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Measurements of R_{b} at $\sqrt{s} = 192 - 208$ GeV

The L3 Collaboration

Abstract

The preliminary measurements of $R_{\mathrm{b}} = \sigma(\mathrm{e^+e^-} \to \mathrm{b\bar{b}})/\sigma(\mathrm{e^+e^-} \to \mathrm{q\bar{q}})$ at centre–of–mass energies of 192 GeV-208 GeV are presented. High energy events, with an effective centre–of–mass energy $\sqrt{s'/s} > 0.85$, are selected. The single-tag method is used, exploiting the relatively large decay length of b-quarks.

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Introduction

The ratio R_{b},

$$R_{\mathrm{b}} = \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{b\bar{b}})}{\sigma(\mathrm{e^+e^-} \to \mathrm{q\bar{q}})}$$

is relevant for precision tests of the Standard Model [1] and sensitive to new physics phenomena [2]. To measure R_{b} [3] hadronic events have to be selected and $\mathrm{b\bar{b}}$ final states have to be separated from other hadronic final states. Therefore, a three-dimensional b-tagging algorithm is performed. This algorithm is based on the decay length of b-quarks which is significantly larger than for other quark flavours [4]. The b-tagging algorithm performs the calculation of the probability for reconstructed tracks not to originate from the primary vertex. High energy events are selected, with an effective centre–of–mass energy, $\sqrt{s'/s} > 0.85$. These measurements are performed according to the single-tag-method.

Event selection

The data are collected with the L3 detector at centre–of–mass energies from 192 GeV to 208 GeV [5]. The centre–of–mass energies and the corresponding integrated luminosities are summarized in Table 1.
The selection of hadronic events at high energies requires an effective centre–of–mass energy of $\sqrt{s'/s} > 0.85$. Additionally, the visible energy is required to be larger than 70% of $\sqrt{s}$ in order to reject remaining radiative events. The quantity y_{23} describes the transition from two to four jets and is computed using the DURHAM algorithm [6] for jet clustering. This quantity is required to be greater than $-log(y_{23}) > 3.5$ to reduce contributing non-$\mathrm{q\bar{q}}$ background. The number of jets per event is required to be $N_{Jet} < 4$ to reduce the $\mathrm{W^+W^-}$ background. All quantities used for hadronic event selection are listed in Table 2.

Monte Carlo processes

All background processes that have been studied are listed in Table 3 together with the corresponding Monte Carlo event generators. The numbers of events for the different centre–of–mass energies for data and Monte Carlo are listed in Table 4. The non-$\mathrm{q\bar{q}}$ background is of the order of 5%-6% for all centre–of–mass energies. The contribution of pair-produced W-events dominates the non-$\mathrm{q\bar{q}}$ background. The background of remaining events with a reconstructed $\sqrt{s'/s} > 0.85$ and a generated $\sqrt{s'/s} < 0.85$, is of the order of 5% to 6% for all investigated centre–of–mass energies. The increasing non-$\mathrm{q\bar{q}}$ background contribution is due to increasing cross section of the process $\mathrm{e^+e^-} \to \mathrm{W^+W^-}(\gamma)$ while the cross section of $\mathrm{e^+e^-} \to \mathrm{q\bar{q}}(\gamma)$ is decreasing with increasing centre–of–mass energies.

R_{b}-Measurement

After hadronic events are selected, the number of $\mathrm{b\bar{b}}$-events in the sample are determined using the three-dimensional b-tag algorithm. This algorithm is based on a decay length tag [4]. Due to low statistics the single-tag-method is applied [3]. For each reconstructed track the probabilitity, P_{Track} to originate from the primary vertex is calculated. The event probability

P is obtained by combining all values P_{Track} for each event separately. One obtains a so-called discriminant variable D, $D = -\log_{10}P$. Events with high D value are most likely $\mathrm{b\bar{b}}$-events that originate from secondary decay vertices. A cut on D ($D = 2.5$) has been applied to the selected sample in order to obtain high purity (more than 70%) and a sufficient high tagging efficiency for b-quarks (more than 40%). Since the number of tagged background events have to be taken into account, R_{b} can easily be derived from the following formula:

$$R_{\mathrm{b}} = \frac{1}{\varepsilon_b - \varepsilon_{uds}} \left[\frac{N^t_{obs} - N^t_{bkg} - N^t_{ISR}}{N_{obs} - N_{bkg} - N_{ISR}} - \varepsilon_c R_{\mathrm{c}} - \varepsilon_{uds}(1 - R_{\mathrm{c}}) \right]. \tag{1}$$

The tagging efficiencies ε_b, ε_c and ε_{uds} are derived from Monte Carlo for all different quark flavours and listed in Table 5.

$$\epsilon_{MC} = \frac{N^{tagged}_{MC} - N^{tagged}_{ISR}}{N^{all}_{MC} - N^{all}_{ISR}} \tag{2}$$

The efficiencies as well as the number of selected and tagged events in data are corrected for events with a reconstructed $\sqrt{s'/s} > 0.85$ and a generated $\sqrt{s'/s} < 0.85$, so called ISR events. Their number is evaluated from Monte Carlo generated $\mathrm{q\bar{q}}$-events and is of the order of 5%-6%. R_{c} is calculated by ZFITTER 6.30 [7] as Standard Model expectation for all centre–of–mass energies taking into account weak corrections, initial state radiation, final state radiation and initial-final state radiation interference.

Statistical and Systematic Errors

Since the number of tagged events is a sub-sample of the number of selected events, the calculation of the statistical error is performed according to binomial error transition law. For the number of selected events, N_{sel}, out of a sample of known number N the statistical errror is given by

$$\Delta N_{sel} = \sqrt{N\varepsilon(1-\varepsilon)}, \tag{3}$$

whereas ε is the selection efficiency. Hence, the statistical error for the selection efficiency taken from Monte Carlo is calculated by

$$\Delta\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N^{MC}}}. \tag{4}$$

The systematic errors have been investigated by varying the corresponding selection quantities within reasonable ranges. The systematic error on R_{b} resulting from finite Monte Carlo statistics for tagging efficiencies is obtained by varying the efficiencies corresponding to their statistical errors and taking the variation of R_{b} as systematic error. Systematic errors from quark modelling are obtained taking Monte Carlo events generated at the Z resonance. The discriminant distribution of these events is reweighted according to errors of the modelling parameters like lifetime, branching fractions etc.. Hence, the deviations of the tagging efficiencies are computed and are considered to be the systematic errors of the tagging efficiencies. The errors are then propagated to high centre–of–mass energies presuming the errors of these parameters are independent from the centre–of–mass energies and presuming that the sample of tagging efficiencies is of the same order w.r.t. the sample at the Z resonance. R_b is then computed with the now different tagging efficiencies. The difference to the measured value of R_b is listed in Table 6. The sign denotes the correlation (positive sign) or anti-correlation (negative sign) to R_b. All single contributions are summed in quadrature and considered as systematic error of R_b. The systematic error contribution from non-$\mathrm{q\bar{q}}$ background and from the ISR correction are computed from their selection efficiencies and the generated number of non-$\mathrm{q\bar{q}}$ background and events with ISR information respectively:

$$N_{bkgd}^{sel} = \varepsilon_{bkgd}^{sel} N_{bkgd}^{gen} \tag{5}$$

$$N_{ISR}^{sel} = \varepsilon_{ISR}^{sel} N_{ISR}^{gen}. \tag{6}$$

Computing the errors of the efficiencies according to (4) and vary the efficiencies within their errors gives the error on R_b.
The error contributions resulting from tracking effects are obtained by tuning the b-tag again. For this purpose the values for DCA shifts and multiple scattering effects are varied by their errors and the tuning is done again for each quantity separately.
R_b is anti-correlated with R_c and the dependence can be parametrised as

$$\Delta R_\mathrm{b} = a(R_\mathrm{c})(R_\mathrm{c} - R_\mathrm{c}^\mathrm{SM}). \tag{7}$$

The values for $a(R_\mathrm{c})$ are listed in Table 7 together with the values of R_c^SM. The summary of all error contributions is listed in Table 8. Table 9 presents the preliminary results of the R_b measurement with L3 detector in 1999 and 2000 for the high energy sample. The measured values of R_b are shown in figure 2 together with the measured points of the published analysis from 130 GeV to 189 GeV [3].

References

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$\sqrt{s}$/ GeV	$\mathcal{L}_{int}/\mathrm{pb}^{-1}$
191.6	29.7
195.5	83.7
199.5	82.8
201.7	37.0
205.2	75.9
206.7	139.1

Table 1: The centre–of–mass energies and integrated luminosities that have been investigated.

Quantity	Number
$\sqrt{s'/s}$	> 0.85
$E_{vis}/\sqrt{s}$	> 0.70
y_{34}	< 0.006
$Acollinearity$	> 2.8

Table 2: Selection criteria for events with $\sqrt{s'/s} > 0.85$.

Background Process	MC Generator
$\mathrm{e^+e^-} \to \mathrm{q\bar{q}}(\gamma)$	KK2F [8]
$\mathrm{e^+e^-} \to \mathrm{ZZ}$	PYTHIA [9]
$\mathrm{e^+e^-} \to \mathrm{Zee}$	PYTHIA
$\mathrm{e^+e^-} \to \tau^+\tau^-$	KORALZ [10]
hadronic two-photon collisions	PHOJET [11]
$\mathrm{e^+e^-} \to \mathrm{We}\nu$	EXCALIBUR
$\mathrm{e^+e^-} \to \mathrm{W^+W^-}(\gamma)$	KORALW [12]

Table 3: Background processes and corresponding Monte Carlo event generators.

$\sqrt{s}$/ GeV	data/expected in MC
192	546/526.1
196	1411/1407.0
200	1289/1302.0
202	604/579.2
205	1166/1131.0
207	2073/2032.4

Table 4: Numbers of high energy events selected from data and expected numbers of events in Monte Carlo.

$\sqrt{s}$/ GeV	ε_b	ε_c	ε_{uds}
192	0.427 ± 0.010	0.0492 ± 0.003	0.0203 ± 0.0010
196	0.432 ± 0.007	0.0464 ± 0.002	0.0201 ± 0.0010
200	0.406 ± 0.007	0.0503 ± 0.002	0.0199 ± 0.0010
202	0.407 ± 0.010	0.0464 ± 0.003	0.0203 ± 0.0010
205	0.393 ± 0.008	0.0477 ± 0.002	0.0203 ± 0.0006
207	0.393 ± 0.003	0.0474 ± 0.001	0.0203 ± 0.0004

Table 5: Efficiencies for all studied centre–of–mass energies for b, c and light quark flavours.

Source	ΔR_{b}					
	192 GeV	196 GeV	200 GeV	202 GeV	205 GeV	207 GeV
b fragmentation parameter:						
$\langle x_E(b)\rangle$	0.0019	0.0017	0.0017	0.0025	0.0019	0.0024
b decay parameters:						
b lifetime τ_b	0.0005	0.0004	0.0004	0.0006	0.0005	0.0006
b decay multiplicity	0.0015	0.0013	0.0013	0.0019	0.0014	0.0018
Fractions in $c\bar{c}$-events:						
D^+	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004	-0.0004
$\mathrm{D_s}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Λ_c	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Gluon splitting in $c\bar{c}$-events:						
$g \to c\bar{c}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$g \to b\bar{b}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
c decay parameters:						
D^0 lifetime	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
D^+ lifetime	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
$\mathrm{D_s}$ lifetime	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Λ_c lifetime	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
c lifetime:	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
c decay multiplicity:						
$\mathrm{D}^+ \to 1$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D}^+ \to 5$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D}^0 \to 0$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D}^0 \to 4$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D}^0 \to 6$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D_s} \to 1$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D_s} \to 5$ prong	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$\mathrm{D_s} \to K^0_S$	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
c fragmentation parameter:						
$\langle x_E(c)\rangle$	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003
Fractions in uds-events:						
$K^0 and \Lambda$	-0.0003	-0.0004	-0.0004	-0.0003	-0.0004	-0.0004
Gluon splitting in uds-events:						
$g \to c\bar{c}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
$g \to b\bar{b}$	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
total	0.0026	0.0023	0.0023	0.0033	0.0025	0.0032

Table 6: Systematic error contribution from quark modelling. The negative sign indicates the anti-correlation between these quantities and R_{b}. The total modelling uncertainty is the quark-modelling error in Table 8.

$\sqrt{s}$/ GeV	$a(R_c)$	R_c^{SM}
192	-0.0710	0.2520
196	-0.0638	0.2530
200	-0.0788	0.2540
202	-0.0673	0.2545
205	-0.0736	0.2553
207	-0.0718	0.2556

Table 7: Coefficients $a(R_c)$ for all centre–of–mass energies and the corresponding values for R_c^{SM} calculated by ZFITTER 6.30 taking weak corrections, initial state radiation, final state radiation, initial final state radiation interference and an angle cut ($\cos\Theta < 0.98$) into account.

Source	ΔR_b					
	192 GeV	196 GeV	200 GeV	202 GeV	205 GeV	207 GeV
Event selection						
$\frac{E_{vis}}{\sqrt{s}}$	0.001	0.005	0.002	0.005	0.004	0.003
$-log(y_{23})$	0.003	0.004	0.003	0.005	0.001	0.003
N_{jet}	0.004	0.009	0.006	0.012	0.009	0.010
Acolinearity	0.004	< 0.001	0.003	0.004	0.003	0.004
Event selection total	0.006	0.011	0.008	0.014	0.010	0.011
quark-modelling	0.003	0.002	0.002	0.003	0.003	0.003
finite MC stat.	0.005	0.003	0.003	0.006	0.002	0.002
Background	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
ISR-correction	0.001	0.001	0.001	0.001	0.001	0.001
Tracking effects.	0.003	0.003	0.003	0.003	0.003	0.003
Total	0.007	0.012	0.009	0.016	0.011	0.012

Table 8: Systematic error contributions from all investigated sources.

$\sqrt{s}$/ GeV	$R_b^{meas.}$	R_b^{SM}
192	$0.170 \pm 0.022 \pm 0.007$	0.1673
196	$0.149 \pm 0.013 \pm 0.012$	0.1667
200	$0.142 \pm 0.013 \pm 0.008$	0.1661
202	$0.208 \pm 0.024 \pm 0.016$	0.1657
205	$0.149 \pm 0.014 \pm 0.011$	0.1653
207	$0.184 \pm 0.010 \pm 0.012$	0.1651

Table 9: Preliminary results of R_b measurements for selected high energy events. In comparison the Standard Model expectation for R_b^{SM} are calculated with ZFITTER 6.30 taking into account weak corrections, initial state radiation, final state radiation, initial final state radiation interference and an angular cut ($\cos\Theta < 0.98$). Statistical and systematic errors are given.

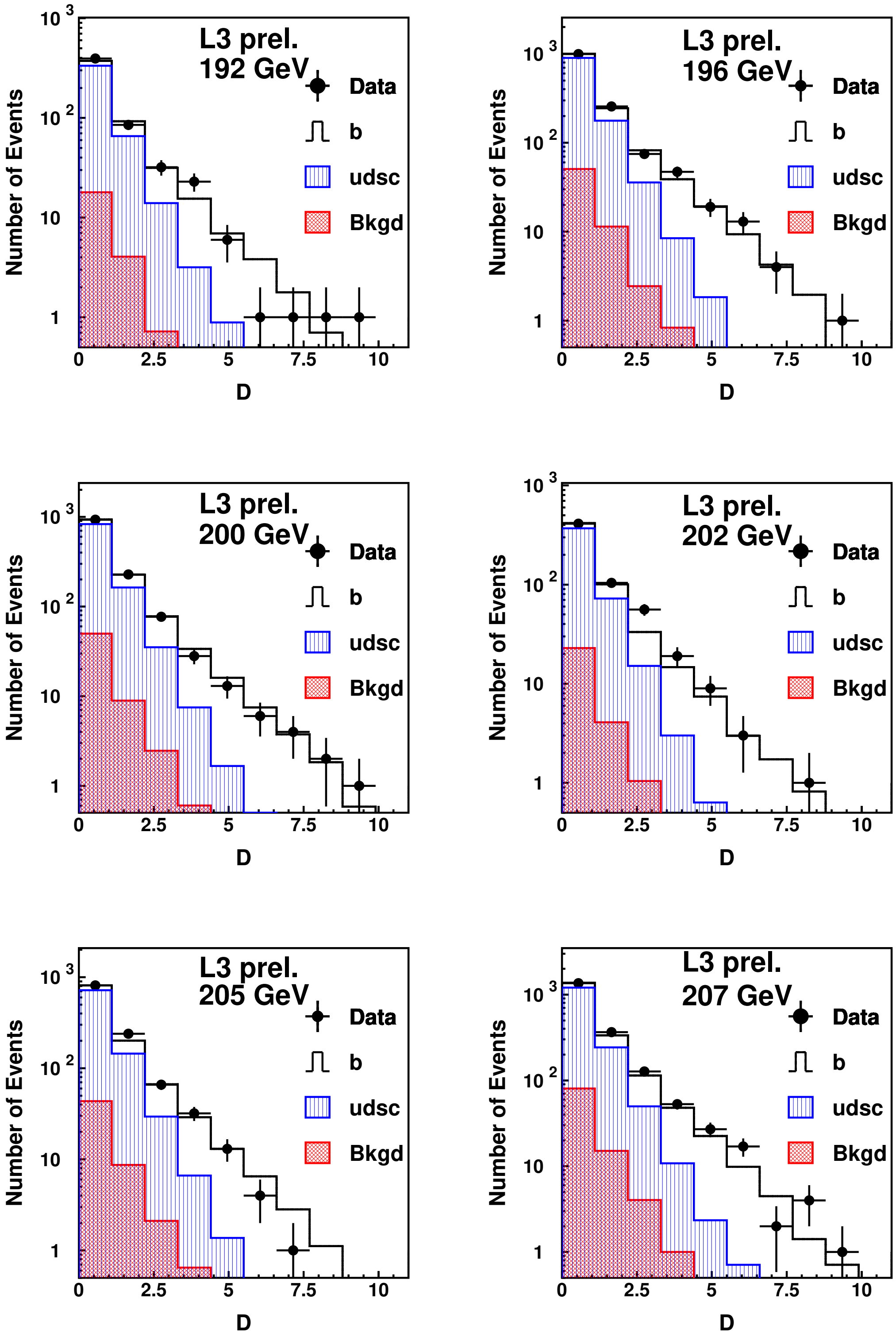

Figure 1: Discriminant distributions for all investigated centre–of–mass energies. The black dots are the data, the open histograms are all Monte Carlo generated events and the hatched histograms are the light quark and the non-$q\bar{q}$ background contributions.

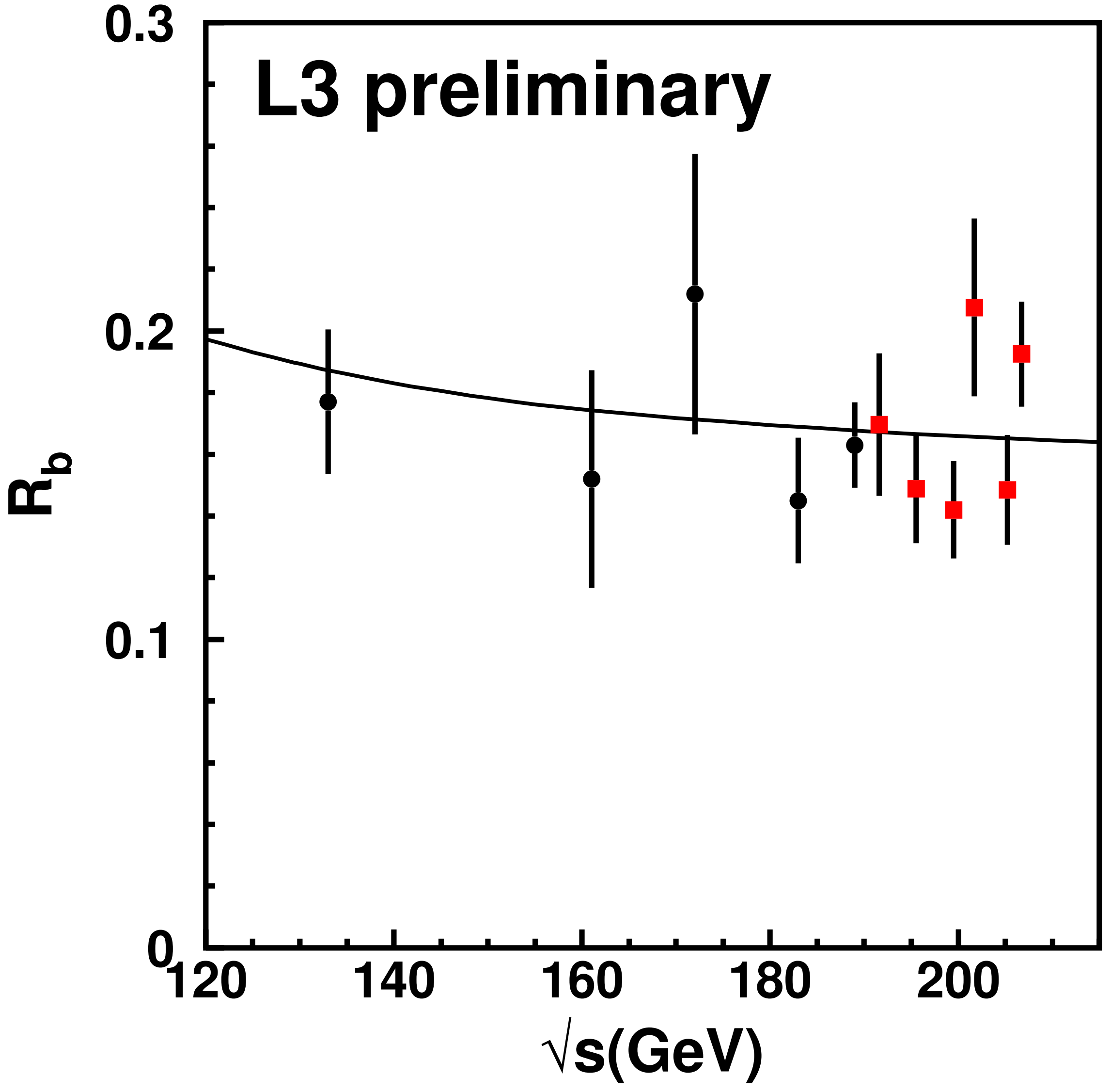

Figure 2: The R_b measurements in comparison to SM expectation. The black dots represent the published measurements from 130 GeV to 189 GeV [3]. The squares represent the results of this analysis.