Study of the Proton Mesonic Content via Backward Hard Exclusive Processes

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Centre de Physique Théorique – Ecole Polytechnique

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IPNL, Lyon

Collaborative work with S.J. Brodsky, B. Pasquini, B. Pire and L. Szymanowski

Part I

The usual tools to study the proton (structure): form factors and (generalised) parton distributions

The proton as a whole . . .

➟ Static properties of the proton (seen from far away):

- Charge: $+1$
- Mass: M_p
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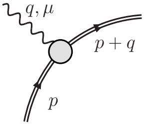

$$\Gamma_\mu(q) = F_1(q^2)\gamma_\mu + \frac{i}{2M_p} F_2(q^2)\sigma_{\mu\nu} q^\nu$$

"How a proton absorbs a photon and stays intact" (Elastic scattering)

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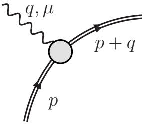

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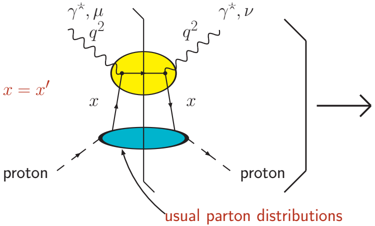
➡ Static limit:

- $F_1(0)$=+1: its charge
- $F_2(0) = \mu_p - 1$

The proton apart . . .

➡ Study of the proton content via (deeply) inelastic scattering (DIS):



$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1(x, q^2) + \frac{\mathcal{P}_\mu \mathcal{P}_\nu}{P.q} F_2(x, q^2)$$

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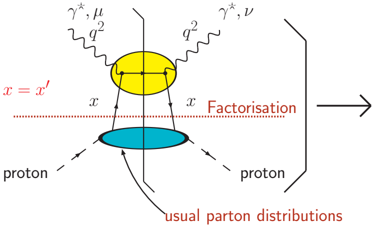

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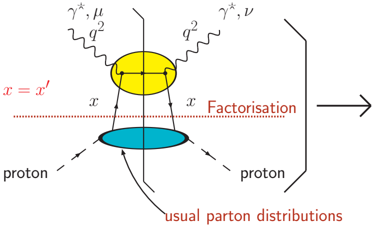

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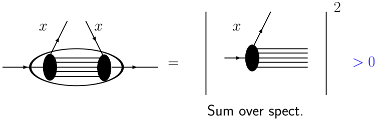
- Probability Distribution, since being an amplitude squared



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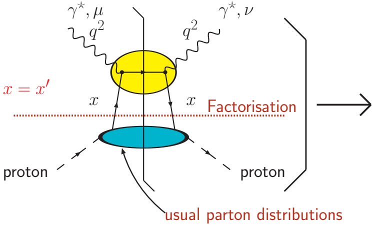

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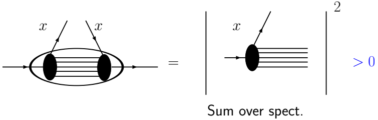

- Probability to find a parton with a momentum fraction x: $q(x)$

$$F_2(x, q^2) = x \sum_q e_q^2 \, q(x, q^2)$$

Interferences in the proton. . .

➡ Study of interferences in the proton
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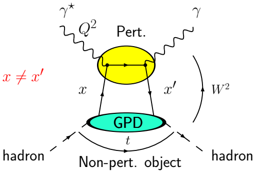

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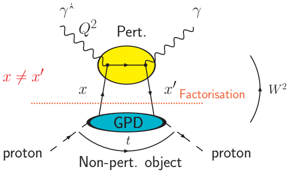

For $Q^2 \gg t$, described in terms of 4 generalised parton distribution: GPDs

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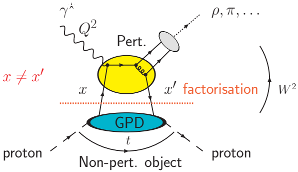

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idem for meson electroproduction

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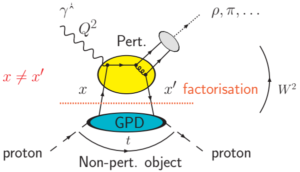

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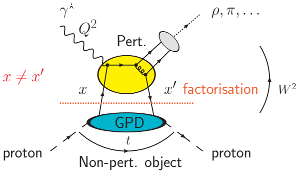

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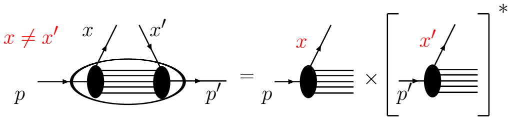

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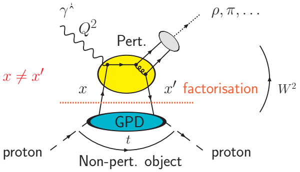

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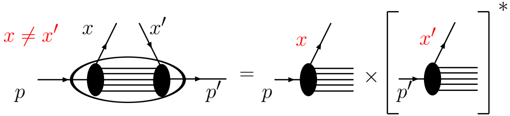

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➟ Interpretation only at the amplitude level

Amplitude of probability

for a proton to emit a quark with x & to absorb another with x'

Part II

A new look at the proton (structure): backward exclusive processes

Hard limit for backward exclusive processes

➠ Let us analyse the Hard Electroproduction of a meson

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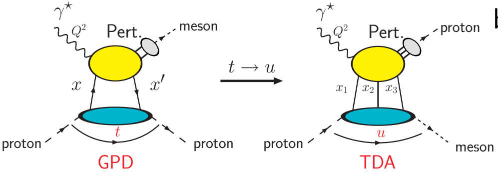

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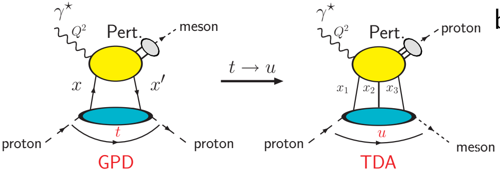

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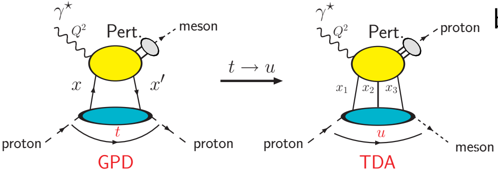

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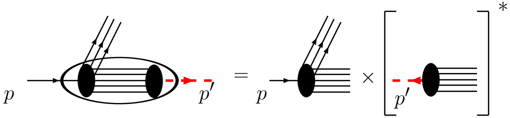

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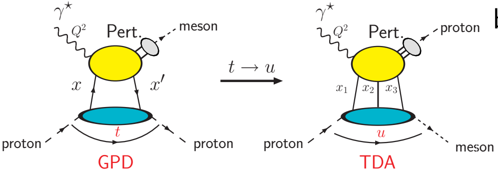

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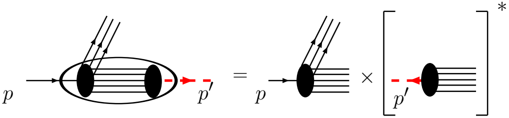

➟ Interpretation at the amplitude level (for $x_i > 0$)

Amplitude of probability to find a meson within the proton !

More quantitatively: the pionic content of the proton

JPL, B. Pire, L. Szymanowski,PRD 75:074004,2007

➠ Using the soft pion theorem, one may write

$$\langle \pi^a(k)|\mathcal{O}|p(p,s)\rangle = -\frac{i}{f_\pi}\langle 0|[Q_5^a,\mathcal{O}]|p(p,s)\rangle + \frac{i g_A}{4 f_\pi p\cdot k}\sum_{s'}\langle 0|\mathcal{O}|p(p,s')\rangle \bar{u}(p,s')\not{k}\gamma_5\tau^a u(p,s)$$

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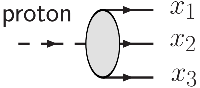

- Direct relations between the TDAs, $\langle \pi^a(k)|\mathcal{O}|p(p,s)\rangle$, and the proton wavefunction (DAs), $\langle 0|\mathcal{O}|p(p,s)\rangle$

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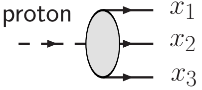
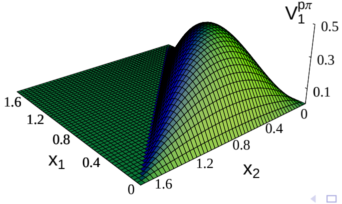


➡ Direct relations between the TDAs, $\langle \pi^a(k)|\mathcal{O}|p(p,s)\rangle$, and the proton wavefunction (DAs), $\langle 0|\mathcal{O}|p(p,s)\rangle$

➡ Can also be computed using e.g. the pion cloud model (not only for $p_\pi \to 0$ then)

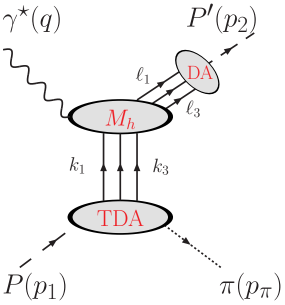
B. Pasquini, *et al.* **PRD 80:014017,2009.**



Backward electroproduction of a pion

➟ First study of backward electroproduction of a pion for $p_\pi \to 0$

JPL, B. Pire, L. Szymanowski,PRD 75:074004,2007



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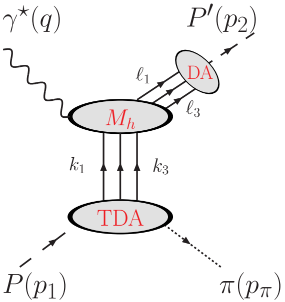
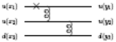


➡ To be compared with the pion cloud model and extended to $\Delta_T \neq 0$

JPL, B. Pasquini, B. Pire, L. Szymanowski, in progress

Hard part: M_h for $\gamma^\star p \to p\pi^0$ at $\Delta_T = 0$



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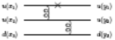

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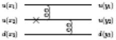

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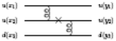

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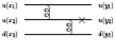

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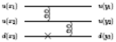

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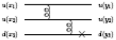

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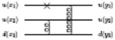

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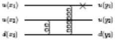

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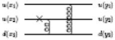

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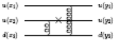

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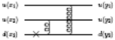

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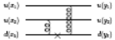

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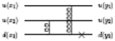

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Backward Electroproduction of a pion: II

JPL, B. Pire, L. Szymanowski, PRD 75:074004,2007

➠ The amplitude at the Leading-twist accuracy:

$$\mathcal{M}^{\lambda}_{s_1 s_2} = -i\frac{(4\pi\alpha_s)^2\sqrt{4\pi\alpha_{em}}f_N^2}{54 f_\pi Q^4}\bar{u}(p_2,s_2)\not{\epsilon}(\lambda)\gamma^5 u(p_1,s_1)$$

$$\times \int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y \left(2\sum_{\alpha=1}^{7} T_\alpha + \sum_{\alpha=8}^{14} T_\alpha\right)$$

Backward Electroproduction of a pion: II

JPL, B. Pire, L. Szymanowski, PRD 75:074004,2007

➟ The amplitude at the Leading-twist accuracy:

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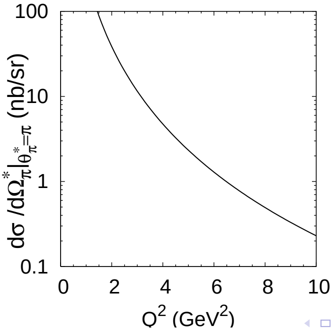
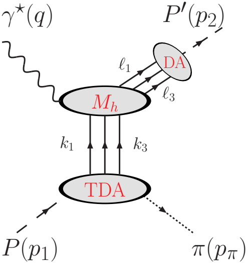
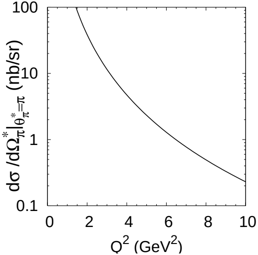


Backward Electroproduction of a pion: III



JPL, B. Pire, L. Szymanowski,PRD 75:074004,2007



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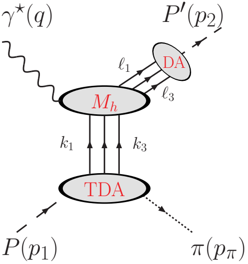

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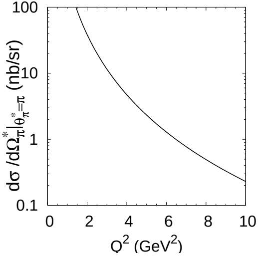

➡ Data from JLab exist for the π *Analysis on-going*

➡ "Visible peak in the yield of ω at 180°" (*G. Huber (JLab, Hall C), Sept. 2009*)

➡ Data for the electrodruction of η *To be modelled*

➡ We are working on the theory
($\Delta_T \neq 0$, DGLAP-region contribution, other models, ...)

TDAs in exclusive processes at GSI/FAIR

➡ $p \longrightarrow \pi$ TDAs can be studied in $\bar{p}p \longrightarrow \gamma^{\star}{}_{(Q^2)}\pi^0 \longrightarrow \ell^+\ell^-\pi^0$

JPL, B. Pire, L. Szymanowski PRD76 :111502(R),2007

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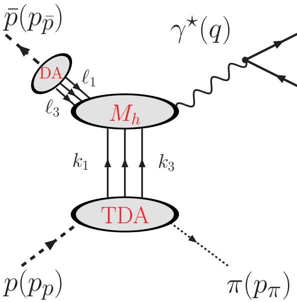

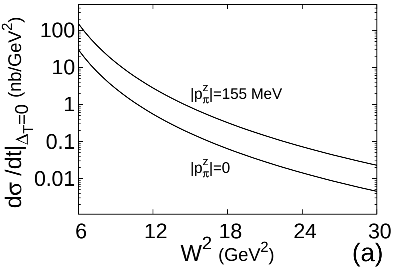

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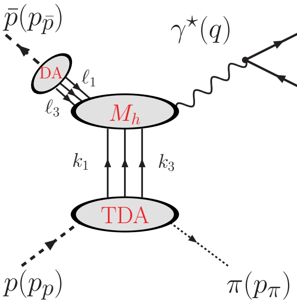
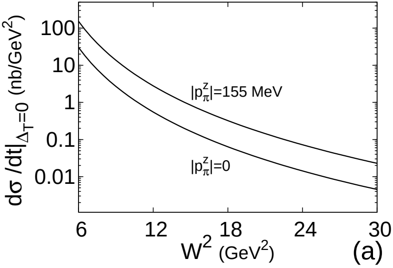




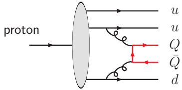
➡ Strictly the same TDAs as for electroproduction (JLab)

➡ Planned to be done with the proton FF studies in the timelike region

Physics Performance Report for PANDA, 0903.3905 [hep-ex]

Heavy quarks in the proton . . .

➟ Protons can contain nonperturbative fluctuations of charm quarks $c\bar{c}$



S.J. Brodsky *et al.* **PLB93:451-455,1980**

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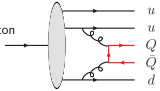

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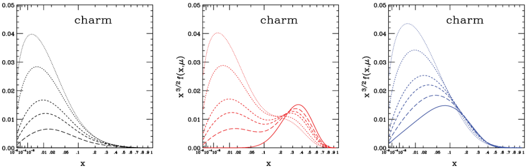

$\mu = 1.3 \longrightarrow 100$ GeV

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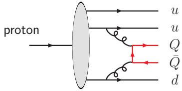

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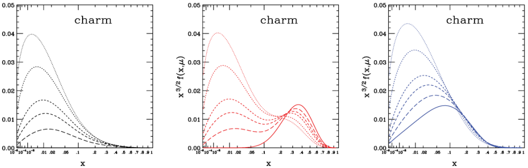

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S.J Brodsky, J.P.L , arXiv:0908.0754 [hep-ph]

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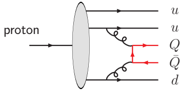

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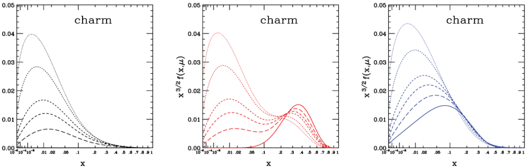

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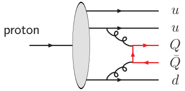

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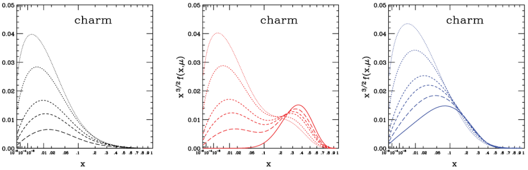

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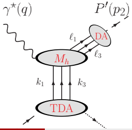
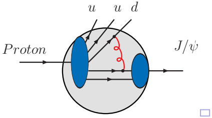
➠ Dedicated test: $\gamma^\star p \rightarrow p\, J/\psi$ with sufficient W^2 S.J. Brodsky, JPL, work in progress





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- Modelling the proton to charmonium TDA (pseudoscalar case)
  - → "SU(4)" spin-flavour symmetry: only one TDA

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$$\psi(x_1, x_2, x_3, x_c, x_{\bar{c}}, Q^2) = \delta(1 - \sum_i x_i) \frac{\Gamma}{(m_p^2 - \hat{m}_c^2(\frac{1}{x_c} + \frac{1}{x_{\bar{c}}}) - \hat{m}_q^2(\frac{1}{x_1} + \frac{1}{x_2} + \frac{1}{x_3}))} \quad (1)$$

(Effective masses (from the k_T integration) $\hat{m}_c^2 \simeq 1.8$ GeV, $\hat{m}_q^2 \simeq 0.45$ GeV)

  - Only in ERBL region $(x_i > 0)$

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  - Stay tuned !

Part III

Perspectives

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- ➠ Soft pion limit, pion cloud model: OK
- ➠ 4-ple distribution (spectral representation: double distr. for GPD): to be done
- ➠ TDA moments can be computed on the lattice
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  - etc.

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- ...expected from

  - JLab-6 GeV: Backward electroproduction of π, η, ω
  - GSI: $p\bar{p} \to \gamma^\star \pi^0$, $p\bar{p} \to J/\psi \pi^0$, $p\bar{p} \to \gamma^\star \gamma$, ...
  - JLab-12 GeV: e.g. DVCS on pion
  - *B*-factories ($\gamma^\star \gamma \to MM$) possible: TDA $\gamma \to M$
  - COMPASS (?): $\gamma^\star p \to pJ/\psi$

Part IV

Back-up

$p \longrightarrow \pi$: parametrisation

➩ $p \longrightarrow \pi$ (at Leading twist)

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

TDA

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

DA (Chernyak-Zhitnitsky)

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

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$$V_1^{\pi^0} \longrightarrow D^{\uparrow}_{\uparrow\downarrow,\uparrow} + D^{\uparrow}_{\downarrow\uparrow,\uparrow}$$
$$A_1^{\pi^0} \longrightarrow D^{\uparrow}_{\uparrow\downarrow,\uparrow} - D^{\uparrow}_{\downarrow\uparrow,\uparrow}$$
$$T_1^{\pi^0} \longrightarrow D^{\uparrow}_{\uparrow\uparrow,\downarrow}$$

B. Pasquini *et al.*

$p \longrightarrow \pi$: parametrisation

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

$$4\langle \pi^0(p_\pi)|\, \epsilon^{ijk} u^i_\alpha(z_1 n) u^j_\beta(z_2 n) d^k_\gamma(z_3 n)\,|p(p_1, s)\rangle = \frac{i f_N}{f_\pi} \times$$
$$\Big[V_1^{\pi^0}(x_i, \xi, \Delta^2)(\not p\, C)_{\alpha\beta}(N^+)_\gamma + V_2^{\pi^0}(x_i, \xi, \Delta^2)(\not p\, C)_{\alpha\beta}(\not\Delta_T N^+)_\gamma$$
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$$+T_3^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{p\mu} C)_{\alpha\beta}(\sigma^{\mu\Delta_T} N^+)_\gamma + T_4^{\pi^0}(x_i,\xi,\Delta^2)(\sigma_{p\Delta_T} C)_{\alpha\beta}(\not\Delta_T N^+)_\gamma\Big]$$

B. Pasquini *et al.*

$$V_2^{\pi^0} \longrightarrow D^{\uparrow}_{\downarrow\uparrow,\downarrow} + D^{\uparrow}_{\uparrow\downarrow,\downarrow} \qquad A_2^{\pi^0} \longrightarrow D^{\uparrow}_{\downarrow\uparrow,\downarrow} - D^{\uparrow}_{\uparrow\downarrow,\downarrow}$$
$$T_2^{\pi^0} \longrightarrow D^{\uparrow}_{\uparrow\uparrow,\uparrow} + D^{\uparrow}_{\downarrow\downarrow,\uparrow} \qquad T_3^{\pi^0} \longrightarrow D^{\uparrow}_{\uparrow\uparrow,\uparrow} - D^{\uparrow}_{\downarrow\downarrow,\uparrow}$$
$$T_4^{\pi^0} \longrightarrow D^{\uparrow}_{\downarrow\downarrow,\downarrow}$$