Extraction of the Compton Form Factor $\mathcal{H}$ from DVCS measurements in the quark sector

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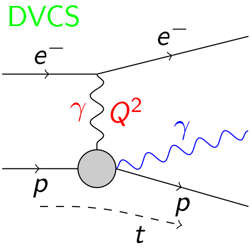
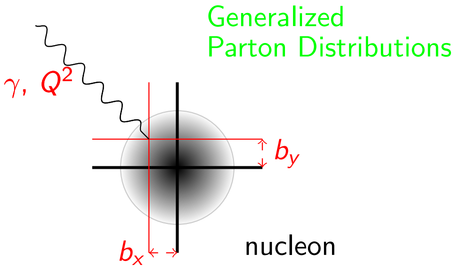
Trento 2010 - 11 / 10 / 2010

Generalized Parton Distributions.

Viewing nucleon structure in 3d.





- Correlation of the **longitudinal momentum** and the **transverse position** of the struck quark.

Generalized Parton Distributions.

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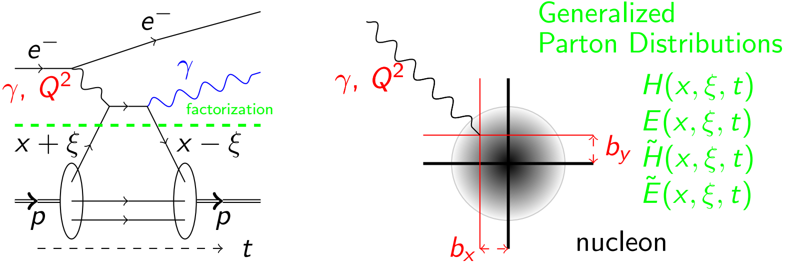
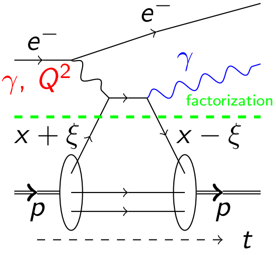
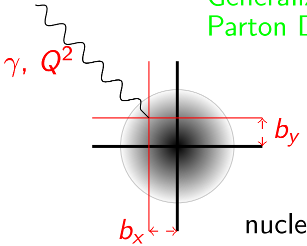


- Correlation of the **longitudinal momentum** and the **transverse position** of the struck quark.
- **3-dimensional** description of the nucleon.
- Insights on :
  - spin structure,
  - energy-momentum structure.

Generalized Parton Distributions.

Viewing nucleon structure in 3d.

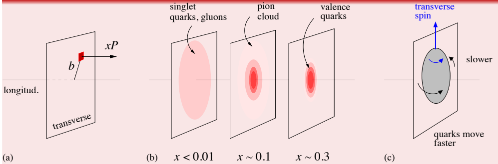




Generalized Parton Distributions

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

How to obtain this 3d picture from DVCS measurements ?



C. Weiss, AIP Conf. Proc. 1149, 150 (2009)

DVCS described by 4 Compton Form Factors.

Approximations : quark sector, leading twist and leading order.

- Example : GPD H

$$\mathcal{H} = \int_{-1}^{+1} dx\, H(x,\xi,t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

- Integration yields **real** and **imaginary** parts to $\mathcal{H}$:

$$Re\mathcal{H} = \mathcal{P} \int_{-1}^{+1} dx\, H(x,\xi,t) \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right)$$

$$Im\mathcal{H} = \pi \Big(H(\xi,\xi,t) - H(-\xi,\xi,t) \Big)$$

- Relation between $Im\mathcal{H}$ and $Re\mathcal{H}$ **weakly constrained** by dispersion relations. However see :

K. Kumericki and D. Müller, Nucl. Phys. **B841**, 1 (2010)

G. Goldstein and S. Liuti, DIS2009

Current extraction methods on the market.

Problem : How to reduce the model dependence ?

Local fits

Take each kinematic bin independantly of the others.
Extraction of $Re\mathcal{H}$, $Im\mathcal{H}$, ... as independent parameters.

Global fit

Take all kinematic bins at the same time. Use a parametrization of GPDs or CFFs.

Hybrid : Local / global fit

Combine two previous methods to estimate model dependence.

Neural networks

Work in progress. Results reported at Exclusive 2010 Workshop.

Selected DVCS measurements.

Fine kinematic binning, large kinematic coverage, several observables.

Hall A : helicity-dependent and independent cross sections

(C. Muñoz Camacho et al., Phys. Rev. Lett. 97 (2006) 262002)

- Helicity-dependent cross sections :
  - Q^2 : 1.5 $\rightarrow$ 2.3 GeV^2
  - t : -0.33 $\rightarrow$ -0.17 GeV^2
- Helicity-independent cross sections :
  - Q^2 : 2.3 GeV^2
  - t : -0.33 $\rightarrow$ -0.17 GeV^2

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Hall A : helicity-dependent and independent cross sections

C. Muñoz Camacho *et al.*, Phys. Rev. Lett. **97**, 262002 (2006)

Restricted kinematic range, highly-precise helicity-dependent cross sections.

Hall B : Beam Spin Asymmetries

(F.-X. Girod et al., Phys. Rev. Lett. 100 (2008) 162002)

- x_B : $0.11 \longrightarrow 0.58$
- Q^2 : $1 \longrightarrow 4.8$ GeV^2
- t : $-1.8 \longrightarrow -0.09$ GeV^2

Selected DVCS measurements.

Fine kinematic binning, large kinematic coverage, several observables.

Hall A : helicity-dependent and independent cross sections

C. Muñoz Camacho *et al.*, Phys. Rev. Lett. **97**, 262002 (2006)

Restricted kinematic range, highly-precise helicity-dependent cross sections.

Hall B : Beam Spin Asymmetries

F.-X. Girod *et al.*, Phys. Rev. Lett. **100**, 162002 (2008)

Wide kinematic range, precise BSAs.

Hermes : BSAs, BCAs, TSAs

A. Airapetian *et al.*, JHEP **0806**, 017 (2008)

D. Zeiler *et al.*, arXiv:0810.5007 [hep-ex]

- x_B : $0.08 \longrightarrow 0.12$
- Q^2 : $1.9 \longrightarrow 3.5$ GeV^2
- t : $-0.42 \longrightarrow -0.03$ GeV^2

Selected DVCS measurements.

Fine kinematic binning, large kinematic coverage, several observables.

Hall A : helicity-dependent and independent cross sections

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Wide kinematic range, precise BSAs.

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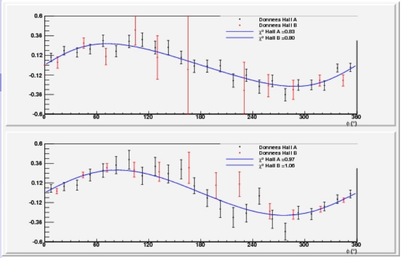
A. Airapetian *et al.*, JHEP **0806**, 017 (2008)
D. Zeiler *et al.*, DIS2008
Restricted kinematic range, several different observables.

Comparison of Hall A and B DVCS data.

A cross-check.



Two points for comparisons :

- Hall A :

x_B	$Q^2(GeV^2)$	$t(GeV^2)$
0.36	2.3	-0.17
0.36	2.3	-0.28

- Hall B :

x_B	$Q^2(GeV^2)$	$t(GeV^2)$
0.3215	2.2170	-0.1719
0.3431	2.3060	-0.3012

Analytic $ep \to ep\gamma$ cross sections.

Interference between Bethe-Heitler and VCS processes treated exactly.

Example : DVCS helicity-dependent cross section at twist 2

- BKM formalism :

$$C_1 \ \sin \ \phi \ Im \ \left(\mathcal{H} + \frac{x_B}{2 - x_B}\left(1 + \frac{F_2}{F_1}\right)\tilde{\mathcal{H}} - \frac{t}{4M^2}\frac{F_2}{F_1}\mathcal{E}\right)$$

A.V. Belitsky, D. Mueller and A. Kirchner
Nucl. Phys. **B629**, 323 (2002)

- GV formalism :

$$C_2 \ \sin\phi \ Im\left(\mathcal{H} + \ c_{\mathcal{E}} \ \ \mathcal{E} + \ c_{\tilde{\mathcal{H}}} \ \ \tilde{\mathcal{H}} + \ c_{\tilde{\mathcal{E}}} \ \ \tilde{\mathcal{E}}\right)$$

P.A.M. Guichon and M. Vanderhaeghen, unpublished

Analytic $ep \to ep\gamma$ cross sections.

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Example : DVCS helicity-dependent cross section at twist 2

- BKM formalism : arXiv:1005.5209

$$C_1 \ \sin\ \phi \ Im \ \left(\mathcal{H} + \frac{x_B}{2 - x_B}\left(1 + \frac{F_2}{F_1}\right)\tilde{\mathcal{H}} - \frac{t}{4M^2}\frac{F_2}{F_1}\mathcal{E}\right)$$

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Interference between Bethe-Heitler and VCS processes treated exactly.

Example : DVCS helicity-dependent cross section at twist 2

- BKM formalism : coefficients do not depend on Q^2

$$C_1 \ \sin \ \phi \ Im \ \left(\mathcal{H} + \frac{x_B}{2 - x_B} \left(1 + \frac{F_2}{F_1} \right) \tilde{\mathcal{H}} - \frac{t}{4M^2} \frac{F_2}{F_1} \mathcal{E} \right)$$

A.V. Belitsky, D. Mueller and A. Kirchner
Nucl. Phys. **B629**, 323 (2002)

- GV formalism : coefficients depend on Q^2

$$C_2 \ \sin \phi \ Im \left(\mathcal{H} + \underbrace{c_{\mathcal{E}}}_{20\ \%} \mathcal{E} + \underbrace{c_{\tilde{\mathcal{H}}}}_{20\ \%} \tilde{\mathcal{H}} + \underbrace{c_{\tilde{\mathcal{E}}}}_{30\ \%} \tilde{\mathcal{E}} \right)$$

P.A.M. Guichon and M. Vanderhaeghen, unpublished

Main assumptions.

Expectation : extraction of $\mathcal{H}$ with $\geq$ 40 % total uncertainty.

- **Twist 2 accuracy**
  - Early Q^2-scaling was observed in Hall A.
    C. Muñoz Camacho et al.
    Phys. Rev. Lett. **97**, 262002 (2006)
  - Similar recent result concerning a subset of JLab data.
    M. Guidal, Phys. Lett. **B689**, 156 (2010)
  - Small higher twist contribution in Hermes data.
    D. Zeiler *et al.*, DIS2008
- ***H*-dominance**
  - Dramatically decreases the number of degrees of freedom in the fits.
  - Expectations : **systematic error between 20 and 50 %**.
  - Systematic error $\lesssim$ 25 % from direct test of hypothesis with VGG model.
  - The most questionable assumption so far ?

Local fits.

Fits on each kinematic bin to twist 2 expressions.

- Keep bins with $\frac{|t|}{Q^2} < \frac{1}{2}$.
- Low model dependence (H-dominance, twist 2).
- But fits may still be underconstrained.
- **Estimation** of systematic errors caused by ***H*-dominance hypothesis** by fitting data with subdominant GPDs set to 0 or to their VGG value.

Global fit.

Fit to a parametrization from the dual model.

- DVCS cross sections depend on singlet combination H_+ :

$$H_+(x,\xi,t,Q^2) = H(x,\xi,t,Q^2) - H(-x,\xi,t,Q^2)$$

- Dual model parametrization of H_+ :

$$2\sum_{n=0}^{\infty}\sum_{l=0}^{n+1} B_{nl}(t,Q^2)\,\theta\left(1-\frac{x^2}{\xi^2}\right)\left(1-\frac{x^2}{\xi^2}\right)\;C_{2n+1}^{\frac{3}{2}}\left(\frac{x}{\xi}\right)\quad P_{2l}\left(\frac{1}{\xi}\right)$$

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$$2 \sum_{n=0}^{\infty} \sum_{l=0}^{n+1} \underbrace{B_{nl}(t, Q^2)}_{\text{Model t-dep.}} \theta \left(1 - \frac{x^2}{\xi^2}\right) \left(1 - \frac{x^2}{\xi^2}\right) C_{2n+1}^{\frac{3}{2}}\left(\frac{x}{\xi}\right) \quad P_{2l}\left(\frac{1}{\xi}\right)$$

with $B_{nl}(t, Q^2) = \left(\ln \frac{Q_0^2}{\Lambda^2} / \ln \frac{Q^2}{\Lambda^2}\right)^{\frac{\gamma_p}{\beta_0}} B_{nl}(t, Q_0^2)$.

Global fit.

Fit to a parametrization from the dual model.

- DVCS cross sections depend on singlet combination H_+ :

$$H_+(x, \xi, t, Q^2) = H(x, \xi, t, Q^2) - H(-x, \xi, t, Q^2)$$

- Dual model parametrization of H_+ :

$$2 \sum_{n=0}^{N} \sum_{l=0}^{n+1} \underbrace{B_{nl}(t, Q^2)}_{\text{Model t-dep.}} \theta\left(1 - \frac{x^2}{\xi^2}\right) \left(1 - \frac{x^2}{\xi^2}\right) C_{2n+1}^{\frac{3}{2}}\left(\frac{x}{\xi}\right) \quad P_{2l}\left(\frac{1}{\xi}\right)$$

$$\text{with } B_{nl}(t, Q^2) = \left(\ln \frac{Q_0^2}{\Lambda^2} / \ln \frac{Q^2}{\Lambda^2}\right)^{\frac{\gamma_p}{\beta_0}} \quad \frac{a_{nl}}{1+b_{nl}(t-t_0)^2}.$$

- Non-trivial correlation between x and t.
- a_{nl} and b_{nl} are fitted. t_0 is chosen prior to the fits.

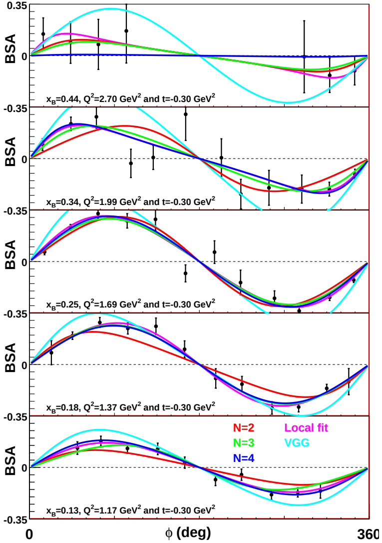
Global fit.

Iterative fitting procedure and systematic uncertainties.

- Keep bins with $\frac{|t|}{Q^2} < \frac{1}{2}$ (1001 ϕ-bins fitted).
- $\frac{N(N+3)}{2}$ fitted coefficients for a given truncation N.
  - 10, 18 and 28-parameter fits for $N = 2$, 3 and 4.
  - **Estimation** of the **truncation error** by comparison of the results of these 3 fits.
- Iterative fitting procedure to handle large number of parameters.
- **Estimation** of systematic errors caused by ***H*-dominance hypothesis** by fitting data with subdominant GPDs set to 0 or to their VGG value.
- Purpose : smooth parametrization of data. **No extrapolation** outside the domain of the fit.

Effect of the truncation of the series.

Hall B data.



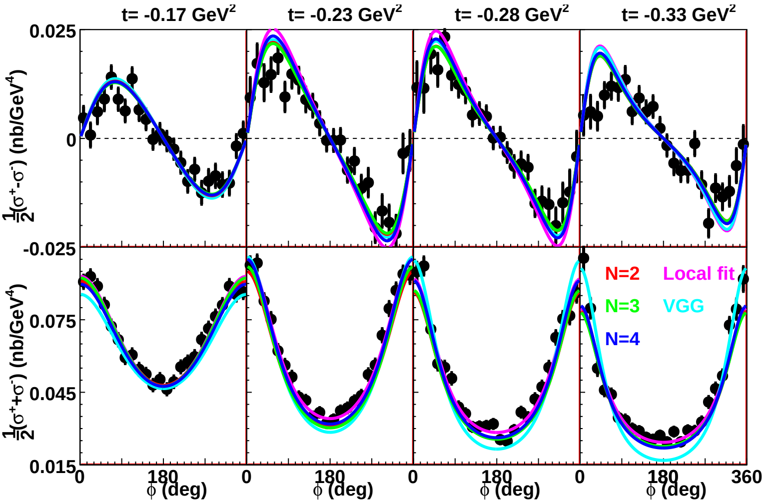
- 3 global fits qualitatively similar :

N	$\chi^2/\text{d.o.f.}$
2	1.73
3	1.61
4	1.78

- No differences on Hall A data (next slide).
- $N=2$ fails to reproduce BSAs at small ξ.
- $N=3$ always good and close to local fits.
- $N=4$ is uncontrolled at large ξ.

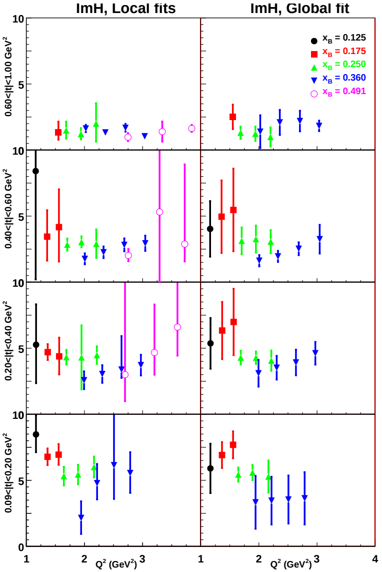
Effect of the truncation of the series.

Hall A data.



$Im\mathcal{H}$ on Hall B kinematics.

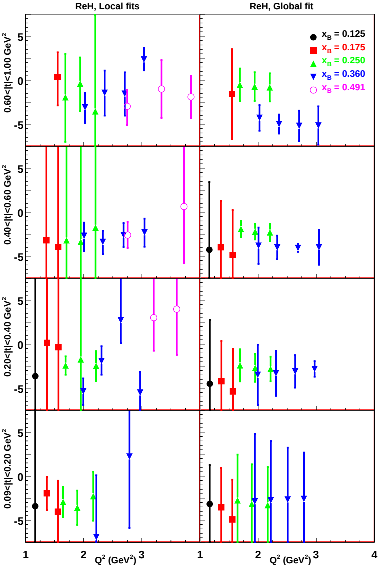
Q^2-dependence.



- Compatible results of local and global fits : **strong consistency check**.
- **Realistic estimation of systematic uncertainties** :
  - Comparable accuracy from local and global fits.
  - Accuracy in agreement with expectations.
- Restricted kinematic region **suitable for GPD-analysis**.

$Re\mathcal{H}$ on Hall B kinematics.

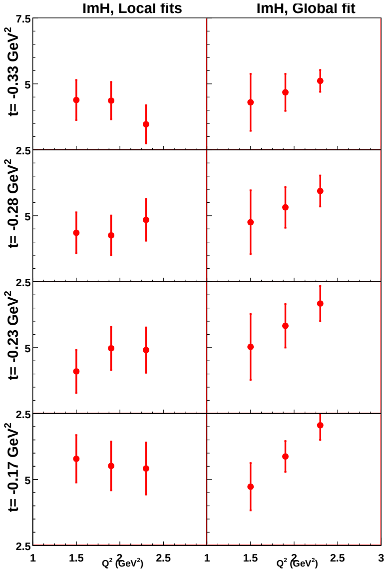
Q^2-dependence.



- **Large fluctuations in** $Re\mathcal{H}$ from local fits. Global fit is smoother.
- Unreliable extraction of $Im\mathcal{H}$ or $Re\mathcal{H}$ at large ξ.
- $Re\mathcal{H}$ **weakly constrained**.

$Im\mathcal{H}$ on Hall A kinematics.

t-dependence.



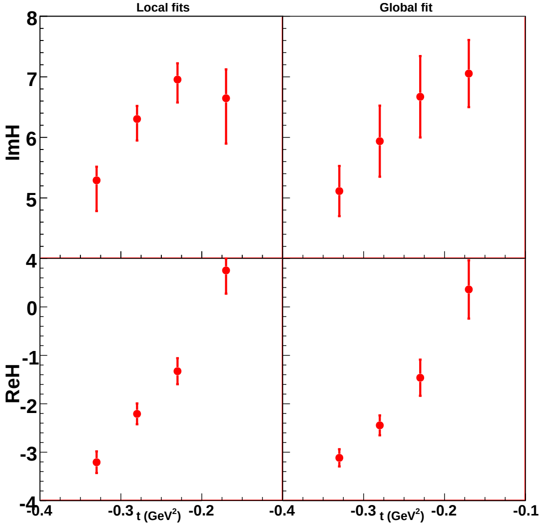
- Good agreement between results of local and global fits but. . .
- Discrepancy seems to be larger at small $|t|$!
- Sizeable scaling deviation for t = -0.17 GeV^2.
- Noticeable deviations if

$$\xi = x_B \frac{1 + \frac{t}{2Q^2}}{2 - x_B + \frac{x_B t}{Q^2}} \rightarrow \frac{x_B}{2 - x_B}$$

- Call for a **twist 3 analysis** !?

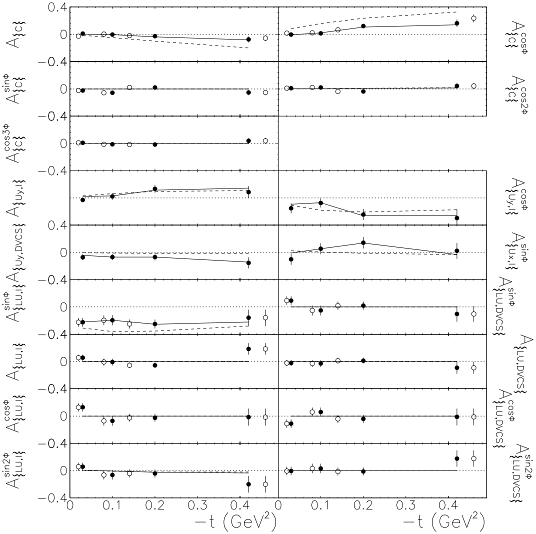
$Im\mathcal{H}$ and $Re\mathcal{H}$ on Hall A kinematics.

t-dependence.



Hermes data (local fits).

Data show a small higher-twist contribution.



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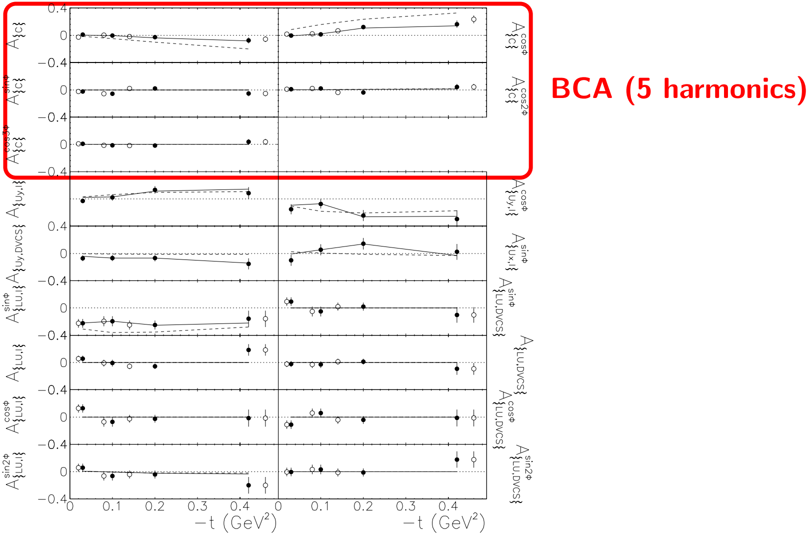

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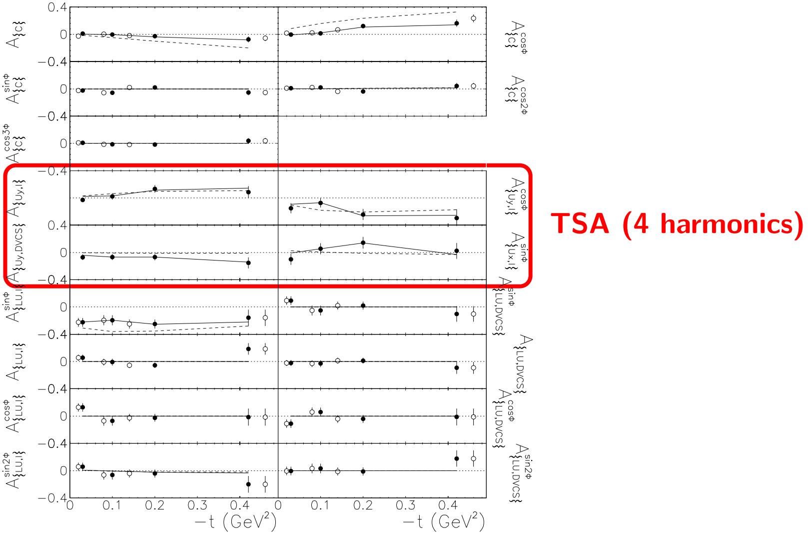

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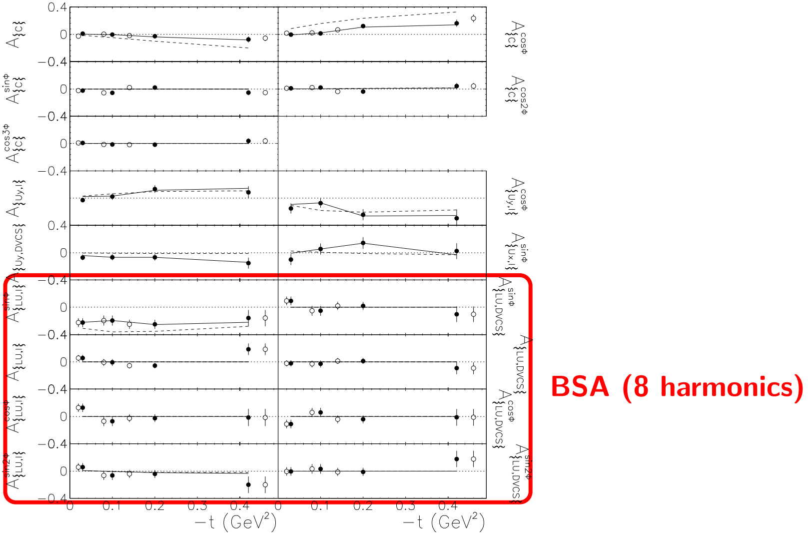
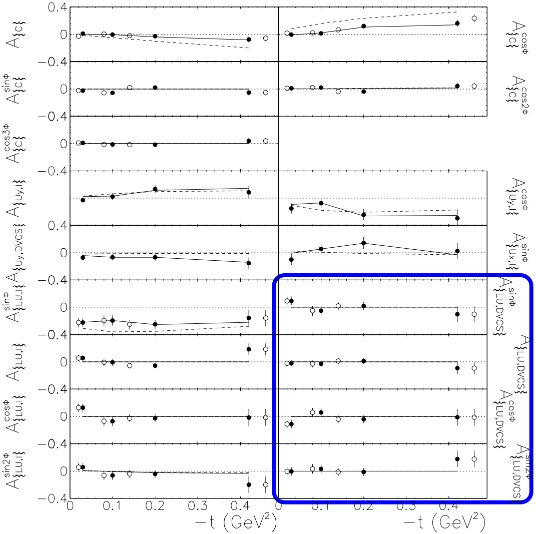


Hermes data (local fits).

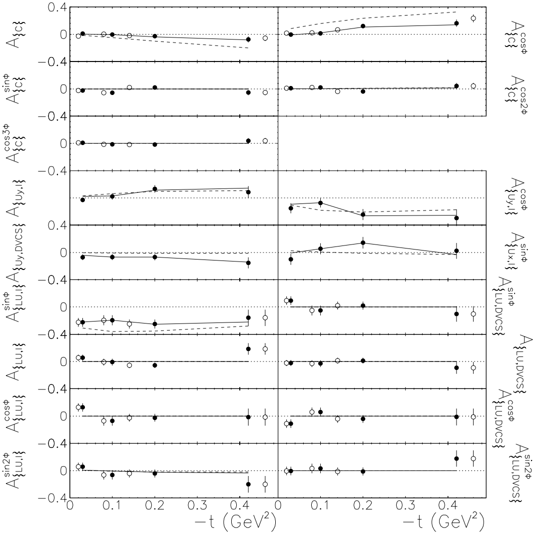
Data show a small higher-twist contribution.



$A_{\mathrm{LU}}^{\mathrm{DVCS}} = 0$ at twist 2

Hermes data (local fits).

Data show a small higher-twist contribution.

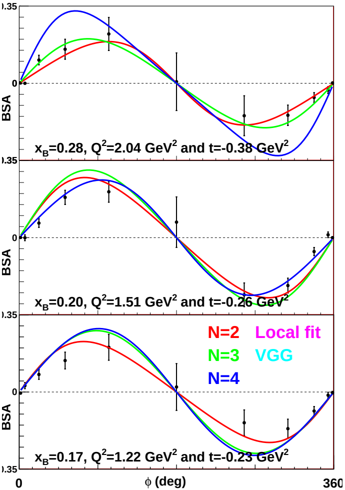


- ○ Original point
- ● Fitted point
- —— Fit
- - - - VGG

- Small higher twist effect.
- All observables are fitted at the same time.

Comparison with other CLAS BSAs.

Check with data in same kinematic region.



- G. Gavalian *et al.*, Phys. Rev. **C80**, 035206 (2009)
- Restricted kinematic range :
  - x_B : 0.17 $\rightarrow$ 0.28
  - t : -0.23 $\rightarrow$ -0.38 GeV^2
  - Q^2 : 1.22 $\rightarrow$ 2.04 GeV^2
- Reasonnable agreement (systematics not shown).

Comparison with other studies (Hall A data).

Several approaches : BKM, BKM + "hot fix", GV, VGG.

- First extraction : BKM formalism without "hot fix".

  C. Muñoz Camacho *et al.*
  Phys. Rev. Lett. **97**, 262002 (2006)

- Model-dependent prediction. Fit in progress.

  S. Ahmad *et al.*, arXiv:0708.0268

- VGG fitter code.

  M. Guidal, Eur. Phys. J. **A37**, 319 (2008)
  M. Guidal, Phys. Lett. **B689**, 156 (2010)

- "Hot fix" for power suppressed contributions in BKM.

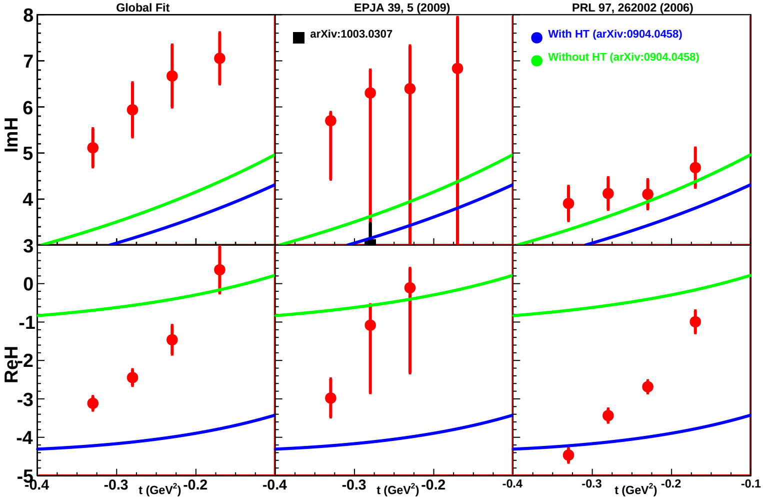
  A. Belitsky and D. Müller, Phys. Rev. **D79**, 014017 (2009)

- Global fit for all unpolarized proton target with BKM + "hot fix".

  K. Kumericki and D. Müller, Nucl. Phys. **B841**, 1 (2010)

Comparison with previous studies (Hall A data).

Where are we today ?



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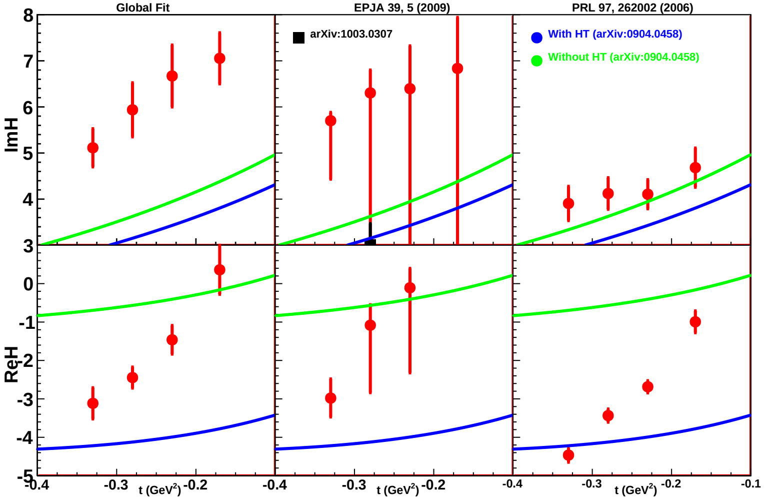
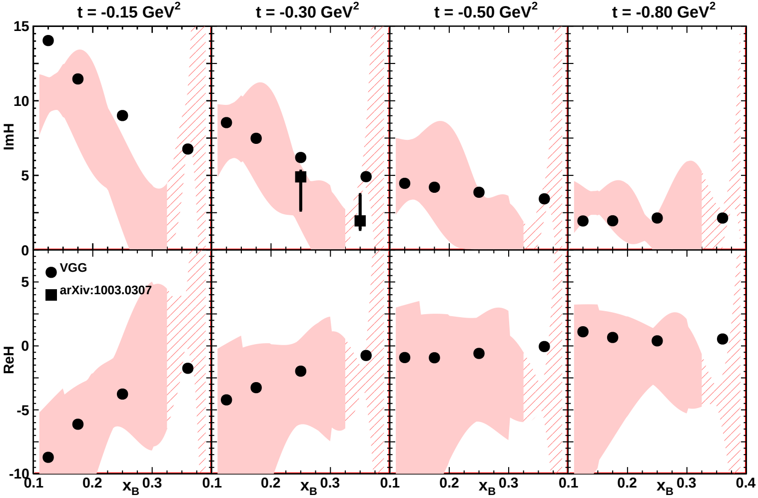
Where are we today ?



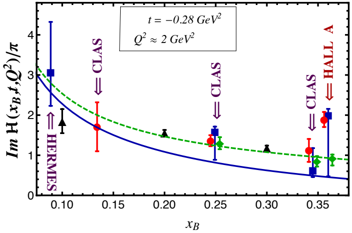
Hybrid fitting strategy results compared to VGG.

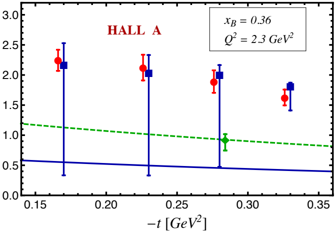
Similar x_B-dependence but loss of information during the extraction.



Results on data from Halls A and B.

Reasonnable agreement on Hall B.





K. Kumericki and D. Müller, Exclusive 2010

Degrees of freedom.

How many parameters for local and global fits ?

- Local fits are not enough :
  - 8 free parameters per kinematic bin.
  - Extrapolations ($\xi \to 0$, $t \to 0$) difficult if even possible.
  - Make assumptions on kinematical binning $\Rightarrow$ systematic uncertainties.
- Global fits : way to go, but :
  - Model dependence ?
  - Number of free parameters (beyond H-dominance) ?

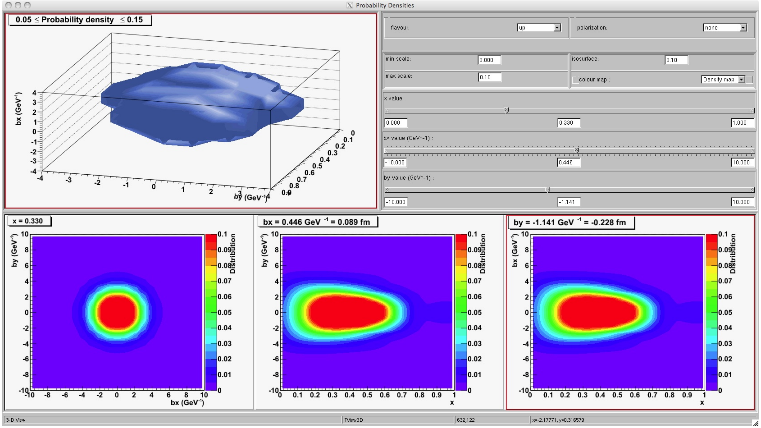
Software and data.

Developpment of an object-oriented fitting framework.

- Need of **fast**, **easy-to-use** and **flexible** software environnement :
  - Add new data in global fits and evaluate impact of a given data set on fit results.
  - Test several parametrizations and theoretical assumptions, (twist 2, evoluation, a.s.o.).
  - Visualize results (GPDs and related quantities) and compare extractions to models.
- Work in progress : Developpement of a ROOT/C++ extraction tool.
  - Experiment database.
  - Fitting procedure.
  - Graphical user interface for visualization.

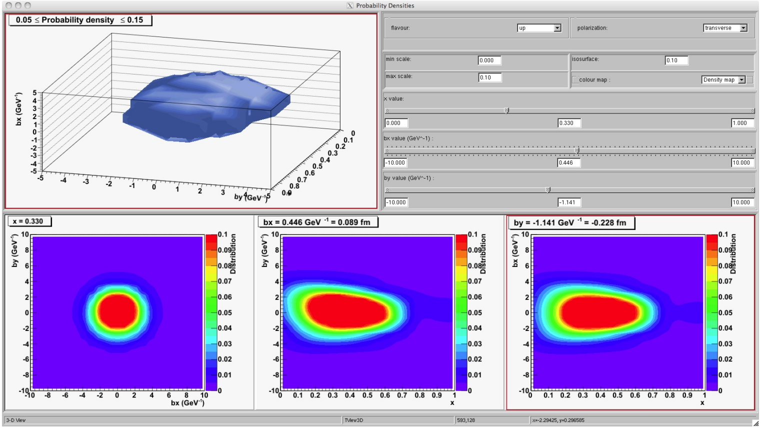
Software and data.

Work in progress : visualization.



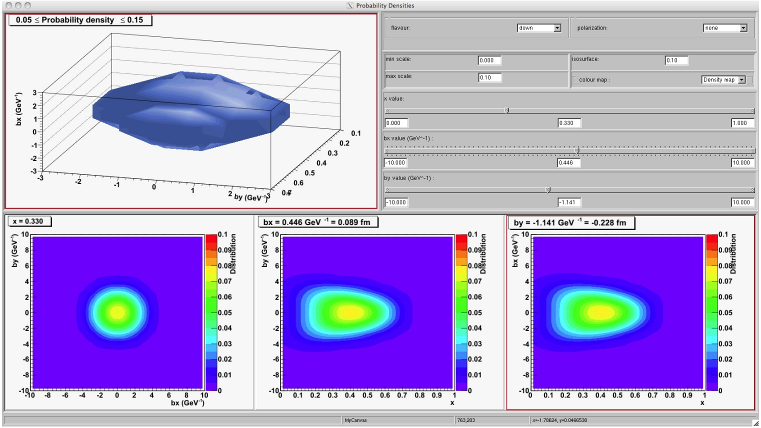
Software and data.

Work in progress : visualization.



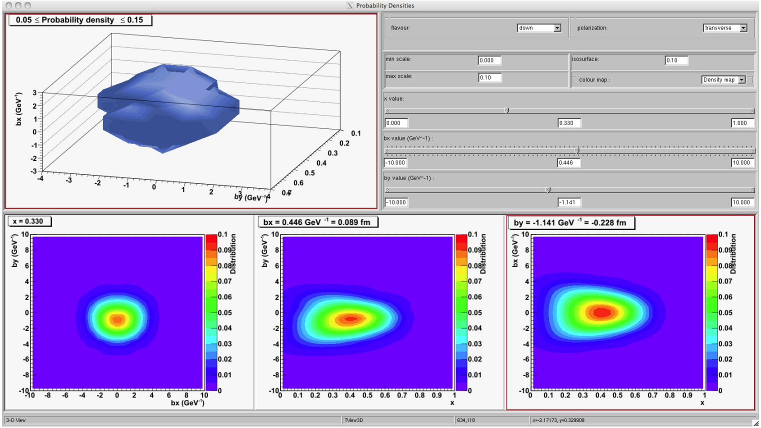
Software and data.

Work in progress : visualization.



Software and data.

Work in progress : visualization.



Conclusions.

DVCS measurements are still a challenge to phenomenology.

- $Im\mathcal{H}$ extracted with 20 to 50 % accuracy on a wide kinematic range.
- $Re\mathcal{H}$ still poorly known.
- In progress : software for large-scale GPD fitting and data manipulation.
- In progress : Working without *H*-dominance hypothesis.
- A global fitting strategy to obtain an "experimental" 3d nucleon picture is still missing...
- .. But encouraging results have already been obtained !

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