Basics of Higgs Physics

Sven Heinemeyer, IFCA (Santander)

Karlsruhe, 07/2007

1. The Higgs Boson in the SM

2. The Higgs Boson in the MSSM

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2. The Higgs Boson in the MSSM

The Higgs Boson in the SM

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1. Higgs Theory
2. Electroweak Precision Observables
3. Properties of the SM Higgs boson
4. SM Higgs boson Searches at LEP
5. SM Higgs boson Searches at the Tevatron
6. SM Higgs boson Searches at the LHC
7. SM Higgs boson precision physics at the ILC

The Higgs Boson in the SM

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Karlsruhe, 07/2007

1. Higgs Theory

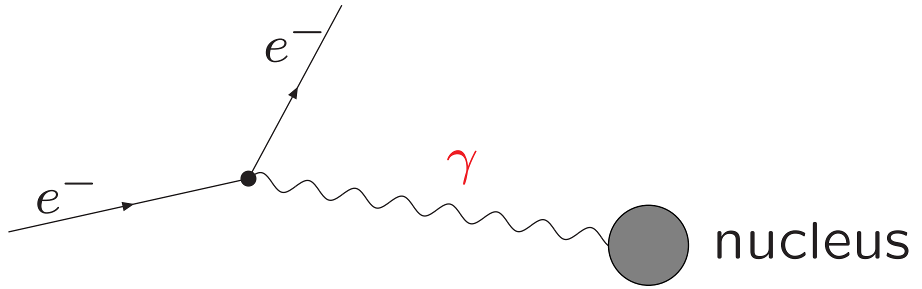
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory $\Rightarrow$ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ



$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

$\Psi \to e^{i\,e\,\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu \lambda(x)$

mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant

$\Rightarrow$ A_μ is massless gauge field

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

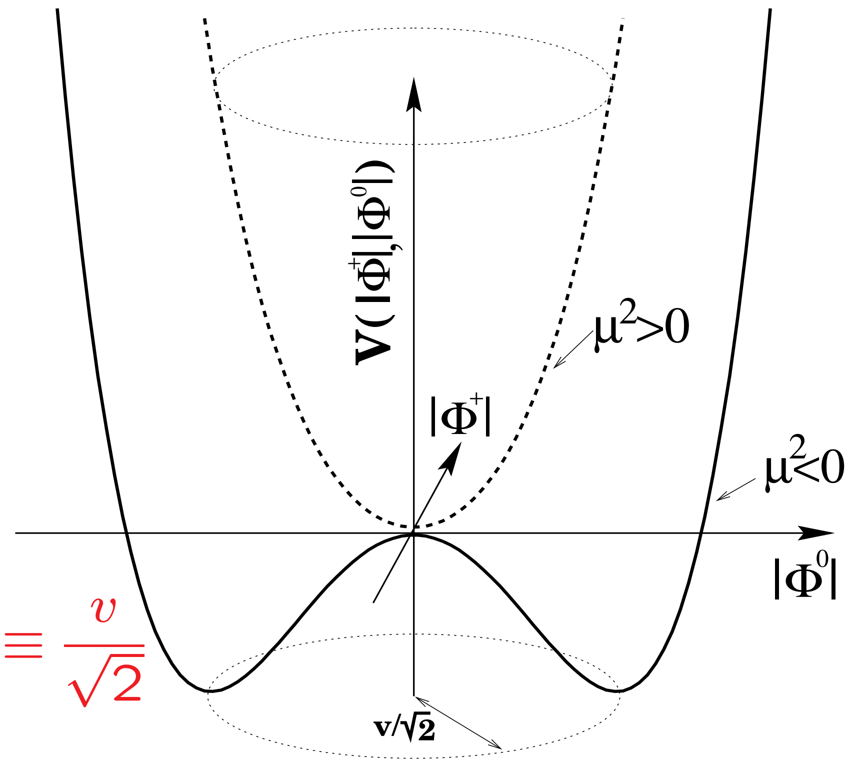
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\mathrm{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R - g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

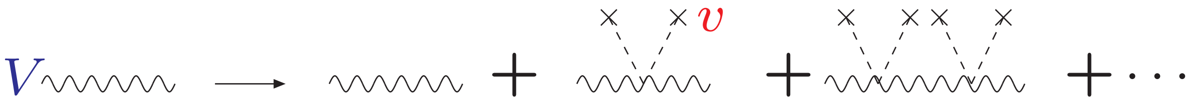
with

$$\begin{aligned} iD_\mu &= i\partial - g_2 \vec{I}\vec{W} - g_1 Y B \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

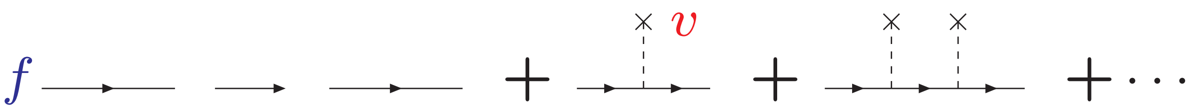
$\Rightarrow$ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



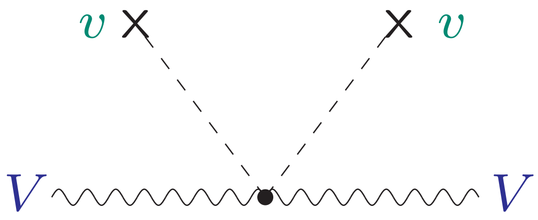
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2 \frac{v^2}{2}$$

2.) fermion mass terms: Yukawa couplings:

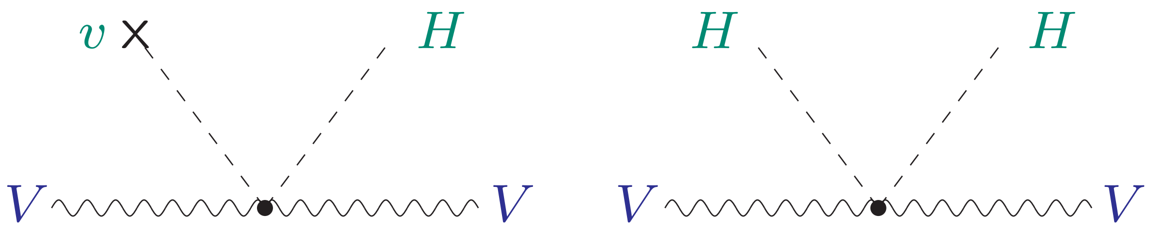


$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \; : \; m_f = g_f \frac{v}{\sqrt{2}}$$

1.) $VV\Phi\Phi$ coupling:



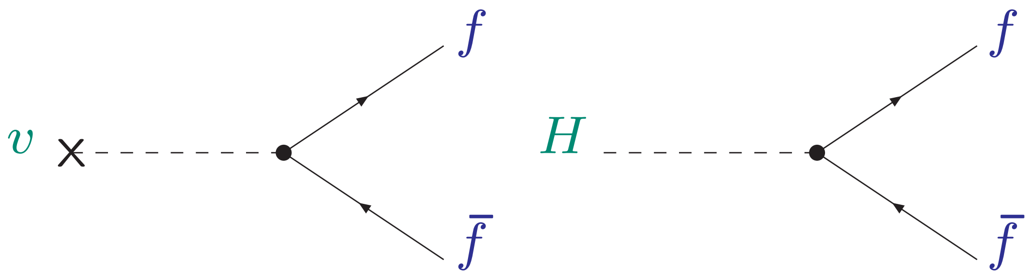
$\Rightarrow$ VV mass terms: $g_2^2 v^2/2 \equiv M_W^2,\ (g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$



$\Rightarrow$ triple/quartic couplings to gauge bosons

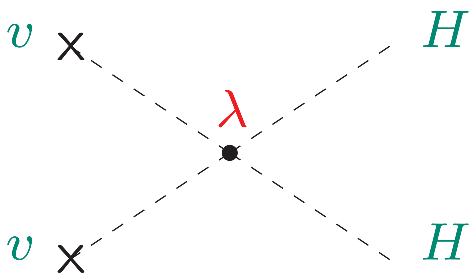
$\Rightarrow$ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2 / v$

$M_H = v\sqrt{\lambda}$ free parameter

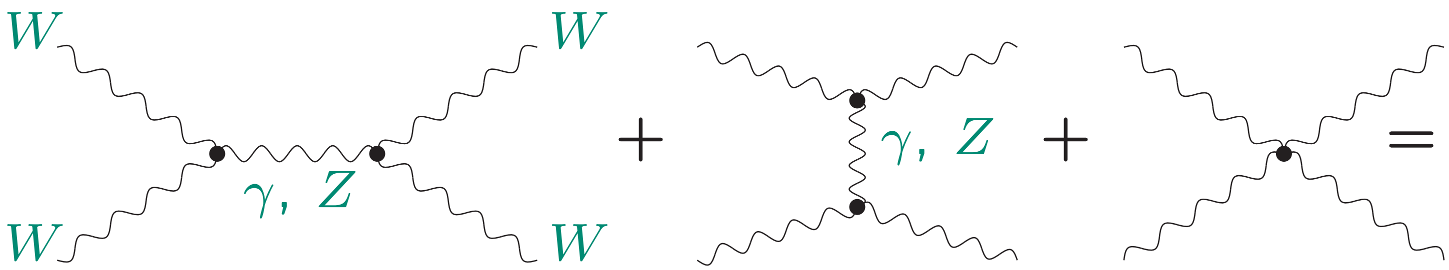
$\rightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

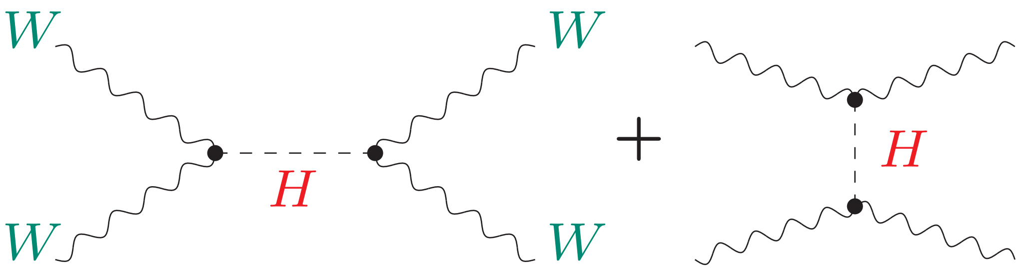


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$ for $E \to \infty$

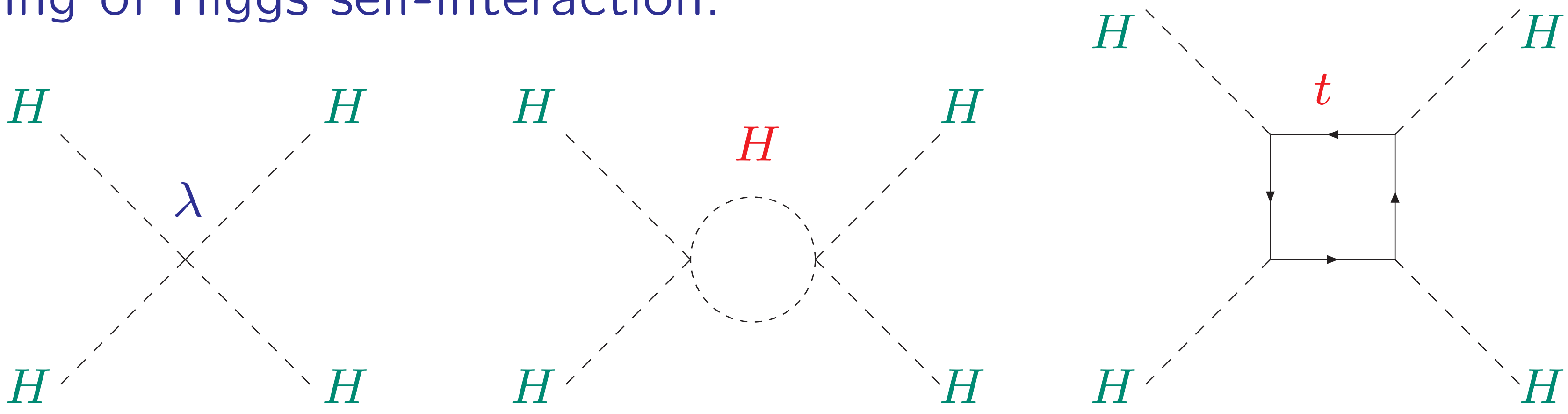
$$\mathcal{M}_{\rm tot} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2 M_W^2\right) + \dots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

What else do we know about the Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right] , \quad t = \log\left(\frac{Q^2}{v^2}\right)$$

Two conditions:

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[\lambda^2\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2}\log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \Rightarrow M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)} \quad \text{: upper bound on } M_H$$

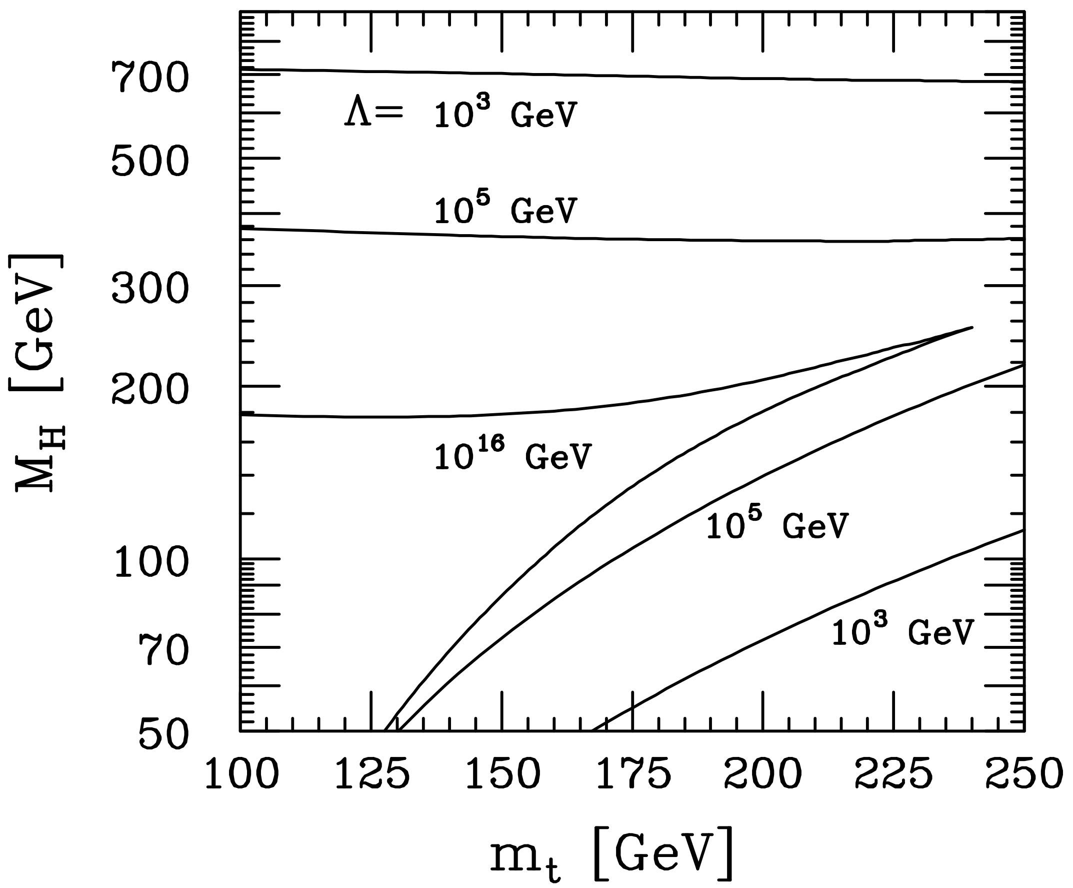
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

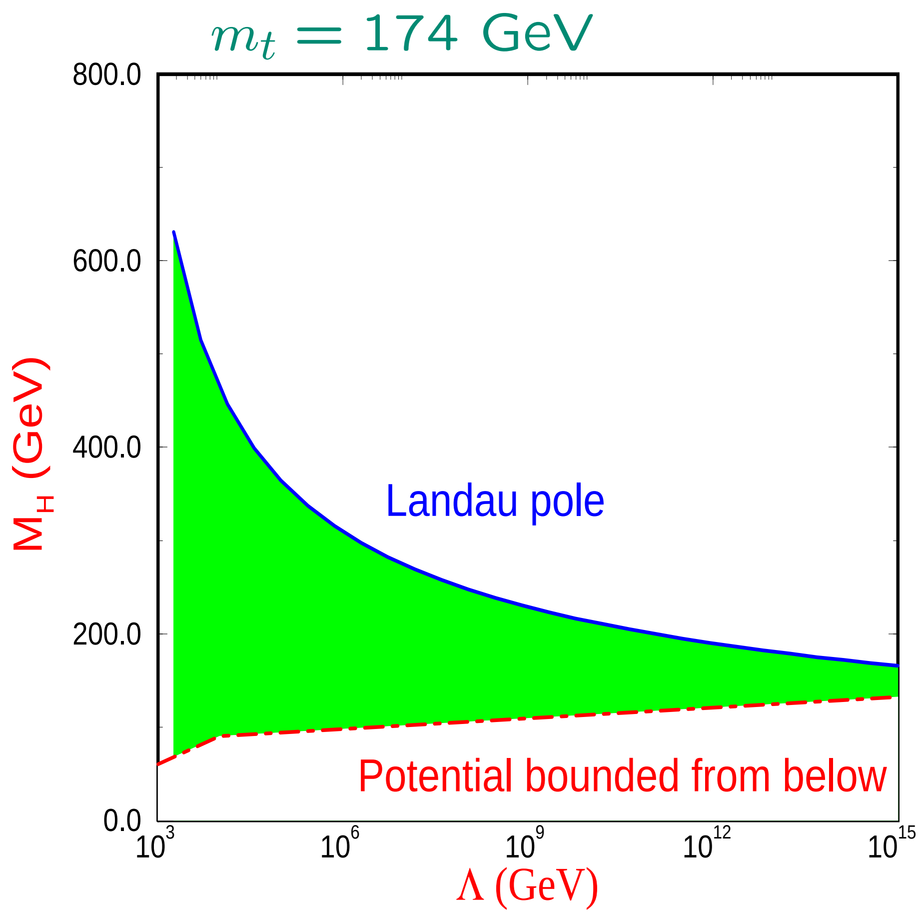
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \lambda(v^2)\frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \Rightarrow M_H^2 > \frac{v^2}{4\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{v^2}\right) \text{ : lower bound}$$

Both limits combined:





Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$

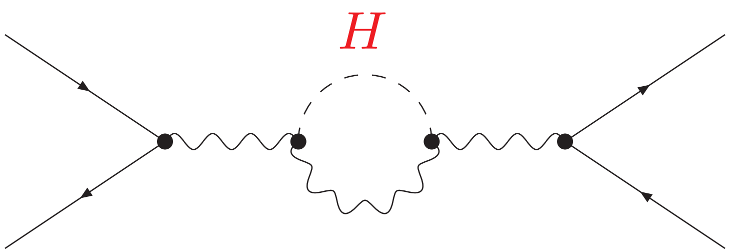
2. Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: prediction of M_W

Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{\text{1-loop}} = \quad \Delta\alpha \quad - \quad \frac{c_W^2}{s_W^2}\Delta\rho \quad + \quad \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

Comparison of SM prediction of M_W with direct measurements:

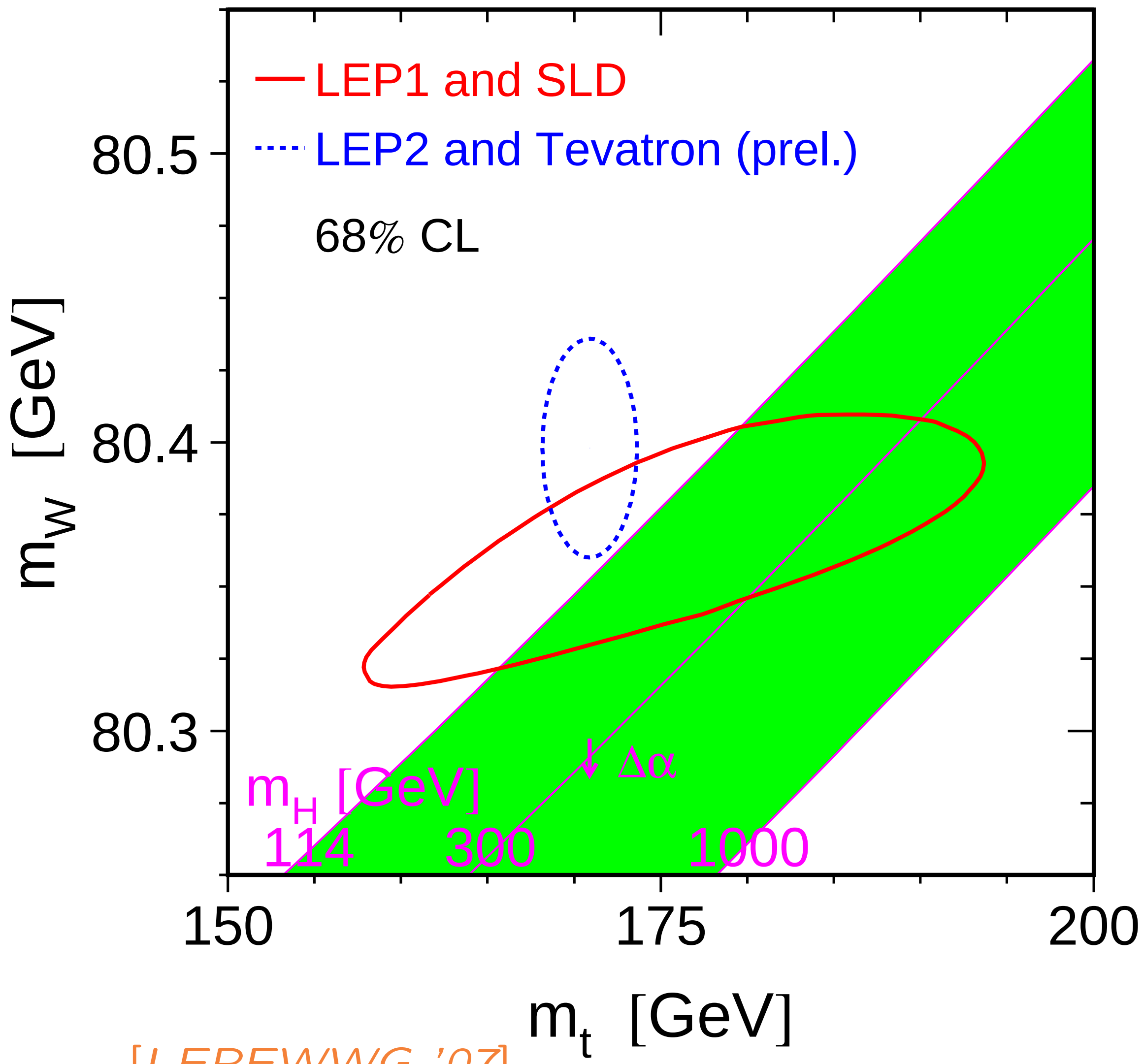
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2}\right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



[LEPEWWG '07]

⇒ light Higgs boson preferred

Results for M_H from other EWPO:

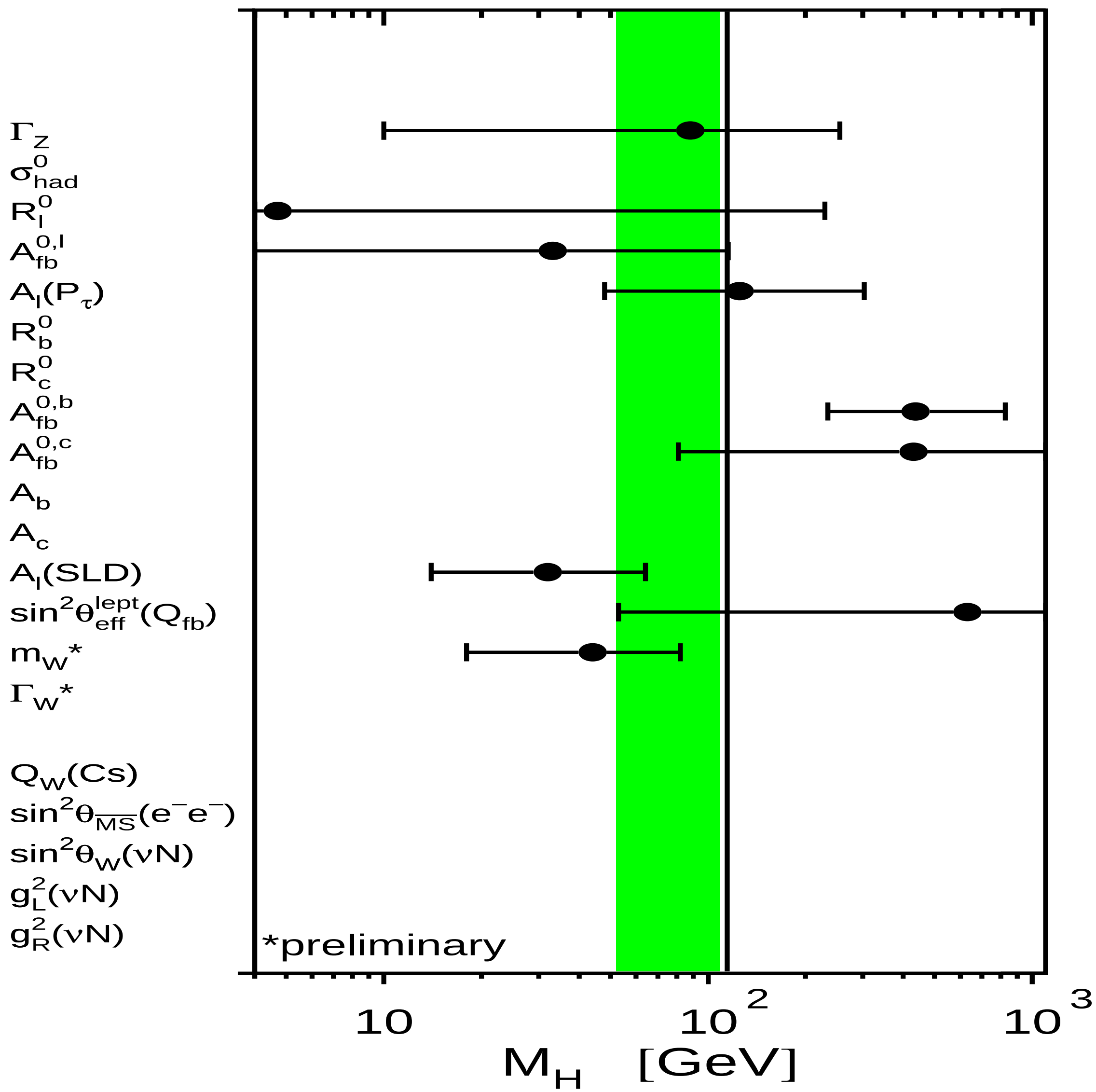
light Higgs preferred by:

M_W, A_l^{LR} (SLD)

heavier Higgs preferred by:

A_b^{FB} (LEP)

$\Rightarrow$ keeps SM alive



[*LEPEWWG '07*]

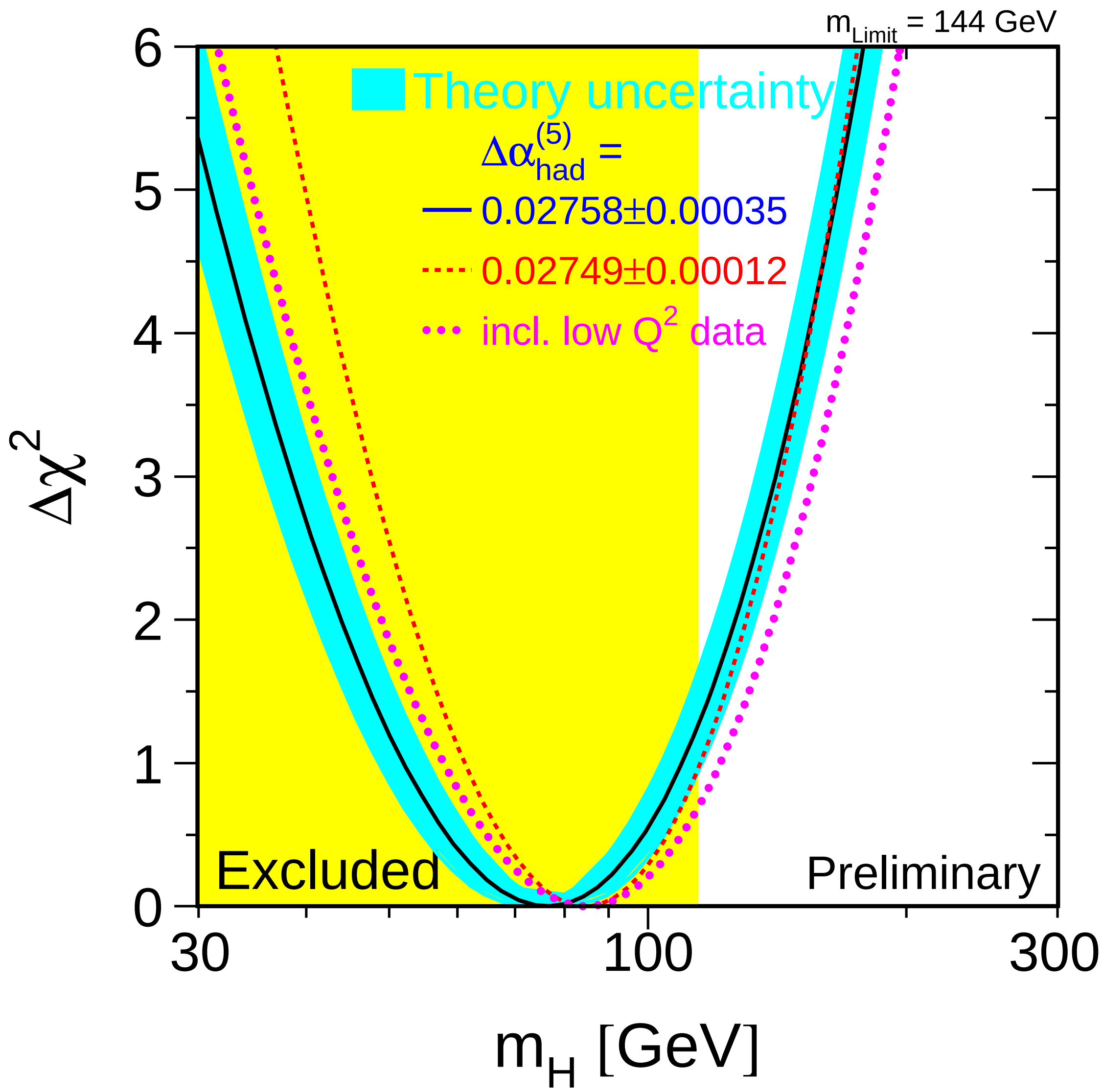
$\Rightarrow$ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '07*]

$\Rightarrow M_H = 76^{+33}_{-24}$ GeV

$M_H < 144$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 150$ GeV

3. Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\, G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

Dominant decay process: $H \to b\bar{b}$

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2 \left[\sqrt{2}\, G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

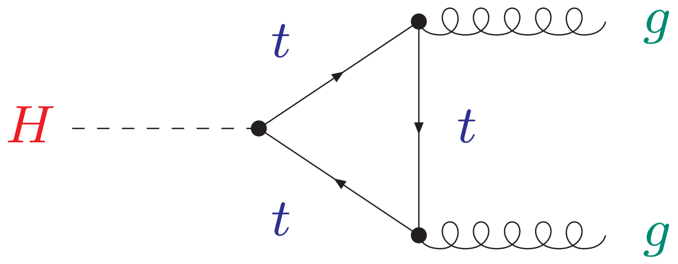
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

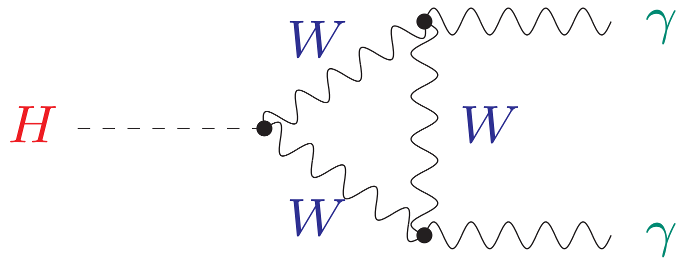
with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):





$$\Gamma(H \to gg) = \frac{G_\mu \, \alpha_s^2(M_H^2) \, M_H^3}{36\sqrt{2}\,\pi^3} \left[1 + C \frac{\alpha_s(\mu)}{\pi} \right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6} \log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

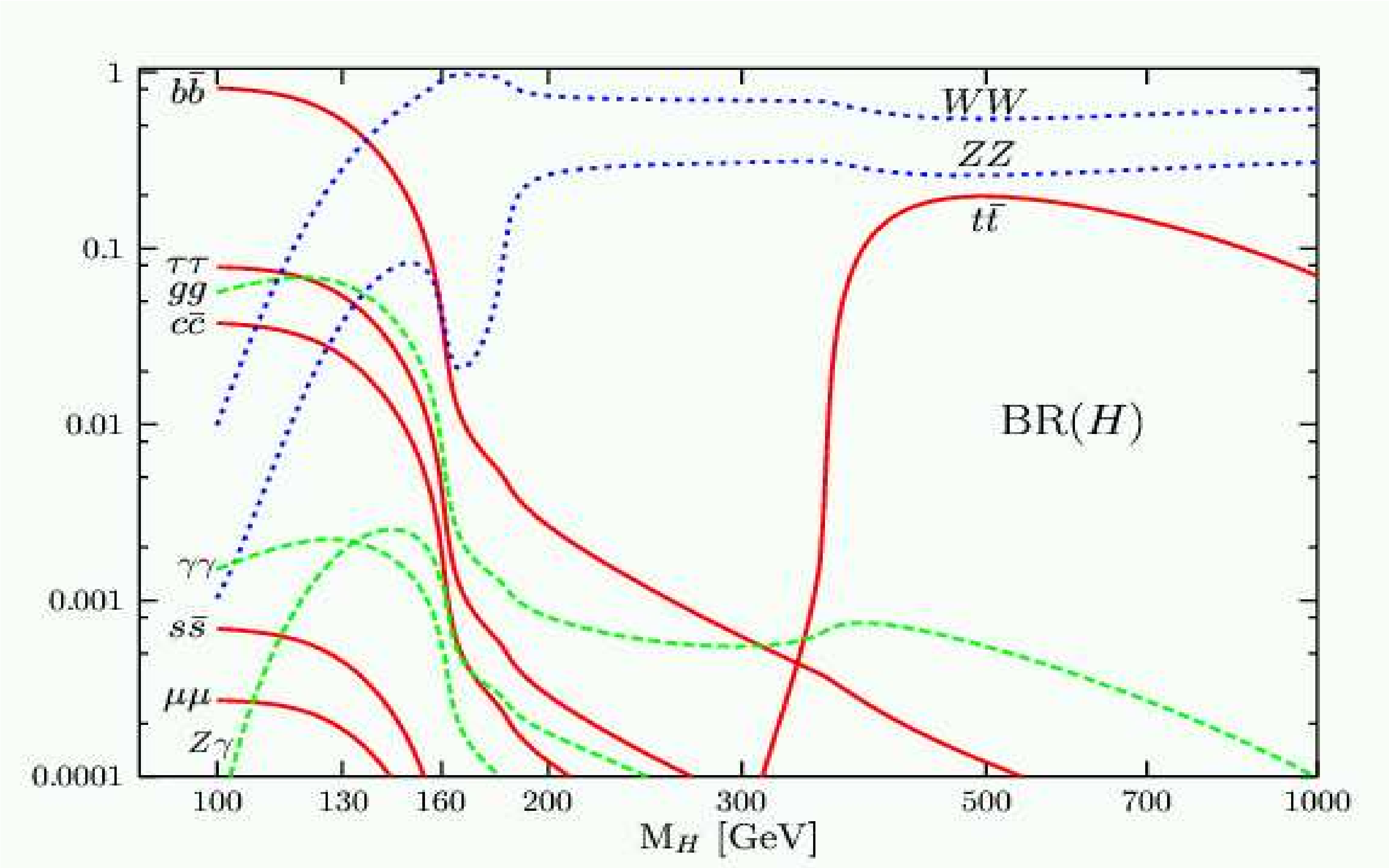
$\Rightarrow$ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\sqrt{2}\,\pi^3} \left| \frac{4}{3} e_t^2 - 7 \right|^2$$

via the top quark and W boson loop

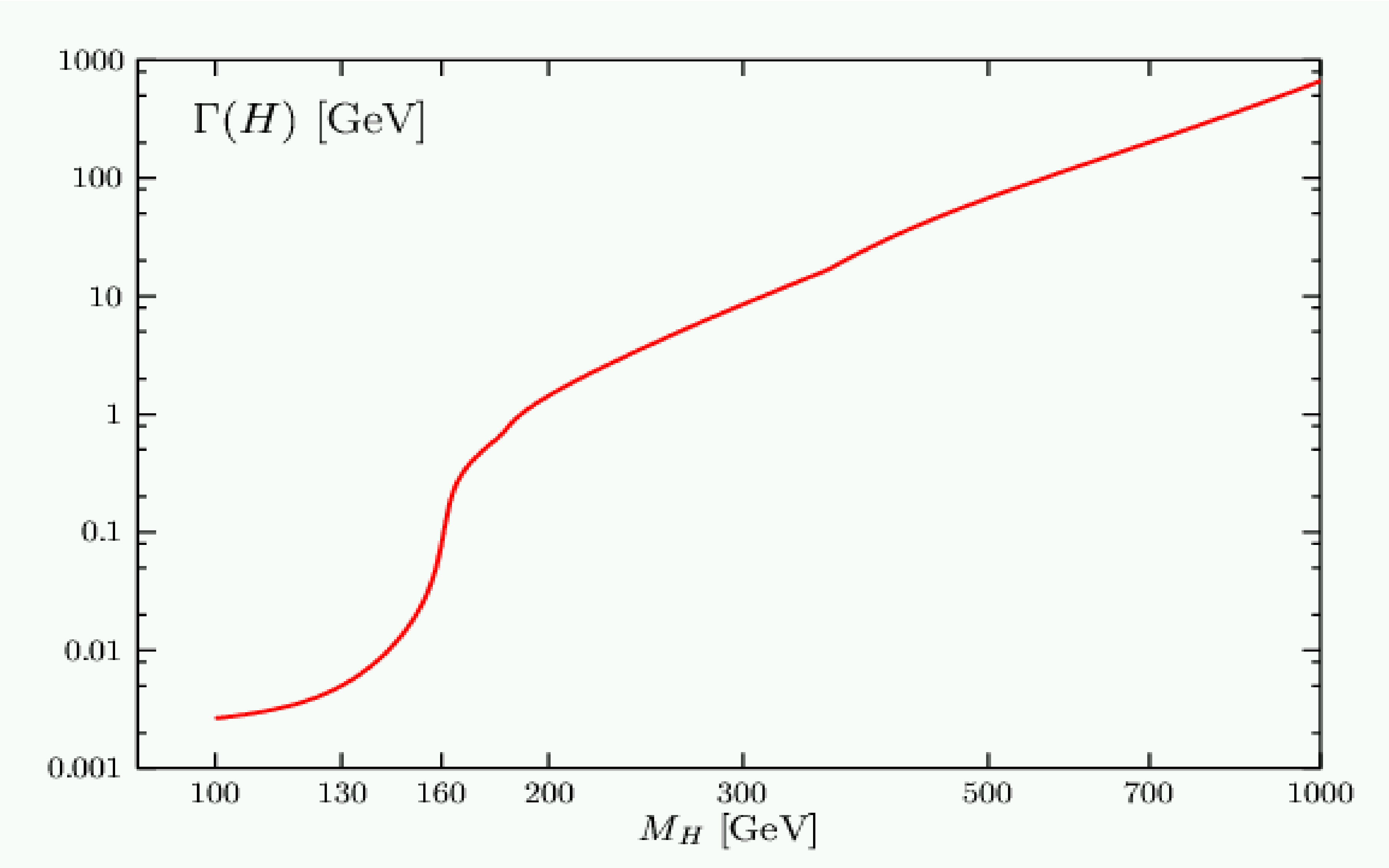
Overview of the branching ratios:

[*taken from hep-ph/0503172*]



The total SM Higgs boson width:

[*taken from hep-ph/0503172*]



Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)
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4. measure couplings to fermions

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Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T
2. measure its mass ($\Rightarrow$ ok?)	T
3. measure coupling to gauge bosons	
4. measure couplings to fermions	
5. measure self-couplings	
6. measure spin, ...	

T = Tevatron,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L
2. measure its mass ($\Rightarrow$ ok?)	T	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, . . .		

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L	I
2. measure its mass ($\Rightarrow$ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .			I

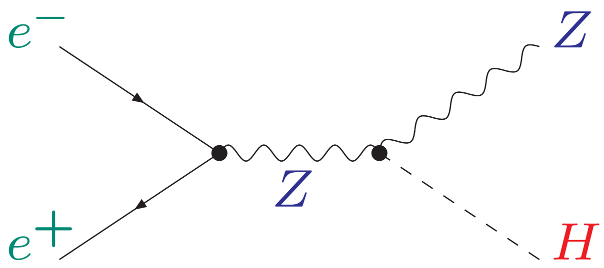
T = Tevatron, L = LHC, I = ILC (International Linear e^+e^- collider)

We need the LHC and the ILC to find the Higgs
and to establish the Higgs mechanism!

The LHC can do a crucial part . . .

4. SM Higgs search at LEP:

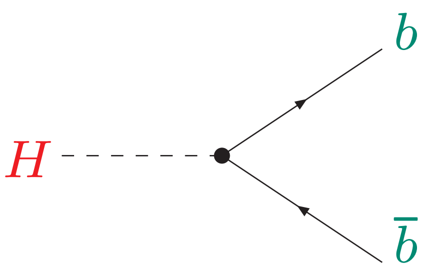
Dominant production process:
$e^+e^- \to ZH$:



$$\sigma(e^+e^- \to ZH) = \frac{G_\mu^2 M_Z^4}{96\,\pi\,s} \left[v_e^2 + a_e^2\right] \beta\, \frac{\beta^2 + 12 M_Z^2/s}{(1 - M_Z^2/s)^2}$$

with $\beta^2 = (1 - (M_H + M_Z)^2/s)\,(1 - (M_H - M_Z)^2/s)$ (1)

Dominant decay process: $H \to b\bar{b}$



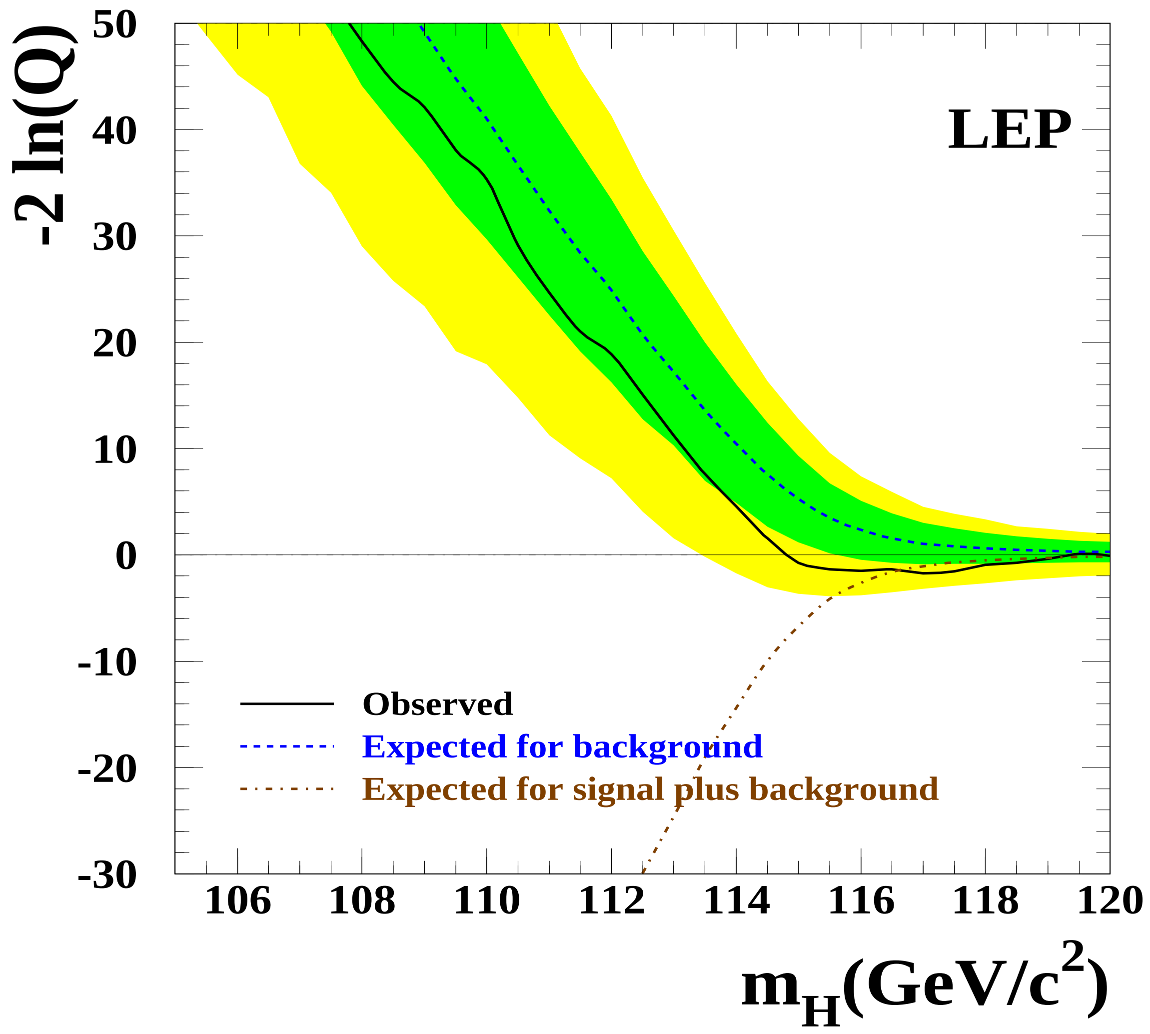
Search for the Standard Model Higgs at LEP: [*LEP Higgs WG '03*]

Exclusion limit
at the 95% C.L.:

$M_H > 114.4$ GeV

expected: 115.3 GeV

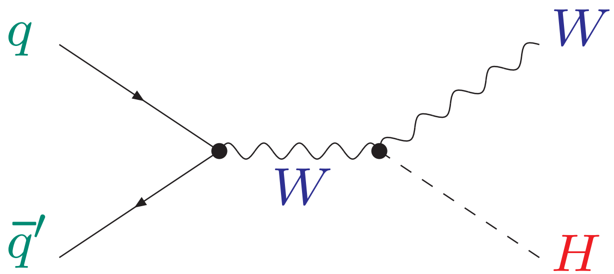
(LEP has seen exactly as many Higgs-like events as could be expected for $M_H \approx 116$ GeV, not more, not less)

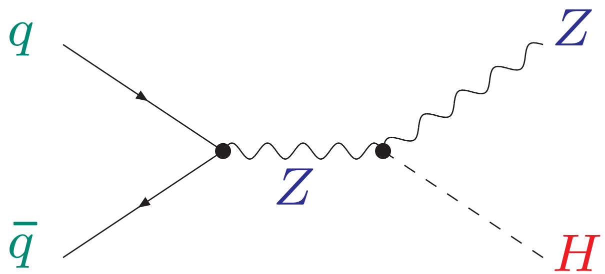


5. SM Higgs search at the Tevatron

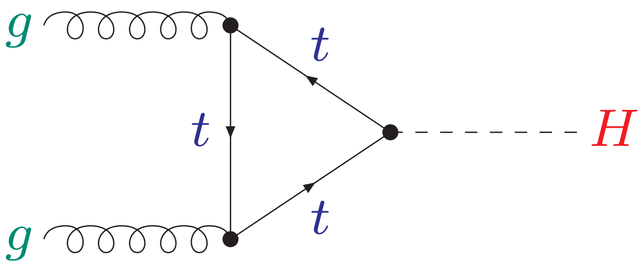
Tevatron: $p\bar{p}$ accelerator: $\rightarrow$ T

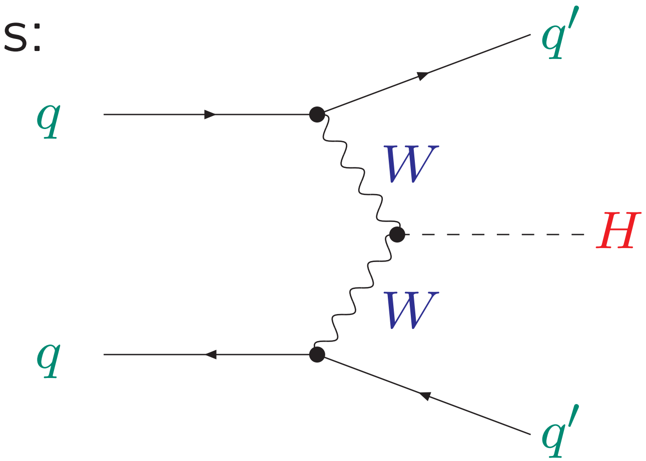
Production processes as at LEP:



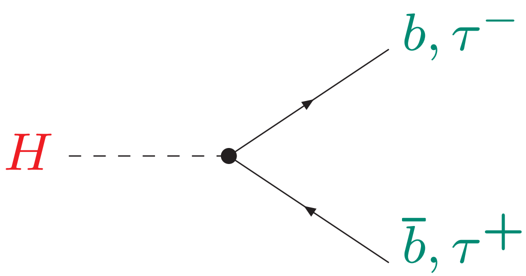


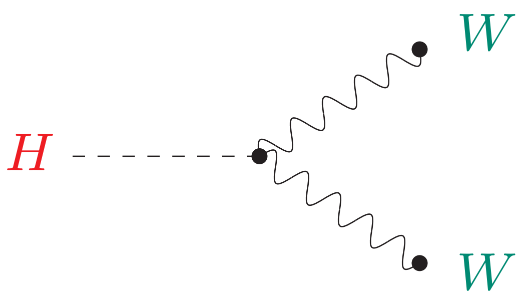
Other important production channels:





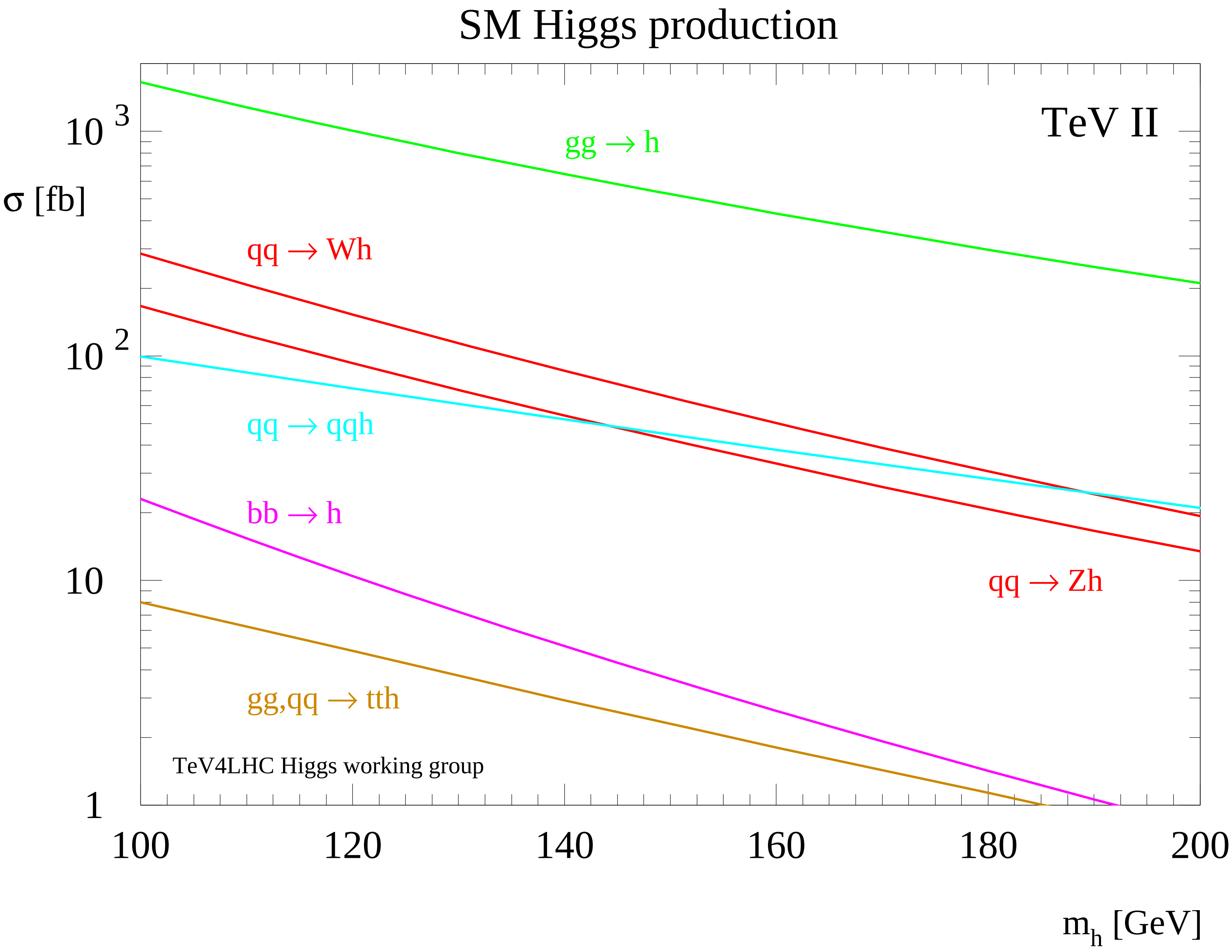
Dominant decays:



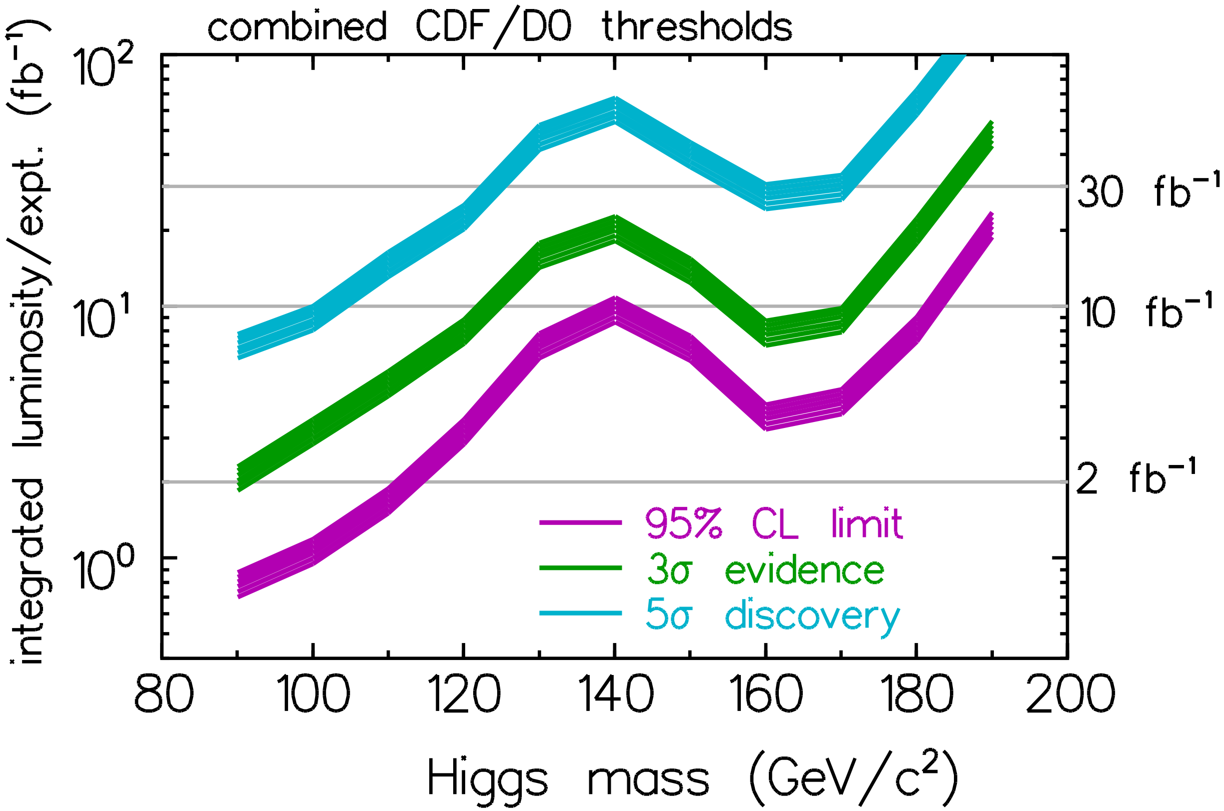


Overview of production cross sections:

[F. Maltoni et al. '05]



Expectations for Higgs discovery at the Tevatron:



Unfortunately: luminosity problems in the start of RunII
$\Rightarrow$ progress slower than anticipated

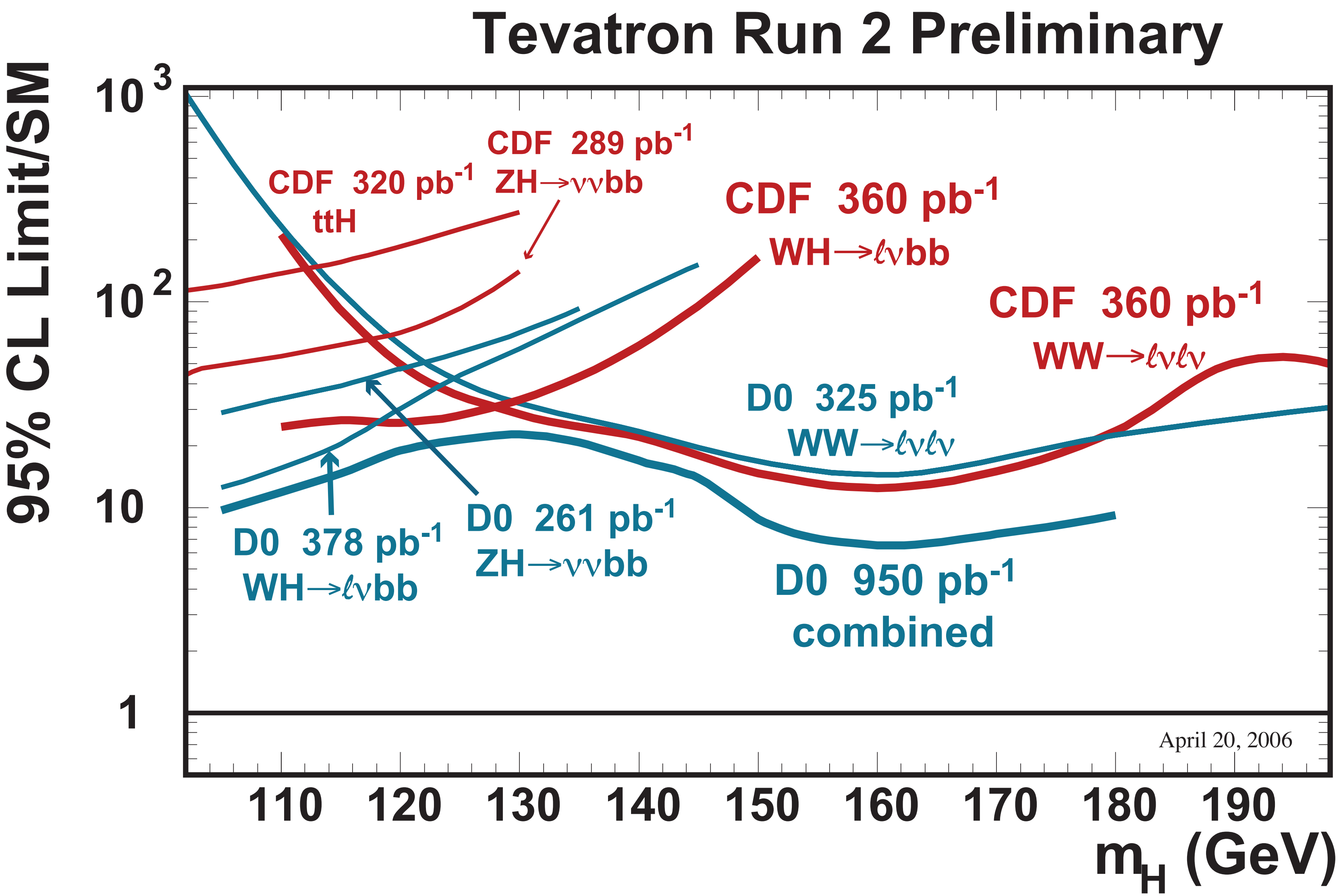
For SM Higgs boson with $M_H \sim 120$ GeV:

$\approx$ 2008/09: sensitivity for 95% C.L. exclusion

$\approx$ 2009: sensitivity for 3σ evidence
or exclude SM Higgs with $M_H \lesssim 130$ GeV

Results for various search channels for SM Higgs:

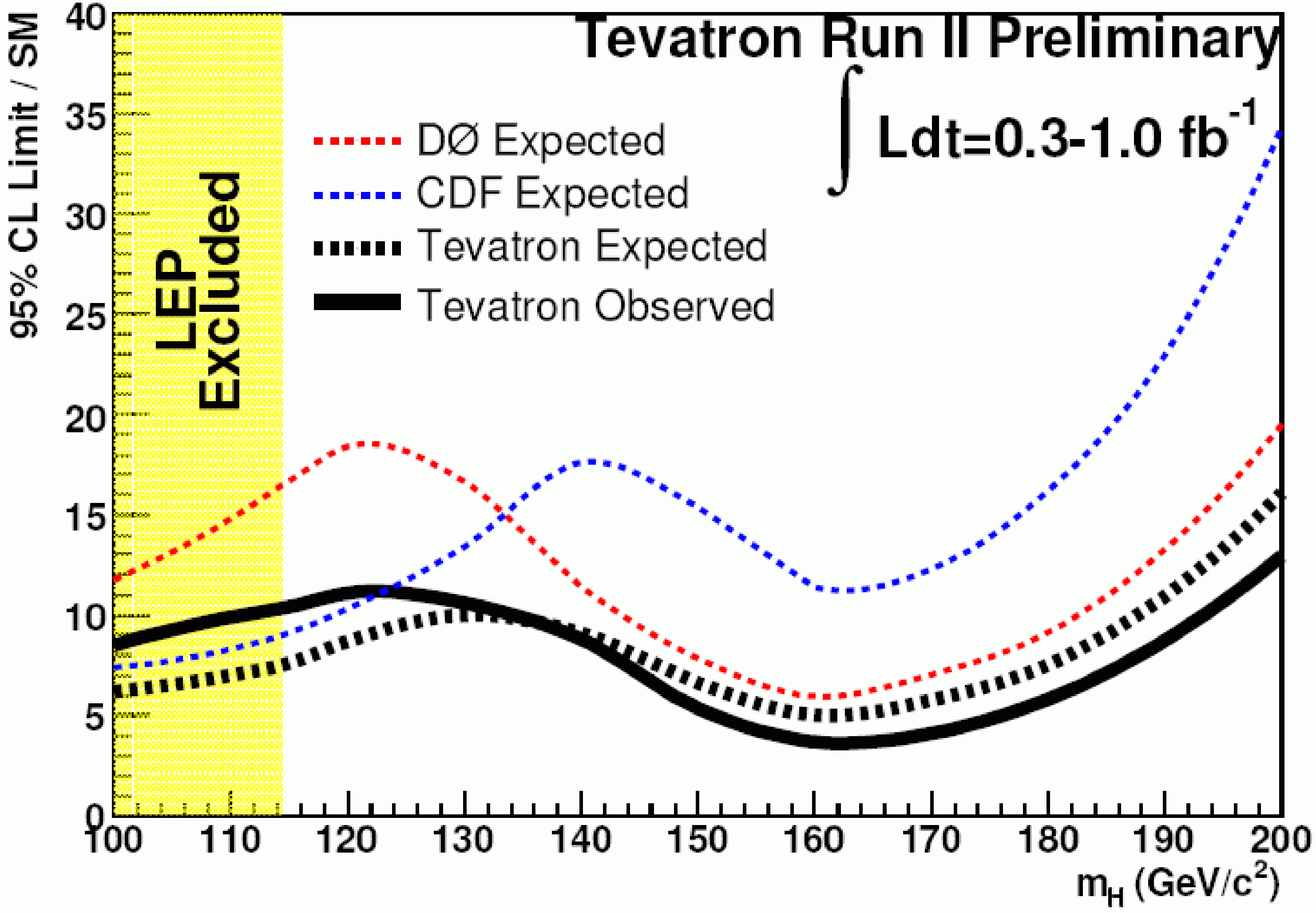
[*CDF, D0 '06*]



Can they close the gap?

Current status (latest results) of SM Higgs search:

[*CDF, D0 '06*]



Can they close the gap?