

# $\pi N$ TDAs from charmonium production in association with a forward pion at $\bar{P}$ ANDA

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**Abstract.** Charmonium production in association with a forward or backward pion in nucleon-antinucleon annihilation is one of the most promising reaction to access nucleon-to-pion transition distribution amplitudes (TDAs) at  $\bar{P}$ ANDA. We briefly review the description of this reaction in terms of  $\pi N$  TDAs within the collinear factorization approach and present the first results of dedicated feasibility studies for the  $\bar{P}$ ANDA experimental setup.

## 1. Introduction

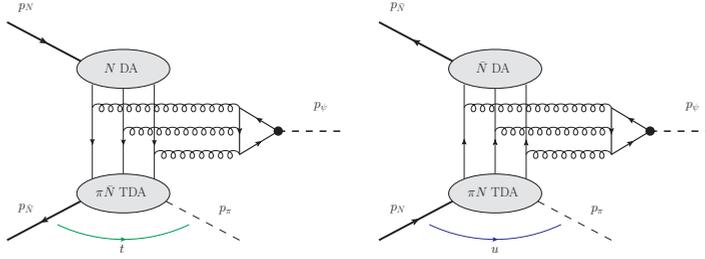
Baryon-to-meson transition distribution amplitudes (TDAs) [1–7] are universal non-perturbative objects which share common features both with generalized parton distributions (GPDs) and baryon distribution amplitudes (DAs) and arise in the collinear factorized description of several classes of hard exclusive reactions.

Dedicated studies of hard exclusive reactions providing access to baryon-to-meson TDAs were suggested [8] as a part of the future experimental program of  $\bar{P}$ ANDA facility [9], which is currently under construction at GSI-FAIR. Extracting baryon-to-meson TDAs from the experimental measurements will provide valuable complementary information on the hadronic structure and deepen our understanding of the strong interaction phenomena (see *e.g.* the discussion in Refs. [5, 6]).

The  $\bar{P}$ ANDA experimental setup provides several options to access hard exclusive reactions admitting description in terms of baryon-to-meson TDAs. Prominent examples are nucleon-antinucleon annihilation into the high invariant mass lepton pair [3, 7] (or charmonium [10]) in association with a pion. Detailed feasibility studies of the corresponding reactions are of major importance since measurements at  $\bar{P}$ ANDA will give the unique opportunity to check explicitly the universality [11] of baryon-to-meson TDAs providing information on the time-like regime, which is complementary to that from the lepton beam induced reactions, which can be studied *e.g.* at JLab [2, 6].

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**Figure 1.** Collinear factorization of the annihilation process (1). Left panel: forward kinematics ( $t \sim 0$ ). Right panel: backward kinematics ( $u \sim 0$ ).  $N(\bar{N})$  DA stands for the distribution amplitude of antinucleon (nucleon);  $\pi\bar{N}(\pi N)$  TDA stands for the transition distribution amplitude from an antinucleon (nucleon) to a pion.

## 2. QCD description of charmonium plus pion production in antinucleon-nucleon annihilation

Study of charmonium production in association with a pion in proton-antiproton annihilation can be seen as the one of the most perspective ways to access  $\pi N$  TDAs at PANDA. Indeed, historically [12] the description of charmonium exclusive decays into hadrons has been one of the first examples of successful applications of perturbative QCD methods for hard exclusive reactions. The annihilation of the  $c\bar{c}$  pair into the minimal possible number of gluons producing quark-antiquark pairs, which then form outgoing hadrons, was recognized to be the dominant mechanism. The factorized description of

$$\bar{N}(p_{\bar{N}}) + N(p_N) \rightarrow J/\psi(p_\psi) + \pi(p_\pi) \quad (1)$$

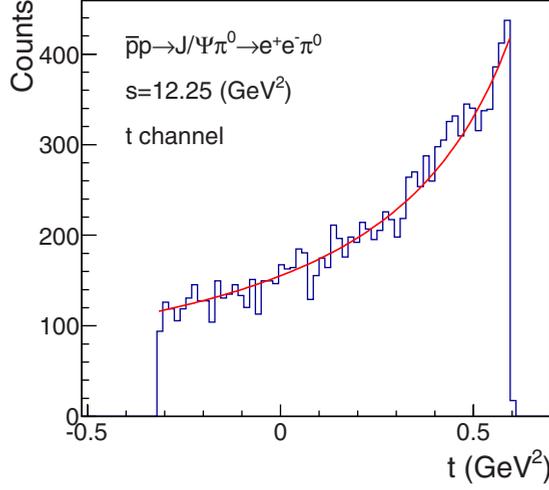
in terms of  $\pi N$  TDAs and nucleon DAs proposed in [10] is based on the extension of the same perturbative QCD framework. The  $\bar{N}N$  center-of-mass energy squared  $s = (p_N + p_{\bar{N}})^2 = W^2$  and the charmonium mass squared  $M_\psi^2$  introduce the natural hard scale for the problem. It is argued that the reaction (1) admits a factorized description in the near forward ( $t \equiv (p_\pi - p_{\bar{N}})^2 \sim 0$ ) and near backward ( $u \equiv (p_\pi - p_N)^2 \sim 0$ ) kinematical regimes. The corresponding mechanisms are presented on Fig. 1. Similarly to the case of  $\bar{N}N$  annihilation into a high invariant mass lepton pair in association with a pion,  $C$  invariance results in the perfect symmetry between the forward and backward regimes of the reaction (1).

Below for definiteness we consider the near forward regime. The  $z$  axis is chosen along the colliding  $\bar{N}N$  with the positive direction along the antinucleon beam. We introduce the light-cone vectors satisfying  $2p^+ \cdot n^+ = 1$  and define the  $t$ -channel skewness variable  $\xi \equiv -\frac{(p_\pi - p_{\bar{N}}) \cdot n^+}{(p_\pi + p_{\bar{N}}) \cdot n^+} \simeq \frac{M_\psi^2}{2W^2 - M_\psi^2}$ . Following [13], in our calculation we set the relevant masses to the average value  $M_\psi \simeq 2m_c \simeq \bar{M} = 3$  GeV. The physical kinematical domain for the reaction (1) in the backward regime is determined by the requirement that the transverse momentum transfer should be space-like:  $(p_\pi - p_{\bar{N}})_T^2 \equiv \Delta_T^2 \leq 0$ , where  $\Delta_T^2 = \frac{1-\xi}{1+\xi} \left( t - 2\xi \left[ \frac{m_{\bar{N}}^2}{1+\xi} - \frac{m_\pi^2}{1-\xi} \right] \right)$ .

The leading order amplitude of the reaction (1) from the mechanism presented on Fig. 1 was computed in [10]. It reads:

$$\mathcal{M}_\lambda^{S_N S_{\bar{N}}} = \mathcal{C} \frac{1}{\bar{M}^5} \bar{V}(p_{\bar{N}}, S_{\bar{N}}) \left[ \hat{\mathcal{E}}^*(\lambda) \gamma_5 \mathcal{J}(\xi, t) - \frac{1}{m_N} \hat{\mathcal{E}}^*(\lambda) \hat{\Delta}_T \gamma_5 \mathcal{J}'(\xi, t) \right] U(p_N, S_N), \quad (2)$$

were  $U$  and  $V$  are the usual Dirac spinors,  $\hat{\mathcal{E}}$  denotes the charmonium polarization vector and  $\mathcal{J}, \mathcal{J}'$  stand for the convolutions of the hard kernels with  $\pi\bar{N}$  TDAs and nucleon DAs. The explicit expressions for  $\mathcal{J}, \mathcal{J}'$  worked out in [10] allow the calculation of these convolutions within specific



**Figure 2.** Counting rates for  $2 \text{ fb}^{-1}$  integrated luminosity for the near forward regime of the reaction (1) from the “PpbarJpsiPi0” event generator model in the PANDARoot. The blue histogram shows the results from the generator for bins in  $t$  down from  $t_{\text{max}}$  (corresponding to exactly forward  $\pi$  production). The red line shows the shape of the theoretical prediction from the nucleon pole exchange model used as the normalization input for the event generator.

phenomenological models for  $\pi N$  TDAs. The normalization factor  $\mathcal{C}$  in (2) reads  $\mathcal{C} = (4\pi\alpha_s)^3 \frac{f_N^2 f_\psi}{f_\pi} \frac{10}{81}$ , where  $\alpha_s$  is the strong coupling,  $f_\pi = 93 \text{ MeV}$  is the usual pion decay constant and  $f_\psi = 413 \pm 8 \text{ MeV}$  is the normalization constant of the heavy quarkonium wave function. Its value is fixed from the charmonium leptonic decay width  $\Gamma(J/\psi \rightarrow e^+ e^-)$ .

Within the suggested reaction mechanism it is the transverse polarization of charmonium that is relevant to the leading twist accuracy. Summing over the transverse polarizations of charmonium and averaging over spins of initial nucleon and antinucleon we get

$$|\overline{\mathcal{M}}_T|^2 \equiv \sum_{\lambda_T} \frac{1}{4} \sum_{s_N s_{\bar{N}}} \mathcal{M}_\lambda^{s_N s_{\bar{N}}} (\mathcal{M}_{\lambda'}^{s_N s_{\bar{N}}})^* = \frac{1}{4} |\mathcal{C}|^2 \frac{2(1+\xi)}{\xi \bar{M}^8} \left( |\mathcal{J}(\xi, t)|^2 - \frac{\Delta_T^2}{m_N^2} |\mathcal{J}'(\xi, t)|^2 \right). \quad (3)$$

Therefore, the leading twist differential cross section of  $N + \bar{N} \rightarrow J/\psi + \pi$  reads

$$\frac{d\sigma}{dt} = \frac{1}{16\pi\Lambda^2(s, m_N^2, m_{\bar{N}}^2)} |\overline{\mathcal{M}}_T|^2, \quad \text{where } \Lambda(x, y, z) = \sqrt{x^2 + y^2 + z^2 - 2xy - 2xz - 2yz}. \quad (4)$$

### 3. Counting rates studies for PANDA

The dedicated feasibility studies of the reactions admitting description in terms of baryon-to-meson TDAs are now coming into the focus of intensive studies of several experimental groups involved into the PANDA project. The new event generator within the PANDARoot framework was developed by one of us (Bingsong Ma) in close collaboration with Beatrice Ramstein. It allows the estimation of the expected counting rates for the reaction (1) in the near forward and near backward kinematical regimes. Below we show the first results for the near forward regime for  $s = 12.25 \text{ GeV}^2$ . As the model input for the cross section the estimates of Ref. [10] within the nucleon pole model [5] for  $\pi N$  TDAs are employed.

With the integrated luminosity  $2 \text{ fb}^{-1}$  (which corresponds to 4 months of beamtime at full luminosity) and assuming for the moment 100% particle detection efficiency the expected total number

of events is  $N_{\text{tot}} = 13000$  for near forward  $\pi^0$  emission. Moreover, even better statistics can be expected if one simultaneously takes into account the information from the backward regime. On Fig. 2 we show the results of studies of counting rates. The blue histogram shows the results from the generator for bins in  $t$ . The bin size is  $0.015 \text{ GeV}^2$ . The red line shows the shape of the theoretical prediction from the nucleon pole exchange model. The expected large statistics makes us hope for the bright perspectives of accessing  $\pi N$  TDAs through (1) at PANDA.

We would like to thank B. Ramstein for her useful help and advises. We also acknowledge helpful discussions with T. Hennino, J.P. Lansberg, F. Maas and M. Zambrana. This work is supported in part by the Polish Grant NCN No DEC-2011/01/B/ST2/03915, the Joint Research Activity “Study of Strongly Interacting Matter” (acronym HadronPhysics3, Grant 283286) under the Seventh Framework Programme of the European Community and by the COPIN-IN2P3 Agreement and by the Tournesol 2014 Wallonia-Brussels-France Cooperation Programme.

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