Λ polarization in unpolarized hadron reactions

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Abstract:
The transverse polarization observed in the inclusive production of Λ hyperons in the high energy collisions of unpolarized hadrons is tackled by considering a new set of spin and $k_\perp$ dependent quark fragmentation functions. Simple phenomenological expressions for these new “polarizing fragmentation functions” are obtained by a fit of the data on Λ’s and ¯Λ’s produced in $p - N$ processes.

1. Introduction

Λ hyperons produced with $x_F \gtrsim 0.2$ and $p_T \gtrsim 1$ GeV/c in the collision of two unpolarized hadrons, $AB \rightarrow \Lambda^\uparrow X$, are strongly polarized perpendicularly to the production plane, as allowed by parity invariance; despite a huge amount of available experimental information on such single spin asymmetries \cite{1}:\footnote{Talk delivered by U. D’Alesio at the International Workshop “Symmetries and Spin” Praha-SPIN-2000, July 17-22, 2000, Prague}

$$P_\Lambda = \frac{d\sigma^{AB\rightarrow\Lambda^\uparrow X} - d\sigma^{AB\rightarrow\Lambda^\downarrow X}}{d\sigma^{AB\rightarrow\Lambda^\uparrow X} + d\sigma^{AB\rightarrow\Lambda^\downarrow X}}, \quad (1)$$

going the theoretical explanation or understanding of the phenomenon exist \cite{2}. The perturbative QCD dynamics forbids any sizeable single spin asymmetry at the
partonic level; the polarization of hyperons must then originate from nonperturbative features, presumably in the hadronization process.

In the last years a phenomenological description of other single spin asymmetries observed in $p^\uparrow p \to \pi X$ reactions has been developed with the introduction of new distribution $D$ and/or fragmentation $D$ functions which are spin and $k_\perp$ dependent; $k_\perp$ denotes either the transverse momentum of a quark inside a nucleon or of a hadron with respect to the fragmenting quark.

We consider here an effect similar to that suggested by Collins, namely a spin and $k_\perp$ dependence in the fragmentation of an unpolarized quark into a polarized hadron: a function describing this mechanism was first introduced in Ref. [9] and denoted by $D_{1T}^\perp$. More details on this type of definition of fragmentation (or decay) functions can be found in Refs. [7, 9, 10].

In the notations of Ref. [8] a similar function is defined as: $\Delta^N D_{h\uparrow/a}(z, k_\perp) \equiv \hat{D}_{h\uparrow/a}(z, k_\perp) - \hat{D}_{h\uparrow/a}(z, -k_\perp)$, and denotes the difference between the density numbers $\hat{D}_{h\uparrow/a}(z, k_\perp)$ and $\hat{D}_{h\uparrow/a}(z, -k_\perp)$ of spin 1/2 hadrons $h$, with longitudinal momentum fraction $z$, transverse momentum $k_\perp$ and transverse polarization $\uparrow$ or $\downarrow$, inside a jet originated by the fragmentation of an unpolarized parton $a$.

In the sequel we shall refer to $\Delta^N D_{h\uparrow/a}$ and $D_{1T}^\perp$ as “polarizing fragmentation functions”.

In analogy to Collins’ suggestion for the fragmentation of a transversely polarized quark $\bar{\Lambda}$, we write:

$$\hat{D}_{h\uparrow/q}(z, k_\perp) = \frac{1}{2} \hat{D}_{h/q}(z, k_\perp) + \frac{1}{2} \Delta^N D_{h\uparrow/q}(z, k_\perp) \frac{\hat{P}_h \cdot (p_\perp \times k_\perp)}{|p_\perp \times k_\perp|}$$

(2)

for an unpolarized quark with momentum $p_h$ which fragments into a spin 1/2 hadron $h$ with momentum $p_h = z p_q + k_\perp$ and polarization vector along the $\uparrow = \hat{P}_h$ direction; $\hat{D}_{h/q}(z, k_\perp)$ is the $k_\perp$ dependent unpolarized fragmentation function, with $k_\perp = |k_\perp|$. From Eq. (2) it is clear that the function $\Delta^N D_{h\uparrow/a}(z, k_\perp)$ vanishes in case the transverse momentum $k_\perp$ is parallel to the transverse spin $\hat{P}_h$.

By taking into account intrinsic $k_\perp$ in the hadronization process, and assuming that a QCD factorization theorem holds also when $k_\perp$’s are included [9], one has:

$$\frac{E_{\Lambda} d^3 \sigma_{AB \to \Lambda X}}{d^3 p_{\Lambda}} P_{\Lambda} = \sum_{a,b,c,d} \int dx_a dx_b dz \frac{d^2 k_\perp}{\pi z^2} f_{a/A}(x_a) f_{b/B}(x_b)$$

$$\times \hat{s} \delta(\hat{s} + \hat{t} + \hat{u}) \frac{d \hat{\sigma}_{ab \to cd}}{dt}(x_a, x_b, k_\perp) \Delta^N D_{\Lambda\uparrow/a}(z, k_\perp).$$

(3)

Eq. (3) holds for any spin 1/2 baryon; we shall use it also for $\bar{\Lambda}$’s, with $D_{\Lambda/q} = D_{\bar{\Lambda}/q}$ and $\Delta^N D_{\Lambda\uparrow/q} = \Delta^N D_{\bar{\Lambda}\uparrow/q}$.

Notice that, in principle, there might be another contribution to the polarization of a final hadron produced at large $p_T$ in the high energy collision of two unpolarized
hadrons; in analogy to Sivers’ effect \cite{4,5} one might introduce a new spin and \(k_\perp\) dependent distribution function (\(h_1^\perp\) in \cite{6}): \(\Delta^N f_{a\perp/A}(x_a, k_\perp a) \equiv \hat{f}_{a\perp/A}(x_a, k_\perp a) - \hat{f}_{a\perp/A}(x_a, k_\perp a)\).

We shall not consider this contribution here; not only because of the theoretical problems concerning \(\Delta^N f_{a\perp/A}(x_a, k_\perp a)\), but also because the experimental evidence of the hyperon polarization suggests that the mechanism responsible for the polarization is in the hadronization process. A clean test of this should come from a measurement of \(P_\Lambda\) in unpolarized DIS processes, \(\ell p \rightarrow \Lambda^+ X\) \cite{14}.

The main difference between the function \(\Delta^N D_{h/a\perp}\) as originally proposed by Collins, and the function under present investigation \(\Delta^N D_{h^\perp/a}\), is that the former is a so-called chiral-odd function, whereas the latter function is chiral-even. Since the pQCD interactions conserve chirality, chiral-odd functions must always be accompanied by a mass term or appear in pairs. Both options restrict the accessibility of such functions. On the other hand, the chiral-even fragmentation function can simply occur accompanied by the unpolarized (chiral-even) distribution functions allowing for a much cleaner extraction of the fragmentation function itself.

We only consider the quark fragmenting into a \(\Lambda\) and use effective – totally inclusive – unpolarized and polarizing \(\Lambda\) fragmentation functions to take into account secondary \(\Lambda\)'s from the decay of other hyperons, like the \(\Sigma^0\). This is justified on the basis that the main \(\Sigma^0 \rightarrow \Lambda \gamma\) background does not produce a significant depolarizing effect for the transverse \(\Lambda\) polarization.

### 2. Numerical fits and results

Eq. (3) can be schematically expressed as

\[
d\sigma^{pN\rightarrow AX} P_\Lambda = d\sigma^{pN\rightarrow \Lambda^+ X} - d\sigma^{pN\rightarrow \Lambda\perp X} = \sum_{a,b,c,d} f_{a/p}(x_a) \otimes f_{b/N}(x_b) \\
\otimes [d\hat{\sigma}^{ab\rightarrow cd}(x_a, x_b, k_\perp) - d\hat{\sigma}^{ab\rightarrow cd}(x_a, x_b, -k_\perp)] \otimes \Delta^N D_{\Lambda^\perp/c}(z, k_\perp) \tag{4}
\]

which shows clearly that \(P_\Lambda\) is a higher twist effect, despite the fact that the polarizing fragmentation function \(\Delta^N D_{h^\perp/a}\) is a leading twist function: this is due to the difference in the square brackets, \(d\hat{\sigma}(+k_\perp) - d\hat{\sigma}(-k_\perp) \sim k_\perp/p_T\). More details can be found in \cite{14}.

We now use Eq. (4) in order to see whether or not it can reproduce the data and in order to obtain information on the new polarizing fragmentation functions. To do so we introduce a simple parameterization for these functions and fix the parameters by fitting the existing data on \(P_\Lambda\) and \(P_\Lambda\) \cite{13,14}.

We assume that \(\Delta^N D_{\Lambda^\perp/c}(z, k_\perp)\) is strongly peaked around an average value \(k_\perp^0\) lying in the production plane, so that we can expect:

\[
\int_{(+k_\perp)} d^2 k_\perp \Delta^N D_{\Lambda^\perp/c}(z, k_\perp) F(k_\perp) \sim \Delta_0^N D_{\Lambda^\perp/c}(z, k_\perp^0) F(k_\perp^0). \tag{5}
\]

\(^1\)The appearence of this function requires initial state interactions.
Figure 1: Our best fit to $P_{\Lambda}$ data from $p$–$Be$ reactions [13]-[16] as a function of $p_T$. For each $x_F$-bin, the corresponding theoretical curve is evaluated at the mean $x_F$ value in the bin.

The average $k^0_\perp$ value depends on $z$ and we parameterize this dependence in a most natural way: $k^0_\perp(z)/M = K z^{a(1-z)^b}$, where $M$ is a momentum scale ($M = 1$ GeV/$c$).

We parameterize $\Delta_0^N D_{\Lambda^+}/c(z, k^0_\perp)$ in a similar simple form but taking into account the positivity condition $|\Delta_0^N D_{h^+}/q(z, k_\perp)| \leq \hat{D}_{h/q}(z, k)$. However, for reasons related to kinematical effects relevant at the boundaries of the phase space (see [11]) we prefer to impose the more stringent bound $|\Delta_0^N D_{\Lambda^+}/c(z, k^0_\perp)| \leq D_{\Lambda^+}/c(z)/2$, by taking:

$$\Delta_0^N D_{\Lambda^+}/q(z, k^0_\perp) = N_q z^{c_q(1-z)^d_q} \frac{D_{\Lambda^+}/q(z)}{2}, \quad (6)$$

where we require $c_q > 0$, $d_q > 0$, and $|N_q| \leq 1$.

We consider non vanishing contributions in Eq. (6) only for $\Lambda$ valence quarks, $u$, $d$ and $s$. We use the set of unpolarized fragmentation functions of Ref. [17], which allows a separate determination of $D_{\Lambda/q}$ and $D_{\bar{\Lambda}/q}$; in this set the non strange fragmentation functions $D_{\Lambda/u} = D_{\bar{\Lambda}/d}$ are suppressed by an $SU(3)$ symmetry breaking factor $\lambda = 0.07$ as compared to $D_{\Lambda/s}$. In our parameterization of $\Delta_0^N D_{\Lambda^+}/q(z, k^0_\perp)$, Eq. (6), we keep the same parameters $c_q$ and $d_q$ for all quark flavours, but different values of $N_u = N_d$ and $N_s$.

Our best fit results ($\chi^2$/d.o.f. = 1.57) are shown in Figs. 1-3.

In Fig. 1 we present our best fits to $P_{\Lambda}$ as a function of $p_T$ for different $x_F$ values, as indicated in the figure. The famous approximately flat $p_T$ dependence, for $p_T$ greater than 1 GeV/$c$, is well reproduced. Such a behaviour, as expected, does not continue indefinitely with $p_T$ and we have explicitly checked that at larger values

1Analogous results have been found for the other $x_F$-bins not shown here [11].
of $p_T$ the values of $P_\Lambda$ drop to zero. It may be interesting to note that this fall-off has not yet been observed experimentally, but is expected to be first seen in the near-future BNL-RHIC data. Also the increase of $|P_\Lambda|$ with $x_F$ at fixed $p_T$ values can be well described, as shown in Fig. 2.

Experimental data [13]-[16] are collected at two different c.m. energies, $\sqrt{s} \simeq 82$ GeV and $\sqrt{s} \simeq 116$ GeV. Our calculations are performed at $\sqrt{s} = 80$ GeV; we have explicitly checked that by varying the energy between 80 and 120 GeV, our results for $P_\Lambda$ vary, in the kinematical range considered here, at most by 10%, in agreement.
with the observed energy independence of the data.

In Fig. 3 we show our best fit results for $P_\Lambda$ as a function of $p_T$ for different $x_F$ values: in this case all data are compatible with zero.

The fitted average $k_0^\perp$ value of a $\Lambda$ inside a jet turns out to be very reasonable: $K = 0.69$, $a = 0.36$ and $b = 0.53$. Also, mostly $u$ and $d$ quarks contribute to $P_\Lambda$, resulting in a negative value of $N_u$; instead, $u$, $d$ and $s$ quarks all contribute significantly to $P_\Lambda$ and opposite signs for $N_u$ and $N_s$ are found, inducing cancellations.

We have also considered a second – $SU(3)$ symmetric – set of fragmentation functions $D_{\Lambda/q}^{18}$. One reaches similar conclusions about the polarizing fragmentation functions $\Delta^N D_{\Lambda^+/u,d}$: $N_{u,d} \neq N_s$ and not only is there a difference in magnitude, but once more one finds negative values for $\Delta^N D_{\Lambda^+/u,d}$ and positive ones for $\Delta^N D_{\Lambda^+/s}$. This seems to be a well established general trend.

3. Conclusions

We have considered here the well known and longstanding problem of the polarization of $\Lambda$ hyperons, produced at large $p_T$ in the collision of two unpolarized hadrons in a generalized factorization scheme – with the inclusion of intrinsic transverse motion – with pQCD dynamics. The new, spin and $k_\perp$ dependent, polarizing fragmentation functions $\Delta^N D_{\Lambda^+/q}$ have been determined by a fit of data on $p Be \rightarrow \Lambda^+ X$, $p Be \rightarrow \bar{\Lambda}^+ X$ and $p p \rightarrow \Lambda^+ X$.

The data can be described with remarkable accuracy in all their features: the large negative values of the $\Lambda$ polarization, the increase of its magnitude with $x_F$, the puzzling flat $p_T \simeq 1$ GeV/c dependence and the $\sqrt{s}$ independence; also the tiny or zero values of $\bar{\Lambda}$ polarization are well reproduced.

Our parameterization of $\Delta^N D_{\Lambda^+/q}$ should allow us to give predictions for $\Lambda$ polarization in other processes; a study of $\ell p \rightarrow \Lambda^+ X$, $\ell p \rightarrow \ell' \Lambda^+ X$ and $e^+ e^- \rightarrow \Lambda^+ X$ is in progress.

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