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Prospects for the Standard Model Higgs Boson Search in the LEP 2000 Run

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Abstract

A study has been performed of the discovery and exclusion potential of LEP expected in 2000 for the Higgs boson predicted by the Standard Model. The tradeoff factors between increasing the luminosity at $\sqrt{s} = 204$ GeV and reduced integrated luminosity at $\sqrt{s} = 206$ GeV were studied. It was shown that only in case some evidence for a signal is observed it might be worth to increase the integrated luminosity at the lower center-of-mass energy, otherwise, LEP should aim at the highest possible center-of-mass energy. The ultimate expected exclusion limit (at the 95% confidence level) of LEP (with $\sqrt{s} = 206$ GeV) is estimated to be m_H ~114 GeV.

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1 Introduction

The study of the discovery and exclusion potential of LEP which we performed two years ago [1] has been updated to include the improved energy and luminosity performance of LEP expected in 2000. The performance of LEP at $\sqrt{s} = 202$ GeV was taken as a reference point for the extrapolation. In addition, the generation of Monte Carlo events and computation of the Higgs cross-sections are done with HZHA03 [2] which includes the interference between the $WW \to H^0$ ("fusion") and H^0Z^0 ("Higgsstrahlung") diagrams that contribute to the "Missing Energy" final state ($e^+e^- \to \nu\bar{\nu}H^0$).

An extrapolation is necessary because the highest center-of-mass energy where the experiments have well-defined analyses (at the time of writing this paper) is 202 GeV, while LEP is expected to provide a maximum center-of-mass energy in the neighborhood of 206 GeV [3].

The study is carried out by producing signal and background events with Monte Carlo event generators and treating the resulting 4-vectors with a simple parameterization of the performance of the OPAL detector, taken to be a typical LEP detector. An analysis was performed on the smeared 4-vectors which emulates the sophisticated analyses actually performed on the data and on simulated data produced in a detailed detector simulation.

The method used to extract confidence levels for signal exclusion and discovery significance takes as inputs expected signal and background rates and the distributions of discriminating variables for signal and background processes.

The cuts in the emulated analysis were tuned to reproduce the signal efficiencies and expected background rates for the OPAL experiment at a center-of-mass energy of 202 GeV. The discriminating variables were the reconstructed masses of the selected events.

The details of this analysis including the fast Monte Carlo description, the cuts and the explanation of the CL_S method and its implementation in this analysis were given in reference [1].

Several experiments (like DELPHI), have search channels with a two-dimensional discriminating distribution (e.g. reconstructed mass versus a "Higgs-tag"). These analyses are usually more efficient, in particular in the four-jets channel. In order to reflect the sensitivity of this improved analysis, additional tuning of the inputs to agree with the DELPHI expected search sensitivity at $\sqrt{s} = 202$ GeV was performed.

The spirit of this study is to make a few, precise extrapolations of the expected performance of LEP for making a discovery or setting exclusion limits in the energy range accessible to LEP in the year 2000.

Note that except from section 2, all luminosities in this report are per LEP experiment and the search potentials and expected limits are obtained by combining the results of the four experiments.

2 Previous performance of prospects extrapolation

In 1998 we performed a similar study of the discovery and exclusion potential of LEP under the assumption that the available center-of-mass energies would be 189, 198, and possibly 200 GeV [1]. At this time full-simulation results were available for the Higgs search at $\sqrt{s}$ =183 GeV and were used to tune the emulated detector and analysis performance. The results of this a-priori prediction of the expected exclusion limits for the 189 GeV data are compared in Fig. 1 to the expected and observed limits extracted from the actual search analyses and data. Preliminary expected limits at the time of the summer '98 conferences for the individual experiments (lowest cluster of bullets), published results by the experiments (middle cluster of bullets), and the combined LEP result [4] (the highest bullet) are in good agreement with the predictions. This gives us confidence that both the relative improvement, and even the absolute performance of the combined LEP Higgs search at a new center-of-mass energies and luminosities, can be estimated with our procedure.

3 Final tuning of analysis emulation

Before proceeding to the prediction of search potentials at higher center-of-mass energies and luminosities, the potentials obtained with the emulated analysis were compared to those obtained with the preliminary DELPHI analysis of $\sqrt{s} = 202$ GeV data [5]. The emulated analysis was found to be slightly optimistic for exclusion and significantly pessimistic for discovery. This is presumably due to a combination of two differences between the OPAL and DELPHI analyses. First, the DELPHI analysis at that time did not yet take into account the contributions to the cross-section of the $\nu\bar{\nu}H^0$ final state from $WW \rightarrow H^0$ fusion and the interference with the Higgsstrahlung process. Second, the DELPHI analysis takes into account a second discriminating variable in addition to the reconstructed mass which improves significantly the sensitivity of searches for Higgs masses below the kinematic limit. As several of the experiments have similar analyses, we decided to adjust the background rate of the four-jets final state ($H^0q\bar{q}$) to make the exclusion and discovery potentials agree qualitatively somewhat better. Increasing the four-jets background rate by 5% gave the results shown in Fig. 2 for the exclusion potential, while reducing the four-jets background by a factor 0.55 gave the results in Fig. 3 for the discovery potential. Based on these OPAL-DELPHI tuning plots we believe our analysis can be taken as typical for a LEP detector.

4 Exclusion, observation, discovery potentials

Since it is difficult to predict the performance of LEP precisely, and it is not our goal to compute search potentials for all possible configurations of beam energy and luminosity, we have computed search potentials for a scan of the highest center-of-mass energy we consider assuming some initial data-taking at lower energies. In addition we have computed search potentials for a short, specific list of varied energy-luminosity scenarios [6]. Note that all scans take into account an integrated luminosity of 80 and 40 pb^{-1} already collected by each of the experiments at center-of-mass energies of 200 and 202 GeV respectively.

4.1 Exclusion scan

The sensitivity for exclusion is defined in terms of the expected Higgs mass limit. This mass limit corresponds to a 50% exclusion potential at a given luminosity where the exclusion potential is defined as the probability to exclude a signal hypothesis if it is false. In other words, the experiment has the sensitivity to exclude a Higgs boson with a mass m_H if the fraction of gedanken background experiments which satisfy $1-CL_s(m_H) \geq 95\%$ is 50%, where CL_s is the signal confidence level.

We have computed the search potentials for a hypothetical scan of the higher center-of-mass energies assuming that there will be a “burn-in” period for LEP in 2000 corresponding to 40 pb^{-1} at $\sqrt{s} = 202$ GeV. We then assume either additional integrated luminosity collected at $\sqrt{s} = 204$ GeV or running as much as possible at $\sqrt{s} = 206$ GeV after first collecting 40 pb^{-1} at $\sqrt{s} = 204$ GeV.

Fig. 4 shows the results of the scans sketched above. The curve to the left shows the expected limit on the Higgs mass as a function of the integrated luminosity at $\sqrt{s} = 202$ GeV. The circle corresponds to an integrated luminosity of 40 pb^{-1} and $m_H = 109.2$ GeV is our expectation for the combined limit of LEP with the data taken at 1999. This expectation is a by-product of the tuning process.

Assuming LEP will collect an additional 40 pb^{-1} at $\sqrt{s} = 202$ GeV (indicated by the long arrow) the next curve shows the luminosity required to obtain a given expected exclusion limit on the Higgs mass when taking data at $\sqrt{s} = 204$ GeV.

The shorter arrow indicates the jump to data-taking at $\sqrt{s} = 206$ GeV after the first 40 pb^{-1} at $\sqrt{s} = 204$ GeV. Table 1 shows the relative amount of **additional** luminosity (again, after the first 40 pb^{-1}) at $\sqrt{s} = 204$ GeV compared to $\sqrt{s} = 206$ GeV required in order to achieve the given expected exclusion limit on the Higgs mass. These tradeoff factors (as they will be called from now on) start at 2.9 and increase rapidly as a function of the expected Higgs mass limit (obviously they become infinitely large as one passes the kinematic wall of H^0Z^0 production at the lower center-of-mass energy where only the $WW \rightarrow H^0$ fusion and off-shell Z^0 processes and their interference contribute to the cross section).

m_H (GeV)	Tradeoff
112.0	2.9
112.5	2.9
113.0	3.3
113.5	4.0

Table 1: Tradeoff factors for the exclusion scan described in the text.

4.2 Observation scan

Somewhere between exclusion at the 95% confidence level and a convincing discovery (probability of a background fluctuation less than that corresponding to a 5 standard deviations fluctuation in a normal distribution), evidence of a signal may start to accumulate. A reasonable place to set a threshold for "observation" is at the level of a three standard deviations fluctuation. One should be aware though that a three sigma effect could be a result of a fluctuation, and will not necessarily evolve to a significant discovery.

The observation sensitivity is therefore defined as that Higgs mass for which the probability to confirm the signal hypothesis if it is true and exclude the background hypothesis with a significance of 3σ is 50%. In other words the fraction of signal gedanken experiments with $1 - CL_b(m_H) \leq 0.27\%$ is 50%, where CL_b is the background confidence level.

Fig. 5 and Table 2 summarize the results of a scan of the observation potential of LEP under the same luminosity-energy conditions as for exclusion in the previous section. An interesting feature of the results is that the curves for 3σ observation lie about 0.3 GeV under those for exclusion over the whole range of luminosities that were explored. The tradeoff factors at the higher masses are somewhat larger than for exclusion, but it must be remembered that the tradeoff is evaluated at a desired mass limit and additional luminosity is required to overcome the 0.3 GeV shift with respect to exclusion mentioned above. The tradeoffs are quite favorable because the interesting mass region is close to the kinematic limit where the cross-section is falling rapidly and increases in beam energy compensate for this fall.

m_H (GeV)	Tradeoff
111.5	2.4
112.0	2.6
112.5	3.6
113.0	4.5

Table 2: Tradeoff factors for the 3σ observation scan described in the text.

4.3 Discovery scan

Fig. 6 and Table 3 summarize the results of a scan of the discovery sensitivity of LEP under the same luminosity-energy conditions as for exclusion and observation in the previous sections. In the figure we see the Higgs mass corresponding to a 50% discovery potential at a given luminosity. The discovery potential is defined as the probability to confirm the signal hypothesis if it is true and exclude the background hypothesis with a significance of 5σ, i.e., the fraction of signal gedanken experiments with $1 - CL_b(m_H) \leq 5.7 \times 10^{-7}$.

The tradeoff factors are somewhat lower than for exclusion in the mass region below $m_H \sim 111$ GeV where a 5σ discovery appears accessible. For the luminosities considered realistic the discovery criteria can only be met with the relatively large cross-sections below the kinematic limit where increases in beam energy give relatively small tradeoff factors. This means that if evidence for the Higgs started to accumulate in this mass region, a careful comparison of the LEP performance to the tradeoff factor should be made. For this comparison the LEP performance during the running should be compared to tradeoff factors computed with the experiments' analyses updated for high-energy running.

The curves for the discovery scan do not have the same mass dependence as those for exclusion or observation, but in general tend to lie 2 GeV or more below. For example, if the Higgs is observed at the observation limit ($m_H = 113$ GeV) after the first 40 pb^{-1} of data-taking at $\sqrt{s} = 206$ GeV, an additional ~ 100 pb^{-1} at $\sqrt{s} = 206$ GeV would be required to confirm the observation at the 5σ level. This corresponds to about six additional months of LEP running [3].

m_H (GeV)	Tradeoff
110.0	1.7
111.0	2.1
111.5	3.0

Table 3: Tradeoff factors for the 5σ discovery scan described in the text.

4.4 The "look elsewhere" effect

In the computation of the observation and discovery potentials, the reduction of the significance due to the fact that the background can fluctuate anywhere, and not just at the particular hypothetical mass where the potentials are evaluated (the so called "look elsewhere" effect [7]), has been neglected. The significances tend to be reduced by a fraction of a standard deviation, corresponding to a couple hundred MeV in the expected limits. This bias is comparable to the precision we expect for our absolute extrapolations and improvements one can expect from optimizing the analyses at the highest accessible Higgs masses. The effect of such a bias on the tradeoff factors is negligible and is likely to be small compared to the natural, statistical spread of the results (e.g. the spread of results in Fig. 1).

4.5 Other scenarios

The expected mass limits for four other energy-luminosity scenarios are given in Table 4. They are perhaps most useful as reference points for comparisons with other analyses. All four scenarios begin with the data collected up to the end of 1999. Beyond that they consist of:

1. 160 pb^{-1} at $\sqrt{s} = 202$ GeV
2. 140 pb^{-1} at $\sqrt{s} = 204$ GeV
3. 100 pb^{-1} at $\sqrt{s} = 206$ GeV
4. 120 pb^{-1} at $\sqrt{s} = 204$ GeV plus 30 pb^{-1} at $\sqrt{s} = 206$

Scenario	95% exclusion	3σ observation	5σ discovery
1	111.3	110.9	109.2
2	113.0	112.7	110.8
3	114.6	114.4	111.9
4	113.7	113.5	111.3

Table 4: Expected Higgs mass limits (the mass, in GeV, where the potential is 50%) for exclusion, observation and discovery, for the four energy-luminosity scenarios described in the text.

We find expected exclusion limits typically a few hundred MeV (approaching 1 GeV at the highest luminosities) higher than those computed with an analytical extrapolation by P. Janot [3]. Part of the difference is attributed to the fact that Janot is calculating the average sensitivity while this calculation is deriving the sensitivity at the median. But as stated in the introductory section, our approach is more focused to be precise as possible for a few scenarios, while Janot's approach is to get a complete scan of all possible scenarios in order to deduce an optimal strategy for running LEP. Since the two calculations are systematically shifted with respect to each other, the luminosity-energy tradeoff factors are quite similar and his conclusions with regards to run strategies are supported by our results. Our prospective LEP sensitivities are also more realistic since our work is based on recent detector simulations and search analyses. In addition, the LEP collaborations will keep trying to improve their analyses, in particular for high Higgs masses, resulting in improved sensitivities.

5 Comments on fusion

It is to be noted that no attempt was made in this analysis to derive analyses which are optimized exclusively for very high Higgs masses (close to or above the H^0Z^0 kinematic wall). The $WW \to H^0$ fusion channel is an example of a process that contributes to the Higgs production rate above the H^0Z^0 kinematic wall. Due to constructive interference between the $H^0Z^0 \to H^0\nu_e\bar{\nu}_e$ and the $e^+e^- \to \nu_e\bar{\nu}_eH^0$ fusion processes, the "missing energy" cross-section increases. Fig. 7 shows the contributions of the fusion (dotted), Higgsstrahlung (dashed) and their constructive interference (dash-dotted) to the total cross-section (full line) of Higgs production in the "missing-energy" channel at $\sqrt{s} = 206$ GeV. One can clearly see that the Higgsstrahlung process continues to contribute to the cross-section even when the Z^0 goes off shell above the kinematic wall at $\sqrt{s} - m_Z = 115$ GeV and is even contributing more than the fusion channel at or a bit above the wall.

This increase in cross-section is taken into account in this analysis. However, no attempt was made to derive an analysis which tries to take advantage of the different kinematic nature of the fusion channel. Such an attempt was made in the past [8]. The main difference between the channels is that in the fusion channel the Higgs boson does not recoil against a Z^0 boson. Removal of the Z^0 recoil mass constraint increases the efficiency in the fusion channel for $m_H >> M_Z$. But the price is the degradation in the mass resolution. As a result the gain in the combined LEP exclusion sensitivity is marginal and we have shown that naively this gain is no more than a few hundred MeV (~ 200) when each experiment collects a luminosity of about 100 pb^{-1}, while there is no gain in the discovery sensitivity [8]. We therefore believe that the sensitivities quoted above will remain valid with a margin of a few hundred MeV even after the LEP collaborations have developed dedicated high-mass analyses for the "missing energy" channel. Better sensitivities might be achieved, though, if such high-mass analyses will be developed for the "4-jets" channel as well, because there is life beyond the wall even if the Z^0 boson goes off-shell (as could be seen in Fig. 7).

6 Conclusions

We have updated our two-year old study of the exclusion and discovery potential for the Higgs boson predicted by the Standard Model for the final year of running of LEP with increased center-of-mass energies. We have evaluated the search potentials for educated guesses of reachable center-of-mass energies (202, 204, 206 GeV) and corresponding integrated luminosities.

The ultimate expected exclusion limit (at the 95% confidence level) of LEP is estimated to be $m_H \sim$114 GeV. The expected observation limit (signal significance corresponding to 3 standard deviations) tends to be only a few hundred MeV less than the exclusion limit while the discovery limit (signal significance corresponding to 5 standard deviations) tends to be 2 GeV or more below this. For example, a 3σ observation of $m_h = 113$ GeV after taking 40 pb^{-1} at 206 GeV will require an additional run of approximately 100 pb^{-1} at 206 GeV to confirm the observation at the 5σ significance level.

We have studied the relative value of luminosity taken at 206 GeV compared to continuing to run at 204 GeV after an initial sample of $40pb^{-1}$ and found a factor 2-4 for exclusion and observation depending on the previously established mass limit. This factor tends to be less than 2 for discovery. This indicates that if evidence of a signal starts to accumulate below $m_H \sim 111$ GeV, the relative luminosity performance of LEP may motivate lowering the center-of-mass energy in order to confirm the observation as rapidly as possible. In the absence of any evidence of a signal, additional running at the highest energy should give the most rapid increase of the exclusion limit.

Finally it is to be noted that a development of analyses dedicated to high Higgs masses might increase the sensitivity. But that can happen only if such analyses are developed for all channels. A dedicated analysis in the fusion channel by itself is unlikely to improve the limit significantly.

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[3] P. Janot, "Priorities for LEP in 2000", talk in given in the Xth SPS and LEP Performance Workshop, Chamonix (January 2000); See also minutes of the pre-Chamonix meeting: http://alephwww.cern.ch/∼janot/LEPCO/.

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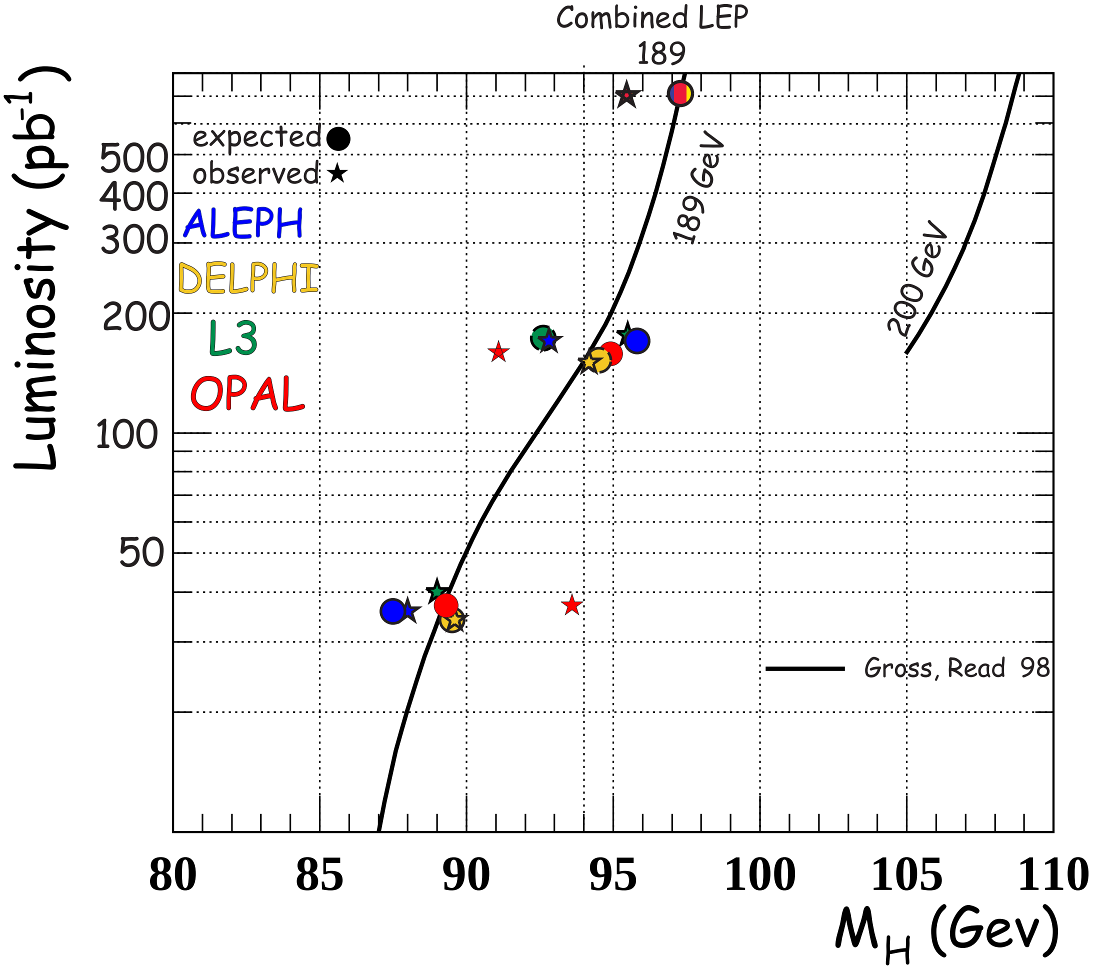

Figure 1: Prediction of luminosity required to obtain a given expected Higgs mass exclusion limit (curves) compared to expected and observed experimental results for data take with center-of-mass energy of 189 GeV.

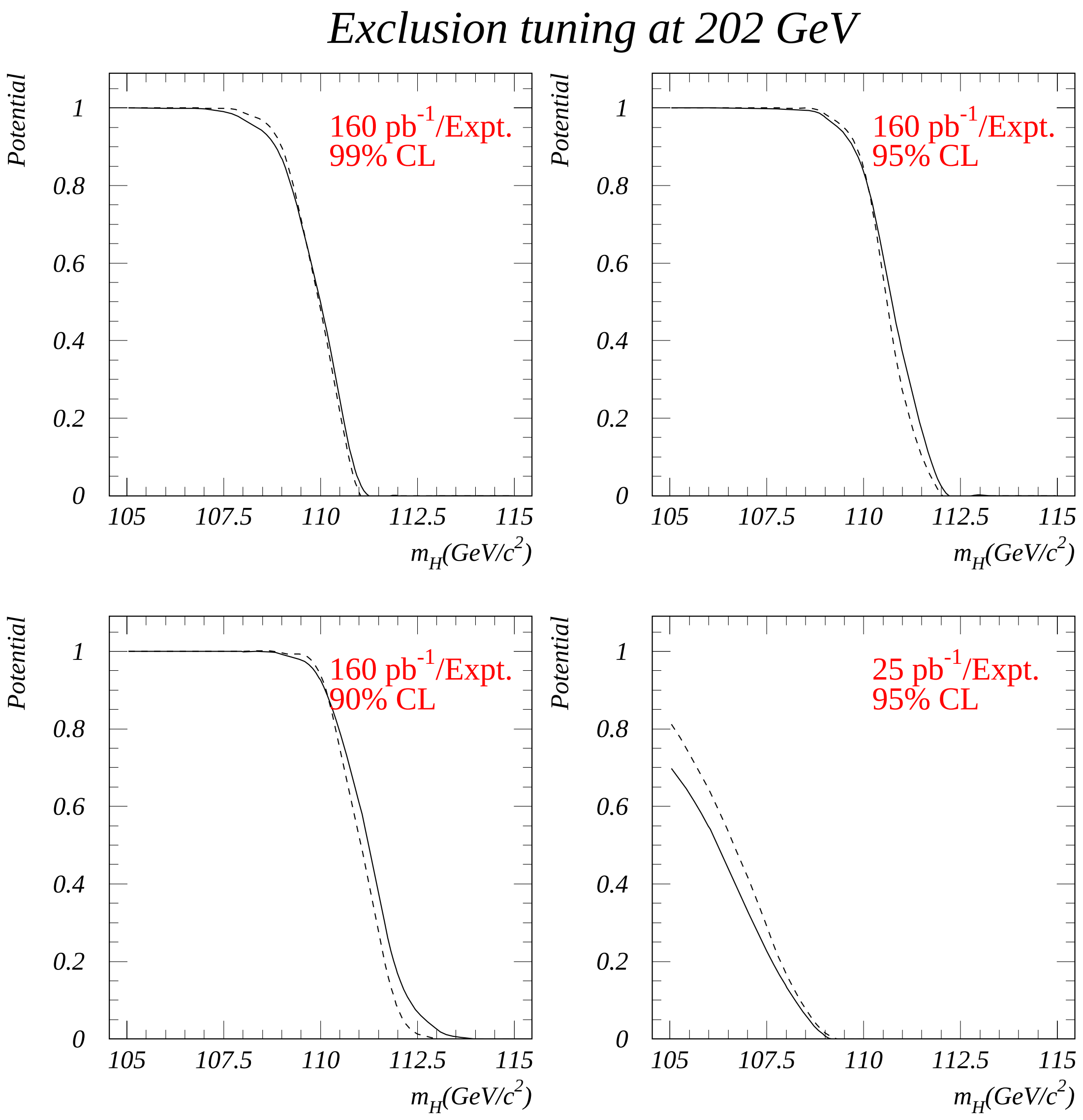

Figure 2: Exclusion potentials of DELPHI 202 GeV analysis (dashed curves) and emulated OPAL 202 analysis after tuning (solid curves) versus Higgs mass for several confidence levels and integrated luminosities.

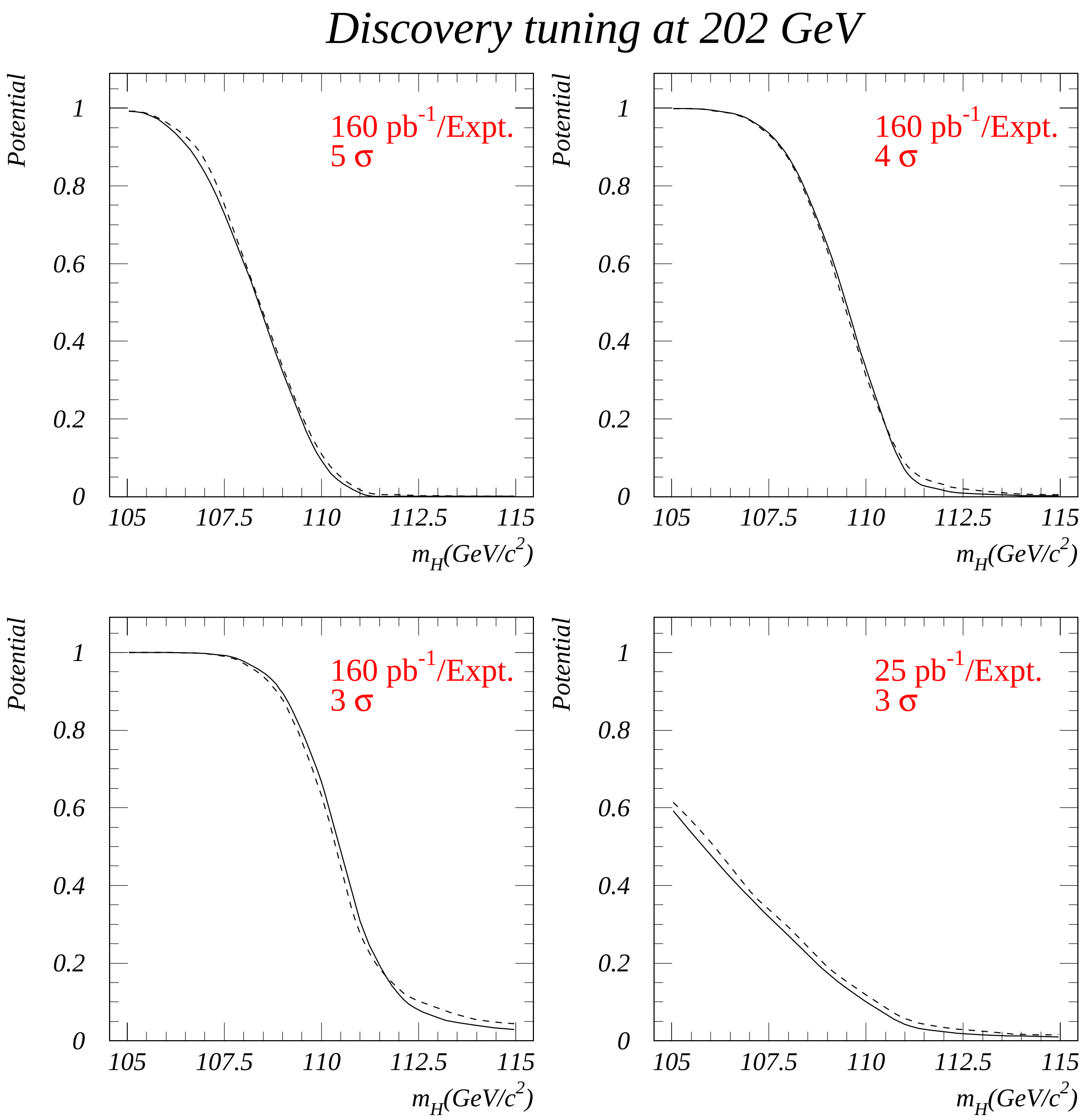

Figure 3: Discovery potentials of DELPHI 202 GeV analysis (dashed curves) and emulated OPAL 202 analysis after tuning (solid curves) versus Higgs mass for several signal significance levels and integrated luminosities.

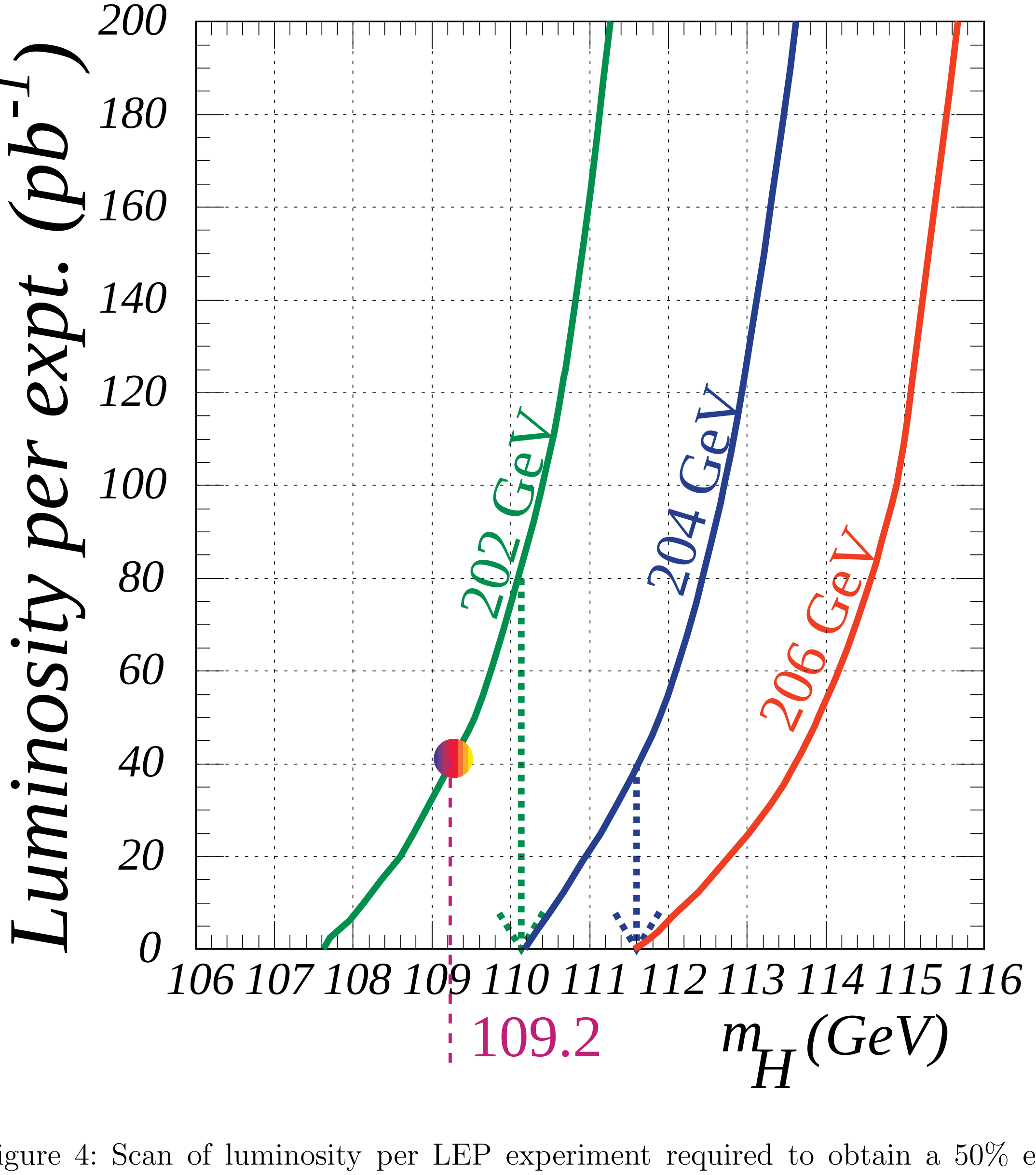

Figure 4: Scan of luminosity per LEP experiment required to obtain a 50% exclusion potential versus Higgs mass as described in the text.

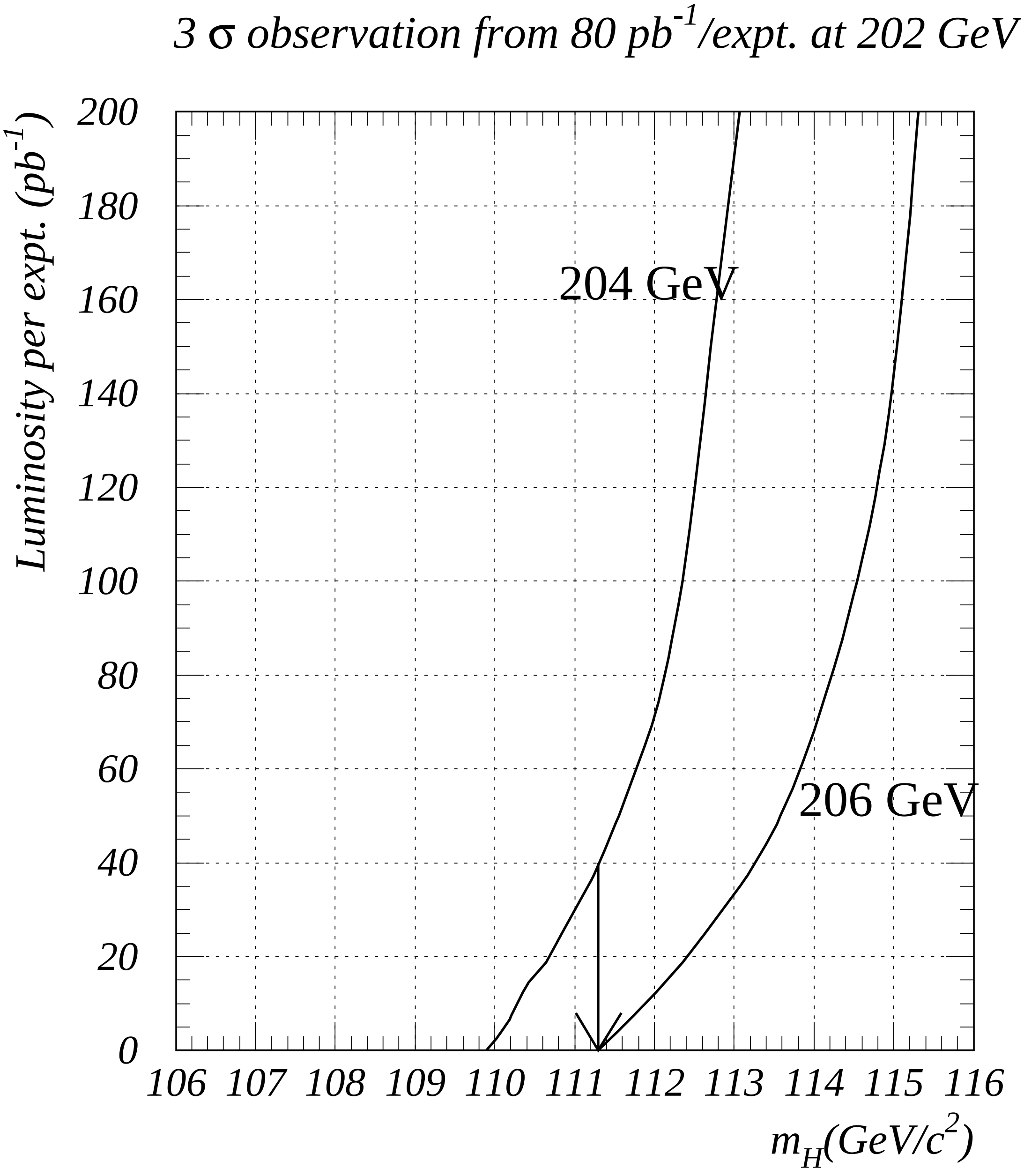

Figure 5: Scan of luminosity per LEP experiment required to obtain a 50% observation potential versus Higgs mass as described in the text.

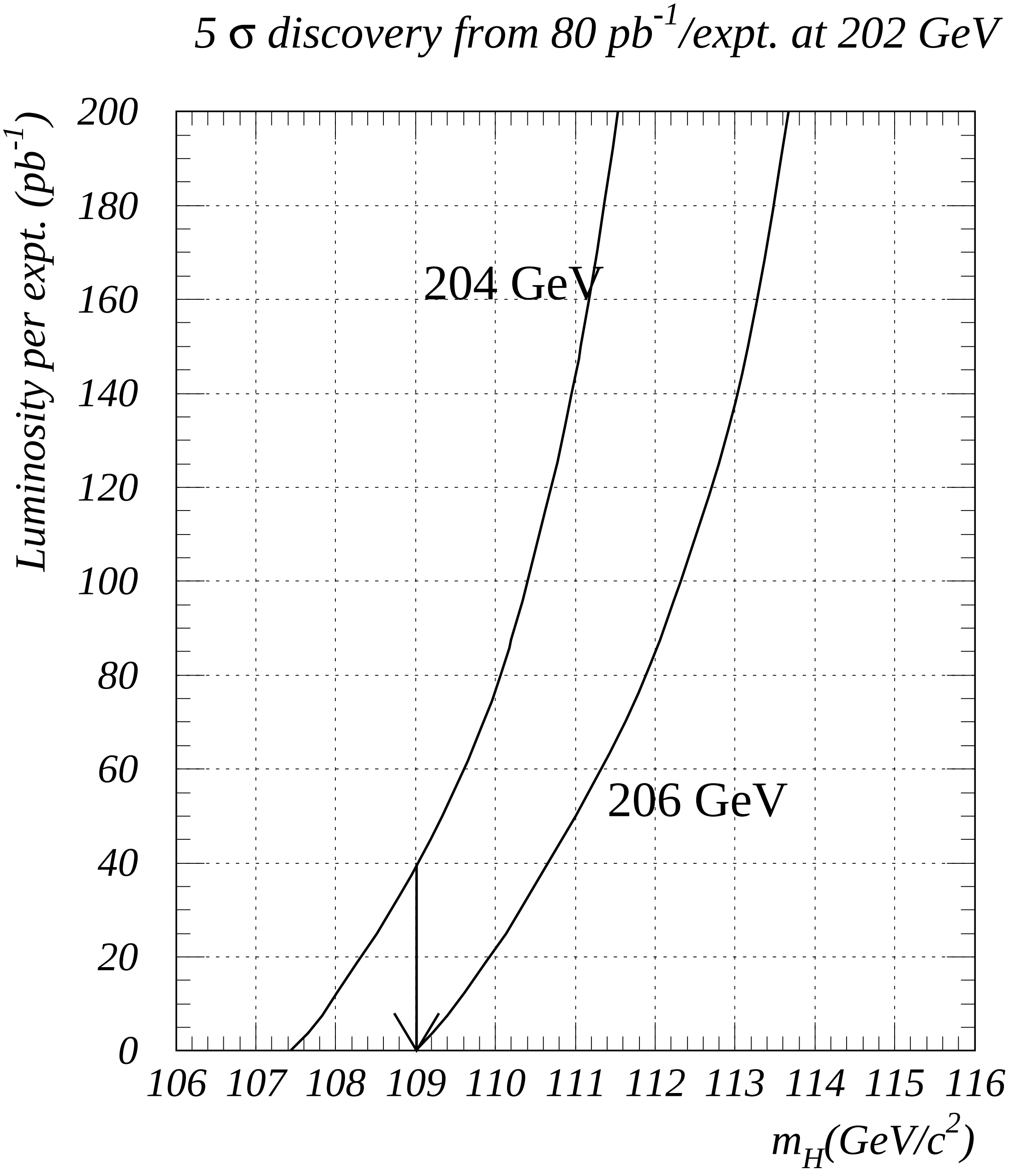

Figure 6: Scan of luminosity per LEP experiment required to obtain a 50% discovery potential versus Higgs mass as described in the text.

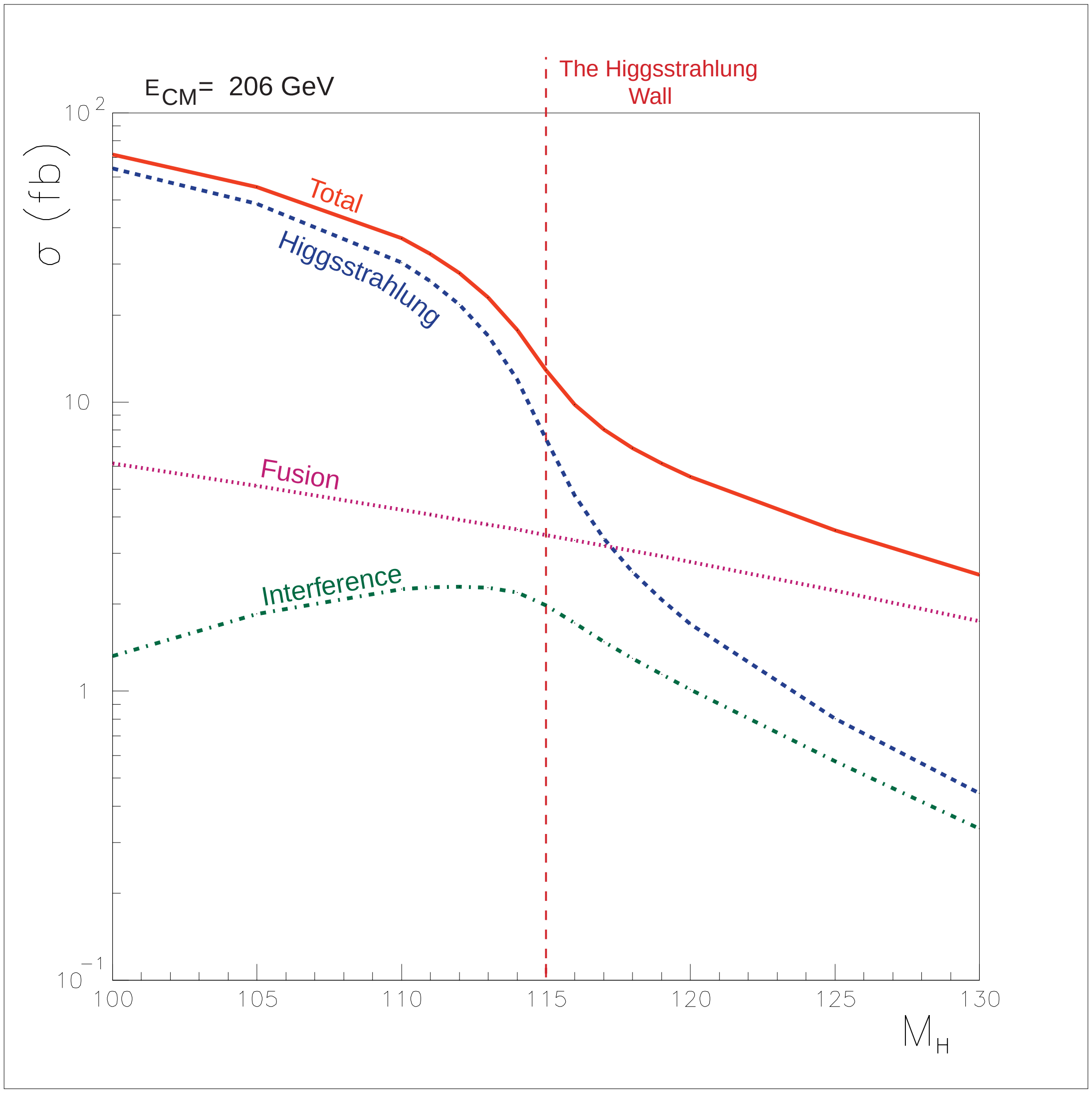

Figure 7: The cross-section (in fb) for Higgs production in the "missing-energy" channel. The Higgsstrahlung (dashed), fusion (dotted) and their interference (dash-dotted) contributions to the total cross section (full line) as a function of the Higgs boson mass at a center-of-mass energy of 206 GeV.