Probing polarized valence quark distributions in W$^-$-boson production

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March 23, 1995

Abstract

While EMC-SMC-E142 data sheds new light on the behavior of polarized parton distributions at small and intermediate x, it may be also interesting to study valence quark polarizations at large x, where spectator quark counting rules and Carlitz-Kaur type models predict different behavior for down quark polarizations. The article examines the possibility to test the ratio $\Delta d_V(x)/d_V(x)$ at $x \to 1$ in the inclusive production of W^--bosons.

HEP-PH-9503419

In the last years much attention of HEP community is attracted to the physics of polarized hadron interactions, to great extent due to the recent interesting data on polarized inclusive [1] and semi-inclusive [2] deep-inelastic scattering. The EMC-SMC-E142 data already allow to make several conclusions about the nucleon spin structure at $Q^2 \simeq 2 \div 10\ GeV^2$ and values of Bjorken $x \simeq 0.003 \div 0.7$. The analysis of these data in the framework of perturbative QCD provides information on longitudinal polarized parton distributions $\Delta q_i(x, Q^2)$, interpreted as the differences of probabilities $q^{+/-}(x, Q^2)$ for finding partons of the type i with spin parallel/antiparallel to the spin of the parent nucleon. However in the region of $x \geq 0.1$ the experimental errors have a tendency to grow, while at $x \geq 0.7$ there is still no data at all. On the other hand, precise studies of various polarized processes at large x may provide valuable information about the behavior of longitudinal valence quark polarizations $\Delta q_V(x)$, that are dominant in this region compared to sea quarks and gluons.

So far the common opinion on how the polarized quark distributions $\Delta u_V(x)$ and $\Delta d_V(x)$ should behave at large x is not fully established. The experimental information in this region is not precise enough to fix Δq_V's unambiguously. The theoretical description is also not unique. This problem was examined as far as in mid-70's, but not solved to the end. Since that time the majority of theoretical models, describing valence quarks at $x \sim 1$, falls into two general categories.

The qualitative analysis of the distinctions between these two approaches can be based on the representation of a nucleon as composed from the valence quark carrying a large portion of nucleon's momentum, and a diquark with $x \sim 0$ [3]; in good approximation the contribution of the sea may be neglected. The experimental results (for example, the behavior of the ratio of nucleon structure functions $F_2^n(x,Q^2)/F_2^p(x,Q^2)$ at $x \to 1$) convincingly indicate that the $SU(6)$-symmetry of the nucleon wavefunction is violated, so that the states containing diquarks with certain spin-isospin numbers S, S_z, I, I_z are suppressed compared to the situation of the exact $SU(6)$-symmetry.

The models of the first type follow the works of Carlitz and Kaur [4] and assume that diquarks in this region must be in a $S = 0$ rather than in a $S = 1$ state. On the other hand, the models motivated by perturbative QCD start from the assumption that only diquarks in a $S_z = 1$ state are suppressed. One of the pioneering works in the framework of the second approach was published by Farrar and Jackson [6].

The different mechanism of $SU(6)$-breaking in these two approaches leads to different predictions for several quantities measured both in unpolarized and polarized reactions. The most known of them is the ratio $F_2^n(x,Q^2)/F_2^p(x,Q^2)$, which tends in these models correspondingly to 1/4 or 3/7. Most part of the existing data on the structure functions $F_2^{p,n}$ at large x evidences in favor of 1/4 value, providing that perturbative-QCD result is not valid. As for the polarized nucleon interactions, so far no experiment, allowing to discriminate one model from another, was staged on the existing colliders.

Such an experiment can be based on the fact that Carlitz-Kaur (CK) and Farrar-Jackson (FJ) models disagree about the behavior of valence d-quark polarizations at large x. While in CK model $\Delta d_V(x)/d_V(x) \to -1/3$, the FJ approach predicts that $\Delta d_V(x)/d_V(x) \to 1$. The information about the limiting behavior of $\Delta d_V(x)$ may be obtained in various experiments, for instance, deep-inelastic scattering; however, it may also be interesting to carry out a straightforward measurement of the ratio $\Delta d_V(x)/d_V(x)$.

If at least one polarized proton beam is available, one can measure longitudinal single-spin asymmetries A_L in the inclusive production of W^--bosons $p^{\rightarrow}p \to W^-X$ or $p^{\rightarrow}\bar{p} \to W^-X$; in the appropriate kinematical range these asymmetries will be directly proportional to the ratio $\Delta d_V(x)/d_V(x)$. In fact, it is not necessary to measure W^--asymmetries in the region of x very close to 1. The behavior of $\Delta d_V(x)$ in CK and FJ models should be very different already at $x \sim 0.5 \div 0.7$, where the cross-sections are still noticeable. This paper is dedicated to the discussion of the opportunity to study polarized valence distributions in W^--boson production, especially to the explicit evaluation of the kinematical region, where the event rates will be high enough to make definite conclusions about the magnitude of $\Delta d_V(x)/d_V(x)$. But, to begin, let us briefly review the description of valence quark distributions in CK and FJ models.

Since the behavior of parton distributions is determined by the properties of hadrons at large distances, where the running coupling of quark-gluon interactions is not small, the perturbative QCD arguments are not directly relevant to their analysis at arbitrary values of Bjorken x. However, the situation when the struck parton carries almost all of the nucleon's momentum corresponds to very far off-shell configuration of nucleon constituents [5, 6, 9]. Such a configuration can be obtained from the nucleon state with the lowest orbital momentum and the finite invariant masses of partons only by exchange of hard gluons. In this case the dominant contribution to the amplitude of deep-inelastic scattering is provided by Feynman graphs with minimal number of gluon propagators tying quarks into a single hadron.

The straightforward calculation of these graphs shows that the falloff of helicity-dependent quark distributions is described by the power-law dependence,

$$q^{+/-}(x) \sim (1-x)^p, \tag{1}$$

where

$$p = 2n - 1 + 2\Delta S_z, \tag{2}$$

n is the minimal number of spectator quarks and $\Delta S_z = 0$ for $q^+(x)$ or 1 for $q^-(x)$. The slowest falloff corresponds to the valence quark distributions, for which $p = 3$. The essential feature of (2) is that the power-law falloff does not depend on the flavor of quarks. Therefore the perturbative result prescribes the distributions of valence up and down quarks to be proportional in the limit $x \to 1$, and the coefficient of proportionality can be found to be 1/5 [9, 10]. It also implies that, independently of quark flavor, the helicity of a quark with $x \to 1$ must match the helicity of the parent hadron, so that $\Delta q_{iV}(x)$ should approach $q_{iV}(x)$. For valence d-quarks this means that $\Delta d_V(x)$, which is negative at small and intermediate x^*, must change sign at some x, typically chosen to be around $0.4 \div 0.7$.

It is necessary to mention that equation (2) provides only upper limit for the magnitudes of quark distributions, which is achieved only if there are no other sources of suppression. Meanwhile, there is strong experimental evidence that at large x d-quarks are suppressed compared to u-quarks. In particular, most part of the experimental information about the ratio of nucleon structure functions $F_2^n(x, Q^2)/F_2^p(x, Q^2)$, including the most recent NMC data [7], shows that it falls lower than the limiting value 3/7 predicted by perturbative-QCD based approach. The fit of the overall world data on F_2^n/F_2^p, presented in [7], tends to 1/4, which is the limiting value for this ratio when $d_V(x)$ falls faster than $u_V(x)$.

Such a suppression of valence d-quarks is an essential feature of another model, proposed by Carlitz and Kaur [4]. The valence distributions in this approach are built using simple quark model considerations, especially the assumption that all diquarks with $S = 1$, $I = 1$ are suppressed relative to those with $S = 0$. The relation $d_V(x)/u_V(x) \to 1/5$, obtained in FJ model, should not hold in CK approach, and valence quark distributions can be easily accommodated to satisfy the tendency of F_2^n/F_2^p to 1/4. Just as in FJ model, $\Delta u_V(x)/u_V(x) = 1$ as $x \to 1$, but the behavior of valence d-quarks is different and $\Delta d_V(x)/d_V(x) = -1/3$. For typical parameterizations of

*At these values of x, the negative $\Delta d_V(x)$ was anticipated from theoretical considerations, especially from the sign of its first moment $\int_0^1 \Delta d_V(x)dx \simeq -0.46 \pm 0.04$; these anticipations were recently confirmed by the experimental values of $\Delta d_V(x)$, derived from the analysis of nucleon and deuteron DIS data [2].

Carlitz-Kaur cosines, describing dilution of the valence quark spin in the parton sea and quickly approaching 1 at intermediate and large x, $\Delta d_V/d_V$ is close to its limiting value already at $x \sim 0.3 \div 0.4$.

The latter distinction between FJ and CK models (the retention of valence d-quark helicity in the first case and d-quark negative polarization of $-1/3$ in the second) may serve as a basis for one more experimental test of proton inner structure. The inclusive production of W^--bosons in pp- or $p\bar{p}$-collisions is very suitable for the investigation of this distinction. Since parity is not conserved in weak interactions, only one polarized initial beam is necessary to get nonzero cross-section asymmetries. Thus, one opportunity for this experiment may arise if a polarized proton beam will be put into operation at TEVATRON. It will be also possible to investigate W^--boson asymmetries in proton-proton interactions at BNL-RHIC collider.

On the parton level the first-order contribution to W^--production is provided by the quark-antiquark annihilation $d\bar{u} \to W^-$. For the reaction $\vec{p}p \to W^- X$ the cross-section $d\sigma_{pp}^{W^-}/dy$ and the corresponding single-spin asymmetry A_L are written as

$$\frac{d\sigma_{pp}^{W^-}}{dy} = \frac{1}{3} G_F \sqrt{2} \tau \pi \left(d(x_a, M_W^2)\, \bar{u}(x_b, M_W^2) + \bar{u}(x_a, M_W^2)\, d(x_b, M_W^2) \right) \quad (3)$$

and

$$A_L(y) = \frac{\Delta d(x_a, M_W^2)\, \bar{u}(x_b, M_W^2) - \Delta \bar{u}(x_a, M_W^2)\, d(x_b, M_W^2)}{d(x_a, M_W^2)\, \bar{u}(x_b, M_W^2) + \bar{u}(x_a, M_W^2)\, d(x_b, M_W^2)}. \quad (4)$$

Here M_W and y are the mass and rapidity of W^--boson, G_F is the Fermi constant and

$$x_a = \sqrt{\tau} e^{y},\ x_b = \sqrt{\tau} e^{-y} \text{ with } \tau = M_W^2/s.$$

The $p\bar{p}$ cross-section $d\sigma_{p\bar{p}}^{W^-}/dy$ and asymmetry A_L can be obtained from (3,4) by substituting $\bar{u}(x_b, M_W^2)$ and $d(x_b, M_W^2)$ correspondingly for $u(x_b, M_W^2)$ and $\bar{d}(x_b, M_W^2)$. It can be seen that when y tends to upper kinematical bound, $y \to -\ln\sqrt{\tau}$, A_L is directly proportional to $\Delta d(x_a, M_W^2)/d(x_a, M_W^2)$ at $x_a \to 1$. In this limit the other Bjorken variable, x_b is of the order $M_W^2/s \sim 0.03$ for RHIC and 0.002 for TEVATRON. For such x_b's valence quarks become less important compared to the sea, and therefore $u(x_b, M_W^2) \to \bar{u}(x_b, M_W^2)$, $d(x_b, M_W^2) \to \bar{d}(x_b, M_W^2)$. In its turn, this means that pp and $p\bar{p}$ cross-sections, measured at same $\sqrt{s}$, at large y should be described by approximately the same dependence. However, as shown by numerical results, the

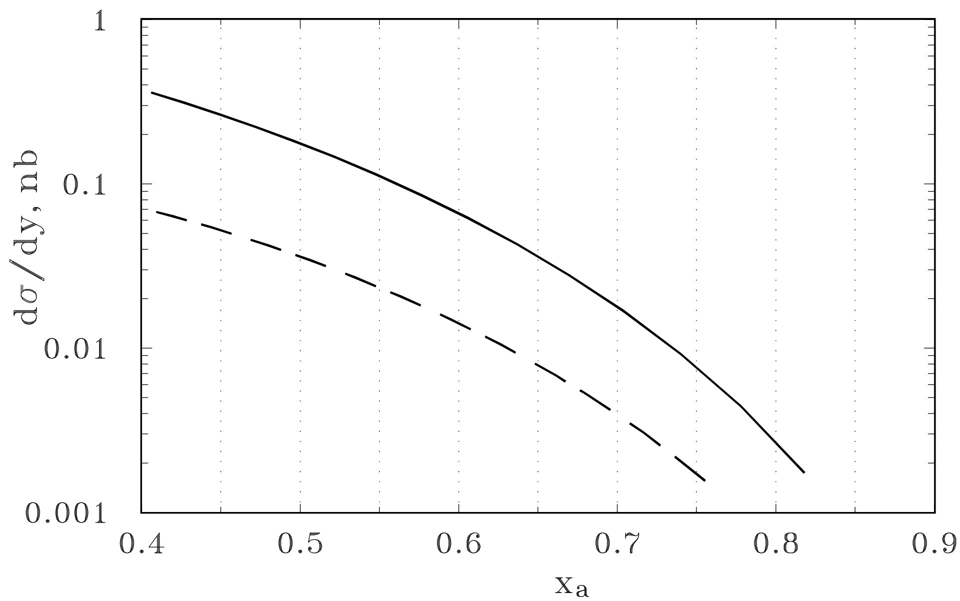

Fig.1. Differential cross-sections of inclusive W^--boson production in pp-collisions at RHIC ($\sqrt{s} = 500\,GeV$, dash line) and in $p\bar{p}$-collisions at TEVATRON ($\sqrt{s} = 1.8\,TeV$, solid line).

cross-sections for typical RHIC energies, assumed to be $\sqrt{s} = 500\,GeV$, in the region of most interest are smaller than TEVATRON ones, calculated for $\sqrt{s} = 1.8\,TeV$.

Fig.1 and 2 show unpolarized cross-sections $d\sigma_{pp}^{W^-}/dy$, $d\sigma_{p\bar{p}}^{W^-}/dy$ and corresponding asymmetries A_L as functions of x_a, varying in the interval $0.4 \leq x_a \leq 0.9$. These values of x_a correspond to W^--boson rapidities $0.9 \leq y \leq 1.7$ for RHIC and $2.2 \leq y \leq 3$ for TEVATRON. The cross-sections were calculated using Glück-Reya-Vogt unpolarized distributions [8].

As can be seen from Fig.1, both pp- and $p\bar{p}$-cross-sections quickly fall down with the increase of x_a, $d\sigma_{pp}^{W^-}/dy$ being smaller than $d\sigma_{p\bar{p}}^{W^-}/dy$. Typical values of cross-sections at $x_a = 0.4$ and 0.7 are 0.07 and $0.003\,nbs$ in pp-channel, 0.3 and $0.015\,nbs$ in $p\bar{p}$-channel. Knowing these cross-sections, it is

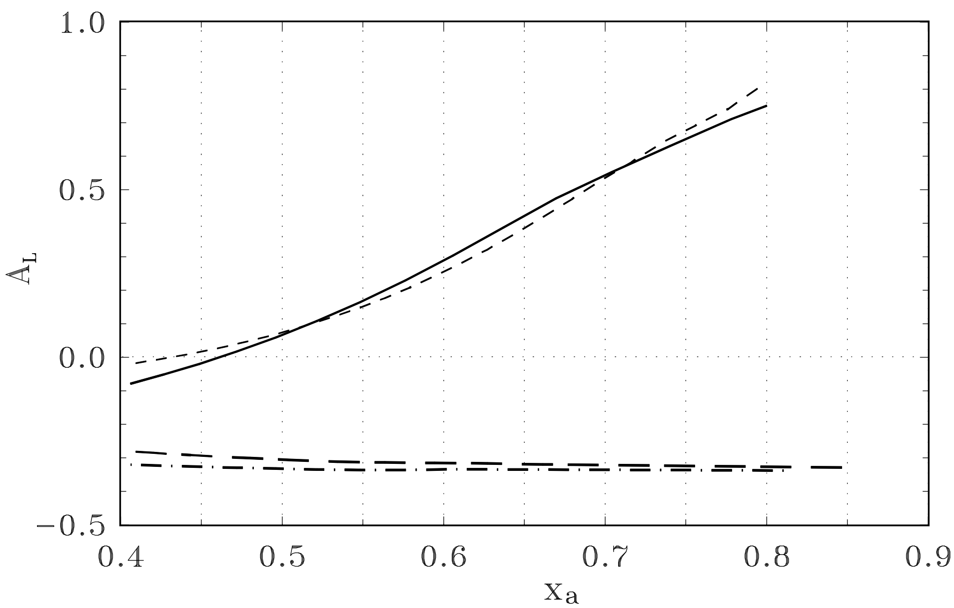

Fig.2. Single-spin longitudinal asymmetries A_L in inclusive W^--boson production. Short dash and solid lines: asymmetries A_L in pp- and $p\bar{p}$-channels for BBS model [9]. Long dash and dot-dash lines: asymmetries A_L in pp- and $p\bar{p}$-channels for CK-type distributions [10]

possible to estimate the statistical error in determination of asymmetry A_L:

$$\delta A_L = \frac{1}{p_{beam}} \frac{1}{\sqrt{N}} = \frac{1}{p_{beam}} \frac{1}{\sqrt{L \cdot T \cdot C}} \frac{1}{\sqrt{d\sigma/dy}}. \tag{5}$$

Here p_{beam} is polarization of the beam and N is the number of events, expressed as a product of the corresponding cross-section, beam luminosity L, pure running time T and combined trigger and reconstruction efficiency C. Assuming that $L = 10^{32}\, cm^{-2}s^{-1}$ for RHIC and $10^{31}\, cm^{-2}s^{-1}$ for TEVATRON, $T = 10^7\, s$ (about 4 months), $p_{beam} = 0.8$ and $C = 0.5$ it is easy to obtain that

$$\delta A_L\Big|_{x_a=0.4} = 0.007,\ \ \delta A_L\Big|_{x_a=0.7} = 0.03 \tag{6}$$

for RHIC and

$$\delta A_L\Big|_{x_a=0.4} = 0.01,\ \ \delta A_L\Big|_{x_a=0.7} = 0.045 \tag{7}$$

for TEVATRON.

Fig.2 shows the asymmetries A_L in pp- and $p\bar{p}$-channels both for CK and FJ-type polarized distributions, represented correspondingly by set 1 distributions from [10] and by recently proposed Brodsky-Burkardt-Schmidt (BBS) distributions from [9]†. As expected from the above discussion, already at intermediate x the behavior of A_L in CK and FJ models is very different: while the former is close to $-1/3$, the latter is around zero and grows. In BBS model $\Delta d_V(x)$ changes sign approximately at $x = 0.5$. It can be seen that even if the zero point is located at larger x, e.g. $x = 0.7$, the precision of the experiment still allows to reliably discriminate one model from another.

To conclude, though the problem of the description of helicity-dependent down quark distributions at large x is very old and well-known, no direct experimental test of $\Delta d_V(x)$ at $x \to 1$ has been done yet. The study of polarized W^- production at RHIC or TEVATRON colliders may provide important experimental information on the behavior of $\Delta d_V(x)/d_V(x)$ and help clarify this interesting question.

Acknowledgements

I express my thanks to S.M. Troshin for his help during the work on this paper. I am also grateful to W.-D. Nowak, who provided me the formula for estimating the errors of asymmetry measurement.

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†In BBS model $d_V(x)$ is not suppressed and behaves like $(1-x)^3$; this leads to larger unpolarized cross-sections of W^--production compared to those obtained with standard unpolarized distributions. Nevertheless, the conclusions about A_L are influenced only slightly, since A_L practically depends only on the ratio $\Delta d_V(x)/d_V(x)$.

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