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Electroweak Precision Tests with a Future Linear Collider

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Abstract

Future high energy linear electron positron colliders with centre-of-mass enegies between 90 and 1000 GeV offer a unique opportunity to study precisely the Standard Model and phenomena from new physics. Most important, the mechanism of electroweak symmetry breaking can be established in full depth if one or more Higgs bosons are observed. Precision measurements of electroweak processes open a window into the multi-TeV energy range for searching for new physics, which is of particular importance if no light Higgs boson is observed.

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1 Framework

The physical motivation and the technical feasibility of linear electron-positron colliders (LC) has been intensively studied in the past years in Japan (JLC [1]), the US (NLC [2]) and Europe (TESLA [3]). The energy of such a machine would be 500 GeV in a first phase with upgrade potential to about 1 TeV.

A LC has a very rich physics potential covering both the study of new phenomena (Higgs physics, Supersymmetry and alternative physics) and precision tests of the Standard Model (SM) (top quark physics, electroweak physics and QCD). Here only prospects for precision Higgs measurements and precision electroweak measurements in the context of strong electroweak symmetry breaking (EWSB) will be described. The results presented here are based on integrated luminosities of 500 to 1000 fb^{-1} and on realistic simulations of detector performance and background conditions.

2 Higgs Physics

In the SM and many of its extensions, EWSB proceeds via the Higgs mechanism leading to one or more physical Higgs bosons. The mass of the lightest Higgs boson is bounded from above on theoretical grounds, requiring perturbativity of the Higgs coupling up to a high energy scale. Experimentally, $m_{\mathrm{H}} < 200\,\mathrm{GeV}$ is obtained from the interpretation of electroweak precision measurements within the SM.

While a Higgs boson, if it exists, is very likely to be found at Tevatron or LHC, the precise measurement of its properties and couplings can only be performed at the LC.

The main production mechanisms for the SM-Higgs boson at the LC are Higgsstrahlung ($\mathrm{e^+e^-} \to \mathrm{ZH}$) and WW-fusion ($\mathrm{e^+e^-} \to \nu_e\bar{\nu}_e\mathrm{H}$). This gives $O(10^5)$ Higgs bosons per year for a light Higgs. Furthermore the Yukawa process $\mathrm{e^+e^-} \to \mathrm{t\bar{t}H}$ and the double Higgsstrahlung process $\mathrm{e^+e^-} \to \mathrm{ZHH}$ can be exploited. The Higgs boson itself can be detected independent of its decay products through the observation of a mass peak in the invariant mass spectrum recoiling against a lepton pair from the Z-decay in the Higgsstrahlung process. Furthermore, all relevant Higgs boson decays ($\mathrm{b\bar{b}}$, $\mathrm{c\bar{c}}$, $\tau^+\tau^-$, gg, $\mathrm{W^+W^-}$, ZZ, $\gamma\gamma$, $\mathrm{t\bar{t}}$) can be observed exclusively in the detector under study.

This large variety of accessible production mechanisms and decay modes in conjunction with the well defined initial state and clean environment of $\mathrm{e^+e^-}$-collisions allows the determination of the complete profile of the observed Higgs particle.

The coupling g_{HZZ} of the Higgs boson to the Z can be derived in a model independent way from the observed cross-section of the Higgsstrahlung process with leptonically decaying Z-boson [4] (Fig. 1). The coupling g_{HWW} can be derived from the cross-section for WW-fusion using $\mathrm{H} \to \mathrm{b\bar{b}}$ decays [5]. This cross-section can be disentangled from the Higgsstrahlung contribution with $\mathrm{Z} \to \nu\bar{\nu}$ exploiting the different distributions of the missing invariant mass (Fig. 2).

An essential prediction of the Higgs mechanism is the Yukawa coupling of the Higgs boson to fermions being proportional to the fermion mass. This prediction can be accurately tested by measuring the Higgs boson decay branching ratios. The different hadronic Higgs boson decays $\mathrm{b\bar{b}}$, $\mathrm{c\bar{c}}$ and gg as well as $\tau^+\tau^-$ can be disentangled using the excellent flavour tagging capabilities of a LC detector [6]. The expected precision of the branching ratio measurement is ranging from 2 % (for $\mathrm{b\bar{b}}$) to approximately 10 % (for gg) for a light Higgs boson ($m_{\mathrm{H}} < 160\,\mathrm{GeV}$) (Fig. 3).

The double Higgsstrahlung process $\mathrm{e^+e^-} \to \mathrm{ZHH}$ gives access to the triple Higgs coupling λ_{HHH} of the Higgs boson. This coupling determines the shape of the Higgs potential which is exactly predicted in terms of the Higgs mass in the SM and thus provides a rigorous test of the Higgs mechanism. Since the cross-section for this process is small (0.35 fb for $m_{\mathrm{H}} = 120\,\mathrm{GeV}$ at $\sqrt{s} = 500\,\mathrm{GeV}$), a very high luminosity is essential. A realistic study shows that 20 % precision of λ_{HHH} seems possible for a light Higgs boson [7].

From the precision measurements of cross-sections and branching ratios the couplings of the Higgs boson to the different gauge bosons and fermions can be extracted [8]. The expected precision ranges from 1.2 % (for g_{HZZ}) up to 3.7 % (for

$g_{Hc\bar{c}}$) for a light Higgs boson ($m_H = 120\,\text{GeV}$). As an example, Figure 4 shows the sensitivity of the couplings g_{Hbb} and g_{Hcc} at a LC to the mass of the pseudoscalar Higgs boson A in the MSSM.

3 Strong Electroweak Symmetry Breaking

Even if no light Higgs boson is found, the LC can contribute to the understanding of EWSB and the search for new physics. Unitarity requires that the interaction of gauge bosons becomes strong at high energies. Without knowing the details of the new strong interaction, an effective Lagrangian can be used to describe the interactions of electroweak gauge bosons [9]. Its coupling parameters α_1, α_2 and α_3 describe non-standard triple gauge boson couplings (TGC), and α_4 and α_5 describe non-standard quartic gauge boson couplings (QGC), assuming $SU(2)_c$ invariant and linearly breaking operators, which conserve C and P. Each α_i is related to an energy scale of new physics Λ_i^* by

$$\frac{\alpha_i}{16\pi^2} = \left(\frac{246\,\text{GeV}}{\Lambda_i^*}\right)^2. \tag{1}$$

The couplings are normalised in such a way that they are of $O(1)$ for new physics around 3 TeV.

TGCs can be measured in the most general way in W-pair production. A realistic study of the semi-leptonic decay channel $W^+W^- \to q\bar{q}l\bar{\nu}_l$ at an energy of 800 GeV shows that the expected errors for anomalous TGCs [11] Δg_Z^1, $\Delta\kappa_\gamma$ and λ_γ are in the order of 10^{-4} [10], which is up to two orders of magnitude better than at LEP [12] or Tevatron. This includes the use of polarised electrons ($\pm 80\,\%$) and positrons ($\mp 60\,\%$).

The α parameters are a linear combination of Δg_Z^1, $\Delta\kappa_Z$ and $\Delta\kappa_\gamma$. Unfortunately this transformation is singular and only two out of three couplings can be measured independently in this process, resulting in a blind direction in the parameter space. Figure 5 shows the expected errors using the TGC measurement. The expected errors for α_2 and α_3 can be interpreted by equation (1) as limits on the energy scale of new physics. Using electron polarisation ($\pm 80\,\%$) yields 8.7 TeV for Λ_2^* and 11.6 TeV for Λ_3^* at 800 GeV at 68 % confidence level assuming $\Delta\alpha_1 = 0$. These limits can be increased by a factor of 1.2 using also positron polarisation ($\mp 60\,\%$).

The parameter α_1 can be independently obtained from electroweak precision observables at the Z-Pole. Figure 5 shows also the expected error on α_1 from a measurement at GigaZ. This option of a LC describes a high luminosity run at the Z-pole ($\sqrt{s} \approx 91\,\text{GeV}$). A limit of 5.9 TeV for Λ_1^* at 68 % confidence level can be obtained.

The QGC parameters α_4 and α_5 can be measured in the processes $e^+e^- \to \nu_e\bar{\nu}_e W^+W^-$ and $e^+e^- \to \nu_e\bar{\nu}_e ZZ$. A realistic study of the fully hadronic decay channel was performed at a centre-of-mass energy of 800 GeV [13]. The couplings are extracted by fitting the total cross-section and differential distributions. The use of left-handed electrons ($-80\,\%$) and right-handed positrons (40 %) improves the result significantly. The combination of both channels removes ambiguities and increases the sensitivity. The expected errors on α_4 and α_5 can again be interpreted as a limit on the energy scale of new physics. Using equation (1) gives 2.3 TeV for Λ_4^* and 3.1 TeV for Λ_5^* at 68 % confidence level. The limits improve asymptotically as $1/\sqrt{\mathcal{L}}$, where $\mathcal{L}$ is the integrated luminosity.

4 Conclusion

An electron positron linear collider in the $90 - 1000\,\text{GeV}$ regime allows very significant insights into physics at the electroweak scale. The essential parts of the Higgs mechanism of electroweak symmetry breaking can be fully established through precision measurements of Higgs boson properties. If no light Higgs boson is found, electroweak precision measurements of triple and quartic gauge boson couplings can extend the energy range for searches for new physics far into the multi-TeV energy range.

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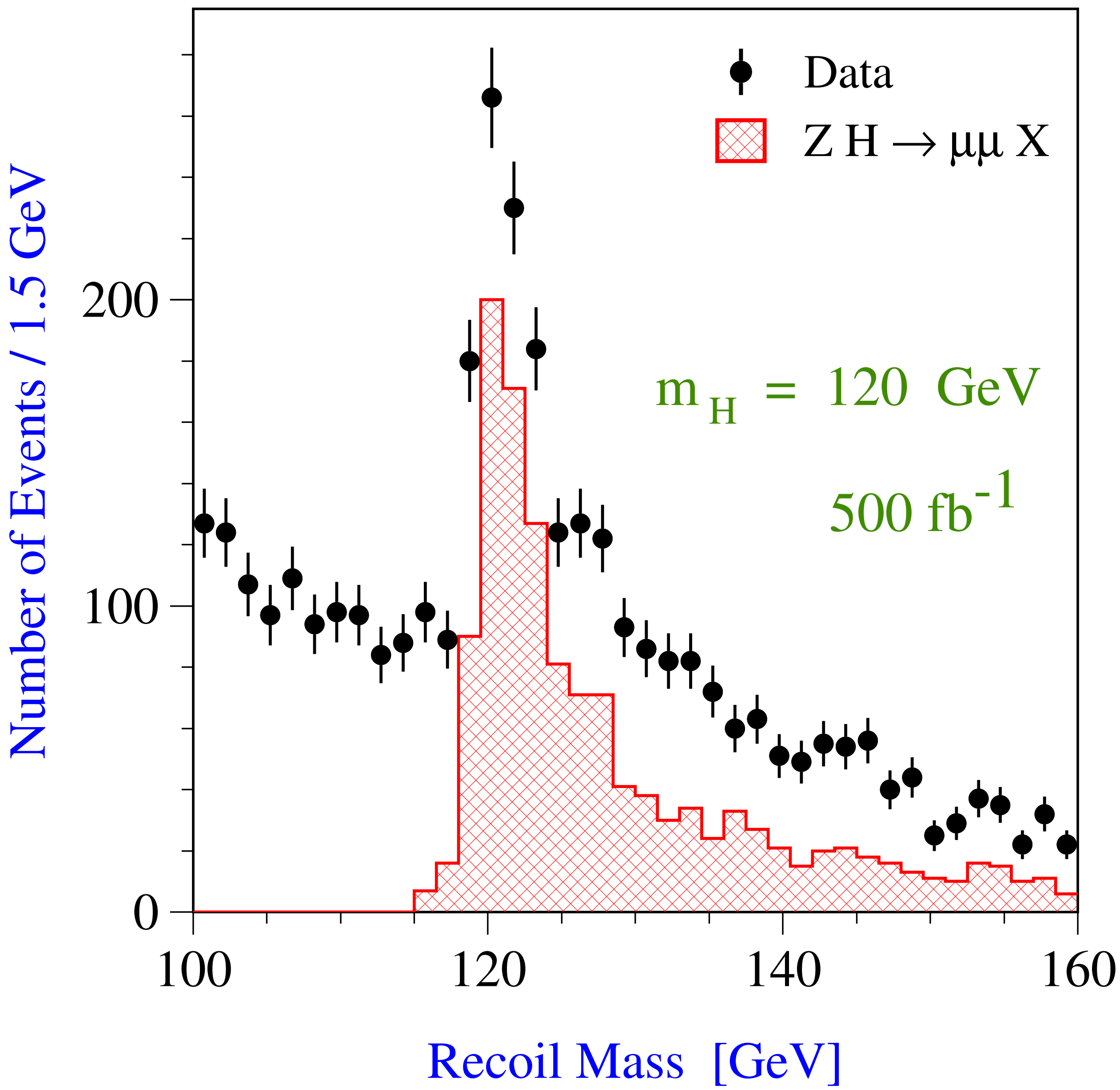

Figure 1: Higgs boson signal in the recoil mass distribution to a muon pair compatible with a Z decay for a simulated Higgs boson mass $m_H = 120\,\mathrm{GeV}$ and $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 350\,\mathrm{GeV}$.

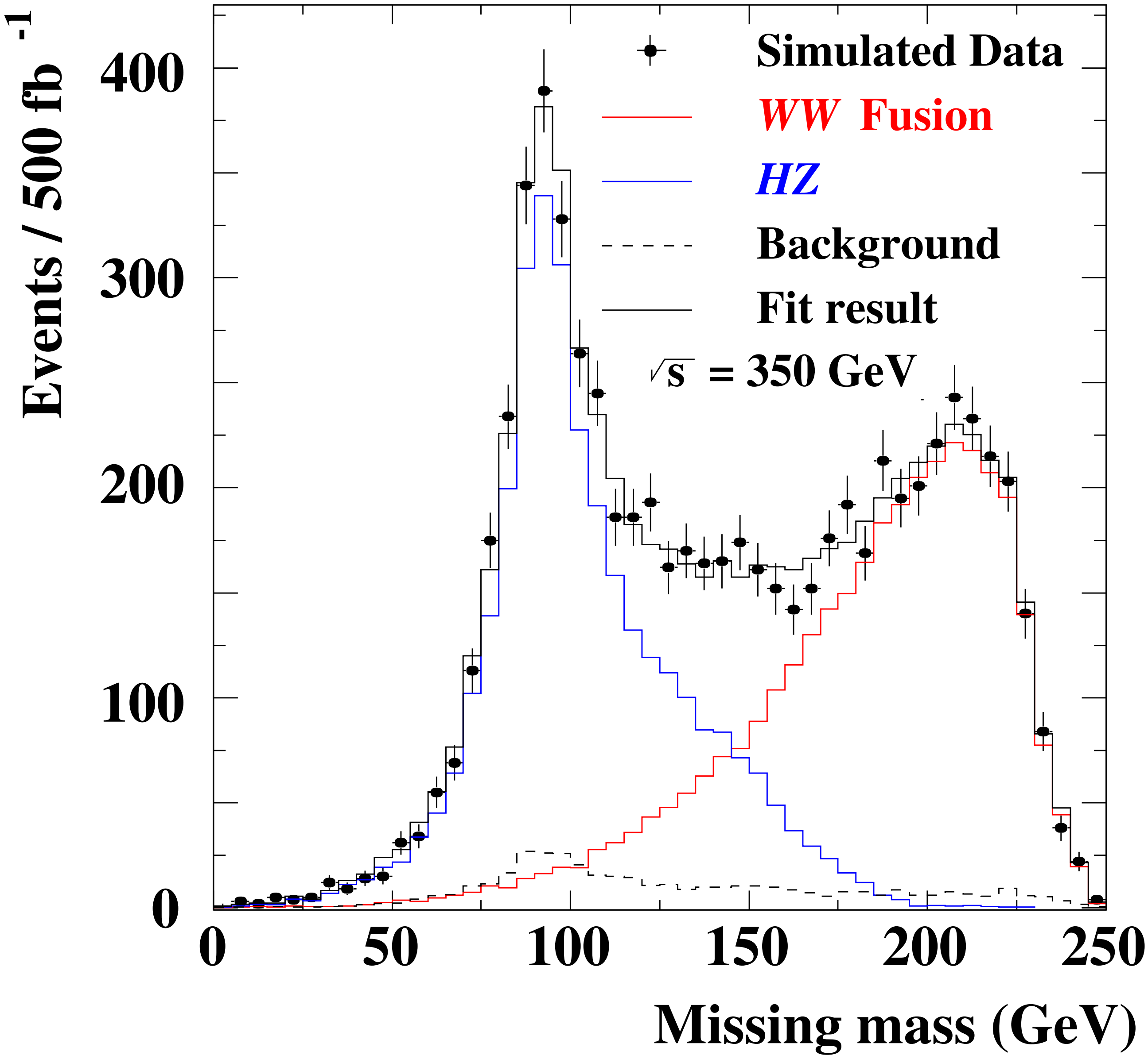

Figure 2: Missing mass distribution in events with two b-jets with an invariant mass compatible with the Higgs boson mass for $500\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 350\,\mathrm{GeV}$.

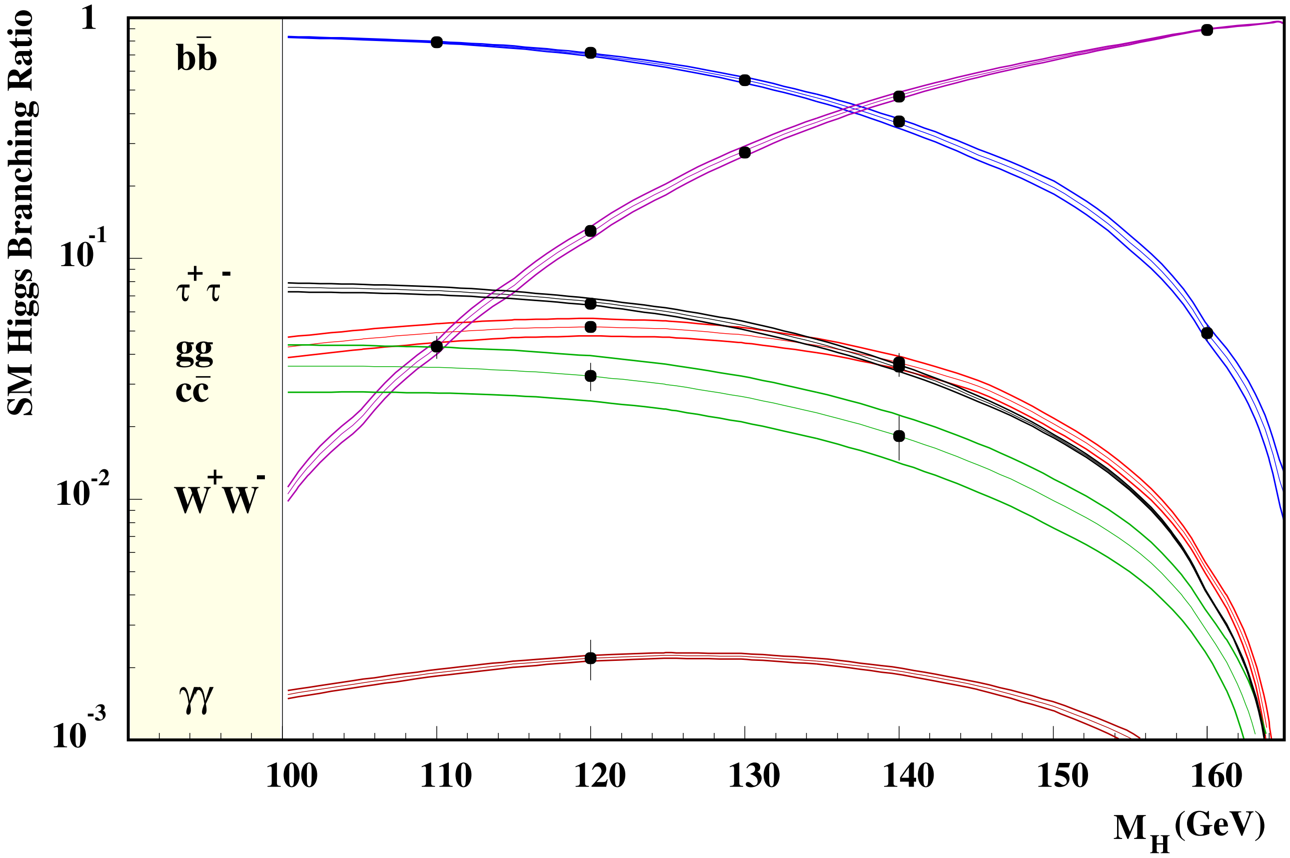

Figure 3: The SM prediction for the decay branching ratios of the Higgs boson. The points with error bars indicate the achievable experimental precision for 500 fb^{-1}. The bands indicate the theoretical uncertainties of the prediction.

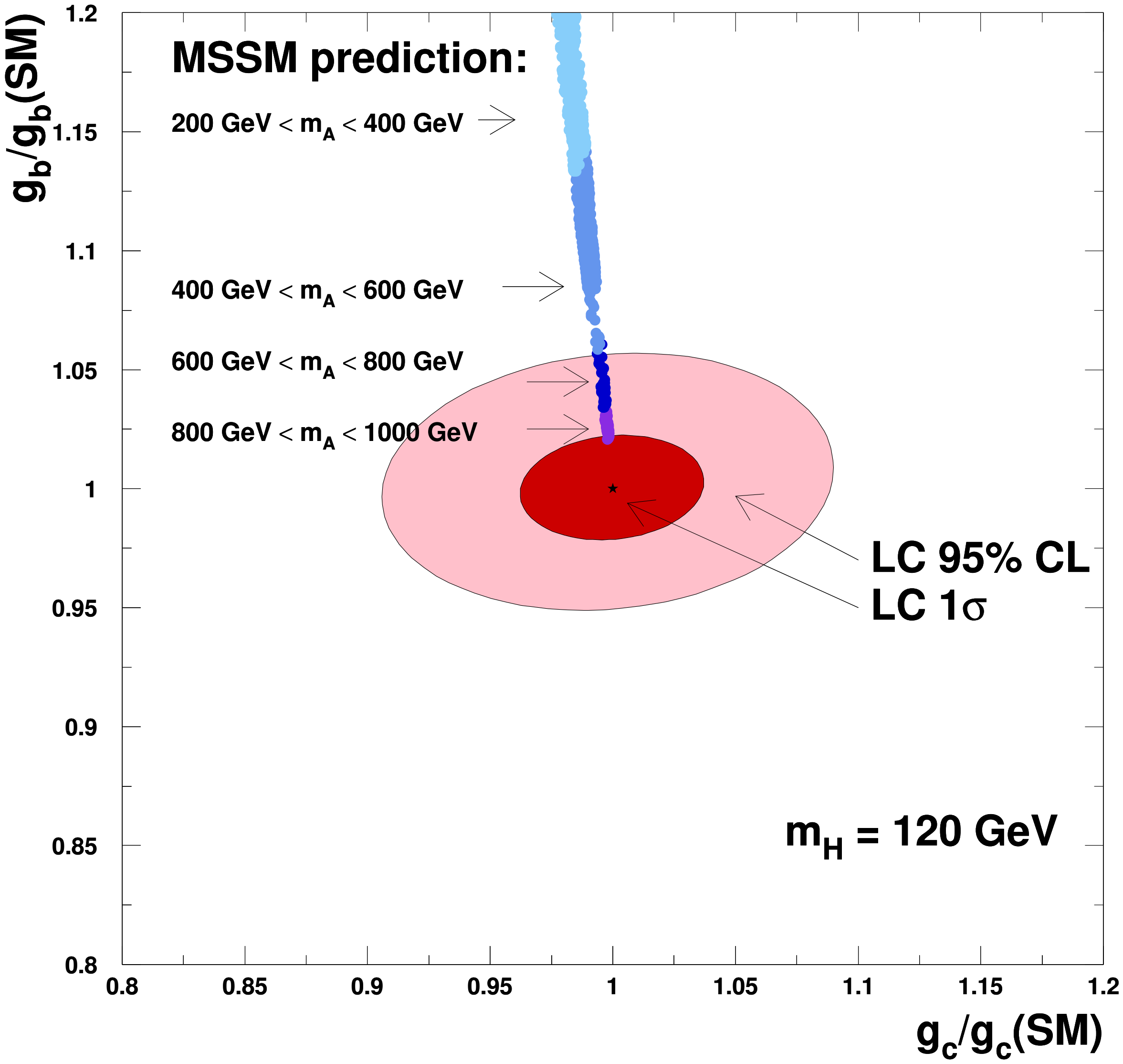

Figure 4: Expected sensitivity of the Higgs couplings $g_{\rm Hbb}$ vs. $g_{\rm Hbb}$ for a Higgs bosons mass $m_{\rm H} = 120\,{\rm GeV}$ and $500\,{\rm fb}^{-1}$.

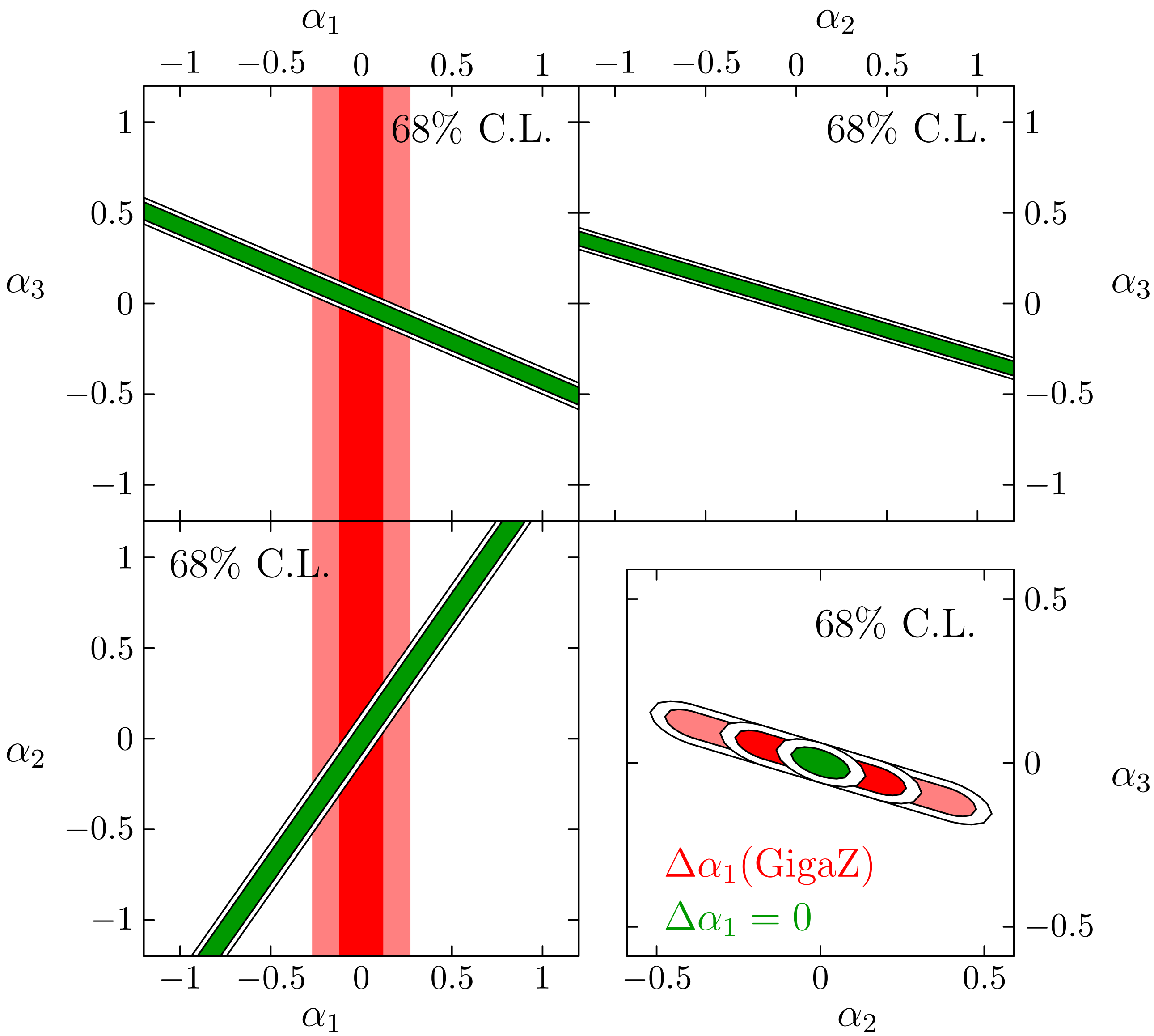

Figure 5: Sensitivity for the strong EWSB parameters $\alpha_{1,2,3}$ from a TGC measurement at 800 GeV and 1000 fb^{-1} using polarised electrons ($\pm$ 80 %) and positrons ($\mp$ 60 %).