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TESTS OF THE STANDARD MODEL AND DEFINITION OF ERRORS AT LEP

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Abstract

The most recent data from the four LEP Collaborations are used for a high precision test of the minimal standard model. Various results concerning the unknown parameters of the theory are presented and discussed. A critical analysis of the conventions usually adopted for reporting the errors on physical quantities is performed. In particular the strategy for assigning Confidence Level intervals to the Lagrangian parameters (m_t, α_s, m_H) as well as to the Z^0 parameters (M_Z, Γ_Z, R_l etc...) is reexamined in the light of the increasing experimental precision.

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for ALEPH (see the first paper in [7]). In Fig. 2 we report in the plane $m_t - \alpha_s$ the exact contours of constant $\Delta\chi^2$ with the corresponding ellipses derived under the assumption of a parabolic χ^2. The differences are, in some cases, not negligible. For the sake of completeness, Fig. 3 shows the exact contours at $\Delta\chi^2 = 1$ and 2.30 (a and b respectively) in the plane $m_t - \alpha_s$ for ALEPH (dotted line), DELPHI (dash-dotted line) L3 (solid line) and OPAL (dashed line) [7].

To give a further example let us consider a set of electroweak parameters as reported by the experimental Collaborations [8]:

$$\begin{aligned}
\Gamma_Z &= 2.488 \pm 0.007\,\mathrm{GeV}, \quad \sigma^0 = 41.44 \pm 0.17\,\mathrm{nb}, \\
R_L &= 20.83 \pm 0.06, \quad A^0_{FB}(l) = 0.0164 \pm 0.0021, \\
M_W &= 79.91 \pm 0.39\,\mathrm{GeV}, \quad M_W/M_Z = 0.8807 \pm 0.0031, \\
\Gamma_b/\Gamma_h &= 0.220 \pm 0.003, \quad A^0_{FB}(b) = 0.098 \pm 0.009, \\
A^\tau_{pol} &= 0.142 \pm 0.017.
\end{aligned}$$

We would like to make some prediction for the Higgs boson mass. The idea is to consider the $\Delta\chi^2 = const$ curves in the $m_t - m_H$ plane for fixed α_s and $M_Z = 91.187\,\mathrm{GeV}$. These curves are reported in Fig. 4, where we can compare $\Delta\chi^2 = 1$ with $\Delta\chi^2 = 2.30$ which give informations on the 68% of probability for m_t, m_H separately or jointly. From these curves we learn, first of all, that the standard model is compatible with the data at the 68% of probability for a considerably high Higgs boson mass, and that to conclude that relatively low Higgs boson masses are favored on the basis of the $\Delta\chi^2 = 1$ curve is misleading, since in this way the correlation with m_t is lost. Moreover we learn that a prediction for m_H is heavily correlated with the value of α_s and it is enough to consider $\alpha_s \approx 0.125$ for being well above that value of m_H where perturbation theory breaks down in the scalar Higgs sector. To use the projection of the $\Delta\chi^2 = 1$ curve for giving a qualitative estimate is more

have an uncorrelated error, which is a quadratic sum, statistical $\oplus$ point-to-point systematic error. Moreover we assume a common normalization factor with variance around 1 given by the relative normalization error. Whenever

of the theoretical error on the determination of the unknown parameters of the standard model. For definiteness we have considered our predictions for L3 (electron channel) where the typical situation is as given in Tab. 1. The largest relative error for the lineshape into electrons is $\approx 0.2\%$ (away from the Z^0 peak) while the largest absolute error on the forward-backward asymmetry into electrons is ≈ 0.0025 (again away from the Z^0 peak), but usually and expecially around the resonance they are considerably smaller. The estimates of the error, as returned by the integration routines, can be considered as a sort of systematics and we have made an attempt in order to understand its possible influence. In the minimization procedure we have modified the residuals in the electron channel and the total χ^2 as follows

$$\chi^2 = \Delta^t C^{-1} \Delta + \left(\frac{\lambda - 1}{\Delta\lambda}\right)^2 + \left(\frac{\rho}{\Delta\rho}\right)^2, \tag{2}$$

where

$$\Delta_i(\text{electrons}) = \frac{\lambda\sigma^{th} - \sigma^{exp}}{\Delta\sigma^{exp}} \tag{3}$$

or

$$\Delta_i(\text{electrons}) = \frac{A_{FB}^{th} + \rho - A_{FB}^{exp}}{\Delta A_{FB}^{exp}}, \tag{4}$$

where we assumed conservatively $\Delta\lambda = \Delta\rho = 2 \times 10^{-3}$. The result of the fit and its modification with respect to a situation where the theoretical errors are not included is

		no theor. err.	$\rightarrow$	+theor. err.
χ^2/dof	=	0.949	$\rightarrow$	0.949,
M_z	=	91.193 GeV	$\rightarrow$	91.193 GeV,
m_t	=	81.4 GeV	$\rightarrow$	80.7 GeV,
α_s	=	0.1431	$\rightarrow$	0.1431,
λ	=	1	$\rightarrow$	0.99972,
ρ	=	0	$\rightarrow$	0.59986×10^{-3}.

Therefore we may conclude that the situation is well under control even in the presence of a theoretical error due to the numerical integration over a complicated phase space.

In the end we are interested in presenting results for the secondary parameters and in identifying the correct definition for their errors. The covariance matrix is, in our opinion, totally inadequate for this purpose and we tend to attribute a scarce relevance to the variance

$$var\,(\Gamma_z) = \sum_{i,j=1}^{3} \frac{\partial \Gamma_z}{\partial x_i} C_{ij} \frac{\partial \Gamma_z}{\partial x_j}, \tag{5}$$

where $x_1 = M_z, x_2 = m_t$ and $x_3 = \alpha_s$, C_{ij} being the estimate of the covariance of $\overline{x}_i$ and $\overline{x}_j$

$$C_{ij} = covar\,(\overline{x}_i, \overline{x}_j)\,, \qquad C_{ii} = var\,(\overline{x}_i)\,. \tag{6}$$

Instead of considering the variance of the secondary parameters we prefer to adopt the following procedure. As a result of a 3 parameter fit we consider the region R_p corresponding to $p\%$ of probability distribution for the three parameters. For instance if $p = 0.68$ then we are discussing the region R_p bounded by $\Delta\chi^2 = 3.53$. Next we define the range of variation of the secondary parameter f as

$$f_{min} = f\,(\overline{x}_1, \overline{x}_2, \overline{x}_3)\,, \tag{7}$$

$$f_+ = \max_{x \in R_p} f, \qquad f_- = \min_{x \in R_p} f, \tag{8}$$

and therefore

$$f = f_{min}\,{}^{+\delta f^+}_{-\delta f^-}, \qquad \delta f^{\pm} = |\, f_{\pm} - f_{min}\,|\,. \tag{9}$$

The resulting *errors* are rather conservative estimates of the allowed variations since they turn out to be larger, in general, than the corresponding variances. We have illustrated the general idea by taking the ALEPH data sample and a fixed value for M_z, i.e $M_z = 91.187$ GeV. In this case $p = 0.68$ is given by the region in the $m_t - \alpha_s$ plane bounded by the $\Delta\chi^2 = 2.30$ curve. This curve is reported in Fig. 10 together with the curves corresponding to the maxima and minima of Γ_z, Γ_h and R_l. In a field-theoretical language we attribute a primary significance to the unknown Lagrangian parameters of the standard model and derive a region which reflects some content of probability that the standard model is consistent when the parameters are inside that region. Secondary parameters are those parameters which do not appear directly in the Lagrangian of the standard model and moreover are not obtainable as a consequence of a direct experimental observation but rather follow from a fit to some set of data. For these parameters we prefer to give the minimum and maximum values over the relevant region of the primary parameters. In any case the non-linearity of the model is such that the exact distribution of the various quantities is not known and the associated probabilities as deduced from a comparison with the chi-square distribution will only be approximately correct.

The outlined strategy has been followed in obtaining the results shown in Tab. 2-5. The best values for a 3-parameter fit (M_Z, m_t and α_s) to lineshape and asymmetry data are quoted (Tab. 2-5a) together with the error estimate as given by the covariance matrix (cov.), the intersection method (int.) or the projection method (proj.). The data sample used are the most recently published by the four LEP experiments [7]. In general and within the errors we find a reasonable agreement between m_t as obtained from our global fit to the data and m_t as reported by the LEP Collaborations as a consequence of a model independent fit. Perhaps the largest difference in the central value is for L3 where we find $m_t = 72^{+59}_{\cdots}$ GeV from a fit to the fully extrapolated observables or $m_t = 83^{+54}_{\cdots}$ GeV from a fit to the realistic observables vs a reported value of 132^{+44}_{-63} GeV. A closer study of the fit could be done by looking at the residuals, which directly measure the deviations between the experimental observables and the fitted values. The examination of the fit should be done in terms of the stretch functions or *pulls*. Given a $\chi^2 = \Delta^t C^{-1} \Delta$ with $\Delta_i = x_i - \eta_i, (i = 1, \ldots, n)$ then the i-th *pull* can be expressed as

$$z_i = \frac{x_i - \eta_i}{\sqrt{\sigma^2(x_i) - \sigma^2(\eta_i)}}. \tag{10}$$

The *pull* z_i is anticipated to have a distribution which is fairly close to $N(0,1)$. If, in a fit, we find that one of the z_i deviates very much from the others then the corresponding experimental point should be abandoned if it looks suspicious. For our case the lineshape into μ's has a *pull* of 3.9 at $\sqrt{s} = 91.222$ GeV and of 2.8 at $\sqrt{s} = 93.228$. If the muons are excluded from the fit we obtain instead $m_t = 145^{+41}_{-56}$ GeV.

In Tab. 2-5b the corresponding best values for the Z^0 parameters Γ_h, Γ_Z, R_l and σ_h^0 are reported together with the error estimate as given by the covariance matrix and by the projection method. As can be seen, whereas different error estimates lead to almost equivalent results in the case of Lagrangian parameters, in the case of Z^0 parameters the projection method gives asymmetric errors which in most cases are almost a factor of 2 larger then the corresponding (symmetric) errors as estimated by means of the covariance matrix. Tab. 6 a and b collect the weighted average over the four experiments for Lagrangian and Z^0 parameters respectively. The weighted average has been obtained by following the iterative procedure described in [15]. While in each entry the errors are more or less halved, the same relation between the various kinds of error estimates is maintained.

We are indebted with the DELPHI collaboration for having provided the '91 results on cross sections and asymmetries. We are also grateful to G. Zumerle for his continuous support, to M. Consoli for several stimulating discussions and to G. Pollarolo for his helpful assistance in numerical and graphical problems. INFN, Sezioni di Pavia e Torino, are acknowledged for having provided computer resources.

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Figure and Table Captions

Fig. 1 - The curves $\Delta\chi^2 = 1$ (solid line) and $\Delta\chi^2 = 2.30$ (dashed line) in the $(\Delta R_l, \Delta\Gamma_Z)$ plane. The region which contains the 68% of the probability distribution for R_l and Γ_Z jointly is bounded by the $\Delta\chi^2 = 2.30$ ellipse.

Fig. 2 - The exact contours of constant $\Delta\chi^2$ for $\Delta\chi^2 = 1$ (a) and 2.30 (b) in the $m_t - \alpha_s$ plane, to be compared with the corresponding ellipses as derived under the assumption of parabolic χ^2. ALEPH data sample.

Fig. 3 - The exact contours of constant $\Delta\chi^2$ for $\Delta\chi^2 = 1$ (a) and 2.30 (b) in the $m_t - \alpha_s$ plane, for ALEPH (dotted line), DELPHI (dash-dotted line), L3 (solid line) and OPAL (dashed line).

Fig. 4 - The contours at $\Delta\chi^2 = 2.30$ and 1 (a and b respectively) in the $m_t - \ln(m_H/M_Z)$ plane for $M_Z = 91.187$ GeV and $\alpha_s = 0.118$ (solid line), 0.128 (dashed line) and 0.138 (dotted line).

Fig. 5 - The contours at $\Delta\chi^2 = 1$ (dash-dotted line) and 2.30 (solid line) in the plane $m_t - \ln(m_H/M_Z)$ for $\alpha_s = 0.138$ (a) and 0.118 (b). ALEPH data sample.

Fig. 6 - The same as Fig. 5 for DELPHI data sample.

Fig. 7 - The same as Fig. 5 for L3 data sample.

Fig. 8 - The same as Fig. 5 for OPAL data sample.

Fig. 9 - $\Delta\chi^2 = 2.30$ contours in the plane $m_t - \alpha_s$ from covariance matrix (dash dotted line) and from full calculation (solid line). ALEPH data sample.

Fig. 10 - The $\Delta\chi^2 = 2.30$ contour in the plane $m_t - \alpha_s$ from full calculation (solid line) and the curves corresponding to the maxima and minima of Γ_z, Γ_h and R_l. ALEPH data sample.

Tab. 1 - Our prediction for cross sections and forward-backward asymmetries in the electron channel for the L3 experimental setup together with the numerical errors coming from the integration over the realistic phase space.

Tab. 2a - The best values of a 3-parameter fit (M_Z, m_t and α_s) to lineshape and asymmetry data together with the errors estimate as given by the covariance matrix (cov.), the intersection (int.) and the projection (proj.) method. The dots indicate a lower value below open top production. ALEPH data sample.

Tab. 2b - The best values of the Z^0 parameters corresponding to the Lagrangian parameters of Tab. 2a together with the errors estimate as given by the covariance matrix and the projection method. ALEPH data sample.

Tab. 3a - The same as Tab. 2a for DELPHI data sample.

Tab. 3b - The same as Tab. 2b for DELPHI data sample.

Tab. 4a - The same as Tab. 2a for L3 data sample.

Tab. 4b - The same as Tab. 2b for L3 data sample.

Tab. 5a - The same as Tab. 2a for OPAL data sample.

Tab. 5b - The same as Tab. 2b for OPAL data sample.

Tab. 6a - Weighted average of the Lagrangian parameters of Tab. 2-5a.

Tab. 6b - Weighted average of the Z^0 parameters of Tab. 2-5b.

e^+e^- Observables				
$M_Z = 91.193\,\mathrm{GeV}$ $m_t = 100\,\mathrm{GeV}$ $m_H = 300\,\mathrm{GeV}$ $\alpha_s = 0.140$				
$\sqrt{s}\,(\mathrm{GeV})$	$\sigma\,(\mathrm{nb})$	$\Delta\sigma \times 10^3(\mathrm{nb})$	A_{FB}	$\Delta A_{FB} \times 10^2$
88.231	0.36752	0.41	0.40563	0.157
89.236	0.51184	0.43	0.31480	0.111
90.238	0.81996	0.47	0.20640	0.070
91.230	1.0604	0.50	0.11008	0.053
92.226	0.66936	0.48	0.07670	0.076
93.228	0.38229	0.49	0.10970	0.141
94.223	0.26000	0.55	0.17373	0.250
88.480	0.39372	0.41	0.38520	0.146
89.470	0.56530	0.44	0.29061	0.100
90.228	0.81593	0.47	0.20751	0.070
91.222	1.0615	0.50	0.11066	0.053
91.254	1.0568	0.50	0.10836	0.053
91.967	0.78418	0.51	0.07793	0.069
92.966	0.43543	0.55	0.09657	0.053
93.716	0.31022	0.50	0.13924	0.183

Tab. 1

ALEPH - Lagrangian parameters						
χ^2=102.538 (χ^2/dof = 1.1923)						
	central	cov.	+err. (int.)	-err. (int.)	+err. (proj.)	-err. (proj.)
M_Z	91.182 GeV	5.9 MeV	5.9 MeV	5.9 MeV	6 MeV	6 MeV
m_t	170 GeV	40 GeV	33 GeV	40 GeV	36 GeV	46 GeV
α_s	0.121	0.014	0.013	0.013	0.014	0.014

Tab. 2 a

ALEPH - Z^0 parameters				
	central	cov.	+err. (proj.)	-err. (proj.)
Γ_h	1742 MeV	8 MeV	15 MeV	15 MeV
Γ_Z	2494 MeV	10 MeV	18 MeV	18 MeV
R_l	20.78	0.11	0.20	0.20
σ_h^0	41.46 nb	0.09 nb	0.17 nb	0.18 nb

Tab. 2 b

DELPHI - Lagrangian parameters						
χ^2=57.486 (χ^2/dof = 1.08453)						
	central	cov.	+err. (int.)	-err. (int.)	+err. (proj.)	-err. (proj.)
M_Z	91.191 GeV	7.4 MeV	7.1 MeV	7.1 MeV	7.4 MeV	6.8 MeV
m_t	117 GeV	76 GeV	53 GeV	...	59 GeV	...
α_s	0.136	0.019	0.017	0.017	0.019	0.019

Tab. 3 a

DELPHI - Z^0 parameters				
	central	cov.	+err. (proj.)	-err. (proj.)
Γ_h	1744 MeV	11 MeV	19 MeV	19 MeV
Γ_Z	2493 MeV	13 MeV	23 MeV	25 MeV
R_l	20.90	0.14	0.35	0.26
σ_h^0	41.34 nb	0.13 nb	0.09 nb	0.34 nb

Tab. 3 b

L3 - Lagrangian parameters						
χ^2=90.024 (χ^2/dof = 0.88258)						
	central	cov.	+err. (int.)	-err. (int.)	+err. (proj.)	-err. (proj.)
M_Z	91.193 GeV	5.5 MeV	5.7 MeV	5.7 MeV	5.9 MeV	5.7 MeV
m_t	72 GeV	79 GeV	59 GeV	...	68 GeV	...
α_s	0.143	0.015	0.013	0.013	0.030	0.016

Tab. 4 a

L3 - Z^0 parameters				
	central	cov.	+err. (proj.)	-err. (proj.)
Γ_h	1743 MeV	8 MeV	15 MeV	18 MeV
Γ_Z	2491 MeV	9 MeV	18 MeV	25 MeV
R_l	20.96	0.11	0.29	0.22
σ_h^0	41.28 nb	0.10 nb	0.12 nb	0.12 nb

Tab. 4 b

OPAL - Lagrangian parameters						
χ^2=41.116 (χ^2/dof = 0.88258)						
	central	cov.	+err. (int.)	-err. (int.)	+err. (proj.)	-err. (proj.)
M_Z	91.184 GeV	6.3 MeV	7.0 MeV	7.0 MeV	7.0 MeV	7.0 MeV
m_t	73 GeV	78 GeV	65 GeV	...	69 GeV	...
α_s	0.132	0.015	0.015	0.015	0.019	0.016

Tab. 5 a

OPAL - Z^0 parameters				
	central	cov.	+err. (proj.)	-err. (proj.)
Γ_h	1736 MeV	9 MeV	18 MeV	18 MeV
Γ_Z	2484 MeV	11 MeV	22 MeV	26 MeV
R_l	20.88	0.11	0.30	0.22
σ_h^0	41.35 nb	0.09 nb	0.14 nb	0.25 nb

Tab. 5 b

AVERAGE - Lagrangian parameters			
	cov.	int.	proj.
M_Z	91.188 ± 0.003 GeV	91.188 ± 0.003 GeV	91.188 ± 0.003 GeV
m_t	134 ± 30 GeV	120^{+31}_{-26} GeV	115^{+37}_{-28} GeV
α_s	0.132 ± 0.008	0.133 ± 0.007	$0.131^{+0.010}_{-0.008}$

Tab. 6 a

AVERAGE - Z^0 parameters		
	cov.	proj.
Γ_h	1741 ± 4 MeV	1741 ± 9 MeV
Γ_Z	2491 ± 5 MeV	2491^{+11}_{-12} MeV
R_l	20.88 ± 0.006	$20.87^{+0.15}_{-0.12}$
σ_h^0	41.37 ± 0.05 nb	$41.34^{+0.08}_{-0.13}$ nb

Tab. 6 b

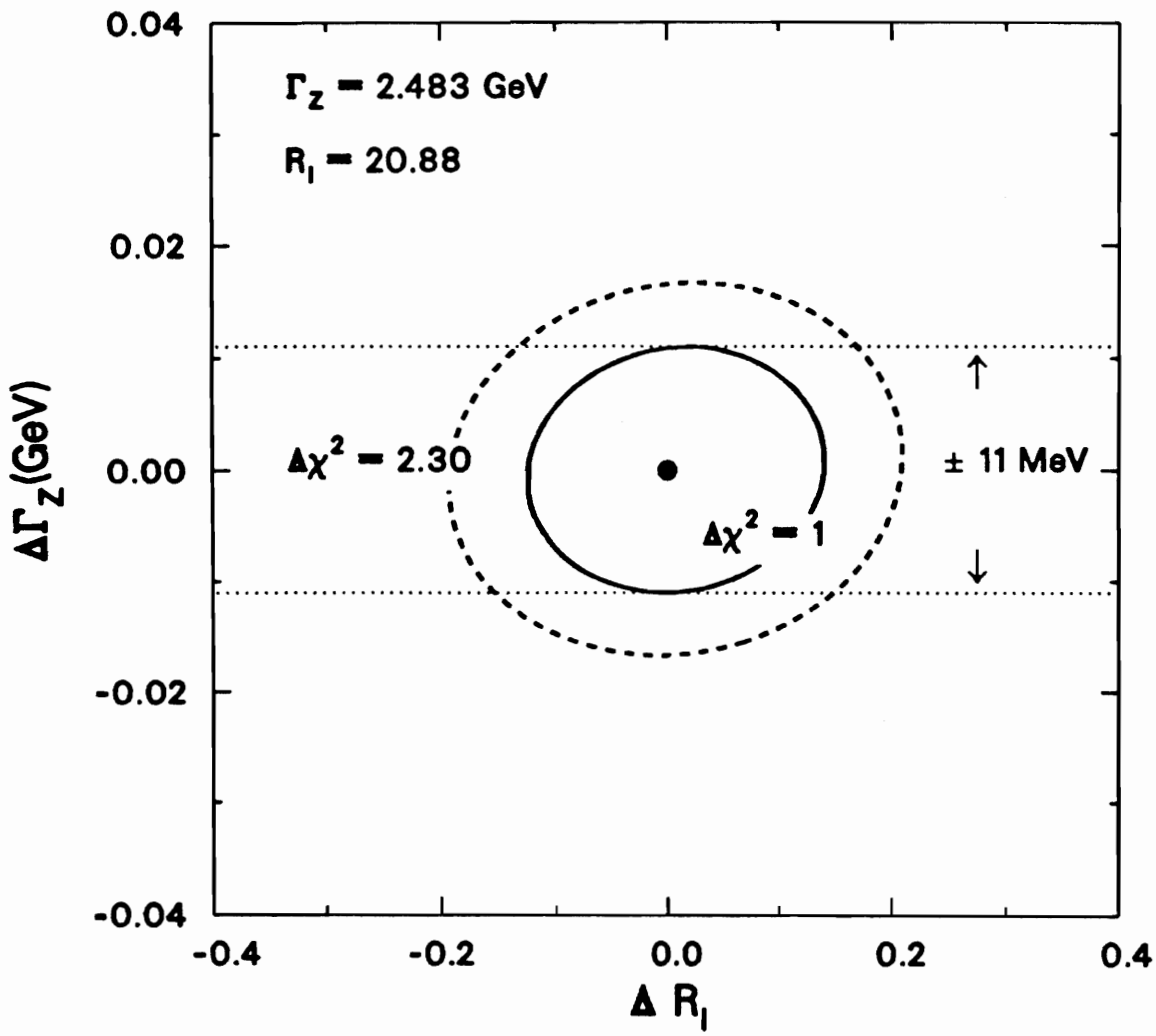
0.04
0.02
0.00
-0.02
-0.04
-0.4
-0.2
0.0
0.2
0.4
Γ_Z = 2.483 GeV
R_l = 20.88
$\Delta\chi^2$ = 2.30
$\Delta\chi^2$ = 1
± 11 MeV
$\Delta\Gamma_Z$(GeV)
ΔR_l

Fig. 1

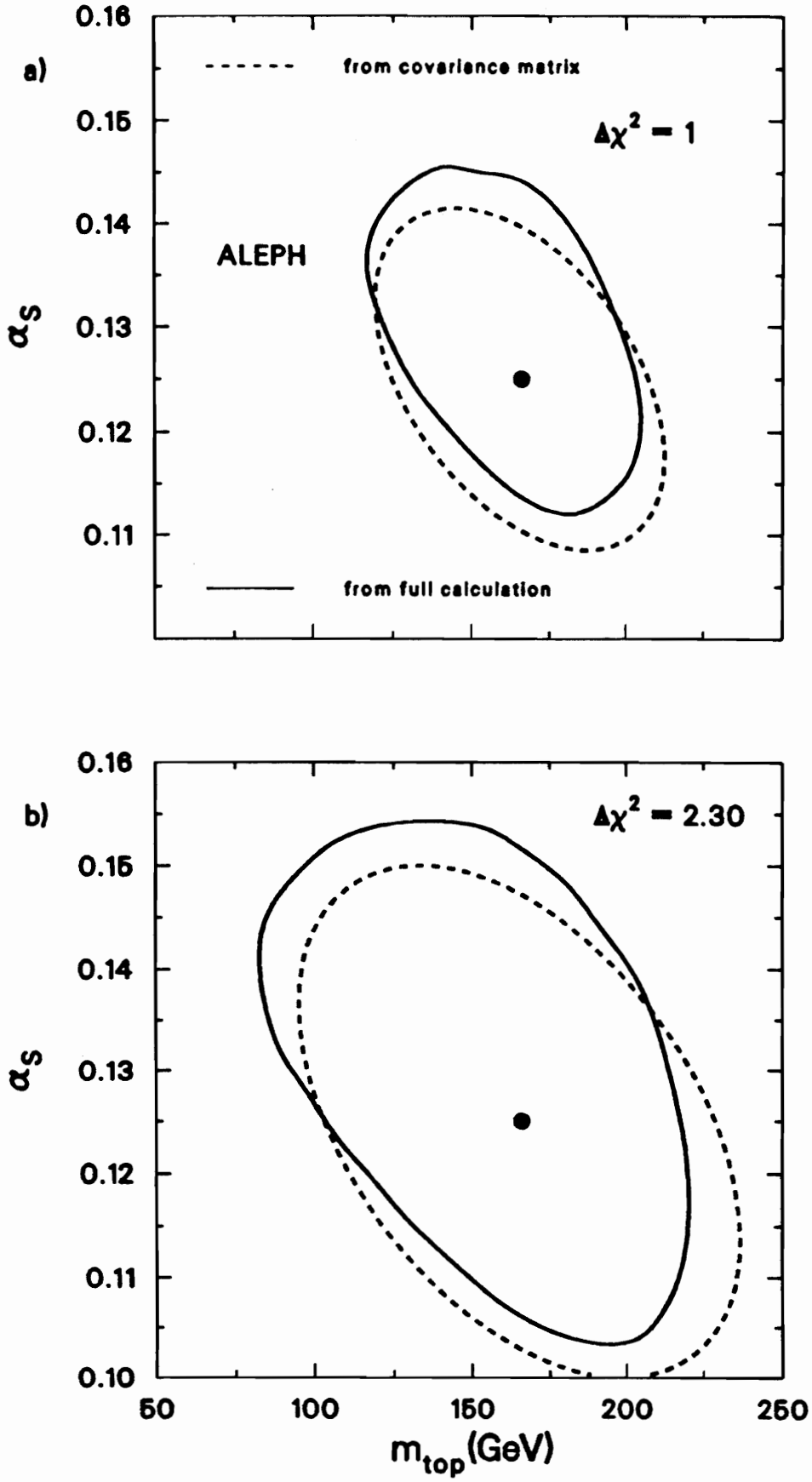
a)
from covariance matrix
$\Delta\chi^2 = 1$
ALEPH
from full calculation
α_s
0.16
0.15
0.14
0.13
0.12
0.11
b)
$\Delta\chi^2 = 2.30$
0.10
50
100
150
200
250
m_{top}(GeV)

Fig. 2

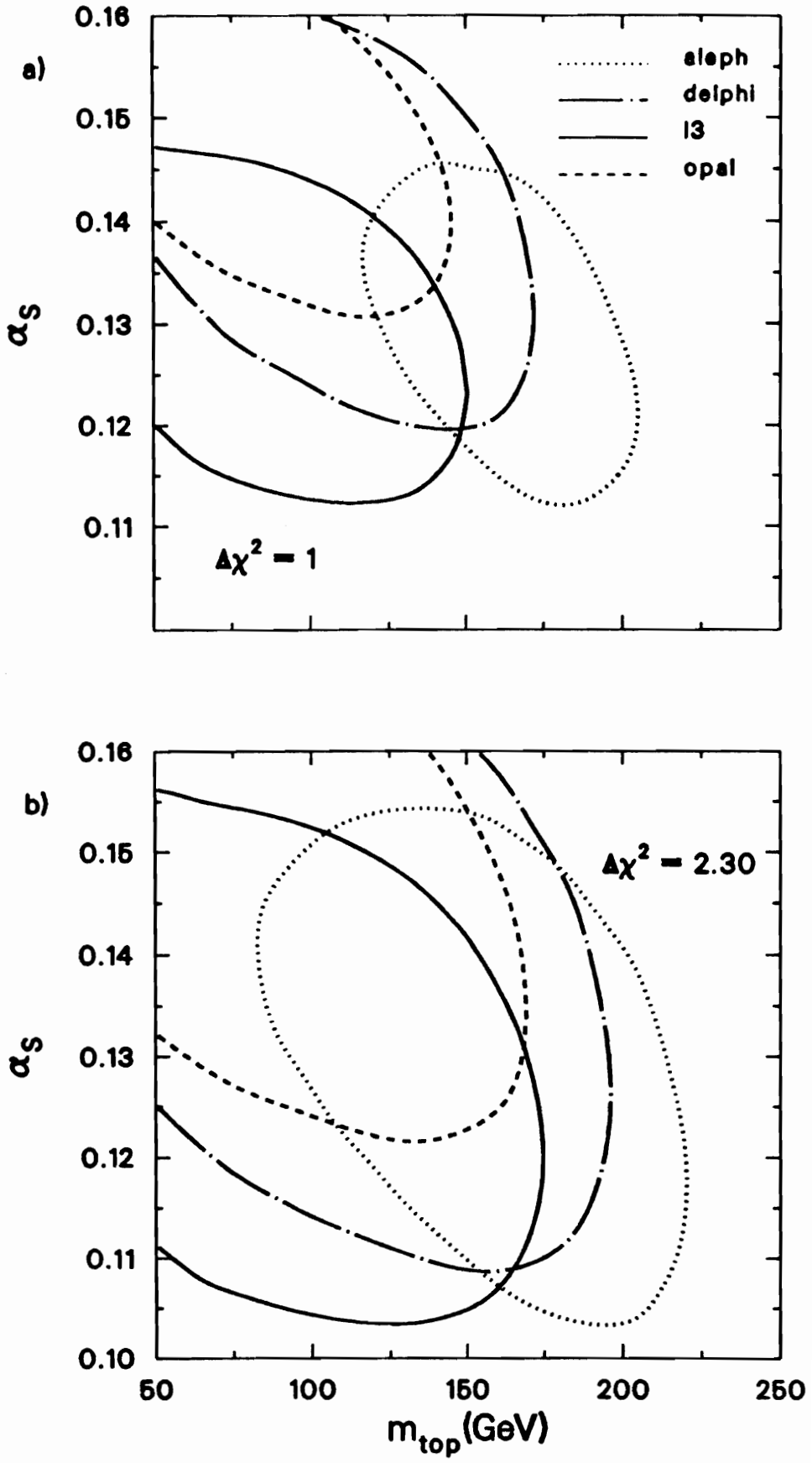
a)
b)
aleph
delphi
l3
opal
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.30$
α_s
0.16
0.15
0.14
0.13
0.12
0.11
0.10
50
100
150
200
250
m_{top}(GeV)

Fig. 3

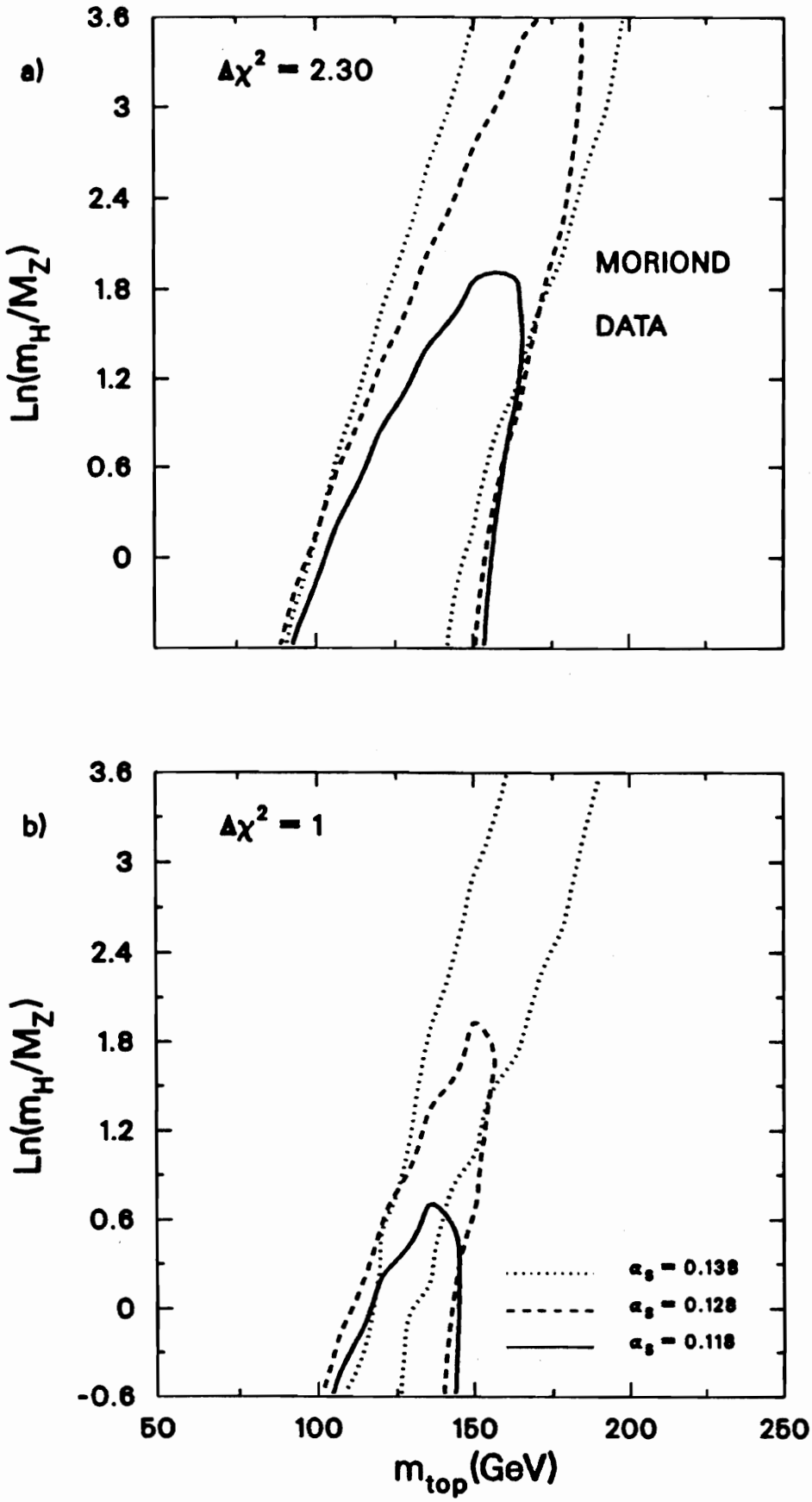
a)
$\Delta\chi^2 = 2.30$
MORIOND
DATA
$Ln(m_H/M_Z)$
3.6
3
2.4
1.8
1.2
0.6
0
b)
$\Delta\chi^2 = 1$
$\alpha_s = 0.138$
$\alpha_s = 0.128$
$\alpha_s = 0.118$
-0.6
50
100
150
200
250
m_{top}(GeV)

Fig. 4

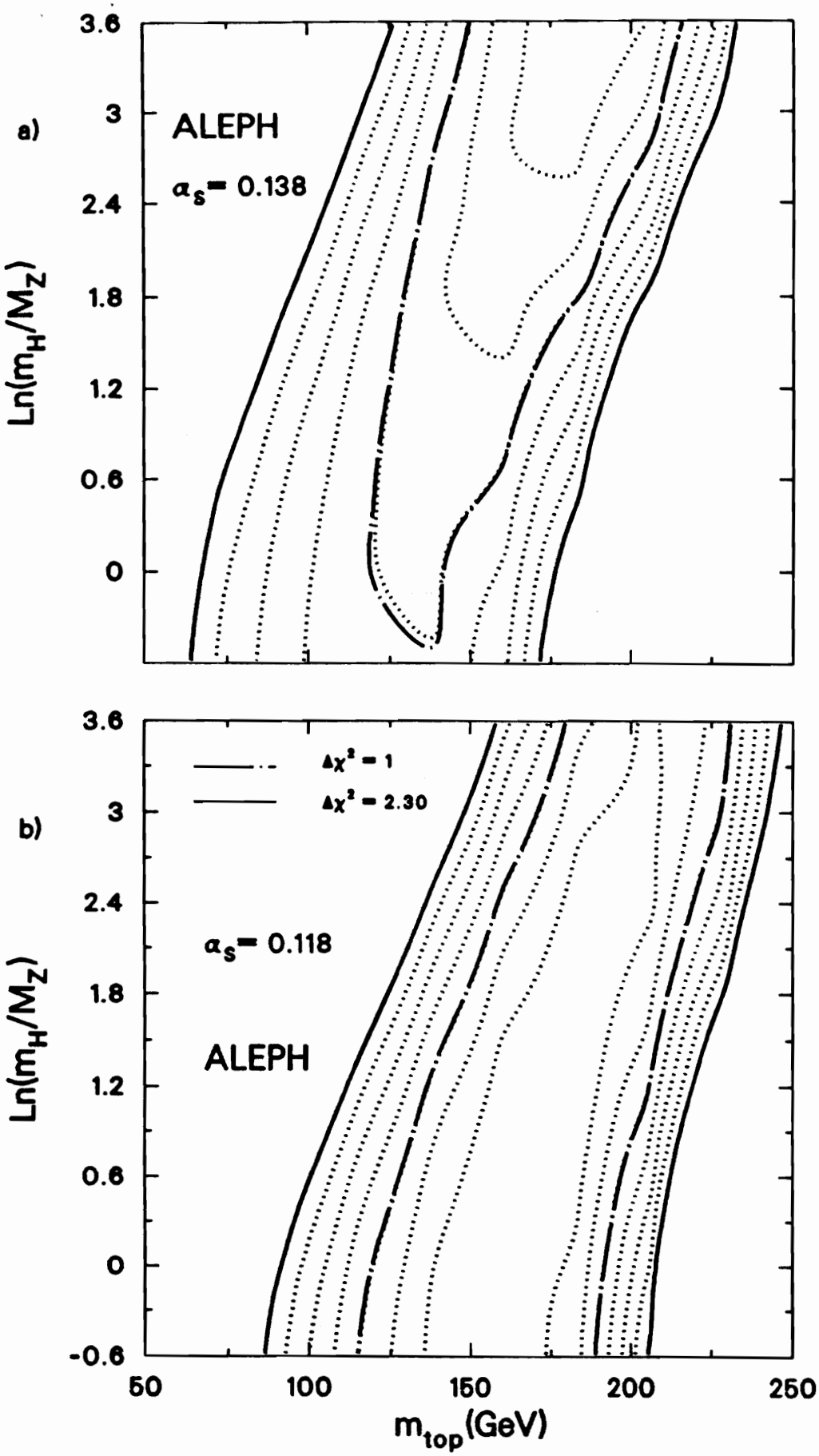
a)
ALEPH
α_s= 0.138
b)
$\Delta\chi^2$ = 1
$\Delta\chi^2$ = 2.30
α_s= 0.118
ALEPH
Ln(m_H/M_Z)
m_{top}(GeV)
3.6
3
2.4
1.8
1.2
0.6
0
-0.6
50
100
150
200
250

Fig. 5

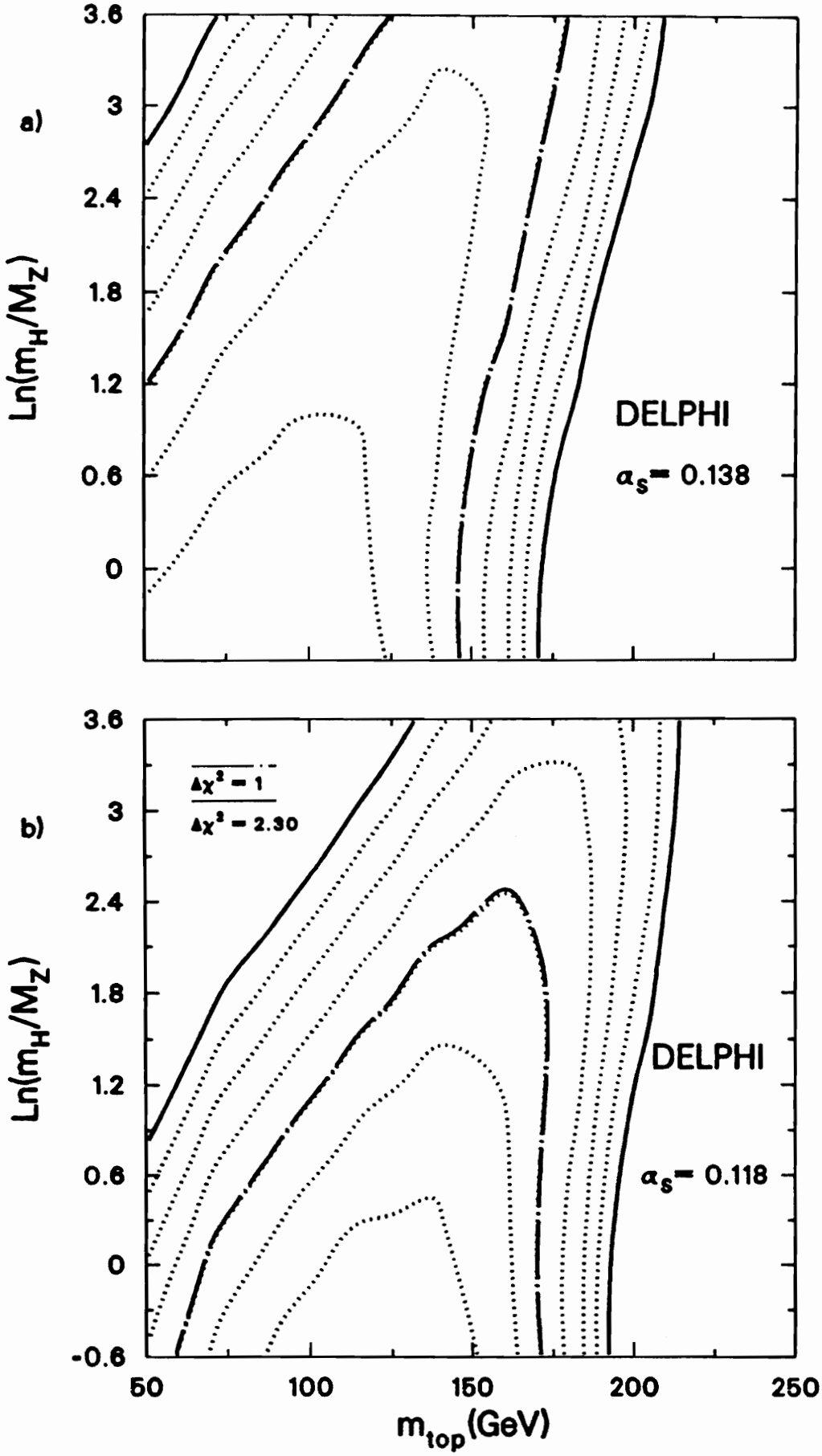
a)
b)
DELPHI
α_s= 0.138
DELPHI
α_s= 0.118
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.30$
Ln(m_H/M_Z)
m_{top}(GeV)
3.6
3
2.4
1.8
1.2
0.6
0
-0.6
50
100
150
200
250

Fig. 6

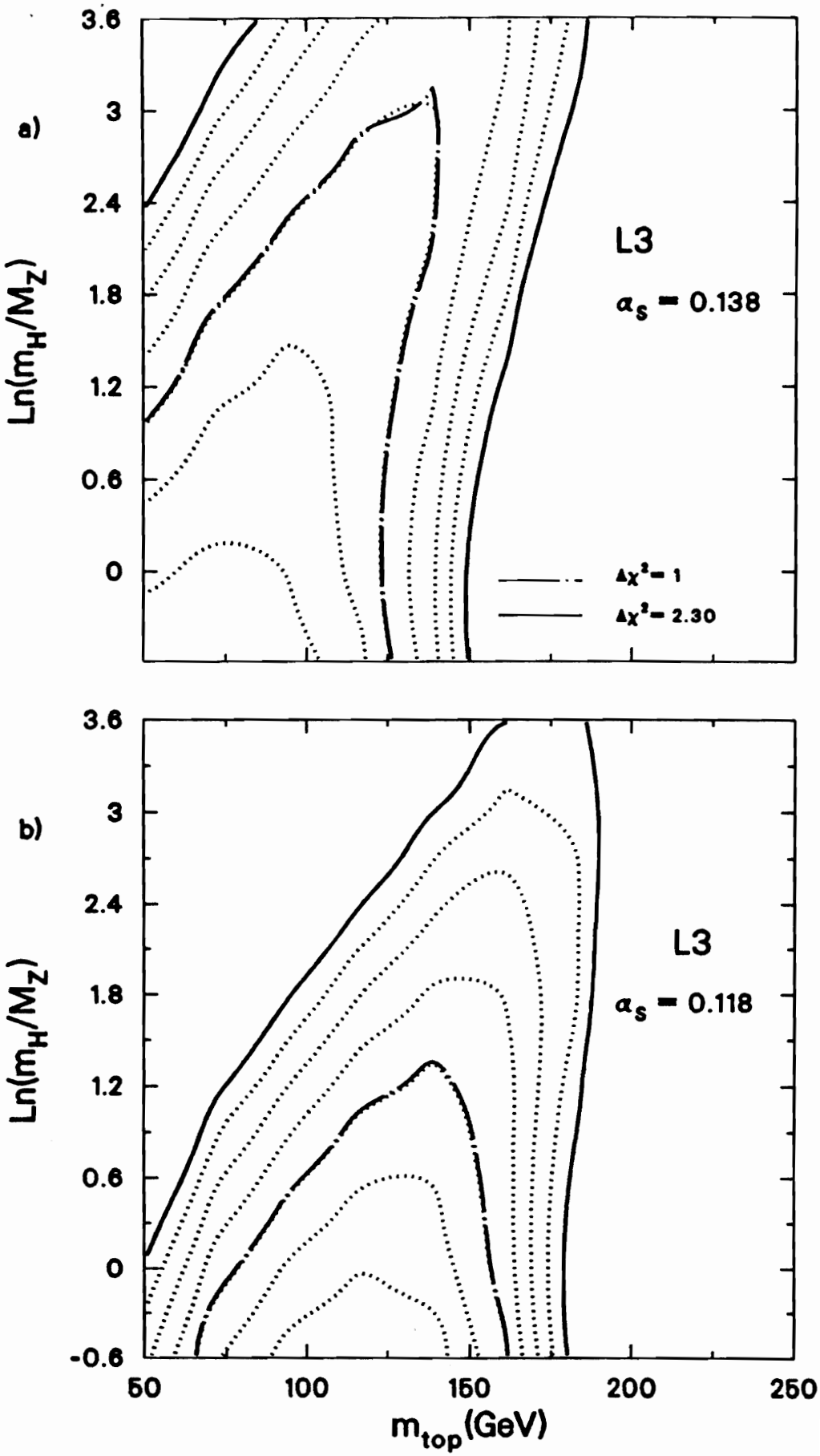
a)
b)
L3
α_s = 0.138
L3
α_s = 0.118
$\Delta\chi^2$ = 1
$\Delta\chi^2$ = 2.30
Ln(m_H/M_Z)
m_{top}(GeV)
3.6
3
2.4
1.8
1.2
0.6
0
-0.6
50
100
150
200
250

Fig. 7

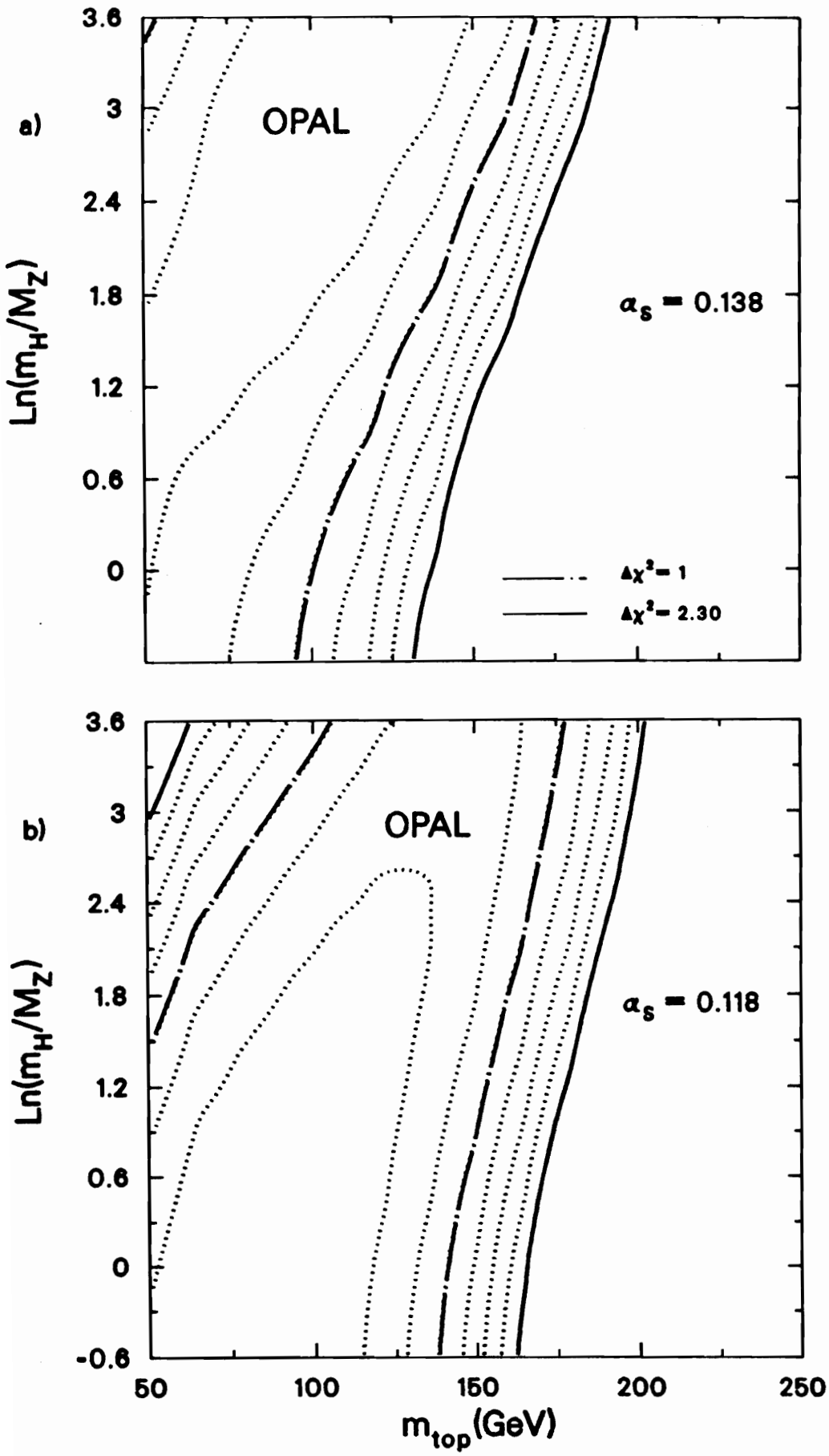
a)
OPAL
$\alpha_s = 0.138$
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.30$
$Ln(m_H/M_Z)$
3.6
3
2.4
1.8
1.2
0.6
0
b)
OPAL
$\alpha_s = 0.118$
$Ln(m_H/M_Z)$
3.6
3
2.4
1.8
1.2
0.6
0
-0.6
50
100
150
200
250
m_{top}(GeV)

Fig. 8

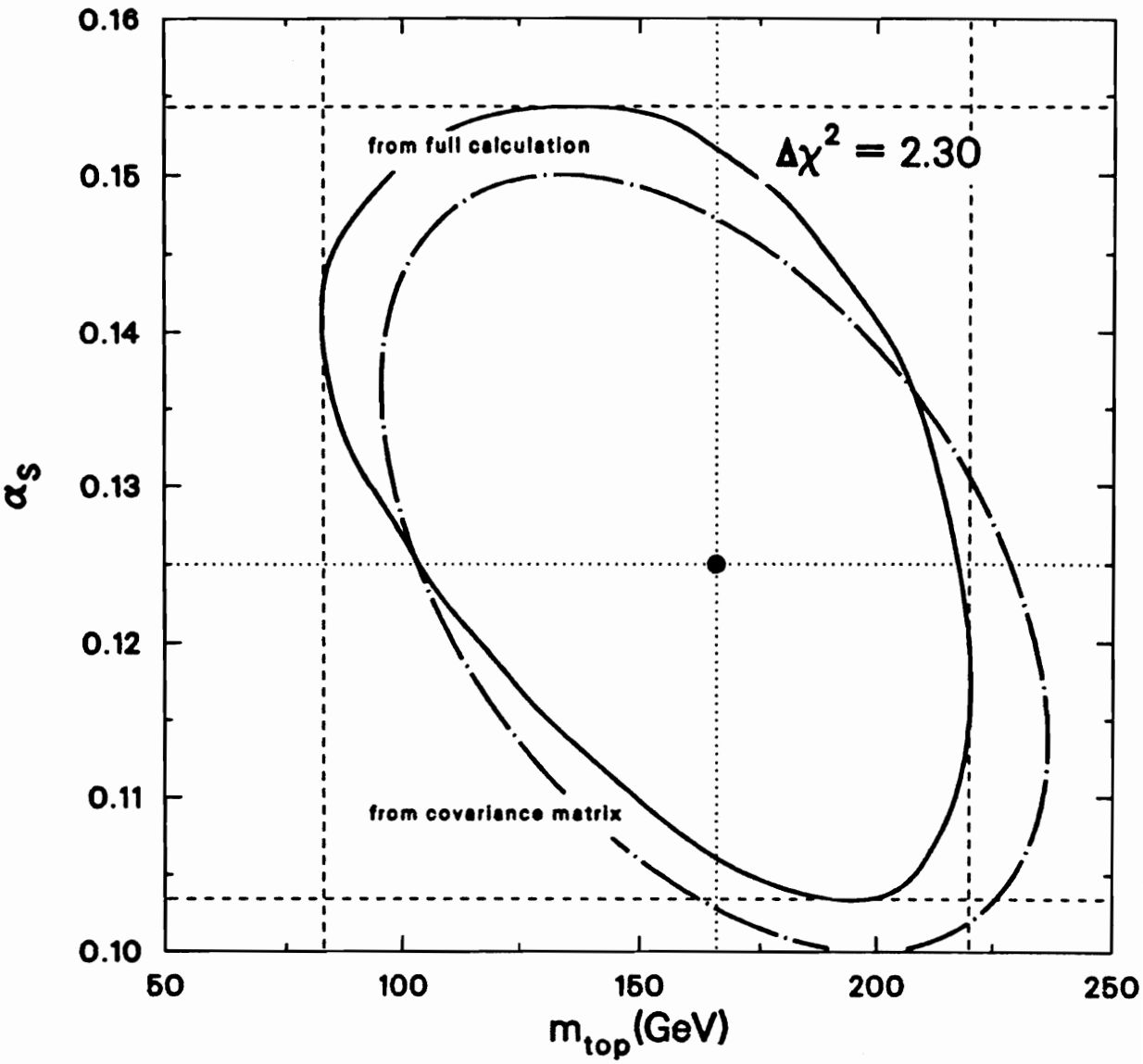
0.16
0.15
0.14
0.13
0.12
0.11
0.10
α_s
50
100
150
200
250
m_{top}(GeV)
from full calculation
$\Delta\chi^2 = 2.30$
from covariance matrix

Fig. 9

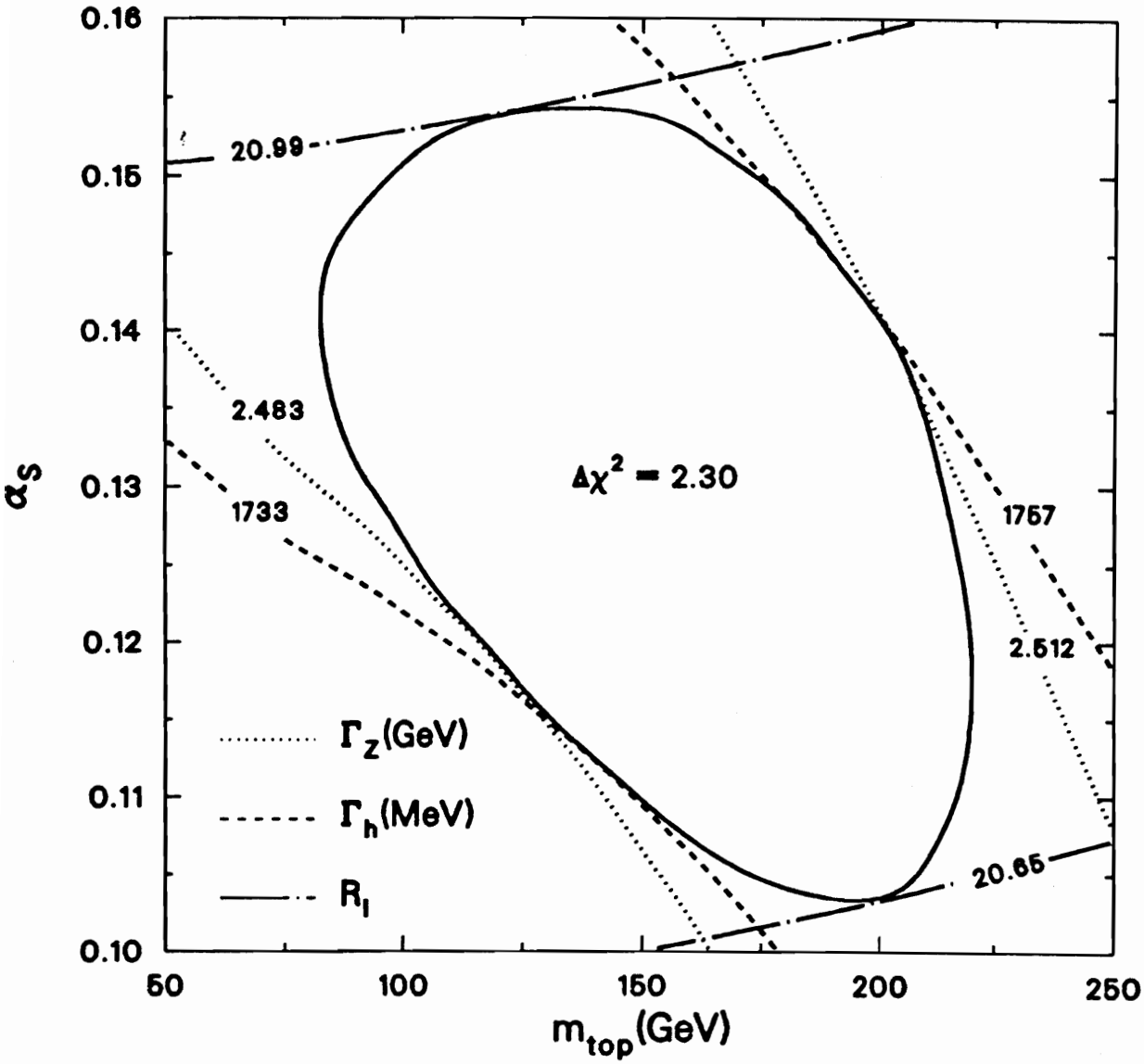
0.16
0.15
0.14
0.13
0.12
0.11
0.10
α_s
50
100
150
200
250
m_{top}(GeV)
20.99
2.483
1733
$\Delta\chi^2 = 2.30$
1757
2.512
20.65
Γ_Z(GeV)
Γ_h(MeV)
R_l

Fig. 10