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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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TDAs: a new tool to study exclusive reactions

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TDAs : a new tool to study exclusive reactions

Conference on Perspectives in Hadronic Physics
22-26 May 2006, ICTP Trieste Italy

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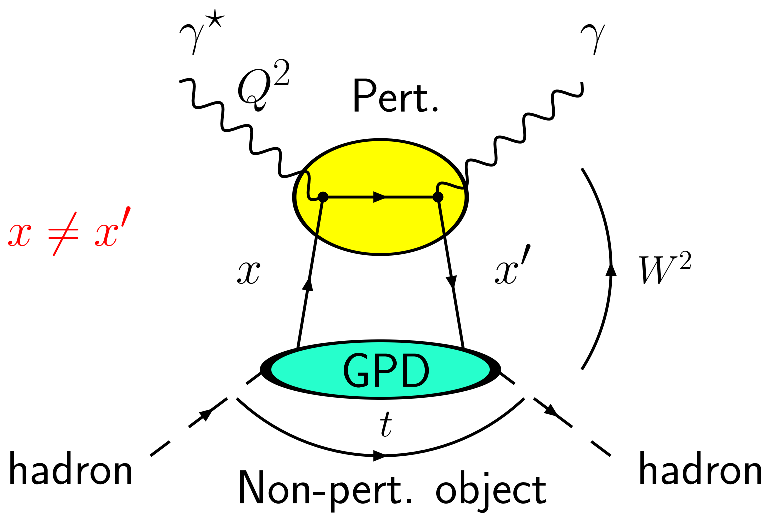
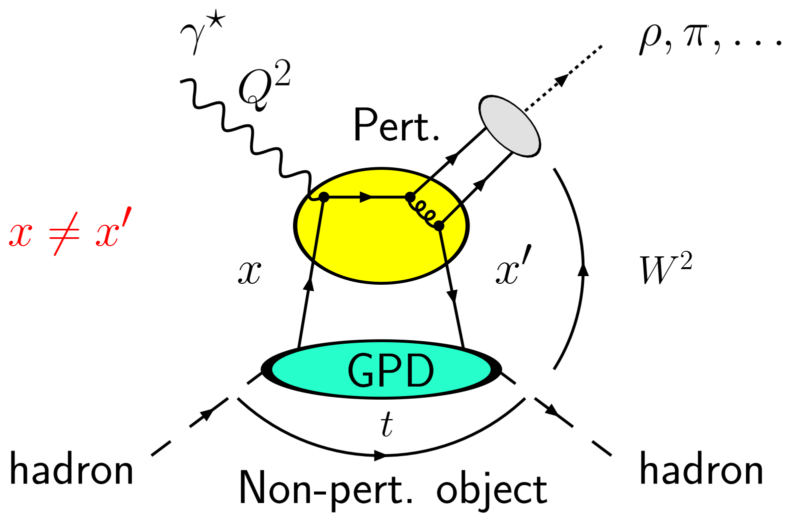
in collaboration with B. Pire and L. Szymanowski

Reminder on Generalised Parton Distributions

DVCS



Mesons Production



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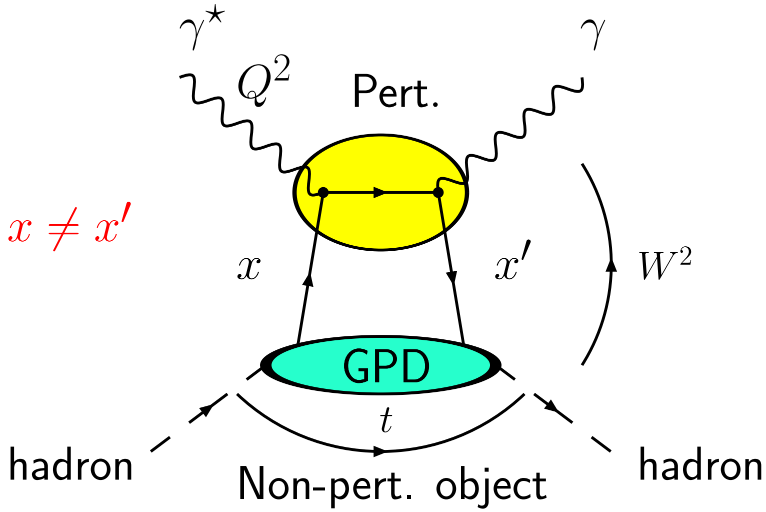

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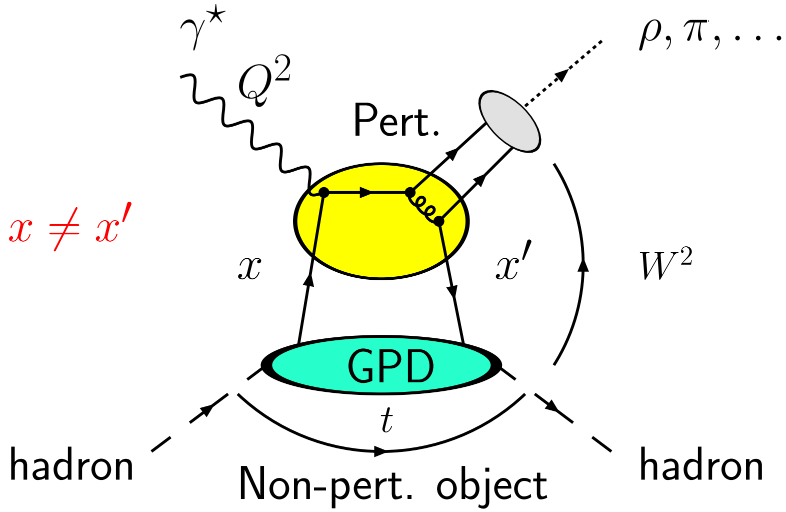

➯ Factorisation between the hard part (perturbatively calculable) and the soft part (non-perturbative) demonstrated for

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

TDAs : transition distribution amplitudes

B. Pire, L. Szymanowski, PRD 71 :111501,2005 ; PLB 622 :83,2005.

➫ For $u \ll$ DVCS, the non-perturbative part does not describe anymore a $H \to H$ transition, but rather

a hadron-photon or baryon-meson transition.

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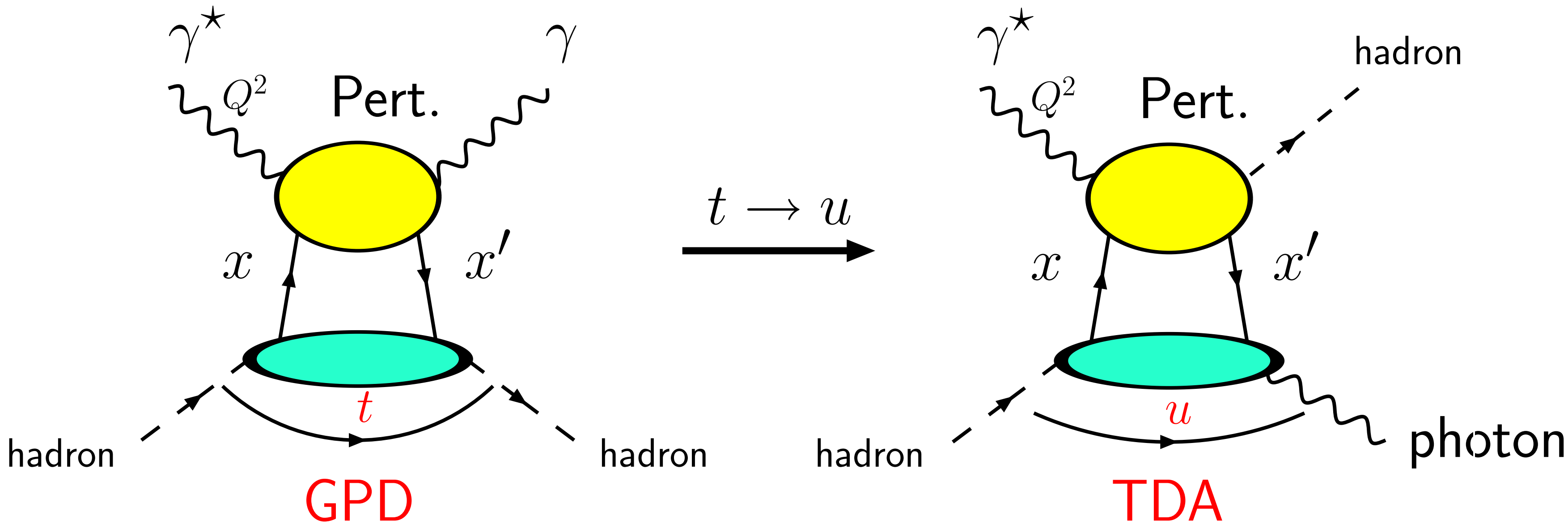

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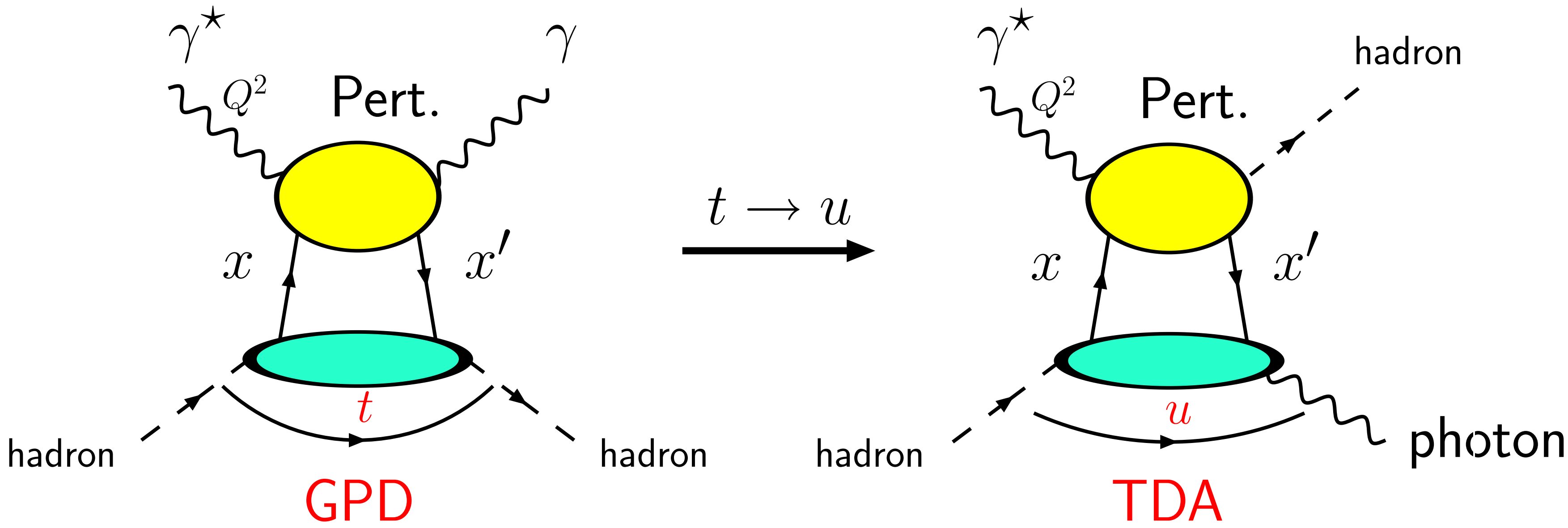
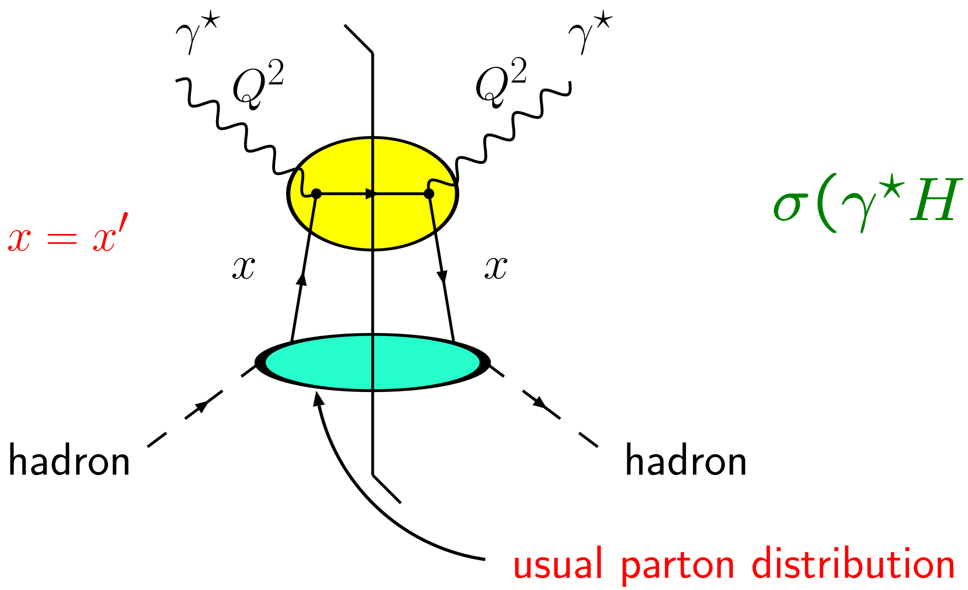


➩ The same occurs in $p\bar{p} \to \gamma\gamma^\star$ reactions at $t \ll$ (GSI)

➩ and in $\gamma\gamma^\star \to \pi\pi$ reactions at $t \ll$ (through e^+e^- collisions)

GPD in terms of *usual* parton distributions



$$\sigma(\gamma^\star H \to X) \propto \Im m(\mathcal{A}^{diag}(\gamma^\star H \to \gamma^\star H))$$

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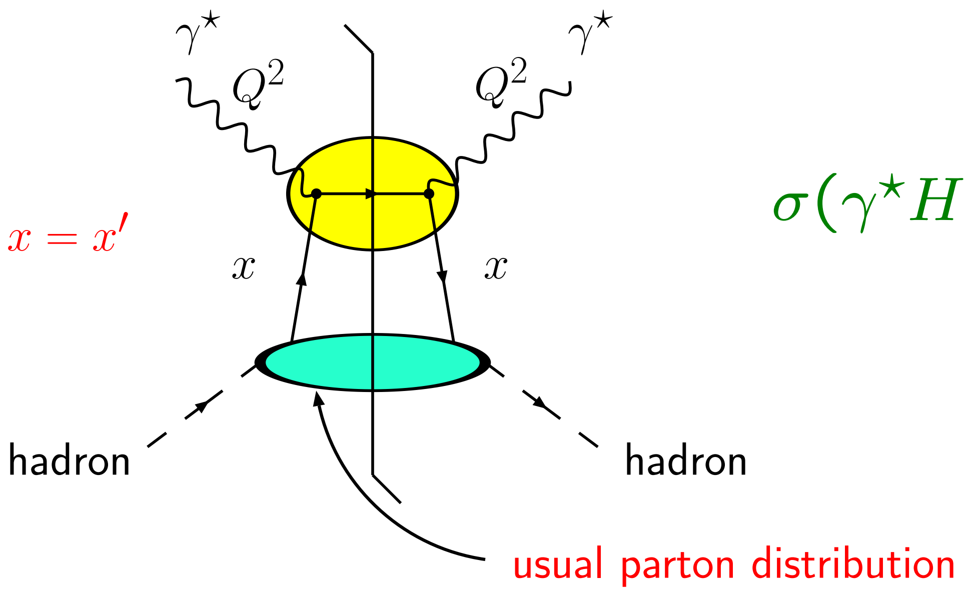

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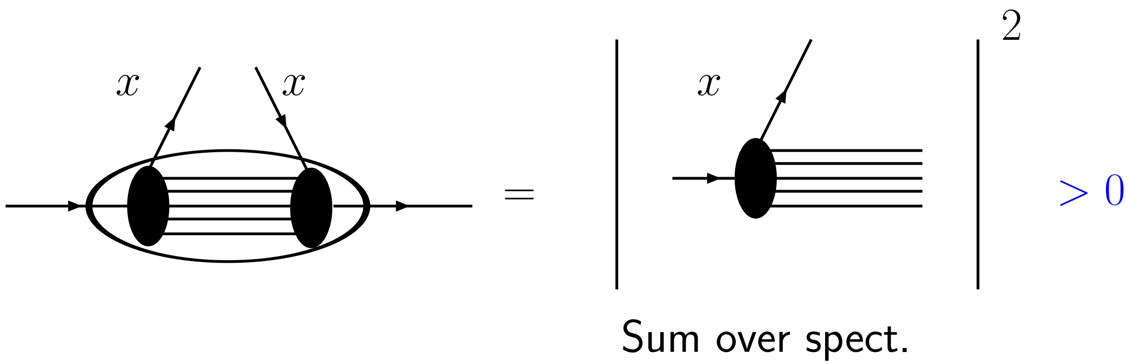
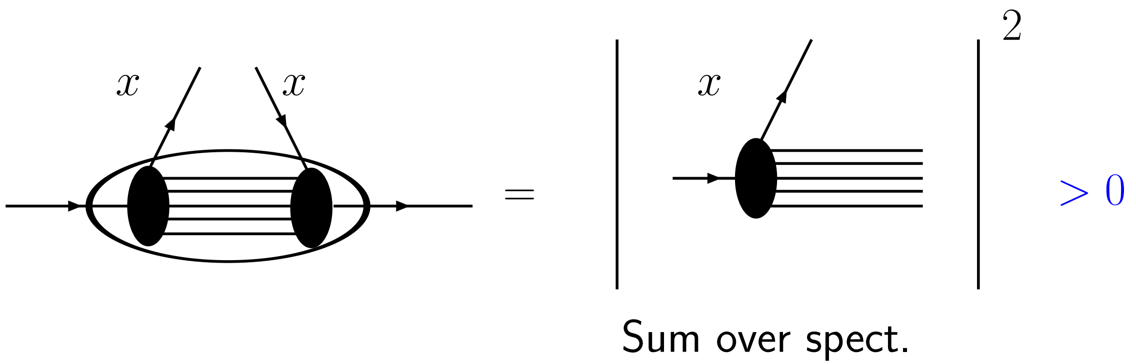


➾ The PDFs give the probability to find, within the hadron, a parton with a momentum fraction x.

GPD in terms of *usual* parton distributions



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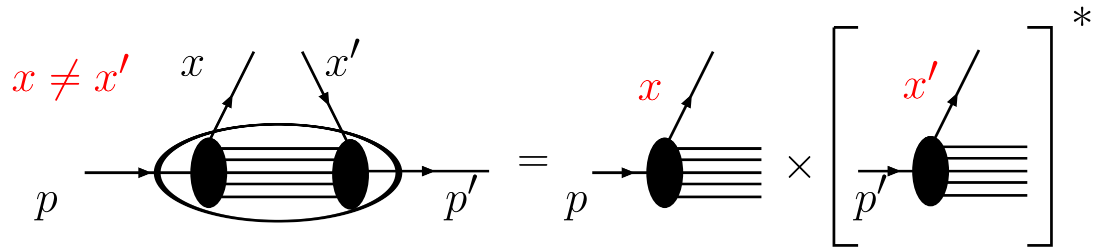
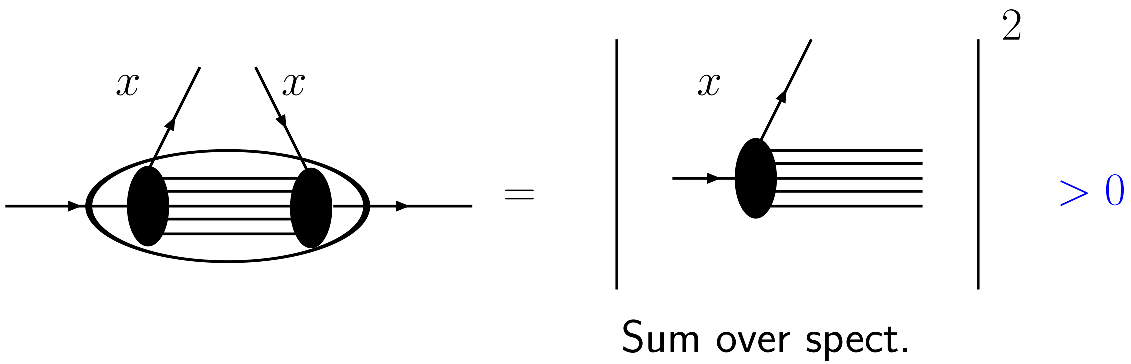


➩ The GPDs possess an interpretation at the amplitude level and provide with information about correlations between quarks



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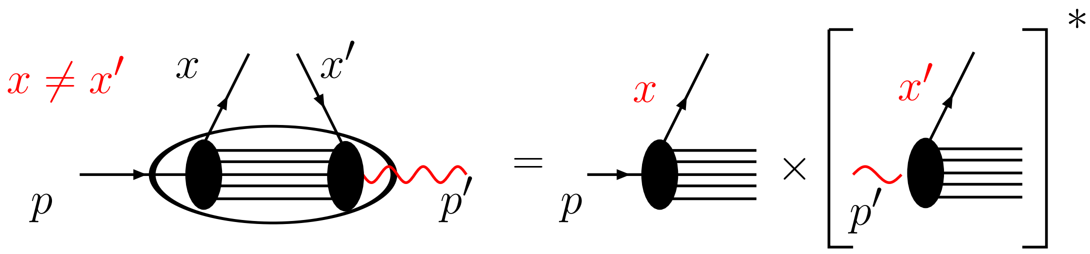
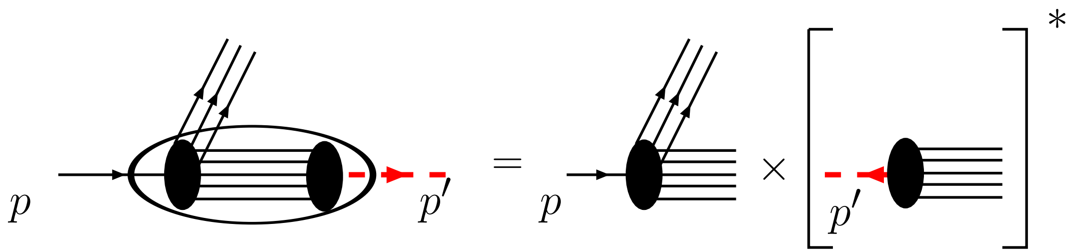
Interpretation of the TDAs



➾ The mesonic TDAs possess an interpretation at the amplitude level and provide with information on how a meson looks like photon

whereas



➾ The baryonic TDAs rather provide information on how one can find a meson or a photon in it

TDAs vs GPDs : meson case

	GPDs	TDAs
Matrix elements	$\langle M(p')\vert\Phi^\dagger(z)\Phi(0)\vert M(p)\rangle$	$\langle\gamma(p',\varepsilon)\vert\Phi^\dagger(z)\Phi(0)\vert M(p)\rangle$
Diagonal limit $\xi \to 0$, $t \to 0$	**GPDs $\to$ PDFs** $H^q(x,0,0) = q(x)$	**N/A**
Sum rules : $\int dx$ $\to$ local operator	$\int dx H(x,\xi,t) = F(t)$	$\int dx T(x,\xi,t) = F_{A\to B}(t)$

➯ **In view of the sum rules, both GPDs and TDAs are such that their integral on x is independent of ξ !**

➟ **possible modelling of the TDAs through double distributions (cf. Radyushkin)**

Example : $\gamma \rightarrow \pi$ TDAs

JPL, B. Pire, L. Szymanowski, PRD 73 :074014,2006.

There are 4 leading-twist helicity amplitudes for $\gamma \rightarrow q\bar{q}\pi$

$\rightarrow$ 4 TDAs : A, V, T_1 and T_2

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p_{\pi^-}) | \bar{d}(-\frac{z}{2})[..]\gamma^\mu u(\frac{z}{2}) | \gamma(p_\gamma, \varepsilon)\rangle \Big|_{z^+=0,\, z_T=0} = \frac{1}{P^+}\frac{i\,e}{f_\pi}\epsilon^{\mu\varepsilon P \Delta_\perp} V^{\pi^-}(x,\xi,t)$$

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p_{\pi^-}) | \bar{d}(-\frac{z}{2})[..]\gamma^\mu \gamma^5 u(\frac{z}{2}) | \gamma(p_\gamma, \varepsilon)\rangle \Big|_{z^+=0,\, z_T=0} = \frac{1}{P^+}\frac{e}{f_\pi}(\varepsilon\cdot\Delta) P^\mu A^{\pi^-}(x,\xi,t),$$

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p_{\pi^-}) | \bar{d}(-\frac{z}{2})[..]\sigma^{\mu\nu} u(\frac{z}{2}) | \gamma(p_\gamma, \varepsilon)\rangle \Big|_{z^+=0,\, z_T=0}$$
$$= \frac{e}{P^+}\epsilon^{\mu\nu\rho\sigma} P_\sigma \Big[\varepsilon_\rho T_1^{\pi^-}(x,\xi,t) - \frac{1}{f_\pi}(\varepsilon\cdot\Delta)\Delta_{\perp\rho} T_2^{\pi^-}(x,\xi,t)\Big]$$

Example : $\gamma \to \pi$ TDAs

➯ Sum Rules :

➠ $\pi^{\pm}$: $$\int_{-1}^{1} dx \begin{Bmatrix} A^{\pi^{\pm}} \\ V^{\pi^{\pm}} \end{Bmatrix} (x,\xi,t) = \frac{f_\pi}{m_\pi} F^{\pi^{\pm}}_{\left\{ {A \atop V} \right\}}(t)$$

F_A et F_V are measured (cf. PDG)

➠ π^0 : $$\int_{-1}^{1} dx \left(Q^u\, V_u^{\pi^0}(x,\xi,t) + Q^d\, V_d^{\pi^0}(x,\xi,t) \right) = f_\pi\, F_{\pi^0 \gamma^\star \gamma}(t)$$

NB : Sum rule for A^{π^0}
$\to \pi^0 \to Z^0\gamma \to \nu\bar{\nu}\gamma$ **(not measurable) or**
$\to \pi^0 \to Z^0\gamma \to \ell^+\ell^-\gamma$ **(with huge background from the electromagnetic process) ;**

Example : $\gamma \to \pi$ TDAs

For $G = (A, V)$, $G^{(0)}(x,\xi) \equiv \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(x-\beta-\xi\alpha) f(\beta,\alpha)$ with $f(\beta,\alpha) = q(\beta)h(\beta,\alpha)$

and a profile function $h^{(b)}(\beta,\alpha) = \dfrac{\Gamma(2b+2)}{2^{2b+1}\Gamma^2(b+1)} \dfrac{[(1-|\beta|)^2-\alpha^2]^b}{(1-|\beta|)^{2b+1}}$.

(b characterises the strength of the ξ−dependence.)

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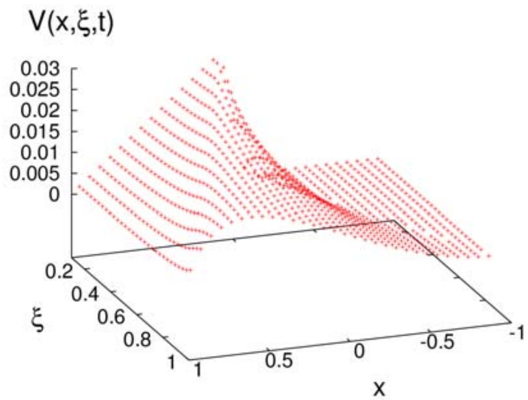
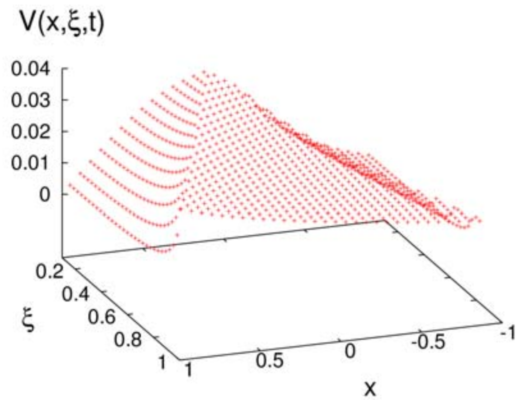
The t-dependence is implemented to get the sum rule :

$$G(x,\xi,t) = G^{(0)}(x,\xi) \cdot \frac{f_\pi}{m_\pi} F_G(t)\ .$$

Setting $b = 1$ and taking the β−dependence of q to be $q(\beta) = 2\,(1-\beta)\,\theta(\beta)$.

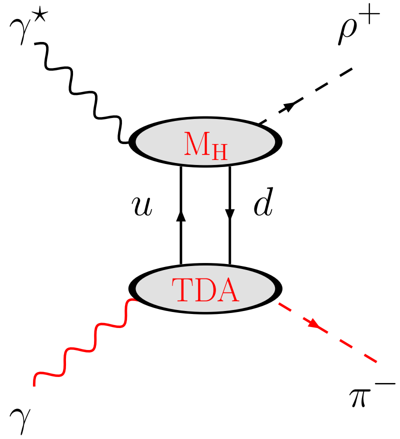


This Model (1)



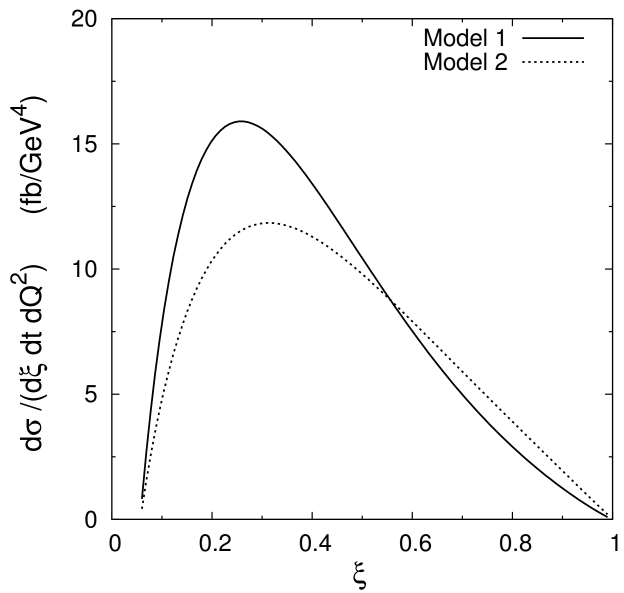
Tiburzi's Model (2)

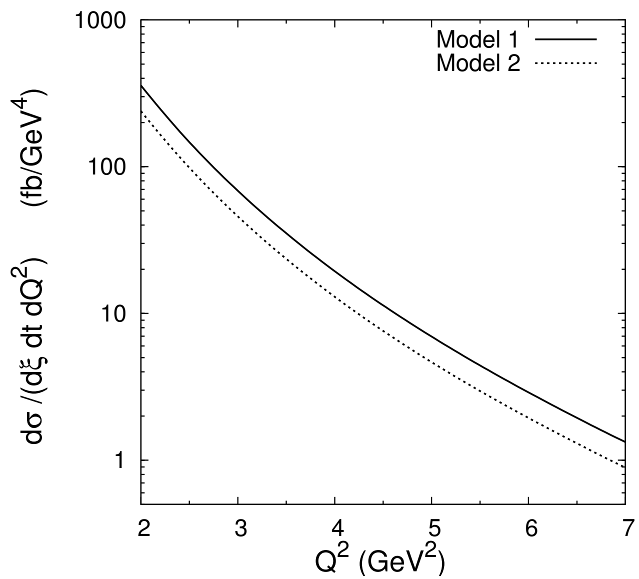
$\gamma \rightarrow \pi$ TDAs :Application



- $\rho - \pi$ pair production at small t
  - cross section for $e\ \gamma \rightarrow e'\rho\ \pi$
  - π flies in the direction of the γ
    ($\leftrightarrow \sim 180^\circ$ between ρ and π or large W)
  - Complementary kinematics compared to GDAs
  - No Bremßtrahlung

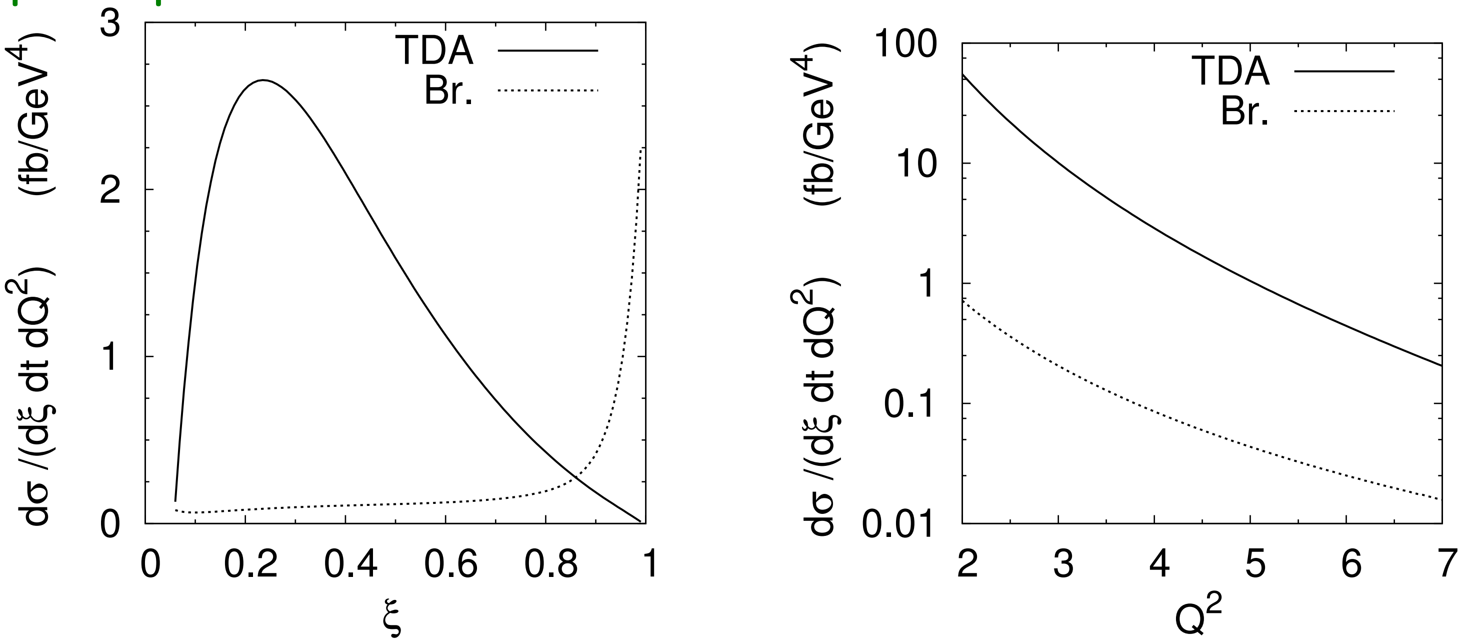
$s_{e\gamma} = 40$ GeV^2, $t = -0.5$ GeV^2, $Q^2 = 4$ GeV^2 and $\xi = 0.2$





$\gamma \to \pi$ TDAs :Application

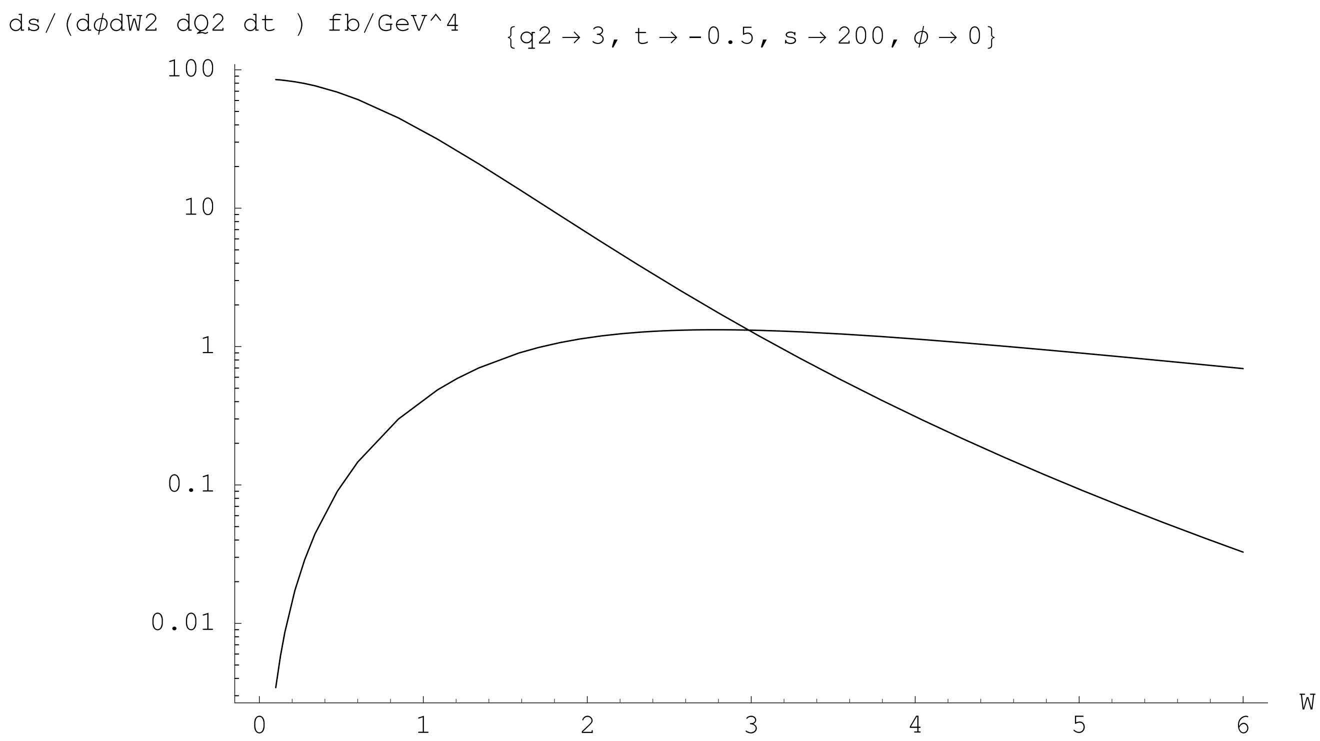
➡ $\pi - \pi$ pair production at small t



➡ Any measurement of $e\gamma \to e'\pi^0\pi^0$ would provide with information on the Axial Transition Form factor $F_A^{\pi^0}$.

TDAs vs GDAs

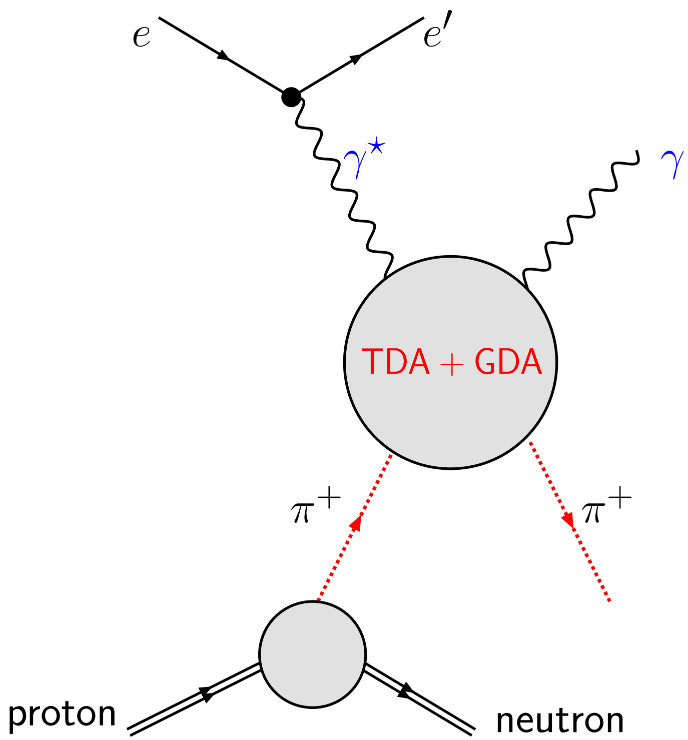
➠ **Expected behaviour :** $\dfrac{\sigma_{TDA}}{\sigma_{GDA}} \longrightarrow \dfrac{t}{Q^2}\dfrac{W^2}{Q^2}$



DVCS on pion

➩ **To be analysed by HERMES through :** $ep \to e'\gamma\pi^+ n$

- ➟ **Non-trivial kinematics ; DVCS subset of** $2 \to 4$ **process**
- ➟ **Cannot trivially distinguish between the small** t **(GPD) and small** u **(TDA) regions**



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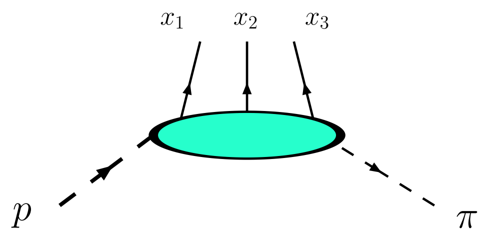
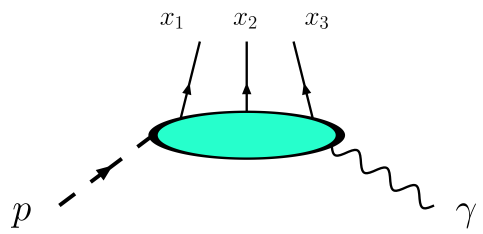


proton $\rightarrow \pi$



proton $\rightarrow \gamma$

➯ More than the two regions ERBL and DGLAP

➯ In principle, one has Sum rules

$\rightarrow$ ξ-independence of the moments of the TDA

- ➠ Triple distributions ?
- ➠ Diquark picture and double distribution ?

would suit some regions only ?

➯ Closest object : Baryon Distribution Amplitude : $\rightarrow$ SOFT LIMIT ?

$p \longrightarrow \pi$: parametrisation

➡ $p \longrightarrow \pi$ **(at Leading twist accuracy)**

➟ $\Delta_T = 0$ **: 3 TDAs** ($3 \times p(\uparrow) \to uud(\uparrow\uparrow\downarrow) + \pi$)

(similar to Baryon DAs)

TDA	**DA**
$4\langle \pi^0 \vert\, \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n)\, \vert p\rangle \propto$	$4\langle 0 \vert \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n) \vert p\rangle \propto$
$\Big[V_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\, C)_{\alpha\beta}(N)_\gamma +$	$\Big[V(x_i)(\not{p}C)_{\alpha\beta}(\gamma^5 N)_\gamma +$
$A_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\, \gamma^5 C)_{\alpha\beta}(\gamma^5 N)_\gamma - 3$	$A(x_i)(\not{p}\gamma^5 C)_{\alpha\beta} N_\gamma +$
$T_1^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\rho P} C)_{\alpha\beta}(\gamma^\rho N)_\gamma \Big]$	$T(x_i)(i\sigma_{\rho p}\, C)_{\alpha\beta}(\gamma^\rho \gamma^5 N)_\gamma \Big]$

$p \longrightarrow \pi$: parametrisation

- $p \longrightarrow \pi$ **(at Leading twist accuracy)**
  - $\Delta_T = 0$ **: 3 TDAs** ($3 \times p(\uparrow) \to uud(\uparrow\uparrow\downarrow) + \pi$)

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TDA

$$4\langle \pi^0 | \, \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n) \, |p\rangle \propto \Big[V_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\, C)_{\alpha\beta}(N)_\gamma + A_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\,\gamma^5 C)_{\alpha\beta}(\gamma^5 N)_\gamma - 3\, T_1^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\rho P} C)_{\alpha\beta}(\gamma^\rho N)_\gamma \Big]$$

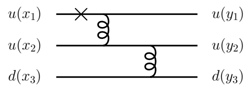
DA

$$4\langle 0 | \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n) |p\rangle \propto \Big[V(x_i)(\not{p} C)_{\alpha\beta}(\gamma^5 N)_\gamma + A(x_i)(\not{p}\gamma^5 C)_{\alpha\beta} N_\gamma + T(x_i)(i\sigma_{\rho p}\, C)_{\alpha\beta}(\gamma^\rho \gamma^5 N)_\gamma \Big]$$

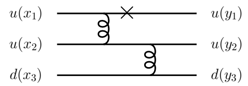
  - $\Delta_T \neq 0$ **: 8 TDAs** ($\frac{1}{2} \times 2 \times (2 \times 2 \times 2) \times 1$)

$$\begin{aligned} 4\langle \pi^0(p_\pi) | \, \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n) \, | p(p_1, s)\rangle &= -\frac{f_N}{2 f_\pi} \times \\ \Big[V_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\, C)_{\alpha\beta}(N)_\gamma &+ V_2^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\, C)_{\alpha\beta}(\not{\Delta}_T N)_\gamma \\ + A_1^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\,\gamma^5 C)_{\alpha\beta}(\gamma^5 N)_\gamma &+ A_2^{\pi^0}(x_i,\xi,\Delta^2)(\not{P}\,\gamma^5 C)_{\alpha\beta}(\not{\Delta}_T \gamma^5 N)_\gamma \\ -3 T_1^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\rho P} C)_{\alpha\beta}(\gamma^\rho N)_\gamma &+ T_2^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\Delta_T P} C)_{\alpha\beta}(N)_\gamma \\ + T_3^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\mu P} C)_{\alpha\beta}(\sigma^{\mu \Delta_T} N)_\gamma &+ T_4^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{\Delta_T P} C)_{\alpha\beta}(\not{\Delta}_T N)_\gamma \Big] \end{aligned} \quad (1)$$

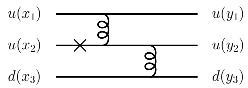
$\bar{p}p \longrightarrow \gamma^\star \pi^0$ at $\Delta_T = 0$



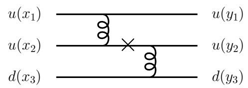
$$\frac{4}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_3+i\epsilon)(1-y_1)^2 y_3}$$



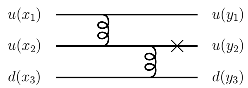
$$0$$



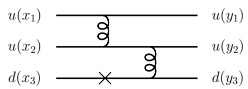
$$-\frac{4}{3}\frac{\mathcal{T}}{(x_1+i\epsilon)(2\xi-x_2+i\epsilon)(x_3+i\epsilon)y_1(1-y_2)y_3}$$



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



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



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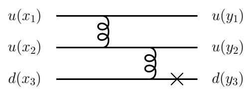
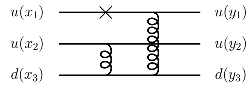
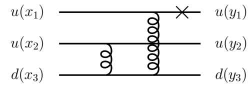


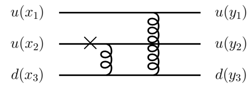
$$-\frac{2}{3}\frac{\mathcal{V}}{(2\xi-x_3+i\epsilon)^2(1-y_3)^2}\left(\frac{1}{(x_1+i\epsilon)y_1}+\frac{1}{(x_2+i\epsilon)y_2}\right)$$



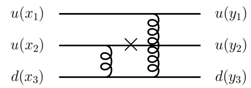
$$0$$



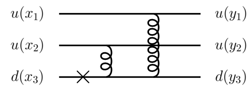
$$\frac{2}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_2+i\epsilon)(1-y_1)^2 y_2}$$



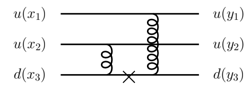
$$\frac{2}{3}\frac{\mathcal{V}+\mathcal{T}}{(2\xi-x_1+i\epsilon)^2(x_2+i\epsilon)(1-y_1)^2 y_2}$$



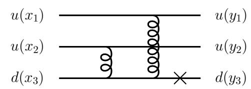
$$0$$



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



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



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

$$\mathcal{M}^\mu \;=\; -ie_p\bar{v}(k,\lambda)\gamma^\mu\gamma^5 u(p,s)\frac{f_N^2}{2f_\pi}\frac{(4\pi\alpha_S(Q^2))^2}{54\,Q^4}\int_{1+\xi}^{-1+\xi} d^3x \int_0^1 d^3y \sum_{\alpha=1}^{14} T_\alpha(x_i,y_j) \tag{2}$$

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

$p \longrightarrow \gamma$: parametrisation

➭ $p \longrightarrow \gamma$ (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 $\varepsilon.n = 0$:

$$4\langle\gamma(p_\gamma)|\,\epsilon^{ijk}u^i_\alpha(z_1 n)u^j_\beta(z_2 n)d^k_\gamma(z_3 n)\,|p(p_1,s)\rangle = f_N \times$$
$$\Big[V_1^\varepsilon(x_i,\xi,\Delta^2)(\not p C)_{\alpha\beta}(\not\varepsilon N^+)_\gamma$$
$$+A_1^\varepsilon(x_i,\xi,\Delta^2)(\not p\gamma^5 C)_{\alpha\beta}(\gamma^5\not\varepsilon N^+)_\gamma$$
$$+T_1^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\mu}C)_{\alpha\beta}(\sigma^{\mu\varepsilon}N^+)_\gamma$$
$$+T_2^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\varepsilon}C)_{\alpha\beta}(N^+)_\gamma\Big]$$

$p \to \gamma$: 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 $\varepsilon.n = 0$:

$$
\begin{aligned}
4\langle\gamma(p_\gamma)|\,\epsilon^{ijk}u^i_\alpha(z_1 n)u^j_\beta(z_2 n)d^k_\gamma(z_3 n)\,|p(p_1,s)\rangle = f_N \times \\
\Big[V_1^\varepsilon(x_i,\xi,\Delta^2)(\not{p}C)_{\alpha\beta}(\not{\varepsilon}N^+)_\gamma \\
+A_1^\varepsilon(x_i,\xi,\Delta^2)(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5\not{\varepsilon}N^+)_\gamma \\
+T_1^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\mu}C)_{\alpha\beta}(\sigma^{\mu\varepsilon}N^+)_\gamma \\
+T_2^\varepsilon(x_i,\xi,\Delta^2)(\sigma_{p\varepsilon}C)_{\alpha\beta}(N^+)_\gamma\Big]
\end{aligned}
$$

➟ $\Delta_T \neq 0$ 16 TDAs ($\frac{1}{2} \times 2 \times (2 \times 2 \times 2) \times 2$)

$$
\begin{aligned}
&4\langle\gamma(p_\gamma)|\,\epsilon^{ijk}u^i_\alpha(z_1 n)u^j_\beta(z_2 n)d^k_\gamma(z_3 n)\,|p(p_1,s)\rangle = f_N \times \\
&\Big[V_1^T(\varepsilon.\Delta_T)(\not{p}C)_{\alpha\beta}(N^+)_\gamma + V_1^\varepsilon(\not{p}C)_{\alpha\beta}(\not{\varepsilon}N^+)_\gamma + V_2^T(\varepsilon.\Delta_T)(\not{p}C)_{\alpha\beta}(\not{\Delta}_T N^+)_\gamma + V_2^\varepsilon(\not{p}C)_{\alpha\beta}(\sigma^{\Delta_T\varepsilon}N^+)_\gamma + \\
&A_1^T(\varepsilon.\Delta_T)(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5 N^+)_\gamma + A_1^\varepsilon(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5\not{\varepsilon}N^+)_\gamma + A_2^T(\varepsilon.\Delta_T)(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5\not{\Delta}_T N^+)_\gamma + A_2^\varepsilon(\not{p}\gamma^5 C)_{\alpha\beta}(\gamma^5\sigma^{\Delta_T\varepsilon}N^+)_\gamma + \\
&T_1^T(\varepsilon.\Delta_T)(\sigma_{p\mu}C)_{\alpha\beta}(\gamma^\mu N^+)_\gamma + T_1^\varepsilon(\sigma_{p\mu}C)_{\alpha\beta}(\sigma^{\mu\varepsilon}N^+)_\gamma + T_2^T(\varepsilon.\Delta_T)(\sigma_{p\mu}C)_{\alpha\beta}(\sigma^{\mu\Delta_T}N^+)_\gamma + T_2^\varepsilon(\sigma_{p\varepsilon}C)_{\alpha\beta}(N^+)_\gamma + \\
&T_3^T(\varepsilon.\Delta_T)(\sigma_{p\Delta_T}C)_{\alpha\beta}(N^+)_\gamma + T_3^\varepsilon(\sigma_{p\Delta_T}C)_{\alpha\beta}(\not{\varepsilon}N^+)_\gamma + T_4^T(\varepsilon.\Delta_T)(\sigma_{p\Delta_T}C)_{\alpha\beta}(\not{\Delta}_T N^+)_\gamma + T_4^\varepsilon(\sigma_{p\varepsilon}C)_{\alpha\beta}(\not{\Delta}_T N^+)_\gamma\Big]
\end{aligned}
$$

Conclusions

- **Transition Distribution Amplitudes**

  give new information on hadrons

- **Need non-perturbative inputs**

- **Need precise data expected from**
  - **GSI**
  - **JLab**
  - **Hermes**
  - B**-factories**