What would it mean

if

the LHC finds

no evidence

for the

Higgs Boson ?

No Higgs

at the LHC ?

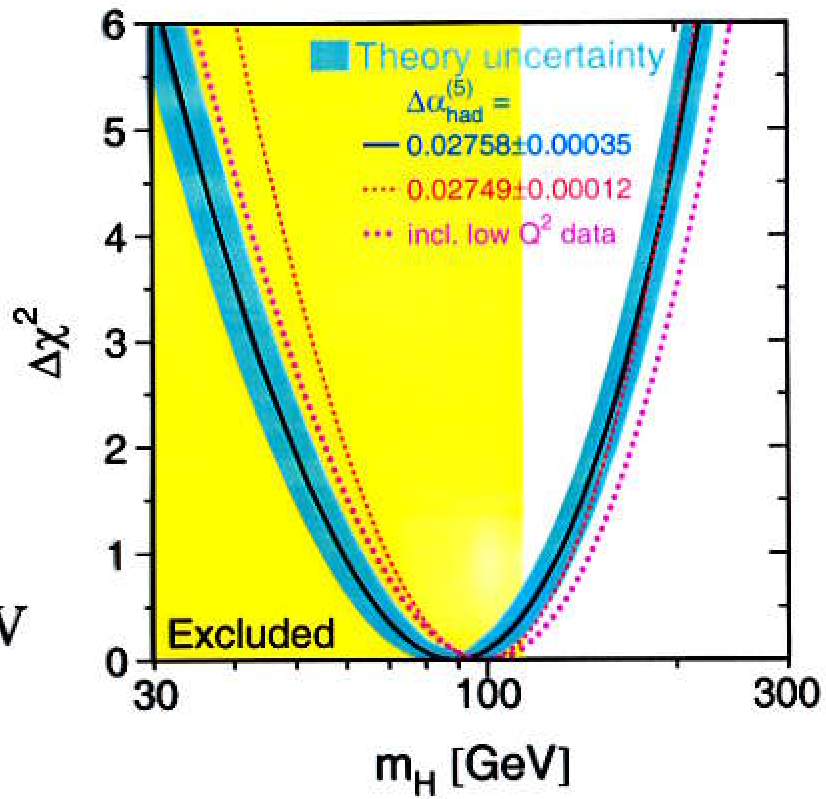
No Higgs

at the LHC !

The EWWG Analysis

The pseudo-observables depend on the mass of the (unobserved) Higgs boson: M_H.

EWWG combines measurements coming from LEP, SLD, CDF, and D0 with SM theoretical predictions in a $\Delta\chi^2$ curve: the Blue Band



$M_H = 89^{+42}_{-30}\,\text{GeV} \quad M_H^{95} = 175\,\text{GeV}$

(`Winter 06`)

Fits to the M_H mass

- **leptonic observables**

$$\left(\sin^2\theta_{eff}\right)_l = 0.23113 \pm 0.00020$$

$$M_H = 51^{+37}_{-22}\,\text{GeV} \qquad M_H^{95} = 124\,\text{GeV}$$

- **combined fit**

$$\left(\sin^2\theta_{eff}\right)_l \text{ and } M_W = 80.404 \pm 0.030\,\text{GeV}$$

$$M_H = 51^{+30}_{-21}\,\text{GeV} \qquad M_H^{95} = 109\,\text{GeV}$$

- **hadronic observables**

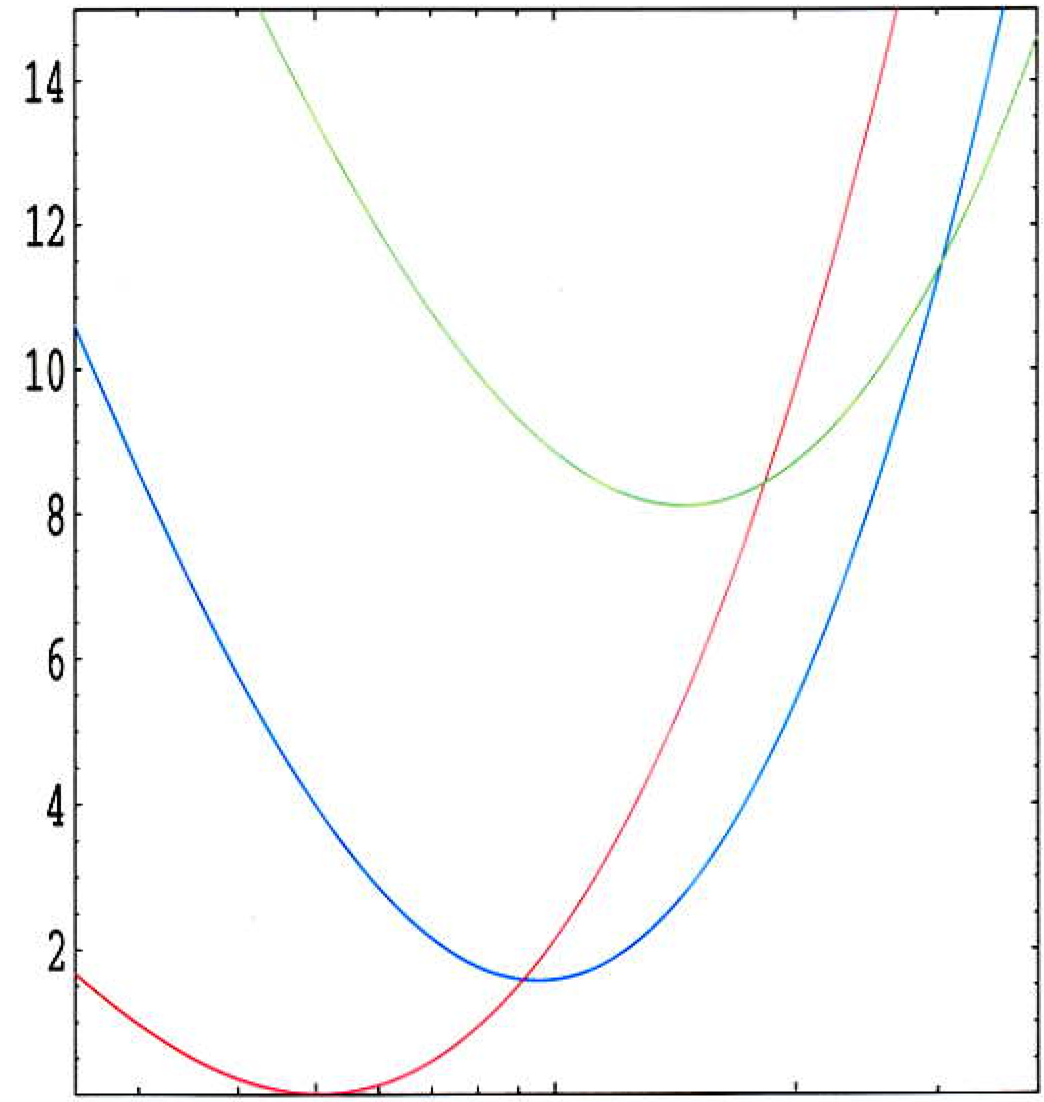
$$\left(\sin^2\theta_{eff}\right)_{\text{bottom}} = 0.23222 \pm 0.00027$$

$$M_H = 488^{+426}_{-219}\,\text{GeV} \qquad (M_H^{95})_{\text{l.b.}} = 181\,\text{GeV}$$

$$m_t = 172.5 \pm 2.3\,\text{GeV} \;\; \Delta\alpha_h^{(5)} = 0.02758 \pm 0.00035$$

$$\alpha_s(M_Z) = 0.118 \pm 0.002$$

χ^2 for $\sin^2\theta_{eff}^{lept}$ and M_W as a function of M_H



The red line corresponds to $\sin^2\theta_{eff}^{lept}$ from leptonic data, the blue one to the world average for $\sin^2\theta_{eff}^{lept}$, and the green one to $\sin^2\theta_{eff}^{lept}$ from the hadronic data

Could the Higgs be too heavy?

($\gtrsim$ 1 TeV)

$m_H^2 = \lambda v^2$ heay Higgs - strong interaction

Difficult question higher loops important

addressed by: (Moriond 1984)

van der Bij, Veltman, Kyriazidou,

Jikia, Borodulin, Ghinculov (2-loop)

Binoth, Akhoury, Wang ($1/N$ expansion)

Dilcher (non perturbative)
Kastening (non-linear model)
Boughezal, Tausk (3-loop)

($\simeq$ 500.000 Feynman graphs)

Answer: no the Higgs cannot be too heavy

with B. Tausk &
R. Boughezal

with

$$\Delta\rho^{(1)} = -\frac{3}{4}\frac{g^2}{16\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{m_H^2}{M_W^2}\right), \tag{41}$$

$$\begin{aligned}\Delta\rho^{(2)} &= \left(\frac{g^2}{16\pi^2}\right)^2\frac{s_W^2}{c_W^2}\frac{m_H^2}{M_W^2}\left(-\frac{21}{64}+\frac{9}{32}\pi\sqrt{3}+\frac{3}{32}\pi^2-\frac{9}{8}C\sqrt{3}\right)\\ &= \left(\frac{g^2}{16\pi^2}\right)^2\frac{s_W^2}{c_W^2}\frac{m_H^2}{M_W^2}\,(\,0.1499\,)\,,\end{aligned} \tag{42}$$

$$\begin{aligned}\Delta\rho^{(3)} &= \left(\frac{g^2}{16\pi^2}\right)^3\frac{s_W^2}{c_W^2}\frac{m_H^4}{M_W^4}\left(-\frac{21}{512}+\frac{729}{512}\pi\sqrt{3}-\frac{3391}{4608}\pi^2-\frac{9}{16}\pi C\right.\\ &\qquad -\frac{1577}{2304}\pi^3\sqrt{3}-\frac{9109}{69120}\pi^4+\frac{99}{16}\sqrt{3}\log 3\,C\\ &\qquad -\frac{297}{32}\sqrt{3}\,\mathrm{Ls}_3(2\pi/3)-\frac{399}{16}\sqrt{3}\,C+\frac{3043}{128}\zeta(3)\\ &\qquad \left.+\frac{567}{32}C^2+\frac{109}{8}U_{3,1}-36\,V_{3,1}\right)\\ &= \left(\frac{g^2}{16\pi^2}\right)^3\frac{s_W^2}{c_W^2}\frac{m_H^4}{M_W^4}\,(\,-1.7282\,)\,.\end{aligned} \tag{43}$$

The constants appearing in $\Delta\rho^{(3)}$ are defined by [24, 25]

$$\begin{aligned}U_{3,1} &= \frac{1}{2}\zeta(4)+\frac{1}{2}\zeta(2)\log^2 2-\frac{1}{12}\log^4 2-\mathrm{Li}_4\left(\frac{1}{2}\right)\\ &= -0.11787599965\end{aligned} \tag{44}$$

$$\begin{aligned}V_{3,1} &= \sum_{m>n>0}\frac{(-1)^m\cos(2\pi n/3)}{m^3 n}\\ &= -0.03901272636\end{aligned} \tag{45}$$

$$C = \mathrm{Cl}_2\,(\pi/3) \tag{46}$$

The log-sine integral is defined by

$$\mathrm{Ls}_3\,(\theta) = -\int_0^\theta \mathrm{d}\phi\,\log^2\left|2\sin\frac{\phi}{2}\right|. \tag{47}$$

Some numerical values are shown in Table 1 and in Figure 4, where we have used

$$g^2 = \frac{e^2}{s_W^2} = \frac{4\pi\alpha}{s_W^2} \tag{48}$$

m_H/M_W	$\Delta\rho^{(1)}$	$\Delta\rho^{(2)}$	$\Delta\rho^{(3)}$	
2	-0.00078	$1.14\,10^{-6}$	$-1.33\,10^{-7}$	
5	-0.0018	$7.14\,10^{-6}$	$-5.20\,10^{-6}$	
6	-0.0020	0.000010	-0.000011	500 GeV
7	-0.0022	0.000014	-0.000020	
8	-0.0024	0.000018	-0.000034	
9	-0.0025	0.000023	-0.000055	
10	-0.0026	0.000029	-0.000083	
15	-0.0031	0.000064	-0.00042	
20	-0.0034	0.00011	-0.0013	
25	-0.0036	0.00018	-0.0032	2 TeV
26	-0.0037	0.00019	-0.0038	
27	-0.0037	0.00021	-0.0044	
28	-0.0038	0.00022	-0.0051	
29	-0.0038	0.00024	-0.0059	
30	-0.0038	0.00026	-0.0067	

Table 1: Corrections to ρ as a function of m_H/M_W

M(inimal) N(on) M(inimal) S(tandard) M(odel)

with: T. Binoth

Stealth model

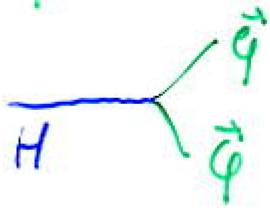
$$\mathcal{L} = -\partial_\mu \phi^+ \partial_\mu \phi - \lambda \left(\phi^+\phi - v^2/2\right)^2$$

$$-\frac{1}{2}\partial_\mu \vec{\varphi}\,\partial_\mu \vec{\varphi} - \frac{1}{2} m^2 \vec{\varphi}^{\,2} - \frac{\kappa}{8N}\left(\vec{\varphi}\right)^2 - \frac{\omega}{2\sqrt{N}}\vec{\varphi}^{\,2}\phi^+\phi$$

$\vec{\varphi}$ N scalar real fields; singlets under $SU(3) \times SU(2) \times U(1)$

$O(N)$-symmetry, renormalizable, few extra parameters

$\langle \vec{\varphi} \rangle = 0 \qquad \langle \phi \rangle = v \neq 0$



$\dfrac{\omega}{\sqrt{N}}$ invisible decay

$$\Gamma_H = \frac{\omega^2}{64\pi^2}\,\frac{v^2}{m_H}$$

ω can be large

$N \to \infty$ possibility non-perturbative $1/N$-expansion

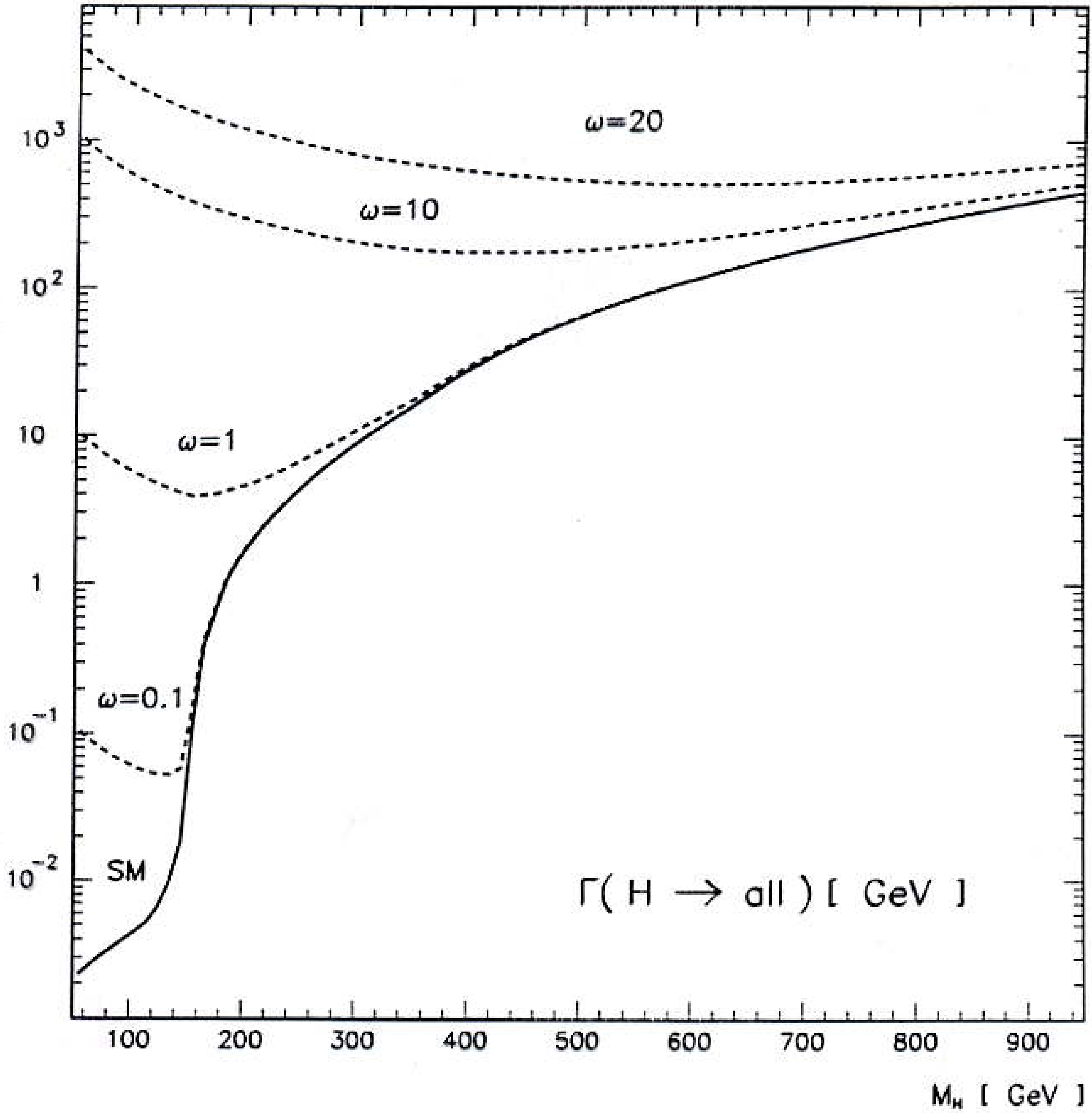


Figure 1: *Higgs width in comparison with the Standard Model.*

Phenomenology

ω large $\rightarrow$ Γ_H large

Branching ratio $\sim 100\%$ invisible

No signal at the LHC, only an enhancement over the background. One needs a very precise knowledge of the background, only possible at e^+e^- machines.

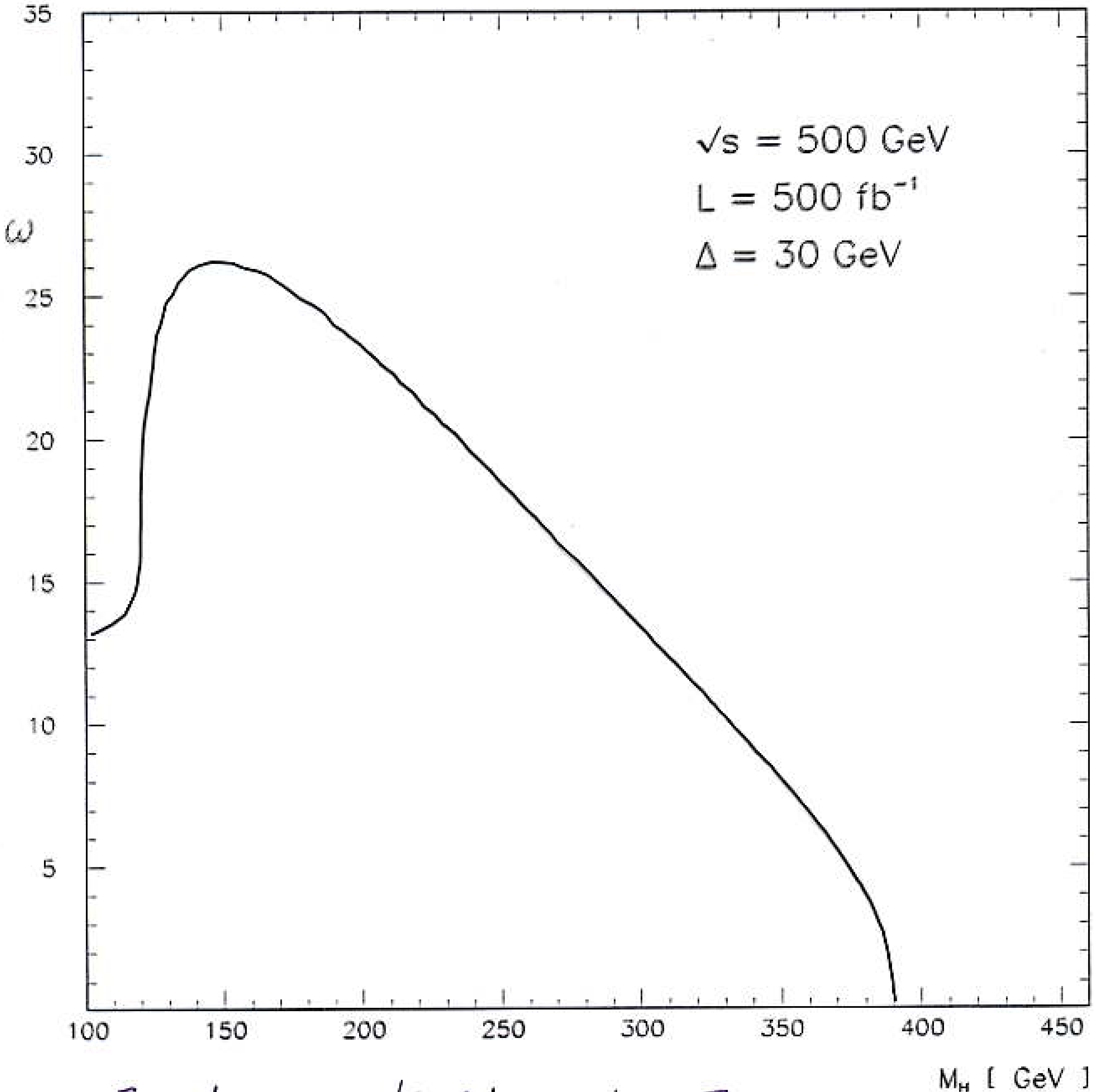
What are the φ ions $\vec{\varphi}$?

Weak interactions with ordinary matter

possible self-interactions $\Big\} \rightarrow$

$\vec{\varphi}$ = Dark Matter ?

~~TESLA~~ ILC



Exclusion limit at TESLA

$$m_H - \Delta < \cancel{E} < m_H + \Delta$$

$$e^+e^- \to Z + H \to l^+l^- + \cancel{E}$$

Extended standard model (with A. Hill)[†]

Higgs-sector

$$\mathcal{L} = -\frac{1}{2}(D_\mu \phi)^\dagger (D^\mu \phi) - \frac{\lambda_1}{8}\left(\phi^\dagger\phi - f_1^2\right)^2$$

$$-\frac{1}{2}(\partial_\mu x)^2 - \frac{\lambda_2}{8}\left(2 f_2 x - \phi^\dagger\phi\right)^2$$

$$M_W = \frac{g f_1}{2}$$

$$m_\pm^2 = \frac{1}{2}\left(\lambda_2 f_2^2 + \lambda_3 f_1^2\right) \pm \left\{\lambda_2^2 f_1^2 f_2^2 + \frac{1}{4}\left(\lambda_2 f_2^2 - \lambda_3 f_1^2\right)^2\right\}^{1/2}$$

$$\sigma - \sigma \quad \text{- - -} \quad = \frac{\alpha}{k^2 + m_+^2} + \frac{1-\alpha}{k^2 + m_-^2}$$

$$x - \sigma \quad \text{—- - -} \quad = \gamma\left(\frac{1}{k^2 + m_-^2} - \frac{1}{k^2 + m_+^2}\right)$$

$$x - x \quad \text{—} \quad = \frac{1-\alpha}{k^2 + m_+^2} + \frac{\alpha}{k^2 + m_-^2}$$

$$\alpha = \frac{m_+^2 - \lambda_2 f_2^2}{m_+^2 - m_-^2} \qquad 0 \leq \alpha \leq 1$$

$$\gamma = \frac{\lambda_2 f_1 f_2}{m_+^2 - m_1^2}$$

Renormalizability

Naively one would expect divergent contributions to x^3 and x^4, but because x is a singlet these terms are not divergent

standard counting: $D = nL - 2I + \delta \qquad L = I - V + 1$

$$\mathcal{L} = a_1 x(\sigma^2+\phi^2) + a_2 \sigma(\sigma^2+\phi^2) + a_3 \sigma W^2 + a_4 \partial\sigma \phi W$$
$$+ a_5 \partial \phi^2 W + a_6 \partial W^3 + a_7 (\sigma^2+\phi^2)^2 + a_8 W^2(\sigma^2+\phi^2) + a_9 W^4$$

$$V_1 = E_x + 2I_x + I_{x\sigma}$$

one finds

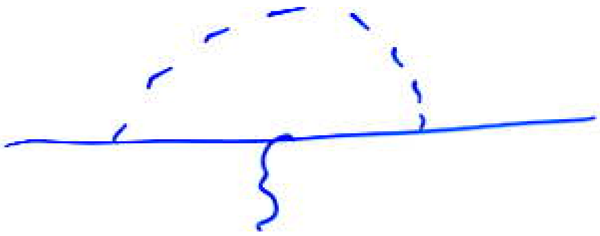
$$D = 4 - V_2 - V_3 - 2I_x - I_{x\sigma} - 2E_x - E_\sigma - E_\phi - E_W$$

Vertex	D_{max}
x^3	-2
x^4	-4
$x^2\sigma$	-1
$x^3\sigma$	-3
$x^2(\sigma^2+\phi^2)$	-2
$x\sigma(\sigma^2+\phi^2)$	-1
$x\sigma W^2$	-1
xW^2	0
x^2W^2	-2

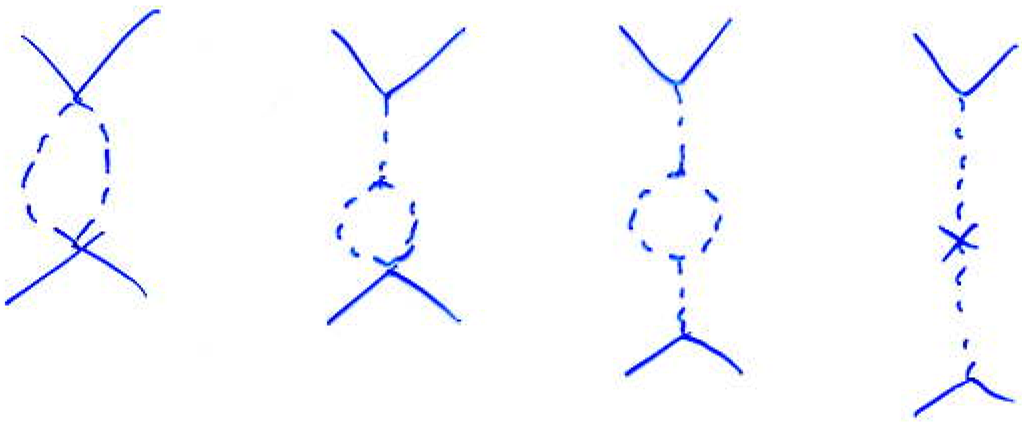
Because of gauge invariance the xW^2 term must b $x F_{\mu\nu}F_{\mu\nu}$ reducing te degree of divergence

$\delta\rho$

$3W$

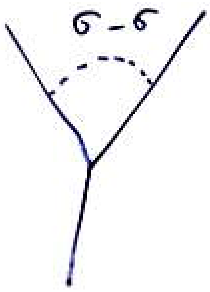


$4W$



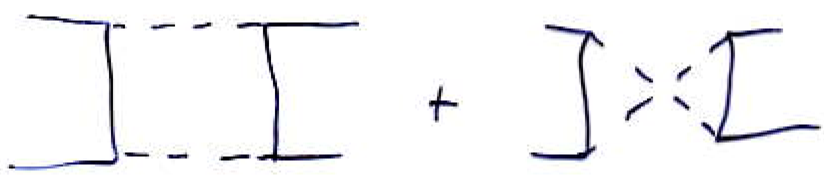
ρ - parameter

and 3-W vertex



$$\ln m_H^2 \longrightarrow \alpha \log(m_+^2) + (1-\alpha) \ln(m_-^2)$$

$$\equiv \log m_-^2 + \alpha \log \beta$$

α_2 

$$\alpha_2 = \frac{1}{12} \frac{1}{16\pi^2} \left\{ \log \frac{m_-^2}{M_W^2} - \frac{\alpha}{m_+^2 - m_-^2} \left[2m_-^2 - \alpha (m_+^2 + m_-^2) \right] \ln \beta \right\}$$

$$\alpha_2 + 2\alpha_3 = \frac{1}{12} \frac{1}{16\pi^2} \alpha (1-\alpha) \frac{1+\beta}{1-\beta} \ln \beta$$

if $m_+ \sim m_-$ indistinguishable from st. model

The generalization to more fields is now straight forward

n Higgses H_i with couplings g_i with $\sum g_i^2 = g_{SM}^2$

which can be generalized to a continuum.

$$\int \rho(s)\, ds = 1$$

General model gives
arbitrary line shape
with arbitrary invisible width

Possibilities

1° Visible peak $\neq$ Standard model

2° Completely invisible decay

3° spread out Higgs

4° singlets too heavy for Higgs to decay into

Special Case

with S. Dilcher

Higher dimensional Singlet

Few Parameters!

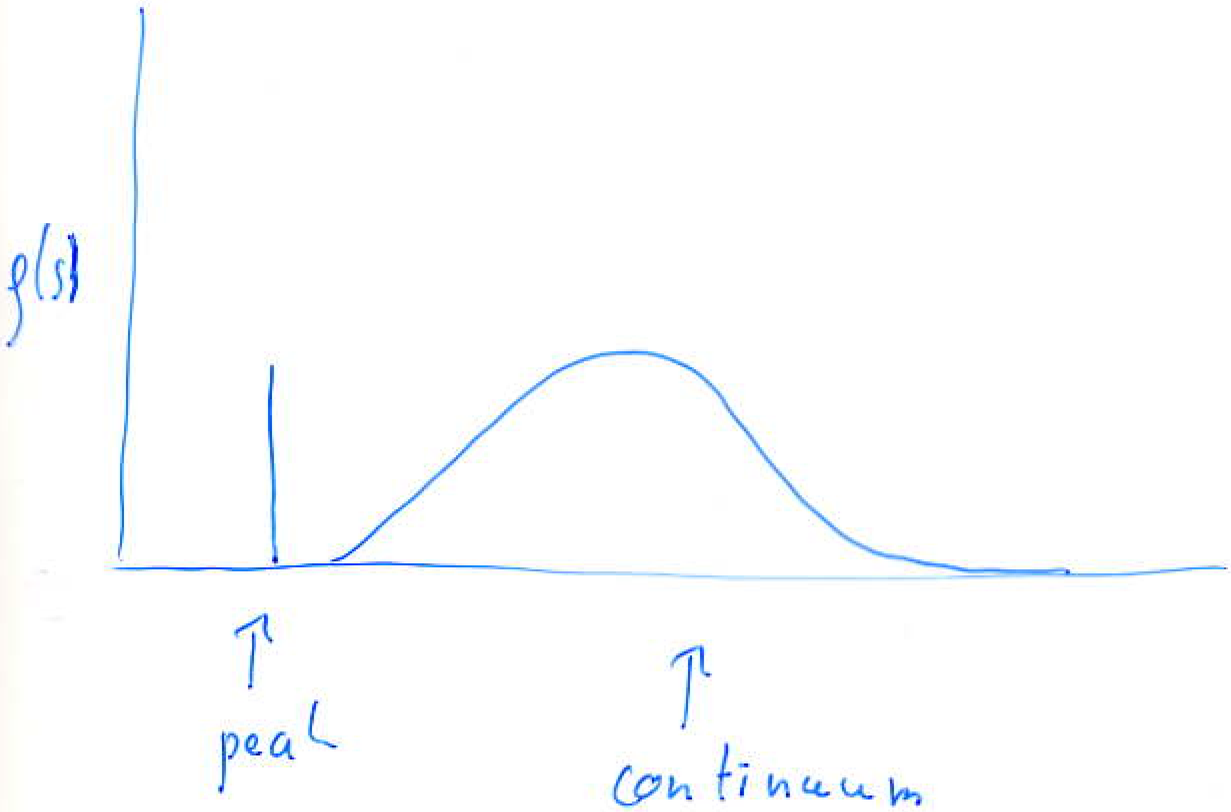
Higgs Propagator!

$$\left(q^2 + M^2 - \mu^{8-d} \left(q^2+m^2\right)^{\frac{d-6}{2}} \right)^{-1}$$

This is possible up to $d=6$ while

$H \phi^+ \phi$ is superrenormalizable in $d=4$

spectrum looks like



what does LEP 200 say?

LEP 2 Higgs Search

1° Nothing below 95 GeV

2° 2.3 σ peak $\sim$ 98 GeV

3° 1.7 σ peak $\sim$ 115 GeV

4° CL for background lower than expected for $s^{1/2} > 100$ GeV

Interpretation

$m_H > 114.4$ GeV

Impose conditions

$$95\ \text{GeV} < m_{peak} < 101\ \text{GeV}$$

$$0.056 < \frac{g^2 g_8}{g^2_{SM}} < 0.144$$

$$\int_{(100)^2}^{(110)^2} \rho(s)\, ds < 30\%$$

$$\int_{(110)^2}^{(120)^2} \rho(s)\, ds > 30\%$$

$d = 5$

$95\ \mathrm{GeV} < m < 101\ \mathrm{GeV}$

$111\ \mathrm{GeV} < M < 121\ \mathrm{GeV}$

$26\ \mathrm{GeV} < \mu < 49\ \mathrm{GeV}$

fit always possible

$d = 6$

$95\ \mathrm{GeV} < m < 101\ \mathrm{GeV}$

$106\ \mathrm{GeV} < M < 111\ \mathrm{GeV}$

$22\ \mathrm{GeV} < \mu < 27\ \mathrm{GeV}$

only possible in a restricted range

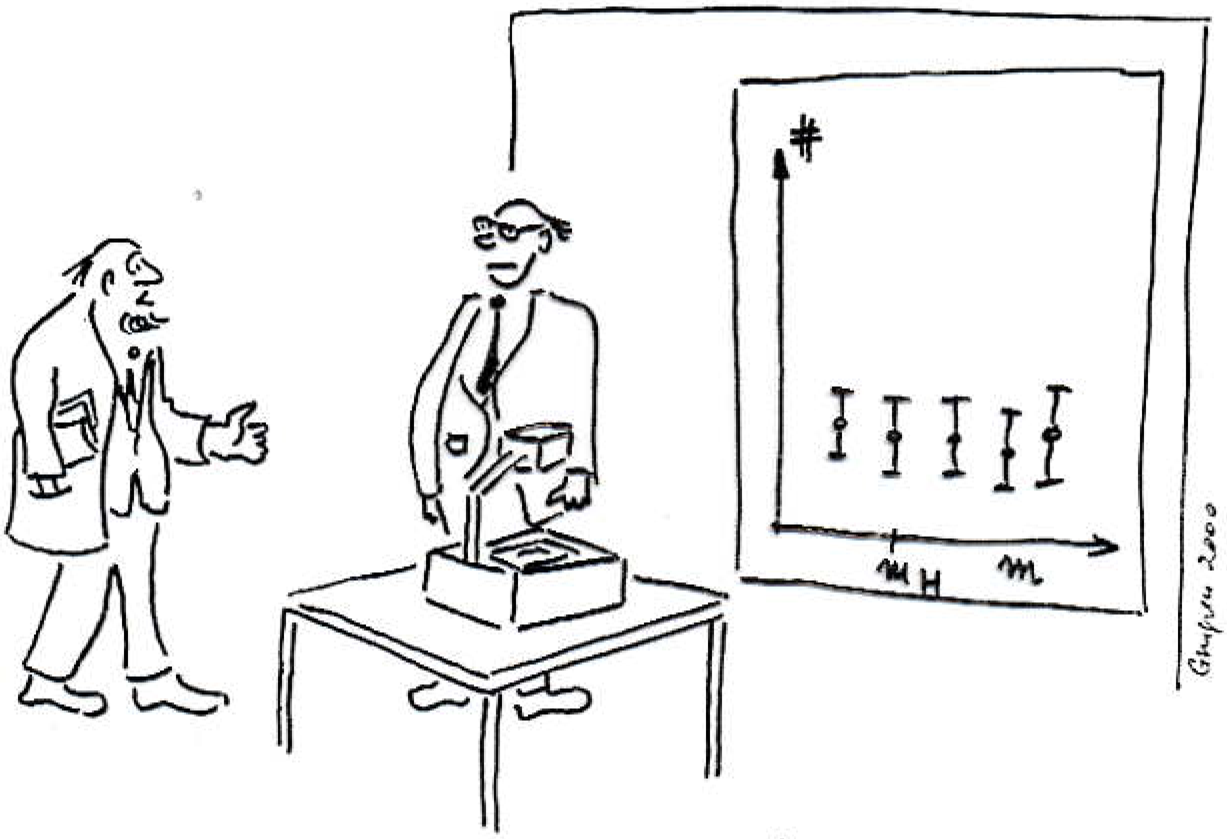
Conclusion

No Higgs at the LHC!

(maybe $3 \sim 4\sigma$ in τ's)

Caveat: significance not clear

Data were not analysed with this type of model in mind



"You call this evidence for the Higgs?"

"Yes! zero lifetime and infinite width!"