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Combination of the LEP 2 $\mathrm{f\bar{f}}$ Results

LEPEWWG $\mathrm{f\bar{f}}$ Subgroup

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Abstract

A preliminary average of the LEP 2 $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$ cross–section and forward–backward asymmetry results from the 4 LEP collaborations is presented using the full LEP 2 data sample. A method for averaging measurements on the production of heavy flavour is discussed and a preliminary average of these results is made.

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1 Introduction

LEP has operated at energies well above the Z-pole since Autumn 1995. During this time data have been collected at centre–of–mass energies of 130.2 and 136.2 GeV (in 1995 and 1997), 161.3 and 172.1 GeV (in 1996), 182.7 GeV (in 1997) and 188.6 GeV (in 1998) and at 4 energies 191.6, 195.5, 199.5 and 201.6 GeV in 1999. In this note we consider the combination of the LEP results on the process $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$.

At the Z-pole the data from the four LEP experiments has been combined at the level of pseudo–observables [1]. This procedure is no longer appropriate at energies well above the Z-pole. Instead we combine directly the measured data in terms of cross–sections (for $\mathrm{q\bar{q}}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states) and forward–backward asymmetries (for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states), and cross–section ratios and asymmetries for heavy flavour production. The $\mathrm{e^+e^-}$ final state is not yet considered, due to the complication of the t-channel effects. Only data corresponding to non-radiative event samples are treated so far.

In [2], a combination of the cross-sections and asymmetries for inclusive hadron and $\mu^+\mu^-$ and $\tau^+\tau^-$ production at 183 and 189 GeV was presented. At that time these datasets had the highest luminosities and centre–of–mass energies. Now the same method is extended to average all data taken up to and including the 189 GeV data. Data taken at energies of 192 GeV and above in 1999 have also been combined, results are shown in figures only. The principle details of the method of combination are given in [2]. The details on how the uncertainites on A_{FB} were handled in the case of samples with low numbers of events are discussed in Section 2.

In Section 3 a method for averaging the heavy flavour results from LEP 2 is discussed. The method is based on that used to combine heavy flavour results at LEP 1 [3]. More details are given in [4]. A preliminary average of measurements of $\mathrm{R_b}$, $\mathrm{R_c}$, $\mathrm{A^b_{FB}}$ and $\mathrm{A^c_{FB}}$ is made, from LEP centre–of–mass energies from 130 to 202 GeV; not every experiment provided all inputs at all energies.

In Section 4 the cross–section and asymmetry results presented in Sections 2 are interpreted in terms of contact interactions between fermions.

2 Averages for Cross–sections and Asymmetries

In this section the results of the preliminary combination are given. This information is also available on the web page [5]. The individual experiments analyses of cross–sections and forward–backward asymmetries are discussed in [6].

In addition to the problems mentioned in [2], the averaging of the data sets at centre–of–mass energies of 130, 136, 161, 172, 192 GeV raise additional problems due to the small numbers of leptonic events in the individual experiments. The standard method for evaluating the statistical uncertainty (in the case of no background) on a forward–backward asymmetry obtained from counting the numbers of events in the forward and backward hemispheres is to calculate

$$\Delta_{A_{\mathrm{FB}}} = \sqrt{((1-(A_{\mathrm{FB}})^2)/N)} \qquad (1)$$

where A_{FB} is the measured asymmetry and N is the observed number of events. This formula has a pathological behaviour: as the measured forward–backward asymmetry approaches unity the calculated uncertainty tends to 0. Thus the quoted error does not represent the true variation of the data which can be large, in the case of low numbers of observed events, and for expected asymmetries not close to unity. In general the uncertainty calculated according to Equation 1 exhibits a strong variation as a function of the measured asymmetry. When trying to average data this means that asymmetries which are fluctuations towards unity are given a larger weight than results which are closer to the expectation, for the same number of measured events. This can bias the averages. To alleviate this problem, we use a statistical uncertainty, computed from Equation 1, with the measured forward–backward asymmetry replaced by the expected (SM) asymmetry for data samples with less than 100 observed events; the number of events is taken as the observed number of events. This has the property that samples with equal numbers of events have equal weights in the average.

Table 1 shows the preliminary combined results corresponding to the signal Definitions 1 of [2] and the difference in the results if Definitions 2 of [2] is used. They show the average cross–sections and leptonic forward–backward asymmetries at each energy, together with the corresponding SM predictions obtained from ZFITTER v6.04 [7]. Due to the method used to correct each data set to a common definition the shifts in the measured values between each definition are identical to the difference in the SM values for the different definitions. The quoted uncertainties on each result do not include the theoretical uncertainties arising from correcting the input data to a common signal definition, which are discussed in Section 4 of [2].

The χ^2 per degree of freedom of the average is 87.3/90. The correlations are rather small, with the largest components at any given pair of energies being between the hadronic cross–sections. The correlations between the averaged hadronic cross–sections are given in Table 3. The other off-diagonal terms in the correlation matrix are smaller than 10%. The full correlation matrix is given at [5].

Figures 1 and 2 show the LEP averaged cross–sections and asymmetries, respectively, (based on Definition 1), as a function of centre–of–mass energy, together with the SM predictions. These figures also include the more preliminary data taken during 1999 at centre–of–mass energies between 192 and 202 GeV. It can be seen that the cross–sections for hadronic final states are somewhat above the SM expectations at each of the four energies taken in 1999. Taking into account the correlations between these data points and also assigning a theory error of $\pm 0.5\%$ [14] to the SM predictions, this cross–section excess is 2.3 standard deviations, when expressed as a single value at an average energy of $\sim$ 198 GeV.

There is good agreement between the SM expectations and the measurements of the individual experiments and the combined averages. There is no evidence in $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$ for physics beyond the SM.

3 Averages for Heavy Flavour Measurements

This section presents a combination of both published [8] and preliminary [9] measurements of $\mathrm{R_b}$, $\mathrm{R_c}$*, and the forward–backward asymmetries $\mathrm{A_{FB}^b}$ and $\mathrm{A_{FB}^c}$ from the LEP collaborations at the centre–of–mass energies in the range of 130 to 202 GeV. Full details can be found in [4]. For the purpose of averaging, a common signal definition has been defined for all the measurements, requiring:

- The effective centre–of–mass energy $\sqrt{\mathrm{s}'} > 0.85\sqrt{\mathrm{s}}$
- The inclusion of ISR and FSR photon interference contribution
- Extrapolation to full angular acceptance

*Unlike at LEP1, $\mathrm{R_q}$ is defined as $\frac{\sigma_{\mathrm{q\bar{q}}}}{\sigma_{\mathrm{had}}}$.

CMS energy (GeV)	Quantity	Average value	SM prediction	Δ
130	$\sigma(q\overline{q})$ [pb]	81.938±2.220	82.803	-0.251
	$\sigma(\mu^+\mu^-)$ [pb]	8.592 ±0.682	8.439	-0.331
	$\sigma(\tau^+\tau^-)$ [pb]	9.082 ±0.931	8.435	-0.108
	$A_{fb}(\mu^+\mu^-)$	0.692 ±0.060	0.705	0.012
	$A_{fb}(\tau^+\tau^-)$	0.663 ±0.076	0.704	0.012
136	$\sigma(q\overline{q})$ [pb]	66.570±1.967	66.596	-0.224
	$\sigma(\mu^+\mu^-)$ [pb]	8.231 ±0.678	7.281	-0.280
	$\sigma(\tau^+\tau^-)$ [pb]	7.123 ±0.821	7.279	-0.091
	$A_{fb}(\mu^+\mu^-)$	0.704 ±0.060	0.684	0.013
	$A_{fb}(\tau^+\tau^-)$	0.752 ±0.088	0.683	0.014
161	$\sigma(q\overline{q})$ [pb]	36.909±1.071	35.247	-0.143
	$\sigma(\mu^+\mu^-)$ [pb]	4.586 ±0.364	4.613	-0.178
	$\sigma(\tau^+\tau^-)$ [pb]	5.692 ±0.545	4.613	-0.061
	$A_{fb}(\mu^+\mu^-)$	0.535 ±0.067	0.609	0.017
	$A_{fb}(\tau^+\tau^-)$	0.646 ±0.077	0.609	0.016
172	$\sigma(q\overline{q})$ [pb]	29.172±0.987	28.738	-0.124
	$\sigma(\mu^+\mu^-)$ [pb]	3.556 ±0.317	3.952	-0.157
	$\sigma(\tau^+\tau^-)$ [pb]	4.026 ±0.450	3.951	-0.054
	$A_{fb}(\mu^+\mu^-)$	0.672 ±0.077	0.591	0.018
	$A_{fb}(\tau^+\tau^-)$	0.342 ±0.094	0.591	0.017
183	$\sigma(q\overline{q})$ [pb]	24.567±0.421	24.200	-0.109
	$\sigma(\mu^+\mu^-)$ [pb]	3.484 ±0.147	3.446	-0.139
	$\sigma(\tau^+\tau^-)$ [pb]	3.398 ±0.174	3.446	-0.050
	$A_{fb}(\mu^+\mu^-)$	0.558 ±0.035	0.576	0.018
	$A_{fb}(\tau^+\tau^-)$	0.608 ±0.045	0.576	0.018
189	$\sigma(q\overline{q})$ [pb]	22.420±0.248	22.156	-0.101
	$\sigma(\mu^+\mu^-)$ [pb]	3.109 ±0.077	3.207	-0.131
	$\sigma(\tau^+\tau^-)$ [pb]	3.140 ±0.100	3.207	-0.048
	$A_{fb}(\mu^+\mu^-)$	0.565 ±0.021	0.569	0.019
	$A_{fb}(\tau^+\tau^-)$	0.584 ±0.028	0.569	0.018

Table 2: *Preliminary combined LEP results for* $e^+e^- \rightarrow f\bar{f}$. *The results all correspond to the signal Definition 1 described in Section 2 of [2]. The difference,* Δ *in the averages for the measurments for Definition 2 relative to Definition 1 are given in the final column. The quoted uncertainties do not include the theoretical uncertainties discussed in section 4 of [2].*

∼ cms energy (GeV)	Correlations 130	136	161	172	183	189
130	1.000	0.066	0.077	0.069	0.106	0.130
136	0.066	1.000	0.072	0.064	0.099	0.122
161	0.077	0.072	1.000	0.077	0.117	0.147
172	0.069	0.064	0.077	1.000	0.104	0.131
183	0.106	0.099	0.117	0.104	1.000	0.205
189	0.130	0.122	0.147	0.131	0.205	1.000

Table 3: *The correlation matrix of the averaged hadronic cross–section results.*

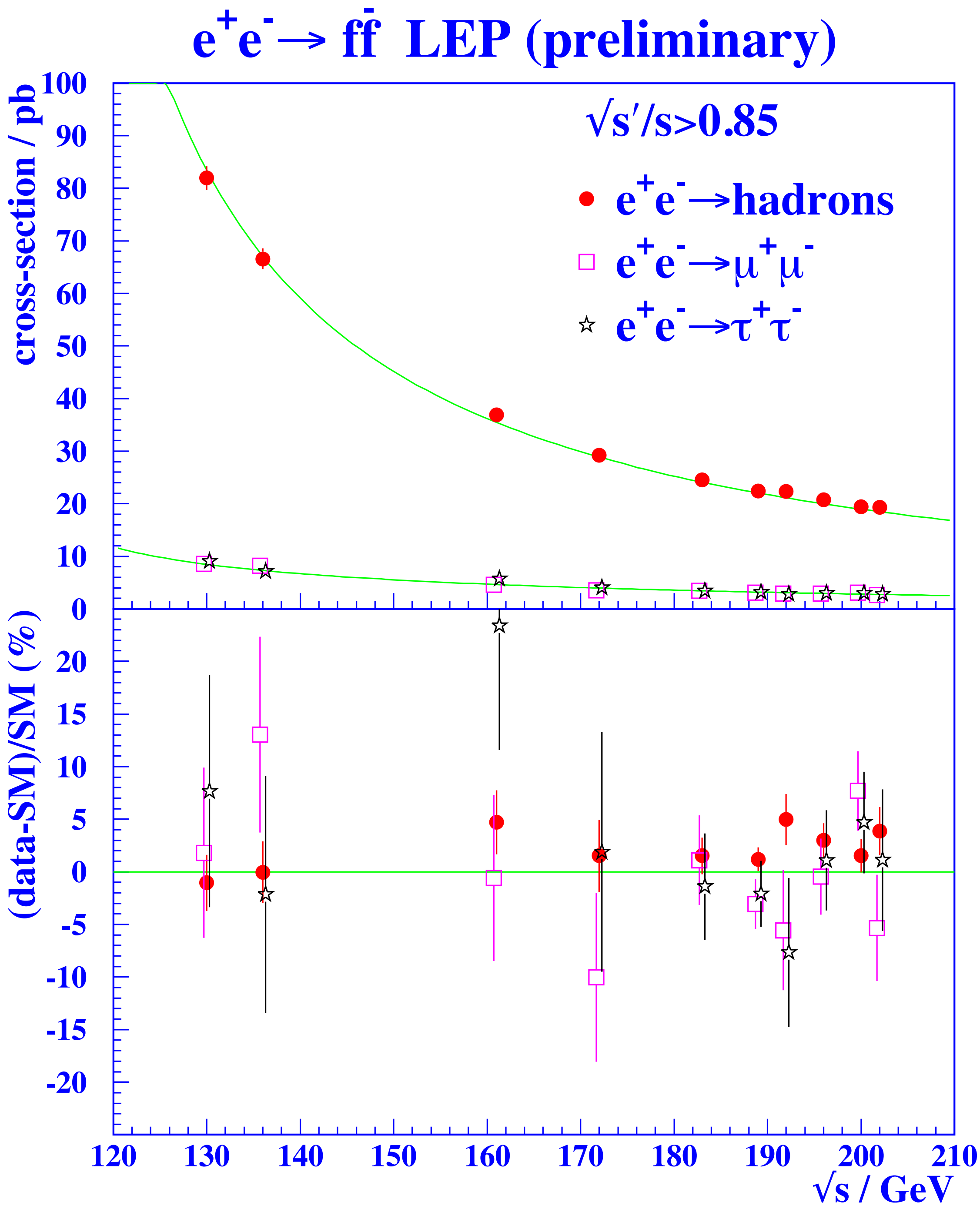

Figure 1: *Preliminary combined LEP results on the cross–sections for* $\mathrm{q\bar{q}}$, $\mu^+\mu^-$ *and* $\tau^+\tau^-$ *final states, as a function of cms energy. The expectations of the SM are also shown. The lower plot shows differences between the data and the SM, divided by the SM prediction.*

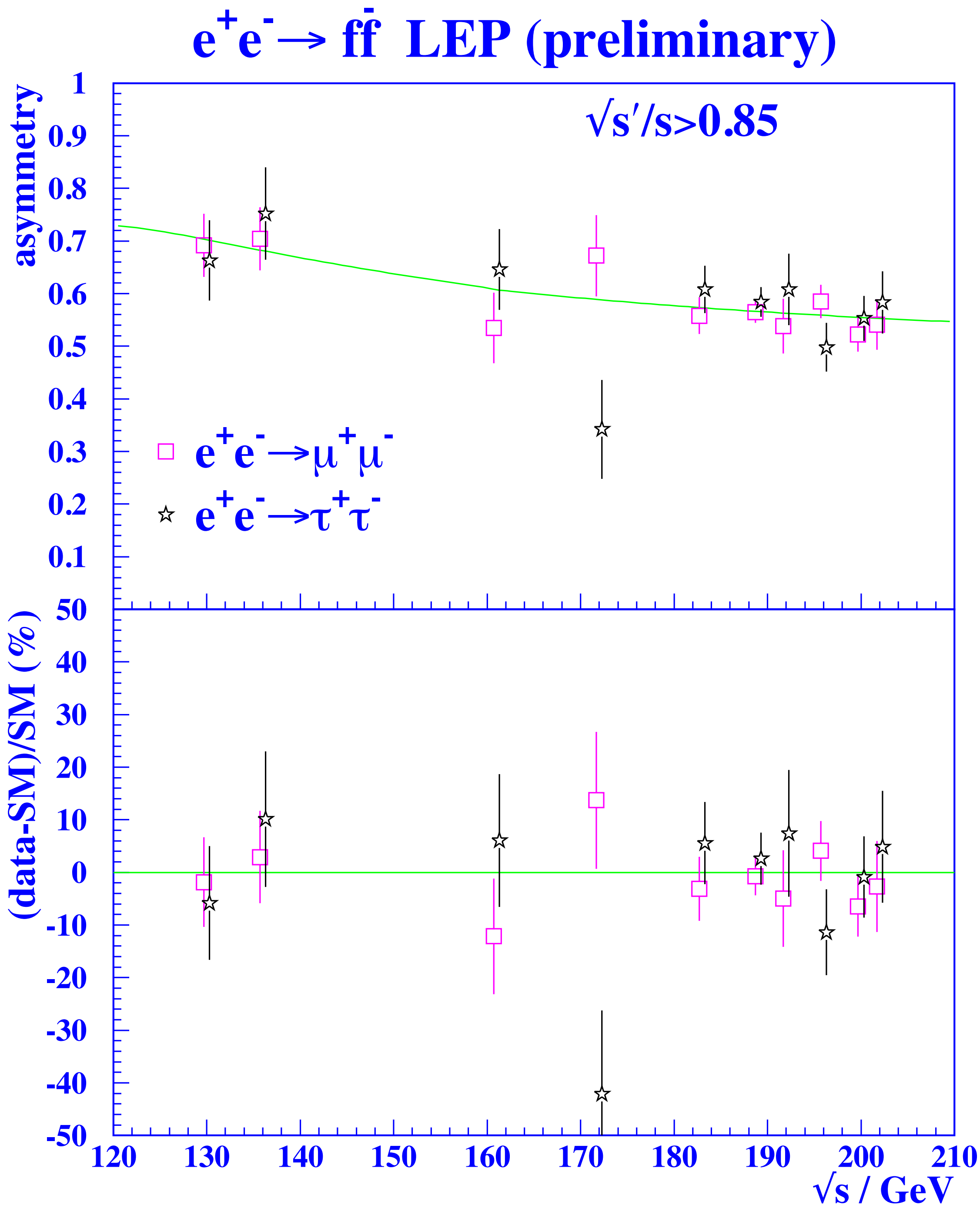

Figure 2: *Preliminary combined LEP results on the forward–backward asymmetry for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states as a function of cms energy. The expectations of the SM are also shown. The lower plot shows differences between the data and the SM, divided by the SM prediction.*

When necessary, these measurements have been corrected to the common signal definition using ZFITTER [10] predictions.

The averaging procedure follows the method described in [3], in particular the dependencies of each of the measurements on the other parameters are explicitly accounted for. Systematic errors are divided into 3 categories: internal errors, errors correlated between the measurements of each experiment and errors common to all experiments. Table 4 summarises the inputs that have been combined, yielding the results presented in Table 5 and Figures 3 and 4. A list of the error contributions from the combination at 189 GeV is shown in Table 6.

4 Contact Interactions

As an example of the sensitivity of the combined results to physics beyond the Standard Model, compared to the results of a single experiment, the combined cross–sections and asymmetries for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ have been used to place limits on contact interactions between leptons. The averaged cross–sections and asymmetries from 130 - 202 GeV have been used. Following reference [12] these interactions are parameterised by an effective Lagrangian, $\mathcal{L}_{eff}$, which is added to the Standard Model Lagrangian and has the form:

$$\mathcal{L}_{eff} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \overline{e}_i \gamma_\mu e_i \overline{f}_j \gamma^\mu f_j,$$

where $g^2/4\pi$ is taken to be 1 by convention, $\delta = 1(0)$ for $f = e (f \neq e)$, $\eta_{ij} = \pm 1$ or 0, Λ is the scale of the contact interactions, e_i and f_j are left or right-handed spinors. By assuming different helicity coupling between the initial state and final state currents and either constructive or destructive interference with the Standard Model (according to the choice of each η_{ij}) a basic set of 6 different models can be defined from this Lagrangian [13], with either constructive (+) or destructive (−) interference between the Standard Model process and the contact interactions. The models LL, RR, VV and AA are considered here since these models lead to large deviations in the $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ channels. The total hadronic cross–section on its own is not particularly sensitive to contact interactions involving quarks. For the purpose of fitting contact interaction models to the data, a new parameter $\epsilon = 1/\Lambda^2$ is defined; with $\epsilon = 0$ in the limit that there are no contact interactions. This parameter is allowed to take both positive and negative values in the fits. Theoretical uncertainties on the SM predictions of $\pm 0.5\%$ [14] on the cross–sections and ± 0.005 on the forward–backward asymmetries, fully correlated between all energies, have been assumed. The values of ϵ extracted for each model were all compatible with the Standard Model expectation $\epsilon = 0$, at the two standard deviation level. These errors on ϵ are typically a factor of two smaller than those obtained from a single LEP experiment with the same data set. The fitted values of ϵ were converted into 95% confidence level lower limits on Λ. The limit are obtained, by by integrating the liklihood function † over the physically allowed values, $\epsilon \geq 0$ for each Λ^+ limits and $\epsilon \leq 0$ for Λ^- limits. The fitted values of ϵ and the extracted limits are shown in Table 7. Figure 5 shows the limits obtained on the scale Λ for the different models assuming universality between contact interactions for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$.

†To be able to obtain confidence limits from the liklihood function it is necessary to convert the liklihood to a probability density function, this is done by mulitplying by a prior probability function. Simply integrating the liklihood is equivalent to multiplying by a uniform prior probability function.

cms energy GeV	R_b				R_c				A_{FB}^b				A_{FB}^c			
133.2	**A**	**D**	L	**O**	x	x	x	x	x	**D**	x	**O**	x	**D**	x	**O**
166.6	**A**	**D**	L	**O**	x	x	x	x	x	**D**	x	**O**	x	**D**	x	**O**
182.7	**A**	D	L	**O**	**A**	x	x	x	**A**	x	x	**O**	A	x	x	**O**
188.6	A	D	L	**O**	x	x	x	x	A	D	L	**O**	x	x	x	**O**
192 to 202	x	D	x	x	x	x	x	x	x	D	x	x	x	x	x	x

Table 4: **Published**, *preliminary (Aleph, Delphi, L3 and Opal) inputs*

Energy GeV	R_b	R_c	A_{FB}^b	A_{FB}^c
133.2	0.1806 ± 0.0134 (0.1853)	- -	0.357 ± 0.251 (0.487)	0.579 ± 0.314 (0.681)
166.6	0.1477 ± 0.0128 (0.1708)	- -	0.616 ± 0.254 (0.561)	0.927 ± 0.344 (0.671)
182.7	0.1619 ± 0.0102 (0.1671)	0.270 ± 0.043 (0.250)	0.525 ± 0.155 (0.578)	0.667 ± 0.209 (0.656)
188.6	0.1552 ± 0.0063 (0.1660)	- -	0.505 ± 0.095 (0.583)	0.451 ± 0.193 (0.649)
191.6	0.1698 ± 0.0266 (0.1655)	- -	0.372 ± 0.302 (0.585)	- -
195.5	0.1663 ± 0.0156 (0.1648)	- -	0.724 ± 0.194 (0.587)	- -
199.5	0.1845 ± 0.0166 (0.1642)	- -	0.744 ± 0.206 (0.590)	- -
201.6	0.1786 ± 0.0234 (0.1638)	- -	0.594 ± 0.284 (0.591)	- -

Table 5: *Results of the global fit, compared to the Standard Model predictions for the signal definition in parentheses. Quoted errors represent the statistical and systematic errors added in quadrature. Due to the large correlation with the measurement of* R_c *at 183 GeV, the error on the measurement of* R_b *at 183 GeV receives an additional contribution, absent at the other energy points. If* R_c *is fixed to the Standard Model value,* R_b *becomes* 0.1636 ± 0.0095 *at 183 GeV.*

Error list	R_b (189 GeV)	A_{FB}^b (189 GeV)	A_{FB}^c (189 GeV)
statistics	0.00577	0.0888	0.1742
internal syst	0.00217	0.0317	0.0650
common syst	0.00121	0.0085	0.0511
total syst	0.00248	0.0328	0.0827
total error	0.00628	0.0947	0.1928

Table 6: *Error breakdown at 189* GeV

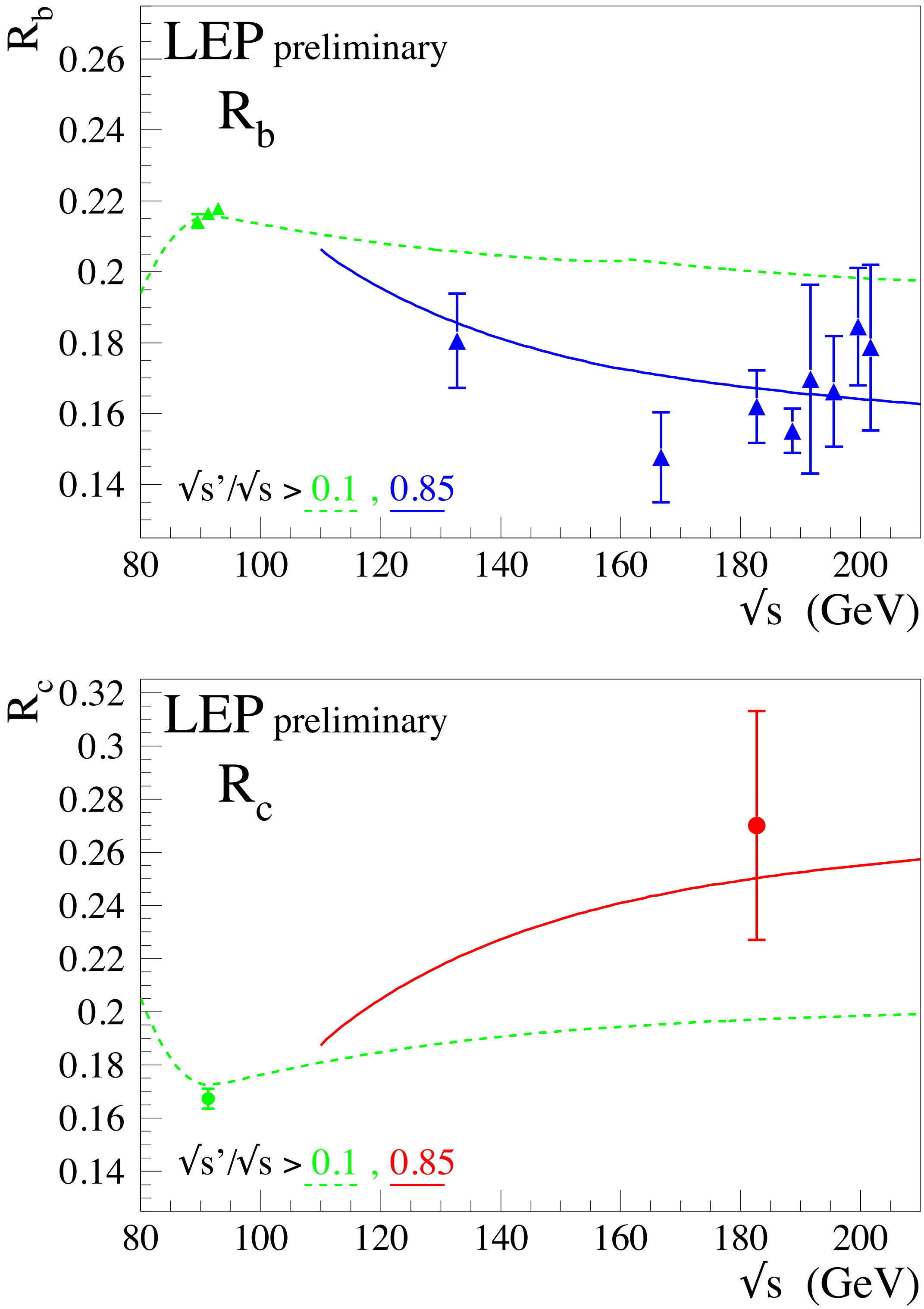

Figure 3: *Preliminary combined LEP measurements of* $\mathrm{R_b}$ *and* $\mathrm{R_c}$*. Solid lines represent the Standard Model prediction for the signal definition and dotted lines the inclusive prediction. Both are computed with ZFITTER [10]. The LEP1 measurements have been taken from [11].*

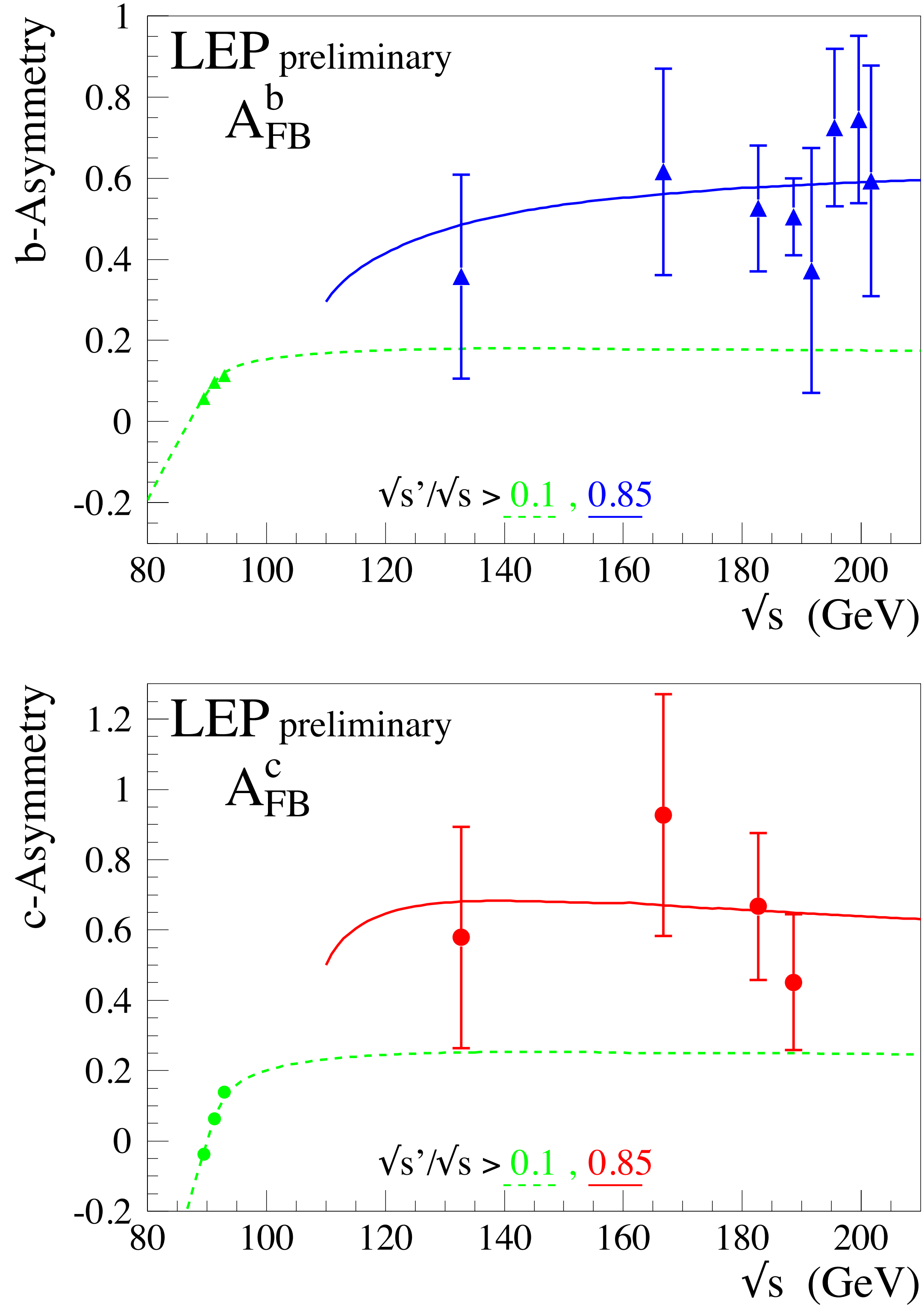

Figure 4: *Preliminary combined LEP measurements of the forward–backward asymmetries* A^b_{FB} *and* A^c_{FB}. *Solid lines represent the Standard Model prediction for the signal definition and dotted lines the inclusive prediction. Both are computed with ZFITTER [10]. The LEP1 measurements have been taken from [11].*

$e^+e^- \to \mu^+\mu^-$			
Model	$\epsilon^{+\sigma_+}_{-\sigma_-}$(TeV^{-2})	Λ^+(TeV)	Λ^-(TeV)
LL	$-0.0016^{+0.0042}_{-0.0053}$	11.2	9.3
RR	$-0.0030^{+0.0066}_{-0.0049}$	10.7	8.9
VV	$-0.0001^{+0.0017}_{-0.0020}$	17.2	16.1
AA	$-0.0025^{+0.0031}_{-0.0019}$	16.0	12.1

$e^+e^- \to \tau^+\tau^-$			
Model	$\epsilon^{+\sigma_+}_{-\sigma_-}$(TeV^{-2})	Λ^+(TeV)	Λ^-(TeV)
LL	$-0.0016^{+0.0062}_{-0.0067}$	9.7	8.4
RR	$-0.0003^{+0.0053}_{-0.0090}$	9.3	8.0
VV	$-0.0011^{+0.0024}_{-0.0026}$	16.3	13.2
AA	$-0.0002^{+0.0038}_{-0.0033}$	12.3	12.2

$e^+e^- \to l^+l^-$			
Model	$\epsilon^{+\sigma_+}_{-\sigma_-}$(TeV^{-2})	Λ^+(TeV)	Λ^-(TeV)
LL	$-0.0016^{+0.0029}_{-0.0042}$	12.8	10.2
RR	$-0.0003^{+0.0026}_{-0.0059}$	12.3	9.7
VV	$-0.0002^{+0.0012}_{-0.0018}$	20.4	17.2
AA	$-0.0002^{+0.0011}_{-0.0034}$	17.6	13.9

Table 7: *Fitted values of ϵ and 95% confidence limits on the scale, Λ, for constructive (+) and destructive interference (−) with the Standard Model, for the contact interaction models discussed in the text. Results are given for $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to l^+l^-$, assuming universality in the contact interactions between $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$.*

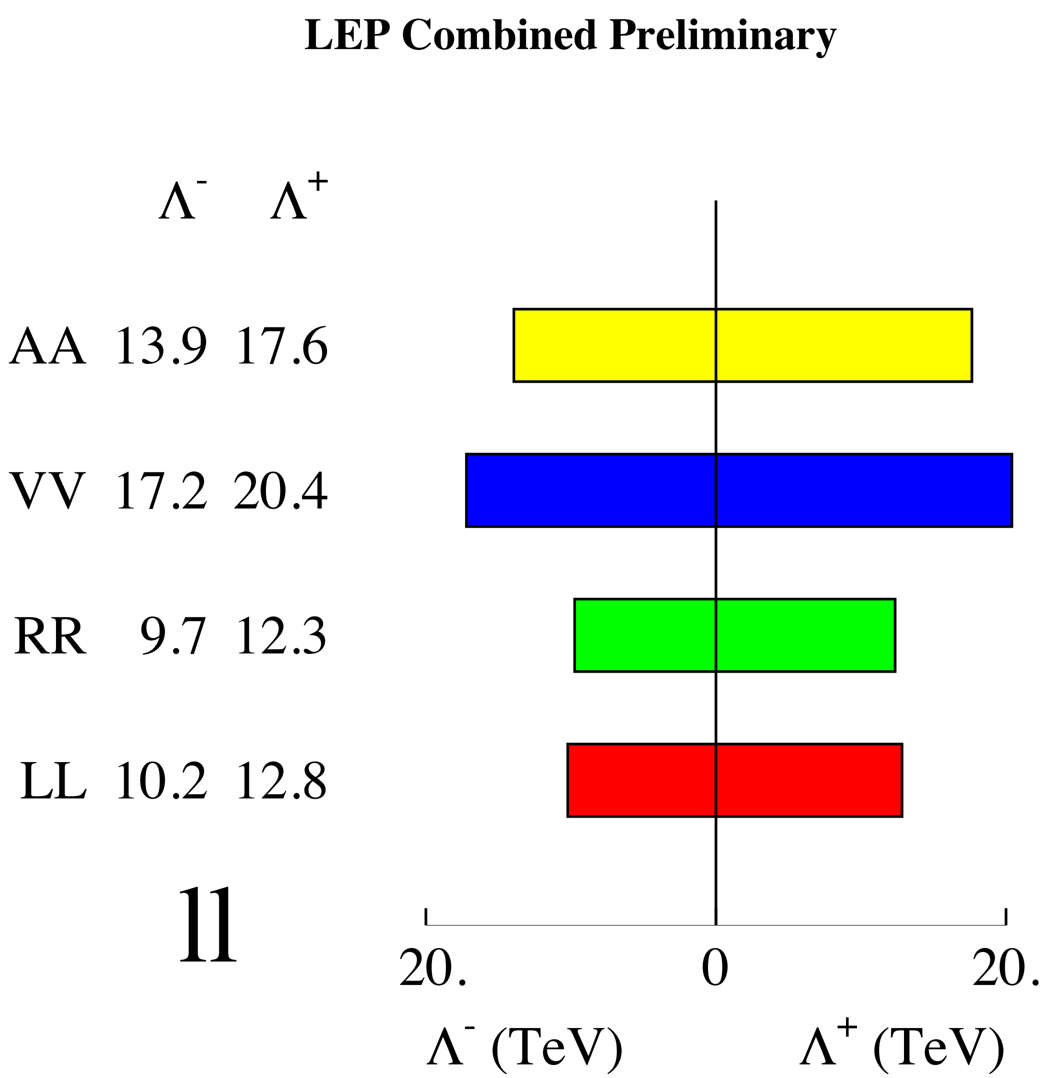

Figure 5: *The limits on Λ for $e^+e^- \to l^+l^-$ assuming universality in the contact interactions between $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$.*

5 Summary and Future Work

A preliminary combination of the LEP 2 $e^+e^- \to f\bar{f}$ cross–section and forward–backward asymmetries from LEP running at energies from 130 to 189 GeV data sets has been made. The results from the four LEP experiments are in good agreement with each other. Furthermore, the combined $q\bar{q}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ cross–sections and the $\mu^+\mu^-$ and $\tau^+\tau^-$ asymmetries are consistent with SM expectations. The results are given in Table 1. These data have also been combined with preliminary results from LEP running in 1999 at energies from 192 to 200 GeV. The averages from these fits are shown graphically in Figures 1 and 2.

An average of results on heavy flavour production at LEP 2 has also been made for measurements of R_b, R_c, A^b_{FB} and A^c_{FB}, using results from LEP centre–of–mass energies from 130 to 202 GeV. Results are given in Table 5 and shown graphically in Figures 3 and 4. The results are in good agreement with the predictions of the SM. Further details are given in [4].

In the future it is planned to include the data taken in 2000. It is also foreseen to use the LEP averages to place limits on various models of physics beyond the SM, in addition to the contact interaction interpretation made here. It is also planned to average $\mu^+\mu^-$ and $\tau^+\tau^-$ differential cross–sections as a function of polar angle of the fermions. These results could be used to investigate models containing physics beyond the Standard Model in which the predicted form of the differential distribution is significantly different from the Standard Model. It is also planned to average the differential cross–sections for e^+e^- final states, where the very different angular acceptances of the experiments and the large contributions from t–channel photon exchange make extrapolation to 4π acceptance inappropriate.

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