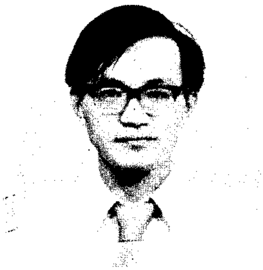
SPIN ASYMMETRIES IN LARGE p_T PRODUCTION OF GAUGE BOSONS BASED ON QUANTUM CHROMODYNAMICS AND ELECTRO-WEAK GAUGE MODEL

Keisho Hidaka
Department of Physics, Westfield College
(University of London), London NW3 7ST, England

(Address after 1 November 1980: Lab. de Phys. Theor.
et Hautes Energies, Univ. de Paris Sud,
Batiment 211, F-91405 Orsay, France)



Abstract

We make definite predictions for spin asymmetries in the production of gauge bosons, such as Z^0, $W^{\pm}$ and real γ, at large p_T ($\gtrsim$ 2 GeV/c) from longitudinally polarized hadron beam and target using QCD perturbation theory and Weinberg-Salam model in the framework of the hard scattering model. Asymmetries typically at the 10-50% and 2-5% level are predicted for the weak bosons and real photon, respectively. Experimental tests should be possible in the near future, eg at Fermilab, ISABELLE and colliding SPS.

In large p_T hadronic production the hard scattering model and quantum chromodynamics have thus far been mainly applied only to the spin-averaged cross sections. Here I want to discuss spin dependence of the cross sections of hadro-production of hadrons and gauge bosons, such as meson, jet, real photon, virtual photon (ie massive lepton pair) and weak bosons. These spin dependences can be definitely predicted in the framework of QCD and the electro-weak gauge model, such as Glashow-Weinberg-Salam model. As explained by Yokosawa in this conference, this type of experiment using polarized hadron beams is now under construction at Fermilab. In the near future they will also be able to be measured at ISABELLE[1)] and colliding SPS. These experiments give us a new kind of test of QCD and the electro-weak gauge models with regard to their spin structures. We can make definite predictions in principle for spin asymmetries of <u>any</u> large p_T process in terms of the gauge models. Here I show how to calculate spin-spin asymmetry in neutral weak boson (Z^0) production at large p_T as an example.

In lowest order QCD perturbation theory[2)] the large transverse momentum (p_T) of Z^0 is basically generated by the hard parton process of quark (q)-antiquark ($\bar{q}$) annihilation into a Z^0-gluon (V) pair (Fig 1b) or by the Compton scattering of quarks and gluons (Fig 1c), whereas the Drell-Yan mechanism of Fig 1a produces only Z^0 with $p_T = 0$ (neglecting the "internal" transverse momentum k_T of partons inside initial hadrons).

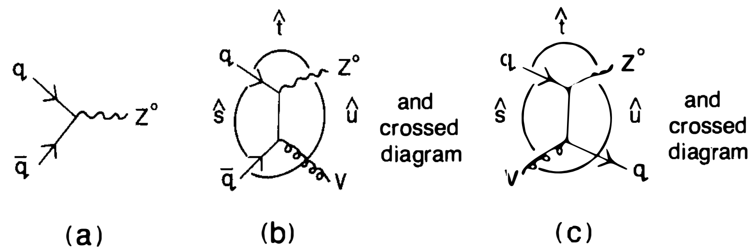


Fig 1

The basic processes of Fig 1b and c have remarkable spin dependences. We obtain differential cross sections for Z^0 production from massless partons with definite helicities in terms of the gauge models as follows:

For $q(h_1) + \bar{q}(h_2) \rightarrow Z^0 + V$

$$\frac{d\hat{\sigma}_{q(h_1)\bar{q}(h_2)}}{d\hat{t}} = (1-h_1h_2)\,\frac{2}{9}\,\frac{\alpha_s(a-h_1b)^2}{\hat{s}^2}\left(\frac{\hat{u}}{\hat{t}}+\frac{\hat{t}}{\hat{u}}+\frac{2M_z^2\hat{s}}{\hat{t}\hat{u}}\right) \tag{1}$$

For $q(h) + V(\lambda) \to Z^0 + q$,

$$\frac{d\hat{\sigma}_{q(h)V(\lambda)}}{d\hat{t}} = -\frac{1}{12}\,\frac{\alpha_s(a-hb)^2}{\hat{s}^2}\,\Big\{(1+\lambda h)\left(\frac{\hat{s}}{\hat{t}}+\frac{\hat{t}}{\hat{s}}+\frac{2M_z^2\hat{u}}{\hat{t}\hat{s}}\right) - 2\lambda h\,\frac{(M_z^2-\hat{t})^2}{\hat{t}\hat{s}}\Big\} \tag{2}$$

Here h_1, h_2, $h(=\pm 1)$ and $\lambda(=\pm 1)$ refer to parton helicities, M_z ($\approx$ 90 GeV) is the mass of Z^0, b and a are the electro-weak vector and axial vector charges of quarks, and α_s is the running QCD coupling. In the Glashow-Weinberg-Salam model one has

$$a_u = -a_d = b_u\cdot\left(1 - \frac{8}{3}\sin^2\theta_W\right)^{-1} = b_d\cdot\left(-1 + \frac{4}{3}\sin^2\theta_W\right)$$

$$= \frac{e}{2\sin 2\theta_W} \tag{3}$$

where u and d refer to up and down quark, e is the proton charge and θ_W is the Weinberg angle ($\sin^2\theta_W \simeq 0.23$). Combining these spin dependences with the experimental fact that the partons in a polarized proton can "remember" the proton's spin[3], we can calculate a spin-spin asymmetry in $p_\uparrow + p_\uparrow \to Z^0 + X$:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \,. \tag{4}$$

Here one has in the hard scattering model

$$\sigma_{H_1H_2} \equiv E\,\frac{d^3\sigma_{H_1H_2}}{d^3p} = \sum_{p_1(\lambda_1)p_2(\lambda_2)}\int dx_1\, D\, p_{1_{\lambda_1 H_1}}(x_1)\, p_{2_{\lambda_2 H_2}}(x_2)\cdot \frac{d\hat{\sigma}_{p_1(\lambda_1)p_2(\lambda_2)}}{d\hat{t}} \tag{5}$$

with

$$D = \frac{s}{\pi}\,\frac{x_1x_2}{x_1 s+u-M_z^2} \quad\text{and}\quad x_2 = \frac{-x_1 t-(1-x_1)M_z^2}{x_1 s+u-M_z^2}\,, \tag{6}$$

where $p_{\lambda H}(x)$ represents the density of type p parton with helicity λ in the incident proton with helicity H.[4] The hadronic invariants s, t and u are analogous to the partonic variables $\hat{s}$, $\hat{t}$ and $\hat{u}$ of Fig 1;

$$\hat{s} = x_1 x_2 s, \quad \hat{t} = x_1 t + (1-x_1)M_Z^2 \quad \text{and} \quad \hat{u} = x_2 u + (1-x_2)M_Z^2 . \tag{7}$$

The function $\Delta p(x) \equiv p_{++}(x) - p_{-+}(x)$ represents the probability that the parton p "remembers" the spin of the parent proton. (Note that the usual unpolarized distribution is given by $p(x) = p_{++}(x) + p_{-+}(x)$.) For quarks the spin distribution $\Delta p(x)$ can be determined directly by measurement of the deep inelastic scattering cross section of polarized leptons and hadrons at SLAC.[3,5] For antiquarks and gluons the spin distributions cannot be determined by the SLAC measurement[6]. We can, however, estimate the distributions for these partons using the QCD Bremsstrahlung model[5,7] along the same lines as the QCD application to scaling violations[8].

We can roughly estimate the typical size of the asymmetry A_{LL} thus:

$$A_{LL} \stackrel{\sim}{\sim} \frac{\Delta p_1}{p_1} \cdot \frac{\Delta p_2}{p_2} \cdot \hat{A}_{LL}^{p_1 p_2} \quad \text{from eqs. (4) and (5).}$$

Here parton scattering asymmetry $\hat{A}_{LL}^{p_1 p_2} \equiv \dfrac{\hat{\sigma}_{++} - \hat{\sigma}_{+-}}{\hat{\sigma}_{++} + \hat{\sigma}_{+-}}$ $\left(\hat{\sigma}_{\lambda_1 \lambda_2} \equiv \dfrac{d\hat{\sigma}_{p_1(\lambda_1) p_2(\lambda_2)}}{d\hat{t}}\right)$ is typically at the 100% level (see eqs. (1) and (2)). The SLAC data[3] suggest quark polarization $\Delta q(x)/q(x) \stackrel{\sim}{\sim} +\frac{1}{2}$ at an intermediate value of x. The QCD model[5,7] predicts $\Delta \bar{q}(x)/\bar{q}(x) = \Delta V(x)/V(x) \stackrel{\sim}{\sim} +\frac{1}{5}$. Hence $|A_{LL}| \sim \frac{1}{2} \cdot \frac{1}{5} \cdot 100\% \sim 10\%$ typically.

Predictions for Z^0 production in proton-proton scattering with the model distributions of Ref. 5 are shown in Fig 2.[9] The distributions are defined as follows.

"Conservative model" : $\bar{u} = \bar{d} = (0.39/x)(1-x)^{10}(1+(1-x)^2)$, $u = u_v + \bar{u}$, $d = d_v + \bar{d}$, $V = (1.97/x)(1-x)^6(1+(1-x)^2)$, $\Delta\bar{u} = \Delta\bar{d} = 0.13(2-x)(1-x)^{10}$, $\Delta u_v = 0.44 u_v$, $\Delta d_v = -0.35 d_v$, $\Delta u = \Delta u_v + \Delta\bar{u}$, $\Delta d = \Delta d_v + \Delta\bar{d}$ and $\Delta V = 0.66(2-x)(1-x)^6$.

"Carlitz-Kaur (plus gluon) model" : $\bar{u} = \bar{d} = (0.6/x)(1-x)^{10}$, $u = u_v + \bar{u}$, $d = d_v + \bar{d}$, $V = (1.97/x)(1-x)^6(1+(1-x)^2)$, $\Delta\bar{u} = \Delta\bar{d} = 0$, $\Delta u = \cos(2\theta)(u_v - \frac{2}{3} d_v)$, $\Delta d = -\frac{1}{3}\cos(2\theta) d_v$ and $\Delta V = 0.43(2-x)(1-x)^6$ with a dilution factor $\cos(2\theta) = (1 + 0.052 x^{-\frac{1}{2}}(1-x)^2)^{-1}$. Here $u_v = u_{FF} - \bar{u}_{FF}$

and $d_v = d_{FF} - \bar{d}_{FF}$ where v and FF refer to valence and Field-Feynman[10]. Both model distributions for quarks reproduce well the measured spin asymmetry in polarized lepton-hadron deep inelastic scattering[3,5].

Here we note that at sufficiently high energy (ie $s >> M_Z^2$) A_{LL} scales with x_F and x_T in our model with parton distributions which themselves scale.

In the same way we can make definite predictions of the spin-spin asymmetry A_{LL} for the large p_T production of charged weak bosons ($W^{\pm}$), real photons (γ), virtual photons ($\mu^-\mu^+$ pair)[11], mesons (π etc) and jets[5,12] in polarized proton-proton scattering. Typical sizes of $|A_{LL}|$ for these processes are summarized in Table 1. I am planning to publish elsewhere[13] the full results of this article (including predictions for parity violating spin asymmetries in weak boson production).

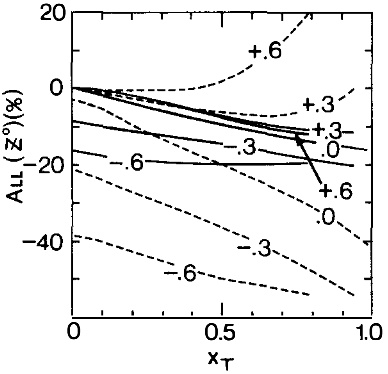


Fig 2: The gauge model predictions for the asymmetry A_{LL} plotted against $x_T = 2p_T/\sqrt{s}$ at $\sqrt{s}$ = 800 GeV. The numbers on curves refer to values of $x_F = 2p_{/\!/}/\sqrt{s}$. Solid curves: "Conservative model". Dashed curves: "Carlitz-Kaur model".

Table 1

	Z^0	W^+	W^-	γ	$\gamma^*(\mu^-\mu^+)$	π	jet
$\lvert A_{LL}\rvert$ (%)	10-20	20-60	10-30	2-5	5-10	5-30	5-30

Asymmetries of the size predicted here can be measured[14] in the polarized beam experiments at Fermilab[15] (now under construction), ISABELLE[1] and colliding SPS (possible). These experiments provide rather direct information on the spin dependence of the basic parton hard scattering processes and can be used to test various models[16]. As for the gauge boson production at large x_T the quark-gluon Compton diagram of Fig 1c is dominant in the framework of the hard scattering model, QCD and the electro-weak gauge model. The measurement of spin asymmetries in this process at large $x_T \gtrsim 0.2$ is therefore a direct way to confirm the role of the gluons in the gauge boson production and to learn about their spin distributions. What we have shown in this note is that the approach based on the electro-weak gauge model and QCD which explains well the observed large p_T hadro-production of hadrons, real photon and virtual photon (ie lepton pair), leads to sizeable spin asymmetries in the large p_T production of the gauge bosons ($\gamma, \gamma^*(\mu^-\mu^+), W^\pm$ and Z^0) as well as in that of hadrons[5,12]. These will provide a new type of stringent test for the QCD picture and the electro-weak gauge models (such as Glashow-Weinberg-Salam model) with regard to their spin structure.

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14. The best way to detect Z^0 is perhaps to observe lepton pair from the decay $Z^0 \to \ell^-\ell^+$. (See Ref. 1 for $W^\pm$)

15. A.Yokosawa, talk given at this Conference

16. For example, the measurement of parity violating spin asymmetries in weak boson production provides information on the relative sign of vector and axial vector couplings of quarks to weak bosons.