Single spin asymmetry of vector meson production
as a probe of asymmetry of parton scattering

J. Czyżewski*

Institute of High-Energy Physics, University of Nijmegen,
Toernooiveld 1, NL-6525 ED Nijmegen, The Netherlands

Abstract

Azimuthal asymmetry of vector-meson production in single-transversely polarized proton-proton collisions ($p'^p$) is calculated in the string model of particle production. The asymmetry is generated only during fragmentation of a high-energy quark into hadrons. The obtained asymmetry of the $\rho^\pm$ is opposite in sign to that of $\pi^\pm$ mesons. On the other hand, an asymmetry appearing during parton scattering would contribute with the same sign to that of vector and pseudoscalar mesons. Thus, a combined measurement of both can be used to estimate the contribution to the asymmetry from parton scattering.

* On leave from Institute of Physics, Jagellonian University, ul. Reymonta 4, PL-30-059 Kraków, Poland
Introduction

Measurement of single transverse-spin azimuthal asymmetries of particle production in $p↑p$ collisions can provide information about transversely polarized quark distributions in the proton [1]. However, to extract information about the latter from the experimental data, one has to know the mechanism generating the asymmetry. It has been shown recently [2] that the asymmetries of pion production measured by the E704 experiment in the forward region can be explained by the Collins effect [3], i.e. the asymmetry appearing at the level of the fragmentation of a transversely polarized high-energy quark into hadrons. In Ref. [2] the string model was used to describe the fragmentation, and the polarization effects were parametrized as prescribed by the Lund model [4]. Positive asymmetry was obtained for $π^+$ and $π^0$ production and negative for $π^-$, resulting from upward (downward) polarizations of the $u$ ($d$) valence quark in the proton polarized upwards.

Different mechanisms leading to the azimuthal asymmetry are however possible. Szwed has shown [5,6] that the asymmetry can appear due to double gluon exchange during scattering of a quark on an external strong field. This asymmetry vanishes at a sufficiently high energy due to chiral symmetry and the resulting helicity conservation. Nevertheless, it can be measurable at finite energies.

In this note we present a method of distinguishing between the two scenarios. We calculate the asymmetry for vector mesons $ρ^\pm$ along the lines of Ref. [2]. This asymmetry appears to be opposite in sign to that of pions. On the contrary, if the asymmetry were determined at the hard or semi-hard scattering, like in the approach of Szwed, then the asymmetries of pseudoscalar (PS) and vector (V) mesons would not differ strongly.

To be more precise, we consider the reaction:

$$p↑ + p → h + X,$$

(1)

where $↑$ refers to the projectile proton polarized vertically upwards (parallel to the $\hat{y}$ axis) if the beam momentum points in the $\hat{z}$ direction. The produced hadron $h$ carries the fraction $x_F = 2p_z/\sqrt{s}$ of the center-of-mass longitudinal momentum and the transverse momentum $p_\perp$. In measurements of the asymmetry, the polarized cross-section $dσ↑$ is assumed to behave as

$$dσ↑(x_F, p_\perp) = dσ(x_F, p_\perp)[1 + A_N(x_F, p_\perp)\cos(\phi)],$$

(2)

where $dσ$ denotes the unpolarized cross-section. This defines the asymmetry $A_N$. $\phi$ is the azimuthal angle of the transverse momentum $p_\perp$ of the hadron, measured with respect to the $\hat{x}$ axis.

If one assumes factorization, the cross-section for the reaction (1) can be written as a convolution of the parton distribution functions $G_{q/p}(x, q_\perp)$ and $G_{r/p}(y, r_\perp)$ in the projectile and the target protons, the cross-section $d^2σ$ for the parton scattering $q + r → q' + r'$ and the fragmentation function $D_{h/q'}$ of the quark $q'$:

$$\frac{dσ↑}{d^3p} = \int dx \, d^2q_\perp \, G_{q/p}(x, q_\perp) \int dy \, d^2r_\perp \, G_{r/p}(y, r_\perp) \times$$
\[ \int d\cos \hat{\theta} d\hat{\varphi} \frac{d\hat{\sigma}(\vec{P}_q, \hat{\theta}, \hat{\varphi})}{d\hat{\Omega}} \int dz d^2 \vec{h}_\perp D_{h/q'}(\vec{P}_{q'}, z, \vec{h}_\perp) \delta^3(\vec{p} - z\vec{q}' - \vec{h}_\perp). \]  

(3)

The summation over the flavours of \( q, q', r \) and \( r' \) is understood. \( \vec{P}_q \) is the polarization vector of the quark \( q \). Its magnitude is defined by the transversity distribution [7]:

\[ P_q = \frac{\Delta \perp G_{q/p}}{G_{q/p}} = \frac{G_{q\uparrow}/p\uparrow - G_{q\downarrow}/p\uparrow}{G_{q/p}} \]  

(4)

The spin effects have been included by the dependence of \( D_{h/q} \) on \( \vec{P}_{q'} \) (Collins effect) and of \( d\hat{\sigma} \) on \( \vec{P}_q \) (Szwed effect). The polarization \( \vec{P}_{q'} \) of the scattered quark \( q' \) does not differ strongly from \( \vec{P}_q \) since the depolarization factor is close to unity at typical small scattering angles \( \hat{\theta} \) [3].

Theoretically, two extreme cases could be defined:

a) the asymmetry appears only in the fragmentation function as calculated in Ref. [2]. It manifests itself in a dependence of the fragmentation function \( D_{h/q'} \) on the azimuthal angle of the transverse momentum \( \vec{h}_\perp \) of the hadron \( h \). This is the case of the high-energy limit since any asymmetry appearing at the parton level (in \( d\hat{\sigma} \)) must vanish in that region due to chiral symmetry. In this case the asymmetry can depend on whether \( h \) is a PS or a V meson.

b) the asymmetry appears only at the parton level i.e. \( d\hat{\sigma} \) depends on the azimuth \( \hat{\varphi} \) of the parton scattering plane. It has been shown by Szwed in [5] that this mechanism can lead to significant asymmetries at the beam energy of the order of \( 10 - 20 \) GeV. Here, if the flavour of \( q \) (and also \( \vec{P}_q \)) is defined, the final asymmetry does not depend on whether \( h \) is a PS or a V meson. This, at high \( x_F \), means that the asymmetries of e.g. \( \pi^+ \) and \( \rho^+ \) are close to each other since both mesons origin from fragmentation of a \( u \) quark polarized equally in both cases.

In the reality, one can expect a mixture of the two effects with the second one vanishing at a sufficiently high energy. We shall concentrate on the case a) and calculate the asymmetry of vector mesons therein.

**Asymmetry of pions**

For the production of pions, it was assumed in [2] that the cross-section for the reaction (1) can be divided into three parts:

\[ \frac{d\sigma^{p\to h}}{dx_F d^2 \vec{p}_\perp} = \left[ \frac{d\sigma^{p\to h}}{dx_F d^2 \vec{p}_\perp} \right]_{\text{rank}=1}^{\text{quark}} + \left[ \frac{d\sigma^{p\to h}}{dx_F d^2 \vec{p}_\perp} \right]_{\text{rank} \geq 2}^{\text{quark}} + \left[ \frac{d\sigma^{p\to h}}{dx_F d^2 \vec{p}_\perp} \right]_{\text{diquark}}^{\text{rank} \geq 2} \]  

(5)

† In Ref. [5] the factorization-breaking recombination model of fragmentation was used. In that approach, both the quark and the antiquark forming the produced meson originate from the projectile proton. They scatter independently but each of them feels different Coulomb field.
with the successive terms being contributions from observing a leading hadron of a string spanned by a quark coming from the projectile, a nonleading one of that string and a nonleading particle of the string spanned by the remnant projectile diquark (the leading hadron of that string is a baryon). The asymmetry appears in the first term:

\[
\frac{1}{\sigma^{p \to \pi}_{\text{tot}}} \left[ \frac{d\sigma^{p \to \pi}}{dx d^{2}\vec{p}_{\perp}} \right]_{\text{rank}=1} = \sum_{q=u,d} \int dx \, dz \, d^{2}\vec{q}_{\perp} \, d^{2}\vec{\bar{q}}_{\perp} \, G_q(x, \vec{q}_{\perp}) \, D^{\text{rank}=1}_{\pi/q}(z)
\]

\[
\times \frac{1}{4} \left( 1 - \vec{P}_q \cdot \vec{P}_{\bar{q}}(\vec{q}_{\perp}) \right) \rho(\vec{q}_{\perp}) \, \delta(x_F - xz) \, \delta^2(\vec{p}_{\perp} - \vec{q}_{\perp} - \vec{\bar{q}}_{\perp}),
\]

where \( D^{\text{rank}=1} \) denotes the part of the fragmentation function corresponding to the leading meson,

\[
\rho(\vec{q}_{\perp}) = \frac{1}{\kappa} \exp \left( -\pi \frac{\vec{q}_{\perp}^2}{\kappa} \right)
\]

is the distribution of the transverse momentum of the antiquark \( \bar{q} \) of the rank-one \( q\bar{q} \) pair produced in the string; \( \kappa \) is the string tension. The production of the subleading hadrons (the second and the third term in Eq. (5)) are assumed to be azimuthally symmetric. Those two remaining terms have a form similar to Eq. (6); they have the nonleading parts of the fragmentation function \( D^{\text{rank}} \geq 2 \) and do not have the polarization factor \( (1 - \vec{P}_q \cdot \vec{P}_{\bar{q}}) \).

No parton scattering is included in Eq (6).

\( \vec{P}_q \) is the polarization of the leading quark \( q \). The polarization \( \vec{P}_{\bar{q}} \) of the antiquark created in the string is correlated to its transverse momentum \( \vec{q}_{\perp} \):

\[
\vec{P}_{\bar{q}} = \frac{-2\vec{q}_{\perp}(\hat{z} \times \vec{q}_{\perp})}{\kappa + 2\vec{q}_{\perp}^2}
\]

according to the Lund model prescription [4]. This causes the azimuthal asymmetry which arises in (6) due to the term

\[
\frac{1}{4} (1 - \vec{P}_{\bar{q}} \cdot \vec{P}_{\bar{q}})
\]

corresponding to the probability that \( q \) and \( \bar{q} \) form a spin-singlet state.

**Asymmetry of vector mesons**

The corresponding probability of forming a spin-1 state is

\[
\frac{3}{4} \left( 1 + \frac{1}{3} \vec{P}_q \cdot \vec{P}_{\bar{q}} \right).
\]

Thus, the leading quark contribution to the \( \rho \)-meson production reads:
\[
\frac{1}{\sigma_{\pi^+\pi^-}^{\text{tot}}} \left[ \frac{d\sigma_{\pi^+\pi^-}^{\pi^0}}{dx_F d^2\vec{p}_\perp} \right]_{\text{quark}}^{\text{rank}=1} = \sum_{q=u,d} \int dx \, dz \, d^2\vec{q}_\perp \, G_q(x, \vec{q}_\perp) \, D_{\rho/q}^{\text{rank}=1}(z) \times \frac{3}{4} \left( 1 + \frac{1}{3} \vec{P}_q \cdot \vec{P}_q(\vec{q}_\perp) \right) \rho(\vec{q}_\perp) \delta(x_F - xz) \delta^2(\vec{p}_\perp - \vec{q}_\perp - \vec{q}_\perp) \quad (11)
\]

One can notice that here the asymmetry is opposite in sign and smaller by the factor \( \frac{1}{3} \) in magnitude than that of the PS mesons.

The formulae (6) and (11), as they stand, would give the PS to V meson production ratio equal 1 : 3 if the fragmentation functions \( D_{\pi} \) and \( D_{\rho} \) were identical. This is due to factors \( \frac{1}{4} \) and \( \frac{3}{4} \) in (9) and (10). In the string model, the fragmentation functions for PS and V mesons contain another factors compensating those in (9) and (10) so that the final PS:V ratio becomes 1:1. They arise due to the larger mass of the V mesons. In any case, they do not influence the asymmetry since they appear equally in all the three terms in the cross-section (5).

**Results**

In the calculation of the asymmetry we used the same parameters as in Ref. [2]. We used the quark distribution functions \( G_{u/p}(x, \vec{q}_\perp) = 2G_{d/p}(x, \vec{q}_\perp) = \frac{2}{5} x^{1/2}(1-x)\rho(\vec{q}_\perp) \); the intrinsic transverse momentum distribution was assumed to be the same as the tunneling transverse momentum distribution (7) in the string. We used the string tension \( \kappa = 0.17 \text{ GeV}^2 \) and the flavour-abundance ratio in pair production was taken to be \( u : d : s = 3 : 3 : 1 \). The used string splitting function was that of the Standard Lund model, \( f(z) = (1+C)(1-z)^C \), with \( C = 0.3 \). The leading part of the fragmentation function is \( D_{h/q}^{\text{rank}=1}(z) = c_h f(z) \), where \( c_h \) is an appropriate flavour factor [2]. As motivated by the results of [2] and comparison to the data [8,9] we took the maximal possible polarizations of the \( u \) and \( d \) valence quarks in a transversely polarized proton: \( \vec{P}_u = +1 \) and \( \vec{P}_d = -1 \) at \( x = 1 \).

In Fig. 1 we show the results obtained for the asymmetry \( A_N \) of the \( \rho^\pm \) mesons production, at 200 GeV beam momentum, compared to that of the charged pions coming from the Ref. [2]. The pion data of the E704 collaboration [8] are also shown. The full and the dashed lines correspond to different dependences of the quark transversity \( \vec{P}_q \) on the momentum fraction \( x \). They were chosen to be decreasing towards small \( x \) as \( x^2 \) and \( x \), respectively. These parametrizations gave in [2] the best agreement with \( x_F \)-dependence of the data. The \( p_\perp \) cuts are the same for \( \rho \) mesons as for the pions and correspond to the experimental ones. The asymmetry of the \( \rho^0 \) mesons is shown in Fig. 2 also compared to that of \( \pi^0 \) and to the data [9]. The asymmetries are here smaller than in the case of the charged mesons. Nevertheless, a measurement of \( \rho^0 \) can be easier.

As already argued, the ratio of the asymmetries

\[
R_{\rho/\pi} = \frac{A_N^{\rho}}{A_N^{\pi}} \quad (12)
\]
is equal \(-\frac{1}{3}\). It would be of large interest to verify this prediction experimentally.

This result is more general than the used model. One can expect such a ratio in any calculation where the asymmetry arises in fragmentation due to a correlation between the spin and the transverse momentum of the antiquark accompanying the leading quark to form the meson and where the nonrelativistic quark model is assumed for this meson.

**Asymmetry of parton scattering**

Violating the rule (12) can be an indication of appearing of the Szwed effect [5,6] i.e. significant asymmetry in parton scattering. In that model, originally constructed to describe the polarization of hyperons \(\Lambda\) [6], the asymmetry of a transversely polarized quark scattered on a Coulomb-like field is given by:

\[
\mathcal{A}_{q \rightarrow q'} = 2C_S\alpha_S \frac{mk\sin^3(\theta/2)\ln[\sin(\theta/2)]}{[m^2 + k^2\cos^2(\theta/2)]\cos(\theta/2)} \frac{\vec{k} \times \vec{k}'}{|\vec{k} \times \vec{k}'|} \tag{13}
\]

where \(m, \vec{k}\) and \(\vec{k}'\) are the mass, the initial and the final momentum of the scattered quark and \(k = |\vec{k}|\). \(\theta\) is the scattering angle in the frame where \(|\vec{k}| = |\vec{k}'|\). \(C_S\) is the constant characterizing the external strong field. The sign of the asymmetry depends on the sign of the constant \(C_S\) in (13) or on whether the field source is “quark-like” or “antiquark-like”. In the first case \(C_S\) is positive and the asymmetry \(\mathcal{A}_{q \rightarrow q'}\) negative, in the latter \(C_S\) is negative and \(\mathcal{A}_{q \rightarrow q'}\) positive. It would be interesting to see what the asymmetry is in quark–gluon scattering. The formula (13) comes from a second-order calculation in QED and can only have intuitive meaning for the strong interactions.

Hence, if the asymmetry of quark scattering is treated as a correction to that of fragmentation, \(R_{\rho/\pi} < -\frac{1}{3}\) will mean negative \(\mathcal{A}_{q \rightarrow q'}\) or scattering off a “quark-like” field and \(-\frac{1}{3} < R_{\rho/\pi} < 0\) will mean positive \(\mathcal{A}_{q \rightarrow q'}\) and “antiquark-like” field. As explicitly seen from Eq. (13), at sufficiently high energy \((k \gg m)\) the asymmetry of quark scattering vanishes. The energy scale where it appears can be an interesting hint about the scale of the masses of partons being scattered in a \(pp\) collision.

\(R_{\rho/\pi} \neq -\frac{1}{3}\) could also mean a violation of the nonrelativistic quark model, from which formulae (9) and (10) come form. If this were the case, then the high-energy limit of \(R_{\rho/\pi}\) could be taken as the reference value, instead of \(-\frac{1}{3}\) and the above analysis could be also made.

**Conclusions**

To summarize, we have calculated the single spin asymmetry of \(\rho\) meson production in \(p\bar{p}\) collisions in the framework of Ref. [2], where the asymmetry of pions has been obtained. The asymmetry was generated only in the fragmentation function. The two asymmetries are found to by opposite in sign, the ratio of that of \(\rho\) to that of \(\pi\) being \(-1/3\). Violating this rule can indicate a significant contribution from the asymmetry of the transversely polarized parton subprocess.

However, one should note that the proposed measurement would be possible only if the asymmetry of \(\rho\) mesons were compared to that of directly produced pions (not coming
from decays of $V$ mesons). If no such cuts were made (as is the case in the E704 data) the method would have to be modified. Another important constraint is the fact that the discussed model is a good approximation only in the region of high $x_F$. For smaller $x_F$ it includes more assumptions and approximations. For example, the asymmetry of higher-rank hadrons has not been taken into account.

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Figure captions

Fig. 1 Single spin asymmetry of charged $\rho$ mesons compared to that of charged pions and the E704 data [8].
Fig. 2 Asymmetries of neutral $\rho$ and $\pi$. The $\pi^0$ asymmetry data are from [9].
This figure "fig1-1.png" is available in "png" format from:

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Fig. 1

(a) $p \rightarrow \pi^+$

(b) $P_q \propto x$

$p \rightarrow \rho^-$

$p \rightarrow \pi^-$

$0.7 < p_T < 2.0 \text{GeV}$
This figure "fig1-2.png" is available in "png" format from:

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