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MEASURING POLARIZED PARTON DISTRIBUTIONS FROM ELECTROWEAK INTERACTIONS

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Abstract. We will try to review different methods based on electroweak interactions which can be used to extract polarized parton distributions. Our basic knowledge on parton distributions, coming from deep inelastic scattering in leptoproduction, will be reexamined and we will present a simple construction for unpolarized and polarized structure functions in terms of Fermi-Dirac distributions. We will also emphasize the importance of longitudinally and transversely polarized proton-proton and proton-neutron collisions at high energies for improving the determination of polarized quark distributions, in particular by means of gauge bosons and lepton-pair production.

1. INTRODUCTION

The spin structure of the nucleon is not yet fully understood and in spite of some recent measurements in polarized deep inelastic scattering, several puzzling questions remain unanswered. The spin dependent structure functions for proton and neutron are now more accurately determined in the low Q^2 region, but the validity or breakdown of the corresponding first moments sum rules are still the subject of many theoretical speculations. According to the standard interpretation of the data, it seems that only one third of the nucleon spin is carried by the quarks, a small fraction indeed, when compared to what one would naively expect. The amount of the proton spin carried by the sea quarks and the antiquarks is not firmly established and we still don't know what is the role of the axial anomaly and how much the gluon participates in the nucleon spin. These are some the reasons why polarized parton distributions are still so important and the purpose of this lecture is to review different methods involving electroweak interactions, which allow to measure these fundamental physical quantities.

The outline of the paper is as follows. In section 2 we will present a construction for the neutron and proton unpolarized structure functions in terms of Fermi-Dirac distributions by means of a very small number of parameters. By making some reasonable and simple assumptions, one can relate unpolarized and polarized quark distributions and predict the proton and neutron

spin dependent structure functions. In section 3 this set of polarized quark distributions will be used to study various helicity asymmetries for $W^{\pm}, Z$ and dilepton production in pp and pn collisions with longitudinally polarized protons at RHIC. Section 4 will be devoted to the case of transversely polarized protons, transverse spin asymmetries and in particular, we will stress the relevance of lepton-pair and Z production to determine quark transversity distributions.

2. DEEP INELASTIC SCATTERING

We will start by studing deep inelastic scattering and we will make use of some simple observations and advocate the Pauli exclusion principle, to construct a reliable set of quark, antiquark and gluon distributions.

Many years ago Feynman and Field made the conjecture[1] that the quark sea in the proton may not be flavor symmetric, more precisely $\bar{d} > \bar{u}$, as a consequence of Pauli principle which favors $d\bar{d}$ pairs with respect to $u\bar{u}$ pairs because of the presence of two valence u quarks and only one valence d quark in the proton. This idea was confirmed by the results of the NMC experiment[2] on the measurement of proton and neutron unpolarized structure functions, $F_2(x)$. It yields a fair evidence for a defect in the Gottfried sum rule[3] and one finds

$$I_G = \int_0^1 \frac{dx}{x}[F_2^p(x) - F_2^n(x)] = 0.235 \pm 0.026 \qquad (1)$$

instead of the value 1/3 predicted with a flavor symmetric sea, since we have in fact

$$I_G = 1/3(u + \bar{u} - d - \bar{d}) = 1/3 + 2/3(\bar{u} - \bar{d}). \qquad (2)$$

A crucial role of Pauli principle may also be advocated to understand the well known dominance of u over d quarks at high x,[4] which explains the rapid decrease of the ratio $F_2^n(x)/F_2^p(x)$ in this region. Let us denote by $q^{\uparrow}(q^{\downarrow})$, u or d quarks with helicity parallel (antiparallel) to the proton helicity. The double helicity asymmetry measured in polarized muon (electron) - polarized proton deep inelastic scattering allows the determination of the quantity $A_1^p(x)$ which increases towards one for high x,[5,6] suggesting that in this region $u^{\uparrow}$ dominates over $u^{\downarrow}$, *a fortiori* dominates over $d^{\uparrow}$ and $d^{\downarrow}$, and we will see now, how it is possible to make these considerations more quantitative. Indeed at $Q^2 = 0$ the first moments of the valence quarks are related to the values of the axial couplings

$$u^{\uparrow}_{\rm val} = 1 + F, \quad u^{\downarrow}_{\rm val} = 1 - F, \quad d^{\uparrow}_{\rm val} = \frac{1 + F - D}{2}, \quad d^{\downarrow}_{\rm val} = \frac{1 - F + D}{2}, \qquad (3)$$

so by taking $F = 1/2$ and $D = 3/4$ (rather near to the quoted values[7] 0.461 ± 0.014 and 0.798 ± 0.013) one has $u^{\uparrow}_{\rm val} = 3/2$ and $u^{\downarrow}_{\rm val} = 1/2$ which is at the center of the rather narrow range $(d^{\uparrow}_{\rm val}, d^{\downarrow}_{\rm val}) = (3/8, 5/8)$. The abundance of each of these four valence quark species, denoted by $p_{\rm val}$, is given by eq. (3) and we assume that the distributions at high Q^2 "keep a memory" of the properties of the valence quarks, which is reasonable since for $x > 0.2$ the sea is rather small. So we may write for the parton distributions

$$p(x) = F(x, p_{\rm val}) \tag{4}$$

where F is an increasing function of $p_{\rm val}$. The fact that the dominant distribution at high x is just the one corresponding to the highest value of $p_{\rm val}$, gives the correlation *abundance - shape* suggested by Pauli principle, so we expect broader shapes for more abundant partons. If $F(x, p_{\rm val})$ is a smooth function of $p_{\rm val}$, its value at the center of a narrow range is given, to a good approximation, by half the sum of the values at the extrema, which then implies[8]

$$u^{\downarrow}_{\rm val}(x) = 1/2 d_{\rm val}(x). \tag{5}$$

This leads to

$$\Delta u_{\rm val}(x) \equiv u^{\uparrow}_{\rm val}(x) - u^{\downarrow}_{\rm val}(x) = u_{\rm val}(x) - d_{\rm val}(x) \tag{6}$$

and, in order to generalize this relation to the whole u quark distribution, we assume that eq. (6) should also hold for quark sea and antiquark distributions, so we have

$$\Delta u_{sea}(x) = \Delta \bar{u}(x) = \bar{u}(x) - \bar{d}(x) \ . \tag{7}$$

Moreover as a natural consequence of eq. (3), we will assume

$$\Delta d_{\rm val}(x) = (F - D) d_{\rm val}(x) \ . \tag{8}$$

Finally we will suppose that the d sea quarks (and antiquarks) and the strange quarks (and antiquarks) are not polarized i.e.

$$\Delta d_{\rm sea}(x) = \Delta \bar{d}(x) = \Delta s(x) = \Delta \bar{s}(x) = 0 \ . \tag{9}$$

Clearly the above simple relations (6)-(9) are enough for fixing the determination of the spin dependent structure functions $xg_1^{p,n}(x, Q^2)$, in terms of the spin average quark parton distributions. We now proceed to present our approach for constructing the nucleon structure functions $F_2^{p,n}(x, Q^2)$, $xF_3^{\nu N}(x, Q^2)$, etc... in terms of Fermi-Dirac distributions which is motivated

by the importance of the Pauli exclusion principle, as we stressed above. Let us consider u quarks and antiquarks only, and let us assume that at fixed $Q^2, u^{\uparrow}_{\rm val}(x)$, $u^{\downarrow}_{\rm val}(x)$, $\bar{u}^{\uparrow}(x)$ and $\bar{u}^{\downarrow}(x)$ are expressed in terms of Fermi-Dirac distributions, in the scaling variable x, of the form

$$xp(x) = a_p x^{b_p} / (exp((x - \tilde{x}(p))/\bar{x}) + 1) \ . \tag{10}$$

Here $\tilde{x}(p)$ plays the role of the "thermodynamical potential" for the fermionic parton p and $\bar{x}$ is the "temperature" which is a universal constant. Since valence quarks and sea quarks have very different x dependences, we expect $0 < b_p < 1$ for $u^{\uparrow,\downarrow}_{\rm val}(x)$ and $b_p < 0$ for $\bar{u}^{\uparrow,\downarrow}(x)$. Moreover $\tilde{x}(p)$ is a constant for $u^{\uparrow,\downarrow}_{\rm val}(x)$, whereas for $\bar{u}^{\uparrow,\downarrow}(x)$, it has a smooth x dependence. This might reflects, the fact that parton distributions contain two phases, a gas contributing to the non singlet part with a constant potential and a liquid, which prevails at low x, contributing only to the singlet part with a potential slowly varying in x, that we take linear in $\sqrt{x}$. In addition, in a statistical model of the nucleon[9], we expect quarks and antiquarks to have opposite potentials, consequently the gluon, which produces $q\bar{q}$ pairs, will have a zero potential. Moreover, since in the process $G \to q_{\rm sea} + \bar{q}$, $q_{\rm sea}$ and $\bar{q}$ have opposite helicities, we expect the potentials for $u^{\uparrow}_{\rm sea}$ (or $\bar{u}^{\uparrow}$) and $\bar{u}^{\downarrow}$ (or $u^{\downarrow}_{\rm sea}$) to be opposite. So we take

$$\tilde{x}(\bar{u}^{\uparrow}) = -\tilde{x}(\bar{u}^{\downarrow}) = x_0 + x_1\sqrt{x} \ . \tag{11}$$

The d quarks and antiquarks are obtained by using eqs. (5) and (7) and concerning the strange quarks, we take in accordance with the data[10] $s(x) = \bar{s}(x) = (\bar{u}(x) + \bar{d}(x))/4$. Finally for the gluon distribution, for the sake of consistency, we take a Bose-Einstein expression given by

$$xG(x) = a_G x^{b_G} / (exp(x/\bar{x}) - 1) \tag{12}$$

with the same temperature $\bar{x}$ and a vanishing potential, as we discussed above. Since it is reasonable to assume that for very small x, $xG(x)$ has the same dependence as $x\bar{q}(x)$, we will take $b_G = 1 + \bar{b}$, where $\bar{b}$ is b_p for the antiquarks. So, except fo the overall normalization a_G, $xG(x)$ has no free parameter. All the distributions considered so far depend upon *eight* free parameters[1] which have been determined by using the most recent NMC data[2] on $F_2^p(x)$ and $F_2^n(x)$ at $Q^2 = 4GeV^2$ together with the most accurate neutrino data from CCFR[10,12] on $xF_3^{\nu N}(x)$ and the antiquark distribution $x\bar{q}(x)$ [10].

As an example of the results of our fit, $xF_3^{\nu N}(x)$ is presented in Fig. 1. As shown in ref.[11] the description of the data is very satisfactory, taking

[1] To identify them, see ref.[11] where their values are also given.

into account the fact that we only have *eight* free parameters and this certainly speaks for Fermi-Dirac distributions. Note that we find $I_G = 0.228$ in beautiful agreement with eq. (1). The steady rise of $x\bar{q}(x)$ at small x leads to a rise of F_2^p which is consistent[11] with the first results from Hera.

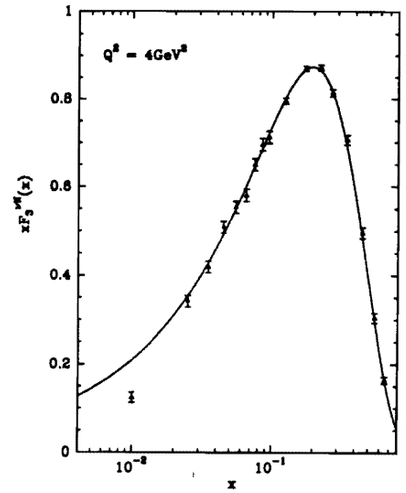

Fig.1 - The structure function $xF_3^{\nu N}(x)$ versus x. Data are from ref.[12] at $Q^2 = 3GeV^2$ and the solid line is the result of our fit from ref.[11].

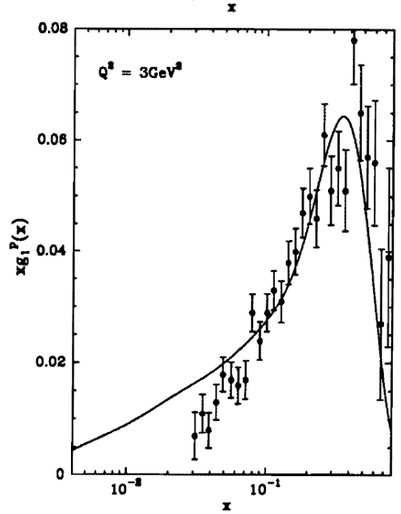

Fig.2 - $xg_1^p(x)$ at $< Q^2 >= 3GeV^2$ versus x. Data are from ref.[6] and solid line is our prediction.

Let us now turn to the polarized structure functions $xg_1^{p,n}(x, Q^2)$ which will allow to test our simple relations (6)-(9). We show in Fig. 2 our prediction together with the recent proton data from SLAC[6] at $Q^2 = 3GeV^2$ and we find

$$I_p = \int_0^1 g_1^p(x)dx = 0.138 \tag{13}$$

which is consistent with the evaluation of ref.[6], $I_p = 0.127 \pm 0.004$ (*stat.*) ± 0.010 (*syst.*). It is well below the Ellis-Jaffe sum rule[14] prediction of 0.160 ± 0.006 and we interpret it as being due to a large negative contribution of Δu_{sea} and $\Delta\bar{u}$ in the small x region (see eq. (7)).

Concerning the neutron polarized structure function $xg_1^n(x)$ we show in Fig. 3 a comparison of the SLAC data[13] at $Q^2 = 2GeV^2$ with our theoretical calculations. The dashed line corresponds to the case where d quarks are assumed to be unpolarized and it clearly disagrees with the data. However by including the d valence quark polarization according to eq. (8), we obtain the solid line in perfect agreement with the data and we find for $Q^2 = 2GeV^2$

$$I_n = \int_0^1 g_1^n(x)dx = -0.020\ . \tag{14}$$

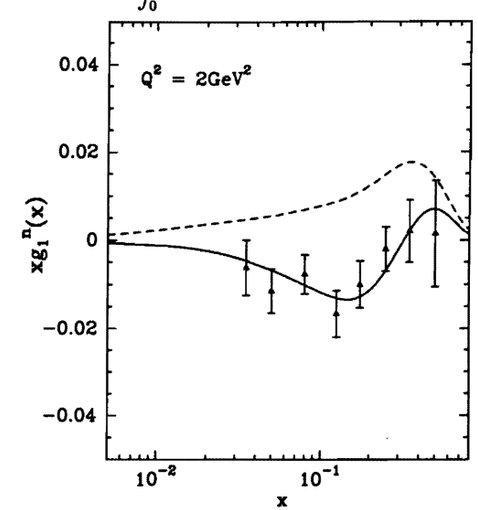

Fig.3 - $xg_1^n(x)$ at $< Q^2 >= 2GeV^2$ versus x. Data are from ref.[13] together with our predictions at $Q^2 = 2GeV^2$ from ref.[11] (Dashed line is the contribution of $\Delta u(x)$ and $\Delta\bar{u}(x)$ only and solid line contains, in addition, the contribution of $\Delta d_{\rm val}(x)$).

Finally our results for the parton polarizations $\Delta q(x)/q(x)$ at $Q^2 = 4GeV^2$ are shown in Fig. 4 and we will now discuss how polarized pp and pn collisions at high energies can provide an independent determination of these polarized distributions.

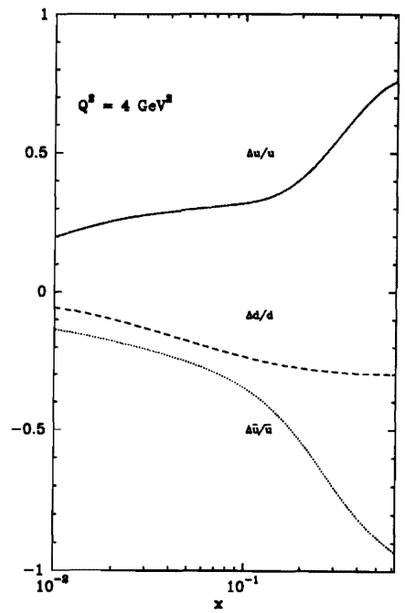

Fig.4 - Parton polarizations $\Delta q(x)/q(x)$ versus x at $Q^2 = 4GeV^2$ obtained from eqs.(6)-(9).

3. HELICITY ASYMMETRIES AT RHIC

A Relativistic Heavy Ion Collider (RHIC) is now under construction at Brookhaven National Laboratory and, already more than three years ago, it was realized that one should propose a very exciting physics programme[15], provided this machine could be ever used as a polarized pp collider. Of course all these considerations relie on the foreseen key parameters of this new facility, i.e. a luminosity up to $2.10^{32} cm^{-2} sec^{-1}$ and an energy of $50 - 250$ GeV per beam with a polarization of about 70%. Since then, the RHIC Spin Collaboration (RSC) has produced a letter of intent[16] and has undertaken

several serious studies in various areas which have led to a proposal[17] which has now been fully approved.

A very copious production of $W^{\pm}$ and Z bosons[18] is expected at RHIC, because in three months running, the integrated luminosity at $\sqrt{s} = 500GeV$ will be $800pb^{-1}$. In a recent article[19], it was shown that unpolarized cross section in pp and pn collisions allow an independent test of the flavor asymmetry of the light sea quarks mentioned above i.e. $\bar{d}(x) > \bar{u}(x)$, but here we will only recall some of the results obtained for the various spin-dependent observables.

3.1 Parity-violating asymmetries A_L, A_{LL}^{PV} and $\bar{A}_{LL}^{PV}$

Since RHIC is planned to be used as a polarized pp collider, let us now investigate what we can learn from the measurement of the helicity asymmetries and in particular from parity-violating asymmetries which involve the electroweak Standard Model couplings. In principle one can consider three parity-violating asymmetries defined as

$$A_L = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \quad , \quad A_{LL}^{PV} = \frac{\sigma_{--} - \sigma_{++}}{\sigma_{--} + \sigma_{++}} \quad , \quad \overline{A}_{LL}^{PV} = \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}} \tag{15}$$

where $\sigma_{h_1 h_2}$ is the cross section where the initial protons have helicities h_1 and h_2 and σ_h is the case where only one of the proton beam is polarized. Clearly if parity is conserved $\sigma_{h_1 h_2} = \sigma_{-h_1 -h_2}$, $\sigma_h = \sigma_{-h}$ so all these asymmetries vanish. Because of the axial vector couplings this is not the case in the Standard Model and these helicity asymmetries will be expressed in terms of the parton helicity asymmetries $\Delta f(x, Q^2)$ which are known at $Q^2 = 4GeV^2$ from the above analysis. In the Standard Model the W is a purely left handed current and A_L, in W^+ production, reads simply

$$A_L(y) = \frac{\Delta u\,(x_a, M_W^2)\,\overline{d}\,(x_b, M_W^2) - (u \leftrightarrow \overline{d})}{u\,(x_a, M_W^2)\,\overline{d}\,(x_b, M_W^2) + (u \leftrightarrow \overline{d})} \tag{16}$$

assuming the proton a is polarized, and a similar expression can be written for the case of pn collisions[19].

Turning to the double helicity asymmetries A_{LL}^{PV} and $\bar{A}_{LL}^{PV}$, for pp collisions they are explicitely given in ref.[20] and one finds that A_{LL}^{PV} is symmetric in y whereas $\overline{A}_{LL}^{PV}$ is antisymmetric, so we have

$$A_{LL}^{PV}(y) = A_{LL}^{PV}(-y) \quad , \quad \overline{A}_{LL}^{PV}(y) = -\overline{A}_{LL}^{PV}(-y). \tag{17}$$

A priori these helicity asymmetries are three independent observables, but if one makes the reasonable assumption $\Delta u \Delta \overline{d} << u\overline{d}$ for all x, one gets the two following relations

$$A_{LL}^{PV}(y) = A_L(y) + A_L(-y) \tag{18}$$

$$\overline{A}_{LL}^{PV}(y) = A_L(y) - A_L(-y). \tag{19}$$

So within this approximation, the double spin asymmetries A_{LL}^{PV} and $\overline{A}_{LL}^{PV}$ do not contain any additional information than that contained in the single spin asymmetry $A_L(y)$ and in particular at $y = 0$, where the cross section is maximum, $A_{LL}^{PV} = 2A_L$ and $\overline{A}_{LL}^{PV} = 0$. In order to calculate these asymmetries we have used the above model for the various parton helicity asymmetries Δu_v, Δu_s, $\Delta\overline{u}$, Δd_v, Δd_s, $\Delta\overline{d}$ evaluated at $Q^2 = M_W^2$.

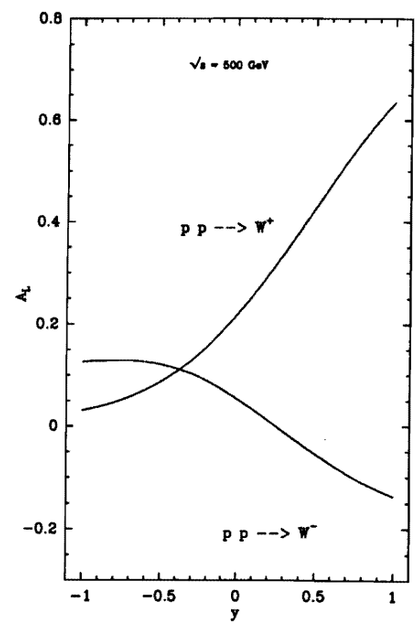

Fig.5 Parity-violating helicity asymmetry A_L versus y for W^+ and W^- production in pp collisions at $\sqrt{s} = 500\ GeV$.

The results of our calculations for $W^\pm$ production are presented in Fig.5 for A_L with this choice of polarized parton distributions. The general trend of A_L can be understood as follows: from eq.(16) and a similar expression for

W^- production by permuting u and d, one sees that for $y = 0$

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta u}{u} - \frac{\Delta\overline{d}}{\overline{d}}\right) \quad \text{and} \quad A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta d}{d} - \frac{\Delta\overline{u}}{\overline{u}}\right) \tag{20}$$

evaluated at $x = M_W/\sqrt{s}$, for $y = -1$ one has

$$A_L^{W^+} \sim -\frac{\Delta\overline{d}}{\overline{d}} \quad \text{and} \quad A_L^{W^-} \sim -\frac{\Delta\overline{u}}{\overline{u}} \tag{21}$$

evaluated at $x = 0.059$ and for $y = +1$ one has

$$A_L^{W^+} \sim \frac{\Delta u}{u} \quad \text{and} \quad A_L^{W^-} \sim \frac{\Delta d}{d} \tag{22}$$

evaluated at $x = 0.435$.

So the region $y \simeq +1$ is controled by valence quark polarizations while $y \simeq -1$ is very sensitive to the sea quark polarizations. Similar calculations have been done for pn collisions[19] and also for Z production.

Finally by using eqs.(18) and (19), one obtains from Fig.5 the following rather good estimates i.e. $0.40 \leq A_{LL}^{PV} \leq 0.60$ for W^+ production and $\overline{A}_{LL}^{PV} \simeq 0$ for W^- production in pp collisions.

3.2 Parity-conserving asymmetries A_{LL}

In pp collisions where both proton beams are polarized, there is another observable which is very sensitive to antiquark polarizations, that is the parity-conserving double helicity asymmetry A_{LL} defined as

$$A_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}\,. \tag{23}$$

This asymmetry, in W^+ production, reads simply

$$A_{LL}(y) = -\frac{\Delta u\,(x_a,\ M_W^2)\,\Delta \leq d\,(x_b,\ M_W^2) + (u \leftrightarrow \bar{d})}{u\,(x_a,\ M_W^2) \leq d\,(x_b,\ M_W^2) + (u \leftrightarrow \bar{d})}\,. \tag{24}$$

For W^- production quark flavors are interchanged. It is clear that $A_{LL}(y) = A_{LL}(-y)$ and that $A_{LL} \equiv 0$ if the antiquarks are not polarized, i.e. $\Delta \leq u(x) = \Delta\bar{d}(x) \equiv 0$. Similarly for Z production we find

$$A_{LL}(y) = -\frac{\sum\limits_{i=u,d} (a_i^2 + b_i^2)\left[\Delta q_i\,(x_a, M_Z^2)\,\Delta\bar{q}_i\,(x_b, M_Z^2) + (x_a \leftrightarrow x_b)\right]}{\sum\limits_{i=u,d} (a_i^2 + b_i^2)\left[q_i\,(x_a, M_Z^2)\,\bar{q}_i\,(x_b, M_Z^2) + (x_a \leftrightarrow x_b)\right]} \tag{25}$$

which will vanish for unpolarized antiquarks. We show in Fig. 6 our predictions for the three cases at $\sqrt{s} = 500GeV$. Clearly as a consequence of eq. (9) $A_{LL} \equiv 0$ for W^+ production but if $\Delta\bar{d}(x) \neq 0$, it would be non-zero and of opposite sign to $\Delta\bar{d}(x)$. For W^- production for $y = 0$ we get $A_{LL} = -\frac{\Delta d}{d}\frac{\Delta\bar{u}}{\bar{u}}$ evaluated at $x = M_W/\sqrt{s}$ which gives around -10% and from the trend of the d and $\bar{u}$ polarizations similar to that shown in Fig. 4, we also expect A_{LL} to be almost constant for $-1 < y < +1$. For Z production as a consequence of eq. (9) $A_{LL} \simeq +10\%$ and does not depend on the d quark polarization.

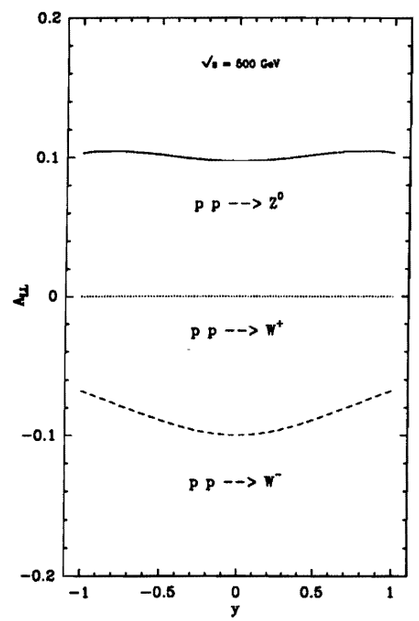

Fig.6 - Parity-conserving double helicity asymmetry A_{LL} versus y for $W^\pm$ and Z production in pp collisions at $\sqrt{s} = 500\ GeV$.

Finally let us consider lepton-pair production and in this case the expression for $A_{LL}(y)$ follows from eq.(25) where a_i is replaced by e_i, the electric charge of q_i, and $b_i = 0$. We have calculated A_{LL} at $\sqrt{s} = 100GeV$ which seems more appropriate to the acceptance of the detectors at RHIC and the results are shown in Fig.7. We observe that A_{LL} increases for an increasing lepton-pair mass M and of course for $\Delta\bar{u} = 0$ we would have $A_{LL} = 0$.

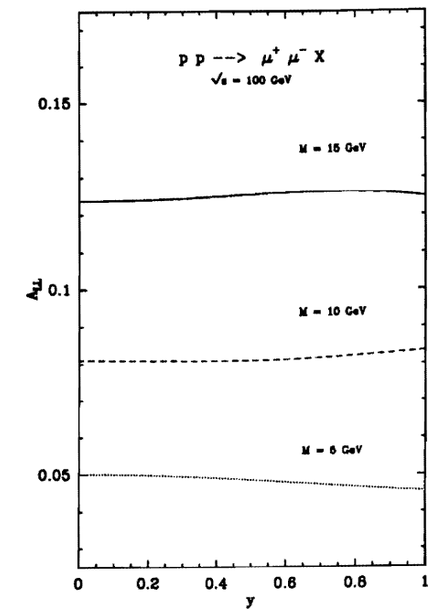

Fig.7 - Parity-conserving double helicity asymmetry A_{LL} versus y for dilepton production at $\sqrt{s} = 100GeV$ and different values of the lepton-pair mass.

4. DOUBLE SPIN TRANSVERSE ASYMMETRIES A_{TT}

So far we have considered collisions involving only longitudinally polarized proton beams, but of course at RHIC, transversely polarized protons will be available as well[17]. This new possibility is extremely appealing because of recent progress in understanding transverse spin effects in QCD, both at leading twist[21] and higher twist levels[22]. For the case of the nucleon's helicity, its distribution among the various quarks and antiquarks can be obtained in polarized deep inelastic scattering from the measurement of the structure function $g_1(x)$ mentioned above. However this is not possible for the *transversity* distribution $h_1(x)$ which describes the state of a quark (antiquark) in a transversely polarized nucleon. The reason is that $h_1(x)$, which measures the correlation between right-handed and left-handed quarks, decouples from deep inelastic scattering. Indeed like $g_1(x)$, $h_1(x)$ is leading - twist and it can be measured in Drell-Yan lepton-pair production with both initial proton

beams transversely polarized[21]. Other possibilities have been suggested[23] but in the framework of this lecture, we will envisage also a practical way to determine $h_1(x)$, by using gauge boson production in pp collisions with protons transversely polarized. Let us consider the double spin transverse asymmetry defined as

$$A_{TT} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} \tag{26}$$

where $\sigma_{\uparrow\uparrow}(\sigma_{\uparrow\downarrow})$ denotes the cross section with the two initial protons transversely polarized in the same (opposite) direction. Assuming that the underlying parton subprocess is quark-antiquark annihilation, we easily find for Z production

$$A_{TT} = \frac{\sum_{i=u,d} (b_i^2 - a_i^2) \left[h_1^{q_i}(x_a) h_1^{\bar{q}_i}(x_b) + (x_a \leftrightarrow x_b)\right]}{\sum_{i=u,d} (a_i^2 + b_i^2) \left[q_i(x_a)\bar{q}_i(x_b) + (x_a \leftrightarrow x_b)\right]} \cdot \tag{27}$$

This result generalizes the case of lepton-pair production[21] through an off shell photon γ^* and corresponding to $b_i = 0$ and $a_i = e_i$, as mentioned above. For $W^\pm$ production, which is pure left-handed and therefore does not allow right-left interference, we expect $A_{TT} = 0$, since in this case $a_i^2 = b_i^2$. This result is worth checking experimentally.

So far there is no experimental data on these distributions $h_1^q(x)$ (or $h_1^{\bar{q}}(x)$), but there are some attempts to calculate them either in the framework of the MIT bag model[21] or by means of QCD sum rules[24]. However the use of positivity yields to derive a model-independent constraint on $h_1^q(x)$ which restricts substantially the domain of allowed values[25]. Indeed one has obtained

$$q(x) + \Delta q(x) \geq 2|h_1^q(x)|. \tag{28}$$

which is much less trivial than

$$q(x) \geq |h_1^q(x)|, \tag{29}$$

as proposed earlier in ref.[21].

In the MIT bag model, let us recall that these distributions read[21]

$$q = f^2 + g^2, \ \Delta q = f^2 - 1/3g^2 \ \text{ and } \ h_1^q = f^2 + 1/3g^2 \tag{30}$$

and they saturate (28). In this case, we observe that $h_1^q(x) \geq \Delta q(x)$ but this situation cannot be very general because of eq.(28). As an example let us assume $h_1^q(x) = 2\Delta q(x)$. Such a relation cannot hold for all x and we see that

eq.(28), in particular if $\Delta q(x) > 0$, implies $q(x) \geq 3\Delta q(x)$. This is certainly not satisfied for all x by the present determination of the u quark helicity distribution, in particular for large x where $A_1^p(x)$ is large[5,6]. The simplifying assumption $h_1^q(x) = \Delta q(x)$, based on the non-relativistic quark model, which has been used in some recent calculations[19,23] is also not acceptable for all x values if $\Delta q(x) < 0$ because of eq.(28). To illustrate the practical use of eq.(28), let us consider eqs.(6) and (7). It is then possible to obtain the allowed range of values for $h_1^u(x)$, namely

$$u(x) - \frac{1}{2}d(x) \geq |h_1^u(x)| \tag{31}$$

which is shown in Fig.8. In this case, we have checked that for $x > 0.5$, both the results of the MIT bag model[21] and the QCD sum rule[24] violate this positivity bound, combined with low Q^2 data. A similar calculation can be done for the d quarks to get the allowed region for $h_1^d(x)$ [25].

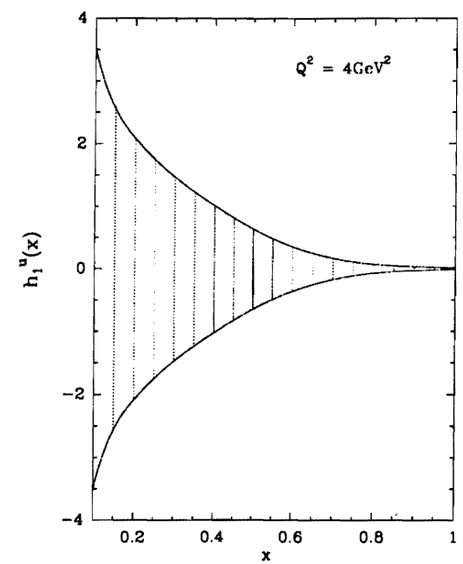

Fig.8 The striped area represents the domain allowed for $h_1^u(x)$ using eq.(31).

Finally we show in Fig.9 the results of our calculation for A_{TT} in the case of Z production by assuming the equality sign in eq.(28) and $h_1^u(x) > 0$,

$h_1^{\bar{u}}(x) < 0$. Clearly this prediction is only a guide for a future experiment at RHIC which will lead to the actual determination of $h_1(x)$.

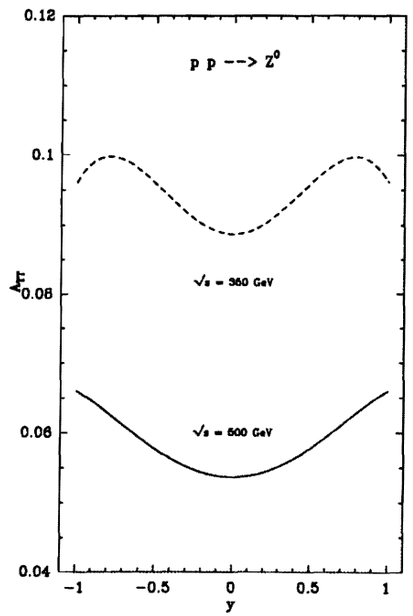

Fig.9 Double spin transverse asymmetry A_{TT} versus y for Z production in pp collisions at $\sqrt{s} = 350$ and 500 GeV.

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