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Polarization of weak bosons produced in high-energy collisions

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In high-energy collisions the detection of longitudinally polarized weak bosons is an indication of associated production of a weak boson and a Higgs boson or an indication of production of heavy particles, such as Higgs bosons and Z' bosons, which decay into weak bosons.

In this paper we point out that the polarization of a weak boson (W or Z) produced together with a Higgs boson in $q+\bar{q}\rightarrow(W \text{ or } Z)+H$ process is predominantly longitudinal, while that of the weak boson produced together with other partons (quarks, antiquarks, gluons, photons, and/or weak boson) is predominantly transverse at high energies. The polarization of weak bosons which are decay products of heavy particles (such as Higgs bosons, Z' bosons, etc.) produced in high-energy collisions has also been shown to be longitudinal.[1,2]

Information on the polarization of the weak boson is obtained by measuring the angular distribution of its decay products, $q\bar{q}$ and $l\bar{l}$ pairs, in the helicity rest frame,[3] which is the rest frame of the weak boson with the z axis along the direction of the momentum of the weak boson and with the x axis in the production plane and (positive x axis) pointing to decreasing scattering angle direction.

The cross section for the $q_i+\bar{q}_j\rightarrow W^*\rightarrow W+H\rightarrow q+\bar{q}$ (or $l+\bar{l}$)$+H$ process in the tree approximation is given by

$$\begin{aligned} d^3\sigma/dz\,d\cos\theta\,d\phi = C_W p\hat{s}^{-1/2}(\hat{s}-M^2)^{-2}\{ &(E/M)^2(1-z^2)\sin^2\theta+(E/M)z(1-z^2)^{1/2}\sin2\theta\cos\phi \\ &+z^2\cos^2\theta+1-(1-z^2)\sin^2\theta\sin^2\phi \\ &\pm2[z\cos\theta+(E/M)(1-z^2)^{1/2}\sin\theta\cos\phi]\}\ , \end{aligned} \quad (1)$$

where θ and ϕ are polar and azimuthal angles of q or l in the helicity rest frame, E, p, and z are the energy and momentum of W and cosine of the scattering angle between the momenta of q and W in the center-of-mass frame of the subprocess ($q+\bar{q}\rightarrow W+H$), respectively, $\hat{s}$ is the square of the center-of-mass energy of the subprocess, and M is the mass of W.

The constant C_W in Eq. (1) is given by

$$C_W=\tfrac{1}{128}(\alpha/\sin^2\theta_W)^2|V_{ij}|^2M^2B(W\rightarrow q\bar{q} \text{ or } l\bar{l})\ , \quad (2)$$

where V_{ij} is the Kobayashi-Maskawa matrix element for the initial $q_i\bar{q}_j$, and θ_W is the Weinberg angle. In Eq. (1) the + (−) sign applies to q and l ($\bar{q}$ and $\bar{l}$).

The cross section (1) has two features. The first feature is the following limit as $\hat{s}\rightarrow\infty$:

$$\hat{s}\,d^3\sigma/dz\,d\cos\theta\,d\phi=\text{const}\times(1-z^2)\sin^2\theta\ , \quad (3)$$

which indicates that the polarization of the produced weak boson is predominantly longitudinal since $|d^1_{\pm1,0}(\theta)|^2\propto\sin^2\theta$ (helicity of $\bar{q}q$ or $l\bar{l}$ is 1 or −1). The origin of the longitudinal-polarization dominance is due to E and p which appear in the polarization four-vector of longitudinally polarized W, $\epsilon^L_\mu=(|\mathbf{p}|,E\mathbf{p}/|\mathbf{p}|)/M$.

The above feature should be compared with the high-energy limits of the cross sections of the subprocesses $a+b\rightarrow W+c$:

$$\hat{s}\,d\sigma/d\cos\theta=A(1+\cos\theta)^2+B(1-\cos\theta)^2\ , \quad (4)$$

where a, b, and c are quarks, antiquarks, gluons, and/or a photon, and A and B are constants. The limit (4) indicates that the polarization of the produced weak boson is predominantly transverse since $|d^1_{\pm1,1}(\theta)|^2=|d^1_{\mp1,-1}(\theta)|^2\propto(1\pm\cos\theta)^2$. It is easy to derive the asymptotic behavior (4) in the tree approximation by direct calculation.[4–7]

The transverse polarization dominance of these subprocesses (4) holds to all orders in perturbative QCD and QED if we neglect quark masses (including the masses of heavy fermions in closed loops). This fact can be proved in the following way. Because of E and p in ϵ^L_μ, one might naively expect that the ratios of the production cross section of the longitudinally polarized weak boson to that of the transversely polarized weak boson σ_L/σ_T increase as $O(\hat{s}/M^2)$ as $\hat{s}\rightarrow\infty$. However, the production amplitudes of the longitudinally polarized weak boson are shown to vanish if we replace the polarization four-vector of the weak boson $\epsilon^L_\mu=(|\mathbf{p}|,E\mathbf{p}/|\mathbf{p}|)M$ by its four-momentum $p_\mu=(E,\mathbf{p})$ and if we notice the conservation of the fermionic contribution to the weak currents which holds when fermion masses are neglected. Hence, we find the transverse-polarization dominance in the limit $\hat{s}\rightarrow\infty$,

$$\sigma_L/\sigma_T=O(M^2/\hat{s})\ , \quad (5)$$

since the production amplitudes of longitudinally polarized weak bosons are reduced by a factor of $O((E-|\mathbf{p}|)/E)=O(M^2/\hat{s})$. The fact that the weak bosons produced in these subprocesses are predominantly transversely polarized has been noticed by Willenbrock.[8] On the other hand, in $q+\bar{q}\to W+H$ process predominantly longitudinally polarized weak bosons are produced by the WWH interaction which arises because of breaking of the SU(2)×U(1) symmetry. Since this part of the weak current does not satisfy $\partial_\mu J^\mu=0$, the arguments above for transverse-polarization dominance do not apply.

Next let us consider productions of pairs of weak bosons ($W^+W^-, W^\pm Z, ZZ$). It is well known that there are gauge cancellations among production amplitudes of longitudinally polarized weak bosons in gauge theories.[9-11] At the tree-level calculation of $q+\bar{q}\to W^+ + W^-, W^\pm + Z, Z+Z$ processes the polarization of weak bosons has been shown to be predominantly transverse.[2,7,12] The transverse-polarization dominance is still valid even if we include the next-to-leading-logarithm QCD corrections.[13]

A second feature of the cross section (1) is the term involving $\cos\phi$ which represents the interference of longitudinally and transversely polarized states. These terms are not negligible even for $E/M\sim 5$. Equation (1) becomes

$$d^2\sigma/dz\,d\phi = C_W p\hat{s}^{-1/2}(\hat{s}-M^2)^{-2} \times[\tfrac{4}{3}(E/M)^2(1-z^2)+2z^2+\tfrac{2}{3} \pm\pi(E/M)(1-z^2)^{1/2}\cos\phi +\tfrac{4}{3}(1-z^2)\cos^2\phi]\,, \quad (6)$$

by integrating over $\cos\theta$.

In the tree approximation terms linear in $\cos\phi$ in $q+\bar{q}\to W+H$ and $q+\bar{q}\to W+g$ cross sections have same sign, while that in $g+q\to W+q$ cross section has an opposite sign. By making use of these two features of the cross section (1), we can enhance the signals from the Higgs-boson production process. For example, if we discard events with $|\cos\theta|>1/\sqrt{2}$, we can enhance the Higgs-boson production by a factor of about 1.4 compared with associated productions of a weak boson and other partons (quark jets, gluon jets, photons, and weak bosons).

The $p+\bar{p}(p)\to W+H$ process is useful in order to search for the Higgs boson with $2m_t<m_H<2M$, where m_t and m_H are masses of the top (t) quark and the Higgs boson, respectively. If we can identify $W\to q+\bar{q}$ and $l+\bar{l}$ decays and if we can distinguish t jets and other parton jets,[14] the main background for the $p+\bar{p}(p)\to W+H$ process is the $p+\bar{p}(p)\to W+g\to W+t+\bar{t}$ process. The cross sections for these two processes have been calculated by Kunszt.[15] The cross section for $p+\bar{p}\to W+H\to(q+\bar{q}$ and $l+\bar{l})+H$ with $|\cos\theta|<1/\sqrt{2}$ and that for $p+\bar{p}\to W+t+\bar{t}\to(q+\bar{q}$ and $l+\bar{l})+t+\bar{t}$ with $0.95m_H<m_{t\bar{t}}<1.05m_H$ and $|\cos\theta|<1/\sqrt{2}$ for $m_t=35$ GeV and $m_H=120$ GeV at Superconducting Super Collider energies are shown in Fig. 1. It is found that the cross section for the former process is larger than that for the latter process. The enhancement of $q+\bar{q}\to W+H$ process by a factor of 1.4 is very effective. For $m_H>2M$ a similar prescription has been used by Gunion, Kunszt, and Soldate,[6] and Duncan[12] in their works on Higgs-boson decays to W- and Z-boson pairs.

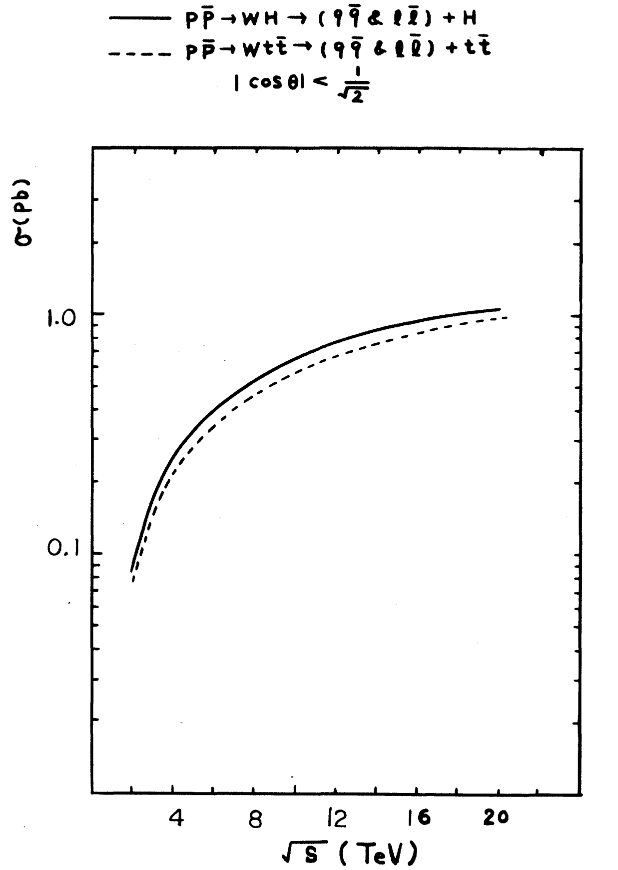

FIG. 1. Total cross sections for $p+\bar{p}\to W+H\to(q+\bar{q}$ and $l+\bar{l})+H$ with $|\cos\theta|<1/\sqrt{2}$ (solid line) and that for $p+\bar{p}\to W+t+\bar{t}\to(q+\bar{q}$ and $l+\bar{l})+t+\bar{t}$ with $0.95m_H<m_{t\bar{t}}<1.05m_H$ and $|\cos\theta|<1/\sqrt{2}$ (dashed line) as functions of incoming energy with $m_t=35$ GeV and $m_H=120$ GeV.

The above arguments for W-boson production apply to Z-boson production. The only difference is the change in the coefficients of the terms with ± sign and the overall coefficient C_W in Eqs. (1) and (6).

In conclusion we have found that in high-energy collisions detection of longitudinally polarized weak bosons is an indication of associated production of a weak boson and a Higgs boson or an indication of production of heavy particles such as Higgs bosons, Z' bosons, fourth-generation fermions, etc., which decay into a weak boson(s). Of course, we have to mention that it may be an indication of multiple production of weak bosons due to strong self-coupling of Higgs bosons ($\lambda\phi^4$) since Higgs bosons couple strongly to longitudinally polarized weak bosons.

Note added. After completing this work we learned of a paper by Tofighi-Niaki and Gunion,[16] in which the longitudinal-polarization content of weak bosons produced in $e^+e^-\to ZW^+W^-$ is calculated as a function of the Higgs-boson mass.

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