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Studying the origin of a new Z' with polarized beams at future colliders

Annie Fiandrino and Pierre Taxil
Centre de Physique Théorique, Centre National de la Recherche Scientifique–Case 907, F-13288 Marseille CEDEX 9, France
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Motivated by recent technical progress in the acceleration and storage of polarized proton beams which would make feasible the measurement of spin-dependent observables at the energies of future colliders, we analyze forward-backward and spin asymmetries in the production of a new neutral gauge boson of E_6 or left-right origin. These asymmetries could be used to probe the couplings of this new object, allowing us to distinguish among the various possible models.

I. INTRODUCTION

It is a remarkable fact that many models, based on various extensions of the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, predict the existence of at least one extra neutral gauge boson (called generically Z' in the following), the discovery of which would provide a particularly clean signature for the presence of new physics beyond the standard model (SM). Concerning the main features and motivations of the various models, detailed review papers already exist [1,2], along with many articles devoted to the eventual consequences of the presence of this new heavy gauge boson on present and future experiments (see references below).

Depending on the various experimental situations, quite different strategies have been developed. At present e^+e^- machines [phase I of the CERN e^+e^- collider LEP, SLAC Linear Collider (SLC)] a massive Z' could manifest itself only indirectly via its mixing with the standard Z^0. Then, isolating these tiny effects at the Z^0 peak would require great control of the standard-model radiative corrections and also they would have to be disentangled from other possible deviations due to various other sources of new physics [3]. Very careful analyses already have obtained some upper bounds on the Z-Z'mixing angle, taking also into account neutral-current data, [4–6] and these bounds, already very restrictive, will be improved soon thanks to the increasing statistics at the Z^0 peak. On the other hand, direct searches at the Fermilab $p\bar{p}$ collider Tevatron are going on, giving some lower limits on the mass of such an object in the range 300–400 GeV[6].

In the near future, in the second phase of LEP ($\sqrt{s}$ around 190 GeV or so), a massive Z', whose peak would certainly lie beyond the kinematic limit, would interfere with γ and Z^0, hence generating new terms contributing to the cross sections and asymmetries and leading to deviations from their standard-model values. Then it will be possible to exclude heavy neutral vector bosons with masses between 500 GeV and 1 TeV [4]. On the contrary, if sensible deviations were observed, one could try to isolate the values of the Z' couplings to fermions, hence allowing a first determination of the theoretical origin of this new boson [7].

Concerning the next decade, the first machines allowing the exploration of the TeV range will certainly be the so-called proton-proton supercolliders: the Superconducting Super Collider (SSC), with $\sqrt{s}=40$ TeV and a luminosity $\mathcal{L}\approx 10^{33}$ cm^2 s^{-1} [8], and the CERN Large Hadron Collider (LHC), with $\sqrt{s}=16$ TeV and hopefully a higher luminosity $\mathcal{L}\approx 5\times 10^{34}$ cm^2 s^{-1} [9]. Amongst various possible manifestations of new physics which could be expected at this scale, direct searches for Z' gauge-boson production could then be performed, with reasonable chances of success if this new object is indeed present [10,11]. Now, the situation is quite different. For instance, a large number of leptonic events

$$pp \to Z' \to l^+l^-X$$

will be detected only for values of the lepton pair invariant mass M close to the value of the Z' mass and the studies of interference effects with γ and Z^0, which are relevant far from the Z' peak, will be difficult due to statistics. Moreover, to perform the task of isolating its couplings to fermions, in the goal of disentangling between various origins of the Z', or to extract the value of unknown parameters relevant to a given class of models, apart from the cross section and some partial widths (essentially leptonic), the only observable quantity will be the forward-backward asymmetry A_{FB}, a quantity which has indeed received much attention in phenomenological studies (see, e.g., Refs. [12,13]). This contrasts with the situation at other machines which are also in project, namely, linear e^+e^- colliders (with a c.m. energy of 0.5 TeV, 1 TeV, or more), where polarization of the beams is recognized to be an important complementary tool [14] that gives access to new, observable spin-dependent quantities. In this case the spin asymmetries would allow one to perform a complete set of precision measurements.

If, in the case of e^+e^- linear colliders, one does not expect to find major difficulties in maintaining a substantial polarization through the beam transport and collision process, the situation in proton-proton colliders is certainly much more complicated from the technical point of view. However, thanks to recent progress in the acceleration of polarized protons [15,16] it seems feasible to study hadronic interactions with polarized beams at high energy and high luminosity. A program of measurements of spin effects using polarized protons in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, with a c.m. energy around 300 or 600 GeV, is now seriously under study [17] and theoretical papers have recently been devoted to the physics case at this new facility [18]. If we turn now to the very-high-energy domain, the physics with polarized beams has been discussed in dedicated workshops [16,19] and high-energy spin physics conferences [20]. A letter of intent for a future SSC experiment has been already written [21]. Recently, a survey of the phenomenology of spin effects at future supercolliders was performed [22] and it was found that large and meaningful polarization asymmetries can be expected, both according to the standard model and to various scenarios of new physics.

The goal of this paper is to present a strategy for the study of an eventual new neutral gauge boson Z' which could be produced at supercolliders, taking advantage of the new facilities provided by the availability of longitudinally polarized proton beams. In Sec. II we give the relevant couplings of the Z' to fermions in the framework of two general classes of models leading to the presence of such an object. In Sec. III we present new observable quantities one can define when at least one beam is polarized and we discuss the ingredients which are necessary for their calculation. Section IV is devoted to the analysis of our results and we present some conclusions in Sec. V.

II. RELEVANT PARAMETERS AND COUPLINGS FOR GENERAL E_6 AND LEFT-RIGHT MODELS

In this section we recall briefly the structure of two typical classes of models leading to the presence of one or more new Z' before setting our conventions for the parametrizations of the relevant axial-vector and vector couplings of the lightest Z' to fermions.

There are many models which contain an additional gauge structure. Our goal is not to be exhaustive but rather to analyze the capabilities of polarized *pp* colliders; hence, we will focus on two wide classes of models: models with an E_6 origin (inspired or not by superstring theories) and general left-right-models.

A detailed survey of E_6 models, motivations, and references to the original literature can be found in Ref. [1]. Superstring theories have provoked a revival of models based on E_6 as the group of grand unification. In fact, in this context, the breaking of E_6 can lead to a rank-5 model: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_\eta$ containing an extra $U(1)_\eta$ which is perfectly determined. As a consequence, in this so-called "η model", definite fermionic couplings of the corresponding new neutral gauge boson Z'_η can be obtained. However, this pattern is not unique: E_6 can also break down to several rank-6 groups, an example being the famous decomposition $E_6 \to SO(10) \otimes U(1)_\psi$ followed by $SO(10) \to SU(5) \otimes U(1)_\chi$. Indeed, one can then define a large class of models [called "effective rank-5 models" (ER5M) in Ref. [1]] including the "η model" as a particular case, where the lightest new Z' can be written as the combination

$$Z'(\beta) = Z'_\chi \cos\beta + Z'_\psi \sin\beta \ , \tag{1}$$

Z'_χ and Z'_ψ being the gauge bosons corresponding to the $U(1)_\chi$ and $U(1)_\psi$ defined above. Thus, one gets quite a general framework, with only one free parameter, which is convenient for phenomenological studies and is not confined to a very specific model like the η (or χ or ψ) model.

Unfortunately, many different conventions have been used by various authors concerning the mixing parameter we have called β in Eq. (1). Here we are following the conventions adopted in recent works on e^+e^- physics [4,7], which is also the one used in the extensive analysis of Amaldi *et al.* [23].

We take $0 \le \beta \le \pi$ ($\sin\beta \ge 0$), defining the "η model" (called $-\eta$ in [23]) as $\cos\beta = -\sqrt{3/8}$, $\sin\beta = \sqrt{5/8}$, i.e., $\beta(\eta) \approx 127.76°$, whereas the perpendicular case $\eta_\perp$ corresponds to $\beta(\eta_\perp) \approx 37.76°$, and χ and ψ to $\beta = 0$ and $\pi/2$, respectively.

It is not possible to give an exhaustive list of all the conventions which have been used by various authors. Nevertheless, for helping the reader we shall give the correspondence between our choice and some which are frequently used in the literature. For instance, θ of Refs. [1,6] is related to β [Eq. (1)] by $\theta = \pi/2 - \beta$, whereas α of Ref. [12] is $\alpha = -\theta$ (see also [22] and [24]). Conversely, some authors prefer to choose the "η model" as the origin; for example, θ_2 of Altarelli *et al.* in Ref. [3] is $\theta_2 = \beta - \beta(\eta)$ in our notation. It has to be noticed (see below) that the couplings entering the various observable quantities are such that the latter are unaltered by the change $\beta \to \beta \pm \pi$. Hence θ_{E_6} of Ref. [25] would give the same results as ours since $\theta_{E_6} = \pi + \beta$.

We can give now the expressions of axial-vector and vector couplings to fermions of a new $Z'(\beta)$ of general E_6 origin. The structure of the current is defined as

$$J_\mu^{Z'}(f) = \bar{f}(v'_f \gamma_\mu - a'_f \gamma_\mu \gamma_5) f \tag{2}$$

and the axial-vector and vector couplings are given in Table I.

In the expressions in Table I we have ignored the influence of an eventual mixing between the Z' and the standard Z:

$$Z' = \cos\theta_M \, Z_0 + \sin\theta_M \, Z'_0 \ , \tag{3}$$

where the physical Z' is expressed in terms of the "mathematical states" Z_0 and Z'_0. In fact, according to some recent analyses from LEP data [26], the possible values of the mixing angle θ_M are already severely restricted ($|\theta_M| \le 0.03-0.01$) and these bounds will become more severe in the near future [4]. In any case, even if very small mixing was detected at LEP, which would be by itself very exciting, its influence on the curves displayed below would be obviously too small to be observed. Note that the complete expressions for the axial-vector and vector couplings of the E_6 models, including the θ_M dependence, can be easily found in the

TABLE I. Vector and axial-vector couplings in effective rank-5 models from $E_6(c_W=\cos\theta_W)$.

	e^-	u	d
v_f'	$\frac{\cos\beta}{\sqrt{6}c_W}$	0	$\frac{-\cos\beta}{\sqrt{6}c_W}$
a_f'	$\frac{\cos\beta}{2\sqrt{6}c_W}+\frac{\sqrt{10}\sin\beta}{12c_W}$	$\frac{-\cos\beta}{2\sqrt{6}c_W}+\frac{\sqrt{10}\sin\beta}{12c_W}$	$\frac{\cos\beta}{2\sqrt{6}c_W}+\frac{\sqrt{10}\sin\beta}{12c_W}$

literature [7]. The above remarks also hold for the case of left-right models we discuss now.

We will consider a rather general left-right model (LRM) [27] based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ where the new "left-right" current can be written as

$$J_{LR}=\alpha J_{3R}-\frac{1}{2\alpha}J_{B-L} , \tag{4}$$

α being a parameter related to the gauge couplings:

$$\alpha\approx\left[\left[\frac{g_R}{g_L}\right]^2\frac{\cos^2\theta_W}{\sin^2\theta_W}-1\right]^{1/2} . \tag{5}$$

It is assumed to range as

$$\frac{1}{\sqrt{2}}\lesssim\alpha\lesssim 1.52\ldots \quad \text{for } \sin^2\theta_W=0.23 , \tag{6}$$

which corresponds to the interval [28]

$$\tfrac{1}{2}g_L^2\le g_R^2\le g_L^2 . \tag{7}$$

The case which is the most frequently considered in the literature is the left-right-symmetric (LRS) case with $g_R=g_L$, implying that α reaches its maximal value. The corresponding axial-vector and vector couplings to fermions of the general Z'_{LR} are given in Table II. Note that for the special value $\alpha=\sqrt{2/3}$ these couplings correspond to the ones in the χ model version of the ER5M [$\cos\beta=1$ in Eq. (1)].

In addition to these two classes of models, there exist also some other realizations of effective rank-5 models from E_6 which lead to an extension of the standard model by an extra SU(2) group (see Ref. [1] for discussion and an extensive list of references). Two cases are frequently considered in the literature.

First, there is the case of the $SU(2)_L\otimes U(1)_Y\otimes SU(2)_I$ model whose generator of the extra $SU(2)_I$ commutes with the electric charge [29]. In fact, the neutral gauge boson Z_I of $SU(2)_I$ is analogous to the boson Z' of the "$\eta_\perp$ model" ($\beta\approx 37.76°$) in the context of ER5M of the type $U(1)_\beta$ discussed above, apart from an overall factor in the couplings which leaves the asymmetries we will be interested in unaffected.

Finally, a second model, the so-called alternative left-right model (ALRM), deserves special attention [30]. The gauge group is now of the type $SU(2)_L \otimes SU(2)_R\otimes U(1)_V$ and it is a particular case of the LRM in the symmetric version ($g_L=g_R$), but with an unconventional assignment of quantum numbers to standard-model fermions. For instance, the $u_{L,R}$ and e_R^-,d_L couplings to the Z' of the ALRM are identical to those of the LRSM but the couplings to e_L^- and d_R are modified. As a consequence, in this model one gets specific vector and axial-vector couplings for the Z' which can be read in Table III. Note that the popularity of the ALRM is also due to the fact that, in this framework, the usual mass limits on the $W_R^\pm$ of the charged sector of $SU(2)_R$ are evaded due to the absence of mixing with the usual W_L. We will refer to Ref. [22] concerning interesting spin effects in the production of $W_R^\pm$.

III. ASYMMETRIES IN Z' PRODUCTION AND DETECTION THROUGH LEPTON PAIRS

At hadron colliders, such as the SSC or LHC, the main channel for the production and detection of a new Z' is a generalization of the Drell-Yan process:

$$p_a p_b\to\gamma,Z,Z'+X\to\mu^+\mu^-+X , \tag{8}$$

where a quark from one of the protons annihilates with an antiquark from the sea of the other proton to form a Z' decaying into a pair of charged leptons (we will call them muons for definiteness). Of course, standard γ and Z amplitudes also contribute to this process.

Indeed, we are obliged to focus on the leptonic decay channel since the Z' detection through jets seems hopeless [31] due to the QCD background. In addition, it has to be mentioned that the fusion subprocess $W^+W^-\to Z'$ is also present in principle, but as the Z' couples only to W^+W^- through $Z^0-Z^{0'}$ mixing [32], this contribution is expected to be small (see, however, the discussion in

TABLE II. Vector and axial-vector couplings in left-right models.

	e^-	u	d
v_f'	$\frac{1}{2\alpha c_W}\left[-\frac{\alpha^2}{2}+1\right]$	$\frac{1}{2\alpha c_W}\left[-\frac{\alpha^2}{2}-\frac{1}{3}\right]$	$\frac{1}{2\alpha c_W}\left[-\frac{\alpha^2}{2}-\frac{1}{3}\right]$
a_f'	$\frac{\alpha}{4c_W}$	$\frac{-\alpha}{4c_W}$	$\frac{\alpha}{4c_W}$

TABLE III. Vector and axial-vector couplings in ALRM. $\alpha_0 \equiv \alpha(g_L = g_R) = (\cos^2\theta_W / \sin^2\theta_W - 1)^{1/2}$.

	e^-	u	d
v'_f	$\frac{1}{2\alpha_0 c_W}\left[-\alpha_0^2+\frac{1}{2}\right]$	$\frac{1}{2\alpha_0 c_W}\left[\frac{\alpha_0^2}{2}-\frac{1}{3}\right]$	$\frac{1}{12\alpha_0 c_W}$
a'_f	$\frac{-1}{4\alpha_0 c_W}$	$\frac{-\alpha_0}{4c_W}$	$\frac{-1}{4\alpha_0 c_W}$

Ref. [22] and also Ref. [33] where a complete set of formulas for polarized WW collisions can be found). On the same line, the channel $Z' \to W^+W^-$ could be interesting but it seems to be ruled out for Z' detection due to the heavy background [34].

The differential cross section for the process Eq. (8) depends on the muon pair invariant mass M, on its rapidity y, on the angle θ in the center of mass of colliding partons, and on the distributions of quarks and antiquarks $q(x,Q^2)$ and $\bar{q}(x,Q^2)$ into the protons.

At the parton level and in the limit of negligible fermion masses, the subprocess helicity-dependent differential cross section for the general case of quark-antiquark annihilation into a pair of final muons in the case of γ, Z, and Z' formation

$$q_i(h)\bar{q}_i(h') \to \gamma, Z, Z' \to \mu^+\mu^- \tag{9}$$

can be written as [$h(h')$ refers to the helicity of polarized quark (antiquark) $(h,h'=\pm 1)$ and i is a quark flavor indice]

$$\frac{d\hat{\sigma}^{h;h'}}{d\cos\theta} = \frac{\pi\alpha^2}{2M^2}\{(1-hh')[G_1^{\text{if}}(M)(1+\cos^2\theta)+2G_2^{\text{if}}(M)\cos\theta]+(h'-h)[G_4^{\text{if}}(M)(1+\cos^2\theta)+2G_5^{\text{if}}(M)\cos\theta]\}\ , \tag{10}$$

where θ is the angle between the quark q_i and the outgoing, negatively charged muon in the $q\bar{q}$ center of mass (we are following some notation used in the case of e^+e^- annihilation [35], other terms, G_3^{if} and G_6^{if}, are present in principle but they are proportional to the masses of the outgoing particles and are neglected here).

We have

$$G_1^{\text{if}}(M) = e_i^2 + \frac{M^4}{|D_Z|^2}(a_i^2+v_i^2)(a_f^2+v_f^2) + \frac{M^4}{|D_{Z'}|^2}(a_i'^2+v_i'^2)(a_f'^2+v_f'^2) - 2M^2\,\text{Re}\left[\frac{1}{D_Z}\right]e_i v_i v_f$$
$$-2M^2\,\text{Re}\left[\frac{1}{D_{Z'}}\right]e_i v_i' v_f' + 2M^4\,\text{Re}\left[\frac{1}{D_Z D_{Z'}^*}\right](v_i v_i' + a_i a_i')(v_f v_f' + a_f a_f')\ , \tag{11}$$

$$G_2^{\text{if}}(M) = 4\frac{M^4}{|D_Z|^2}v_i a_i v_f a_f + 4\frac{M^4}{|D_{Z'}|^2}v_i' a_i' v_f' a_f' - 2M^2\,\text{Re}\left[\frac{1}{D_Z}\right]e_i a_i a_f$$
$$-2M^2\,\text{Re}\left[\frac{1}{D_{Z'}}\right]e_i a_i' a_f' + 2M^4\,\text{Re}\left[\frac{1}{D_Z D_{Z'}^*}\right](v_i a_i' + a_i v_i')(v_f a_f' + a_f v_f')\ , \tag{12}$$

$$G_4^{\text{if}}(M) = 2\frac{M^4}{|D_Z|^2}v_i a_i(a_f^2+v_f^2) + 2\frac{M^4}{|D_{Z'}|^2}v_i' a_i'(a_f'^2+v_f'^2) - 2M^2\,\text{Re}\left[\frac{1}{D_Z}\right]e_i a_i v_f$$
$$-2M^2\,\text{Re}\left[\frac{1}{D_{Z'}}\right]e_i a_i' v_f' + 2M^4\,\text{Re}\left[\frac{1}{D_Z D_{Z'}^*}\right](v_i a_i' + a_i v_i')(v_f v_f' + a_f a_f')\ , \tag{13}$$

$$G_5^{\text{if}}(M) = 2\frac{M^4}{|D_Z|^2}v_f a_f(a_i^2+v_i^2) + 2\frac{M^4}{|D_{Z'}|^2}v_f' a_f'(a_i'^2+v_i'^2) - 2M^2\,\text{Re}\left[\frac{1}{D_Z}\right]e_i a_f v_i$$
$$-2M^2\,\text{Re}\left[\frac{1}{D_{Z'}}\right]e_i a_f' v_i' + 2M^4\,\text{Re}\left[\frac{1}{D_Z D_{Z'}^*}\right](v_i v_i' + a_i a_i')(v_f a_f' + a_f v_f')\ . \tag{14}$$

e_i is the initial quark charge in unit of the electron charge, $a_i, v_i (a_i', v_i')$ are the axial-vector and vector couplings of the quark i to the $Z(Z'), a_f, v_f (a_f', v_f')$ being the same quantities for the final-state muons, and $D_{Z(Z')} = M^2 - M_{Z(Z')}^2 + iM_{Z(Z')}\Gamma_{Z(Z')}$. The primed quantities can be read in Tables I–III and, since we are neglecting the Z-Z' mixing, the couplings to the standard Z are keeping their SM values.

Let us recall first the situation in the unpolarized case.

The unpolarized differential cross section for the process of Eq. (8) is given by

$$\frac{d\sigma}{dM\,dy\,d\cos\theta} = \frac{\pi\alpha^2\tau}{3M^3}\sum_{q_i}[G_1^{\text{if}}(M)g_i^S(y,M)(1+\cos^2\theta) + 2G_2^{\text{if}}(M)g_i^A(y,M)\cos\theta]\ , \tag{15}$$

where

$$g_i^{S(A)}(y,M)=q_i(x_a,M^2)\bar{q}_i(x_b,M^2) \pm q_i(x_b,M^2)\bar{q}_i(x_a,M^2)\ , \tag{16}$$

with $x_{a,b}=\sqrt{\tau}e^{\pm y}$ and $\tau=M^2/s$.

To get some information about the new couplings, performing a complete analysis of this process would require careful studies of the θ dependence of the cross section, which reflects the spin structure of the interaction, of the M dependence, which is sensitive to interference effects between the standard and the new amplitudes, and of the rapidity dependence, which is essentially a consequence of the behavior of the partonic distributions. Obviously, to get a reasonable number of events, one is forced to integrate out some of these variables.

Concerning the angular dependence, a quantity which has received much attention in the literature is the integrated forward-backward asymmetry

$$A_{FB}(y,M)=\frac{d\sigma_{F-B}(y,M)}{d\sigma_{F+B}(y,M)}\ , \tag{17}$$

where

$$d\sigma_{F\pm B}(y,M)=\left[\int_0^1 \pm \int_{-1}^0\right] d\cos\theta \frac{d\sigma}{dM\,dy\,d\cos\theta}\ . \tag{18}$$

$A_{FB}(y,M)$ is an odd function of y and it is zero at zero rapidity, that is, when the lepton pair is at rest in the pp center of mass. Therefore it can be large only at large values of y which can pose a problem due to the decrease in statistics. It is possible to define an asymmetry integrated over the rapidity in the following way:

$$A_{FB}(M)=\frac{\left[\int_0^Y dy - \int_{-Y}^0 dy\right] d\sigma_{F-B}(y,M)}{\int_{-Y}^{Y} dy\, d\sigma_{F+B}(y,M)} = \frac{3}{4}\frac{\sum_{q_i} G_2^{\text{if}}\mathcal{L}_i^A(M)}{\sum_{q_i} G_1^{\text{if}}\mathcal{L}_i^S(M)}\ . \tag{19}$$

where $Y \equiv y_{\max} = \ln(\sqrt{s}/M)$ and

$$\mathcal{L}_i^A(M)=\left[\int_0^Y - \int_{-Y}^0\right] dy\, g_i^A(y,M^2)\ , \tag{20}$$

$$\mathcal{L}_i^S(M)=\int_{-Y}^{Y} dy\, g_i^S(y,M^2)\ . \tag{21}$$

The denominator in Eq. (19) is proportional to $\mathcal{L}_i^S(M)$, which is the "quark-antiquark luminosity" [36], that is, for a given flavor, the number of quark-antiquark collisions per unit of $\tau=M^2/s$ with subprocess energy squared $\hat{s}=M^2$. $\mathcal{L}_i^A(M)$ is the corresponding quantity, suitable for the numerator.

Let us turn now to the polarized case. Since we are facing an interaction [Eq. (2)] which contains parity-violating terms, to get interesting spin effects it is sufficient to consider the case where only one of the proton beams, say the beam a, is longitudinally polarized:

$$\vec{p}_a p_b \to \mu^+\mu^- X\ . \tag{22}$$

We will denote by $q^{\pm}(x,M^2)$ and $\bar{q}^{\pm}(x,M^2)$ the quark and antiquark distributions in a polarized proton either with helicity parallel (+) or antiparallel (−) to the parent proton helicity. Then, the unpolarized distributions are given by $q=q^++q^-$ and $\bar{q}=\bar{q}^++\bar{q}^-$, and we define the polarized distribution functions $\Delta q(x,M^2)$ and $\Delta\bar{q}(x,M^2)$ by $\Delta q=q^+-q^-$ and $\Delta\bar{q}=\bar{q}^+-\bar{q}^-$.

We will consider first an integrated left-right asymmetry $A_{LR}(M)$ for the process [Eq. (22)]. It is defined as

$$A_{LR}(M)=\frac{d\sigma^- - d\sigma^+}{d\sigma^- + d\sigma^+}\ , \tag{23}$$

where $d\sigma^{\pm}$ stands for $d\sigma^{\pm}/dM$ and $\pm$ refers to the helicity states of the proton p_a. From Eq. (10) it is easy to see that $A_{LR}(M)$ is given by

$$A_{LR}(M)=\frac{\sum_{q_i} G_4^{\text{if}}\Delta_1^i(M)}{\sum_{q_i} G_1^{\text{if}}\mathcal{L}_i^S(M)}\ , \tag{24}$$

where

$$\Delta_1^i(M)=\int_{-Y}^{Y} dy[\Delta q_i(x_a,M^2)\bar{q}_i(x_b,M^2) - \Delta\bar{q}_i(x_a,M^2)q_i(x_b,M^2)] \tag{25}$$

is a combination of the "singly polarized luminosities" introduced in Ref. [22]. We have chosen to consider a left-right asymmetry integrated over θ and the rapidity to increase the chance to get precise measurement of parity-violating effects without too much trouble from statistics. Note also that, in contrast with the case of the forward-backward asymmetry A_{FB}, a determination of A_{LR} does not require the identification of the charge of the outgoing leptons, which is not an easy task for tracks up to the TeV momentum range.

Second, still making a parallel with the case of e^+e^- physics, it is possible to introduce another spin-dependent asymmetry: the "polarized forward-backward asymmetry" A_{FB}^{pol} we choose to define as

$$A_{FB}^{\text{pol}}=\frac{(d\sigma_F^- - d\sigma_B^-)-(d\sigma_F^+ - d\sigma_B^+)}{d\sigma_F^- + d\sigma_B^- + d\sigma_F^+ + d\sigma_B^+}\ , \tag{26}$$

where

$$d\sigma_F^{\pm} - d\sigma_B^{\pm} = \left[\int_0^Y - \int_{-Y}^0\right] dy \left[\int_0^1 - \int_{-1}^0\right] \times d\cos\theta \frac{d\sigma^{\pm}}{dM\,dy\,d\cos\theta} \tag{27}$$

are the integrated forward-backward combinations in the two cases where the proton p_a of the polarized beam is prepared with a positive or a negative helicity. One can see easily that in the Drell-Yan formalism A_{FB}^{pol} is given by

$$A_{FB}^{\text{pol}}=\frac{3}{4}\frac{\sum_{q_i} G_5^{\text{if}}\Delta_2^i(M)}{\sum_{q_i} G_1^{\text{if}}\mathcal{L}_i^S(M)}\ , \tag{28}$$

with

$$\Delta_2^i(M) = \left[\int_0^Y - \int_{-Y}^0\right] dy\,[\Delta q_i(x_a,M^2)\bar{q}_i(x_b,M^2) + \Delta\bar{q}_i(x_a,M^2)q_i(x_b,M^2)]\ . \tag{29}$$

Obviously, from the experimental point of view, this quantity possesses both the disadvantages of A_{LR} and A_{FB} since a polarized beam is needed and also one is obliged to identify the sign of the outgoing leptons. Conversely, if high-luminosity polarized beams are available, measuring $A_{FB}^{\rm pol}$ is not much more difficult than measuring A_{FB} in the unpolarized case. We will see below that its measurement would allow us to get information which is complementary to the one obtained with the two other observables.

Before turning to the analysis of our results, let us make a few remarks on the basic ingredients of the actual calculations of these asymmetries.

(i) Polarized quark and antiquark distribution functions $\Delta q_i(x,Q^2)$ and $\Delta\bar{q}_i(x,Q^2)$ are essential quantities in the calculation of any polarization asymmetry. Our knowledge of these distributions is presently incomplete, especially at high Q^2 and very small x values which is the relevant kinematic domain at supercollider energies. However, thanks to forthcoming deep-inelastic-scattering experiments with a polarized lepton beam on a polarized proton target, one can hope that these distributions will be better known in the future [37]. In fact, as advocated many times [22,38] at supercolliders themselves, with polarized beams, some well-know standard-model electroweak processes ($W^\pm$ and Z productions, W^+W^- pair productions, etc.) will give us a very large number of events and large parity-violating asymmetries. These spin effects, which are calculable, will allow us to perform a calibration of the spin-dependent partonic distributions. Hence, the strategy is the same in the polarized case as the one presented in the unpolarized case [36]: the studies of copious well-known standard processes will allow us to calibrate spin-dependent as well as spin-independent distributions.

Following the spirit of our review paper we have chosen for illustration a "reasonable set" of polarized partonic distributions whose parametrization is given in Ref. [22] and which are compatible with the recent European Muon Collaboration (EMC) data on deep-inelastic scattering of polarized muons on a polarized proton target [39]. We are aware that, since the interpretation of the EMC data is still controversial, our wisdom about spin-dependent partonic distributions could change in the future: the magnitude of the effects we present below could be affected but we do not expect that the general behavior of the asymmetries will be deeply modified.

Concerning the ordinary unpolarized distributions, our parameterizations are compatible with those of Eichten Hinchliffe, Lane, and Quigg (EHLQ) [36]. Moreover, since we are considering quantities integrated over the rapidity, the influence of the choice of these distributions will not alter the trend of our results very much.

(ii) Concerning QCD corrections to the partonic Drell-Yan formulas, they have to be taken into account in principle, leading to the presence of so-called K factors in the expression for the cross section in the unpolarized as well as in the polarized case. However, since we are essentially interested in asymmetries, we expect that the influence of such multiplicative factors will drop out in the ratios and we will ignore them.

IV. RESULTS FOR ASYMMETRIES IN E_6, LR, AND ALR MODELS

In the following, we will present the results of our calculations for the asymmetries defined in the preceding section. As few comments are in order.

(i) We will concentrate on quantities calculated at the Z' peak, that is, for the value of the invariant mass of the lepton pair M equal to the Z' mass $M_{Z'}$. Indeed, off-peak studies would allow us to be sensitive to interference effects between the Z', γ, and Z amplitudes as has been advocated in the case of the forward-backward asymmetry A_{FB} [24]. However, this sort of measurement would suffer from great trouble due to the lack of statistics and a conclusion of a recent LHC study [40] is that it would be hopeless or at least very difficult to perform.

(ii) The total width $\Gamma_{Z'}$ of the Z' enters Eqs. (11)–(14). From the couplings displayed in Tables I–III it is straightforward to obtain the total Z' width into the ordinary fermions (the present uncertainty on the top mass will only cause an unsignificant effect). However, as noticed by various authors [12,13], decays into exotic fermions or into supersymmetric particles could contribute to the width of the new gauge boson if these channels are kinematically allowed. Since we are taking into account only events in the vicinity of the Z' peak, as can be seen from Eqs. (11)–(14), the influence of the precise value of $\Gamma_{Z'}$ on the observable quantities is very weak in this case. As a consequence we do not expect that a deviation from the case of conventional decays would alter our results significantly. Finally, instead of taking events at $M=M_{Z'}$ it is more realistic to integrate on the Z' peak (which remains quite narrow in any case). We have checked that this procedure has no effect on the results we present below.

(iii) According to some recent analyses [10,11], the discovery limits for a massive Z' in the type of models we are considering are of the order of 4–5 TeV at the LHC with an integrated luminosity of 10^5 pb^{-1} and 6–8 TeV at the SSC with 10^4 pb^{-1}. However, to measure an asymmetry with enough precision—to allow us to discriminate between the various models, which is the goal of our study—a reasonable number of events are needed. In our illustrative calculations we will restrict to $M_Z=1$ TeV and 2 TeV. In the first case, summing over the electron and muon channels one could expect at least 30 000 events at the LHC and 15 000 events at the SSC. These figures become respectively 2000 and 1200 events for $M_Z=2$ TeV.

Let us start with the case of ER5M from E_6. It is instructive to analyze in some detail what kind of information could be provided by the measurement of A_{FB}, A_{LR}, and $A_{FB}^{\rm pol}$.

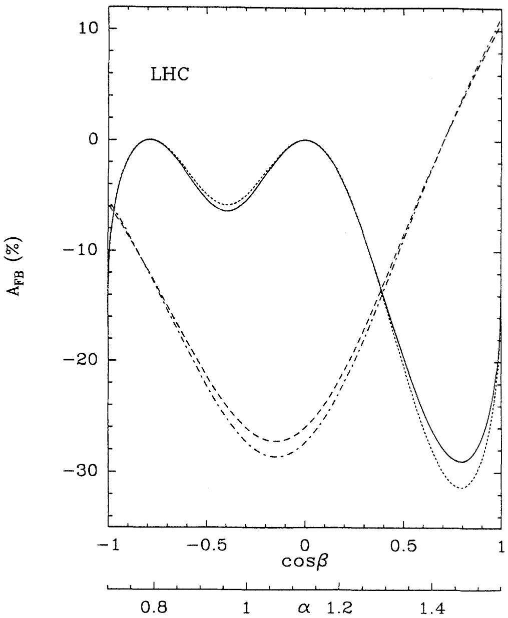

FIG. 1. A_{FB} at the Z' peak at the LHC in ER5M vs $\cos\beta$ for $M_{Z'}=1$ TeV (solid curve) and 2 TeV (dotted curve), and in LRM vs α for $M_{Z'}=1$ TeV (dashed curve) and 2 TeV (dot-dashed curve).

First, we have recalculated the well-known integrated A_{FB} using our set of structure functions. A_{FB} at the LHC and SSC are plotted in Figs. 1 and 2 for $M_{Z'}=1$ and 2 TeV, as a function of the mixing parameter $\cos\beta$. We recover a behavior already displayed in previous analyses [11–13] and which can be understood easily. In this class of models, the nullity of the vector coupling v'_u of the u quark to the Z' simplifies the analysis greatly. As a consequence A_{FB} can be written as

$$A_{FB}=\frac{3}{4}\mathcal{A}'_\mu\mathcal{A}'_d\frac{\mathcal{L}_d^A}{\tilde{\mathcal{L}}} , \tag{30}$$

where $\mathcal{L}_d^A$ is defined in Eq. (20), and

$$\mathcal{A}'_j=\frac{a'_j v'_j}{v_j'^2+a_j'^2},\quad j=\mu,d . \tag{31}$$

The quantity $\tilde{\mathcal{L}}$ is a weighted sum of the u- and d-quark luminosities defined in Eq. (21):

$$\tilde{\mathcal{L}}=\mathcal{L}_u^S\tilde{\mathcal{R}}_{ud}+\mathcal{L}_d^S , \tag{32}$$

with

$$\tilde{\mathcal{R}}_{ud}=\frac{a_u'^2}{v_d'^2+a_d'^2} . \tag{33}$$

Therefore, A_{FB} is proportional to the products of all the axial-vector and vector couplings of initial d quarks and final muons. It will always be negative due to $\mathcal{A}'_\mu=-\mathcal{A}'_d$ (see Table I) and exact double zeros occur when (1) $v'_\mu,v'_d=0$ for $\cos\beta=0$ (that is, for the ψ model) and (2) $a'_\mu=a'_d=0$ for $\cos\beta=-\sqrt{5/8}$ ($\beta=142.2°$). A_{FB} is quite small in the range $80°\le\beta\le160°$, a region in which the quantity $\tilde{\mathcal{L}}$ is large due to a relatively large value for the coefficient $\tilde{\mathcal{R}}_{ud}$. In particular $|A_{FB}|$ is always less than 3% for the important case of the η model which lies in this range. It is only when $\cos\beta$ becomes large and positive that A_{FB} becomes sizable since then the absolute value of the product $\mathcal{A}'_\mu\mathcal{A}'_d$ increases as $\tilde{\mathcal{R}}_{ud}$ decreases in the same time. For example, the case $\eta_\perp(\cos\beta\approx0.79)$

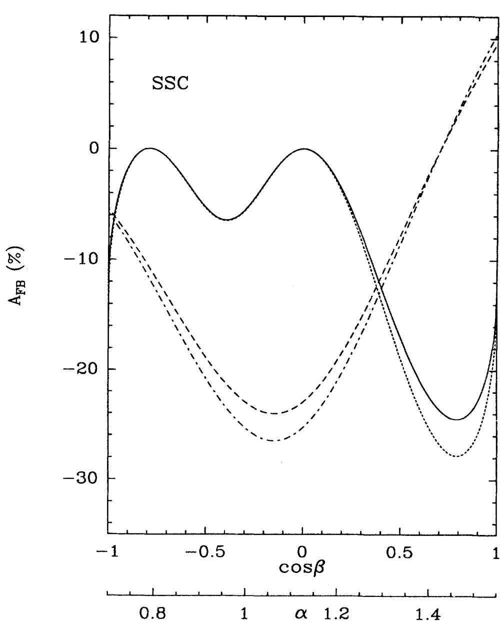

FIG. 2. A_{FB} at the SSC. The legend is the same as in Fig. 1.

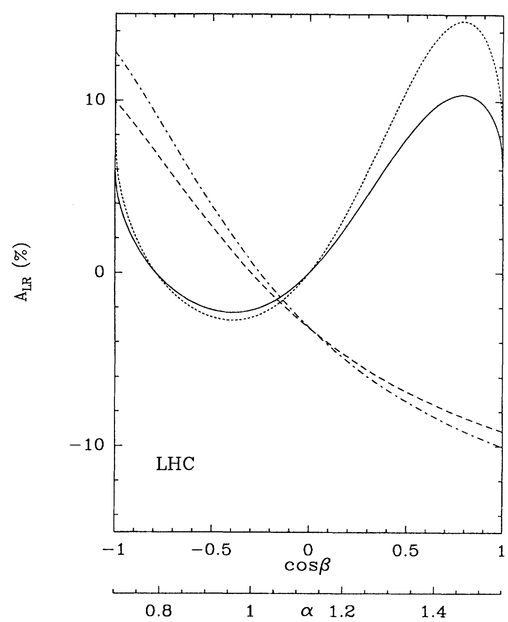

FIG. 3. A_{LR} at LHC, for $M_{Z'}=1$ and 2 TeV. The legend is the same as in Fig. 1.

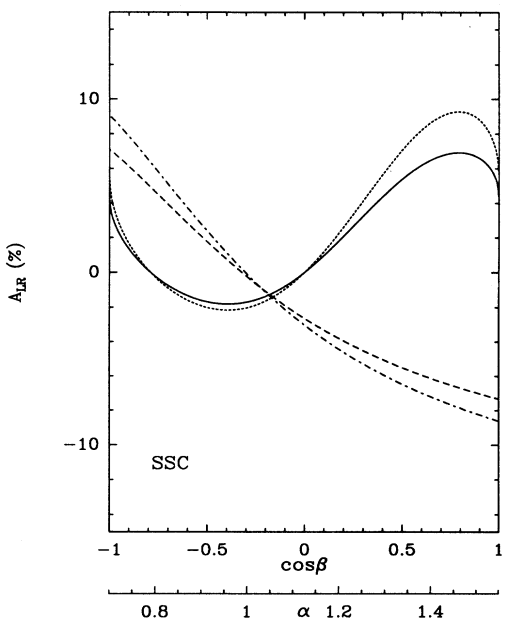

FIG. 4. A_{LR} at SSC, for $M_{Z'}=1$ and 2 TeV. The legend is the same as in Fig. 1.

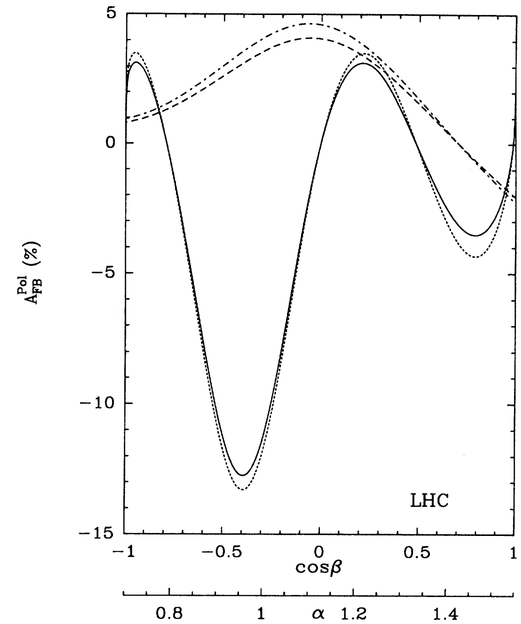

FIG. 5. $A_{FB}^{\rm pol}$ at LHC, for $M_{Z'}=1$ and 2 TeV. The legend is the same as in Fig. 1.

gives a large effect around -24% (-29%) at SSC (LHC) if $M_{Z'}=1$ TeV. Finally, it is clear from Figs. 1 and 2 that in general β cannot be uniquely determined from A_{FB} (modulo the $\beta \to \beta + 180°$ ambiguity which is always present) since two or more values of $\cos\beta$ can give the same asymmetry.

Let us consider now the two other spin-dependent asymmetries.

A_{LR} is displayed in Figs. 3 and 4. Note that for the same value of $M_{Z'}$, A_{LR} is somewhat larger at LHC than at SSC. This is a consequence of the general behavior of the spin-dependent quark distributions [22]: at fixed $M_{Z'}$, if $\sqrt{s}$ is smaller, larger values of x are needed and the $\Delta q_i(x,M^2)$ grow with x at fixed M^2 as is well known [39].

A_{LR} can be written as

$$A_{LR} = \mathcal{A}'_d \frac{\Delta_1^d}{\tilde{\mathcal{L}}} , \tag{34}$$

where Δ_1^d is given in Eq. (25). Now, this asymmetry is directly proportional to the product of the axial-vector and vector couplings of d quarks to the Z' and is independent of the final-state couplings. The integrated quantity Δ_1^d is essentially dependent of the d-quark polarized distribution Δd since the polarization of the sea is small (and positive), which is a reasonable assumption. The former being negative in a polarized proton, Δ_1^d is always strictly negative and A_{LR} will be opposite in sign to $\mathcal{A}'_d$. As a consequence, A_{LR} is positive except in the region $-\sqrt{5/8} \le \cos\beta \le 0$, i.e., between the two exact zeros of $\mathcal{A}'_d$.

A_{LR} possesses the same zeros in $\cos\beta$ as A_{FB} but they are now single zeros. Again, it is the large value of $\tilde{\mathcal{L}}$ which forces A_{LR} to be small, roughly in the same region where A_{FB} is small. For example $|A_{LR}|$ is less than 2% for the η model. In the same way in the vicinity of the $\eta_\perp$ model, A_{LR} is large and positive as already noticed in Ref. [22].

Concerning $A_{FB}^{\rm pol}$ which is displayed in Figs. 5 and 6 one gets

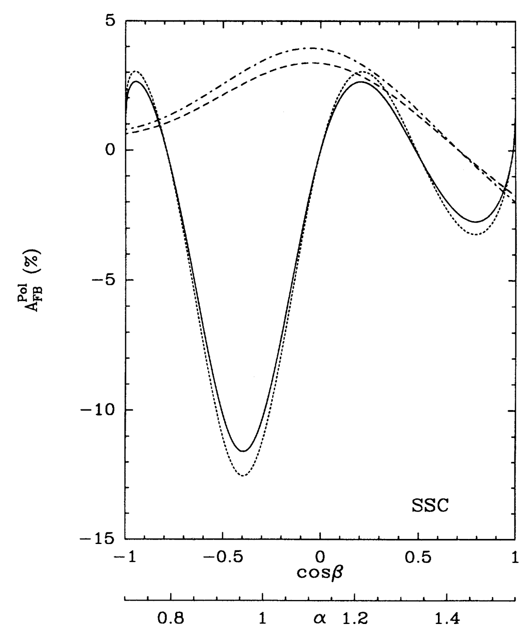

FIG. 6. $A_{FB}^{\rm pol}$ at SSC, for $M_{Z'}=1$ and 2 TeV. The legend is the same as in Fig. 1.

$$A_{FB}^{\rm pol}=\frac{3}{4}\mathcal{A}'_\mu\frac{\Delta_2^d+\Delta_2^u\tilde{\mathcal{R}}_{ud}}{\tilde{\mathcal{L}}}\ , \tag{35}$$

where Δ_2^u and Δ_2^d are given in Eq. (29). This formula implies that the single zeros in $\beta=0°$ and 142.2° are still present, but we also find two other zeros for $\cos\beta>0$. They come from the numerator in Eq. (35) where Δ_2^d and Δ_2^u are opposite in sign. At a variance with the other zeros, the positions of these ones are dependent of the parametrization of the polarized distributions since they depend on the value of $\tilde{\mathcal{R}}_{ud}$ but also on Δ_2^d and Δ_2^u. The main interesting point is that now $|A_{FB}^{\rm pol}|$ is much larger in the main part of the region where A_{LR} and A_{FB} are small. This is due to the presence in the numerator of Eq. (35) of the coefficient $\tilde{\mathcal{R}}_{ud}$ weighting Δ_2^u, which is itself dominant over Δ_2^d. In particular $A_{FB}^{\rm pol}$ is around -7% for the η model, allowing us to get an interesting check of this important case.

A first conclusion for this class of models is that a simultaneous measurement of the three quantities $A_{FB}, A_{LR}, A_{FB}^{\rm pol}$ allows one to isolate some preferred regions in the parameter space. However, it is still true that a unique value of $\cos\beta$ cannot be determined without ambiguity in the general case.

Let us turn now to the case of general left-right models LRM's. We have displayed on Figs. 1–6 the various asymmetries as a function of the parameter α. Since now there is no null property of any coupling in general, we cannot get simplified formulas such as Eqs. (30), (34), (35). The only particular value of α is the one corresponding to the LRS (α maximum). In this case the positive value of A_{FB} is typical [1] but also the large and negative value of

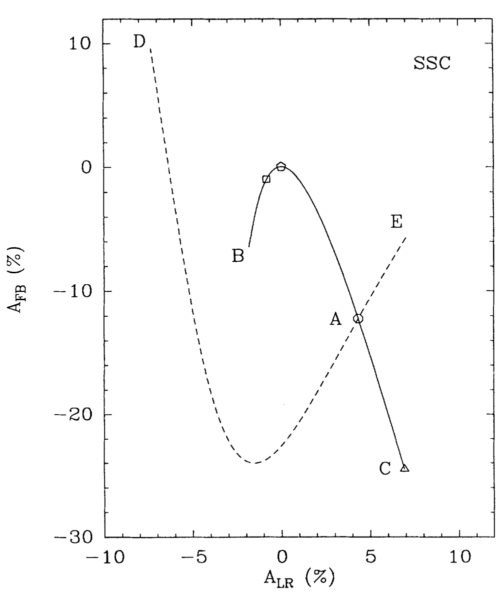

FIG. 7. A_{FB} vs A_{LR} for ER5M (solid curve) and LRM (dashed curve) at SSC for $M_{Z'}=1$ TeV. The points A,B,C,D,E are discussed in the text. On the ER5M curve the square corresponds to the η model, the pentagon to ψ, the circle to χ and the triangle to η_1.

A_{LR}. Conversely $A_{FB}^{\rm pol}$ is small and not so helpful.

We have tried to find if a combined analysis of two observables would allow us to separate the ER5M and LRM classes of models in the general case when $\cos\beta$ and α are allowed to vary in the whole domain. The best way is to plot A_{FB} vs A_{LR} as shown in Fig. 7 from which it is clear that this procedure allows us to fully discriminate between the two types of models (we have chosen to present the case $M_{Z'}=1$ TeV at the SSC; the results in the other cases are very similar). There remains only one intersection point (point A in Fig. 7) which corresponds to $\alpha=\sqrt{2/3}$ and $\cos\beta=\pm1$. On the "ER5M curve" in Fig. 7, $\cos\beta$ varies from -1 to -0.4 (from A to B) and from -0.4 to $\approx 0.79(\eta_1$ model) (from B to C) and finally from this last value to 1 (from C to A). One recovers here the already mentioned difficulty to isolate without ambiguity the precise value of $\cos\beta$. On the "LRM curve" α is maximum in D (the point corresponding to the LRSM which is clearly separated from the "ER5M curve," as expected) and minimum in E.

Finally, the interesting case of the ALRM deserves special attention. In this model the values of the three asymmetries at the SSC and LHC for $M_{Z'}=1$ TeV are

	SSC	LHC
A_{FB}	−20%	−21%
A_{LR}	−22%	−26%
$A_{FB}^{\rm pol}$	7.5%	8%

They are very close to these values for $M_{Z'}=2$ TeV. In this model, the coupling v'_d is quite small and the u terms are dominant, allowing us to write approximately the three asymmetries as

$$\begin{aligned} A_{FB}&\approx\frac{3}{4}\mathcal{A}'_\mu\mathcal{A}'_u\frac{\mathcal{L}_u^A}{\mathcal{L}_u^S}\ ,\\ A_{LR}&\approx\mathcal{A}'_u\frac{\Delta_1^u}{\mathcal{L}_u^S}\ ,\\ A_{FB}^{\rm pol}&\approx\mathcal{A}'_\mu\frac{\Delta_2^u}{\mathcal{L}_u^S}\ . \end{aligned} \tag{36}$$

It is instructive to compare first the ALRM and the LRSM. In the two cases, v'_u and a'_u get the same values but a'_μ (and not v'_μ) changes its sign in the ALRM (see Tables II–III). These properties explain why A_{FB} is negative, compared to the positive value obtained in the LRSM. However, as already noted in the literature [1], measuring A_{FB} is not sufficient to separate the ALRM from the ER5M since one can always find a value for $\cos\beta$ such that A_{FB}(ER5M)$=A_{FB}$(ALRM). The same situation occurs when one compares with the LRM when α is allowed to vary. However, it is completely different concerning the two spin-dependent asymmetries. First, A_{LR}(ALRM) is negative, which is also the case in some parts of the $\cos\beta$ and α domains, but now it is much larger in magnitude since it is essentially dominated by the u-quark polarization [see Eq. (36)] which is large in a polarized proton. For the same reason that A_{FB} changes sign, $A_{FB}^{\rm pol}$ is now positive compared to the LRSM and it reaches a relatively larger value than in any cases of ER5M or LRM models. For these reasons one can conclude that spin asymmetries are very relevant to isolate the ALRM.

V. CONCLUSIONS

In this paper we have shown that the measurement of polarization effects in pp collisions at very high energies could contribute to the analysis of some important questions of new physics beyond the standard model. The availability of polarized beams allows us to introduce new observables in addition to the well-known forward-backward asymmetry A_{FB}: A_{LR} and $A_{FB}^{\rm pol}$. This last quantity, to our knowledge, has never been considered before in the context of very-high-energy polarized pp physics (note, however, that the influence of right-handed currents on the angular distributions of lepton pairs produced with large transverse momentum in polarized hadronic collisions has been discussed in the past [41], but only at the energies of the CERN $p\bar{p}$ collider and of the Tevatron). Measurements of these three asymmetries give access to different combinations of the vector and axial-vector couplings of the Z' to quarks and leptons. To summarize, at the Z' peak, A_{FB} is essentially sensitive to the product of initial- and final-state couplings in $q_i\bar{q}_i \to Z' \to \mu^+\mu^-$ whereas A_{LR} is sensitive to the initial-state couplings and $A_{FB}^{\rm pol}$ to the final-state couplings. Strictly speaking, these behaviors are really observed in the framework of ER5M from E_6 where the situation is simplified by the nullity of the vector coupling of the Z' to the u quark, v_u'. Nevertheless, we have shown that combined measurements of some of these quantities could allow one to distinguish clearly between various classes of models whose theoretical origins are quite different. It is the case in particular if one compares the results for the alternative left-right-symmetric model [which comes from E_6 grand unified theories but corresponds to an extension of the SM by an SU(2) group] to the ER5M case [which is a $U(1)_\beta$ extension of the SM] or to general left-right models. Also, apart in a very restricted region of the parameter space, it will be possible to disentangle between ER5 and LR models without too much difficulty. Therefore, one could obtain at polarized supercolliders the same kind of information which could be extracted in principle from an e^+e^- collider such as LEP II (with polarized electrons) [7] but without being restricted to "light" Z' masses in the range of 300–500 GeV.

Let us stress again that the availability of polarized beams at future supercolliders would be an ambitious but very interesting program for such machines which will run for many years. It is clear that the implementation of polarization would influence the whole design of these machines, which means that it is not too early to analyze the interest of polarization for physics at such energies, and that it is a technical challenge. On the other hand, the very exciting polarized proton program at the RHIC, which is in a good way, shows that technical difficulties can be overcome. As shown elsewhere [22], various other manifestations of new physics could give large spin effects: right-handed W's, interactions between subconstituents involving a specific chiral structure, production of supersymmetric particles, etc. Therefore, we feel that in the very-high-energy domain where new phenomena could happen, some of them completely unexpected, the measurement of some spin-dependent quantities would be an important clue to the origin of new physics and that, in some sense, only polarization could allow for a full exploitation of the future supercolliders.

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