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# Single spin asymmetries in $p\uparrow p \to \pi X$ and $\bar{p}\uparrow p \to \pi X$ *

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**Abstract.** We study the inclusive production of charged and neutral pions in the reactions $p\uparrow p \to \pi X$ and $\bar{p}\uparrow p \to \pi X$ in the framework of single spin asymmetries. We propose a two components model where production of pions occurs both by recombination of the constituents present in the initial state and by fragmentation of quarks in the final state. Taking the Thomas precession mechanism in the recombination component into account, we obtain a good description of the experimentally observed single spin asymmetries. We show that the observed single spin asymmetries are consistent with the measured spin alignment in the polarized proton as measured by HERMES and SMC.

## 1 Introduction

The Fermilab E704 collaboration observed a strong asymmetry in inclusive production of charged [1] and neutral [2] pions using polarized protons and anti-protons [3]. The so-called single spin asymmetry is defined as

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}, \quad (1)$$

where $d\sigma^{\uparrow}(d\sigma^{\downarrow})$ stands for the differential cross section $d\sigma^{\uparrow}/dx_F dp_T$ ($d\sigma^{\downarrow}/dx_F dp_T$) and the arrow refers to the spin of the incident proton. It is *up* $\uparrow$ or *down* $\downarrow$ with respect to the scattering plane. The E704 collaboration measured the $x_F$ and $p_T$ dependence of $A_N$ in the production of $\pi^+$, $\pi^-$, $\pi^0$. The asymmetry $A_N$ has been observed in other particle species, but here we will refer to pions only.

These experimental results are consistent with a model of polarization for hyperons in which the Thomas precession mechanism is responsible for spin alignment [4,5]. Here we estimate the spin asymmetry in the framework of a two components model where recombination and fragmentation play a role in the formation of pions.

We show that there is a direct dependence of single spin asymmetries upon the contribution of $u$ and $d$ quarks to the spin of the proton. We find the contribution to be in agreement with the measured values of HERMES and SMC [6].

In a two components model, the total cross section for the production of pions is given by

$$\frac{d\sigma^{\pi}}{dx_F dp_T} = \frac{d\sigma^{\pi}_{\rm rec}}{dx_F dp_T} + \frac{d\sigma^{\pi}_{\rm frag}}{dx_F dp_T}, \quad (2)$$

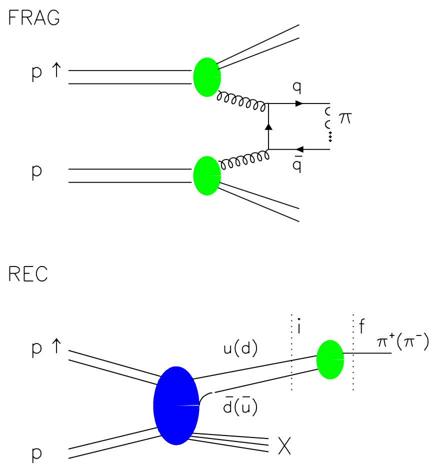


**Fig. 1.** The two processes involved in inclusive production of pions. In the recombination process (denoted by rec) the constituents of the proton coalesce to form the meson. In the fragmentation process the quark–anti-quark in the final state hadronize losing memory of the spin in the initial state

where the labels indicate the process involved, namely, recombination (rec) and fragmentation (frag). Figure 1 shows a typical QCD process where fragmentation produces a pion as well as the recombination mechanism.

Two component models have been succesfully used to describe the production asymmetry of charm particles before [7]. The so-called leading effect can be explained by considering the initial state in the hadronization process. This phenomenon has been found to play a major role in the hadronization following hadron–hadron collisions [8].

In the following section we will describe the recombination component and the mechanism of Thomas precession that enters when the meson is formed. In Sect. 3 we

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will describe the fragmentation mechanism and will explain how this component is introduced into the model. Section 4 resumes the calculation of the single spin asymmetry and compares the model with experimental results. In Sect. 5 we describe the model for $\bar{p}p$ collisions. A comparison with experimental results is also shown. In Sect. 6 we make some final remarks.

## 2 The recombination process

The initial state in a proton–proton collision contains the valence quarks $uud$. Pions are made of $\pi^+(u\bar{d})$ and $\pi^-(\bar{u}d)$ valence quarks so that a $\pi^+$ could be formed if a $u$ quark in the proton joins a $\bar{d}$ from its sea. The $u$ quark, being part of the projectile, goes into the produced pion. It inherits therefore a particularly high longitudinal momentum.

Valence quarks carry a larger momentum than quarks in the sea. For this reason, in the process of a $\pi^+$ ($\pi^-$) formation by recombination, the $\bar{d}$ ($\bar{u}$) will be accelerated. Under these circumstances, Thomas precession operates on the spin of the sea quark as an alignment mechanism.

The differential cross section for $\pi^+$ production via recombination when the proton comes with the spin up can be written as

$$\left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right|_{\pi^+} \sim g_u^{\uparrow} \mid M_{\bar{d}}^{\downarrow} \mid^2 + g_u^{\downarrow} \mid M_{\bar{d}}^{\uparrow} \mid^2, \quad (3)$$

where $g_u^{\uparrow}$ denotes the probability of finding a $u$ quark aligned in the proton ($\uparrow$) and $g_u^{\downarrow}$ the probability of finding it anti-aligned. The amplitude $M_{\bar{d}}^{\uparrow,\downarrow}$ gives the probability of spin flip up (down) at the moment of recombination of the $\bar{d}$ quark.

Correspondingly, the differential cross section for $\pi^+$ production via recombination when the proton comes with the spin down can be written as

$$\left.\frac{\mathrm{d}\sigma^{\downarrow}_{\mathrm{rec}}}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right|_{\pi^+} \sim h_u^{\uparrow} \mid M_{\bar{d}}^{\downarrow} \mid^2 + h_u^{\downarrow} \mid M_{\bar{d}}^{\uparrow} \mid^2, \quad (4)$$

where $h_u^{\uparrow}$ denotes the probability of finding a $u$ quark anti-aligned in a proton ($\downarrow$) and $h_u^{\downarrow}$ the probability of finding it aligned. Obviously $g_u^{\uparrow} = h_u^{\downarrow}$ and $g_u^{\downarrow} = h_u^{\uparrow}$.

We will compute the $x_{\mathrm{F}}$ and $p_{\mathrm{T}}$ dependence of the single spin asymmetry using the same criteria as in [4], where the polarization of hyperons is calculated.

In the recombination scenario, the scattering amplitude for $p \uparrow p \to \pi X$ is inversely proportional to the energy difference between initial (i) and final state (f),

$$M_{\mathrm{S}} = \frac{1}{(\Delta E + \boldsymbol{S} \cdot \boldsymbol{\omega}_{\mathbf{T}})}; \quad (5)$$

here $\Delta E$ represents the change in energy in going from the quarks to the final state in the absence of spin effects. $\boldsymbol{\omega}_{\mathbf{T}}$ is the Thomas frequency. For a $\pi^+$ the $\Delta E$ is given by

$$\Delta E = (p_u^2 + m_u^2)^{1/2} + (p_{\bar{d}}^2 + m_{\bar{d}}^2)^{1/2} - (p_\pi^2 + m_\pi^2)^{1/2}. \quad (6)$$

In the infinite momentum frame it can be written as

$$\Delta E = \frac{1}{2x_{\mathrm{F}}p}\left[\frac{p_{u\mathrm{T}}^2 + m_u^2}{1-\xi} + \frac{p_{\bar{d}\mathrm{T}}^2 + m_{\bar{d}}^2}{\xi} - p_{\pi\mathrm{T}}^2 - m_\pi^2\right], \quad (7)$$

with $x_{\mathrm{F}} = x_u + x_d$ and $\xi = x_d/x_{\mathrm{F}}$. As in [4]

$$\omega_{\mathrm{T}} = \frac{\langle \sin\theta \rangle}{\Delta t}\frac{\Delta p}{m}\boldsymbol{n}. \quad (8)$$

where $\Delta p$ is the change in momentum of the $\bar{d}$ quark (for $\pi^+$ formation)

$$\Delta p = (x_{\mathrm{F}}/2 - x_{\bar{d}})p. \quad (9)$$

In order to calculate the asymmetry, $\omega_{\mathrm{T}}$, $\Delta E$ and therefore $\Delta p$ must be averaged over the appropiate parton distributions. To carry out the average we need to know the pion wave function. In (9), we use 1/2 of the pion's momentum as a mean value of the quark momentum fraction.

As in [4]

$$\omega_{\mathrm{T}} = \frac{1}{x_{\mathrm{F}}p}\frac{4}{\Delta x_0}\frac{(1-2\xi)}{(1+2\xi)^2}p_{\mathrm{T}\pi}. \quad (10)$$

In the amplitude for pion production via recombination we use the $m_u$, $p_{\mathrm{T}u}$ and $m_d$, $p_{\mathrm{T}d}$, masses and the transverse momentum of the $u$ and $d$ quarks respectively, and $m_\pi$ and $p_{\mathrm{T}\pi}$, the mass and transverse momentum of the $\pi$.

We take $m_u = 0.005\,\mathrm{GeV}$, $m_d = 0.01\,\mathrm{GeV}$ in agreement with the PDG values [9]. These values satisfy $m_u/m_d = 1/2$ as quoted there too.

As in [4] $\langle p_{\mathrm{T}}^2 \rangle_{u,d} = p_{\mathrm{T}\pi}^2/4 + \langle k_{\mathrm{T}}^2 \rangle$ with $\langle k_{\mathrm{T}}^2 \rangle = 0.25\,\mathrm{GeV}^2$. The scale $\Delta x_0$ is fixed to $5\,\mathrm{GeV}^{-1}$ as a reasonable recombination scale. It has been used before to explain the polarization of baryons with exactly the same value. It is a reasonable number considering that it corresponds to the space extension of the order of 1 fm where recombination takes place. It remains fixed for all particle species. Since it has a physical meaning, it does not represent a free parameter in a strict sense.

To give a quantitative prediction for the polarization, De Grand and Miettinen take a linear parameterization for $\xi(x_{\mathrm{F}})$ and obtain a good description of the experimental data [4].

In [10] $\xi(x_{\mathrm{F}})$ is explicitly computed using a recombination model for $\Lambda_0$ formation. There we found that the results do not change drastically when a linear parametrization is used. Henceforth we take

$$\xi(x_{\mathrm{F}}) = \frac{1}{2}(1 - x_{\mathrm{F}}) + 0.1x_{\mathrm{F}}, \quad (11)$$

for the sake of simplicity.

The single spin asymmetry will be calculated after we take into account that pions originate not only by a recombination mechanism but also in a more conventional fragmentation process.

## 3 The fragmentation process

There are reasons to believe that most of the pions are actually coming from a fragmentation process after a hard

QCD interaction. The differential distribution of pions has been studied in $e^+e^-$ annihilations [11]. In this reaction the initial state does not contribute to hadronization and therefore one observes purely the spectra from pions that originate in the fragmentation of two quarks in the final state.

One finds that this distribution is given by an exponential of the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_\mathrm{F}} = A\mathrm{e}^{-Bx_\mathrm{F}}. \tag{12}$$

The normalization of this distribution may change with the energy in the center of mass of the reaction, the $B$ parameter, however, does not.

The differential cross section for $\pi^+$ production via fragmentation in proton–proton collisions, can be written as

$$\left.\frac{\mathrm{d}\sigma^{\downarrow}_{\mathrm{frag}}}{\mathrm{d}x_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right|_{\pi^+} = \left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{frag}}}{\mathrm{d}x_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right|_{\pi^+} \sim A\mathrm{e}^{-Bx_\mathrm{F}}, \tag{13}$$

where the value of $B$ is given by experimental measurements in $e^+e^-$ annihilation [11]. The normalization contained in $A$ reflects the fraction of pions coming from the fragmentation.

## 4 Single spin asymmetries

In the scenario where $\pi$'s originate in two different processes, the asymmetry would be given by

$$A_N = \frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}} - \mathrm{d}\sigma^{\downarrow}_{\mathrm{rec}}}{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}} + \mathrm{d}\sigma^{\downarrow}_{\mathrm{rec}} + 2\mathrm{d}\sigma_{\mathrm{frag}}}, \tag{14}$$

where $\mathrm{d}\sigma_{\mathrm{frag}}$ stands for the differential cross section of pions coming from a fragmentation process. Spin asymmetries arising from fragmentation have not been observed and we therefore assume $\sigma^{\uparrow}_{\mathrm{frag}} = \sigma^{\downarrow}_{\mathrm{frag}}$, so that any possible contribution in the denominator cancels.

The asymmetry for $\pi^+$ is then given by

$$A_N^{\pi^+} = \frac{(g_u^{\uparrow} - g_u^{\downarrow}) \mid M_{\bar{d}}^{\downarrow} \mid^2 + (g_u^{\downarrow} - g_u^{\uparrow}) \mid M_{\bar{d}}^{\uparrow} \mid^2}{\mid M_{\bar{d}}^{\uparrow} \mid^2 + \mid M_{\bar{d}}^{\downarrow} \mid^2 + 2\mathrm{d}\sigma^{\pi^+}_{\mathrm{frag}}}, \tag{15}$$

where (3) and (4) have been used. After some algebra, the single spin asymmetry for $\pi^+$ can be written as

$$A_N^{\pi^+} = \frac{\Delta u}{u}\left(\frac{\omega_\mathrm{T}}{\Delta E} - 2\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{\mathrm{d}\sigma^{\pi^+}_{\mathrm{frag}}}{1/\Delta E^2 + 2\mathrm{d}\sigma^{\pi^+}_{\mathrm{frag}}}\right]\right). \tag{16}$$

The whole procedure can be applied to $\pi^-$ and the spin asymmetry one obtains is

$$A_N^{\pi^-} = \frac{\Delta d}{d}\left(\frac{\omega_\mathrm{T}}{\Delta E} - 2\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{\mathrm{d}\sigma^{\pi^-}_{\mathrm{frag}}}{1/\Delta E^2 + 2\mathrm{d}\sigma^{\pi^-}_{\mathrm{frag}}}\right]\right). \tag{17}$$

For the $\pi^0$ case one should consider its wave function, $(1/2^{1/2})(u\bar{u} - d\bar{d})$, and take the combination of states in the cross section:

$$\left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}}}{\mathrm{d}x_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right|_{\pi^0} \sim g_d^{\uparrow} \mid M_{\bar{d}}^{\downarrow} \mid^2 + 2g_u^{\uparrow} \mid M_{\bar{u}}^{\downarrow} \mid^2 + g_d^{\downarrow} \mid M_{\bar{d}}^{\uparrow} \mid^2 + 2g_u^{\downarrow} \mid M_{\bar{u}}^{\uparrow} \mid^2, \tag{18}$$

$$\left.\frac{\mathrm{d}\sigma^{\uparrow}_{\mathrm{rec}}}{\mathrm{d}x_\mathrm{F}\mathrm{d}p_\mathrm{T}}\right|_{\pi^0} \sim h_d^{\uparrow} \mid M_{\bar{d}}^{\downarrow} \mid^2 + 2h_u^{\uparrow} \mid M_{\bar{u}}^{\downarrow} \mid^2 + h_d^{\downarrow} \mid M_{\bar{d}}^{\uparrow} \mid^2 + 2h_u^{\downarrow} \mid M_{\bar{u}}^{\uparrow} \mid^2 . \tag{19}$$

The asymmetry becomes

$$A_N^{\pi^0} = \frac{1}{3}\left(\frac{\Delta d}{d} + 2\frac{\Delta u}{u}\right) \times \frac{\mid M_{\bar{d}}^{\downarrow} \mid^2 - \mid M_{\bar{d}}^{\uparrow} \mid^2}{(\mid M_{\bar{d}}^{\downarrow} \mid^2 + \mid M_{\bar{d}}^{\uparrow} \mid^2) + 2\mathrm{d}\sigma^{\pi^0}_{\mathrm{frag}}}. \tag{20}$$

The amplitudes $\mid M \mid$ above are given according to (5) by

$$\mid M_{\bar{d}}^{\downarrow} \mid = \frac{1}{(\Delta E_{\bar{d}} - \omega_\mathrm{T}/2)},$$
$$\mid M_{\bar{u}}^{\downarrow} \mid = \frac{1}{(\Delta E_{\bar{u}} - \omega_\mathrm{T}/2)},$$
$$\mid M_{\bar{d}}^{\uparrow} \mid = \frac{1}{(\Delta E_{\bar{d}} + \omega_\mathrm{T}/2)},$$
$$\mid M_{\bar{u}}^{\uparrow} \mid = \frac{1}{(\Delta E_{\bar{u}} + \omega_\mathrm{T}/2)},$$

with the corresponding $\Delta E_{\bar{q}}$ as in (7) and $\omega_\mathrm{T}/2$ as in (10).

Figure 2 shows the contributions of up and down quark to the spin of the proton as measured in HERMES [6]. In Fig. 2 the values have been mapped to $x_\mathrm{F}$ according to (11). The curve is a fit to a polynomial function. We will use this fit as input ($\Delta d/d$ and $\Delta u/u$) in (16), (17) and (20). The single spin asymmetry obtained is shown in Fig. 3 for $\pi^{\pm}$. The experimental data as a function of $x_\mathrm{F}$ are also shown [1]. In (16), (17) and (20), $\mathrm{d}\sigma^{\pi}_{\mathrm{frag}}$ is given by (12). The parameter $B$ is extracted from results of $e^+e^-$ experiments [11]. The spin asymmetry is not too sensitive to the value of $B$.

Figure 4 shows the predicted single spin asymmetries for $\pi^{\pm}$ in different $p_\mathrm{T}$ intervals as a function of $x_\mathrm{F}$ together with the experimental data [1].

Figure 5 shows the single spin asymmetries for $\pi^0$ as obtained from (20) compared with experimental results and as a function of $x_\mathrm{F}$ at two different energies and $p_\mathrm{T}$ intervals [2].

## 5 Single spin asymmetries in $\bar{p} \uparrow p$ collisions

In $\bar{p} \uparrow p$ collisions the recombination scheme changes according to the quark content of the projectile.

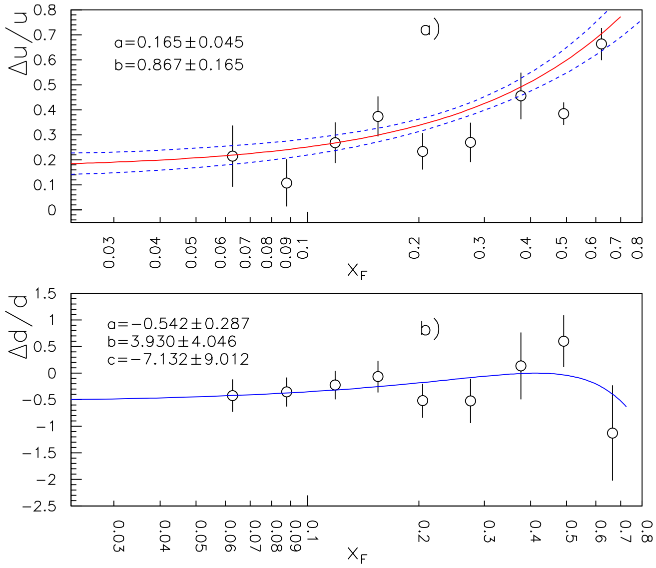


**Fig. 2a,b.** Contributions of up and down quark to the spin of the proton as measured in HERMES. The curve is a fit to a polynomial function. In **a** the function used was $f = a + bx_\mathrm{B}$. In (b) $f = a + bx_\mathrm{B} + cx_\mathrm{B}^2$. Here $x_\mathrm{B}$ is the Bjorken variable. It is mapped to $x_\mathrm{F}$ according to (11)

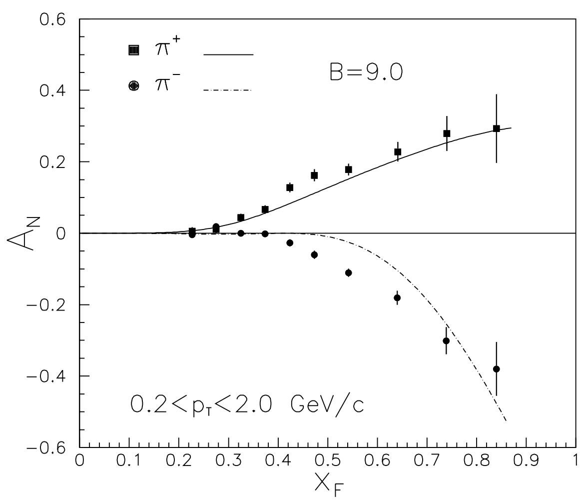


**Fig. 3.** Single spin asymmetries for $\pi^\pm$ in $p\uparrow p$ collisions compared with experimental results as a function of $x_\mathrm{F}$

As shown in Fig. 6, while in *pp* collisions (Fig. 6a) the quarks provided by the projectile are $u$ ($d$), in the $\bar{p}p$ interaction they are $\bar{u}$ ($\bar{d}$) (Fig. 6b). This simple fact explains why the single spin asymmetries in charged pions appear with opposite sign with respect to those in *pp* collisions.

After some algebra one obtains the expressions of the asymmetry in $\bar{p}\uparrow p$ collisions,

$$A_{N,\bar{p}p}^{\pi^+} = \frac{\Delta d}{d}\left(\frac{\omega_\mathrm{T}}{\Delta E} - 2\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{\mathrm{d}\sigma_\mathrm{frag}^{\pi^+}}{1/\Delta E^2 + 2\mathrm{d}\sigma_\mathrm{frag}^{\pi^+}}\right]\right), \quad (21)$$

$$A_{N,\bar{p}p}^{\pi^-} = \frac{\Delta u}{u}\left(\frac{\omega_\mathrm{T}}{\Delta E} - 2\frac{\omega_\mathrm{T}}{\Delta E}\left[\frac{\mathrm{d}\sigma_\mathrm{frag}^{\pi^-}}{1/\Delta E^2 + 2\mathrm{d}\sigma_\mathrm{frag}^{\pi^-}}\right]\right). \quad (22)$$

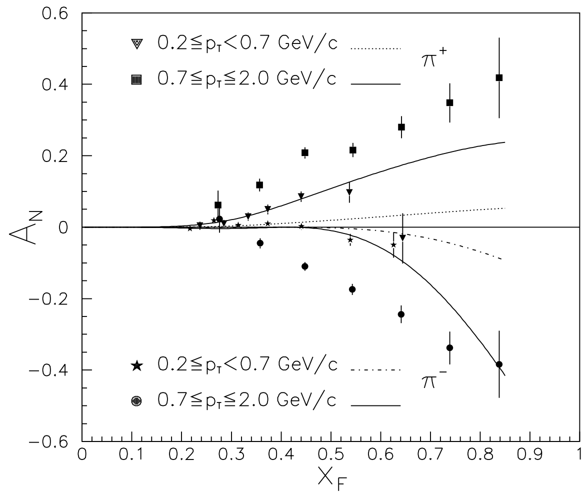


**Fig. 4.** Single spin asymmetries for $\pi^\pm$ in $p\uparrow p$ collisions compared with experimental results as a function of $x_\mathrm{F}$ and for different $p_\mathrm{T}$ intervals

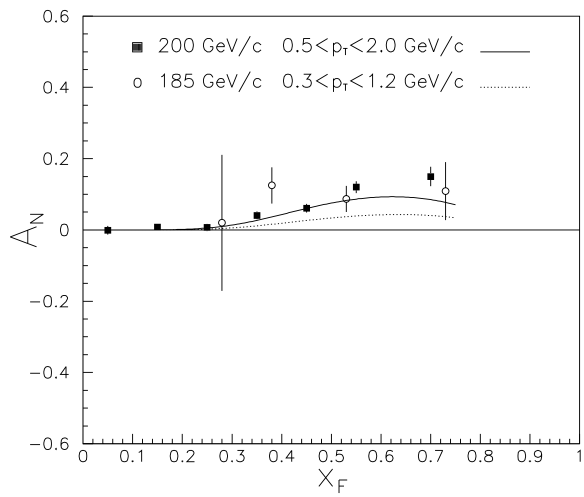


**Fig. 5.** Single spin asymmetries for $\pi^0$ in $p\uparrow p$ collisions compared with experimental results as a function of $x_\mathrm{F}$ at two different energies

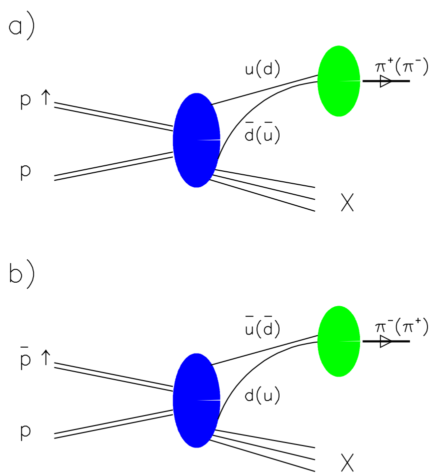


**Fig. 6a,b.** Recombination scheme in $p\uparrow p$ collisions **a** and $\bar{p}\uparrow p$ collisions **b**

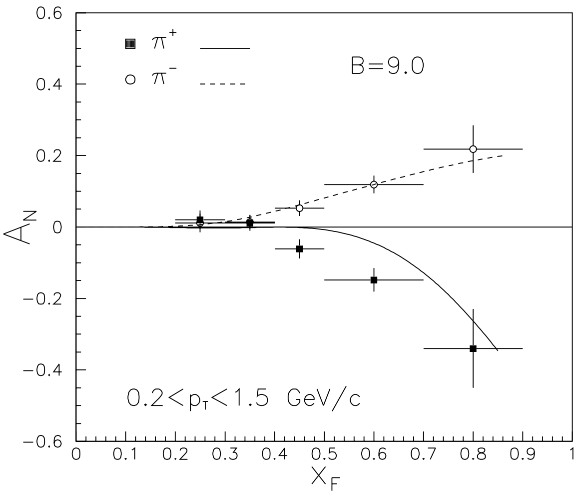


**Fig. 7.** Single spin asymmetries for $\pi^{\pm}$ in $\bar{p} \uparrow p$ collisions compared with experimental results as a function of $x_{\mathrm{F}}$ in $0.2 < p_{\mathrm{T}} < 1.5\,\mathrm{GeV}/c$

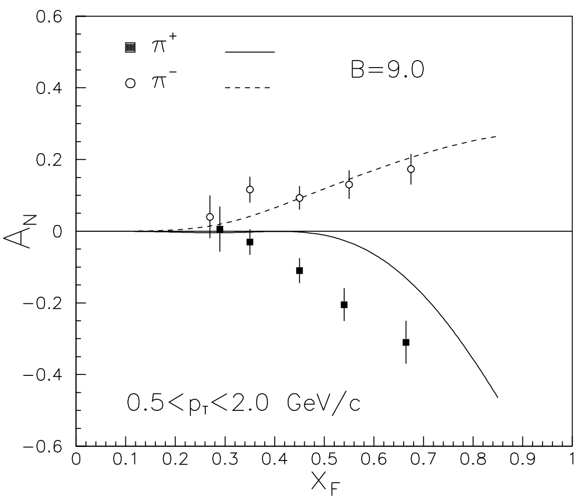


**Fig. 8.** Single spin asymmetries for $\pi^{\pm}$ in $\bar{p} \uparrow p$ collisions compared with experimental results as a function of $x_{\mathrm{F}}$ in $0.5 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$

As one can see, the coefficients $\Delta d/d$ and $\Delta u/u$ appear now interchanged.

Figure 7 shows the single spin asymmetry for $\pi^{\pm}$ in $\bar{p} \uparrow p$ collisions compared with experimental results as a function of $x_{\mathrm{F}}$ in $0.2 < p_{\mathrm{T}} < 1.5\,\mathrm{GeV}/c$. Figure 8 shows the asymmetry in $0.2 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$ [3].

The asymmetry for $\pi^0$, however, remains the same:

$$A_{N,\bar{p}p}^{\pi^0} = \frac{1}{3}\left(\frac{\Delta d}{\mathrm{d}} + 2\frac{\Delta u}{u}\right) \times \frac{|\, M_{\bar{d}}^{\downarrow}\,|^2 - |\, M_{\bar{d}}^{\uparrow}\,|^2}{(|\, M_{\bar{d}}^{\downarrow}\,|^2 + |\, M_{\bar{d}}^{\uparrow}\,|^2) + 2\mathrm{d}\sigma_{\mathrm{frag}}^{\pi^0}}; \tag{23}$$

this is expected, given the quark wave function of a $\pi^0$. In the $\bar{p}p$ scenario the $u$ (or $d$) quark would come from the sea of the anti-proton in the same way as in $pp$ interactions the $\bar{u}$ (or $\bar{d}$) originates from the sea of the proton. The Thomas precession will have exactly the same effect.

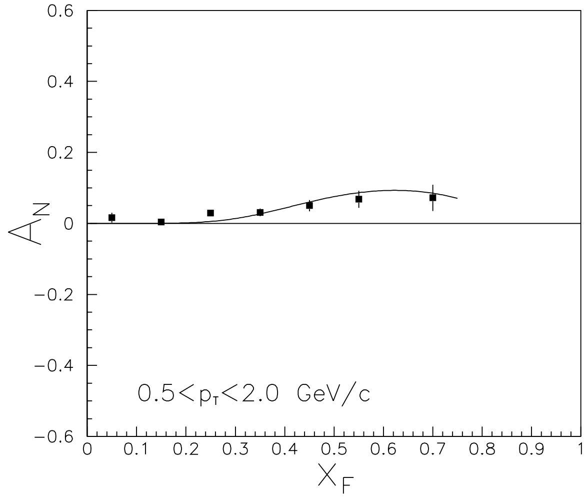


**Fig. 9.** Single spin asymmetries for $\pi^0$ in $\bar{p} \uparrow p$ collisions compared with experimental results as a function of $x_{\mathrm{F}}$

Figure 9 shows the single spin asymmetries for $\pi^0$ in $\bar{p} \uparrow p$ collisions compared with experimental results as a function of $x_{\mathrm{F}}$ [3].

## 6 Conclusions

We studied single spin asymmetries in the inclusive production of pions in proton–proton and anti-proton–proton collisions. We propose a two components model that gives a good description of the asymmetry. It is also in good agreement with the present knowledge of the internal spin structure of the proton as measured by HERMES and SMC.

The two components model is able to explain leading particle effects and has been succesfully applied to charm production. The production of pions from recombination is certainly an accepted fact, although the formal description is not yet on good footing.

It is interesting to note that the model presented here predicts

$$A_N^{\pi^+}(pp) = A_N^{\pi^-}(\bar{p}p),$$
$$A_N^{\pi^-}(pp) = A_N^{\pi^+}(\bar{p}p),$$
$$A_N^{\pi^0}(pp) = A_N^{\pi^0}(\bar{p}p).$$

The two components model presented here reproduces the single spin asymmetry of pions both in proton and anti-proton collisions. It also accounts for the asymmetry of $\eta$ mesons as was shown in our previous letter [5]. Here we present a more refined version of the model.

The single spin asymmetry for photons in our model should be zero. The photon cannot be produced in a recombination scheme. Our prediction is therefore that there is no asymmetry for photons as observed experimentally [12].

We are studying the single spin asymmetry of kaons and have results in good agreement with models like the one presented in [13]. We decided to publish this in a separate paper. The strange quark being part of the sea in the proton and valence quark in the kaon introduces a new aspect of particle production which is interesting by itself. It offers the possibility of learning some particular features of fragmentation. These studies will be presented in a separate work now in preparation.

We are also applying the model to vector mesons. These may offer a good way of testing the model as soon as the measurements come out. In a work now in preparation we will show the single spin asymmetries for particles that have not yet been measured [14].

The origin of single spin asymmetries has been attributed to several different aspects of particle production. In general terms, the possibility of having polarized structure functions,

$$\Delta f_{a/p}(x_a) = f_{a/p\uparrow}(x_a) - f_{a/p\downarrow}(x_a), \tag{24}$$

where $\Delta f_{a/p}(x_a)$ is the difference between the density of partons $a$ with all possible polarization and momentum fraction $x_a$ in a proton with spin up $p\uparrow$ or down $p\downarrow$, as well as polarized fragmentation functions,

$$\Delta D_{h/a\uparrow}(z) = D_{h/a\uparrow}(z) - D_{h/a\downarrow}(z), \tag{25}$$

where the $D_{h/a\uparrow,\downarrow}$ represent the density numbers of hadrons $h$, with longitudinal momentum fraction $z$ in a jet originated by the fragmentation of a polarized parton with spin up $\uparrow$ or down $\downarrow$, has been explored [13].

We address the problem in a phenomenological way in order to understand the physical mechanism behind (24) and (25). The proposed model with Thomas precession in a particle production scheme with recombination may give physical ground to further studies.

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