Generalizing the GPDs for $\bar{p}p$ interactions : Transition Distribution Amplitudes

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+ work in collaboration with **J.Ph Lansberg, M. Segond and S. Wallon**

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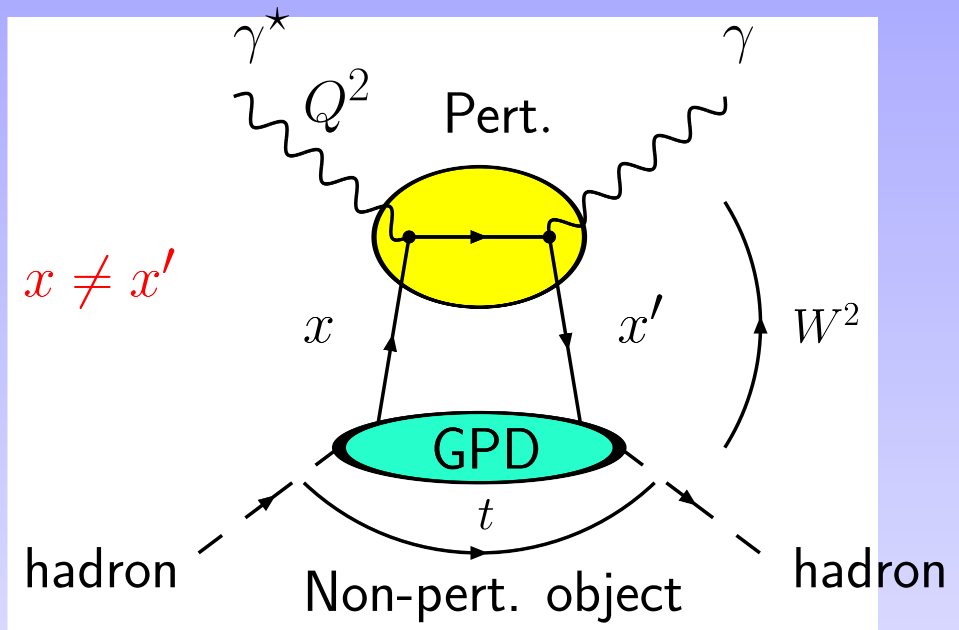
Factorized framework for Hard exclusive reactions

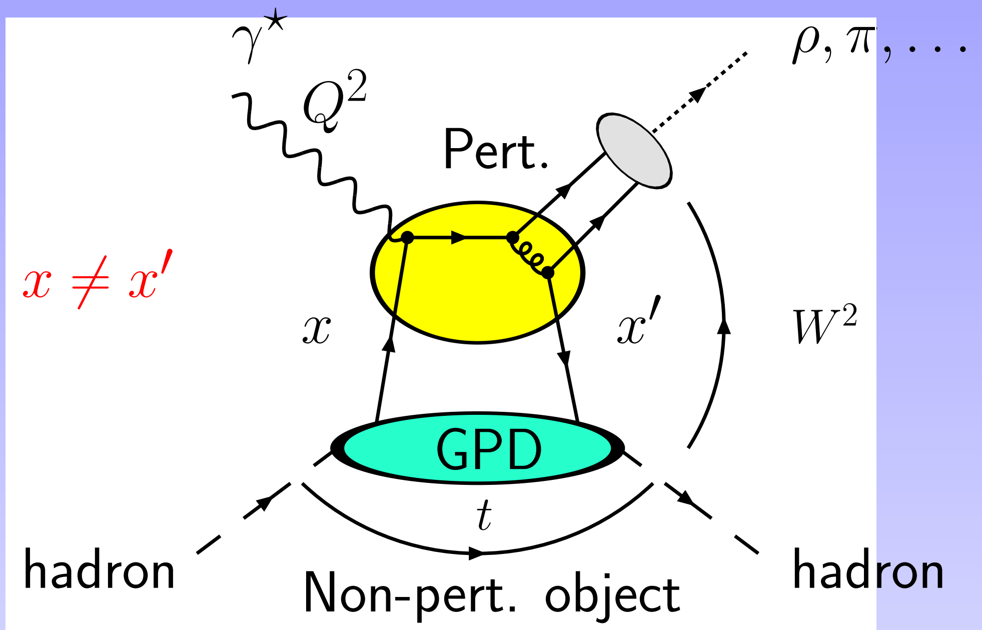
DVCS example



Factorisation between the hard part (perturbatively calculable) and the soft part (non-perturbative) demonstrated for

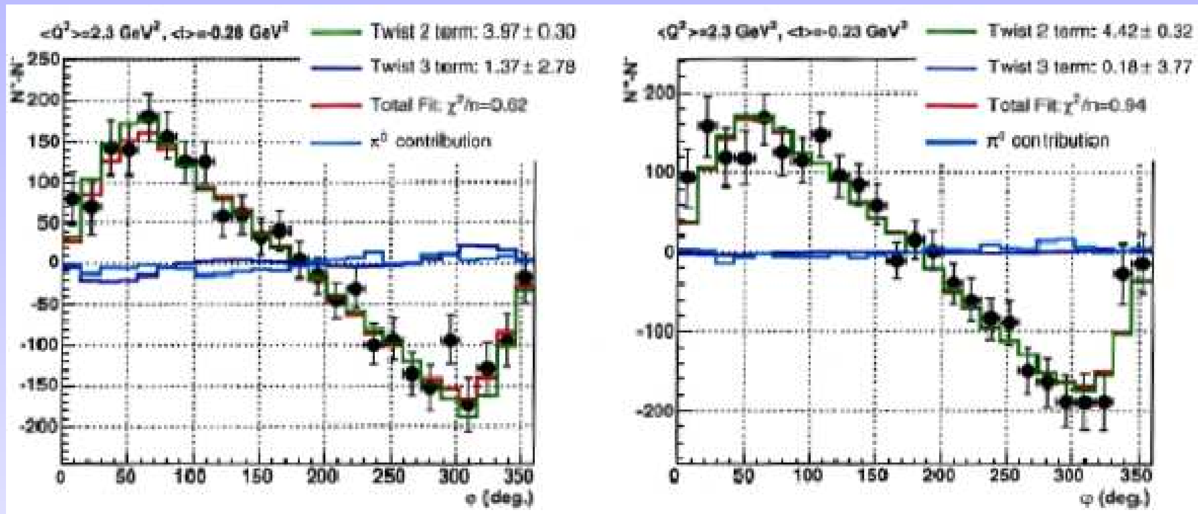
$$Q^2 \to \infty,\ x_B = \frac{Q^2}{Q^2+W^2} \text{ fixed and } t \ll \text{ fixed}$$

Also true for meson electroproduction

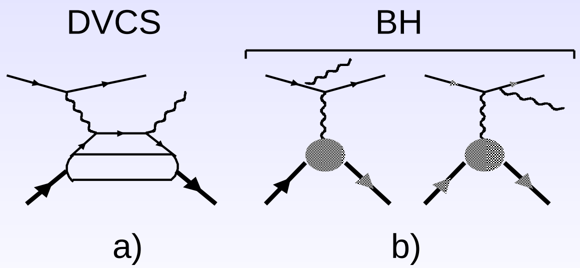


Hard exclusive reactions : Success of Factorized framework

• Deeply Virtual Compton Scattering $ep \to e\gamma p'$
Angular dependence of asymmetries coming from Bethe Heitler / DVCS interference

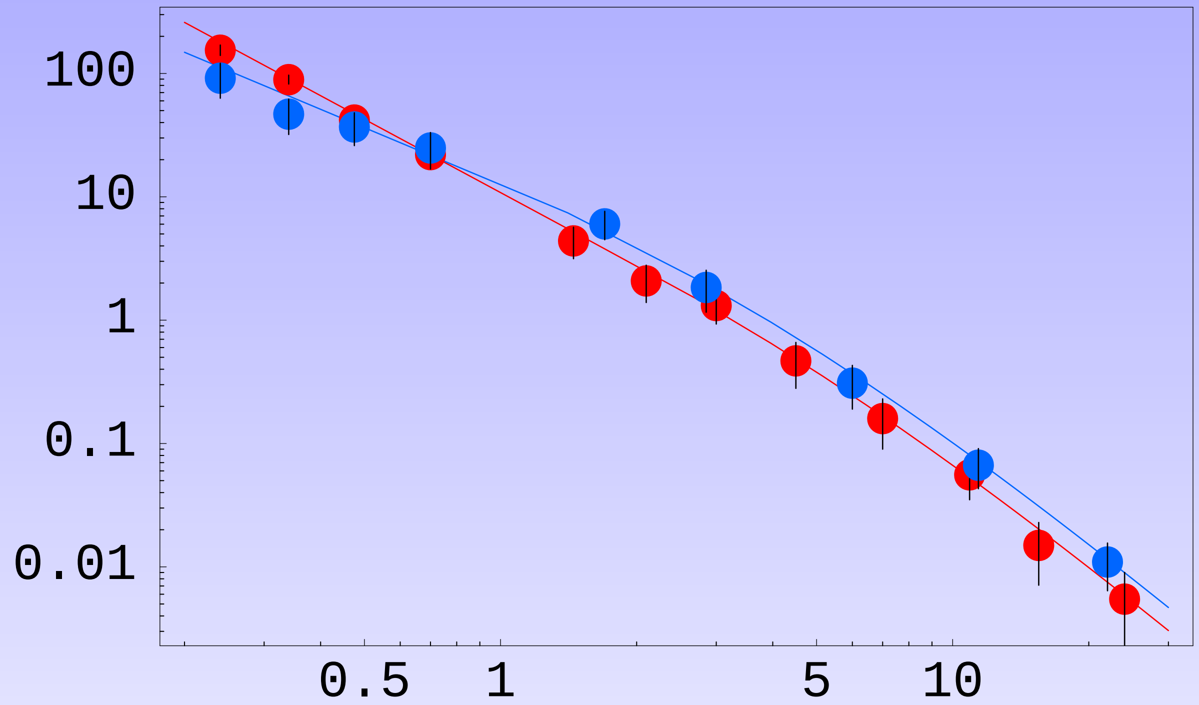


JLab data at $Q^2 = 2.3\,\mathrm{GeV}^2$,
$t = -0.28$ and $-0.23\,\mathrm{GeV}^2$
• $\to$ early scaling at JLab



Factorization regime seen in crossed process $\gamma^*\gamma$

- LEP2 data : EARLY SCALING



Q^2 dependence of $\gamma^*\gamma \longrightarrow \rho^+\rho^-$ and $\gamma^*\gamma \longrightarrow \rho^0\rho^0$

blue red

Extension

- Deep VCS under control in the near forward direction
- What about backward direction ?
- Related question : What can pQCD say about

$\bar{p}N \to \gamma^*\gamma$ and $\bar{p}N \to \gamma^*\pi$

PANDA-PAX programs at GSI-FAIR

New factorization $P \to \gamma$, $P \to \pi$ TDA

Transition Distribution Amplitudes

$$\langle \pi(p')|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle\Big|_{z^+=0,\, z_T=0}$$

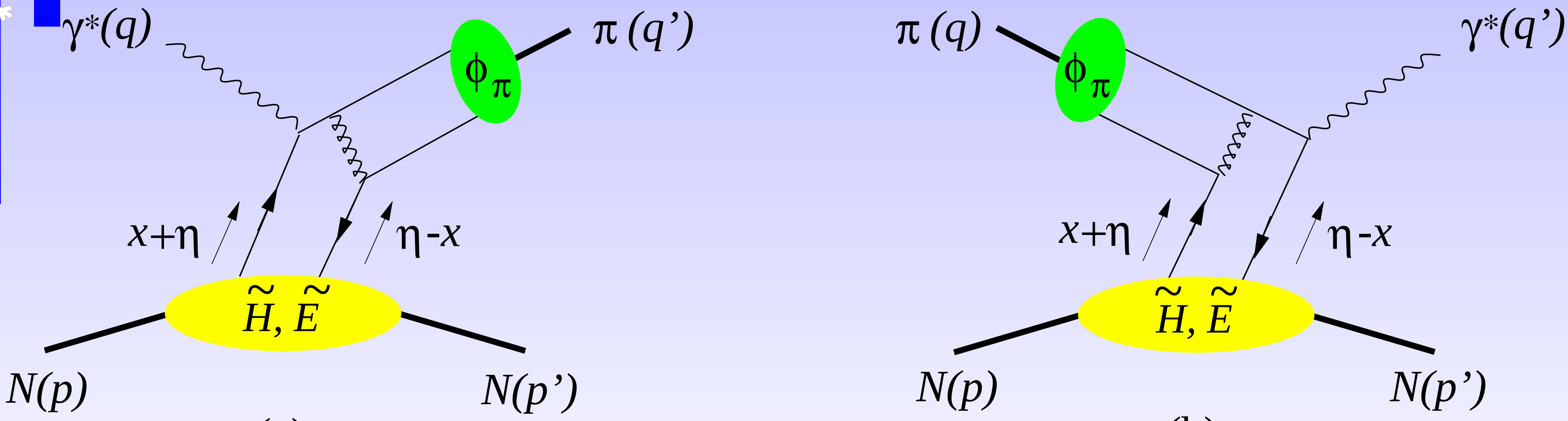
$$\langle \gamma(p',\epsilon')|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle\Big|_{z^+=0,\, z_T=0}$$

Arguments for Factorization

PROOFS EXIST for

• Factorization of deep exclusive π electroproduction on meson target. *Collins Frankfurt Strikman*

• Time inversion : Factorization of $\pi N \longrightarrow \gamma^* N'$ on meson target. *Berger Diehl BP*



(a) (b)

Arguments for Factorization

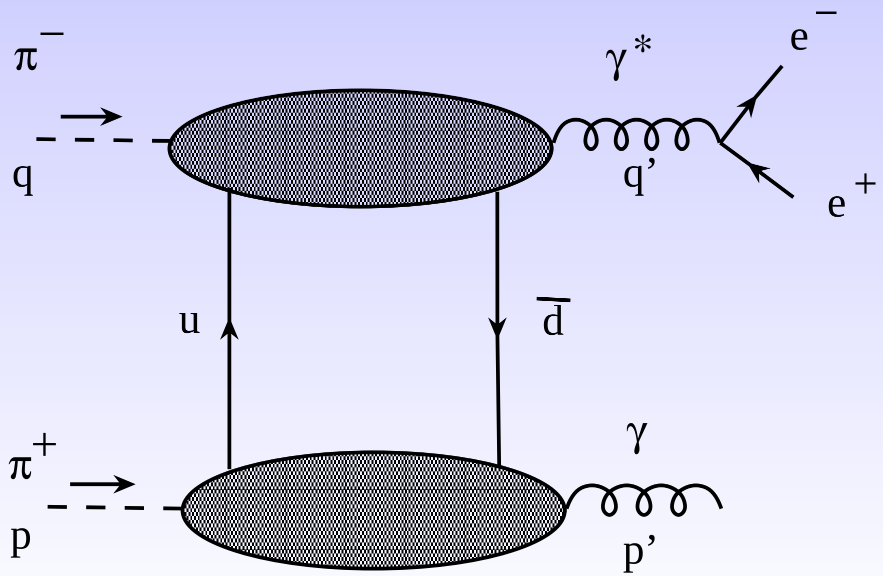
- Change $N' \to \gamma$

Remember : Photon structure function factorizes in the same way as meson structure function !

$\to$ Factorization of TDA in

$$\pi\pi \to \gamma^*\gamma$$

in the forward direction (*where cross section is bigger.*)



Perturbative example: $\gamma^*(Q_1)\gamma^*(Q_2) \to \rho_L \rho_L$

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forward kinematics $\quad t = t_{min} = -\frac{Q_1^2\, Q_2^2}{s}$

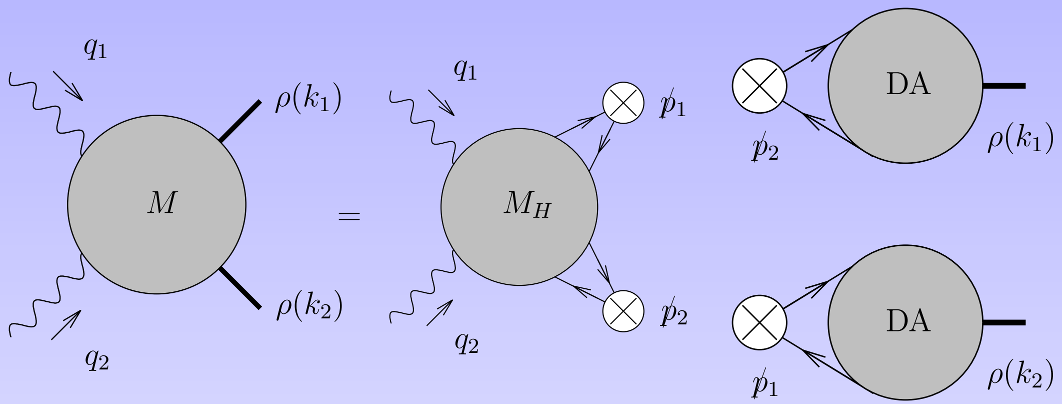


Figure 1: The amplitude of the process $\gamma^*(Q_1)\gamma^*(Q_2) \to \rho_L^0(k_1)\rho_L^0(k_2)$ in the collinear factorization.

$$M = \epsilon_\mu(q_1)\, \epsilon_\nu(q_2) \int M_H^{\mu\nu}\, \phi_\rho\, \phi_\rho$$

factorization with two DAs of ρ's

Direct calculations: $\gamma^*\gamma^* \to (q\bar{q})(q\bar{q})$

20 diagrams like in the $\gamma\gamma \to \pi\pi$, large t Brodsky+Lepage

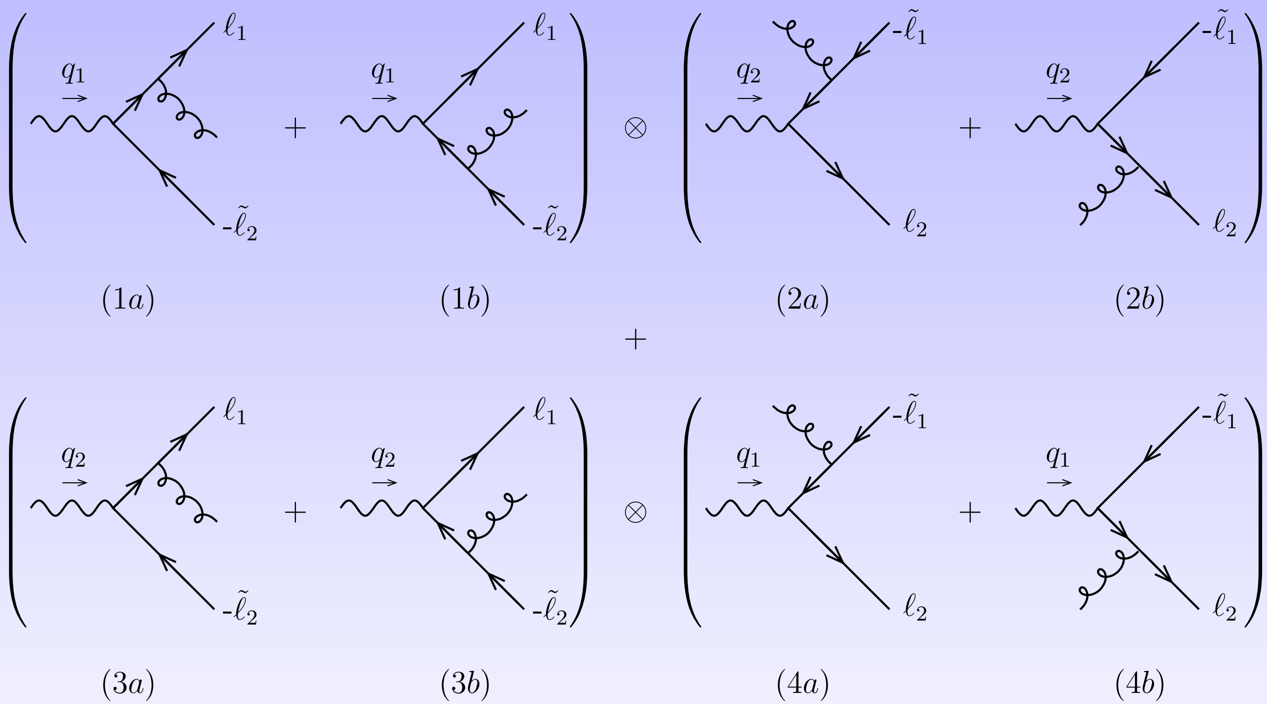


Figure 1: Feynman diagrams contributing to M_H, in which the virtual photons couple to different quark lines.

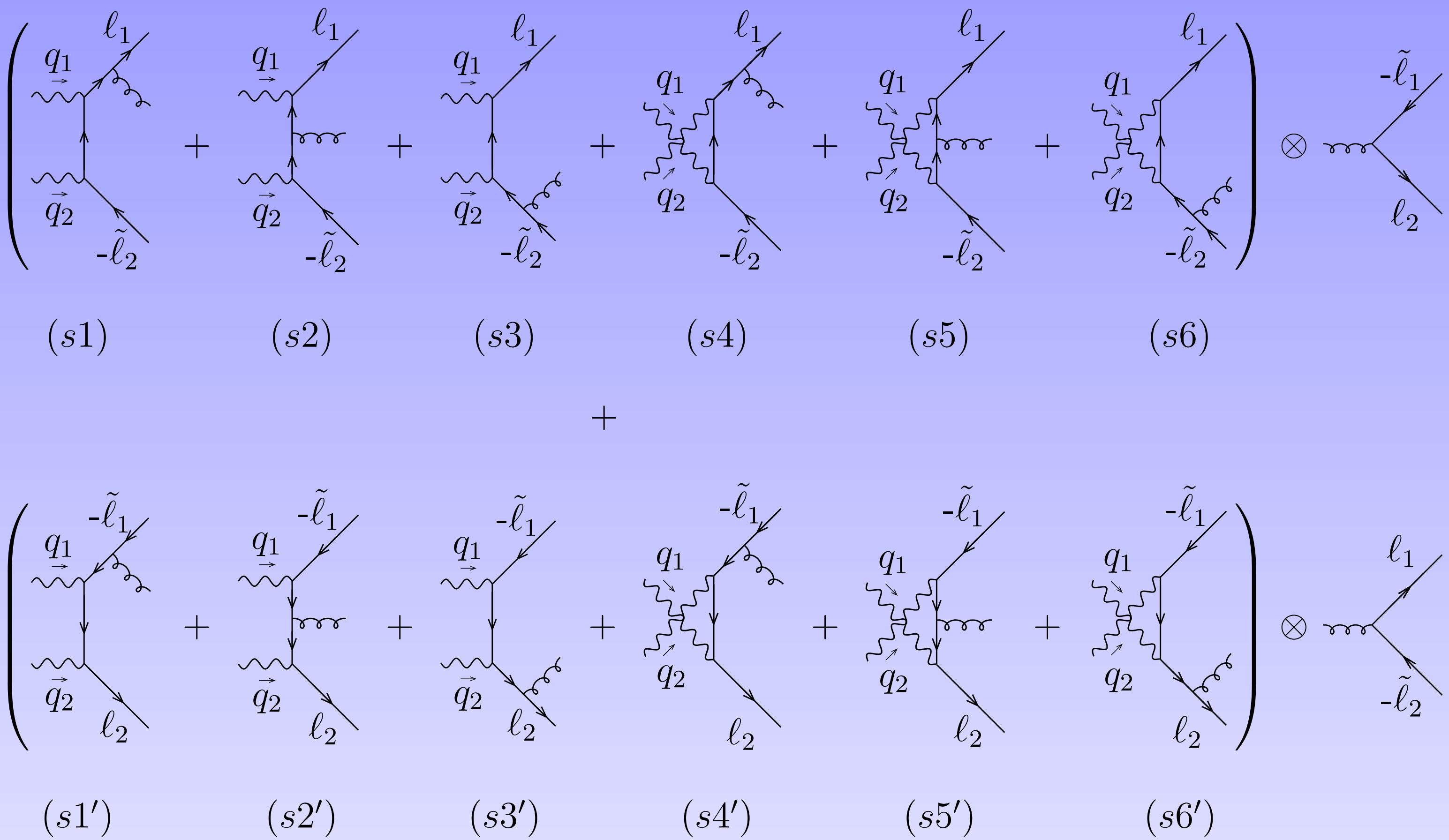


Figure 1: Feynman diagrams corresponding to the coupling of the virtual photons to a single quark line.

Results

general structure:

$$\mathcal{A} = T^{\mu\,\nu}\epsilon_\mu(q_1)\epsilon_\nu(q_2)\ ,$$

the tensor $T^{\mu\,\nu}$ has a simple decomposition consistent with Lorentz covariance and e-m gauge invariance

$$T^{\mu\,\nu} = \tfrac{1}{2} g_T^{\mu\,\nu}\ (T^{\alpha\,\beta} g_{T\,\alpha\,\beta})$$
$$+(p_1^\mu + \tfrac{Q_1^2}{s} p_2^\mu)(p_2^\nu + \tfrac{Q_2^2}{s} p_1^\nu)\ \tfrac{4}{s^2}(T^{\alpha\,\beta} p_{2\,\alpha}\, p_{1\,\beta})\ ,$$

and $g_T^{\mu\,\nu} = g^{\mu\nu} - (p_1^\mu p_2^\nu + p_1^\nu p_2^\mu)/(p_1.p_2)$.

first term $\longrightarrow$ transversally polar. γ^*'s
second term $\longrightarrow$ longitudinally polar. γ^*'s

transverse γ^*

$$T^{\alpha\,\beta} g_{T\,\alpha\,\beta} = -\frac{e^2 (Q_u^2 + Q_d^2)\, g^2\, C_F\, f_\rho^2}{4\, N_c\, s} \int\limits_0^1 dz_1\, dz_2\, \phi(z_1)\, \phi(z_2)$$

$$\Bigg\{ 2\left(1 - \frac{Q_2^2}{s}\right)\left(1 - \frac{Q_1^2}{s}\right)\left[\frac{1}{(z_2 + \bar{z}_2 \frac{Q_1^2}{s})^2 (z_1 + \bar{z}_1 \frac{Q_2^2}{s})^2} + \frac{1}{(\bar{z}_2 + z_2 \frac{Q_1^2}{s})^2 (\bar{z}_1 + z_1 \frac{Q_2^2}{s})^2}\right] +$$

$$\left(\frac{1}{\bar{z}_2\, z_1} - \frac{1}{\bar{z}_1\, z_2}\right)\left[\frac{1}{1 - \frac{Q_2^2}{s}}\left(\frac{1}{\bar{z}_2 + \frac{z_2 Q_1^2}{s}} - \frac{1}{z_2 + \frac{\bar{z}_2 Q_1^2}{s}}\right) - \frac{1}{1 - \frac{Q_1^2}{s}}\left(\frac{1}{\bar{z}_1 + \frac{z_1 Q_2^2}{s}} - \frac{1}{z_1 + \frac{\bar{z}_1 Q_2^2}{s}}\right)\right]$$

all integrations converge $\longrightarrow$ factorization with ρ DAs longitudinal γ^*

$$T^{\alpha\,\beta} p_{2\,\alpha}\, p_{1\,\beta} =$$

$$-\frac{s^2 f_\rho^2 C_F e^2 g^2 (Q_u^2+Q_d^2)}{8 N_c Q_1^2 Q_2^2} \int_0^1 dz_1\, dz_2\, \phi(z_1)\, \phi(z_2)$$

$$\times \left\{ \frac{(1-\frac{Q_1^2}{s})(1-\frac{Q_2^2}{s})}{(z_1+\bar{z}_1\frac{Q_2^2}{s})(z_2+\bar{z}_2\frac{Q_1^2}{s})} + \frac{(1-\frac{Q_1^2}{s})(1-\frac{Q_2^2}{s})}{(\bar{z}_1+z_1\frac{Q_2^2}{s})(\bar{z}_2+z_2\frac{Q_1^2}{s})} + \frac{1}{z_2\bar{z}_1} + \frac{1}{z_1\bar{z}_2} \right\} ,$$

all integrals converge $\longrightarrow$ factorization with ρ DAs o.k.

Factorization with GDA

$$\frac{W^2}{Q_1^2} = \frac{s}{Q_1^2}\left(1 - \frac{Q_1^2}{s}\right)\left(1 - \frac{Q_2^2}{s}\right) \approx 1 - \frac{Q_1^2}{s} \ll 1$$

$g_\perp^{\mu\nu} \longrightarrow$ factor. with GDA of $\gamma_T^*\gamma_T^* \to \rho_L^0\rho_L^0$ in the generalized Bjorken limit

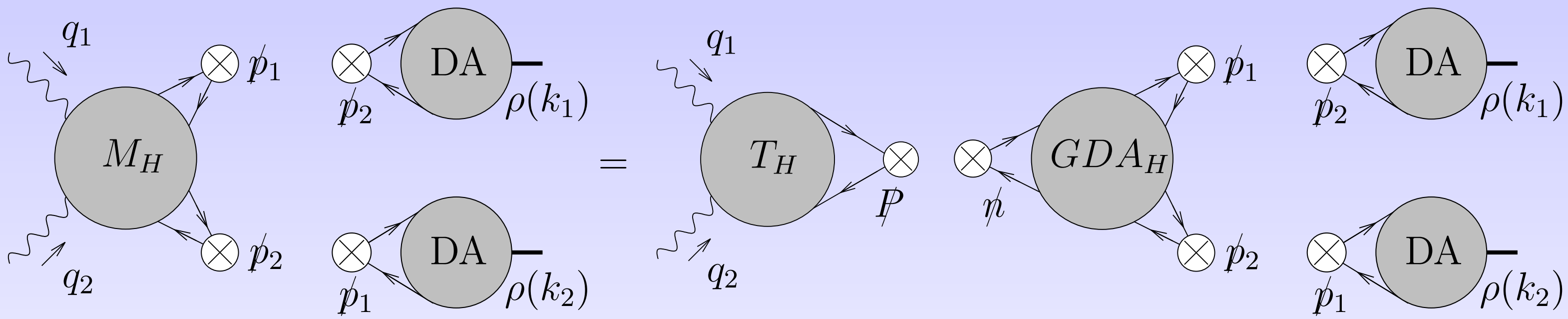


Figure 1: Factorisation of the amplitude in terms of a GDA.

for γ_T^*'s:

$$T^{\alpha\,\beta} g_{T\,\alpha\,\beta} = \frac{e^2}{2}\left(Q_u^2 + Q_d^2\right)$$

$$\int_0^1 dz \left(\frac{1}{\bar{z} + z\frac{Q_2^2}{s}} - \frac{1}{z + \bar{z}\frac{Q_2^2}{s}} \right) \Phi^{\rho_L \rho_L}(z, \zeta \approx 1, W^2)$$

with

$$\Phi^{\rho_L \rho_L}(z, \zeta \approx 1, W^2) = -\frac{f_\rho^2\, g^2\, C_F}{2\, N_c\, W^2}$$

$$\int_0^1 dz_2\, \phi(z)\, \phi(z_2) \left[\frac{1}{z\,\bar{z}_2} - \frac{1}{\bar{z}\, z_2} \right]$$

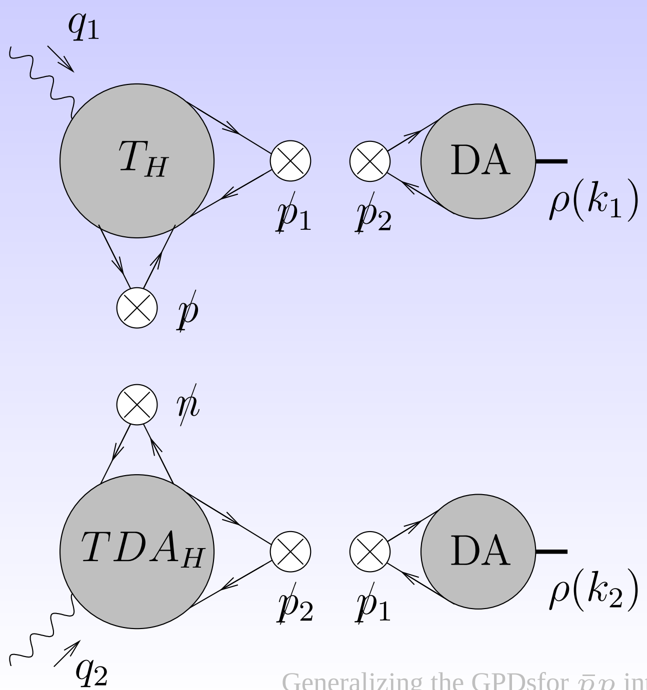
Factorization with TDA

$$Q_1^2 \quad >> \quad Q_2^2$$

$(p_1^\mu + \frac{Q_1^2}{s} p_2^\mu)(p_2^\nu + \frac{Q_2^2}{s} p_1^\nu) \longrightarrow \gamma_L^*$'s and factoriz. with TDA, i.e.

$$\int \frac{dz^-}{2\pi} e^{-ixP^+z^-} < \rho(p_2)|\bar{q}(-z^-/2)\gamma^+ q(z^-/2))|\,\gamma(q_2) >$$

of $\gamma_L^* \gamma_L^* \rightarrow \rho_L^0 \rho_L^0$ in the generalized Bjorken limit



The perturbative TDA for $\gamma^*(q_2) \to \rho_L^q$

$$\int \frac{dz^-}{2\pi}\, e^{ix(P.z)}\, \langle \rho_L^q(k_2)|\bar{q}(-z/2)\hat{n}\, e^{-ieQ_q \int_{z/2}^{-z/2} dy_\mu\, A^\mu(y)}\, q(z/2)|\gamma^*(q_2)\rangle$$

$$= \frac{e\,Q_q\,f_\rho}{P^+}\,\frac{2}{Q_2^2}\,\epsilon_\nu(q_2)\left((1+\xi)n_2^\nu + \frac{Q_2^2}{s(1+\xi)}n_1^\nu\right)T(x,\xi,t_{min})$$

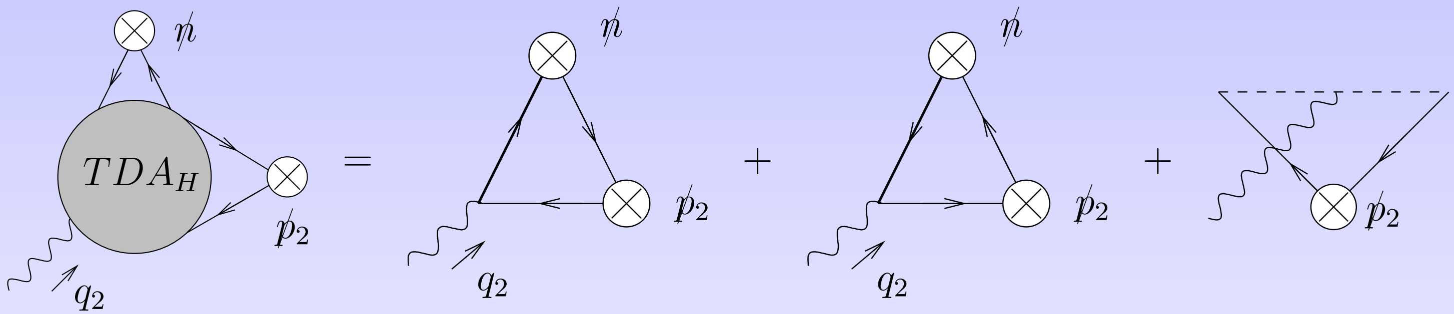


Figure 1: The hard part of the TDA at order $e\,Q_q$.

$$T(x,\xi,t_{min}) \equiv$$

$$N_c\left[\Theta(1\geq x\geq \xi)\,\phi\left(\frac{x-\xi}{1-\xi}\right) - \Theta(-\xi\geq x\geq -1)\,\phi\left(\frac{1+x}{1-\xi}\right)\right]$$

Summary of the factorization with TDA for γ_L^*'s

$$T^{\alpha\beta} p_{2\,\alpha} p_{1\,\beta} = -i f_\rho^2 e^2 (Q_u^2 + Q_d^2) g^2 \frac{C_F}{8N_c}$$
$$\int_{-1}^{1} dx \int_{0}^{1} dz_1 \left[\frac{1}{\bar{z}_1 (x-\xi)} + \frac{1}{z_1 (x+\xi)} \right] T(x,\xi,t_{min})$$

- The $\gamma_L^* \to \rho_L$ TDA has a perturbative expression in terms of DA of ρ
- A non-perturbative approach is needed for a TDA with real γ, e.g. for $\gamma \to \rho$ TDA

Back to the reality...

Arguments for Factorization - continued

• Change Meson $\rightarrow$ Baryon

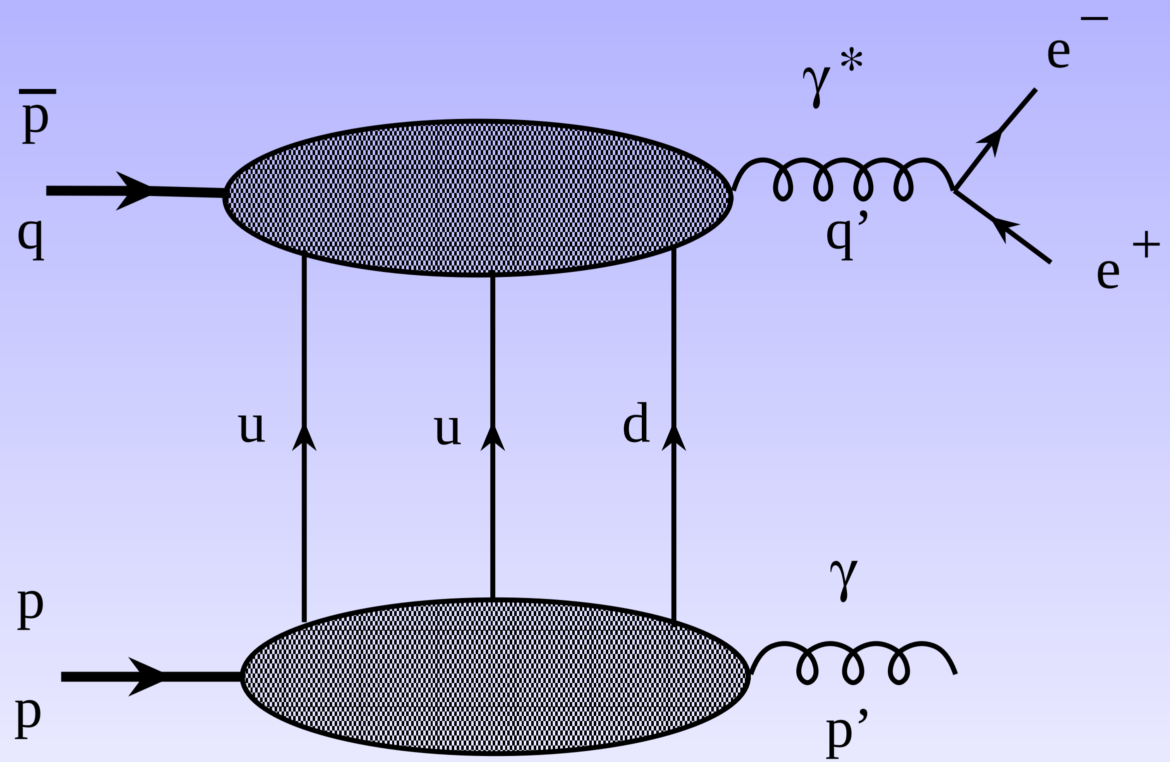
More problematic since 3 quark exchange !

BUT Remember : Baryon Form Facor factorizes in the same way as Meson Form Factor !

$$\longrightarrow \text{Factorization of the } p \longrightarrow \gamma \text{ TDA in } \bar{p}p \longrightarrow \gamma^*\gamma$$

This is NOT a proof ... Hope for a technical derivation

The factorization of $\bar{N}\ N \rightarrow \gamma^*\gamma$



Baryonic case, with $q\ q\ q$ exchange:

- Recall definition of Distribution Amplitudes

$$4\langle 0|\epsilon^{ijk}u^i_\alpha(z_1\,n)u^j_\beta(z_2\,n)d^k_\gamma(z_3\,n)|B(p,s)\rangle = f_N$$
$$V(\hat{p}\,C)_{\alpha\beta}(\gamma^5\,B)_\gamma + A(\hat{p}\,\gamma^5\,C)_{\alpha\beta}B_\gamma + T(p^\nu i\sigma_{\mu\nu}\,C)_{\alpha\beta}(\gamma^\mu\,\gamma^5\,B)_\gamma$$

$i, j, k =$ color indices $\qquad n =$ light cone + direction

- Define $p \to \pi$ Transition Distribution Amplitudes

$$4\langle \pi^0(p')|\,\epsilon^{ijk}u^i_\alpha(z_1\,n)u^j_\beta(z_2\,n)d^k_\gamma(z_3\,n)\,|p(p,s)\rangle =$$
$$\frac{-f_N}{2f_\pi}\Big[V^0_1(\hat{P}C)_{\alpha\beta}(B)_\gamma + A^0_1(\hat{P}\gamma^5C)_{\alpha\beta}(\gamma^5B)_\gamma -$$
$$3T^0_1(P^\nu i\sigma_{\mu\nu}C)_{\alpha\beta}(\gamma^\mu B)_\gamma\Big] + V^0_2(\hat{P}C)_{\alpha\beta}(\hat{\Delta}_T B)_\gamma +$$
$$A^0_2(\hat{P}\gamma^5C)_{\alpha\beta}(\hat{\Delta}_T\gamma^5B)_\gamma + T^0_2(\Delta^\mu_T P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(B)_\gamma$$
$$+T^0_3(P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\sigma^{\mu\rho}\Delta^\rho_T B)_\gamma + \frac{T^0_4}{M}(\Delta^\mu_T P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\hat{\Delta}_T B)_\gamma$$

$p \to \gamma$: parametrisation

$p \to \gamma$ (at Leading twist accuracy)

$\Delta_T = 0$: 4 TDAs

$(3 \times p(\downarrow) \to uud(\uparrow\uparrow\downarrow) + \gamma(\downarrow)$ and $p(\downarrow) \to uud(\downarrow\downarrow\downarrow) + \gamma(\uparrow))$

In the elm gauge $\varepsilon.n = 0$:

$$4\langle\gamma(p_\gamma)|\,\epsilon^{ijk}u^i_\alpha(z_1 n)u^j_\beta(z_2 n)d^k_\gamma(z_3 n)\,|p(p_1,s)\rangle = f_N \times$$

$$\Big[V_1^\varepsilon(x_i,\xi,\Delta^2)(\not{p}C)_{\alpha\beta}(\not{\varepsilon}N^+)_\gamma$$

$$+A_1^\varepsilon(x_i,\xi,\Delta^2)(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5\not{\varepsilon}N^+)_\gamma$$

$$+T_1^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\mu}C)_{\alpha\beta}(\sigma^{\mu\varepsilon}N^+)_\gamma$$

$$+T_2^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\varepsilon}C)_{\alpha\beta}(N^+)_\gamma\Big]$$

- **Fourier transform** each TDA, $\rightarrow$ momentum fractions representation

$$F(z_i P\cdot n) = \int_{-1+\xi}^{1+\xi} d^3x \delta(\sum x_i - 2\xi) e^{-iPn\Sigma x_i z_i} F(x_i, \xi, t, Q^2)$$

- **Factorize** process amplitude :

$$\mathcal{M}(Q^2, \xi, t) = \int dx dy \phi(y_i) T_H(x_i, y_i, Q^2) F(x_i, \xi, t)$$

$\phi =$ DA $\qquad\qquad F =$ TDA

Evolution equations

- QCD radiative corrections $\longrightarrow$ logarithmic scaling violations.

- The scale dependence of $N \rightarrow \pi$ or $N \rightarrow \gamma$ TDAs is governed by evolution equations = an extension of DGLAP/ERBL equations for DAs and GPDs

- Start with quark fields having definite chirality or helicity $q^{\uparrow(\downarrow)} = \frac{1}{2}\left(1 \pm \gamma^5\right) q$

- Separate "minus" components $\longrightarrow$ dominant twist-2 with $\hat{n} = n^\mu \gamma_\mu$

Evolution equations (2)

- Two relevant operators in our problem :

$$B^{1/2}_{\alpha\beta\gamma}(z_i) = \epsilon^{ijk}(\hat{n}q^{\uparrow}_i)_\alpha(z_1 n)(\hat{n}q^{\downarrow}_j)_\beta(z_2 n)(\hat{n}q^{\uparrow}_k)_\gamma(z_3 n)$$

$$B^{3/2}_{\alpha\beta\gamma}(z_i) = \epsilon^{ijk}(\hat{n}q^{\uparrow}_i)_\alpha(z_1 n)(\hat{n}q^{\uparrow}_j)_\beta(z_2 n)(\hat{n}q^{\uparrow}_k)_\gamma(z_3 n)$$

- They obey renormalisation group equation

$\mu\frac{d}{d\,\mu}\; B = H \cdot B$ with

$$H = -\frac{\alpha_s}{2\pi}\left[(1+1/N_c)\,H_h + 3C_F/2\right]$$

- $H_{3/2} = \mathcal{H}^v_{1\,2} + \mathcal{H}^v_{2\,3} + \mathcal{H}^v_{1\,3}$ with $\mathcal{H}^v_{1\,2}B(z_i) =$

$$-\int_0^1 \frac{d\alpha}{\alpha}\left\{\bar{\alpha}\left[B(z^\alpha_{1\,2}, z_2, z_3) - B(z_1, z_2, z_3)\right]\right.$$

$$\left. +\bar{\alpha}\left[B(z_1, z^\alpha_{2\,1}, z_3) - B(z_1, z_2, z_3)\right]\right\}$$

Evolution equations (3)

• $H_{1/2} = H_{3/2} - \mathcal{H}^e_{1\,2} - \mathcal{H}^e_{2\,3}$ where $\mathcal{H}^e_{1\,2} B(z_i) = \int\limits_0^1 d\alpha_1\, d\alpha_2\, d\alpha_3\, \delta(1-\alpha_1-\alpha_2-\alpha_3) B(z_{1\,2}^{\alpha_1}, z_{2\,1}^{\alpha_2}, z_3)$

• Derive the corresponding equation for the matrix element of operators B from the RGE

$$Q\frac{d}{dQ}\,F^{\uparrow\downarrow\uparrow}(x_i) = -\frac{\alpha_s}{2\pi}\left[\frac{3}{2}\,C_F\,F^{\uparrow\downarrow\uparrow}(x_i) - \left(1+\frac{1}{N_c}\right)\mathcal{A}\right]$$

$$\begin{aligned}
\mathcal{A} = \Bigg[\Bigg(&\int_{-1+\xi}^{1+\xi} dx_1' \left[\frac{x_1\rho(x_1',x_1)}{x_1'(x_1'-x_1)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx_2' \left[\frac{x_2\rho(x_2',x_2)}{x_2'(x_2'-x_2)}\right]_+\Bigg) F^{\uparrow\downarrow\uparrow}(x_1',x_2',x_3) \\
&+ \Bigg(\int_{-1+\xi}^{1+\xi} dx_1' \left[\frac{x_1\rho(x_1',x_1)}{x_1'(x_1'-x_1)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx_3' \left[\frac{x_3\rho(x_3',x_3)}{x_3'(x_3'-x_3)}\right]_+\Bigg) F^{\uparrow\downarrow\uparrow}(x_1',x_2,x_3') \\
&+ \Bigg(\int_{-1+\xi}^{1+\xi} dx_2' \left[\frac{x_2\rho(x_2',x_2)}{x_2'(x_2'-x_2)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx_3' \left[\frac{x_3\rho(x_3',x_3)}{x_3'(x_3'-x_3)}\right]_+\Bigg) F^{\uparrow\downarrow\uparrow}(x_1,x_2',x_3') \\
&+ \frac{1}{2\xi - x_3}\Bigg(\int_{-1+\xi}^{1+\xi} dx_1' \frac{x_1}{x_1'}\rho(x_1',x_1) + \int_{-1+\xi}^{1+\xi} dx_2' \frac{x_2}{x_2'}\rho(x_2',x_2)\Bigg) F^{\uparrow\downarrow\uparrow}(x_1',x_2',x_3) \\
&+ \frac{1}{2\xi - x_1}\Bigg(\int_{-1+\xi}^{1+\xi} dx_2' \frac{x_2}{x_2'}\rho(x_2',x_2) + \int_{-1+\xi}^{1+\xi} dx_3' \frac{x_3}{x_3'}\rho(x_3',x_3)\Bigg) F^{\uparrow\downarrow\uparrow}(x_1,x_2',x_3')\Bigg]\Bigg\}
\end{aligned}$$

- with integration region restricted by:
$\rho(x, y) = \theta(x \geq y \geq 0) - \theta(x \leq y \leq 0)$,
and $x'_i \in [-1 + \xi, 1 + \xi]$

- Different evolution in the various x_i sectors.
When $x_i > 0 \longrightarrow$ usual ERBL ($x_i \longrightarrow x_i/2\xi$ rescaling).

- Other regions need further study !

Interpretation

- The proton **DA** selects the valence contribution and analyses it from large angle scattering (and Form Factors)

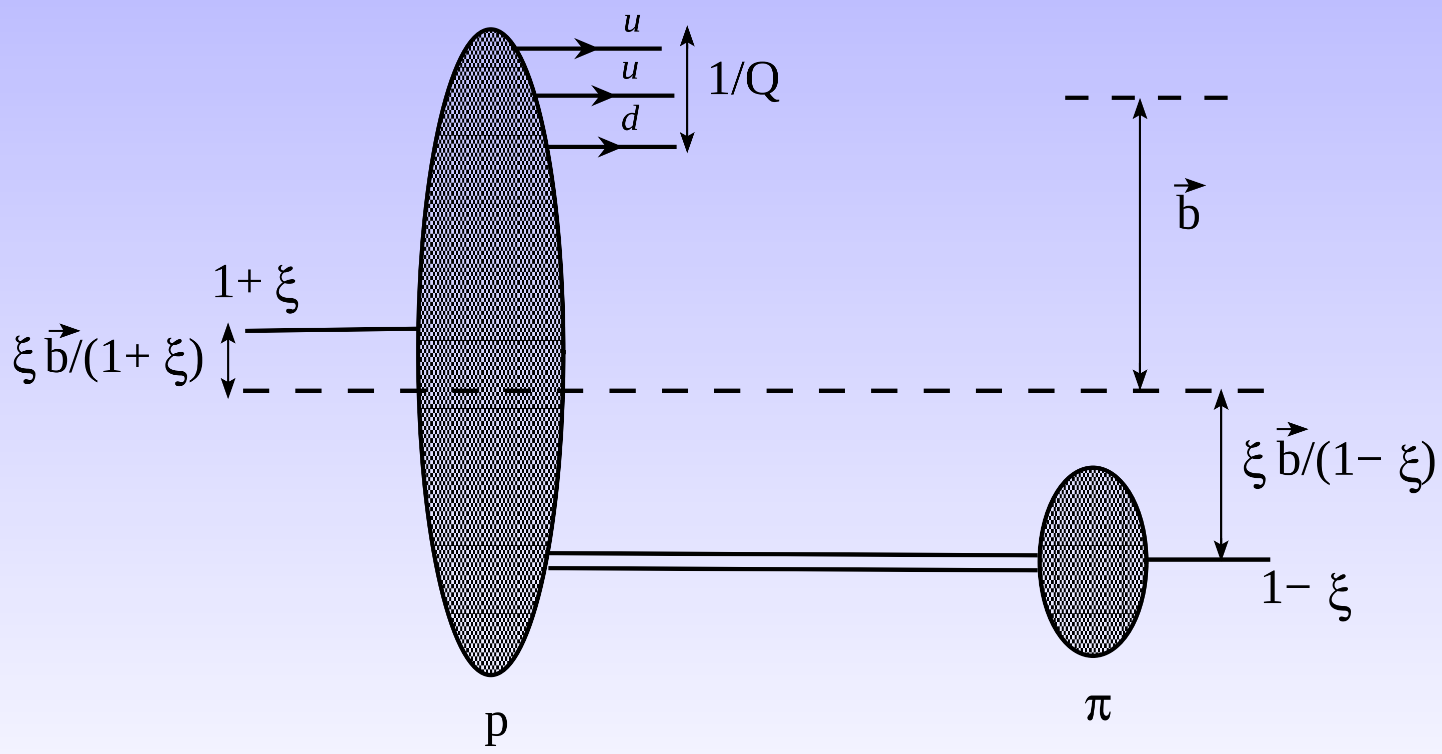
- The proton $\longrightarrow \pi$ **TDA** allows a pion (cloud) around the valence contribution.

- The proton $\longrightarrow \gamma$ **TDA** allows a photon (cloud) around the valence contribution.

- The proton $\longrightarrow \rho$ **TDA**...

Impact parameter interpretation

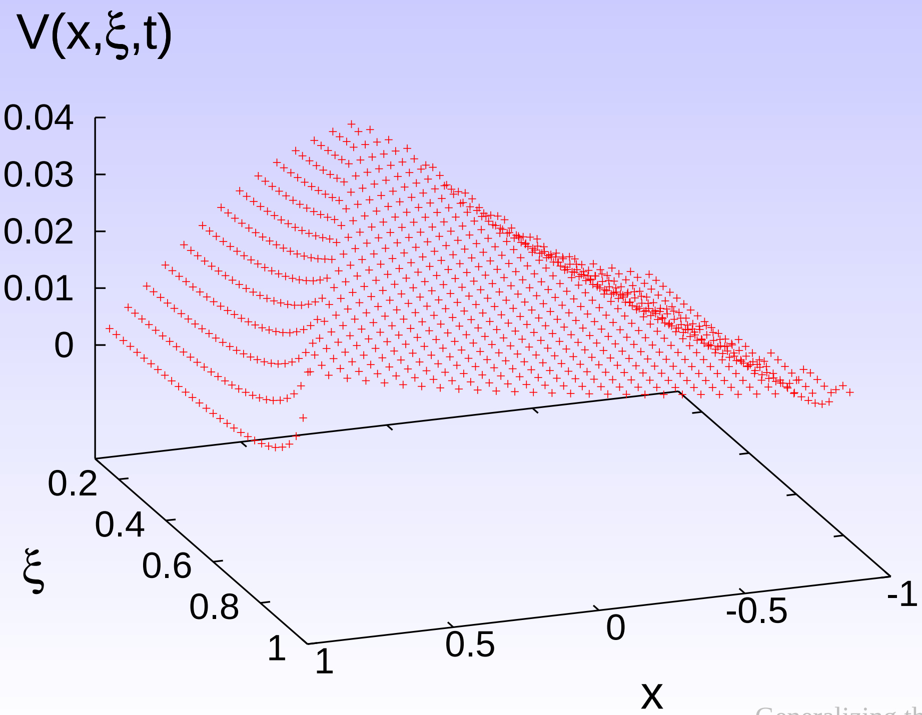
- As for GPDs and GDAs, Fourier transform $t \rightarrow \mathbf{b}$
- Transverse picture of *pion cloud* in the proton



Constructing models for TDAs

- $M \to \gamma$

- double distributions as in GPDs case
- Quark model Tiburzi 2005
- NJL-model Noguera 2006



Constructing models for TDAs

- $p \longrightarrow \gamma$ and $p \longrightarrow \pi$

• quadruple distributions (generalization of DD for GPD)

• $\xi \longrightarrow 1$ “soft limits”

$p \longrightarrow \gamma$ Low thm

$p \longrightarrow \pi$ chiral limit

CHIRAL LIMIT of $p \to \pi$ TDA

- Soft pion theorems$\to$

$$< \pi^a(k)|O|P(p,s) >= \frac{-i}{f_\pi} < 0|[Q_5^a, O]|P(p,s) >$$

$$+ \frac{ig_A}{4 f_\pi p\cdot k} \sum_{s'} \bar{u}(p,s)\hat{k}\gamma_5 \tau^a u(p,s') < 0|O|P(p,s') >$$

1st term $\to$ TDA at threshold ; 2nd term $\to$ nucleon pole.

- Since $[Q_5^b, \psi] = i\frac{\tau^b}{2}\gamma^5\psi$

CHIRAL LIMIT ($\xi \to 1$)

$$
\begin{aligned}
V_1^0(x_1, x_2, x_3) &\to V(z_1, z_2, z_3) \\
&= \left(\phi_N(z_i) + \phi_N(z_2, z_1, z_3)\right)/2
\end{aligned}
$$

$$
\begin{aligned}
A_1^0(x_1, x_2, x_3) &\to A(z_1, z_2, z_3) \\
&= \frac{1}{2}\left(\phi_N(z_i) - \phi_N(z_2, z_1, z_3)\right) \\
T_1^0(x_i) \to T(z_i) &= \frac{1}{2}\left(\phi_N(z_i) + \phi_N(z_2, z_3, z_1)\right)
\end{aligned}
$$

where $z_i = x_i/2$

$\phi_N(z_1, z_2, z_3) =$ standard leading twist DA

Example of a hard part:
$\bar{p}p \longrightarrow \gamma^*\pi$ **or** $\gamma^*\gamma$

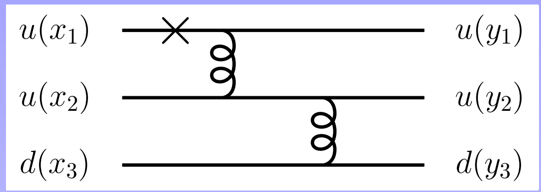
- **Recall factorized amplitude :**

$$\mathcal{M}(Q^2, \xi, t) = \int dx dy \phi(y_i) T_H(x_i, y_i, Q^2) F(x_i, \xi, t)$$

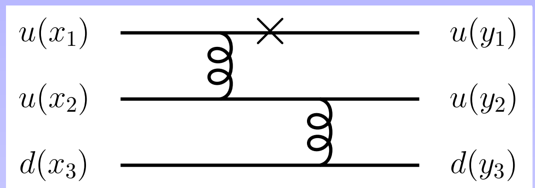
$\phi =$ DA of $\bar{p}$ $\quad$ $F =$ TDA for $p \rightarrow \pi$ or γ

- Calculate hard part $T_H(x_i, y_i, Q^2)$

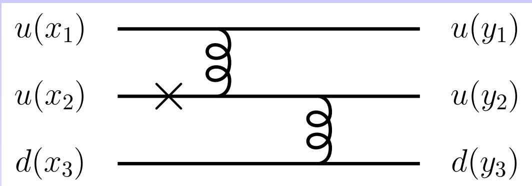
T_H for example $\bar{p}p \to \gamma^\star \pi^0$ at $\Delta_T = 0$



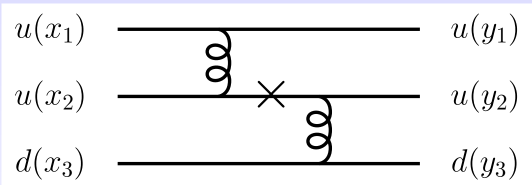
$$\frac{4}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_3+i\epsilon)(1-y_1)^2 y_3}$$



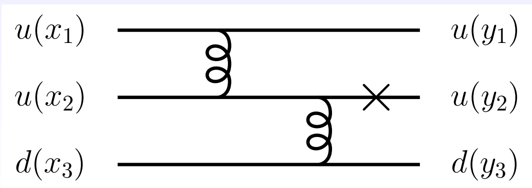
$$0$$



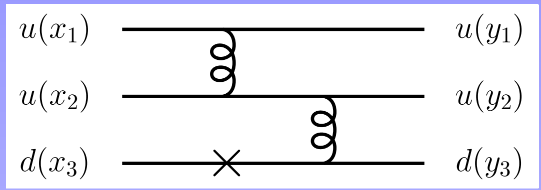
$$-\frac{4}{3}\frac{\mathcal{T}}{(x_1+i\epsilon)(2\xi-x_2+i\epsilon)(x_3+i\epsilon)y_1(1-y_2)y_3}$$



$$\frac{4}{3}\frac{\mathcal{V}}{(x_1+i\epsilon)(2\xi-x_3+i\epsilon)(x_3+i\epsilon)y_1(1-y_1)y_3}$$



$$-\frac{4}{3}\frac{\mathcal{V}}{(x_2+i\epsilon)(2\xi-x_3+i\epsilon)(x_3+i\epsilon)y_2(1-y_1)y_3}$$



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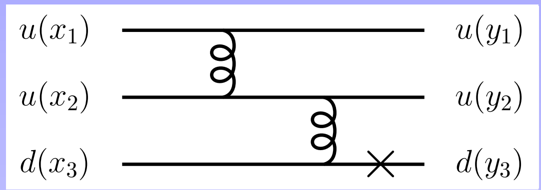
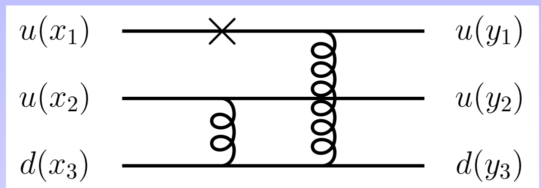


$$-\frac{2}{3}\frac{\mathcal{V}}{(2\xi-x_3+i\epsilon)^2(1-y_3)^2}\left(\frac{1}{(x_1+i\epsilon)y_1}+\frac{1}{(x_2+i\epsilon)y_2}\right)$$



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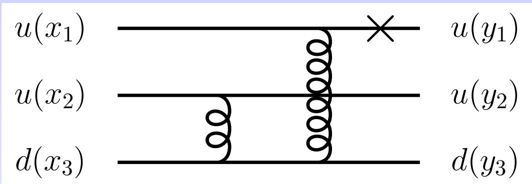
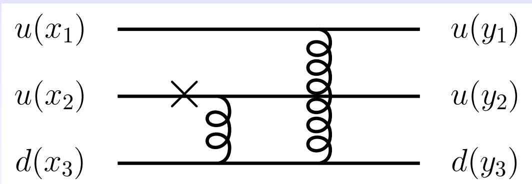
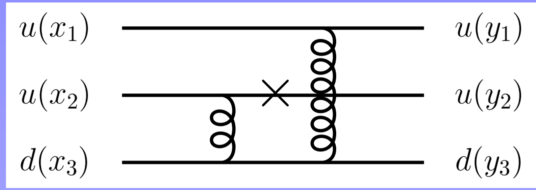


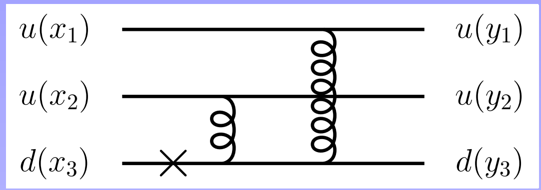
$$\frac{2}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_2+i\epsilon)(1-y_1)^2y_2}$$



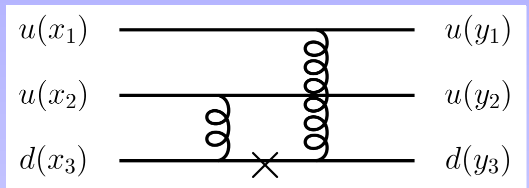
$$\frac{2}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_2+i\epsilon)(1-y_1)^2y_2}$$



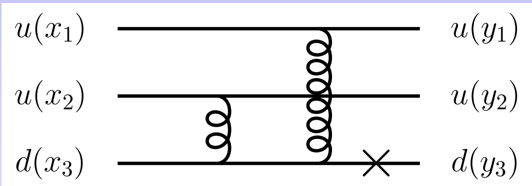
$$0$$



$$\frac{1}{3}\,\frac{\mathcal{V}}{(x_1+i\epsilon)(x_2+i\epsilon)(2\xi-x_3+i\epsilon)y_1(1-y_1)y_2}$$



$$-\frac{1}{3}\,\frac{\mathcal{T}}{(x_1+i\epsilon)(2\xi-x_1+i\epsilon)(x_2+i\epsilon)y_1(1-y_2)y_2}$$



$$\frac{1}{3}\,\frac{\mathcal{V}}{(x_1+i\epsilon)(x_2+i\epsilon)(2\xi-x_1+i\epsilon)x_3y_1y_2(1-y_3)}$$

$$\mathcal{M}^\mu \quad = \quad -ie_p\bar{v}(k,\lambda)\gamma^\mu\gamma^5u(p,s)\frac{f_N^2}{2f_\pi}\frac{(4\pi\alpha_S(Q^2))^2}{54\,Q^4}\int\limits_{1+\xi}^{-1+\xi}d^3x\int\limits_0^1 d^3y\sum_{\alpha=1}^{14}T_\alpha(x_i,y_j)$$

with $\mathcal{V}(x_j,y_i,\xi,t)=[V(y_i)-A(y_i)]\cdot[V_1(x_j,\xi,t)-A_1(x_j,\xi,t)]$ $\mathcal{T}(x_j,y_i,\xi,t)=-12[T(y_i)].[T_1(x_j,\xi,t)]$.

To test these ideas: Model-independent predictions for $\gamma^* p \to p\pi, p\gamma$ and $p\bar{p} \to \gamma^* \pi, \gamma^* \gamma$

- scaling law for the amplitudes :

$\mathcal{M}(Q^2, \xi) \sim \frac{\alpha_s(Q^2)^2}{Q^4}$, (up to logarithmic corrections).

- Ratios :

$$\frac{\mathcal{M}(\gamma^* p \to p\pi)}{\mathcal{M}(\gamma^* p \to p\gamma)}, \frac{\mathcal{M}(\gamma^* p \to p\gamma)}{\mathcal{M}(\gamma^* p \to p)} \text{ and } \frac{d\sigma(\bar{p}p \to l^+ l^- \pi^0)/dQ^2}{d\sigma(\bar{p}p \to l^+ l^-)/dQ^2}$$

almost Q^2 independent.

- γ^*_T dominates $\rightarrow \frac{d\sigma(p\bar{p} \to l^+ l^- \pi)}{\sigma d\theta} \sim 1 + cos^2\theta$

(θ = lepton angle in γ^* CMS)

QCD factorization implies the universality of TDAs

$\longrightarrow$ the same TDAs appear in the electroproduction and in the $\bar{p}p$ processes

• $\bar{p}p \to \gamma^*\gamma \quad \leftrightarrow \quad$ backward VCS $\gamma^* P \to P'\gamma$

• $\bar{p}p \to \gamma^*\pi$ or $\gamma^*\rho \quad \leftrightarrow$
backward meson electroproduction $\gamma^* P \to P'\pi$;
or $\gamma^* P \to P'\rho$ ...

Data exist (JLab) for Q^2 up to 1 GeV^2.
JLb @ 12 GeV $\to Q^2 > 1$GeV^2

Data from HERMES ?

CONCLUSIONS

- Backward VCS and backward meson electroproduction factorizable
- TDAs are a new tool to understand the deep structure of the proton
- Transition Distribution Amplitudes will reveal the dynamics of the *next to lowest* Fock state
- $\bar{p}p \longrightarrow \gamma^*\pi$ and $\gamma^*p \longrightarrow p\pi$ explore the pion cloud.
- $\bar{p}p \longrightarrow \gamma^*\rho$ and $\gamma^*p \longrightarrow p\rho$ explore the ρ cloud.
- $\bar{p}p \longrightarrow \gamma^*\gamma$ and $\gamma^*p \longrightarrow p\gamma$ explore the photon cloud.
- Detectors should be ready to measure these reactions at FAIR and JLab@12 GeV
- If *Polarized* beam and target $\longrightarrow$ spin structure too!
- NOT SO SMALL CROSS-SECTIONS AND BIG REWARDS. More work needed ...