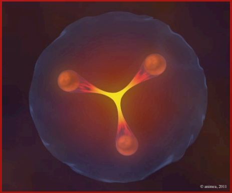
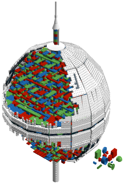
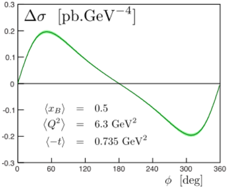
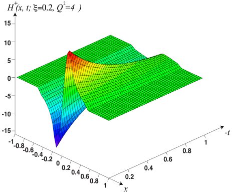
DE LA RECHERCHE À L'INDUSTRIE

Global Analysis of Generalized Parton Distribution Data: Tools and Strategy







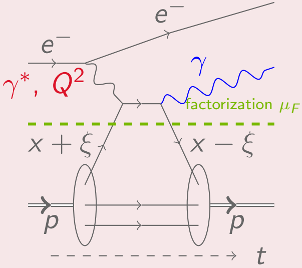


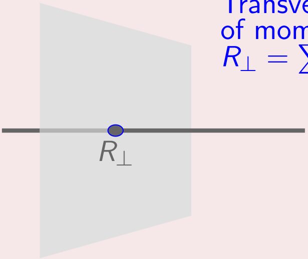
SPhN Scientific Council | Hervé MOUTARDE

May 23$^{\mathrm{rd}}$, 2014

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in the nucleon.
- Deeply Virtual Compton Scattering (DVCS) recognized as the theoretically cleanest channel to access GPDs.

DVCS and GPDs





Transverse center of momentum $R_\perp$

$R_\perp = \sum_i x_i r_{\perp i}$

Anatomy of the nucleon.

GPDs, 3D nucleon imaging, and beyond (1/4).

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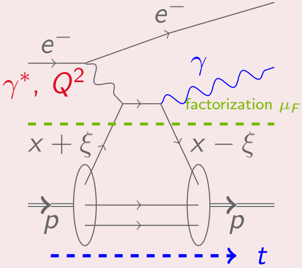

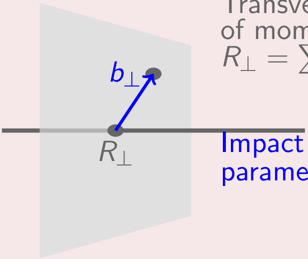

Transverse center of momentum $R_\perp$
$R_\perp = \sum_i x_i r_{\perp i}$

Impact parameter $b_\perp$

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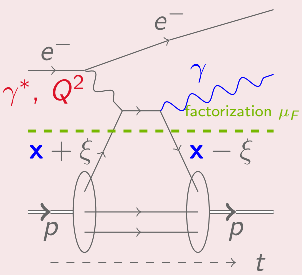
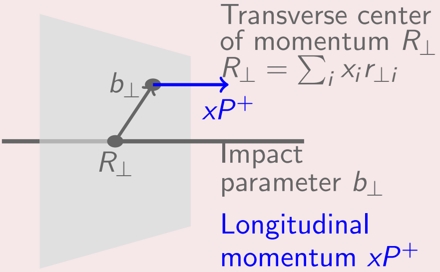
DVCS and GPDs





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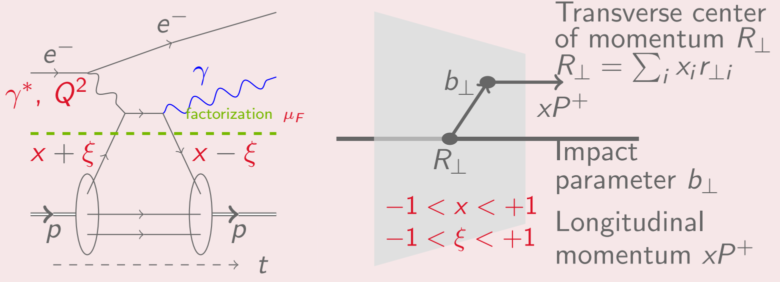
DVCS and GPDs



- GPD $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \ldots$

Anatomy of the nucleon.

GPDs, 3D nucleon imaging, and beyond (2/4).

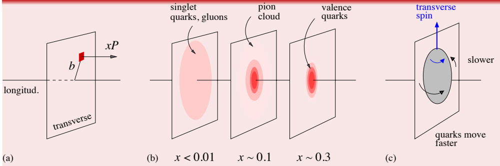
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2}\left[H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S_\perp^i}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) + \lambda\lambda_N \tilde{H}(x, 0, b_\perp^2)\right]$$

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

Burkardt, Phys. Rev. **D62**, 071503 (2000)

Can we obtain this picture from exclusive measurements?



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

Anatomy of the nucleon.

GPDs, 3D nucleon imaging, and beyond (3/4).

- Most general structure of matrix element of energy momentum tensor between nucleon states:

$$\left\langle N, P+\frac{\Delta}{2}\right| T^{\mu\nu} \left| N, P-\frac{\Delta}{2}\right\rangle = \bar{u}\left(P+\frac{\Delta}{2}\right)\left[A(t)\gamma^{(\mu}P^{\nu)} + B(t)P^{(\mu}i\sigma^{\nu)\lambda}\frac{\Delta_\lambda}{2M} + \frac{C(t)}{M}(\Delta^\mu\Delta^\nu - \Delta^2\eta^{\mu\nu})\right]u\left(P-\frac{\Delta}{2}\right)$$

with $t = \Delta^2$.

- Key observation: **link between GPDs and gravitational form factors**

$$\int \mathrm{d}x\, x H^q(x, \xi, t) = A^q(t) + 4\xi^2 C^q(t)$$

$$\int \mathrm{d}x\, x E^q(x, \xi, t) = B^q(t) - 4\xi^2 C^q(t)$$

Ji, Phys. Rev. Lett. **78**, 610 (1997)

- Spin sum rule:

$$\int \mathrm{d}x\, x\left(H^q(x,\xi,0) + E^q(x,\xi,0)\right) = A^q(0) + B^q(0) = 2J^q$$

Ji, Phys. Rev. Lett. **78**, 610 (1997)

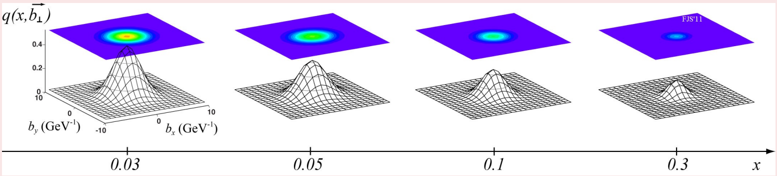
- **Shear** and **pressure** of the nucleon considered as a continuous medium:

$$\left\langle N \middle| T^{ij}(\vec{r}) \middle| N \right\rangle N = s(r)\left(\frac{r^i r^j}{\vec{r}^2} - \frac{1}{3}\delta^{ij}\right) + p(r)\delta^{ij}$$

Polyakov and Shuvaev, hep-ph/0207153

1. Study of exclusive processes
2. Metrology of Generalized Parton Distributions
3. Understanding of QCD dynamics through GPD modeling

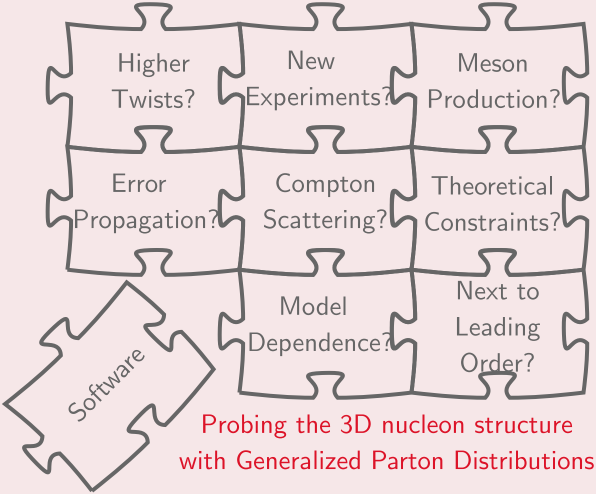
What do we learn from this picture?



Anatomy of the nucleon.

Three generic motivations for the study of parton correlations.

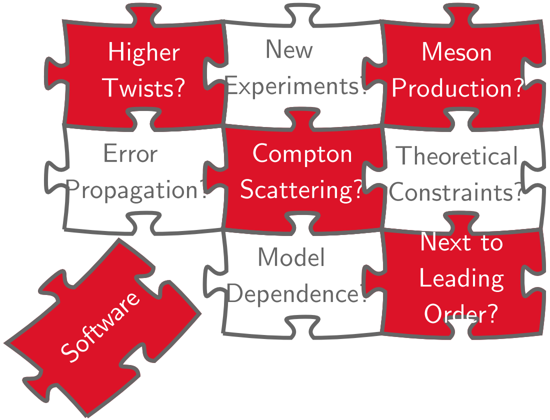
Common tools for different technical questions.



Probing the 3D nucleon structure
with Generalized Parton Distributions

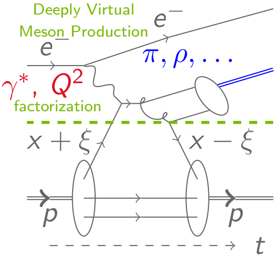
Study of exclusive processes

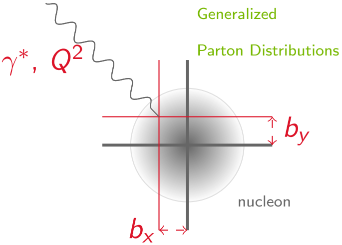
Study of exclusive processes

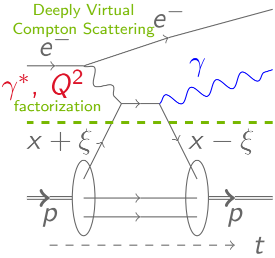


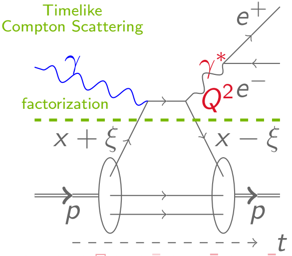
Exclusive processes of present interest.

Factorization and universality.





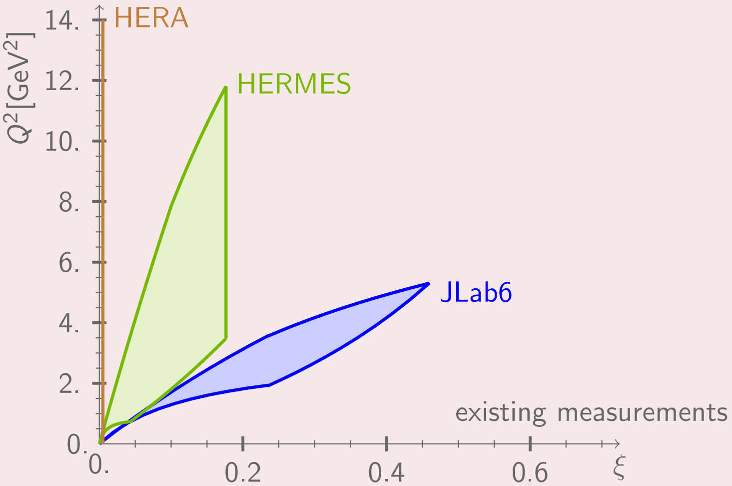




Need for global fits of world data.

Different facilities will probe different kinematic domains.

Kinematic reach of existing or near-future DVCS measurements



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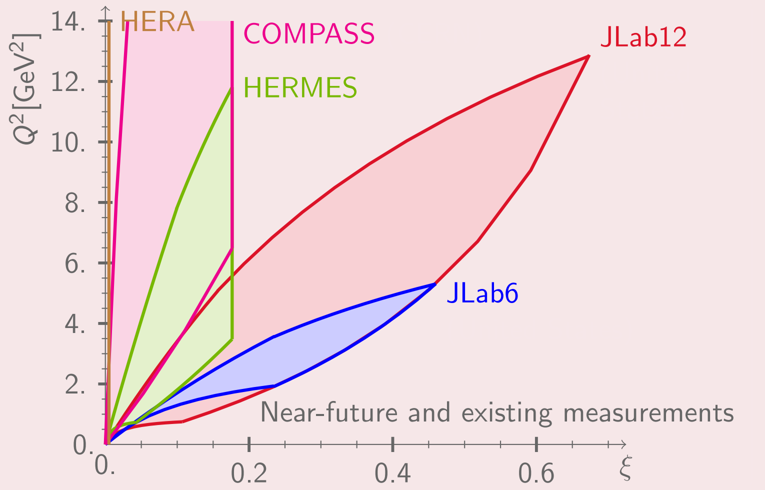

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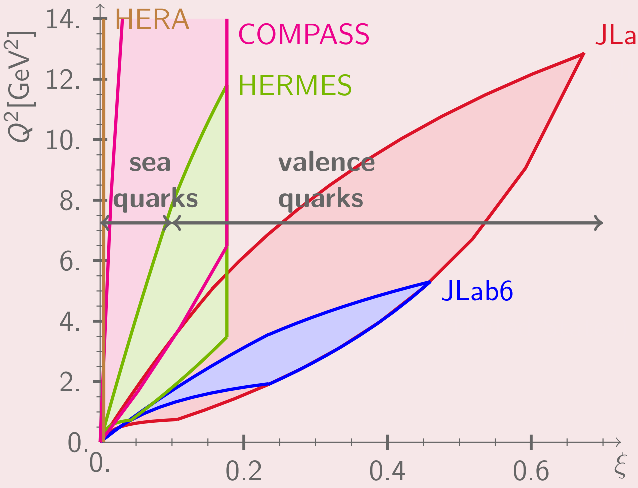

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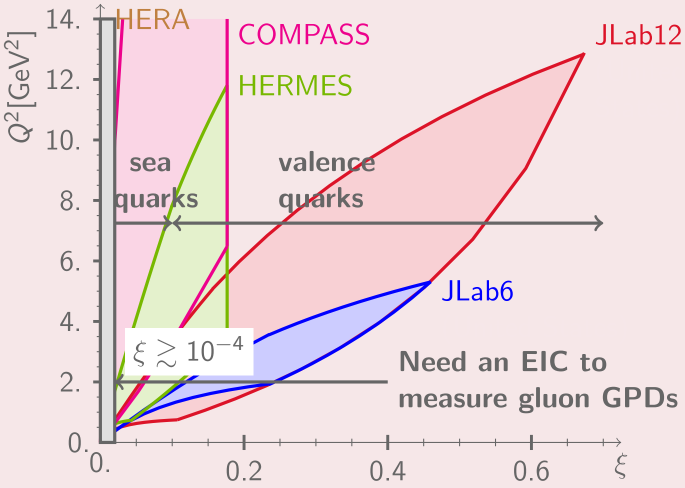

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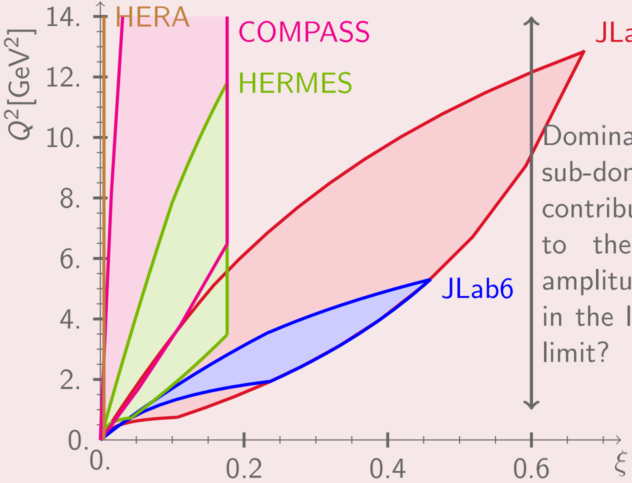
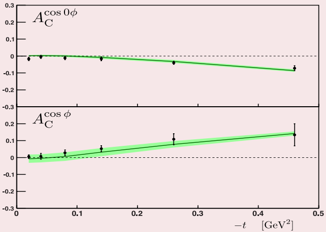


Dominant and sub-dominant contributions to the DVCS amplitude in the large Q^2 limit?

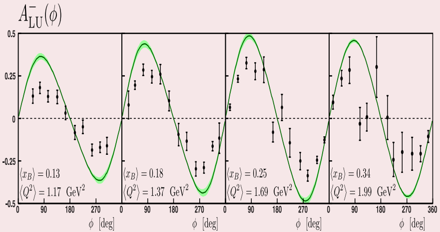
A DVMP-based model vs DVCS data.

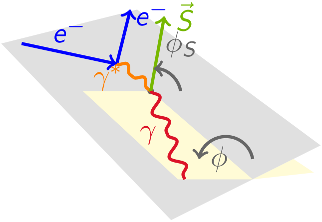
Are the GPDs extracted from DVMP and DVCS really the same?

Beam charge asymmetry HERMES



Beam spin asymmetry CLAS



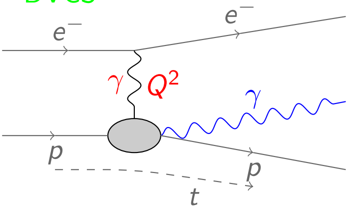


First universality check

- **No model parameter** was tuned to analyse DVCS.
- Comparison to all DVCS data.

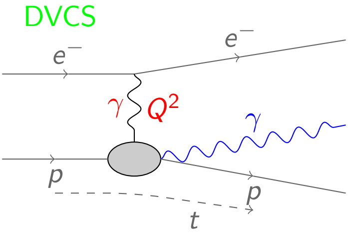
Kroll *et al.*
Eur. Phys. J. **C73**, 2278 (2013)

DVCS



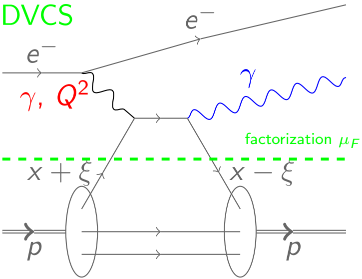
Compton Form Factors (CFF)

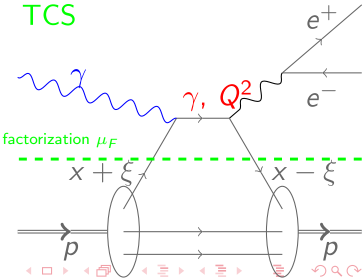
- Parametrize amplitudes.

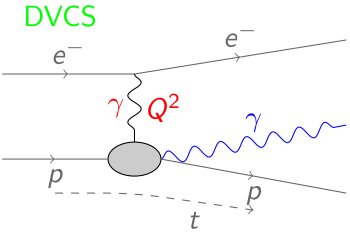


Compton Form Factors (CFF)

- Parametrize amplitudes.
- Evaluation at LO.

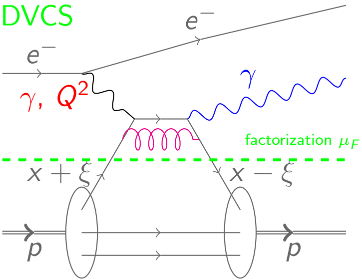


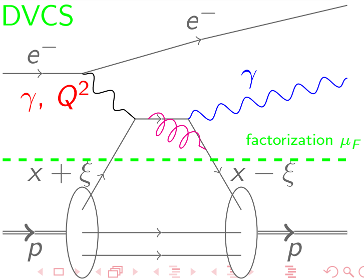


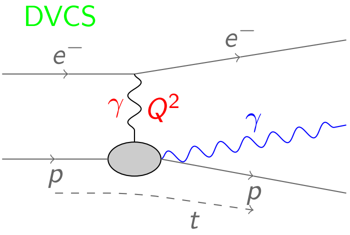


Compton Form Factors (CFF)

- Parametrize amplitudes.
- Evaluation at LO.
- Evaluation at NLO.

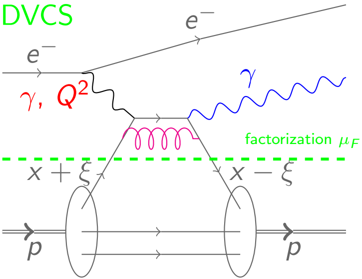


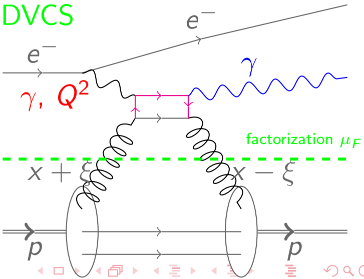




Compton Form Factors (CFF)

- Parametrize amplitudes.
- Evaluation at LO.
- Evaluation at NLO.
- Other diagrams at NLO, including gluon GPDs.

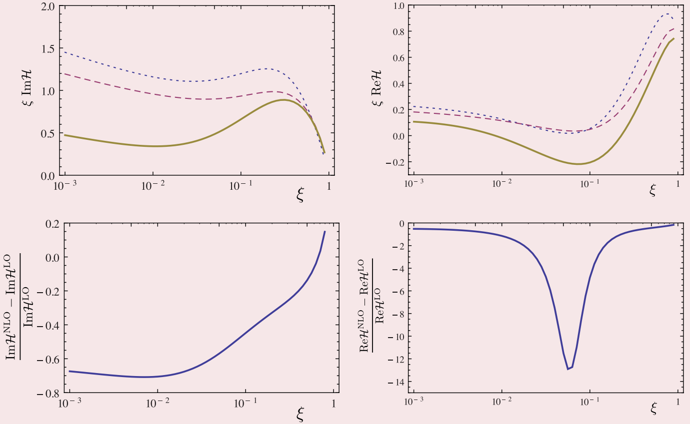




Spacelike CFF $\mathcal{H}$: large NLO contribution.

Mostly due to gluons, maximum in HERMES / COMPASS kinematic region.

$Re\mathcal{H}$ at LO and NLO ($t = -0.1$ GeV^2, $Q^2 = \mu_F^2 = 4.$ GeV^2)



Moutarde *et al.* , Phys. Rev. **D87**, 054029 (2013)

dotted: LO   dashed: NLO quark corrections   solid: full NLO

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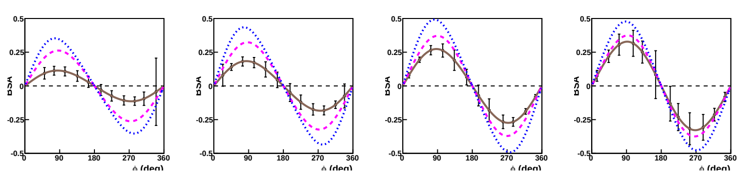
Preliminary result



dotted: LO   dashed: NLO quark corrections   solid: full NLO

- Comparison with KG model.

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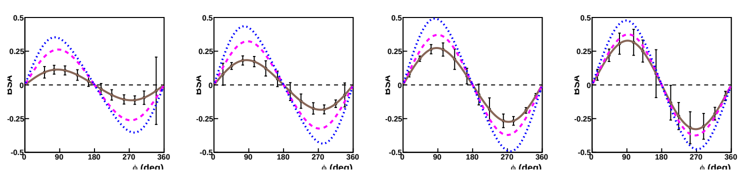

dotted: LO dashed: NLO quark corrections solid: full NLO

- Comparison with KG model.
- Compare differences between LO and NLO computations to **experimental statistical uncertainty** considering full NLO computation as nominal result.

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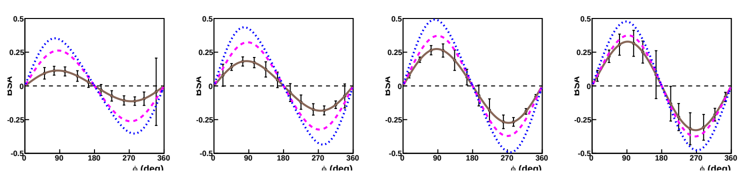
Preliminary result



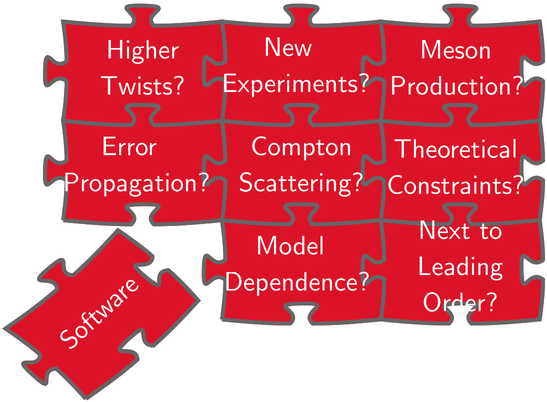
dotted: LO   dashed: NLO quark corrections   solid: full NLO

- Comparison with KG model.
- Compare differences between LO and NLO computations to **experimental statistical uncertainty** considering full NLO computation as nominal result.
- Need resummed expressions!

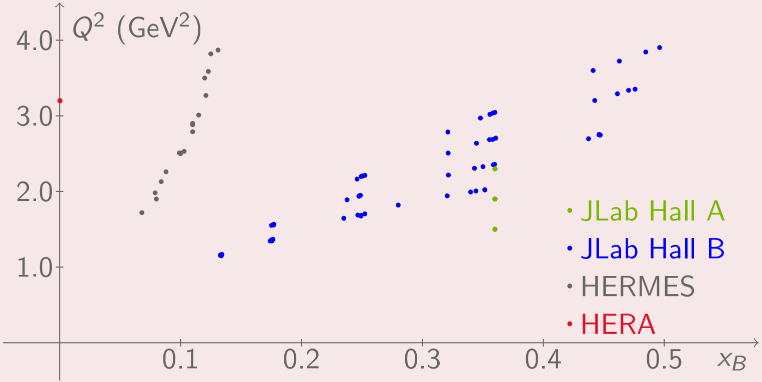
Altinoluk *et al.*, JHEP **1210**, 049 (2012)

Metrology of Generalized Parton Distributions

Metrology of Generalized Parton Distributions



What is large Q^2 ?



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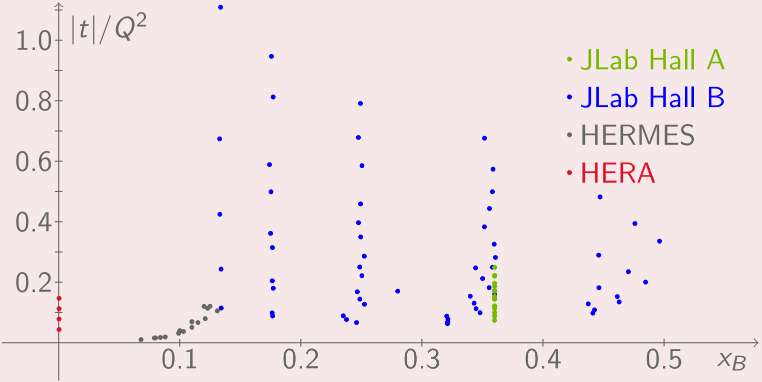

- Q^2 is **not so large** for most of the data.

Kinematics of existing DVCS measurements.

Looking for the Bjorken regime.

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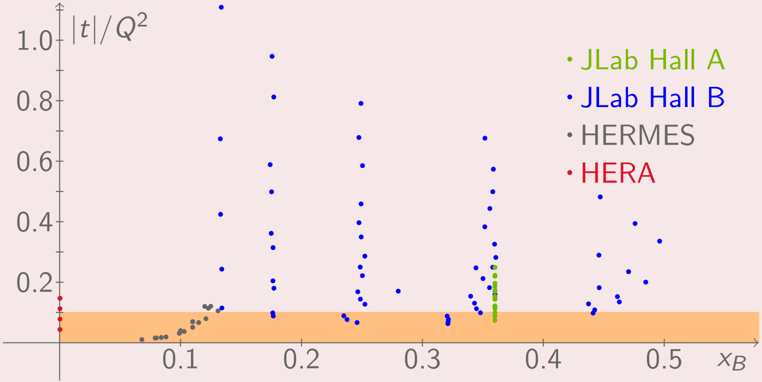

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- **Higher twists**, finite-t and target mass corrections?

Kinematics of existing DVCS measurements.

Looking for the Bjorken regime.

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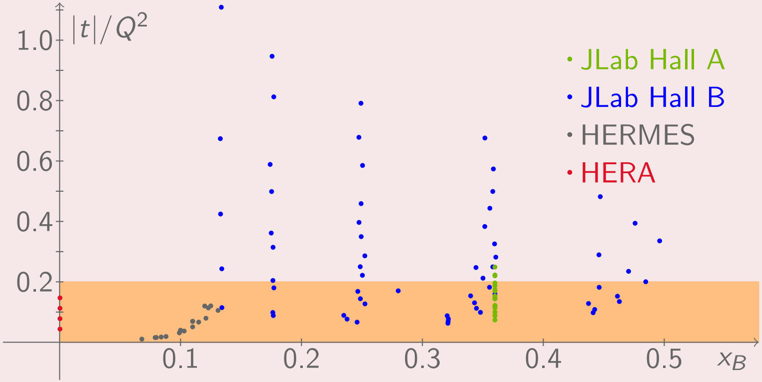


- Q^2 is **not so large** for most of the data.
- **Higher twists**, finite-t and target mass corrections?
- **Consistent modeling** of GPDs beyond leading twist?

Overview of current extraction methods.

Understanding of DVCS? Metrology of GPDs? Understanding of nonperturbative QCD?

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

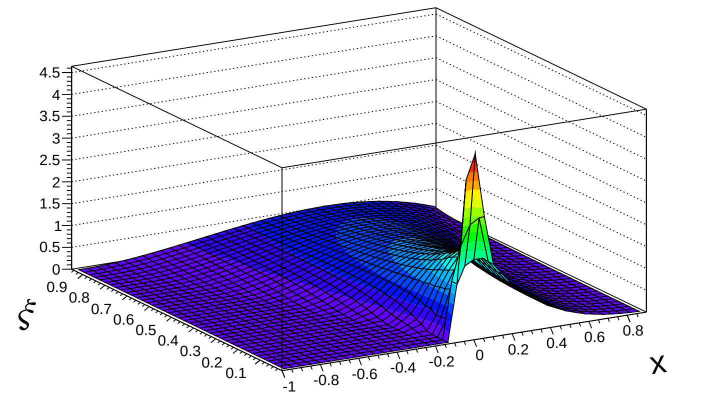
Exploratory stage for GPDs.

Summary of first extractions.

Feasibility of twist-2 analysis of existing data.

- **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 sizable **higher twist contamination** for DVCS measurements.
- Already some indications about the **invalidity** of the H-dominance hypothesis with **unpolarized data**.

GPD H at $t = -0.23$ GeV^2 and $Q^2 = 2.3$ GeV^2.

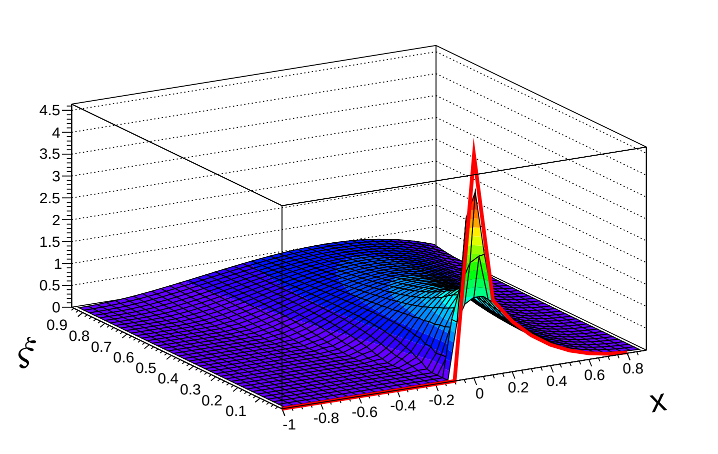


GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

From principles to actual data.

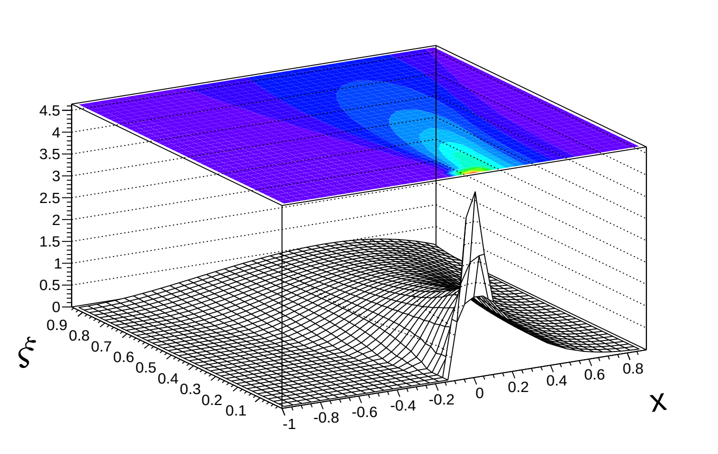
Direct experimental access to a restricted kinematic domain.

Need to know $H(x, \xi = 0, t)$ to do transverse plane imaging.



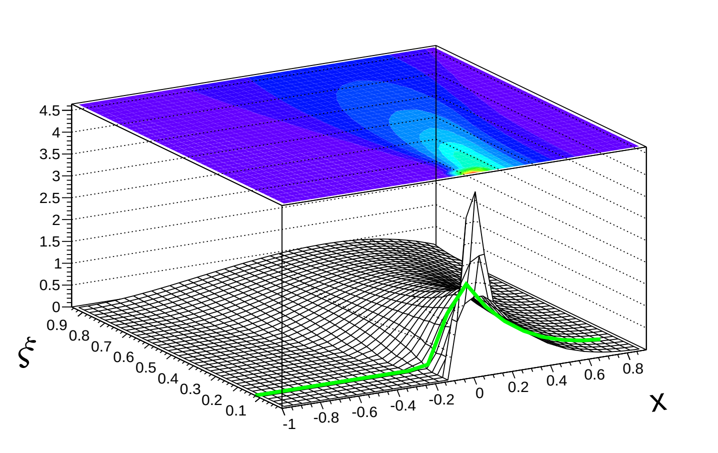
GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

What is the physical region?



GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

$\xi_{\min}$ from finite beam energy.



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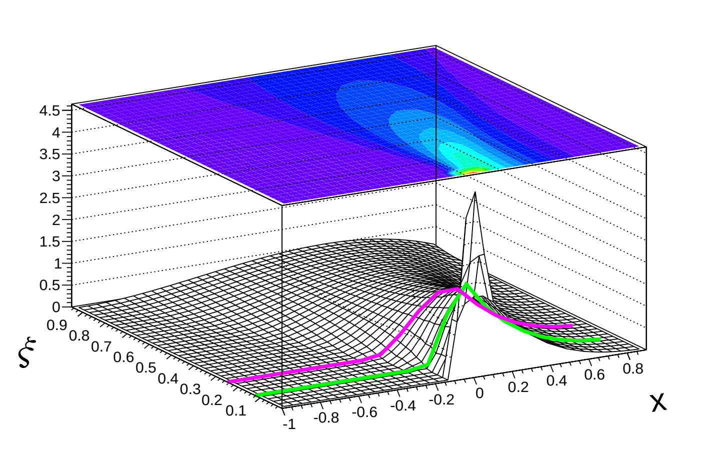
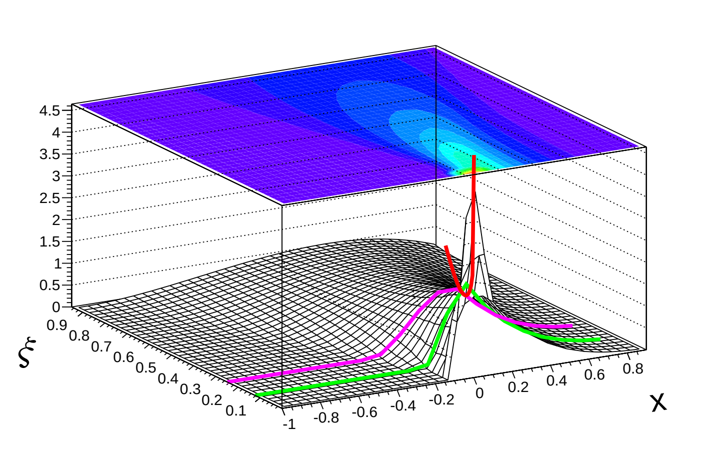
ξ_{max} from kinematic constraint on 4-momentum transfer.



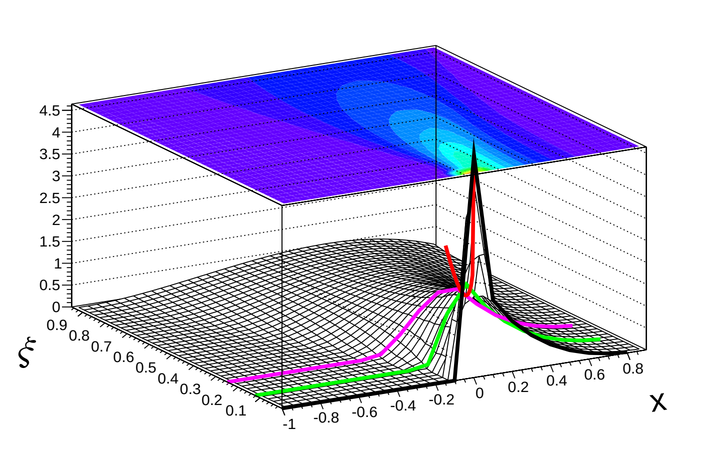
GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

The cross-over line $x = \xi$.



GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

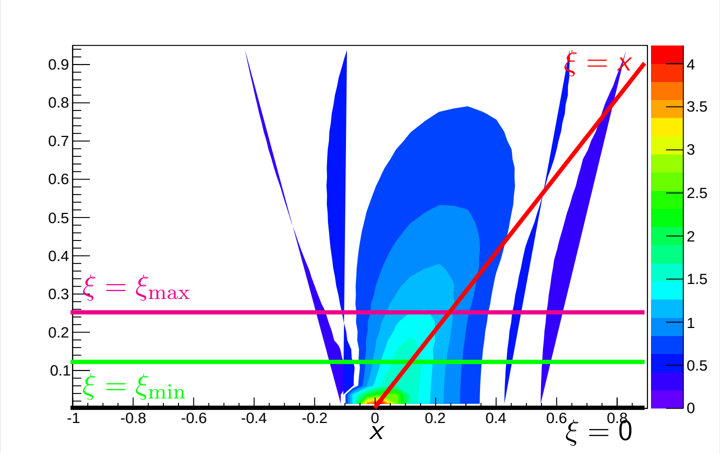
The black curve is what is needed for transverse plane imaging!



GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

From principles to actual data.
Direct experimental access to a restricted kinematic domain.

Density plot of H at $t = -0.23$ GeV^2 and $Q^2 = 2.3$ GeV^2



GPD model: see Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

- Systematic and statistical errors **added in quadrature**. No distinction yet between different experiments.
- Evaluation of model-dependence:
  - Local fits: **almost model-independent** but low interpretation capability.
  - Global fits: test parameterization and extracting strategy on **pseudo-data generated from models in database**.
- Opportunities: neural networks, bayesian analysis?
- **Programming to an interface**: existing C++ software already allows transparent change of GPD models.
- **Code refactoring** (design patterns) to incorporate proper GPD evolution.
- Planned: scripts for **systematic studies** *e.g.* impact of a given dataset on J^u, etc.

- **All-order proof of factorization** of DVCS amplitude.
  Collins and Freund, Phys. Rev. **D59**, 074009 (1999)
- Hard scattering kernel computed at **next-to-leading order** at leading twist.
  Belistky and Müller, Phys. Lett. **B417**, 129 (1998)
- Evolution equations computed at **next-to-leading order**.
  Belitsky *et al.* , Nucl. Phys. **B574**, 347 (2000) and ref. therein
- Finite-t and target mass corrections computed at **leading order**: kinematic power corrections to **twist 4 accuracy**.
  Braun *et al.* , Phys. Rev. Lett. **109**, 242001 (2012)

GPD fitting: 3 to 4 active teams worldwide

- Theory status **does play in favor of** "GPD being the most attractive sector in the study of nucleon structure".

From first principles to experimental data.

Very good theoretical control, but not easy to implement!

- **All-order proof of factorization** of DVCS amplitude.
  Collins and Freund, Phys. Rev. **D59**, 074009 (1999)
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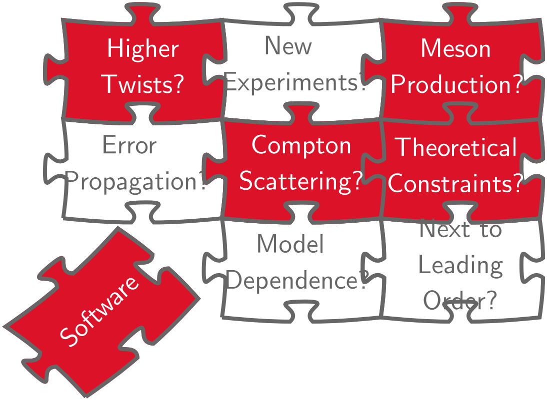
GPD "measurements" ?

- **Already achieved**: experimentally constrained models.
- Next steps: **Measured** transverse plane images and information on **nonperturbative QCD**?

Understanding of QCD dynamics through GPD modeling

Understanding of QCD dynamics through GPD modeling

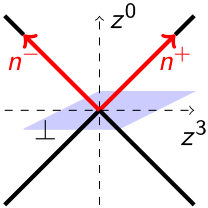


$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p' \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right) \right| p\rangle_{z^+=0, z_\perp=0}$$

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

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

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



References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)

Ji, Phys. Rev. Lett. **78**, 610 (1997)

Radyushkin, Phys. Lett. **B380**, 417 (1996)

Definition.

Matrix elements of twist-2 bilocal operators.

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

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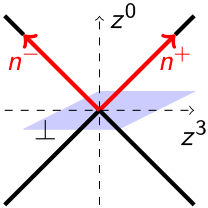
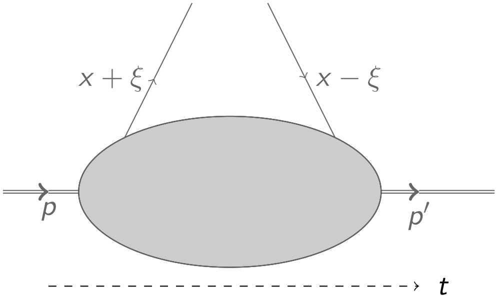
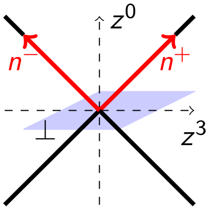


8 GPDs per parton type at twist 2

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





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.

- PDF **forward limit**

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

- PDF **forward limit**
- Form factor **sum rule**

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

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**

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

Properties.

Generalization of form factors and Parton Distribution Functions.

- PDF **forward limit**
- Form factor **sum rule**
- **Polynomiality**
- **Positivity**

$$H^q(x, \xi, t) \leq \sqrt{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}$$

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- **Soft pion theorem** (pion target)

$$H^{I=1}(x, \xi = 1, t = 0) = \phi_\pi \left(\frac{1+x}{2} \right)$$

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Numerous theoretical constraints on GPDs.

- There is no known GPD parameterization **relying only on first principles**.
- Modeling becomes a key issue.

Double Distribution models.

GK model (Goloskokov and Kroll).

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

$$
\begin{aligned}
H_i(x,\xi,t) &= \int_{|\alpha|+|\beta|\leq 1} d\beta d\alpha\, \delta(\beta+\xi\alpha-x) f_i(\beta,\alpha,t) \\
f_i(\beta,\alpha,t) &= e^{b_i t}\frac{1}{|\beta|^{\alpha' t}} h_i(\beta)\pi_{n_i}(\beta,\alpha) \\
\pi_{n_i}(\beta,\alpha) &= \frac{\Gamma(2n_i+2)}{2^{2n_i+1}\Gamma^2(n_i+1)}\frac{(1-|\beta|)^2-\alpha^2]^{n_i}}{(1-|\beta|)^{2n_i+1}}
\end{aligned}
$$

- Expressions for h_i and n_i:

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

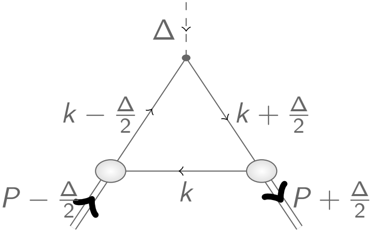
- Designed to study DVMP. Recently applied to DVCS.

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

Kroll *et al.* , Eur. Phys. J. **C73**, 2278 (2013)

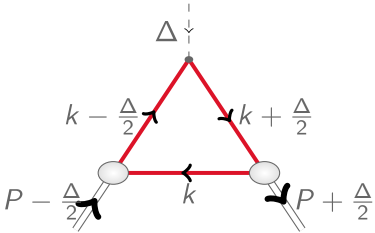
Mezrag *et al.* , Phys. Rev. **D88**, 014001 (2013)

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$



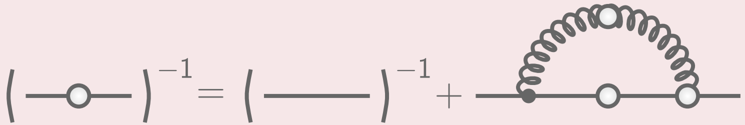
- Compute **Mellin moments** of the pion GPD H.

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$



- Compute **Mellin moments** of the pion GPD H.
- Resum **infinitely many** contributions.

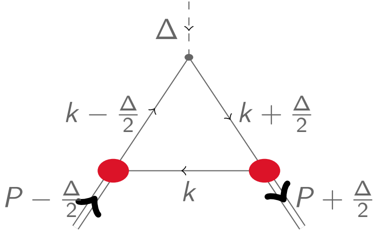
Dyson - Schwinger equation



Dyson - Schwinger and Bethe - Salpeter.

First step towards the modeling of nucleon GPDs.

$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \left| \bar{q}(0)\gamma^+ (i\overleftrightarrow{D}^+)^m q(0) \right| \pi, P - \frac{\Delta}{2} \right\rangle$$



- Compute **Mellin moments** of the pion GPD H.
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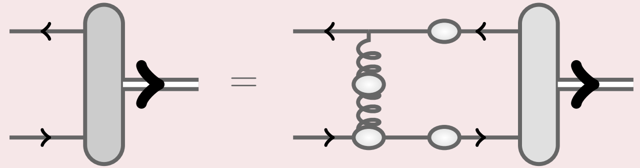
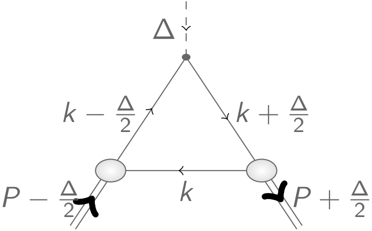
Bethe - Salpeter equation

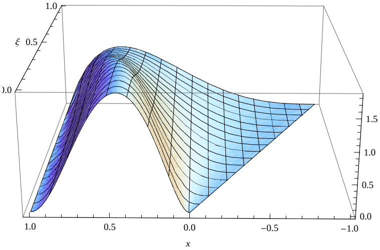


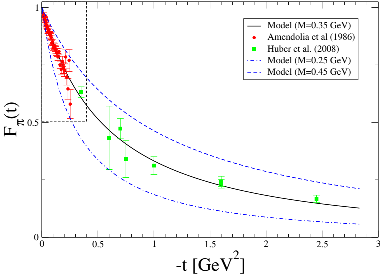
$$\langle x^m \rangle^q = \frac{1}{2(P^+)^{n+1}} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| \pi, P - \frac{\Delta}{2} \right\rangle$$



- Compute **Mellin moments** of the pion GPD H.
- Resum **infinitely many** contributions.
- **Nonperturbative** modeling.

- Most GPD properties **satisfied by construction**.





Mezrag *et al.* , *in preparation.*

Links between dipole models and GPDs.

Two different views of the same process.

- Helicity amplitude $\gamma_L^* N(p) \to V_L N(p')$ (small-t limit):
  - Modified Perturbative Approach (MPA) result:

$$\mathcal{I}m\,\mathcal{M}^g_{V,\{0+,0+\}} = -\int_0^1 dy \int d^2\underline{r} \sum_f C_V^f \left(\hat{\Psi}_V(y,-\underline{r}) \hat{\Psi}^f_{\gamma_L^*}(y,\underline{r}) \right) \times \left(\frac{\pi\sqrt{2\pi}}{N_c\, y\bar{y}} \alpha_s \frac{H^g(\xi,\xi,0)}{2\xi} \right)$$

Besse, *in preparation.*

  - k_T-factorization and dipole models result:

$$\mathcal{I}m\,\mathcal{M}^g_{V,\{0+,0+\}} = -\int_0^1 dy \int d^2\underline{r} \sum_f C_V^f \left(\hat{\Psi}_V(y,-\underline{r}) \hat{\Psi}^f_{\gamma_L^*}(y,\underline{r}) \right) \times \left(\frac{s\,\hat{\sigma}(x,\underline{r})}{2\sqrt{2\pi}} \right)$$

Besse *et al.* , Nucl. Phys. **B867**, 19 (2013)

- Identify terms:

$$\hat{\sigma}(x,\underline{r}) \quad \leftrightarrow \frac{\pi^2}{N_c} \left(\frac{4}{y\bar{y}Q^2} \right) \alpha_s H^g(\xi,\xi,0) = \frac{\pi^2}{N_c}\, \underline{r}_0^2\, \alpha_s H^g(\xi,\xi,0)$$

$$\text{with } \underline{r}_0^2 = \frac{4}{y\bar{y}Q^2}$$

Summary

French National Research Agency
ANR grant: 2012-16
P.I.: Irfu/SPhN

The project federates **french experimentalists and theorists** of the field.

- 10 staff
- 2 post-docs
- 2 PhD students
- 1 software engineer

Joint work in progress

Experimental data analysis

New experiment design (*e.g.* JLab Hall C)

World data fits

GPD modeling

Perturbative QCD expertise

Database

- World experimental data.
- Theoretical predictions.

Visualizing software

- 3D nucleon imaging.
- Measurements vs model expectations.

Interactive web site

- Free access to models and measurements.
- Popularization.

Design and performance

- **Uncertainties** propagation: statistical and systematic.
- **Fitting** engine.
- **Versatility**: comprehensive studies varying models and approximations.
- **Reliability** and **speed**: 0.1 % numerical accuracy, $\simeq$ 50 times faster than Mathematica (achieved on existing parts).

Conclusions and prospects.

Facing very exciting times for GPDs !

- Last decade demonstrated **relevance of GPD measurements**.
- **New facilities** will explore new kinematic ranges or provide challenging constraints for phenomenology.
- Field **mature** for **phenomenology**.
- **Get ready** for phenomenological analysis of forthcoming CLAS and COMPASS data.
- Need for **QCD-inspired models** to make progress.
- **Numerous results** on GPD phenomenology.
- Project **rescheduling** due to work in new directions:
  - DVMP software (originally end of project).
  - GPD modeling in Dyson - Schwinger approach.
- **Software package** expected to be ready for use in 2016.

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33(0)1 69 08 73 88 | F. +33(0)1 69 08 75 84

Etablissement public à caractère industriel et commercial | R.C.S. Paris B 775 685 019

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