Eur. Phys. J. C 51, 619–624 (2007)
DOI 10.1140/epjc/s10052-007-0312-9

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

# Single spin asymmetry for charm mesons

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Received: 31 October 2006 / Revised version: 17 February 2007 /
Published online: 17 May 2007 – 

**Abstract.** We study single spin asymmetries of $\bar{D}^0$ and $D^-$ mesons in polarized proton–proton collisions. A two component model is used to describe charm meson production. The production of $D$ mesons occurs by recombination of the constituents present in the initial state as well as by fragmentation of quarks in the final state. This model has proved to describe the production of charm. The recombination component involves a mechanism of spin alignment that ends up in a single spin asymmetry. Experimental measurements of single spin asymmetry for pions at RHIC are compared with the model. Predictions for the asymmetry in $D$ mesons are presented.

## 1 Introduction

Single spin asymmetries have received much attention in recent years. This is so mainly because this asymmetry has implications for our understanding of quantum chromodynamics (QCD). A model calculation in a gauge theory has been undertaken in [1]. In that work it is shown that final state interactions in deep inelastic lepton–proton scattering lead to single spin asymmetries at leading twist in perturbative QCD. Single spin asymmetries are produced by the interference of complex phases in the amplitudes that couple to the same final state.

The Fermilab E704 Collaboration [2–4] observed a strong asymmetry in inclusive production of charged and neutral pions with polarized proton and anti-proton beams. This experiment found a strong dependence on $x_\mathrm{F}$ of this asymmetry. Other measurements are now available [5–8].

The single spin asymmetry is defined by

$$A(x_\mathrm{F}, p_\mathrm{T}) = \frac{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow}{\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow} \tag{1}$$

where $\mathrm{d}\sigma^\uparrow$ and $\mathrm{d}\sigma^\downarrow$ represent the differential cross section of particle production when the proton comes with spin up or down with respect to the production plane.

To explain single spin asymmetries, several models have been proposed [9–18]. The Collins effect considers single spin asymmetries as the result of different hadronizations for quarks with different polarization. Along these lines we present here a mechanism that would explain such a difference. Anselmino et al. [19] predict a single spin asymmetry in $D$ mesons at RHIC energies. They obtained a positive and small asymmetry.

In a two component model, the total cross section for the production of $D$ mesons is given by

$$\frac{\mathrm{d}\sigma^D}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}p_\mathrm{T}} = \frac{\mathrm{d}\sigma^D_\mathrm{rec}}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}p_\mathrm{T}} + \frac{\mathrm{d}\sigma^D_\mathrm{frag}}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}p_\mathrm{T}} \tag{2}$$

where the label indicates the process involved, "rec" stands for recombination, and "frag" stands for fragmentation and represents the contribution of quarks that hadronize in the final state. Measurements of $\pi^0$ production at RHIC show a single spin asymmetry, which is positive and large at high $x_\mathrm{F}$ [20].

Charm mesons represent a new system where a heavy quark is produced. It is therefore interesting to look at single spin asymmetries in this framework. Production of heavy quarks have been extensively studied both experimentally and theoretically. This sets the guideline to study new phenomena, namely spin asymmetries, in the production of heavy quarks.

## 2 The two component model

A two component model has been successfully used to describe the production asymmetry of charm hadrons [21–23]. The leading particle effect can be explained by considering the initial state in the hadronization process. The two component model takes into account the initial state in the collision of hadrons. The remnants of colliding particles modify the differential cross section of the produced particles. In what follows we will study the effects of the initial spin of the proton on each of these processes, namely recombination and fragmentation.

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### 2.1 The recombination process

In recombination, the production of hadrons occurs when, e.g., a quark from the sea of the proton joins a valence quark present in the initial state. In this process the sea quark is accelerated and Thomas precession seems to have an impact on the final state [24, 25]. In the recombination mechanism, we make use of the correlation between the polarized proton and the orientation of the $u$ quark. In order to produce a $\bar{D}^0$ meson, the valence $u(\uparrow)$ quark in the upwards polarized proton recombines with a $\bar{c}$ from the sea. The $\bar{c}$ quark must flip its spin down to form a $D$ scalar meson. In order to produce a $D^-$ meson, the valence $d(\downarrow)$ quark from the upwards polarized proton recombines with a $\bar{c}$ quark from the sea.

In the recombination process, the differential cross section for $\bar{D}^0$ production when the proton comes with the spin up can be written

$$\left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}}\right|_{\bar{D}^0} \sim g^{\uparrow}_{u}|M^{\downarrow}_{\bar{c}}|^2 + g^{\downarrow}_{u}|M^{\uparrow}_{\bar{c}}|^2 \,, \tag{3}$$

where $g^{\uparrow}_{u}$ represents the probability of finding a $u$ quark in the proton aligned with the proton spin and $g^{\downarrow}_{u}$ the probability of finding it anti-aligned.

For the case when the proton comes with spin down, the differential cross section can be written as

$$\left.\frac{\mathrm{d}\sigma^{\downarrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}}\right|_{\bar{D}^0} \sim h^{\uparrow}_{u}|M^{\downarrow}_{\bar{c}}|^2 + h^{\downarrow}_{u}|M^{\uparrow}_{\bar{c}}|^2 \tag{4}$$

where $h^{\uparrow}_{u}(h^{\downarrow}_{u})$ denotes the probability of finding a $u$ quark in a proton anti-aligned (aligned) with its spin down. In both cases, $M$ denotes the probability of spin flip at the moment of recombination for the $\bar{c}$ quark.

For $D^-$ production, the differential cross section via recombination when the proton comes with spin up (down) is given by

$$\left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}}\right|_{D^-} \sim g^{\uparrow}_{d}|M^{\downarrow}_{\bar{c}}|^2 + g^{\downarrow}_{d}|M^{\uparrow}_{\bar{c}}|^2 \tag{5}$$

$$\left.\frac{\mathrm{d}\sigma^{\downarrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}}\right|_{D^-} \sim h^{\uparrow}_{d}|M^{\downarrow}_{\bar{c}}|^2 + h^{\downarrow}_{d}|M^{\uparrow}_{\bar{c}}|^2 \tag{6}$$

where $g^{\uparrow}_{d}(g^{\downarrow}_{u})$ denotes the probability of having a $d$ quark aligned (anti-aligned) with the proton spin and similarly $h^{\uparrow}_{d}(h^{\downarrow}_{u})$ when the proton comes with its spin down.

We will follow the lines of the recombination model used in [24, 25]. According to that, the scattering amplitude for $p(\uparrow,\downarrow) \to D + X$ is inversely proportional to the energy difference between intermediate (i) and final state (f) [24, 25], i.e.

$$M_s \propto \frac{1}{\Delta E \pm \mathbf{S}\cdot\omega_{\mathrm{T}}} \,, \tag{7}$$

where $\Delta E$ represents the change in energy in going from the quarks to the hadronic final state in the absence of the spin effect, $\omega_{\mathrm{T}}$ denotes the Thomas frequency, and the sign depends on the orientation of the spin. In the infinite momentum frame, $\Delta E$ for $\bar{D}^0$ production can be written as

$$\Delta E_{\bar{D}^0} = \frac{1}{2x_{\mathrm{F}}p}\left[\frac{p^2_{\mathrm{T}_{\bar{u}}} + m^2_{\bar{u}}}{1-\xi} + \frac{p^2_{\mathrm{T}_c} + m^2_c}{\xi} - p^2_{\mathrm{T}_{\bar{D}^0}} - m^2_{\bar{D}^0}\right] \tag{8}$$

with $\xi = \frac{x_{\bar{c}}}{x_{\mathrm{F}}}$ and $x_{\mathrm{F}} = x_u + x_{\bar{c}}$. Here $m_{\bar{u}}$ and $m_c$ are the masses of the quarks involved in the recombination process, and $m_{\bar{D}^0}$ is the mass of the charm meson formed with transverse momentum $p_{\mathrm{T}_{\bar{D}^0}}$. The quarks have a transverse momenta $p_{\mathrm{T}_{\bar{u}}}$ and $p_{\mathrm{T}_c}$ at the moment of coalescence. We assume that the $x_{\mathrm{F}}$ carried by the meson is given by the sum of the momentum fraction of the quarks that recombine to build it. In that process $\xi$ is a function describing the momentum transfer of the $\bar{c}$ quark during meson formation, i.e. it maps the momentum of the quark in the initial state to the final momentum of the meson.

The Thomas frequency is given by

$$\omega_{\mathrm{T}} = \frac{4(1-2\xi)}{x_{\mathrm{F}}p\Delta X_0(1+2\xi)^2}p_{\mathrm{T}_h} \,. \tag{9}$$

As in (8), $p$ is the momentum in the center of mass of the collision. $\Delta X_0$ is the scale where recombination takes place. A more detailed presentation of the precession model can be found in [24, 25].

In [26], $\xi(x_{\mathrm{F}})$ is explicitly computed using a recombination model for the $\Lambda^0$ baryon formation. According to the results presented in [26], the effect does not change drastically when a linear parametrization for $\xi(x_{\mathrm{F}})$ is used. Henceforth we use

$$\xi(x_{\mathrm{F}}) = \frac{1}{2}(1-x_{\mathrm{F}}) + 0.1x_{\mathrm{F}} \tag{10}$$

for the sake of simplicity [24, 25]. We take $m_u = 0.005$ GeV, $m_d = 0.010$ GeV and $m_c = 1.5$ GeV in agreement with the PDG values [27]. As in [24, 25], we use $\langle p^2_{\mathrm{T}}\rangle_{u,d} = p^2_{\mathrm{T}_h}/4 + \langle k^2_{\mathrm{T}}\rangle$ with $\langle k^2_{\mathrm{T}}\rangle = 0.25\,\mathrm{GeV}^2$. The scale $\Delta X_0$ is fixed to $5\,\mathrm{GeV}^{-1}$, which is a reasonable value considering the scale of the recombination process. Finally $m_{\bar{D}^0} = 1.864$ GeV and $m_{D^-} = 1.869$ GeV.

### 2.2 The fragmentation process

We assume that particles created by the fragmentation process lose information about the spin polarization of the proton in the initial state. They do not contribute to the single spin asymmetries, i.e.

$$\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{frag}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}\sigma^{\downarrow}_{\mathrm{frag}}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p_{\mathrm{T}}} \,. \tag{11}$$

The differential cross section for $D$ meson production is usually characterized as follows:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}p^2_{\mathrm{T}}} \sim (1-|x_{\mathrm{F}}|)^n \exp(-bp^2_{\mathrm{T}}) \,. \tag{12}$$

This parametric equation describes the experimental data very well. Here $n$ depends on the type of hadron produced in the fragmentation and it grows with increasing energy. We use $n = 8.6$ and $b = 0.8$ at $\sqrt{s} = 38.8$ GeV for $pp$ interactions and $D$ meson production [28]. The final results do not depend strongly on the values of $n$ and $b$. We studied the behavior of the spin asymmetries for different values of these parameters and found no significant change. The change in the values $n$ from say 4 to 12 (or $b$ from 0.3 to 4) change the lower part of $x_\mathrm{F}$ in the asymmetry, but the difference is too small to be considered. This is expected since the asymmetry is generated by the recombination component in the production.

## 3 Single spin asymmetries

In the scenario where the $\bar{D}^0$ and $D^-$ meson originate from two different processes, the single spin asymmetry (1) is given by

$$A_N(x_\mathrm{F}, p_\mathrm{T}) = \frac{\mathrm{d}\sigma^\uparrow_\mathrm{rec} - \mathrm{d}\sigma^\downarrow_\mathrm{rec}}{\mathrm{d}\sigma^\uparrow_\mathrm{rec} + \mathrm{d}\sigma^\downarrow_\mathrm{rec} + 2\,\mathrm{d}\sigma_\mathrm{frag}}\,. \tag{13}$$

The fragmentation components in the numerator cancel each other; see (11). Using (3) and (4) we obtain

$$A_N^{\bar{D}^0}(x_\mathrm{F}, p_\mathrm{T}) = \frac{(g_u^\uparrow - g_u^\downarrow)(|M_{\bar{c}}^\downarrow|^2 - |M_{\bar{c}}^\uparrow|^2)}{(g_u^\uparrow + g_u^\downarrow)(|M_{\bar{c}}^\downarrow|^2 + |M_{\bar{c}}^\uparrow|^2) + 2\,\mathrm{d}\sigma_\mathrm{frag}}\,. \tag{14}$$

Using (7) for the amplitudes $M_{\bar{c}}{}^\uparrow$ and $M_{\bar{c}}^\downarrow$, the single spin asymmetries for $\bar{D}^0$ production can be written as

$$A^{\bar{D}^0}(x_\mathrm{F}, p_\mathrm{T}) = \frac{g_u^\uparrow - g_u^\downarrow}{g_u^\uparrow + g_u^\downarrow}\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{1}{1 + \frac{\Delta E^2\,\mathrm{d}\sigma_\mathrm{frag}}{g_u^\uparrow + g_u^\downarrow}}\right]. \tag{15}$$

In a similar way, for a $D^-$ meson we obtain

$$A_N^{D^-}(x_\mathrm{F}, p_\mathrm{T}) = \frac{g_d^\uparrow - g_d^\downarrow}{g_d^\uparrow + g_d^\downarrow}\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{1}{1 + \frac{\Delta E^2\,\mathrm{d}\sigma_\mathrm{frag}}{g_d^\uparrow + g_d^\downarrow}}\right], \tag{16}$$

where $\frac{\delta u}{u} = \frac{g_u^\uparrow - g_u^\downarrow}{g_u^\uparrow + g_u^\downarrow}$ and $\frac{\delta d}{d} = \frac{g_d^\uparrow - g_d^\downarrow}{g_d^\uparrow + g_d^\downarrow}$ represent the transversities of the quarks in the proton. The transversity distribution is the difference in the number of quarks with transverse polarization parallel and antiparallel to the proton transverse polarization. It is of fundamental importance for our understanding of the nucleon structure.

## 4 Transversity distribution models

The transversity gives the distribution of quarks with transverse spin inside a transversely polarized hadron. We do not know much about transversities. The transversity distributions $\frac{\delta q}{q}$ have never been measured. The reason is that the usual source of information on the nucleon partonic structure is deep inelastic scattering, but transversity distributions are chirally odd in inclusive processes of DIS, and observable effects are therefore absent. It has been suggested that transversities can be measured through spin asymmetries, but as we will show here, asymmetries are a combined effect of $\frac{\delta q}{q}$ and the spin dependent hadronization. Some estimates of the transversities have been worked out and we will use some of them to get some insight into the effect they may have upon single spin asymmetries.

### 4.1 Naive model of transversity

Theoretically one can obtain some constraints on $\frac{\delta q}{q}$ [15–18]. The wave function of the proton can be used to determine the polarization of the valence quarks inside. In accordance with this, $\frac{5}{3}$ of the $u$ valence quarks in a polarized proton on average are aligned in the same direction as the proton spin. On the other side, $\frac{1}{3}$ of the $d$ valence quarks are aligned with the proton spin. In this model, the sea quark pairs are not polarized. A parametrization for the quark distribution [29, 30] is used and the transversities are

$$\frac{\delta u}{u} = \frac{2}{3}$$
$$\frac{\delta d}{d} = -\frac{1}{3}\,. \tag{17}$$

Figure 1 shows the transversity together with other model predictions. Note that the transversity for $d$ is smaller than for $u$ quarks.

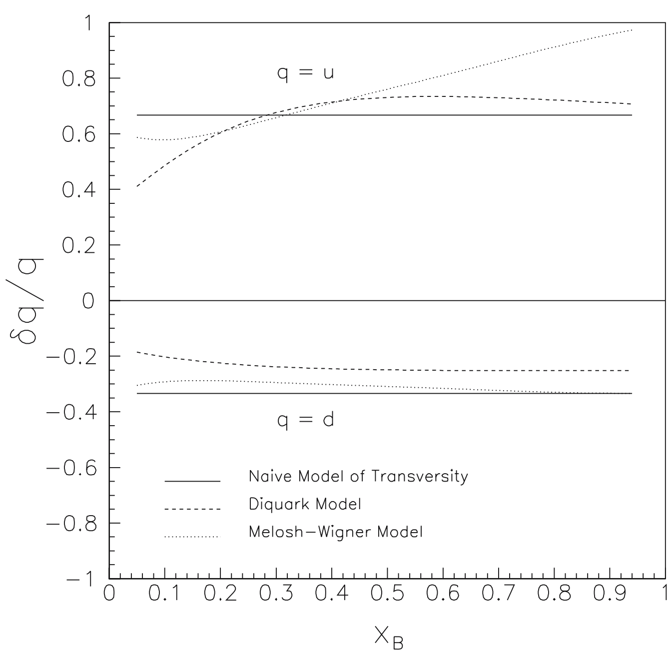


**Fig. 1.** Transversities of the proton according to the three models in [15–18, 31–40], discussed in the text

### 4.2 Diquark model of transversity

Within the framework of the quark–diquark model, the diquark serves as an effective particle, which is called the spectator [31–33]. In the quark–diquark model a two-quark function is used to describe hadrons with spin 0 or 1. Some nonperturbative effects, such as gluon exchange in the hadronic debris, can be effectively taken into account by the mass of the diquark spectator. More explicitly, the unpolarized valence quark distribution in the proton can be expressed as the probability of finding a quark $q$ to be scattered, while the diquark spectator is in a $D$ state (S or V) and the transversity distribution can be written

$$\begin{aligned}\frac{\delta u}{u} &= \frac{2}{3}\left\{\frac{(xM_P+m_u)^2[9\hat{R}_{\mathrm{V}}^6-\hat{R}_{\mathrm{S}}^6]}{(xM_P+m_u)^2(3\hat{R}_{\mathrm{V}}^6+\hat{R}_{\mathrm{S}}^2)+3\hat{R}_{\mathrm{S}}^2\hat{R}_{\mathrm{V}}^6+\hat{R}_{\mathrm{V}}^2\hat{R}_{\mathrm{S}}^6}\right\}\\ \frac{\delta d}{d} &= -\frac{2}{3}\frac{(xM_P+m_d)^2}{[2(xM_P+m_d)^2+\hat{R}_{\mathrm{V}}^2]}\,,\end{aligned} \tag{18}$$

where $\hat{R}_{\mathrm{V}}$ and $\hat{R}_{\mathrm{S}}$ are given by

$$\hat{R}_{\mathrm{V}} = \sqrt{\Lambda_0^2(1-x)+xm_{\mathrm{V}}-x(1-x)M_p^2}$$
$$\hat{R}_{\mathrm{S}} = \sqrt{\Lambda_0^2(1-x)+xm_{\mathrm{S}}-x(1-x)M_p^2}$$

here $\Lambda_0$ is a mass parameter and we adopted a value of 0.5 GeV in our numerical calculation. In a similar way, $m_{\mathrm{S}}$ and $m_{\mathrm{V}}$ are the masses of the diquark in a scalar and vector spin state and $M_p$ the mass of the proton. We use the following values in our simulation: 0.9 GeV, 1.1 GeV and 0.938 GeV, respectively. The quark masses are taken as $m_u = m_d = 0.35$ GeV [31–33].

### 4.3 Melosh–Wigner model of transversity

The quantity $\frac{\delta q}{q}$ to be measured in polarized deep inelastic scattering is defined by the axial current matrix element. In the light-cone or quark–parton description, $\frac{\delta q}{q} = q^{\uparrow}(x) - q^{\downarrow}(x)$, where $q^{\uparrow}(x)$ and $q^{\downarrow}(x)$ are the probabilities of finding a quark or antiquark with longitudinal momentum fraction $x$ and polarization parallel or antiparallel to the proton spin in the infinite momentum frame. The Wigner rotation factor ranges from 0 to 1; thus $\frac{\delta q}{q}$ measured in polarized deep inelastic scattering cannot be identified with the spin carried by each quark flavor in the proton rest frame. They write quark transversity distributions for $u$ and $d$ (the light-cone SU(6) quark-spectator model) as [34–40] follows:

$$\begin{aligned}\delta u &= \left[u_{\mathrm{V}}(x)-\frac{1}{2}d_{\mathrm{V}}(x)\right]W_{\mathrm{S}}(x)+\frac{1}{6}d_{\mathrm{V}}(x)W_{\mathrm{V}}(x)\\ \delta d &= -\frac{1}{3}d_{\mathrm{V}}(x)W_{\mathrm{V}}(x)\,,\end{aligned} \tag{19}$$

where $W_{\mathrm{S}}(x)$ and $W_{\mathrm{V}}(x)$ are the Melosh–Wigner rotation factors. They use the GRV parameterization of unpolarized quark distributions [41] as input for $u, d$ quarks.

In Fig. 1, we show the transversity for these models as a function of $x_B$.

## 5 Results

A similar analysis has been done for pion production with a polarized beam. As in charm meson production, pions may be produced by recombination. As in the case of charm mesons the pions are formed by a valence quark present in the initial state, which coalesces with a sea quark. We test the ideas presented here with the data already available in pion production. Figures 2 and 3 show single spin asymmetries measured for $\pi^0$, with transverse momentum $0.2 < p_{\mathrm{T}} < 2.0$ GeV and $0.3 < p_{\mathrm{T}} < 1.2$ GeV in proton–proton collisions [2–4]. The curves correspond to the model presented here and with transversities as discussed above. We can see that the diquark model [31–33] shows a good behavior at small $x_{\mathrm{F}}$, and it describes the data at high values of $x_{\mathrm{F}}$ too.

We next go to higher energies and compare the result with the data obtained at RHIC [20]. Figure 4 shows the single spin asymmetry for $\pi^0$ [20] as a function of $x_{\mathrm{F}}$ for $p_{\mathrm{T}} > 1.0$ GeV. The models using the three transversity parametrizations are shown together.

As in the case of Figs. 2 and 3, the model of [31–33] has a good behavior at small and high $x_{\mathrm{F}}$.

Figure 5 shows the single spin asymmetries for $\bar{D}^0$ and $D^-$ production, with three different transversities, as it would be seen at RHIC energies. The asymmetry

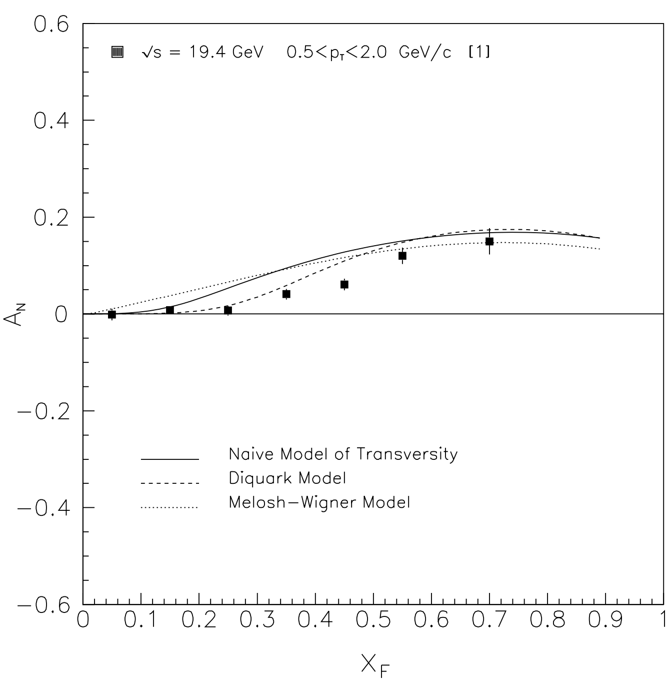


**Fig. 2.** Single spin asymmetry for $\pi^0$ [2–4] in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]. The center of mass energy of the reaction is $\sqrt{s} = 19.4$ GeV

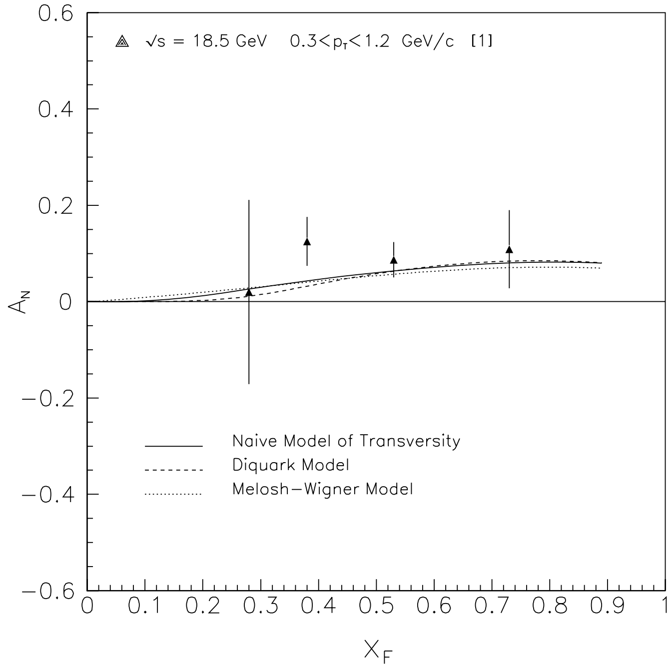


**Fig. 3.** Single spin asymmetry for $\pi^0$ [2–4] in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]. The center of mass energy of the reaction is $\sqrt{s} = 18.5$ GeV

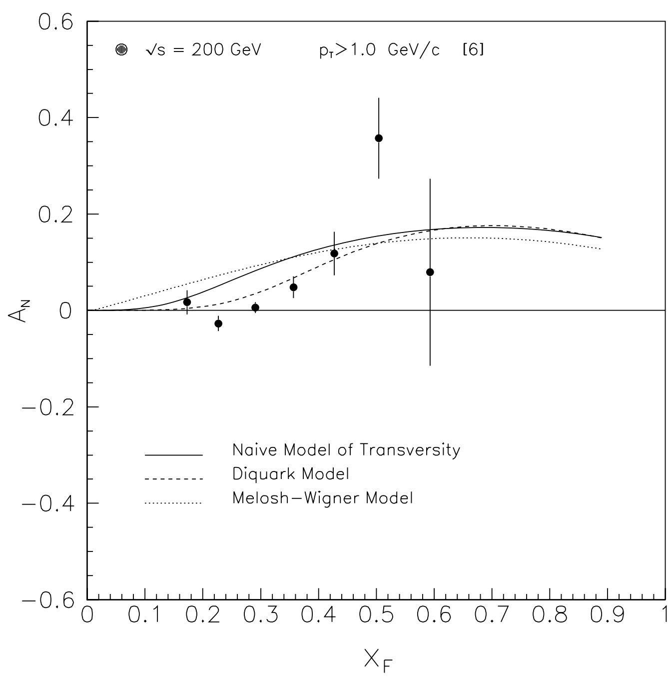


**Fig. 4.** Single spin asymmetry for $\pi^0$ [20] in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]. The center of mass energy of the reaction is $\sqrt{s} = 200$ GeV

grows with $x_{\mathrm{F}}$ up to a maximum value. Note that the vertical scale is different from the one used in Figs. 2 and 3.

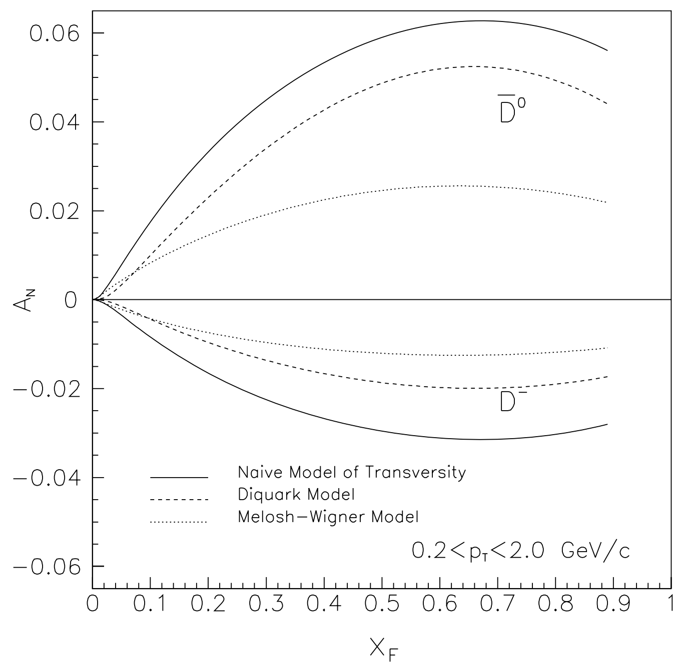


**Fig. 5.** Single spin asymmetry for $\bar{D}^0$ and $D^-$ in the framework of the two component model with three different transversity parametrizations [15–18, 31–40]

The single spin asymmetries predicted for charm mesons are smaller than for $\pi^0$.

The origin of single spin asymmetries has been attributed to the different aspects of particle production: polarized structure functions and polarized fragmentation functions.

In [1] the authors use a QCD motivated quark–diquark model of a nucleon to calculate single spin asymmetries in semi-inclusive electroproduction. Single spin asymmetries in deep inelastic scattering have also been studied in [42]. The authors present a discussion of different approaches and relate some aspects that may link with the physics behind. In [43] the transverse momentum distributions are associated with nonperturbative QCD effects.

Here we present a two component model to explain the phenomena. In general terms the model describes quantitatively the experimental data.

A prediction for $\bar{D}^0$ and $D^-$ at RHIC energies is obtained using three different transversity parametrizations. The models for the transversity used here seem to have a small effect on the final prediction. However, it is important to mention that in using transversities we assumed factorization (see (3) and (4)) for the parton densities. At the slender level of rigor of our model we use this approach, which could be solved with a more involved procedure and deeper knowledge of the parton functions.

Figure 6 shows the asymmetries obtained with the model presented here with those in [19]. The two curves of the model by Anselmino et al. correspond to (a) the maximized quark Siver function keeping the gluon Sivers function to zero and (b) to a maximized gluon Sivers function with the corresponding quark function set to zero. In

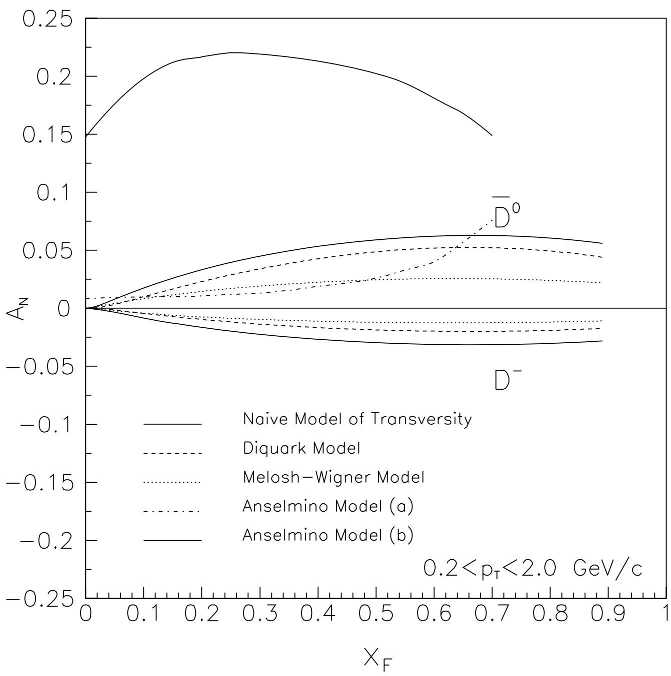


**Fig. 6.** Comparison of the single spin asymmetries obtained with the model presented here (*solid*, *dash* and *dotted curves*) with those obtained by Anselmino et al. [19] (*solid* in the upper part and *dot dashed curve*)

their model, Anselmino et al. obtain these asymmetries for $D = D^0, \bar{D}^0, D^+, D^-$. Henceforth, measuring the sign of the asymmetry for $D^-$ would be a good test of the ideas presented here.

## References

1. S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B **530**, 99 (2002)
2. D.L. Adams et al., Phys. Lett. B **264**, 462 (1991)
3. D.L. Adams et al., Phys. Lett. B **261**, 201 (1991)
4. A. Bravar et al., Phys. Rev. Lett. **77**, 2626 (1996)
5. R.D. Klem et al., Phys. Rev. Lett. **36**, 929 (1976)
6. W.H. Dragoset et al., Phys. Rev. D **18**, 3939 (1978)
7. B.E. Bonner et al., Phys. Rev. D **41**, 13 (1990)
8. S. Saroff et al., Phys. Rev. Lett. **64**, 995 (1990)
9. D. Sivers, Phys. Rev. D **43**, 261 (1991)
10. M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B **362**, 164 (1995)
11. J. Collins, Nucl. Phys. B **396**, 161 (1993)
12. X. Artru, J. Czyzewski, H. Yabuki, Z. Phys. C **73**, 527 (1997)
13. J. Qiu, G. Sterman, Phys. Rev. D **59**, 014 004-1 (1998)
14. K. Suzuki, N. Nakajima, H. Toki, Mod. Phys. Lett. A **14**, 1403 (1999)
15. C. Boros, Z.-T. Liang, T.-C. Meng, Phys. Rev. Lett. **70**, 1751 (1993)
16. C. Boros, Z.-T. Liang, T.-C. Meng, Phys. Rev. D **49**, 3759 (1994)
17. C. Boros, Z.-T. Liang, T.-C. Meng, Phys. Rev. D **51**, 4867 (1995)
18. C. Boros, Z.-T. Liang, T.-C. Meng, Phys. Rev. D **54**, 4680 (1996)
19. M. Anselmino, M. Boglione, U. D'Alesio, E. Leader, F. Murgia, Phys. Rev. D **70**, 074 025 (2004)
20. J. Adams et al., Phys. Rev. Lett. **92**, 171 801 (2004)
21. R. Vogt, S.J. Brodsky, Nucl. Phys. B **478**, 311 (1996)
22. E. Cuautle, G. Herrera, J. Magnin, Eur. Phys. J. C **2**, 473 (1998)
23. G. Herrera, J. Magnin, Eur. Phys. J. C **2**, 477 (1998)
24. T.A. DeGrand, H.I. Miettinen, Phys. Rev. D **23**, 1227 (1981)
25. T.A. DeGrand, H.I. Miettinen, Phys. Rev. D **24**, 2419 (1981)
26. G. Herrera, L.M. Montaño, Phys. Lett. B **381**, 337 (1996)
27. Particle Data Group, Eur. Phys. J. C **15**, 1 (2004)
28. R. Ammar et al., Phys. Rev. Lett. **61**, 2185 (1988)
29. T. Gehrmann, W.J. Stirling, Phys. Rev. D **53**, 6100 (1996)
30. A.D. Martin, R.G. Roberts, W.J. Stirling, Phys. Lett. B **354**, 155 (1995)
31. J.-J. Yang, Nucl. Phys. A **699**, 562 (2002)
32. R. Jakob, P.J. Mulders, J. Rodrigues, Nucl. Phys. A **626**, 937 (1997)
33. M. Nzar, P. Hoodbhoy, Phys. Rev. D **51**, 32 (1995)
34. B.-Q. Ma, A. Schäfer, Phys. Lett. B **378**, 307 (1996)
35. B.-Q. Ma, A. Schäfer, Phys. Lett. B **380**, 495 (1996) [Erratum]
36. B.-Q. Ma, Phys. Lett. B **375**, 320 (1996)
37. B.-Q. Ma, Phys. Lett. B **380**, 494 (1996)
38. B.-Q. Ma, I. Schmidt, J. Soffer, Phys. Lett. B **441**, 461 (1998)
39. B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Rev. D **63**, 037 501 (2001)
40. B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Rev. D **65**, 034 010 (2002)
41. M. Glück. E. Reya, A. Vogt, Z. Phys. C **67**, 433 (1995)
42. X. Ji, J.W. Qiu, W. Vogelsang, F. Yuan, Phys. Lett. B **638**, 178 (2006)
43. L.P. Gamberg, G.R. Goldstein, AIP Conf. Proc. **792**, 941 (2005)