The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1751 - 2

Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Hard Exclusive Reactions and Hadron Structure: Some New Results

B. PIRE
Ecole Polytechnique
CPHT
Route de Saclay
F-91128 Palaiseau Cedex
FRANCE

Hard exclusive reactions and hadron structure : some new results

B. Pire and L. Szymanowski

École Polytechnique, Palaiseau, Universite de Liège and Soltan Inst. for Nucl. Studies, Warsaw

.

Based on work in collaboration with

I. Anikin, R. Enberg, J.Ph Lansberg, O. Teryaev and S. Wallon

ICTP- Perspectives in hadronic physics - May 22nd, 2006

Factorization of Hard Exclusive processes

• DIS : INCLUSIVE / Large vs Short distance $\longrightarrow$
Stucture Function =Pert. Coef. Funct. $\times$ Parton dist.

• DVCS : EXCLUSIVE $\gamma^* \ N \ \longrightarrow \ \gamma \ N'$
$\longrightarrow$ Amplitude =Pert. Coef. Funct. $\times$ GPD
Generalized Parton Distributions

• Deep EXCLUSIVE meson production
Amplitude =Pert. Coef. Funct. $\times$ GPD $\times$ DA

• CROSSING $\longrightarrow$ $\gamma^*\gamma \longrightarrow M_1 \ M_2$ near threshold
Amplitude =Pert. Coef. Funct. $\times$ GDA
Generalized Distribution Amplitude

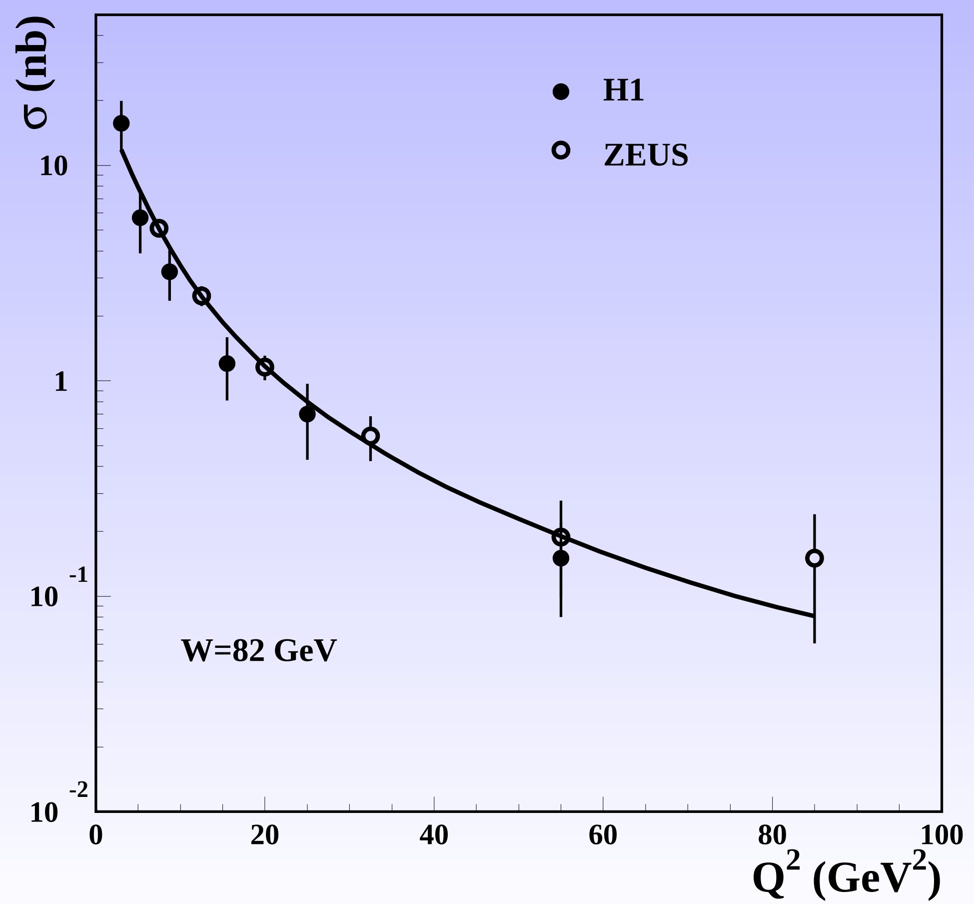
Successes of Factorized framework

• Consistent picture in QCD
Evolution Equations interpolate between DGLAP (e.g. for structure functions) and ERBL (e.g. for form-factors) equations

• SCALING, e.g.
handbag dominance $\equiv$ (generalized) Bjorken scaling

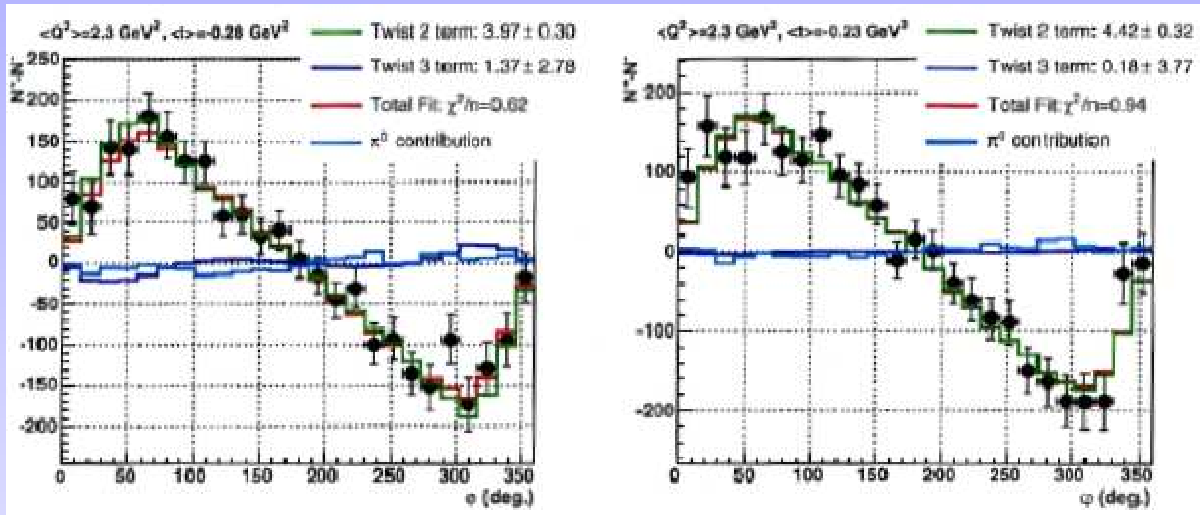
Successes of Factorized framework

• Right order of magnitudes with experimental results, for DVCS (Guzey + Polyakov 2005)

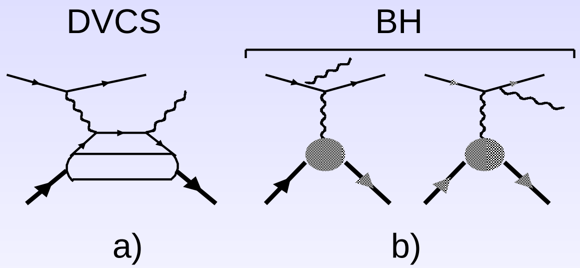


Successes of Factorized framework

• Angular dependence of asymmetries coming from Bethe Heitler / DVCS interference



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



Generalized Parton Distributions

• *Non forward* Matrix elements of non-local light-cone operators, e.g. for a nucleon

$$\langle N(p,\lambda)|\bar{\psi}(-z/2)\Gamma[-z/2;z/2]\psi(z/2)|N'(p',\lambda')\rangle$$
$$\Gamma = \gamma_\mu \ , \quad \gamma_\mu\gamma^5 \ , \quad \sigma_{\mu\,\nu}$$

• Fourier Transform + Decomposition $\longrightarrow$ 8 GPDs :

chiral even:

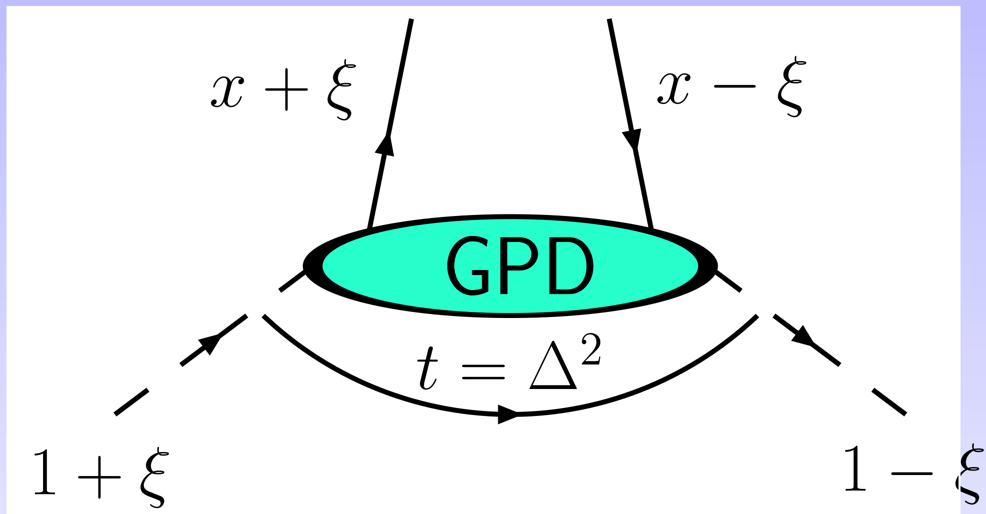
$H(x,\xi,t), E(x,\xi,t), \tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

chiral odd:

$H_{Ti}(x,\xi,t), i = 1,..,4$ (transversity)

Kinematics:

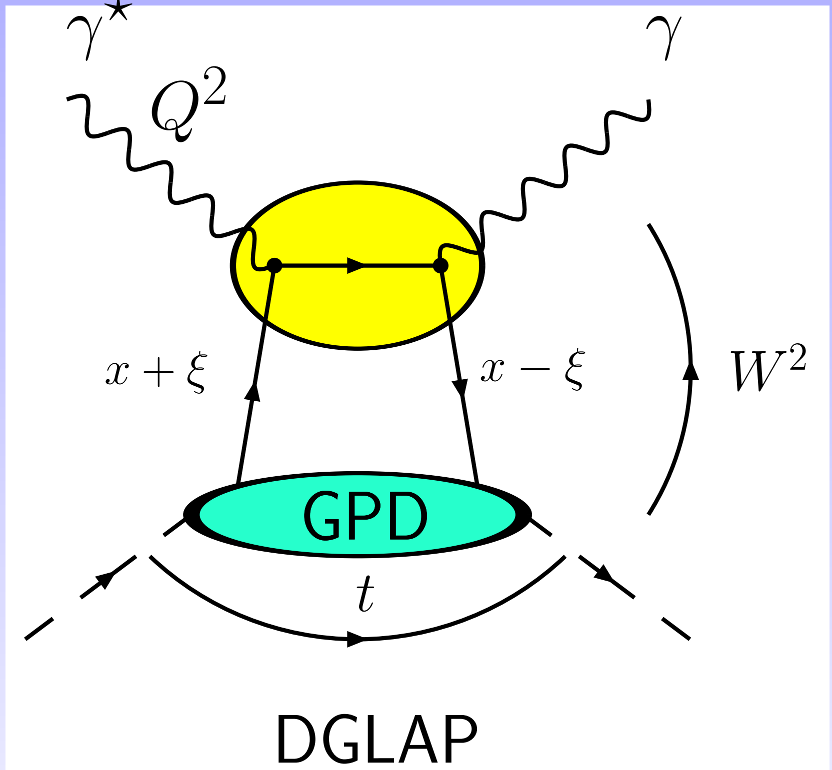
• Notation: $\rightarrow \Delta^+ = -2\xi P^+$
$(2P = p + p', \Delta = p' - p)$ ξ = skewedness

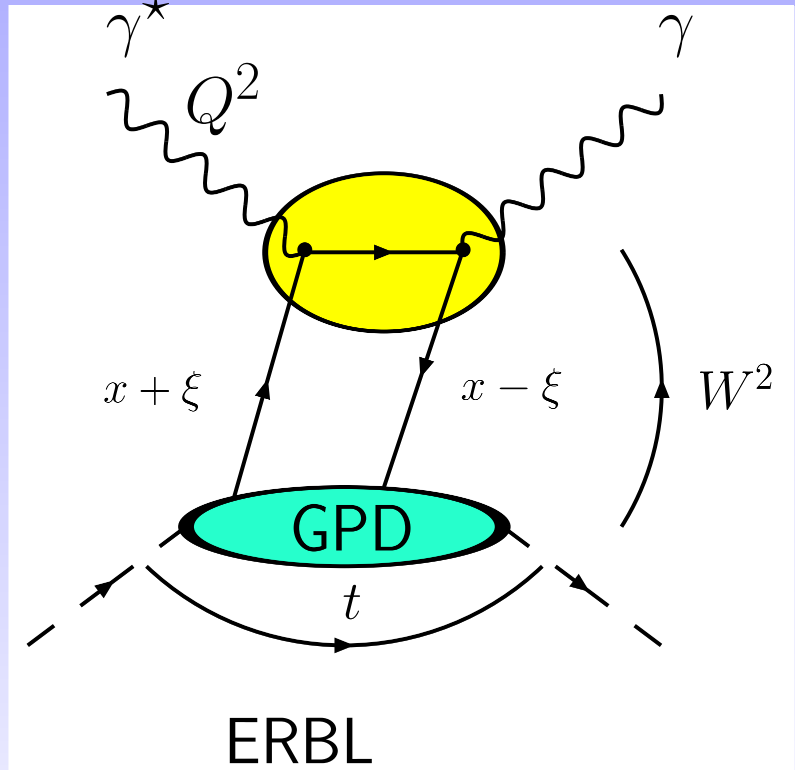


• $\Delta^2 = t << Q^2$ $\quad t-$dependence parametrized as in Form Factors

Properties of Generalized Parton Distributions

- Two quite distinct regions : $x > \xi$: DGLAP
$x < \xi$: ERBL





- Limits at zero skewedness $\longrightarrow$ Usual parton dist.

Properties of Generalized Parton Distributions

- First $x-$moment $\longrightarrow$ Form Factors (ξ independent), e.g.

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

- Second $x-$moment $\longrightarrow$ Spin Sum Rule (through energy-momentum tensor), e.g.

$$2\langle J_q^3\rangle = \int_{-1}^{1} dx \; x \; [H_q(x, \xi, t=0) + E_q(x, \xi, t=0)]$$

Properties of Generalized Parton Distributions

- Lorentz invariance $\longrightarrow$ Polynomiality ($\longrightarrow$ Double distributions), e.g.

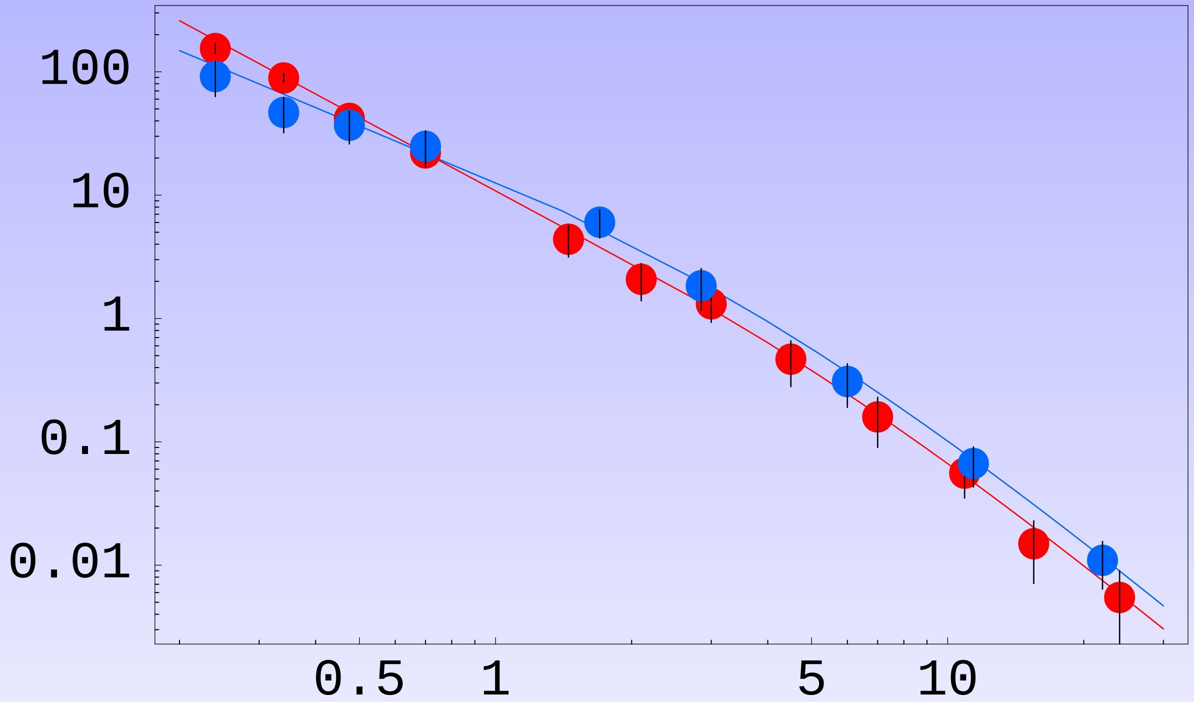
$$\int_{-1}^{1} dx\, x^n\, H^q(x,\xi,t) = \sum_{i=0}^{n} (2\xi)^i A^q_{n+1,i}(t) + \text{'D-term'}$$

- Positivity constraints in DGLAP region, e.g.

$$|H^q_\pi(x,\xi,t)| \leq \sqrt{q_\pi(\frac{x+\xi}{1+\xi}).q_\pi(\frac{x-\xi}{1-\xi})}$$

When do we access the factorization regime ?

- dVCS $\longrightarrow$ wait for experimental talks today ...
- crossed process $\longrightarrow$ LEP2 data : EARLY SCALING

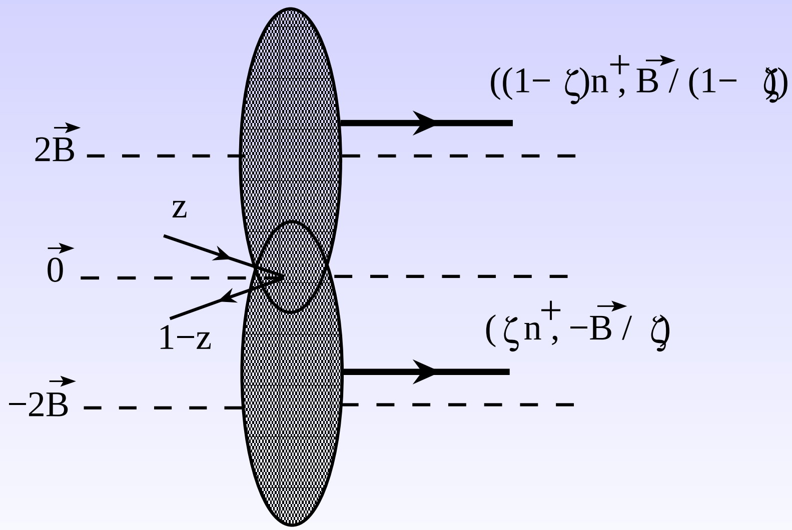


Q^2 dependence of $\gamma^*\gamma \longrightarrow \rho^+\rho^-$ and $\gamma^*\gamma \longrightarrow \rho^0\rho^0$

blue red

Impact picture Representation

• t dependence of GPDs maps transverse position of quarks in proton.
Fourier transform GPD at zero skewedness
$q(x, b_T) = (2\pi)^{-2} \int d^2\Delta e^{i\Delta.b} H(x, \xi = 0, t)$
Generalize at $\xi \neq 0 \rightarrow$ *Quantum femtophotography*.
• W^2 dependence of $\gamma^*\gamma \rightarrow M_1\ M_2$ maps impact representation of hadronization.



Some new results

- Transversity GPDs

- Searching for EXOTIC HADRONS

- Describing other processes through TDAs
$\bar{N}N \to \gamma^*\gamma$ and $\bar{N}N \to \gamma^*\pi$

Transversity GPDs

Transversity dependent quark distribution $h_1(x) \rightarrow$
4 transversity GPDs

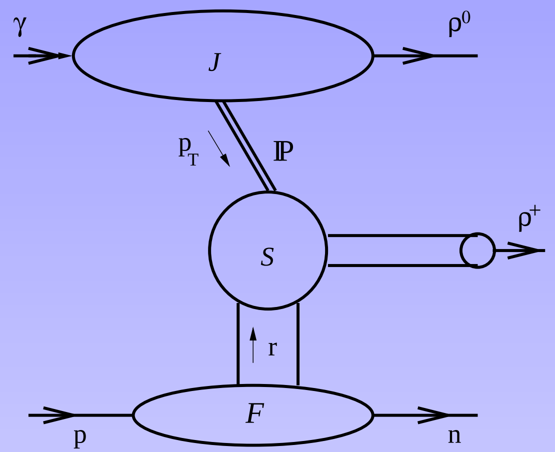
• How to access them ?

Chiral odd functions come in pairs ->
try electroproduction of ρ_T

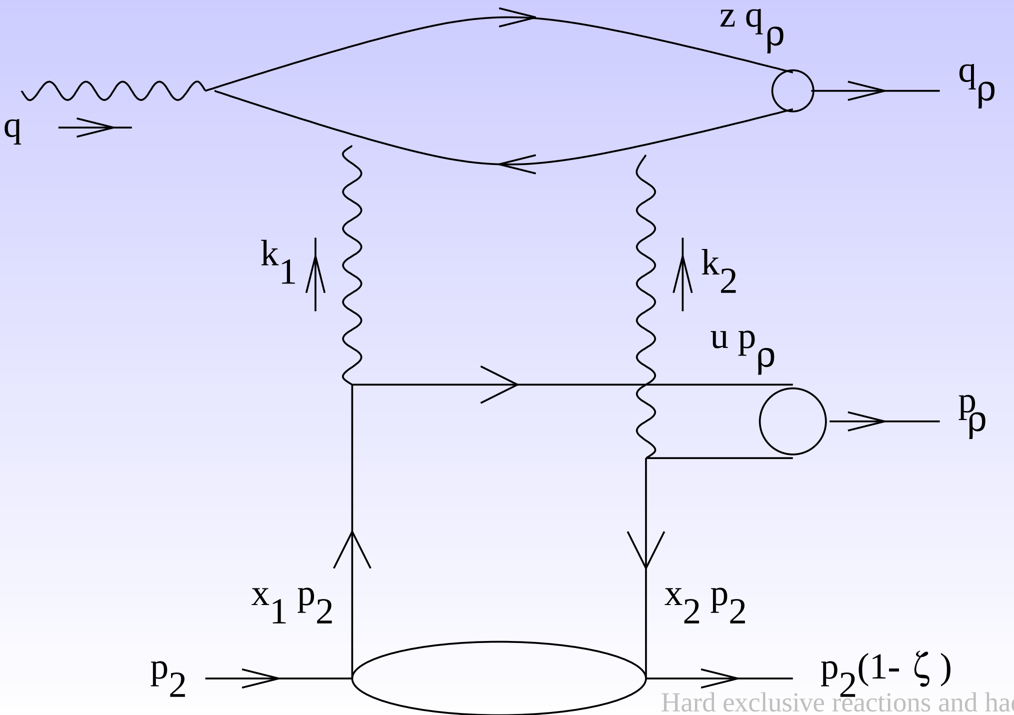
•BUT *zero* amplitude for $\gamma^* N \rightarrow \rho_T N'$:
use Pomeron analog

$\mathcal{P} N \rightarrow \rho_T N'$ *i.e.* $\gamma^* N \rightarrow \rho_L \rho_T N'$

Transversity GPDs



IP =2 gluons, at Born order 6 diagrams, e.g.

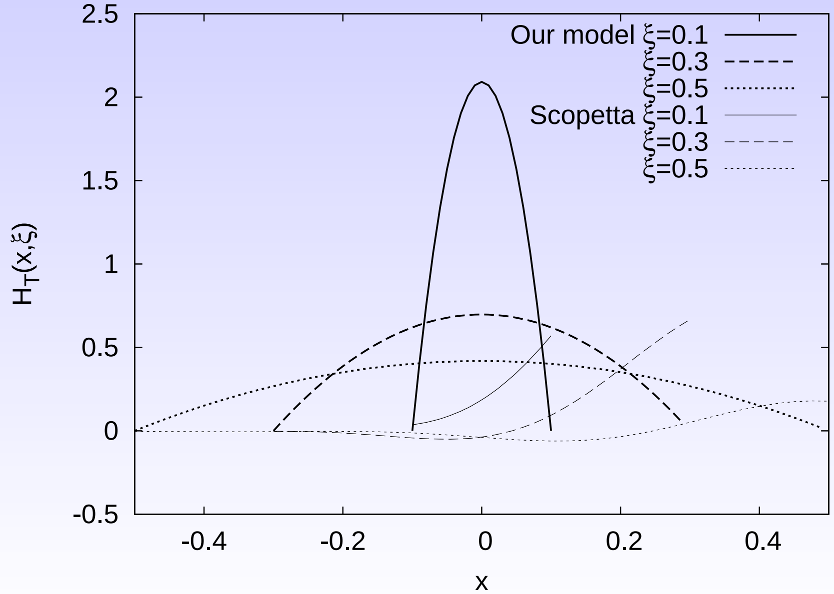


Models for transversity TDA, H_T:

(i) axial meson $A = b_1(1235)$ exchange dominance

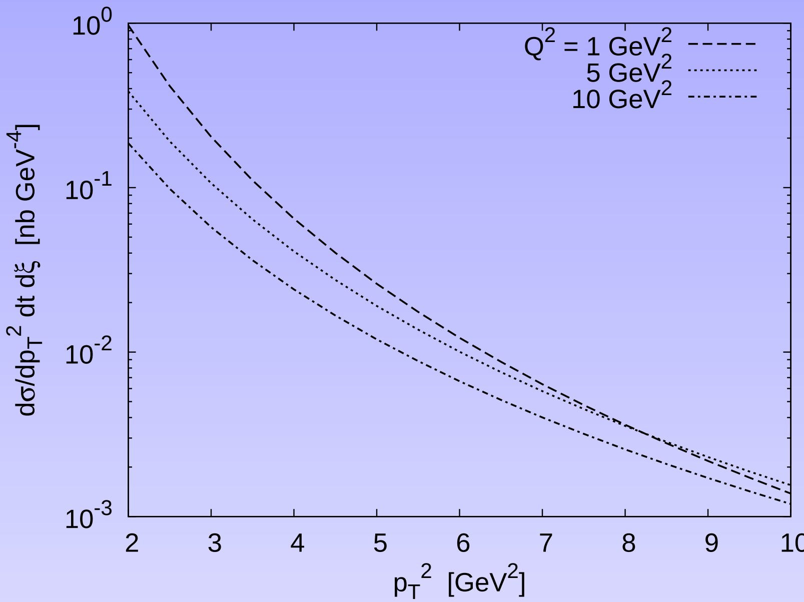
$$H_T^a(x,\xi) = \frac{g_{ANN} f_A^{a\perp} (\Delta \cdot S_T)^2}{2M_N\, m_A^2} \frac{\phi_\perp(\frac{x+\xi}{2\xi})}{2\xi},$$

with b_1 distribution amplitude $\phi_\perp^A(u)$ (only ERBL)
(ii) the bag model of transversity (Scopetta 2005)

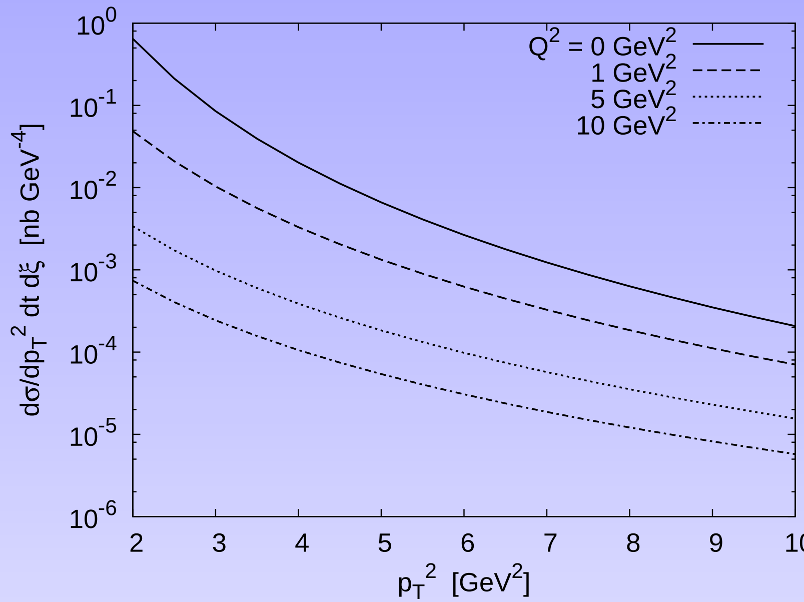


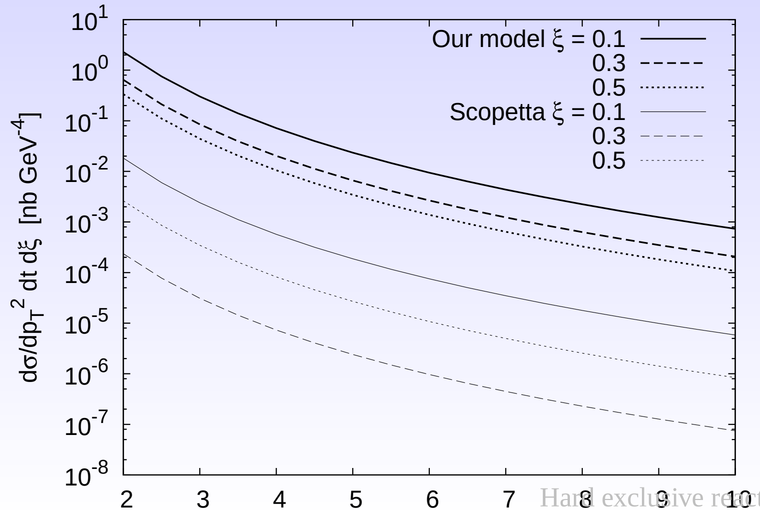
Diff. cross sec. for $\gamma^{(*)}(Q)\, p \to \rho^0_L\, \rho^+_{L,T}\, n$

ρ^+_L



ρ^+_T





Exotic meson exclusive production

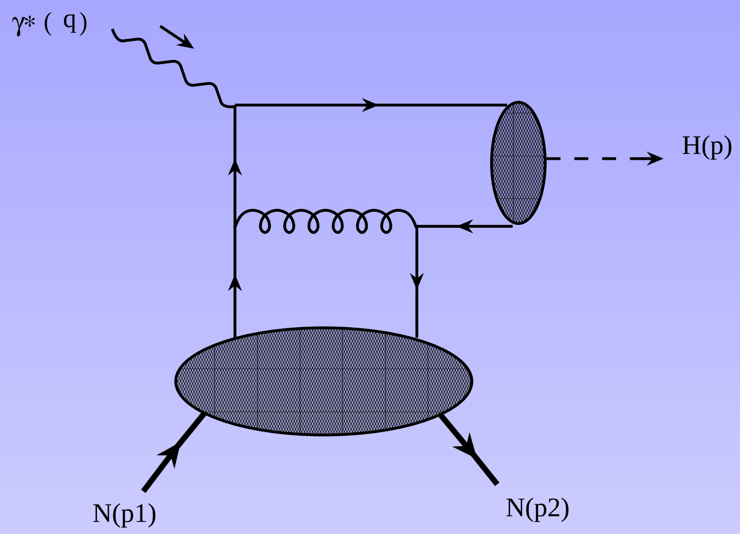
Exotic Hybrid Meson π_1 with $J^{PC} = 1^{-+}$
Define π_1 Distribution Amplitude as usual :

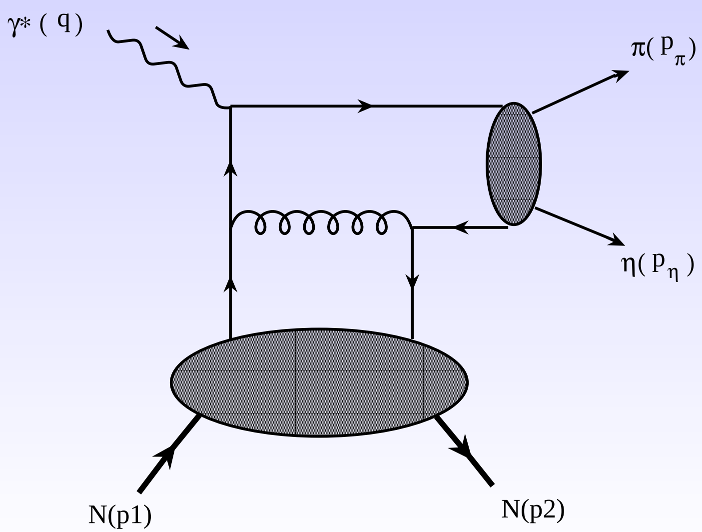
$$\langle \pi_1(p,\lambda)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle =$$

$$i f_{\pi_1} M_{\pi_1} \left[p_\mu \frac{e^{(\lambda)} \cdot z}{p \cdot z} \int_0^1 dy e^{i(\bar{y}-y)p\cdot z/2} \phi_L^H(y) \right]$$

- same twist as ρ Distribution Amplitude
- QCD sum rules $\rightarrow f_{\pi_1} \sim 50$ MeV
- Similar electroproduction cross sections in ep collisions.
- Also possible in $e\gamma$ collisions

Exotic meson exclusive production





Comparison of ρ^0 and $H \equiv \pi_1(1400)$ electroproduction cross sections

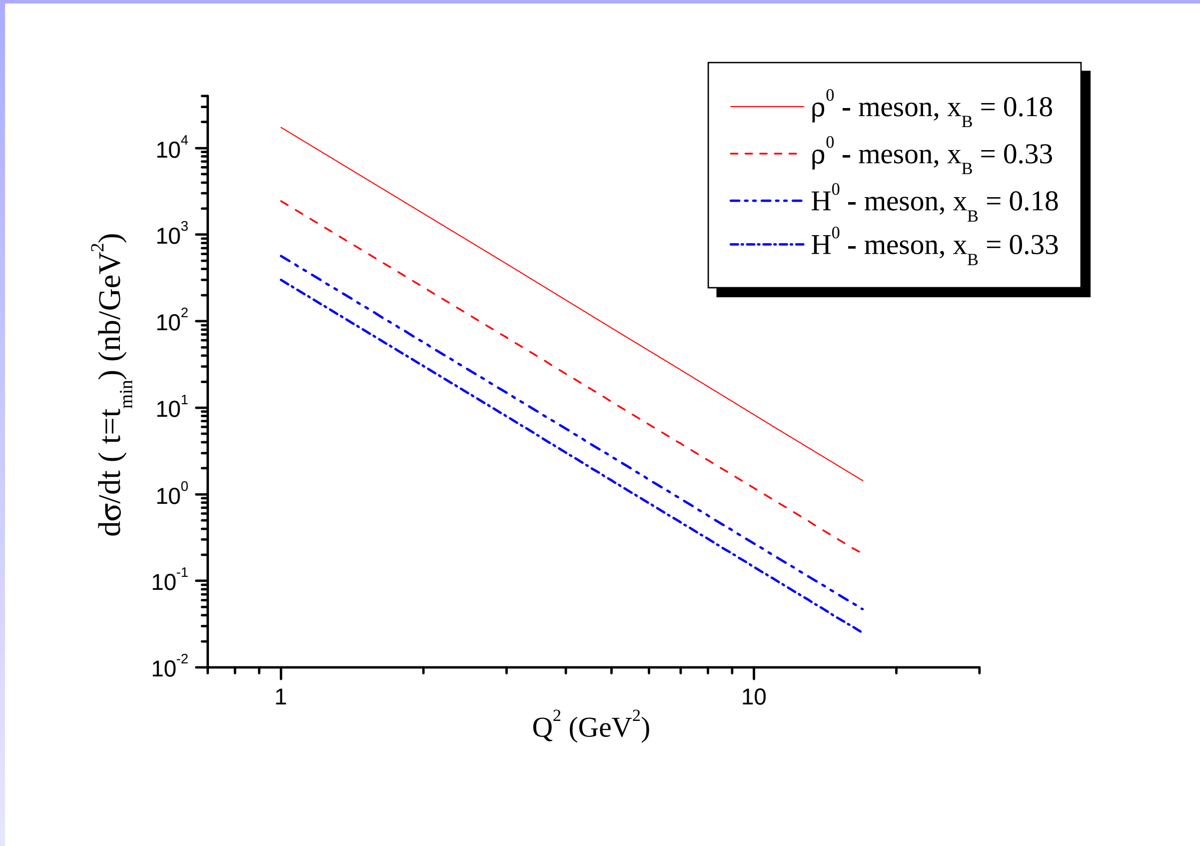


Figure 1:

seems visible $\longrightarrow$ COMPASS, e-RHIC

Extension

- What can pQCD say about other exclusive reactions at large Q^2 such as those of

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

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

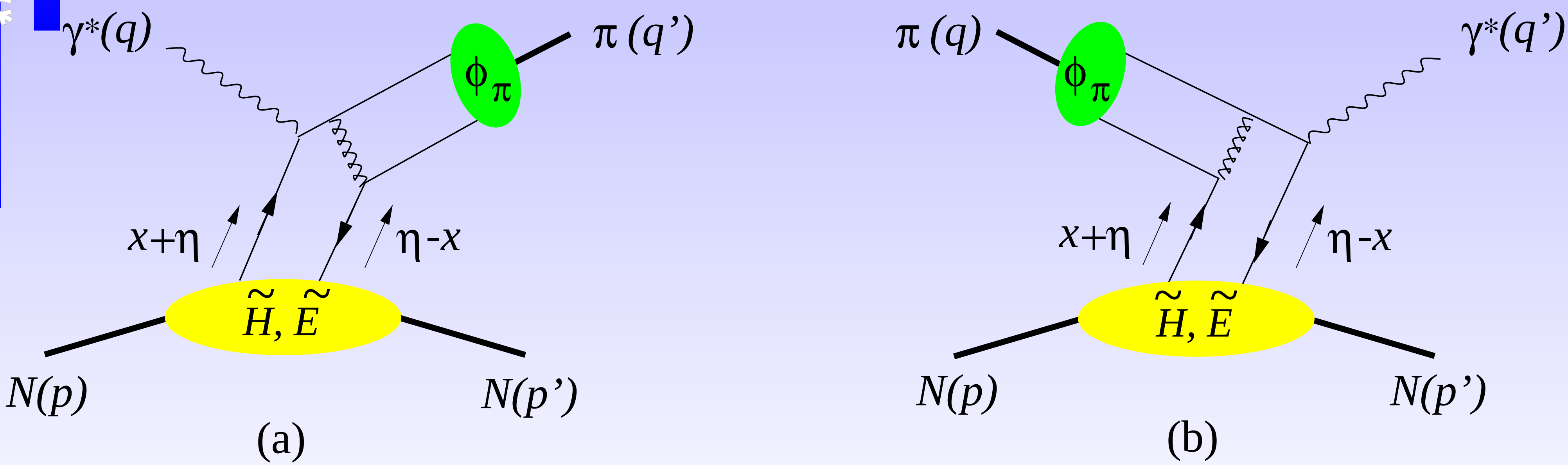
$$\langle \gamma(p',\epsilon')| \, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n) \, |p(p,s)\rangle \Big|_{z^+=0,\, z_T=0}$$

Arguments for Factorization

PROOFS EXIST for

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

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



Arguments for Factorization (continued)

- Choose N = π and N' = ρ

$\longrightarrow$ Factorization of $\pi\pi \longrightarrow \gamma^*\rho$

- Change $\rho \longrightarrow \gamma$

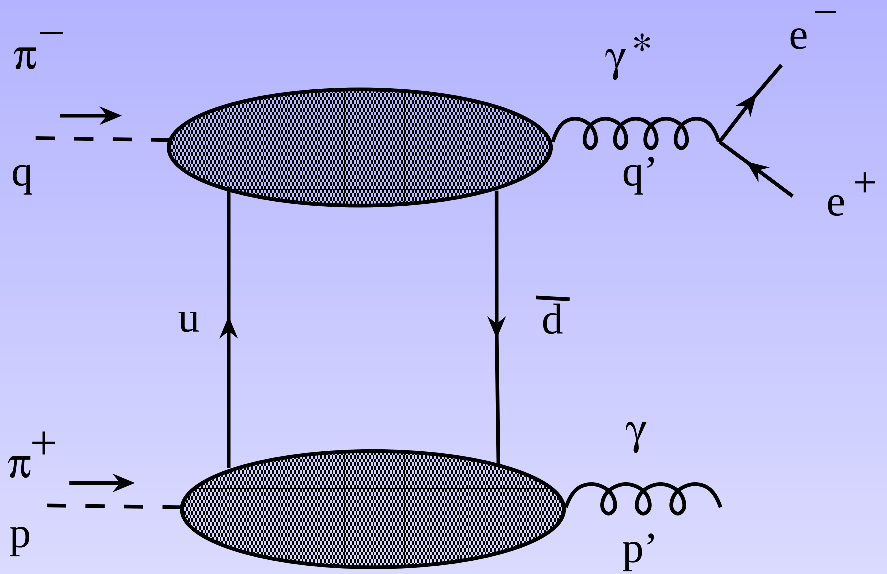
Remember : Photon structure function factorizes in the same way as meson structure function !

$\longrightarrow$ Factorization of TDA in

$$\pi\pi \longrightarrow \gamma^*\gamma$$

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

The factorization of $\pi\ \pi \rightarrow \gamma^*\ \gamma$



Arguments for Factorization - continued

- Change Meson $\rightarrow$ Baryon

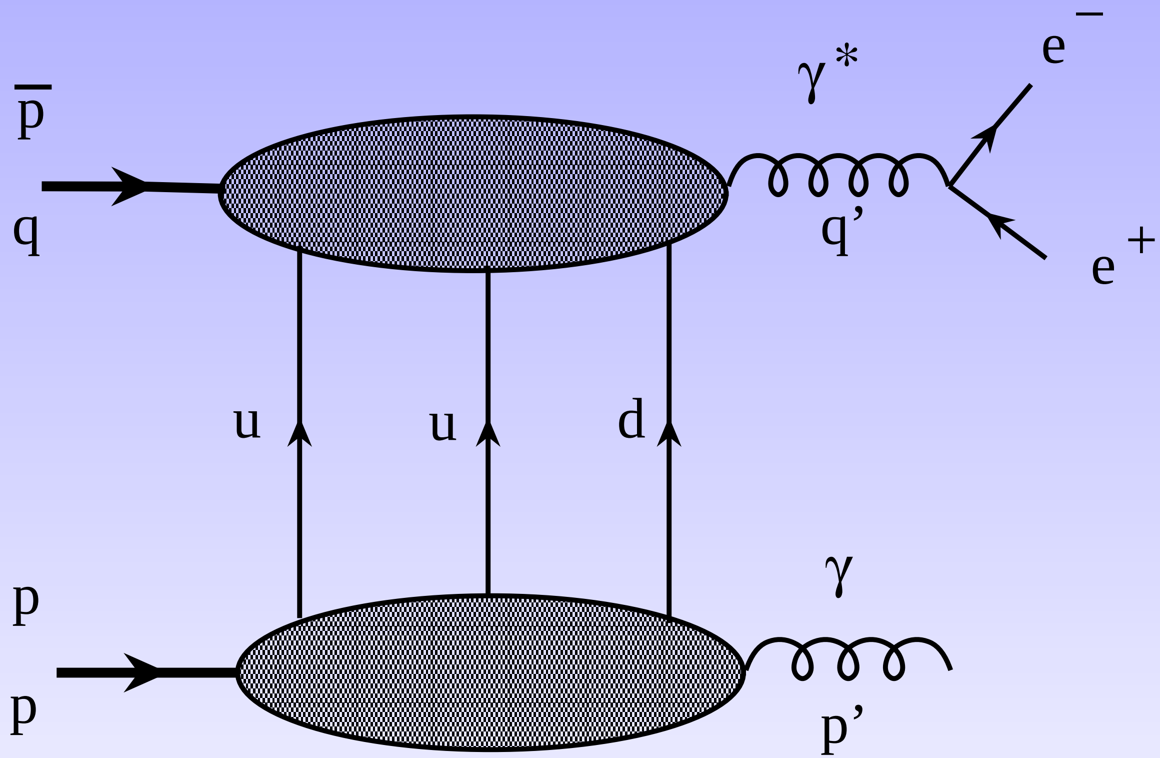
More problematic since 3 quark exchange !

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

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

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

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



From DAs to TDAs

- Recall definition of Distribution Amplitudes

$$4\langle 0|\epsilon^{ijk}u^i_\alpha(z_1\, n)u^j_\beta(z_2\, n)d^k_\gamma(z_3\, n)|B(p,s)\rangle = f_N$$

$$V(\hat{p}\, C)_{\alpha\beta}(\gamma^5\, B)_\gamma + A(\hat{p}\,\gamma^5\, C)_{\alpha\beta}B_\gamma + T(p^\nu i\sigma_{\mu\nu}\, C)_{\alpha\beta}(\gamma^\mu\,\gamma^5\, B)$$

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

- Define Transition Distribution Amplitudes

$$4\langle \pi^0(p')|\, \epsilon^{ijk}u^i_\alpha(z_1\, n)u^j_\beta(z_2\, n)d^k_\gamma(z_3\, n)\, |p(p,s)\rangle\Big|_{z^+=0,\, z_T=0} =$$

$$\frac{-f_N}{2f_\pi}\Big[V^0_1(\hat{P}C)_{\alpha\beta}(B)_\gamma + A^0_1(\hat{P}\gamma^5 C)_{\alpha\beta}(\gamma^5 B)_\gamma -$$

$$3T^0_1(P^\nu i\sigma_{\mu\nu}C)_{\alpha\beta}(\gamma^\mu B)_\gamma] + V^0_2(\hat{P}C)_{\alpha\beta}(\hat{\Delta}_T B)_\gamma +$$

$$A^0_2(\hat{P}\gamma^5 C)_{\alpha\beta}(\hat{\Delta}_T\gamma^5 B)_\gamma + T^0_2(\Delta^\mu_T P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(B)_\gamma$$

$$+T^0_3(P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\sigma^{\mu\rho}\Delta^\rho_T B)_\gamma + \frac{T^0_4}{M}(\Delta^\mu_T P^\nu\sigma_{\mu\nu}C)_{\alpha\beta}(\hat{\Delta}_T B)_\gamma$$

$B =$ nucleon spinor.

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

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

- **Factorize** process amplitude :

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

Evolution equations

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

• The scale dependence of $N \to \pi$ or $N \to \gamma$ 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 :

$$B^{1/2}_{\alpha\beta\gamma}(z_i) = \epsilon^{ijk}(\hat{n}q_i^{\uparrow})_\alpha(z_1 n)(\hat{n}q_j^{\downarrow})_\beta(z_2 n)(\hat{n}q_k^{\uparrow})_\gamma(z_3 n)$$

$$B^{3/2}_{\alpha\beta\gamma}(z_i) = \epsilon^{ijk}(\hat{n}q_i^{\uparrow})_\alpha(z_1 n)(\hat{n}q_j^{\uparrow})_\beta(z_2 n)(\hat{n}q_k^{\uparrow})_\gamma(z_3 n)$$

- 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

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

$$\begin{aligned}
\mathcal{A} = \Bigg[& \left(\int_{-1+\xi}^{1+\xi} dx'_1 \left[\frac{x_1\rho(x'_1,x_1)}{x'_1(x'_1-x_1)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx'_2 \left[\frac{x_2\rho(x'_2,x_2)}{x'_2(x'_2-x_2)}\right]_+ \right) F^{\uparrow\downarrow\uparrow}(x'_1,x'_2,x_3) \\
& + \left(\int_{-1+\xi}^{1+\xi} dx'_1 \left[\frac{x_1\rho(x'_1,x_1)}{x'_1(x'_1-x_1)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx'_3 \left[\frac{x_3\rho(x'_3,x_3)}{x'_3(x'_3-x_3)}\right]_+ \right) F^{\uparrow\downarrow\uparrow}(x'_1,x_2,x'_3) \\
& + \left(\int_{-1+\xi}^{1+\xi} dx'_2 \left[\frac{x_2\rho(x'_2,x_2)}{x'_2(x'_2-x_2)}\right]_+ + \int_{-1+\xi}^{1+\xi} dx'_3 \left[\frac{x_3\rho(x'_3,x_3)}{x'_3(x'_3-x_3)}\right]_+ \right) F^{\uparrow\downarrow\uparrow}(x_1,x'_2,x'_3) \\
& + \frac{1}{2\xi - x_3} \left(\int_{-1+\xi}^{1+\xi} dx'_1 \frac{x_1}{x'_1}\rho(x'_1,x_1) + \int_{-1+\xi}^{1+\xi} dx'_2 \frac{x_2}{x'_2}\rho(x'_2,x_2) \right) F^{\uparrow\downarrow\uparrow}(x'_1,x'_2,x_3) \\
& + \frac{1}{2\xi - x_1} \left(\int_{-1+\xi}^{1+\xi} dx'_2 \frac{x_2}{x'_2}\rho(x'_2,x_2) + \int_{-1+\xi}^{1+\xi} dx'_3 \frac{x_3}{x'_3}\rho(x'_3,x_3) \right) F^{\uparrow\downarrow\uparrow}(x_1,x'_2,x'_3) \Bigg]\Bigg\}
\end{aligned}$$

• 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 $x_i > 0 \rightarrow$ usual ERBL ($x_i \rightarrow x_i/2\xi$ rescaling).

• Other regions need further study !

CHIRAL LIMIT of $p \to \pi$ TDA

- Soft pion theorems$\to$

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

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

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 ($\xi \to 1$)

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

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

where $\phi_N(x_1,x_2,x_3) =$ *standard leading twist DA*

Interpretation

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

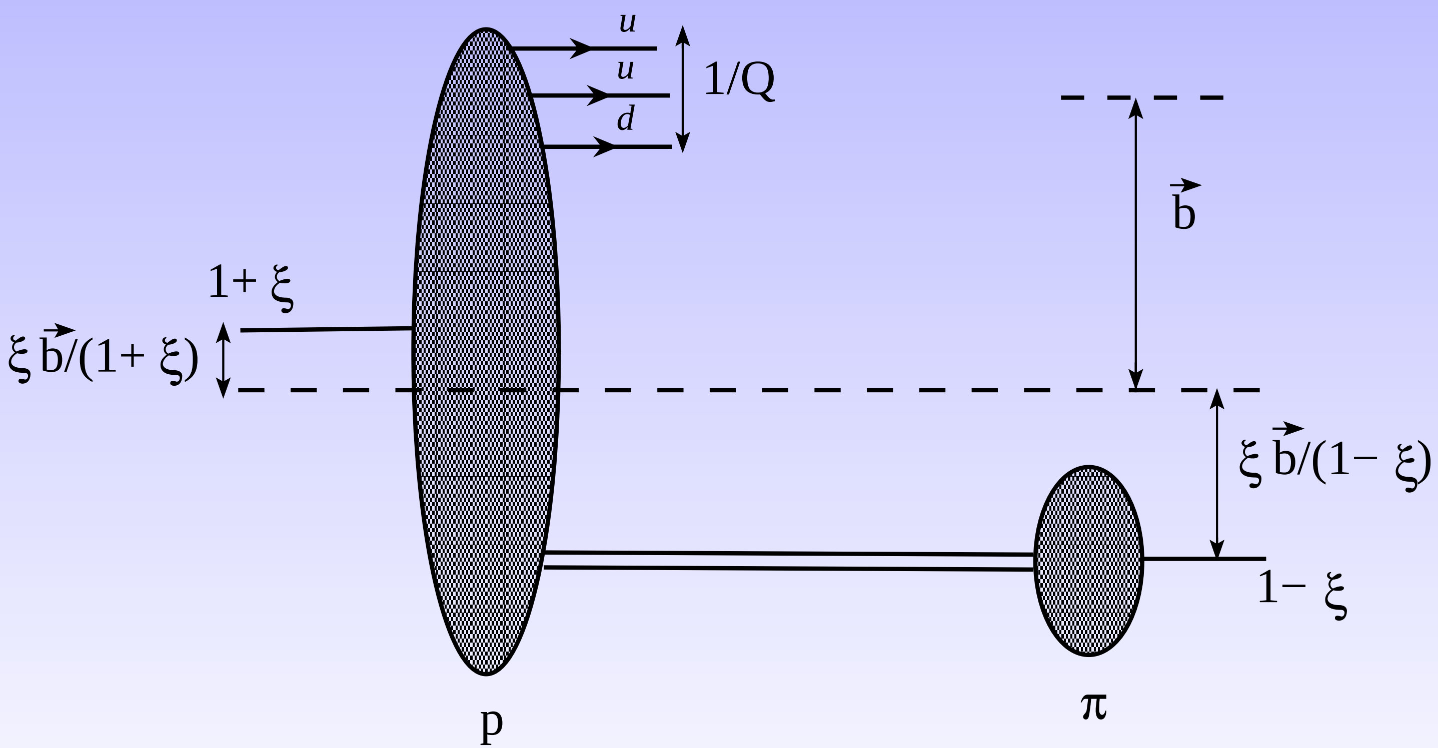
- The proton $\longrightarrow \pi$ **TDA** allows a pion (cloud) around the valence contribution.

- 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 $t \longrightarrow b_T$
- Transverse picture of *pion cloud* in the proton



To test these ideas: Model-independent predictions

• scaling law for the amplitude : $\mathcal{M}(Q^2, \xi) \sim \frac{\alpha_s(Q^2)^2}{Q^4}$,
(up to logarithmic corrections).

• Ratio : $\frac{d\sigma(\bar{p}p \to l^+ l^- \pi^0)/dQ^2}{d\sigma(\bar{p}p \to l^+ l^-)/dQ^2}$ almost Q^2 independent.

• γ^*_T dominates $\longrightarrow \frac{d\sigma(p\bar{p} \to l^+ l^- \pi)}{\sigma d\theta} \sim 1 + cos^2\theta$
(θ = lepton angle in γ^* CMS)

• Choose V, A and T $\longrightarrow$ Estimate threshold cross section in terms of e-m form factor

This description also applies to crossed reactions

• Backward VCS $\gamma^* P \rightarrow \; P'\gamma$
Data exist (JLab) for Q^2 up to 1 GeV^2.

Data from HERMES ?

• and backward meson electroproduction
$\gamma^* P \rightarrow \; P'\pi$; $\gamma^* P \rightarrow \; P'\rho$ ...

• Data exist (JLab) Analysis to be done

$\gamma^*\gamma$ collisions

• One may describe along the same lines the crossed reactions

$$\gamma^* \gamma \to \pi^+ \pi^- \tag{1}$$

$$\gamma^* \gamma \to \pi^\pm \rho^\mp \tag{2}$$

and

$$\gamma^* \gamma \to \rho^+ \rho^- \tag{3}$$

in the near forward region and for large virtual photon invariant mass Q, which may be studied in detail at intense electron colliders such as BABAR and BELLE.

• wait for talk by Jean Philippe Lansberg ...

CONCLUSIONS on TDAs

- FAIR will help to understand the deep structure of the proton
- Transition Distribution Amplitudes will reveal the dynamics of the *next to lowest* Fock state
- $\bar{p}p \longrightarrow \gamma^* \pi$ explores the pion cloud.
- $\bar{p}p \longrightarrow \gamma^* \rho$ explores the ρ cloud.
- $\bar{p}p \longrightarrow \gamma^* \gamma$ explores the photon cloud.
- Detectors should be ready to measure these reactions !
- If *Polarized* beam and target $\longrightarrow$ spin structure too!
- NOT SO SMALL CROSS-SECTIONS AND BIG REWARDS.

CONCLUSIONS

- Exclusive Hard Reactions are revealing much about Hadron structure
- Theoretical progress ongoing ...
- Extremely Good Expriments are being done and prepared
- Nature seems to help us with early scaling !