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Study of Z Boson Pair Production at LEP

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Abstract

Preliminary results are presented on the pair production of Z bosons in the 232,pb^{-1}of data collected in e^+e^- collisions at centre–of–mass energies from 191.6 GeV up to 201.7 GeV by the L3 detector at LEP. The cross section of this process is measured together with those of its final states containing b quarks. The results are found to be in agreement with the Standard Model predictions. Limits on triple couplings between neutral gauge bosons, forbidden in the Standard Model, are derived from these measurements. These results are also interpreted in terms of possible extra space dimensions. All these results are PRELIMINARY.

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1 Introduction

Since 1997 LEP is running at centre–of–mass energies, $\sqrt{s}$, above the production threshold of Z boson pairs. This process is of particular interest as it constitutes an irreducible background for the search of the Standard Model Higgs boson and to several other processes predicted by theories beyond the Standard Model. In addition, it allows the investigation of possible triple neutral gauge boson couplings, ZZZ and ZZγ [1], forbidden at tree level in the Standard Model and presents a high sensitivity to possible effects of extra space dimensions in High Energy Physics processes [2].

The experimental investigation of ZZ production is made difficult by its rather low cross section, compared with competing processes that constitute large and sometimes irreducible backgrounds. The existence at threshold of this process was established at $\sqrt{s} = 183$ GeV [3] and a higher statistics study was presented with the data collected at 189 GeV [4]. The measurement of the cross section for centre–of–mass energies above 190 GeV is presented together with that of final states containing b quarks. These results are interpreted in terms of possible anomalous couplings among neutral gauge bosons and Low Scale Gravity effects.

2 Data and Monte Carlo Samples

The investigated data were collected in 1999 by the L3 detector [5] at centre–of–mass energies between 191.6 GeV and 201.7 GeV, and amount to a total integrated luminosity of $233.1\,\mathrm{pb}^{-1}$. The breakdown into integrated luminosities and centre–of–mass energies reads: $29.7\,\mathrm{pb}^{-1}$ at 191.6 GeV, $83.7\,\mathrm{pb}^{-1}$ at 195.6 GeV, $82.8\,\mathrm{pb}^{-1}$ at 199.6 GeV and $37.0\,\mathrm{pb}^{-1}$ at 201.7 GeV.

The EXCALIBUR [6] Monte Carlo is used to generate events belonging to both the signal and the background neutral–current four–fermion processes. Background from fermion–pair production is described making use of KK2f [7] ($\mathrm{e^+e^-} \rightarrow \mathrm{q\overline{q}}(\gamma)$), KORALZ 4.02 [8] ($\mathrm{e^+e^-} \rightarrow \mu^+\mu^-(\gamma)$ and $\mathrm{e^+e^-} \rightarrow \tau^+\tau^-(\gamma)$) and BHWIDE [9] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}(\gamma)$). Background from charged–current four–fermion processes is generated with EXCALIBUR for the $\mathrm{e}\nu_\mathrm{e}\mathrm{q\bar{q}'}$ and $\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$ ($\ell = \mathrm{e}, \mu, \tau$) final states and KORALW 1.21 [10] for other W-pair mediated processes. Contributions from multiperipheral processes are modelled by PHOJET 1.05c [11] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-q\overline{q}}$) and DIAG36 [12] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}\ell^+\ell^-$).

The L3 detector response is simulated using the GEANT 3.15 program [13], which takes into account the effects of energy loss, multiple scattering and showering in the detector. Time dependent detector inefficiencies, as measured in the data taking period, are reproduced in these simulations.

The definition of the Z pair signal proceeds through kinematic requirements to the four final state fermions [3, 4]: the invariant mass of both the generated fermion pairs must be between 70 GeV and 105 GeV. This criterion has to be satisfied by at least one of the two possible pairings of four same flavour fermions. In five cases the fermion pairs can originate from a charged–current process ($\mathrm{u\bar{u}d\bar{d}}$, $\mathrm{c\bar{c}s\bar{s}}$ and $\nu_\ell\bar{\nu}_\ell\ell^+\ell^-$, with $\ell = \mathrm{e}, \mu, \tau$). If this happens, the invariant masses of the fermion pairs which could come from W decays are required to be either below 75 GeV or above 85 GeV. Events with electrons in the final state are rejected if $|\cos\theta_\mathrm{e}| > 0.95$, where θ_e is the electron polar angle, this requirement reflects the L3 central tracker angular coverage and helps in rejecting multiperipheral contribution to the signal definition. The cross sections for the four considered centre–of–mass energies are, in increasing order of energy, 0.79 pb, 0.92 pb, 1.00 pb and 1.03 pb.

3 Event Selection

All the final states of the Z pair decay are investigated with criteria similar to those used at $\sqrt{s}$ = 189 GeV [4]. The yields of these selections are summarised in Table 1 for the total integrated luminosity sample.

Selection	Data	Signal MC	Background MC
$q\bar{q}\ell^+\ell^-$	31	18.8	5.0
$q\bar{q}\nu\bar{\nu}$	407	45.1	339.2
$q\bar{q}q'\bar{q}'$	530	69.2	445.2
$\ell^+\ell^-\nu\bar{\nu}$	3	3.2	2.5
$\ell^+\ell^-\ell'^+\ell'^-$	3	1.3	1.0

Table 1: Data, signal and background Monte Carlo events selected by each analysis. The numbers include all the centre–of–mass energies. The $\ell^+\ell^-\nu\bar{\nu}$ figures refer only to electrons and muons.

Each selection identifies the most significant variable to distinguish signal and background. For the $e^+e^- \to ZZ \to q\bar{q}\ell^+\ell^-$ final states this variable is the output of a kinematic fit that constrains the hadronic and leptonic systems, within their resolutions, to have the same invariant mass. This variable, M_{5C} is presented in Figure 1 for the full data sample. Both the $e^+e^- \to ZZ \to q\bar{q}\nu\bar{\nu}$ and $e^+e^- \to ZZ \to q\bar{q}q'\bar{q}'$ final states are studied by means of an artificial neural network, whose outputs are plotted for the full data sample in Figure 2, that also presents the sum of the invariant and recoil masses to the lepton pair in the $e^+e^- \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $e^+e^- \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ cases. For this last channel the lepton pair is chosen with the same requirements [4] designed at $\sqrt{s} = 189$ GeV.

4 Measurement of the ZZ Cross Section and b quark content

A binned maximum likelihood fit to the most significant variables described above allows the determination of the ZZ cross section in the individual final states. Assuming the Standard Model predictions for the relative weights of the different channels, the ZZ cross section σ_{ZZ} for each of the investigated energies is found to be:

$$\sigma_{ZZ}(191.6\text{ GeV}) = 0.28^{+0.20}_{-0.23}\,\text{pb}\ \ (\text{SM}: 0.79\,\text{pb})$$

$$\sigma_{ZZ}(195.6\text{ GeV}) = 1.13^{+0.23}_{-0.24}\,\text{pb}\ \ (\text{SM}: 0.92\,\text{pb})$$

$$\sigma_{ZZ}(199.6\text{ GeV}) = 1.22^{+0.24}_{-0.25}\,\text{pb}\ \ (\text{SM}: 1.00\,\text{pb})$$

$$\sigma_{ZZ}(201.7\text{ GeV}) = 0.90^{+0.37}_{-0.38}\,\text{pb}\ \ (\text{SM}: 1.03\,\text{pb})$$

in good agreement with the expected cross sections within the signal definition cuts, reported in the parentheses. The quoted uncertainties are only statistical, the relative systematic uncertainties are comparable to the effects of the sources reported for the 189 GeV analysis. These cross sections are compared in Figure 3 with the expected evolution of the cross section with $\sqrt{s}$.

These results are also customarily reported in term of the NC02 cross section, that refers to the production of the four fermions of the final state by means of the exchange of two Z bosons. The NC02 cross sections are extracted from the previous results as:

$$\sigma_{\mathrm{ZZ}}^{\mathrm{NC02}}(191.6\ \mathrm{GeV}) = 0.27^{+0.20}_{-0.23}\,\mathrm{pb}\ \ (\mathrm{SM}: 0.78\,\mathrm{pb})$$

$$\sigma_{\mathrm{ZZ}}^{\mathrm{NC02}}(195.6\ \mathrm{GeV}) = 1.11 \pm 0.23\,\mathrm{pb}\ \ (\mathrm{SM}: 0.90\,\mathrm{pb})$$

$$\sigma_{\mathrm{ZZ}}^{\mathrm{NC02}}(199.6\ \mathrm{GeV}) = 1.19 \pm 0.24\,\mathrm{pb}\ \ (\mathrm{SM}: 0.98\,\mathrm{pb})$$

$$\sigma_{\mathrm{ZZ}}^{\mathrm{NC02}}(201.7\ \mathrm{GeV}) = 0.89^{+0.36}_{-0.37}\,\mathrm{pb}\ \ (\mathrm{SM}: 1.02\,\mathrm{pb})$$

The SM predictions reported in parentheses are calculated with EXCALIBUR.

The measurement of the b quark content in ZZ events constitutes a sound test of the detector capabilities to identify an heavy particle decaying in b quarks recoiling against a Z boson. This configuration is of fundamental importance at LEP as it occurs in the production of the Higgs boson.

The investigation of the ZZ$\rightarrow$ $\mathrm{b\bar{b}X}$ events proceeds by combining [4] the most significant variables of the final states containing hadrons, plotted in Figures 1 and 2, with a further variable describing the b quark content in the event [14]. The relatively low rate of this process suggests its investigation in terms of a single luminosity averaged centre–of–mass energy, equal to 197.4 GeV. The result for $\sigma_{\mathrm{ZZ\rightarrow b\bar{b}X}}$ reads:

$$\sigma_{\mathrm{ZZ\rightarrow b\bar{b}X}}(197.4\ \mathrm{GeV}) = 0.32 \pm 0.09\,\mathrm{pb},$$

in agreement with the Standard Model prediction of 0.27 pb determined with EXCALIBUR. The errors are statistical only. In this fit the other ZZ final states are fixed to their Standard Model expectations.

5 Anomalous Couplings and Extra Dimensions

The most general parametrisation of the ZZZ and ZZγ anomalous couplings [1] implies four couplings, f_i^{V} ($i = 4, 5; \mathrm{V} = \gamma, \mathrm{Z}$), where the V superscript corresponds to an anomalous vertex ZZV. At tree level these couplings are zero in the Standard Model and a possible non-zero value would change the ZZ cross section but also the shape of the discriminant distributions presented in Figures 1 and 2. These can hence be used to fit the f_i^{V} value favoured by the data via reweighting the four fermion Monte Carlo events according to the anomalous coupling [15].

These binned maximum likelihood are performed for each of the anomalous couplings f_i^{V}, fixing the others to zero and yield results in agreement with the Standard Model, from which 95% confidence level limits on the values of couplings are set as:

$$-0.8 \leq f_4^{\mathrm{Z}} \leq 0.8; \quad -1.9 \leq f_5^{\mathrm{Z}} \leq 2.2; \quad -0.5 \leq f_4^{\gamma} \leq 0.5; \quad -1.2 \leq f_5^{\gamma} \leq 1.2.$$

Limits from the previous analyses at $\sqrt{s} = 183$ GeV [3] and $\sqrt{s} = 189$ GeV [4] are included in the results quoted above. An improvement of more than a factor two is achieved.

A similar fit procedure was applied leaving as a free parameter the scale of Low Scale Gravity, M_S, within the formalism and the framework described in Reference [16]. Good agreement with the Standard Model predictions is again observed and a lower limit at 95% confidence level on M_S is set as:

$$M_S > 1.2 \text{ TeV}.$$

This limit includes the data collected at lower energies for the ZZ process and holds both for constructive and destructive interference between the Standard Model diagrams and those including the exchange of a virtual graviton. It largely improves the previous combined limit from all the fermion and boson pair production final states set at lower energies [16].

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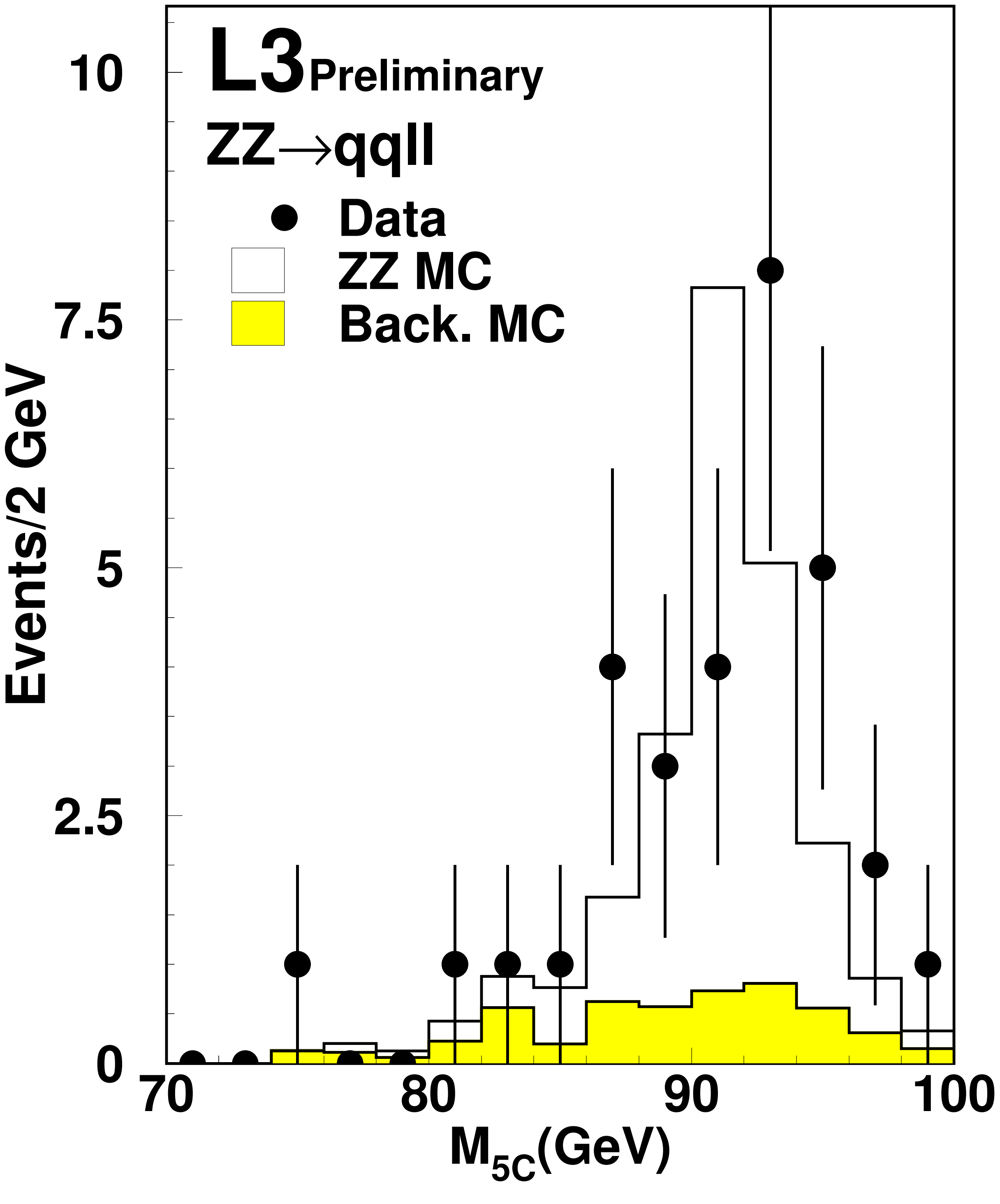

Figure 1: Invariant mass after a kinematic fit, M_{5C}, of the lepton pair for the $q\bar{q}\ell^+\ell^-$ selected events.

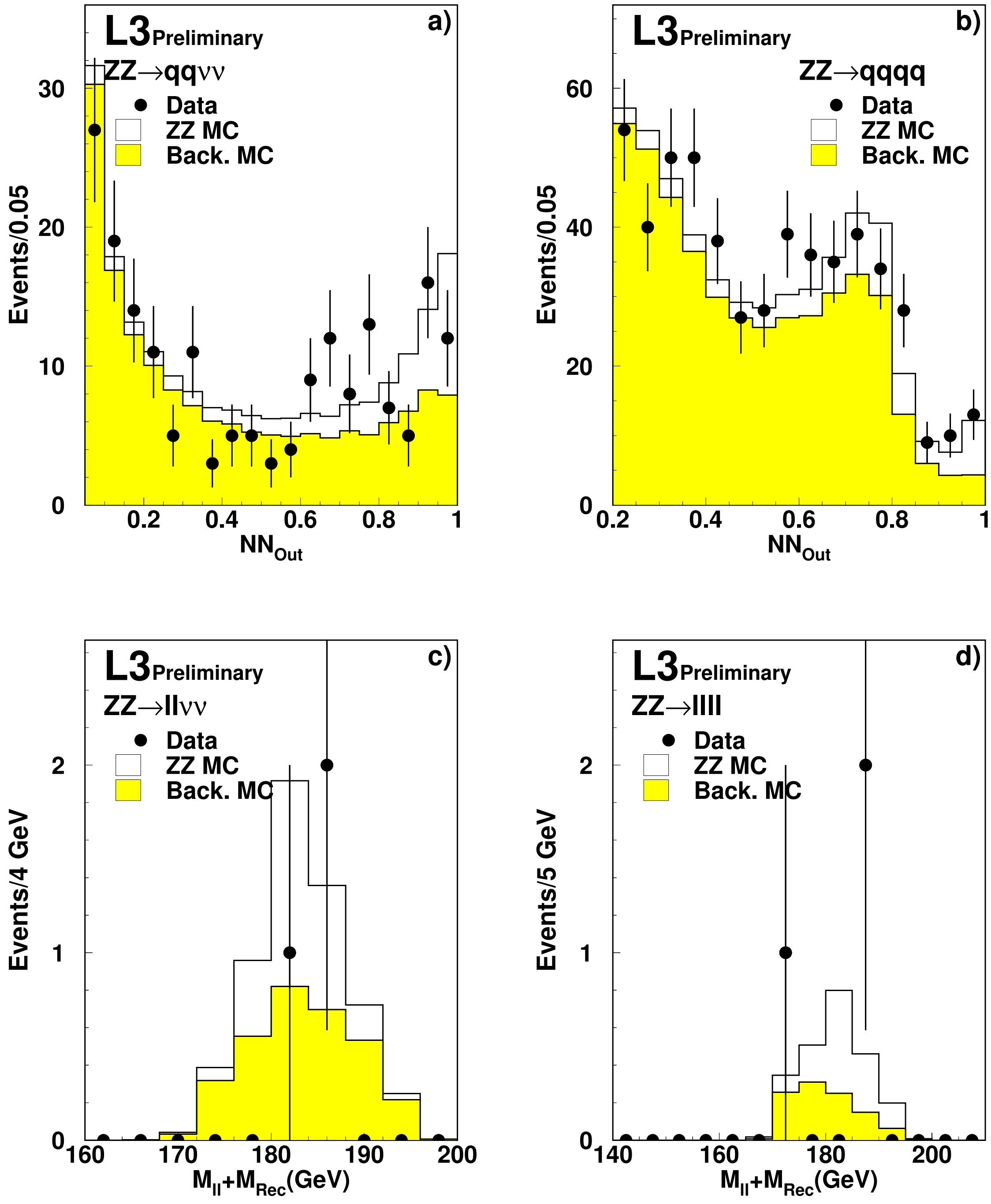

Figure 2: a) and b) neural network output for the $q\bar{q}\nu\bar{\nu}$ and $q\bar{q}q'\bar{q}'$ selected events, c) and d) sum of visible and recoil masses for the $\ell^+\ell^-\nu\bar{\nu}$ and $\ell^+\ell^-\ell'^+\ell'^-$ final states.

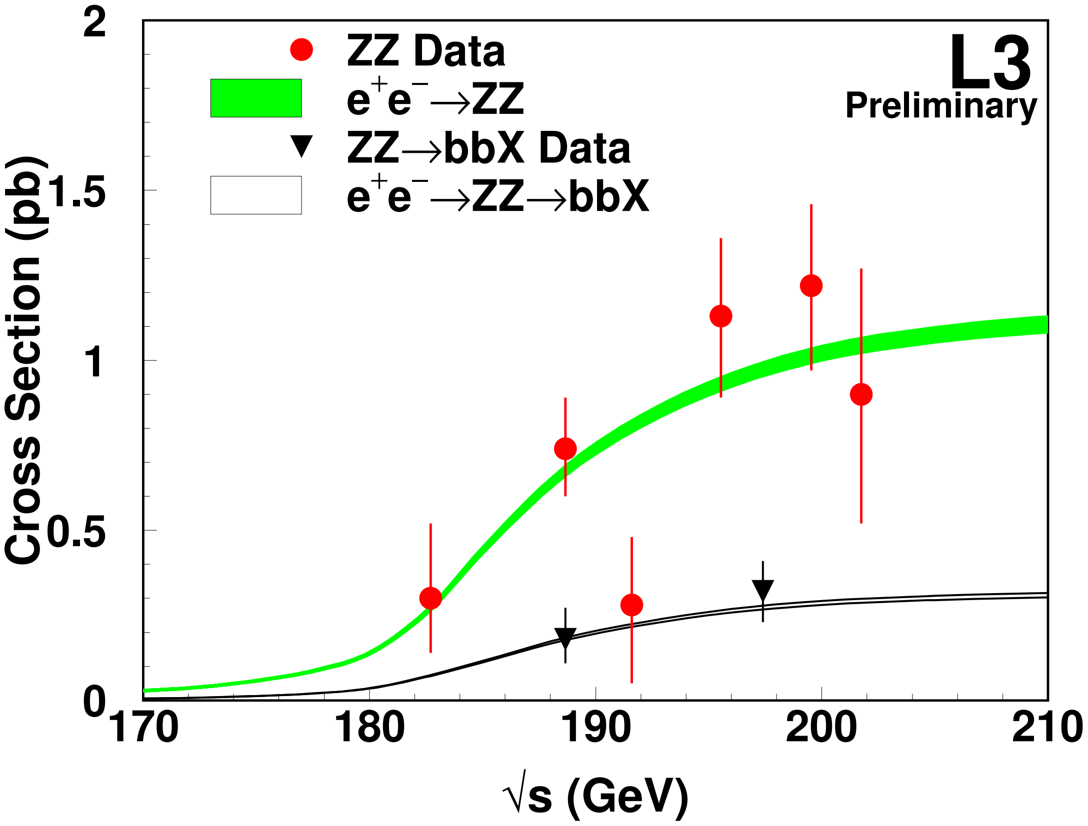

Figure 3: Standard Model prediction for the ZZ and ZZ $\rightarrow$ b$\bar{\text{b}}$X cross sections and the corresponding measurements. Signal definition cuts implemented with the EXCALIBUR Monte Carlo are applied and a 2% uncertainty is associated to the predictions.