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Constraints on leptophobic gauge bosons with polarized neutrons and protons at RHIC

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Abstract. We explore the sensitivity and the physical interest of the measurement of parity-violating spin asymmetries in one-jet production in the presence of a new leptophobic neutral gauge boson, $Z^{'}$, within polarized hadronic collisions at the BNL RHIC. We focus on polarized neutron collisions which could be achieved in a realistic upgrade of the RHIC-spin program. We show that, in the case of a discovery, a compilation of the information coming from both polarized $\vec{p}\vec{p}$ and $\vec{n}\vec{n}$ collisions should constrain the number of Higgs doublets and the presence or absence of trilinear fermion mass terms in the underlying model of new physics.

1 Introduction

The addition of an extra $U(1)'$ gauge factor to the $SU(3) \times SU(2) \times U(1)$ structure is one of the simplest extensions of the standard model (SM). When the symmetry breaking of this extra factor occurs at a scale close to the electroweak scale, one obtains a new neutral gauge boson Z' in the particle spectrum, with a mass accessible to forthcoming experiments.

The strongest experimental constraints on such Z' models come from experiments which analyze some processes involving leptons, either in the initial state and/or in the final state. For instance, the constraints coming from LEP, HERA or the Drell–Yan process at Tevatron are complementary and provide some bounds on the Z' mass of the order of 600–700 GeV for canonical models [1], the precise values depending on the specific model and the relevant process involved in the analysis.

However, when the Z' has zero or very small direct couplings to leptons (leptophobia), the above processes are irrelevant and one has to turn to pure hadronic channels to provide some constraints [1].

The existence of relatively light leptophobic gauge bosons is an attractive possibility, both for phenomenology and because of theoretical arguments. Recent papers advocated a weak-scale supersymmetry (SUSY) scenario in non-minimal SUSY models with an additional extra $U(1)^{'}$. The corresponding Z' could be "light": $M_{Z'} < 1.5\,\text{TeV}$. More precisely, a class of models driven by a large trilinear soft SUSY breaking term prefer the range $M_Z < M_{Z'} < 400\,\text{GeV}$, along with a very small mixing with the standard Z. This particular scenario is only allowed if the model exhibits leptophobic couplings [2]. On the other hand, other models display or can accommodate leptophobia: some are string inspired [3–5], others are non-SUSY [6,7] (for a more complete set of references one can consult our paper [8]). Furthermore, in many models an asymmetry in the left- and right-handed couplings of the $Z^{'}$ to light quarks is preferred or at least allowed. Finally, a small Z–$Z^{'}$ mixing angle is generated in these models, in agreement with electroweak precision data.

In a previous paper [8], we have shown that the measurement of parity violating (PV) spin effects in the production of jets from hard collisions of polarized hadrons could be a way to get a handle on this elusive leptophobic Z' boson.

The situation of interest is the one at Brookhaven National Laboratory where the RHIC machine is operating mainly as a heavy-ion collider but will be used for part of the time as a polarized proton–proton ($\vec{p}\vec{p}$) collider. The RHIC Spin Collaboration (RSC) has performed a first run during the year 2001, with polarized protons, an energy $s^{1/2} = 200\,\text{GeV}$ and a luminosity of a few $10^{30}\,\text{cm}^{-2}\text{s}^{-1}$. Around 2003, one expects to reach $s^{1/2} = 500\,\text{GeV}$ and $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ [9] allowing an exposure of $800\,\text{pb}^{-1}$ in only four months of running. The physics program of the collaboration has been reviewed recently in [10] where many references can also be found (see also [9]). This pro-

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gram will allow first some precise measurements to be made of the polarization of the gluons, quarks and sea-antiquarks in a polarized proton. This will be done thanks to well-known standard model processes: direct photon, W and Z production, Drell–Yan pair production, heavy-flavor production and the production of jets. The helicity structure of perturbative QCD will be thoroughly tested at the same time with the help of parity conserving (PC) double spin asymmetries.

Concerning new physics, it has been noticed that non-zero CP-violating asymmetries can be generated from various mechanisms going beyond the SM [11–13]. On the other hand, the production of high E_{T} jets from polarized protons could allow one to pin down a possible new weak interaction between quarks, provided that parity is violated in the subprocess [8, 14–17]. In the case of a simple phenomenological PV contact term, a search strategy based on the polarized RHIC can be competitive with conventional searches at the Tevatron, or even better [18, 17].

Indeed, the production of jets is largely dominated by QCD, which is a parity conserving theory. However a standard PV spin asymmetry in jet production should be present from tiny QCD–electroweak interference effects, namely the interference between the one-weak boson exchange amplitude and the one-gluon exchange amplitude since, at high E_{T}, the process is dominated by qq scattering. The magnitude and sign of this standard PV asymmetry can be safely estimated from well-known subprocess amplitudes and from our knowledge of the polarized quark distributions in a polarized proton. Note that polarized gluons distributions (which are poorly known) are irrelevant in this process at least at leading order (LO). Therefore, a net deviation from the small expected standard model asymmetry could be a clear signature of the presence of a new force belonging to the quark sector with a peculiar chiral structure.

Models with leptophobic Z's are obviously good candidates to consider in this context. The study presented in [8] has shown that, in order to detect a non-standard effect in $\vec{p}\vec{p}$ collisions at RHIC, besides the necessity of leptophobia plus a low mass, the Z' boson must exhibit an asymmetry in the left and right couplings to u quarks since u quarks dominate in $\vec{p}\vec{p}$ collisions. Fortunately, the existence of such PV couplings for u quarks is a prediction of several leptophobic models constructed up to now [4–7].

Conversely, the PV nature of the Z' couplings to d quarks is much more model dependent. Indeed, it depends on the symmetry breaking scenarios and on the scalar potential assumed for the models. More precisely, we will see that the PV properties of the d couplings are directly connected to the number of Higgs doublets involved in the model and to the presence or absence of trilinear fermion mass terms in the Yukawa lagrangian. So, in case of a discovery, the measurements of these d couplings, or at least the test of their PV nature, should provide unique information on the scalar sector of the underlying theoretical model of new physics.

Unfortunately, within $\vec{p}\vec{p}$ collisions at RHIC the Z' amplitudes involving d quarks in the initial and final states are completely hidden by the u quark contributions. However, a particular feature of the RHIC as a heavy ion collider is to be able to accelerate polarized ^{3}He nuclei, which could mimic high energy polarized neutrons. Indeed, the Pauli exclusion principle implies that the polarized ^{3}He nuclei carries essentially the spin of the neutron since the spins of the protons are in opposite directions.

This possibility has been considered by the RSC and one expects to get some polarized beams of "neutrons" of relatively good quality [19]. Therefore, in the following, we consider polarized $\vec{n}\vec{n}$ collisions at RHIC in order to explore which kind of information could be obtained on the d couplings and on the scalar sector of the new theory.

In Sect. 2, we present the models and the different scalar structures which are considered in our analysis. In Sect. 3, we present the definition of the spin dependent observable that we consider, we summarize our calculations, and we give the limits on the parameter space which could be achieved at RHIC in the case of the various models, within $\vec{n}\vec{n}$ collisions. In the last section, we show a combined analysis of the information which could be provided by both $\vec{p}\vec{p}$ and $\vec{n}\vec{n}$ collisions, in case of a discovery, and therefore the constraints that might be obtained on the Higgs sector of the theory.

2 Classification of the models

The interactions between a new neutral vector gauge boson $Z^{'}$ and up- and down-type quarks are described by the following lagrangian:

$$\mathcal{L}_{Z'} = \kappa \frac{g}{2\cos\theta_{\mathrm{W}}} \times \sum_q Z'^{\mu} \bar{q}\gamma_\mu \left[C_L^q (1-\gamma_5) + C_{\mathrm{R}}^q (1+\gamma_5)\right] q, \tag{1}$$

where $C^q_{\mathrm{L,R}}$ are the couplings to left- and right-handed quarks for each given quark flavor q and the parameter $\kappa = g_{Z'}/g_Z$ is of order one. We restrict our discussion to the light quark flavors u and d since only a Z' which couples to these light quarks may give some observable effects at RHIC energies.

In what follows, we will concentrate on leptophobic $Z^{'}$ models of relatively light masses with chiral couplings to quarks. We refer the reader to [8] and to the original literature for more details on the theoretical motivations and on the underlying structures of each model.

At first, we consider an approach similar to the one of Georgi and Glashow [7] to determine the general conditions imposed by gauge invariance, leptophobia and symmetry breaking on the $U(1)'$ charges. Next, each different general situation will be illustrated by a specific model.

First of all, gauge invariance under the SM group $SU(2)_{\mathrm{L}}$ imposes the universality of the left-handed couplings:

$$C_{\rm L}^u = C_{\rm L}^d \equiv C_{\rm L}. \tag{2}$$

Therefore, in the following, we will suppress the flavor indices on the left-handed couplings.

Initially we can assume that all SM fermions acquire their masses via the trilinear mass terms present in the Yukawa lagrangian:

$$\mathcal{L}_Y = h_u \bar{Q} H_u u_{\rm R} + h_d \bar{Q} H_d d_{\rm R} + h_l \bar{L} H_l e_{\rm R}, \tag{3}$$

where Q is a quark doublet, L a lepton doublet, $u_{\rm R}$, $d_{\rm R}$ and $e_{\rm R}$ are right-handed singlets. $H_{u,d,l}$ represent the corresponding Higgs doublets and $h_{u,d,l}$ are Yukawa coupling matrices. For supersymmetric models, the structure is formally the same on the condition that one replaces the potential by the superpotential and the fields by the superfields.

Gauge invariance under the new $U(1)^{'}$ gauge group associated with the Z', imposes the condition that the sum of the $U(1)^{'}$ charges $Q^{'}$ for each term is zero:

$$Q^{'}(H_u) - Q^{'}(Q) + Q^{'}(u_{\rm R}) = 0, \tag{4}$$

$$Q^{'}(H_d) - Q^{'}(Q) + Q^{'}(d_{\rm R}) = 0, \tag{5}$$

$$Q^{'}(H_l) - Q^{'}(L) + Q^{'}(e_{\rm R}) = 0. \tag{6}$$

The $U(1)'$ charges of the fermions are directly related to their chiral couplings: $Q^{'}(Q) = C_{\rm L}$, $Q^{'}(L) = C_{\rm L}^{e,\nu}$ and $Q^{'}(f_{\rm R}) = C_{\rm R}^f$.

From (6) the condition of leptohobia[1] $Q^{'}(e_{\rm L}) = Q^{'}(e_{\rm R}) = 0$, forces the charge of the Higgs doublet coupling to the lepton field to be zero:

$$Q^{'}(H_l) = 0. \tag{7}$$

Given these assumptions, we will now describe three different scalar structures implying different properties for the right-handed couplings of d quarks to the $Z^{'}$. Of course, one may be surprised by this particular approach where the Q' charges seem to be put in by hand instead of taking a specific model where these charges are fixed and where anomaly cancellation is fulfilled thanks to the presence of exotics. Here we are not interested in these exotics, since we can assume safely that their masses are sufficiently high to avoid detection at existing colliders, including RHIC. Moreover, we want to choose an approach which is the best possible model independent. Since, at RHIC, we can test the PV structure of d quark couplings, we just quote which choice of scalar structure, independently of the choice of a particular new gauge theory, implies a modification in this PV structure.

2.1 Structure I: 2HDM

A first interesting case appears when the Higgs doublet H_d which generates the masses of d-type quarks is identical to the one which yields (charged) lepton masses. This structure corresponds to the two Higgs doublets models (2HDM) and it can be achieved for special values of the Q' charges [7]. In this case, $H_l \equiv H_d$ and we have from (7):

$$Q^{'}(H_d) = 0. \tag{8}$$

This implies from (5) that $Q^{'}(Q) = Q^{'}(d_{\rm R})$ or, in terms of the couplings:

$$C_{\rm R}^d = C_{\rm L}. \tag{9}$$

We see that the d quark couplings are *vector-like* which means that parity is conserved in this quark sector. This is the main characteristic of the models displaying this structure, which we call *Structure I* from now on.

Conversely, if we want the remaining Higgs doublet H_u to play a role in the symmetry breaking of the $U(1)'$ symmetry, then it must be charged under $U(1)'$ in order to acquire a vacuum expectation value that breaks the $U(1)'$ symmetry. So we take $Q'(H_u) \neq 0$, which implies for the couplings (see (4))

$$C_{\rm R}^u \neq C_{\rm L}. \tag{10}$$

From this equation, we see that the u quark couplings cannot be vector-like. Hence, parity will be violated, except for the peculiar axial case where $C_{\rm R}^u = -C_{\rm L}$.

This remark and (10) are also valid for the remaining structures that we will consider, i.e. we always assume that H_u is playing a role in the breaking of the $U(1)'$ symmetry. Note that additional scalars, singlets of $SU(2)_{\rm L}$, can also be present in the breaking scenario, but they have no impact on the PV nature of the d couplings.

An explicit model which can be an illustration of this *Structure I* is the supersymmetric "η-kinetic model" of Babu, Kolda and March-Russell [4], whose properties are parity conservation for d quarks and PV for u quarks. We call it *Model B* to remain coherent with [8]:

$$\text{Model B}: \quad C_{\rm L}^u = C_{\rm L}^d = C_{\rm R}^d = -\frac{1}{2} C_{\rm R}^u = -\frac{5}{18}\sin\theta_{\rm W}. \tag{11}$$

Note that, at variance with the notation of [4], the usual factor of grand unification theories ($(5/3)^{1/2}\sin\theta_{\rm W}$) has been included in the $C_{\rm L,R}^q$ couplings to keep κ of order one.

2.2 Structure II

The first extension of the previous scalar structure is achieved when we allow the third Higgs doublet H_l to be different from H_d. In this case, leptophobia does not provide anymore a direct relation among the couplings $C_{\rm L}$ and $C_{\rm R}^d$, since (5) and (6) are now completely disconnected. For *Structure II* we still asume that (5) is valid, i.e. that d quarks acquire their masses from a trilinear mass term. Conversely, we do not make any assumption on the form of the (charged) lepton mass term which plays no role in the following discussion.

Nevertheless, in many extensions of the SM, particularly in most of the leptophobic $Z^{'}$ models, it is assumed that the symmetry breaking is driven by the two vacuum

[1] In case of gauge kinetic mixing, the Z' actually couples to an effective charge which is a linear combination of Q' and Y (e.g. see [4]). To simplify, we have kept the notation Q' for these effective charges

expectation values of the H_u and H_d Higgs doublets which are of the same order ($v_{H_u} \simeq v_{H_d}$) [7]. Indeed, the constraints from the electroweak precision data impose that the Z–$Z^{'}$ mixing angle, $\theta_{Z-Z'}$ should be very small. This requires that [7]

$$g_{Z'}^2 \left| v_{H_u}^2 Q^{'}(H_u) - v_{H_d}^2 Q^{'}(H_d) \right| << g_Z^2 v^2. \tag{12}$$

With $v_{H_u} \simeq v_{H_d}$, this expression leads us to assume that $Q^{'}(H_u)$ and $Q^{'}(H_d)$ are also of the same order and have the same sign:

$$Q^{'}(H_u) \simeq Q^{'}(H_d). \tag{13}$$

Using the condition of $U(1)'$ gauge invariance of the trilinear u and d mass terms ((4) and (5)), we get the following relation for the chiral couplings:

$$C_{\rm L} - C_{\rm R}^u \simeq C_{\rm L} - C_{\rm R}^d. \tag{14}$$

Thanks to the $SU(2)_{\rm L}$ gauge invariance this gives

$$C_{\rm R}^u \simeq C_{\rm R}^d. \tag{15}$$

This clearly means that the left- or right-handed dominance is the same for u quarks and for d quarks. An example of such models is given by the following right-handed model, which we call *Model C*[2]:

$$\text{Model C}: \quad C_{\rm L} = 0, \quad C_{\rm R}^u = C_{\rm R}^d = \frac{1}{3}. \tag{16}$$

Note that some authors consider (14) and (15) simply as orders of magnitude. For example, the model presented in [6] (which is also the first model of [7]) fits into this scalar *Structure II*, but the $U(1)'$ charges are $Q'(H_u) = -3$, $Q'(H_d) = -2$, $Q'(Q) = C_{\rm L} = -1$, $Q'(u_{\rm R}) = C_{\rm R}^u = 2$, and $Q'(d_{\rm R}) = C_{\rm R}^d = 1$. Therefore, we get PV couplings for u quarks but axial couplings for d quarks.

Then in order to be conservative, one can say that a characteristic of the models with the scalar *Structure II* is that they cannot yield a left-handed (right-handed) dominance for u quarks and a right-handed (left-handed) dominance for d quarks at the same time.

2.3 Structure III

Finally, we can consider the non-minimal scalar structure provided by string derived models as the ones considered by Cvetič, Langacker and collaborators [2]. A peculiarity of these string derived models is that trilinear mass terms appear naturally for u- or d-type quarks but not for both [20]. A correct prediction for the top quark mass is done [21] if one takes a trilinear mass term for the top quark [20]. This choice is made in [2]. In these scenarios, d-type quarks and charged leptons acquire their masses thanks to nonrenormalizable terms (i.e. terms that are not trilinear).

If there is no trilinear mass term in the theory for d quarks, (5) is no longer valid. Therefore, the chiral couplings of the d quarks are completely free. This means that we can have PC couplings (vector-like as in *Structure I*, or axial), or PV couplings with a left-handed or a right-handed dominance, the same as for u quarks (this is similar to *Structure II*), or on the contrary in opposition to the case of u quarks. This situation will characterize *Structure III*.

We have chosen the following phenomenological *Model D* to illustrate this last possibility:

$$\text{Model D}: \quad C_{\rm L} = \frac{1}{3}, \quad C_{\rm R}^u = 0, \quad C_{\rm R}^d = \frac{2}{3}. \tag{17}$$

In addition, the flipped $SU(5)$ model of Lopez and Nanopoulos [5] is another good example of *Structure III*, but now with axial couplings for d quarks. This model, which we call *Model A* from [8], is characterized by

$$\text{Model A}: \quad C_{\rm L} = -C_{\rm R}^d = \frac{1}{2\sqrt{3}}, \quad C_{\rm R}^u = 0. \tag{18}$$

These couplings imply that parity is maximally violated in the u quark sector, whereas it is conserved in the d quark sector because of the purely axial character of the couplings.

3 Observables and results

We concentrate on the inclusive single jet production process $\vec{n}n \to \text{jet} + X$, where the polarization of only one neutron is necessary to define the single helicity PV asymmetry:

$$A_{\rm L} = \frac{{\rm d}\sigma_{(-)} - {\rm d}\sigma_{(+)}}{{\rm d}\sigma_{(-)} + {\rm d}\sigma_{(+)}}, \tag{19}$$

where the signs $\pm$ refer to the helicity of the polarized neutron. The cross section ${\rm d}\sigma_{(\lambda)}$ means the one-jet production cross section estimated at some $s^{1/2}$ for a given jet transverse energy $E_{\rm T}$, integrated over a pseudorapidity interval $\Delta\eta$ centered at $\eta = 0$.

In fact, both ^{3}He beams could be polarized in principle, giving access to doubly polarized neutron collisions $\vec{n}\vec{n} \to \text{jet} + X$ and to double-helicity asymmetries (for a review of definitions and calculations of spin observables one can consult [22]). Then the statistical significance is increased, but a similar amount of information is obtained on the chiral and scalar structures. We prefer to be conservative assuming that only one beam will be polarized.

Concerning the value of $s^{1/2}$, at RHIC, the charged nucleons (protons) of a nucleus are accelerated up to energies of $E_p = 250$–$300\,\text{GeV}$ per nucleon. At first, the machine will run with $E_p = 250\,\text{GeV}$; this is the reason why we have taken a center of mass energy of $s^{1/2} = 500\,\text{GeV}$ for $\vec{p}\vec{p}$ collisions [8]. A ^{3}He nuclei, being accelerated, will get the total energy of its two protons. The neutron will be

[2] This model is analogous to the second model of [7], but we have changed the precise values of the $U(1)'$ charges in order to have $\kappa \simeq 1$

able to reach only one third of this energy, which means that the center of mass energy will be reduced for n–n collisions. To be sensitive to a possible new physics effect, it is necessary to run at the highest possible energy (i.e. $E_p = 300\,\mathrm{GeV}$). Hence, we have $E_{^3\mathrm{He}} = 600\,\mathrm{GeV}$ and $E_n = 200\,\mathrm{GeV}$, $\vec{n}\vec{n}$ (or $\vec{n}n$) collisions reaching an energy $s^{1/2} = 400\,\mathrm{GeV}$ in the center of mass, the value that we take in the following. Concerning the integrated luminosities, we have taken the same values as in [8], namely $L_1 = 800\,\mathrm{pb}^{-1}$ and $L_2 = 3.2\,\mathrm{fb}^{-1}$ for practical comparison with the $\vec{p}\vec{p}$ results, even if these values are certainly a little bit optimistic. However, if we take seriously the possibility of some luminosity upgrades at RHIC in the future [23], these numbers become perfectly realistic.

The dominant subprocess in the E_T range that we consider is quark–quark scattering. Concerning the standard contribution, A_L is given by the expression (in short notation):

$$A_\mathrm{L} \simeq \frac{1}{\mathrm{d}\sigma} \sum_{i,j} \sum_{\alpha,\beta} \int \left(T^{--}_{\alpha,\beta}(i,j) - T^{++}_{\alpha,\beta}(i,j) \right) \times \left[q_i(x_1) \Delta q_j(x_2) + \Delta q_i(x_1) q_j(x_) + (\mathrm{i} \leftrightarrow j) \right]. \quad (20)$$

The $T^{\lambda_1,\lambda_2}_{\alpha,\beta}(i,j)$'s are the matrix element squared with α boson and β boson exchanges in a given helicity configuration for the involved partons i and j. The expressions for the relevant $T_{\alpha,\beta}$'s at leading order (LO) are well known; they can be found e.g. in [24]. We have $\Delta q_i = q_{i+} - q_{i-}$, where $q_{i\pm} \equiv q_{i\pm}(x,\mu^2)$ are the distributions of the polarized quark of flavor i, either with helicity parallel (+) or antiparallel (−) to the parent proton helicity. Summing the two states one recovers $q_{i+} + q_{i-} = q_i(x,\mu^2)$. All these distributions are evaluated at the scale $\mu = E_\mathrm{T}$. The unpolarized cross section $\mathrm{d}\sigma$ is dominated by QCD and must also include all the relevant electroweak and Z' terms and their interference with QCD terms when it is allowed by color rules. Of course, the non-dominant $q(\bar{q})g$ and gg scattering subprocesses have to be included in the part of the cross section which is purely QCD. The resulting standard A_L is positive and increases with the jet transverse energy E_T as soon as E_T is larger than the range $E_\mathrm{T} \approx M_{W,Z}/2$ (see the figures below). This is due to the increasing importance of quark–quark scattering with respect to other subprocesses involving gluons.

If present, the leptophobic Z' contributes to the quark–quark scattering process via new amplitudes which interfere with the single gluon exchange amplitude. It is straightforward to get these amplitudes from the standard ones involving the standard Z. One has also to add the very tiny electroweak–Z' interference which will not yield an observable effect. As was already pointed out in [8], 95% of the effect due to the new boson comes from $Z'.g$ interference terms involving the scattering of identical quarks in the t,u-channels. In the case of $\vec{n}n$ collisions this corresponds essentially to the scattering of d quarks. This dominant contribution can be written as follows:

$$A_\mathrm{L} \cdot \mathrm{d}\sigma \simeq F \int \left[C_\mathrm{L}^2 - C_\mathrm{R}^{d\,2} \right] \left[d\left(x_1,\mu^2\right) \Delta d\left(x_2,\mu^2\right) + \Delta d\left(x_1,\mu^2\right) d\left(x_2,\mu^2\right) \right]_\mathrm{neutron}, \quad (21)$$

where F is a positive factor given by

$$F = \frac{32}{9} \alpha_\mathrm{s} \alpha_z \hat{s}^2 \mathrm{Re} \left(\frac{1}{\hat{t} D^{\hat{u}}_{Z'}} + \frac{1}{\hat{u} D^{\hat{t}}_{Z'}} \right), \quad (22)$$

where $\alpha_z = \alpha / \sin^2\theta_\mathrm{W} \cos^2\theta_\mathrm{W}$ and $D^{\hat{t}(\hat{u})}_{Z'} = \left(\hat{t}(\hat{u}) - M^2_{Z'} \right) + \mathrm{i} M_{Z'} \Gamma_{Z'}$.

Note that the partonic part of (21) corresponds to the polarized and unpolarized d quark distributions in a *neutron*. So, if we want to use an expression with the more familiar definitions of quark distributions in a *proton*, from isospin symmetry, we have to replace $d_\mathrm{neutron}(x,\mu^2)$ and $\Delta d_\mathrm{neutron}(x,\mu^2)$ by the functions $u(x,\mu^2)$ and $\Delta u(x,\mu^2)$, defined for a proton. This means that the partonic part of (21) is positive since Δu_proton is positive as is well known.

We can remark that (21) allows us to easily predict the behavior of the spin asymmetry A_L in the presence of a new Z' contribution. Given the positivity of the factor F and of the partonic part, the direction of a possible deviation from the SM A_L asymmetry will be determined directly by the chiral couplings $C^d_\mathrm{L,R}$, more precisely by the difference $C_\mathrm{L}^2 - C_\mathrm{R}^{d\,2}$. Consequently, a model whose d chiral couplings present left (right) dominance will provide a positive (negative) deviation to the SM A_L asymmetry.

In our LO calculations, all the contributions, dominant or not, are included. Concerning the partonic part we have used the GRSV polarized parton distribution functions (pdf) [25] along with the associated unpolarized pdf's. Remember that the uncertainties due to the imperfect knowledge of the polarized pdf's will be reduced soon thanks to the first part of the RHIC-spin program itself [10].

On the theoretical side some systematic uncertainties are coming from the existence of higher order corrections to the SM prediction for A_L and to the Z' contribution itself. Indeed, at NLO, several new contributions appear [26]. However, the current prejudice is that spin asymmetries which are ratios of cross sections are much less affected than simple cross sections by higher order corrections. This behavior has been confirmed recently by some calculations which have provided some precise results on the small influence of gluons on the standard QCD–electroweak interference term at NLO [27]. A first estimate of the size of NLO corrections to qq scattering is in favor of a relatively small correction, of the order of 10% of the asymmetry itself [28].

Concerning experimental uncertainties, a good knowledge of the beam polarization (±5%) and a very good relative luminosity measurement (10^{-4}) should allow one to get a systematic uncertainty for a single spin measurement of the order of 5% [10]. For the time being, we have taken into account all the present uncertainties by using a global systematic error on the spin asymmetry: $(\Delta A)_\mathrm{syst}/A = 10\%$.

In Figs. 1 and 2 we compare the non-standard asymmetries $A_\mathrm{L}(\vec{p}p)$ and $A_\mathrm{L}(\vec{n}n)$ to the standard one in each case, focusing on Models C and D. We ignore here Models

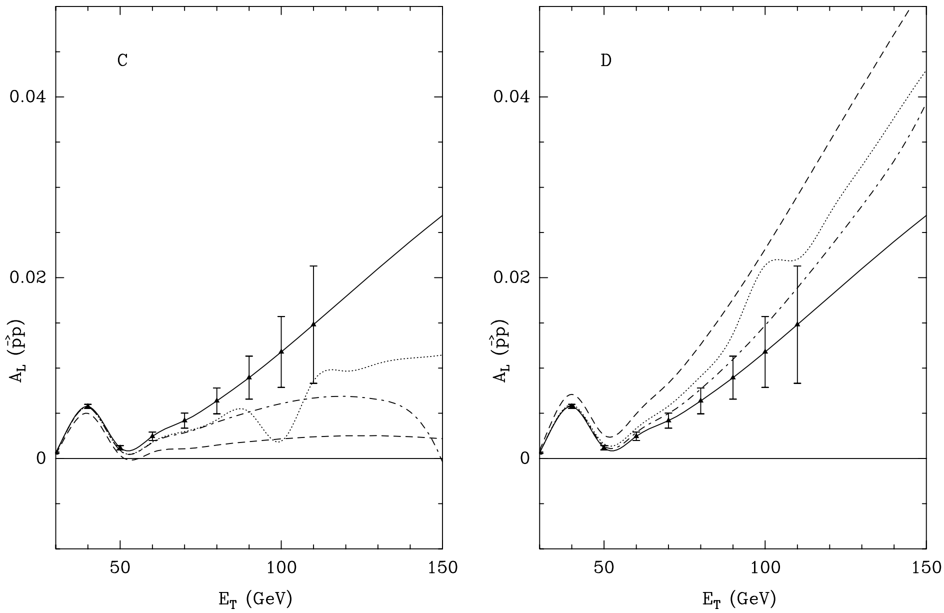

Fig. 1. $A_{\rm L}$ versus $E_{\rm T}$ for Models C (left) and D (right) with $\vec{p}p$ collisions at RHIC at $s^{1/2} = 500\,{\rm GeV}$. The plain curves represent the SM predictions. The dashed, dotted and dash-dotted curves correspond to the cases where the masses are $M_{Z'} = 90, 200$ and $300\,{\rm GeV}$ respectively. The error bars correspond to the integrated luminosity $L_2 = 3.2\,{\rm fb}^{-1}$. $\kappa = 1$ for all cases except for Model C with $M_{Z'} = 300\,{\rm GeV}$ and $\kappa = 1.5$

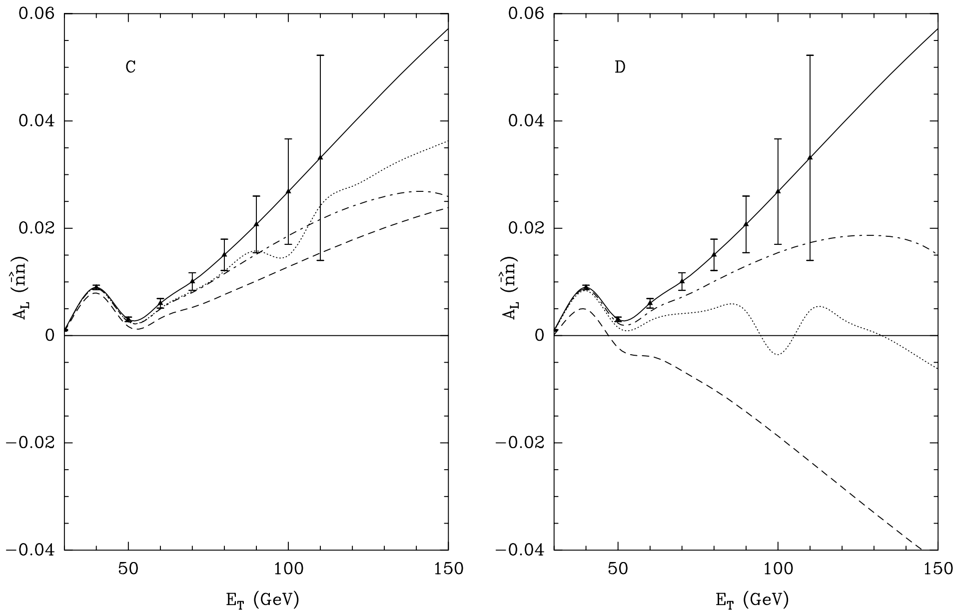

Fig. 2. Same as Fig. 1 for $\vec{n}n$ collisions at $s^{1/2} = 400\,{\rm GeV}$

A and B which do not give any effect on $A_{\rm L}(\vec{n}n)$ since in these models parity is conserved in the interactions between the corresponding Z' and d quarks (axial for Model A and vector-like for Model B). The result of our calculation for these models in the case of $\vec{p}\vec{p}$ collisions has already been displayed in [8].

Concerning the standard asymmetry, one can notice that, in spite of the smaller center of mass energy, the $A_{\rm L}(\vec{n}n)$ is larger than the one calculated for $\vec{p}\vec{p}$ collisions in [10,17] This is due to the larger parity violation in the d quark sector compared to the u quark sector for the SM (i.e. $|C_{\rm L}^2 - {C_{\rm R}^d}^2| >> |C_{\rm L}^2 - {C_{\rm R}^u}^2|$). However, the influence of the reduced energy shows itself on the error bars which are larger than for the ones on $A_{\rm L}(\vec{p}p)$ for the same $E_{\rm T}$ bin. The bumps in the curves correspond to the jacobian peaks due to real W and Z exchanges around $E_{\rm T} \approx M_{W,Z}/2$, or Z' exchange at $E_{\rm T} \approx M_{Z'}/2$. The remaining effects on the whole $E_{\rm T}$ spectrum are due to $Z.g$ and $Z'.g$ interference terms.

One can see that in the framework of Models C and D the effects of the Z' are spectacular, provided its mass is not too high; hence RHIC should not miss them if they are present.

The deviations from the SM expectations are negative in Model C in Figs. 1 and 2 in accordance with the right-handed dominance of both u and d quark couplings. On the other hand, in the case of Model D which is dominantly left-handed for u quarks and right-handed for d quarks, the deviation is positive in $\vec{p}p$ collisions and negative in $\vec{n}n$ collisions.

Finally, in the case of $\vec{n}n$ collisions, if we compare the effects on $A_{\rm L}$ coming from Models C and D for the same Z'

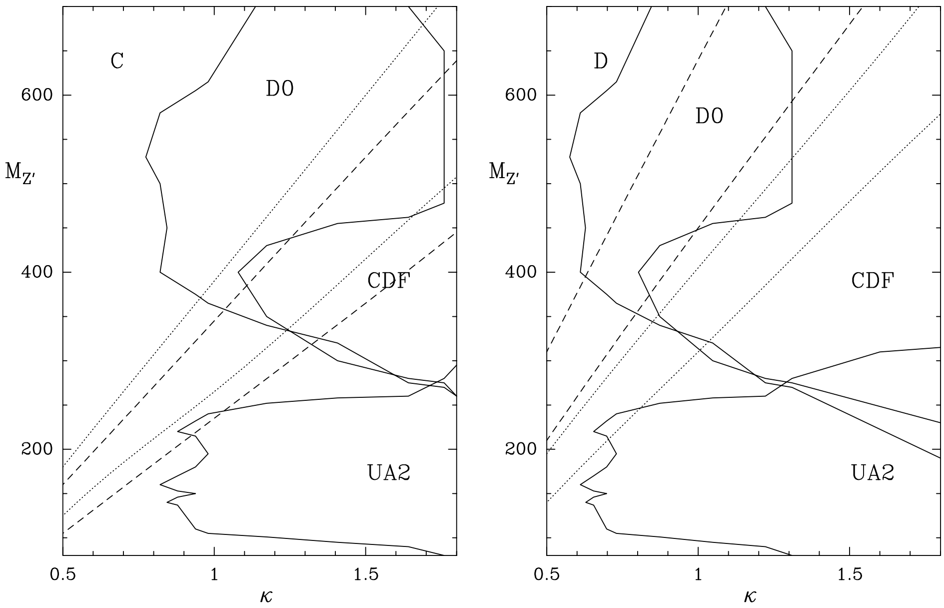

Fig. 3. Bounds on the parameter space $(\kappa, M_{Z'})$ for Models C and D. The dotted and dashed curves correspond respectively to the predicted limits at 95% C.L. from $A_{\rm L}(\vec{p}\vec{p})$ and $A_{\rm L}(\vec{n}\vec{n})$ at RHIC with $s^{1/2} = 500\,{\rm GeV}$ for $\vec{p}\vec{p}$, $s^{1/2} = 400\,{\rm GeV}$ for $\vec{n}\vec{n}$ collisions, and with $L_1 = 800\,{\rm pb}^{-1}$ (lower curves) and $L_2 = 3200\,{\rm pb}^{-1}$ (upper curves)

mass, we see that Model D implies some larger deviations from the SM predictions. This difference is due to the larger parity violation in the d quark sector for Model D as compared to Model C. Indeed, the difference $C_{\rm L}^2 - C_{\rm R}^{d\,2}$ appearing in (21) is equal to 1/9 for Model C and to 1/3 for Model D, implying roughly a three times larger deviation for Model D.

In Fig. 3, we present the limits on the parameter space $(\kappa, M_{Z'})$ that both $A_{\rm L}(\vec{n}n)$ and $A_{\rm L}(\vec{p}p)$ should provide with the integrated luminosities $L_1 = 800\,{\rm pb}^{-1}$ and $L_2 = 3200\,{\rm pb}^{-1}$ for Models C and D. We also display the inferred constraints coming from the dijet cross section studies by the $p\bar{p}$ collider experiments UA2 [29], CDF [30] and D0 [31]. In fact the published results were restricted to the so-called Z' "sequential standard model" (SSM) with $\kappa = 1$. We have easily extrapolated these results to Models C and D by changing the couplings appropriately for a reasonable range of κ values. One can see that these unpolarized collider studies are not constraining a $Z^{'}$ mass as soon as κ is small enough. Also, and this is true in any leptophobic model, some windows were still present around $M_{Z'} = 300\,{\rm GeV}/c^2$ and below $M_{Z'} = 100\,{\rm GeV}/c^2$. With the help of polarized hadronic beams the situation could be greatly improved: in particular the hole centered on $M_{Z'} \approx 300\,{\rm GeV}/c^2$ should be covered provided κ is greater than ≈ 0.7. One gets the same behavior for the bounds in the framework of Models A and B (see [8]).

We remark that $A_{\rm L}(\vec{p}p)$ is slightly more sensitive than $A_{\rm L}(\vec{n}n)$ for Model C. This difference can be explained simply by the reduced center of mass energy for $\vec{n}\vec{n}$ collisions. Indeed for Model C, the parity violation is equal in strength for both the u and d quark sectors, i.e. $C_{\rm L}^2 - C_{\rm R}^{u\,2} = C_{\rm L}^2 - C_{\rm R}^{d\,2}$. Conversely, for Model D we see that the sensitivity is clearly in favor of $A_{\rm L}(\vec{n}n)$ which can be understood due to the relation $|C_{\rm L}^2 - C_{\rm R}^{d\,2}| = 3|C_{\rm L}^2 - C_{\rm R}^{u\,2}|$.

To conclude, the analysis of PV spin asymmetries measured within $\vec{n}n$ collisions is able to constrain the presence of a new weak hadronic interaction in the d quark sector. In the case of a discovery, the deviations from the SM expectations indicate the chirality of the new interaction with respect to d quarks.

4 Constraints on the scalar structure

In this section, we want to analyze which kind of information could be provided by the precise measurements of both spin asymmetries at RHIC, namely $A_{\rm L}(\vec{p}p)$ and $A_{\rm L}(\vec{n}n)$. In particular, we will consider if we are able to discriminate between the three scalar structures we have described in Sect. 2.

At this stage it is worth recalling our assumptions:

(i) the condition of leptophobia plus a small Z–Z' mixing angle;
(ii) the gauge invariance under $U(1)^{'}$ of the fermion mass terms;
(iii) $SU(2)_{\rm L}$ invariance;
(iv) we assume that some PV effects due to a leptophobic $Z^{'}$ have been detected through the measurement of $A_{\rm L}(\vec{p}p)$ in the "first" phase of the RHIC operations with polarized proton beam(s). This means that parity is violated in the u quark sector of the new $U(1)^{'}$.

In Fig. 4, we present $A_{\rm L}(\vec{p}p)$ versus $A_{\rm L}(\vec{n}n)$ for a transverse energy $E_{\rm T} = 70 \pm 5\,{\rm GeV}$. We have chosen this particular interval since its contribution to the χ^2 function involved in the analysis is maximal. Of course, a full integration over the $E_{\rm T}$ range accessible experimentally will reduce the error bars. However, to be realistic, this integration should take into account the details of the jet reconstruction of the RHIC detectors, an analysis which is far beyond the scope of this paper.

In this figure, the central point represents the SM prediction. The error bars correspond to the integrated luminosity $L_2 = 3200\,{\rm pb}^{-1}$. Models A, B, C and D, which were

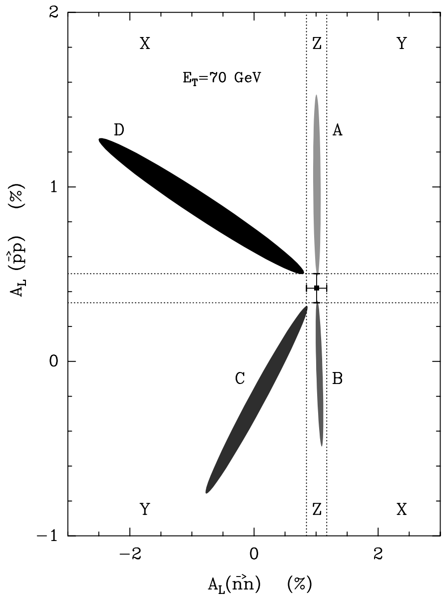

Fig. 4. Predictions of the various models (see text) in the plane $A_L(\vec{p}p)$ versus $A_L(\vec{n}n)$ for $E_T = 70$ GeV. The error bars on the SM point correspond to the integrated luminosity $L_2 = 3.2\,\text{fb}^{-1}$

introduced to illustrate the different scalar structures, are represented each by a shaded ellipse. Each point inside an ellipse corresponds to a precise value of κ and $M_{Z'}$; these values are taken so as to satisfy the present experimental constraints presented in Fig. 3 and in Fig. 1 of [8].

Concerning the shapes of the ellipses, there is no simple dependence on the two parameters κ and $M_{Z'}$ in this plane. However, a point close to the "SM cross" obviously means that one has a small κ and/or a large $M_{Z'}$. Conversely, the largest effect (that is the farthest from the SM point) is obtained for $M_{Z'} = M_Z$ (which is our lowest $M_{Z'}$ value) and for the highest experimentally allowed value of κ within each model.

Remember that *Structure I* is characterized by a vector-like coupling of the d quark to the Z'. Models belonging to *Structure II* should exhibit the same left-handed or right-handed dominance for u and d quarks. This means that the deviations from SM expectations for $A_L(\vec{p}p)$ and for $A_L(\vec{n}n)$ go in the same direction. In the framework of *Structure III*, corresponding to highly non-trivial scalar structures, no predictions are made for the d quark couplings; hence they can be located anywhere in the ($A_L(\vec{p}p)$, $A_L(\vec{n}n)$) plane. However, it is only for this structure that we can have an opposite chirality for u and d quarks couplings. On Fig. 4 we call "X" the two regions which correspond to the latter case in the upper-left and lower-right sectors. Model D is an illustration of this situation. A first conclusion is that experimental results belonging to zone "X" should allow one to eliminate both *Structure I* (i.e. 2HDM) and *Structure II* whose common property is the presence of trilinear mass terms for u and d quarks.

Secondly, we define sector "Y" which is accessible by models from *Structure II* or *Structure III* but which excludes *Structure I*. Concerning *Structure II*, the fact that the points belong to zone "Y" is related to the common property of left-handed dominance (right-handed dominance) for u and d couplings, corresponding to the upper-right (lower-left) sector of the plane. Model C belongs to this category with a right-handed dominance.

Finally, for the models of *Structure I*, like Model B, the d quarks have some vector-like couplings to the Z' and we do not expect any deviation on $A_L(\vec{n}n)$. So, they should be located on the vertical line passing through the SM point. Taking into account the experimental conditions, this line is replaced by the band "Z" whose width is determined by the error on the standard $A_L(\vec{n}n)$. Of course, models belonging to the two other structure can fall into this band (Model A is an illustration from *Structure III*). Conversely, models from *Structure I*, which characterize the 2HDM with trilinear mass terms for all fermions, will be ruled out by the RHIC $\vec{p}p$ and $\vec{n}n$ collision experiments if any effect is observed outside this band.

On the other hand, if for some other phenomenological or theoretical reason it turns out that models from *Structure III* have to be rejected, then the "Z" band should be a clear signature of the simplest 2HDM's of *Structure I*. The only drawback is the case of axial couplings of the d quarks which is forbidden by these models but is allowed as a very particular case of the models of *Structure II*, and which contaminates the "Z" band.

5 Conclusion

The existence of a new weak force between quarks at a not too high energy scale is an attractive possibility which is not ruled out by present data. If a new neutral gauge boson Z' owns the property of leptophobia plus a small Z–Z' mixing angle, it evades the bounds coming from previous experiments and it must be looked for in purely hadronic processes.

The polarized proton beams which are available at RHIC allow the precise measurement to be made of the PV spin asymmetry A_L in the production of jets. As pointed out in our previous papers, and also stressed by some authors [5], such measurements could really lead to a discovery if the new Z' exhibits some handed couplings to u quarks, since u quarks play a dominant role in the collision process. In addition, as usual, measuring a spin asymmetry allows one to get a handle on the chiral structure of the underlying interaction. More precisely, the sign of the deviation from the expected standard value of A_L should allow one to pin down the chiral structure of the new interaction, still in the u quark sector.

In spite of its relatively low center of mass energy (500–600 GeV) the RHIC machine should be a remarkable tool, in particular thanks to the very high luminosity which is expected. Hence, in some models a mass as high as $M_{Z'} = 400$ GeV could give a measurable effect.

Since the acceleration and storage of high intensity polarized ^{3}He ions, which means polarized neutrons, will be a real possibility in a second phase of RHIC, it is valuable to investigate what could be obtained on the d quark sector.

We had already checked that polarized *proton–neutron* collisions could only give access to the effects of a new charged current [16]. For testing the d quark sector of a new $U(1)'$, the use of both "neutron beams" is mandatory.

In this paper, we have checked first that it would be possible to get some valuable information on the chirality of the $Z'd\bar{d}$ vertex thanks to the measurement of the asymmetry $A_{\rm L}(\vec{n}n)$. This could be done with a precision which is comparable to what can be hoped from the measurement of $A_{\rm L}(\vec{p}p)$.

Moreover, getting in the same time information on the u and the d couplings is a way of testing the scalar structure of the underlying model. We have seen that the property of leptophobia, plus some general assumptions like gauge invariance under the standard $SU(2)_{\rm L}$ and under the new $U(1)'$, constrains the Higgs sector of the model.

The simplest case of two Higgs doublet models, with trilinear mass terms and the traditional property $H_d \equiv H_l$, exhibits the interesting consequence of vector-like couplings of the $Z^{'}$ to d quarks along with PV violation in the u quark sector in general. Other models exhibit a more elaborated scalar structure, in particular the scalar sector which gives masses to ordinary quarks could be decoupled from the corresponding sector for leptons. This is the case in our models from *Structure II* where we have considered two Higgs doublets giving masses to u and d quarks along with some phenomenological constraints, without any assumptions on the leptons. In this case parity is violated in general in both the u and d sectors. Measuring $A_{\rm L}(\vec{p}p)$ and $A_{\rm L}(\vec{n}n)$ should allow one to separate the two structures, if an even more general possibility was not present. Conversely, if one does not assume anymore the presence of trilinear mass terms for the quarks (*Structure III*), the situation is more open in the ($A_{\rm L}(\vec{p}p)$,$A_{\rm L}(\vec{n}n)$) plane. Therefore, some definite conclusions could be drawn only if the measurements are in favor of the "sector X" described in Sect. 4: In this case *Structures I and II* are forbidden. Similarly an effect observed outside the "Z band" rules out the 2HDM's (*Structure I*) without any ambiguity.

Our conclusion is that the implementation of polarized "neutron beams" at RHIC should to a great extent complement the program of new physics searches with polarized proton beams, since a non-trivial piece of information could be obtained on the scalar sector of the underlying theory.

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References

1. Particle Data Group, Eur. Phys. J. C **15**, 1 (2000)
2. M. Cvetič et al., Phys. Rev. D **56**, 2861 (1997); see also M. Cvetič, P. Langacker, Phys. Rev. D **54**, 3570 (1996); P. Langacker, J. Wang, Phys. Rev. D **58**, 115010 (1998)
3. J.D. Lykken in Snowmass 1996, edited by D.G. Cassel, L. Trindle Gennari, R.H. Siemann, p. 891; A.E. Faraggi, M. Masip, Phys. Lett. B **388**, 524 (1996)
4. K.S. Babu, C. Kolda, J. March-Russell, Phys. Rev. D **54**, 4635 (1996); D **57**, 6788 (1998)
5. J.L. Lopez, D.V. Nanopoulos, Phys. Rev. D **55**, 397 (1997)
6. K. Agashe, M. Graesser, I. Hinchliffe, M. Suzuki, Phys. Lett. B **385**, 218 (1996)
7. H. Georgi, S.L. Glashow, Phys. Lett. B **387**, 341 (1996)
8. P. Taxil, J.-M. Virey, Phys. Lett. B **441**, 376 (1998)
9. Proceedings of the RIKEN-BNL Workshop, Spin Physics at RHIC in year-1 and beyond, May 2001, Brookhaven, BNL Report 52635
10. G. Bunce, N. Saito, J. Soffer, W. Vogelsang, Ann. Rev. Nucl. Part. Sci. **50**, 525 (2000)
11. S. Kovalenko, I. Schmidt, J. Soffer, Phys. Lett. B **503**, 313 (2001)
12. B. Grzadkowski in [9], p. 75
13. D. Atwood in [9], p. 29
14. M. Tannenbaum, in Polarized Collider Workshop, AIP Conference Proceedings 223, edited by J. Collins, S.F. Heppelmann, R.W. Robinett (AIP, New York 1990), p. 201
15. P. Taxil, J.-M. Virey, Phys. Lett. B **364**, 181 (1995)
16. P. Taxil, J.-M. Virey, Phys. Lett. B **404**, 302 (1997)
17. P. Taxil, J.-M. Virey, hep-ph/0109094, to appear in Phys. Lett. B
18. P. Taxil, J.-M. Virey, Phys. Rev. D **55**, 4480 (1997)
19. E. Courant, Proceedings of the RIKEN-BNL research center workshop, april 1998, BNL Report 65615, p. 275
20. A.E. Faraggi, Phys. Lett. B **377**, 43 (1996)
21. A.E. Faraggi, Phys. Lett. B **274**, 47 (1992)
22. C. Bourrely, F.M. Renard, J. Soffer, P. Taxil, Phys. Reports **177**, 319 (1989)
23. N. Saito in the Proceedings of the 14th International Spin Physics Symposium, Osaka, 2000, edited by K. Hatanaka et al., AIP Conference Proceedings 570 (AIP, New York 2001)
24. C. Bourrely, J.-Ph. Guillet, J. Soffer, Nucl. Phys. B **361**, 72 (1991)
25. M. Glück, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. D **53**, 4775 (1996)
26. J.-M. Virey in Predictions and uncertainties for RHIC Spin Physics and event generators for RHIC Spin Physics III, Proceedings of the RIKEN-BNL Workshop, March 2000, Brookhaven, p. 111
27. J. Ellis, S. Moretti, D.A. Ross, JHEP **06**, 043 (2001); S. Moretti in [9], p. 57
28. W. Vogelsang in [9], p. 63; in The Spin Structure of the Proton and Polarized Collider Physics, Proceedings of the ECT* workshop, July 2001, Trento, Italy, to appear
29. J. Alitti et al., Zeit. f. Phys. C **49**, 17 (1991); Nucl. Phys. B **400**, 3 (1993)
30. F. Abe et al., Phys. Rev. D **55**, R5263 (1997)
31. B. Abbott et al., FERMILAB-Conf-97/356-E