CURRENT STATUS OF SPIN STUDIES

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Abstract

This introduction concentrates on the Electroweak sector of the Standard Model. We explain why the decay $t \to W^+ + b$ is a copious source of longitudinally polarized W's, where the longitudinal component of the W spin wave function is the component which the photon, or any other massless vector boson, does not have. Then we discuss Z production by polarized electrons at the SLC, and the measurements of asymmetric angular distributions for leptons and quarks in the final state. We discuss the measurements of final state fermion helicities from $Z \to f + \bar{f}$, where the Z's are produced by unpolarized $e^+ + e^-$ collisions at LEP. The fragmentation process does not destroy the helicity of the primary quark. Finally, we attempt to relate transverse quark polarization in Z decay to the observation that meson beam fragmentation produces polarized Λ's.

1 Three Components of the W spin

The W and Z weak vector bosons are very massive, and are therefore entitled to three components of the spin angular momentum. The photon and the gluon are massless, and have only two angular momentum components. The number of components increases discontinuosly as the mass increases from zero. The spin wave functions for the two component case, in four vector notation, are often written:

$$\varepsilon^{(+)} = (0, -1/\sqrt{2}, -i/\sqrt{2}, 0) \tag{1}$$

$$\varepsilon^{(-)} = (0, 1/\sqrt{2}, -i/\sqrt{2}, 0). \tag{2}$$

These components are called right handed and left handed respectively. The vector boson momentum four vector in the same notation is:

$$q = ((M^2 + q^2)^{1/2}, 0, 0, |\vec{q}|) \tag{3}$$

If $M \neq 0$, then there is a third polarization component, called the longitudinal component, and written:

$$\varepsilon^{(3)} = (|\vec{q}|/M, 0, 0, (M^2 + q^2)^{1/2}/M). \tag{4}$$

These components are all spacelike, orthogonal to each other, and orthogonal to the momentum four vector:

$$\varepsilon^{(\lambda)} \cdot \varepsilon^{*(\lambda')} = -\delta_{\lambda,\lambda'} \tag{5}$$

$$\varepsilon^{(\lambda)} \cdot q = 0. \tag{6}$$

Table 1: Fermion couplings to Vector Bosons

B	C_V	C_A
γ	$-ieQ_f$	0
W^-	$(-ie/\sqrt{2})/2sin(\theta_W)$	$(ie/\sqrt{2})/2sin(\theta_W)$
Z	$-ie(T_{3f} - 2Q_f sin^2(\theta_W)/sin(2\theta_W)$	$ieT_{3f}/sin(2\theta_W)$

Table 2: Fermion Electroweak Parameters

fermion	Q_f	T_{3f}
ν_e, ν_μ, ν_τ	0	1/2
e,μ, τ	-1	-1/2
u,c	2/3	1/2
d,s,b	-1/3	-1/2

The vector and axial vector couplings at the f-f-B vertex, where B is a generic vector boson, are:

$$C_V(\bar{u}(p_2)\gamma^\mu u(p_1)\varepsilon*_\mu) \tag{7}$$

$$C_A(\bar{u}(p_2)\gamma^\mu \gamma^5 u(p_1)\varepsilon*_\mu). \tag{8}$$

The vector and axial vector coefficients are given in Table 1 for the vector bosons γ, W^-, and Z. The charge and weak isospin assignments for the leptons and quarks are defined in Table 2. The weak mixing angle is approximately $sin^2(\theta_W)$=0.231, the fine structure constant is $e^2/4\pi$=1/137, and the Fermi constant is related to the weak mixing angle and the W mass through $G_F/\sqrt{2} = e^2/8M_W^2 sin^2(\theta_W)$. These are all leading order formulas. It is interesting to note that the Z vector coupling to charged leptons vanishes for $sin^2(\theta_W)$=.25, which is almost true, so the Z is almost pure axial vector for Q_f=-1. The quarks have fractional charge, and have larger vector coupling coefficients.

These formulas will be used throughout the present paper, but the important point to note here is that in the limit $m_f \rightarrow$0, neither the vector nor the axial vector currents couple to $\varepsilon^{(3)}$. This is true for $f + \bar{f} \rightarrow W/Z$ regardless of the polarization state of the initial fermion. $e^+e^- \rightarrow W^+W^-$ does not produce longitudinally polarized W's either, except very near threshold. Thus although the W and Z are very massive, they might just as well have only two spin components. In fact the probability for $\varepsilon^{(3)} \sim m_f^2$, which is just like the fermion coupling to the Higgs. In the spontaneous symmetry breaking, $\varepsilon^{(3)}$ and the Higgs scalar share a common origin. The vacuum expectation value of the Higgs potential, which breaks the SU(2) xU(1) symmetry spontaneously, creates three massless Goldstone bosons, and the massive scalar Higgs field.

After a suitable gauge transformation the Goldstone bosons disappear, leaving behind the three longitudinal spin components of the $W^{\pm}$ and Z.

2 $t \to W^+ + b$

The approximation $m_f \sim 0$ is poor for the top quark, which has a mass $m_t = 175.9 \pm 4.8(stat) \pm 4.9(sys) GeV/c^2$ [1]. In fact the dominant decay mode for the top quark is $t \to W^+ + b$, or $\bar{t} \to W^- + \bar{b}$, and the fraction of longitudinally polarized W^-'s is

$$\begin{aligned} F_0 &= \Gamma(\varepsilon^{(3)})/(\Gamma(\varepsilon^{(3)} + \Gamma(\varepsilon^{(-)}) \\ &= (m_t^2/2M_W^2)/(1 + m_t^2/2M_W^2) \\ &= 70.6 \pm 1.6\% \end{aligned} \tag{9}$$

using the quoted top quark mass and $M_W = 80.410 \pm 0.180 GeV/c^2$ [2].

The CDF top events have been described in several publications [1 3 4]. The total data sample in hand corresponds to an integrated luminosity of $110 pb^{-1}$ for $\bar{p}p$ collisions at 1.8 TeV. The measured cross section for $\bar{p} + p \to \bar{t} + t + X = 7.6 \pm 1.6$ pb [5]. So with 100% detection efficiency one would expect about 800 events. There are two paths to the top candidates: events with two oppositely charged high p_t leptons (e or μ) from the leptonic decays of the W's and two jets from the b and $\bar{b}$ quarks; and events with one high p_t lepton and three or four jets detected with $E_t \geq 15$ GeV. The dilepton candidates can be identified at the trigger level. They have a small branching ratio - 4/81 - but also have a small background fraction. The branching ratio for the second category is 24/81. These top candidates are obtained by applying the jet requirements on the $W \to l + \nu$ data sample of about 100,000 events. There are a total of four jets: two from the decay $W \to \bar{q}q$, and two from the b and $\bar{b}$ quarks. The b jets can be 'tagged', which has been a very powerful technique for background rejection.

The silicon vertex detector (SVX) of CDF was used to tag b quark decays. The mean transverse displacement of the b vertex from top decay is about 3 mm, and the SVX resolution in this distance is typically 130 μm. The efficiency for tagging at least one b quark in a $\bar{t}t$ event is estimated to be $42 \pm 5\%$ from monte carlo. A breakdown of the number of top candidates and the estimated backgrounds for the various categories is shown in Table 3. The SLT tag refers to soft leptons in the jets, used as another signature of the b quark - $b \to e\nu_e$ or $\mu\nu_\mu + X = 10\%$. The fourth jet in the notag sample was required to have $E_t \geq 15$ GeV, while in the tagged sample jet E_t was reduced to 8 GeV. The

Table 3: CDF top quark sample

sample type	number of events	background estimate
dilepton	7	0.76 ± 0.21
SVX tag	34	9.2 ± 1.2
SLT tag	14	5.6 ± 1.2
Notag	43	23.6 ± 6.5
lepton+jet tot	91	38.3 ± 6.7
total leptons	105	39.1 ± 6.7

W polarization measurement was based on the lepton angular distribution, so the dilepton events counted twice.

The principle of the measurement of the W polarization is based on the angular distribution of the leptons relative to the W line of flight in the top rest frame [6]. For $W^- \to l^- \bar{\nu}_l$ the angular distribution of l^- in the W rest frame is $(1 + cos(\theta))^2$ with polarization vector $\varepsilon^{(-)}$, and $sin^2(\theta)$ with polarization vector $\varepsilon^{(3)}$. Figure 1 shows the data and the templates used to fit to the two spin states. Preliminary results are:

$$F_0 = 0.55 \pm 0.32(stat) \pm 0.12(sys) \tag{10}$$

Thus the $\varepsilon^{(3)}$ term is about two σ from zero. It is anticipated that the next collider run, beginning in the year 2000, will give an integrated luminosity of $2fb^{-1}$, and about 1000 b tagged events, which should lead to a statistical error on F_0 of about 0.1. The polarization of the W in top quark decay will remain a fruitful subject for study, partly because W's are usually not created in the $\varepsilon^{(3)}$ state, and partly because of the remarkable origin of this component of the polarization in the spontaneous symmetry breaking of the standard model.

3 Polarization at the Z peak - SLC

The Stanford Linear Collider has operated for five years with 75% polarized e^- and unpolarized e^+ [7] at the Z resonance peak. During this time the SLD detector has recorded about 500,000 Z's [8]. If $x = cos(\theta)$, where θ is the polar angle between the incoming e^- and the outgoing fermion f, then the x distribution is given by the formula:

$$d\sigma/dx = (1 - P_e A_e)(1 + x^2) + 2A_f(A_e - P_e)x, \tag{11}$$

where

$$A_f = (2C_V^f C_A^f)/((C_V^f)^2 + (C_A^f)^2), \tag{12}$$

and C_V, C_A are given in Tables 1 and 2. With $sin^2(\theta_W)$=0.231, the numbers are A_f=0.15 for e, μ, and τ, A_f=0.67 for u,c,and A_f=0.94 for d,s,b. The cross sections are shown in Figure 2. The relative normalizations of the plots are correct, but the overall normalization is arbitrary.

One property of Eq (11) is that the total cross section, or the symmetric integral, depends only on the product $P_e A_e$, so if the beam polarization is known independently, the electron asymmetry A_e can be measured from the total event rates summed over all final states for left and right handed electrons. Thus

$$\sigma_L = \int_{-1}^{1} (d\sigma_L/dx)dx \tag{13}$$

$$\sigma_R = \int_{-1}^{1} (d\sigma_R/dx)dx \tag{14}$$

$$(\sigma_L - \sigma_R)/sum = P_e A_e. \tag{15}$$

The electron asymmetry parameter depends directly on the weak mixing angle $\sin^2(\theta_W)$.

$$A_e = (2(1 - 4sin^2(\theta_W))/(1 + (1 - 4sin^2(\theta_W))^2). \tag{16}$$

The measurement of the electron polarization is based on the spin dependence of the Compton cross section, which can be calculated by QED. Circularly polarized laser light is focused on the electron beam downstream of the collision point, and back scattered electrons, with energy well below the beam energy, are magnetically deflected and counted to measure the spin dependent asymmetry $\sigma_{LL} - \sigma_{LR}$ The final electron beam polarization error is dominated by systematic uncertainties. Preliminary results for 1996, 97, and 98 runs are $P_e = 0.765 \pm 0.005, 0.733 \pm 0.008$, and 0.731 ± 0.008 respectivly. The corresponding preliminary asymmetry values are $A_e = 0.1570 \pm 0.0057 \pm 0.0011, 0.1475 \pm 0.0042 \pm 0.0016$, and $0.1487 \pm 0.0031 \pm 0.0017$, giving the weighted grand average for the SLC of

$$A_e = 0.1510 \pm 0.0025 \tag{17}$$

$$sin^2(\theta_W) = 0.23101 \pm 0.00031. \tag{18}$$

This value for the weak mixing angle agrees with the current world average [9]. Equation (11) can be integrated over hemispheres to cancel the $P_e A_e$

term, and measure A_f. Define

$$\begin{aligned} F_L &= \int_0^1 (d\sigma_L/dx)dx \\ B_L &= \int_{-1}^0 (d\sigma_L/dx)dx \\ \tilde{A}_{FB} = ((F-B)_L - (F-B)_R)/(F+B)_L &+ (F+B)_R) \\ &= 3P_eA_f/4 \end{aligned} \tag{19}$$

The measurement of A_f for μ^- is straightforward. While A_τ is not so simple, it is still manageable. For the quarks, we expect $A_u = A_c$, and $A_d = A_s = A_b$. These asymmetry parameters represent special challenges, because the quarks are not directly observed. The fragmentation process results in hadrons in the final state, from which we must work backwards to determine the flavor of the initial quark. Primary up and down quarks are the most difficult to sort out. The primary b quark, which fragments into B mesons and sometimes B baryons, is perhaps the easiest to identify, because of the large b quark mass and the long lifetime. Strange particles in the final state can be used to tag primary s quarks, if one is careful to veto heavier flavors which give strange particles in their decay sequences. The jet charge method together with detection of a secondary vertex has been successfully used to identify b quarks and determine the quark charge [10]. A review of the current status of A_q measurements has been presented by Fahey at Vancouver [11]. The tool kit includes secondary vertex detection, measurement of the visible mass of that vertex, looking for a high p_t lepton from the vertex, where p_t is defined relative to the jet thrust axis, and observing exclusive final states.

One of the more difficult quarks to sort out is the c, which fragments into charmed D mesons. The c is lighter than the b, has a shorter lifetime, and D mesons appear in the decay chain of B mesons, so the various techniques listed above tend to bury the c quarks in the b sample. Figure 4 shows the secondary vertex mass corrected for the missing p_t. This correction was determined from the minimum p_t needed to bring the total momentum vector of the tracks from the secondary vertex in line with the direction from the primary to the secondary vertex. Note the broad b distribution, which masks the smaller masses from c quarks. The secondary vertex requirement suppresses the total c signal. The following cuts were used to extract inclusive charm in a given hemisphere:

1. $0.55 < M_{vtx} < 2$ GeV (c), or $M_{vtx} > 2$ GeV (b)
2. $P_{vtx} > 5$GeV

3. $P_{vtx} - 15M_{vtx} > -10$ GeV

4. Vtx significance $D/\sigma_D > 4$ (c), or $D/\sigma_D > 5$(b).

If the opposite hemisphere satisfied the b requirements, the event was vetoed. The third requirement works for $1 < M_{vtx} < 2$ GeV, and forces the momentum to be greater than 5 GeV if the mass is in this range. This cut is based on the observation that the D meson tends to have a higher momentum if it comes from a primary c quark than if it is a daughter from B decay. The overall efficiency of these cuts was 28%, and the purity of the resulting c sample was 81% [12]. Figure 4 gives a chart of the A_c measurements at SLD and LEP. There is good agreement among the various numbers, and also with expectations of the standard model.

4 Final state fermion helicity - LEP

At LEP the e^+e^- are unpolarized, which simplifies the cross section formula

$$d\sigma/dx = 1 + x^2 + 2A_f A_e x. \tag{20}$$

Asymmetry effects are generally smaller in this case than for 75% polarized incident electrons, since $A_e = 15\%$. The final state fermions, however, can be strongly polarized. This is particularly true for the quarks, as shown in Figure 3. The question naturally arises: can this helicity be observed after the hadronization process?

The OPAL collaboration has used $\Lambda \to p\pi^-$ to determine the helicity of the primary strange quark [13]. The quark diagram for the fragmentation of a polarized strange quark is shown in Figure 6. A (u,d) diquark from the sea combines in a singlet spin state with the polarized s to form a Λ with the same polarization. If this were the only mechanism to create Λ's, their polarization would be -91%. There are however other sources of baryons besides the leading s quark fragmentation illustrated. Λ's created entirely by the fragmentation process, or from a (u,s) or (d,s) diquark attached to a leading d or u quark respectively would lead to zero Λ helicity. Λ's from decays of Σ^0, Σ^*, Ξ, and Ξ^*, in which the primary s quark is contained in the heavier hyperon, are expected to retain some of the polarization of the s quark. The momentum fraction $x_E = 2p_\Lambda/M_Z$ is a kinematic variable that can be used to differentiate among the various sources. In general, a Λ with large x_E is more likely to contain the primary s quark than one with $x_E < .3$, say. A fragmentation monte carlo was used to determine the relative yields of hyperons as a function of x_E. High momentum Λ's are a problem for the LEP detectors, because the flight path of a 45 GeV/c Λ is 3.2 m. The Λ polarization as a function of x_E is shown in Figure 7. The results are in agreement with expectations, and show that the spin information carried by the primary quark is not destroyed by the fragmentation process - at least not in the helicity case.

The OPAL group [13] also looked for transverse Λ polarization. In this case the lowest order Electroweak calculation gives zero, and the NLO QCD calculation gives [14]:

$$\vec{P} \cdot \hat{n} = 2\alpha_s m_f sin(2\theta)/(3Q(1 + cos^2(\theta)), \tag{21}$$

where $\hat{n}$ is the normal to the plane defined by the incident e^- and the outgoing fermion momenta, and θ is the polar angle between those two vectors. Q is of the order of the Z mass, so $\alpha_s m_f/Q$ is about 0.01 for b quarks - a very small effect.

It is possible that the fragmentation process creates a transverse component of the Λ polarization, where the plane is defined by $\vec{p}_{jet} \times \vec{p}_\Lambda$. One can imagine that this plane is formed when the diquark attaches to the primary quark, thus deflecting the final hyperon. Studies of $Z \rightarrow$jet + jet have shown that when a baryon-antibaryon pair is produced, they tend to both be in the same hemisphere [15], so the picture of the diquark-antidiquark pair is reasonable.

Experimental evidence for proton beam fragmentation into polarized hyperons has been reviewed many times at these conferences [16]. While proton fragmentation may be more complex than the simple fragmentation of a strange quark in $Z \rightarrow \bar{s}s$ decay, it seems plausible that beam fragmentation of mesons may not be so different. Indeed, strong Λ polarization has been observed in the beam fragmentation region for $K^- + p \rightarrow \Lambda + X$ [17], and also for $K^+ + p \rightarrow \bar{\Lambda} + X$ [18]. Baryon and antibaryon polarizations have the same sign. In the quark picture, these effects are the same as dressing a leading s or $\bar{s}$ quark with an appropriate (u,d) or $(\bar{u}, \bar{d})$ diquark to form a leading polarized Λ or $\bar{\Lambda}$. Hence the quark diagram of Figure 6, or its charge conjugate, should apply, and there should be a transverse polarization of about +20% normal to the plane defined by $\vec{p}_{jet} \times \vec{p}_\Lambda$ for Λ or $\bar{\Lambda}$ with $p_t > .4$GeV and $x_F > .4$.

Unfortunately, no transverse polarization is observed [13]. Using our sign convention, their results are $P_T^\Lambda = (-0.9 \pm 0.9 \pm 0.3)\%$ for $p_t > .3GeV/c$, where p_t is defined as the Λ momentum component normal to the jet thrust direction.

Why is no transverse Λ polarization observed in Z decay? We know that the helicity is not destroyed by the fragmentation. Polarization components add in quadrature, so a 20% transverse polarization would have little effect on the longitudinal component. The LEP experiments have good statistics, so that is not the problem. The quark picture is based on the premise that the observed Λ comes from a leading s quark - surely true for K^- fragmentation.

However, the $Z \to \Lambda$ events have a mixed origin. About 90% of them have $x_E < .3$. Perhaps there are not enough events at large x_E, where leading s quarks should predominate. There is also the experimental fact that $\pi^- \to \Lambda$ in the beam fragmentation region leads to a Λ polarization of the opposite sign [19]. Of course it is possible that the transverse polarization of the strange quark in K^- fragmentation arises when the $\bar{u}$ quark is stripped off. Given the simple structure of the quark final state in Z decay before hadronization, it would certainly be gratifying to be able to relate polarization phenomena in hadronic reactions to the Z laboratory, but so far it seems that we have had no luck.

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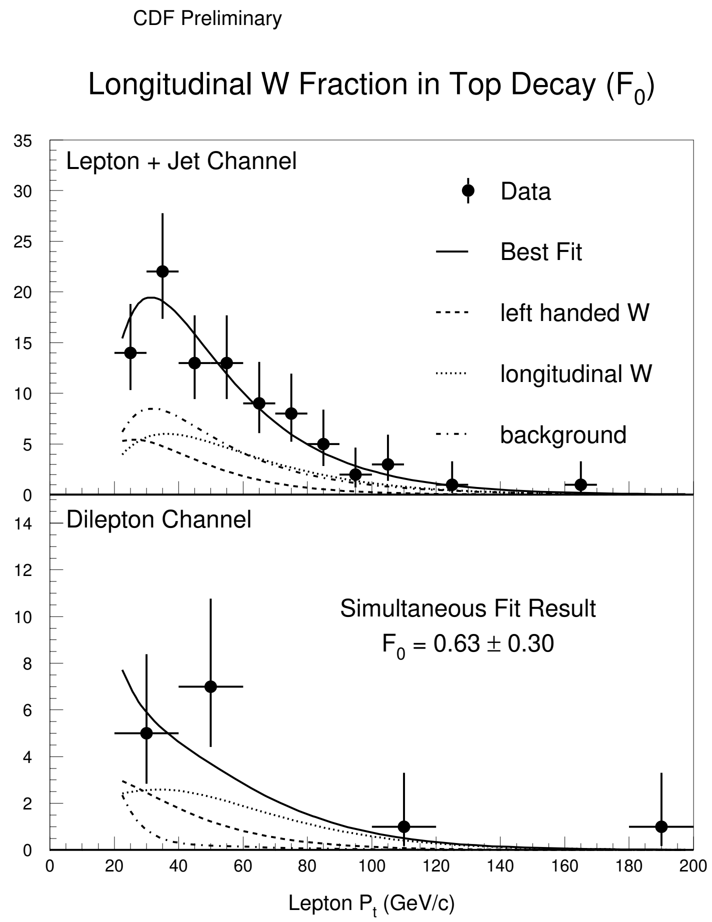

Figure 1: Fit of the lepton P_t distributions to ε^3 and ε^- + background hypothesis

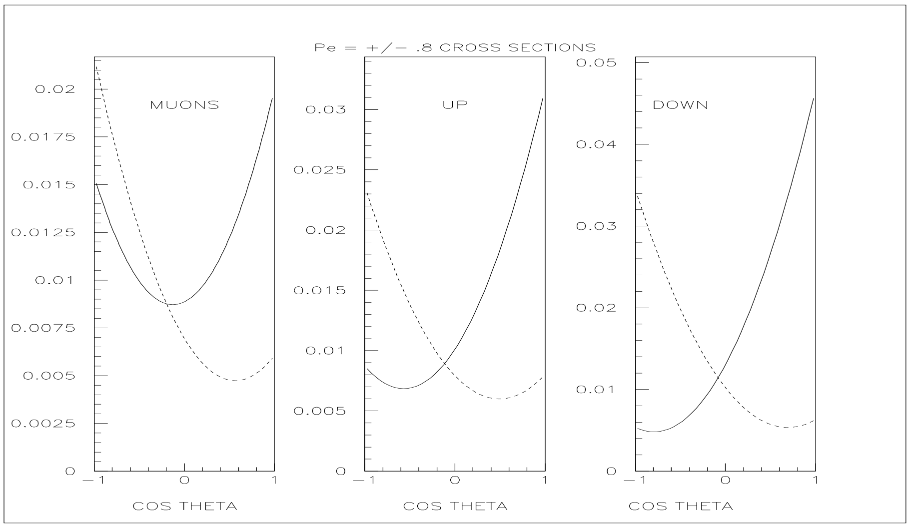

Figure 2: Plots of the cross section formulas for 80% polarized e^- and unpolarized e^+ at the Z peak using Eq.11

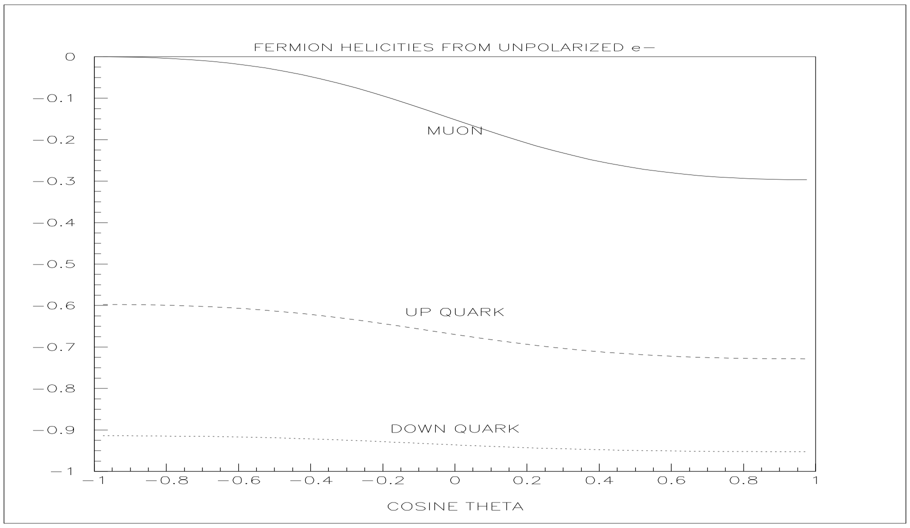

Figure 3: Plots of the lepton and quark helicities in the final state for $Z \to \bar{f}f$, with the Z produced by unpolarized e^+e^-

A_q

All measurements share a similar analysis flow:

1. Select Z^0 to hadrons events
2. Tag events with the correct quark flavor
   - Look for a displaced vertex with the appropriate mass (b,c)
   - Or with no displaced vertex (s)
3. Tag the quark charge (and direction)
   - By summing the track charge in the jet
   - Or with an identified e, μ, K, Λ, D^{*+}, D^+, D^0

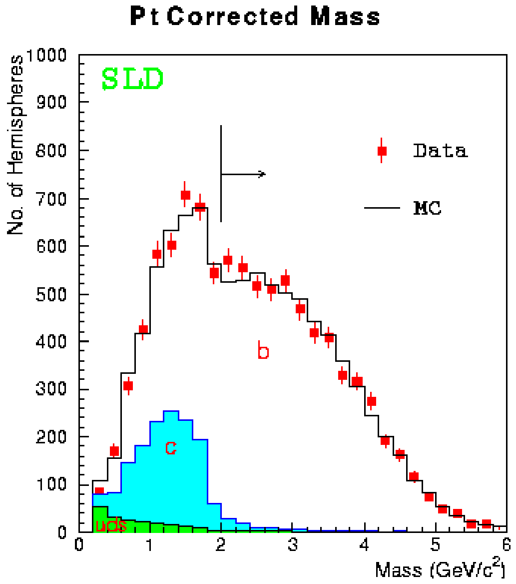

Figure 4: p_t corrected secondary vertex mass, showing the contributions expected from the various quark flavors

A_c

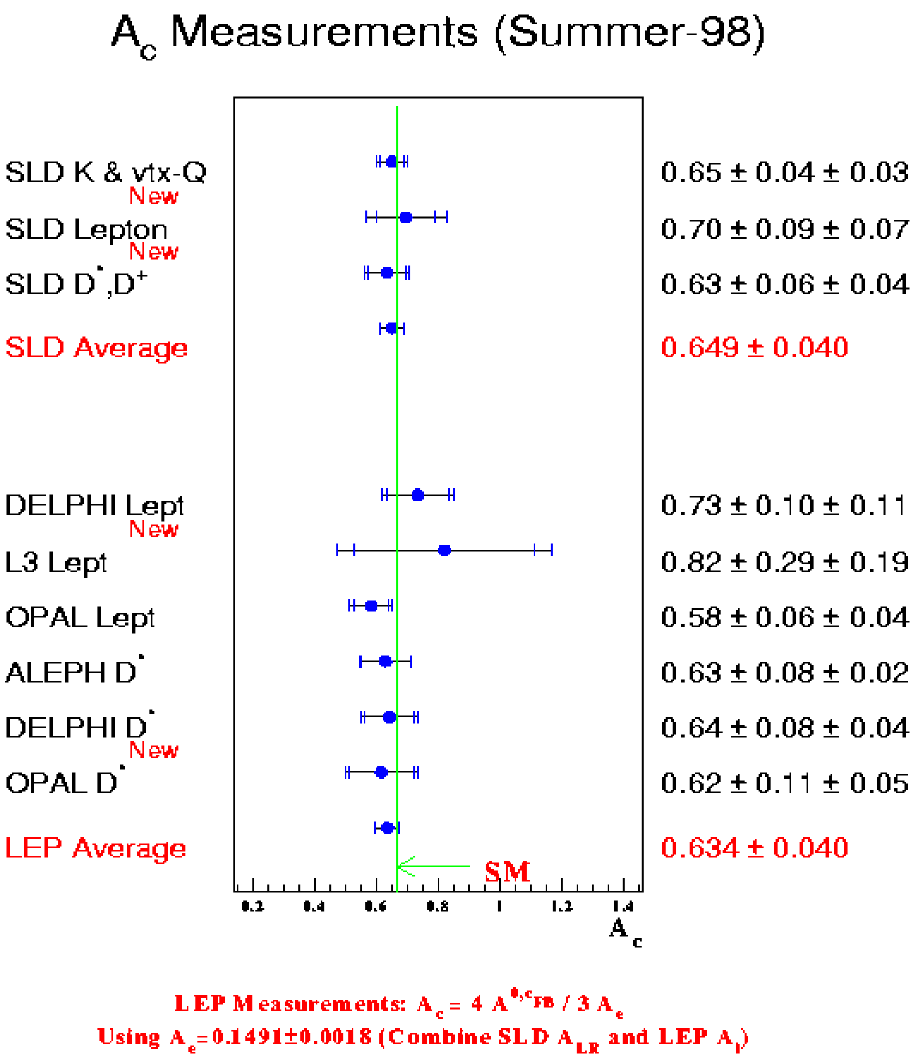

Figure 5: World average results for the charm quark asymmetry parameter from Z decay

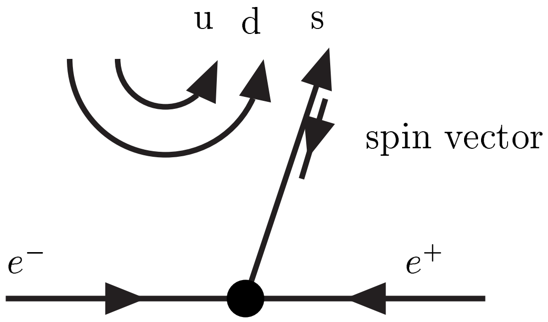

Figure 6: Fragmentation of polarized strange quark from $e^- e+ \to Z \to s\bar{s}$

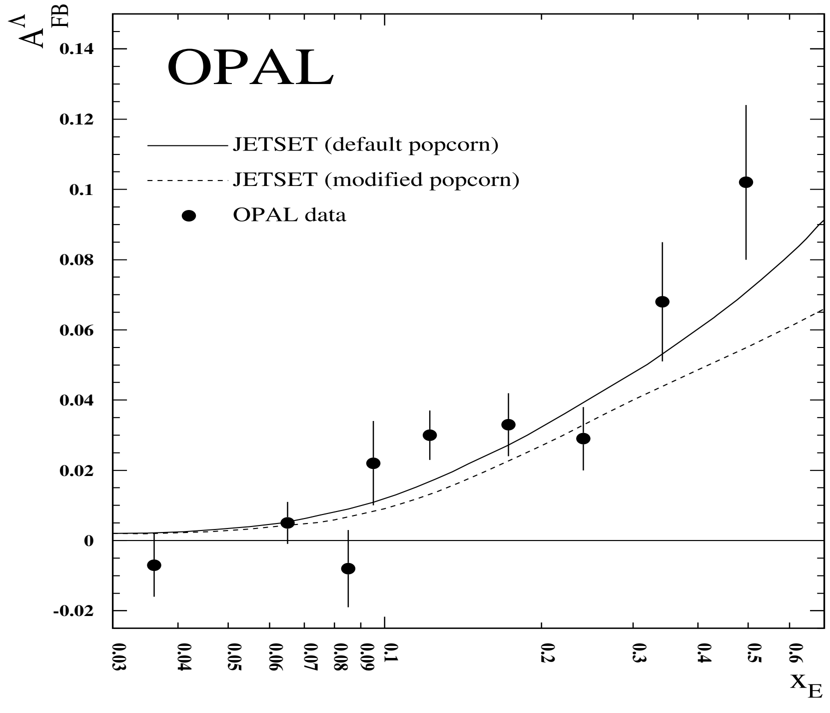

Figure 7: Lambda helicity as a function of x_E as a measure of s quark helicity in $Z \to \bar{s}s$