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Production of Charm and Beauty in e^+e^- with Polarized Electron Beam [1]

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Abstract

The test of the Standard Model through the measurements of Z^0 to fermion couplings can benefit from much enhanced sensitivity by using longitudinally polarized electron beams. This report reviews preliminary electroweak measurements from SLD on heavy quark production at the Z^0, using 150,000 hadronic Z^0 decays accumulated during the 93-95 runs with high electron beam polarization. The parity violating parameters A_b and A_c of the Zbb and Zcc couplings are measured directly from the left-right forward-backward asymmetries. A measurement of R_b with a lifetime double tag and a summary of the preliminary measurement of $A_{\rm LR}$ from the 93-95 SLD data are also included in this report.

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The measurements of the Z^0 couplings to the variety of fermions is an important part of the precision tests of the Standard Model (SM). Possible new physics beyond the Standard Model may manifest themselves through the radiative corrections to these couplings. The measurements of Z^0 couplings to heavy quarks are of especial interest due to the expectation of more pronounced radiative corrections to the ZQQ vertex with Q being a heavy quark, both within the SM and from extensions beyond the SM.

The SLC operates with e^+e^- beams colliding at the Z^0 resonance energy. The successful deployment of a strained lattice GaAs photocathode as the source of a highly polarized electron beam, presents the opportunity for a unique set of precision electroweak measurements with enhanced sensitivity for the test of the SM. The SLD experiment at SLC has collected 100,000 hadronic Z^0 events in the 1994-1995 run, with a preliminary measurement of the average luminosity-weighted electron beam longitudinal polarization of 77.3$\pm$0.6%. All preliminary measurements described in this report are based on these data and are combined with the measurements from the 50,000 Z^0's taken during the 1993 run with 63.0$\pm$1.1% polarization. Descriptions of the SLD detector components can be found in the reference sections of the individual analysis papers cited.

1 The $A_{\rm LR}$ Measurement

The left-right asymmetry is defined and related to the SM parameters as

$$A^0_{\rm LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e = \frac{2v_e a_e}{v_e^2 + a_e^2} = \frac{2[1-4\sin^2\theta_W^{\rm eff}]}{1+[1-4\sin^2\theta_W^{\rm eff}]^2}$$

where σ_L and σ_R are the $e^+e^- \to Z^0$ production cross sections at the Z^0 pole for a left- and right-handed electron beam respectively. This indicates that $A_{\rm LR}$ is very sensitive to $\sin^2\theta_W^{\rm eff}$ with $\delta A_{\rm LR} \sim 8 \cdot \delta \sin^2\theta_W^{\rm eff}$ for $\sin^2\theta_W^{\rm eff} = 0.23$. The analysis method of the SLD preliminary measurement of $A_{\rm LR}$ with 1994-1995 data is similar to that for the 1993 data [1]. The preliminary 1994-1995 measurement of $A_{\rm LR}$ (after dividing the beam polarization from the raw left-right asymmetry, and including small corrections for background, detector, and center of mass energy effects) is:

$$A^0_{\rm LR} = 0.1524 \pm 0.0042\ ({\rm stat}) \pm 0.0012\ ({\rm sys}).$$

The preliminary result combining all 1992-1995 data from SLD is:

$$A^0_{\rm LR} = A_e = 0.1551 \pm 0.0040$$

$$\sin^2\theta_W^{\rm eff} = 0.23049 \pm 0.00050,$$

which is the most precise single measurement of $\sin^2\theta_W^{\mathrm{eff}}$. This result is consistent with the combined LEP $\sin^2\theta_W^{\mathrm{eff}}$ result using all measurements from the $Z^0 \to \ell\ell$ events [4] assuming lepton universality: $A_\ell = 0.1464 \pm 0.0039$ and $\sin^2\theta_W^{\mathrm{eff}} = 0.23160 \pm 0.00049$.

2 The R_b Measurement

The preliminary SLD R_b measurement [3] uses a lifetime double-tag technique similar to the method used by ALEPH [2]. This method allows a simultaneous measurement of R_b and the hemisphere b-tag efficiency ϵ_b to reduce systematics associated with Monte Carlo (MC) modelling of ϵ_b. The unambiguous 3D hits from the SLD CCD pixel vertex detector enable a cleaner track reconstruction such that the impact parameter distribution tails are well reproduced by the MC. The overall track impact parameter resolutions are 11 μm and 38 μm in the $r\phi$ and rz projections respectively at high momentum, while multiple scattering contributions are $70/p\sin^{3/2}\theta$ in both projections. The average interaction point in the $r\phi$ view from $\sim$30 sequential hadronic events provides a robust estimate of the event primary vertex (PV) at 7 μm precision, while the event by event determination of the PV z coordinate has a precision of $\sim$35 μm [5].

The hemisphere probability of all tracks compatible with the PV is calculated from individual track 3D impact parameters and used to tag the hemispheres in $b\bar{b}$ events. For the nominal R_b result, a cut of $\log_{10}$(Hemisphere Prob.) <-3 is used to tag b-hemispheres. The choice of this cut is based on an optimization for a minimal total R_b error, as can be seen from Fig. 1. The efficiencies of tagging uds and c hemispheres according to MC are 2.3% and 0.087% respectively at this cut. The b-hemisphere correlations also estimated from the MC are -0.2%. The measured ϵ_b from the data is $31.3 \pm 0.6_{\mathrm{stat}}$%, consistent with the MC prediction of 30.6%. The corresponding hemisphere b-tag purity is 94%.

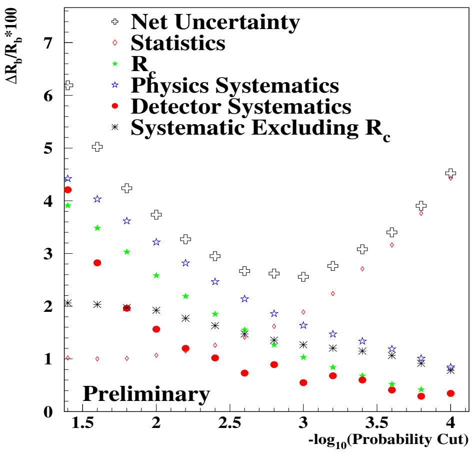

Figure 1: R_b measurement error components as a function of the hemisphere probability tag.

Systematic source	$\delta R_b/R_b$	Systematic source	$\delta R_b/R_b$
Correlation systematics		Charm systematics	
B lifetime	0.03%	D lifetime	0.15%
B-decay multiplicity	0.14%	D-decay multiplicity	0.87%
$B \to D$ model	0.02%	$c \to D$ fractions	0.57%
b fragmentation	0.30%	c fragmentation	0.56%
Λ_b fraction	0.31%	$R_c = 0.171 \pm 0.017$	1.05%
MC statistics	0.41%	MC statistics	0.26%
Light quark systematics		Detector systematics	
K, Λ production	0.04%	V^0 rejection	0.85%
$g \to c\bar{c}, b\bar{b}$	0.19%	Tracking efficiency	0.41%
MC statistics	0.11%	Impact resolutions	0.35%
		Beam position tails	0.29%

Table 1: R_b measurement systematic errors.

Assuming a SM value of $R_c = 0.171 \pm 0.17$, the obtained preliminary result is

$$R_b = 0.2171 \pm 0.0040\ (\text{stat}) \pm 0.0037\ (\text{sys}) \pm 0.0023\ (R_c).$$

A detailed breakdown of the systematic errors is shown in Table 1. Similar to many other R_b measurements, the b-tag purity of 94% can be improved slightly by sacrificing efficiency, but it is still difficult to contain the systematics to well below 1%. The development of an ultrahigh purity ($\sim$99%) b-tag is needed to improve systematics in conjunction with more data in the future.

3 The A_b, A_c Measurements

The extent of parity violation in the Zff coupling for fermion f can be expressed as the observable

$$A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{2v_f a_f}{v_f^2 + a_f^2},$$

which is complimentary to the observables measuring the coupling strengths $\propto v_f^2 + a_f^2$, such as R_b. In particular, A_b, A_c are more sensitive to the right-handed Zbb, Zcc couplings than R_b, R_c, which are predominantly left-handed observables. For $Z^0 \to f\bar{f}$ events with final state fermion f at polar angle $z = cos\theta$, with respect to the electron beam, the Born level expression for conventional forward-backward asymmetry is

$$A_{\text{FB}}^f(z) = \frac{\sigma^f(z) - \sigma^f(-z)}{\sigma^f(z) + \sigma^f(-z)} = A_e A_f \frac{2z}{1+z^2}.$$

The availability of the electron beam helicity information allows the formation of the left-right forward-backward asymmetry

$$\tilde{A}^f_{\mathrm{FB}}(z) = \frac{[\sigma^f_L(z) - \sigma^f_L(-z)] - [\sigma^f_R(z) - \sigma^f_R(-z)]}{[\sigma^f_L(z) + \sigma^f_L(-z)] + [\sigma^f_R(z) + \sigma^f_R(-z)]} = |P_e| A_f \frac{2z}{1+z^2},$$

where P_e is the electron beam longitudinal polarization. The use of $\tilde{A}^f_{\mathrm{FB}}$ eliminates the dependence on the initial state A_e, to measure the final state A_f directly. The achieved high $|P_e|$ of $\sim$77% at SLC/SLD also brings a large gain of $(P_e/A_e)^2 \sim 25$ in statistics, compared to conventional A^f_{FB} on the sensitivity to A_f. The effects of detector acceptance and efficiency non-uniformity also cancel to first order for this double asymmetry. All asymmetry measurement results described in this section include QCD corrections in the final fit. Most measurements apply $cos\theta$-dependent QCD corrections, including quark mass effects at $\mathcal{O}(\alpha_s)$ and using massless quark calculations at $\mathcal{O}(\alpha_s^2)$ according to Ref. [7].

3.1 The A_c measurement using reconstructed D^{*+}, D^+

This is an updated analysis from the measurement on the 1993 data [6] to include all 1993–1995 data. The $D^{*+} \to \pi_s^+ D^0$ decays are reconstructed by a combination of kinematic and decay length analyses for the decay modes $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+(\pi^0)$ without explicit π^0 reconstruction. $D^+ \to K^-\pi^+\pi^-$ decays are reconstructed, requiring a good D^+ vertex displaced from the PVBoth the D^* decay length and the D^+ analyses benefit from high resolution 3D vertexing and precise knowledge of the PV at SLD in order to suppress D mesons from $b\bar{b}$ events and the random combinatorial background (RCBG), as they mostly do not point to the PV. The distributions of $D^{*+} - D^0$ mass differences (Δm) and distribution of the $D^+ \to K^-\pi^+\pi^-$ mass are shown in Fig. 2.

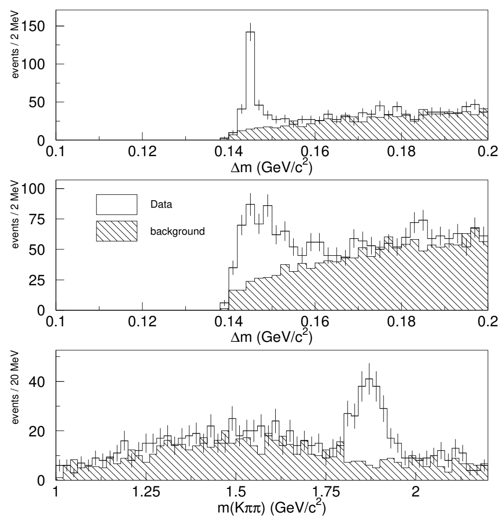

Figure 2: Distributions of $D^* - D^0$ mass difference for $D^0 \to K^-\pi^+$ (top), $D^0 \to K^-\pi^+(\pi^0)$ (middle) modes, and $D^+ \to K^-\pi^+\pi^-$ mass (bottom).

The signal sidebands are used to estimate the background fraction and asymmetry. A maximum likelihood fit for the combined sample is used to extract A_c, taking into account the information on $D^{(*)}$ momentum-dependent fractions of $c\bar{c}, b\bar{b}$ signal and background components. The preliminary result obtained is:

$$A_c = 0.64 \pm 0.11 \text{ (stat)} \pm 0.06 \text{ (sys)}.$$

The dominant systematics related to the RCBG, as shown in Table 2, are largely statistical in nature, so they are expected to be reduced with a larger data sample.

Systematic source	δA_c
RCBG fraction	0.039
RCBG asymmetry	0.028
$c - D/b - D$ fraction	0.011
$b - D$ asymmetry	0.018
b-fragmentation	0.011
c-fragmentation	0.016
Beam polarization	0.007
QCD correction	0.007
$A_b = 0.935 \pm 0.090$	0.012
Total systematic	0.058

Table 2: Systematic errors of A_c measurement from D^{*+}, D^+.

3.2 The A_b, A_c measurements using leptons

This is an updated measurement based on the analysis of the 1993 data [8], to include all 1993-1995 data. The identified muons and electrons are used to enrich the $b\bar{b}, c\bar{c}$ events and the charge of the leptons is used to assign the relevant jet axis direction as quark or antiquark direction. The MC simulation is used to estimate the population fractions of different sources of lepton candidates as a function of the lepton momentum P and transverse momentum P_T to jet axis. The MC B meson semileptonic decay simulation uses the ISGW** model [9] with a 23% D^{**} fraction. A maximum likelihood fit is performed with lepton P, P_T dependent MC weights to extract A_b, A_c simultaneously. The preliminary results combining all 1993-1995 data are:

$$A_b = 0.87 \pm 0.07 \text{ (stat)} \pm 0.08 \text{ (sys)}$$

$$A_c = 0.44 \pm 0.11 \text{ (stat)} \pm 0.13 \text{ (sys)}.$$

The detailed list of the systematic errors can be found in Table 3. The statistical correlation between the A_b and A_c results is 18%. Among the presently significant systematics, jet axis simulation and MC weighting systematics are expected to reduce with improved analysis in the future.

3.3 The A_b measurement using momentum-weighted track charge

This is an improved measurement [10] from the analysis on the 1993 data [11]. This preliminary measurement using all 1993-1995 data, adopts a self-calibrated

Systematic source	δA_b	δA_c	Systematic source	δA_b	δA_c
Lepton mis-ID rate	0.020	0.026	b-fragmentation	0.004	0.016
Background asymmetry	0.010	0.026	c-fragmentation	0.010	0.026
Jet axis simulation	0.043	0.030	$\mathrm{Br}(b \to \overline{c} \to \ell)$	0.003	0.030
MC weights	0.032	0.032	$\mathrm{Br}(b \to \tau \to \ell)$	0.002	0.015
Tracking efficiency	0.012	0.009	$\mathrm{Br}(c \to \ell)$	0.003	0.023
$R_b = 0.218 \pm 0.002$	−0.006	0.006	$b \to \ell$ model	0.008	0.008
$R_c = 0.171 \pm 0.014$	0.006	−0.037	$c \to \ell$ model	0.037	0.042
$\overline{\chi} = 0.120 \pm 0.010$	0.017	0.000	Beam polarization	0.011	0.006
$\mathrm{Br}(b \to \ell) = 10.80 \pm 0.78\%$	−0.016	0.030	QCD correction	0.008	0.040
$\mathrm{Br}(b \to c \to \ell) = 9.3 \pm 1.6\%$	0.011	−0.075	Total systematic	0.078	0.132

Table 3: Systematic errors for A_b, A_c measurements using leptons.

technique to measure the analyzing power (AP) from the data, resulting in a much reduced MC dependency. The $b\overline{b}$ events are tagged at 61% efficiency by requiring ≥ 3 tracks with $r\phi$ impact parameter $> +3\sigma$ from the PV. The tagged sample contains 12000 events with 89% b-purity. The hemisphere momentum-weighted track charge sum and difference for each event are calculated from

$$Q_{\text{sum}} = \sum_{\text{tracks}} q_i |(\vec{p}_i \cdot \hat{T})|^{\kappa} \qquad \text{and} \qquad Q_{\text{diff}} = -\sum_{\text{tracks}} q_i \cdot \mathrm{sgn}(\vec{p}_i \cdot \hat{T}) |(\vec{p}_i \cdot \hat{T})|^{\kappa}$$

where q_i and $\vec{p}_i$ are the track charge and momentum, and $\hat{T}$ is the unit vector along the thrust axis, signed so that $Q_{\text{diff}} > 0$, making $\hat{T}$ an estimator of the b quark direction. A value of $\kappa = 0.5$ ius chosen to maximize the AP. The tagged-event raw signed thrust axis $\cos\theta$ distributions from left-handed and right-handed electron beams are shown in Fig. 3 for the 1994-1995 data. The correct b direction signing probability for an event with $|Q| = |Q_{\text{diff}}|$ is parameterized as $P(Q) = 1/(1 + e^{-\alpha_b |Q|})$ where α_b is calibrated using the measured widths of the Q_{sum} and $|Q_{\text{diff}}|$ distributions from the data. This calibration includes a correction for an $\sim 3\%$ hemisphere charge correlation estimated from the MC, is mainly due to the event overall charge conservation imposed on the hadronization process. A maximum likelihood fit is used to extract A_b, taking into account $|Q|$-dependent AP and event flavor composition as a function of b-tag track multiplicity. The preliminary result, including all 1993-1995 data, is:

$$A_b = 0.843 \pm 0.046 \text{ (stat)} \pm 0.051 \text{ (sys)}.$$

A breakdown of systematic errors is listed in Table 4. Among the significant systematic errors, the hemisphere charge correlation systemic is estimated from the difference between various MC fragmentation models. The calibration statistical

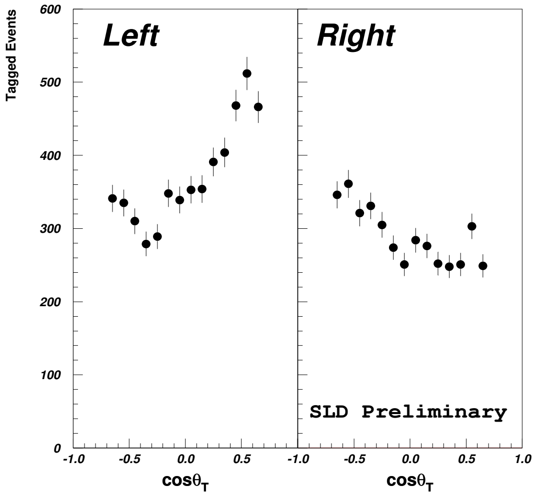

Figure 3: Distributions of raw signed thrust axis cosθ for 1994-1995 data.

Systematic source	$\delta A_b/A_b$
α_b calibration statistics	3.4%
$P(Q)$ shape	1.0%
cosθ dependence of α_b	1.5%
Hemisphere charge correlation	3.7%
Light flavor subtraction	0.2%
$c\bar{c}$ analyzing power	0.2%
b-tag flavor composition	2.6%
$A_c = 0.67 \pm 0.07$	1.0%
$A_{bckg} = 0 \pm 0.50$	0.6%
Beam polarization	0.8%
QCD correction	0.9%
Total	6.2%

Table 4: Relative systematic errors on the A_b measurement using momentum weighted track charge.

error and b-tag composition systematic will improve with more data in the future and adjustments in the b-tag procedure.

3.4 The A_b measurement using identified charged kaons

The exploration of the abundant $\overline{B} \rightarrow D \rightarrow K^-$ decay signal for $B/\overline{B}$ separation has been widely promoted as a new technique for a variety of B physics measurements. This new preliminary measurement [12] is the first application of this technique for a b-asymmetry measurement. Charged kaons with a momentum of 3–20 GeV are identified using the gas-radiator data of the SLD Cerenkov Imaging Detector. The MC $\pi \rightarrow K$ mis-identification rate is corrected via a calibration using tracks in the 1-prong and 3-prong τ decays that have well known small rates of $K^\pm$ production.

The $b\bar{b}$ events are selected with a 2D impact parameter tag similar to that described in the last subsection. Particle identifications corresponding to a $K : \pi$ efficiency ratio of $\sim$ 12 : 1 are performed on selected tracks with an $r\phi$ impact parameter $> +1.5\sigma$. The kaon candidate charges are summed in each hemisphere and the difference between the two hemisphere charges is used to determine the polarity of the thrust axis for b-quark direction. The kaon charge signing is successful for 30% of the tagged events, and 71% of the $b\bar{b}$ events have correct b direction signing. For events with both hemispheres signed by kaons, the hemisphere charge opposite-sign fractions are $62.4 \pm 2.9\%$ and $61.9 \pm 1.5\%$ in the data and MC, respectively. This gives a consistency check of the MC analyzing power.

The $udsc$ background subtracted left-right forward-backward b asymmetry, $\tilde{A}^{\rm corr}_{\rm data}$, is then formed as a function of cosθ. The $\tilde{A}^b_{\rm MC}$ is formed from MC b events through the same analysis. The A_b measurement is obtained by scaling $\tilde{A}^b_{\rm MC}$ to fit the data, as shown in Fig. 4. This fit effectively includes QCD corrections as in the JETSET MC. The preliminary result from the 1994-1995 data is:

$$A_b = 0.91 \pm 0.09 \text{ (stat)} \pm 0.09 \text{ (sys)}.$$

The systematic errors are listed in Table 5. Most of the detector and physics systematics associated with the uncertainty of b-event analyzing power can be removed with a calibration from the double hemisphere charge comparison, trading for a calibration statistical error when more data are included in the future.

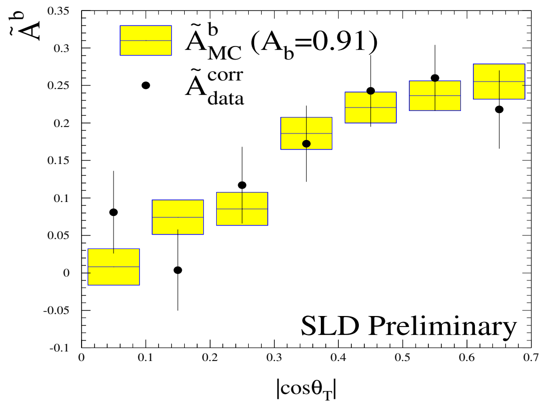

Figure 4: Distribution of kaon signed left-right forward-backward asymmetry.

Systematic source	$\delta A_b/A_b$
Kaon mis-ID	0.053
Tracking efficiency	0.019
MC statistics	0.030
B production/mixing	0.040
$B \to D$ model	0.011
B vertex K yield	0.041
Charm decay K yield	0.030
uds K production	0.011
b, c-fragmentation	0.007
Tag composition	0.002
$A_c = 0.666 \pm 0.070$	−0.014
Beam polarization	0.007
QCD correction	0.009
Total systematic	0.094

Table 5: Systematics of the A_b measurement using identified $K^{\pm}$.

3.5 The combined A_b, A_c results

The preliminary SLD measurements presented in this section are combined with a simultaneous fit to A_b and A_c, taking into account the systematic correlations between measurements. The assumed values and uncertainties of other related parameters are listed, together with the combined results in Table 6. These results can be compared with the average LEP measurements of $A_b = 0.884 \pm 0.032$ and $A_c = 0.642 \pm 0.053$, as well as with the SM prediction of $A_b = 0.935$ and $A_c = 0.666$. The LEP averages are derived from the $A_{\rm FB}^{0,b}$ and $A_{\rm FB}^{0,c}$ results [4], assuming $A_e = 0.1506 \pm 0.0028$ from a combination of the SLD $A_{\rm LR}$ and the LEP A_ℓ results mentioned in Section 1.

Assumed parameters	
R_b	0.218 ± 0.002
R_c	0.171 ± 0.014
$\mathrm{Br}(b \to \ell)$ (%)	10.80 ± 0.78
$\mathrm{Br}(b \to c \to \ell$ (%)	9.3 ± 1.6
B mixing $\overline{\chi}$	0.130 ± 0.010
Combined results	
A_b	0.858 ± 0.054
A_c	0.577 ± 0.097
A_b, A_c correlation	12.3%

Table 6: Combined SLD A_b, A_c results and assumed parameter values.

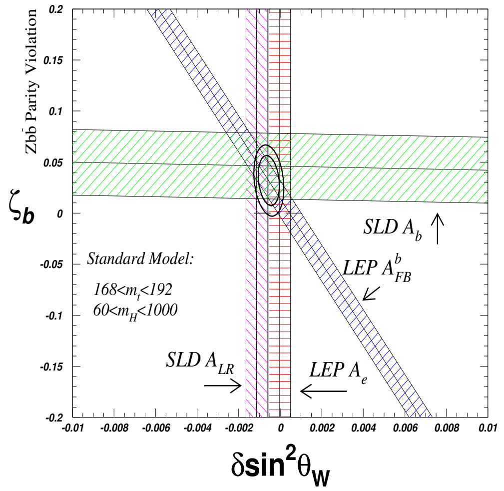

Figure 5: *Zbb* coupling parity violation versus $\sin^2\theta_W^{\rm eff}$.

Following the scheme of a full *Zbb* coupling analysis proposed by Takeuchi *et al.* [13], the deviations from the SM can be generally represented as a cross section like variable ξ_b and a parity violation like variable ζ_b, in addition to $\delta\sin^2\theta_W^{\rm eff}$. The ζ_b versus $\delta\sin^2\theta_W^{\rm eff}$ plot for various current experimental results is shown in Fig. 5. The SM point at (0,0) is defined by m_t=180 GeV, m_H=300 GeV, α_s=0.117 and α_{em}=1/128.96. The thin horizontal band around (0,0) corresponds to the SM m_t, m_H variations indicated in the plot. The 68% and 90% C.L. contours for the best fit to all measurements are also shown.

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