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SMR.1317 - 7

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

STANDARD MODEL AND HIGGS PHYSICS

Lecture IV

J. ELLIS
CERN, Geneva, SWITZERLAND

Please note: These are preliminary notes intended for internal distribution only.

4 – Searches for Higgs et al.

• recall end of Lecture 2

4.1 – Technicolour

4.2 – Higgs search @ LEP 2

4.3 – What if $m_H = 115$ GeV?

4.4 – Where do we go from here?

prospects @ LHC et al.

the missing link ...

The Higgs Boson

massless gauge boson: e.g. γ, g

2 polarization states: $\rightarrow$ $\leftarrow$ ± 1

massive gauge boson: e.g. $W^{\pm}, Z^{0}$

3 polarization states: $\rightarrow$ $\cdot$ $\leftarrow$ $0, \pm 1$

Need supplementary spin-0 field

with non-zero isospin: $m_{W^{\pm}, Z^{0}} \neq 0$

Minimal choice:

complex doublet with $I = \frac{1}{2}$: $\begin{pmatrix} H^{+} \\ H^{0} \end{pmatrix}, \begin{pmatrix} \bar{H}^{0} \\ H^{-} \end{pmatrix}$

4 degrees of freedom

− 3 eaten by $W^{\pm}, Z^{0}$

= 1 physical Higgs boson

Mass free parameter: $m_H^2 = 2\mu^2$

Couplings completely determined: $g_{Hf\bar{f}} = \frac{m_f}{v}$

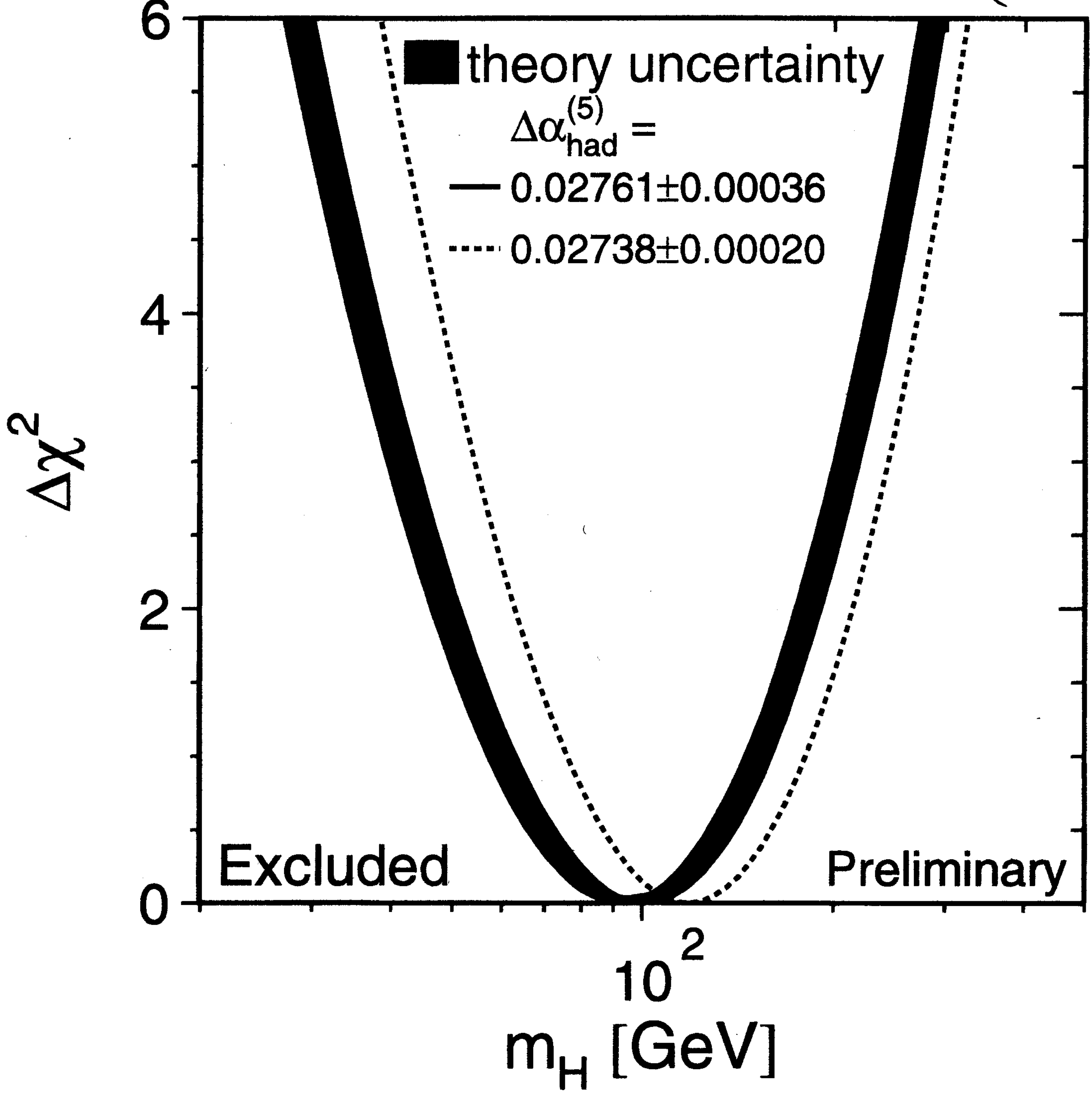
Predictable production, decay

e.g. $e^{+}e^{-} \rightarrow Z + H$ (J.E. + Gaillard + Nanopoulos : 1975

Electroweak fit for m_H

predicts $\boxed{m_H = 98^{+58}_{-38}\ \text{GeV}}$

(LEPEWWG:



The Electroweak Vacuum

Generating particle masses requires breaking gauge symmetry:

$$m_{W,Z} \neq 0 \iff \langle 0|X_{I,I_3}|0\rangle \neq 0$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \simeq 1 \Longleftarrow I = \tfrac{1}{2}$$

$$m_f \neq 0 \iff \langle 0|X_{\frac{1}{2},\pm\frac{1}{2}}|0\rangle \neq 0$$

$m_f \bar{f}_L f_R$

$I = \frac{1}{2}$ $\quad$ $I = 0$

What is X ?

Elementary ?	Composite ?
Higgs boson: $\langle 0\|H^0\|0\rangle \neq 0$	$\bar{F}F$ condensate: $\langle 0\|\bar{F}F\|0\rangle \neq 0$
problems with loops:	cf QCD: $\langle 0\|\bar{q}q\|0\rangle \neq 0$
	superconductivity
$\delta m_H^2 \simeq O\left(\frac{\alpha}{\pi}\right)\Lambda^2$	$\bar{t}t$ condensate ?
cutoff from	wanted $m_t \gtrsim 200$ GeV
Supersymmetry ?	Technicolour ?
$\Lambda \Leftrightarrow \tilde{m} \lesssim 1$ TeV	minimal model $\times$ by $\gtrsim 5\sigma$

1.1 - Technicolour

composite Higgs à la QCD:

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \Longrightarrow \quad \langle 0|\bar{Q}_L Q_R|0\rangle \neq 0$$

breaks isospin: $I = \frac{1}{2}$ new strong interactions:

$$\Lambda_{QCD} < 1\ \text{GeV} \quad \Longrightarrow \quad \Lambda_{TC} \sim 1\ \text{TeV}$$

$$f_\pi \sim 100\ \text{MeV} \quad \Longrightarrow \quad m_W = \frac{g}{2} F_\pi \Leftarrow \sim 250\ \text{GeV}$$

cf QCD: 3 massless technipions 

1 massive scalar $\sim$ TeV $\simeq$ "heavy Higgs"

Single TC doublet not enough:

anomalies, give fermion masses, ...

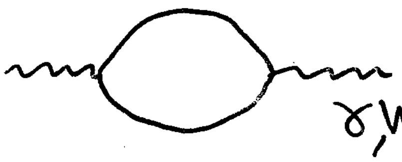
Single Technigeneration Model:

$$\begin{pmatrix} \nu \\ l \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_{1,2,3} \qquad \begin{pmatrix} N \\ L \end{pmatrix}_{1,\dots,N_{TC}} \quad \begin{pmatrix} U \\ D \end{pmatrix}_{\substack{1,\dots,N_{TC} \\ 1,2,3}}$$

study models as functions of (N_{TC}, N_{TF})

technicolours, techniflavours

General Parametrization of (1-loop: no vertices) Radiative Corrections



γ, W, Z

Electroweak observables given by 3 combinations of vacuum polarizations:

e.g. $T \equiv \epsilon_1/\alpha \equiv \Delta\rho/\alpha$ (Altarelli + Barbieri + Caravaglios) (Peskin + Takeuchi)

measures isospin breaking:

$$\Delta\rho = \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} - 2\tan\theta_W \frac{\Pi_{\gamma Z}(0)}{m_Z^2}$$

$$T = \frac{3}{16\pi}\frac{1}{\sin^2\theta_W\cos^2\theta_W}\left(\frac{m_t^2}{m_Z^2}\right) - \frac{3}{16\pi\cos^2\theta_W}\ln\left(\frac{m_H^2}{m_Z^2}\right) + \cdots$$

also $$S \equiv \frac{4\sin^2\theta_W}{\alpha}\epsilon_3 = \frac{1}{12\pi}\ln\left(m_H^2/m_Z^2\right) + \cdots$$

$$U \equiv -\frac{4\sin^2\theta_W}{\alpha}\epsilon_2$$

use data to constrain $\epsilon_{1,2,3}$ (S, T, U)

and extensions of Standard Model with:

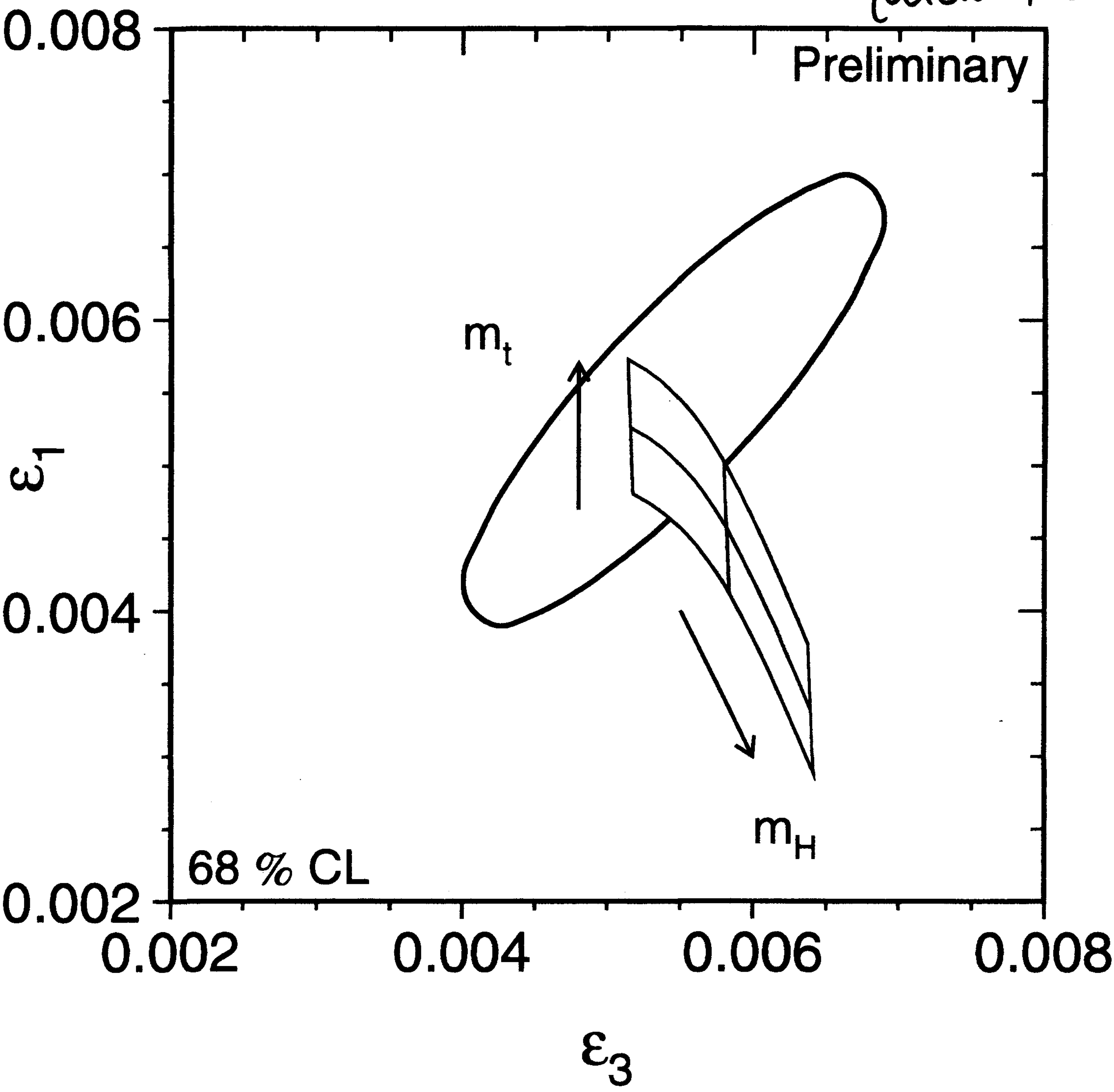
- same gauge group: $SU(2) \times U(1)$
- extra matter particles: e.g. technicolour

Beware of vertices, 2-Loop effects, ...

can parametrize $Z \to \bar{b}b$ vertex by ϵ_b

Fit to vacuum polarizations

(LEPEWWG:01



Comparison with TC

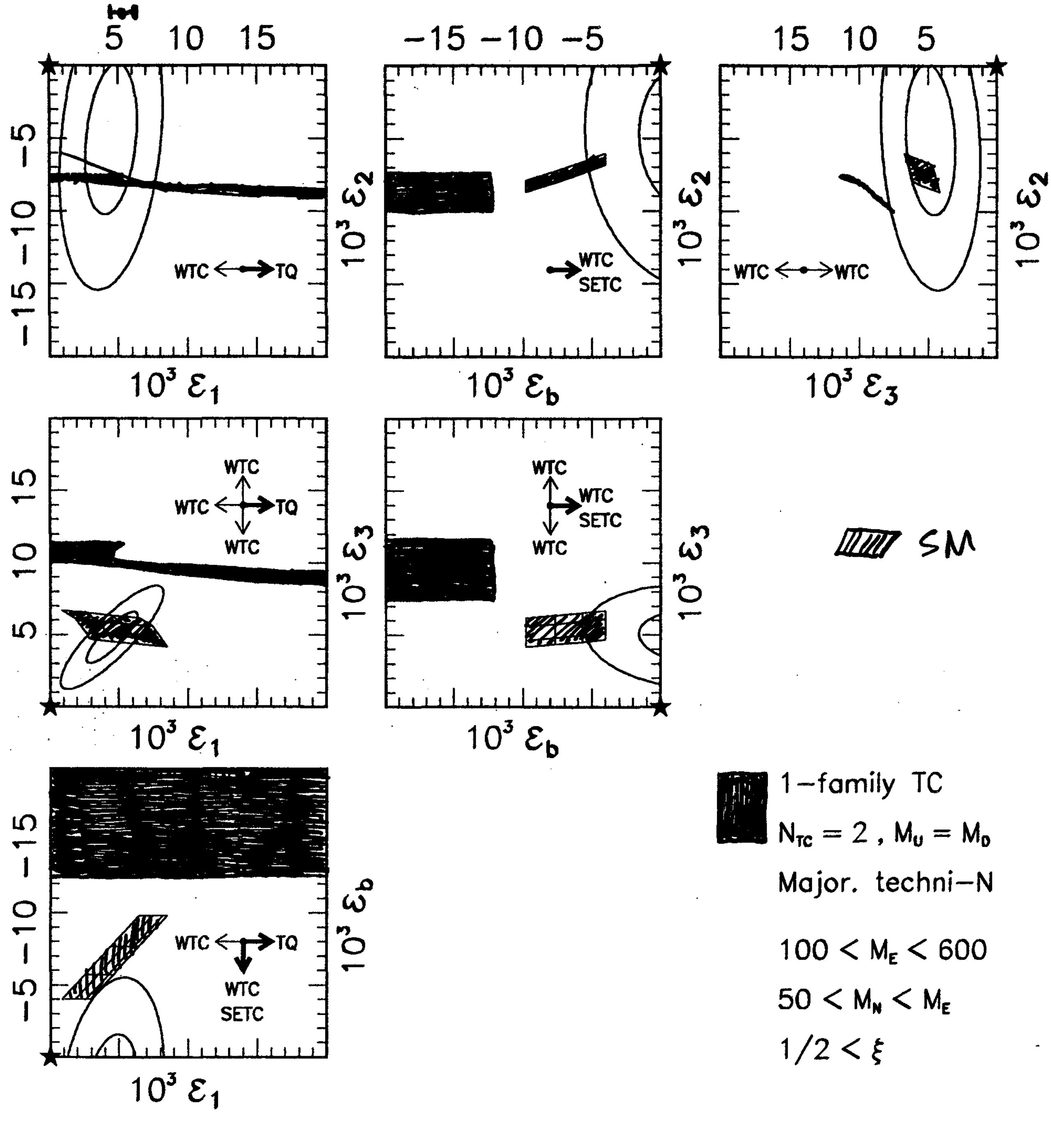
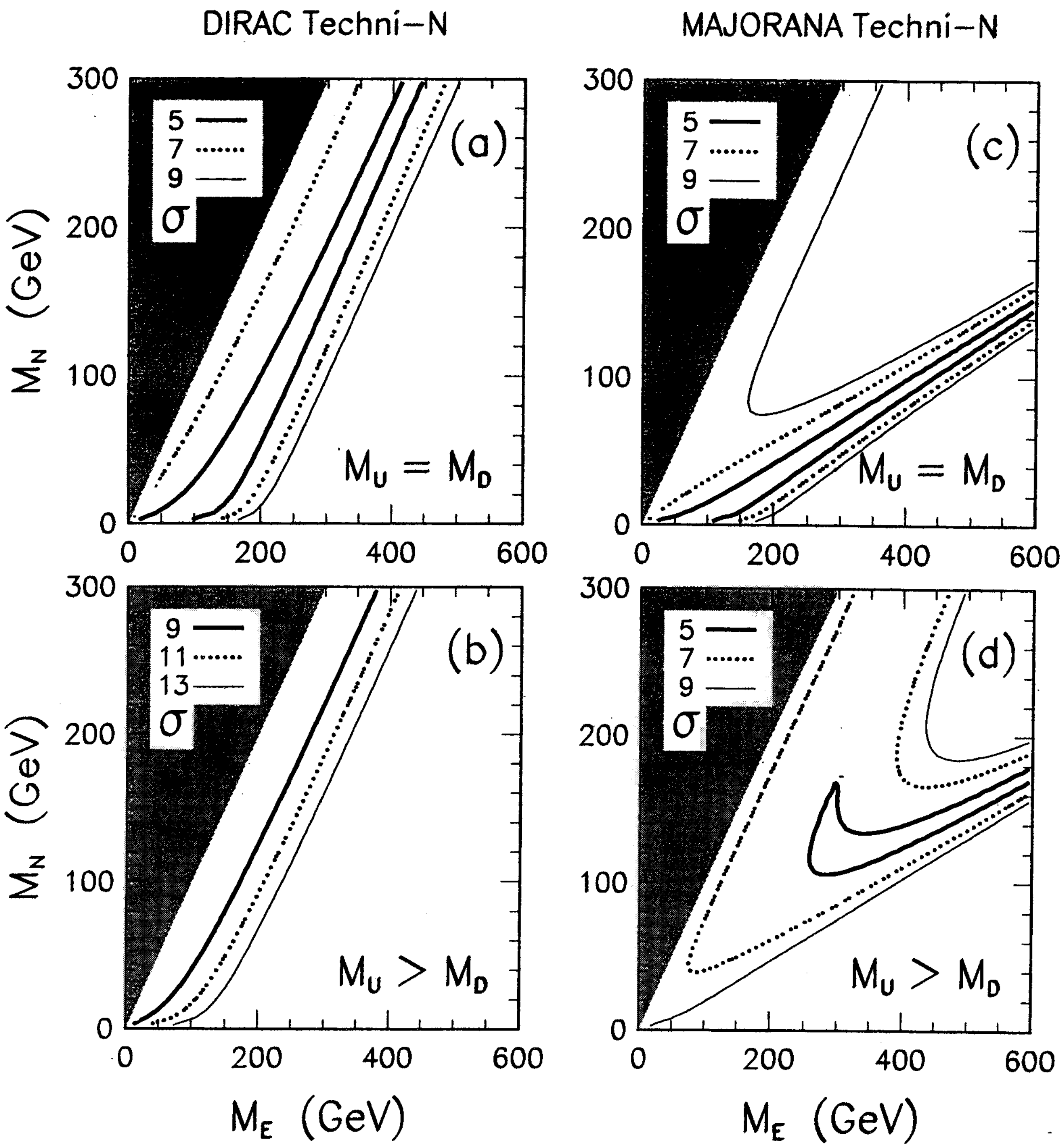


Fig. 3

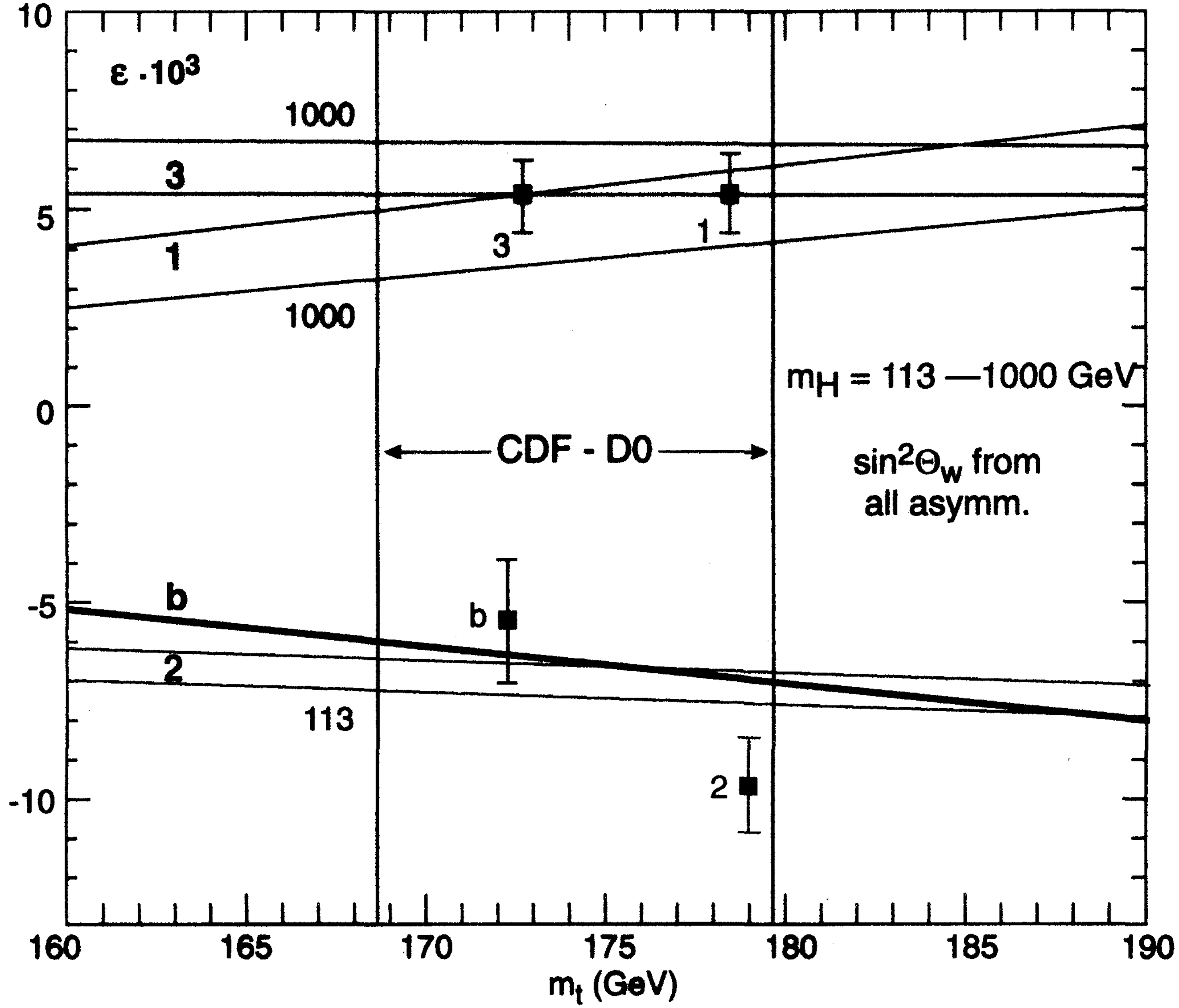
(J.E.+Fogli+Lisi: 95

Exclusion of one-generation technicolour

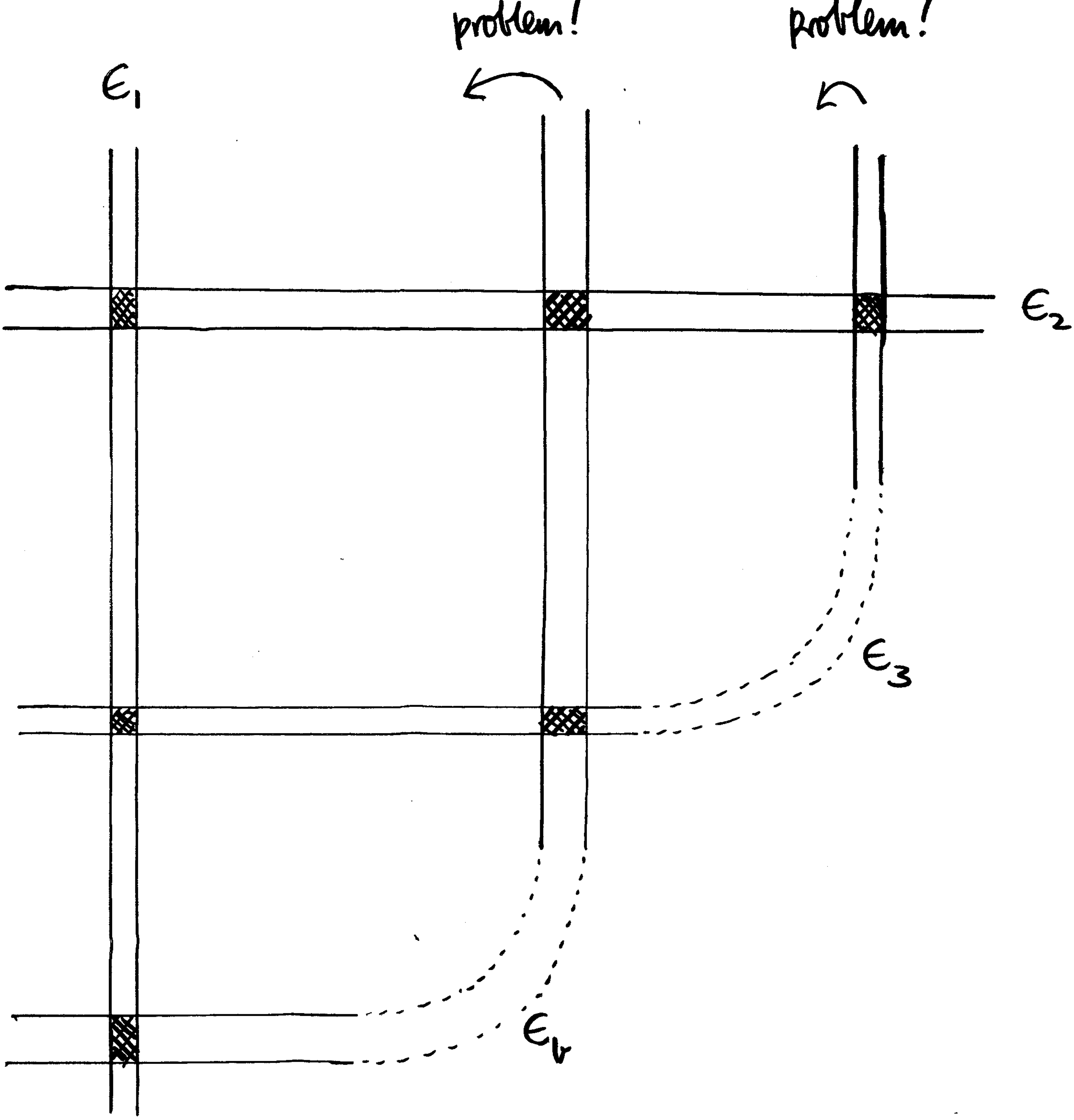


(J.E. + Fogli + Lisi : 95

Fig. 4



2001 update to (Altarelli+Barbieri+Caravaglios:9



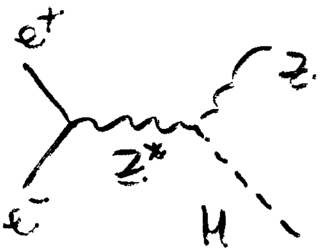
(Altarelli + Caravaglios + Giudice + Gambino + Ridolfi: 01

Cross Section for Higgs Production

(J.E. + Gaillard + Nanopoulos
(Ioffe + Khoze
(Lee + Quigg + Thacker

$e^+e^- \to Z^0 + H$

dominant in Standard Model



$$\sigma = \frac{G_F^2 m_Z^4}{96\pi s}\left(v_e^2 + a_e^2\right)\lambda^{\frac{1}{2}}\ \frac{\lambda + 12 m_Z^2/s}{\left(1 - m_Z^2/s\right)^2}$$

where $a_e = -1, \quad v_e = -1 + 4\sin^2\theta_W$ $\bar{e}eZ$ couplings

$$\lambda \equiv \left(1 - m_H^2/s - m_Z^2/s\right)^2 - 4\frac{m_H^2 m_Z^2}{s^2}$$ 2-body phase space.

- small electroweak radiative corrections

$$\delta\sigma/\sigma \lesssim 1.5\%$$

- important initial-state radiation (ISR)

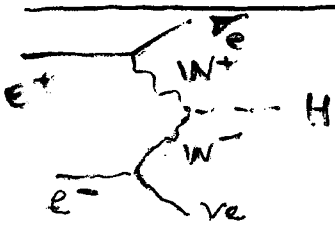
$$\langle\sigma\rangle = \int_{x_H}^{1} dx\, G(x)\, \sigma(xs)$$ (LEP 2 YB

where $x_H = m_H^2/s$, $G(x)$ is known "radiator function"
to $O(\alpha^2)$

- allow for finite-width, off-shell Z^0

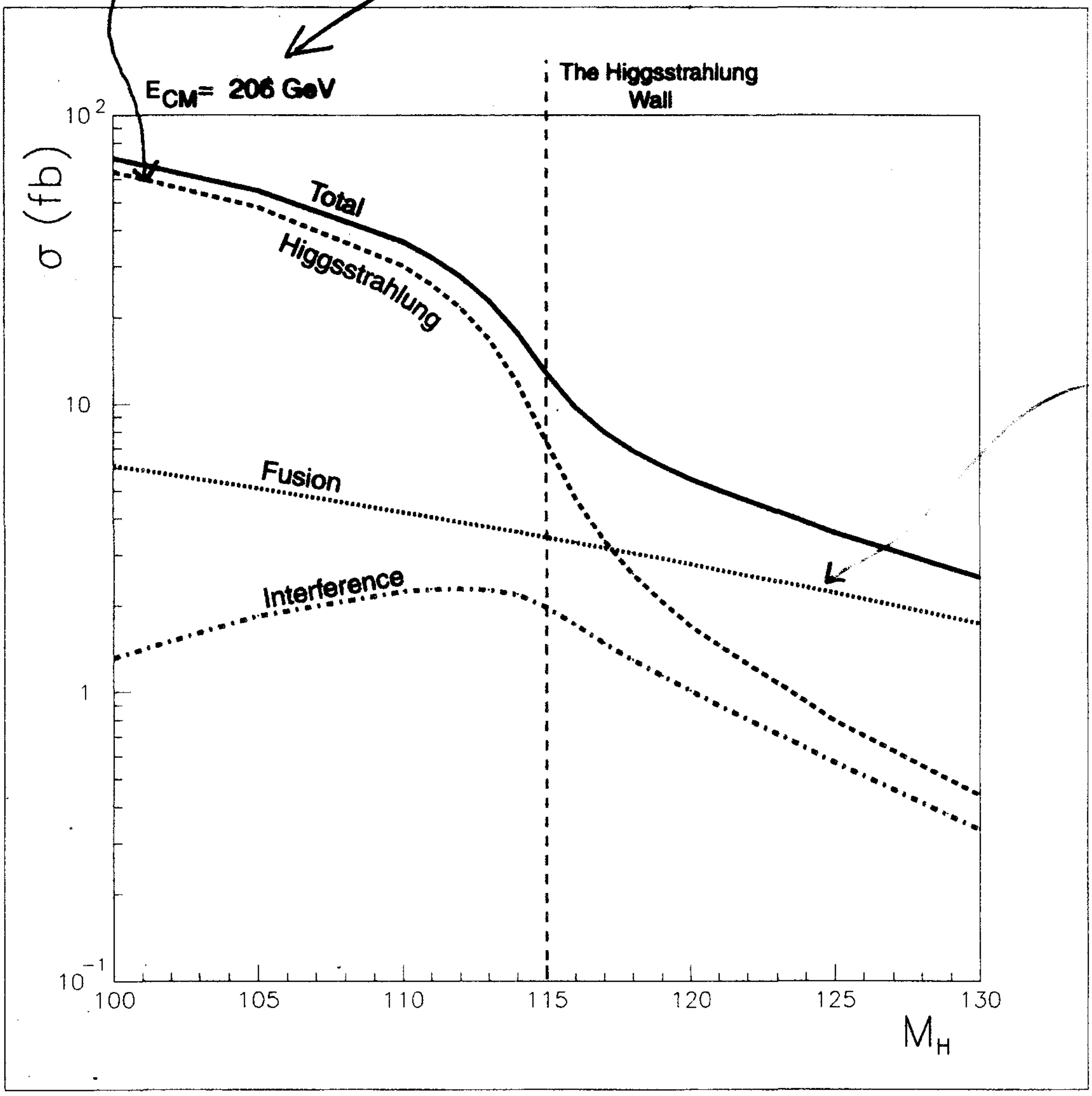
$e^+e^- \to \nu_e\bar{\nu}_e + H$

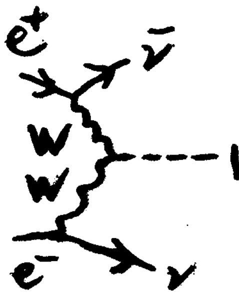
by W^+W^- fusion (Jones + Petcov



could extend mass reach by a few (valuable) GeV?

(J.E.+Gaillard
+Nanopoulos,
Ioffe+Khoze)





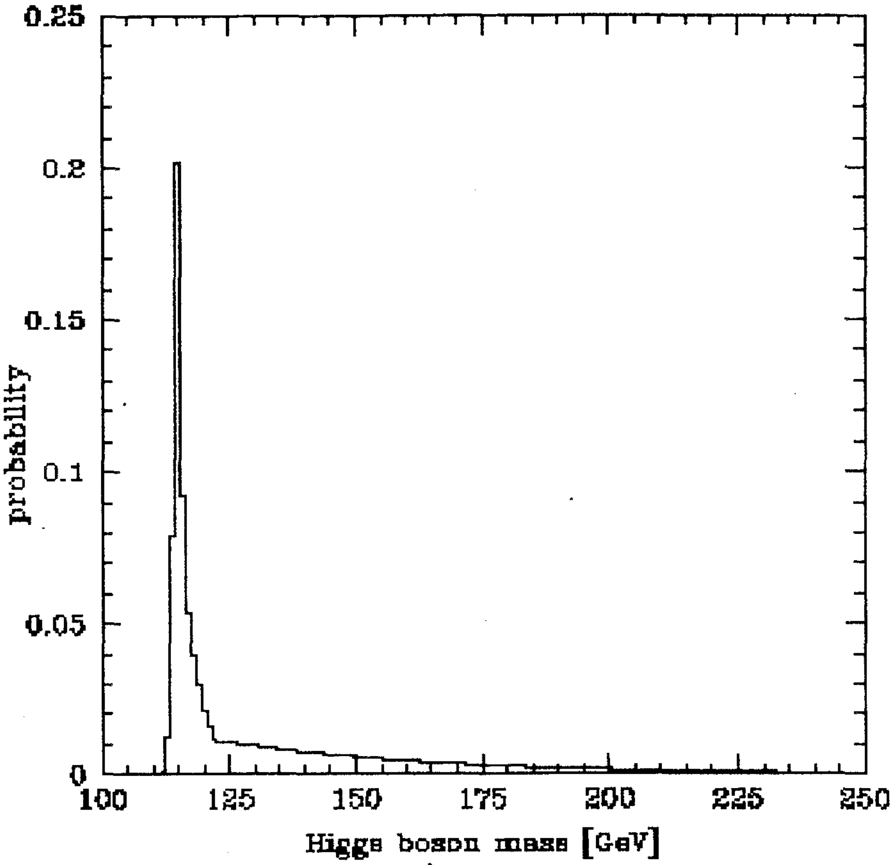
(Jones+
Petcov

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.

(Gross+Read)

Probability Distribution for Higgs Mass

combining precision measurements
⊕ direct limits

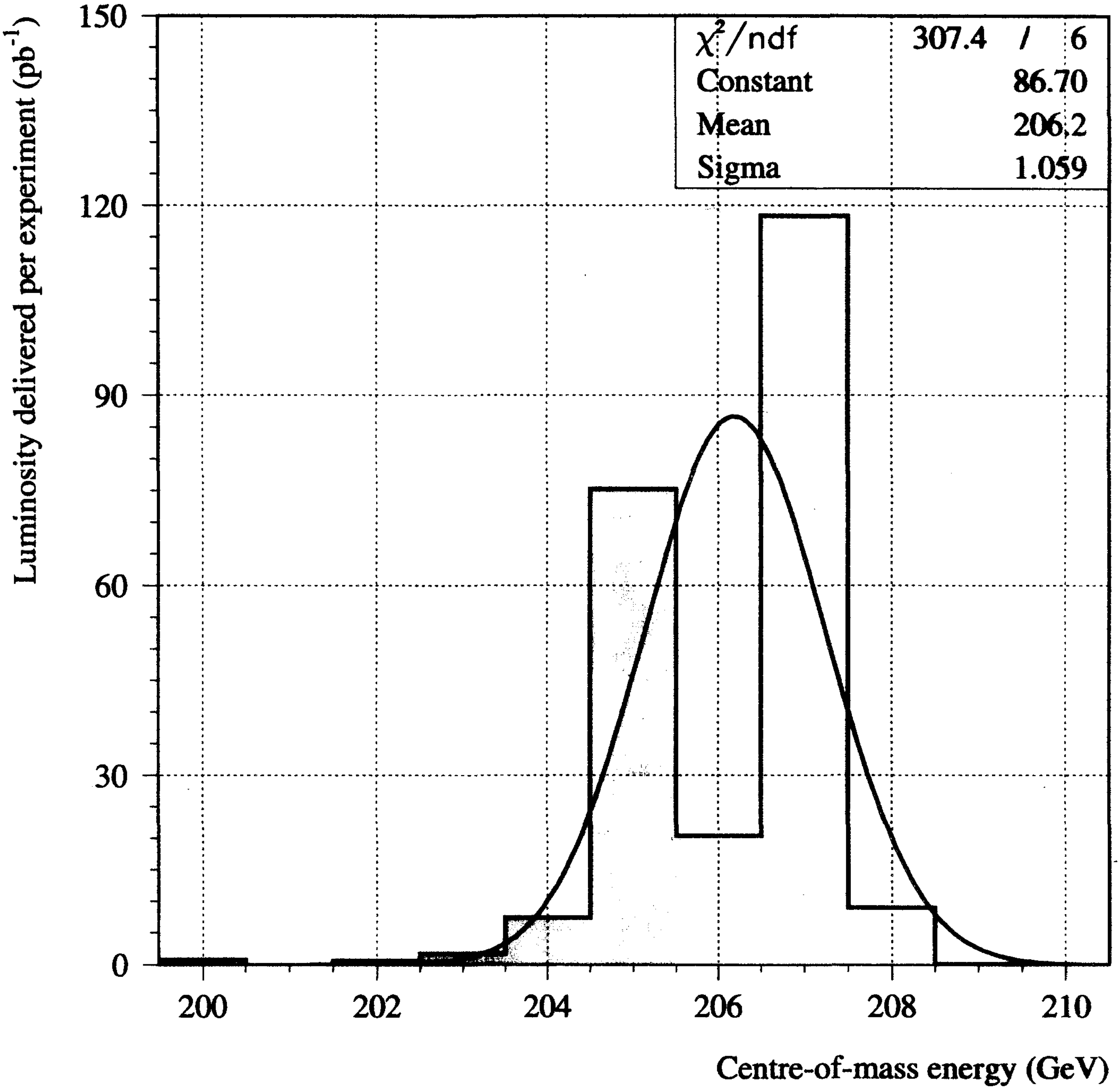


Standard Model

(Erler:
hep-ph/0010153

Distribution of E_{cm} @ LEP

in 2000



Made on 29-Aug-2000 20:36:27 by konstant with DALI_F1
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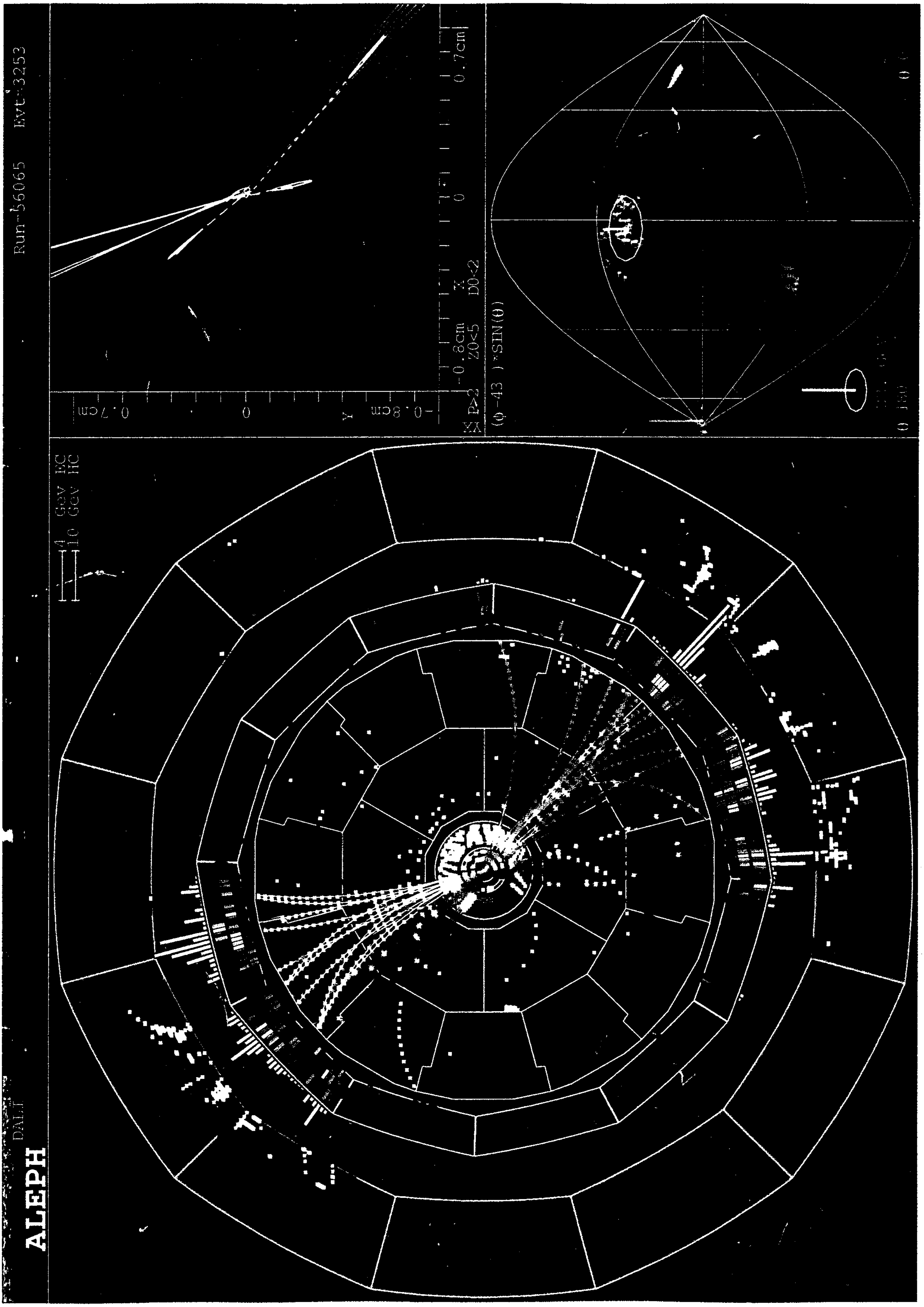


52 GeV

60 GeV

Higgs mass: 114.4 GeV

2K146lb

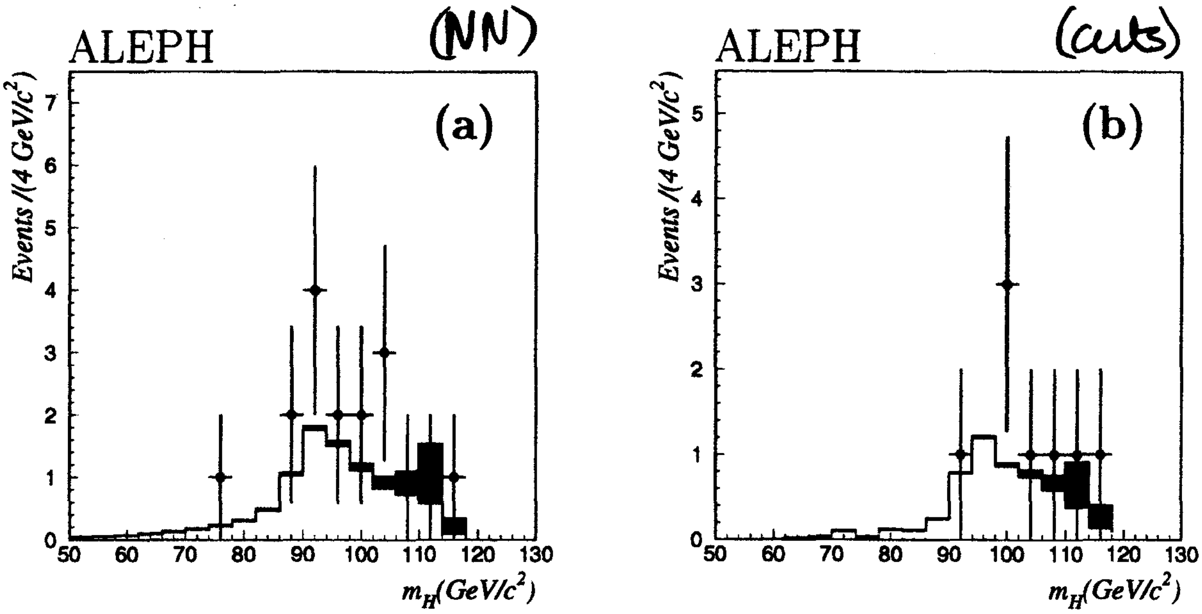


Figure 9: High purity ($s/b = 1.5$) reconstructed Higgs boson mass distributions for the (a) NN and (b) cut selections for the data (dots with error bars), the expected background (light histogram), and the expected signal with a Higgs boson mass of $114\,\mathrm{GeV}/c^2$ (dark histogram).

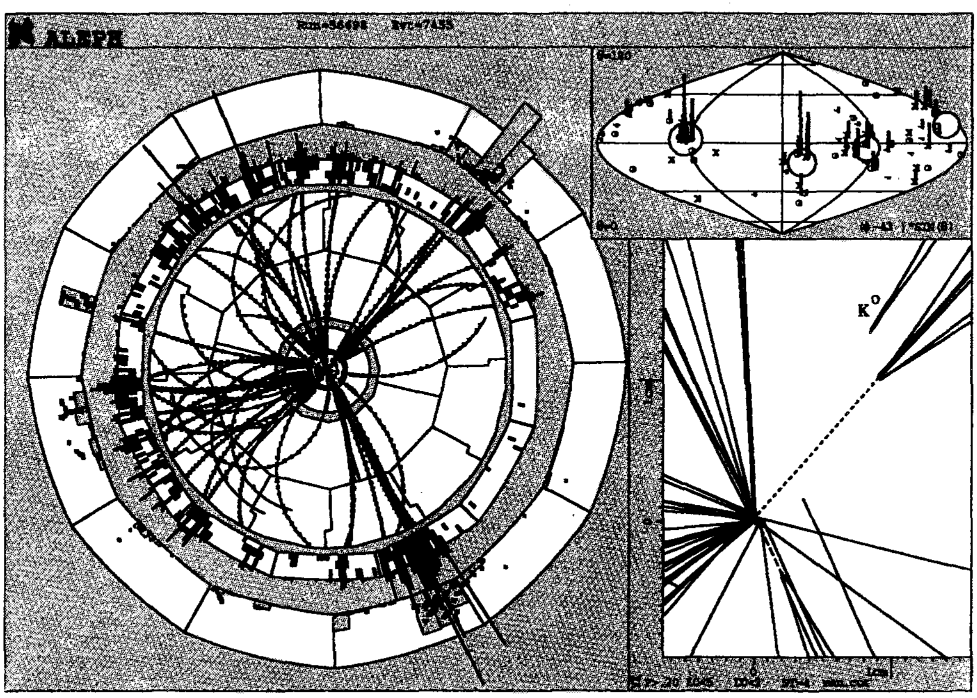


Figure 10: Four-jet Higgs boson candidate (a) with a reconstructed Higgs boson mass of $110.0\,\mathrm{GeV}/c^2$. Three of the four jets are well b tagged. The event is shown in the view transverse to the beam direction, the θ-$\phi\sin\theta$ view, and in a closeup of the charged particles in the vertex region.

two different analyses

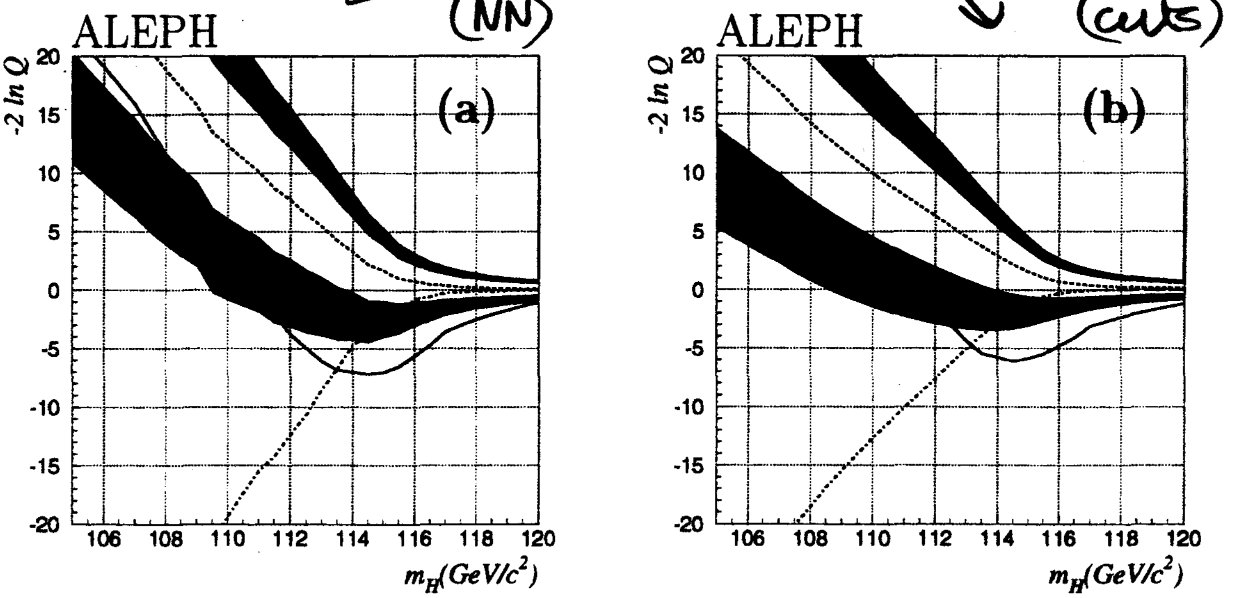


Figure 4: The log-likelihood estimator $-2\ln Q$ for the (a) NN and (b) cut streams as a function of the mass of the Higgs boson for the observation (solid) and background-only expectation (dashed). The light and dark grey regions around the background expectation represent the one and two sigma bands, respectively. The dash-dotted curves show the medians of the log-likelihood estimator as a function of the Higgs boson mass for the signal hypothesis.

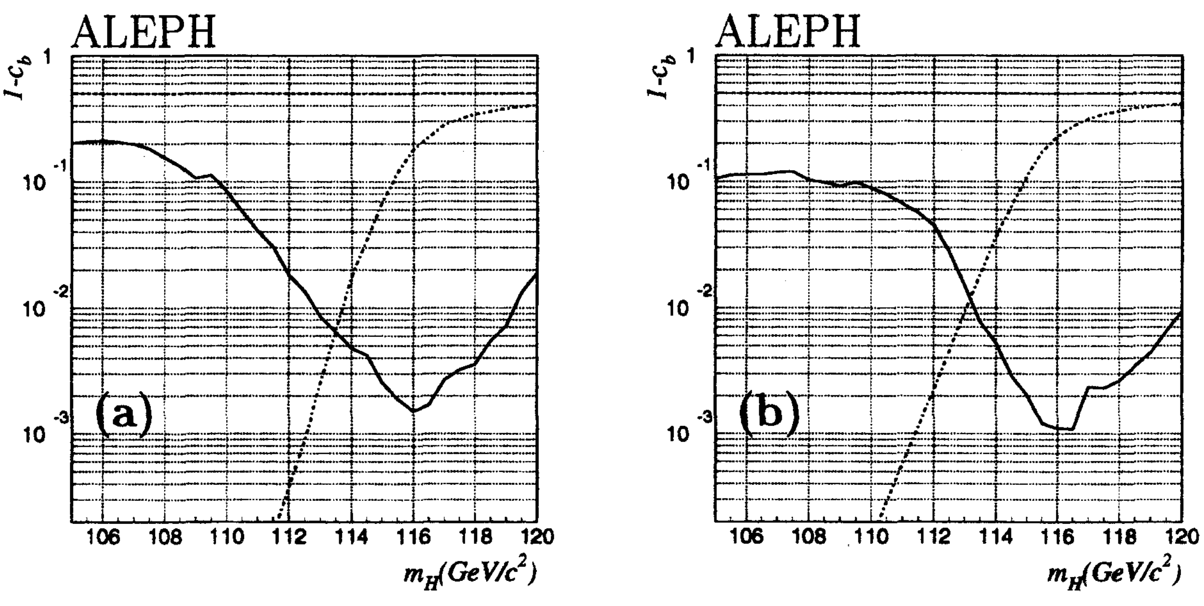


Figure 5: Observed (solid) and expected (dashed) CL curves for the background hypothesis as a function of the hypothesized Higgs boson mass for the (a) NN and (b) cut streams. The dash-dotted curves indicate the location of the median CL for a Higgs boson signal as a function of the Higgs boson mass.

No excess @ large mass

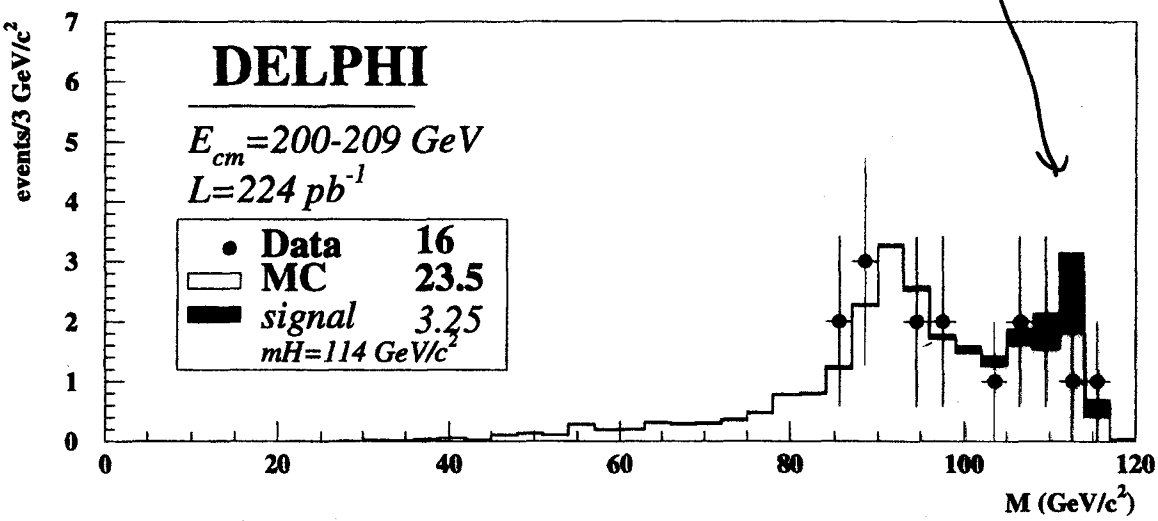
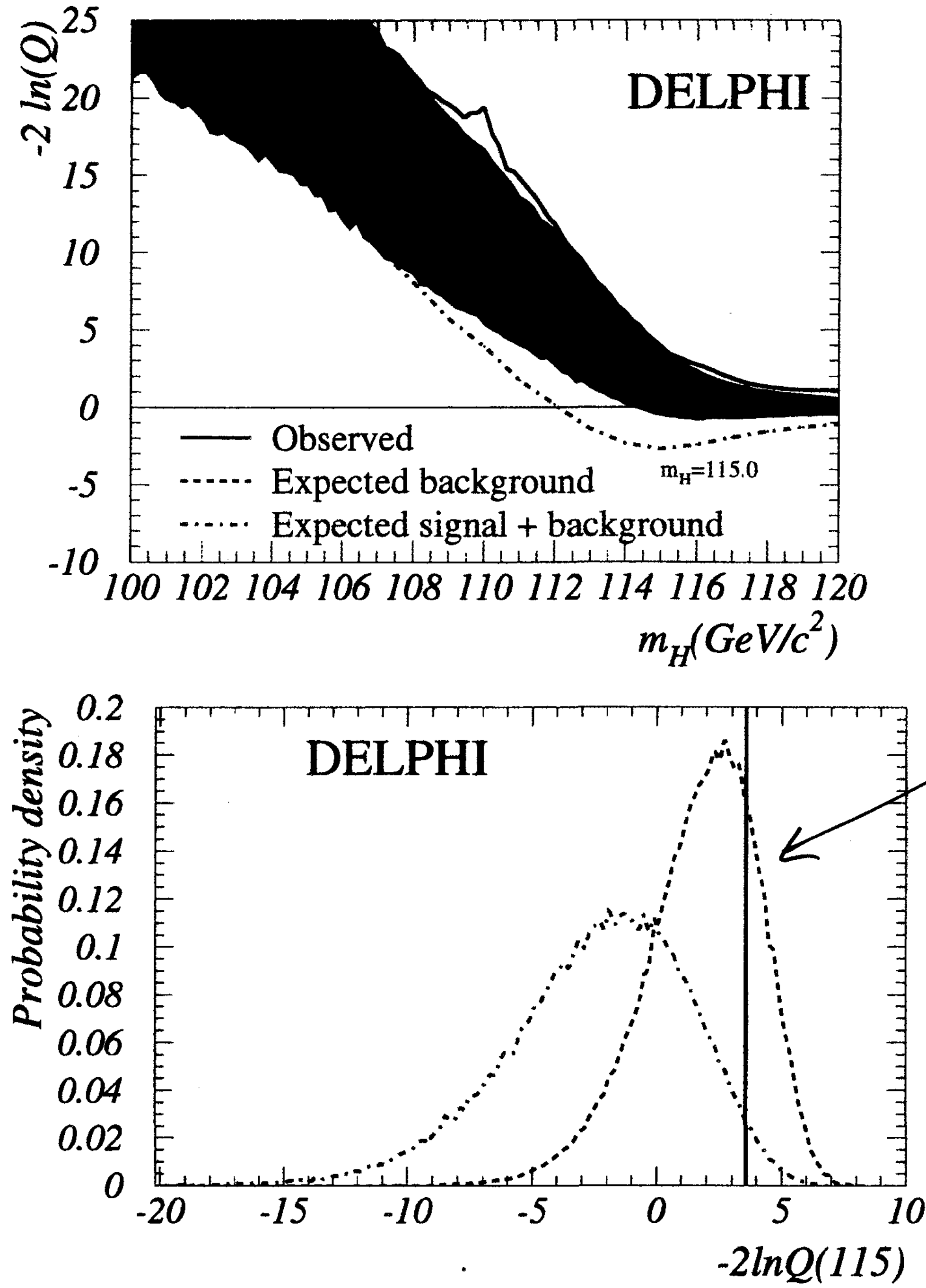


Figure 7: Distribution of the reconstructed mass of the candidates when combining all HZ analyses at 200-209 GeV in the year 2000. Data (dots) are compared with the Standard Model background expectations (light shaded histogram) and with the normalised 114 GeV/c^2 signal spectrum added to the background contributions (dark shaded histogram).

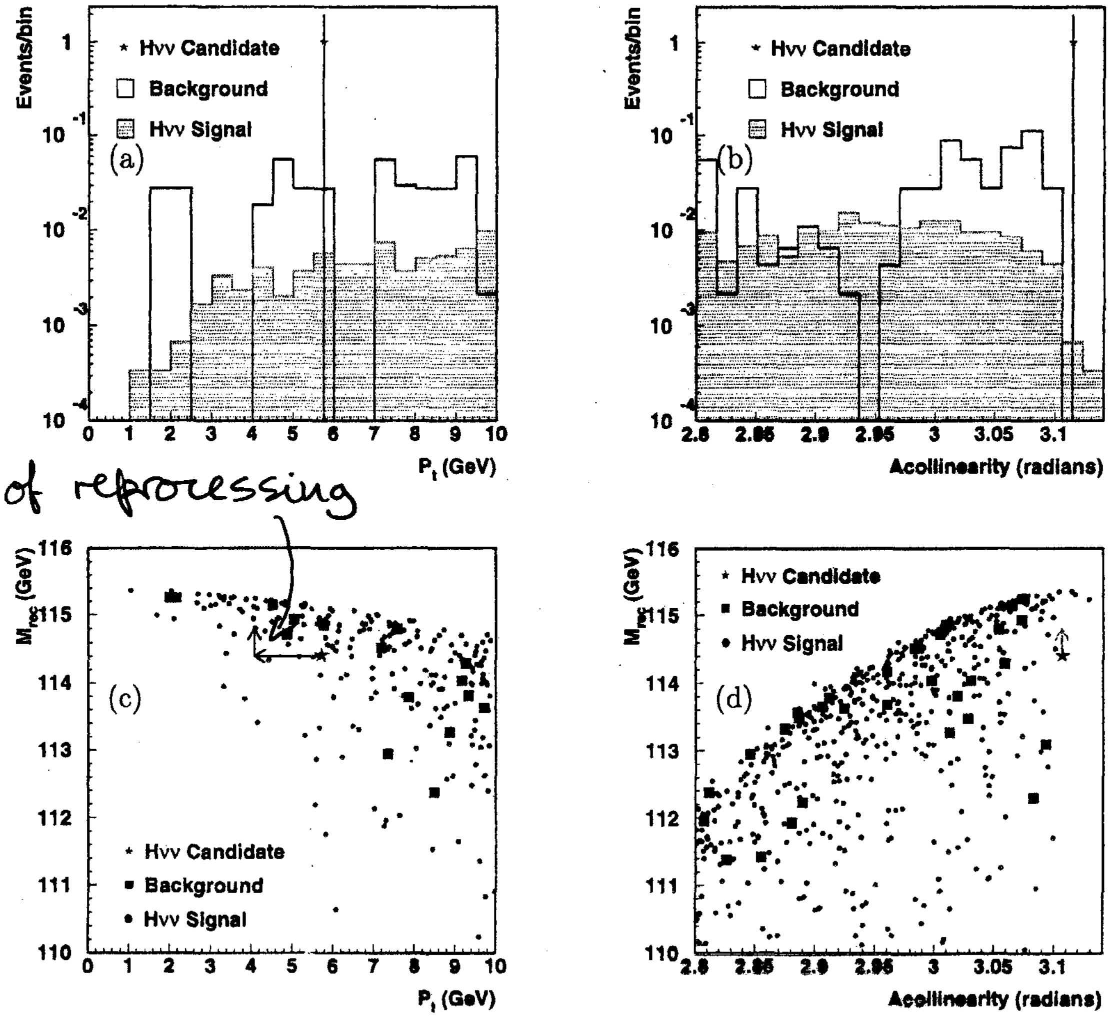


background alone preferred

Figure 9: Top: the test-statistic (negative log-likelihood ratio) as a function of m_H. The observed value, full line, is compared to the expectation for the background only hypothesis, represented by the dashed line and the symmetric 68% and 95% probability shaded bands. The dot-dashed line shows the average expected result for a hypothetical Higgs mass of 115 GeV/c^2. Bottom: vertical slice of the previous plot for a mass value of 115 GeV/c^2, showing the sensitivity of the DELPHI result to this hypothesis. The dot-dashed line shows the expected distribution for signal plus background, the dashed line that for background only. The vertical line represents the data. The fractional area below the dashed curve and to the right of the data is CL_b: for the dot-dashed curve it is $CL_{(s+b)}$.

Kinematics of L3 $H\nu\bar{\nu}$ Candidate Event

likely effect of reprocessing



acollinearity angle

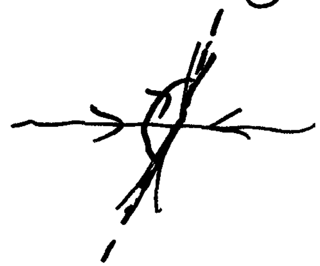


Figure 6: For events with a neural network output in excess of 0.9 and with a reconstructed mass in excess of $110\,\mathrm{GeV}/c^2$, distributions expected from signal and background of (a) missing transverse momentum; (b) acollinearity; (c) missing transverse momentum vs reconstructed mass; and (d) acollinearity vs reconstructed mass. The selected candidate event is indicated by a star.

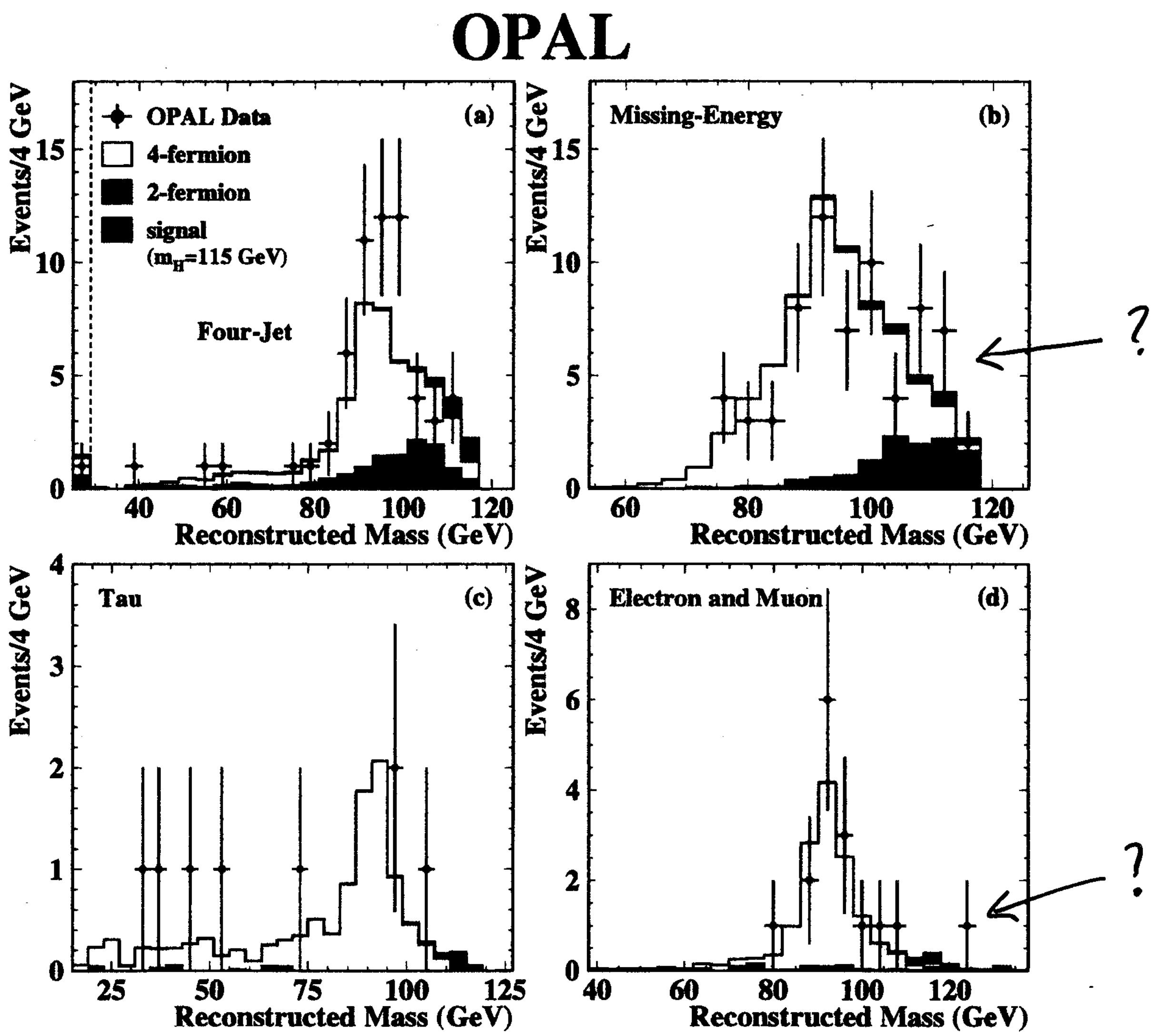


Figure 3: *The reconstructed mass distribution for the selected events in the 1999 and 2000 data for (a) the four-jet channel, (b) the missing-energy channel, (c) the tau channels, and (d) the electron and muon channels combined. The first bin in (a) contains all events with χ^2 probability of the $\mathrm{H}^0\mathrm{Z}^0$ 5C kinematic fit $< 10^{-5}$ for chosen jet-pairings. The dark (light) grey area shows the expected contribution from the $\mathrm{q}\bar{\mathrm{q}}(\gamma)$ (four-fermion) process. The Standard Model signal expectation for 115 GeV is shown with the very dark histograms on top of the Standard Model backgrounds.*

no clear preference
S+B vs B

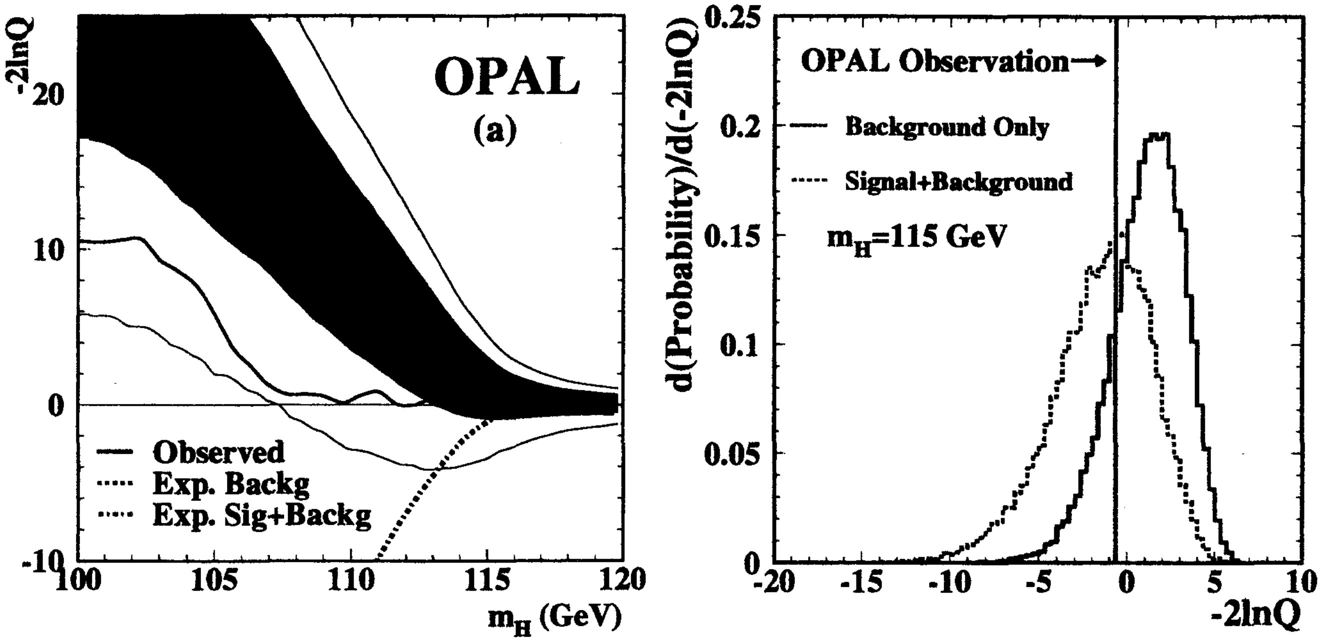
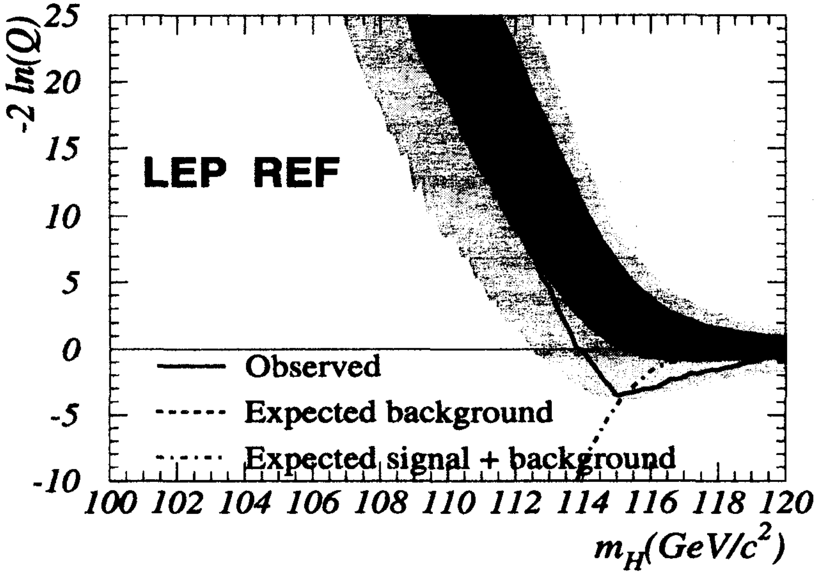
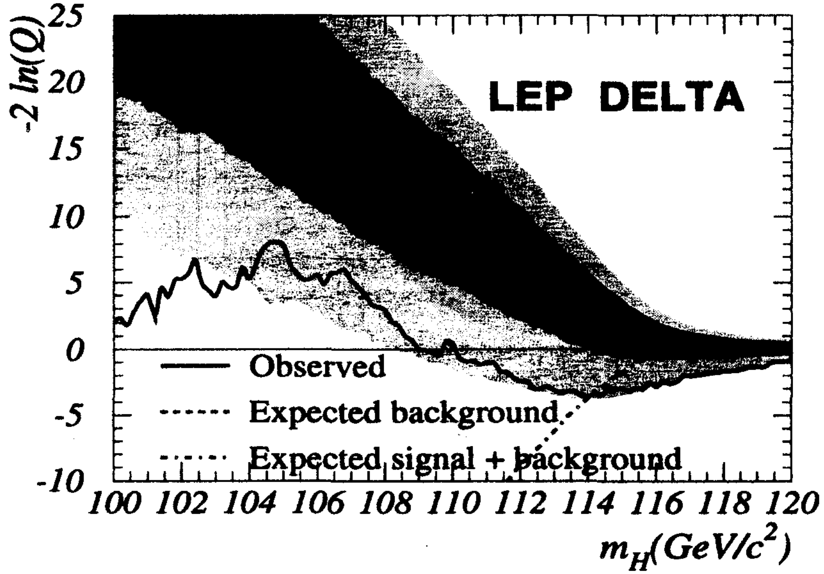
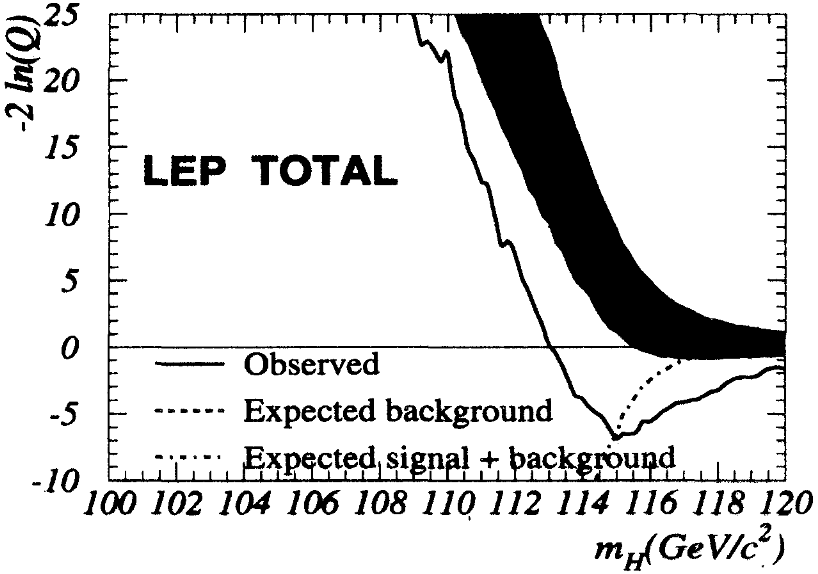


Figure 7: *(a) The log-likelihood ratio* $-2\ln Q$ *comparing the relative consistency of the data with the signal+background hypothesis and the background-only hypothesis, as a function of the test mass* m_{H}*. The observation for the data is shown with a solid line. The dashed line indicates the median background expectation and the dark (light) shaded band shows the 68% (95%) probability intervals centred on the median. The median expectation in the presence of a signal is shown with a dot-dashed line where the hypothesized signal mass is the test mass. (b) The* $-2\ln Q$ *distribution expected in a large number of fictitious background-only experiments (solid histogram), and in a large number of fictitious experiments in the presence of a 115 GeV Higgs boson (dashed histogram). The observation in the data is shown with a vertical solid line.*

$-2\ln(Q)$ ... REF, DELTA, TOTAL







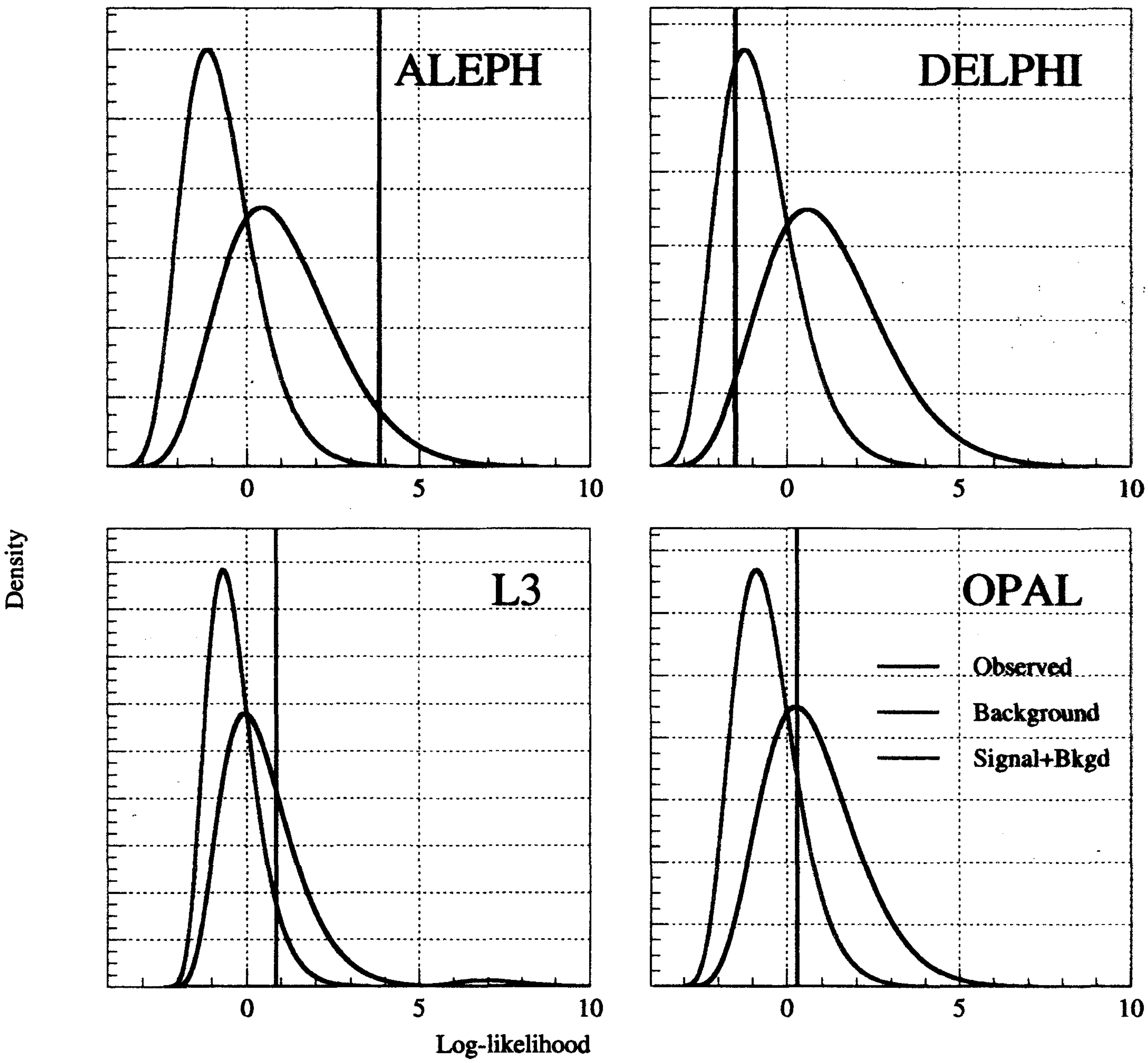
$\Leftarrow$

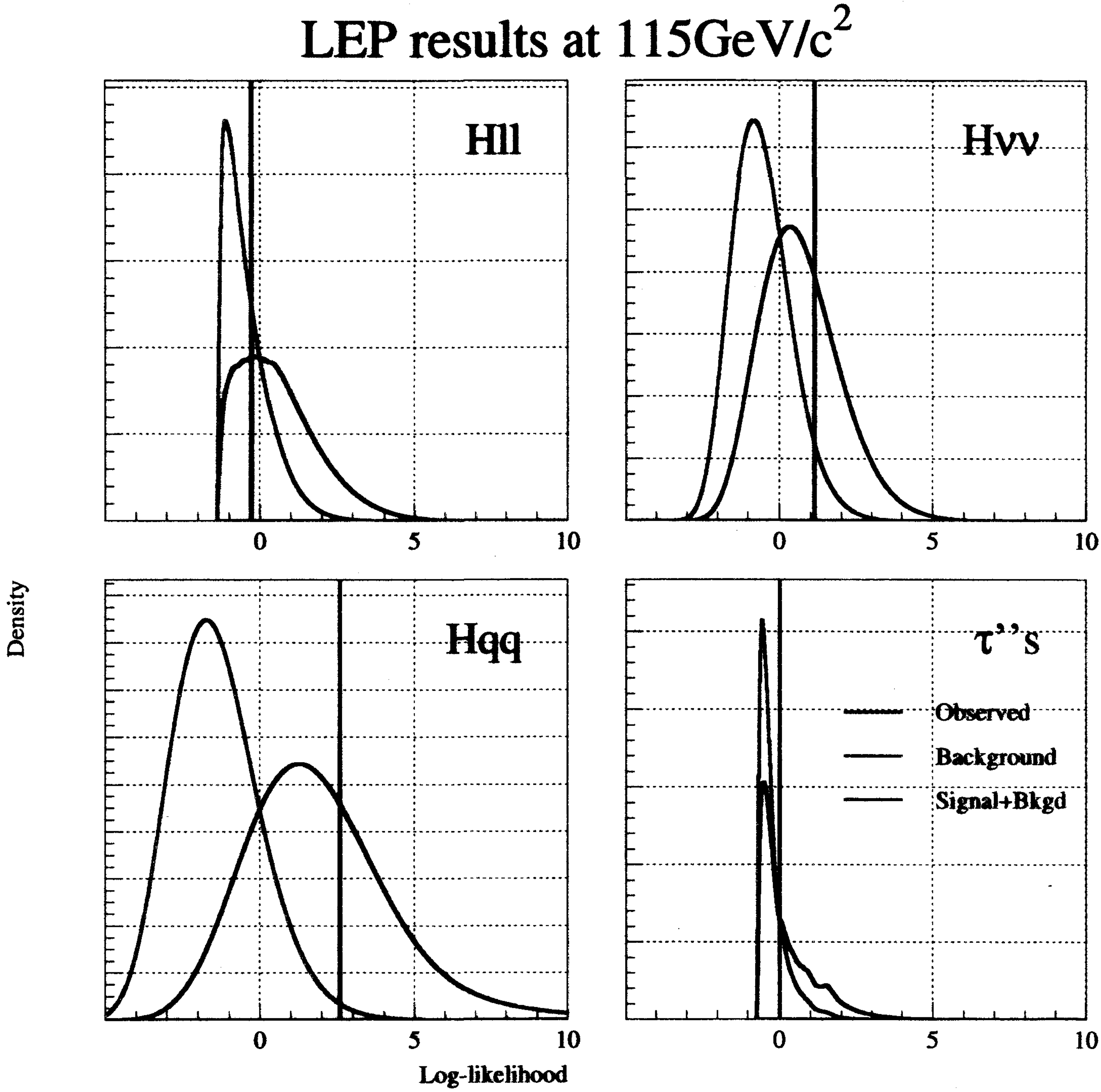
Minimum @$m_H \approx 115$ GeV

Agreement with SM Higgs cross-sect. for

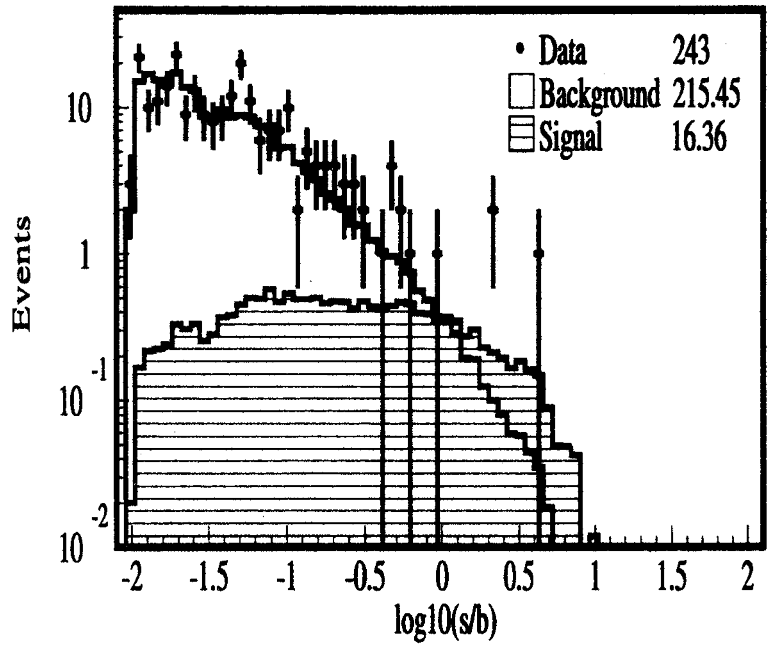
$$m_H = 115.0^{+1.3}_{-0.9}\ \text{GeV}$$

Experiments results at 115GeV/c²




LEP results at 115GeV/c^2
Hll
Hνν
Hqq
τ's
Observed
Background
Signal+Bkgd
0
5
10
Density
Log-likelihood

Expected rates @$m_H = 115$ GeV ..... TOTAL



Integrating bkgd, signal and data ...

for $s/b \gtrsim 1$

		Backgd	Signal	Candidates
ADLO	**4-jet**	**0.93**	**1.60**	**3**
	E-miss	**0.30**	**0.46**	**1**
	Lept	**0.35**	**0.68**	**0**
	Taus	**0.14**	**0.29**	**0**
ADLO	**All chan.**	**1.72**	**3.03**	**4**

Probability distribution for M_H

precision electroweak data combined with LEP 2 signal

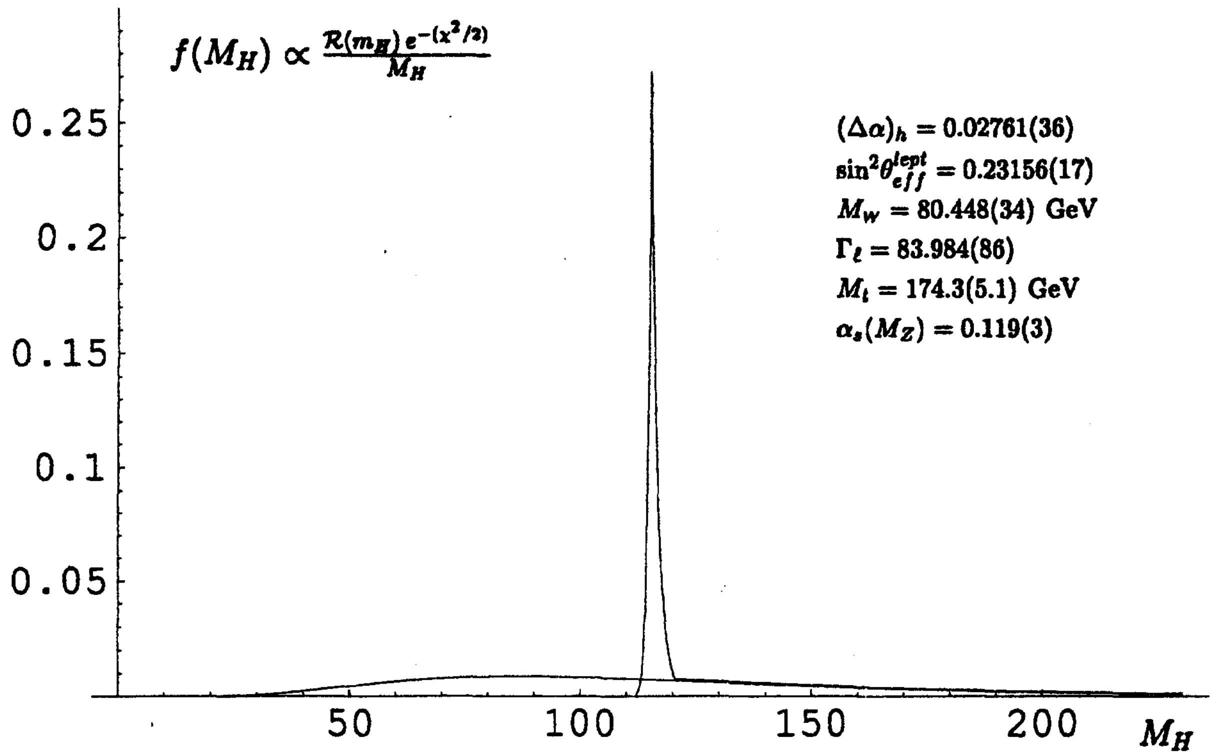
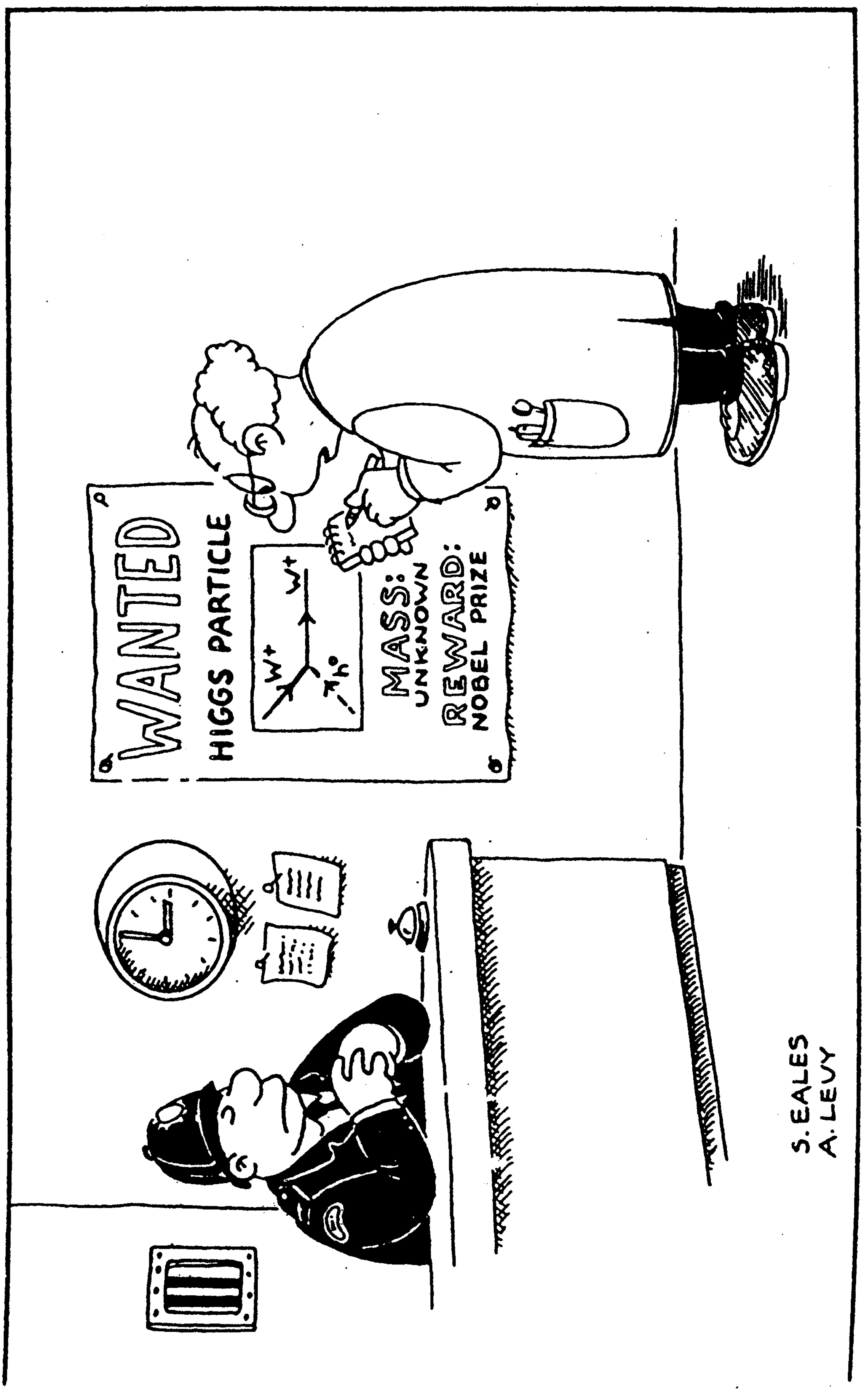


Figure 7: Probability density function $f(M_H)$. The lower curve shows the indirect measurements alone and the curve with the spike at ~115 GeV shows the combination with the direct search.


WANTED
HIGGS PARTICLE
W+
W+
h0
MASS:
UNKNOWN
REWARD:
NOBEL PRIZE
S. EALES
A. LEVY

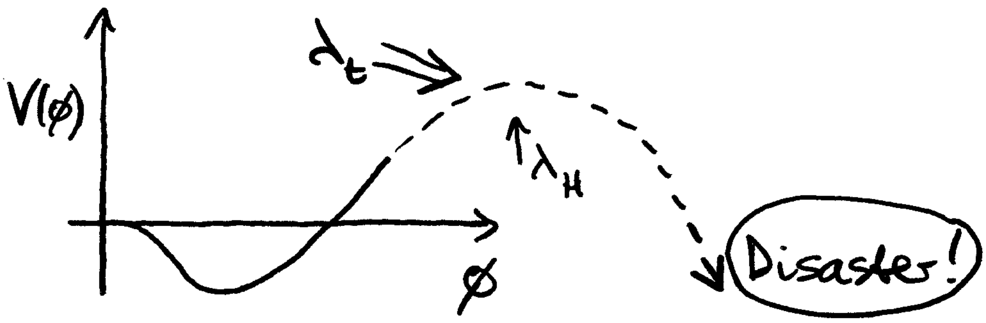
13 What if $m_H = 115$ GeV?

(J.E. + Ganis + Nanopoulos + Olive: hep-ph/000935

Standard Model

It must break down @ $E \lesssim 10^6$ GeV

because the effective potential becomes unstable



λ_t beats λ_H

$m_H^2 \sim \lambda_H \langle 0|H|0\rangle^2$

need new physics @ $E < 10^6$ GeV
bosonic!

Technicolour

predicts composite 'Higgs' scalar weighing

$$m_H \sim 1 \text{ TeV}^\dagger$$

and also 'light' pseudoscalars weighing

$$m_P \lesssim 100 \text{ GeV}$$

but small coupling to $Z^\dagger$

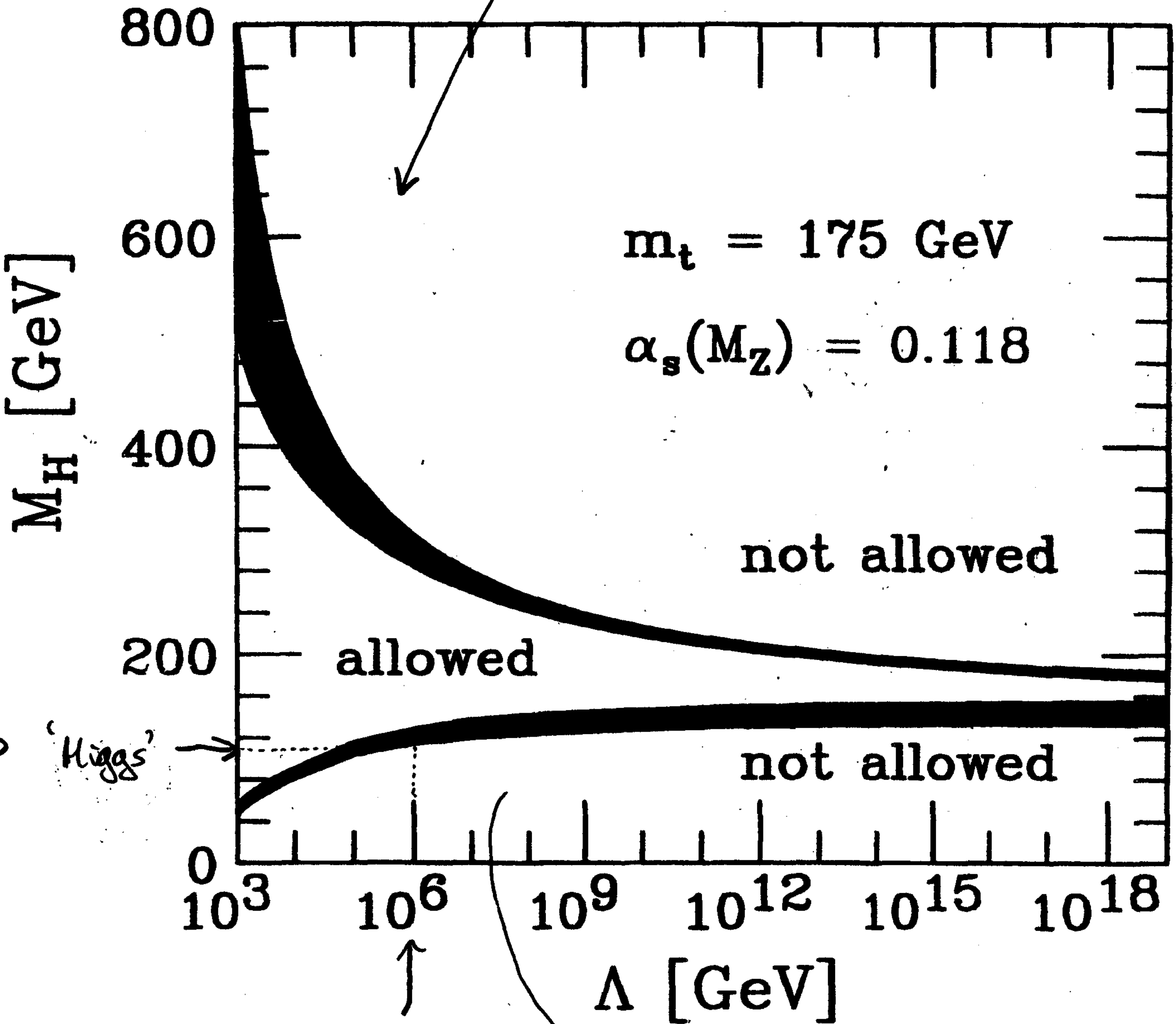
we need a weakly-coupled theory

Topcolour

predicts $\quad m_H \gtrsim 300 \text{ GeV}^\dagger$

Limitations of the Standard Model

couplings blow up!

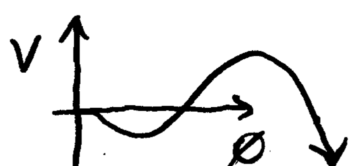


LEP 'Higgs'

scale by which new physics must appear!

(Hambye + Riesselmann

potential unstable!

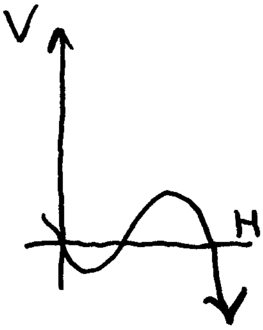


(Altarelli + Isidori

It Quacks like Supersymmetry

To avoid vacuum collapse (Charybdis

must introduce new bosons



$\lambda_{22} |H|^2 |\phi|^2$

N_I isomultiplets I

RGE solutions very sensitive to λ_{22}

danger of non-perturbative blow-up (Scylla

can only be avoided by coupling to fermions, ...

to survive up to $m_P \sim 10^{19}$ GeV

couplings must be finely tuned

automatic within supersymmetry

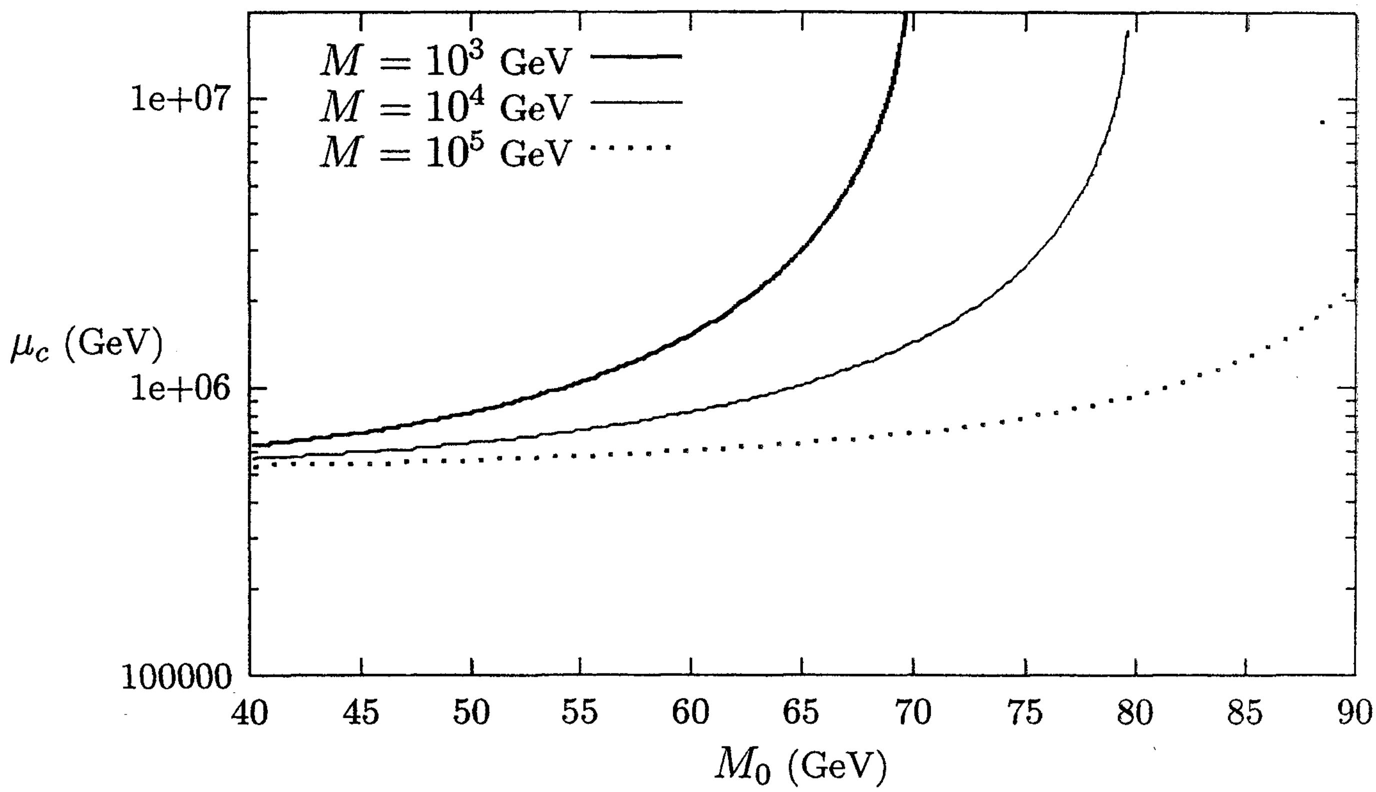
(J.E. + D.Ross:
hep-ph/0012067

Introducing new bosons

$$M^2|\phi|^2 + \lambda_{22}|H|^2|\phi|^2 \quad : \quad m_0^2 = \lambda_{22} v^2$$

can postpone collapse of potential

if $M \lesssim 10^5$ GeV



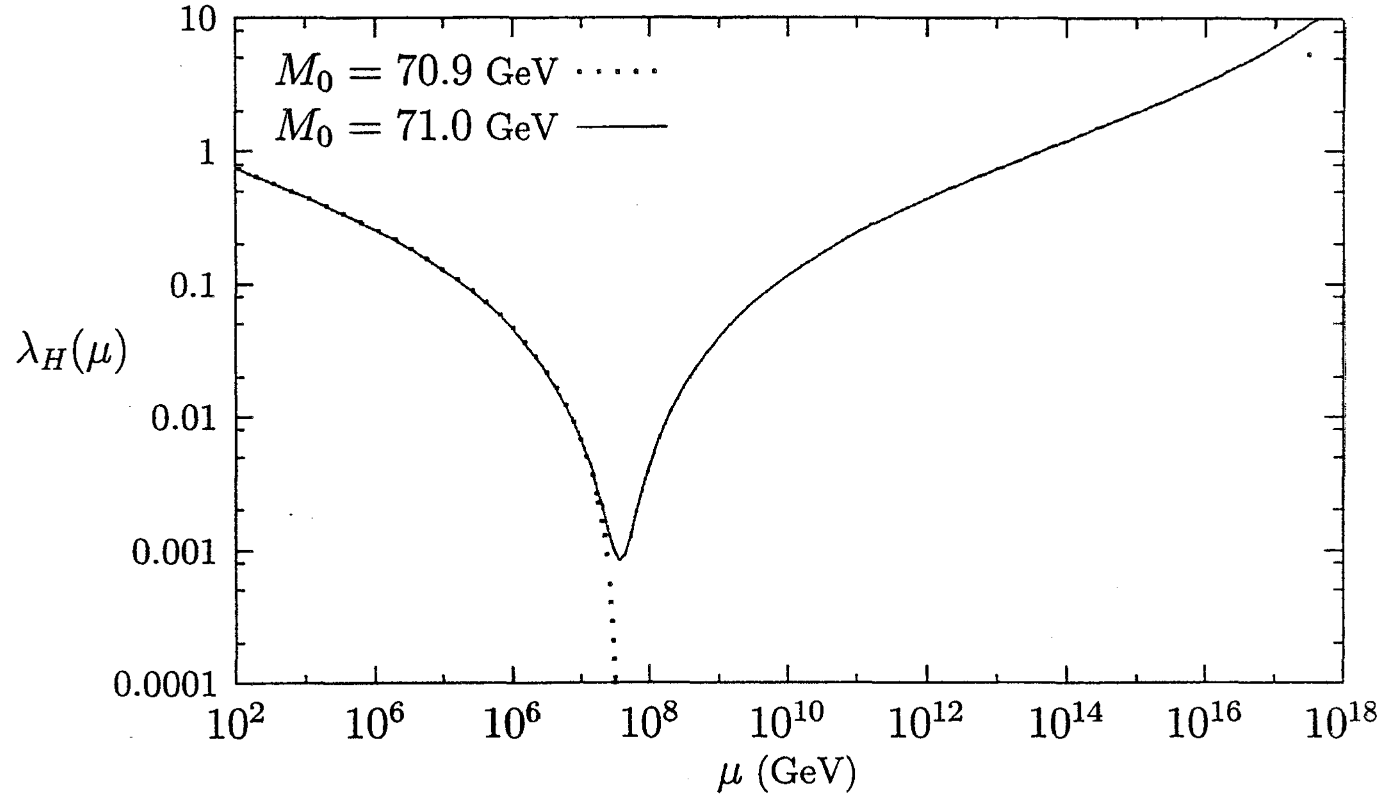
(J.E. + D. Ross:
hep-ph/0012067

New physics must be fine-tuned

to steer between

potential collapse

blow-up of couplings

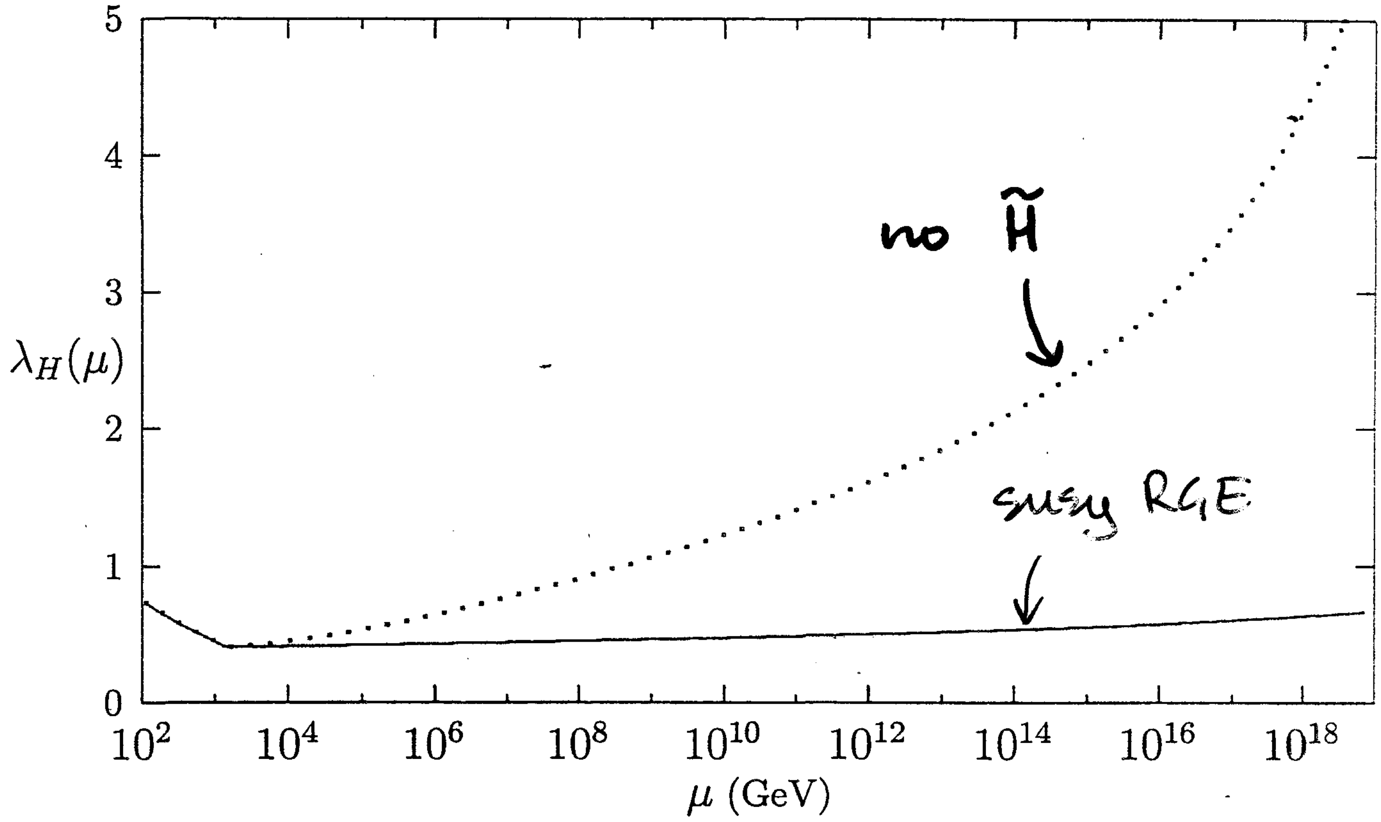


(J.E. + D. Ross -
hep-ph/0012067

Fine-tuning quacks like supersymmetry

need relation: $\lambda_H \Leftrightarrow \lambda_t, g$

natural in susy with $\tilde{t}, \tilde{H}$



(J.E. + D. Ross –
hep-ph/0012067

Where are the non-renormalizable interactions

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} O_6$$

how large must Λ be?

$$\Lambda \gtrsim \text{few TeV} \gg m_H$$

Dimensions six operators			$m_h = 115\,\mathrm{GeV}$		$m_h = 300\,\mathrm{GeV}$		$m_h = 800\,\mathrm{GeV}$	
			$c_i = -1$	$c_i = +1$	$c_i = -1$	$c_i = +1$	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB}$	$=$	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10	7.5	—	—	—
$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$	4.6	5.6	3.4	—	2.8	—
$\mathcal{O}_{LL}$	$=$	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1	—	—	—	—
$\mathcal{O}'_{HL}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8	7.5	—	—	—
$\mathcal{O}'_{HQ}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8	—	—	—	—
$\mathcal{O}_{HL}$	$=$	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2	—	—	—	—
$\mathcal{O}_{HQ}$	$=$	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4	—	—	—	—
$\mathcal{O}_{HE}$	$=$	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7	—	—	—	—
$\mathcal{O}_{HU}$	$=$	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3	—	—	—	—
$\mathcal{O}_{HD}$	$=$	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5	—	—	—	—

Table 1: 95% *lower bounds on* $\Lambda/$ TeV *for the individual operators and different values of* m_h. $\chi^2_{\min}$ *is the one in the SM for* $m_h > 115\,\mathrm{GeV}$.

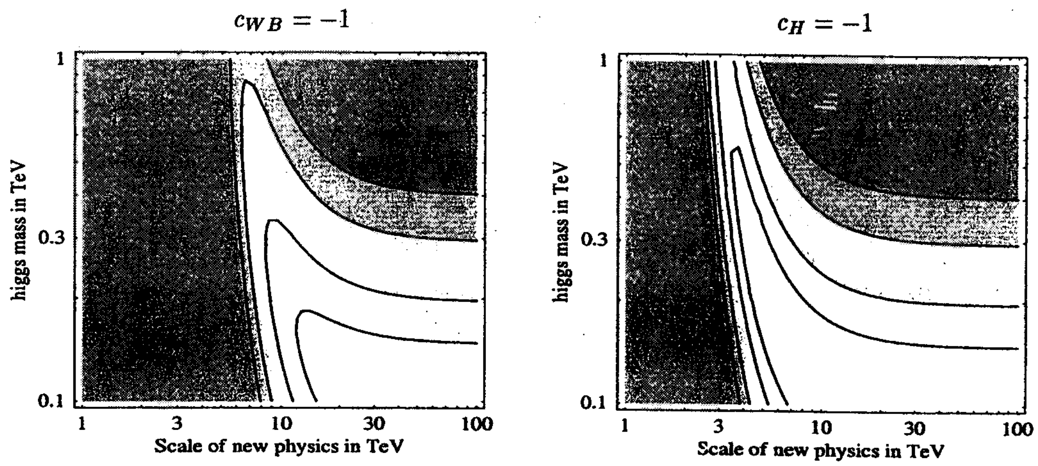


Figure 2: *Level curves of* $\Delta\chi^2 = \{1, 2.7, 6.6, 10.8\}$ *that correspond to* $\{68\%, 90\%, 99\%, 99.9\%\}$CL *for the first 2 operators in table 1* ($\mathcal{O}_{WB}$ *and* $\mathcal{O}_H$) *and* $c_i = -1$.

There must be a hierarchy!

(Barbieri + Strumia

1.4 Where do we go from here?

Prospects for Higgs Discovery

Tevatron — will have chance if $m_H = 115\,GeV$

if heavier?

not before 2007?

LHC — will discover it @ any mass

will observe 2 or 3 decay modes

measure mass to ~ 1%

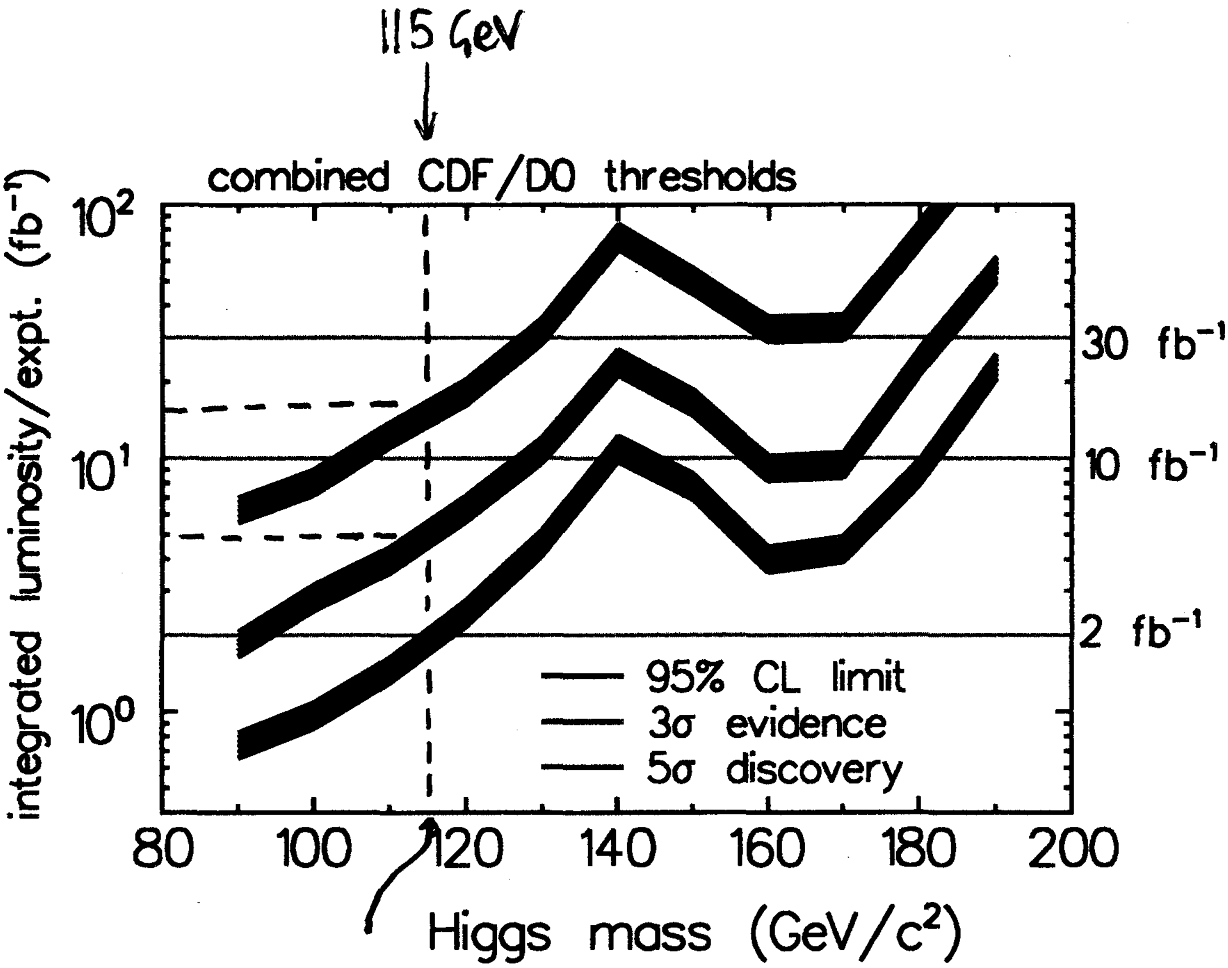
cover MSSM parameter space

→ several times?

new analysis including LEP, universality, cosmology

measure MSSM parameters?

Prospects for the Tevatron Collider

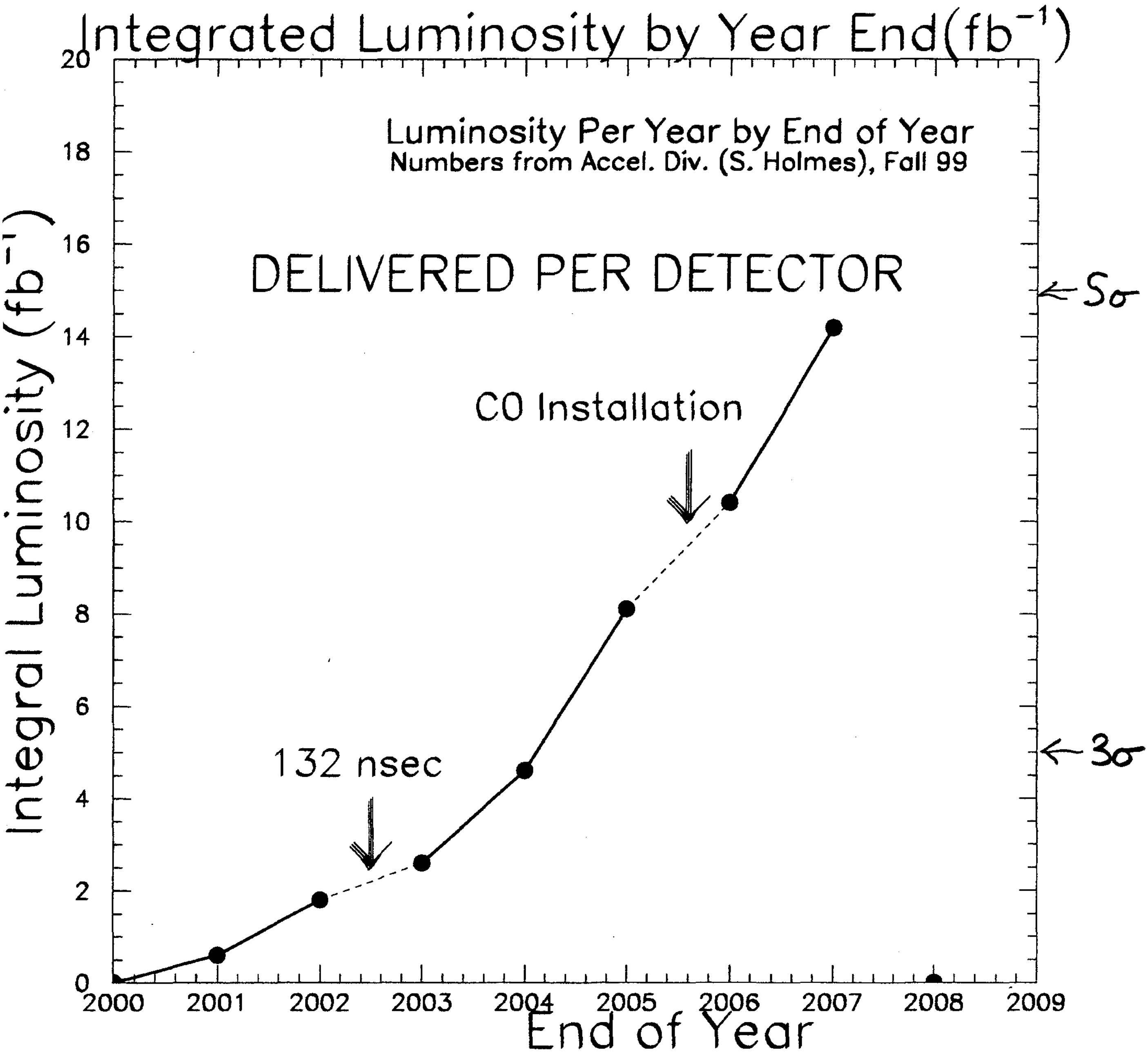


5 fb^{-1} needed to duplicate LEP 'signal'

15 fb^{-1} needed for 5σ discovery

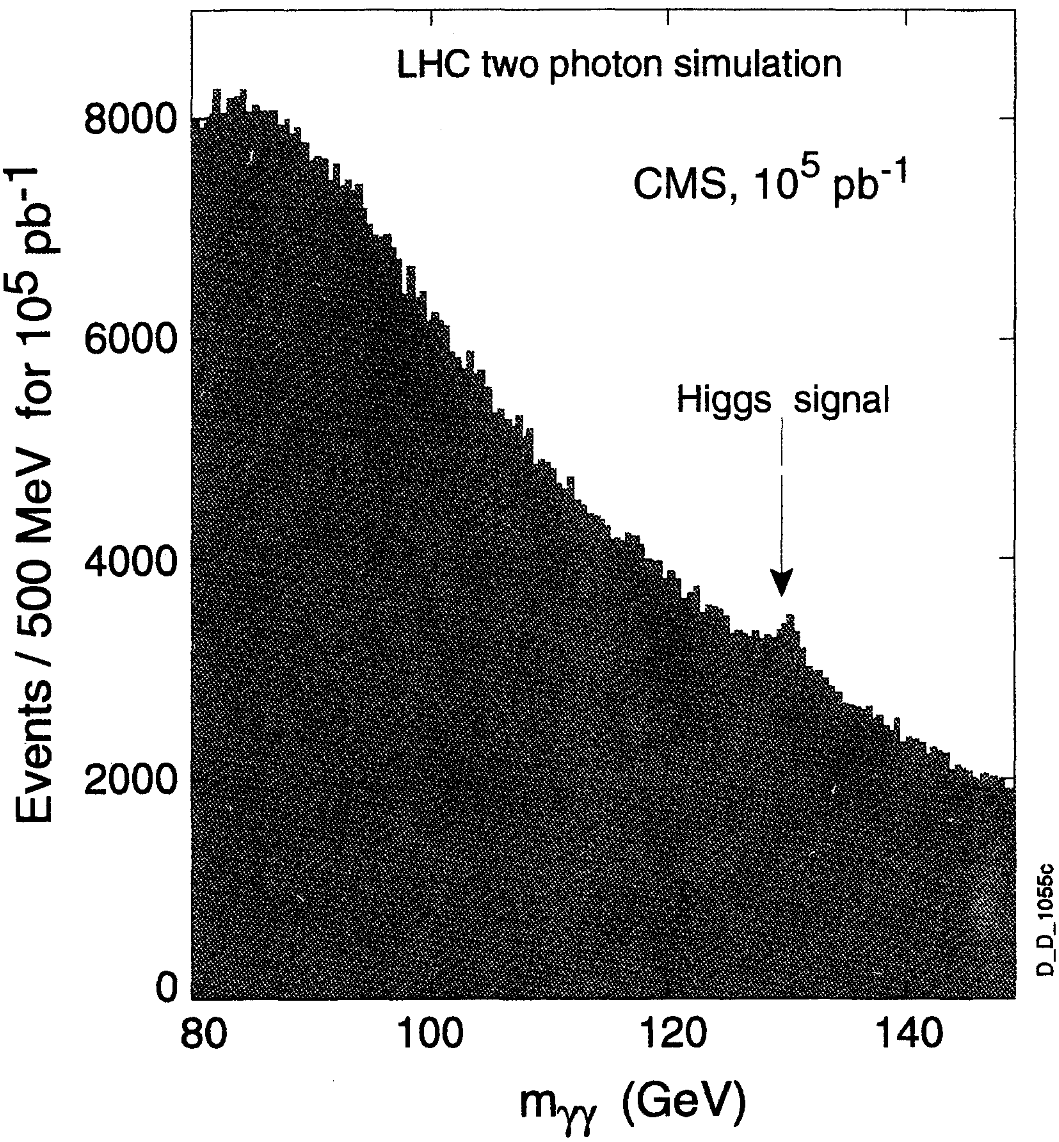
(Tevatron Higgs Working Group

Scenario for Tevatron Luminosity Growth



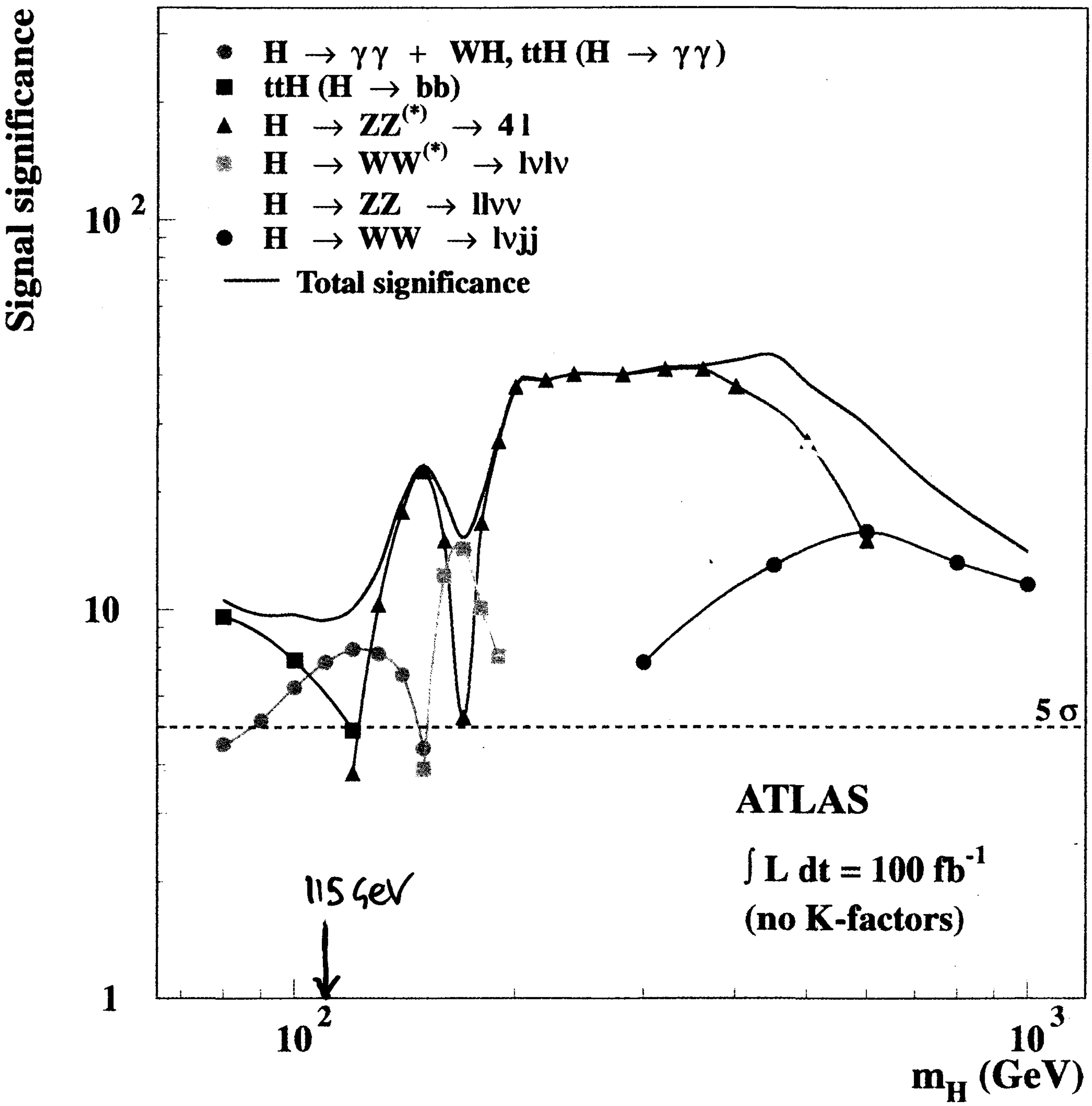
$$H \longrightarrow \gamma\gamma$$

Simulated 2γ mass plot
for 10^5 pb^{-1} $m_H = 130$ GeV
in the lead tungstate calorimeter



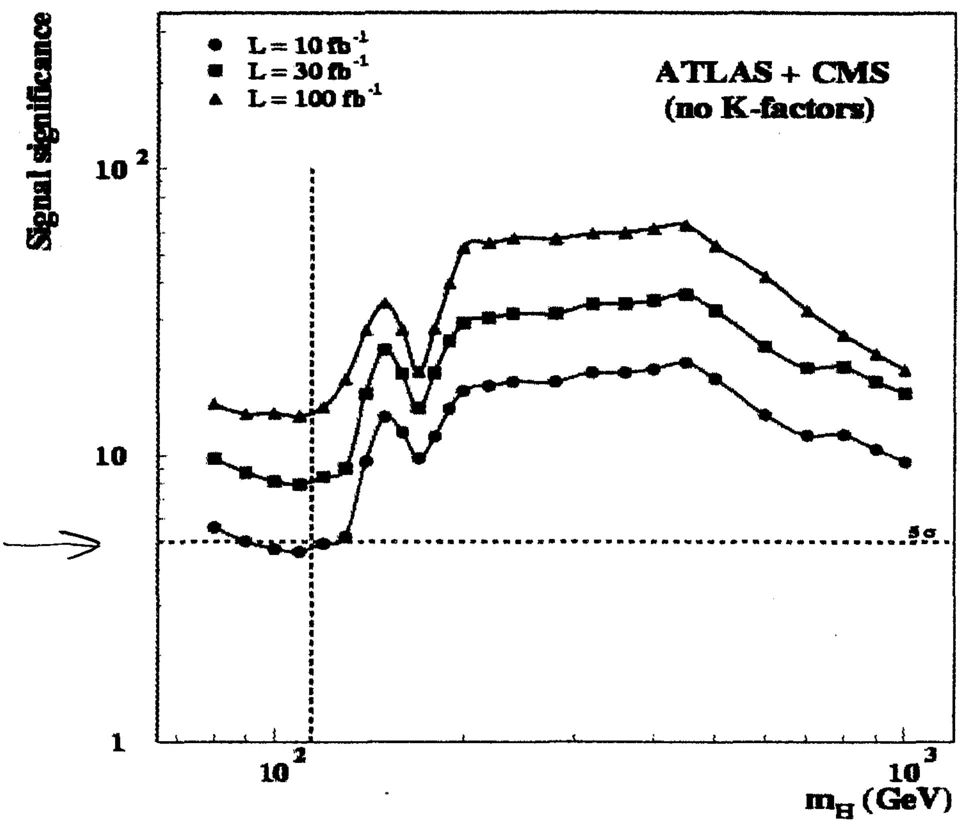
(CMS)

Prospects for Higgs Discovery @ LHC



Detectability of Higgs @ LHC

'discovery' →



expect ~ $1 fb^{-1}$ in first year

~ $10 fb^{-1}$ second