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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 $\boldsymbol{k}_\perp$ 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 $\bar{\Lambda}$'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, $AB \to \Lambda^\uparrow X$, 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 [1]:

$$P_\Lambda = \frac{d\sigma^{AB\to\Lambda^\uparrow X} - d\sigma^{AB\to\Lambda^\downarrow X}}{d\sigma^{AB\to\Lambda^\uparrow X} + d\sigma^{AB\to\Lambda^\downarrow X}}, \tag{1}$$

no convincing theoretical explanation or understanding of the phenomenon exist [2]. The perturbative QCD dynamics forbids any sizeable single spin asymmetry at the

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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 [3, 4, 5, 6] and/or fragmentation [7, 8, 9] functions which are spin and $\boldsymbol{k}_\perp$ dependent; $\boldsymbol{k}_\perp$ 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 $\boldsymbol{k}_\perp$ 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: $\Delta^N D_{h^\uparrow/a}(z, \boldsymbol{k}_\perp) \equiv \hat{D}_{h^\uparrow/a}(z, \boldsymbol{k}_\perp) - \hat{D}_{h^\downarrow/a}(z, \boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/a}(z, \boldsymbol{k}_\perp) - \hat{D}_{h^\uparrow/a}(z, -\boldsymbol{k}_\perp)$, and denotes the difference between the density numbers $\hat{D}_{h^\uparrow/a}(z, \boldsymbol{k}_\perp)$ and $\hat{D}_{h^\downarrow/a}(z, \boldsymbol{k}_\perp)$ of spin 1/2 hadrons h, with longitudinal momentum fraction z, transverse momentum $\boldsymbol{k}_\perp$ 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*" [11].

In analogy to Collins' suggestion for the fragmentation of a transversely polarized quark [7], we write:

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

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

By taking into account intrinsic $\boldsymbol{k}_\perp$ in the hadronization process, and assuming that a QCD factorization theorem holds also when $\boldsymbol{k}_\perp$'s are included [7], one has:

$$\begin{aligned} \frac{E_\Lambda\, d^3\sigma^{AB\to\Lambda X}}{d^3\boldsymbol{p}_\Lambda}\, P_\Lambda \;&=\; \sum_{a,b,c,d} \int \frac{dx_a\, dx_b\, dz}{\pi z^2}\, d^2\boldsymbol{k}_\perp\, f_{a/A}(x_a)\, f_{b/B}(x_b) \\ &\times\;\; \hat{s}\, \delta(\hat{s} + \hat{t} + \hat{u})\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(x_a, x_b, \boldsymbol{k}_\perp)\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_\perp)\,. \qquad (3) \end{aligned}$$

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

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 [4, 5] one might introduce a new spin and $\boldsymbol{k}_\perp$ dependent distribution function ($h_1^\perp$ in [6]): $\Delta^N f_{a^\uparrow/A}(x_a, \boldsymbol{k}_{\perp a}) \equiv \hat{f}_{a^\uparrow/A}(x_a, \boldsymbol{k}_{\perp a}) - \hat{f}_{a^\downarrow/A}(x_a, \boldsymbol{k}_{\perp a}) = \hat{f}_{a^\uparrow/A}(x_a, \boldsymbol{k}_{\perp a}) - \hat{f}_{a^\uparrow/A}(x_a, -\boldsymbol{k}_{\perp a})$.

We shall not consider this contribution here; not only because of the theoretical problems† concerning $\Delta^N f_{a^\uparrow/A}(x_a, \boldsymbol{k}_{\perp a})$, 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_Λ in unpolarized DIS processes, $\ell p \to \Lambda^\uparrow X$ [12].

The main difference between the function $\Delta^N D_{h/a^\uparrow}$ as originally proposed by Collins, and the function under present investigation $\Delta^N D_{h^\uparrow/a}$, 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 Λ and use effective – totally inclusive – unpolarized and polarizing Λ fragmentation functions to take into account secondary Λ's from the decay of other hyperons, like the Σ^0. This is justified on the basis that the main $\Sigma^0 \to \Lambda\gamma$ background does not produce a significant depolarizing effect for the transverse Λ polarization.

2. Numerical fits and results

Eq. (3) can be schematically expressed as

$$d\sigma^{pN\to\Lambda X}\, P_\Lambda = d\sigma^{pN\to\Lambda^\uparrow X} - d\sigma^{pN\to\Lambda^\downarrow X} = \sum_{a,b,c,d} f_{a/p}(x_a) \otimes f_{b/N}(x_b)$$
$$\otimes \left[d\hat{\sigma}^{ab\to cd}(x_a, x_b, \boldsymbol{k}_\perp) - d\hat{\sigma}^{ab\to cd}(x_a, x_b, -\boldsymbol{k}_\perp)\right] \otimes \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_\perp) \tag{4}$$

which shows clearly that P_Λ is a higher twist effect, despite the fact that the polarizing fragmentation function $\Delta^N D_{h^\uparrow/a}$ is a leading twist function: this is due to the difference in the square brackets, $[d\hat{\sigma}(+\boldsymbol{k}_\perp) - d\hat{\sigma}(-\boldsymbol{k}_\perp)] \sim k_\perp/p_T$. More details can be found in [11].

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_Λ and $P_{\bar{\Lambda}}$ [13]-[16].

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

$$\int_{(+k_\perp)} d^2\boldsymbol{k}_\perp\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_\perp)\, F(\boldsymbol{k}_\perp) \simeq \Delta_0^N D_{\Lambda^\uparrow/c}(z, k_\perp^0)\, F(\boldsymbol{k}_\perp^0)\,. \tag{5}$$

†The appearence of this function requires initial state interactions.

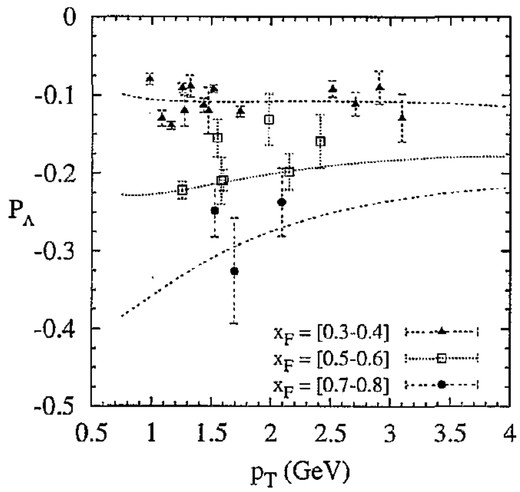

Figure 1: Our best fit to P_Λ data from p–Be reactions [13]-[16] as a function of p_T. For each x_F-bin, the corresponding theoretical curve is evaluated at the mean x_F value in the bin.

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

We parameterize $\Delta_0^N D_{\Lambda^\uparrow/c}(z, k_\perp^0)$ in a similar simple form but taking into account the positivity condition $|\Delta^N D_{h^\uparrow/q}(z, k_\perp)| \leq \hat{D}_{h/q}(z, k_\perp)$. 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 $|\Delta_0^N D_{\Lambda^\uparrow/c}(z, k_\perp^0)| \leq D_{\Lambda/c}(z)/2$, by taking:

$$\Delta_0^N D_{\Lambda^\uparrow/q}(z, k_\perp^0) = N_q\, z^{c_q}(1-z)^{d_q}\, \frac{D_{\Lambda/q}(z)}{2}\,, \tag{6}$$

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

We consider non vanishing contributions in Eq. (6) only for Λ 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 $D_{\Lambda/u} = D_{\Lambda/d}$ are suppressed by an $SU(3)$ symmetry breaking factor $\lambda = 0.07$ as compared to $D_{\Lambda/s}$. In our parameterization of $\Delta_0^N D_{\Lambda^\uparrow/q}(z, k_\perp^0)$, 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 (χ^2/d.o.f. = 1.57) are shown in Figs. 1-3.

In Fig. 1 we present our best fits to P_Λ 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

[‡]Analogous results have been found for the other x_F-bins not shown here [11].

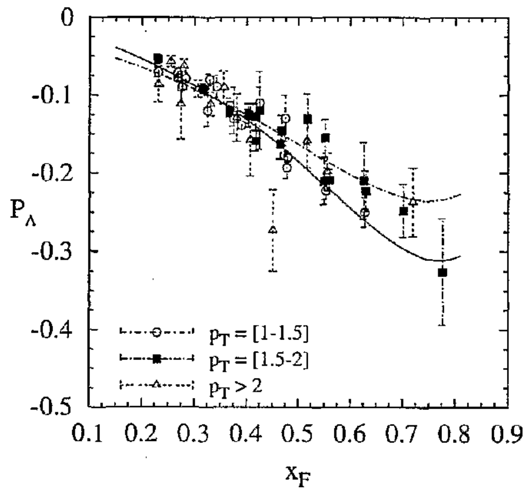

Figure 2: P_Λ data for p–Be reactions [13]-[16], as a function of x_F. The two theoretical curves correspond to $p_T = 1.5$ GeV/c (solid) and $p_T = 3$ GeV/c (dot-dashed).

of p_T the values of P_Λ 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.

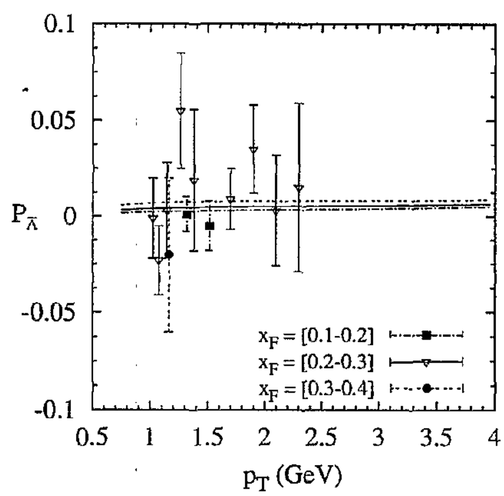

Figure 3: Our best fit to $P_{\bar\Lambda}$ data from p–Be reactions [13, 15], as a function of p_T.

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_Λ 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 $P_{\bar{\Lambda}}$ as a function of p_T for different x_F values: in this case all data [13, 15] are compatible with zero.

The fitted average $k_\perp^0$ value of a Λ 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_Λ, resulting in a negative value of N_u; instead, u, d and s quarks all contribute significantly to $P_{\bar{\Lambda}}$ 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 $\Delta^N D_{\Lambda^\uparrow/q}$: $N_{u,d} \neq N_s$ and not only is there a difference in magnitude, but once more one finds negative values for $\Delta_0^N D_{\Lambda^\uparrow/u,d}$ and positive ones for $\Delta_0^N D_{\Lambda^\uparrow/s}$. This seems to be a well established general trend [11].

3. Conclusions

We have considered here the well known and longstanding problem of the polarization of Λ 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 $\boldsymbol{k}_\perp$ dependent, polarizing fragmentation functions $\Delta^N D_{\Lambda^\uparrow/q}$ have been determined by a fit of data on $p\,Be \to \Lambda^\uparrow X$, $p\,Be \to \bar{\Lambda}^\uparrow X$ and $p\,p \to \Lambda^\uparrow X$.

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

Our parameterization of $\Delta^N D_{\Lambda^\uparrow/q}$ should allow us to give predictions for Λ polarization in other processes; a study of $\ell p \to \Lambda^\uparrow X$, $\ell p \to \ell' \Lambda^\uparrow X$ and $e^+e^- \to \Lambda^\uparrow X$ is in progress [12].

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References

[1] For a review of data see, *e.g.*, K. Heller, in Proceedings of Spin 96, C.W. de Jager, T.J. Ketel and P. Mulders, Eds., World Scientific (1997); or A.D. Panagiotou, *Int. J. Mod. Phys.* **A5** (1990) 1197

[2] For a recent and complete review of all theoretical models see J. Félix, *Mod. Phys. Lett.* **A14** (1999) 827

[3] J.P. Ralston and D.E. Soper, *Nucl. Phys.* **B152** (1979) 109

[4] D. Sivers, *Phys. Rev.* **D41** (1990) 83; **D43** (1991) 261

[5] M. Anselmino, M. Boglione and F. Murgia, *Phys. Lett.* **B362** (1995) 164

[6] D. Boer and P.J. Mulders, *Phys. Rev.* **D57** (1998) 5780

[7] J.C. Collins, *Nucl. Phys.* **B396** (1993) 161

[8] M. Anselmino, M. Boglione and F. Murgia, *Phys. Rev.* **D60** (1999) 054027

[9] P.J. Mulders and R.D. Tangerman, *Nucl. Phys.* **B461** (1996) 197; *Nucl. Phys.* **B484** (1997) 538 (E)

[10] M. Boglione, these proceedings

[11] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, e-Print Archive: hep-ph/0008186

[12] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, work in progress

[13] K. Heller *et al.*, *Phys. Rev. Lett.* 41 (1978) 607

[14] K. Heller *et al.*, *Phys. Rev. Lett.* **51** (1983) 2025

[15] B. Lundberg *et al.*, *Phys. Rev.* **D40** (1989) 3557

[16] E.J. Ramberg *et al.*, *Phys. Lett.* **B338** (1994) 403

[17] D. Indumathi, H.S. Mani and A. Rastogi, *Phys. Rev.* **D58** (1998) 094014

[18] D. de Florian, M. Stratmann and W. Vogelsang, *Phys. Rev.* **D57** (1998) 5811