



# Study of the Proton Mesonic Content via Backward Hard Exclusive Processes

**J.P. Lansberg**

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:  $M_p$
- Anomalous Magnetic Moment:  $\mu_p = 2.79$

# The proton as a whole . . .

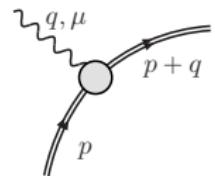
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→ Simplest dynamical object: Form factors

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

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



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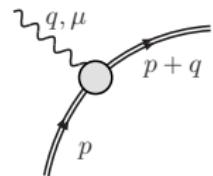
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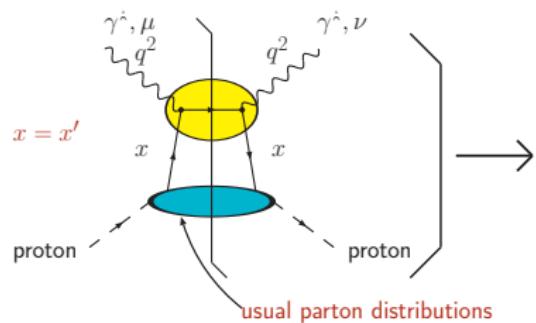


→ Static limit:

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

# The proton apart . . .

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

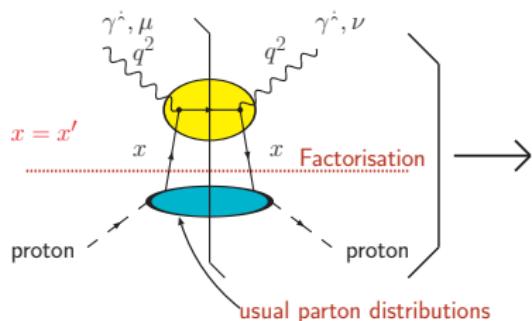


$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1(x, q^2) + \frac{\mathcal{P}_\mu \mathcal{P}_\nu}{\mathcal{P} \cdot q} F_2(x, q^2)$$

$$\mathcal{P} = P_\mu - \frac{P \cdot q}{q^2} q_\mu$$

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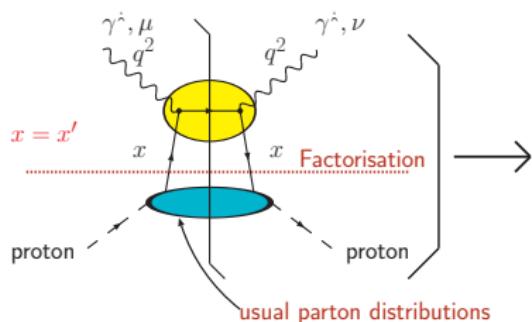
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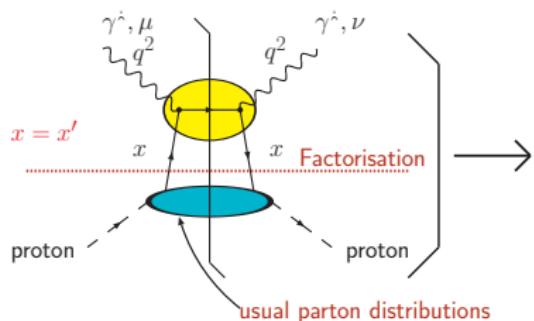
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- Probability Distribution, since being an amplitude squared

$$\left| \sum \text{over spect.} \right|^2 > 0$$

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A diagram illustrating the factorization of a proton into two partons. On the left, a horizontal oval represents a proton, with two diagonal lines labeled  $x$  exiting from it. This is followed by an equals sign. To the right of the equals sign is a vertical bracket containing two horizontal ellipses representing partons. From each ellipse, three horizontal lines emerge. The entire expression is enclosed in a vertical bracket with a superscript  $2$  and a blue label " $> 0$ ". Below the bracket, the text "Sum over spect." is written.

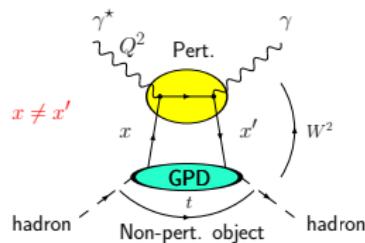
- Probability to find a parton with a momentum fraction  $x$ :  $q(x)$

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

# Interferences in the proton...

→ Study of interferences in the proton

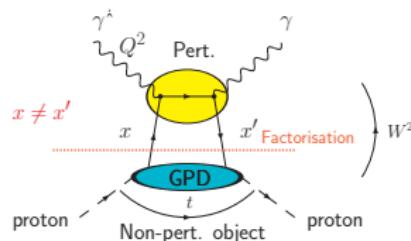
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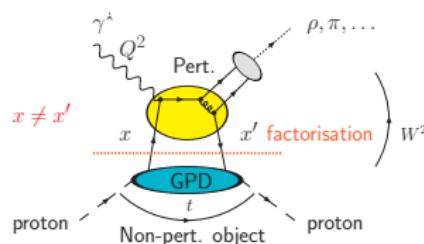
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For  $Q^2 \gg t$ , described in terms of 4 generalised parton distribution: GPDs

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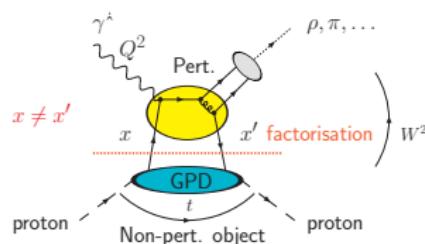


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idem for meson electroproduction

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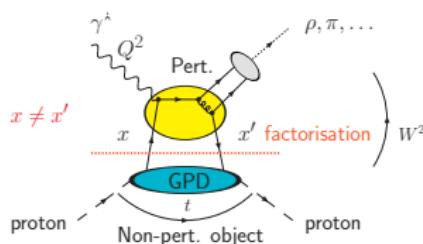


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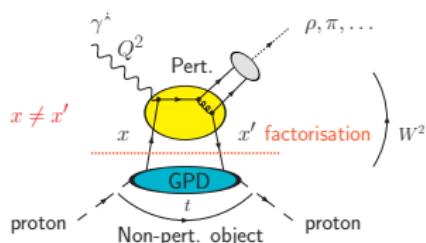
- Factorisation in the generalised Bjorken limit:  $Q^2 \rightarrow \infty$ ,  $t, x$  fixed
- The GPDs are not probability distributions

The diagram illustrates the factorisation of a GPD. On the left, a proton  $p$  with momentum  $p$  and longitudinal fraction  $x \neq x'$  interacts with a non-perturbative object, represented by two ovals. The final state is a proton  $p'$  with momentum  $p'$ . This is equated to the product of a proton  $p$  with momentum  $p$  and longitudinal fraction  $x$  interacting with a non-perturbative object, and a proton  $p'$  with momentum  $p'$  and longitudinal fraction  $x'$  interacting with a non-perturbative object. The result is enclosed in brackets with a superscript asterisk (\*).

but are universal !

# Interferences in the proton...

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- Factorisation in the generalised Bjorken limit:  $Q^2 \rightarrow \infty$ ,  $t, x$  fixed
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The diagram illustrates the factorisation of a proton's internal structure. On the left, a proton with momentum  $p$  emits a quark with momentum  $x$  and an antiquark with momentum  $x'$ . This is represented by a quark-gluon vertex and a gluon-gluon vertex. On the right, the process is shown as a product of two factors: a quark-gluon vertex and a gluon-gluon vertex. The quark-gluon vertex is associated with a proton with momentum  $p'$  and a quark with momentum  $x$ . The gluon-gluon vertex is enclosed in brackets with a superscript asterisk (\*), indicating it is a complex conjugate or a related quantity.

but are universal !

- 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

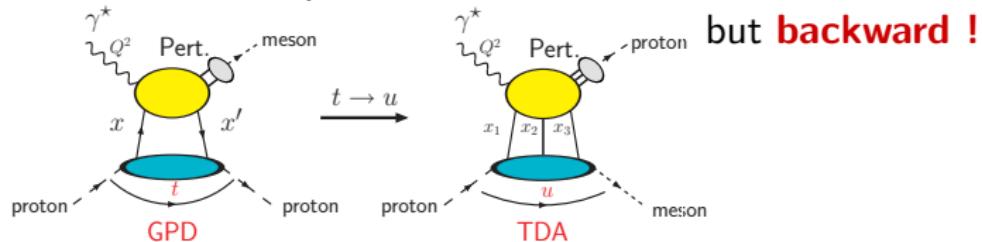
### A new look at the proton (structure): backward exclusive processes

# Hard limit for backward exclusive processes

→ Let us analyse the Hard Electroproduction of a meson

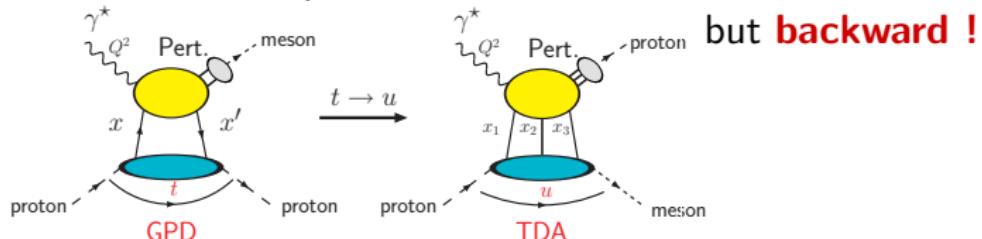
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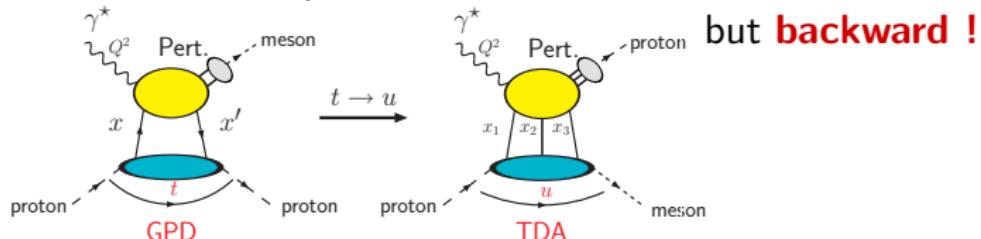


- The kinematics imposes **the exchange of 3 quarks** in the  $u$  channel
- Factorisation** in the generalised Bjorken limit:  $Q^2 \rightarrow \infty$ ,  $u, x$  fixed

B. Pire, L. Szymanowski, PLB 622:83,2005.

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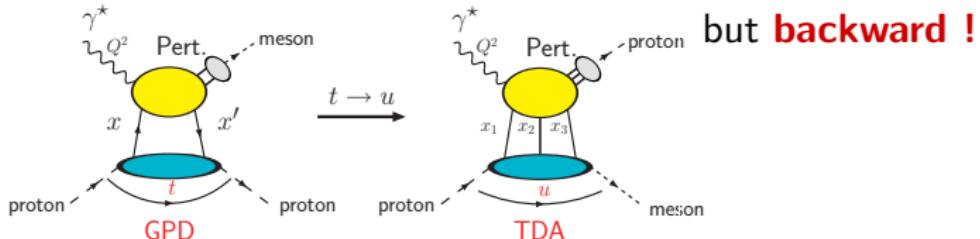
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- The object factorised from the hard part is a **Transition Distribution Amplitude (TDA)**

$$p \rightarrow \text{elliptical quark-gluon loop} \rightarrow p' = p \rightarrow \text{elliptical quark-gluon loop} \times \left[ \text{quark-gluon loop} \right]^*$$

# Hard limit for backward exclusive processes

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$$p \rightarrow \text{meson} = p \rightarrow \text{meson} \times \left[ \begin{array}{c} \text{meson} \\ \text{meson} \end{array} \right]^*$$

- 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

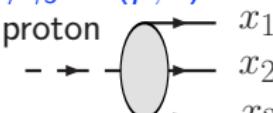
$$\langle \pi^a(k) | \mathcal{O} | p(p, s) \rangle = -\frac{i}{f_\pi} \langle 0 | [Q_5^a, \mathcal{O}] | p(p, s) \rangle + \frac{ig_A}{4f_\pi p \cdot k} \sum_{s'} \langle 0 | \mathcal{O} | p(p, s') \rangle \bar{u}(p, s') \not{k} \gamma_5 \tau^a u(p, s)$$

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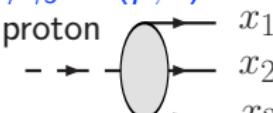
proton  
- - - - -  


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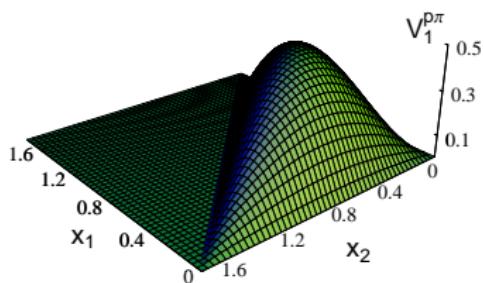
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- Can also be computed using e.g. the pion cloud model (not only for  $p_\pi \rightarrow 0$  then)

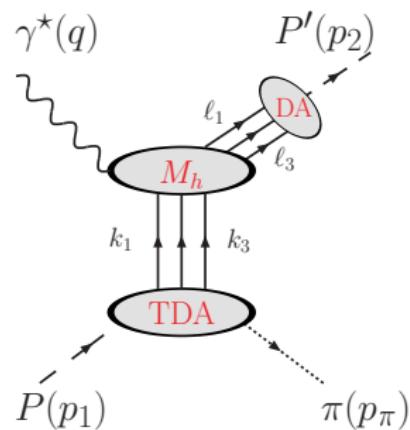
B. Pasquini, et al. PRD 80:014017, 2009.



# Backward electroproduction of a pion

→ First study of backward electroproduction of a pion for  $p_\pi \rightarrow 0$

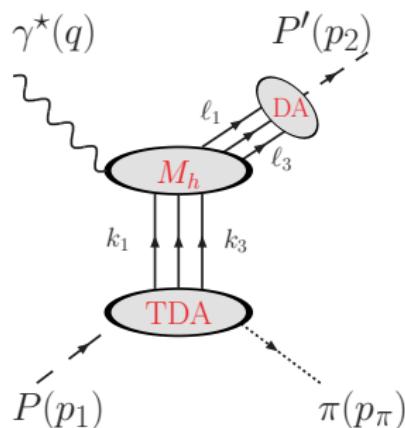
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→ To be compared with the pion cloud model and extended to  $\Delta_T \neq 0$

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

# Hard part: $M_h$ for $\gamma^* p \rightarrow p\pi^0$ at $\Delta_T = 0$

$$\begin{array}{c} u(x_1) \\ u(x_2) \\ d(x_3) \end{array} \xrightarrow{\quad \text{---} \quad} \begin{array}{c} u(p_1) \\ u(p_2) \\ d(y_3) \end{array}$$

$$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0} - A_1^{p\pi^0})(V^p - A^p) + 4T_1^{p\pi^0} T^p]}{(2\xi - x_1 - i\epsilon)^2(x_2 - i\epsilon)(1 - y_1)^2 y_3}$$

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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:

$$\begin{aligned} \mathcal{M}_{s_1 s_2}^{\lambda} = & -i \frac{(4\pi\alpha_s)^2 \sqrt{4\pi\alpha_{em}} f_N^2}{54f_{\pi}Q^4} \bar{u}(p_2, s_2) \not{e}(\lambda) \gamma^5 u(p_1, s_1) \\ & \times \int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y \left( 2 \sum_{\alpha=1}^7 T_{\alpha} + \sum_{\alpha=8}^{14} T_{\alpha} \right) \end{aligned}$$

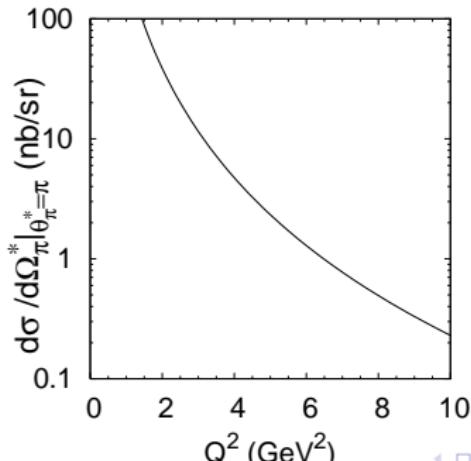
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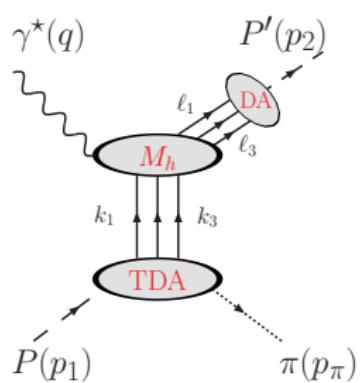
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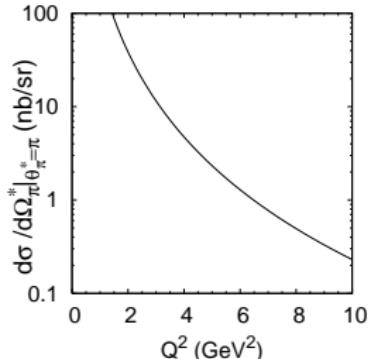
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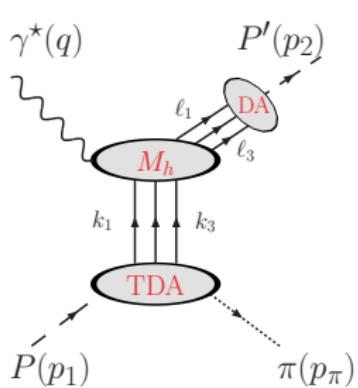
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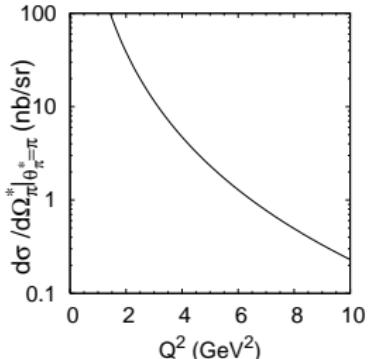
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# Backward Electroproduction of a pion: III



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



- Data from JLab exist for the  $\pi$  *Analysis on-going*
- “Visible peak in the yield of  $\omega$  at  $180^\circ$ ” (*G. Huber (JLab, Hall C), Sept. 2009*)
- Data for the electroproduction of  $\eta$  *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

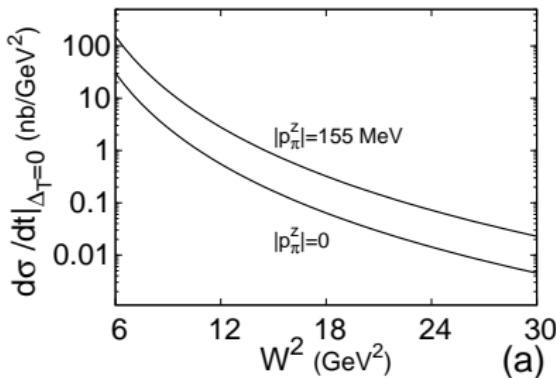
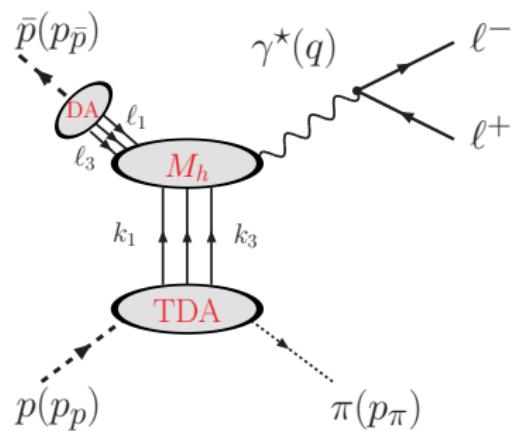
→  $p \rightarrow \pi$  TDAs can be studied in  $\bar{p}p \rightarrow \gamma^*(Q^2)\pi^0 \rightarrow \ell^+\ell^-\pi^0$

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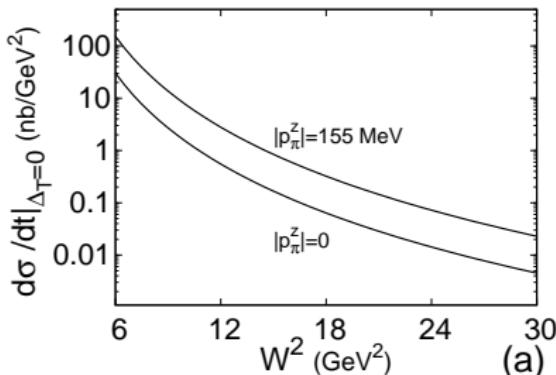
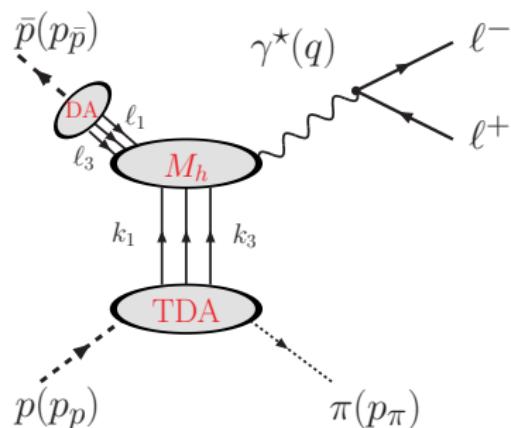
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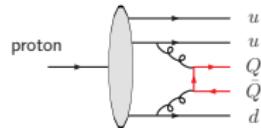


- Strictly the same TDAs as for electroproduction (JLab)
- Planned to be done with the proton FF studies in the timelike region

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

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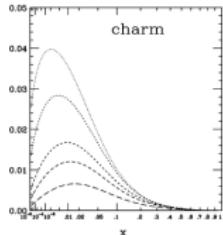
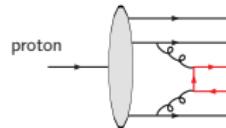
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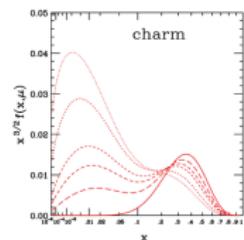
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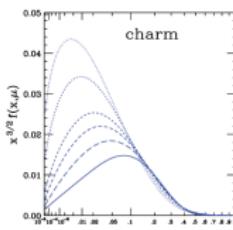
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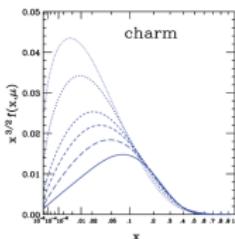
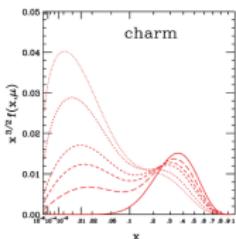
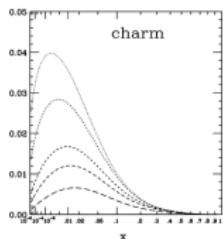
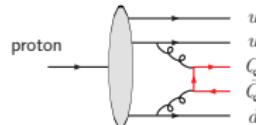
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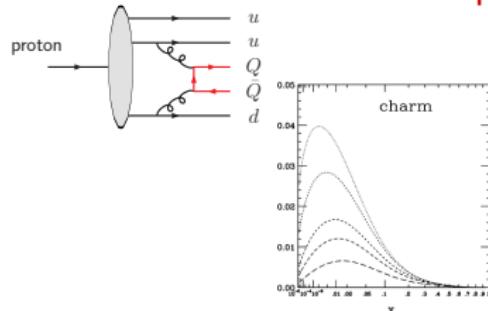
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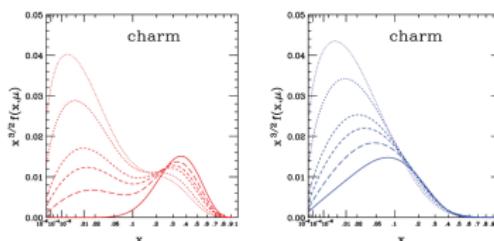
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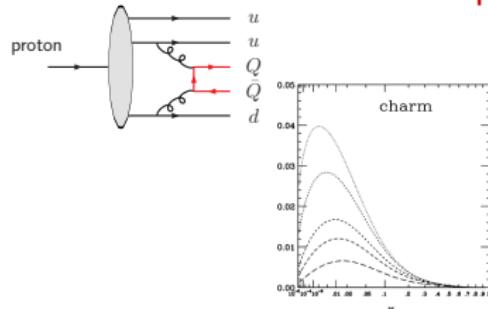
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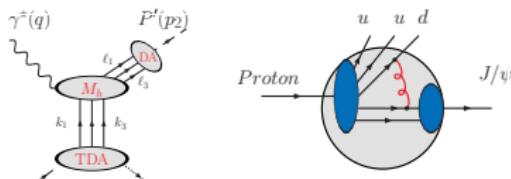
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- Dedicated test:  $\gamma^* p \rightarrow p J/\psi$  with sufficient  $W^2$

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

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- Stay tuned !

## Part III

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  - ⇒ Soft pion limit, pion cloud model: OK
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- ...expected from
  - ⇒ JLab-6 GeV: Backward electroproduction of  $\pi$ ,  $\eta$ ,  $\omega$
  - ⇒ GSI:  $p\bar{p} \rightarrow \gamma^*\pi^0$ ,  $p\bar{p} \rightarrow J/\psi\pi^0$ ,  $p\bar{p} \rightarrow \gamma^*\gamma$ , ...
  - ⇒ JLab-12 GeV: e.g. DVCS on pion
  - ⇒ *B*-factories ( $\gamma^*\gamma \rightarrow MM$ ) possible: TDA  $\gamma \rightarrow M$
  - ⇒ COMPASS (?):  $\gamma^*p \rightarrow pJ/\psi$

## Part IV

### Back-up

# $p \rightarrow \pi$ : parametrisation

$\Leftrightarrow p \rightarrow \pi$  (at Leading twist)

$\Rightarrow \Delta_T = 0$ : 3 TDAs ( $3 \times p(\uparrow) \rightarrow uud(\uparrow\uparrow\downarrow) + \pi$ )  
TDA

DA (Chernyak-Zhitnitsky)

$$4\langle \pi^0 | \epsilon^{ijk} u_\alpha^i(z_1 n) u_\beta^j(z_2 n) d_\gamma^k(z_3 n) | p, s_p \rangle \propto \\ \left[ V_1^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} C)_{\alpha\beta} (N_{s_p}^+)_\gamma + \right. \\ A_1^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} \gamma^5 C)_{\alpha\beta} (\gamma^5 N_{s_p}^+)_\gamma + \\ \left. T_1^{\pi^0}(x_i, \xi, \Delta^2) (\sigma_{\rho p} C)_{\alpha\beta} (\gamma^\rho N_{s_p}^+)_\gamma \right]$$

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$$\begin{aligned} V_1^{\pi^0} &\rightarrow D_{\uparrow\downarrow,\uparrow}^\uparrow + D_{\downarrow\uparrow,\uparrow}^\uparrow \\ A_1^{\pi^0} &\rightarrow D_{\uparrow\downarrow,\uparrow}^\uparrow - D_{\downarrow\uparrow,\uparrow}^\uparrow \\ T_1^{\pi^0} &\rightarrow D_{\uparrow\uparrow,\downarrow}^\uparrow \end{aligned}$$

B. Pasquini et al.

# $p \rightarrow \pi$ : parametrisation

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$$4\langle \pi^0(p_\pi) | \epsilon^{ijk} u_\alpha^i(z_1 n) u_\beta^j(z_2 n) d_\gamma^k(z_3 n) | p(p_1, s) \rangle = \frac{i f_N}{f_\pi} \times$$
$$\left[ V_1^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} C)_{\alpha\beta} (N^+)_\gamma + V_2^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} C)_{\alpha\beta} (\not{\Delta}_T N^+)_\gamma \right.$$
$$+ A_1^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} \gamma^5 C)_{\alpha\beta} (\gamma^5 N^+)_\gamma + A_2^{\pi^0}(x_i, \xi, \Delta^2) (\not{p} \gamma^5 C)_{\alpha\beta} (\gamma^5 \not{\Delta}_T N^+)_\gamma$$
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B. Pasquini et al.

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