Discovery potential for New Physics in view of the RHIC-Spin upgrade

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Abstract

In view of a possible upgrade of the RHIC-Spin program at BNL, concerning both the machine and the detectors, we give some predictions concerning the potentialities of New Physics detection with polarized proton beams. We focus on parity-violating asymmetries in one-jet production due to contact terms or to a new leptophobic neutral gauge boson. We comment on the main uncertainties and we compare with unpolarized searches at Tevatron.

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1 Introduction

There is a growing interest on the physics program which will be achieved at RHIC-Spin, that is at the Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC), running in the polarized $\vec{p}\vec{p}$ mode.

Actually, during the year 2001 the RHIC-Spin Collaboration (RSC) will perform the first polarized run at a c.m. energy of $\sqrt{s} = 200$ GeV and a luminosity of a few $10^{30} cm^{-2}s^{-1}$.

The nominal energy of $\sqrt{s} = 500$ GeV and luminosity $\mathcal{L} = 2.10^{32} cm^{-2}s^{-1}$ should be reached in the early months of 2003, allowing an exposure of $800 pb^{-1}$ in four months of running.

Physics at RHIC-Spin has been extensively covered in a recent review paper \[1\], where many references can also be found (see also \[2\]). The first part of the program will include 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.

It has been first noticed more than ten years ago \[3\] that the production of high $E_T$ jets from polarized protons could allow to pin down a possible new interaction, provided that parity is violated in the subprocess.

Since QCD is parity conserving and dominates the process, according to the Standard Model (SM), the expected Parity Violating (PV) spin asymmetry in jet production should come from tiny electroweak effects. Hence, a net deviation from the small expected Standard Model asymmetry could be a clear signature of the presence of New Physics.

Due to the energy reach of the machine the New Physics scale should not be too high to yield a contribution: fortunately some scenarios are still allowed by present data, in particular the existence of a new weak force belonging uniquely to the quark sector.

In previous papers, we have explored the very phenomenological case of a PV contact interaction between quarks \[4\], various situations with a new $Z'$ with nearly zero couplings to leptons (the so-called leptophobic $Z'$) \[5\] and also a scenario with a right-handed $W'$ decaying into quarks in the case of a very massive right-handed neutrino \[6\].

In this letter we will explore the potentialities of RHIC-Spin in view of the two kinds of possible upgrades \[7\]. The improved machine could reach $\sqrt{s} = 650$ GeV with an integrated luminosity $L = 20 fb^{-1}$ in a few months running and the STAR detector could greatly improve the angular coverage with new end-caps. We compare also with the limits which could be obtained with the (unpolarized) Tevatron in Run-II. Concerning theoretical uncertainties, we comment the situation on higher-order calculations when they are available.
2 Sources of PV effects in jet production

The production of high $E_T$ jets is dominated by QCD, in particular by quark-quark scattering. The existence of $W$ and $Z^0$ adds a small standard contribution to the cross section $^8$. On the other hand the interference of weak amplitudes with QCD amplitudes will be the main Standard source of PV helicity asymmetries in this process. A peak in the asymmetries at $E_T \approx M_{W,Z}/2$ is also the main signature for a pure electroweak contribution.

All the tree-level polarized cross sections for these standard subprocesses can be found in Ref. $^9$. Predictions using updated polarized partonic distributions can be found in $^5$ or $^1$. The effects of some possible Non Standard PV interactions have been studied in recent years:

- First $^4$ one can think to a simple phenomenological contact interaction which could represent the consequences of quark compositeness. Such (color singlet and isoscalar) terms are usually parametrized following Eichten et al. $^{10}$:

$$
\mathcal{L}_{qqq} = \varepsilon g^2 \frac{8\Lambda^2}{\mu^2} \bar{\Psi} \gamma_\mu (1 - \eta \gamma_5) \Psi \Psi \gamma_\mu (1 - \eta \gamma_5) \Psi
$$

(1)

where $\Psi$ is a quark doublet, $\varepsilon$ is a sign and $\eta$ can take the values $\pm 1$ or 0. $g$ is a new strong coupling constant usually normalized to $g^2 = 4\pi$ and $\Lambda$ is the compositeness scale.

In the following we will consider the $LL^{-}$ case with Left-handed chiralities ($\eta = 1$) and constructive interference with QCD amplitudes which corresponds to $\varepsilon = -1$.

- Second, we can consider some new neutral gauge bosons with general Left and Right-handed couplings to each given quark flavor $q$:

$$
\mathcal{L}_{Z'} = \kappa \frac{g}{2 \cos \theta_W} Z'^\mu \bar{q} \gamma_\mu [C_L^q (1 - \gamma_5) + C_R^q (1 + \gamma_5)] q
$$

(2)

the parameter $\kappa = g_{Z'}/g_Z$ being of order one. For a recent review on $Z'$ phenomenology (in the context of $e^+e^-$ collisions), one can consult $^{11}$. A particular class of models, called leptophobic $Z'$, is poorly constrained by present data since they evade the LEP constraints. Such models appear in several string-inspired scenarios $^{12, 13}$. Non supersymmetric models can also be constructed $^{14}$. Other references can be found in $^5$. In addition, it was advocated in $^{15}$ that such a boson could appear with a mass close to the electroweak scale and a mixing angle to the standard $Z^0$ close to zero.

In this letter we will focus for illustration on the flipped-SU(5) model of Lopez and Nanopoulos $^{12}$ (model A of $^9$) in which parity is maximally violated in the up-quark sector. Therefore the couplings in eq.(2) take the following values: $C_L^u = C_L^d = -C_R^d = 1/(2\sqrt{3})$ and $C_R^u = 0$, the ratio $\kappa$ being a free parameter. In this scenario, 95% of the new PV effect will come from the interference between the $Z'$ exchange and the one-gluon exchange amplitudes in the scattering of $u$ quarks in the $t$-channel.
3 Results

For Spin experiments, the most important quantities in practice are not the polarized cross sections themselves, but the spin asymmetries.

At RHIC, running in the $\vec{p}\vec{p}$ mode, it will be possible to measure with a great precision the single PV asymmetry $A_L$:

$$A_L = \frac{d\sigma(-) - d\sigma(+) \pm \Delta d\sigma}{d\sigma(-) + d\sigma(+)}$$  \hspace{1cm} (3)

where only one of the proton is polarized, or the double helicity PV asymmetry:

$$A_{PV}^{LL} = \frac{d\sigma(-)(-) - d\sigma(+) (+) \pm \Delta d\sigma}{d\sigma(-)(-) + d\sigma(+) (+)}$$  \hspace{1cm} (4)

where both polarizations are available. In the above quantities the signs $\pm$ 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 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 quantities will exactly yield the same amount of information. From now we will discuss only the single PV asymmetry.

All the present calculations use polarized parton distribution functions $\Delta f_i(x, Q^2)$ which have been parametrized from deep-inelastic data e.g. GRSV distributions. The polarized quark distributions $\Delta q(x, Q^2)$ which play a dominant role in our calculation at high $E_T$ are the most reliable: in any case they will be much better measured soon thanks to the first part of the RHIC-Spin program itself.

We give in Table 1 the 95% C.L. limits on $\Lambda \equiv \Lambda_{LL}$ (eq.1) one gets, at lowest order, from a comparison between the SM asymmetry $A_L$ and the Non-Standard one. We have taken into account the statistical error, which for small asymmetries is given by:

$$\Delta A_L = \frac{1}{P} \frac{1}{\sqrt{N}}$$  \hspace{1cm} (5)

where $P$ is the degree of polarization of the beams, expected to be $P = 0.7$. Systematics are assumed to be low [1] (see comments below), and we have taken the conservative value $\delta_{syst} \equiv (\Delta A)_{syst}/A = 10\%$.

One can compare the bounds at $\sqrt{s} = 500$ GeV and $L = 0.8 fb^{-1}$ with the ones after the energy and/or luminosity upgrade. $4 fb^{-1}$ ($100 fb^{-1}$) represents 5 × 4 months running with the presently designed (future) nominal luminosity. On the other hand, the cross section being essentially flat in rapidity in the interval which is accessible to experiment, an increase in rapidity from $\Delta \eta = 1$ to 2.6 is equivalent to a substantial increase in luminosity.

Since the statistical error goes like $(1/P)(1/\sqrt{N})$, reducing the degree of polarization $P$ by a factor $\epsilon$ is equivalent to a factor $\epsilon^2$ in luminosity. In practice, varying the designed value $P = 0.7$ by 10% will change the limits by roughly 6%.
This table can be compared with the last published analysis of the D0 experiments at Tevatron \(^{17}\): \(\Lambda > 2.2\) TeV (95% C.L.) from the dijet mass cross section. From these figures we have extrapolated a limit at Tevatron of 3.2 TeV (3.7 TeV) with a 1 \(fb^{-1}\) (10 \(fb^{-1}\)) exposure.

Turning now to the case of a leptophobic \(Z'\), we present in Fig.1 the constraints on the parameter space \((\kappa, M_{Z'})\) obtained from \(A_L\) in the flipped SU(5) model. The dotted curves correspond to \(\sqrt{s} = 500\) GeV and the dashed curves to \(\sqrt{s} = 650\) GeV. From bottom to top they correspond to an integrated luminosity \(L = 1, 10, 100\ \text{fb}^{-1}\). It appears that the increase in luminosity is more efficient than the increase in energy. Therefore the high luminosity scenario has to be supported even if the RHIC \(pp\) c.m. energy remains at its ”low” value.

We display also in Fig.1 the inferred constraints coming from the published results of UA2 \(^{18}\), CDF \(^{19}\) and D0 \(^{20}\) experiments. The form of the forbidden areas result from a combination of statistical and systematic errors. For high \(M_{Z'}\) one looks for some unexpected high-\(E_T\) jet events and the main uncertainty is statistical in nature. For instance, the upper part of the ”CDF area” is well below the one of D0 because of the well-known excess observed by CDF at high-\(E_T\). In the future (run II) the increase in statistics will improve the bounds in the \((\kappa, M_{Z'})\) plane by enlarging the upper part of the CDF and D0 areas (or will lead to a discovery). For relatively low \(M_{Z'}\) values, the main problem comes from the large systematic errors for ”low” \(E_T\) jets. Due to these systematics, at Tevatron, even with a high statistics it will be difficult to probe the low \(\kappa\) region for \(M_{Z'} \leq 400\) GeV or to close the windows around \(M_{Z'} \simeq 300\) and 100 GeV. In this respect, as can be seen from Fig.1, the RHIC-Spin measurements at high luminosity should allow to cover this region and to get definite conclusions, if the new interaction violates parity.

4 Comments

Concerning experimental uncertainties, with a good knowledge of the beam polarization (\(\pm 5\%\)) and a very good relative luminosity measurement (\(10^{-4}\)), the systematic scale of uncertainty for a single spin measurement should be of the order of 5\% \(^{21}\). Hence
we have been conservative in taking $\delta_{\text{syst}} = 10\%$. For instance, one should get higher limits with the former figure: $\Lambda = 9.0(10.35)$ TeV with $100 \text{ fb}^{-1}$ at 500 (650) GeV, with $\Delta \eta = 1$. The consequences of a smaller systematical error are more sizeable at high luminosity where the statistical error becomes very small.

On the theoretical side, the current prejudice is that spin asymmetries are much less affected than simple cross sections by higher order corrections. Indeed, recent calculations confirm this simple behaviour.

Concerning SM PV effects, their precise knowledge is mandatory to extract any signal of New Physics. It has been stressed in Ref. [21] that corrections to the QCD-Electroweak interference terms, at the order $\alpha_s^2\alpha_W$, might be important in the quark-quark channel and also that there were some new contributions from this order in quark-gluon scattering. Recently, the authors of Ref. [22] have carried out the calculation of the one-loop weak corrections to polarized $q-g$ scattering and the corresponding crossed channels. It appears that the PV effects involving gluons are relatively small, i.e. at most 10% of the tree-level contribution. Moreover, any effect at the partonic level will not be enhanced by a possibly large polarization of the gluons, $\Delta G$, because in the large $x$ region which is of interest here the gluon distributions are small. We have implemented the NLO amplitudes of Ref. [22] in our code, and we have verified that the corrections on $A_L$ are of the order of 5% (7%) on the whole $E_T$ spectrum at a c.m. energy of 500 GeV (650 GeV). It was also straightforward to add the effect of the presence of a new $Z'$ in the one-loop amplitude: it turns out that the contribution is negligible.

Concerning $q-q$ scattering, the NLO calculations are not available but we hope to have them in a not too distant future [23]. However, as shown recently by Vogelsang [24], a relatively good estimate of the size of these corrections can be obtained by performing some gluon resummations. Results of a calculation on $A_L$ at RHIC, after resummation at the Leading-Log level, indicate a relatively small correction, of the order of 10% at high $E_T$. However more precise calculations at the Next-to-Leading-Log level are necessary to get a definite conclusion.

5 Conclusions

Qualitatively new measurements will be allowed by the RHIC-Spin experiment. Parity violation searches for physics beyond the Standard Model will be competitive with unpolarized searches at the Fermilab Tevatron, in particular in the upgraded version of the machine and of the detector(s). It is worth stressing that an increase in luminosity of the RHIC $\vec{p}\vec{p}$ machine and/or an improvement of the angular coverage of the detectors seem more efficient than an increase in energy above $\sqrt{s} = 600$ GeV.

From now the precise amount of systematic uncertainties is not accurately known. However experts at RHIC are confident in the capacities of polarimetry and luminosity calibrations. On the other hand, some recent theoretical results indicate that the tree-level prediction for the SM parity-violating asymmetry is quite stable. Hence definite results could be obtained from the measurement of $A_L$ : in particular it has to be emphasized
that the existence of a new weak force between quarks only is not in contradiction with present data. It might also explain the small discrepancies which still exists between leptonic and hadronic observables in LEP and SLC results.

Concerning an other possible step for the program, the possibility of colliding polarized protons against polarized (or unpolarized) $^3\text{He}$ nuclei has been discussed. This could allow to measure some spin asymmetries in $\vec{p}$-$\vec{n}$ and/or $\vec{p}$-$\vec{n}$ collisions and also possibly in $\vec{n}$-$\vec{n}$ collisions via polarized $^3\text{He}$-$^3\text{He}$ collisions. In this case a new charged vector boson (e.g. a massive right-handed $W_R$) could also mediate some visible effects (see Ref.[6]).

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Figure 1: Bounds on the parameter space for leptophobic flipped SU(5) Z' models (see text).