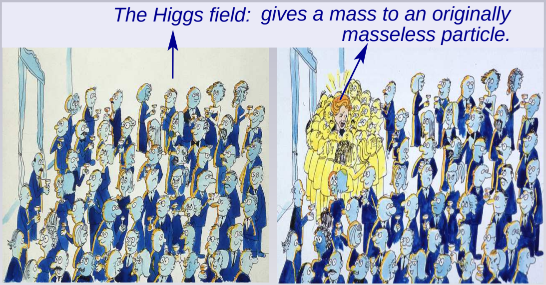
Sandra Horvat
Max-Planck-Institut für Physik, München

Standard Model Higgs searches at the LHC

3rd MPI Young Scientists Workshop
Ringberg Castle • October 27, 2004

The Higgs Mechanism...



...and the Higgs Boson

The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L$xU(1) electroweak theory contains massless gauge bosons (**W**, B) and fermions (ψ).

$$\mathcal{L} = -\frac{1}{4}\left(\partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\epsilon^{ijk} W^j_\mu W^k_\nu\right)\left(\partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g\epsilon^{ijk} W^{j\mu} W^{k\nu}\right)$$
$$-\frac{1}{4}\left(\partial_\nu B_\mu - \partial_\mu B_\nu\right)\left(\partial^\nu B^\mu - \partial^\mu B^\nu\right)$$
$$+i\bar{\psi}_R\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}Y_R B_\mu\right)\psi_R + i\bar{\psi}_L\gamma^\mu\left(\partial_\mu + i\frac{g}{2}\tau_i {W^i}_\mu + i\frac{g'}{2}Y_L B_\mu\right)\psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field Φ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} \quad ; \quad V(\Phi) = -\lambda v^2 |\Phi^\dagger\Phi| + \lambda\left(|\Phi^\dagger\Phi|\right)^2$$

$$\mathcal{L}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - g_f\left(\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right) - V(\Phi)$$

The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L$xU(1) electroweak theory contains massless gauge bosons (**W**, B) and fermions (ψ).

$$\mathcal{L} = -\tfrac{1}{4}\left(\partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\epsilon^{ijk} W^j_\mu W^k_\nu\right)\left(\partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g\epsilon^{ijk} W^{j\mu} W^{k\nu}\right)$$
$$-\tfrac{1}{4}\left(\partial_\nu B_\mu - \partial_\mu B_\nu\right)\left(\partial^\nu B^\mu - \partial^\mu B^\nu\right)$$
$$+i\bar{\psi}_R\gamma^\mu\left(\partial_\mu + i\tfrac{g'}{2}Y_R B_\mu\right)\psi_R + i\bar{\psi}_L\gamma^\mu\left(\partial_\mu + i\tfrac{g}{2}\tau_i {W^i}_\mu + i\tfrac{g'}{2}Y_L B_\mu\right)\psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field Φ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}; \quad V(\Phi) = -\lambda v^2|\Phi^\dagger\Phi| + \lambda\left(|\Phi^\dagger\Phi|\right)^2$$

$$\mathcal{L}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - g_f\left(\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right) - V(\Phi)$$

The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L$xU(1) electroweak theory contains massless gauge bosons (**W**, B) and fermions (ψ).

$$\mathcal{L} = -\frac{1}{4}\left(\partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\epsilon^{ijk} W^j_\mu W^k_\nu\right)\left(\partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g\epsilon^{ijk} W^{j\mu} W^{k\nu}\right) - \frac{1}{4}\left(\partial_\nu B_\mu - \partial_\mu B_\nu\right)\left(\partial^\nu B^\mu - \partial^\mu B^\nu\right) + i\bar{\psi}_R\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}Y_R B_\mu\right)\psi_R + i\bar{\psi}_L\gamma^\mu\left(\partial_\mu + i\frac{g}{2}\tau_i W^i{}_\mu + i\frac{g'}{2}Y_L B_\mu\right)\psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field Φ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}; \quad V(\Phi) = -\lambda v^2|\Phi^\dagger\Phi| + \lambda\left(|\Phi^\dagger\Phi|\right)^2$$

$$\mathcal{L}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - g_f\left(\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right) - V(\Phi)$$

$\Downarrow$

interaction with gauge bosons

$$m_{W^\pm} = \frac{gv}{2}, \quad m_Z = \frac{v\sqrt{(g^2+g'^2)}}{2}$$

The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the $SU(2)_L xU(1)$ electroweak theory contains massless gauge bosons (**W**, B) and fermions (ψ).

$$\mathcal{L} = -\frac{1}{4}\left(\partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\epsilon^{ijk} W^j_\mu W^k_\nu\right)\left(\partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g\epsilon^{ijk} W^{j\mu} W^{k\nu}\right)$$
$$-\frac{1}{4}\left(\partial_\nu B_\mu - \partial_\mu B_\nu\right)\left(\partial^\nu B^\mu - \partial^\mu B^\nu\right)$$
$$+i\bar{\psi}_R\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}Y_R B_\mu\right)\psi_R + i\bar{\psi}_L\gamma^\mu\left(\partial_\mu + i\frac{g}{2}\tau_i {W^i}_\mu + i\frac{g'}{2}Y_L B_\mu\right)\psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field Φ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}; \quad V(\Phi) = -\lambda v^2 |\Phi^\dagger\Phi| + \lambda\left(|\Phi^\dagger\Phi|\right)^2$$

$$\mathcal{L}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - g_f\left(\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right) - V(\Phi)$$

$\Downarrow$

interaction with fermions

$$m_f = \frac{g_f v}{\sqrt{2}}$$

The Higgs Mechanism

The invariant Lagrangian $\mathcal{L}$ of the SU(2)$_L$xU(1) electroweak theory contains massless gauge bosons (**W**, B) and fermions (ψ).

$$\mathcal{L} = -\frac{1}{4}\left(\partial_\nu W_\mu^i - \partial_\mu W_\nu^i + g\epsilon^{ijk} W_\mu^j W_\nu^k\right)\left(\partial^\nu W^{i\mu} - \partial^\mu W^{i\nu} + g\epsilon^{ijk} W^{j\mu} W^{k\nu}\right) - \frac{1}{4}\left(\partial_\nu B_\mu - \partial_\mu B_\nu\right)\left(\partial^\nu B^\mu - \partial^\mu B^\nu\right) + i\bar{\psi}_R\gamma^\mu\left(\partial_\mu + i\frac{g'}{2}Y_R B_\mu\right)\psi_R + i\bar{\psi}_L\gamma^\mu\left(\partial_\mu + i\frac{g}{2}\tau_i {W^i}_\mu + i\frac{g'}{2}Y_L B_\mu\right)\psi_L.$$

P.W.Higgs 1964; F.Englert and R.Brout 1964;

Introduction of a scalar field Φ provides for the particle masses.

$$\Phi = \begin{pmatrix} \phi^\dagger \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}; \quad V(\Phi) = -\lambda v^2|\Phi^\dagger\Phi| + \lambda\left(|\Phi^\dagger\Phi|\right)^2$$

$$\mathcal{L}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - g_f\left(\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right) - V(\Phi)$$

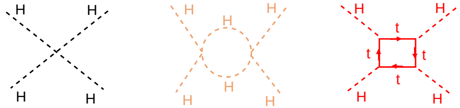
$\Downarrow$

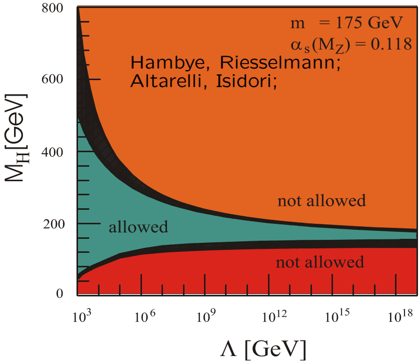
self-interaction

Existence of a spin $-$ 0 particle, the Higgs boson with a mass $m_H = \sqrt{2\lambda}v$.

Not specified explicitelly, but...

Bounds derived from the evolution of the self-coupling λ with energy:





Upper bound:

SM valid up to the scale Λ

$\lambda(\Lambda) < \infty$

Lower bound:

vacuum stability

(finite minimum for $V(\Phi)$)

$\lambda(\Lambda) > 0$

The Higgs boson discovery can provide the constraints on the validity of the Standard Model.

Current experimental status

by Claus Grupen

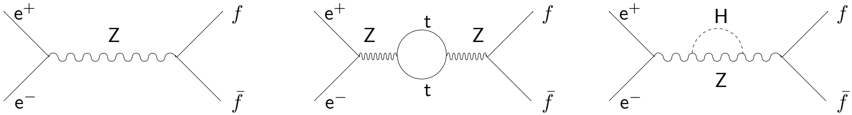
Experimental Data

Collider	Running Period	Beam	$\sqrt{s}$ (GeV)
LEP1	1989-1995	e^+e^-	91
SLC	1991-1998	e^+e^-	91
LEP2	1995-2000	e^+e^-	$\sim$ 209
TEVATRON	2001-	$p\bar{p}$	1 800
LHC	2007-	pp	14 000
LINEAR COLLIDER?	???	e^+e^-	500

Experimental Data

Collider	Running Period	Beam	$\sqrt{s}$ (GeV)
LEP1	1989-1995	e^+e^-	91
SLC	1991-1998	e^+e^-	91
LEP2	1995-2000	e^+e^-	$\sim$ 209
TEVATRON	2001-	$p\bar{p}$	1 800
LHC	2007-	pp	14 000
LINEAR COLLIDER?	???	e^+e^-	500

indirect tests, setting bounds on the Higgs mass
from precision measurement of electroweak observables
taking into account the radiative corrections

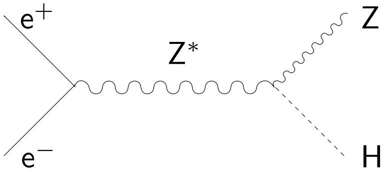


$$\propto Log\frac{m_H^2}{m_z^2}$$

Experimental Data

Collider	Running Period	Beam	$\sqrt{s}$ (GeV)
LEP1	1989-1995	e^+e^-	91
SLC	1991-1998	e^+e^-	91
LEP2	1995-2000	e^+e^-	$\sim$ 209
TEVATRON	2001-	$p\bar{p}$	1 800
LHC	2007-	pp	14 000
LINEAR COLLIDER?	???	e^+e^-	500

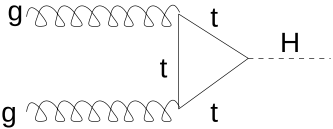
direct search, Higgs produced by Higgs-Strahlung;
large coupling to Z, all other processes negligible

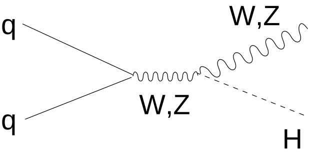


Experimental Data

Collider	Running Period	Beam	$\sqrt{s}$ (GeV)
LEP1	1989-1995	e^+e^-	91
SLC	1991-1998	e^+e^-	91
LEP2	1995-2000	e^+e^-	$\sim$ 209
TEVATRON	2001-	$p\bar{p}$	1 800
LHC	2007-	pp	14 000
LINEAR COLLIDER?	???	e^+e^-	500

direct searches; Higgs produced by
gluon fusion and Higgs-Strahlung

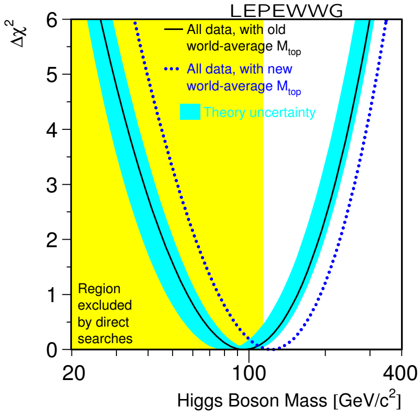




Indirect and Direct Searches at LEP

Precision measurements of electroweak observables:

- Z boson lineshape
- forward-backward asymmetries
- W boson mass



With the recent world average value m_{top}=(178.0±4.3) GeV (April 2004):

$$m_H = 117^{+67}_{-45}\ \text{GeV}$$

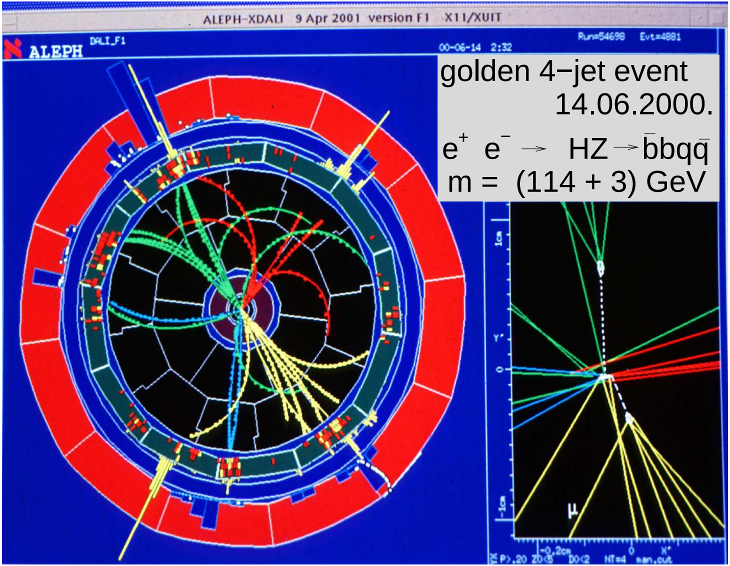
m_H <251 GeV, 95% confidence level

Direct searches

in the production channel $e^+e^- \to Z^* \to HZ$ give the lower bound

$$m_H > 114.4\ \text{GeV}$$

Observed Higgs event?



All other channels in all experiments are compatible with background!

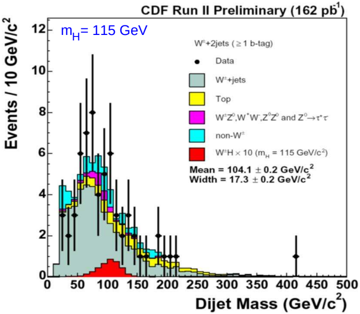
Higgs Search at the Tevatron

- collected integrated luminosity of $\sim$0.4 fb^{-1}, $\sim$0.2 fb^{-1} analysed so far
- goal: 4-9 fb^{-1} by the end of 2009
- still an early stage of data taking, emphasis on understanding the detector performance
- the Higgs search has begun

Main signatures for the Standard Model Higgs boson:

- For m_H <130 GeV: $q\bar{q} \to (W/Z)H \to (W/Z)b\bar{b}$
- For m_H >130 GeV: $gg \to H \to WW^* \to 2l2\nu$

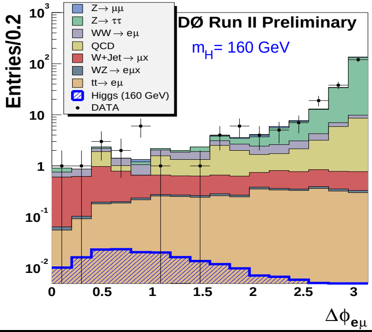
Recent Tevatron Results (July 2004)



$WH \rightarrow Wb\bar{b}$

- leptonic W-decay
- 2 jets required, $\leq$1 b-tagged

  $\sigma(Wbb) < 20.3$ pb
  $\sigma(WH)xB(H \rightarrow b\bar{b}) < 12.4$ pb



$H \rightarrow WW^* \rightarrow 2l2\nu$

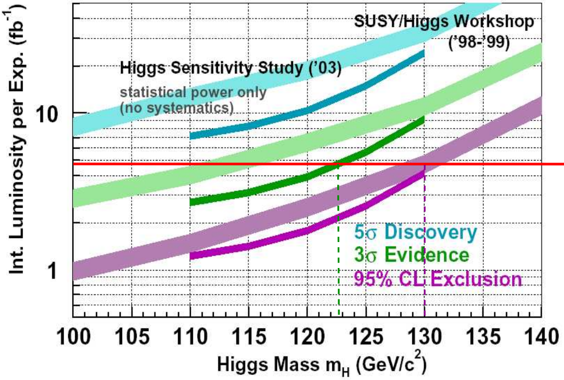
- 2 high-p_T leptons
- large missing energy
- spin correlation
  (charged leptons are collinear)

  $\sigma xB(H \rightarrow WW) < 5.7$ pb

Tevatron Discovery Potential

Higgs discovery in a single channel is not possible.

Combined CDF/D0 discovery reach up to 2009:



worst case scenario, $L=4.4\ \mathrm{fb}^{-1}$

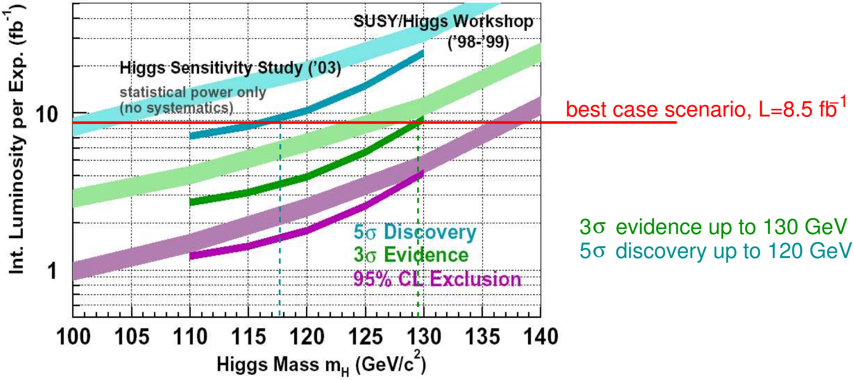
115–130 GeV covered for exclusion

3σ evidence up to 125 GeV

Tevatron Discovery Potential

Higgs discovery in a single channel is not possible.

Combined CDF/D0 discovery reach up to 2009:

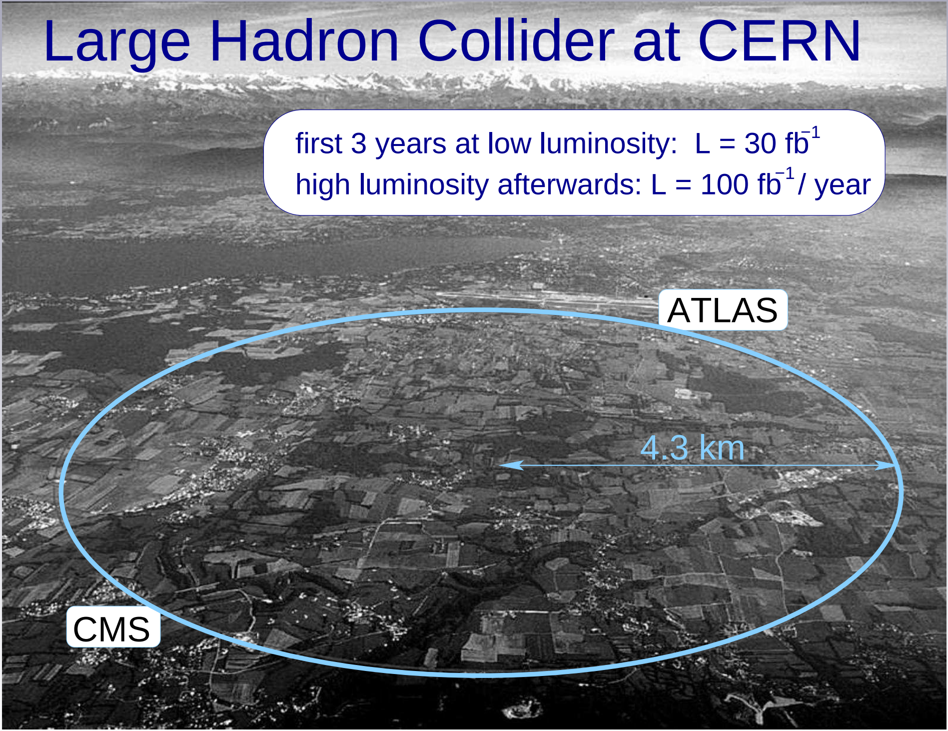


3σ evidence up to 130 GeV

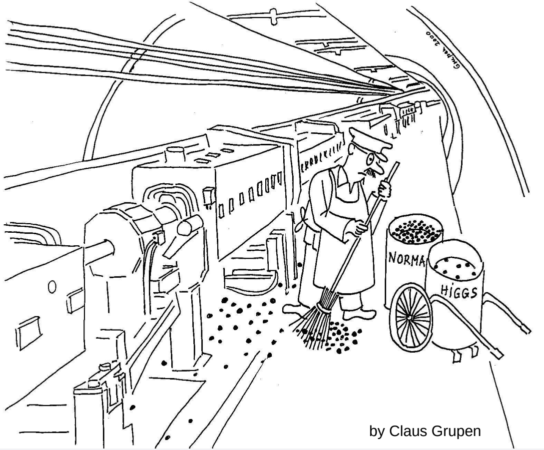
5σ discovery up to 120 GeV

Large Hadron Collider at CERN

first 3 years at low luminosity: L = 30 fb^{-1}
high luminosity afterwards: L = 100 fb^{-1} / year

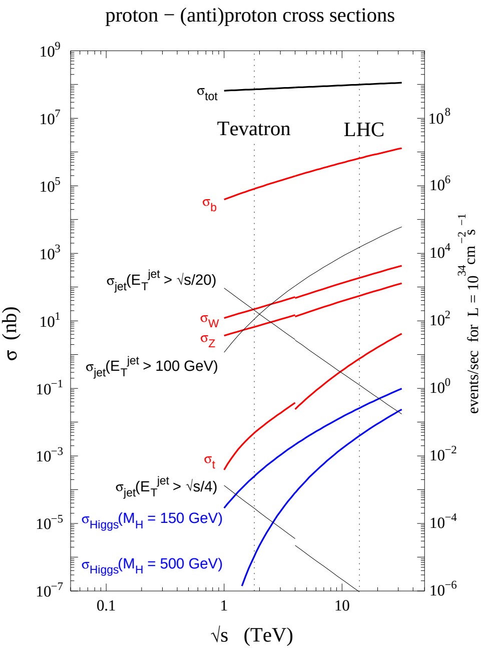


Higgs Signatures at the LHC



by Claus Grupen

Overall LHC Rates



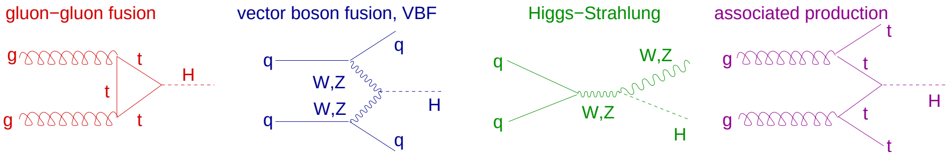
The Higgs signal hidden behind the large background contributions.

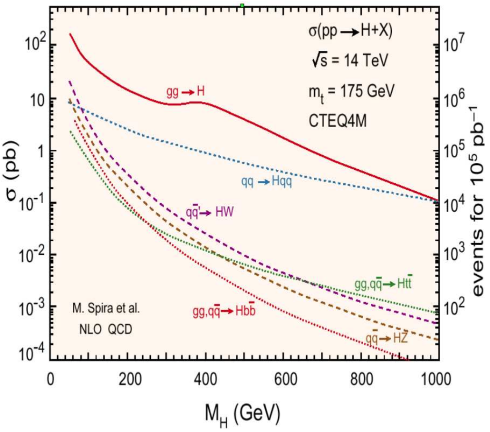
⇓

Challenging detector performance needed:

- powerfull trigger
- high granularity
- radiation hardness
- high particle detection efficiency and resolution

Higgs Production Mechanisms

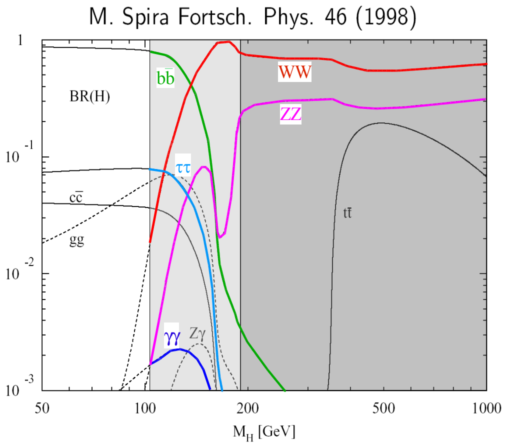




10 000 - 1 000 000
Higgs Bosons
produced per year
at high luminosity

Decay Channels

Branching ratios are completely determined by the Higgs mass.



Low mass $m_H < 2m_Z$:

- The most difficult region, combining several channels:
  $H \to b\bar{b}$, $H \to \gamma\gamma$,
  $H \to \tau^+\tau^-$ (via VBF),
  $H \to ZZ^* \to 4l$,
  $H \to WW^* \to 2l2\nu$ (via VBF)

Large mass $m_H > 180$ GeV:

- the gold-plated channel
  $H \to ZZ \to 4l$
- supplemetary channel at very high masses (>800 GeV)
  $H \to WW \to l\nu jj$

Search Strategy

Hadronic final states dominate for all values of m_H,
but are difficult to distinguish from large QCD background.

We rather look for final states with leptons, photons, missing energy.

LHC Detectors

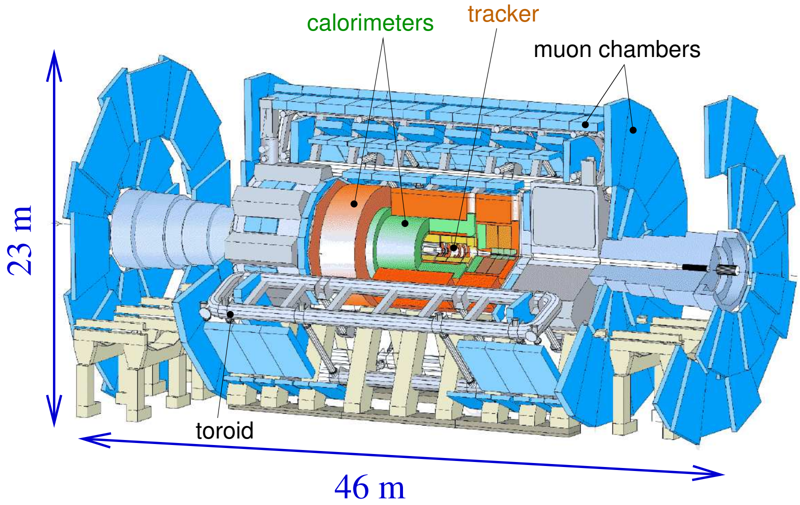
Ladbrokes
(the biggset betting company in the world):

As of August 2004
accepts the bets on finding the Higgs boson at LHC before 2010,
the odds are set to 6 to 1 .

ATLAS (A Toroidal LHC ApparatuS)

Design optimized for the Higgs discovery in a wide mass range:

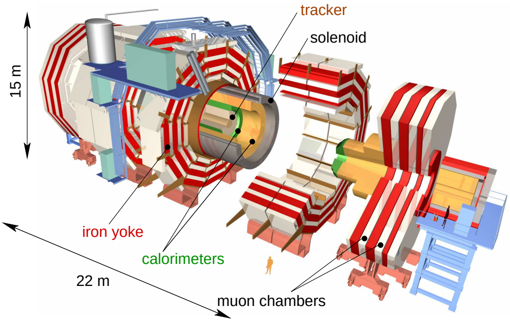
- large solid angle, efficient and precise particle detection, good calorimetry and missing energy measurement



CMS (Compact Muon Solenoid)

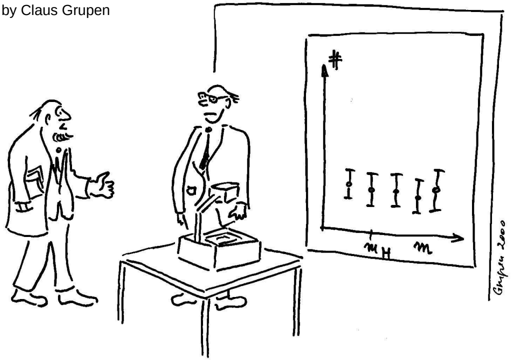
Design optimized for the Higgs discovery in a wide mass range:

- large solid angle, efficient and precise particle detection, good calorimetry and missing energy measurement



Discovery Potential

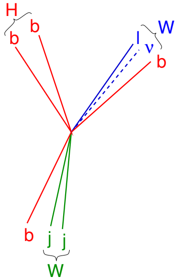
by Claus Grupen



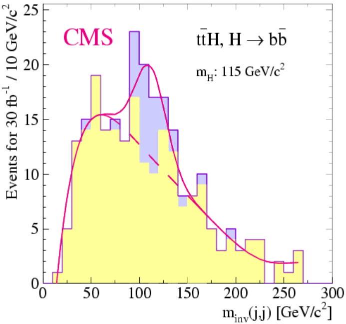
"You call this evidence for the Higgs?"
"Yes! Zero lifetime and infinite width!"

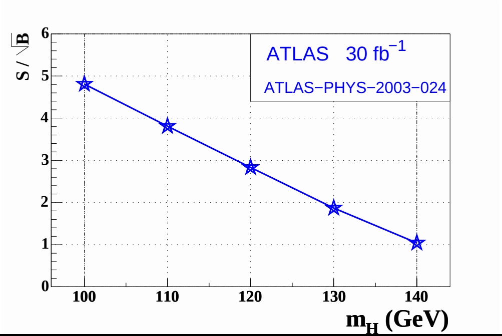
Low-mass Higgs: $t\bar{t}H, H \to b\bar{b}$

- identification via top-quark tagging
  1.) $t \to Wb \to l\nu b$: lepton used for triggering
  2.) $t \to Wb \to jjb$
- selecting final states with 4 b-tagged jets, precise vertexing needed
- need for a very good understanding of background (ttbb, ttjj, Ztt)



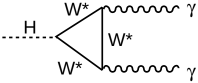
Signal significance $(S/\sqrt{B})$ at 30 fb^{-1}: 3.4σ for m_H =115 GeV





Low-mass Higgs: $H \to \gamma\gamma$

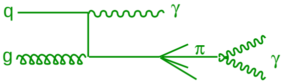
$B(H \to \gamma\gamma) = 10^{-3}\, B(H \to b\bar{b})$ only, but $H \to \gamma\gamma$ is a clean channel.



Main background processes:

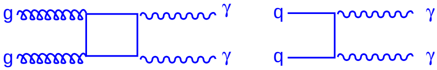
- reducible: $qg \to q\gamma \to q\gamma\gamma$
  need excellent γ/jet separation,
  (in particular γ/π^0),
  high granularity detectors

reducible background



- irreducible: $gg \to \gamma\gamma$, $q\bar{q} \to \gamma\gamma$
  subtraction of a smooth
  continuous background,
  excellent calorimetry needed
  for a narrow $m_{\gamma\gamma}$-resonance

irreducible background



Additional improvement:

- assosiated Higgs production: WH, ZH and $t\bar{t}H$,
  process triggered by a lepton from W, Z or t

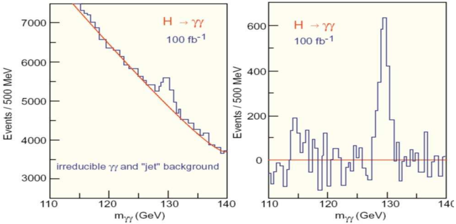
Low-mass Higgs: $H \to \gamma\gamma$

Signal significance ($S/\sqrt{B}$) at 100 fb^{-1}: 3-4σ for m_H <150 GeV

CMS has a 10% better calorimeter resolution than ATLAS.

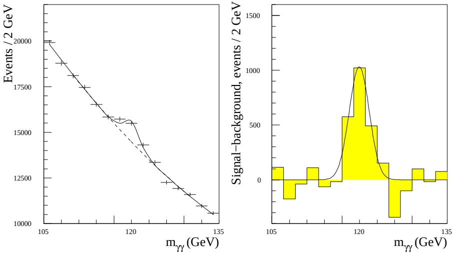
CMS

100 fb^{-1}



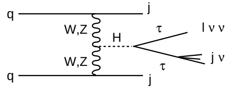
ATLAS

100 fb^{-1}

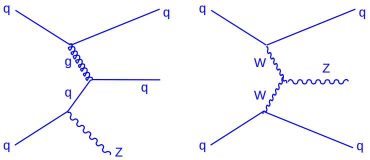


Low-mass Higgs: $qqH,\ H \to \tau^+\tau^-$

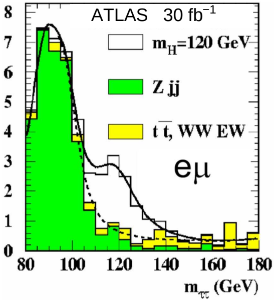
- hadronic jets in forward-backward region,
  forward jet-tagging, central jet veto
- leptonic or hadronic decay in τ-direction,
  missing p_T measurement
  lepton identification
- background: Zjj, $t\bar{t}$+jets, WWjj

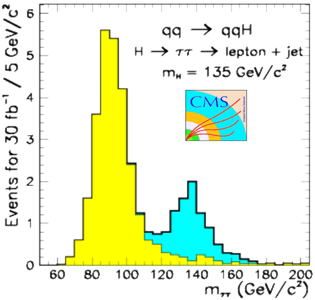


Zjj background



Signal significance $(S/\sqrt{B})$ at 40 fb^{-1}: $>5\sigma$ for $m_H < 140$ GeV



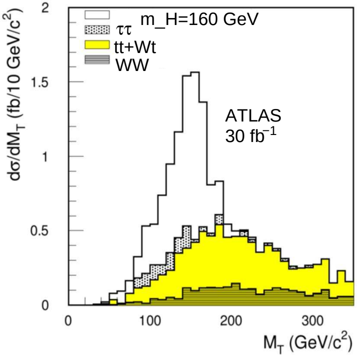


Low-mass Higgs: $(qq)H,\ H \to WW^{(*)} \to l\nu l\nu$

This is the main decay channel in the region around m_H=170 GeV. A good missing energy measurement is needed.

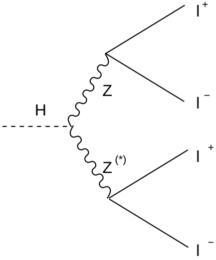
Main backgrounds:

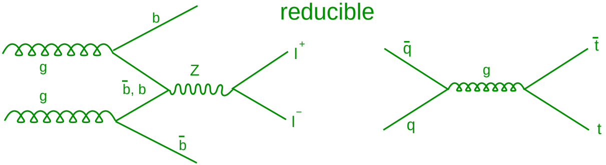
- WW, $WbW\bar{b}$ - suppressed by WW spin correlations in the signal
- Drell-Yan $ee, \mu\mu$ - lepton cuts (p_T^{miss} >30 GeV, $m < 75$ GeV)
- $t\bar{t}$, $\tau\tau$ - b-jet and τ veto in the central region

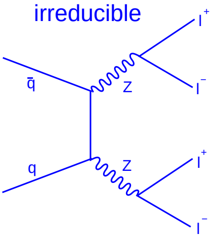


Signal significance ($S/\sqrt{B}$) of 5σ reachable at 10 fb^{-1} for $m_H \approx$170 GeV.

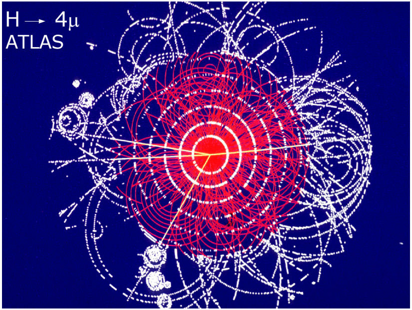
- relatively clean signature
  one pair with m_{2l}-peak at the Z-resonance
- reducible background: $Zb\bar{b}$, $t\bar{t}$
  lepton isolation, small impact parameter
- irreducible background: $ZZ \rightarrow 4l$



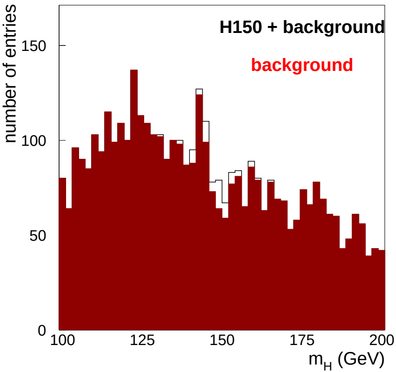




Particularly clean signature from muons:

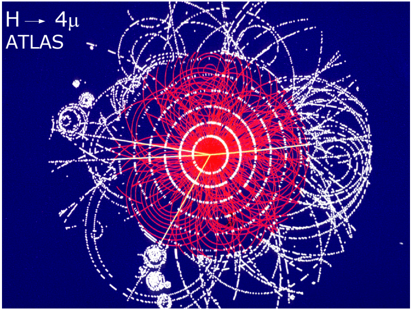


- no cuts applied on the muon tracks
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter

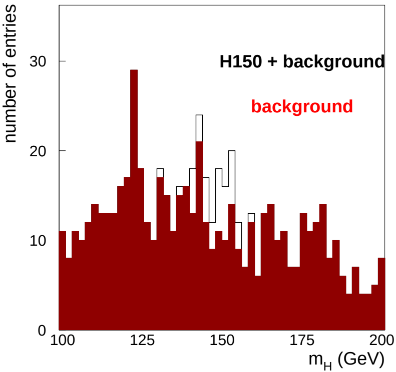


Signal significance for $H \to 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

Particularly clean signature from muons:



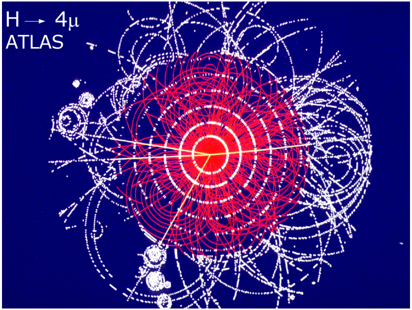
- no cuts applied on the muon tracks
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter

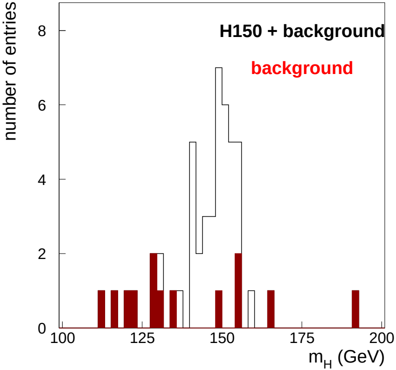


Signal significance for $H \rightarrow 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

Particularly clean signature from muons:

- no cuts applied on the muon tracks
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter



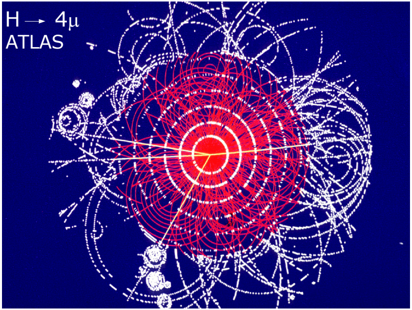


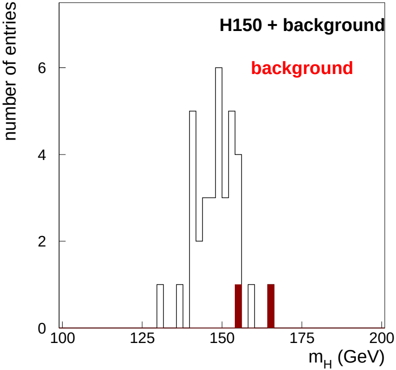
Signal significance for $H \to 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

Low-mass Higgs: $H \to ZZ^* \to 4l$

Particularly clean signature from muons:

- no cuts applied on the muon tracks
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter

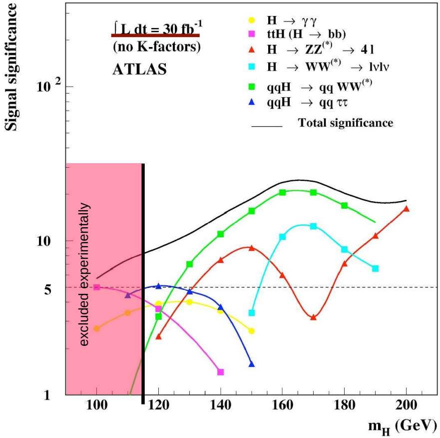


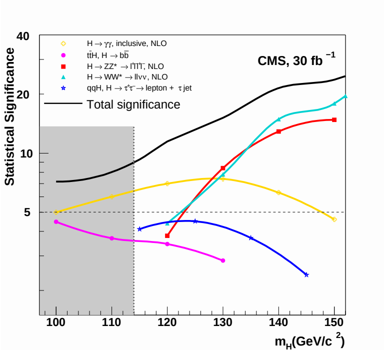


Signal significance for $H \to 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

Discovery potential for a low Higgs mass

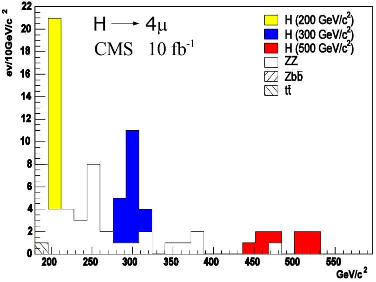
- combination of all channels is needed for the 5σ discovery in the first three years of running LHC

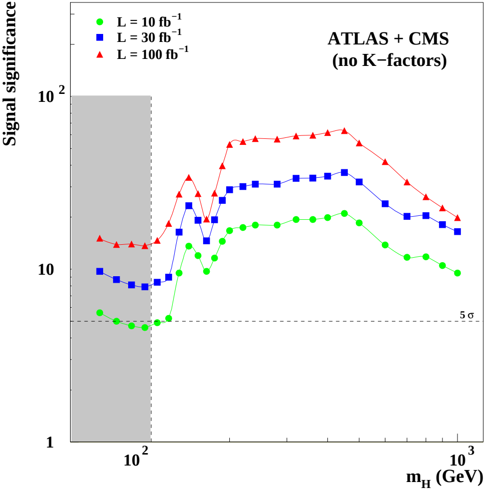




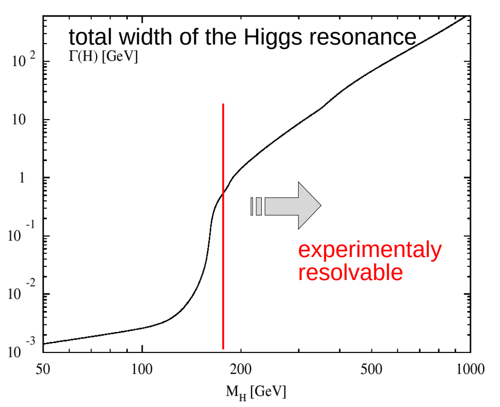
Discovery potential at the LHC

- $H \to ZZ \to 4l$ gives a clean signature for the region m_H >200 GeV
- complete coverage of the theoretically allowed mass range m_H; 5σ discovery possible already in the first year

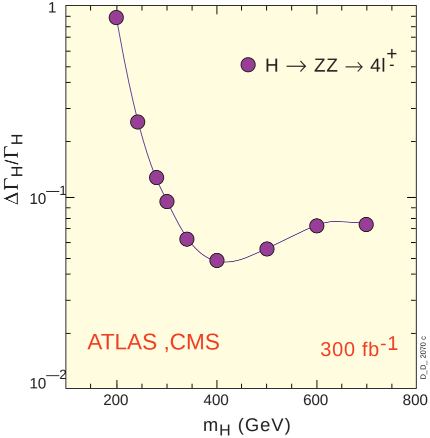


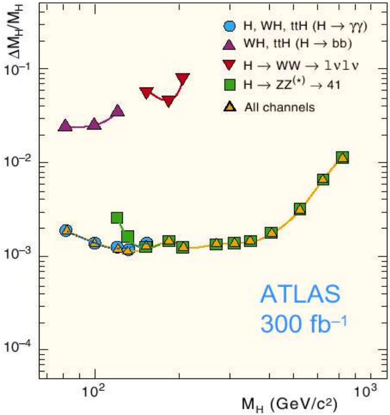


Precision Measurements of Higgs Properties



Mass and Width





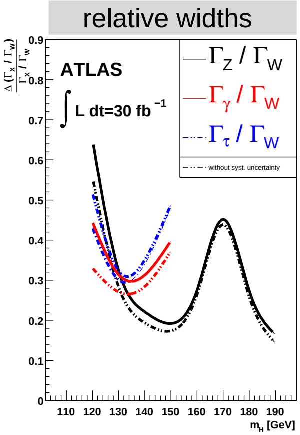
Width measurement:

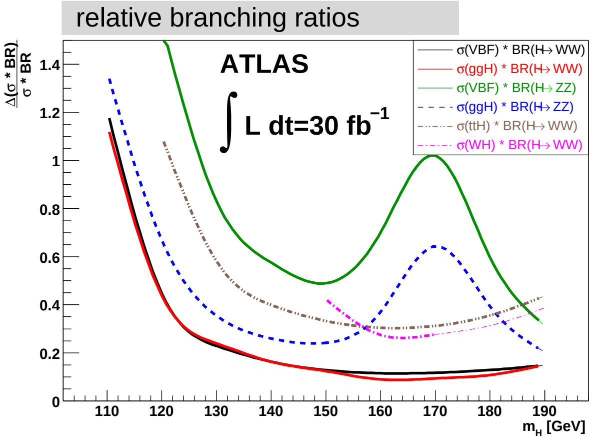
6% for m_H >300 GeV

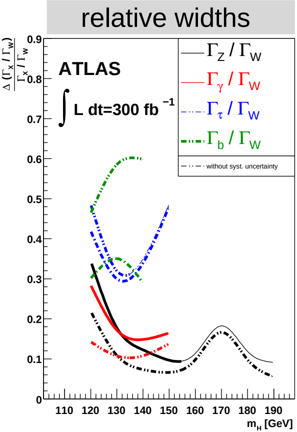
Mass measurement:

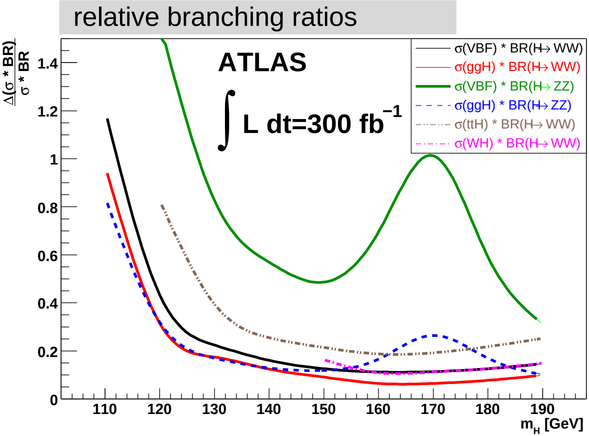
<1% for all m_H

Relative widths and branching ratios

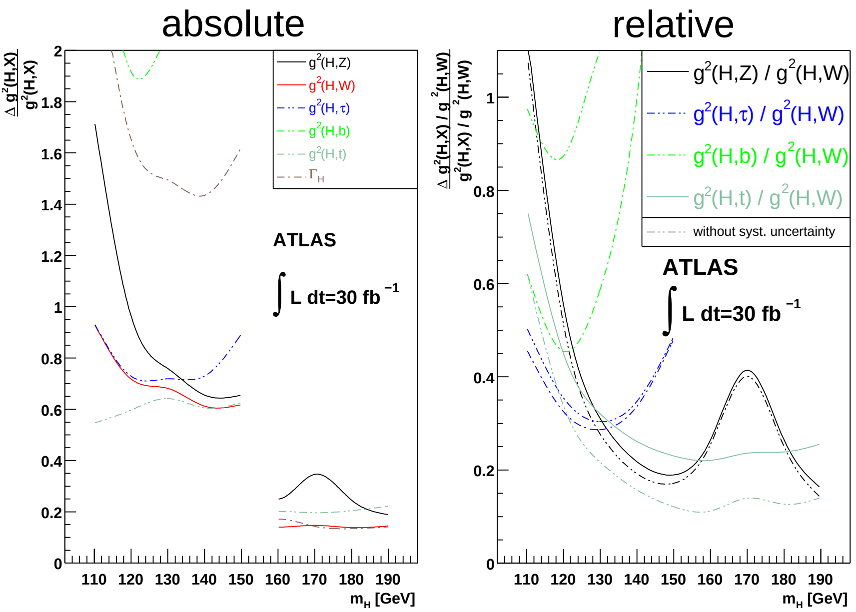




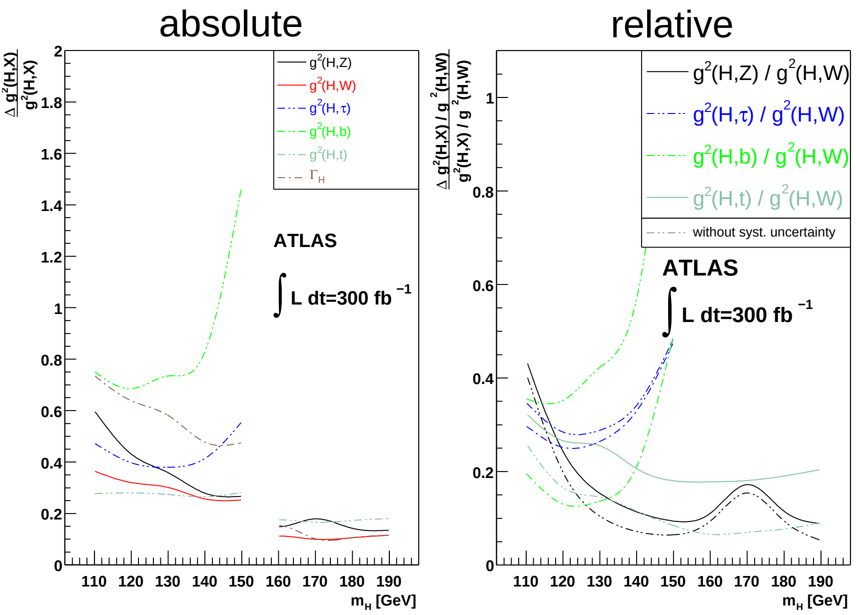

relative widths
ATLAS
$\int$ L dt=300 fb^{-1}
Γ_Z / Γ_W
Γ_γ / Γ_W
Γ_τ / Γ_W
Γ_b / Γ_W
without syst. uncertainty
$\frac{\Delta(\Gamma_x / \Gamma_W)}{\Gamma_x / \Gamma_W}$
m_H [GeV]


relative branching ratios
ATLAS
$\int$ L dt=300 fb^{-1}
σ(VBF) * BR(H→ WW)
σ(ggH) * BR(H→ WW)
σ(VBF) * BR(H→ ZZ)
σ(ggH) * BR(H→ ZZ)
σ(ttH) * BR(H→ WW)
σ(WH) * BR(H→ WW)
$\frac{\Delta(\sigma * BR)}{\sigma * BR}$
m_H [GeV]

Couplings to fermions and gauge bosons



Couplings to fermions and gauge bosons



Summary

- The first pp-collisions at the LHC are expected end of 2007.
- The LHC detectors (ATLAS, CMS) are designed for the Higgs search covering the full mass spectrum.
- The 5σ-discovery limit can be reached in the whole mass range already after one year.
(However, a time will be needed to understand the detectors.)
- Physics studies are currently concentrated on the more difficult region of lower Higgs masses, which is favoured by the theoretical and experimental observations.
- If the Standard Model Higgs boson exists,
it will be seen at the LHC.

Searching Beyond the Standard Model...