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

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Abstract

We explore the sensitivity and the physics 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 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.

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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, at 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 or/and 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. At the same time the $Z - Z'$ mixing angle $\theta_{Z-Z'}$ is constrained to be very small. 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 from 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" : $M_{Z'} < 1.5$ TeV. More precisely, a class of models driven by a large trilinear soft SUSY breaking term, prefer the range $M_{Z} < M_{Z'} < 400$ GeV, along with a very small mixing with the standard $Z$. This particular scenario is only allowed if the model exhibits leptophobic couplings [4]. On the other hand, other models display or can accommodate leptophobia : some are string inspired [3, 4, 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.

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 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 $\sqrt{s}$ = 200 GeV and a luminosity of a few $10^{30} cm^{-2} s^{-1}$. Around 2003, it is expected to reach $\sqrt{s}$ = 500 GeV and $\mathcal{L}$ = 2.10$^{32} cm^{-2} s^{-1}$ [9] allowing an exposure of 800 $pb^{-1}$ in only four months of running. The physics program of the collaboration has been reviewed recently in ref.[10] where many references can also be found (see also [11]). This program will allow first some precise measurements 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, 12, 13]. On the other hand, the production of high $E_T$ jets from polarized protons could allow to pin down a possible new weak interaction between quarks, provided that parity is violated in the subprocess [14, 15, 16, 8, 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 $q-q$ 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 protons. 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 $p\bar{p}$ 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 $p\bar{p}$ collisions. Fortunately, the existence of such PV couplings for $u$ quarks is a prediction of several leptophobic models constructed up to now [4, 5, 6, 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 tri-linear 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 a unique information on the scalar sector of the underlying theoretical model of New Physics.

Unfortunately, within $p\bar{p}$ 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 $^3He$ nuclei, which could mimic high energy polarized neutrons. Indeed, the Pauli exclusion principle implies that the polarized $^3He$ 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 it is expected to get some polar-
ized beams of “neutrons” of relatively good quality [19]. Therefore, in the following, we consider polarized $\bar{n}n$ 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 section two, we present the models and the different scalar structures which are considered in our analysis. In section three, 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 $\bar{n}n$ collisions. In the last section, we show a combined analysis of the information which could be provided by both $\vec{p}\vec{p}$ and $\bar{n}n$ 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:

$$\mathcal{L}_{Z'} = \kappa \frac{g}{2\cos\theta_W} \sum_q Z'^\mu \bar{q} \gamma^\mu \left[ C^q_L (1 - \gamma_5) + C^q_R (1 + \gamma_5) \right] q$$

where $C^q_{L,R}$ are the couplings to left and right handed quarks for each given quark flavor $q$ and the parameter $\kappa = g_{Z'}/g_Z$ being 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 ref.[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. Then, each different general situation will be illustrated by a specific model.

First of all, gauge invariance under the SM group $SU(2)_L$ imposes the universality of the left-handed couplings:

$$C^u_L = C^d_L \equiv C_L$$

Therefore, in the following, we will suppress the flavour indice 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:
\[ \mathcal{L}_Y = h_u Q H_u u_R + h_d Q H_d d_R + h_l H_l e_R \]  
\[ (3) \]

where \( Q \) is a quark doublet, \( L \) a lepton doublet, \( u_R, d_R \) and \( e_R \) 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 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 that the sum of the \( U(1)’ \) charges \( Q’ \) for each term is zero:

\[ Q'(H_u) - Q'(Q) + Q'(u_R) = 0 \]  
\[ (4) \]

\[ Q'(H_d) - Q'(Q) + Q'(d_R) = 0 \]  
\[ (5) \]

\[ Q'(H_l) - Q'(L) + Q'(e_R) = 0 \]  
\[ (6) \]

The \( U(1)’ \) charges of the fermions are directly related to their chiral couplings: \( Q'(Q) = C_L, Q'(L) = C^e_L \) and \( Q'(f_R) = C^d_R \).

From eq.(6) the condition of leptohobia \( Q'(e_L) = Q'(e_R) = 0 \), forces the charge of the Higgs doublet coupling to the lepton field to be zero:

\[ Q'(H_l) = 0 \]  
\[ (7) \]

Given these assumptions, we will describe now 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 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 as most as 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.

- **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 eq.(7):

\[ Q'(H_d) = 0 \]  
\[ (8) \]

This implies from eq.(5) \( Q'(Q) = Q'(d_R) \) or, in terms of the couplings:

\[ C^d_R = C_L \]  
\[ (9) \]
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 that we call *structure I* from now.

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 eq.(4)):

$$C_{R}^{u} \neq C_{L}$$

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 $C_{R}^{u} = -C_{L}$.

This remark and eq.(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 $SU(2)_L$, 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 reference [8]:

$$Model \ B \ : \ \ C_{L}^{u} = C_{L}^{d} = C_{R}^{d} = -\frac{1}{2}C_{R}^{u} = -\frac{5}{18}\sin\theta_{W}$$

Note that, at a variance with the notations of ref.[4] the usual factor of Grand Unification Theories ($\sqrt{\frac{5}{3}}\sin\theta_{W}$) has been included in the $C_{L,R}^{u}$ couplings to maintain $\kappa$ of order one.

• **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 $C_L$ and $C_R^{d}$, since eq.(5) and eq.(6) are now completely disconnected. For *structure II* we still consider that eq.(5) is valid, *i.e.* that $d$ quarks acquire their masses from a trilinear mass term. Conversely, we don’t 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 expectation values of the $H_u$ and $H_d$ Higgs doublets which are of the same order ($v_{H_u} \simeq v_{H_d}$) [4]. 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 [4]:
\[ g^2 Z \mid v^2_{H_u} Q'(H_u) - v^2_{H_d} Q'(H_d) \mid << g^2 v^2 \]  

(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:

\[ Q'(H_u) \simeq Q'(H_d) \]  

(13)

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

\[ C_L - C_{uR} \simeq C_L - C_{dR} \]  

(14)

Thanks to the SU(2)_L gauge invariance this gives:

\[ C_{uR} \simeq C_{dR} \]  

(15)

It 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 we call Model C:

\[ Model C : \quad C_L = 0, \quad C_{uR}^u = C_{dR}^d = \frac{1}{3} \]  

(16)

Note that some authors consider eq.(14) and eq.(15) simply as orders of magnitude. For example, the model presented in [8] (which is also the first model of [1]) fits into this scalar structure II, but the U(1)' charges are: \( Q'(H_u) = -3, Q'(H_d) = -2, Q'(Q) = C_L = -1, Q'(u_R) = C_{uR}^u = 2, \) and \( Q'(d_R) = C_{dR}^d = 1 \). 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.

- Structure III:

Finally, we can consider the non-minimal scalar structure provided by string derived models as the ones considered by Cveti\v{c}, 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 [4]. In these scenarios, d-type quarks and charged leptons acquire their mass thanks to nonrenormalizable terms (i.e. not trilinear).

If there is no trilinear mass term in the theory for d-quarks, eq.(5) is no longer valid. Therefore, the chiral couplings of the d quarks are completely free. It means that we

\[^1\text{This model is analogous to the second model of [1], but we have changed the precise values of the } U(1)' \text{ charges in order to have } \kappa \simeq 1.\]
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:

$$
\text{Model D : } C_L = \frac{1}{3}, \quad C^{u}_{R} = 0, \quad C^{d}_{R} = \frac{2}{3}
$$

(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, that we call Model A from reference [8], is characterized by:

$$
\text{Model A : } C_L = - C^{d}_{R} = \frac{1}{2\sqrt{3}}, \quad C^{u}_{R} = 0
$$

(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 $\bar{n}n \rightarrow jet + X$, where the polarization of only one neutron is necessary to define the single helicity PV asymmetry:

$$
A_L = \frac{d\sigma(-) - d\sigma(+)}{d\sigma(-) + d\sigma(+)}
$$

(19)

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

In fact, both $^3He$ beams could be polarized in principle, giving access to doubly polarized neutron collisions $\bar{n}n \rightarrow jet + X$ and to double-helicity asymmetries (for a review on definitions and calculations of spin observables one can consult ref. [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 considering that only one beam will be polarized.

Concerning the value of $\sqrt{s}$, at RHIC, the charged nucleons (protons) of a nuclei are accelerated up to energies of $E_p = 250 - 300$ GeV per nucleon. At first, the machine will run with $E_p = 250$ GeV, it is the reason why we have taken a center mass energy $\sqrt{s} = 500$ GeV for $\bar{p}p$ collisions [8]. A $^3He$ nuclei, being accelerated, will get the total energy of its two protons. The neutron will be 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. \( E_p = 300 \text{ GeV} \)). Hence, we have \( E_{Hc} = 600 \text{ GeV} \) and \( E_n = 200 \text{ GeV} \), \( \bar{n}n \) (or \( n\bar{n} \)) collisions reaching an energy \( \sqrt{s} = 400 \text{ GeV} \) in the center of mass, value that we take in the following. Concerning the integrated luminosities, we have taken the same values as in [8], namely \( L_1 = 800 \text{ pb}^{-1} \) and \( L_2 = 3.2 \text{ fb}^{-1} \) for practical comparison with the \( \bar{p}p \) 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 notations):

\[
A_L \simeq \frac{1}{d\sigma} \sum_{i,j} \sum_{\alpha,\beta} \int \left( T_{\alpha,\beta}^{-}(i,j) - T_{\alpha,\beta}^{+}(i,j) \right) \left[ q_i(x_1)\Delta q_j(x_2) + \Delta q_i(x_1)q_j(x) + (i \leftrightarrow j) \right] \quad (20)
\]

The \( T_{\alpha,\beta}^{\lambda_1,\lambda_2}(i,j) \)'s are the matrix element squared with \( \alpha \) boson and \( \beta \) 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 ref.[24]. \( \Delta q_i = q_{i+} - q_{i-} \) 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 \( \mu = E_T \). The unpolarized cross section \( d\sigma \) is dominated by QCD and must also include all the relevant Electroweak+\( Z' \) terms and their interference with QCD terms when it is allowed by color rules. Of course, the non-dominant \( q\bar{q}gg \) 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 \( E_T \approx M_{W,Z}/2 \) (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 it was already pointed out in reference [8], 95% of the effect due to the new boson comes from \( Z' \)-gluon interference terms involving the scattering of identical quarks in the \( t, u \)-channels. In the case of \( \bar{n}n \) collisions it corresponds essentially to the scattering of \( d \) quarks. This dominant contribution can be written as follows :

\[
A_L \cdot d\sigma \simeq F \int \left[ C_L^2 - C_R^{d2} \right] \left[ d \left( x_1, \mu^2 \right) \Delta d \left( x_2, \mu^2 \right) + \Delta d \left( x_1, \mu^2 \right) d \left( x_2, \mu^2 \right) \right]_{\text{neutron}} \quad (21)
\]

where \( F \) is a positive factor given by
\[ F = \frac{32}{9} \alpha_s \alpha_z s^2 \text{Re} \left( \frac{1}{iD_{Z'}^u} + \frac{1}{iD_{Z'}^d} \right) \]  

(22)

where \( \alpha_z = \alpha / \sin^2 \theta_W \cos^2 \theta_W \) and \( D_{Z'}^{\hat{u}} = \left( \hat{t}(\hat{u}) - M_{Z'}^2 \right) + iM_{Z'} \Gamma_{Z'} \).

Note that the partonic part of eq.(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 \( d_{\text{ neutron}}(x, \mu^2) \) and \( \Delta d_{\text{ neutron}}(x, \mu^2) \) by the functions \( u(x, \mu^2) \) and \( \Delta u(x, \mu^2) \), defined for a proton. It means that the partonic part of eq.(21) is positive since \( \Delta u_{\text{proton}} \) is positive as well-known.

We can remark that eq.(21) allows us to predict easily the behaviour 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 \( C_{dL,R}^d \), more precisely by the difference \( C_L^2 - C_R^2 \). Consequently, a model whose d chiral couplings present a 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) 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.

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. 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 behaviour has been confirmed recently by some calculations who have provided some precise results on the small influence of gluons on the standard QCD-Electroweak interference term at NLO. A first estimate of the size of NLO corrections to \( q - q \) scattering is in favor of a relatively small correction, of the order of 10% of the asymmetry itself.

Concerning experimental uncertainties, a good knowledge of the beam polarization (±5%) and a very good relative luminosity measurement (10^{-4}), should allow 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 \((\Delta A)_{\text{syst}} / A = 10\%\).

In Figures 1 and 2 we compare the non-standard asymmetries \( A_L(\bar{p}p) \) and \( A_L(\bar{n}n) \) to the Standard one in each case, focusing on models C and D. We ignore here models A and B which don’t give any effect on \( A_L(\bar{n}n) \) 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 $\bar{p}p$ collisions has been already displayed in ref. [8].

Figure 1: $A_L$ versus $E_T$ for models C (left) and D (right) with $\bar{p}p$ collisions at RHIC at $\sqrt{s} = 500$ GeV. The plain curves represent the SM predictions. The dashed, dotted and dash-dotted curves correspond to the cases where the masses are $M_{Z'} = 90, 200$ et $300$ GeV respectively. The error bars correspond to the integrated luminosity $L_2 = 3.2$ fb$^{-1}$. $\kappa = 1$ for all cases except for the model C with $M_{Z'} = 300$ GeV and $\kappa = 1.5$.

Concerning the standard asymmetry, one can notice that, in spite of the smaller center of mass energy the $A_L(\bar{p}n)$ is larger than the one calculated for $\bar{p}p$ collisions in ref. [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. $|C^u_L - C^u_R|^2 >> |C^d_L - C^d_R|^2$). However, the influence of the reduced energy shows itself on the error bars which are larger than for the ones on $A_L(\bar{p}p)$ for the same $E_T$ bin. The bumps in the curves correspond to the jacobian peaks due to real $W$ and $Z$ exchanges around $E_T \approx M_{W,Z}/2$, or $Z'$ exchange at $E_T \approx M_{Z'}/2$. The remaining effects on the whole $E_T$ spectrum are due to $Z,g$ and $Z',g$ interference terms.

One can see that, in the framework of the 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 Fig.1 and Fig.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 $\bar{p}p$ collisions and negative in $\bar{n}n$ collisions.
Finally, in the case of $\tilde{n}n$ collisions, if we compare the effects on $A_L$ coming from Models C and D for the same $Z'$ 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 compared to Model C. Indeed, the difference $C_L^d - C_R^d$ appearing in eq. (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 Figure 3, we present the limits on the parameter space $(\kappa, M_{Z'})$ that both $A_L(\tilde{n}n)$ and $A_L(\bar{p}p)$ should provide with the integrated luminosities $L_1 = 800 \text{ pb}^{-1}$ and $L_2 = 3200 \text{ pb}^{-1}$ 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 $\kappa$ values. One can see that these unpolarized collider studies are not constraining a $Z'$ mass as soon as $\kappa$ is small enough. Also, and this is true in any leptophobic model, some windows were still present around $M_{Z'} = 300 \text{ GeV}/c^2$ and below $M_{Z'} = 100 \text{ GeV}/c^2$. With the help of polarized hadronic beams the situation could be greatly improved: in particular the hole centered on $M_{Z'} \approx 300\text{GeV}/c^2$ should be covered provided $\kappa$ is greater than $\approx 0.7$. One gets the same behaviour for the bounds in the framework of Models A and B (see ref. [8]).

We remark that $A_L(\bar{p}p)$ is slightly more sensitive than $A_L(\tilde{n}n)$ for model C. This difference can be explained simply by the reduced center of mass energy for $\tilde{n}\bar{n}$ collisions.
Indeed for the model $C$, the parity violation is equal in strength for both the $u$ and $d$ quark sectors, i.e. $C^2_L - C^u_R = C^d_L - C^d_R$. Conversely, for Model $D$, we see that the sensitivity is clearly in favour of $A_L(\bar{n}n)$ which can be understood thanks to the relation $|C^2_L - C^d_R| = 3|C^2_L - C^u_R|$. 

To conclude, the analysis of PV spin asymmetries measured within $\bar{n}n$ 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 in respect of $d$ quarks.

### 4 Constraints on the scalar structure

In this part, we want to analyze which kind of information could be provided by the precise measurements of both spin asymmetries at RHIC, namely $A_L(\bar{p}p)$ and $A_L(\bar{n}n)$. In particular, are we able to discriminate between the three scalar structures we have described in Section 2?

At this stage it is worth recalling our assumptions:

1) the condition of leptophobia plus a small $Z - Z'$ mixing angle,
the gauge invariance under $U(1)'$ of the fermion mass terms,

iii) $SU(2)_L$ invariance,

iv) we assume that some PV effects due to a leptophobic $Z'$ have been detected through the measurement of $A_L(\bar{p}p)$ 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 figure 4, we present $A_L(\bar{p}p)$ versus $A_L(\bar{n}n)$ for a transverse energy $E_T = 70\pm5\ GeV$. We have chosen this particular interval since its contribution to the $\chi^2$ function involved in the analysis is maximal. Of course, a full integration over the $E_T$ 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 $L_2 = 3200\ pb^{-1}$. The models $A$, $B$, $C$ and $D$, which were introduced to illustrate the different scalar structures, are represented each one by a shaded ellipse. Each point inside an ellipse corresponds to a precise value of $\kappa$ and $M_{Z'}$, these values are taken as to satisfy the present experimental constraints presented in Fig.3 and in Fig.1 of Ref.[8].

Concerning the shapes of the ellipses, there is no simple dependence on the two parameters $\kappa$ and $M_{Z'}$ in this plane. However, a point close to the "SM cross" obviously means that one has a small $\kappa$ and/or a large $M_{Z'}$. Conversely, the biggest 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 $\kappa$ 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. It means that the deviations from SM expectations for $A_L(\bar{p}p)$ and for $A_L(\bar{n}n)$ 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 plane ($A_L(\bar{p}p)$, $A_L(\bar{n}n)$).

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 to eliminate both structure I (i.e. the 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-
Figure 4: Predictions of the various models (see text) in the plane $A_L(\bar{p}p)$ versus $A_L(\bar{n}n)$ for $E_T = 70 \text{ GeV}$. The error bars on the SM point correspond to the integrated luminosity $L_2 = 3.2 \text{ fb}^{-1}$. 
like couplings to the $Z'$ and we don't expect any deviation on $A_L(\bar{n}n)$ . 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 $A_L(\bar{n}n)$ . 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 $\bar{p}p$ and $\bar{n}n$ 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, it evades the bounds coming from LEP/SLC experiments and it must be looked for in purely hadronic processes.

The polarized proton beams which are available at RHIC allow the precise measurement 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 \cite{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 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 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 $^3He$ 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 \cite{10}. 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 $A_L(\bar{n}n)$ . This could be done with a precision which is comparable to what can be
hoped from the measurement of $A_L(\vec{p}p)$.

Moreover, getting in the same time an 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 $SU(2)_L$ and under the new $U(1)'$, constrains the Higgs sector of the model.

The simplest case of 2-Higgs Doublet Models, with trilinear mass terms and the traditional property $H_d \equiv H_1$, 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 $A_L(\vec{p}p)$ and $A_L(\vec{nn})$ should allow 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 plane ($A_L(\vec{p}p)$, $A_L(\vec{nn})$). Therefore, some definite conclusions could be yielded only if the measurements are in favor of the ”sector X” described in section 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 greatly 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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