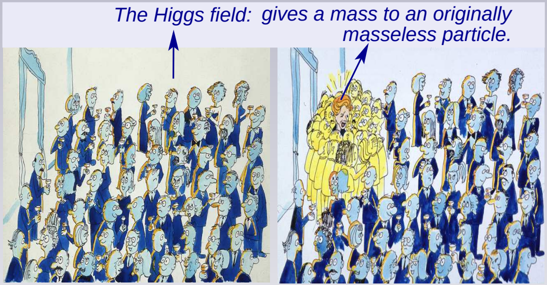
Sandra Horvat
Max-Planck-Institut für Physik, München

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).

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

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

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

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

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$\Downarrow$

interaction with gauge bosons

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

The Higgs Mechanism

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$\Downarrow$

interaction with fermions

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

The Higgs Mechanism

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$\Downarrow$

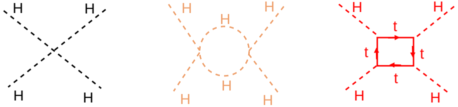
self-interaction

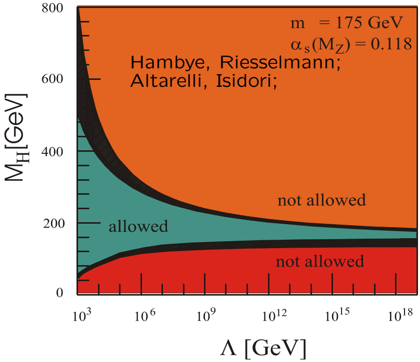
Existence of a spin $-$ 0 particle, the Higgs boson with a mass $m_H = \sqrt{2\lambda}v$.

The Higgs Boson Mass

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

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

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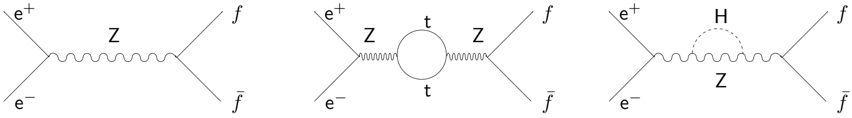
indirect tests, setting bounds on the Higgs mass
from precision measurement of electroweak observables
taking into account the radiative corrections



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

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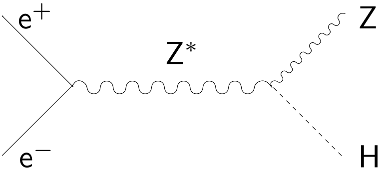
direct search, Higgs produced by Higgs-Strahlung;
large coupling to Z, all other processes negligible



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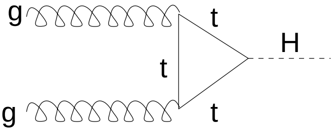
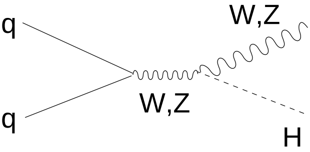
direct searches; Higgs produced by gluon fusion and Higgs-Strahlung

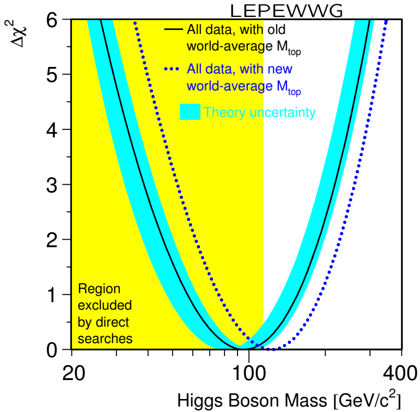




Indirect and Direct Searches at LEP

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):

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

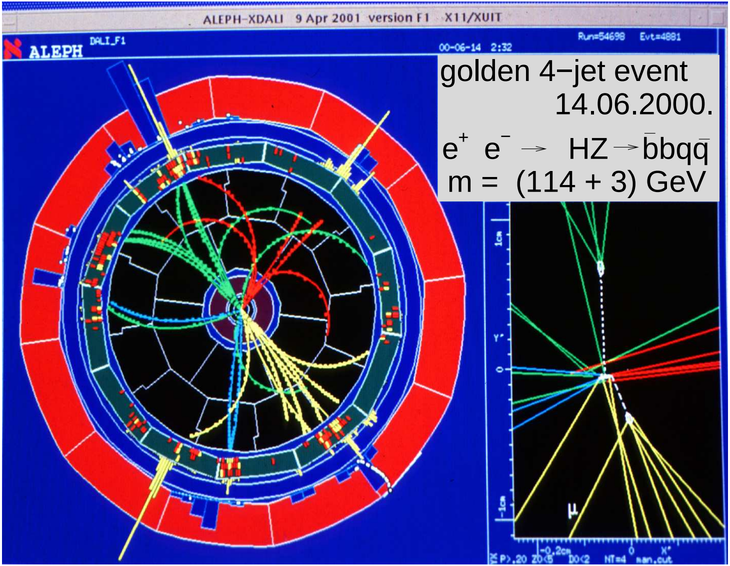
m_H <251 GeV, 95% confidence level

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?



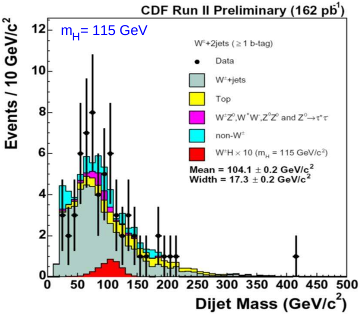
All other channels in all experiments are compatible with background!

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:

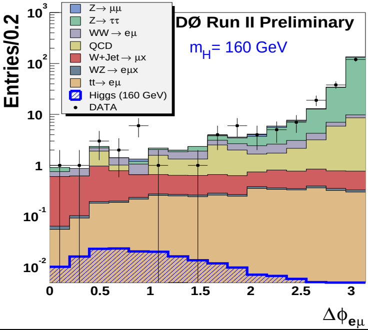
- For m_H <130 GeV: $q\bar{q} \to (W/Z)H \to (W/Z)b\bar{b}$
- For m_H >130 GeV: $gg \to H \to WW^* \to 2l2\nu$



$WH \to Wb\bar{b}$

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

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



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

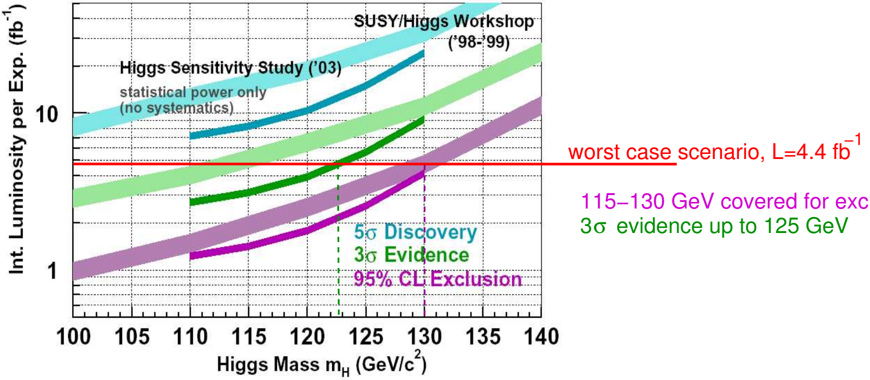
- 2 high-p_T leptons
- large missing energy
- spin correlation
  (charged leptons are collinear)

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

Tevatron Discovery Potential

Higgs discovery in a single channel is not possible.

Combined CDF/D0 discovery reach up to 2009:



115–130 GeV covered for exclusion

3σ evidence up to 125 GeV

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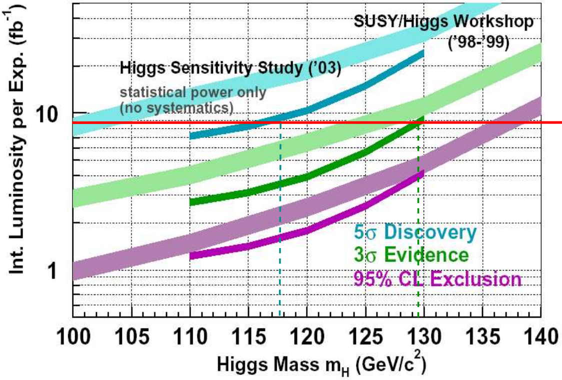
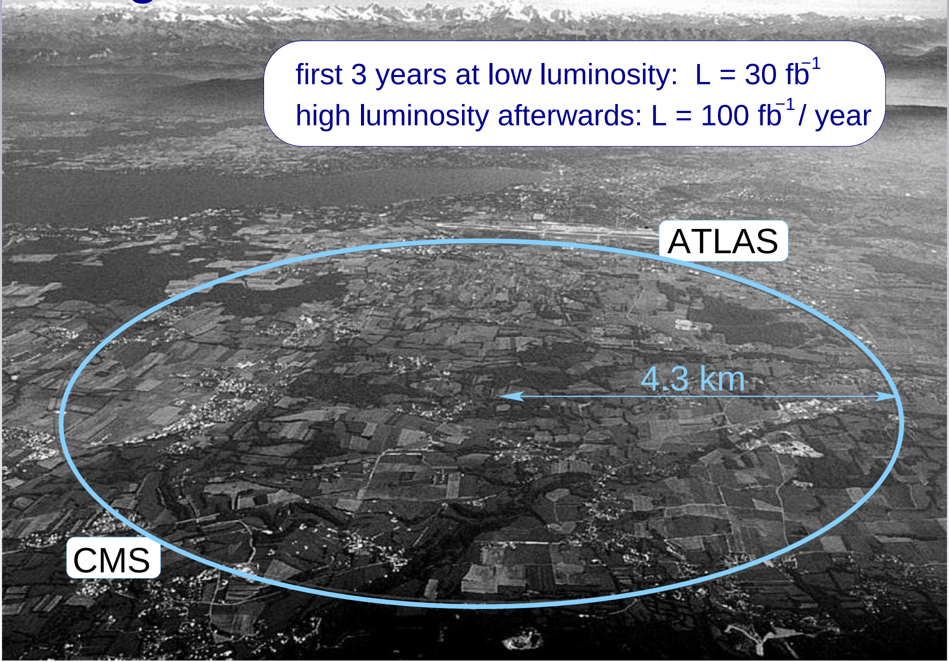


best case scenario, L=8.5 fb^{-1}

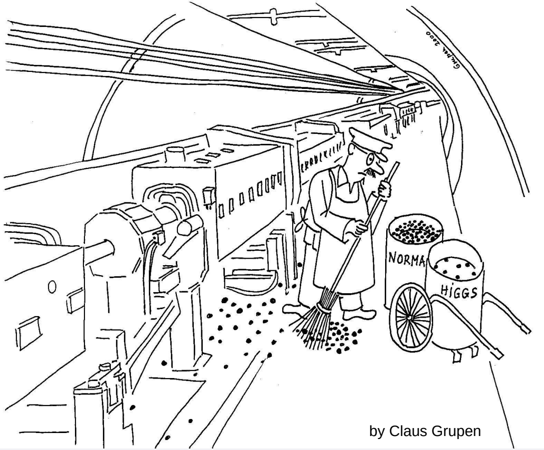
3σ evidence up to 130 GeV
5σ discovery up to 120 GeV

Large Hadron Collider at CERN

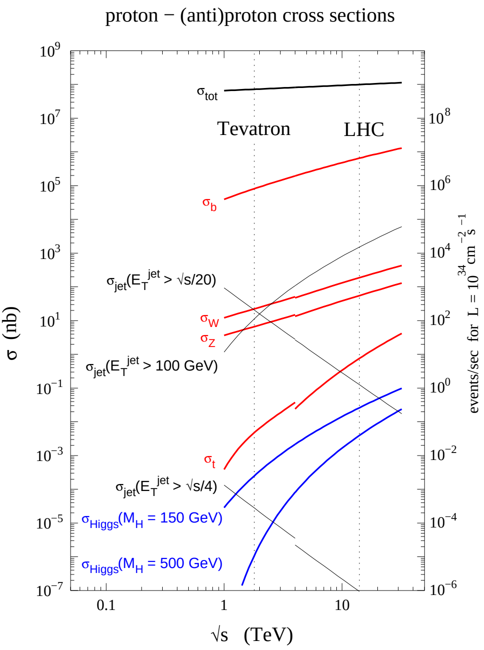
first 3 years at low luminosity: $L = 30\ fb^{-1}$
high luminosity afterwards: $L = 100\ fb^{-1}$ / year



Higgs Signatures at the LHC



Overall LHC Rates



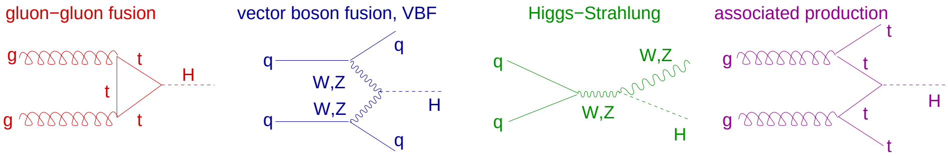
The Higgs signal hidden behind the large background contributions.

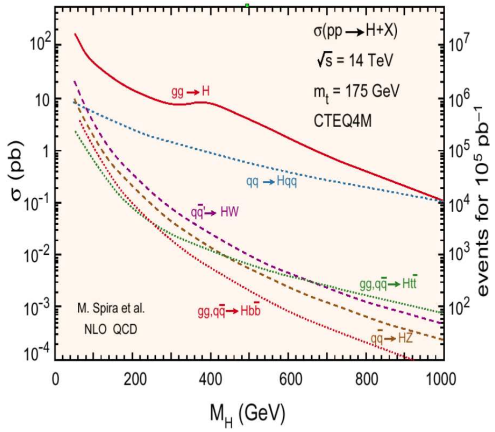
⇓

Challenging detector performance needed:

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

Higgs Production Mechanisms



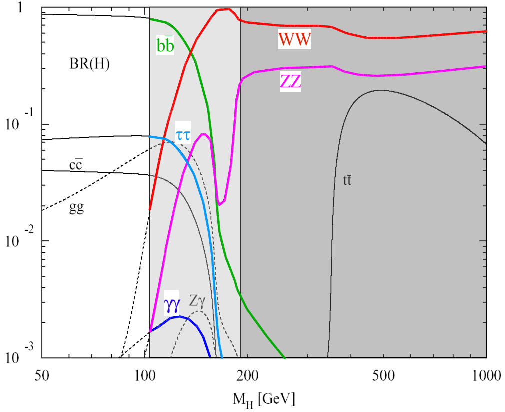


10 000 - 1 000 000
Higgs Bosons
produced per year
at high luminosity

Decay Channels

Branching ratios are completely determined by the Higgs mass.

M. Spira Fortsch. Phys. 46 (1998)



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

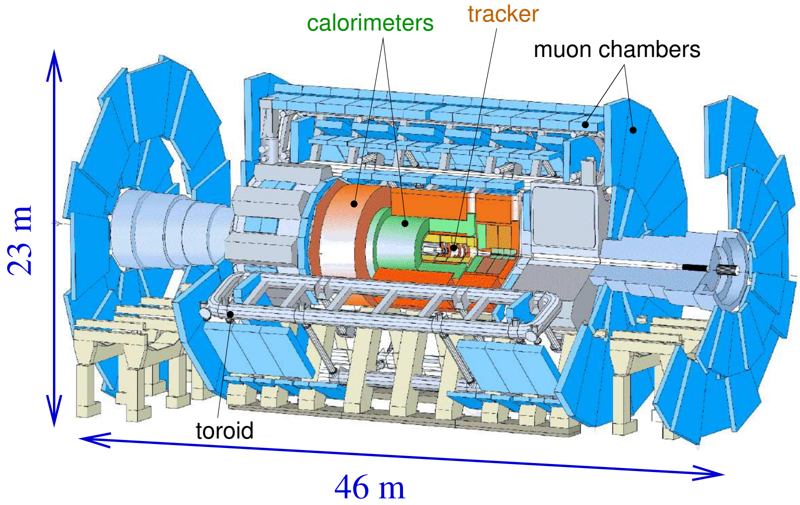
Ladbrokes
(the biggset betting company in the world):

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:

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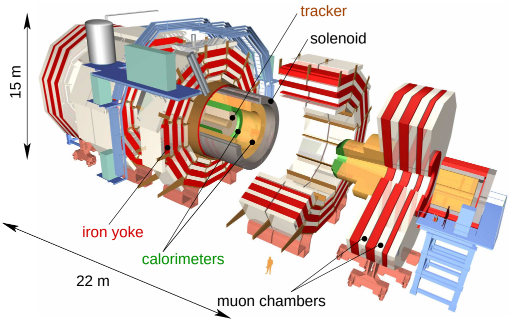
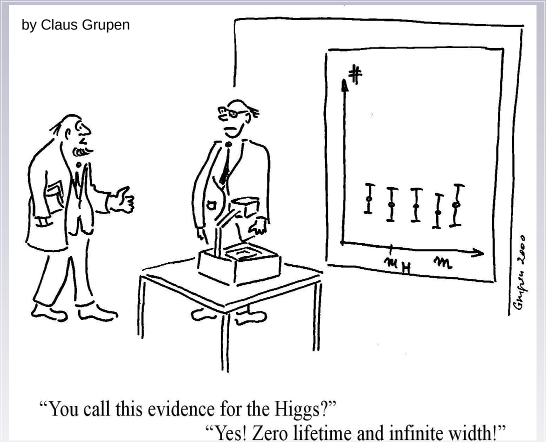
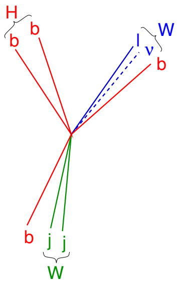


Discovery Potential

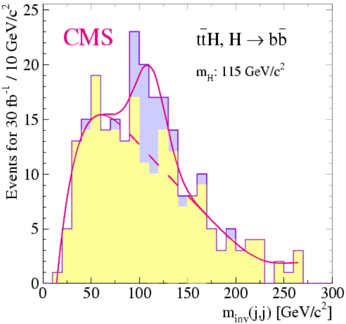


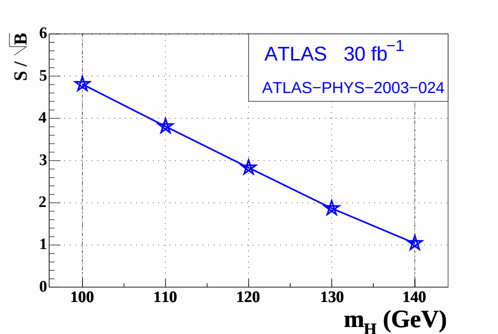
Low-mass Higgs: $t\bar{t}H, H \to b\bar{b}$

- 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)



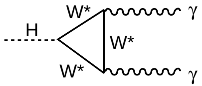
Signal significance $(S/\sqrt{B})$ at 30 fb^{-1}: 3.4σ for m_H =115 GeV





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

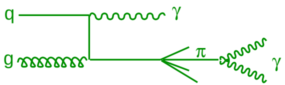
$B(H \to \gamma\gamma) = 10^{-3}\, B(H \to b\bar{b})$ only, but $H \to \gamma\gamma$ is a clean channel.



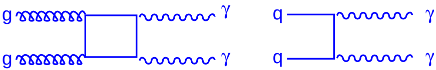
Main background processes:

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

reducible background



irreducible background



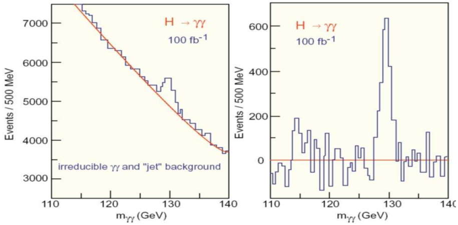
Additional improvement:

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

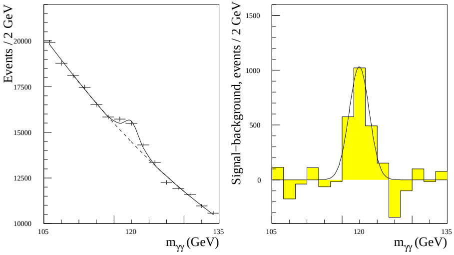
Signal significance ($S/\sqrt{B}$) at 100 fb^{-1}: 3-4σ for m_H <150 GeV

CMS has a 10% better calorimeter resolution than ATLAS.

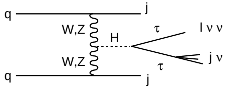
CMS
100 fb^{-1}



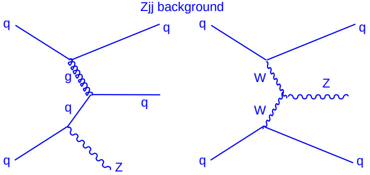
ATLAS
100 fb^{-1}



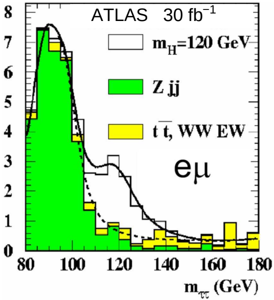
Low-mass Higgs: $qqH,\ H \to \tau^+\tau^-$

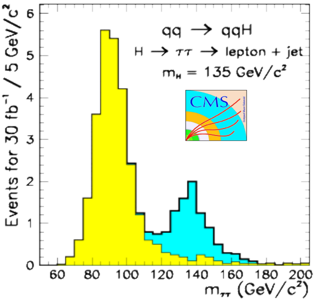


- hadronic jets in forward-backward region,
  forward jet-tagging, central jet veto
- leptonic or hadronic decay in τ-direction,
  missing p_T measurement
  lepton identification
- background: Zjj, $t\bar{t}$+jets, WWjj



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



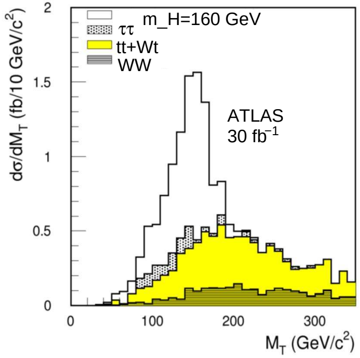


Low-mass Higgs: $(qq)H,\ H \to WW^{(*)} \to l\nu l\nu$

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

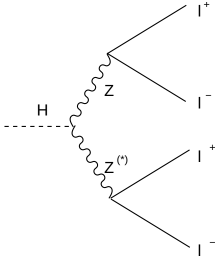
Main backgrounds:

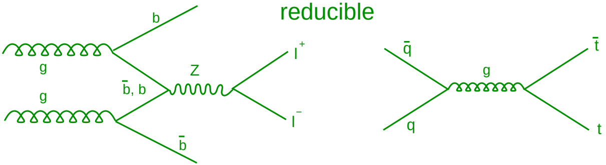
- WW, $WbW\bar{b}$ - suppressed by WW spin correlations in the signal
- Drell-Yan $ee, \mu\mu$ - lepton cuts (p_T^{miss} >30 GeV, $m < 75$ GeV)
- $t\bar{t}$, $\tau\tau$ - b-jet and τ veto in the central region

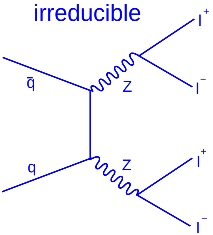


Signal significance ($S/\sqrt{B}$)
of 5σ reachable at 10 fb^{-1}
for m_H ≈170 GeV.

- 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: $ZZ \to 4l$

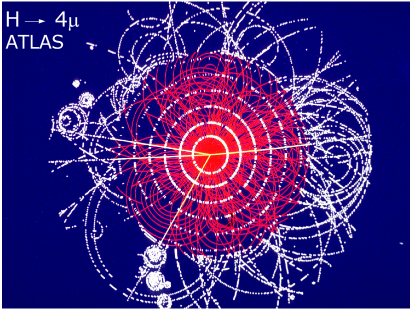


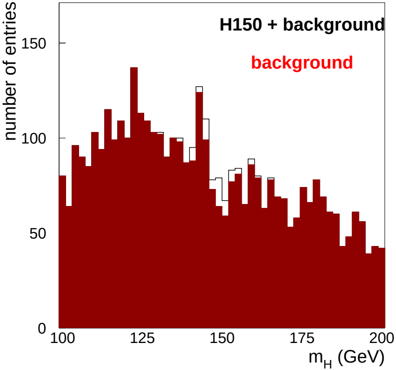




Particularly clean signature from muons:

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

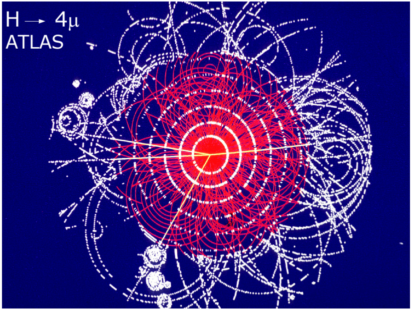




Signal significance for $H \to 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

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

Particularly clean signature from muons:



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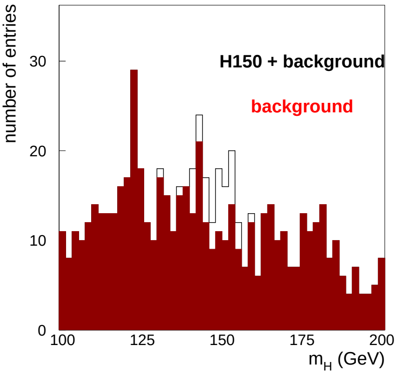
- selecting isolated leptons
- cut on the impact parameter



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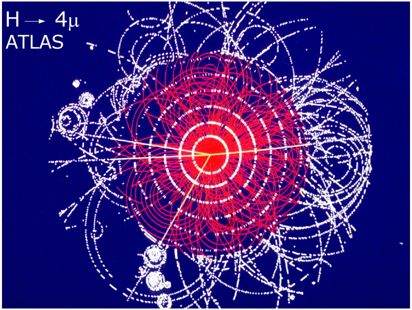

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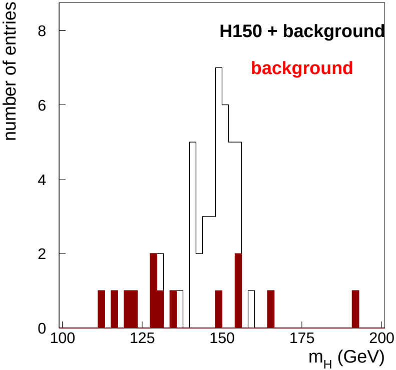
- $m_{2\mu} = (m_Z \pm 2\Gamma_Z)$
- selecting isolated leptons
- cut on the impact parameter



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

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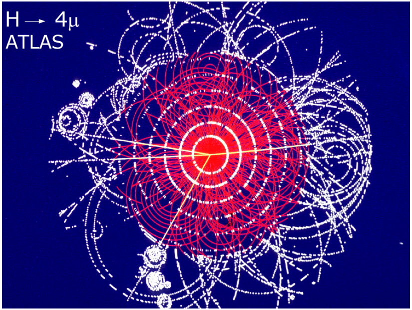

- no cuts applied on the muon tracks
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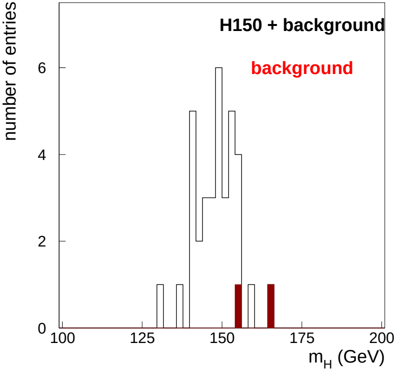
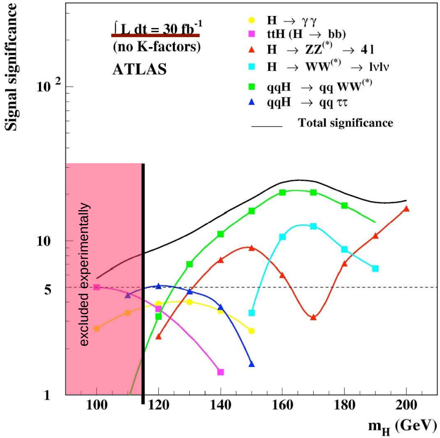
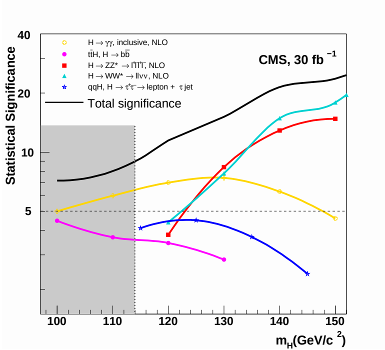


Signal significance for $H \rightarrow 4l$ at 30 fb^{-1}: 3-5σ for m_H <200 GeV.

Discovery potential for a low Higgs mass

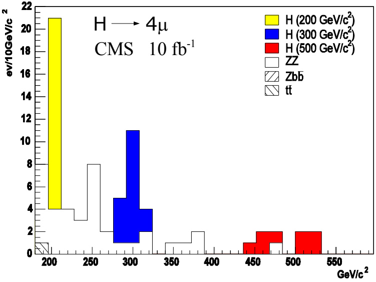
- combination of all channels is needed for the 5σ discovery in the first three years of running LHC

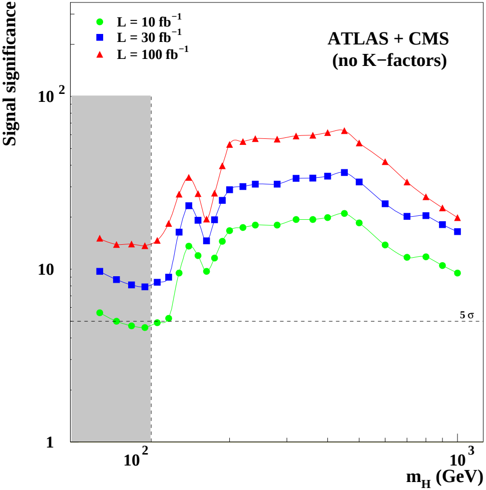




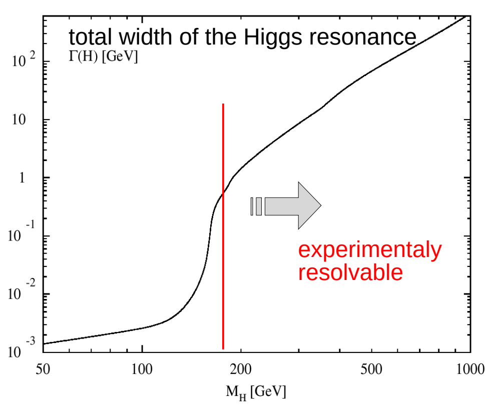
Discovery potential at the LHC

- $H \to ZZ \to 4l$ 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

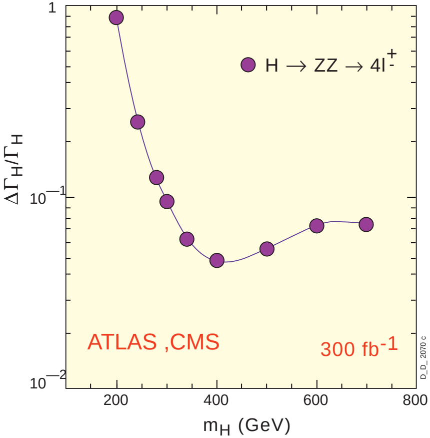


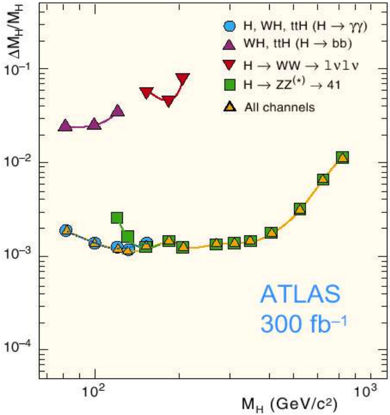


Precision Measurements of Higgs Properties



Mass and Width





Width measurement:

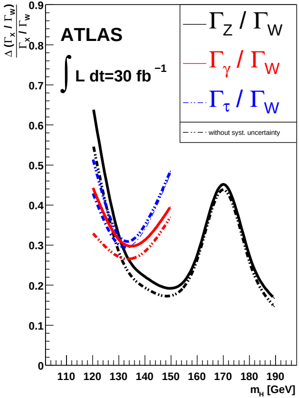
6% for m_H >300 GeV

Mass measurement:

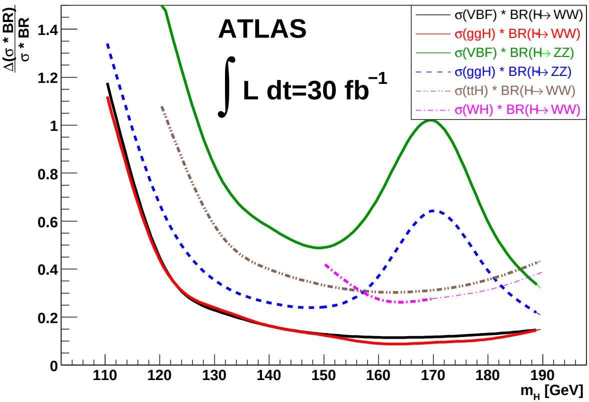
<1% for all m_H

Relative widths and branching ratios

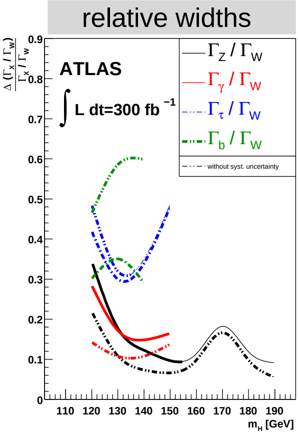
relative widths

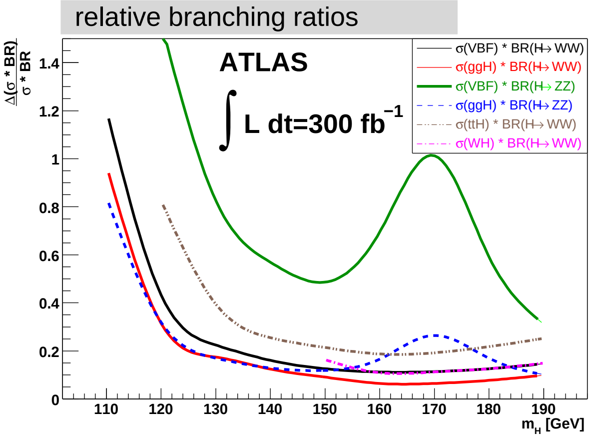


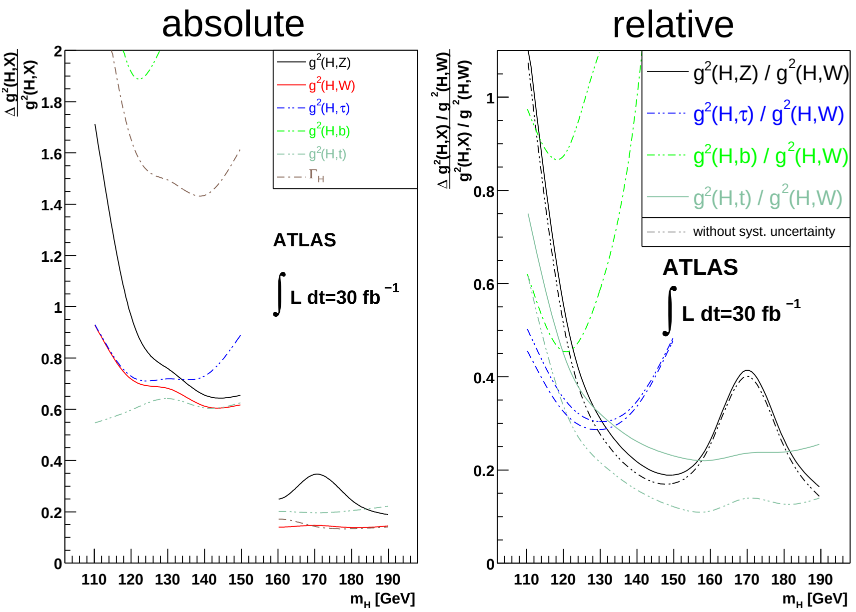
relative branching ratios



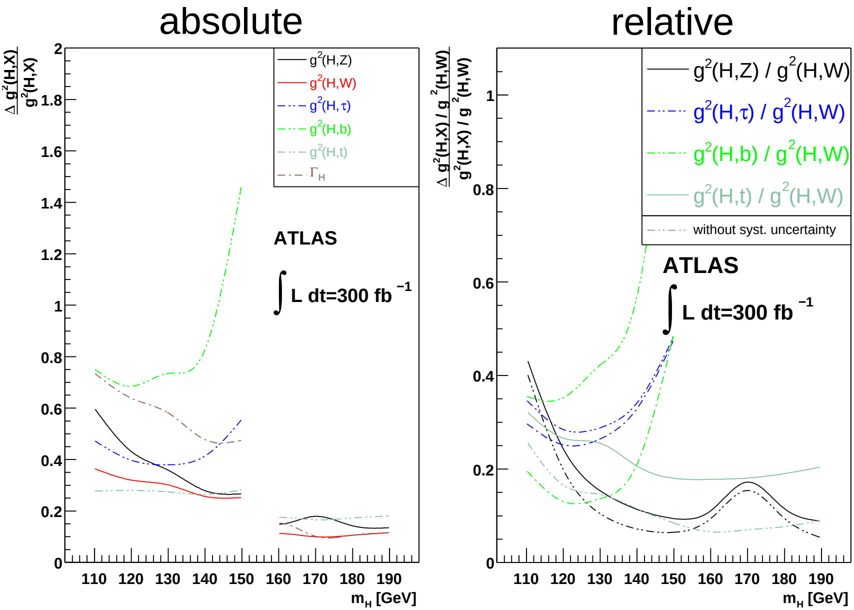
Relative widths and branching ratios






absolute
relative
$\frac{\Delta g^2(H,X)}{g^2(H,X)}$
$g^2(H,Z)$
$g^2(H,W)$
$g^2(H,\tau)$
$g^2(H,b)$
$g^2(H,t)$
Γ_H
ATLAS
$\int L\,dt = 30\ fb^{-1}$
m_H [GeV]
$\frac{\Delta g^2(H,X)/g^2(H,W)}{g^2(H,X)/g^2(H,W)}$
$g^2(H,Z) / g^2(H,W)$
$g^2(H,\tau) / g^2(H,W)$
$g^2(H,b) / g^2(H,W)$
$g^2(H,t) / g^2(H,W)$
without syst. uncertainty
ATLAS
$\int L\,dt = 30\ fb^{-1}$
m_H [GeV]

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...