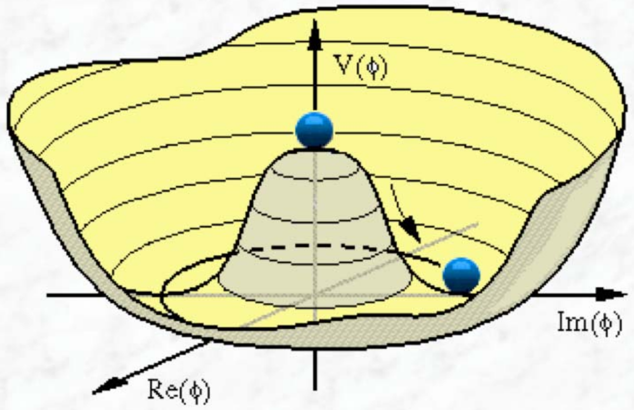
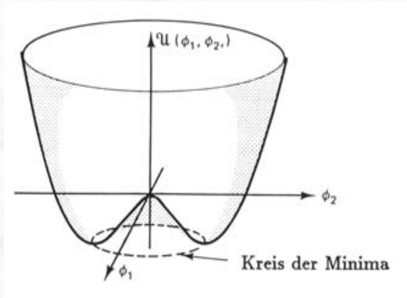
Physics at the LHC

Part 3

Search for the Higgs Boson

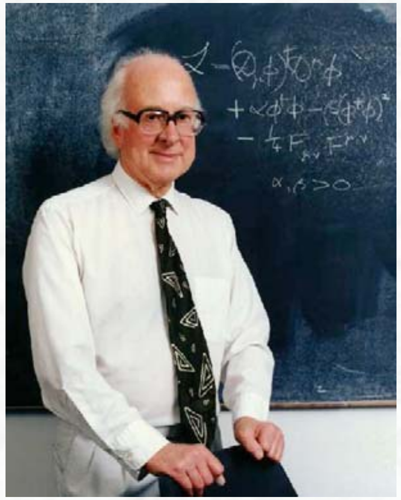


The Search for the Higgs Boson



- „Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics"

- „A new collider, such as the LHC must have the potential to detect this particle, should it exist."



Why do we need the Higgs Boson?

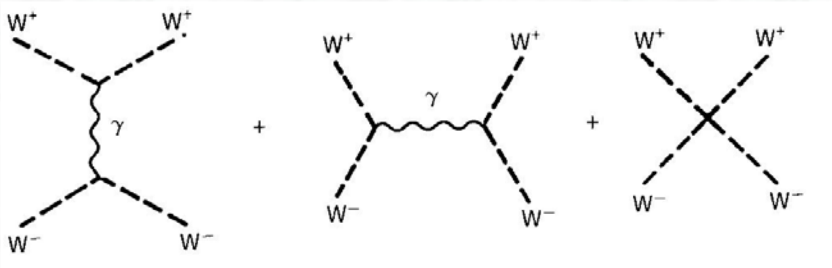
The Higgs boson enters the Standard Model to solve two fundamental problems:

- Masses of the vector bosons W and Z:

Experimental results: $M_W = 80.399 \pm 0.023$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

A local gauge invariant theory requires massless gauge fields

- Divergences in the theory (scattering of W bosons)



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

Solution to **both** problems:

- create mass via spontaneous breaking of electroweak symmetry

- introduce a scalar particle that regulates the WW scattering amplitude

➔ **Higgs Mechanism**

The structure of the Standard Model

Fundamental principle: **Local gauge invariance**
Prototype: **Quantum Electrodynamics (QED)**

Free Dirac equation: $i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$

Lagrangian formalism: $L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi$

Local gauge transformation: $\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$

(derivative: $\partial_{\mu}\psi \rightarrow e^{i\alpha(x)}\partial_{\mu}\psi + ie^{i\alpha(x)}\psi\partial_{\mu}\alpha$,
$\delta_{\mu}\alpha$ term breaks the invariance of L)

Invariance of L under local gauge transformations can be accomplished by introducing a gauge field A_{μ}, which transforms as:

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha$$

where $e = g_e/4\pi$ = coupling strength

Can be formally achieved by the construction of a “modified” derivative

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

(covariant derivative)

→ Lagrangian of QED:

$$L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi + e\overline{\psi}\gamma^{\mu}A_{\mu}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

interaction term

where $F_{\mu\nu}$ is the usual field strength tensor: $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

Note:

(i) Imposing local gauge invariance leads to the interacting field theory of QED

(ii) A mass term ($\frac{1}{2}m^2 A_{\mu}A^{\mu}$) for the gauge field A_{μ} would violate gauge invariance

Similar for the Standard Model interactions:

Quantum Chromodynamics (QCD):

$$D_\mu = \partial_\mu + igT_a G_\mu^a$$

$$G_\mu^a \rightarrow G_\mu^a - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G_\mu^c$$

SU(3) transformations, 8 gauge fields,
8 massless gluons, gluon self-coupling

- T_a (a = 1,…,8) generators of the SU(3) group (independent traceless 3x3 matrices)
- G_μ gluon fields
- g = coupling constant

Electroweak Interaction (Glashow, Salam, Weinberg):

$SU(2)_L \times U(1)_Y$ transformations,
4 gauge fields, (W_μ^1, W_μ^2, W_μ^3, B_μ)

Physical states:

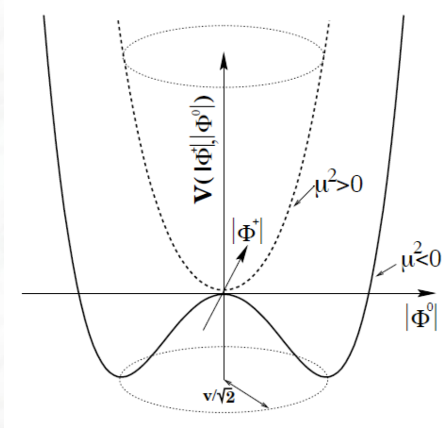
$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right)$$

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3$$

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3$$

The Higgs mechanism

Spontaneous breaking of the SU(2) x U(1) gauge symmetry



- Scalar fields are introduced

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Potential :

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

- Lagrangian for the scalar fields:
  g, g' = SU(2), U(1) gauge couplings

$$L_2 = \left| \left(i\partial_\mu - g\mathbf{T}\cdot\mathbf{W}_\mu - g'\frac{Y}{2}B_\mu \right)\phi \right|^2 - V(\phi)$$

- For $\mu^2 < 0$, $\lambda > 0$,
  minimum of potential:

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v^2 = -\mu^2/\lambda$$

- Perturbation theory around ground state:

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \Rightarrow$$

Masses of the gauge bosons:

$$\left|\left(-ig\frac{\boldsymbol{\tau}}{2}\cdot\mathbf{w}_\mu - i\frac{g'}{2}B\right)\phi\right|^2$$

$$=\frac{1}{8}\left|\begin{pmatrix} gW_\mu^3 + g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g'B_\mu \end{pmatrix}\begin{pmatrix} 0 \\ v \end{pmatrix}\right|^2$$

$$=\frac{1}{8}v^2g^2\left[(W_\mu^1)^2 + (W_\mu^2)^2\right] + \frac{1}{8}v^2(g'B_\mu - gW_\mu^3)(g'B^\mu - gW^{3\mu})$$

$$=\left(\frac{1}{2}vg\right)^2 W_\mu^+W^{-\mu} + \frac{1}{8}v^2(W_\mu^3, B_\mu)\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}$$

Particle content and masses

- Mass terms for the $W^{\pm}$ bosons:

$$M_{W^{\pm}} = \frac{1}{2} v g$$

- Remaining terms off-diagonal in W_μ^3 and B_μ:

$$\frac{1}{8} v^2 (W_\mu^3, B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} = \frac{1}{8} v^2 \left[g W_\mu^3 - g' B_\mu \right]^2 + 0 \left[g' W_\mu^3 + g B_\mu \right]^2$$

- Massless photon:

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} \quad with \quad M_A = 0$$

- Massive neutral vector boson:

$$Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \quad with \quad M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$

Important relations in the Glashow-Salam-Weinberg model:

- Relation between the gauge couplings:

$$\frac{g'}{g} = \tan\theta_W$$

→ Important prediction of the GSW with a Higgs doublet:

$$\frac{M_W}{M_Z} = \cos\theta_W$$

or expressed in terms of the ρ parameter:

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

- From the M_W relation the value of the vacuum expectation value of the Higgs field can be calculated:

$$\frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \qquad \rightarrow \quad v = 246\ GeV$$

where G_F = Fermi constant, know from low energy experiments (muon decay)

Masses of the Fermions:

- The same Higgs doublet which generates $W^{\pm}$ and Z masses is sufficient to give masses to the fermions (leptons and quarks):

  e.g. for electrons: use an arbitrary coupling G_e

$$L_3 = -G_e \left[(\bar{\nu}_e, \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \bar{e}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right]$$

- Spontaneous symmetry breaking:

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

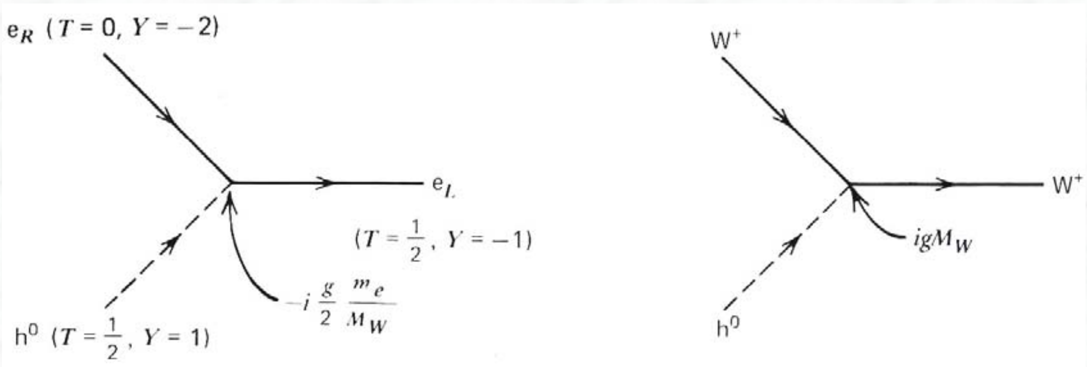
$$L_3 = -\frac{G_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) h$$

mass term

interaction term with the Higgs field

- Important relation: coupling of the Higgs boson to fermions is proportional to their mass

$$G_f = \frac{\sqrt{2}\, m_f}{v}$$



and finally...... a massive scalar with self-coupling, the **Higgs boson**:

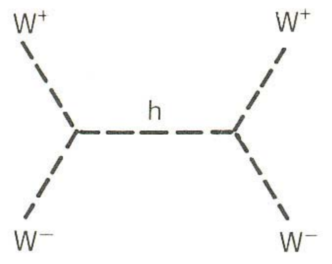
• Mass: $m_h^2 = 2v^2\lambda$

(since λ is not predicted by theory, the mass of the Higgs boson is unknown)

• Self-coupling: $- \lambda v h^3 - \frac{1}{4}\lambda h^4$

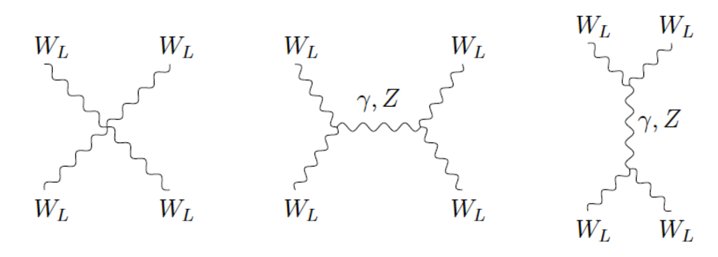
….. and:

• The additional diagram, with Higgs boson exchange, regulates the divergences in the longitudinal WW scattering



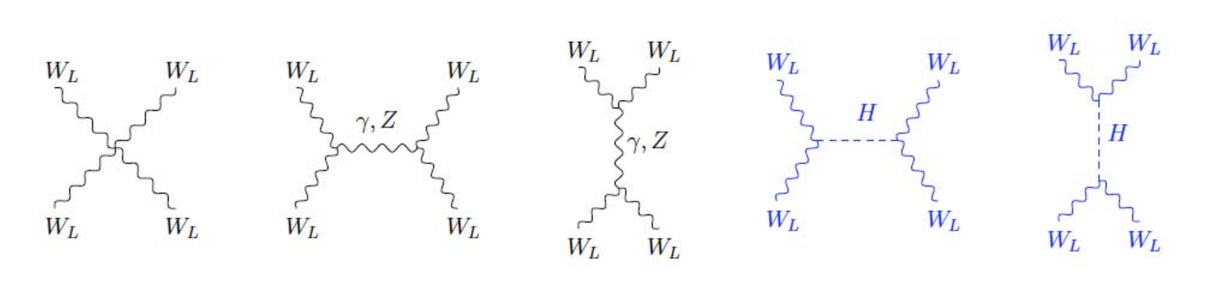
The Higgs boson as a UV regulator

Scattering of longitudinally polarized W bosons



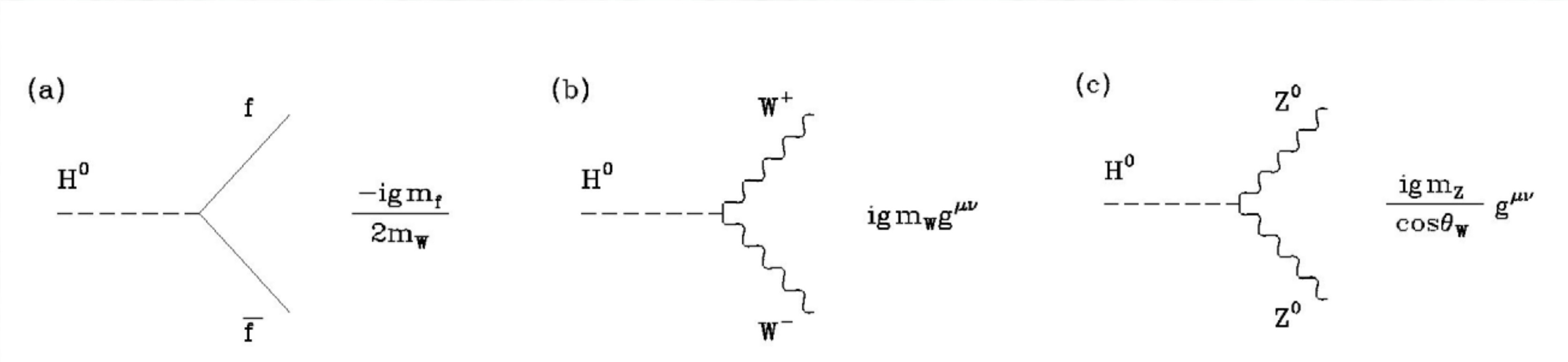
$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{m_W^2} \quad \text{for} \quad s \rightarrow \infty$$

Higgs boson guarantees unitarity (if its mass is < ~1 TeV)



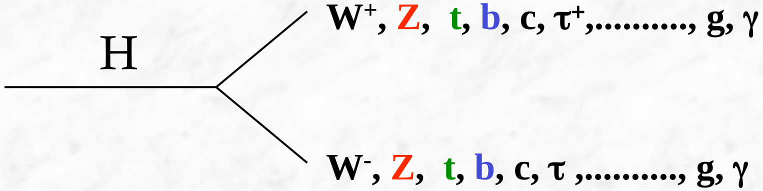
$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$

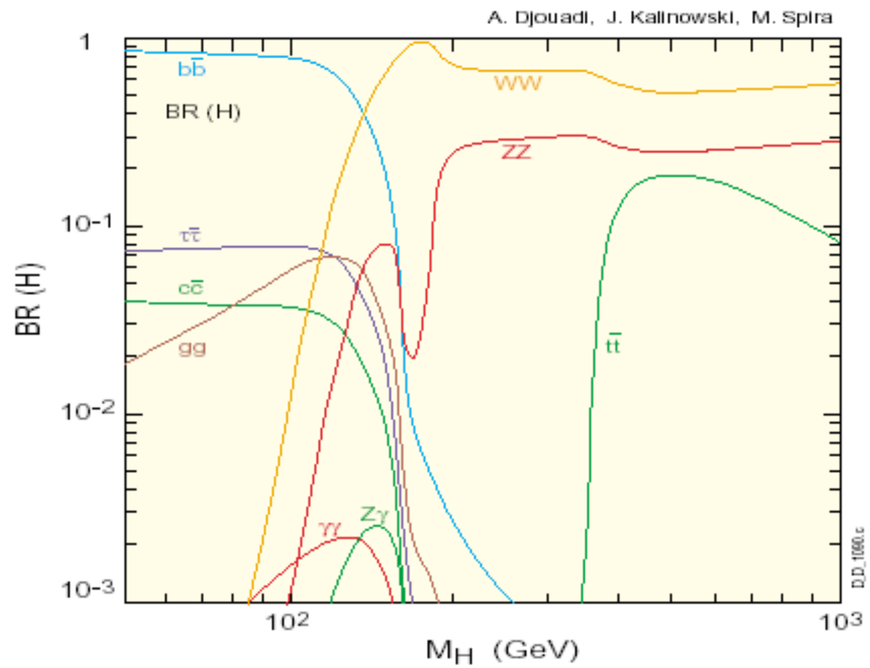
8.2 Higgs boson properties



Properties of the Higgs Boson

The decay properties of the Higgs boson are fixed, if the **mass** is known:





$$\Gamma(H \rightarrow f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H$$

$$\Gamma(H \rightarrow VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2)\beta_V$$

$$\text{where}: \quad \delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_V^2, \quad \beta = \text{velocity}$$

$$\Gamma(\mathrm{H} \rightarrow \mathrm{gg}) = \frac{G_F \alpha_a^2 (M_H^2)}{36\sqrt{2\pi^3}} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_a}{\pi}\right]$$

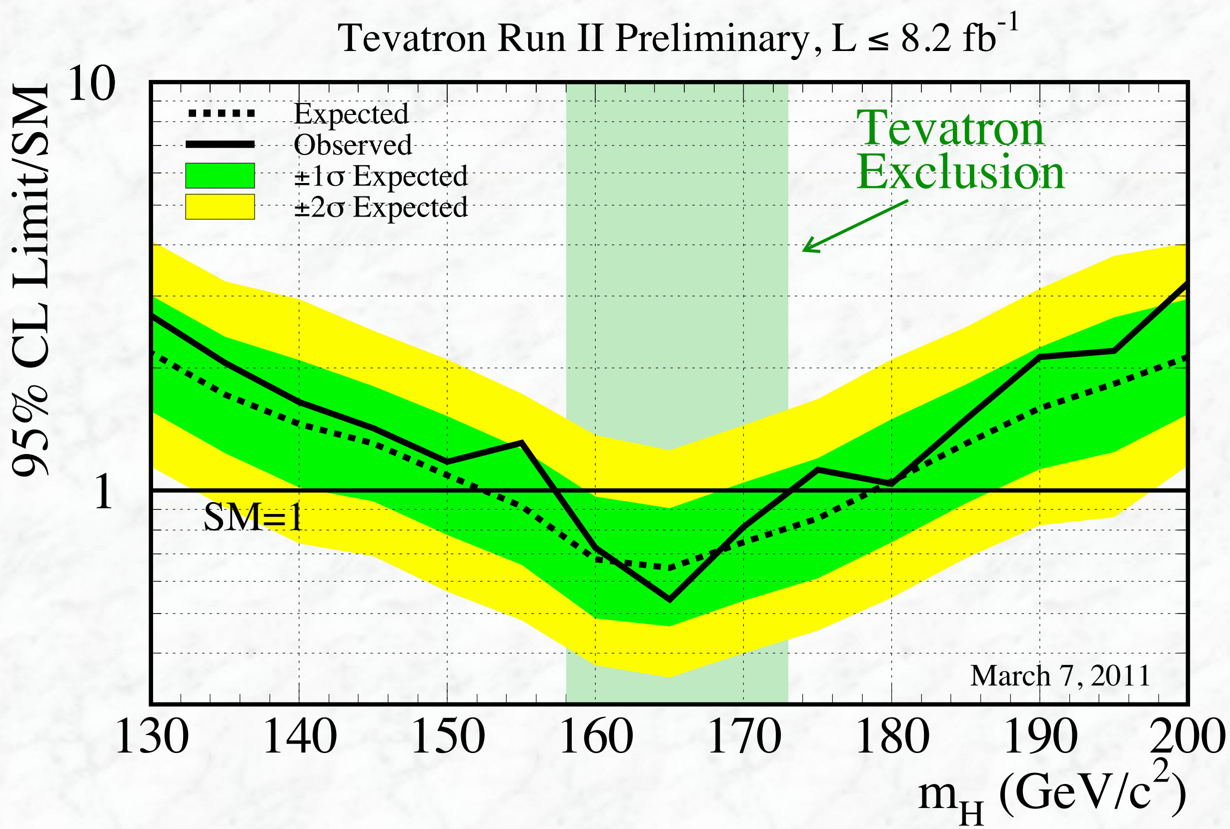
$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha_a^2}{128\sqrt{2\pi^3}} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

The Higgs boson couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

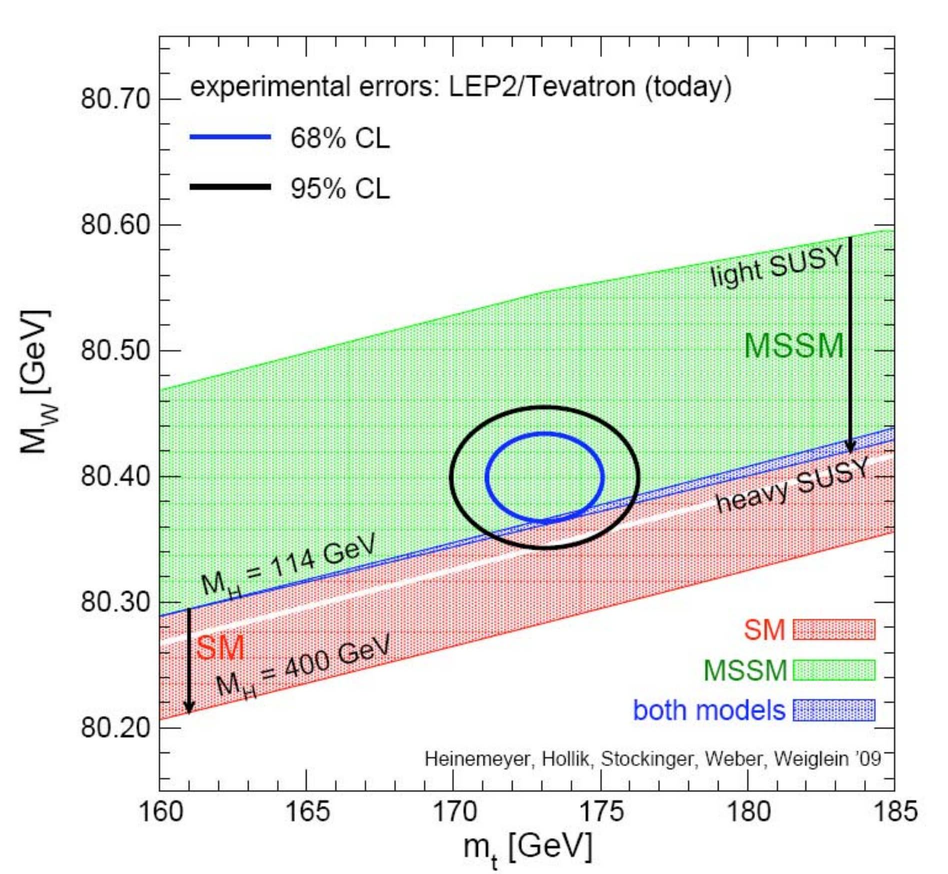
What do we know about the Higgs Boson today?

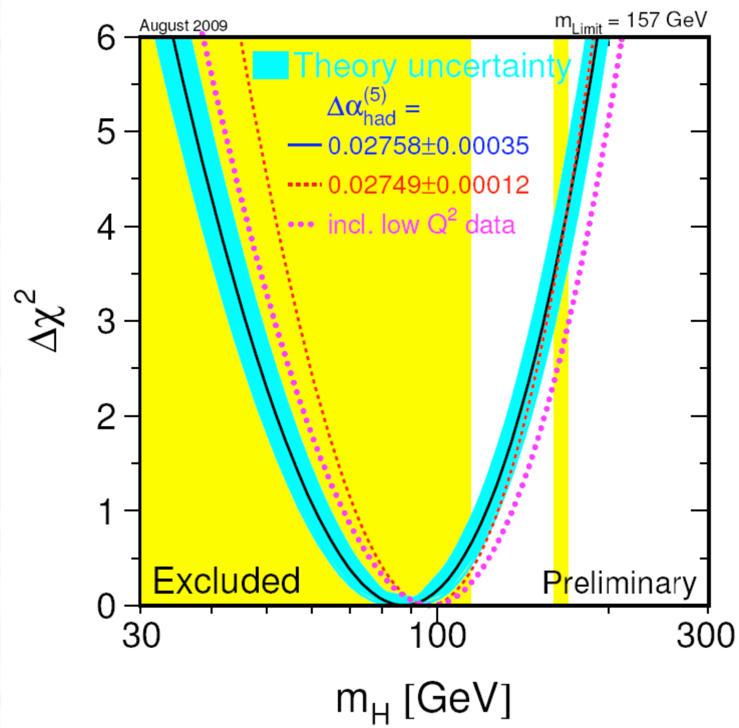
- Mass not predicted by theory, except that m_H < ~1000 GeV
- m_H > 114.4 GeV from direct searches at LEP
  m_H < 158 GeV .or. m_H > 173 GeV from direct searches at the Tevatron



What do we know about the Higgs Boson today? (cont.)

- Indirect limits from electroweak precision measurements (LEP, Tevatron and other experiments….)





m_H = 89 (+35) (-26) GeV/c^2

m_H < 158 GeV/c^2 (95 % CL)

→ Higgs boson could be around the corner !

Addendum:

to convince you that quantum corrections exist and are measurable in the experiments

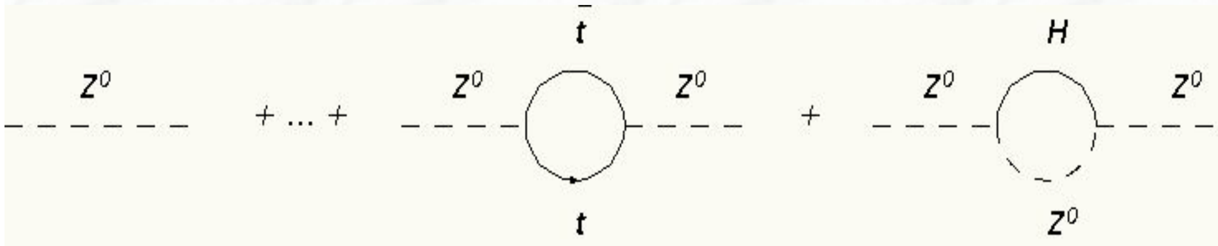
Example I
el.weak corr.

(ii) Indirekte Grenzen (aus Präzisionsmessungen):

- Im Standardmodell sind alle Wechselwirkungen der Teilchen untereinander (Kopplungsstärken) exakt festgelegt

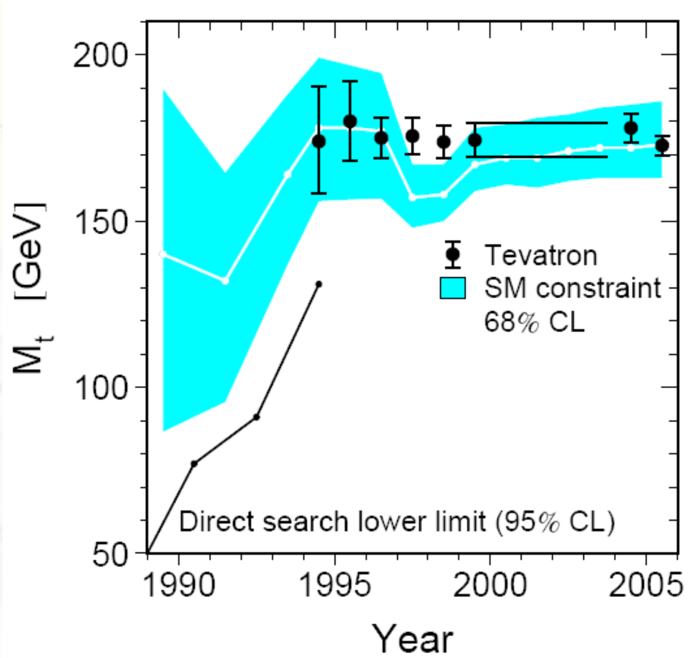
- In der Quantenfeldtheorie müssen auch Quantenkorrekturen in der Berechnung von Streuprozessen, Massen, ... etc. berücksichtigt werden. Hierbei treten Beiträge von sog. virtuellen Teilchen auf, d.h. Teilchen machen sich bereits weit unterhalb ihrer Energie/Massenskala bemerkbar.

Beispiel: Einfluss des Top-Quarks auf die Z^0-Masse (LEP, 1990er Jahre)

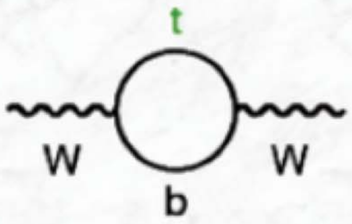


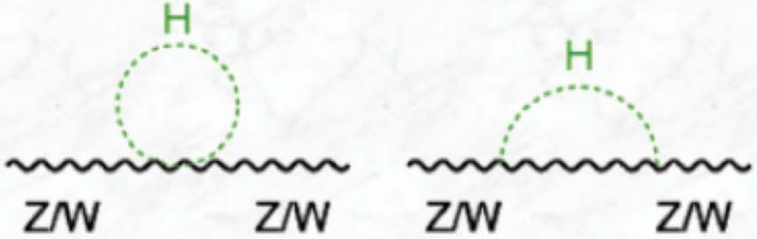
$$m_Z^2 = m_Z^2(0) \cdot (1 + \Delta(m_t, m_H, ...))$$

$$\Delta = ... + c_1 \cdot m_t^2 + ... + c_2 \cdot \ln m_H + ...$$



Electroweak radiative corrections





Standard Model relations
(lowest order)

$$\rho = \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2 \cos^2\theta_{\mathrm{W}}} = 1$$

$$\sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m^2\mathrm{Z}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}}$$

$$\alpha(0)$$

Relations including
radiative corrections

$$\vec{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_{\mathrm{eff}} = (1 + \Delta\kappa)\sin^2\theta_{\mathrm{W}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}} \cdot \frac{1}{(1-\Delta r)}$$

$$\alpha(m_{\mathrm{Z}}^2) = \frac{\alpha(0)}{1-\Delta\alpha}$$

$$\Delta\alpha = \Delta\alpha_{\mathrm{lepl}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{had}}^{(5)}$$

$$\Delta\rho, \Delta\kappa, \Delta r = f(m_t^2, \log(m_{\mathrm{H}}), \ldots)$$

Forward-backward asymmetries and fermion couplings

- Asymmetry at the Z pole (no interference) is small

$$A_{\rm FB} \sim g_{\rm A}^{e} g_{\rm V}^{e} g_{\rm A}^{f} g_{\rm V}^{f}$$

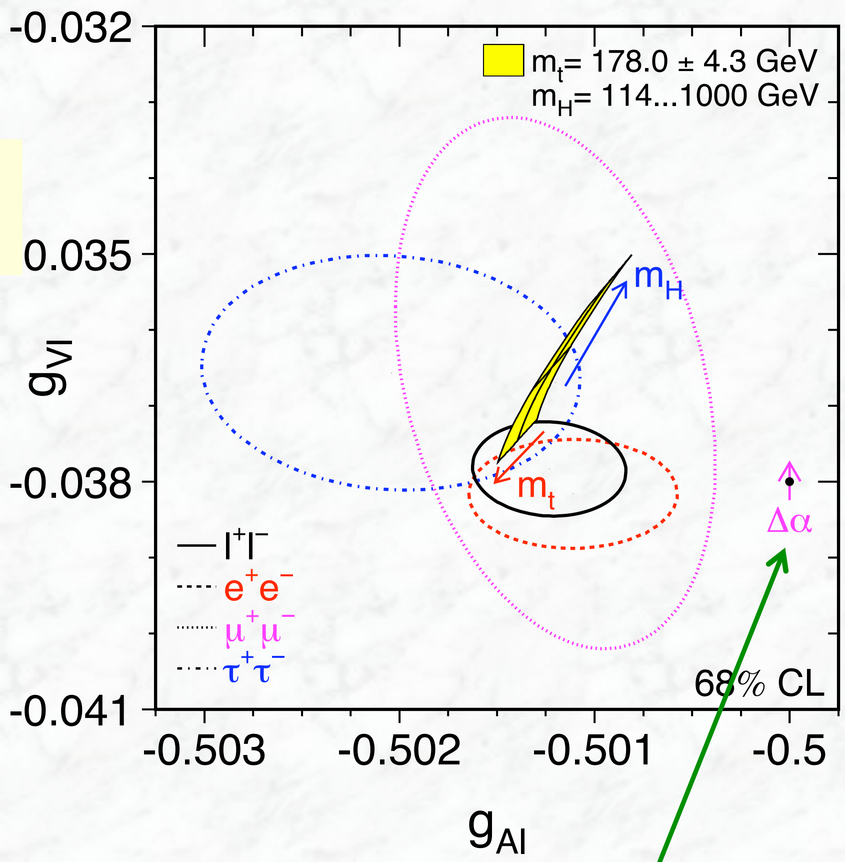
since g_V^f is small (in particular for leptons)

Example II
el.weak corr.

- For off-resonance points, the interference term dominates and gives larger contributions

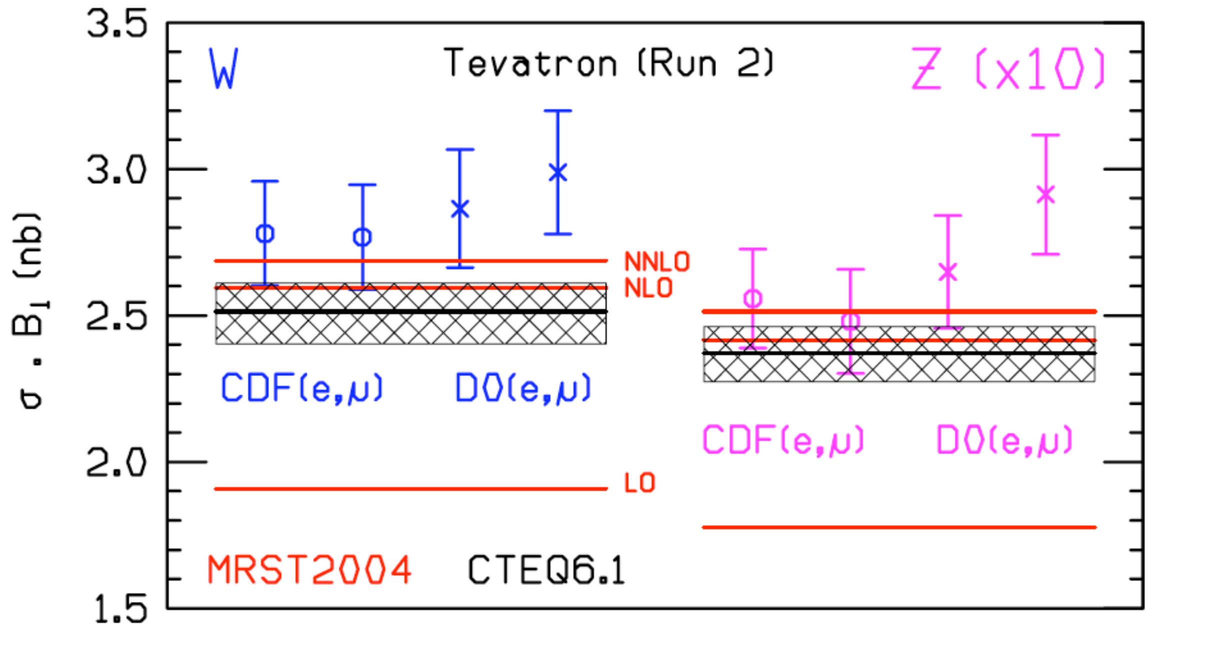
$$A_{\rm FB} \sim g_{\rm A}^{e} g_{\rm A}^{f} \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

- A_{FB} can be used for the determination of the fermion couplings



LO Standard Model prediction:
$g_A = T_3$
$g_V = T_3 - 2\,Q\,\sin^2\theta_W$

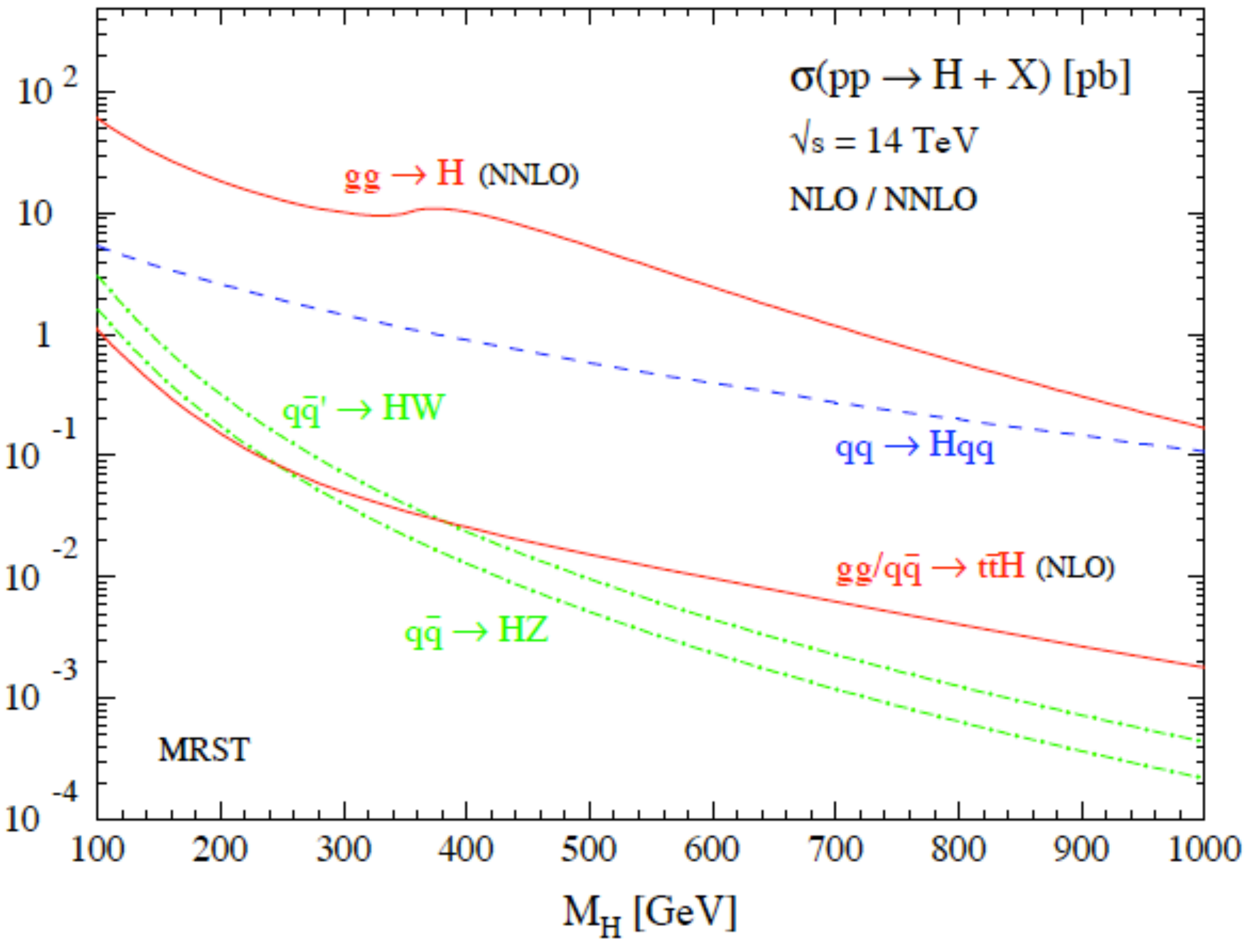
Example III
-QCD corrections-

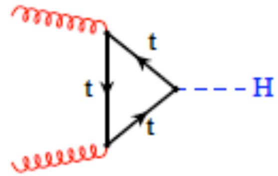


Predictions for the W and Z boson total cross sections at the Tevatron, using the MRST2004 and CTEQ pdfs, compared with measurements from the CDF and D0 collaborations. The predictions are shown at LO, NLO, and NNLO. For the NLO prediction the accompanying pdf uncertainties are shown as band.

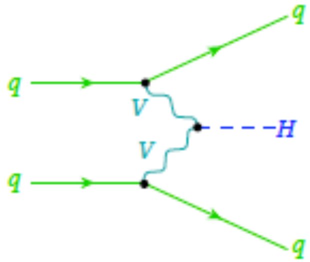
Are you convinced now ?

Higgs boson production at the LHC

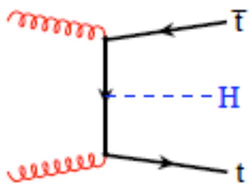




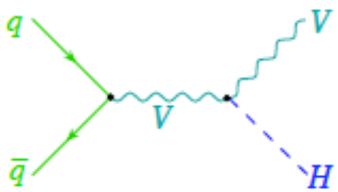
Gluon Fusion



Vector boson fusion

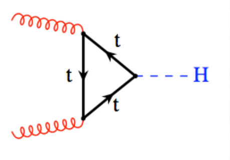


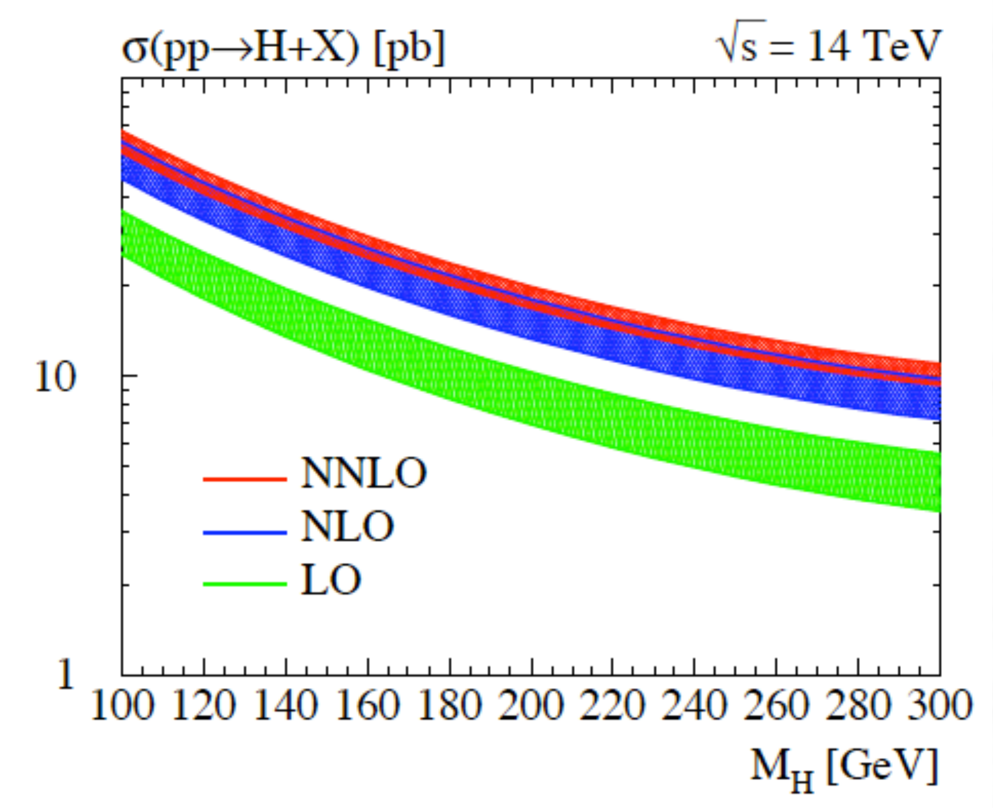
tt associated production



WH/ZH associated production

Higher order corrections:



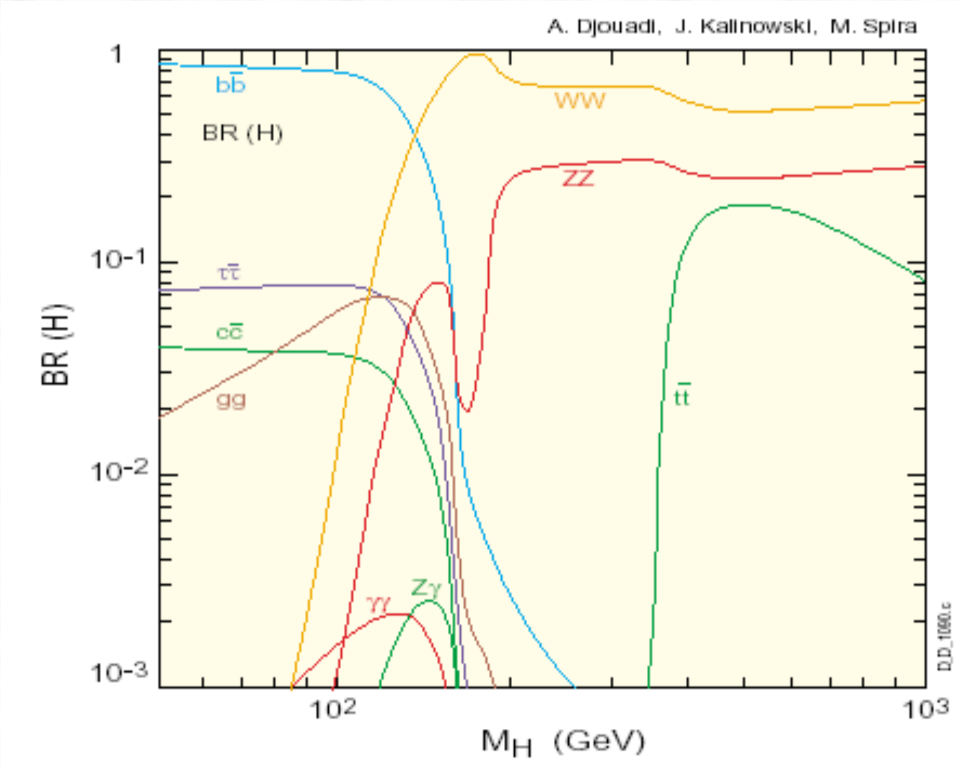


- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)

Independent variation of renormalization and factorization scales
(with $0.5\ m_H < \mu_F, \mu_R < 2\ m_H$)

Useful Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states
(via H → WW , ZZ)

at low mass:

Lepton and Photon final states
(via H → WW*, ZZ*)

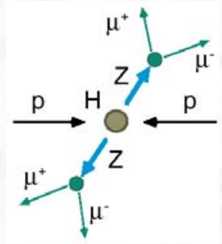
Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH, W/Z H)

(due to the huge QCD jet background, leptons from W/Z or tt decays)

$H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m$_H$ = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

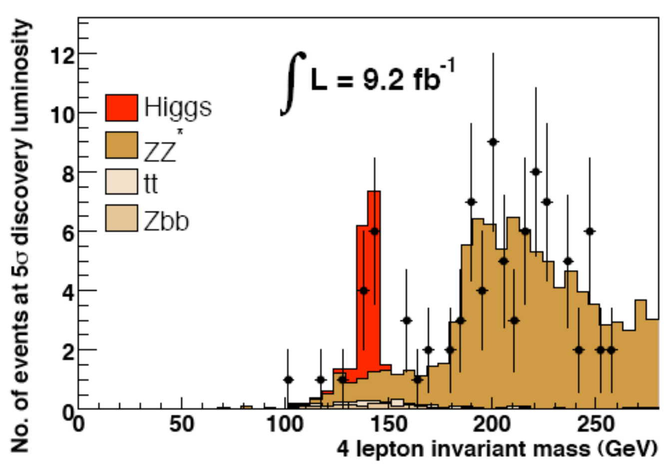
Background: Top production

$tt \rightarrow Wb\ Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$
σ BR $\approx$ 1300 fb

Associated production Z bb

$Z\ bb \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$

Background rejection:
Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)



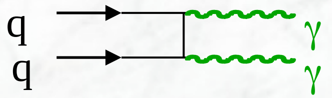
Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c^2

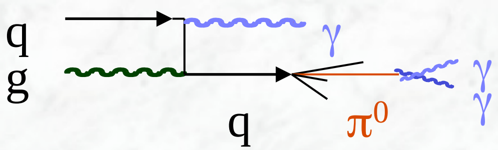
Decay modes at low mass: $H \rightarrow \gamma\gamma$

<u>Main backgrounds:</u>

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



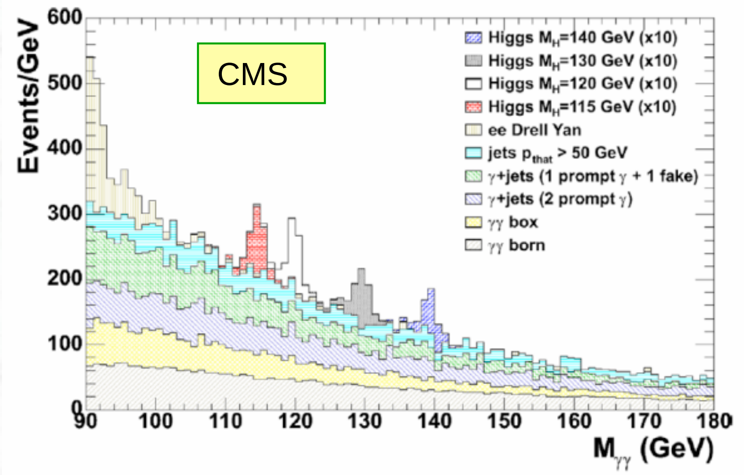
$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$ with large uncertainties

→ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

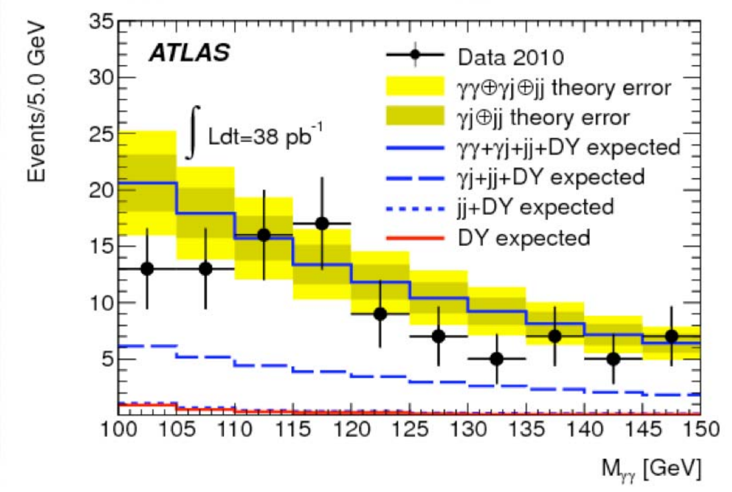
$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

- <u>Main exp. tools for background suppression</u>:
  - photon identification
  - γ / jet separation (calorimeter + tracker)

Sensitivity in the low mass region, however, higher integrated luminosities required



Signal expectation for 10 fb^{-1}



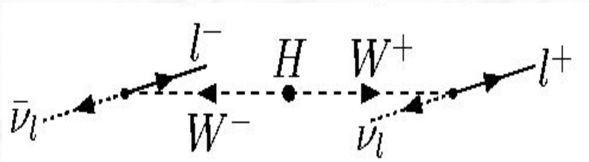
First look at the data: no evidence for an excess, also not yet expected

$H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

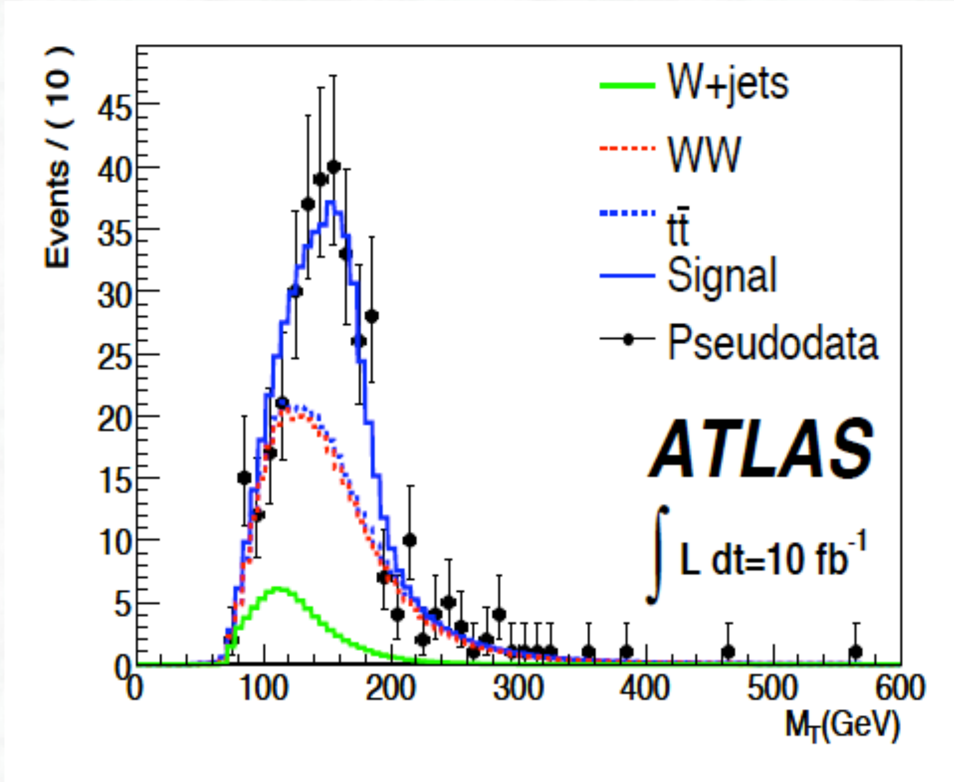
- Large $H \rightarrow WW$ BR for $m_H \sim 160\ GeV/c^2$
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt

- <u>Two main discriminants</u>:

  (i) Lepton angular correlation



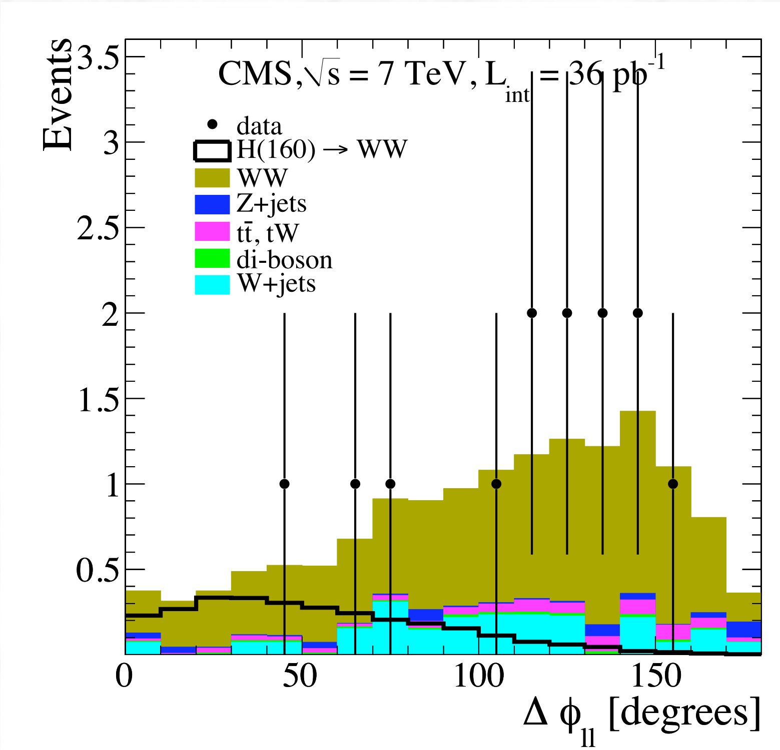
  (ii) Jet veto: no jet activity
  in central detector region

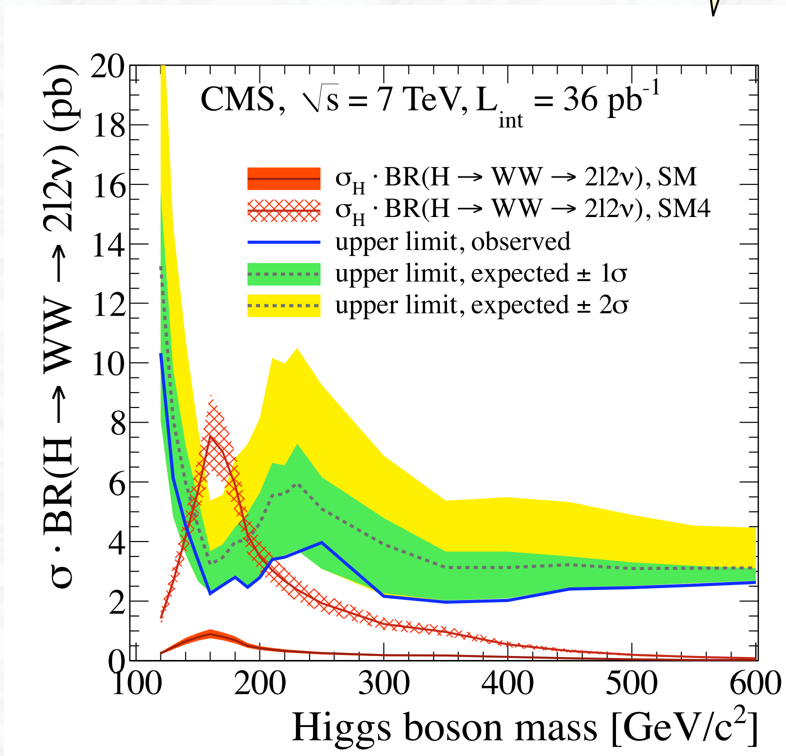


Channel with highest sensitivity !
Sensitive to a Standard Model Higgs boson already now, with 1 fb^{-1},
First sensitive results expected at Summer Conferences 2011 !

First results from the CMS collaboration on the H → WW → ℓν ℓν search:

new





- No evidence for a “Higgs-like” resonance in the first CMS data;
- Contributions form quarks of a possible 4th generation to the Higgs production can be excluded in the mass range around 150 GeV

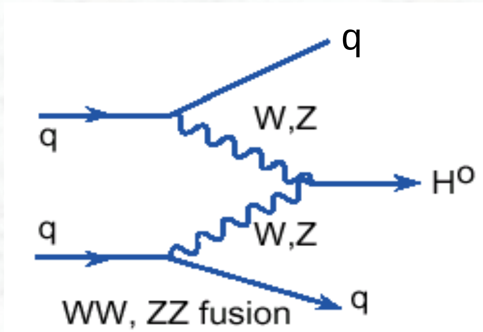
Vector Boson Fusion qq H

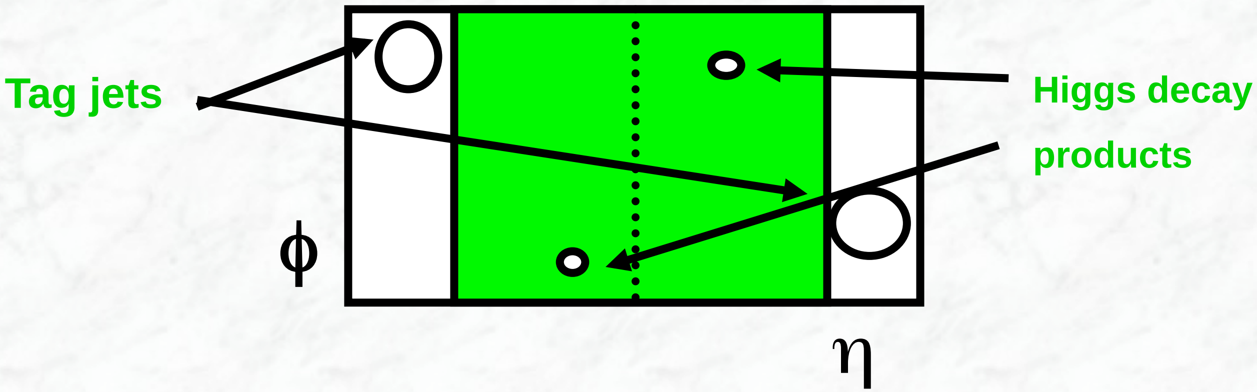
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

Distinctive Signature of:

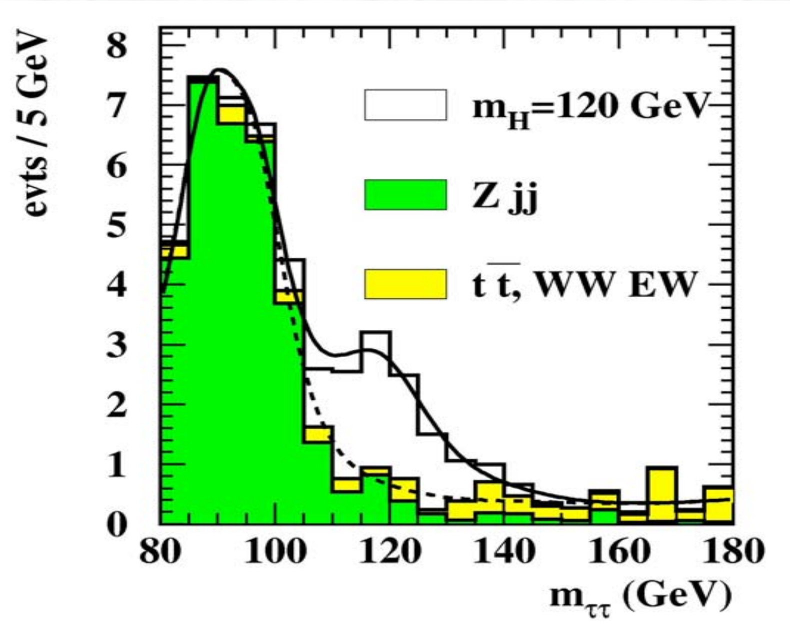
- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto





$H \to \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion

$qq\,H \to qq\,\tau\,\tau$
$\to qq\ \ell\nu\nu\ \ell\nu\nu$
$\to qq\ \ell\nu\nu\ h\nu$



Experimental challenge:

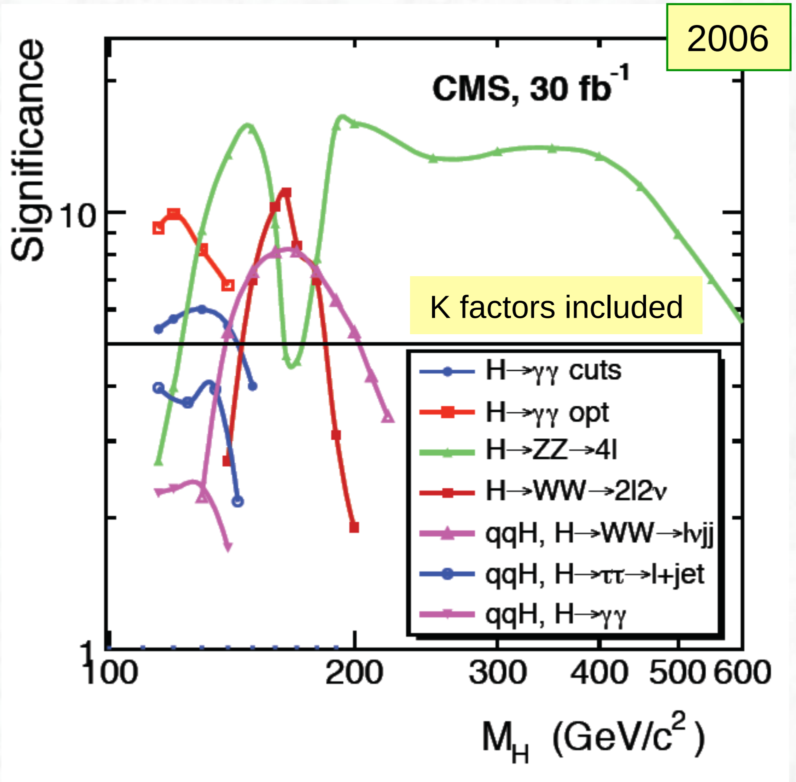
- Identification of hadronic taus
- Good E_T^{miss} resolution
  ($\tau\tau$ mass reconstruction in collinear approximation,
  i.e. assume that the neutrinos go in the direction of the visible decay products,
  good approximation for highly boosted taus)

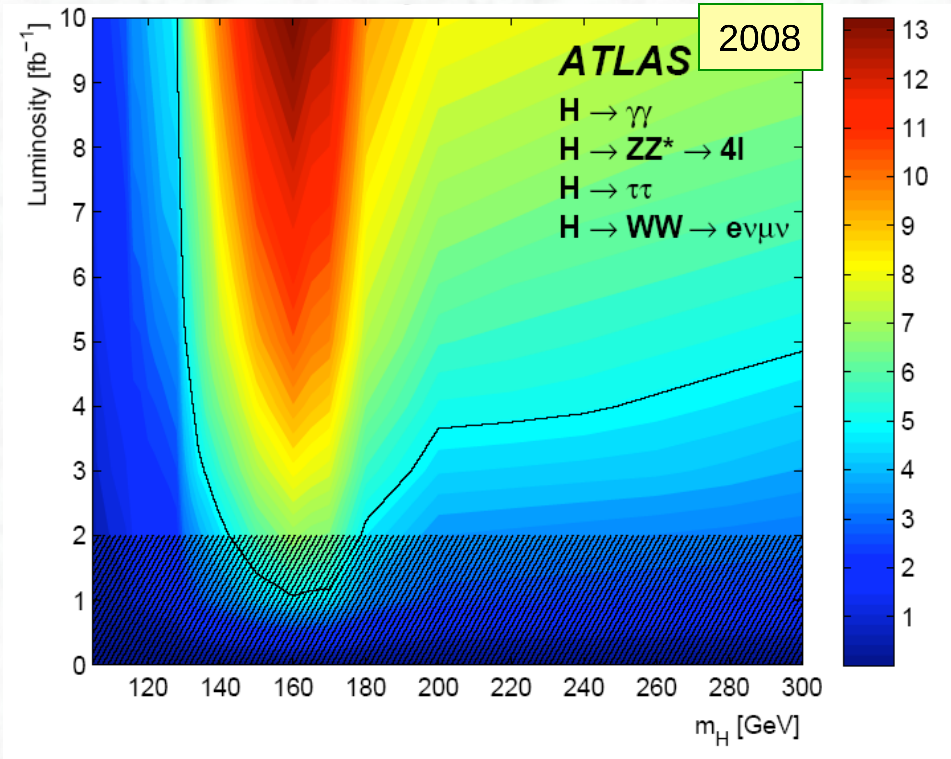
  → Higgs mass can be reconstructed

- Dominant background: $Z \to \tau\tau$

  the shape of this background must be controlled in the high mass region
  → use data ($Z \to \mu\mu$) to constrain it

LHC Higgs boson discovery potential for √s = 14 TeV





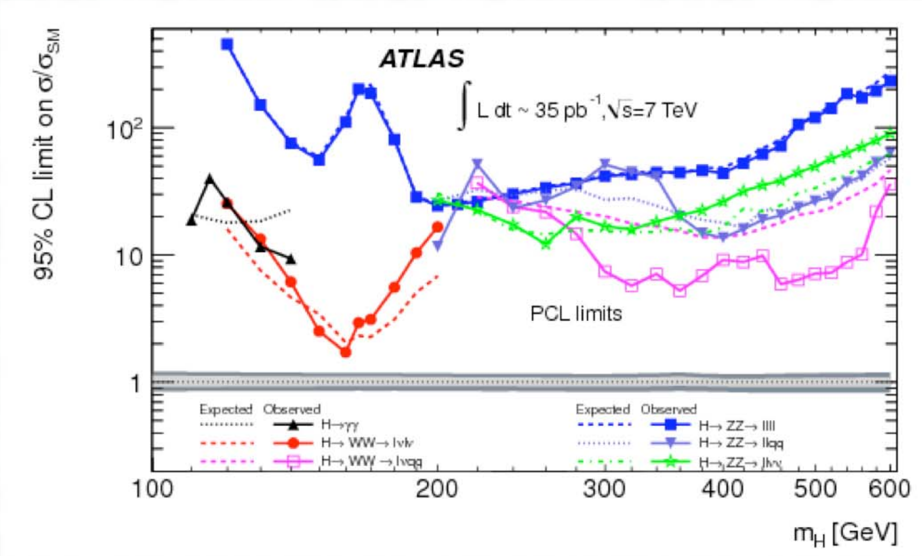
- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]

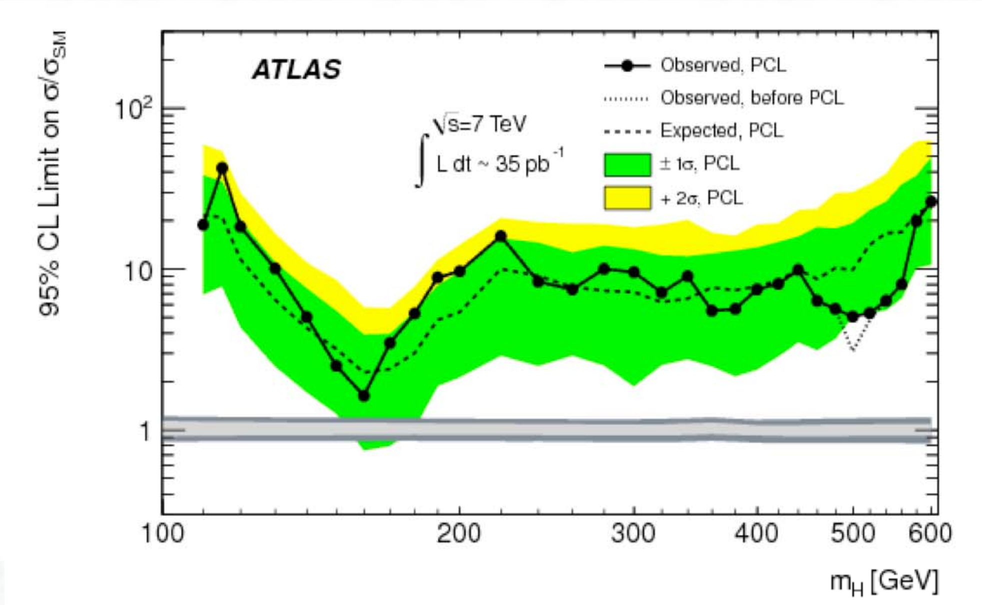
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)

Current status of the Higgs boson search at the LHC

(i) ATLAS exclusion limits based on 2010 data (35 pb^{-1})
Combination of six different channels

new



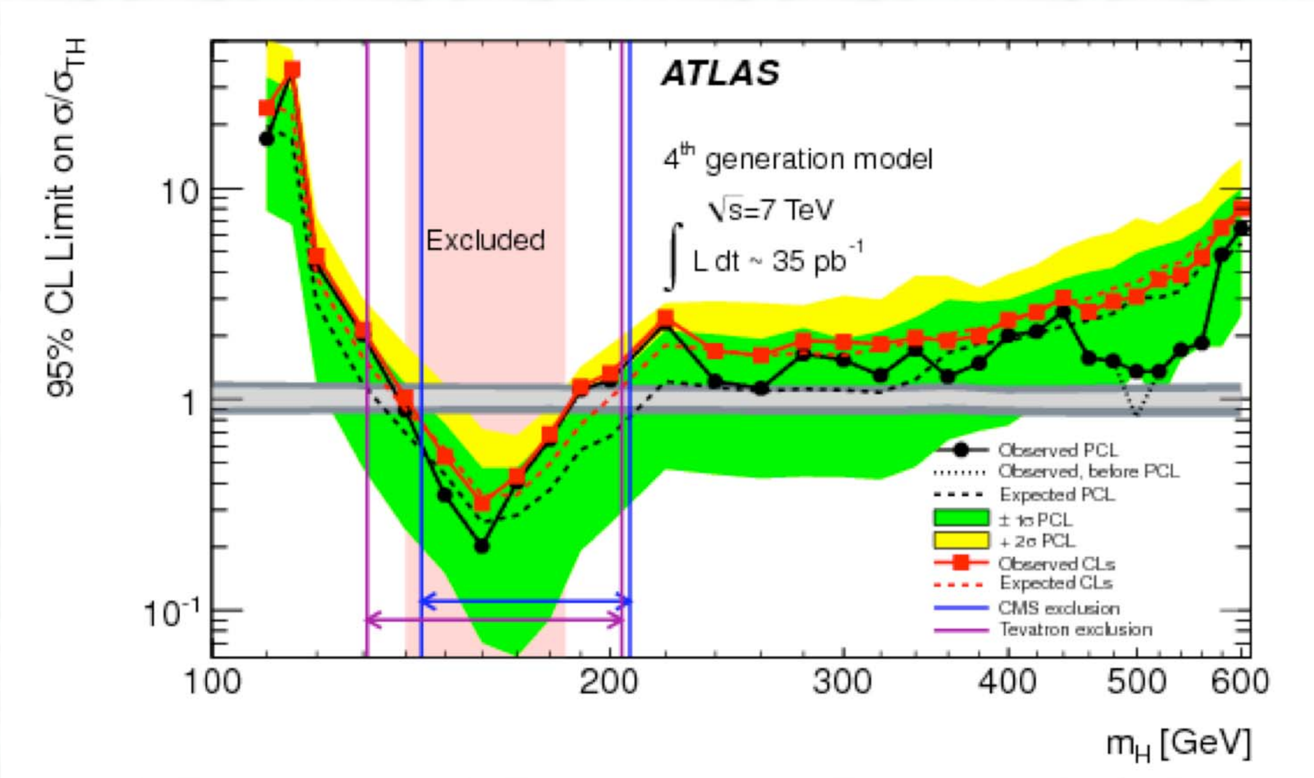


- Combination of all search channels has been performed
- No evidence (yet) for any signal contribution (also no sensitivity yet)
- Highest sensitivity in the mass range around 165 GeV
  Excluded cross section is ~2.3 σ_{SM}

Sensitivity reached for production via 4th generation:

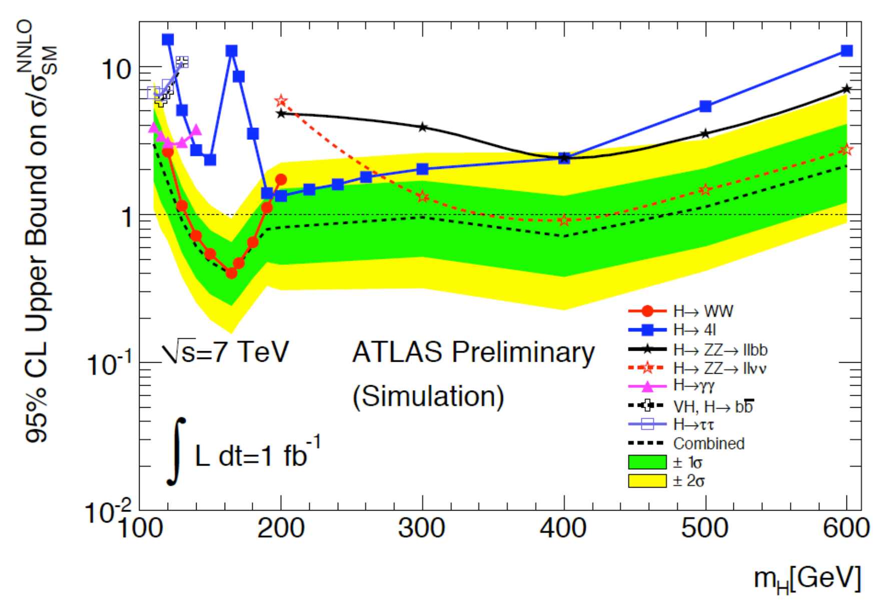
(ii) ATLAS exclusion limits based on 2010 data (35 pb^{-1})
Combination of 7 different channels

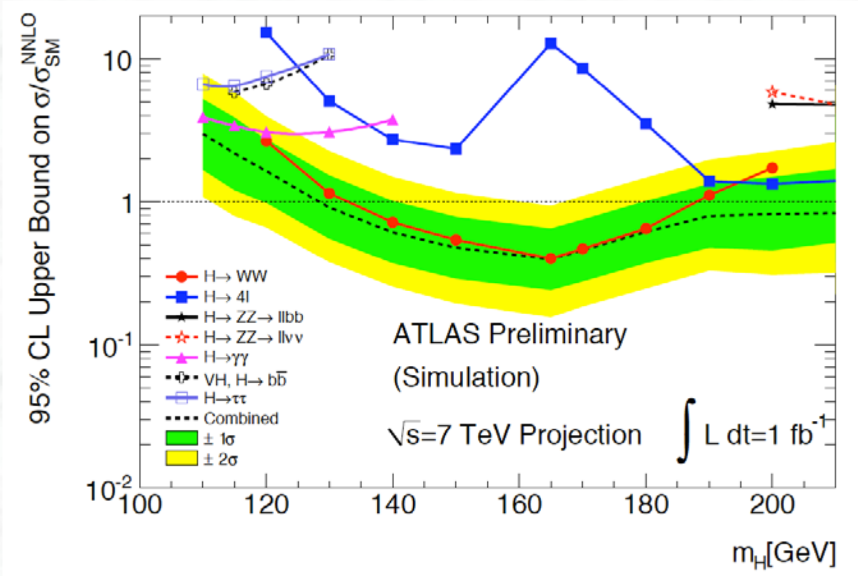
new



- Similar regions excluded by the Tevatron and CMS experiments

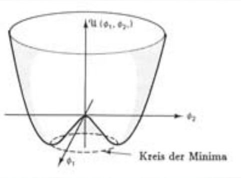
LHC Higgs boson discovery prospects for √s = 7 TeV





The multiple of the cross section of the Standard Model Higgs boson which can be excluded using 1 fb^{-1} of data at 7 TeV. The results for the different channels are plotted in the mass range where they are used in the combination. The plot on the right displays the results in the low mass region, below 200 GeV. The green and yellow bands indicate the 1- and 2-σ ranges in which the limit is expected to lie.

Expect interesting results (exclusion or first evidence) very soon !



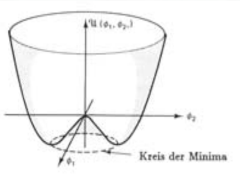
Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs self coupling

Motivation:

- After a discovery of a “Higgs-like” resonance at the LHC one has to measure its parameters and consolidate the evidence for a Higgs boson
- As many parameters as possible have to be measured in as many different production and decay channels as possible ! (global fit, see later)
- Discriminate between: SM Higgs boson,
  MSSM like Higgs boson,
  Composite Higgs boson, ….



Summary: Is it a Higgs Boson ?

1. Mass

Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and ZZ→ 4ℓ resonances

2. Couplings to bosons and fermions

- Ratios of major couplings can be measured with reasonable (~20-30%) precision;
- Absolute coupling measurements need further theory assumptions (Methods established, exp. updates are needed, in particular for VBF channels at high luminosity)

3. Spin and CP

Angular correlations in H → ZZ(*) → 4 ℓ and $\Delta\phi_{jj}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling

No measurement possible at the LHC;
Very difficult at the sLHC, there might be sensitivity in HH → WW WW for m_H ~ 160 GeV
Situation needs to be re-assessed with more realistic simulations