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Analysis of Large-Angle Bhabha Events in 1993 Data

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1 Introduction

The analysis of wide-angle Bhabha events is well established within ALEPH (see, for example, [1]). This analysis differs from those previously performed in ALEPH in the choice of the signal Monte Carlo generator used for the evaluation of selection efficiencies. In this case a relatively new Monte Carlo, UNIBAB, is used. Following a brief review of the selection procedure a detailed discussion and comparison of UNIBAB with its predecessor, BABAMC is made. The evaluation of background levels is presented along with a description of the method for subtracting the t-channel Bhabha cross-section. Finally, results for $\sigma^{e^+e^-}$ and $A_{FB}^{e^+e^-}$ are presented at the four centre of mass energies at which data were taken during 1993.

2 Event selection

The selection procedure for this channel is already well documented in [1, 2], for the sake of completeness however the salient features of the selection are reviewed here :

- ▷ the SLUMOK flag was required to be set.
- ▷ Events with between 2 and 6 'good' tracks were selected. A 'good' track being defined as one having 4 or more TPC space points, momentum greater than 0.1 GeV/c, polar angle $|\cos\theta|$ less than 0.95, $|d_0|$ less than 5 cm and $|z_0|$ less than 2 cm.
- ▷ Those events satifying the above were required to have *either* exactly two tracks with $|d_0|$ less than 5 cm *or* between 2 and 6 tracks with $|d_0|$ less than 2 cm. In addition, at least one track had to have a momentum of 3 GeV/c or more.
- ▷ At least one 'good' track was required in each of the two event hemispheres as defined by the plane perpendicular to the thrust axis.
- ▷ For 5 or 6 'good' track events each track in a hemisphere must lie within the cone of semi-angle $\eta \cos\eta > 0.85$) around the vector sum of that hemisphere's momenta.

- ▷ Spatial acollinearity between the two highest momentum tracks was required to be 20° or less.
- ▷ The sum of the two highest momentum tracks was required to be greater than $0.05\sqrt{s}$.
- ▷ The sum of the track associated ECAL energies was required to exceed $0.20\sqrt{s}$.
- ▷ The sum of the above two items (two track momenta plus ECAL energies) was required to exceed $1.20\sqrt{s}$.
- ▷ The two highest momentum tracks should not be identified as muons by the QMUIDO package.

In those selection criteria requiring the inclusion of ECAL energy the possibility of a radiative event was also considered and consequently the energy of the most energetic ECAL cluster not associated to a track was included as long as the cluster position lay within $\pm 20°$ in both θ and ϕ of its expected position $(\theta_2, \phi_1 + \pi)$, where the subscripts 1 and 2 refer to the most and second most energetic tracks respectively. The possible inclusion of HCAL energy closely associated with either of the most energetic tracks or the photon was also allowed.

In total 1233 runs were considered from the 1993 data-taking period. Since the operating beam energy for the peak runs taken before and during the energy scan were slightly different then these peak data were separated into 'prescan' and 'scan' cases when handling the data. The corresponding luminosities from SiCAL are summarized in Table 1 below (statistical errors only).

LEP Energy (GeV)	Luminosity (pb^{-1})
89.434	8.064759 ± 0.009590
91.290	5.331673 ± 0.007960
91.192	9.130783 ± 0.010408
93.016	8.692181 ± 0.010371
Total	31.219396 ± 0.019267

Table 1: Luminosity as function of LEP energy

3 Selection efficiency - UNIBAB vs. BABAMC

Up to now, BABAMC has been the standard Monte Carlo generator for large angle Bhabha scattering at LEP. However, it only contains complete electroweak corrections up to $O(\alpha)$ and thus allows the emission of just one photon. At the end of 1993, a new Bhabha Monte Carlo generator called UNIBAB became available with the inclusion of higher order QED corrections resummed to all orders. The authors claim a level of precision comparable to the semi-analytical programs [3, 4] already standard in large-angle Bhabha scattering calculations.

In this section, a comparison between the two Monte Carlos with the 1993 data at the peak is performed. As expected, the results show better agreement between UNIBAB and data. However, at large photon-electron angle, this agreement appears to degrade, probably due to the missing non-log $O(\alpha)$ terms in the Monte Carlo. Nevertheless, since this region is excluded by the Bhabha selection, UNIBAB has been used for the calculation of the selection efficiency thus replacing BABAMC which only gave good agreement with data in the regions close to the cuts.

3.1 Theoretical differences

BABAMC [5] became available about one and a half years before LEP startup and includes all one-loop electroweak corrections. Therefore the calculation is complete at $O(\alpha)$ (i.e. LL and NLL are included by explicit calculation) but only one photon can be emitted. At LEP energies this is known to be wrong by about 10% even in the dominant region of collinear radiation. However, in the region where the cuts are applied the agreement with data is good and the selection efficiencies are expected to be accurate enough. Nevertheless, when the 't-channel subtraction' method is used for the Bhabha analysis, the contribution of the t-channel to be subtracted from data cannot be obtained from BABAMC with enough accuracy. Instead, more accurate semi-analytical programs such as ALIBABA [3, 4] which include up to $O(\alpha^2)$ LL QED corrections and soft photon exponentiation have to be used.

UNIBAB [6], written by a German group with the experience gained in HERA, became available in October last year. The major improvement with respect BABAMC is that it contains leading log QED corrections to all orders in a Monte Carlo branching algorithm with exponentiation of the soft photon contributions automatically. The weak corrections have been included using the electroweak library from ALIBABA. However, it does not include interference between initial and final state radiation, which is, in fact, small at and near the Z resonance.

In the Monte Carlo branching algorithm [7], the tranverse component of the photon momentum is determined by a probability distribution according to the pole in the electron propagator

$$P \propto \frac{1}{(p_e + k_\gamma)^2} = \frac{1}{2E_e E_\gamma (1 - \cos\theta_\gamma)}$$

and so the polar angle of the photon is chosen accordingly:

$$P(\cos\theta_\gamma) \propto \frac{1}{(1 - \cos\theta_\gamma)}$$

which is only precise in the collinear limit, $\theta_\gamma = 0$.

Therefore, UNIBAB allows the emission of more than one photon but, even at $O(\alpha)$, its angle with respect to the fermion is only an approximation ($O(\alpha)$ non-log terms not included), and is only exact in the limit of collinear radiation.

3.2 Experimental differences

To understand the differences between the two Monte Carlos, they have both been compared to 1993 data taken at the peak. The following MINI productions (which were available at the time this comparison was performed) were used:

- ▷ a BABAMC production of 200,000 e^+e^- events at 91.25 GeV with 1992 ALEPH geometry (GALEPH 255.01 and JULIA 271.07)
- ▷ a UNIBAB production of 100,000 e^+e^- events at 91.25 GeV with 1992 ALEPH geometry (GALEPH 255.01 and JULIA 271.01). This generation required the acollinearity (ξ) of the outgoing electrons to be less than 30° and omitted vertex smearing which should not affect this comparison.

In all the figures, both Monte Carlo have been normalized to the luminosity of the data.

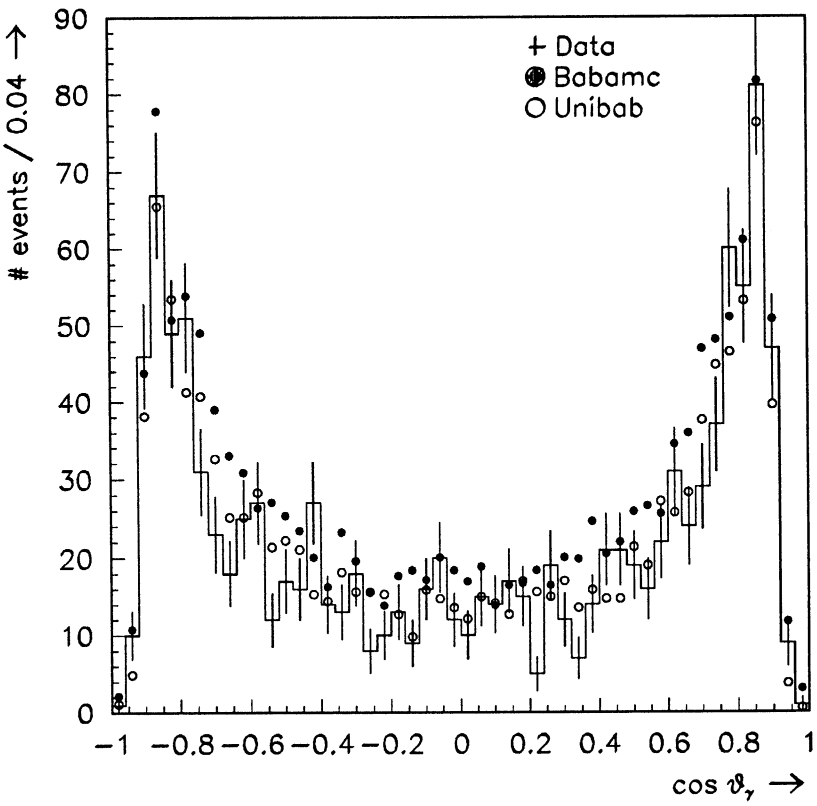

Figure 1: Number of hard photons ($E_\gamma > 5$ GeV) emitted as a function of the cosine of the polar angle of the emitted photon.

Figure 1 shows the number of hard photons ($E_\gamma > 5$ GeV) emitted from both Monte Carlo and data as a function of the cosine of the polar angle of the emitted photon ($|\cos\theta^*| \leq 0.9$). Here all Bhabha selection cuts as described above have been applied with the exception of the spatial acollinearity cut which is replaced by a rapidity cut ($|Y| \leq 0.3$ as in [8]). As expected, the dips between the central and forward/backward region show that collinear radiation is much preferred. Therefore the central region is dominated by final state radiation. In BABAMC this implies that there is no initial state radiation, thus fixing the centre-of-mass energy of the hard scattering process to the energy of the incoming beams. The mean beam energy of the hard scattering process is hence a bit higher than that for the more realistic case of multi-photon radiation. This explains why in the central region, BABAMC is higher than UNIBAB, and thus UNIBAB agrees better with the data.

To illustrate this fact numerically the three distributions are integrated over the range $|\cos\theta_\gamma| \leq 0.7$ (to avoid any effect from the t-channel). The number of events in this band are, for data 581 ± 24, for BABAMC 782 ± 14 and for UNIBAB 633 ± 14. The Monte Carlo to data ratio is 1.35 ± 0.06 for BABAMC and 1.09 ± 0.05 for UNIBAB in agreement with the statement above.

Figure 2 shows the acollinearity and rapidity distributions for all accepted events in the Bhabha selection when all the above cuts except the one on acollinearity or rapidity respectively have been applied ($|\cos\theta^*| \leq 0.9$). Again, UNIBAB shows better agreement with the data than BABAMC which, as explained previously, tends to be higher. However, careful investigation of the figures shows the agreement between UNIBAB and data to be very good up to the respective cut values of $\xi \leq 20°$ or $|Y| \leq 0.3$ after which UNIBAB seems decrease relative to the data whereas BABAMC seems to agree better with the data in this region. This may be a first indication of the missing non-log terms in UNIBAB (indeed, events with high acollinearity or high rapidity correspond to highly radiative and noncollinear events).

To quantify this observation the acollinearity plot is integrated in the limits $1° \leq \xi \leq 20°$ (we ignore the first bin to avoid bias due to its dominant contribution). The results are, for data 5208 ± 72, for BABAMC 6344 ± 39 and for UNIBAB 5289 ± 39 corresponding to MC/data ratios of 1.22 ± 0.02 for BABAMC and 1.02 ± 0.02 for UNIBAB.

However, the integral of the same plot in the limits $20° \leq \xi \leq 30°$ is for data 265 ± 16 for BABAMC 269 ± 8 and for UNIBAB 256 ± 9 thus giving MC/data ratios of 1.01 ± 0.07 for BABAMC and 0.97 ± 0.07 for UNIBAB. If the comparison could be extended to higher acollinearities, the effect would be more important.

It was desirable to integrate over the rapidity cut since this is a direct cut on the energy on the emitted photon [8]. This was not however possible due to an implicit cut on $\xi \leq 30°$ in the UNIBAB sample.

Finally, Figure 3 shows the efficiencies of the Bhabha selection for the two Monte Carlos as a function of $\cos\theta^*$ which preserves the e^+e^- scattering angle even in the case of hard collinear radiation in the initial state. The efficiency is illustrated for the standard selection and in the case where a cut on rapidity replaces that on acollinearity. The behaviour is the same for the two cuts; in the central region both Monte Carlos are compatible (within statistical fluctuations). However, in the most forward and backward region, the efficiency of the selection is clearly reduced for UNIBAB.

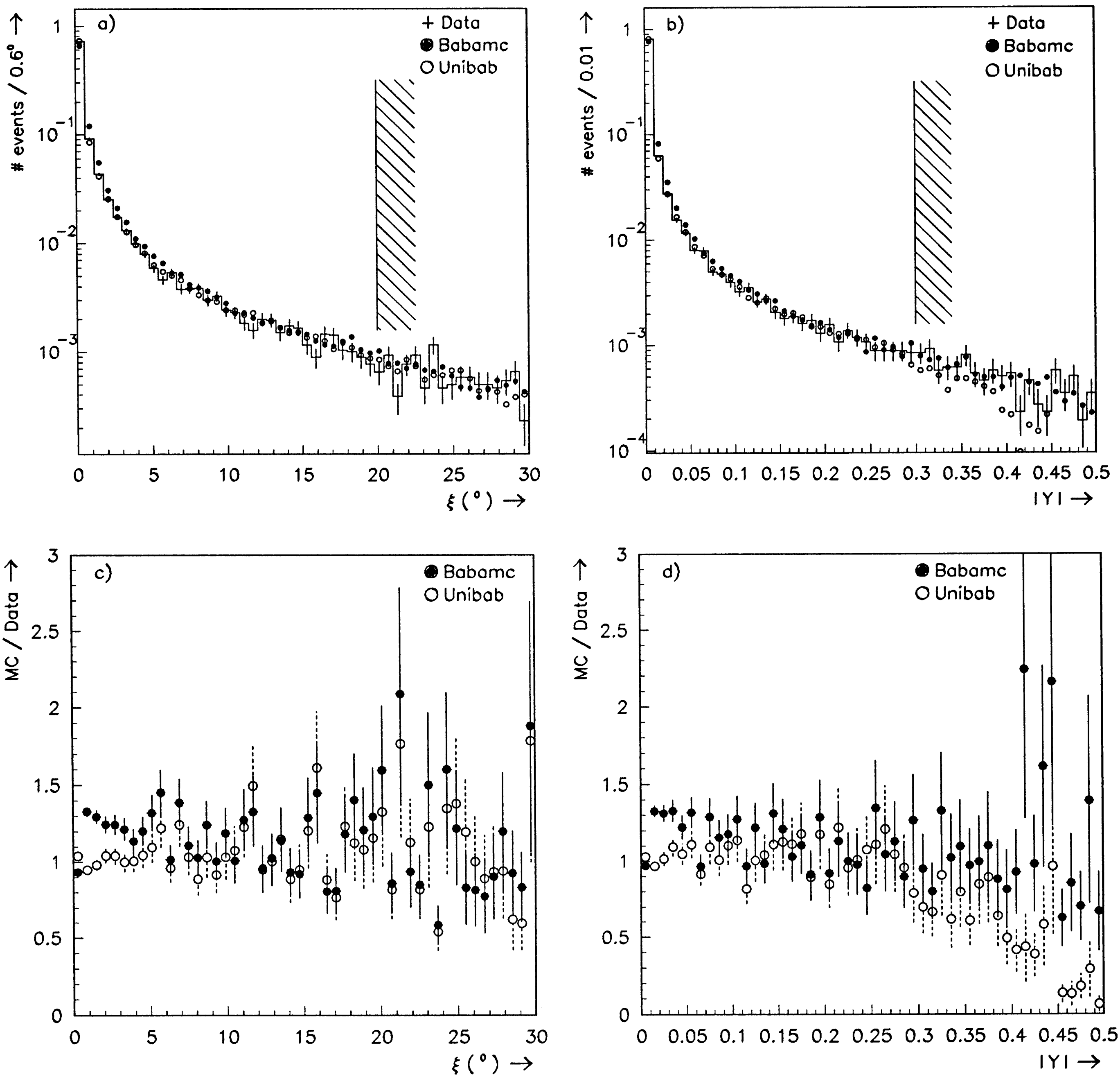

Figure 2: Acollinearity and rapidity distributions for selected Bhabha events. (a),(b) Acollinearity (rapidity) distribution for data, BABAMC and UNIBAB. (c),(d) Ratio of both Monte Carlos to the data for the acollinearity (rapidity) distribution.

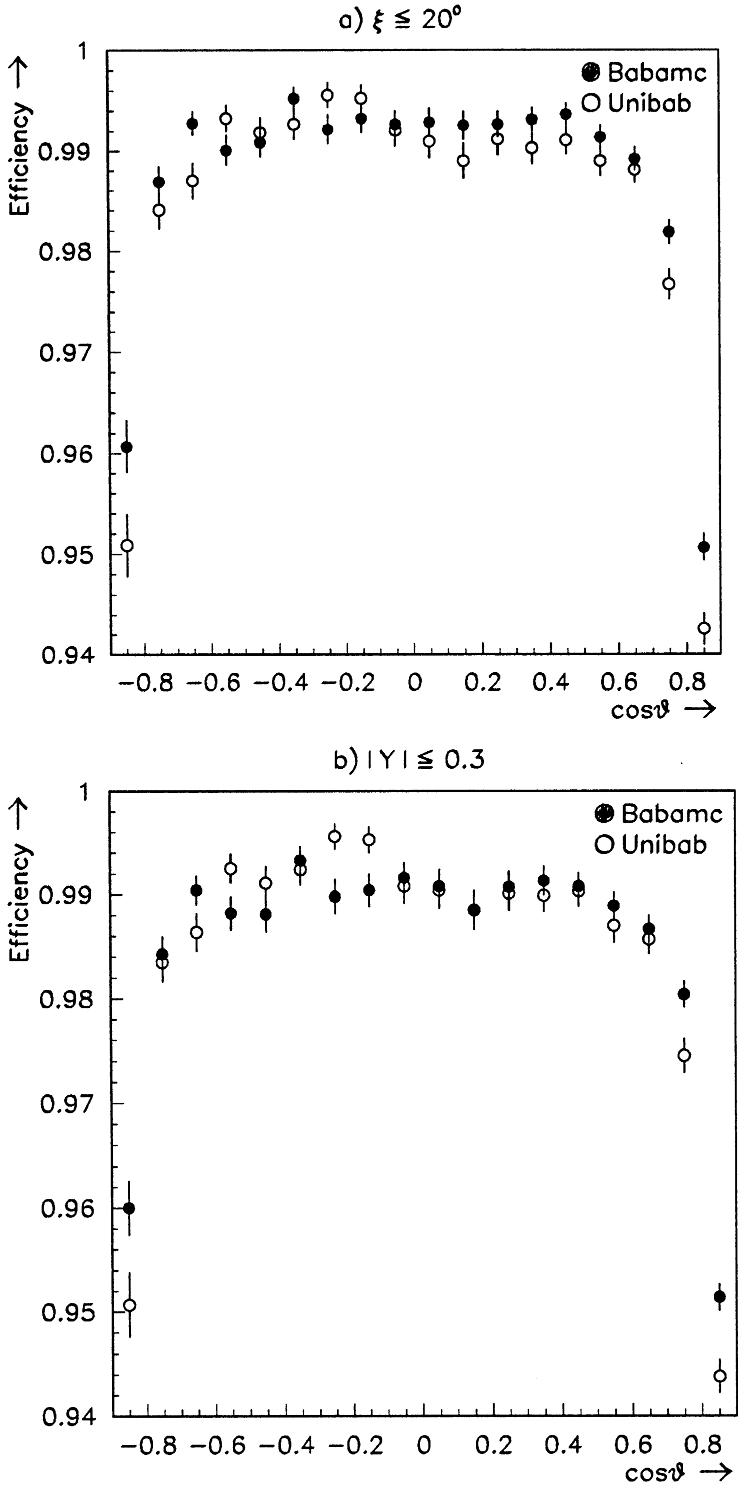

Figure 3: Efficiencies of the Bhabha selection for BABAMC and UNIBAB (a) Standard Bhabha selection, (b) Rapidity cut replaces acollinearity cut

4 τ background evaluation

The main source of background in this channel comes from $\tau^+\tau^-$ events where both taus undergo a decay of the type $\tau \rightarrow e\nu\overline{\nu}$. The level of this background was evaluated by running the selection program on 300,000 $\tau^+\tau^-$ events generated with 1992 geometry, GALEPH 255.01 and JULIA 271.07. The selection efficiency thus calculated is entirely compatible with the values used in previous years and is illustrated in Figure 4 as a function of $\cos\theta^*$.

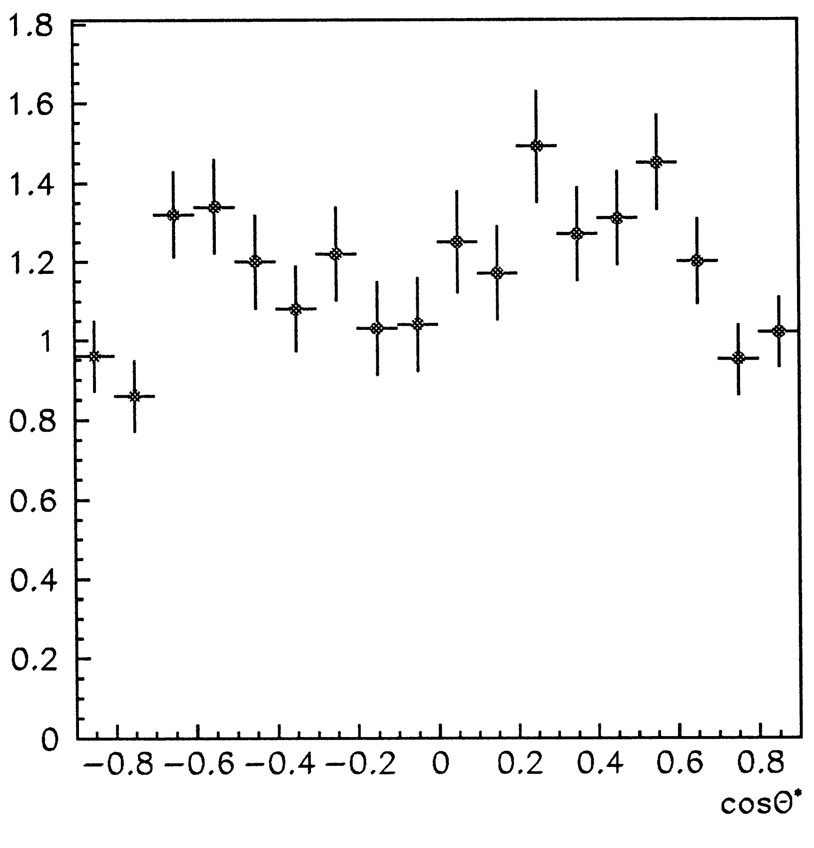

Figure 4: $\tau^+\tau^-$ efficiency (in percent) as a function of $\cos\theta^*$

5 t-channel subtraction

In order to calculate correctly the total cross-section it is necessary to subtract, bin-by-bin and energy-by-energy, the t-channel contribution. It should be noted that what is colloquially referred to as 't-channel subtraction' is, in fact, a subtraction of the t-channel plus interference part of the total cross-section. In order to evaluate this contribution the semi-analytical program ALIBABA [3] was used. The precise algorithm for calculating the 't-channel' cross-section (σ_{t+i}) is

$$\sigma_{t+i}(\theta^*, E) = \sigma_{tot}(\theta^*, E) - \sigma_s(\theta^*, E) - 0.008\sigma_t(\theta^*, E)$$

where σ_{tot}, σ_s and σ_t are the total, s-channel and t-channel contributions respectively. The final term in this expression is a correction for the difference in the way energy cuts are applied experimentally and within ALIBABA and is described in [9]. The parameter values of NCALL and ITMX were set accordance with those documented in [1].

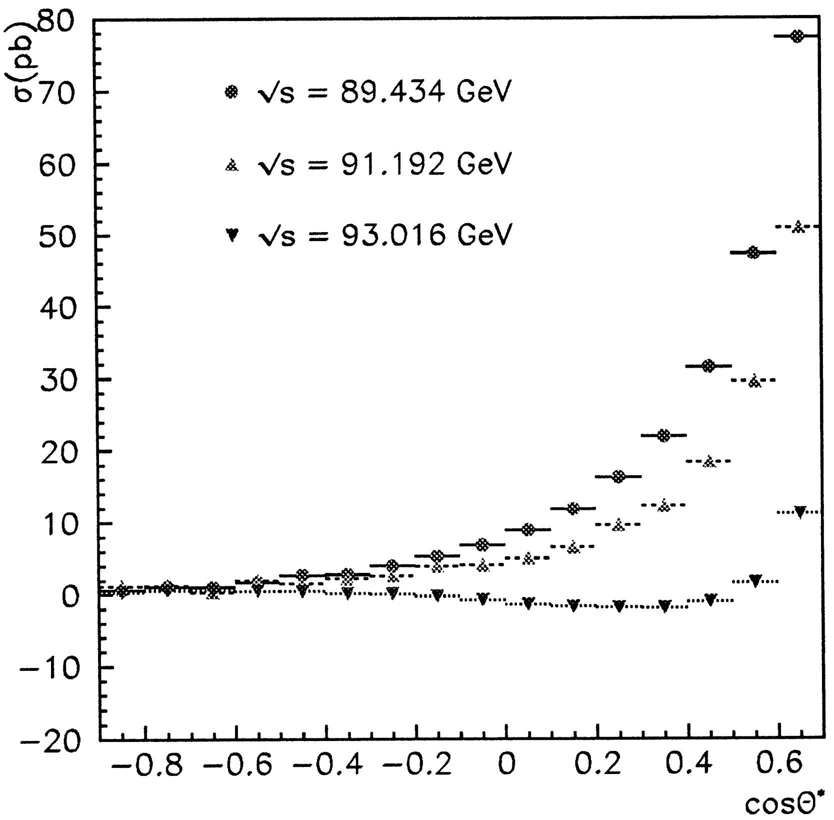

Figure 5: t-channel subtraction cross-section as a function of $\cos\theta^*$ and LEP energy

The final t-channel subtraction cross-section is illustrated in Figure 5. It exhibits the expected behaviour with $\cos\theta^*$ which leads to the cross-sections and forward-backward asymmetries being determined in the angular range $-0.9 < \cos\theta^* < +0.7$, well away from the region where the correction is largest. The subtraction cross-section also decreases dramatically across the Z-pole, this feature will be mentioned again in Section 7.

6 Acceptance correction

To determine a cross-section free from experimental constraints it is necessary to evaluate the impact of the cuts on $\cos\theta^*$ and acollinearity. To avoid the singularity present in the

Bhabha cross-section then this acceptance is calculated using $\mu^+\mu^-$ events generated by KORALZ. 450,000 muon pair events were generated at each of the four centre of mass energies present in this data sample. The results, shown in Table 2 below, showed some discrepancy with those calculated for the previous scan year i.e. 1991.

LEP Energy (GeV)	Acceptance
89.434	0.7512 ± 0.0007
91.290	0.7250 ± 0.0007
91.192	0.7247 ± 0.0007
93.016	0.7090 ± 0.0006

Table 2: Acceptance as function of LEP energy

This was investigated and understood to arise from a different choice of the so-called VVMAX parameter in KORALZ. VVMAX is defined as

$$\mathrm{VVMAX} = 1.0 - \left(\frac{s'}{s}\right)^2$$

and effectively determines the lowest allowable invariant mass (s') of the two muon system in the case where one of the muons has radiated a near-beam energy photon. In 1991 this parameter was set to a value which limited s' to a value of twice the muon rest mass; in order to retain compatibility across lepton species however this value is now hard-wired in KORALZ to a value equivalent to a minumum invariant mass of twice the tau rest mass. This difference is responsible for the discrepancy noted above.

7 Results and errors

7.1 Cross-sections

For each beam energy the data were binned in bins of $\cos\theta^*$ each 0.1 wide. As described previously, the cross-section was calculated in the angular range $-0.9 < \cos\theta^* < +0.7$. The cross-section calculation thus required summing the following expression for each of the 16 $\cos\theta^*$ bins:

$$\sigma_s(\theta^*, E) = \frac{N(\theta^*, E) - \mathcal{L}(E)\mathcal{E}_b(\theta^*)\sigma_t(\theta^*, E)}{\mathcal{L}(E)\mathcal{A}(E)\mathcal{E}_b(\theta^*)(1 + \mathcal{E}_\tau(\theta^*))}$$

where $N(\theta^*, E)$ is the number of observed events, $\mathcal{L}(E)$ is the luminosity, $\mathcal{E}_b(\theta^*)$ is the Bhabha efficiency, $\sigma_t(\theta^*, E)$ is the t-channel subtraction cross-section, $\mathcal{A}(E)$ is the acceptance and $\mathcal{E}_\tau(\theta^*)$ is the τ efficiency.

The systematic errors were calculated by performing the above calculation with the following changes being made one at a time :

- ▹ Backward bin selection efficiency was changed by ± 1.0%.
- ▹ Selection efficiency was changed by ± 0.3% for all cos θ^* bins.
- ▹ Luminosity was changed by ± 0.266%.
- ▹ t-channel subtraction term was changed by ± 2.0%.
- ▹ the term due to tau background, i.e. $(1+\mathcal{E}_\tau)$ was changed by ± 0.2%

The final results are presented below, the first error is statistical, the second error is the systematic error. At 89.434 GeV the systematic error is totally dominated by that from the t-channel subtraction.

LEP Energy (GeV)	Cross-section (pb^{-1})
89.434	489.724 ± 11.529 ± 6.913
91.192	1463.463 ± 15.867 ± 7.161
91.290	1494.773 ± 20.790 ± 6.954
93.016	694.786 ± 10.677 ± 2.678

Table 3: Cross-section as function of LEP energy

7.2 Forward-backward asymmetries

In this case for each set of data at a specific energy point the angular distribution, dN/dcos θ^* was fitted to the following expression using a maximum likelihood estimator within MINUIT :

$$N(\theta^*) = \mathcal{E}_b(\theta^*)\left[(1+\mathcal{E}_\tau(\theta^*))\,C\left(c_2 - c_1 + \frac{c_2^3 - c_1^3}{3} + \frac{8}{3}A_{FB}\frac{c_2^2 - c_1^2}{2}\right) + \sigma_t(\theta^*, E)\mathcal{L}(E)\right]$$

where c_1 and c_2 are the lower and upper limits respectively of each cos θ^* bin; $\mathcal{E}_b$,$\mathcal{E}_\tau$,σ_t and $\mathcal{L}$ as before. C and A_{FB} were varied by the fitting program in order to minimize the corresponding log-likelihood function.

The errors coming from systematic effects were evaluated in a similar way to that described previous for the cross-section calculations, i.e. each error source to be varied was changed by the appropriate amount and the fit redone. The results for the forward-backward asymmetries are summarized in tabular form in Table 4 below and graphically in Figure 6.

Acknowledgement

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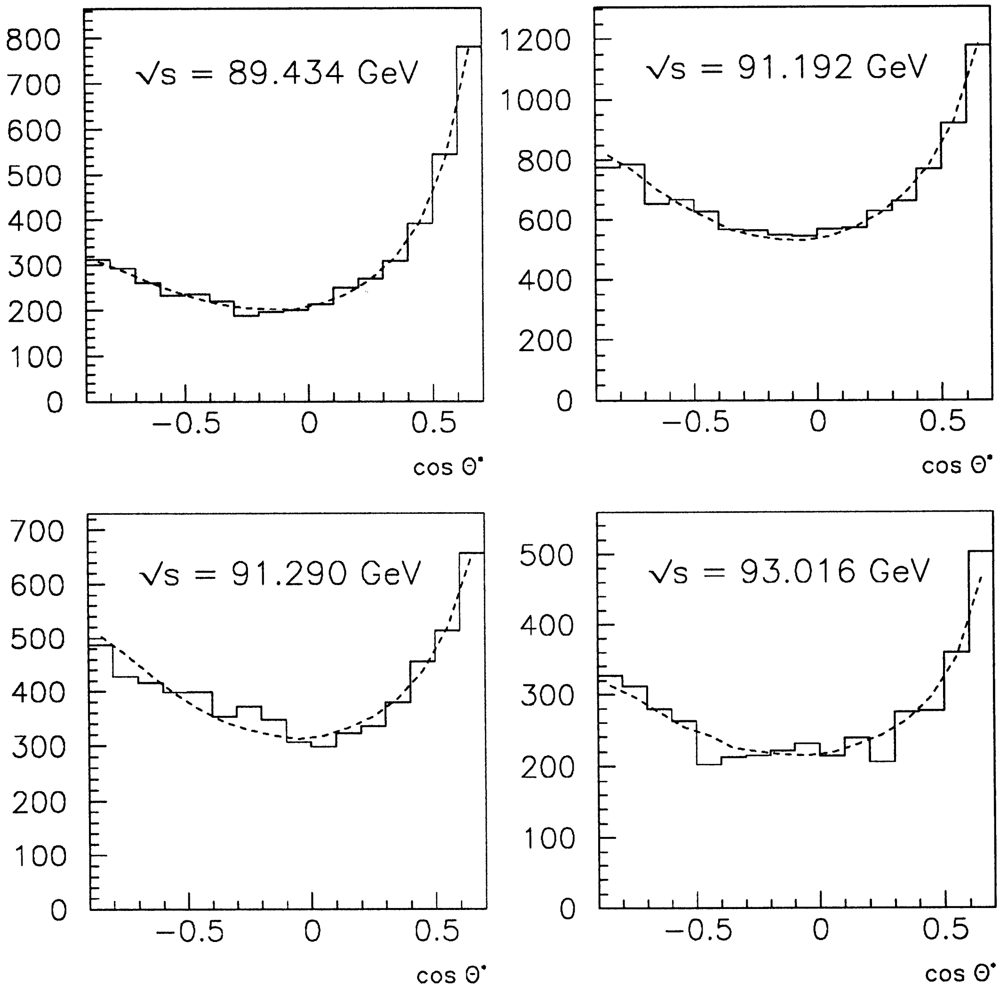

Figure 6: Number of events as a function of cosθ^*. Histogram is data, smooth curve is result of forward-backward asymmetry fit

LEP Energy (GeV)	Asymmetry
89.434	-0.178 $\pm$ 0.030 $\pm$ 0.017
91.192	0.021 $\pm$ 0.012 $\pm$ 0.003
91.290	-0.009 $\pm$ 0.015 $\pm$ 0.003
93.016	0.131 $\pm$ 0.016 $\pm$ 0.001

Table 4: Forward-backward asymmetry as a function of LEP energy

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