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PRECISION TESTS OF THE STANDARD MODEL AT ELECTRON COLLIDERS*

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Abstract

We review electroweak physics studies in high-energy e^+e^- collisions at CERN and SLAC. Studies of couplings of the Z^0 boson to many of the fundmental fermions are now quite detailed, and those of the $W^\pm$ bosons are well under way. Sensitivity to radiative corrections due to the massive top quark, the as yet undiscovered Higgs boson, and new physics at the TeV scale has been achieved. The Standard Model is consistent with all data, although further studies are indicated in several areas. In the absence of new physics, the Higgs mass is limited to <188 GeV/c^2 at 95% C.L.

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1 Introduction

The Standard Model (SM) of elementary particle physics comprises 12 fundamental fermions f, three flavors each of charged leptons ($f = e^-, \mu^-, \tau^-$), neutrinos (ν_e, ν_μ, ν_τ), up-type quarks (u, c, t) and down-type quarks (d, s, b), that interact via three forces. Each force is described by a fundamental symmetry, and we hope to find a higher symmetry that encompasses all three. Here we consider the electroweak (EW) interaction, which is understood in terms of an SU(2)$\times$U(1) gauge symmetry that is broken spontaneously by the 'Higgs mechanism'. Three of the guage bosons, the W^+, W^- and Z^0, become massive, the photon γ is massless and a scalar Higgs boson remains to be discovered.

The EW SM includes ~17 free parameters: 4 are generally considered fundamental constants of nature; 4 describe quark mixing; the rest are particle masses. It is convenient to consider three roughly independent parts of the EW interaction. The γ couples to the electric charge Q_f of a fermion f and accounts for ordinary electromagnetism, which is described by QED with a single fundamental constant $\alpha = 1/137.035989(6)$ [1]. The $W^\pm$ bosons are 'purely weak', coupling to the third component of weak isospin T_3^f with equal and opposite vector (V) and axial-vector (A) contributions proportional to the constant $G_F = 11.6639(1)(\hbar c)^3\mathrm{TeV}^{-2}$ [1]. Lepton flavor changing is not allowed; the only experimental questions are whether $V-A$ suffices to describe the structure of $Wl\nu$ interactions, and if the $We\nu_e$, $W\mu\nu_\mu$ and $W\tau\nu_\tau$ couplings are equal (lepton universality). In the quark sector the Wq_uq_d coupling for any up-type quark $q_u = i$ and any down-type quark $q_d = j$ is proportional to the magnitude of the CKM matrix element V_{ij}. In the SM, $\mathbf{V}$ is unitary, so only four real parameters are needed to describe the nine complex observables.

The Zff couplings include both electromagnetic and weak components, with axial-vector and vector couplings

$$a_f \propto -T_3 \qquad \text{and} \qquad v_f \propto T_3 - 2Q\sin^2\theta_W, \tag{1}$$

respectively, where the weak mixing angle θ_W is predicted given α, G_F and a third fundamental constant, e.g. the Z^0 mass, m_Z. There are 24 experimental observables, conventionally $R_f = \Gamma_{f\bar{f}}/\Gamma_{had} \propto a_f^2 + v_f^2$ and $A_f = 2a_fv_f/(a_f^2 + v_f^2)$, calculable from eqns. (1) at tree level and expected universal ($R_e = R_\mu = R_\tau$, etc.). Measurements of R_f and A_f to a few percent precision test the structure of the theory; more interesting are measurements at the <1% level, at which sizeable radiative corrections are expected from known and potential new physics.

The large radiative corrections due to strong interactions are conventionally absorbed into a total hadronic cross section σ^0_{had}. Others are absorbed into an effective angle $\sin^2\theta_W^{eff}$, which depends linearly on the top mass m_t and logarithmically on the Higgs mass m_H, such that eqns. (1) hold to a good approximation. The values of $\sin^2\theta_W^{eff}$ and m_W are rather sensitive to m_H and a variety of new physics. New physics might also modify a set of R_f or A_f; R_{dsb} and A_{dsb} are particularly sensitive to new left- and right-coupled physics, respectively. New high-scale physics might violate universality, perhaps most strongly for the b-quark.

The R_f are observable as branching ratios, and the A_f via both asymmetric distributions of the angle θ_f between the f and the e^-, and the f-polarizations,

$$d\sigma_f/d\cos\theta_f \quad \propto \quad (1-A_eP_e)(1+\cos^2\theta_f)+2A_f(A_e-P_e)\cos\theta_f, \tag{2}$$
$$P_f \quad \propto \quad (1-A_eP_e)(1+\cos^2\theta_f)A_f+2(A_e-P_e)\cos\theta_f, \tag{3}$$

where the e^- beam has longitudinal polarization P_e and the e^+ beam is unpolarized. For $P_e=0$, $d\sigma_f/d\cos\theta$ is only sensitive to the product of initial and final state couplings A_eA_f and the asymmetries are small. Large $|P_e|$ induces large asymmetries, and using both left- and right-polarized beams, $P_e=-|P_e|$ and $+|P_e|$, allows direct measurements of both A_e and A_f through the difference in total cross sections (left-right asymmetry) and the weighted difference in asymmetries (left-right-forward-backward asymmetry), respectively. The polarization P_f of the outgoing f allows direct access to A_f, via the average $\langle P_f\rangle$, and A_e, via the dependence on $\cos\theta_f$. The expected P_f is large for the quarks, but the f must be spin analyzed, which has so far only been done for $f=\tau^-$.

Programs to study this physics in detail have been under way for a decade at the LEP ring at CERN and the SLAC Linear Collider (SLC). LEP is a conventional e^+e^- storage ring that delivered 4 million hadronic events at a center-of-mass energy $E_{CM}=m_Z$ to each of four experiments, and has since been increasing E_{CM}, delivering substantial data above W^+W^- threshold. A higher energy e^+e^- storage ring would require a dramatic increase in size from LEP's 27 km circumference. The SLC is a step in an alternative direction; it is a single-pass collider featuring high $|P_e|=0.73$ and a very small transverse collision region, 0.8×1.8 μm, which both increases luminosity (enhanced by the recently observed pinch effect) and greatly enhances the flavor tagging capabilites of the experiment. SLC shut down last year after achieving impressive luminosity and delivering over 0.5 million hadronic Z^0s. The four LEP experiments, ALEPH, DELPHI, L3 and OPAL, and the SLD experiment at SLC, were designed with unprecedented hermeticity, luminosity monitoring, vertexing, and lepton (L3) and hadron (DELPHI, SLD) identification, which have been instrumental to the physics program.

2 Physics of the Z^0 Boson

The Z^0 resonance is a very clean experimental environment. Real Z^0 production is the dominant process and easy to separate from other physics and backgrounds. Negligible energy is lost to initial state radiation. The Z^0 decays into $\nu\bar{\nu}$ are not detected, but the charged lepton ($Z^0\to l^+l^-$) decays are identified easily. At $E=45.6$ GeV, $e^\pm$ and $\mu^\pm$ are stable; e^+e^- or $\mu^+\mu^-$ decays yield back-to-back 45.6 GeV/c tracks that deposit their energy in the EM calorimeter or penetrate the muon detectors, respectively. The $\tau^\pm$ decays include 1–5 fairly energetic collinear tracks. The lepton flavor and the l^- polar angle are thus measured readily.

The $q\bar{q}$ decays are problematic; since the strong interaction is confining, quarks are not observable directly, but appear as jets of $\sim$20 hadrons. At high energy, the multiplicity and

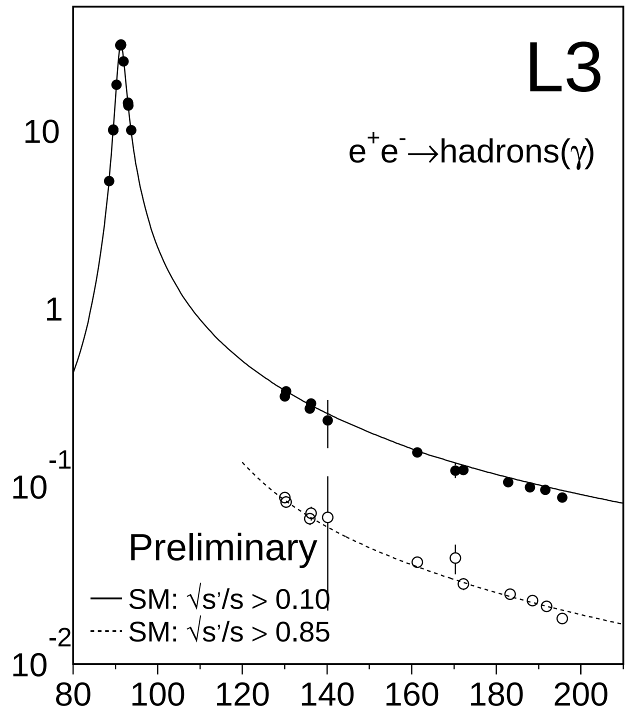

Figure 1: Hadronic cross section in pb vs. cm-energy in GeV.

topology of back-to-back, collimated jets identify $q\bar{q}$ decays and allow the measurement of $|\cos\theta_q|$. The experimental challenge is to identify the event flavor (for R_q), and to separate the q-jet from the $\bar{q}$ jet (for A_q).

A The Total Hadronic Cross Section

The cross section for inclusive hadronic final states has been measured at many E_{CM} at LEP. Data from L3 are shown in fig. 1; the Z^0 resonance is prominent with a long radiative tail. Events with $E_{visible} > 0.85 E_{CM}$ (open circles) account for under half the data and show the expected $1/E^2_{CM}$ behaviour for $E_{CM} \gg m_Z$. A SM fit (solid line) describes the data well. Current LEP average parameter values from such fits are [2]:

$$
\begin{aligned}
m_Z &= 91.1872 \pm 0.0021 \ \text{GeV/c}^2 \\
\Gamma_Z &= 2.4944 \pm 0.0024 \ \text{GeV} \\
\sigma^0_{had} &= 41.544 \ \pm 0.037 \ \ \text{nb.}
\end{aligned}
$$

The relative precision on m_Z of 2.3×10^{-5} reflects advances in luminosity measurement and theory, detector modelling, and most notably in beam energy monitoring to 1–2 MeV. This quantity is used as the third fundamental constant of the SM, so that any other observable can be predicted modulo corrections due to m_H and new physics. The precision on Γ_Z gives some sensitivity to m_H, with a 95% C.L. upper limit of $\sim$700 GeV/c^2; the exact limit depends on m_t and α_s, for which more precise measurements are desirable.

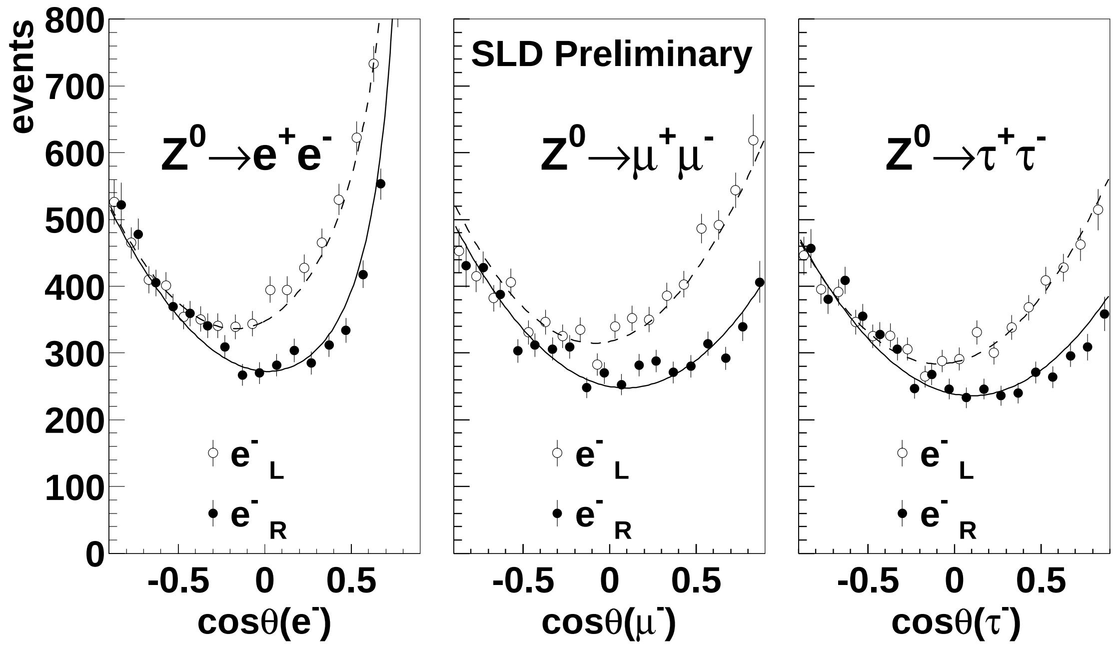

Figure 2: Lepton polar angle distributions with SM fits.

B Couplings to the Charged Leptons

Cross sections for the $Z^0 \to l^+l^-$ have also been measured at LEP; the extracted m_Z and Γ_Z are included in the above averages. Cross section ratios yield [2]

$$1/R_e = 20.803 \pm 0.049, \qquad 1/R_\mu = 20.786 \pm 0.033, \qquad 1/R_\tau = 20.764 \pm 0.045,$$

consistent with the SM and providing a 0.3% test of lepton universality. Taking the SM R_ν, any non-SM decay width of the Z^0 is limited to Γ_{inv} <2.0 MeV at 95% C.L. This implies no undiscovered particle with $m < m_Z/2$; in particular, if a fourth fermion generation exists, it must include a very massive neutrino.

SLD has made a precise measurement of A_e from the left-right cross-section asymmetry, $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$, on the Z^0 peak, where $\sigma_{L(R)}$ is the hadronic cross section for $P_e < 0$ (> 0). A simple counting of hadronic events yields $A_e = 0.1514 \pm 0.0022$ [3], which is statistics dominated due to good understanding of the P_e measurement. The A_l have also been measured using the (left-right-)forward-backward asymmetries in $\cos\theta_l$ (eqn. 2). Distributions measured by SLD for e^-, μ^- and τ^- are shown in fig. 2. The asymmetries are small, but visible, and differences in both normalization and slope between left- and right-polarized e^- beams are evident. Measurements of A_e, A_μ and A_τ with 6–10% precision have been made by each experiment. The LEP experiments have also spin-analyzed the $\tau^\pm$ in several decay modes, measuring P_{τ^-} vs. $\cos\theta_{\tau^-}$ and extracting (eqn. 3) ~6% measurements of A_τ and A_e.

All measurements of lepton asymmetries are consistent, and the world average values [2], $A_e = 0.1513 \pm 0.0019$, $A_\mu = 0.1449 \pm 0.0090$ and $A_\tau = 0.1422 \pm 0.0042$, give a 7% test

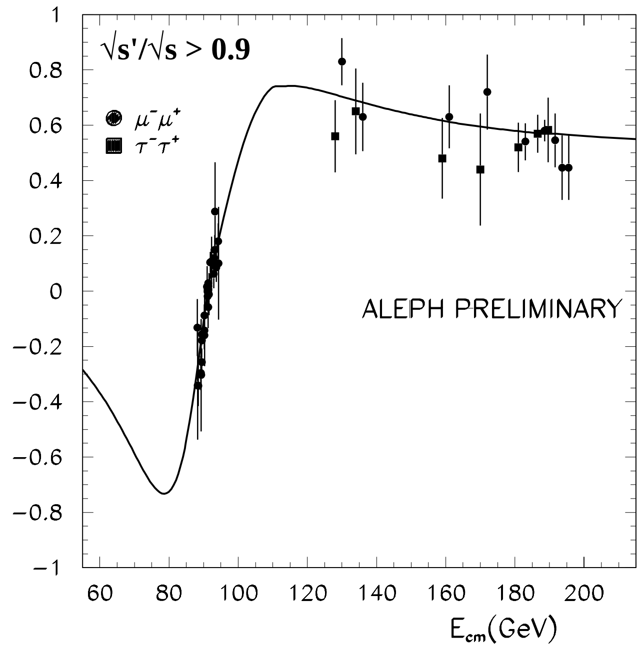

Figure 3: Lepton forward-backward asymmetries $A_{FB}^{\mu,\tau}$ vs. E_{CM}

of lepton universality. Assuming universality, a grand average

$$A_{lepton} = 0.14979 \pm 0.00157, \qquad \sin^2\theta_W^{eff} = 0.23117 \pm 0.00020,$$

is a robust measurement of the effective weak mixing angle with <0.1% precision. Assuming the SM and no new physics, a value of $\ln m_H$ can be extracted, with a 95% confidence interval of $\sim$10< m_H <$\sim$110 GeV/c^2. There is theoretical debate at the few GeV/c^2 level; a better measurement of $\alpha(m_Z^2)$, via the $e^+e^- \rightarrow$hadrons cross section at low energy, would be useful. The upper limit is tantalizingly near the lower limit of $\sim$105 GeV/c^2 from direct searches.

Effective couplings have been measured vs. E_{CM} at LEP. The ALEPH asymmetry data in fig. 3 display the strong dependence on E_{CM}, especially near m_Z, expected in the SM (solid line) due to interference between γ and Z^0 exchange.

C Couplings to the Heavy Quarks

Great strides have been made at SLC and LEP in identifying heavy (b or c) jets. A b-jet contains a massive, energetic, leading bottom (B) hadron that, on average, flies 3 mm at the Z^0 and decays into 10 hadrons. Reconstruction of B hadrons is impractical, but modern vertex detectors can identify displaced vertices inclusively. Very few secondary B hadrons are produced in jet fragmentation, so all five experiments have obtained samples of 98% $b/\bar{b}$ purity with efficiencies of ϵ =20–60%. Separation of b from $\bar{b}$ jets has used the charge of identified $l^{\pm}$ from the decay (low ϵ, high analyzing power ap), identified $K^{\pm}$, or the net charge of tracks in the jet or vertex (high ϵ, low ap). Leading charmed

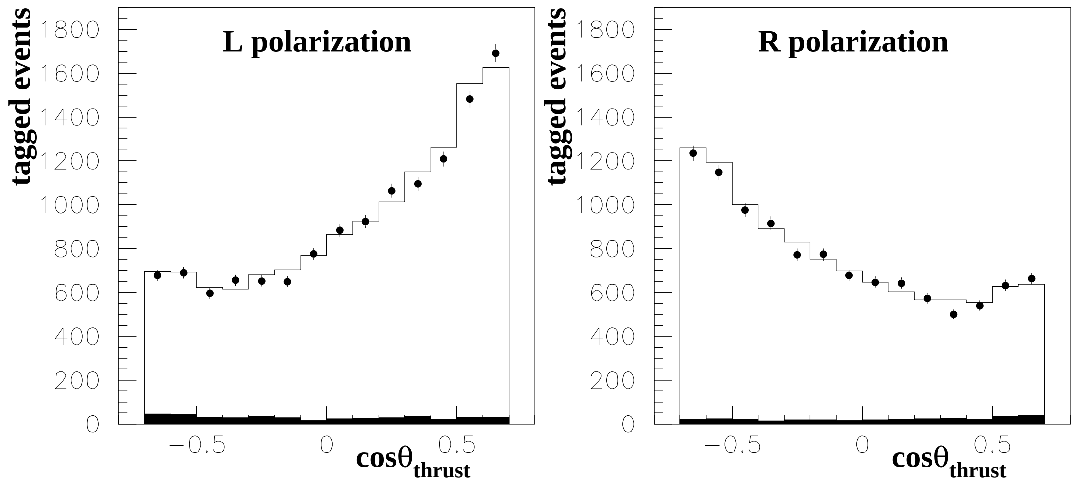

Figure 4: b-quark polar angle distributions.

(D) hadrons in c jets have lower mass, energy, decay multiplicity and lifetime, and are produced rarely in jets but copiously in B decays. Vertex detectors help separate these two sources, making both D reconstruction (unit ap) and inclusive tagging useful.

The key to making precise measurements of R_q (A_q) is to measure the relevant ϵ (and ap) from the data, rather than using a simulation. For R_b, such 'self-calibration' is routine. One can, e.g., define a $b/\bar{b}$ jet tag and take advantage of the presence of both a b and $\bar{b}$ jet by counting the number N_b of tagged jets and N_{bb} of events with a tag in each jet. One solves the two equations

$$\begin{aligned} N_b/2N_{event} &= R_b\epsilon_b + \Sigma_{f=udsc}R_f\epsilon_f \\ N_{bb}/N_{event} &= R_b\epsilon_b^2\lambda_b + \Sigma_{f=udsc}R_f\epsilon_f^2\lambda_f \end{aligned} \tag{4}$$

for R_b and ϵ_b. For high purity, the backgrounds have small effects on the measured values; the correlation λ_b typically dominates the systematic error. The world average $R_b = 0.21642 \pm 0.00073$ [2] has 0.3% precision and is sensitive to m_t; it is consistent with the SM given the known m_t. A few R_c measurements are self-calibrated. Tags for $c/\bar{c}$ have substantial background only from $b/\bar{b}$, and one can, e.g., solve a set of five equations including (4) for R_c, R_b, ϵ_b and the c-tag rates η_c and η_b, since the remaining ϵ_q and η_q are small. The world average value [2] $R_c = 0.1674 \pm 0.0038$ is consistent with the SM within its 2.3% uncertainty.

There are many measurements of A_b and A_c (A_eA_b, A_eA_c at LEP) using a variety of methods. Some are self-calibrated, e.g. a new A_b from SLD that uses the net charge of tracks in a vertex, and derives both its purity and its ap from the data using doubly tagged events and comparing charges. The $\cos\theta_b$ distributions in fig. 4 show large asymmetries and this measurement is the world's most precise. An average A_b can be taken by dividing each LEP A_eA_b by the above A_{lepton}. The result, $A_b = 0.894 \pm 0.015$, is 2.7 standard deviations below the SM prediction $A_b = 0.935$. A similar average $A_c = 0.627 \pm 0.021$ is 2.1σ below the SM prediction $A_c = 0.673$. Further work is clearly needed in this area, especially any using new and/or self-calibrating methods.

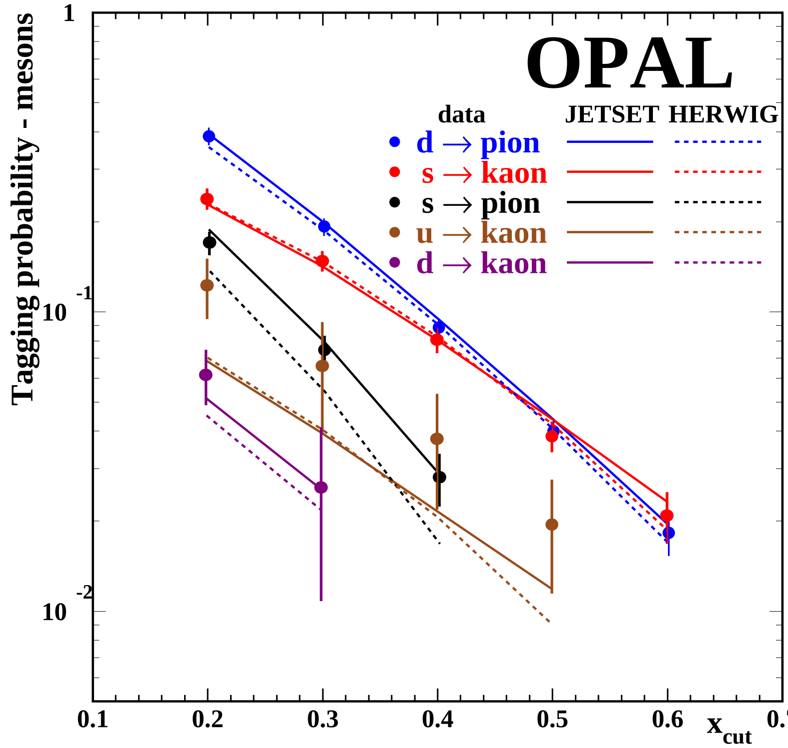

Figure 5: Integral identified particle spectra vs. a cut on $x = 2p/E_{CM}$.

D Couplings to the Light Quarks

In contrast, the field of light-flavor Zuu, Zdd and Zss couplings is in its infancy. Light-flavor jets can also be identified using their leading particles, e.g. an s-jet may produce a leading K^- or Λ^0. However these particles have lower average energy than B or D hadrons and the same particle species are produced copiously in the fragmentation process, as well as in B and D decays, especially at low momentum. Most importantly, a leading K^- (Λ^0) may also be produced in a $\bar{u}$ (u or d) jet.

Since these aspects of jet fragmentation are not well measured, one must either rely on a model or perform a complicated self-calibration. The OPAL collaboration have done the latter [4], using five flavor tags, identified $\pi^\pm$, $K^\pm$, K_s^0, p/$\bar{\text{p}}$, and $\Lambda^0/\bar{\Lambda}^0$ with $p > 22.8$ GeV/c. A set of 20 equations similar to eqns. (4) can be solved for R_u, R_d and 15 ϵ. The equations are not independent, and statistics force a number of reasonable assumptions to be made, including $R_d = R_s$, however the resulting $R_u/(R_u+R_d+R_s) = 0.371 \pm 0.023$ is consistent with the SM prediction and a useful 6% test of up-type universality. To measure the A_q OPAL solves an additional 14 equations for 8 ap using 4 assumptions. The resulting $A_u = 0.36 \pm 0.65$ and $A_d = A_s = 0.61 \pm 0.33$ (where A_e has been divided out) are statistics limited, but this analysis is most encouraging and should be pursued by other experiments. Interesting related measurements include the first $\pi^\pm$ and $K^\pm$ spectra in u, d and s jets [5] shown in fig. 5, which already provide new and stringent model tests.

SLD and DELPHI have concentrated on measuring A_s only, using high-momentum K^- (K^+) to tag s ($\bar{s}$) jets. DELPHI [6] relies on a fragmentation model to predict the

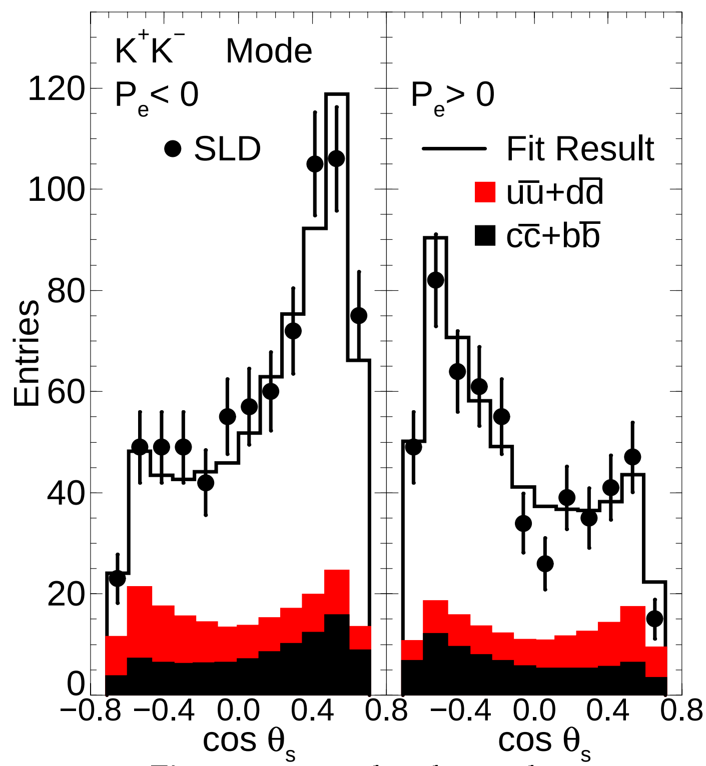

Figure 6: s-quark polar angles.

purity (53%) and ap (74%), obtaining a statistics dominated $A_s = 0.909 \pm 0.108$. SLD [7] require an opposite-sign $K^{\pm}$ or a K^0_s in the opposite jet to enhance signal, obtaining the $\cos\theta_s$ distributions shown in fig. 6. Jets and events with multiple identified kaons are used to calibrate the purity (66%) and ap (82%) with a modest model-dependence, yielding $A_s = 0.895 \pm 0.091$. These results provide an important 7% test of d-type universality, but full self-calibration will be needed for substantial improvement.

3 Physics of the $W^{\pm}$ Bosons

Much W physics is studied via τ decays and B^0-$\bar{B}^0$ mixing at the Z^0. LEP is now delivering the first monoenergetic $W^{\pm}$ samples in $e^+e^- \to W^+W^-$ at $E_{CM} > 2m_W$. Each W decays to 2 jets or an energetic $l\nu$, and progress has been rapid in distinguishing such events from the large backgrounds and measuring their properties.

A Couplings to the Leptons

The constant G_F has been measured precisely at lower energies and is universal within 0.5%. Large samples of polarized $\tau^- \to W^-\nu_\tau, W^- \to e\nu_e, \mu\nu_\mu$ decays allow detailed studies of the structure of the $Wl\nu$ interaction in $e^+e^- \to \tau^+\tau^-$. A general Lorentz-invariant coupling gives a τ-rest-frame spectrum of $x = E_l/E_l^{max}$ (scaled $l^{\pm}$ energy) of the form

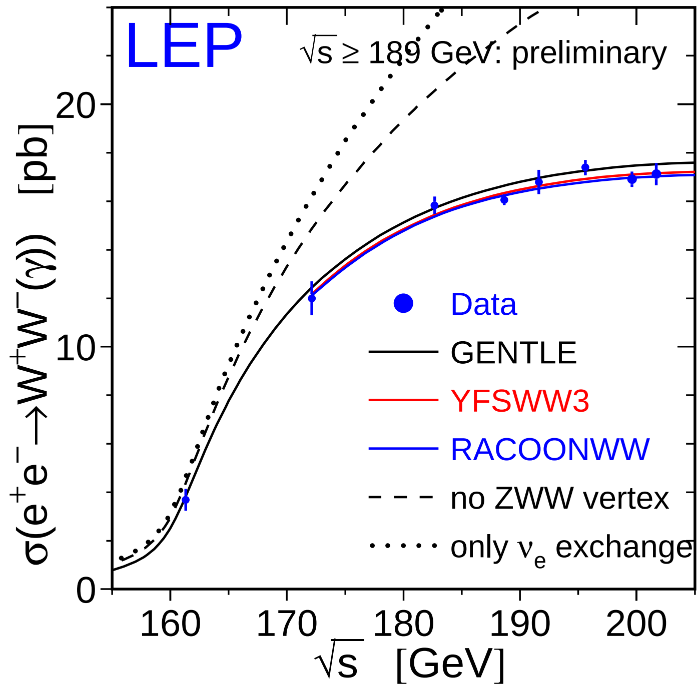

Figure 7: $e^+e^-\to W^+W^-$ cross section.

$d\sigma/x^2dx = 9f_1 + \rho f_2 + 6\eta m_l f_1/x m_\tau - P_\tau \xi \cos\phi\,[3f_1 + \delta f_2]$, where $f_1 = 1-x$, $f_2 = 8x-6$, ϕ is the angle between $\vec{p}_l$ and the τ spin, and in the SM the Michel parameters are $\rho = \delta = 0.75$, $\eta = 0$ and $\xi = 1$. Detailed analyses of lepton spectra at the Z^0 and $\Upsilon(4S)$ exploit the $\cos\theta$-dependence of P_τ and/or the anticorrelation between the τ^+ and τ^- helicities, and yield world averages [8] of

$$\rho = 0.752 \pm 0.008, \qquad \eta = 0.035 \pm 0.031, \qquad \xi = 0.978 \pm 0.031, \qquad \xi\delta = 0.745 \pm 0.021,$$

limiting departures from $V-A$ structure of $Wl\nu$ interactions to the few % level.

Weak dipole moments probe CP-violation and τ substructure. In a general $Z\tau\tau$ coupling $\propto \gamma_\mu(v_\tau - a_\tau\gamma_5) + i\sigma^{\mu\nu}\{a^w_\tau/m_\tau - 2id^w_\tau\gamma_5/e\}\cos\theta_W \sin\theta_W$, the electric d^w_τ and anomalous magnetic moments a^w_τ modify transverse P_τ. All Z^0 experiments (L3 and SLD) have measured a^w_τ (d^w_τ, enhanced by $|P_e| \gg 0$). The averages [9]

$$\begin{array}{llll} Re(a^w\tau) = & 0.22 \pm 1.13 \times 10^{-3} & , & Re(d^w\tau) = -0.02 \pm 0.15 \times 10^{-17}\ \mathrm{e\ cm}, \\ Im(a^w\tau) = & -0.03 \pm 0.66 \times 10^{-3} & , & Im(d^w\tau) = -0.13 \pm 0.29 \times 10^{-17}\ \mathrm{e\ cm}, \end{array}$$

are consistent with zero and becoming sensitive to a variety of new physics.

B Production, Mass, Width and Branching Ratios

Selection of W^+W^- events is well advanced at LEP; the current average cross section, shown vs. E_{CM} in fig. 7, is consistent with the SM and shows that Z^0, γ, t-channel

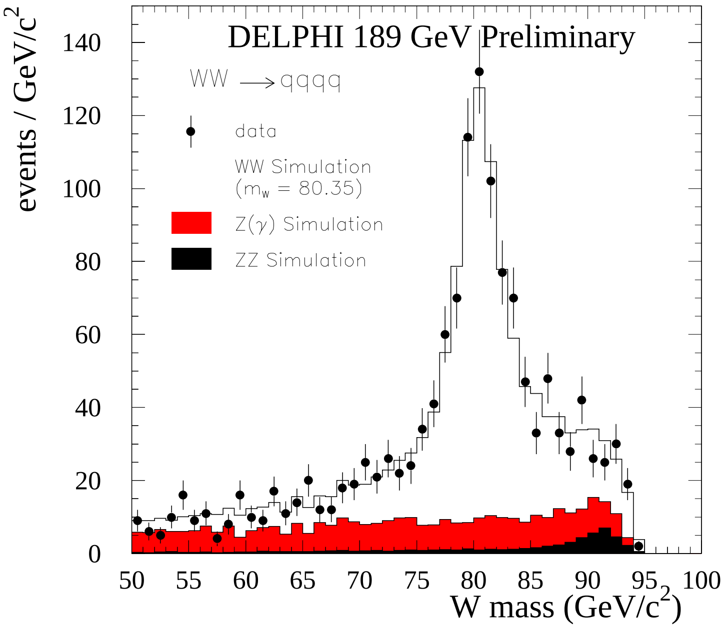

Figure 8: Sample $W^{\pm}$ mass distribution.

neutrino exchange, and their interference are all required to describe the data. Studies are under way of the structure of these events, i.e. W polar angles, helicities, etc., and have already set relative limits of 5–10% on some classses of non-SM contributions [2].

The W boson mass has received much attention due to its sensitivity (given m_Z) to m_H. Individual $W^{\pm}$ masses can be reconstructed from 2-jet or $l\nu$ decays, but the resolution is poor and in 4-jet events there is a 3-fold ambiguity in the jet pairing. Constraints such as 4-momentum conservation, $m_{W^+} = m_{W^-}$, $\vec{p}_{W^+} = -\vec{p}_{W^-}$, etc., give improved resolution, as e.g. in fig. 8 for 4-jet events from DELPHI. The 4-jet events give the best resolution and statistics, but are subject to uncertainties in the mass scale due to final-state interactions. The current LEP average [2]

$$m_W = 80.401 \pm 0.049 \text{ GeV/c}^2$$

corresponds to a rather low $m_H \approx 100$ GeV/c^2.

The SM predicts the W^- decay widths to $l^-\nu_l$ and, in terms of the CKM elements $|V_{ij}|$, to the six allowed $\bar{q}_u q_d$ modes i=u, c, j=d, s, b. As for Z^0s, the $l^-\nu_l$ decays are easy to identify; the $e\nu$, $\mu\nu$ and $\tau\nu$ branching ratios are measured to 3% [2]. They are consistent, with an average of $BR(W \to l\nu) = 10.68 \pm 0.13\%$ that is consistent with the SM.

The ratios R_{ij}=$BR(W^- \to \bar{i}j)/\ BR(W^- \to$ hadrons) provide robust, theoretically clean probes of the relative $|V_{ij}|$. However one must identify the jet flavors, and the $\bar{i}b$ modes are rare. Three experiments have combined vertex and identified $K^{\pm}$ information to separate the two dominant modes, $\bar{u}d$ and $\bar{c}s$, and measure R_{cs}=0.50±0.03 and $|V_{cs}|$=0.99±0.07. The precision is not yet useful, however this result along with the heavy- and light-flavor results from the Z^0 give confidence that precise measurements could be made at a future e^+e^- collider.

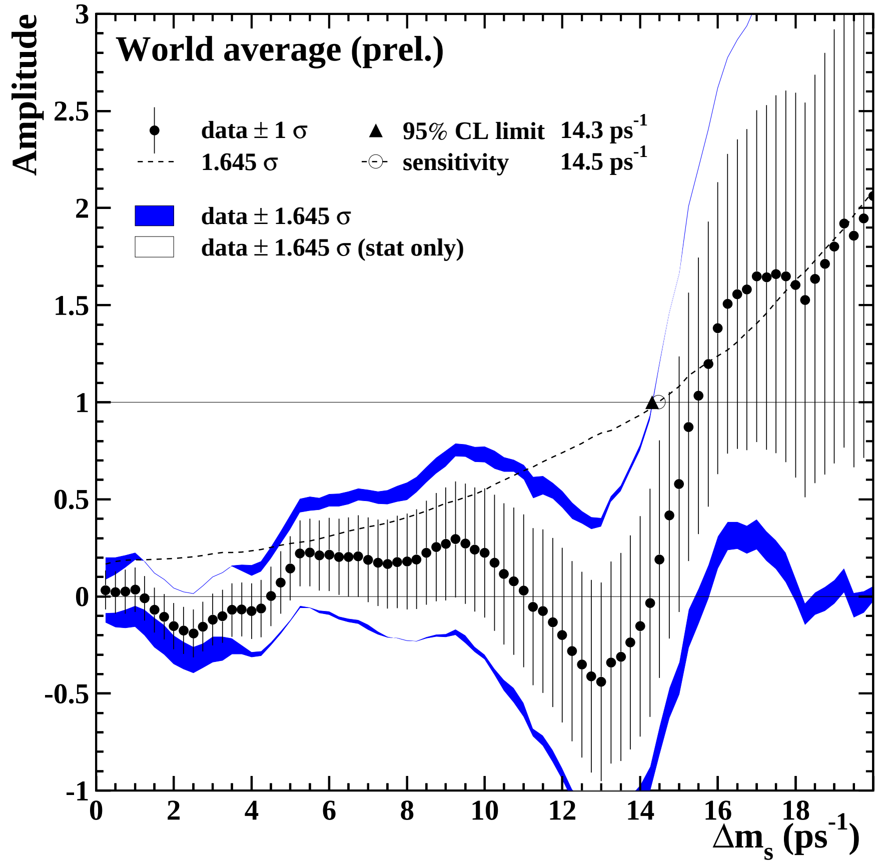

Figure 9: Combined world amplitude plot for B_s^0-$\bar{B}_s^0$ mixing.

C B^0-$\bar{B}^0$ Mixing

The CKM element V_{td} (V_{ts}) can be probed via B_d^0-$\bar{B}_d^0$ (B_s^0-$\bar{B}_s^0$) mixing, but with an unfortunate theoretical uncertainty. To measure Δm_d, one must tag $B_d^0/\bar{B}_d^0$ decays and determine the flavor (B^0 or $\bar{B}^0$) at both production and decay time, preferably vs. proper decay time. Since 40% of b jets give a B_d^0, the above $b/\bar{b}$ and decay flavor tags are used. The flavor at production is tagged using information from the opposite jet, P_e, and same-jet tracks not assigned to the decay. Many measurements from LEP/SLC, and CDF and the $\Upsilon(4S)$ show clear, slow oscillations. The average Δm_d=0.476±0.016 ps^{-1} [10] corresponds to $|V_{td}|$=0.0088±0.0002(expt.)±0.0018(theory).

There is no evidence for B_s^0-$\bar{B}_s^0$ mixing despite valiant effort. Only ~10% of b jets contain a B_s meson and the oscillation is very fast, demanding excellent proper time resolution σ_τ. Theoretical errors partly cancel in the ratio $|V_{ts}|/|V_{td}|$, with implications (below) for the CKM matrix, so much work is going into B_s tagging and σ_τ in the race to observe B_s^0 mixing. In the 'amplitude method', Δm_s is fixed and the amplitude A of an oscillation fitted. If the $\langle A\rangle$ at a given Δm_s is $>1.65\sigma$ below unity, that Δm_s is excluded at the 95% C.L. The world average amplitude plot [10] is shown in fig. 9. The 95% C.L. limit of $\Delta m_s>14.3$ ps^{-1} corresponds to $|V_{td}|/|V_{ts}|<0.228$.

4 Interpretation

Each result given above is consistent with the SM and a fairly low Higgs boson mass m_H. We now consider this body of data as a whole, and include some non-SLC/LEP measurements, notably m_t, m_W and Δm_s from the Tevatron, as well as world averages of the running strong coupling $\alpha_s(m_Z^2)$ and fine structure $\alpha(m_Z^2)$.

A The Standard Model Higgs Boson

The fundamental question of consistency of the SM with the world's body of data is plagued by correlations among the measurements. The LEP ElectroWeak Working Group performs the arduous task of considering all the data [2]. Their global one-parameter fit gives $\ln m_H = 1.82 \pm 0.30$ and $\chi^2/\text{dof} = 22.9/15$. Thus the SM is consistent with the data at 8.5% C.L., and $m_H < 188$ GeV/c^2 at 95% C.L.

Smaller limits are given above, and the χ^2 is driven by the very precise A_{lepton} and A_b. If A_b is removed, $\chi^2/\text{dof} \approx 1$ and $m_H < 110$ GeV/c^2. Several general parametrizations of radiative corrections allow one to look beyond the SM, such as the S-T projection [11], fig. 10. A model gives a point on this plot; the SM with $m_H = 100$ GeV/c^2 and $m_t = 175$

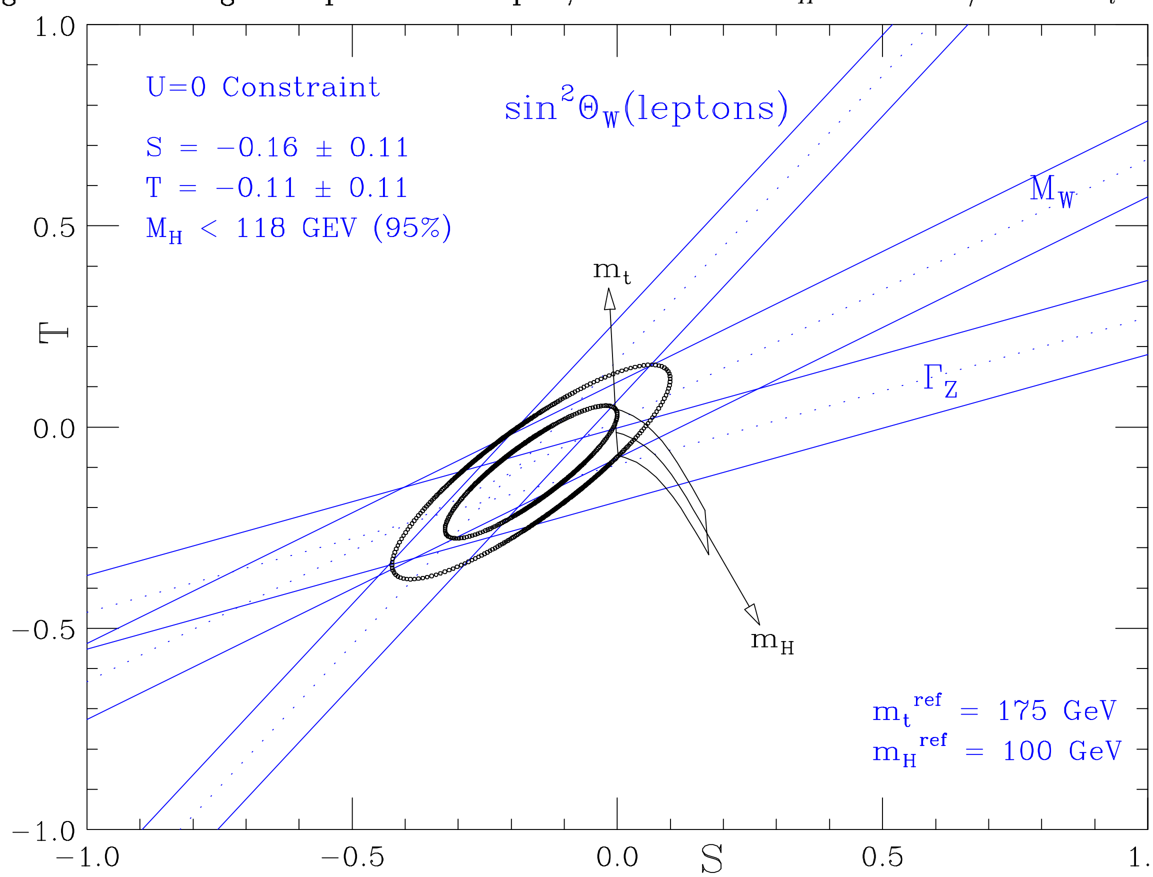

Figure 10: The current S-T plot, along with a fit to non-hadronic data.

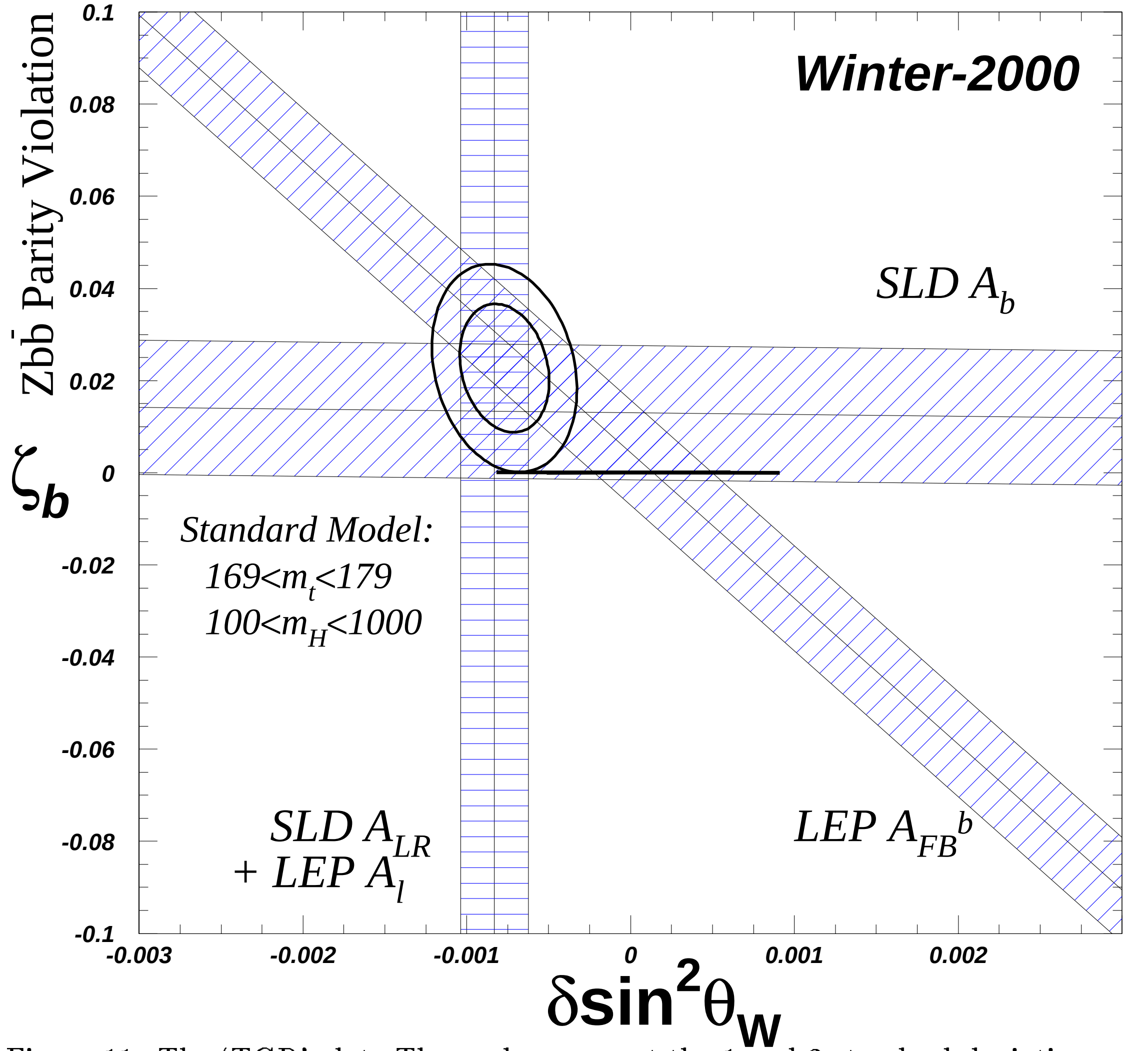

Figure 11: The 'TGR' plot. The ovals represent the 1 and 2 standard deviation contours of a fit to the three measurements.

GeV/c^2 defines the origin; δm_t gives width to an arc representing 0.1< m_H <1 TeV/c^2. A measurement gives a band; three 'clean' measurements sensitive to m_H are shown, A_{lepton}, m_W and Γ_Z. All are consistent with the SM with a low value of m_H and their overlap restricts the parameter space considerably.

Figure 11 [12] shows the status of A_{lepton} and A_b. The A_{lepton} and SLD A_b bands are nearly orthogonal, with the LEP A_eA_b band at about 45°. The measurements are consistent, and a fit is 2.0σ from the SM (thick line through the origin in fig. 11). The discrepancy is not significant, but is in the b sector, has persisited at 2–3.5σ for years, and the A_{lepton} and A_eA_b bands cross the SM 2.7σ apart, so work continues to resolve this issue.

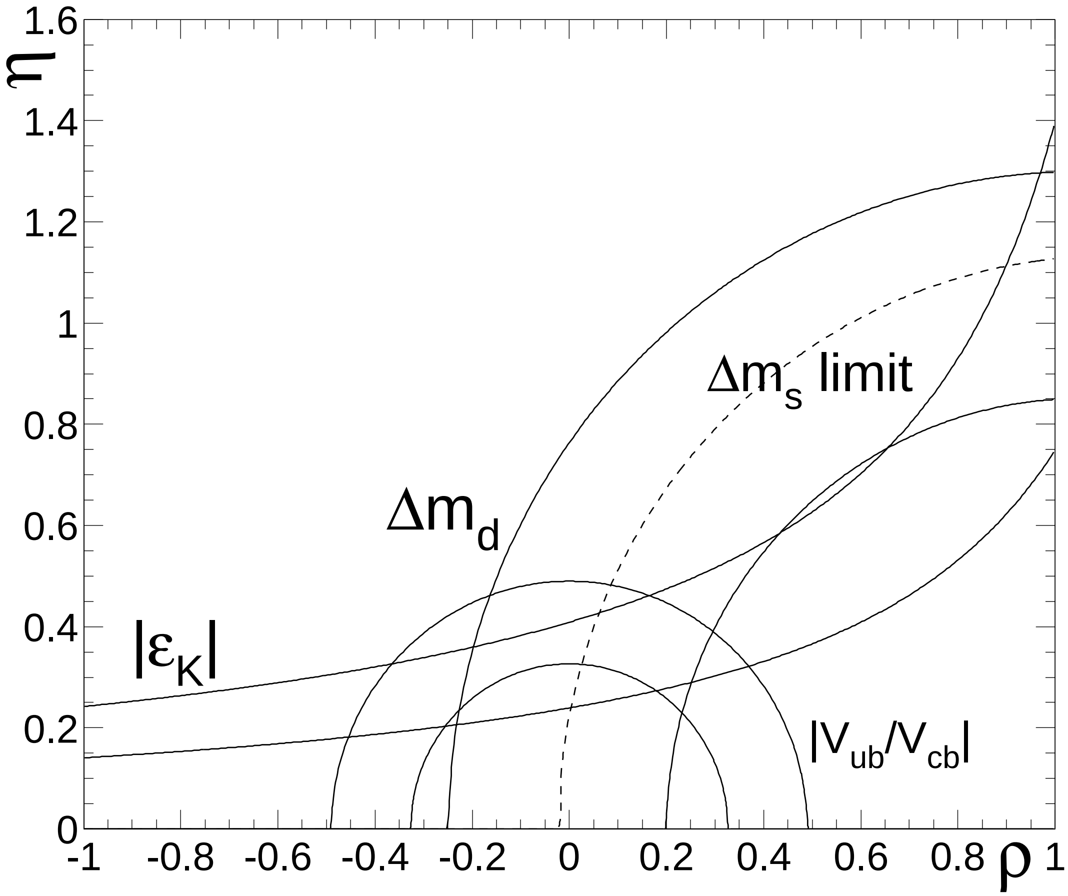

Figure 12: Current experimental limits in the ρ-η plane.

B The Unitarity Triangle

Figure 12 shows a number of limits in the 'ρ-η' plane, a conventional paramatrization of CP violation in the SM context. Bands from K^0 decay (ϵ_K), B decay ($|V_{ub}|/|V_{cb}|$) and B_d^0 mixing overlap, but the errors do not restrict the angles of the unitarity triangle ((0,0), (ρ,η), (0,1)) strongly. In the SM context, the B_s^0 mixing results give an outer limit indicated by the dashed line in fig. 12, that cuts the allowed region in half. As B_s^0 mixing is being pursued vigorously in Z^0 data, we should either observe it soon or restrict the allowed (ρ,η) region considerably.

5 Summary and Conclusion

The high energy e^+e^- programs at CERN and SLAC have had tremendous success in testing the SM precisely, and LEP continues to do exciting $e^+e^- \to W^+W^-$, Z^0Z^0, etc. physics. The Z^0 mass is now known to 2.3×10^{-5} relative, but the Higgs boson remains unseen. Several measurements are sensitive to m_H and new physics via radiative corrections. No non-SM physics has been seen, although a 2σ issue remains in the b sector.

Fitting the world's data yields $m_H <$188 GeV/c^2 at 95% C.L.; the non-b data suggest a limit near the direct search limit, $m_H >$105 GeV/c^2.

We are therefore on the verge of either discovering the Higgs boson or demonstrating the need for non-SM physics, and we will soon observe the very rapid oscillation of B_s mesons or demonstrate non-unitarity of the CKM matrix. The energy and luminosity of current accelerators is, alas, likely to give ambiguous answers to these questions. They can be addressed effectively, and new and existing tests performed precisely, at a future e^+e^- collider with E_{CM} of 90–300 GeV. The time has come for the community to converge on the choice of such a machine.

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