How should we organize the Higgs Safari?

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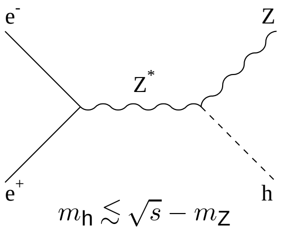
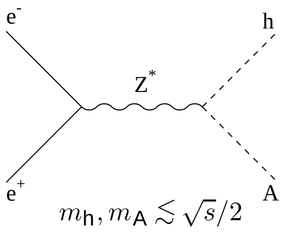
Abstract

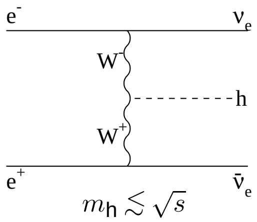
Although the reach of LEP as to the standard model Higgs boson discovery is directly related to the maximal energy achievable, a large integrated luminosity is also needed to cope with the limited production cross section, and it becomes crucial for many other physics issues (search for supersymmetric neutral Higgs bosons, search for charged Higgs boson, precise measurement of the W mass,....). The actual needs in GeV and pb^{-1} are reviewed, and scenarios to optimize both aspects – energy reach and integrated luminosity – during the runs in 1999 and 2000 are discussed.

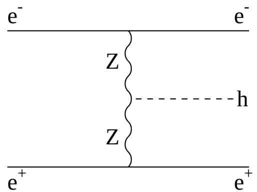
1 INTRODUCTION AND REMINDER

Neutral Higgs Bosons (from the Standard Model or from Supersymmetry) can be produced at LEP 2 through two main channels, the Higgs-strahlung hZ process and the associated hA pair production (in Supersymmetry only), and two “marginal” channels, the WW and ZZ fusion processes. The production *via* the first two diagrams is at first glance kinematically limited to $m_{\mathrm{h}} \lesssim \sqrt{s} - m_{\mathrm{Z}}$ and $m_{\mathrm{h}} \lesssim \sqrt{s}/2$, respectively *i.e.*, to 109 and 100 GeV, for a beam energy of 100 GeV. This is not the case for the fusion processes, only limited to $m_{\mathrm{h}} \lesssim \sqrt{s}$. However, the cross section of the latter is too small for this limit to be approached with the integrated luminosities expected in the last two years of LEP running (Section 2).

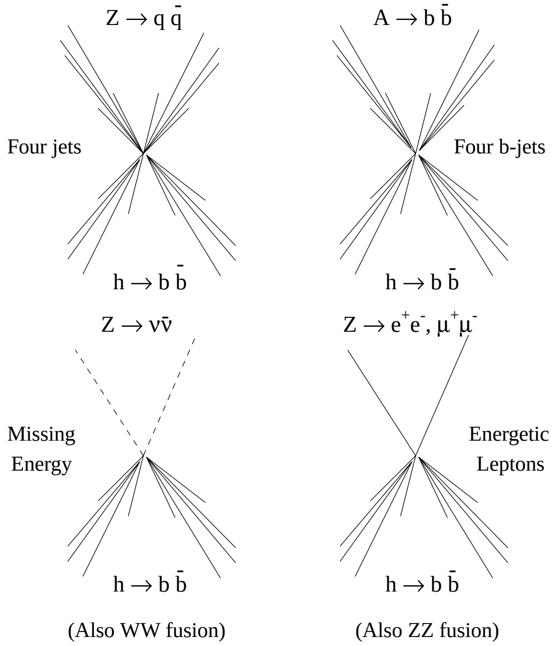




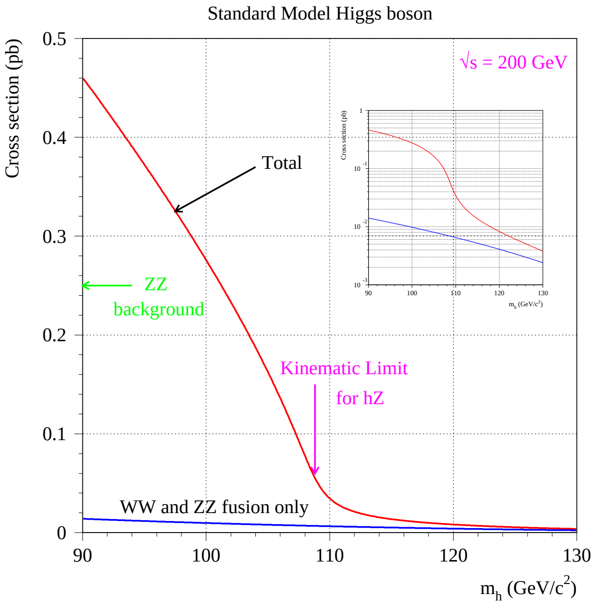




The production is followed by the decays of h, A and Z into two fermions, mostly $\mathrm{b\bar{b}}$ for the Higgs bosons, and all fermion pairs ($\mathrm{q\bar{q}}$, $\ell^+\ell^-$, and $\nu\bar{\nu}$) for the Z. These decays therefore lead to four-fermion final states, with clear experimental signatures (jets with b hadrons, energetic leptons, missing energy), selected with a typical overall efficiency of $\sim 30\%$, and a low irreducible background coming from $\mathrm{e^+e^-} \to \mathrm{ZZ}$ production.

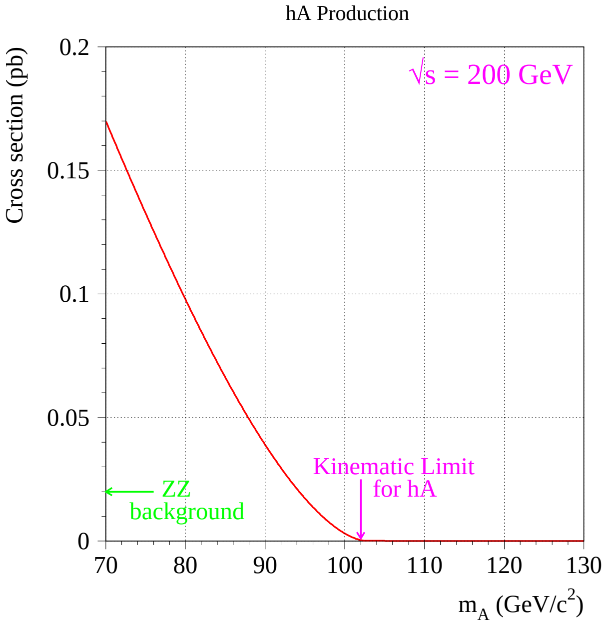


The number of such events expected at a given centre-of-mass energy is the product of the integrated luminosity collected by the four LEP experiments by the theoretical cross section and the aforementioned selection efficiency. The cross section of the Standard Model Higgs boson *via* the Higgs-strahlung and boson fusion processes is given below in pb (or, equivalently, in number of events produced per pb^{-1}) for $\sqrt{s} = 200$ GeV. As can be seen from this curve,



the production is not *stricto sensu* kinematically limited at $\sqrt{s} - m_{\mathrm{Z}}$, partly because of the WW and ZZ fusion processes, but also due to the finite Z width which allows the hZ process cross section not to vanish sharply at the "kinematical limit". At this limit, the cross section amounts to 0.06 pb (*i.e.*, six events produced and about two detected for 100 pb^{-1}), well below the 0.25 pb of the dominant and irreducible ZZ background, with one Z decaying into b$\bar{\mathrm{b}}$. The insertion with a logarithmic scale also shows that the WW and ZZ fusion processes never play a dominant rôle.

In the framework of Supersymmetry, the hA production is complementary to the other processes because it is dominant only when the hZZ or hWW couplings are suppressed. The largest possible hA cross section is displayed below for $\sqrt{s} = 200$ GeV. Since the h and A widths are usually small, the hA production cross section vanishes at the kinematical limit. The dominant and irreducible background $\mathrm{e^+e^-} \to \mathrm{ZZ} \to \mathrm{b\bar{b}b\bar{b}}$ has a small cross section of 0.02 pb.



These observations may lead to naive, although incorrect, *a priori* conclusions. First, the Standard Model Higgs boson production seems not to be kinematically limited, making the integrated luminosity the key issue for its discovery. In contrast, the hA production is kinematically limited, which would make compulsory an increase of the beam energy to extend the reach of the relevant searches.

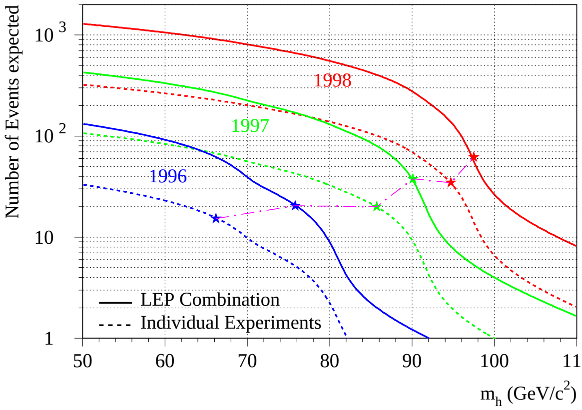
However, and as it will become clear in the next section, the actual conclusions to be drawn are exactly opposite: the Standard Model Higgs boson production cross section is exceedingly small above $\sqrt{s} - m_{\mathrm{Z}}$, and the amount of integrated luminosity needed to be sensitive there is prohibitive. It renders this production effectively kinematically limited, and therefore actually limited by the beam energy. On the other hand, the hA production cross section is small, already 15 GeV below its kinematical limit. A large integrated luminosity seems therefore to be mandatory for this channel, irrespective of the energy.

2 ENERGY OR LUMINOSITY?

A first idea of the energy and the luminosity needed to reach a given m_{h} sensitivity from the Standard Model Higgs boson searches can be obtained from the recent past experience, namely from the search results since 1996. No evidence for a Higgs boson signal has been seen since then, and lower limits on m_{h} were set by each of the LEP experiments and by their combination in 1996 [1], 1997 [2] and 1998 [3], with increasing energy and integrated luminosity (10 pb^{-1} at 161 GeV and 10 pb^{-1} at 172 GeV in 1996, 55 pb^{-1} at 183 GeV in 1997 and 175 pb^{-1} at 189 GeV in 1998, for each of the four LEP experiments).

The 95% C.L. mass limits observed, in agreement with those predicted by the simulation if no signal were present, are displayed in the following table for the individual experiments (*averaged), and for their combination. The numbers of signal events expected to be produced at the expected mass limit are represented by stars in the next figure. While an increase from 15 to 60 events between 1996 and 1998 is observed, no obvious scaling law can be found between the number N of events needed to set the limit and the value m_{h}^{95} of the limit itself. Naively, a simple relation is expected between $N(m_{\mathrm{h}}^{95})$ and the integrated luminosity $\mathcal{L}$: in the presence of background b, the statistical significance of a signal observation equals $N/\sqrt{b}$ when N and b are large enough. Since a 95% C.L. limit is expected to be

Limits in GeV/c^2		Observed Limit	Expected Limit
1996	Individual Experiments*	68.4	66.2
	LEP Combination	77.7	75.8
1997	Individual Experiments*	87.5	85.8
	LEP Combination	90.1	90.1
1998	Individual Experiments*	94.2	94.7
	LEP Combination	?	97.2

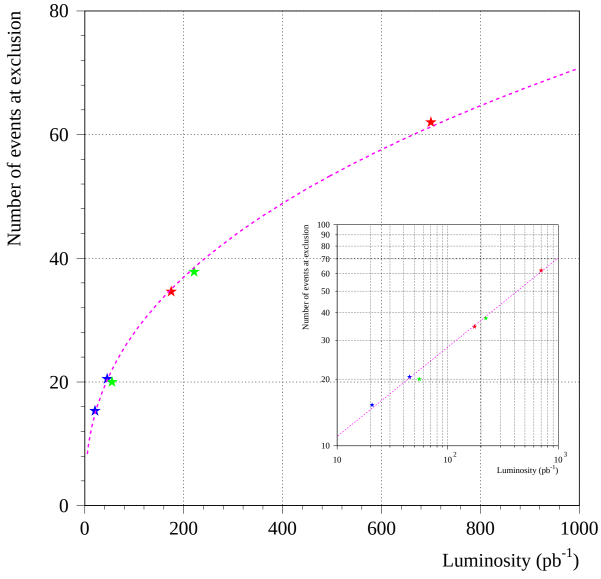


set for a constant expected significance (~ 2), the signal N needed at the expected limit has to increase with $\sqrt{b}$, *i.e.*, $N(m_{\mathrm{h}}^{95}) \propto \mathcal{L}^{0.5}$.

The values of $N(m_{\mathrm{h}}^{95})$ and of the "equivalent" integrated luminosity (*i.e.*, the luminosity needed at the highest energy to have the same sensitivity as with a sample of several beam energies) are displayed below first in a table, followed by bi-dimensional plots with linear and logarithmic scales. It can be noted that the equivalent luminosity is identical (apart in the first line) to that taken at the highest energy, because the lower energies stop playing any significant rôle when their kinematical limit $\sqrt{s}-m_{\mathrm{Z}}$ is exceeded.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N(m_{\mathrm{h}}^{95})$
161–172*	20.7	15.3
161–172†	45.2	20.3
161–183*	55.3	20.0
161–183†	221.2	37.8
161–189*	175.0	34.6
161–189†	700.0	62.0

* Average of individual experiments
† LEP combination

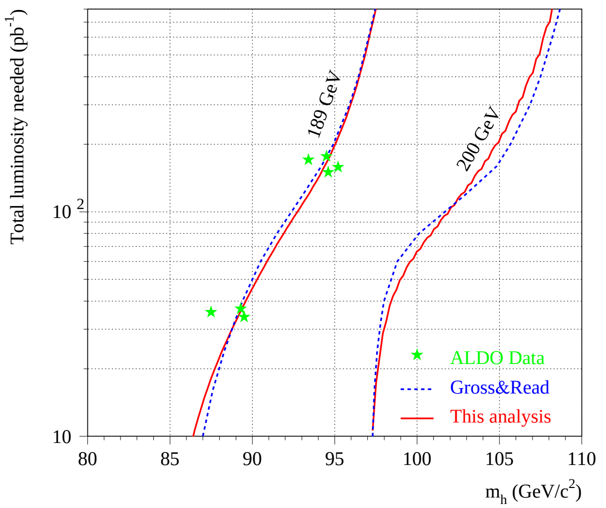


The six points do fit particularly well to a very simple scaling law as indicated by the dashed line:

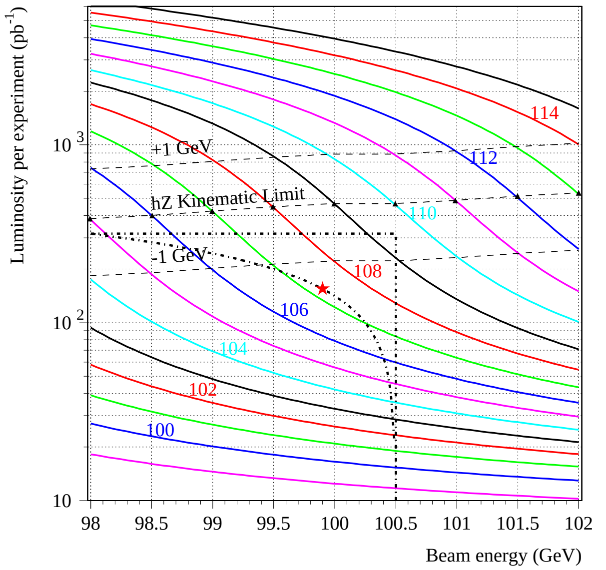
$$\boxed{N(m_{\mathrm{h}}^{95}) \simeq (\sigma_0\mathcal{L})^{0.404} \text{ with } \sigma_0 \simeq 38.2 \text{ pb.}}$$

The exponent differs by 0.1 unit from the naive 0.5. This difference can be understood as a modelling of the improvement of the Higgs boson selections, of the b-tagging tools, of the detector and physics understanding throughout the years. This analytical formula allows, when extrapolated to larger energies and/or luminosities, the expected sensitivity m_{h}^{95} of the standard model Higgs boson searches to be easily foreseen for the last two years of LEP running.

The predictions can be first compared to the work of Gross and Read [4, 5] performed for centre-of-mass energies of 189 and 200 GeV with selection algorithms developed towards the aforementioned final states used in conjunction with a fast detector simulation. The figure presented below was modified [6] with respect to Refs. [4, 5] to allow for a direct comparison of their results with the above analytical expression. An excellent agreement is observed between the two predictions, at the level of ± 300 MeV$/c^2$ for the sensitivity with a given integrated luminosity, and of $\pm 10\%$ on the integrated luminosity for a given mass reach. The uncertainties on the fit parameters could certainly not allow the extrapolation of the above analytical formula to pretend to a more accurate prediction.



Being supported by these detailed studies at $\sqrt{s} = 200$ GeV, the formula can now be used to predict the LEP combined sensitivity of the SM Higgs boson searches by adding, per experiment, a given integrated luminosity, at any fixed beam energy, to the existing data. The lines of combined m_{h} sensitivity (in GeV$/c^2$) are shown below.



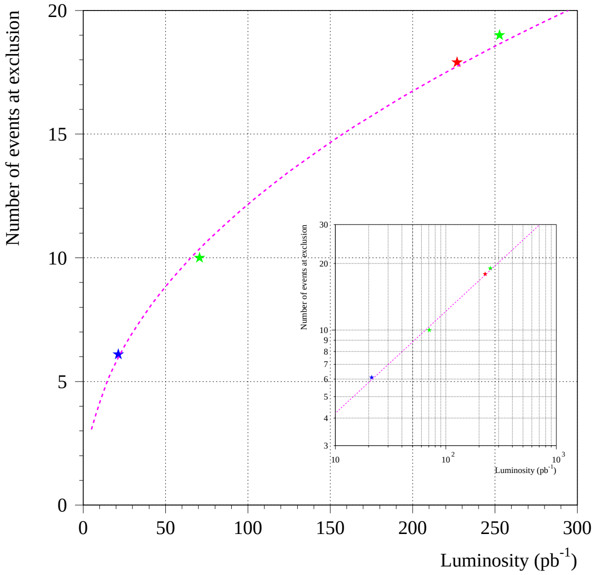
A number of remarks comes from the observation of the previous plot.

- To reach the hZ kinematic limit, an integrated luminosity of 400–500 pb^{-1} per experiment is needed, irrespective of the beam energy;
- A factor of two more luminosity is needed to improve the sensitivity by 1 GeV (and a factor of two less to reach 1 GeV below the kinematic limit).
- The WW/ZZ fusion processes are of no practical use, since more than 1 fb^{-1} per experiment is needed to overtake the hZ threshold. (See also Ref. [5].)
- If the luminosity delivered is independent of the beam energy, the best choice to optimize the standard model Higgs boson search is to go the highest energy allowed by the accelerating gradient, as shown by the dash-dotted square: an increase of the beam energy by 1 GeV increases the m_{h} sensitivity by 2 GeV, for the same integrated luminosity.
- On the other hand, if the luminosity delivered is expected to decrease when the beam energy increases, as shown by the smooth dash-dotted curve, the optimal sensitivity (indicated by a star) is reached for an energy somewhat smaller than what would be allowed by the maximal gradient. However, since this choice may cause a large loss of integrated luminosity with respect to even smaller an energy, this choice might not be optimal for all LEP 2 Physics.

To investigate the consequences of the latter choice, the same extrapolation game was played for hA production. The expected mass limits m_{h}^{95}, the numbers of signal events expected $N(m_{\mathrm{h}}^{95})$ and the equivalent integrated luminosities are known for four different points, displayed in the following figure and table. These numbers satisfy a very similar scaling law as for the standard model Higgs boson results, namely,

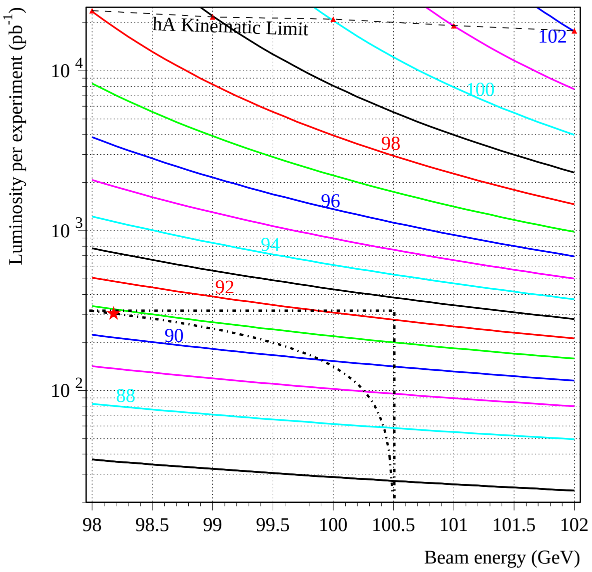
$$\boxed{N(m_{\mathrm{h}}^{95}) \simeq (\sigma_0 \mathcal{L})^{0.461} \text{ with } \sigma_0 \simeq 2.26\,\mathrm{pb}.}$$

The smaller coefficient σ_0 is consistent with an irreducible background cross section 15 times smaller than that of the hZ searches. The LEP-combined sensitivity plot for the hA searches can now be drawn similarly as for the hZ searches, when adding, per experiment, a given integrated luminosity, at any fixed beam energy, to the existing data, and the same kind of remarks can be made.



$\sqrt{s}$ (GeV)	m_{h}^{95} (GeV/c^2)	$N(m_{\mathrm{h}}^{95})$	$\mathcal{L}$ (pb^{-1})**
130–172*	59.5	6.1	21.3
130–183*	72.0	10.0	70.7
130–183†	79.0	19.0	252.7
130–189*	80.0	17.9	227.9

* ALEPH numbers, † LEP combination
** Equivalent luminosity at the highest energy



- About 20 fb^{-1} (!) are needed (per experiment) to reach the hA kinematic limit. In practice, this search is therefore not kinematically limited, and any additional 10 pb^{-1} is welcome. (This is also true for a number of other physics issues at LEP 2, e.g., m_{W} measurement, $\tilde{q}$ and $\tilde{\ell}$ searches, m_χ sensitivity, $\mathrm{H}^\pm$ searches, …)
- For the same luminosity, the beam energy plays a much less crucial rôle than for hZ searches: an increase of the beam energy by 1 GeV increases the m_{h} sensitivity by only 0.5 GeV, while a factor of two more luminosity improves it by 2 GeV.
- If the luminosity delivered is expected to decrease when the beam energy increases, it is better to stay at smaller energies to get the highest integrated luminosity (as shown by the star), in contrast to the hZ situation.

To summarize, the optimization of LEP towards hZ and hA searches simultaneously would require to maximize both the energy (for hZ) and the integrated luminosity (for hA). This optimization is addressed in the next two sections.

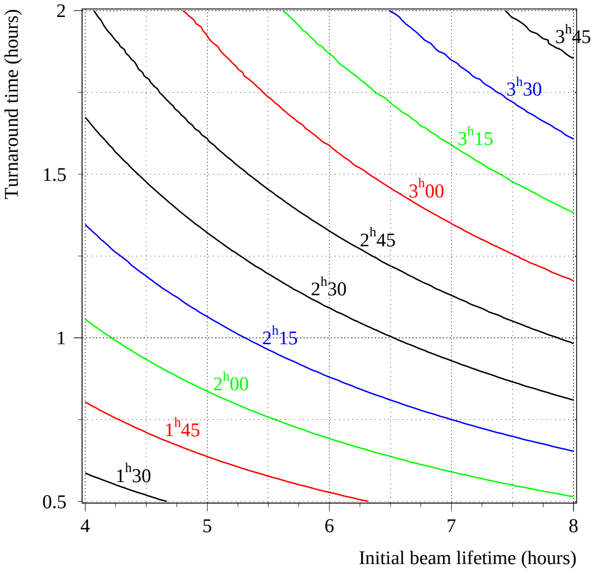
3 RUNNING OPTIMIZATION IN 1999

There is not much freedom as for the beam energy in 1999. The energy increase scenario has been fixed by an official statement from the CERN Research Board [7]:
"The goal in 1999 is to operate LEP at the highest energy consistent with a high integrated luminosity. It is hoped to reach a total energy of 200 GeV well before the end of the year."
This strategy was confirmed by G. Geschonke during this Chamonix workshop [8].

In practice, the RF voltage will be increased towards the highest achievable and compatible with a stable running, with three steps in energy (96, 98 and $\sim$ 100 GeV[1] and at least two steps in total current (6 mA and 8 mA).

In order to be able to make a serious optimization for the year 2000, a record of the machine performance for each fill (beam energy, maximum instantaneous luminosity, beam lifetime, fill duration, integrated luminosity, turnaround time, ...) will have to be kept. For 1999, however, there is not much to optimize while trying to get currents and gradients beyond the original design of the machine.

Still, for a given energy and a given initial instantaneous luminosity, the average integrated luminosity per day depends on the fill duration: if the fill duration is much shorter than the turnaround time, most of the time is used to fill LEP and a very small integrated luminosity is collected. Similarly, if the physics time is much longer than the luminosity lifetime, the time spent with low currents in the machine lead to a sub-optimal integrated luminosity. The optimal physics time is actually an increasing function of the beam current lifetime and of the turnaround time. It is displayed in the previous figure, taking into account the fact that the beam current lifetime increases when the beam current decreases.



For instance, for an initial beam lifetime of six hours and a typical turnaround time of one hour, as was the case in 1998, the optimal physics time is less than two and a half hours, *i.e.*, significantly shorter the routine four hours of 1998. It was agreed during the workshop that the physics coast time in stable running conditions would be reduced to something like three hours [9].

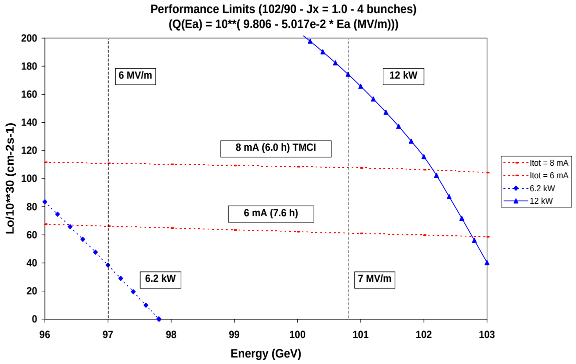
4 RUNNING OPTIMIZATION IN 2000

In 2000 (or at any time in 1999 whenever the highest gradient is reached), the goal is to optimize a known machine

- towards hZ searches, essentially "kinematically limited", *i.e.*, for which beam energy does better than integrated luminosity;
- towards hA searches, in practice not "kinematically limited", *i.e.*, for which integrated luminosity does better than beam energy;
- without penalizing the other physics issues, such as the W mass measurement, for which energy is irrelevant (if above $2m_\mathrm{W}$), or the chargino searches for which luminosity is irrelevant (if above 10–20 pb^{-1}).

Two extreme cases can be studied [10]:

Case#1: RF Gradient limited



In this extreme and simplest case, the luminosity is limited by the maximal current which can be injected in LEP and the energy by the maximal gradient operationally viable. As already mentioned in Section 2, and if the operational efficiency is identical for all gradients, LEP has obviously to be operated at the highest energy.

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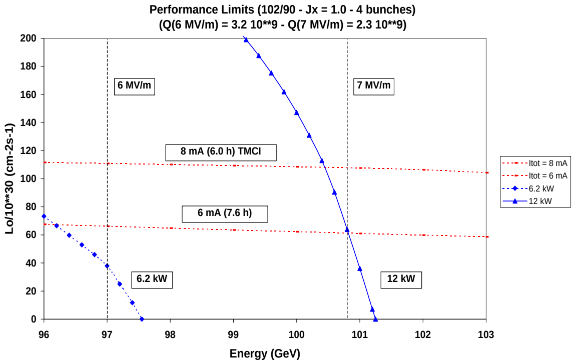
[1] An energy larger than 100 GeV is perfectly acceptable!

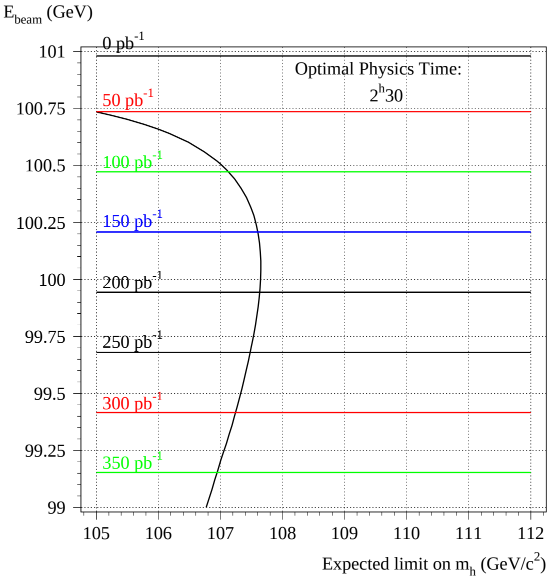
Case#2: Cryogenic power (or efficiency) limited



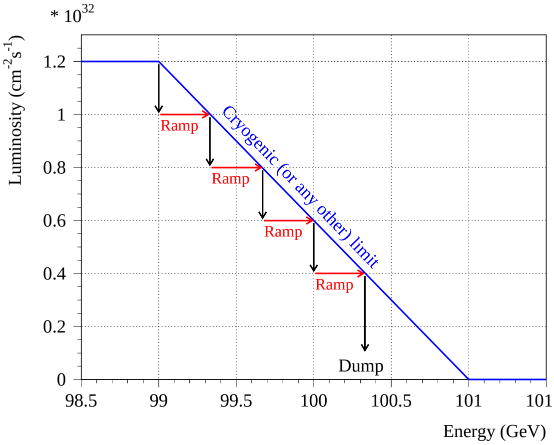
In this second case or, equivalently, in the situation where the operational efficiency is a function of the beam current and of the RF gradient, the highest energy (here 101.3 GeV) corresponds to a vanishing luminosity, and the highest luminosity corresponds to a somewhat smaller energy (here, below 100.4 GeV). The optimal working point is not as obvious as in Case#1: it depends on the physics issue as explained in Section 2, and on the running scheme.

To determine this working point, a number of assumptions have to be made. (The actual values will be known better at the end of 1999.) For the sake of definiteness, it was assumed *(i)* a total of 150 physics days in 2000; *(ii)* an operational efficiency of 50% (it amounted to 46% in 1998); *(iii)* a typical turnaround time of one hour (as was routinely achieved in 1998); *(iv)* a maximal luminosity of 1.2×10^{32} cm^{-2}s^{-1} for a beam energy $E_{\mathrm{min}} = 99$ GeV; and *(v)* a vanishing luminosity for $E_{\mathrm{max}} = 101$ GeV.

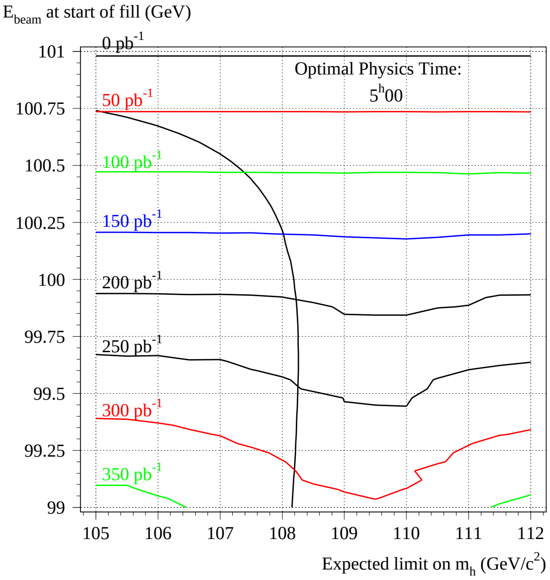
Two different running schemes were considered. In a first scheme, LEP is run at a *fixed* beam energy between E_{min} and E_{max}, and the beam energy is chosen to optimize the sensitivity to the standard model Higgs boson. The expected limit on m_{h} is displayed in the next graph, together with the total integrated luminosity collected, as a function of the beam energy. For an energy close to E_{min}, the integrated luminosity is large (370 pb^{-1}) and the hZ search becomes kinematically limited, while, for an energy close to E_{max} the integrated luminosity vanishes and the hZ search is meaningless. The optimal energy for the hZ searches is reached for a beam energy of 100.1 GeV, with 180 pb^{-1} per experiment, for which the expected limit on m_{h} is 107.6 GeV. The optimal energy for the hA searches, however, is 99 GeV with twice more integrated luminosity, which lowers the expected limit on m_{h} to 106.8 GeV.



The second running scheme is therefore aimed at having high energy and large luminosity simultaneously, putting into practice an original idea of Alain Blondel [11]: the energy is first set to E_{min}, with the highest luminosity. After some time, when the currents have naturally decreased, a mini-ramp is performed towards a higher energy, and the operation is repeated until the beams are eventually dumped.



If the mini-ramps are done quasi-adiabatically, without beam separation, to optimize the operation efficiency, the result is as follows, as a function of the beam energy at start of fill.



As anticipated, the working point with the largest integrated luminosity (330 pb^{-1} per experiment) is close to be that with the best sensitivity to the standard model Higgs boson, with an expected limit of 108.2 GeV/c^2, *i.e.*, 1.2 GeV/c^2 above the first running scheme with the same luminosity. An interesting feature is the optimal running time of ~ 5 hours, needed to reach the larger energies with the successive mini-ramps.

The fact that the centre-of-mass energy would change for each event could be considered as a possible drawback for the data analysis. However, although a little bit less convenient, this scheme should present no practical difficulties if the parameters needed to determine the beam energy are measured and recorded permanently.

Whether the possibility of performing mini-ramps during physics coasts is operationally viable or not is still to be settled. It was concluded during the workshop that such mini-ramps would be tried in 1999 at the end of a few fills [9].

5 CONCLUSIONS

This study of the Higgs safari optimization during the last two years of LEP running can be summarized in the following way.

1. Higgs boson searches need both high centre-of-mass energy and large integrated luminosity to give meaningful results;
2. The hZ search reaches the kinematical limit (within 1 GeV) with 200 pb^{-1} per experiment. An improvement of 1 GeV requires a doubling of the luminosity, or only a 0.5 GeV increase of the beam energy;
3. The hA search is in practice not kinematically limited: an improvement of 1 GeV requires only 50% more luminosity, or a 2 GeV increase of the beam energy;
4. In 1999, priority will be given to the understanding of the machine while increasing the gradient, but it should not be done at the expense of a loss of integrated luminosity; slightly shorter physics coasts under stable running conditions would be helpful in this respect.
5. In 2000, depending on the limitations of the machine, various schemes exist (at least on paper) to optimize its performance both on the energy and the luminosity fronts. A complete optimization should be done when the parameters for an operation at high energy are mastered.
6. Finally, a few pb^{-1} (10?) at the highest centre-of-mass energy would be useful to improve the sensitivity of the search for charginos.

Clearly, this optimization of the LEP running will require a tremendous work to reliably operate the machine. The running period could even be prolonged in Winter 2000 in case of a hint for a discovery. The analysis and combination teams should therefore be ready for a regular result delivery over the year 2000, *e.g.*, each time the luminosity is doubled.

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I also would like to thank in advance all my colleagues of the LEP experiments and of the SL division for their full and enthusiastic cooperation during the next, last, and hopefully best, two years of LEP operation.

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