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**Abstract**

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# Beam polarization at LHC and SSC. Expected asymmetries in the Bess model and comparison with other models ☆

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In view of recent and foreseen technical advances in beam polarization in future proton colliders we discuss possible tests of non-standard physics at LHC and SSC assuming initial proton polarization, specifically to test for a strong electroweak sector and comparing with different extended gauge models. We examine lepton pair production, studying left–right and forward–backward asymmetries, assuming quark–antiquark and WW fusion production mechnisms. We discuss the uncertainties related to polarized proton structure functions.

## 1. Introduction

It is well known that polarization of the beams – when available – is an important complementary tool which gives access to new spin-dependent observable quantities. Until now, polarized proton–proton collisions have been restricted to fixed target experiments. However, recent technical progress in the acceleration of polarized protons [1,2] may well make possible to study spin effects in hadronic interactions with a much higher energy and also at high luminosity at the future generation of colliders.

These new possibilities have triggered an important activity both on the experimental and the theoretical side [2]. An option with polarized proton beams is very seriously considered at RHIC with $\sqrt{s}=50$–$500$ GeV and $\mathscr{L}=2\times10^{32}$ cm$^2$s$^{-1}$ [3,2] and various theoretical studies have been performed recently for example on spin asymmetries in jet or direct photon production [4].

Concerning the very high energy domain which is relevant at LHC and SSC, besides dedicated workshops [2,5], an extensive survey of the phenomenology of the spin effects at the future supercolliders has been performed [6] and it was found that large and meaningful spin asymmetries can be expected both according to the standard model and to various scenarios of new physics. In particular the interest of polarized beams in order to study the origin of new neutral gauge bosons has been recently emphasized [7].

In this note we shall mainly study inclusive lepton pair production in the high energy collision of a longitudinally polarized proton against another unpolarized proton, assuming as main production mechanisms quark–antiquark (Drell–Yan) or $W^+W^-$ (fusion) annihilation into the lepton pair.

We shall discuss the additional information one could obtain about a possible strong electroweak sector from

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the availability of polarized beams. The calculations will be performed using the BESS model [8] (Breaking the Electroweak Symmetry Strongly). Spin asymmetries different from those predicted by the standard model could be interpreted as manifestations of the strong sector, particularly in the case when unpolarized data were not sufficient to signal its possible presence. Bounds on the parameter space of BESS will depend on the assumed mass for the V-particles contained in the model, and of course on the experimental conditions (LHC and SSC energies and luminosities, experimental errors etc.)

The vector resonances (V-particles) of the BESS model are bound states of a strongly interacting sector. In this sense they are similar to ordinary ρ-mesons or to the techni-ρ particle of technicolor theories. The V-particles are expected to mix, due to their composite nature, to the photon and to the W and Z vector bosons. A non-trivial behaviour under the electromagnetic gauge group $U(1)_{em}$ is thus expected. Using this and the isotriplet character of the V's under the SU(2)-custodial group, one can easily construct the most general mixing of the V-particles with the ordinary vector bosons. The parameters of the model are $M_V$, the mass of the V particle ($V^0$ and $V^{\pm}$ are degenerate in mass if one neglects the electroweak couplings $g$, $g'$), and its gauge coupling $g''$. The standard model is formally recovered in the classical lagrangian in the limit $g''\to\infty$. The V-particles couple to the fermions through their mixing (of order $g/g''$) with the ordinary vector bosons. In addition, however, a direct coupling, described by a further parameter $b$, is possible. The complete list of couplings to fermions can be found in refs. [8,9]. The parameter space of the model is given by $(g, g', v, M_V, g'', b)$. We trade off $(g, g', v)$ for $(\alpha_{em}, G_F, m_Z)$ and we remain with $(M_V, g'', b)$. In turn, the parameter $v$ can be reexpressed in terms of $m_W$. The expression of $(g, g', m_W)$ in terms of $(\alpha_{em}, G_F, m_Z)$ can be found in ref. [9]. The limitations on the parameter space given by the most recent LEP and CDF data can be found in ref. [10].

For the Drell–Yang mechanism, which appears as dominant with respect to fusion, in the cases we consider, we have employed different sets of structure functions. Of course, polarized quark and antiquark distribution functions are essential quantities in the calculation of any polarization asymmetry. Our knowledge of these distributions is presently incomplete and also the situation after the striking EMC results will have to be clarified [11]. Hopefully, forthcoming deep inelastic scattering experiments with a polarized lepton beam on a polarized proton or deuteron target and future results from polarized RHIC should improve our knowledge [12]. In fact, it can be advocated [6,13] that at the supercolliders themselves, with polarized beams, the asymmetries for the very copious, well known standard electroweak processes would allow to perform a "calibration" of the spin-dependent partonic distributions.

In the case in which unpolarized data have already indicated at some mass a bump in the invariant lepton pair mass, polarized asymmetries would be useful to distinguish among the various models with additional vector bosons, including BESS. We shall compare BESS, two E6 models, and a LR model, also studying the effect of combining left–right asymmetries measurements with unpolarized forward–backward asymmetry. We shall also comment on production of $\ell^{\pm}\nu$ and WZ pairs with polarized beams, and on its possible use to distinguish among models.

## 2. The left–right asymmetry

Lepton pair production by very high energy proton–proton collisions could test BESS in two different situations:

(a) A massive vector boson V has not been discovered in the analogous process with unpolarized beams. This could happen, for example, if the experimental mass resolution is larger than the resonance width. In this case an appreciable difference with respect to the standard model predictions for the spin asymmetries could signal the existence of a strongly interacting sector, or of other possibilities, which will have to be quantitatively compared with data.

(b) In the invariant mass distribution of the $\ell^+\ell^-$ pair in the process $pp\to\ell^+\ell^-X$, where both protons are unpolarized, a resonance has been discovered at $\sqrt{M^2}=\sqrt{s\tau}=M_V$ (alternatively one could have discovered a bump in the lepton transverse momentum distribution for the process $pp\to\ell\nu X$). In this case, but also in the previous one (a), it would still be necessary to discriminate among different models predicting new vector bosons.

We shall mainly discuss the process

$$\vec{p}_1 p_2 \to \ell^+ \ell^- X \,, \tag{1}$$

where $\vec{p}_1$ is a longitudinally polarized proton. The other processes relevant in this context will be examined later on. We distinguish two different subprocesses leading to $\ell^+\ell^-$ in the final state: $q\bar{q}\to\ell^+\ell^-$ (hereafter denoted as Drell–Yan) and $W^+W^-\to\ell^+\ell^-$ (fusion). The left–right asymmetry $A_{LR}$ is defined as

$$A_{LR} = \frac{d\sigma(-) - d\sigma(+)}{d\sigma(-) + d\sigma(+)} \equiv \frac{d\Delta\sigma}{d\sigma} \,, \tag{2}$$

where $d\sigma(+)$ $(d\sigma(-))$ corresponds to a positive (negative) longitudinally polarized proton beam. The contribution of the Drell–Yan mechanism to the numerator (which we denote $\Delta\sigma^{DY}$) and the denominator ($\sigma^{DY}$) of (2) can be computed using factorization. One gets

$$\frac{d\Delta\sigma^{DY}}{dM^2\,dy} = \frac{4\pi\alpha^2 M^2}{9s} \sum_q G_1' [f^{\bar{q}}(x_2)\, \delta f^q(x_1) - (q \leftrightarrow \bar{q})] \,, \tag{3}$$

$$\frac{d\sigma^{DY}}{dM^2\,dy} = \frac{4\pi\alpha^2 M^2}{9s} \sum_q G_1 [f^{\bar{q}}(x_2) f^q(x_1) + (q \leftrightarrow \bar{q})] \,, \tag{4}$$

where $x_1\sqrt{\tau}\,e^y$, $x_2=\sqrt{\tau}\,e^{-y}$, $M$ is the lepton pair invariant mass and $y$ is the rapidity; $f(x)$ and $\delta f(x)$ are unpolarized and polarized proton structure functions that we shall discuss below. More precisely $\delta f^q(x) = f^{q(+)}(x) - f^{q(-)}(x)$, where $f^{q(+)}$ $(f^{q(-)})$ are the helicity distributions parallel (antiparallel) to the proton helicity. $G_1$ and $G_1'$ are as follows:

$$G_1 = \frac{e_q^2 e_\ell^2}{M^4} + \sum_{j=V,Z} \left( D_j(M^2) [(a_\ell^j)^2 + (b_\ell^j)^2][(a_q^j)^2 + (b_q^j)^2] + 2 e_\ell e_q a_q^j a_\ell^j \frac{M^2 - M_j^2}{M^2} D_j(M^2) \right)$$
$$+ 2(a_\ell^V a_\ell^Z + b_\ell^V b_\ell^Z)(a_q^V a_q^Z + b_q^V b_q^Z) D_Z(M^2) D_V(M^2) [(M^2 - M_V^2)(M^2 - M_Z^2) + M_V M_Z \Gamma_V \Gamma_Z] \,, \tag{5}$$

$$G_1' = \sum_{j=V,Z} \left( 2 a_q^j b_q^j [(a_\ell^j)^2 + (b_\ell^j)^2] D_j(M^2) + 2 e_\ell e_q a_\ell^j b_q^j \frac{M^2 - M_j^2}{M^2} \right)$$
$$+ 2(a_\ell^V a_\ell^Z + b_\ell^V b_\ell^Z)(a_q^Z b_q^V + a_q^V b_q^Z) D_Z(M^2) D_V(M^2) [(M^2 - M_V^2)(M^2 - M_Z^2) + M_V M_Z \Gamma_V \Gamma_Z] \,.$$

In eq. (5) $D_j(M^2)$ are related to the propagator of the vector mesons $j=V$, Z:

$$D_j(M^2) = \frac{1}{(M^2 - M_j^2)^2 + M_j^2 \Gamma_j^2} \,, \tag{6}$$

$M_j$ and $\Gamma_j$ are the mass and full width of the vector mesons; $a_q^j$ and $b_q^j$ ($a_\ell^j$ and $b_\ell^j$) are the vector and axial-vector couplings to quarks (to leptons): $\bar{q}\gamma^\mu(a - b\gamma_5)q$.

Let us briefly discuss the proton structure functions we use in (3) and (4). We employ unpolarized structure functions as given in ref. [14], which provide a description of deep inelastic scattering on unpolarized target which is sufficiently accurate for our purposes. As for polarized partonic densities, we mainly use the parametrization of ref. [15], hereafter denoted as CN, which implements positivity constraints, Regge behaviour for $x\to 0$, quark counting rules for $x\to 1$, the $U(1)_A$ Goldberger–Treiman relation, and is in agreement with EMC and SLAC data [11,16]. Both sets of structure functions are computed at a particular value of $Q^2$ and then evoluted according to Altarelli–Parisi equations [17]. We have also considered two other parametrizations for the structure functions. The first one (BSRT) uses polarized parton densities as given in ref. [6] and unpolarized densities of ref. [18], the latter being compatible with those; the second one (AS) is based on polarized densities of ref. [19] and unpolarized structure functions of ref. [20]. We shall discuss the uncertainties introduced by the use of different sets of structure functions later on.

## 3. The fusion process

In order to complete the analysis we now discuss the fusion subprocesses. Their contribution can be computed in the so-called effective W approximation, according to which one writes (for a discussion see refs. [6,21] and references therein) in a shorthand notation:

$$\frac{d\Delta\sigma^F}{dM^2\,dy}=\frac{2}{s}\sum_{i,j=0,\pm} f_{W_j/P}(x_2)\,\delta f_{W_i/P}(x_1)\sigma(W_iW_j)\,,\quad \frac{d\sigma^F}{dM^2\,dy}=\frac{2}{s}\sum_{i,j=0,\pm} f_{W_j/P}(x_2) f_{W_i/P}(x_1)\sigma(W_iW_j)\,, \tag{7}$$

where $\sigma(W_iW_j)$ are cross sections for the subprocesses $W_iW_j\to e^+e^-$; $i$ and $j$ refer to the three polarization states of W. The W distribution functions inside the proton are as follows:

$$f_{W_j/P}(x)=\sum_q \int_x^1 \frac{dy}{y} f_{W_j/q}\left(\frac{x}{y}\right) f^q(y)\,,\quad \delta f_{W_j/P}(x)=\sum_q \int_x^1 \delta f_{W_j/q}\left(\frac{x}{y}\right)\delta f^q(y)\,. \tag{8}$$

The vector boson distributions inside the quarks, which appear in eq. (8), are

$$f_{W\pm/q}(x)=\frac{\alpha}{4\pi}\frac{L}{x}\left[(a_q\pm b_q)^2+(1-x)^2(a_q\mp b_q)^2\right]\,,\quad f_{W0/q}(x)=\frac{\alpha}{\pi}\frac{1-x}{x}(b_q^2+a_q^2)\,,$$

$$\delta f_{W\pm/q}(x)=\pm\frac{\alpha}{4\pi}\frac{L}{x}\left[(a_q\pm b_q)^2-(1-x)^2(a_q\mp b_q)^2\right]\,,\quad \delta f_{W0/q}(x)=\frac{\alpha}{\pi}\frac{1-x}{x}2b_q a_q\,, \tag{9}$$

where $\alpha$ is the fine structure constant, $a_q$ and $b_q$ describe the coupling to fermions: $\bar{q}\gamma^\mu(a_q-b_q\gamma_5)q$ ($b_q=a_q$ for W), and $L=\ln(sx^2/M_W^2)$. We note the presence in (9) of the depressing factor $\alpha/\pi$, which should render the contribution of fusion diagrams small in average. We have explicitly checked that this is what happens in our case, where the relative contributions from fusion, as compared to Drell–Yan, is roughly $10^{-2}$ or less to both numerator and denominator in (2) at LHC, and less than 10% at SSC.

## 4. Numerical results

Let us now discuss our results. First we consider the integrated left–right asymmetry, which is obtained by integrating numerator and denominator of (2) in $y$ and around the resonance peak assuming a mass resolution of the calorimeter of 20 GeV [22],

$$A_{LR}^I=\Delta\sigma^I/\sigma^I\,, \tag{10}$$

where

$$\Delta\sigma^I=\int_{M_V-R}^{M_V+R} dM^2 \int_{-\ln\sqrt{s}/M_V}^{\ln\sqrt{s}/M_V} dy\frac{d\Delta\sigma}{dM^2\,dy}\,,\quad \sigma^I=\int_{M_V-R}^{M_V+R} dM^2 \int_{-\ln\sqrt{s}/M_V}^{\ln\sqrt{s}/M_V} dy\frac{d\sigma}{dM^2\,dy}\,. \tag{11}$$

If the $V^0$ width is smaller than the calorimeter resolution the peak contribution to (10) is computed according to the narrow width approximation.

In order to get bounds in the parameter space of the BESS model we plot in fig. 1 the 90% confidence level

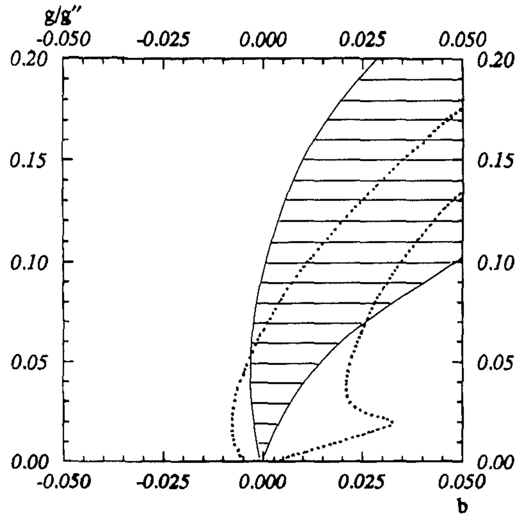


Fig. 1. 90% CL contour in the plane $(b, g/g'')$ for $M_V = 500$ GeV, from left–right asymmetry (continuous line) and present LEP data (dotted line).

Table 1
Left–right asymmetry (in %) for two sets of BESS parameters: BESS1 ($b = -5\times10^{-3}$, $g/g'' = 0.032$) and BESS2 ($b = 0.025$, $g/g'' = 0.10$), using three choices of structure functions: Chiappetta-Nardulli (CN), Bourrely et al. (BSRT) and Altarelli–Stirling (AS).

| Structure function | BESS1 | BESS2 |
|---|---|---|
| CN | 11.74 | 2.49 |
| BSRT | 12.87 | 2.40 |
| AS | 8.1 | 1.25 |

region for $M_V = 500$ GeV at LHC (assuming an integrated luminosity of $10^5$ pb$^{-1}$, which is certainly optimistic for polarized beams). We have considered only the statistical error on the asymmetry:

$$\delta A^{\mathrm{l}}_{\mathrm{LR}} = 2\left(\frac{N_+ N_-}{(N_+ + N_-)^3}\right)^{1/2}, \tag{12}$$

where $N_+$ $(N_-)$ is the expected number of events with positively (negatively) longitudinally polarized protons. Polarization will improve the present LEP bounds since, using left–right asymmetry, the region corresponding to negative $b$ values will be quite completely excluded if no deviation from the standard model is seen. Also an additional region will be excluded for positive $b$, as can be seen in fig. 1. For larger $V^0$ masses, or at SSC energy assuming an integrated luminosity of $10^4$ pb$^{-1}$, the restrictions on parameter space are less severe than the existing limits [23]. The dependence of these results on the choice of polarized parton densities is shown in table 1 for $M_V = 500$ GeV and for two illustrative BESS parameter values: $(g/g'', b) = (0.032, -0.005)$, here denoted as BESS1, and (0.10, 0.025) denoted as BESS2. BSRT and CN sets give very close results (differing by less than 10%), whereas AS parametrization leads to smaller polarized asymmetries. This is due to the fact that AS quark structure functions carry less proton spin than the previous sets and the contribution of gluons is more relevant.

## 5. Comparison of models

A different analysis could be done by assuming that in pp collisions with unpolarized beams a bump has already been seen in the lepton pair invariant mass distribution at some $M_V$ mass. Under these circumstances some light could be shed on the underlying mechanism by use of polarized beams, which would allow to discriminate among different models predicting extra neutral vector bosons. In figs. 2 and 3 we report integrated asymmetries for several $V^0$ masses and different theoretical models for both LHC and SSC. We consider the BESS model for two different choices of the parameters $b$ and $g/g''$, two E6 models (obtained from the general case by specializing the mixing angle $\theta_2$ as defined in ref. [24]: the so-called $\chi$ model, having $\theta_2 = 52.24°$, and the $\eta$

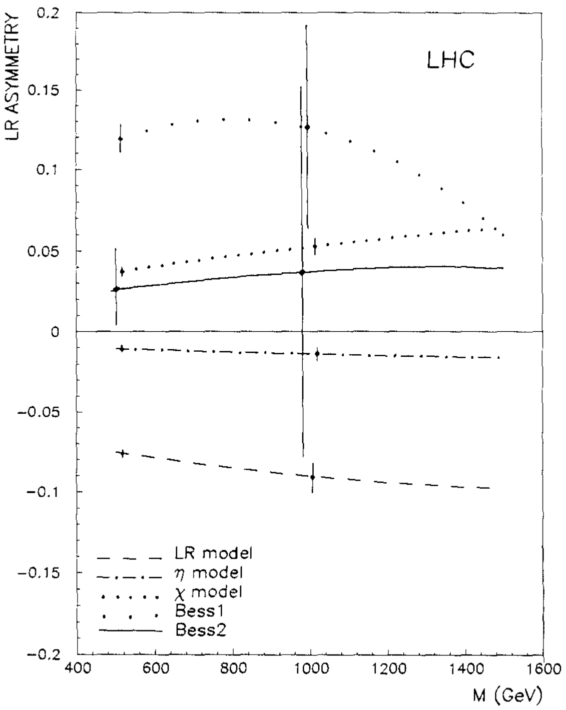


Fig. 2. Left–right asymmetry versus vector boson mass for BESS, χ, η, and LR model at LHC assuming an integrated luminosity of $10^5$ pb$^{-1}$. Only statistical errors have been included.

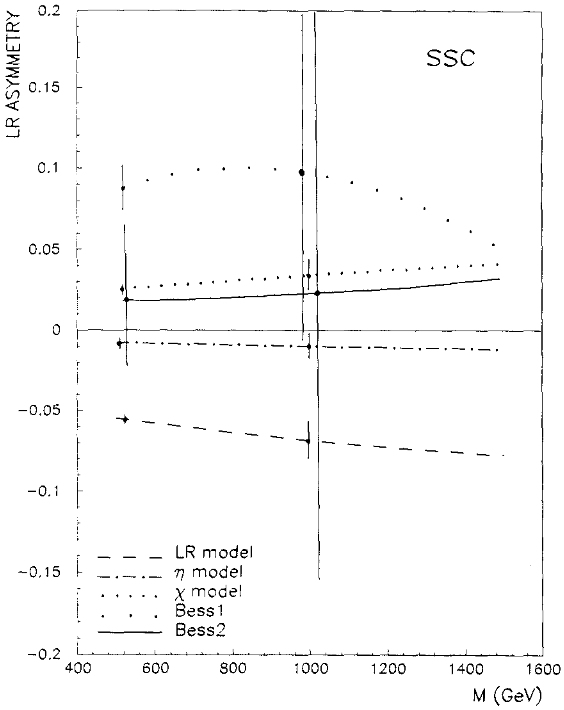


Fig. 3. Left–right asymmetry versus vector boson mass for BESS, χ, η, and LR model at SSC assuming an integrated luminosity of $10^4$ pb$^{-1}$. Only statistical errors have been included.

model, with $\theta_2=0°$), and the left–right model with discrete left–right symmetry ($g_R=g_L$). We see that BESS1 can be clearly discriminated from all the other models for moderate values of $M_{V^0}$, but its predictions become similar to those of the χ model for larger mass values. The η model and the LR model have negative asymmetries, whereas BESS and the χ model have positive values; for some values of the parameters (e.g. BESS2) the BESS model is hardly distinguishable from the χ model. Due to large statistical errors it will be very hard to distinguish BESS from other models for masses of the $V^0$ larger than 1 TeV. According to the philosphy of refs. [7,25], we shall show that a combined measurement of left–right asymmetry and unpolarized forward–backward asymmetry would allow to distinguish clearly among BESS and other models of different origin. This is done in figs. 4 and 5 at LHC and SSC energies where the BESS domain, as derived from LEP bounds (see fig. 1), lies always in the upper right quadrant of the ($A_{LR}$, $A_{FB}$) plane and is always distinguishable from the η, χ and LR models. These conclusions remain valid if we consider all classes of E6 and LR models as can be inferred from fig. 7 of ref. [7]. Polarized forward–backward asymmetry will not add complementary information.

Concerning $V^\pm$ bosons, the leptonic channel, i.e. $pp\to V^\pm\to \ell^\pm\nu$ is not an interesting one for two reasons. Firstly, the unpolarized cross section is dominated by background from top and inclusive W production. Secondly, polarization would not allow to distinguish $V^\pm$ from $W^\pm$ by measurement of integrated LR asymmetry alone, since the coupling is of the same $\gamma^\mu(1-\gamma_5)$ type. Such polarization measurement would be useful to discriminate between a left-handed W and a right-handed W. As for WZ final state, LHC and SSC colliders have been shown to be very efficient to detect a $V^\pm$ resonance up to masses of 2–2.5 TeV through this final state [26]. However, in the case of polarized beams, left–right asymmetry could allow to distinguish a $V^\pm$- from a $W_R$-boson [27] in the kinematical region where the Drell–Yan subprocess dominates, whereas, for production ini-

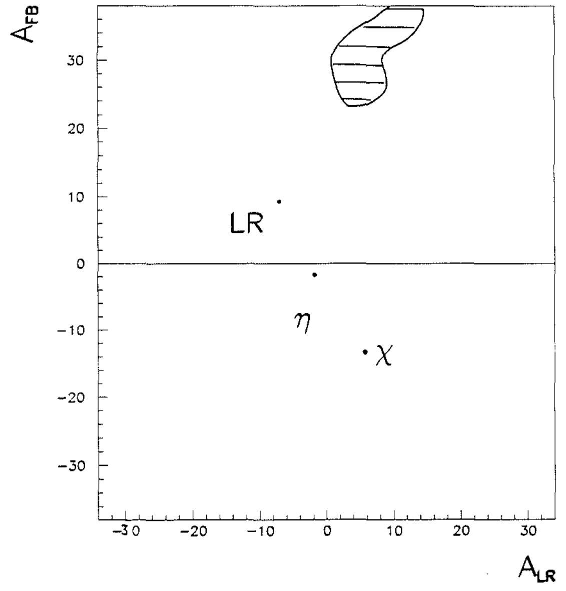


Fig. 4. Unpolarized forward–backward asymmetry versus left–right asymmetry (in %) at LHC for $M_V = 500$ GeV. The shaded area corresponds to BESS model for parameter values compatible with LEP data.

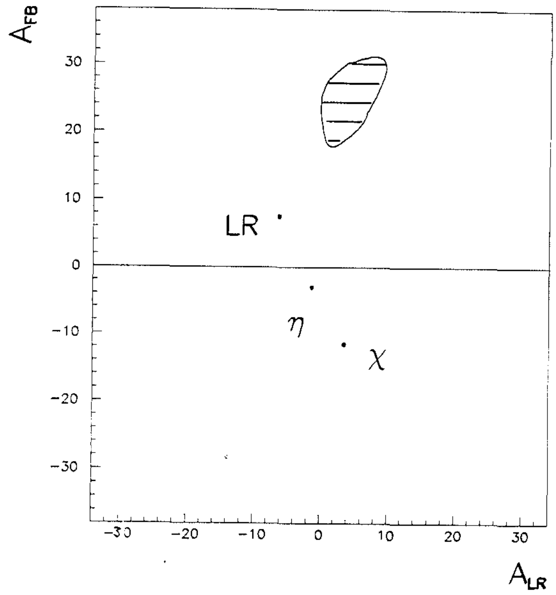


Fig. 5. Same as in fig. 4 at SSC.

tiated by fusion, $A_{LR}$ is less useful since it would reflect the couplings of quarks to W and not the BESS model interaction.

## 6. Conclusions and outlook

In view of growing interest on spin effects, as triggered by recent technical progress and ideas in accelerating polarized protons, we have performed a study of some possible non-standard model effects in the high energy domain (LHC and SSC). Although our study is based on great optimism concerning the experimental possibilities that may become available in a reasonable future, we feel that the present discussion could stimulate further thinking both at the technical and at the physical level.

Our principal interest has been in examining what additional information could be provided by polarized beams in exploring a possible strongly interacting electroweak sector. We have performed the calculations within the BESS model and considered both $q\bar{q}$ processes and WW fusion. Both LHC and SSC energies and luminosities have been considered.

It appears from the calculations that the study of LR asymmetry with a polarized proton beam would improve on the best existing bounds (from LEP) on the BESS parameter space, or, said otherwise, increase the detectability region, if the resonant vector particles V of BESS are low in mass (say 500 GeV). On the other hand for larger masses the improvement seems less substantial.

In the case, instead, where evidence of the resonance were supposed to be already available at the time of experimenting, then the availability of a polarized proton beam would be useful to distinguish among models, that is BESS and various unified models with extra gauge bosons, of E6 or LR character. Again it appears that the discrimination on the basis of left–right asymmetry may become less clear for larger vector boson masses (especially between BESS with certain values of parameters and the so called $\chi$ model). In order to make a clear discrimination it is useful to add information from the unpolarized forward–backward asymmetry.

Our conclusions are essentially for final lepton–antilepton pair production. We find the final lepton–neutrino or WZ channels are less interesting, except perhaps for distinguishing from right-handed gauge bosons.

We have everywhere taken only statistical errors into account; however, needless to say, our assumptions about the reachable polarized luminosities are probably optimistic.

Also among the three sets of structure functions we use, one set leads to substantially different figures (factors of two). However, at the time when such experiments will be done there will already exist better tested sets of structure functions for polarized protons so that such ambiguity will be definitely reduced.

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