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Measurement of the Total Hadronic Cross Section and Determination of γ-Z Interference in e^+e^- Annihilation

TOPAZ Collaboration

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Abstract

The total hadronic cross section in e^+e^- annihilation was measured at $\sqrt{s}$=57.77 GeV to be σ_h = 143.6±1.5(stat)±4.5(sys) pb with only the QED corrections. The measurement was based on data corresponding to an integrated luminosity of 90.8pb^{-1} accumulated by the TOPAZ detector at TRISTAN. Our data point put stringent constraints on the size of the γ-Z^0 interference and the Z^0 mass. Combining our data with the OPAL data at LEP, we obtained the coefficient of the interference and the Z^0 mass to be J_{had}=0.10±0.26 and $\bar{M}_Z$=91.151±0.008 GeV, respectively, in a model-independent analysis.

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1 Introduction

The total hadronic cross section in e^+e^- annihilation is one of the most fundamental observables used to test the Standard Model (SM)[1]. Our previously published results were based on data taken during the 1987-1989 period at $\sqrt{s} = 50.0 \sim 61.4$GeV with an integrated luminosity of 29pb^{-1}[2]. They were presented as the Born cross section corrected using the electroweak theory.

It was recently pointed out that measurements of the total hadronic cross section at TRISTAN are indispensable for a model-independent determination of the Z^0 mass by a four-parameter fit using the S-matrix approach[3]. In fact, if we do not assume the SM for γ-Z^0 interference, the error of the Z^0 mass becomes as large as 15MeV[3]. This error can be reduced by a simultaneous fit to the total cross sections at the LEP and TRISTAN energies. Since the published TRISTAN results were presented as the Born cross section, they could not be easily used for such a purpose.

In this paper we present the total cross section with only the QED corrections in Ref.[4]. Since the QED corrections are solely determined by long-distance physics, our result is insensitive to any unknown parameters in short-distance physics, such as the masses of the top quark and the Higgs boson. The obtained results can therefore be used to determine the γ-Z^0 interference without assuming the SM. The used data comprised about 10^4 multi-hadronic events collected by the TOPAZ detector during the 1990-1992 period after installation of a new luminosity monitor[5]. The center-of-mass energy ($\sqrt{s}$) was 57.77GeV[6], and the integrated luminosity was 90.8pb^{-1}, which provided about three-times larger statistics than that of our previously published result. The enhanced statistics led us to a better understanding of the detector system, thereby reducing any systematic errors.

2 Total hadronic cross-section measurement

2.1 Event selection

We selected hadronic events using a Time Projection Chamber (TPC)[7] and a Barrel Calorimeter (BCL) [8]. Our selection criteria were as follows: (1) The number of good tracks had to be ≥ 5, where a good track was required to have (i) a transverse momentum to the beam axis larger than 150 MeV, (ii) a distance of

closest approach to the beam axis(z) less than 5cm in the xy-plane, as well as in the z-direction, and (iii) a polar angle satisfying $0.02 \leq |\cos\theta| \leq 0.77$ to be well-contained in the detector. (2) The visible energy (E_{vis}) had to satisfy $E_{vis} \geq$ the beam energy (E_{beam}), where E_{vis} was the sum of the momenta of the good tracks and the energies of BCL clusters of $E_{BCL} \geq 0.1$GeV. (3) The longitudinal momentum balance had to be $|\sum P_z|/E_{beam} \leq 0.4$, where the P_z's were longitudinal momenta of the good tracks or longitudinal energies of the BCL clusters. This cut, together with cut (2), eliminated most of the two-photon events. (4) The larger of the hemisphere invariant masses had to be ≥ 2.5GeV, where the two hemispheres separated by a plane perpendicular to the thrust axis. The background from τ pairs was effectively eliminated by this cut. (5) Those events with two or more large energy clusters of $E_{BCL} > 0.5E_{beam}$ were discarded in order to reject Bhabha events. (6) In addition, the following cut was employed in order to explicitly veto hard photon radiations from the initial states: there had to be no cluster of $E_{BCL} > 0.7E_{beam}$. These cuts when applied simultaneously yielded 9146 hadronic events in total.

2.2 Derivation of the total hadronic cross section

From the number of the selected events (N_{obs}), the total hadronic cross section can be derived using

$$\sigma_h = \frac{N_{obs} - N_{BG}}{L(1+\delta_{QED})\varepsilon}, \quad (1)$$

where L, $1+\delta_{QED}$, ε, and N_{BG} are the integrated luminosity, the QED correction factor, the efficiency, and the number of estimated background events, respectively.

The integrated luminosity was measured by a Forward Calorimeter (FCL)[5]. The FCL consists of four identical modules. Two of them are placed at Z=±60cm, and called the " Forward-Backward Calorimeter (FBC)"; the remaining two at Z=±120cm are called the "Luminosity Monitor(LUM)". Each module is azimuthally segmented into 12 blocks made of a "BGO crystal" with its front face equipped with a 12-fold-radially-segmented "Si-strip" detector to measure the polar angles (θ) of scattered electrons. The FCL covers an angular region of $3.6° < \theta < 13.6°$. Bhabha events for luminosity determination were selected based on the following criteria: (1) There had to be two energy clusters, one in the forward and the other in the backward BGO calorimeters, each exceeding 15GeV. (2) The difference in the azimuthal angles of the clusters determined by the BGO crystals ($\delta\phi$) had to satisfy

$135° \leq \delta\phi \leq 225°$ in order for the clusters to be back-to-back in ϕ. (3) The polar angles of the clusters were limited to fiducial volumes defined by the Si-strip detectors: we required one Si-strip hit in $3.70° \leq \theta \leq 5.34°$ and, on the opposite z-side, another one in $3.46° \leq \theta \leq 6.3°$ for Bhabha events detected in the LUM, or one in $7.09° \leq \theta \leq 10.2°$ and another in $6.63° \leq \theta \leq 12.0°$ for those detected in the FBC.

The integrated luminosity was determined to be 90.85±0.14(stat)±2.27(sys) pb^{-1}, whose systematic error is described in the next section.

As mentioned in the previous section, the factor $1+\delta_{QED}$ comprises the model-independent QED corrections described in Ref.[4]. The $1+\delta_{QED}$ was calculated using KORALZ3.8[9] in the $O(\alpha^2)+$ exponentiation mode, which is the highest order calculation available at present. In this mode, the interference of the initial and final radiations is not taken into account. Although the interference affects the forward-backward asymmetry by about 1% for quark pair production, the contribution to the total cross section is expected to be negligibly small; it was estimated to be less than 0.06% in the $O(\alpha)$ mode. The resultant value of $1+\delta_{QED}$ is 1.193 for $k_{max} = 0.99E_{Beam}$, M_Z=91.187GeV, M_{Top}=174GeV, and M_{Higgs}=100GeV at $\sqrt{s}$=57.77GeV, while its dependence on the values of M_{Top} and M_{Higgs} was found less than the statistical error of event generation (0.1%). Another calculation of $1+\delta_{QED}$ was executed with the interference of the initial and final radiations using ZFITTER4.5[10], resulting in a $1+\delta_{QED}$ value of 1.193, which agrees with that determined by KORALZ3.8.

Contrary to the situation of the LEP experiments at Z^0, we had a significant number of events discarded by either the visible energy cut [cut (2)] or the longitudinal momentum balance cut [cut (3)], due to undetected hard photons. The estimation of the photonic effects must be more carefully carried out in our case; although the $O(\alpha)$ corrections, containing hard photon radiation, dominantly affected the detection efficiency, higher order QED corrections increased $1+\delta_{QED}$ by 1%, through the effect of multiple emission of soft photons. We thus employed KORALZ in the $O(\alpha^2)+$ exponentiation mode as our event generator in order to estimate the efficiency (ε) together with $1+\delta_{QED}$. The parton showering and hadronization were carried out using LUND6.3[11] with the tuned parameters described in the next section. The generated events were processed through the TOPAZ detector simulator and the aforementioned event selection. The resultant efficiency was ε=57.93% at $k_{max} = 0.99E_{beam}$.

The main background processes were τ pairs and two-photon events. For an

	Total observed events	9146 events
	τ pair	98.9±2.5 events
	Bhabha	≤3.8 events
	$e^+e^- \to \gamma\gamma$	≤ 0.7 events
Two photon	Anti tagged.	7.3 events
	Single tagged.	20.4 events

Table 1: Physical backgrounds

estimation of the τ pair background, we generated 4×10^4 events using the full electroweak calculation of $O(\alpha)$ which was used in our published lepton-pair production analysis[12]. The contributions from two-photon events were estimated based on the Monte-Carlo simulations used in our photon structure function measurement[14] and the inclusive jet measurement[13] for single-tagged and anti-tagged events, respectively. Together with other less-important background processes, their contributions are summarized in Table 1, which were subtracted as in Eq.(1).

For precision measurements, reliable efficiency and background estimations are crucial, which, in turn, require good agreement between the data and the Monte-Carlo simulations. Here, we compare the experimental distributions of key variables with the Monte-Carlo expectations in order to demonstrate the validity of our simulations. In the comparisons, we apply all of the cuts except for the one concerning the quantity in question. Figure 1(a) plots the multiplicity distribution of the good tracks (points with error bars) to be compared with the solid histogram, which is the Monte-Carlo expectation consisting of both the signal and the background. The dashed histogram in the same figure is the sum of all the considered background contributions, which is clustered in the low-multiplicity region and is dominated by τ pair events (shaded histogram). The discrepancies at the lowest two bins are mostly due to cosmic-ray, $e^+e^- \to \mu^+\mu^-(\gamma)$, and $e^+e^- \to e^+e^-l^+l^-$ events, which were not included in our Monte-Carlo simulations, since they were negligible after cut (1). The agreement between the data and the Monte-Carlo prediction is indeed reasonably good above the selection cut indicated in the figure, justifying the use of the Monte-Carlo simulations for both acceptance and background estimations. Figure 1(b) shows, on the other hand, the distribution of the visible energy. The Monte-Carlo prediction (solid histogram) sufficiently well describes the data (points with error bars) above the cut indicated in the figure. The dashed histogram again represents the background total, which is dominated by two-photon events in the low-E_{vis} region and by τ pair events in the high-E_{vis} region. The same kind of observation can be made for Figs.1(c) and (d), which are the distributions of the P_z balance and the larger hemisphere mass, respectively. Notice, in particular, that the background (dashed histogram) in Fig.1(d) comes mainly from τ pair events to which cut (4) is useful.

2.3 Systematic errors

At present, the largest source of systematic errors is the uncertainty in the integrated luminosity measurement by the FCL. The accuracy of the FCL construction and its relative positioning error from the beam line have been described in detail elsewhere[5]. The error of these geometrical origins was estimated to be only 0.45%. On the other hand, the systematic errors due to the uncertainties in the absolute energy scale of the BGO blocks and the efficiency of Si strips were estimated from the difference among the integrated luminosities measured in six angular regions: $3.7° < \theta < 3.9°$, $3.9° < \theta < 4.5°$, $4.5° < \theta < 5.0°$ in the LUM, $7.1° < \theta < 7.5°$, $7.5° < \theta < 8.6°$, and $8.6° < \theta < 9.6°$ in the FBC. The maximum difference was 2.2%. Including theoretical ambiguity[15], the total systematic error of the luminosity determination was 2.5%.

Any disagreement between the simulations and the data induces systematic errors in the estimation of ε. Here, we discuss the systematic errors introduced by small discrepancies noticeable in Figs. 1(a)$\sim$(d). The charged multiplicity distribution of the Monte-Carlo data showed a small offset with respect to that of the real data. There also seemed to be a systematic scale difference between the visible energy distributions of the Monte-Carlo and the real data. The errors in the efficiency estimation from these discrepancies were evaluated by calculating the efficiency after off-setting the Monte-Carlo charged-multiplicity distribution and rescaling the visible energy distribution of the Monte-Carlo data. We also checked, by rescaling, the error due to uncertainties of the longitudinal momentum balance and that due to energy scale ambiguities of the hard BCL cluster in cuts (5) and (6). Including the statistical error of the detector simulation (10^5 events), these errors amounted to a detector-induced systematic uncertainty of 1.5% in the efficiency. The error due to the larger hemisphere mass cut was estimated in a similar way and was found to

Luminosity		2.5% by FCL
Rad. correction	M_{top},M_{Higgs} dependence	$\leq$0.1%
	initial/final interference	$\leq$0.06%
Detector simulation		1.5%
fragmentation parameter		0.9%
Background estimation		0.3%
Total		3.1%

Table 2: Systematic Errors

be negligibly small.

The error due to fragmentation and hadronization was also estimated. In this analysis, the fragmentation parameters (b, Λ, and σ_q) were detuned by $\pm$1-σ from the optimized values (a was fixed at 0.361 because it strongly correlates with b, and the best-fit values of these three parameters were $b = 0.914 \pm 0.016$, $\Lambda = 0.378 \pm 0.010$GeV, and $\sigma_q = 0.355 \pm 0.005$GeV)[16]. The difference in the estimated efficiencies between the optimized Monte-Carlo simulation and the detuned one was 0.9%.

As for the background estimation, the largest uncertainty came from two-photon processes, for which we conservatively assumed a 100% theoretical ambiguity. The error estimated this way was 0.3% at most. The uncertainty of the τ pair background was less than 0.1%.

The k_{max} dependence of $\varepsilon(1 + \delta_{QED})$ was found to be less than the statistical error (0.3%) of the Monte-Carlo simulation; selection criterion (6) is expected to make negligible the effect of hard photon emissions.

Summing all of these systematic errors in quadrature, we obtained a total systematic error of 3.1%. The systematic errors are summarized in Table 2; compared with our previously published values[2] they show that the errors due to the radiative corrections became considerably smaller since the present ones correspond to the QED corrections. In addition, the other errors were also significantly (by about 50%) reduced owing to the new luminosity monitor(FCL) and an improved understanding of the detectors due to the increased statistics.

2.4 Results

The total hadronic cross section was obtained to be

$$\sigma_h = 143.6 \pm 1.5(\text{stat}) \pm 4.5(\text{sys}) \ \ \text{pb} \tag{2}$$

after the QED corrections. This value is consistent with the Standard Model prediction of 142.2pb with M_Z=91.187GeV, M_{top}=174GeV, M_{Higgs}=100GeV, and $\alpha_s(M_Z^2)$ = 0.12, where the QCD correction was calculated up to $O(\alpha_s{}^3)$[18].

From this result the QED effective form factor ($\bar{\alpha}(q^2)$) corresponding to $\gamma\gamma$ propagator [17] was directly obtained to be

$$1/\bar{\alpha}(q^2) = 128.6^{+0.9}_{-0.8}(\text{stat})^{+2.7}_{-2.5}(\text{sys}) \quad \text{at} \ \ q^2 = (57.77\text{GeV})^2,$$

which is the first direct measurement of $\bar{\alpha}(q^2)$ at high energy. Our result is in good agreement with the SM prediction of 129.47±0.10.

3 The determination of γ-Z interference

After the QED corrections the total cross section can be expressed by the following formula in the S-matrix formalism[19, 10]:

$$\sigma_h = \frac{4\pi\alpha^2}{3}\left[\frac{R_\gamma}{s} + \frac{sR}{(s-\bar{M}_Z^2)^2 + \bar{M}_Z^2\bar{\Gamma}_Z^2} + \frac{(s-\bar{M}_Z^2)J_{had}}{(s-\bar{M}_Z^2)^2 + \bar{M}_Z^2\bar{\Gamma}_Z^2}\right] \equiv \sigma^{smat}(s), \tag{3}$$

where the first and second terms correspond to γ and Z^0 exchanges, respectively, while the last one corresponds to their interference. The conventional formalism using the s-dependent width of Z^0 contains the parameters M_Z and Γ_Z, which are related to those in the S-matrix one by[20]

$$\bar{M}_Z = M_Z[1 + \Gamma_Z^2/M_Z^2]^{-\frac{1}{2}} \approx M_Z - 34\text{MeV} \tag{4}$$

and

$$\bar{\Gamma}_Z = \Gamma_Z[1 + \Gamma_Z^2/M_Z^2]^{-\frac{1}{2}} \approx \Gamma_Z - 1\text{MeV}. \tag{5}$$

In order to determine the Z^0 parameters in a model-independent way, we need to introduce four free parameters: $\bar{M}_Z$, $\bar{\Gamma}_Z$, R, and J_{had}, assuming that R_γ is theoretically well understood. Among the four parameters, $\bar{M}_Z$ has a strong correlation with J_{had}, as can be clearly seen in Eq.(3), while $\bar{\Gamma}_Z$ is strongly correlated with

R because the Z^0 pole cross section (σ_h at $\sqrt{s} = \bar{M}_Z$) is given by $R/\bar{\Gamma}_Z^2$. In the usual three-parameter fit, however, the coefficient of the interference term (J_{had}) is assumed to be given by the SM[19, 10].

As shown in Fig.2(a), the J_{had} dependence of the total cross section is significant at TRISTAN, unlike at LEP. TRISTAN data are therefore indispensable to model independent determinations of the Z^0 parameters. Combining our result with the published data of OPAL[21], we performed a four-parameter fit using the following assumptions. The energy-dependent difference of J_{had} at LEP and J_{had} at TRISTAN is negligible in the fit, since it is expected to be small[17] (~0.6% in the SM), and the QCD corrections are given by the $O(\alpha_s^3)$ equation in Ref.[18]. The χ^2 we minimized was the sum of the χ^2's for the TOPAZ and the OPAL data:

$$\chi^2 = \chi^2_{TOPAZ} + \chi^2_{OPAL}, \tag{6}$$

where χ^2_{TOPAZ} and χ^2_{OPAL} were given by

$$\chi^2_{TOPAZ} = \frac{[\sigma_h^{TOPAZ} - \sigma^{smat}(s)]^2}{(\delta\sigma_{stat})^2 + (\delta\sigma_{sys})^2} \tag{7}$$

and

$$\chi^2_{OPAL} = \sum_{i,j} \Delta_i V_{ij}^{-1} \Delta_j \quad \text{with} \quad \Delta_i = \sigma_i^{OPAL}(s_i) - \sigma_{tot}(s_i). \tag{8}$$

The diagonal element (V_{ii}) of the error matrix (V) was calculated by summing the statistical, systematic point-to-point, and normalization errors of the i-th data point. The off-diagonal element (V_{ij}) was the product of the normalization errors (0.7%) of the i-th and j-th data points. Since the OPAL data (σ_i^{OPAL}) have been presented with only the acceptance corrections, the corresponding theoretical cross sections ($\sigma_{tot}(s)$) were calculated by convoluting $\sigma^{smat}(s)$ given by Eq.(3) with the radiator function provided by the ZFITTER.

From the combined fit we obtained J_{had} = 0.10±0.26 and $\bar{M}_Z$ = 91.151±0.008 GeV, to be compared with J_{had} = −0.34±0.98 and $\bar{M}_Z$ = 91.157±0.016 GeV obtained without the TOPAZ data. These results were translated into the total hadronic cross sections and are shown in Fig.2(b), which clearly demonstrates the importance of our data contribution. In Fig.3 the resultant 1-σ contour from the combined fit in the $\bar{M}_Z$-J_{had} plane is plotted together with the result obtained from the OPAL data alone. The vertical line in the figure indicates the center value of the SM prediction of J_{had} = 0.220 ± 0.035(M_{Top}) ± 0.011(M_{Higgs})[3]. Although the results from the two fits are consistent with the SM, our data reduced the error on $\bar{M}_Z$ by 50% in the model-independent analysis. The resultant error on $\bar{M}_Z$ is now comparable with that assuming the SM (see Fig.3).

4 Conclusions

Based on 9146 multi-hadronic events collected at $\sqrt{s}$=57.77GeV, the total hadronic cross section in e^+e^- annihilation was measured to be σ_h = 143.6±1.5(stat)±4.5(sys) pb after the QED corrections. It is consistent with the Standard Model prediction of 142.2pb for M_Z=91.187GeV, M_{Top}=174GeV, M_{Higgs}=100GeV, and $\alpha_s(M_Z{}^2)$=0.12.

We demonstrated that our results put a stringent constraint on the γ-Z^0 interference at LEP energies. Combing this result with the published data of the OPAL group, we obtained, from a model-independent four-parameter fit, J_{had}=0.10±0.26 and $\bar{M}_Z$=91.151±0.008 GeV, where the J_{had} was consistent with the SM value of J_{had}=0.220. Our data thus significantly improved the error on $\bar{M}_Z$ in the model-independent analysis and made it comparable with that assuming the Standard Model.

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Figure captions

Fig.1 Distributions of the observables used for event selection: (a) the number of good tracks. (b) the visible energy, (c) P_z, and (d) the larger jet mass. The real data (points with error bars) are well reproduced by the Monte-Carlo simulation of signal+background (solid histogram). The background total was shown by the dashed histograms of which the τ-pair contribution was indicated by shaded histograms.

Fig.2 Total hadronic cross section as a function of $\sqrt{s}$: (a) with both the TOPAZ and the LEP-combined[22] data plotted in the same figure, while (b) with the TRISTAN energy region magnified. Our data point is at $\sqrt{s}$=57.77GeV with the error bar representing the statistical and systematic errors summed in quadrature. The solid line is the SM prediction for M_Z=91.187GeV, M_{Top}=174GeV, M_{Top}=100GeV, and $\alpha_s(M_Z{}^2)$=0.12, while the dashed lines show the 1σ bound from the OPAL measurement alone. The dot-dashed lines in (b), on the other hand, represent that from the combined fit.

Fig.3 1-σ contours in the $\bar{M}_Z$-J_{had} plane from the four-parameter line shape fit described in the text. The larger contour is from the OPAL data alone. The inclusion of our data significantly improves the errors on both $\bar{M}_Z$ and J_{had} (see the smaller contour).

Figure 1

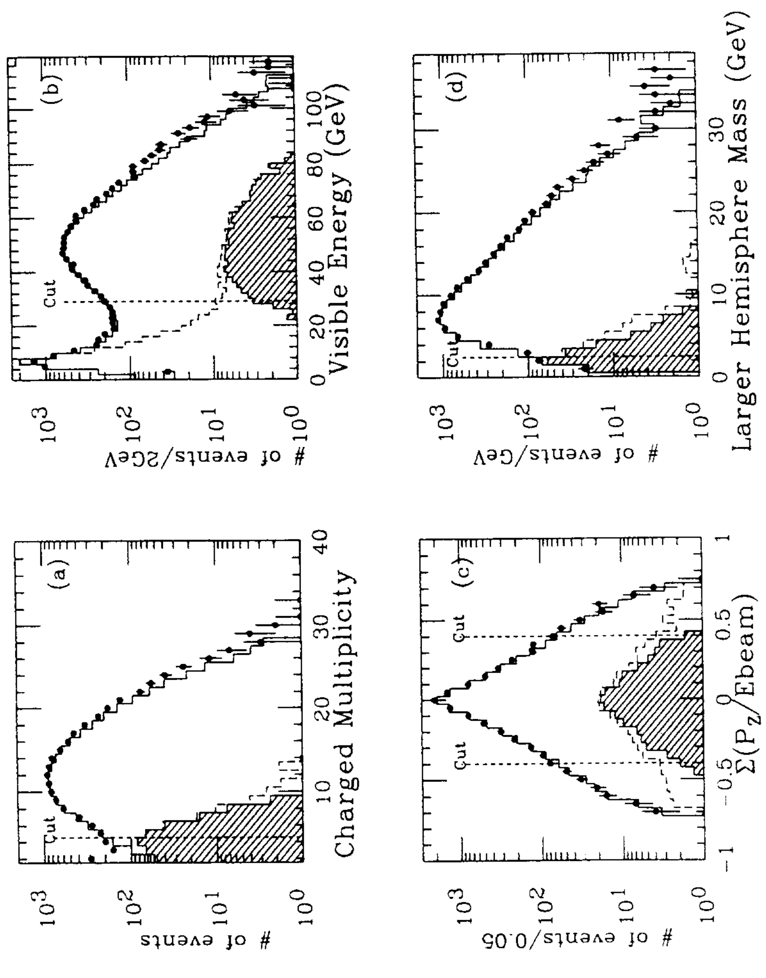


Figure 2

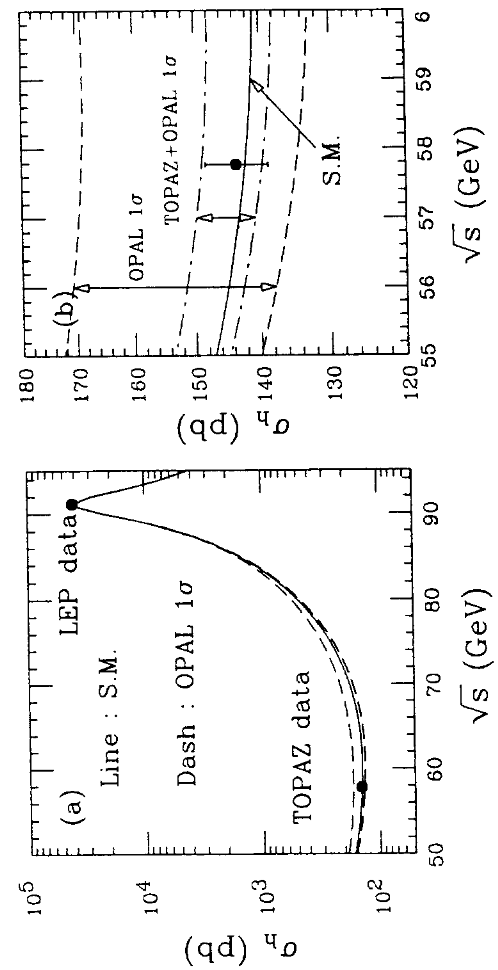
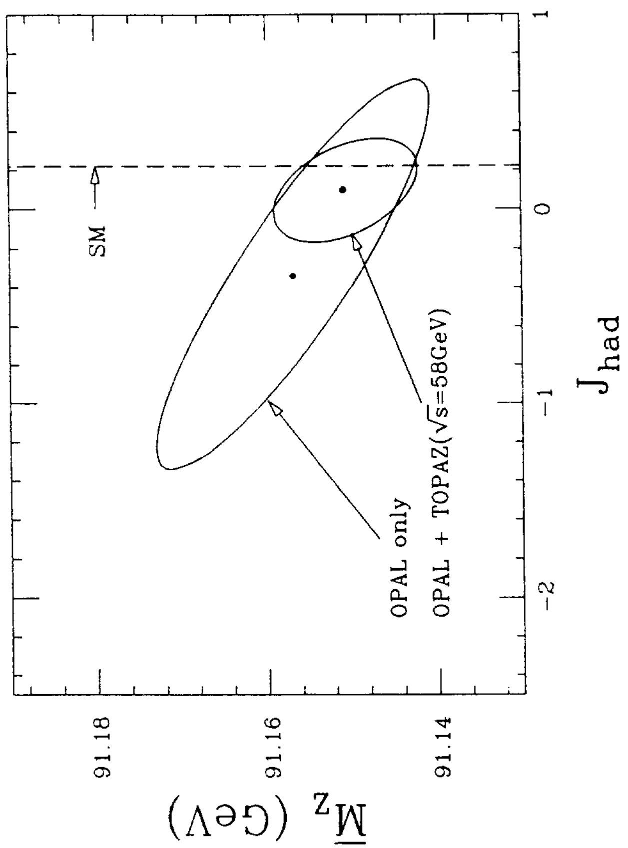


Figure 3



$\overline{M}_Z$ (GeV)
91.18
91.16
91.14
J_{had}
−2
−1
0
1
SM
OPAL only
OPAL + TOPAZ(√s=58GeV)