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A B S T R A C T

Assuming that polarized beams will be available at future super-colliders, we review some recent studies showing the relevance of spin effects in very highly energetic proton-proton or electron-positron collisions.

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ABSTRACT

Assuming that polarized beams will be available at future supercolliders, we review some recent studies showing the relevance of spin effects in very highly energetic proton-proton or electron-positron collisions.

INTRODUCTION

Serious projects of very high energy machines are now developing. Chances are high to see built the so-called proton-proton supercolliders in the next decade: the SSC project in the United States¹ with an energy of 20 TeV per beam and a luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, the LHC, to be hosted in the LEP tunnel² (8 TeV or so per beam and perhaps a higher luminosity) and the UNK-3³ project at Serpukhov (3 TeV per beam). Concerning the e^+e^- machines, the design of linear colliders in the 0.5 to 2 TeV range is under study²⁻⁵: TLC at SLAC, CLIC at CERN and VLEPP in USSR.

The goal of these machines is the study of physics at the energy scale of about 1 TeV (in the e^+e^- or in the parton-parton centre of mass), a scale which defines the frontier of our ignorance on which new phenomena must occur. Indeed, in spite of the present success of the Standard Model (SM), many fundamental questions have not been answered yet: in particular, a deeper understanding of the symmetry breaking sector is necessary and the scale of 1 TeV is precisely a bound for the Higgs mass. There are also strong motivations, which have been reviewed in many places^{6,7}, to expect some manifestations of new physics around this scale. One may think of new gauge bosons, supersymmetry, compositeness... In the case of unpolarized beams, many phenomenological studies have been devoted to the physics at future pp ^{5,7} and e^+e^- ^{4,5} machines. Since we know that polarization gives access to new observables and that it was shown to be a very powerful tool of analysis at lower energies, it is natural to ask whether spin effects will be important in this new energy range and whether physics will require polarized beams in these new machines. As regards the multi-TeV proton-proton colliders, these questions have been studied in great detail by Bourrely et al.⁸ (referred below as BRST) and we will select here a few topics showing the interest of spin measurements. We will discuss later some aspects of polarized e^+e^- physics in the TeV domain.

Ia pp COLLISIONS: SPIN EFFECTS IN THE STANDARD MODEL

At high energy, a proton beam is an unseparated beam of constituent partons and all fundamental interactions involve the collisions of quarks and gluons at short distances. Typical hadronic cross-sections will be of the order of lpb (10^{-36} cm²) or less, and it is often emphasized that a very high luminosity (10^{33} - 10^{34} cm⁻²s⁻¹) ^{5,1} is needed, along with very energetic proton beams, to get a reasonable number of events. The ingredients entering into any cross-section calculation for a hard-scattering process between a parton i and a parton j are: - the elementary cross-sections σ_{ij} which are calculable in perturbation theory, at least at first order; - the parton distributions $f_i(x, Q^2)$ extracted from deep-inelastic scattering experiments and evolved, according to QCD, up to a scale Q^2 which is defined in terms of the invariants of the subprocess. At supercolliders the relevant range of kinematical variables is enormous: $10^2 < Q^2 < 10^8$ GeV² and $10^{-4} < x < 10^{-1}$. As Q^2 increases, there are more and more partons at low x , consequently a determination of parton distributions in this region, which is not probed by present experiments, will be crucial for future phenomenological studies.

In the case of longitudinally polarized proton beams, one can define correspondingly polarized distributions f^+ and f^- in a polarized proton, with helicity parallel (+) or antiparallel (-) to the parent proton helicity. The various parton helicity asymmetries are defined as usual by the differences $\Delta f_i = f_i^+ - f_i^-$. To calculate a (single A_L or double A_{LL}) helicity asymmetry at the proton level, one has to convolute the corresponding subprocess asymmetry ($\hat{a}_L$ or $\hat{a}_{LL}$) with one or two $\Delta f_i(x, Q^2)$. Examples are given below.

Quark helicity asymmetries, $\Delta q_i(x, Q^2)$, and the corresponding quantities for gluons, $\Delta G(x, Q^2)$, are present in any calculation. Our knowledge of these distributions is presently incomplete, especially at very high Q^2 and very small x values. For illustration we have chosen a set of polarized parton distributions obtained in terms of simple analytic parametrization of their x and Q^2 dependences⁹. With this choice, quarks, gluons and the sea carry respectively 75%, 20% and 5% of the proton spin. This is perhaps a "conservative" parametrization in view of the recent results of the EMC experiment¹⁰, whose interpretation is still controversial¹¹. Clearly, the magnitude of any spin effect is dependent of this input and one may hope that better information will be obtained by future experiments.

As a first example of standard process, consider the case of hadronic jet production

$$P_a + P_b \rightarrow \text{jet} + X \quad (1)$$

which will be extremely copious at SSC since one expects about one event per second yielding at least one jet with $p_T > 1$ TeV/c! This process will constitute the main source of conventional background to new physics. It is a parity-conserving process and only the double helicity asymmetry A_{LL} defined as

$$A_{LL} = \frac{d\sigma_{a(+)b(+)} - d\sigma_{a(+)b(-)}}{d\sigma_{a(+)b(+)} + d\sigma_{a(+)b(-)}} \quad (2)$$

will be different from zero. It is given by

$$A_{LL} \cdot d\sigma = \sum_{i,j} \frac{1}{1+\delta_{ij}} \int dx_a dx_b [\Delta f_i^{(a)}(x_a, Q^2) \Delta f_j^{(b)}(x_b, Q^2) + (i \leftrightarrow j)] \hat{a}_{LL}^{ij} \cdot d\hat{\sigma}_{ij} \quad (3)$$

$d\hat{\sigma}_{ij}$ and $\hat{a}_{LL}^{ij}$ are known from perturbative QCD, the $\hat{a}_{LL}^{ij}$ are positive for the dominant subprocesses and they are twice diluted in the calculation of A_{LL} due to the presence of two Δf_i . Consequently, A_{LL} is small and positive as shown in Fig. 1.

Fig. 1. A_{LL} in $pp \rightarrow \text{jet} + X$ at zero rapidity, versus p_T for three different centre-of-mass energies.

We will get larger single spin asymmetries

$$A_L = \frac{d\sigma_{a(-)b} - d\sigma_{a(+)b}}{d\sigma_{a(-)b} + d\sigma_{a(+)b}} \quad (4)$$

in the study of standard electroweak processes where parity is violated. Consider the case of single W^+ or W^- production which can be computed directly in terms of the dominant quark-antiquark fusion reactions $u\bar{d} \rightarrow W^+$ and $\bar{u}d \rightarrow W^-$. At SSC one will be able to produce every second about 200 $W^\pm$'s (and 60 Z^0 's), so these impressive production rates will be also of great interest because the standard production mechanism being known, they will allow for a precise calibration of the parton distributions. In the polarized case, since the W is a pure left-handed current, the single spin subprocess asymmetry $\hat{a}_L = 100\%$ and, after dilution, one gets the large observable asymmetries displayed in Fig. 2 as a function of the centre-of-mass energy $\sqrt{s}$.

Fig. 2. A_L in $pp \rightarrow W^+ + X$ and $pp \rightarrow W^- + X$.

A careful study of the rapidity dependence of these asymmetries⁸ would allow us to extract some information on $\Delta u(x)$ and $\Delta d(x)$.

Moreover, still due to chirality properties of the W, reactions dominated by the subprocess

$$q_1 \bar{q}_j \rightarrow W^\pm(M) \rightarrow \text{any state} \quad (5)$$

will exhibit universal asymmetries displayed in Fig. 3 where M is the invariant mass of the produced particles. Examples of such reactions are $pp \rightarrow W^\pm \gamma$, $W^\pm Z^0$, $W^\pm H^0$.

Fig. 3. Universal asymmetries for reaction (5) at three different energies.

Studies of A_L for other electroweak processes: lepton pair production, $W^\pm + \text{jet}$, production of $Z^0 Z^0$ or $Z^0 \gamma$, have been performed in BRST.

The case of $W^+ W^-$ pair production (1000 pairs per day at SSC) deserves special attention because, due to the presence of the triple gauge boson vertex, this reaction is a laboratory to test the structure of the SM. We show in Fig. 4 the single spin asymmetry one gets in this reaction using the standard value $g_Z = \cot \theta_W$ for the ZWW coupling, together with the resulting A_L in the absence of this coupling, i.e., $g_Z = 0$.

Fig. 4. A_L for $W^+ W^-$ pairs produced with an invariant mass M .

Ib pp COLLISIONS: BEYOND THE STANDARD MODEL

First, one can think of minimal extensions of the SM such as left-right symmetric models¹² where parity violation is considered as a "low energy" phenomenon. These models imply the existence of massive right-handed W 's and A_L for the production of a W_R^+ or W_R^- of mass M can be read from the universal curves of Fig. 3 with a change of sign in each case coming from the change of sign of the axial coupling. Other interesting cases like charged Higgses $H^\pm$ production, pair production of heavy leptons or other new gauge boson production have been treated in BRST.

Second, one can search for the consequences of compositeness. The proliferation of quarks and leptons has inspired the speculation that they are composite structures and many models have been built¹³ in which the constituents could interact by means of a new interaction whose chirality structure is arbitrary: in particular there is no reason to assume that this new interaction will conserve parity. Usually compositeness effects are taken into account by assuming the existence of an effective four-fermion amplitude normalized to a

certain compositeness scale Λ . For example, a contact interaction would produce an additional yield in the p_T distribution of a single outgoing jet or direct photon (at SSC energies, cross-section studies will be sensitive to Λ up to 10-20 TeV depending upon the process⁷). If this new contact interaction is handed, the consequence will be dramatic for such hard processes: A_L is no longer zero, as can be seen in Fig. 5, for single-jet production according to QCD + left-handed contact interaction.

Fig. 5. A_L in $pp \rightarrow \text{jet} + \text{anything}$ at $\sqrt{s} = 10$ TeV and $y = 0$, with different values of the left-handed contact interaction scale Λ .

Such effects can also be observed in direct photon or in Drell-Yan lepton pair production⁸ where one can see that polarization would increase notably the sensitivity to the presence of compositeness, allowing also to obtain a unique information on the chirality structure of a new interaction. In addition, compositeness could manifest itself through anomalous behaviours in gauge boson pair production. In particular, introducing anomalous magnetic moments in the coupling of the W to γ and Z changes drastically the pattern of Fig. 4⁸. Other particles like an isoscalar vector boson Y, excited W's or Z's, or particles predicted by technicolour would show up as new bumps in the cross-sections and polarization would help to disentangle the various possibilities.

Other exotic particles are those predicted by supersymmetric (SUSY) theories¹⁴. SUSY partners of ordinary particles differ from them by half unit of spin, hence their production with polarized beams should present different polarization asymmetries. Moreover in much models the production of SUSY particles is characterized by missing energy-momentum events due to the escaping photinos: here also polarization will be very useful because such events are always difficult to interpret! For example, in the strong sector, scalar

quarks and gluinos will be copiously produced at supercolliders even if they are quite massive^{6,7}, leading to a signature of jets plus missing energy. Since parity is conserved in this strong process, we are concerned only with double helicity asymmetries A_{LL} . For the subprocesses where a pair of SUSY particles is produced in the final state, the $\hat{a}_{LL}^{ij}$ are all -100% in the limit of massless squarks and gluinos¹⁵, due to helicity conservation. This gives a corresponding A_{LL} , displayed in Fig. 6., which is now negative and larger in magnitude than in the standard case (Fig. 1), and this pattern survives mass effects⁸.

Fig. 6. A_{LL} in the production of one strongly interacting SUSY particle at $y = 0$, versus p_T , for three different energies.

Interesting effects have also been obtained in BRST for the super-electroweak sector in the production of scalar leptons and of the spin $\frac{1}{2}$ partners of the gauge bosons. In conclusion for SUSY, let us stress that the best signature for SUSY events is missing energy associated to a specific polarization asymmetry.

II ELECTRON-POSITRON COLLISIONS

Proton-proton and e^+e^- colliders will play different and complementary rôles in the exploration of the TeV domain. Proton-proton colliders will be very useful for exploratory searches but only the availability of e^+e^- machines will allow to perform very precise measurements. Concerning spin effects, it seems that there will be no major difficulties to maintain a substantial polarization through the beam transport and collision process at a linear e^+e^- collider and a recent report⁴ shows that the e^+e^- physics community is already aware that "...one should plan for polarization as an integral part of the collider design..." because polarization will be an essential tool in the study of the e^+e^- reaction in the TeV regime. We stress below a few aspects of this physics.

First, all e^+e^- annihilation reactions have some dependence on beam polarization due to the interference between the virtual γ and Z^0 contributions and, since above 200 GeV weak interactions contribute as strongly as the electromagnetic interactions, one expects large polarization effects. Indeed, far above thresholds the values of the single helicity asymmetry A_L (often denoted A_{LR} or A_{pol}) are respectively 7% for $e^+e^- \rightarrow \ell^+\ell^-$, 15% for $\nu\bar{\nu}$, 34% for $u\bar{u}$, $c\bar{c}$, $t\bar{t}$, 62% for $d\bar{d}$, $s\bar{s}$, $b\bar{b}$, 32% for $e^+e^- \rightarrow Z^0Z^0$, and 94% for $e^+e^- \rightarrow W^+W^-$. These numbers are now quantitative predictions⁴ and each prediction constitutes a test of the SM. In particular the last reaction, $e^+e^- \rightarrow W^+W^-$, has an exceptionally large polarization dependence since the cross-section falls by a factor of 30 when one switches from e_L^- to e_R^- . Hence, very sensitive studies of the well-known vertices may be performed¹⁶ and also, if W^+W^- production becomes a standard background to new processes, it can be essentially eliminated by adjusting the electron helicity.

Beyond the SM, measurements of spin effects will be an important clue to the origin of new physics. Consider for example the appearance of a new boson Z' expected in many theoretical speculations on grand unification or superstring-inspired models¹⁷. Obviously, this Z' would show up as a new peak in the e^+e^- cross-section, but even away from the resonance it will have significant effects on A_L as can be seen from Figs. 7.

Fig. 7. A_L for the production of μ , b and t pairs in the SM (left) and including the effects of a Z' of mass 600 GeV/c² (right) (from Ref. 4).

Careful studies of A_L (and also of A_{FB}) would allow us to extract the couplings of the Z' to the various fermions.

Moreover, polarization extends in some sense the energy reach of an e^+e^- collider: as already emphasized at LEP/SLC energies¹⁸, precise measurements of A_L at some energy allow us to get an insight on physics at higher energies, thanks to virtual effects. For example, if $\delta A_L = 1\%$, any Z' below 4 TeV would produce visible effects⁴. Polarization would allow us also to push higher the scale of compositeness⁶ and of course typical asymmetries are expected in the

production of SUSY particles^{4,19} where both transverse and longitudinal polarizations may be interesting as already emphasized at LEP/SLC energies²⁰.

III VECTOR BOSON-VECTOR BOSON COLLISIONS

A new class of collision processes will be provided by very high energy e^+e^- and also pp colliders: quasi-real vector boson-vector boson collisions which generalize the well-known $\gamma\gamma$ processes. These processes have been studied extensively in the polarized case²¹. An interesting illustration is provided by WW fusion into a Higgs boson $W^+W^- \rightarrow H^0$ where the W's are coming from e^+e^- (or quark) lines, a production process which is dominant for a large range of values for the mass of a heavy Higgs. In this reaction, A_L is typical of $W^\pm$ exchange, i.e., 100% in e^+e^- collisions and substantial at pp colliders²¹. This could help to isolate this process from the background.

CONCLUSION

With a few illustrations we have tried to show the interest of polarization for physics in a very high energy domain. Let us mention for completeness the exciting possibilities of polarized e-p collisions at LEP/LHC, upgrading up to 1.8 TeV the energy range of HERA²². In this case, like in pp and e^+e^- collisions discussed above, we are convinced that only polarized beams will allow for a full exploitation of the future colliders.

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