Lectures

on

Higgs Physics

Content of Lectures

1. Overview: Mr., Mrs, Miss Higgs, perhaps the whole family.
2. Lecture1: Standard model Higgs boson
3. Lecture2: Weakly-coupled extensions
4. Lecture3: Strongly-coupled extensions

Overview

The Higgs boson is perhaps one of the most elusive particle in the particle world – The longest time gap between proposal and discovery/ruling-out.

Peoples seem know a lot about it – SM Higgs boson, but know little or even nothing about the actual particle(s) that are responsible for EWSB.

While Higgs has been one of the most popular names in the news or blogs recently.

NewScientist: Higgs seen at the LHC

TIME: Higgs Boson: A Ghost in the Machine

TIMESONLINE: *The God Particle*

PopularMechanics: *World's Biggest Science Project Aims to Unlock "God Particle"*

Technology Review: *The large hadron collider may solve nature's great mysteries*

The Buffalo News: *Chasing the "Godparticle"*

International Herald Tribune: *"Father" of elusive Higgs boson is almost sure collider will find it*

... ...

REUTERS: Key Scientists sure “God particle” will be found soon

Higgs said he hoped the elusive boson – which an earlier but less powerful collider at CERN and another at the U.S. Fermilab had failed to detect – would be identified before his 80th birthday in 2009.

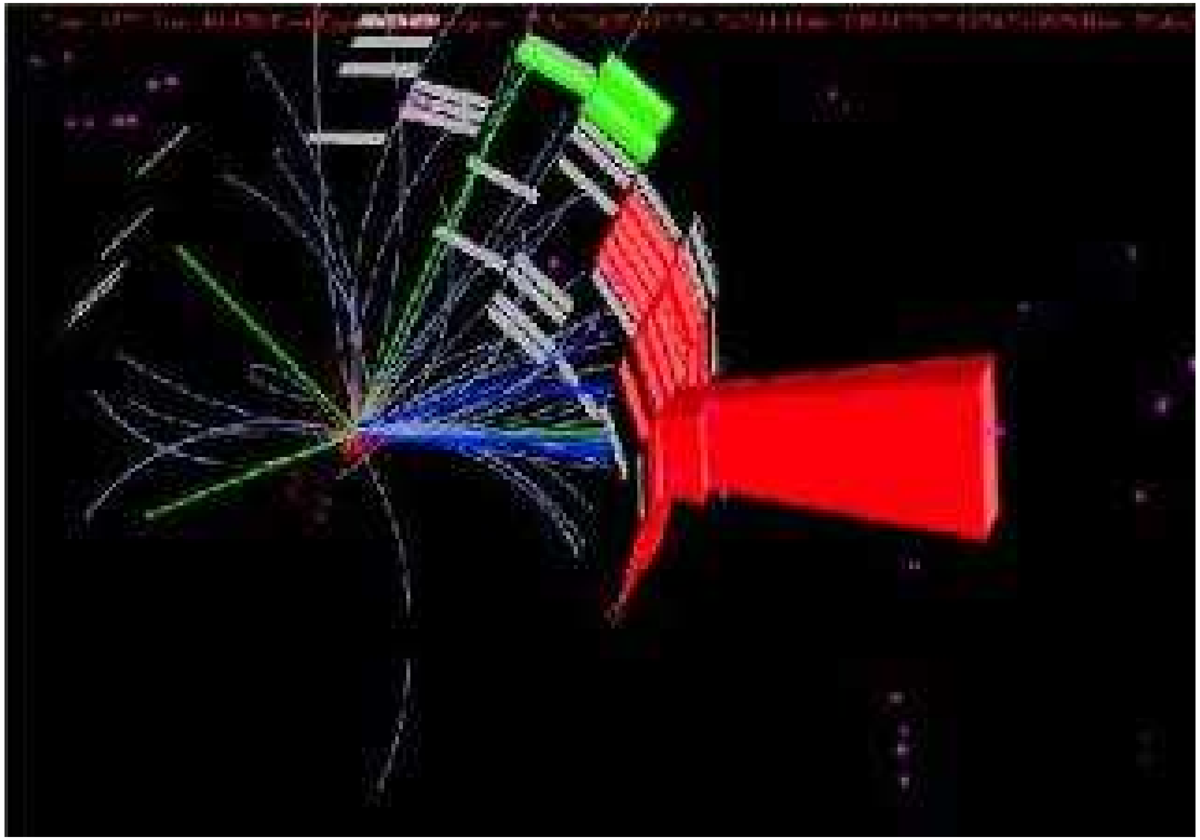
“If it doesn’t,” he said, ”I shall be very, very puzzled.”

But there may be no immediate visible proof – despite some fanciful portrayals of what it might look like – of the boson’s appearance on the ultra-sophisticated computers used by CERN scientists to track the billions of collisions in the LHC.

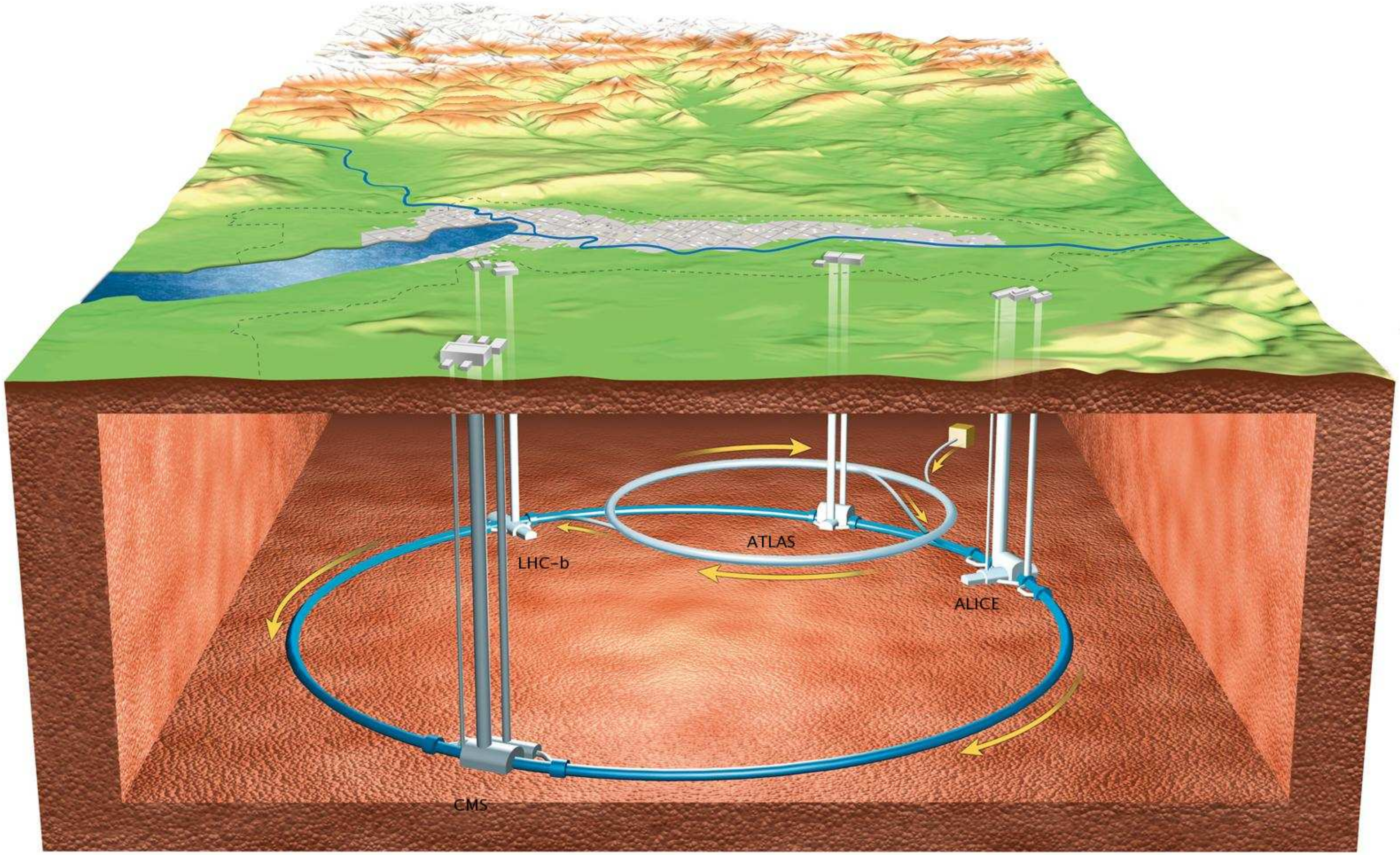
“It all happens so fast that the appearance of the boson may be hidden in the data collected, and it could take a long time for the analysis to find it,” said Higgs.

”I may have to keep the champagne on ice for a while yet.”

Scientific American: This is what the Higgs boson looks like



Overview of LHC experiments

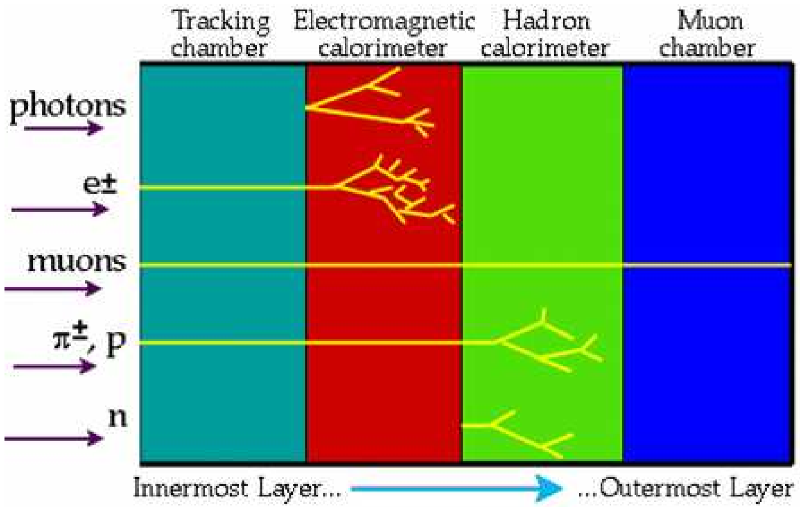


Collider experiments: ATLAS and CMS

Physicists smash particles into each other with two main objectives:

- to find out what is inside them
- to use the energy available in the collision to "create" new particles.

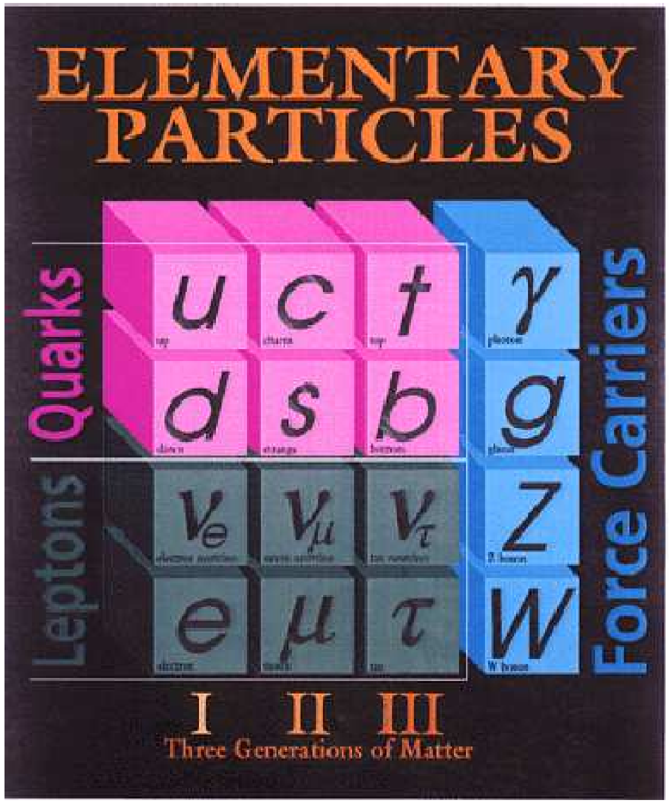
Physicists need "particle detectors" to see new particles.



A detector consists of tracking systems, calorimeters, muon systems to identify various particles.

Questions that the LHC wants to address

- What's the origin of the mass of particles?



The answer may lie within the Standard Model, in an idea called the Higgs mechanism. The Higgs field has at least one new particle associated with it, the Higgs boson. If such particle exists, the LHC will be able to make it detectable.

- Can the electroweak and the strong forces be unified?
- What is “Dark matter” made of?

Lecture1: SM Higgs boson

- Importance of Higgs boson
- Theoretical constraints on Higgs mass
- Decays
- Production

Importance of the Higgs Boson

- The Higgs boson is the masterpiece of the modern particle theories.
- Theories relies on gauge symmetry. The simplest example is QED with a local $U(1)$ symmetry:

$$\mathcal{L} = \bar{\psi} i \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

  where $D_\mu = \partial_\mu + ieQ_\psi A_\mu$ is the covariant derivative.

- The $U(1)$ transformation involves

$$\psi(x) \to e^{-ieQ_\psi \alpha(x)} \psi(x) \,, \qquad A_\mu \to A_\mu + \partial_\mu \alpha(x)$$

- In this $U(1)$ example, the fermion has a mass. Nothing wrong about that.
- However, our world cannot be described just by $U(1)$. For example, the nuclear beta decay, observed well before the SM, cannot be accounted for by an $U(1)$. With just $U(1)$'s all fermions are stable

against decays. Muons cannot decay. We need an $SU(2)_L$ to describe the weak decay.

- The problem of $SU(2)_L$ is that fermions cannot have mass!!

$$-m\bar{\psi}\psi = -m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

forbidden by the $SU(2)_L$ symmetry.

- Introduce a Higgs doublet field with a hypercharge (1/2) and form a gauge-invariant term with the fermion field:

$$-y\,\overline{\psi_L}\,\phi\,\psi_R + h.c.$$

- When the neutral component of ϕ develops a VEV value due to a potential, the mass term for fermion is obtained

$$-\frac{yv}{\sqrt{2}}\,\overline{\psi_L}\psi_R + h.c.$$

- So the mass equals to $m_\psi = yv/\sqrt{2}$. The SM did not address the pattern of mass spectrum.

- In order to give masses to the up-type and down-type, a hypercharge $Y/2 = 1/2$ and another hypercharge $Y/2 = -1/2$ are needed. In the SM with one doublet, one can construct it by

$$i\tau^2\phi^*$$

In the 2HDM, we actually have 2 doublets: H_u and H_d:

$$\overline{Q}H_u u_R, \qquad \frac{Y}{2}(\overline{Q}, H_u, u_R) = \left(-\frac{1}{6}, -\frac{1}{2}, \frac{2}{3}\right)$$

$$\overline{Q}H_d d_R, \qquad \frac{Y}{2}(\overline{Q}, H_d, d_R) = \left(-\frac{1}{6}, \frac{1}{2}, -\frac{1}{3}\right)$$

In the MSSM, since one fermionizes one doublet to give a hypercharge $1/2$ fermionic doublet. In order to cancel the anomaly, one needs an additional fermionic $-1/2$ doublet. Therefore, one has to start with 2 Higgs doublets with hypercharge $\pm 1/2$.

- One can add singlets to the Higgs sector. For example, the NMSSM has one additional singlet Higgs field, which was used to solve the μ problem. The Higgs boson phenomenology is richer.

Summary

- The Higgs boson is the master-piece of the SM.
- It can be as simple as a single Higgs boson, but can also be as complicated as one can imagine.
- We need to find it and measure its couplings to fermions.
- In addition to fermions, the Higgs boson also couples to gauge bosons.

Theoretical constraints on Higgs mass

The Higgs potential

$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

When μ^2 becomes negative for some reasons, the ϕ develops a nontrivial VEV

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

and gives a physical Higgs boson of mass

$$m_H = \sqrt{2\lambda} v$$

where $v = 246$ GeV. So it appears that the Higgs mass scales as $\sqrt{\lambda}$, which is the self coupling of the Higgs field.

- Unitarity:The scattering amplitude when breaking down into partial-wave coefficients should be within the unitarity circle

$$|a_{ij} - \frac{i}{2}| < 1$$

There are similar definitions, but naively the coefficients are smaller than $O(1)$. In general, the $L = 0$ is the largest partial-wave coefficient. The lowest order diagram in the coupling λ should not be too large to break the unitarity. In this way, an upper bound on the Higgs mass is obtain

$$m_H < \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} \approx 1 \text{ TeV}$$

For example, the unitarity bound from the scattering of longitudinal gauge bosons.

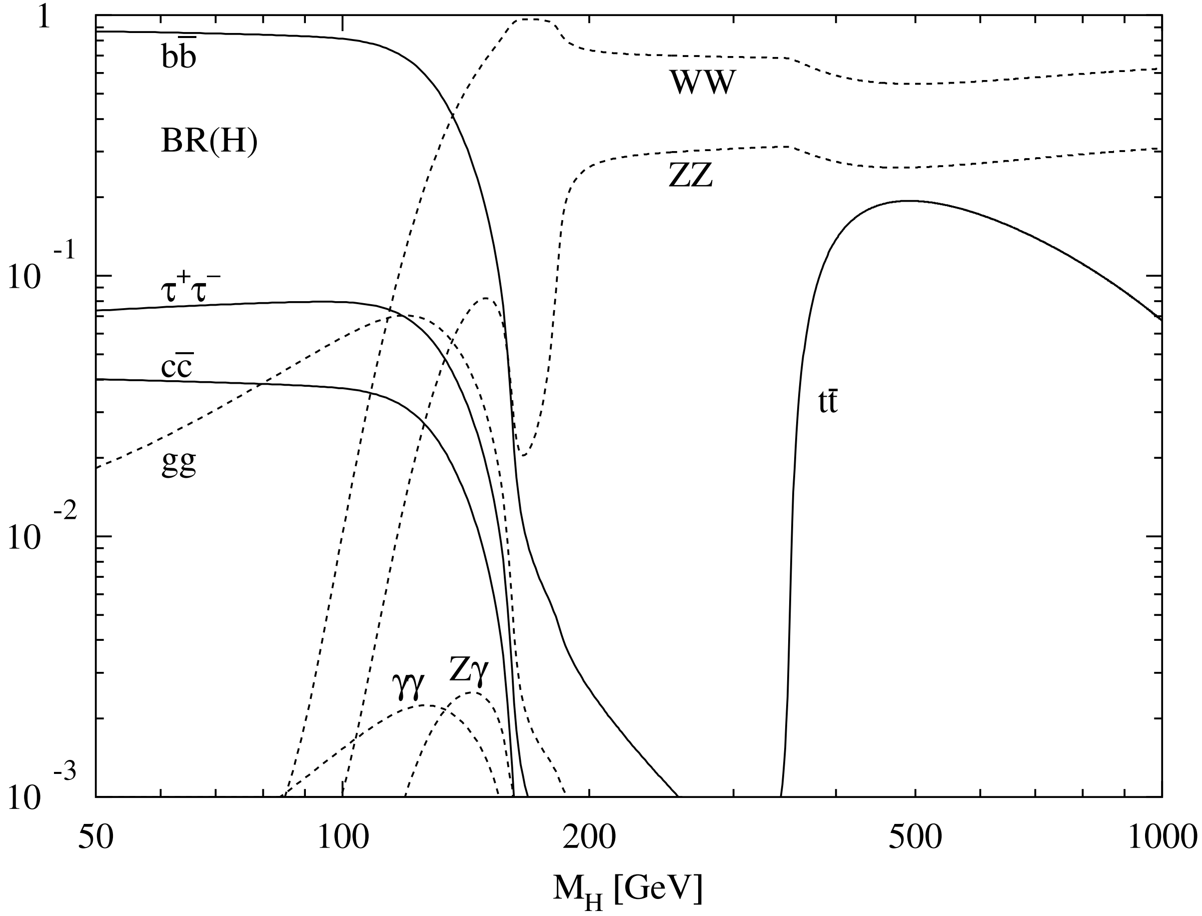
- Perturbativity of λ: If we require λ to remain perturbative when evolved up to GUT scale, the upper bound of the Higgs mass should be about $100 - 200$ GeV.
- Lower limit on λ: There exists a lower limit on λ due to effective self-interactions from diagrams containing virtual gauge bosons, fermions, etc, which are in addition to the bare $\lambda\phi^4$ term. Since the coupling of the scalar field to the virtual fields is of order g or e, it

ends up $\lambda \gtrsim \alpha^2$. A better estimate leads to

$$m_H^2 \geq \frac{3\sum_V M_V^4 + \sum_S m_S^4 - 4\sum_f m_f^4}{16\pi^2 v^2}$$

However, since the top mass is so heavy that this bound is not meaningful anymore.

SM Higgs boson decays (HDECAY)



Decay Widths

The Higgs boson couples to almost everything with a coupling proportional the mass of the particle. So if kinematically allowed the Higgs boson will decay into the heaviest possible particle, in general. Especially, the mode into W^+W^- and ZZ. These two are in general the most important modes.

Decay Width:

- $H \to WW, ZZ$: The couplings of H to WW and ZZ are

$$\mathcal{L} = g m_W \, H \, W^{+\,\mu} \, W^-_\mu + \frac{1}{2} g_z m_Z H \, Z \, Z$$

The decay widths into WW and ZZ can be easily obtained as

$$\Gamma(H \to W^+W^-) = \frac{g^2}{64\pi} \frac{m_H^3}{m_W^2} (1 - 4\lambda_W)^{1/2} (1 - 4\lambda_W + 12\lambda_W^2)$$

Similarly, the partial width into ZZ is

$$\Gamma(H \to ZZ) = \frac{g^2}{128\pi}\frac{m_H^3}{m_W^2}(1-4\lambda_Z)^{1/2}(1-4\lambda_Z+12\lambda_Z^2)$$

where $\lambda_W = m_W^2/m_H^2$.

For accuracy in the mass range just below WW threshold the off-shell decay should be taken into account $H \to WW^*, ZZ^*$.

- $H \to f\bar{f}$: The decay into a fermion pair is given by

$$\mathcal{L} = -\frac{gm_f}{2m_W} H\,\bar{f}\,f$$

The partial width is then given by

$$\Gamma(H \to f\bar{f}) = N_f \frac{g^2 m_f^2 m_H}{32\pi m_W^2}\left(1-\frac{4m_f^2}{m_H^2}\right)^{3/2}$$

where $N_f = 1$ (3) for a lepton (quark).

Large logarithms that appear in QCD radiative corrections can be resummed by using the running quark mass $\bar{m}_Q(m_H)$ evaluated at the scale m_H. Naively, the running quark mass is given by

$$\bar{m}_Q(\mu) = \bar{m}_Q(M_Q)\frac{c(\alpha_s(\mu)/\pi)}{c(\alpha_s(M_Q)/\pi)}$$

where the running $\overline{MS}$ mass $\bar{m}_Q$ at the scale of *pole* mass M_Q is given by

$$\bar{m}_Q(M_Q) = \frac{M_Q}{1+\frac{4}{3}\frac{\alpha_s(M_Q)}{\pi}+K_Q\left(\frac{\alpha_s(M_Q)}{\pi}\right)^2}$$

The function $c(x)$ is given by

$$\begin{aligned}
c(x) &= \left(\frac{25}{6}x\right)^{\frac{12}{25}}\left[1+1.014x+1.389x^2\right] \qquad \text{for } M_c<\mu<M_b \\
c(x) &= \left(\frac{23}{6}x\right)^{\frac{12}{23}}\left[1+1.175x+1.501x^2\right] \qquad \text{for } M_b<\mu<M_t \\
c(x) &= \left(\frac{21}{6}x\right)^{\frac{12}{21}}\left[1+1.398x+1.793x^2\right] \qquad \text{for } M_t<\mu
\end{aligned}$$

- $H \to gg$: Higgs decays into a pair of gluons via a triangular loop of quarks. It can be described by an effective Lagrangian

$$\mathcal{L} = -\frac{g^2}{2m_W}\,\frac{\alpha_s(m_H)}{12\pi}\; I\, G^a_{\mu\nu}\, G^{a\,\mu\nu}\, H$$

where

$$I = \sum_q I_q, \qquad I_q = 3[2\lambda_q + \lambda_q(4\lambda_q - 1)f(\lambda_q)]$$

and

$$f(\lambda) = \begin{cases} -2\left(\sin^{-1}\frac{1}{2\sqrt{\lambda}}\right)^2, & \text{for } \lambda > \frac{1}{4} \\ \frac{1}{2}\left(\ln\frac{\eta^+}{\eta^-}\right)^2 - \frac{\pi^2}{2} + i\pi\ln\frac{\eta^+}{\eta^-}, & \text{for } \lambda < \frac{1}{4} \end{cases}$$

with $\eta^{\pm} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \lambda}$. With the effective Lagrangian the partial width into a gluon pair is calculated to be

$$\Gamma(H \to gg) = \frac{g^2\alpha_s^2(m_H)}{288\pi^3}\,\frac{m_H^3}{m_W^2}|I|^2$$

- $H \to \gamma\gamma, Z\gamma$: Higgs decay into a pair of photons via triangular loops of quarks, leptons, the W boson, and charged bosons if there exist.

Again, the decay can be described by an effective Lagrangian

$$\mathcal{L} = -\frac{g^2}{2m_W}\frac{\alpha}{8\pi}\; I\; F^a_{\mu\nu}\, F^{a\,\mu\nu}\; H$$

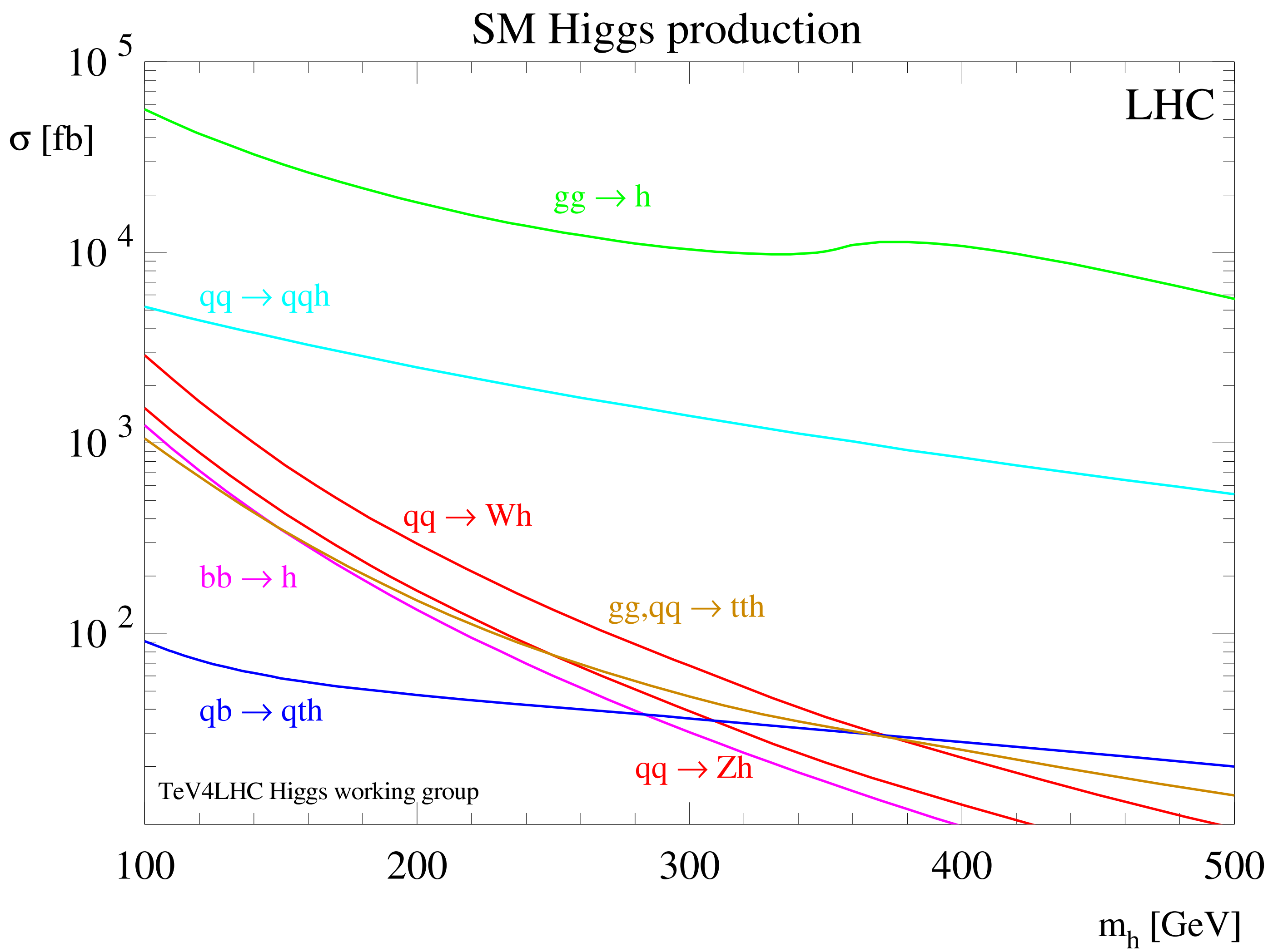
where

$$I = \sum_q Q_q^2 I_q + \sum_\ell Q_\ell^2 I_\ell + I_W + I_S$$

The individual I_i are given by

$$\begin{aligned}
I_q &= 3[2\lambda_q + \lambda_q(4\lambda_q - 1)f(\lambda_q)] \\
I_\ell &= 2\lambda_\ell + \lambda_\ell(4\lambda_\ell - 1)f(\lambda_\ell) \\
I_W &= 3\lambda_W(1 - 2\lambda_W)f(\lambda_W) - 3\lambda_W - \frac{1}{2} \\
I_S &= -\lambda_S[1 + 2\lambda_S f(\lambda_S)]
\end{aligned}$$

Production of the SM Higgs boson



- Gluon fusion: Because of large gluon luminosity at the LHC, this turns out to be the most dominant channel, though it is loop suppressed. The top quark in the loop dominates. In the large m_t limit, it can be described by an effective Lagrangian:

$$\mathcal{L} = \frac{\alpha_s}{12\pi} \frac{H}{v} (1 + \Delta) \, \mathrm{Tr} \, G_{\mu\nu} G^{\mu\nu}$$

  where the coefficient Δ is known up to $O(\alpha_s^3)$. The NLO calculation gives a K factor of about $0.8 - 1.0$ of the LO calculation. The NNLO calculation was done in the large m_t limit, the K factor of which is about $10 - 25\%$ of the NLO result. The scale dependence is reduced substantially. Further corrections are also calculated.

- Gauge boson fusion: This is the exact calculation of the WW fusion in the *effective W approximation*. The kinematics of the accompanied quarks are obtained. These two jets turn out to be energetic and forward. Since the exchanged W bosons are colorless, there are no hadronic radiations between the two quark jets (*rapidity gap*). The QCD calculation was calculated to be small.

- Associated production with a gauge boson: The associated production with a W or a Z boson has been the most useful channel to search for the Higgs boson at the Tevatron and at LEP. Leptonic decays of W and Z are most useful to separate from the backgrounds

$$pp \to WH \to (\ell\nu)(b\bar{b})$$

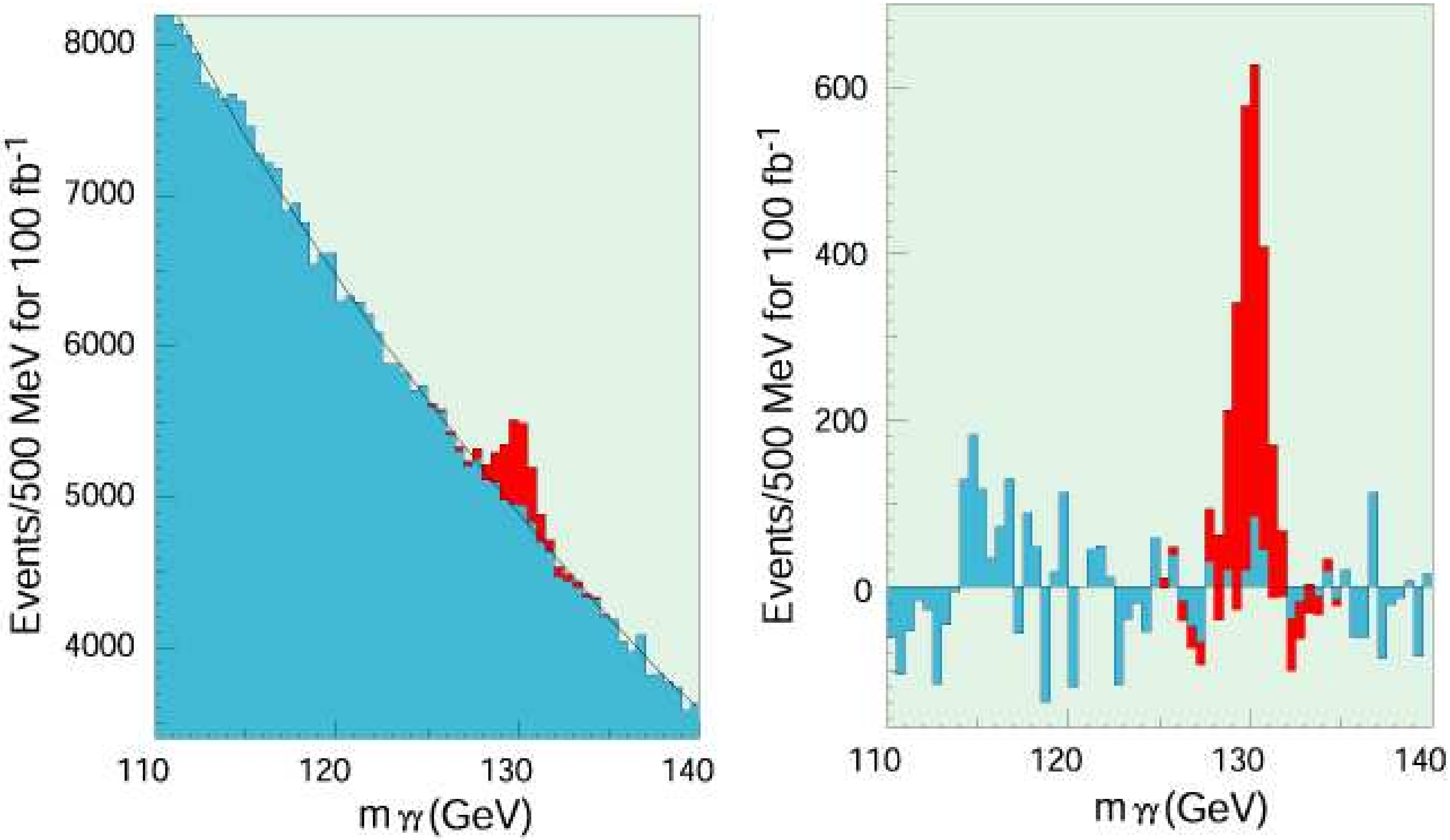
$$pp \to ZH \to (\ell^+\ell^-)(b\bar{b})$$

- Associated production with a $t\bar{t}$ pair: Since the top-yukawa coupling is large, the associated production is reasonably large. This is also one of the good channels to measure the top Yukawa coupling. The QCD correction is order 20%.

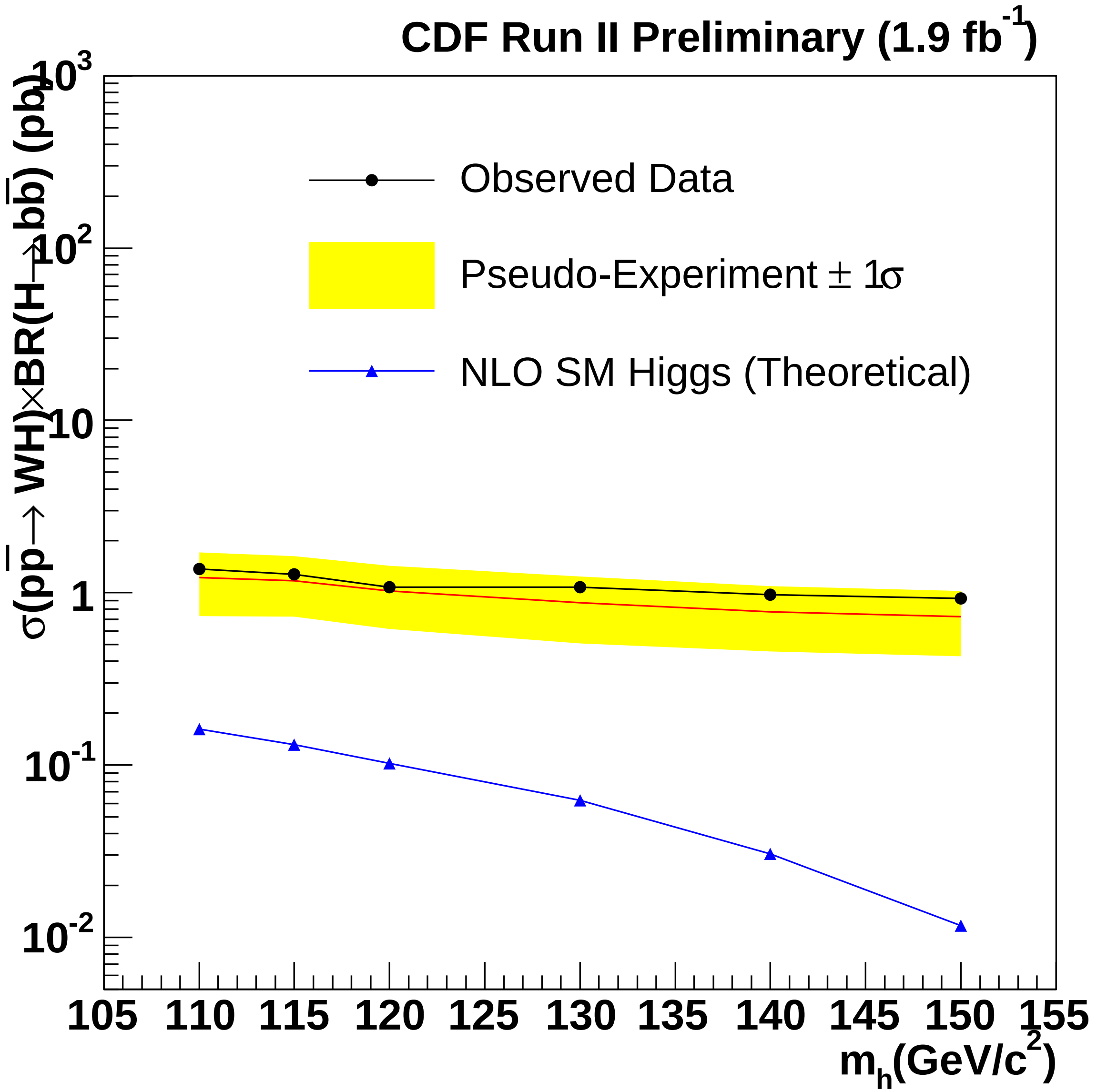
- $b\bar{b}$ and gb fusion:This is usually small. But for some SUSY models with large $\tan\beta$ the bottom-Yukawa is enhanced.

Detection and searches of the SM Higgs boson

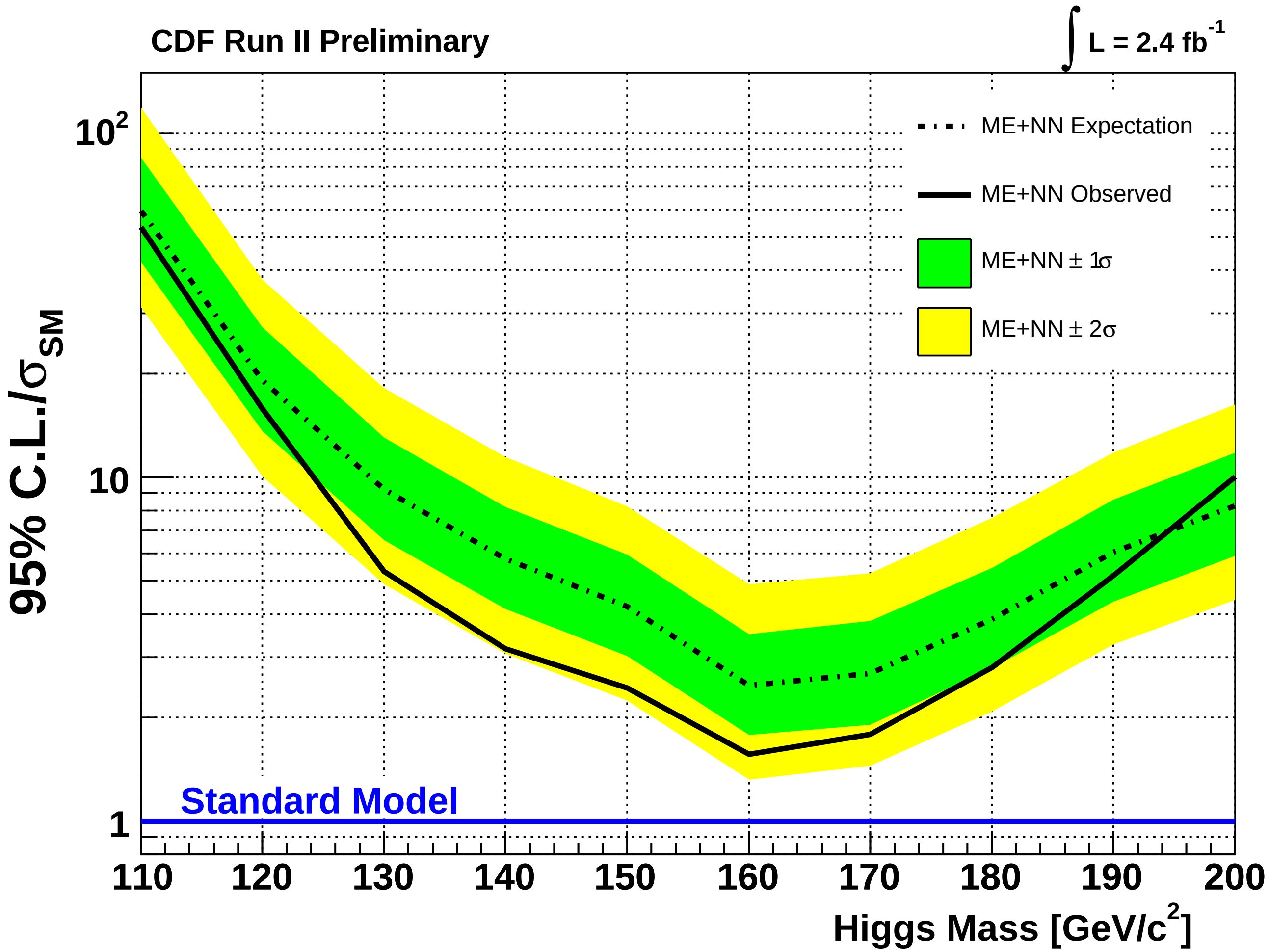
- $gg \to h \to \gamma\gamma$: for $m_H \lesssim 130$ GeV this is one of the important channel for the discovery of intermediate Higgs boson. But this mode will contain uncertainties due to new physics. New particles can exist in the triangular loop that may decrease or increase the rate.


8000
7000
6000
5000
4000
Events/500 MeV for 100 fb-1
110
120
130
140
m γγ (GeV)
600
400
200
0
Events/500 MeV for 100 fb-1
110
120
130
140
m γγ (GeV)

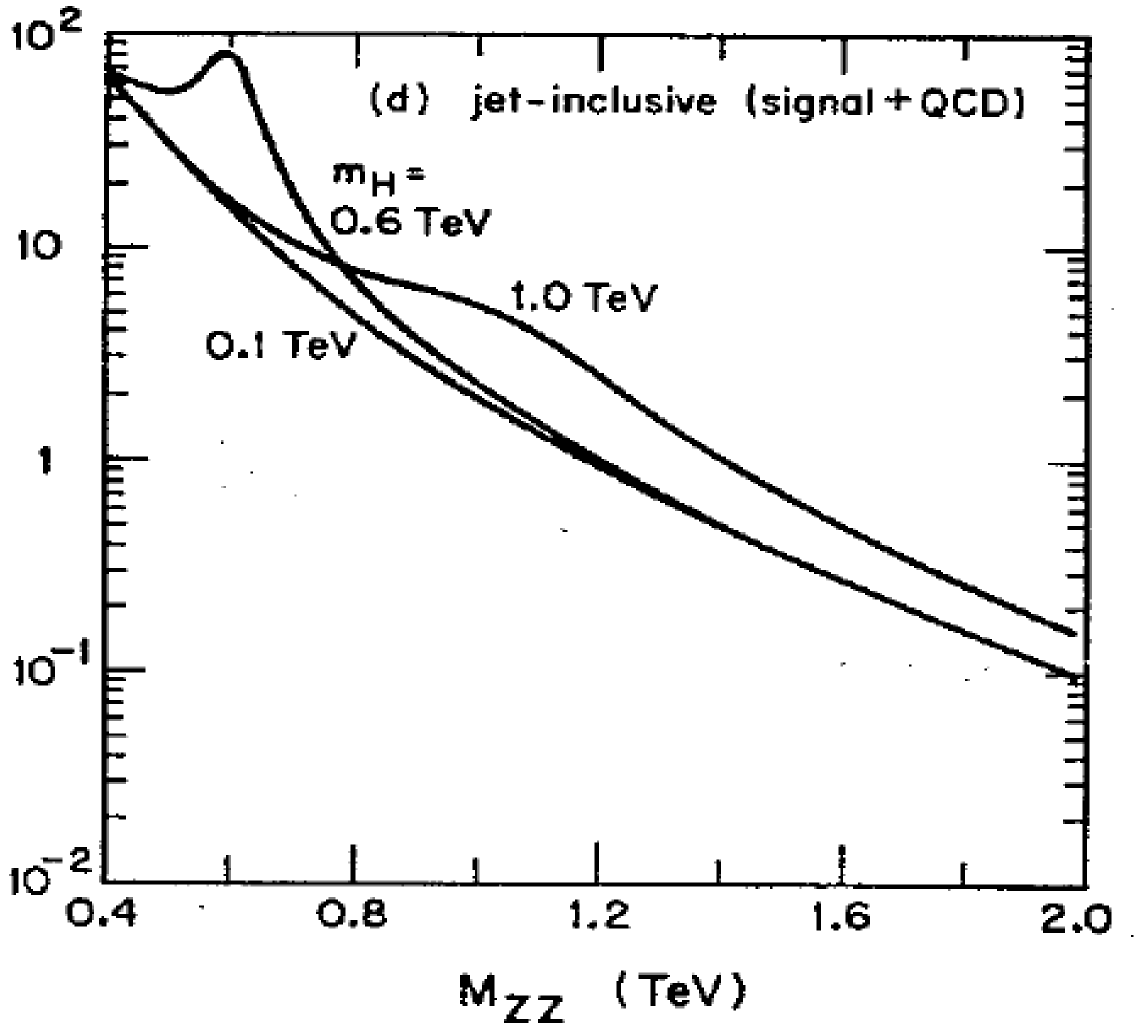
- For m_h upto about 130 GeV, $h \to b\bar{b}$ dominates. Besides the $\gamma\gamma$ mode one can make use of the associated production to look at the $b\bar{b}$ mode. In fact, Tevatron has been searching for the Higgs boson using this mode. Current limits from the Tevatron:


CDF Run II Preliminary (1.9 fb^{-1})
Observed Data
Pseudo-Experiment ± 1σ
NLO SM Higgs (Theoretical)
$\sigma(p\bar{p} \rightarrow WH) \times BR(H \rightarrow b\bar{b})$ (pb)
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
105 110 115 120 125 130 135 140 145 150 155
m_h(GeV/c^2)

- For $m_h \gtrsim 160$ GeV the mode $h \to WW^* \to (\ell\nu)(\ell\nu)$ becomes important.



- For even heavier Higgs $h \to ZZ \to (\ell\bar{\ell}\ell\bar{\ell})$ is the golden mode.



Current limits on Higgs boson mass

- Negative results in search in quarkonium decays. It ruled out the Higgs boson mass lighter than the Υ. Higgs boson couples to the heavy quark, one can search for

$$V(Q\bar{Q}) \to H\gamma, \qquad Q = c, b$$

The decay rate normalized to the lepton width is

$$\frac{\Gamma(V \to H\gamma)}{\Gamma(V \to e^+e^-)} \simeq K \frac{G_F m_V^2}{4\sqrt{2}\pi\alpha} \left(1 - \frac{m_H^2}{m_V^2}\right) \simeq 10^{-4} K \left(\frac{m_V}{1\ \text{GeV}}\right)^2 \left(1 - \frac{m_H^2}{m_V^2}\right)$$

- Search at LEPI and II:

$$Z \to f\bar{f}h\,, \qquad e^+e^- \to Zh \to (\ell^+\ell^-,\, b\bar{b},\, \nu\bar{\nu},\, q\bar{q})\,(b\bar{b},\, \tau^+\tau^-)$$

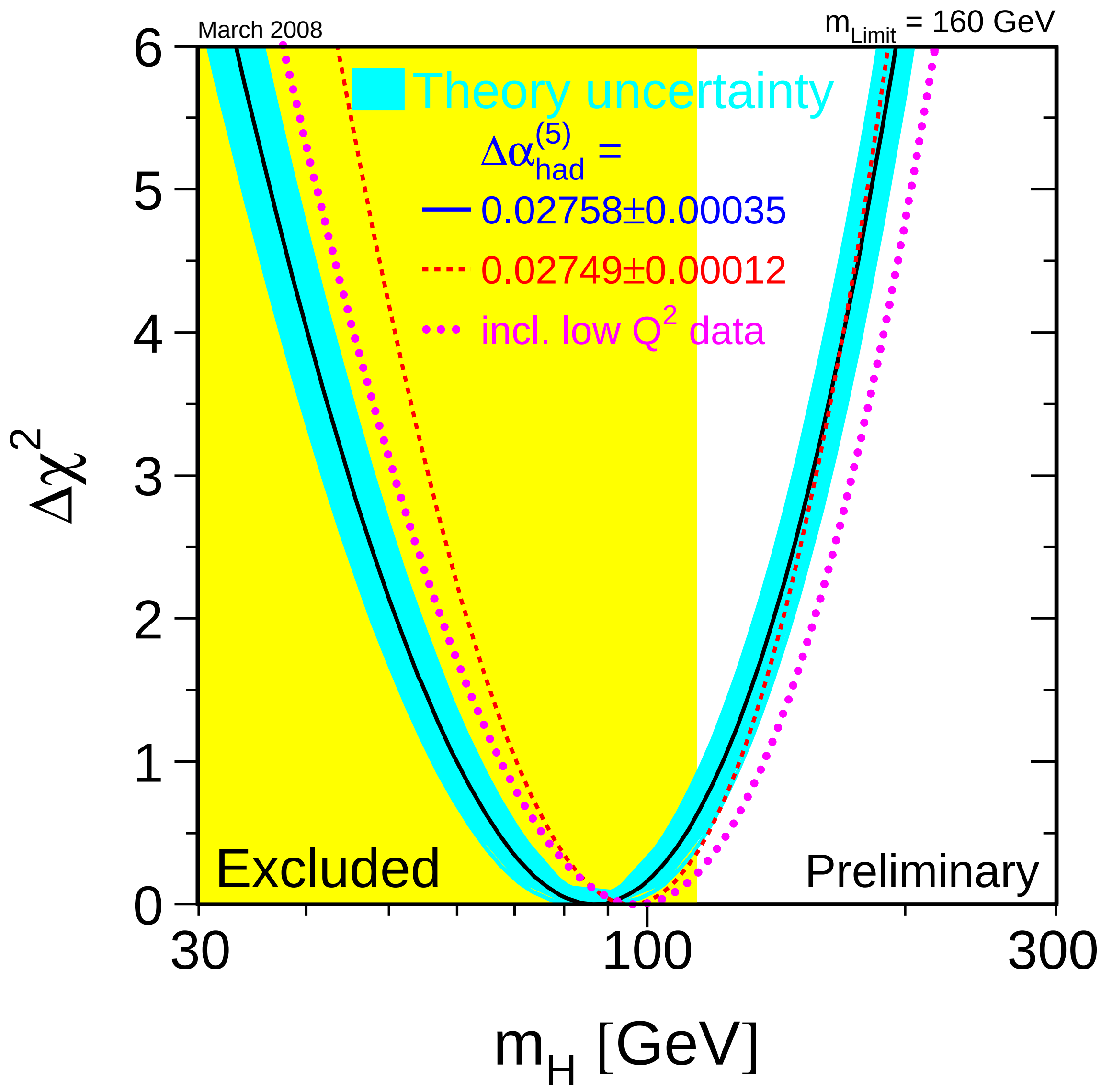
Negative results put $m_h > 114.4$ GeV

- Search at the Tevatron:

$$p\bar{p} \to W^{\pm}h \to (\ell\nu,\, q\bar{q})\,(b\bar{b},\, \tau^{+}\tau^{-})$$

  Negative results has given upper limits on the production cross sections as a function of m_H.

- Precision electroweak data and measured top-quark and W boson masses have put an upper bound on m_H.


March 2008
m_{Limit} = 160 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
0
1
2
3
4
5
6
30
100
300