Spin asymmetries in one-jet production at RHIC with polarized proton beams: the effects of a hadrophilic $Z'$

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Abstract

We show that the measurement of some parity violating asymmetry in the production of a large $E_T$ jet could reveal the presence of a new hadrophilic $Z'$ such as the one recently introduced to interpret possible departures from the Standard Model predictions both at LEP and at CDF. Such a measurement could be performed within a few years by the RHIC Spin Collaboration (RSC) using the Relativistic Heavy Ion Collider (RHIC) as a polarized proton-proton collider.

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1 Introduction

Very recently, the CDF collaboration has reported an excess of jets at large $E_T$ with respect to the QCD prediction [1]. Although these anomalies have to be confirmed, they have triggered new speculations about the possible existence of New Physics beyond the Standard Model (SM) whose direct effects could be within the reach of forthcoming experiments.

The most straightforward interpretation of these data is to invoke the presence of a quark substructure. If the effect on the high $E_T$ jet spectrum is parametrized conventionally à la Eichten et al. [2], the value obtained by CDF for the compositeness scale $\Lambda$ is $\Lambda = 1.6$ TeV.

On the other hand, some authors [3, 4] have related these anomalies to the LEP results on $R_b$ and $R_c$ which deviate from the SM predictions by about $3.5\sigma$ and $2.\sigma$ respectively [5]. The idea is to introduce an extra heavy neutral vector boson (called $Z'$ in the following) which couples dominantly to quarks. Then a small $Z^0 - Z'$ mixing can modify the rate of $b - \bar{b}$ and $c - \bar{c}$ pair productions at the $Z^0$ peak provide that the direct $Z'$ couplings to quarks are sufficiently large. In the same time, in hadronic collider experiments, this $Z'$, with a mass around 0.8 - 1.0 TeV and large couplings to quarks, can mediate a new interaction between quarks via virtual exchange, hence affecting the probability of producing energetic jets.

Since these papers have appeared, it has been stressed that, in the production of a top quark pair at FNAL, the additional contribution due to this $Z'$ improves the agreement between experiment and theory [6]. A more precise measurement of $\sigma_{t\bar{t}}$ should clarify this point. Concerning $e^+e^-$ physics, the potentialities of LEP2 for the observability of hadrophilic $Z'$ effects have been explored in Ref. [4].

It is of some importance to investigate if some other kind of decisive signal could be obtained within a few years, using machines and detectors which are now under construction. In fact, a new neutral vector boson, whose couplings to quarks exhibit a particular chiral structure, will be at the origin of some new parity violating (PV) effects in many processes. Such effects have been investigated some time ago in the context of LEP2 [6] and of the NLC [5] (with polarized beams in both cases). In this respect, hard scattering in hadronic processes present a particular interest -provide that polarized beams are available- since one cannot gets any PV effect from QCD. Then, a non-zero PV asymmetry could reveal the presence of a new interaction. Of course, one has also to take carefully into account the influence of Standard electroweak interactions, which are well controlled and give in any case a PV effect with a definite sign.

In a few years from now, the RHIC Spin Collaboration (RSC) will run the heavy ion collider RHIC in the $pp$ mode with polarized beams at a center-of-mass energy from 50 to 500 GeV [3]. If one compares with the Tevatron, the deficit in energy is compensated by the very high luminosity of the machine which increases with the energy, reaching $\mathcal{L} = 2.10^{32} cm^{-2} s^{-1}$ at $\sqrt{s} = 500$ GeV. These figures yield an integrated luminosity $\int \mathcal{L} dt = 800 pb^{-1}$ in a few months running.
In a recent paper [10] we have considered the inclusive production of one high $E_T$ jet at this machine. Focusing on the double helicity PV asymmetry $A_{LL}^{PV}$, we have found that the presence of a new PV contact interaction between quarks could yield some small but measurable deviations from the expected SM asymmetry which is mainly due to the interference between QCD and Weak terms. The magnitude of the predicted asymmetry, in an $E_T$ range between 60 GeV and 100 GeV, allows to probe the compositeness scale up to a value $\Lambda \approx 2. - 2.5$ TeV, as soon as parity is maximally violated by the new effective interaction.

Concerning new massive vector bosons, many studies have considered the Drell-Yan lepton pair production channel when the partonic c.m. is allowed to be of the same order of magnitude as the $Z'$ mass. In this case, relevant at Hadronic Supercolliders only, it has been shown that polarized beams should be very efficient in the quest for the identification of the theoretical origin of the new boson [11], a task which is much more difficult than the discovery itself (see e.g. Ref. [12]).

Given the maximal RHIC energy, if the $Z'$ is heavier than 800 GeV, it is hopeless to get a signal in this channel and to measure a spin asymmetry. Conversely, the hadronic channel is particularly well-suited for a $Z'$ which goes preferentially into quarks like the candidate from Refs. [3, 4].

In this paper, we assume that such a $Z'$ is indeed exchanged in the $t$-channel of the quark-quark scattering process and we investigate the consequences on the one-jet asymmetry $A_{LL}^{PV}$ which will be measured with great precision by the RSC.

2 The parameter space

One considers a new neutral vector boson which couples universally to $u$- and $d$- type quarks with the following structure:

$$\mathcal{L}_{Z'} = \frac{g}{2 \cos \theta_W} Z'^\mu q_i \gamma^\mu \left[ C_{iL} (1 - \gamma_5) + C_{iR} (1 + \gamma_5) \right] q_i$$  \hspace{1cm} (1)

for each given quark flavor $i$ (the $Z'$ $\bar{q}q$ couplings are normalized in the same way as the $Z^0$ $\bar{q}q$ ones).

Constraints from LEP/SLC data forces the leptonic couplings to be very small. Neglecting the latter, the $Z'$ width is given by the general expression (for $M_{Z'} >> m_q$):

$$\Gamma_{Z'} = N_g \frac{G_F M_{Z'}^2}{\pi \sqrt{2}} M_{Z'} (C_{uL}^2 + C_{dL}^2 + C_{uR}^2 + C_{dR}^2)$$  \hspace{1cm} (2)

The heavy $Z'$ which has been considered in Refs. [3, 4] does not belong to any particular model (there is a vast literature on massive $Z'$ 's, corresponding to various extensions of the SM, for a recent review one can consult Ref. [12] and references therein). Since the analysis of Ref. [3] imposes more restrictions on the parameter space, we follow these authors first, and for comparison we treat in a second step the extra freedom allowed in Ref. [4].
In Ref. [3], a first constraint comes from assuming equality of the left-handed couplings within one $SU(2)_L$ doublet:

$$C_{uL} = C_{dL}$$

(3)

On the other hand, the two right-handed couplings are left free. Following the notations of Ref. [3] one has $C_{uL} = C_{dL} \equiv x$; $C_{uR} \equiv y_u$ and $C_{dR} \equiv y_d$.

Then, after adjusting $M_{Z'}$ at 1 TeV, it seems possible to fit all the LEP/SLC observables, including $R_b$ and $R_c$, and the CDF jet cross sections in the same time. The quark couplings which are obtained are quite large. As a consequence the $Z'$ resonance can be very wide. We will consider as reasonable an upper limit around 500 GeV for $\Gamma_{Z'}$. Therefore, we retain from Ref. [3] the following values:

$$-1.5 \leq x \leq -0.5, \quad 2 \leq y_u \leq 2.5 \quad \text{and} \quad y_d = 0$$

(4)

It will be also the case for our results presented below. This parameter interval contains the ”final fit” [3] values for the parameters:

$$x = -1, \quad y_u = 2.2, \quad y_d = 0$$

(4)

Finally, using the approximate scaling advocated in Ref. [3] for the best fit values of the parameter:

$$x, y_u, y_d \sim \frac{M_{Z'}}{M_Z}$$

(5)

one can easily control the (tiny) consequences of varying the $Z'$ mass down to $\sim 800$ GeV.

In Ref. [3] the authors have preferred to compare the magnitude of $Z'$ couplings with those of the $Z^0$ coupling. They have defined the ratios of the vector and axial-vector couplings (with a $\gamma_\mu [g_{V_i} - g_{A_i} \gamma_5]$ structure):

$$\xi_{V_i(A_i)} \equiv \frac{g_{V_i(A_i)}}{g_{V_i(A_i)}}.$$  

The relationship with the parameters $x, y_u, y_d$ is:

$$\xi_{V_i} = \frac{x + y_i}{T^i_3 - 2Q^i \sin^2 \theta_W}, \quad \xi_{A_i} = \frac{x - y_i}{T^i_3}$$

(6)

where $T^i_3$ is the third component of the weak isospin of the quark $i$ and $Q^i$ its electric charge.

Imposing some values of the couplings smaller than the QCD strength ($\alpha_s \approx 0.12$), one gets $|\xi_{V_u}| < 16$; $|\xi_{V_d}| < 10$ and $|\xi_{A_u,d}| < 7$. The values we have retained above respect comfortably these constraints. In Ref. [4] a smaller ($\leq 200$ GeV) $Z'$ width is preferred. On the other hand, the constraint eq.(3) is not retained. Therefore, the parameter space is enlarged if we still impose $\Gamma_{Z'} \leq 500$ GeV. Given this extra freedom, we choose two ”extreme cases” which maximize PV effects, with a $Z'$ strongly coupled to $u$–quarks, namely:

- a left-handed $Z'$

$$\xi_{A_u} = 5.8; \quad \xi_{V_u} = 15.2; \quad \xi_{A_d,V_d} = 0 \quad \text{corresponding to} \quad x_u = 2.9, y_u = 0, x_d = y_d = 0$$

(7)

with $x_{u,d} \equiv C_{(u,d)L}$. 

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- a right-handed $Z'$ is obtained by changing the sign of $\xi_{Au}$:

$$\xi_{Au} = -5.8 \quad \xi_{V u} = 15.2 \quad \xi_{Ad,V d} = 0 \quad \text{corresponding to} \quad x_{u,d} = 0, y_u = 2.9, y_d = 0 \quad (8)$$

In both cases we have $\Gamma_{Z'} \sim 500 \text{ GeV}$. The last parameter of these models is the amount of $Z^0 - Z'$ mixing. LEP data constrain in any cases the mixing angle $\xi_{M}$ to be very small (at most a few $10^{-3}$). Since we are interested into a direct effect of the $Z'$ we can safely neglect this mixing.

### 3 Calculation and results

It is easy to check that, at a variance with the situation at FNAL, at RHIC, due to the low value of the maximal c.m. energy, it is hopeless to get a conclusive signal from the measurement of the unpolarized $pp$ jet cross section alone. We then turn to the question of PV spin asymmetries.

To build a PV asymmetry one single polarized beam is sufficient. However, our recent experience [10] taught us that a larger effect can be obtained using both polarized colliding beams which are available at RHIC. One can define the double helicity PV asymmetry:

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

where the signs ± refer to the helicities of the colliding protons. The cross section $d\sigma_{(\lambda_1)(\lambda_2)}$ means the one-jet production cross section in a given helicity configuration, $p_1^{(\lambda_1)} p_2^{(\lambda_2)} \rightarrow jet + X$, estimated at $\sqrt{s} = 500$ GeV for a given $E_T$, integrated over a pseudorapidity interval $\Delta \eta = 1$ centered at $\eta = 0$. We have also integrated over an $E_T$ bin of 10 GeV.

In the $E_T$ range of interest the contribution of quark-quark scattering is by far dominant. In short notations $A_{PV}^{LL}$ is given by the expression:

$$A_{PV}^{LL} \simeq \frac{1}{d\sigma} \sum_{i,j} \sum_{\alpha,\beta} \int \left( T_{\alpha,\beta}^{--}(i,j) - T_{\alpha,\beta}^{-+}(i,j) \right) \left[ q_i(x_1, \mu^2) \Delta q_j(x_2, \mu^2) + \Delta q_i(x_1, \mu^2) q_j(x_2, \mu^2) + (i \leftrightarrow j) \right]$$

(10)

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 $j$. $\Delta q_i = q_{i+} - q_{i-}$ where $q_{i\pm}(x, \mu^2)$ 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 $\mu = E_T$ and we have checked that the precise choice for $\mu$ has no influence on our results. 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 $q(\bar{q})g$ and $gg$ scattering subprocesses have to be included in the part of the cross section which is purely QCD.
Concerning the numerator of $A^{PV}_{LL}$, the SM contribution has been already discussed in Ref.\[10\]. The correct expressions for the relevant $T_{\alpha,\beta}$’s can be found in ref. \[13\]. Since we are in a regime where $\hat{s} \ll M_{Z'}^2$, the non-standard effect will be dominated by the interference between SM amplitudes and the amplitude due to $Z'$ exchange. In fact, 90% of the effect will come from the interference between the $Z'$ and one-gluon exchange graphs for identical quarks. Due to color rules there is no such interference in case of quarks of different flavors.

Then, for $q_i q_i \rightarrow q_i q_i$ one has:

$$T_{\lambda_1,\lambda_2}^{Z'}(i, i) = \frac{8}{9} \alpha_s \alpha_Z \left[ (1-\lambda_1)(1-\lambda_2)C_{iL}^2 + (1+\lambda_1)(1+\lambda_2)C_{iR}^2 \right] \hat{s}^2 \text{Re} \left( \frac{1}{iD^u_{Z'}} + \frac{1}{iD^d_{Z'}} \right)$$

(11)

where $\alpha_Z = \alpha / \sin^2 \theta_W \cos^2 \theta_W$, and :

$$D^{i(\bar{u})}_{Z'} = (\hat{t}(\bar{u}) - M_{Z'}^2) + iM_{Z'} \Gamma_{Z'}$$

(12)

Therefore:

$$T_{g,Z'}^{-+}(i, i) - T_{g,Z'}^{++}(i, i) \sim (C_{iL}^2 - C_{iR}^2) \times \text{positive terms}$$

(13)

In the actual calculation, all the LO terms, involving quarks or antiquarks, are added along with the very tiny Electroweak-$Z'$ interference terms. We restricted to LO terms since no NLO calculation for the $Z'$ contribution is available. $A^{PV}_{LL}$ being a ratio of cross-sections, we expect also that NLO corrections will not change the trend of our results.

Since real gluons are not involved in this process, our results are not plagued by the uncertainties associated to the imperfect knowledge of the polarized gluon distributions $\Delta G(x, \mu^2)$. Concerning the polarized quark (and antiquark) densities, we have used some recent sets of distributions which fit all the available data. The GS \[14\] and GRV \[15\] distributions yield very similar results for $A^{PV}_{LL}$. The effect obtained using the BS \[16\] distributions being simply larger in magnitude, we adopt a conservative attitude and we retain the former choice. It has to be kept in mind that our knowledge about these polarized partonic distributions will improve drastically in the future, thanks to the HERMES experiment at HERA \[17\] and, especially, thanks to the RSC program itself \[18\].

We present in Fig. 1 the results of our complete calculation for $A^{PV}_{LL}$ versus $E_T$, including all terms, for $M_{Z'} = 1$ TeV (with GRV distributions). The expected SM asymmetry is shown for comparison. The error bars correspond to the statistical error for an integrated luminosity of $L_1 = 800pb^{-1}$ (large bars) or $L_2 = 4 \times 800pb^{-1}$ (smaller bars). As can be seen, the high luminosity at RHIC allows some very small statistical uncertainty \[18\] on $A^{PV}_{LL}$. This uncertainty is given roughly by :

$$\Delta A \simeq \frac{1}{P^2} \frac{1}{\sqrt{N_{++}^{exts} + N_{--}^{exts}}}$$

(14)

where $P = 0.7$ is the degree of polarization of one beam. As a consequence, the measurement of an asymmetry at the level of a percent or even less is realistic in this channel.
As already shown [10, 19], the SM asymmetry due to QCD-Weak interference is clearly positive: at $E_T$ around 80 GeV, with $L_1$, it lies at 2$\sigma$ above zero according to GRV or GS distributions (4$\sigma$ above zero according to BS distributions). The rise with $E_T$ is due to the increasing importance of quark-quark scattering with respect to other subprocesses involving gluons.

We have checked that no "usual" $Z'$ from an extra U(1) or from a Left-Right symmetric extension of the SM can induce a sizable deviation from the expected SM asymmetry. On the other hand, as can be seen from Fig. 1, the presence of the hadrophilic $Z'$ introduces a strong perturbation. With the "final fit" values of Ref. [3] given in eq.(4), one gets for $A_{PV}^{LL}$ a value which is compatible with 0. It is clearly negative in the most favorable case corresponding to $x = -0.5, y_u = 2.5, y_d = 0$. For comparison, we show the consequences of the two extreme cases of eqs.(7,8) corresponding to a Right-handed or a Left-handed $Z'$ allowed by the analysis of Ref.[4].

Of course, the statistical error also increases with $E_T$ at a fixed integrated luminosity. In Fig. 2, we show $A_{PV}^{LL}$ versus $x$ for different $y_u$ values allowed in Ref.[3] (with $y_d = 0$), at a chosen intermediate $E_T = 80 \pm 5$ GeV.

Let us comment these results in more details:

- First, one has to note that the the $d-$quark polarized distribution $\Delta d$ (which is usually negative) has a minor influence on our results: as a consequence moving the right-handed coupling $y_d$ away from the zero value has no visible effect on $A_{PV}^{LL}$. Note also that changing the signs of the left or right couplings has no influence on $A_{PV}^{LL}$ (see eq.(13)).

- The behavior of $A_{PV}^{LL}$ is then governed by the ratio $|x|/y_u$: $A_{PV}^{LL}$ decreases and tends to become negative when this ratio decreases. Let us consider the restricted parameter space of Ref.[3] according to Section 2. Taking an integrated luminosity $L_1$, one gets an asymmetry which is at least more than 1$\sigma$ below its SM value, provide that $|x| < 1$, and 2$\sigma$ below in the most favorable situation of large $y_u$ and small $|x|$. In any case, the effect should be confirmed without any ambiguity with the enlarged statistics corresponding to $L_2$.

- If one applies the scaling according to eq.(5), lowering the $Z'$ mass down to 800 GeV doesn't change appreciably the values of $A_{PV}^{LL}$ since the quark couplings are lowered in the same time.

- The "extreme" cases from Ref.[4] are also shown on this plot, along with the very similar results one gets from the presence of an effective handed interaction due to a contact term between quarks [2] (calculations are described in Ref.[10]):

$$L_{qqqq} = \epsilon \frac{\pi}{2\Lambda_{qqqq}^2} \bar{\Psi} \gamma_\mu (1 - \eta \gamma_5) \Psi \bar{\Psi} \gamma^\mu (1 - \eta \gamma_5) \Psi$$

where $\Psi$ is a quark doublet and $\epsilon$ a sign. We have chosen the case of constructive interference with QCD amplitudes ($\epsilon = -1$, see [2, 10]) and of maximal PV corresponding to $\eta = 1$(left-handed) or -1 (right-handed), with the $\Lambda_{qqqq}$ value extracted by CDF.
In these cases the effects on $A_{LL}^{PV}$ are important, which is not surprising since $\Lambda_{qqqq} \sim 1.6\text{ TeV}$ is a relatively low value according to our previous calculations \cite{10}.

Of course, the distinction between a possible $Z'$ effect and an effect due to compositeness is quite artificial since it relies on the particular normalization of the contact interaction and on the precise chosen value for $\eta$ in eq. (15). Only experiments at higher energies and/or a careful study of the invariant mass distribution of di-jets events at the Tevatron should allow to disentangle the two possibilities.

4 Conclusion

In this letter we have shown that a new $Z'$, with a mass in the TeV range, could induce some visible effects in the asymmetry $A_{LL}^{PV}$ for inclusive one-jet production in the collision of polarized beams at $\sqrt{s} = 500\text{ GeV}$ with a high luminosity.

The two conditions which are to be fulfilled are an enhanced coupling of the $Z'$ to quarks and an important asymmetry between Left and Right-handed couplings. The expected SM asymmetry being small and positive, the most spectacular effect should come from the observation of a zero or negative asymmetry or of a large and positive one. According to Ref.\cite{3}, $y_u \gtrsim 2|\epsilon| \sim 2$ is a general tendency of the fitted values of the parameters. It means that, concerning $u-$quarks, there is a dominance of the right coupling on the left coupling to the $Z'$. Furthermore, the role of $d-$quarks, which is not dominant, is further suppressed by the choice $y_d = 0$. Then, the predicted values of $A_{LL}^{PV}$ tend to be significantly below the positive values expected in the SM. On the other hand, the parameter space of Ref.\cite{4} larger, which implies more freedom for the resulting $A_{LL}^{PV}$ values. However, pure Left-handed as well as pure Right-handed interactions are allowed : these two cases give of course some large effects.

It can be surprising that measuring a spin asymmetry gives more chances for a discovery than the simpler measurement of an unpolarized cross section. In fact, the situation is reminiscent of the polarized DIS experiment performed at SLAC in the seventies \cite{20} where an effect of $\sim 10^{-4}$, due to the Standard $Z^0$, was seen in the PV left-right helicity asymmetry. In the same time, such an electroweak effect was far too small to be observed from the unpolarized cross section.

The availability of high-intensity polarized beams at RHIC should allow to carry on the same kind of program, in the more difficult context of hadronic collisions.

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Figure captions

Fig. 1 $A_{LL}^{PV}$ for one-jet inclusive production, versus $E_T$, at $\sqrt{s} = 500$ GeV, integrated luminosities $L_1$ (large error bars) and $L_2$ (small error bars). SM expectation (plain curve); $Z'$ effect with "final fit" values $x = -1, y_u = 2.2, y_d = 0$ (dotted curve), maximal effect with $x = -0.5, y_u = 2.5, y_d = 0$ (dashed curve) both from Ref.[3]; $Z'_L max$ and $Z'_R max$ correspond to two extreme cases from Ref.[4] with maximal parity violation. The calculations are performed with GRV distributions.

Fig. 2 $A_{LL}^{PV}$ at $E_T = 80$ GeV versus $x$ with different values for $y_u$ and $y_d = 0$ (same conditions as in Fig.1). The dotted lines correspond to $y_u = 2.0; 2.2; 2.5$ from top to bottom. Also shown the two cases $\eta = \pm 1$ for a compositeness scale $\Lambda = 1.6$ TeV and the positions of the extreme cases $Z'_L max$ and $Z'_R max$. 

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$E_T = 80$ GeV

$\eta = +1$

$Z'_L \text{max}$

$A_{LL}^{PV}$

$Z'_R \text{max}$

$\eta = -1$

$x$

Fig 2