2.4$ GeV$^2$ fixed

Fit to data

VGG model twist-2

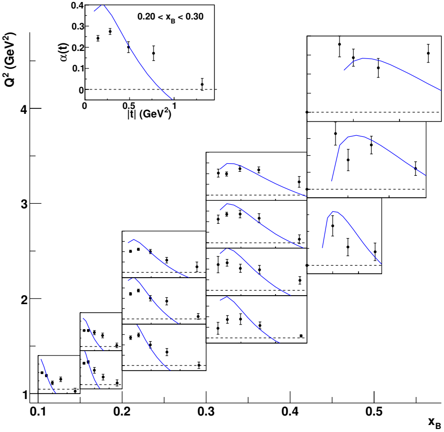
VGG model twist-3 WW




$0.2 < -t < 0.4$ $0.4 < -t < 0.6$ $0.6 < -t < 1.$ GeV$^2$

# Confrontation with data

$t$ dependancy for twist-3 in WW "approximation"




Qualitative disagreement with $\phi$ shape

Quantitative disagreement in $t$ slope

# Confrontation with data

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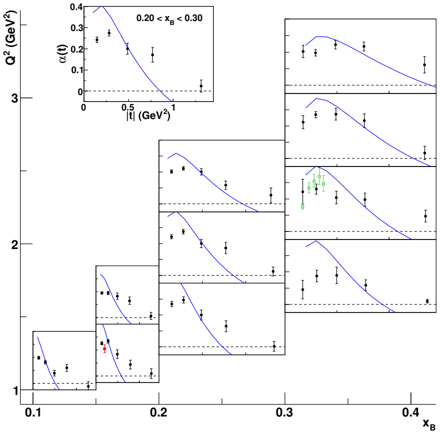


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# Confrontation with data

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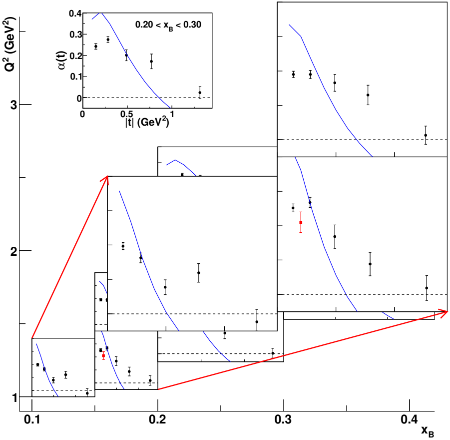


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$\phi$ dependancy for twist-3 in WW "approximation"

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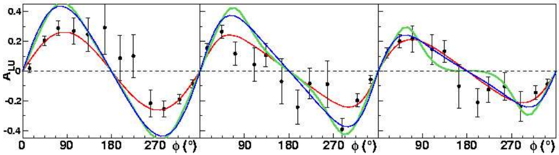
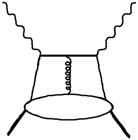
Fit to data
VGG model twist-2
VGG model twist-3 WW



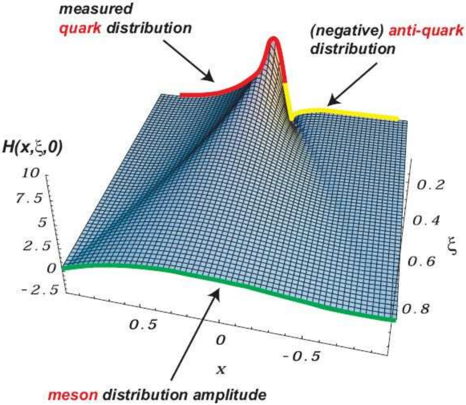

$0.2 < -t < 0.4$ $0.4 < -t < 0.6$ $0.6 < -t < 1.$ GeV$^2$

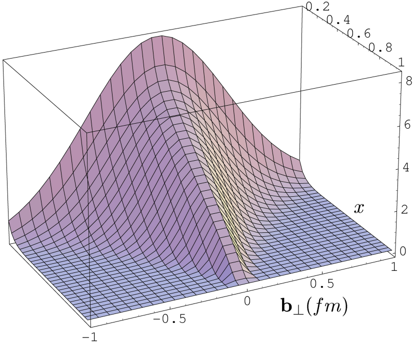
WW approximation for twist-3 :
needs improvement
*IF* true disagreement : $\bar{q}Gq$ correlations ?
Large $|t|$ measurements are important



# Perspectives : determination of $H$ by a global fit

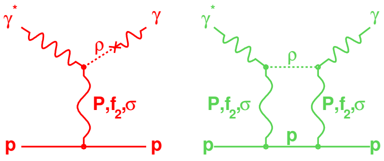
Large data sample $\Rightarrow$ need a global adjustment
to extract precisely
the intertwined correlations in $H(x, \xi, t)$

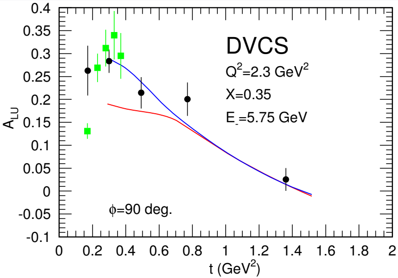


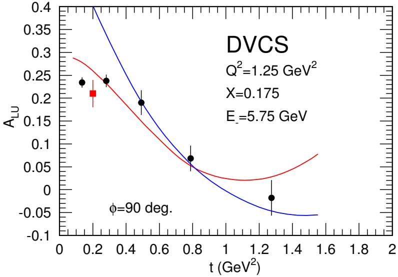



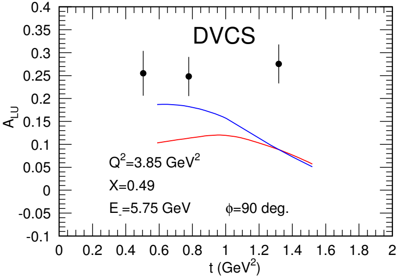
# A Regge model

poles+cuts



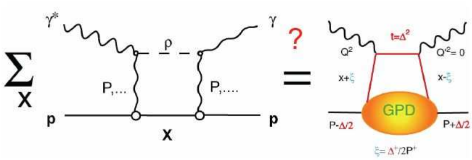



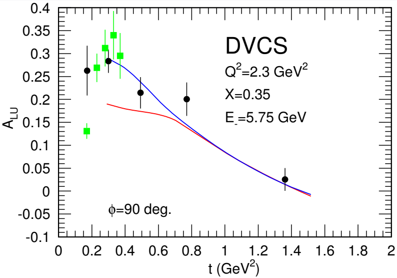



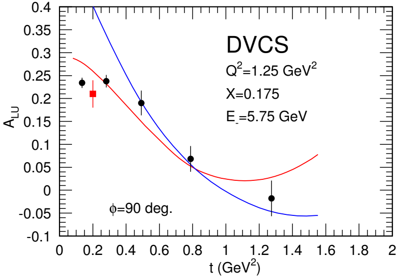



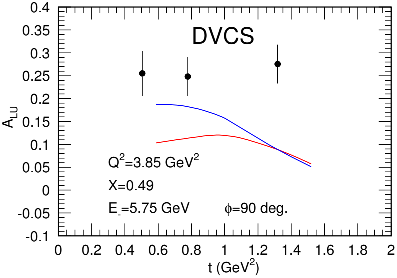
# A Regge model

## Towards a duality ?

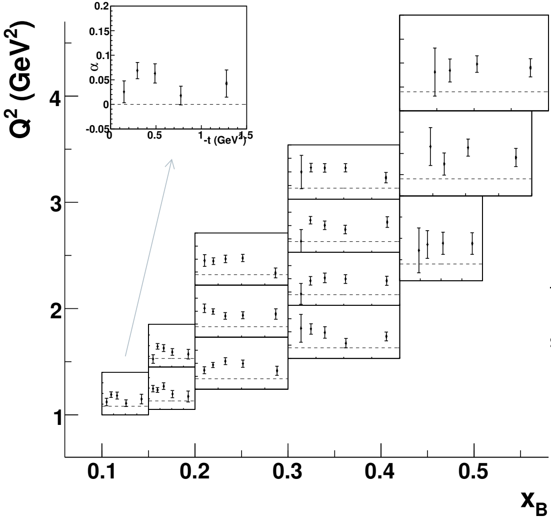


# Pseudo-scalar meson electroproduction : $\pi^0$ (R. De Masi)




PRELIMINARY

Fit with $\alpha \sin\phi$

Clear indication of LT interferences

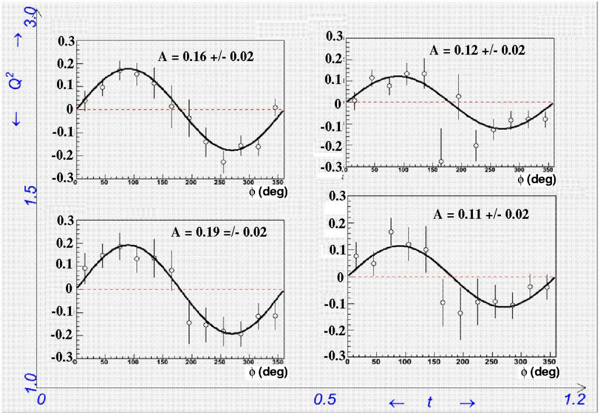
Need Rosenbluth separation

to extract longitudinal part

**IF** factorisation holds

sensitive to $2\tilde{H}^u + \tilde{H}^d$ and $2\tilde{E}^u + \tilde{E}^d$

# Pseudo-scalar meson electroproduction : $\eta$ (B. Zhao)




PRELIMINARY

Fit with $\alpha \sin\phi$

Clear indication of LT interferences

Need Rosenbluth separation to extract longitudinal part

**IF** factorisation holds

sensitive to $2\tilde{H}^u - \tilde{H}^d - 2\tilde{H}^s$ and $2\tilde{E}^u - \tilde{E}^d - 2\tilde{E}^s$

# Conclusion

The e1dvcs experiment with CLAS :

- has benefited from excellent performances of the new equipment.
- achieved full exclusivity of the reaction.
- provides first constraints on a vast kinematical domain for a global fit of GPDs.

# What is next ?

Perspectives :

- Experiments :
  - CLAS/DVCS : $A_{LU}$ and $A_{UL}$
  - Hall A : $\Delta\sigma$ and $\sigma$ for DVCS, $d\sigma_L$ and $d\sigma_T$ for $\pi^0$
  - DESY : H1/ZEUS $\sigma$ for DVCS
  - DESY : HERMES $A_C$, $A_{LU}$
  - COMPASS $\sigma$, $A_C$
  - JLab 12 GeV
- Phenomenology :
  - Encouraging results towards GPDs extraction.
  - Twist-3 WW, $\bar{q}Gq$ correlations ?
  - Pseudoscalar meson electroproduction and $\chi$SM
  - Hadronic femtophotography

# Projected results 12 GeV