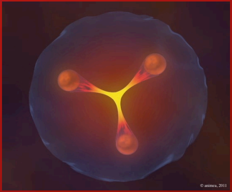
AGENCE NATIONALE DE LA RECHERCHE ANR

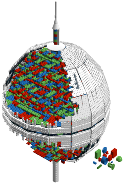
PARTONS

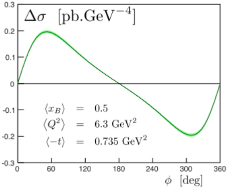
Vector Meson Production:

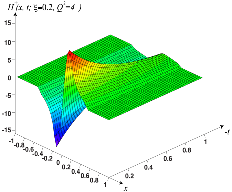
Impact Parameter Description of the Modified Perturbative Approach at small x_B

-Preliminary results-









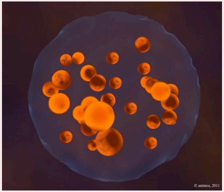
NPQCD 2014 | Hervé MOUTARDE

Oct 3rd, 2014

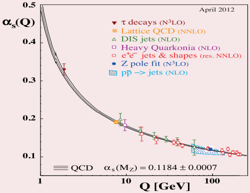
Motivation.

Nucleon structure studies shed new light on nonperturbative QCD.

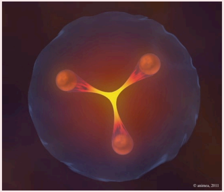
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD

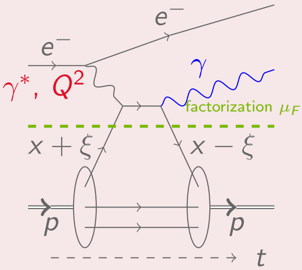


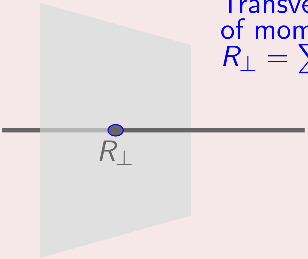
Perturbative AND nonperturbative QCD at work

- Define **universal** objects describing 3D nucleon structure: **Generalized Parton Distributions** (GPD).
- Relate GPDs to measurements using **factorization**: **Virtual Compton Scattering** (DVCS, TCS), **Deeply Virtual Meson production** (DVMP).
- Get **experimental knowledge** of nucleon structure.

- 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 (1/2).

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in the nucleon.
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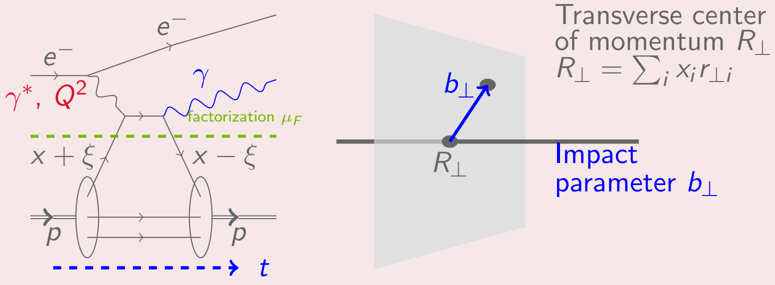
DVCS and GPDs



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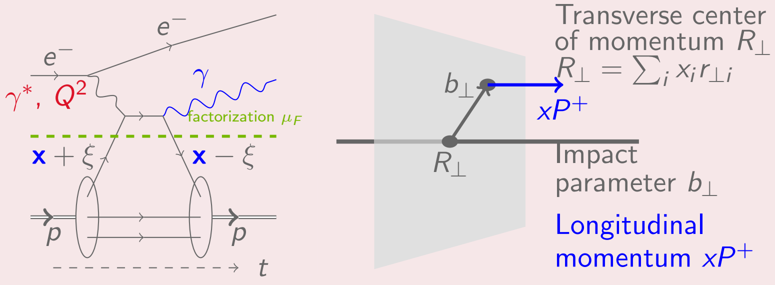
DVCS and GPDs



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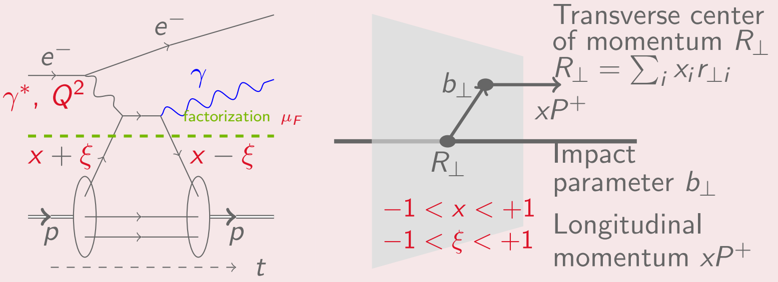
DVCS and GPDs



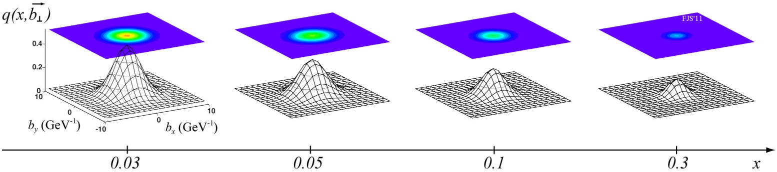
- GPD $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \ldots$

- **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. **D62**, 071503 (2000)



From Theory to Data

Exclusive processes of present interest (1/2).

Factorization and universality.

Vector Meson Production at small x_B

Introduction

From theory to data

Factorization

Kinematic reach

Observables

CFF extraction

Higher order

Higher twist

Impact parameter

Kinematics

Helicity amplitude

MPA Result

t-channel quark exchange

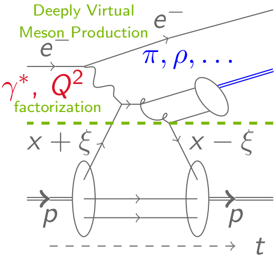
k_T-factorization

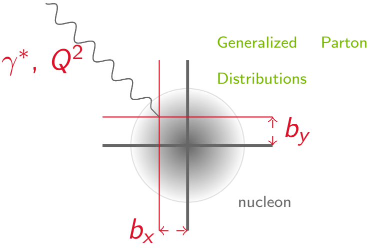
Results

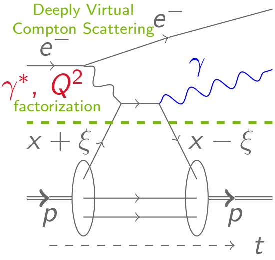
Models

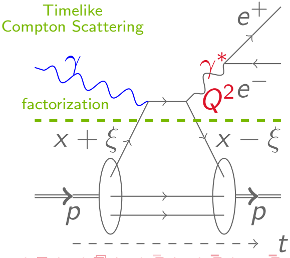
Leading twist results

Conclusions









Exclusive processes of present interest (2/2).

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**.

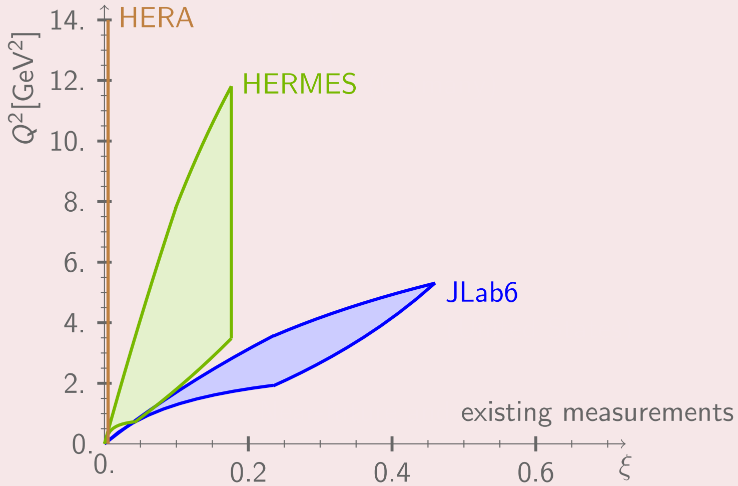
- GPDs enter DVCS through **Compton Form Factors** :

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

for a given GPD F.

- CFF $\mathcal{F}$ is a **complex function**.

Kinematic reach of existing or near-future DVCS measurements



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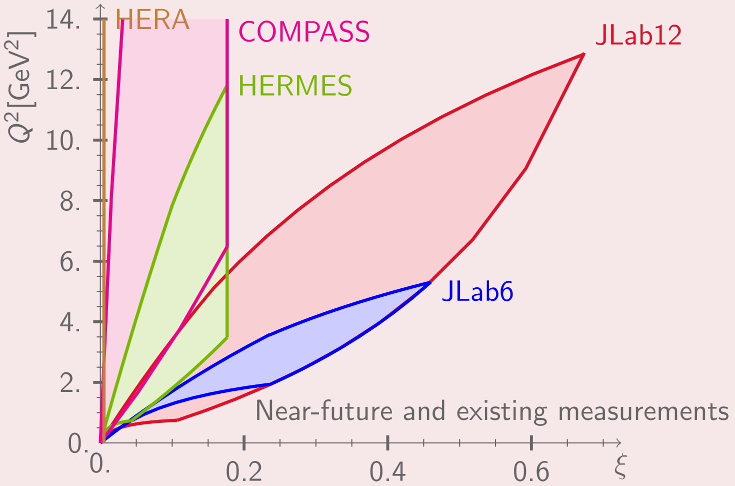
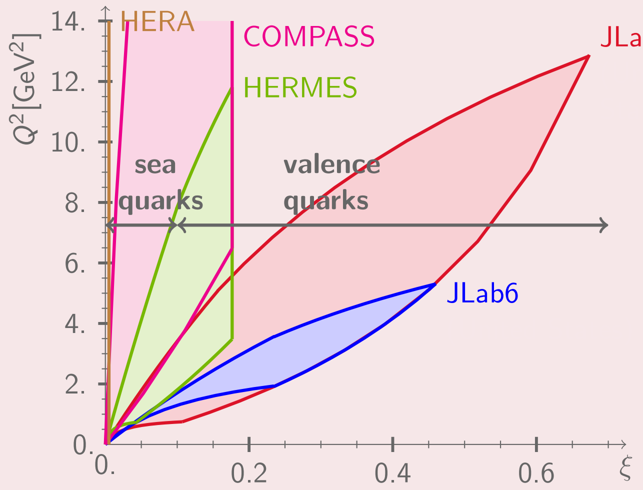


Global analysis of world experimental data.

Different facilities will probe different kinematic domains.

Kinematic reach of existing or near-future DVCS measurements



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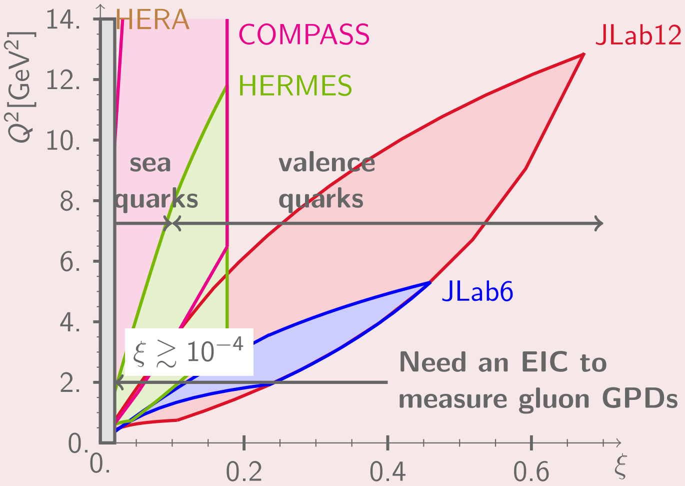
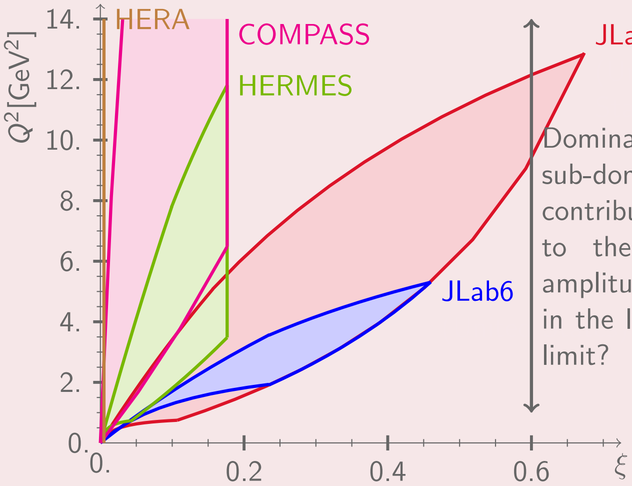


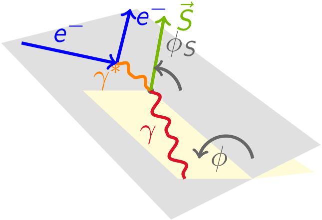
Kinematic reach of existing or near-future DVCS measurements



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

Definition of observables (1/3).

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



- Study the **harmonic structure** of $ep \to ep\gamma$ amplitude.

Diehl *et al.*, Phys. Lett. **B411**, 193 (1997)

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

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

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

- 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.

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]
HERA	0.001	8.00	-0.30
COMPASS	0.05	2.00	-0.20
HERMES	0.09	2.50	-0.12
CLAS	0.19	1.25	-0.19
HALL A	0.36	2.30	-0.23

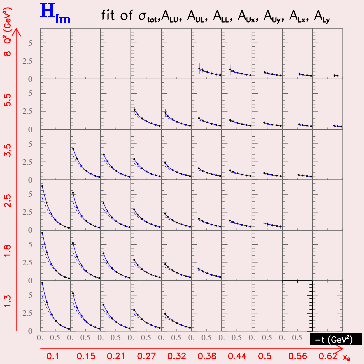
Definition of observables (3/3).

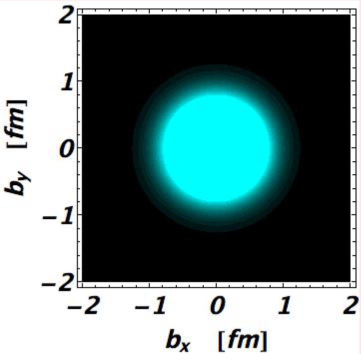
What are the probed combinations of CFFs ?

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	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos \phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

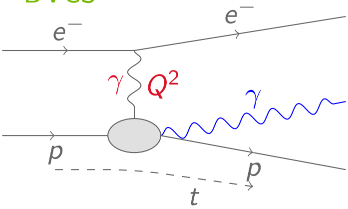
Contour plot of the spatial charge density ($x_B = 0.25$)





Guidal *et al.*, Rept. Prog. Phys. **76**, 066202 (2013)

DVCS

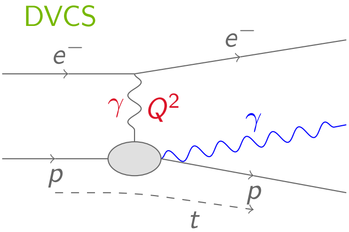


Compton Form Factors (CFF)

- Parametrize amplitudes.

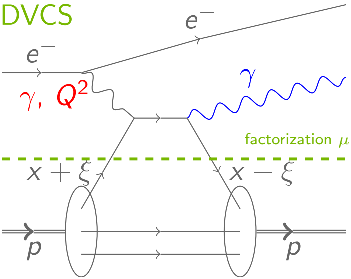
Timelike and spacelike Compton Scattering.

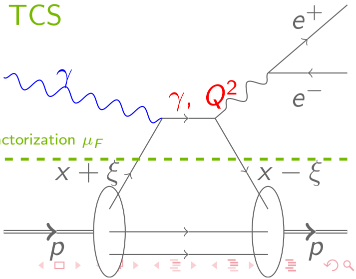
Scattering amplitudes and their partonic interpretation.

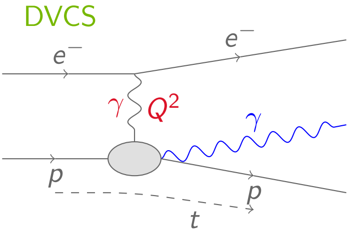


Compton Form Factors (CFF)

- Parametrize amplitudes.
- Evaluation at LO.

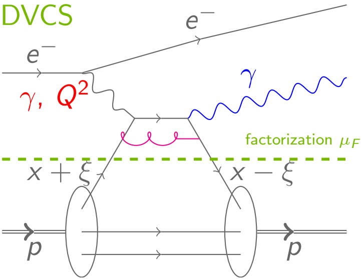


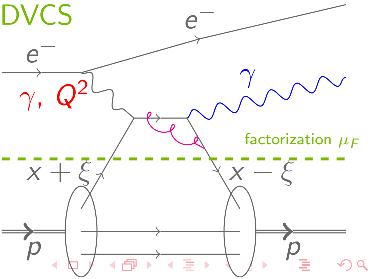


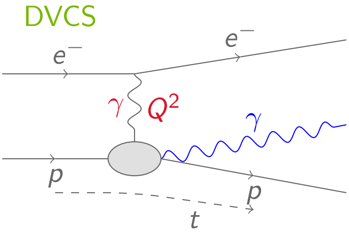


Compton Form Factors (CFF)

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

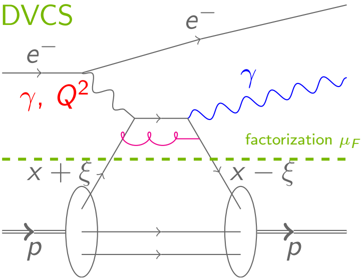


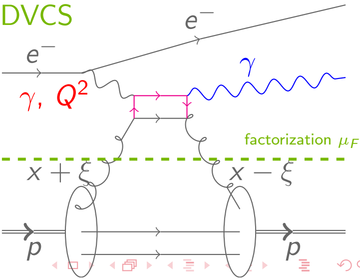




Compton Form Factors (CFF)

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





Explicit expressions.

Quark and gluon contributions to the CFF $\mathcal{H}$ at LO and NLO.

- Convolution of singlet GPD $H_q^+(x) \equiv H_q(x) - H_q(-x)$:

$$\mathcal{H}_q(\xi, Q^2) = \int_{-1}^{+1} dx\, H_q^+(x, \xi, \mu_F)\; T_q\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) + \int_{-1}^{+1} dx\, H_g(x, \xi, \mu_F)\; T_g\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right)$$

Belistky and Müller, Phys. Lett. **B417**, 129 (1998)
Pire *et al*, Phys. Rev. **D83**, 034009 (2011)

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$$\mathcal{H}_q(\xi, Q^2) \stackrel{\text{LO}}{=} \int_{-1}^{+1} dx\, H_q^+(x, \xi, \mu_F)\; C_0^q(x, \xi) + \int_{-1}^{+1} dx\, H_g(x, \xi, \mu_F)\; 0$$

Belistky and Müller, Phys. Lett. **B417**, 129 (1998)
Pire *et al*, Phys. Rev. **D83**, 034009 (2011)

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

$$Im\mathcal{H}_q(\xi, Q^2) \stackrel{\text{LO}}{=} \pi H_q^+(\xi, \xi, \mu_F)$$

Explicit expressions.

Quark and gluon contributions to the CFF $\mathcal{H}$ at LO and NLO.

- Convolution of singlet GPD $H_q^+(x) \equiv H_q(x) - H_q(-x)$:

$$\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \int_{-1}^{+1} dx\, H_q^+(x, \xi, \mu_F) \left[C_0^q + C_1^q + \frac{1}{2} \ln \frac{|Q^2|}{\mu_F^2} C_{\text{Coll}}^q \right] + \int_{-1}^{+1} dx\, H_g(x, \xi, \mu_F) \left(0 + C_1^g + \frac{1}{2} \ln \frac{|Q^2|}{\mu_F^2} C_{\text{Coll}}^g \right)$$

Belistky and Müller, Phys. Lett. **B417**, 129 (1998)
Pire *et al*, Phys. Rev. **D83**, 034009 (2011)

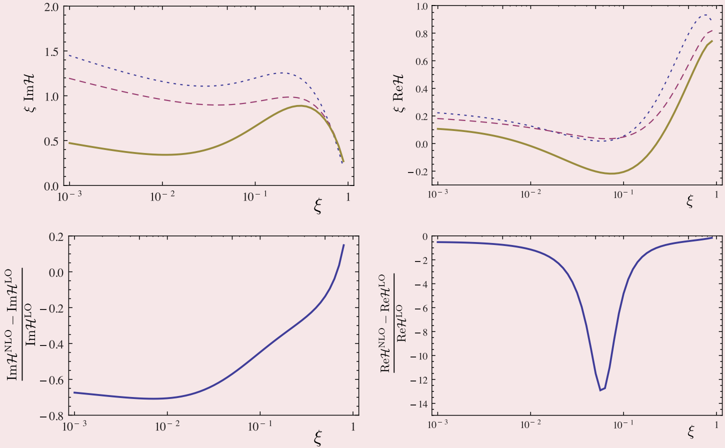
- Integration yields **imaginary** parts to $\mathcal{H}$:

$$Im\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi) H_q^+(\xi, \xi, \mu_F) + \int_{-1}^{+1} dx\, \mathcal{T}^q(x) \Big(H_q^+(x, \xi, \mu_F) - H_q^+(\xi, \xi, \mu_F) \Big) + \text{gluon contributions.}$$

Spacelike CFF $\mathcal{H}$: Large NLO corrections.

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

BMP Compton form factors (CFFs)

- Photon helicity amplitudes can be expanded in a given set of spinor bilinears

$$\mathcal{A}_q^{a\pm} = \mathbb{H}^q_{a\pm}\, h + \mathbb{E}^q_{a\pm}\, e \mp \widetilde{\mathbb{H}}^q_{a\pm}\, \tilde{h} \mp \widetilde{\mathbb{E}}^q_{a\pm}\, \tilde{e}$$

with, e.g. Belitsky, Müller, Ji: NPB **878** (2014) 214

$$h = \frac{\bar{u}(p')\,(\not{q} + \not{q}')u(p)}{P\cdot(\not{q} + \not{q}')} \qquad \ldots$$

- The results read Braun, Manashov, Pirnay: PRL109 (2012) 242001

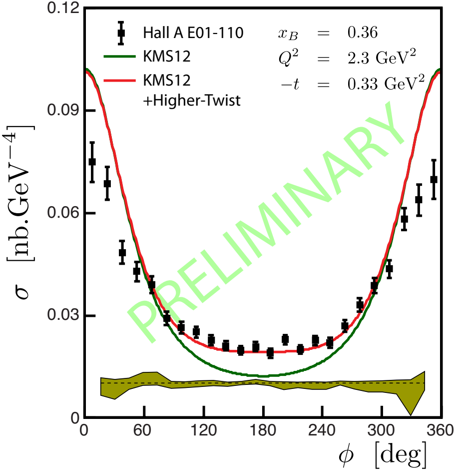
$$\mathbb{H}_{++} = T_0 \circledast H + \frac{t}{Q^2}\left[-\frac{1}{2}T_0 + T_1 + 2\xi D_\xi\, T_2\right] \circledast H + \frac{2t}{Q^2}\xi^2\partial_\xi \xi\, T_2 \circledast (H+E)$$

$$\mathbb{H}_{0+} = -\frac{4|\xi P_\perp|}{\sqrt{2}Q}\left[\xi\partial_\xi\, T_1 \circledast H + \frac{t}{Q^2}\partial_\xi \xi\, T_1 \circledast (H+E)\right] - \frac{t}{\sqrt{2}Q|\xi P_\perp|}\xi\, T_1 \circledast \left[\xi\,(H+E) - \widetilde{H}\right]$$

$$\mathbb{H}_{-+} = \frac{4|\xi P_\perp|^2}{Q^2}\left[\xi\partial_\xi^2 \xi\, T_1^{(+)} \circledast H + \frac{t}{Q^2}\partial_\xi^2 \xi^2\, T_1^{(+)} \circledast (H+E)\right] + \frac{2t}{Q^2}\xi\left[\xi\partial_\xi \xi\, T_1^{(+)} \circledast (H+E) + \partial_\xi\, \xi\, T_1 \circledast \widetilde{H}\right]$$

Finite-t and target mass corrections.

Much more complex structure of DVCS to the twist-4 accuracy.



Sabatié, DIS2014

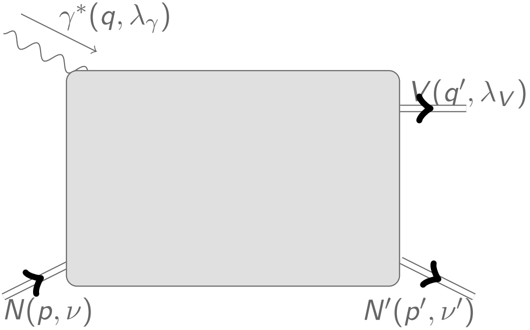
- **Large effect** near $\phi = 180°$.
- Only twist-2 GPDs.
- Similar effect for DVMP observables?

The explicit computation of observables from different hard exclusive channels is necessary to probe GPD models.

- CFF extraction techniques offer **viable experimental information**, but the interpretation in terms of GPDs is obscured by **higher-order** and **higher-twist** contributions.
- CFF extraction **ready for DVCS and TCS**. DVMP and DIS should be taken into account to test the **universality** of GPDs.
- Sophisticated GPD modeling is highly desirable. Non trivial task because of numerous **theoretical constraints** and **curse of dimensionality**.
- These issues may become crucial with the **high precision measurements** expected after JLab's upgrade at 12 GeV.

Impact Parameter Description of Collinear Factorization and Modified Perturbative Approach

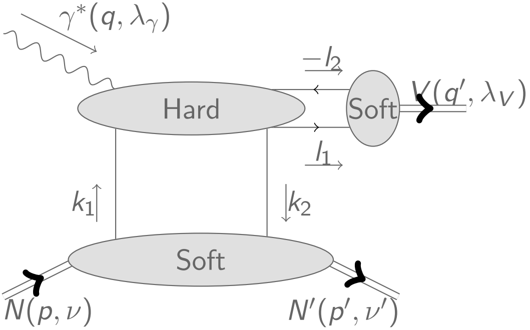
- Consider **longitudinal** virtual photon γ^* and vector meson V: $\lambda_\gamma = \lambda_V = 0$.



Kinematics of hard meson production.

Hadronic process and parton picture.

- Consider **longitudinal** virtual photon γ^* and vector meson V: $\lambda_\gamma = \lambda_V = 0$.
- Assume **large virtuality** $Q^2 = -q^2$ of the incoming photon and invoke **collinear factorization**.



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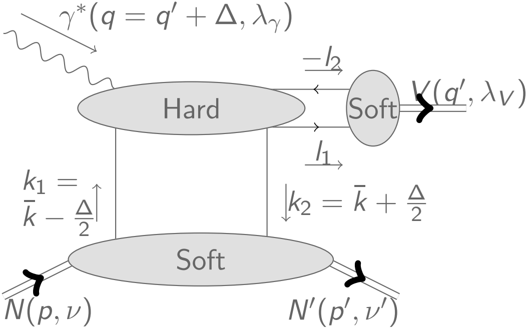


Lightlike p_1 and p_2 *s.t.* $p_1 \cdot p_2 = 1$.

$$\begin{aligned} p &\simeq (1+\xi)p_2 \\ p' &\simeq (1-\xi)p_2 \\ \Delta &\simeq -2\xi p_2 \\ q &\simeq \Delta + \frac{Q^2}{4\xi}p_1 \\ q' &\simeq \frac{Q^2}{4\xi}p_1 \end{aligned}$$

with $\Delta = p' - p$ and $\xi = -2\Delta^+/(p+p')^+$. Also $n = 4\xi/Q^2 p_2$.

- The transition between two states $(\lambda_\gamma, \lambda_V)$ with **different polarizations** requires a non-vanishing momentum in t-channel.
- Only available Lorentz structure $\underline{\epsilon}_V \cdot \underline{\Delta}$ which induces a $\sqrt{-t}$ **suppression for small** t.
- Focus on **small-**t limit and **longitudinal** photon and vector meson.
- From **parity invariance** of strong and electromagnetic interactions:

$$\mathcal{M}_{-\lambda_V-\nu',-\lambda_\gamma-\nu} = (-1)^{(\lambda_V-\nu')-(\lambda_\gamma-\nu)} \mathcal{M}_{\lambda_V\nu',\lambda_\gamma,\nu}$$

- In the small-t limit:

$$\left.\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}\right|_{t=0} = \frac{1}{\text{flux}} \left|\mathcal{M}_{0+,0+}\right|^2$$

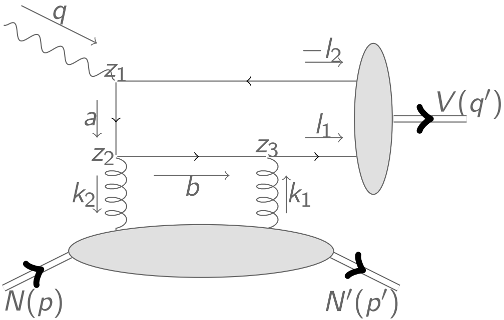
- Separate contributions from different **quark flavors** to S-matrix element:

$$V^g_{V,\{0+,0+\}} = \sum_q C^q_V S^g_{q,\{0+,0+\}}$$

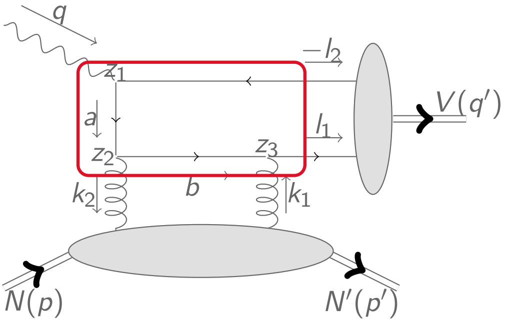
where, for $V \in \{\rho, \omega, \phi\}$:

$$C^u_\rho = -C^d_\rho = C^u_\omega = C^d_\omega = \frac{1}{\sqrt{2}} \text{ and } C^s_\phi = 1$$

- Compute only 2 out of 6 diagrams with t-channel gluon exchange due to **symmetry considerations**:
  - Exchange of quark and antiquark: $l_1 \leftrightarrow l_2$.
  - Exchange of gluon momenta: $k_1 \leftrightarrow k_2$.
- Work in the **light-cone gauge** $p_1 \cdot A = 0$.



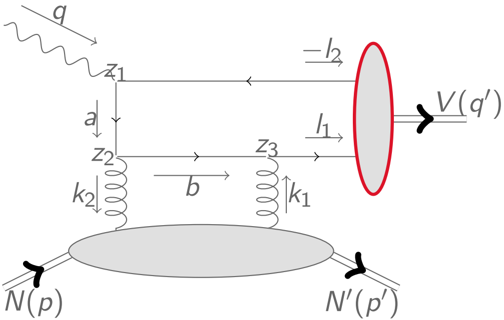
- **Longitudinal momentum fractions τ** and $\bar{\tau} = 1 - \tau$ of the vector meson carried by the quarks.



- **Longitudinal momentum fractions** τ and $\bar{\tau} = 1 - \tau$ of the vector meson carried by the quarks.

- **Collinear approximation** in hard scattering part H:

$$H(l_1, l_2) = H(\tau q', \bar{\tau} q')$$



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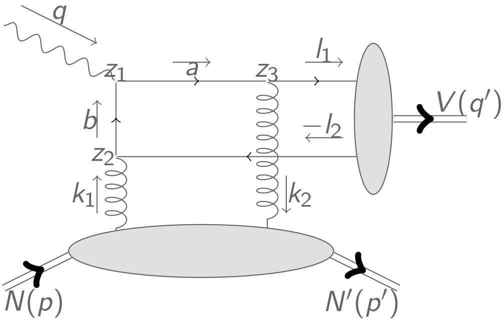
- **Collinear approximation** in hard scattering part H:

$$H(l_1, l_2) = H(\tau q', \bar{\tau} q')$$

- Twist-2 meson DA $\phi_{\parallel}(\tau, \mu^2)$.

$$\langle \frac{1}{\tau} \rangle = \int_0^1 \mathrm{d}\tau \, \frac{1}{\tau} \phi_{\parallel}(\tau, \mu^2)$$

Ball *et al.*, Nucl. Phys. **B543**, 201 (1999)



- Trace of left diagram vanishes.
- Obtain result for all 6 diagrams by changing $\tau \to \bar{\tau}$ and $x \to -x$.

- Full **leading twist** gluon contribution $\mathcal{M}^g_{V,\{0+,0+\}}$:

$$\mathcal{M}^g_{V,\{0+,0+\}} = -e\frac{8\pi\alpha_s}{N_c Q} f_V \int_0^1 \mathrm{d}x \, \frac{\sum_q e_q C_V^q H^g(x,\xi,t)}{(x+\xi-i\epsilon)(x-\xi+i\epsilon)} \langle \frac{1}{\tau} \rangle$$

and $f_V \sum_q e_q C_V^q = \sqrt{3 m_V \Gamma_{V\to e^+e^-}/(4\pi\alpha)}$.

- Introduced to overcome **end-point divergency** problem by keeping **transverse** degrees of freedom in the perturbative hard subprocess.

Botts and Sterman, Nucl. Phys. **B325**, 62 (1989)
Nan Li and Sterman, Nucl. Phys. **B381**, 129 (1989)
Goloskokov and Kroll, Eur. Phys. J. **C42**, 281 (2005)
Eur. Phys. J. **C50**, 829 (2007)
Eur. Phys. J. **C53**, 367 (2008)

- Difference between leading twist and MPA result in treatment of hard scattering part. Here keep outgoing quark and antiquark on the mass-shell:

$$l_1 = \tau q' + \bar{\tau}\frac{m_V^2}{2} n + l_\perp$$

$$l_2 = \bar{\tau} q' + \tau\frac{m_V^2}{2} n - l_\perp$$

Besse *et al.*, *in preparation*

- Introduce **vector meson wavefunction** $\Psi^{*(\lambda_V)}_{V,\bar{h}h}$ parameterizing the valence $q\bar{q}$ Fock state of the vector meson V:

$$\langle V(p_V)| = \sqrt{4\pi N_c} \int \mathrm{d}k^+ \int \frac{\mathrm{d}^2\underline{k}}{16\pi^3} \frac{\Psi^{*(\lambda_V)}_{V,\bar{h}h}(k^+/q'^+, \underline{k})}{\sqrt{k^+(q'^+ - k^+)}} \langle 0| b_h d_{\bar{h}}$$

Forshaw and Sandapen, JHEP **1110**, 093 (2011)

- Perturbative calculation of the virtual photon wavefunction $\Psi^{*(\lambda_\gamma)}_{\gamma^*,\bar{h}h}$:

$$\Psi^{(\lambda_\gamma)}_{\gamma^*,h\bar{h}}(\tau, \underline{l}) = \delta_{h,-\bar{h}}\, e\, e_q \sqrt{\frac{N_c}{4\pi}} \frac{2\tau\bar{\tau}Q}{\underline{l}^2 + \tau\bar{\tau}Q^2}$$

Dosch *et al.*, Phys. Rev. **D55**, 2602 (1997)
Lepage and Brodsky, Phys. Rev. **D22**, 2157 (1980)

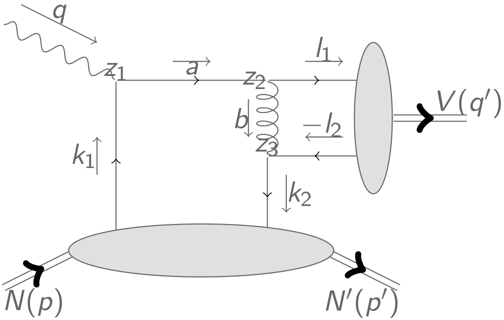
- Express final result in terms of Fourier transforms $\hat{\Psi}$ of wavefunctions in **transverse coordinate space**:

$$\mathcal{M}^g_{V,\{0+,0+\}} = \sum_q C^q_V \int_0^1 \mathrm{d}\tau \int \mathrm{d}^2\underline{r} \sum_{h,\bar{h}} \hat{\Psi}^q_{V,\bar{h}h}(\tau, -\underline{r}) \hat{\Psi}^q_{\gamma^*,h\bar{h}}(\tau, \underline{r}) \times \frac{4\pi\alpha_s}{N_c} \frac{1}{\tau\bar{\tau}} \int_0^1 \mathrm{d}x \frac{H^g(x,\xi,t)}{(x+\xi-i\epsilon)(x-\xi+i\epsilon)}$$

  where $r = |\underline{r}|$ is the size of the **color dipole** formed by the $q\bar{q}$ pair.
- Recover leading twist result by taking meson wavefunction at $\underline{r} = 0$.

Contribution of quark GPDs.
Modified Perturbative Approach result (1/2).

- From symmetry consideration, restrict to 2 diagrams.



- Polarization of longitudinal virtual photon:

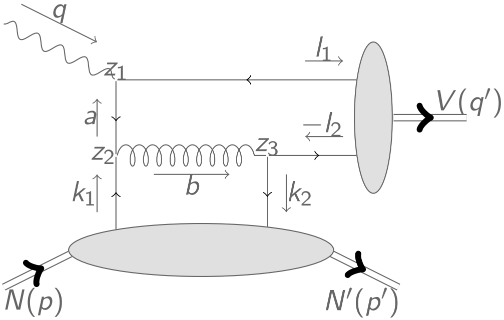
$$\epsilon^\mu(q) = \frac{q^\mu + 4\xi p_2}{Q}$$

- From Ward identity:

$$\not{\epsilon} \to \frac{4\xi}{Q} \not{p}_2$$

- Above diagram vanishes at leading twist due to traces with structure $\not{p}_2 \not{p}_2$.

Contribution of quark GPDs.
Modified Perturbative Approach result (2/2).



- Compute only 1 diagram.
- Get other diagrams by exchanging roles of quark and antiquark:

$$x \leftrightarrow -x$$
$$\tau \leftrightarrow \bar{\tau}$$

- Quark contribution:

$$\mathcal{M}^q_{V,\{0+,0+\}} = \sum_q C^q_V \int_0^1 d\tau \int \mathrm{d}^2\underline{r} \sum_{h,\bar{h}} \hat{\Psi}^q_{V,\bar{h}h}(\tau,-\underline{r})\hat{\Psi}^q_{\gamma^*,h\bar{h}}(\tau,\underline{r})$$
$$\times \frac{4\pi\alpha_s}{N_c}\frac{1}{\tau\bar{\tau}}\int_{-1}^1 \mathrm{d}x \frac{C_F\, x\, H^q(x,\xi,t)}{(x+\xi-i\epsilon)(x-\xi+i\epsilon)}$$

- Modified Perturbative Approach result ($Q^2 \simeq 2\xi s$):

$$\mathcal{I}m\,\mathcal{M}_{V,\{0+,0+\}} = \int_0^1 \mathrm{d}\tau \int \mathrm{d}^2\underline{r} \sum_{h,\bar{h}} \sum_q C_V^q \left(\hat{\Psi}^q_{V,\bar{h}h}(\tau,-\underline{r})\hat{\Psi}^q_{\gamma^*,h\bar{h}}(\tau,\underline{r})\right)$$

$$\times \left[s\frac{\alpha_s \pi^2}{N_c}\frac{4}{\tau\bar{\tau}Q^2}\left(H^g(\xi,\xi,0) + C_F \xi H^q_S(\xi,\xi,0)\right)\right]$$

with $H^q_S(x,\xi,t) = H^q(x,\xi,t) - H^q(-x,\xi,t)$.

Besse *et al., in preparation.*

- k_T−factorization and dipole models result:

$$\mathcal{I}m\,\mathcal{M}^g_{V,\{0+,0+\}} = \int_0^1 \mathrm{d}\tau \int \mathrm{d}^2\underline{r} \sum_{h,\bar{h}} \sum_q C_V^q \left(\hat{\Psi}^q_{V,\bar{h}h}(\tau,-\underline{r})\hat{\Psi}^q_{\gamma^*,h\bar{h}}(\tau,\underline{r})\right)$$

$$\times \left[\mathrm{Im}\,\mathcal{N}^{q\bar{q}}\left(x, \xi = \frac{x}{2}, \underline{r}\right)\right]$$

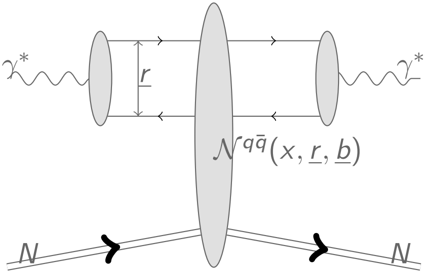
Besse *et al.*, Nucl. Phys. **B867**, 19 (2013)

- Identify gluon contributions:

$$\mathrm{Im}\,\mathcal{N}^{q\bar{q}}\left(x, \xi = \frac{x}{2}, \underline{r}\right) = s\frac{\alpha_s \pi^2}{N_c}\frac{4}{\tau\bar{\tau}Q^2}H^g(\xi, \xi, 0)$$

Besse *et al., in preparation.*

- **Connection** between two **different objects** coming from two **different formalisms**!



Phenomenology

- **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 :

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

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

- Comparison to **existing DVCS measurements** at LO.

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

- Asymptotic leading twist DA:

$$\phi_{\|}(\tau) = 6\tau\bar{\tau}$$

- Fit $B(Q^2)$-slope from experimental data (H1 Coll.):

$$\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}(t) \simeq e^{-B(Q^2)|t|} \left.\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}\right|_{t=0}$$

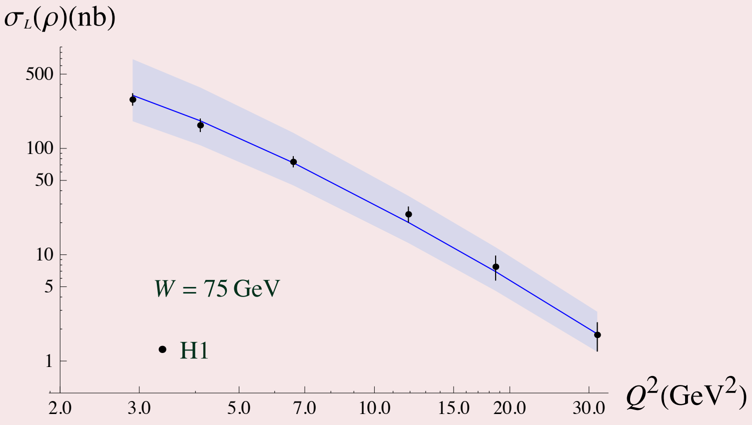
Aaron *et al.*, JHEP **05**, 032 (2010)

- Factorization scale:

$$\mu = \sqrt{Q^2 + m_V^2}$$

with systematic uncertainty evaluated by covering the range between $\sqrt{Q^2 + m_V^2}/4$ and $4\sqrt{Q^2 + m_V^2}$.

Electroproduction of ρ meson vs H1 data at $W = 75$ GeV.



Besse *et al.*, *in preparation*

Leading twist description.

Preliminary results.

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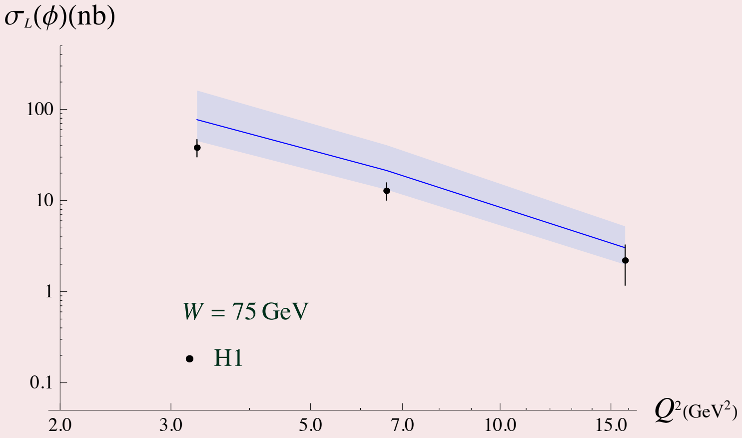

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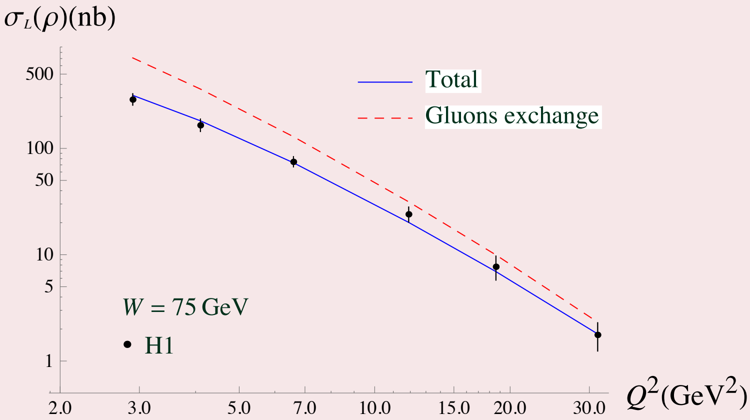

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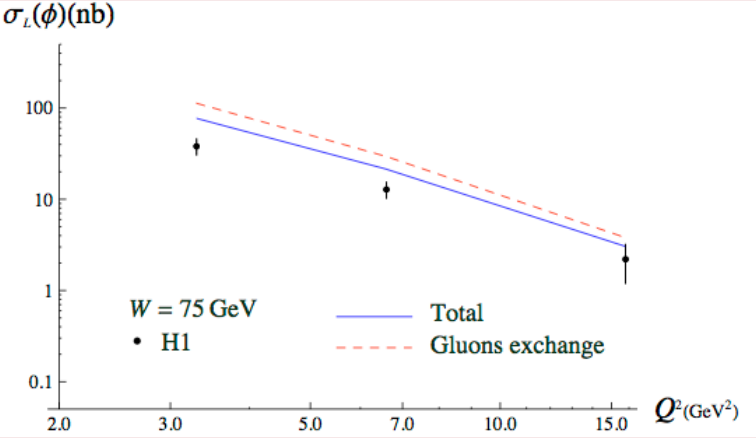

Besse *et al., in preparation*

Conclusions

- The GPD physics program is a mature field dealing with **well-defined** theoretical objects, **cleanly** related to experimental data, with present **experimental relevance**.
- To make one further step, one requires:
  - Better GPD and meson DA **models**.
  - Better control of **subdominant effects** on theoretical description of experimental channels.
  - Combined analysis of hard exclusive channels.
- Implementation of a DVMP computational code in an **software platform** for multi-channel GPD analysis.
- Intriguing relation between **GPD / collinear factorization** and **color dipole / k_T factorization** pictures. Open the way to alternative discussions of **saturation** physics?

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