Visualizing the Nucleon Structure With Generalized Parton Distributions

Nucleon Structure Visualization

Theoretical framework
- How are GPDs defined ?
- How are GPDs measured ?
- Approximations

From theory to measure
- Models
- Universality tests
- Going further

From measure to theory
- Fitting strategies
- First extractions
- Going further

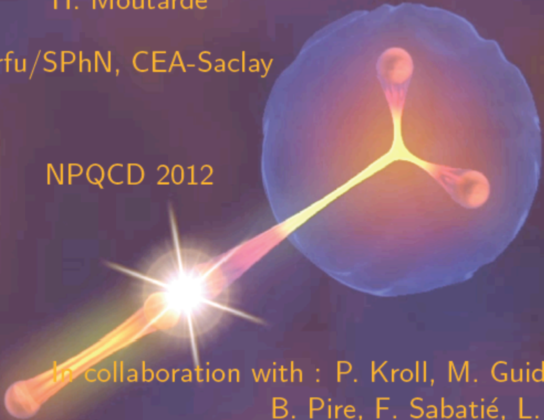
Preparing the future
- Experimental developments
- GPD toolkit

Conclusions

H. Moutarde

Irfu/SPhN, CEA-Saclay

NPQCD 2012

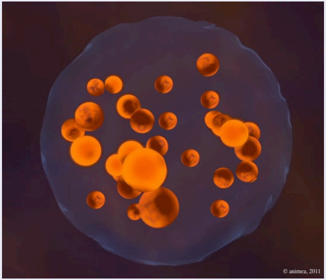


In collaboration with : P. Kroll, M. Guidal, C. Mezrag, B. Pire, F. Sabatié, L. Szymanowski, M. Vanderhaeghen and J. Wagner

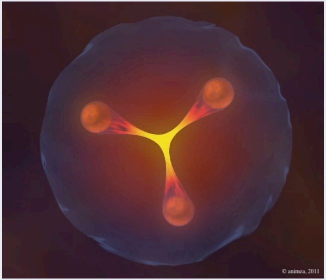
Motivation.

The bridge between perturbative and non-perturbative QCD.

Perturbative QCD



Non-perturbative QCD



Perturbative AND non-perturbative QCD at work

- Define **universal** objects describing nucleon structure.
- Relate them to measurements using **factorization**.

Definition.

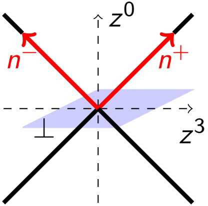
Matrix elements of twist-2 bilocal operators.

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle p' \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)\right| p\right\rangle_{z^+=0, z_\perp=0}$$

$$= \frac{1}{2P^+}\left[H^q \bar{u}(p')\gamma^+ u(p) + E^q \bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p)\right]$$

$$\tilde{F}^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle p' \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+\gamma_5 q\left(\frac{z}{2}\right)\right| p\right\rangle_{z^+=0, z_\perp=0}$$

$$= \frac{1}{2P^+}\left[\tilde{H}^q \bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q \bar{u}(p')\frac{\gamma^5\Delta^+}{2M}u(p)\right]$$



References

Müller *et al.*, Fortschr. Phys. **42** (1994) 101
Ji, Phys. Rev. Lett. **78** (1997) 610
Radyushkin, Phys. Lett. B **380** (1996) 417

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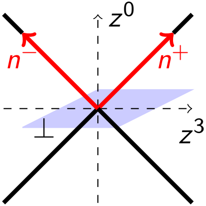
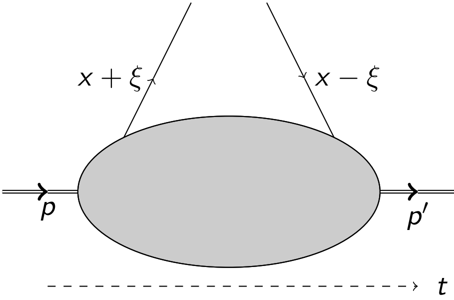


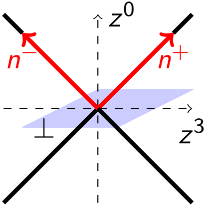
12 GPDs at twist 2

- Partons with a **light-like** separation.
- **Quarks**, **gluon** and **transversity** GPDs.
- $\text{GPD}^{q,g} = \text{GPD}^{q,g}(x, \xi, t)$.

Definition.

Matrix elements of twist-2 bilocal operators.





Interpretation

- $x \in [\xi, 1]$: q emitted + q absorbed.
- $x \in [-\xi, +\xi]$: $\bar{q}$ emitted + q absorbed.
- $x \in [-1, -\xi]$: $\bar{q}$ emitted + $\bar{q}$ absorbed.

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Properties (1/2).

Generalization of nucleon Form Factors and Parton Distribution Functions.

- **Forward limit**

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

- **Sum rule**

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

- **Polynomiality**

$$\int_{-1}^{+1} dx\, x^n H^q(x,\xi,t) = \text{polynomial in } \xi$$

Ji sum rule

$$2J^q = \int_0^1 dx\, x[q(x)+\bar{q}(x)] + \int_{-1}^{+1} dx\, xE^q(x,0,0)$$
$$= \Delta\Sigma + 2L^q$$

Ji, Phys. Rev. Lett. **78** (1997) 210

Properties (2/2).

3d imaging of nucleon's partonic content.

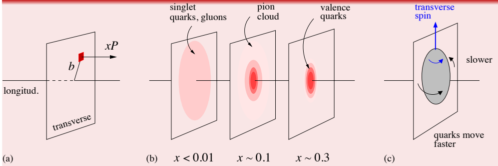
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2}\left[H(x, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S_\perp^i}{M} \frac{\partial E}{\partial b_\perp^2}(x, b_\perp^2) + \lambda\lambda_N \tilde{H}(x, b_\perp^2) \right]$$

- Notations : quark helicity λ, nucleon longitudinal polarization λ_N and nucleon transverse spin $S_\perp$.

Burkardt, Phys. Rev. D **62** (2000) 071503

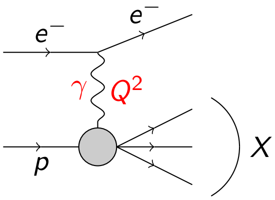
Obtain this 3d picture from exclusive measurements ?

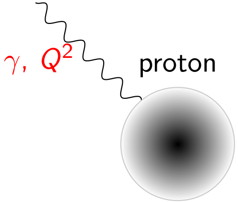


Weiss, AIP Conf. Proc. 1149, 150 (2009)

A partonic picture of hadronic processes (1/2).

Exclusive processes, **factorization** and **universality**.





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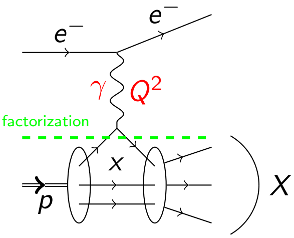

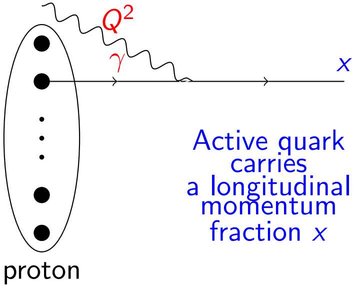

Active quark carries a longitudinal momentum fraction x

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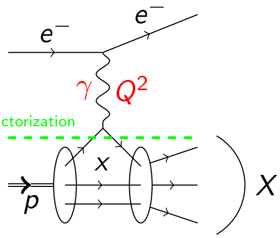

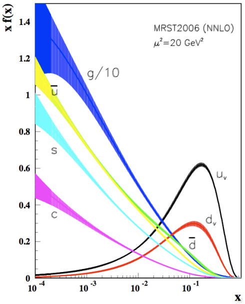

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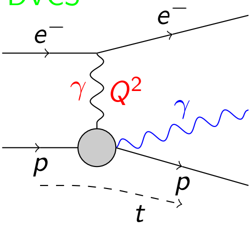
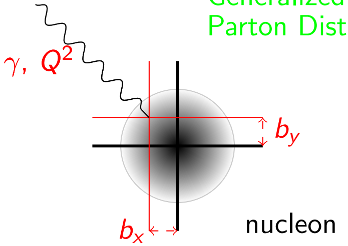
DVCS



Generalized Parton Distributions



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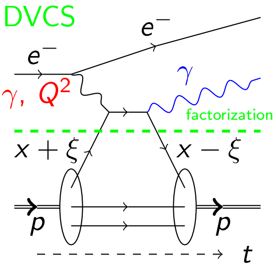

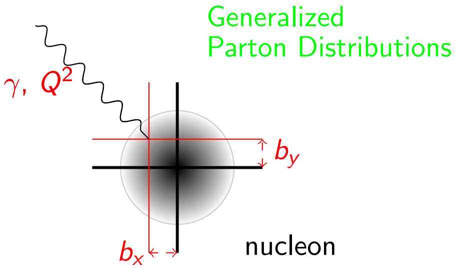

A partonic picture of hadronic processes (1/2).

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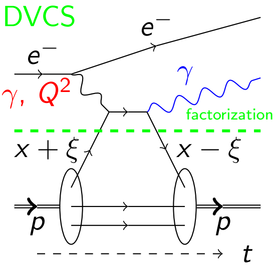

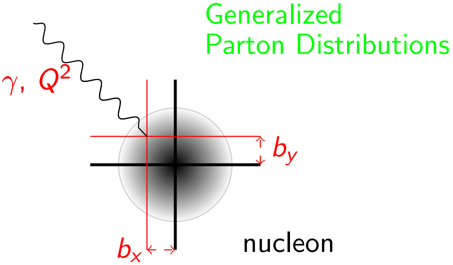

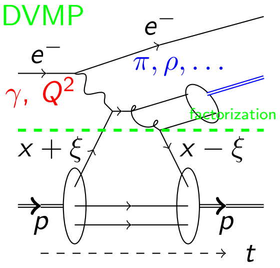

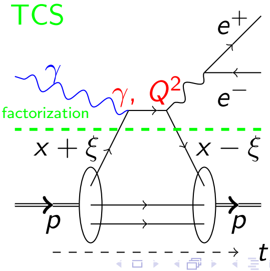

A partonic picture of hadronic processes (2/2).

Exclusive processes, **factorization** and **universality**.

Bjorken regime : large Q^2 and fixed $xB \simeq 2\xi/(1+\xi)$

- Partonic interpretation relies on factorization theorems.
- All-order proofs for DVCS, TCS and some DVMP.
- GPDs depend on a (arbitrary) factorization scale μ_F.
- Consistency requires the study of different channels.

- GPDs enter DVCS through **Compton Form Factors** :

$$\mathcal{F}(\xi, t, \mu_F, Q^2) = \int_{-1}^{1} dx\, C\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

  for a given GPD F.
- Integration kernels C have been worked out at NLO.
  Belitsky and Müller, Phys. Lett. B **417** (1998) 129
- CFF $\mathcal{F}$ is a **complex function**.

Definition of observables (1/3).

Harmonic structure of $ep \to ep\gamma$ amplitude.

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- Study the **harmonic structure** of $ep \to ep\gamma$ amplitude.
  Diehl *et al.*, Phys. Lett. B **411** (1997) 193
- Angle ϕ between leptonic and hadronic planes

$$|\mathcal{M}_{\mathrm{BH}}|^2 \propto \frac{1}{|t|}\frac{1}{P(\cos\phi)}\sum_{n=0}^{3}\left[c_n^{\mathrm{BH}}\cos(n\phi)+s_n^{\mathrm{BH}}\sin(n\phi)\right]$$

$$|\mathcal{M}_{\mathrm{DVCS}}|^2 \propto \sum_{n=0}^{3}\left[c_n^{\mathrm{DVCS}}\cos(n\phi)+s_n^{\mathrm{DVCS}}\sin(n\phi)\right]$$

$$\mathcal{M}_{\mathrm{I}} \propto \frac{1}{|t|}\frac{1}{P(\cos\phi)}\sum_{n=0}^{3}\left[c_n^{\mathrm{I}}\cos(n\phi)+s_n^{\mathrm{I}}\sin(n\phi)\right]$$

- Use expressions for s_n for c_n with **exact treatment** of all contributions apart from OPE in the hadronic tensor.
  P. Guichon and M. Vanderhaeghen (2008)

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Definition of observables (2/3).

Single and double asymmetries.

- Combined beam-spin and charge asymmetries :

$$d\sigma^{h_e,Q_e}(\phi) = d\sigma_{\mathrm{UU}}(\phi)\,[1 + h_e A_{\mathrm{LU,DVCS}}(\phi) + Q_e h_e A_{\mathrm{LU,I}}(\phi) + Q_e A_{\mathrm{C}}(\phi)]$$

- Single beam-spin asymmetry :

$$A_{\mathrm{LU}}^{Q_e}(\phi) = \frac{d\sigma_{\rightarrow}^{Q_e} - d\sigma_{\leftarrow}^{Q_e}}{d\sigma_{\rightarrow}^{Q_e} + d\sigma_{\leftarrow}^{Q_e}}$$

- Relation between observables :

$$A_{\mathrm{LU}}^{Q_e}(\phi) = \frac{Q_e A_{\mathrm{LU,I}}(\phi) + A_{\mathrm{LU,DVCS}}(\phi)}{1 + Q_e A_{\mathrm{C}}(\phi)}$$

- Compute Fourier coefficients of asymmetries.

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Definition of observables (3/3).

What are the probed combinations of CFFs ?

Typical kinematics

Experiment	**Kinematics**		
	x_B	Q^2 [GeV^2]	t [GeV^2]
HERMES	0.09	2.50	-0.12
CLAS	0.19	1.25	-0.19
HALL A	0.36	2.30	-0.23
HERA	0.001	8.00	-0.30

Definition of observables (3/3).

What are the probed combinations of CFFs ?

Selection of observables

Experiment	Observable	Normalized CFF dependence
HERMES	$A_{\mathrm{C}}^{\cos 0\phi}$	$\mathrm{Re}\mathcal{H} + 0.06\mathrm{Re}\mathcal{E} + 0.24\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{C}}^{\cos\phi}$	$\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\mathcal{E} + 0.15\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{LU,I}}^{\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.05\mathrm{Im}\mathcal{E} + 0.12\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{+,\sin\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.10\mathrm{Im}\mathcal{H} + 0.01\mathrm{Im}\mathcal{E}$
CLAS	$A_{\mathrm{LU}}^{-,\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.06\mathrm{Im}\mathcal{E} + 0.21\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{-,\sin\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.12\mathrm{Im}\mathcal{H} + 0.04\mathrm{Im}\mathcal{E}$
HALL A	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

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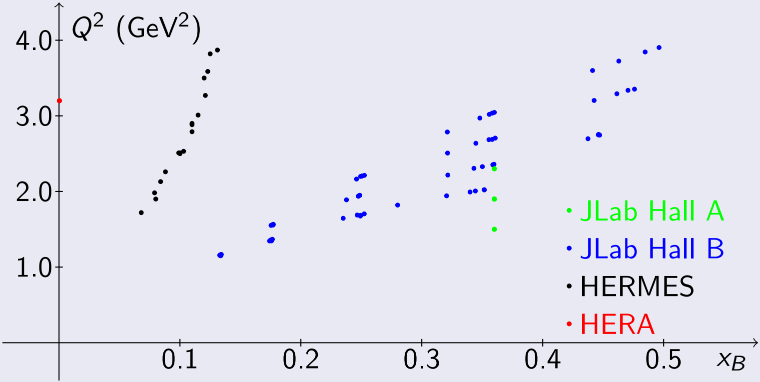
Kinematic region of existing DVCS measurements.

Looking for the Bjorken regime.

What is large Q^2 ?



- World data cover **complementary kinematic regions**.

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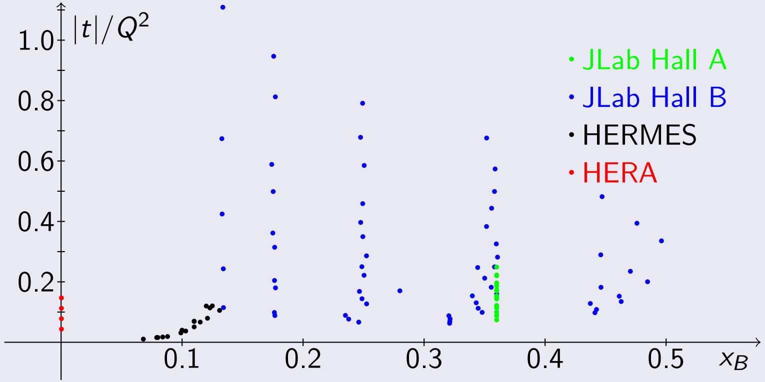

- World data cover **complementary kinematic regions**.
- Q^2 is **not so large** for most of the data.

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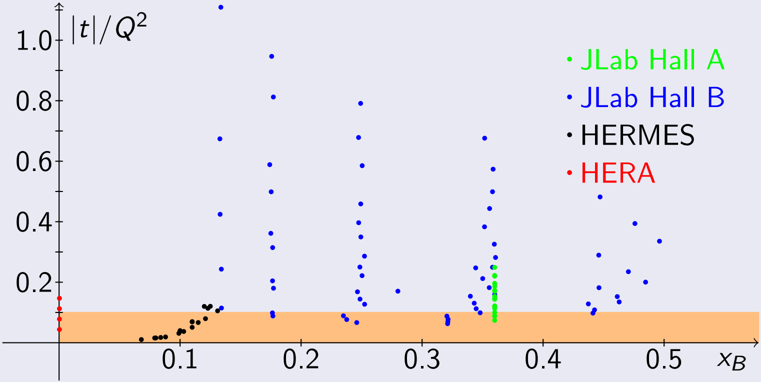
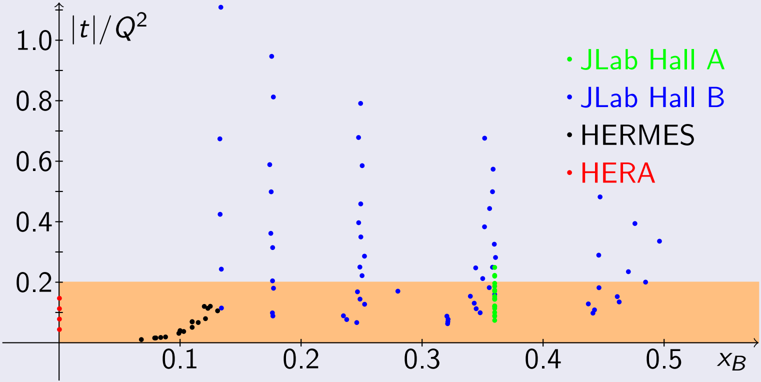


- World data cover **complementary kinematic regions**.
- Q^2 is **not so large** for most of the data.
- Higher twists, finite-t and target mass corrections ?

Kinematic region of existing DVCS measurements.

Looking for the Bjorken regime.

What is large Q^2 ?



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Approximations.

First systematic study of DVCS polarized and unpolarized observables.

Unless explicitly stated

- Work at twist 2 accuracy.
- Use LO expression of kernel $C(x, \xi)$.
- No finite$-t$ or target mass corrections (higher twist).

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Double Distribution models.

Description of a model designed to study DVMP (1/2).

- **Factorized Ansatz**. For $i = g$, sea or val :

$$H_i(x, \xi, t) = \int_{|\alpha|+|\beta|\leq 1} d\beta d\alpha\, \delta(\beta + \xi\alpha - x) f_i(\beta, \alpha, t)$$

$$f_i(\beta, \alpha, t) = e^{b_i t} \frac{1}{|\beta|^{\alpha' t}} h_i(\beta) \pi_{n_i}(\beta, \alpha)$$

$$\pi_{n_i}(\beta, \alpha) = \frac{\Gamma(2n_i + 2)}{2^{2n_i+1}\Gamma^2(n_i + 1)} \frac{(1 - |\beta|)^2 - \alpha^2]^{n_i}}{(1 - |\beta|)^{2n_i+1}}$$

- Expressions for h_i and n_i :

$$\begin{aligned} h_g(\beta) &= |\beta| g(|\beta|) & n_g &= 2 \\ h^q_{\rm sea}(\beta) &= q_{\rm sea}(|\beta|)\mathrm{sign}(\beta) & n_{\rm sea} &= 2 \\ h^q_{\rm val}(\beta) &= q_{\rm val}(\beta)\Theta(\beta) & n_{\rm val} &= 1 \end{aligned}$$

Goloskokov and Kroll, Eur. Phys. J. **C42**, 281 (2005)

Double Distribution models.

Description of a model designed to study DVMP (2/2).

- Choose a PDF-like parametrization for $E(x, \xi = 0, t = 0)$ and use a factorized Double Distribution Ansatz.
- Normalize E_{val} with the contribution of quarks to the proton anomalous magnetic moment κ.
- Fix t-dependence by computation of F_2.
- Constrain E_g and E_{sea} by saturating positivity bound.
- Variants :
  - Opposite sign for E_{sea}.
  - Do not saturate positivity bound.
  - $E_{\mathrm{sea}} = 0$.

Goloskokov and Kroll, Eur. Phys. J. **C59**, 809 (2009)
Diehl *et al.*, Eur. Phys. J. **C39**, 1 (2005)

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Other GPD models.

A selection of popular current GPD models.

- Double Distribution model : VGG model

  Guichon and Vanderhaeghen, Prog. Part. Nucl. Phys. **41** (1998) 125

- Conformal partial wave expansion + Mellin Barnes integral

  Müller and Schäfer, Nucl. Phys. B**739** (2006) 1

- Conformal partial wave expansion + dual parametrization

  Polyakov and Shuvaev, arXiv:hep-ph/0207153

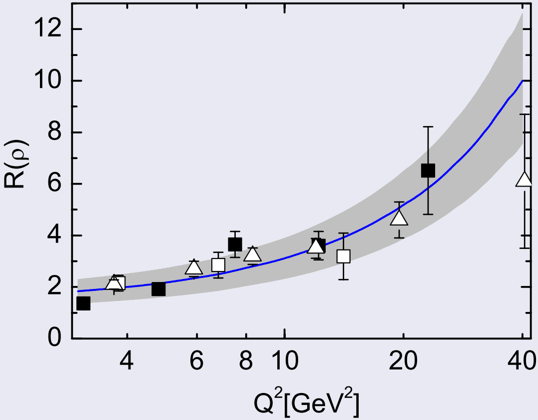
- Reggeized quark - diquark model

  Goldstein *et al.*, Phys. Rev. D**84** (2011) 034007

Goloskokov-Kroll (GK) model on DVMP.

The GK model **was tuned** to analyse DVMP.

σ_L/σ_T for ρ^0 at W = 90 GeV



Goloskokov and Kroll, Eur. Phys. J. C**53** (2005) 281

CEA - Saclay

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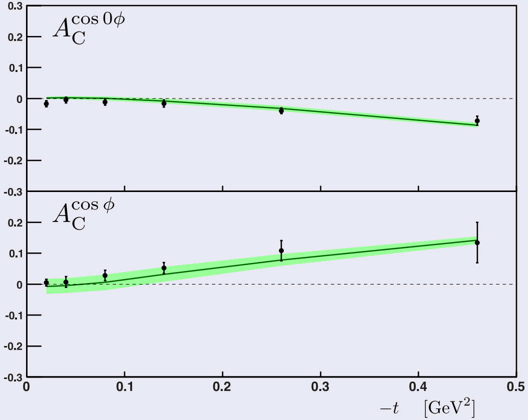
No parameter of the GK model **was tuned** to analyse DVCS.

Beam Charge Asymmetry, HERMES



Kroll, Moutarde, Sabatié, *in preparation*

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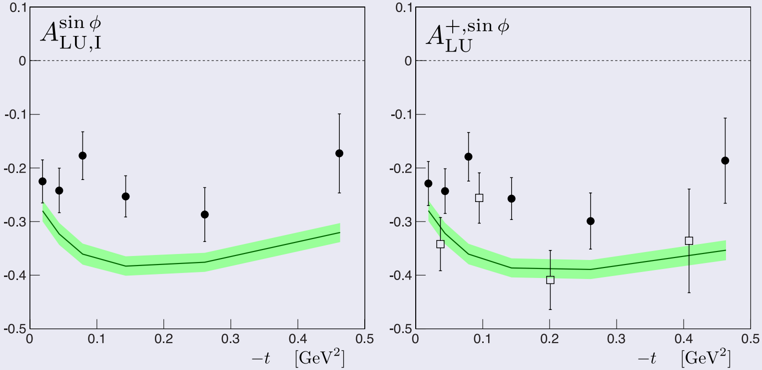

Kroll, Moutarde, Sabatié, *in preparation*

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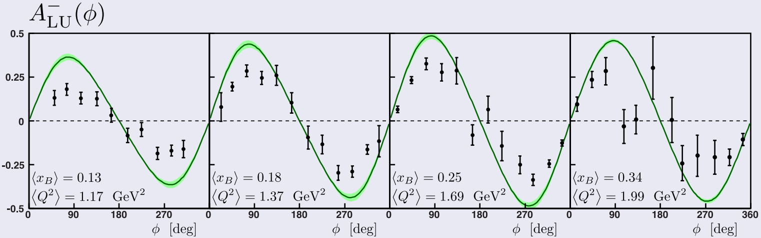
Beam Spin Asymmetry, CLAS



Kroll, Moutarde, Sabatié, *in preparation*

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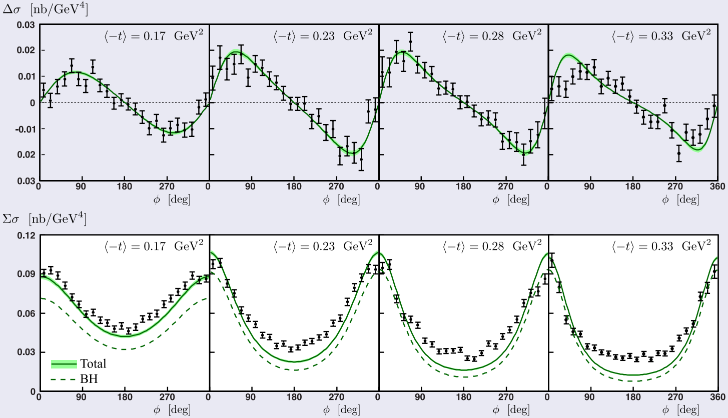
Helicity-dependent and independent cross sections, JLab Hall A



Kroll, Moutarde, Sabatié, *in preparation*

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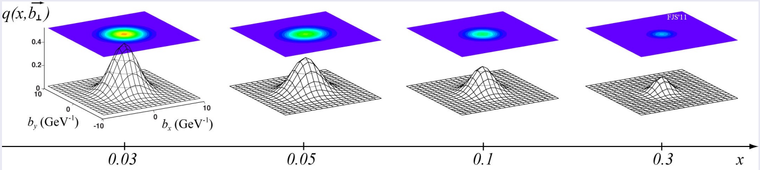
Spin structure with GK model (quoted at 4 GeV^2)

- $J^u \simeq 0.250$, $J^d \simeq 0.020$, $J^s \simeq 0.015$, $J^g \simeq 0.214$
- $\sum_{q,g} J^{q,g} \simeq 1/2$

3d nucleon structure with GK model

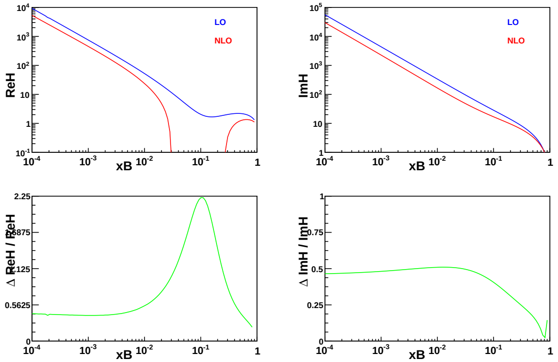


Ways to improve comparison.

Satisfactory agreement but needs improvement in the valence region...

- Implementation of GPD evolution.
- NLO computations and the role of gluons.

Moutarde, Pire, Sabatié, Szymanowski, Wagner, *in preparation*



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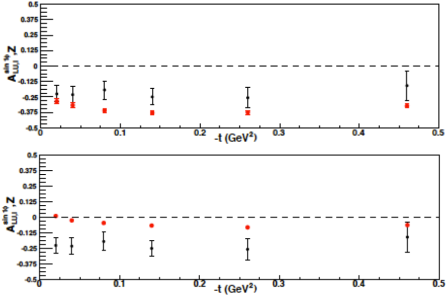

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  Mezrag, Moutarde, Sabatié, *in preparation*

- Finite$-t$ and target mass corrections. Problem recently solved for DVCS.

  Braun *et al.*, arXiv:1209.2559 [hep-ph]

Overview of current extraction methods.

Problems : Model dependence ? Degrees of freedom ? Extrapolations ?

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

Start from local fits and add smoothness assumption.

Neural networks

Already used for PDF fits. Exploratory stage for GPDs.

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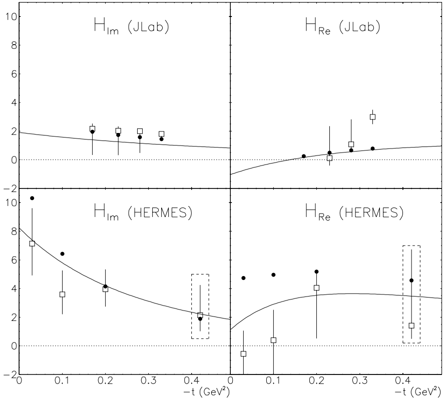

- □ : "7-CFF" fit results.
- • : VGG model.
- – : KM fit.

Guidal and Moutarde, Eur. Phys. J. A **42** (2009) 71

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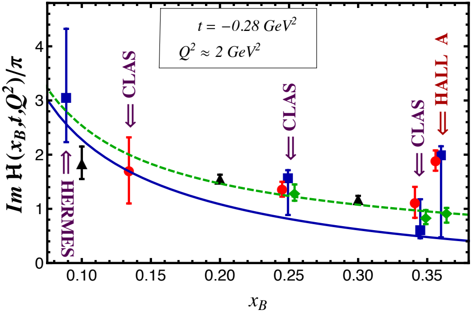

Kumericki and Müller, Exclusive 2010

- Without Hall A data.
- With Hall A data.
- △ : neural network.
- □ : "7-CFF" fit results.
- ◇ : "$\mathcal{H} - \tilde{\mathcal{H}}$".
- ○ : hybrid fits.

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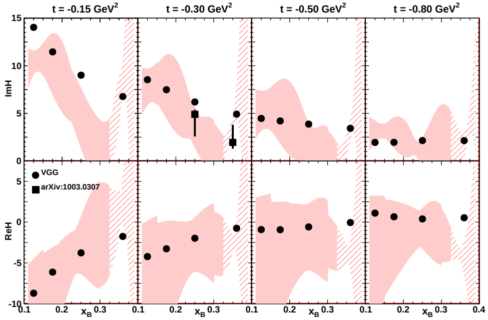

- Comparison to VGG model on JLab Hall B kinematics.
- Loss of information during the extraction.

Moutarde, Phys. Rev. D79 (2009) 094021

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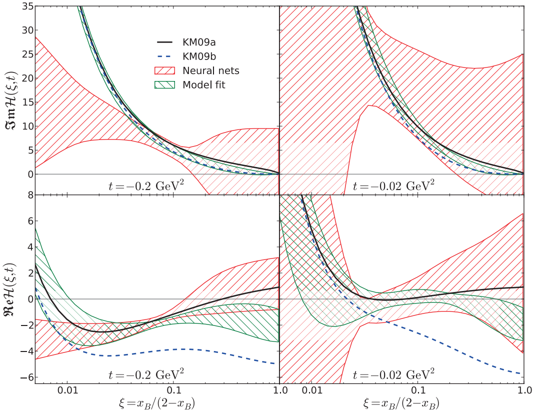

Kumericki, Müller and Schäfer, JHEP **1107** (2011) 073

Summary of first extractions.

Feasibility of twist-2 analysis of existing data.

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- **Dominance** of twist 2 and **validity** of a GPD analysis of DVCS data.
- $Im\mathcal{H}$ **best determined**. Large uncertainties on $Re\mathcal{H}$.
- However sizeable **higher twist contamination** for DVCS measurements.
- Already some indications about the **invalidity** of the H-dominance hypothesis with **unpolarized data**.
- Clear signs that one or several things are missing !

Beyond the first extractions.

Improving the treatment of the soft and hard parts.

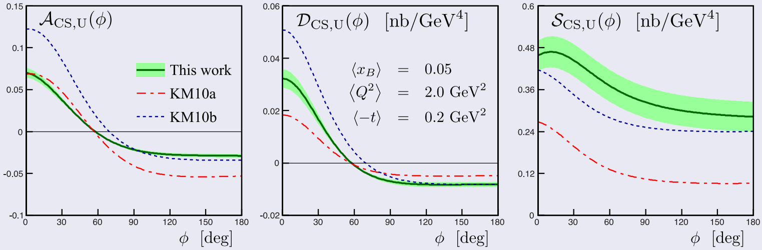
- Hard part :
  - Gluon contributions and resummation.
  - Finite$-t$ and target mass corrections.
- Soft part :
  - "Flexible" models (lot of parameters, few GPDs) ?
  - "Rigid" models (few parameters, lots of GPDs) ?
  - Modeling of higher-twist GPD ?
- Fits :
  - Propagation of statistic and systematic uncertainties.
  - Multi-channels fits.
  - GPD or CFF fitting ?

COMPASS-II.

Kinematic domain in between collider and fixed-target experiments.

- Observables with **beam spin** and **beam charge** differences.

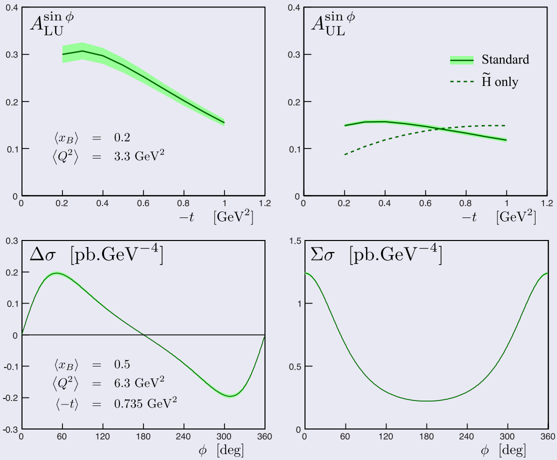
GK model prediction for COMPASS-II



JLab's 12 GeV upgrade.

Dealing with 1 % statistical accuracy.

GK model prediction for JLab 12 GeV



JLab's 12 GeV upgrade.

Testing ground for extraction methods from pseudo data.

- Structure of BSA at twist 2 :

$$\mathrm{BSA} = \frac{a \sin\phi + b \sin 2\phi}{1 + c\cos\phi + d\cos 2\phi + e\cos 3\phi}$$

where

$$\begin{array}{ll} a = \mathcal{O}(Q^{-1}) & d = \mathcal{O}(Q^{-2}) \\ b = \mathcal{O}(Q^{-4}) & e = \mathcal{O}(Q^{-5}) \\ c = \mathcal{O}(Q^{-1}) & \end{array}$$

- **Underconstrained** problem (8 fit parameters : real and imaginary parts of 4 CFFs $\mathcal{H}$, $\mathcal{E}$, $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$).
- Need other asymmetries on **same** kinematic bin (or **add** $\simeq$ 5-10 % **systematic uncertainty**).
- Add physical input : **dispersion relations**, etc.

Guidal, Moutarde and Vanderhaeghen, *work in progress*

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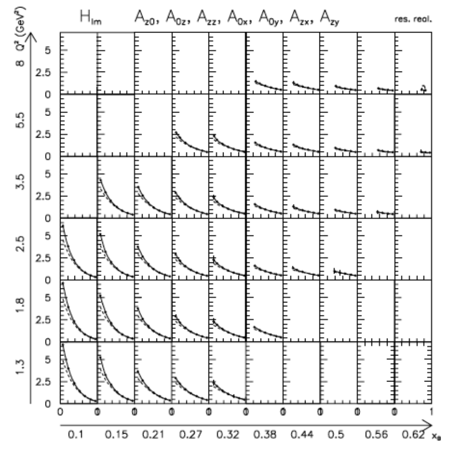
Model-independent extraction of CFFs



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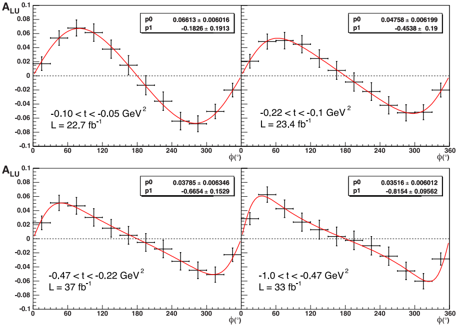
Electron Ion Collider.

Spin observables : both polarized ions and electrons.

- Luminosity : $\simeq 10^{34}\ \mathrm{cm}^{-2}.s^{-1}$.
- Configuration : 20 GeV $\times$ 250 GeV.
- 3 months beam time.
- x_B range : $1.6.10^{-3} \rightarrow 2.5.10^{-3}$.
- Q^2 range : $3.2 \rightarrow 5.6$ GeV^2.
- t range : $-1. \rightarrow -0.05$ GeV^2.



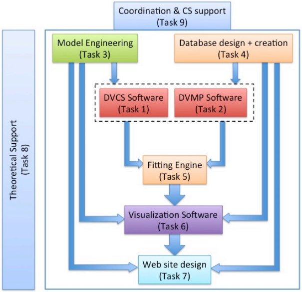
GPD phenomenology toolkit.

The path between models and data.

1. Comprehensive **database of experimental results**.
2. Comprehensive **database of theoretical predictions**.
3. **Fitting engine**.
4. **Propagation** of statistic and systematic **uncertainties**.
5. **Visualizing software** to compare experimental results and model expectations.
6. Connection to **experimental set-up descriptions** to design new experiments.
7. **Interactive website** providing free access to model and experimental values.

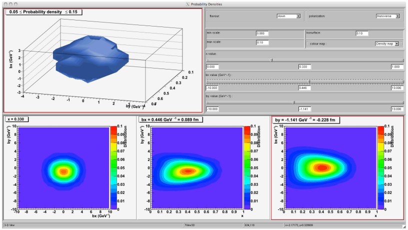
GPD phenomenology toolkit.

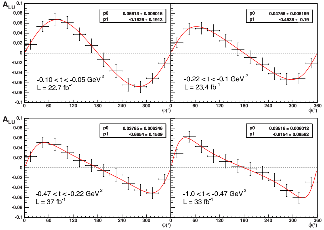
Platform structure, existing pieces and planned development.



News

- 1 grant from French ANR $\Rightarrow$ 1 post-doc position.
- 1 PhD student (starting).
- GPD evolution : end 2012.





Conclusions.

Facing very exciting times for GPDs !

- Important experimental results during the last decade.
- **Encouraging first results** on extraction of GPDs.
- Several points still need to be clarified :
  - Universality.
  - Precise impact of subdominant GPDs and their hierarchy.
  - Modifications to the hard kernel scattering.
- **New facilities** will explore new kinematic ranges or provide challenging constraints for phenomenology.
- Need of a robust and efficient **fitting strategy** for DVCS, DVMP and other channels.
- First steps in the development of a **platform dedicated to global GPD analysis**.

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Many thanks to present and former collaborators.

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- J. Ball
- G. Charles
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- M. Guidal
- G. Magniez
- C. Mezrag
- C. Muñoz Camacho
- S. Procureur
- M. Vanderhaeghen