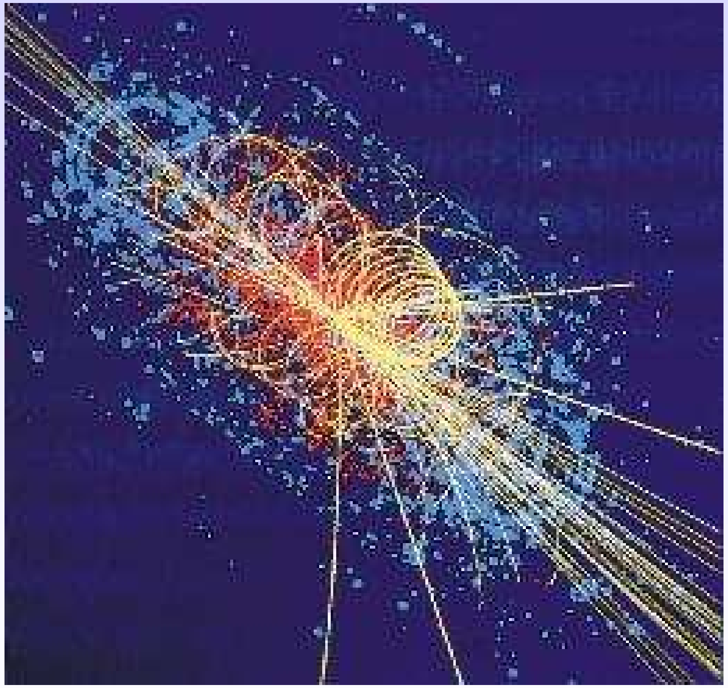
Physics at Hadron Colliders

3. Search for the Higgs boson

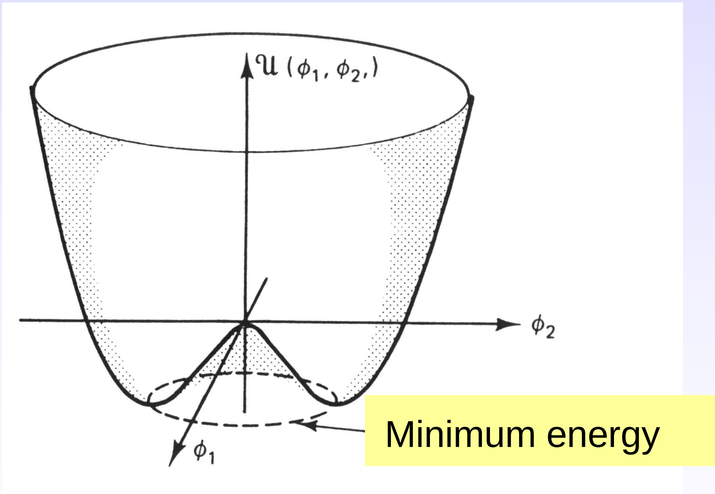


- **Higgs boson production and decay**
- **LHC discovery potential**
- **Tevatron potential**

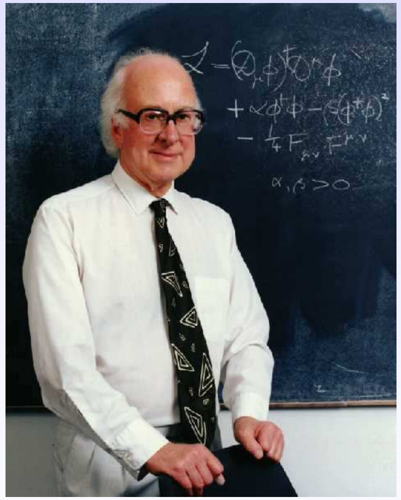
The Search for the Higgs Boson

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

- **The LHC must have the potential to detect this particle, should it exist**

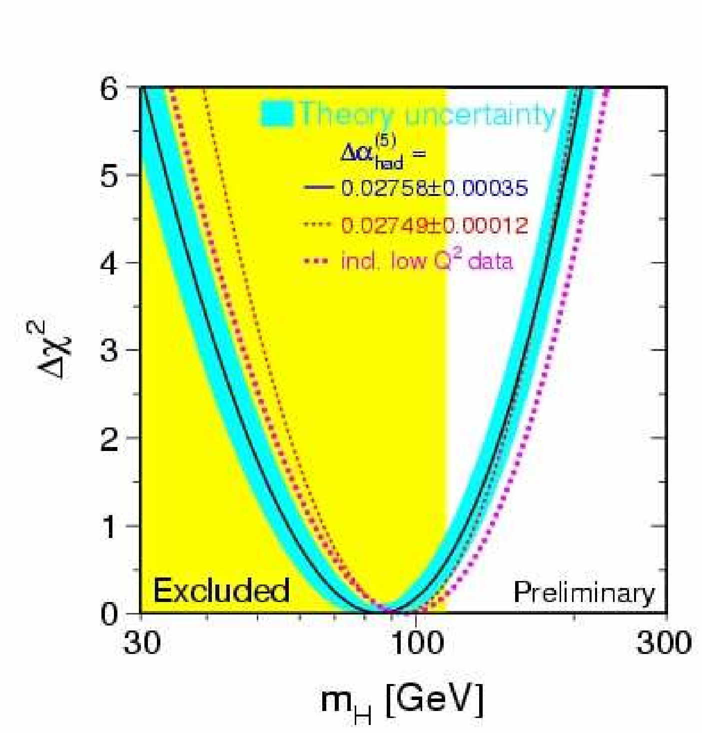


The Higgs potential (1964)



What do we know about the Higgs Boson ?

- Needed in the Standard Model to generate particle masses
- Mass not predicted by theory, except that $m_H <$ ~1000 GeV
- $m_H > 114.4$ GeV from direct searches at LEP
- Indirect limits from electroweak precision measurements (LEP, Tevatron and other experiments....)



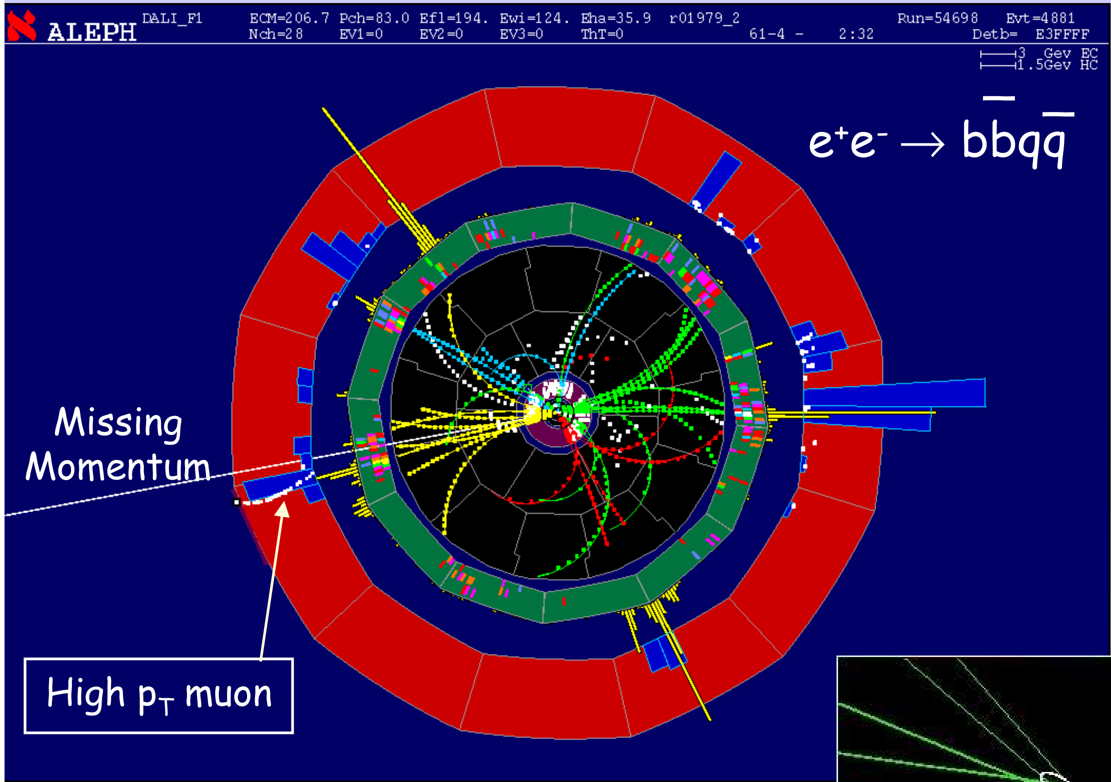
Results of the precision el.weak measurements: (all experiments, July 2006):

M_H = 85 (+39) (-28) GeV/c^2

$M_H <$ 166 GeV/c^2 (95 % CL)

$\longrightarrow$ Higgs boson could be around the corner !

SM Higgs: direct searches at LEP2

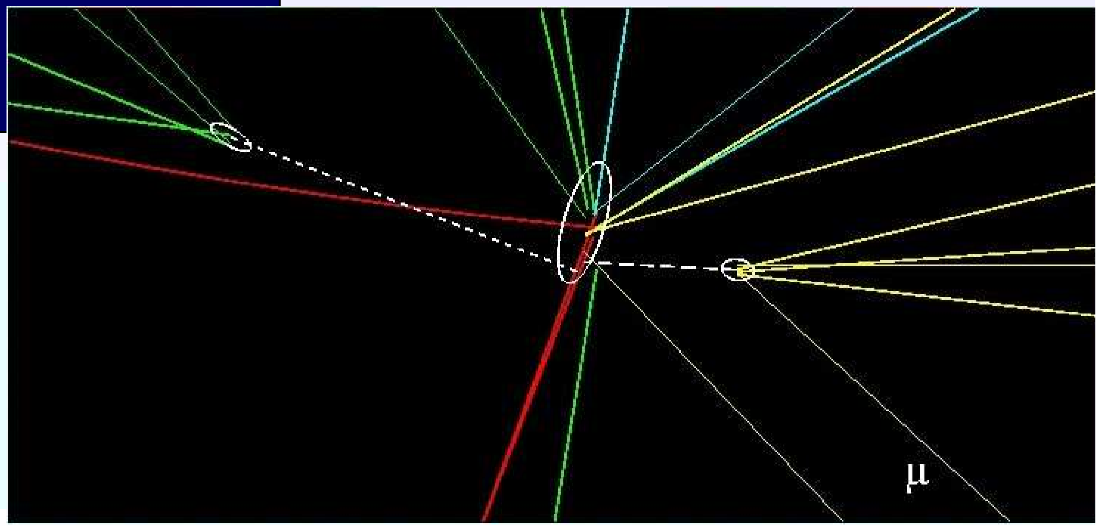


Golden 4-jet event
(ALEPH, 14/06/00, 206.7 GeV)

- **Mass 114 ± 3 GeV**
- **Good HZ fit**
- **Poor WW and ZZ fits**
- **P(Background) ≈ 2%**
- **s/b(115) = 4.6**

b-tagging
(0 = light quarks, 1 = b quarks)

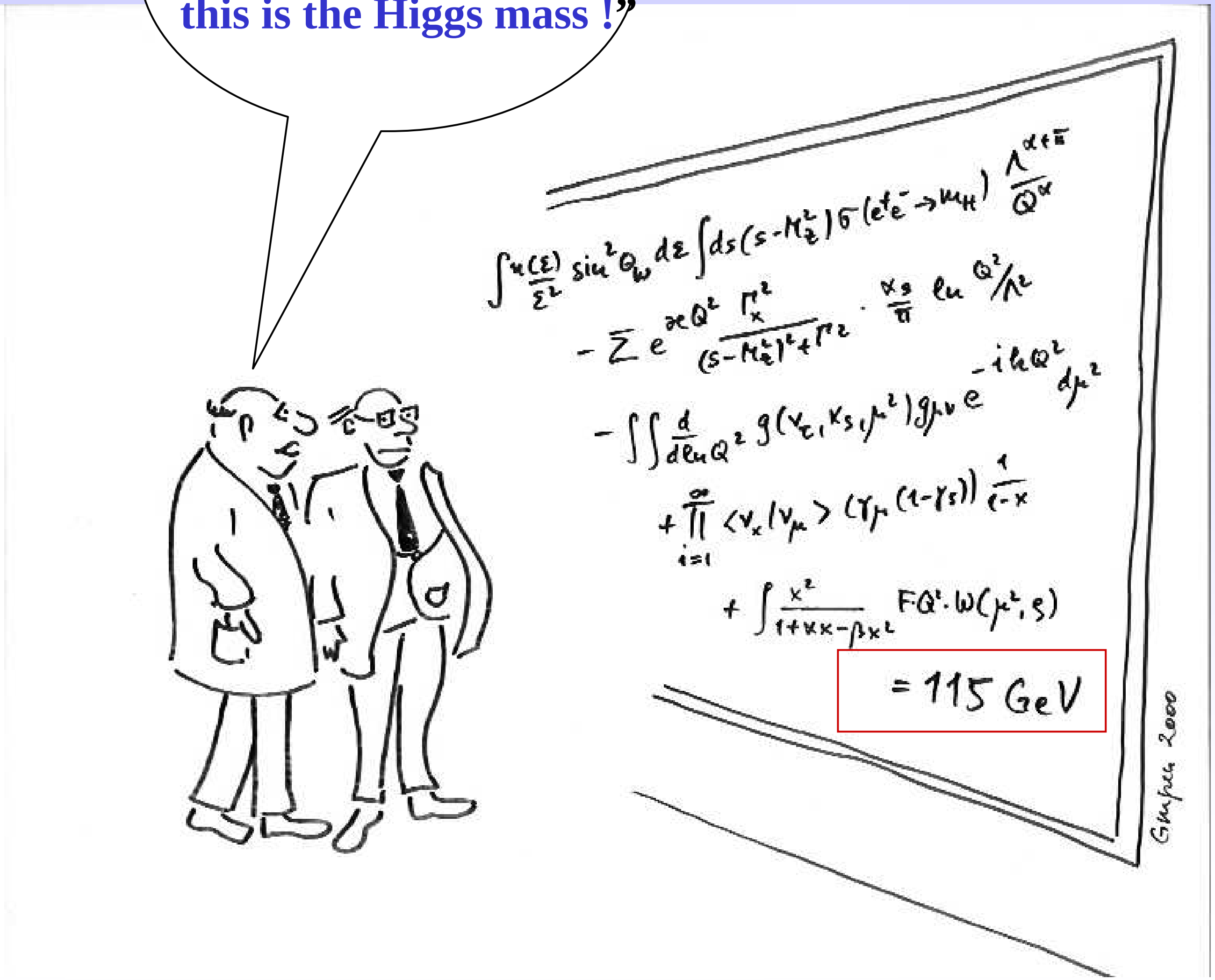
- **Higgs jets: 0.99 and 0.99;**
- **Z jets: 0.14 and 0.01.**



Higgs at LEP: conclusions

"This does not necessarily mean that this is the Higgs mass !"

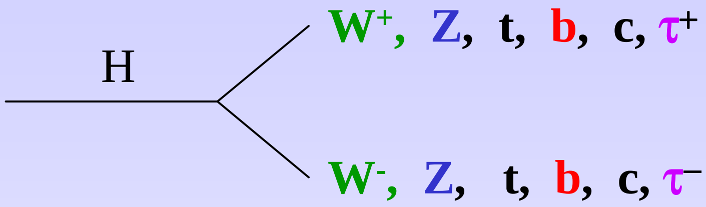
The number 115 GeV will remain stuck in our heads for quite some time

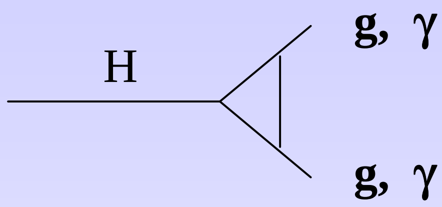


Tevatron ??
LHC ?
2010 (±1 year)?

Decays of the Higgs Boson

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





$\Gamma(H \rightarrow f\,f) \sim G_F\, M_H\, m_f^2$

$\Gamma(H \rightarrow BB) \sim G_F\, M_H^3$

Higgs boson likes mass:

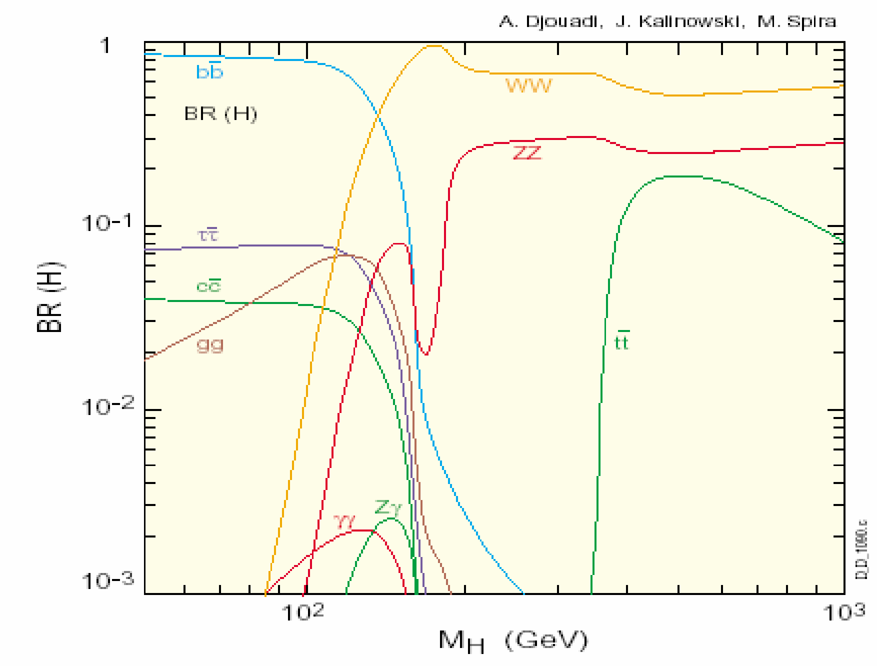
decays preferentially into the heaviest particles kinematically allowed

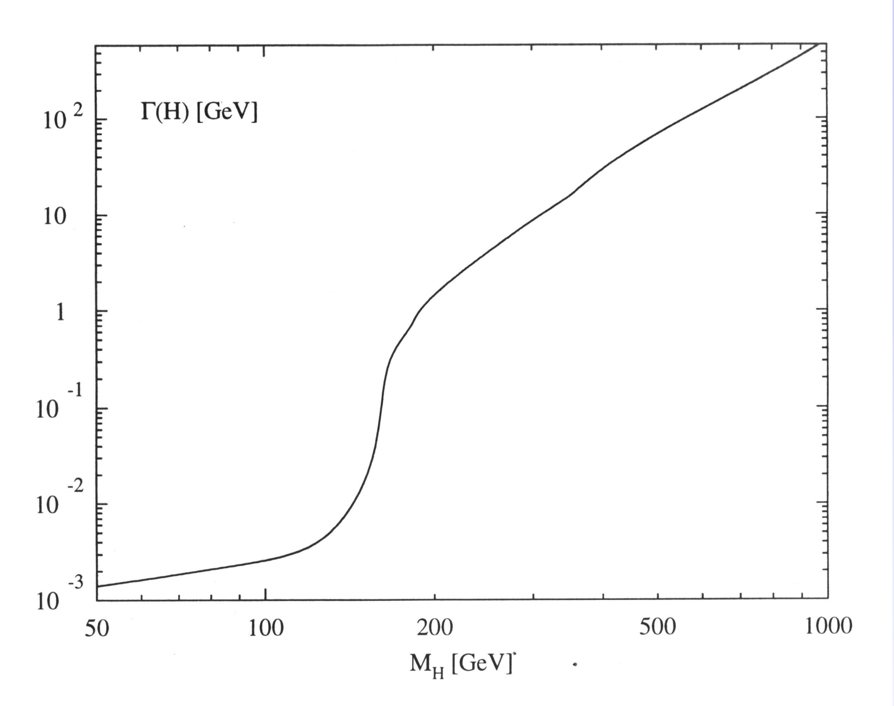
$\Gamma(H \rightarrow gg) \sim \alpha_s^2\, G_F\, M_H^3$

$\Gamma(H \rightarrow \gamma\gamma) \sim \alpha^2\, G_F\, M_H^3$

decays into massless particles are also allowed via loops

BR and width of the Higgs Boson

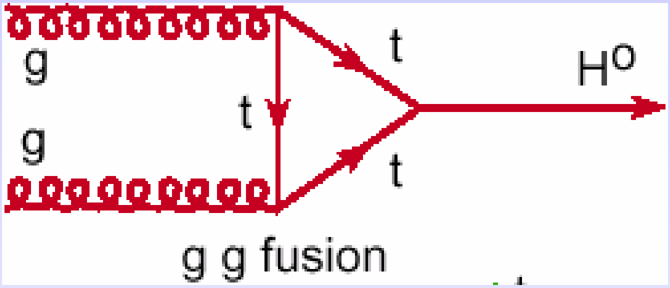




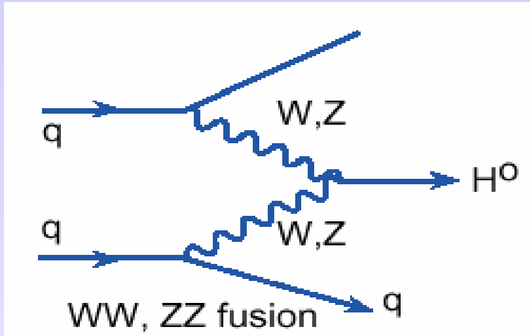
Upper limit on Higgs boson mass: from unitarity of WW scattering **$M_H < 1$ TeV/c^2**

Higgs Boson Production at Hadron Colliders

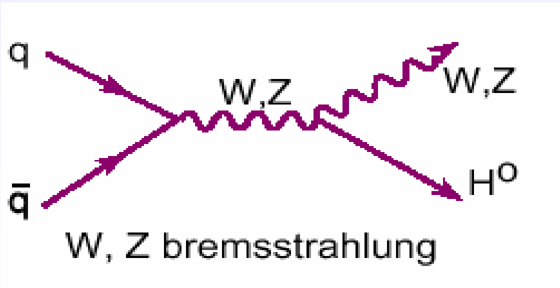
(i) Gluon fusion

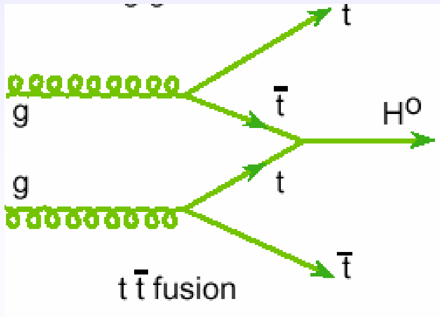


(ii) Vector boson fusion

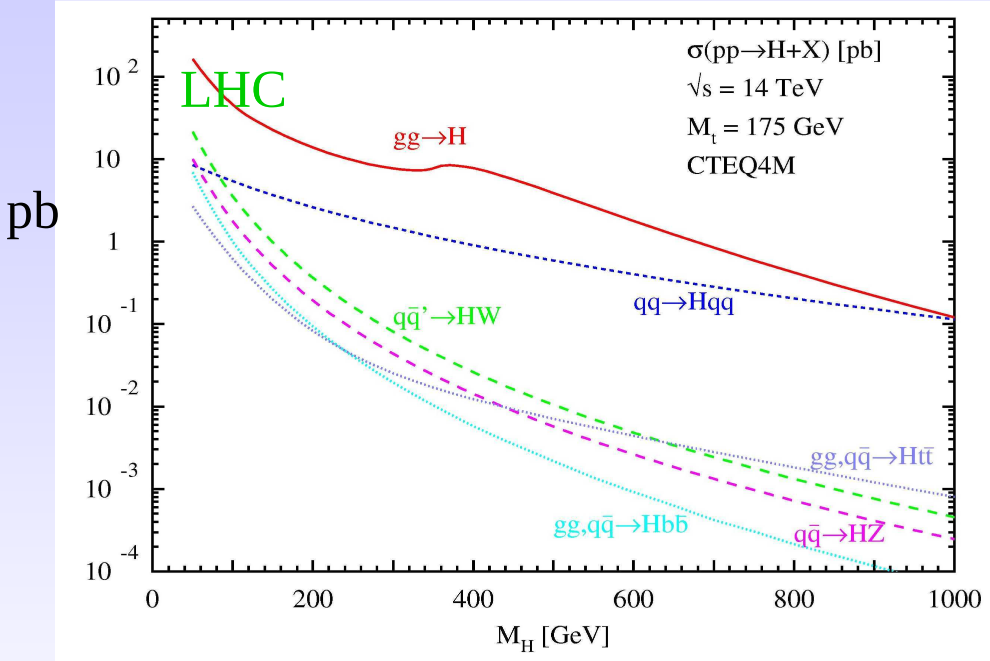


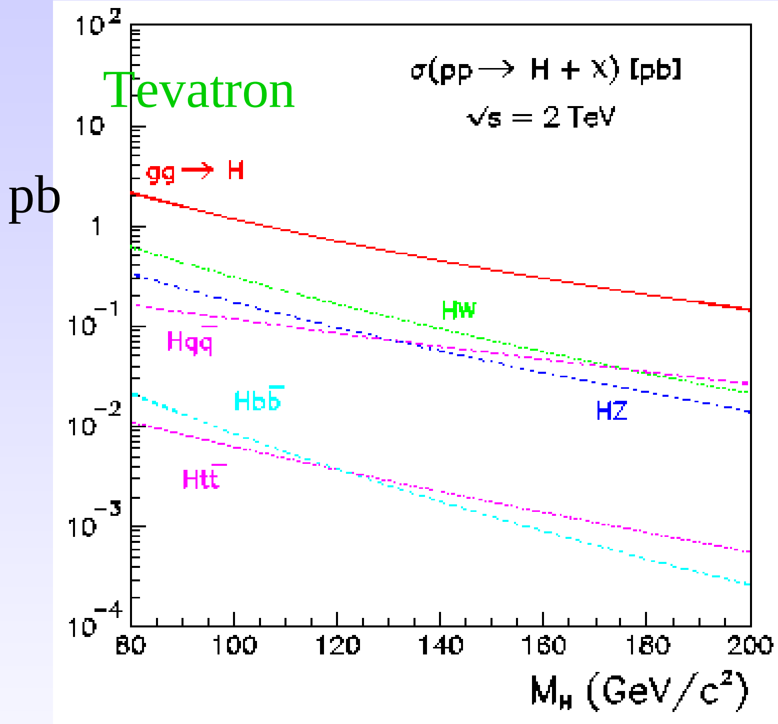
(iii) Associated production (W/Z, tt)





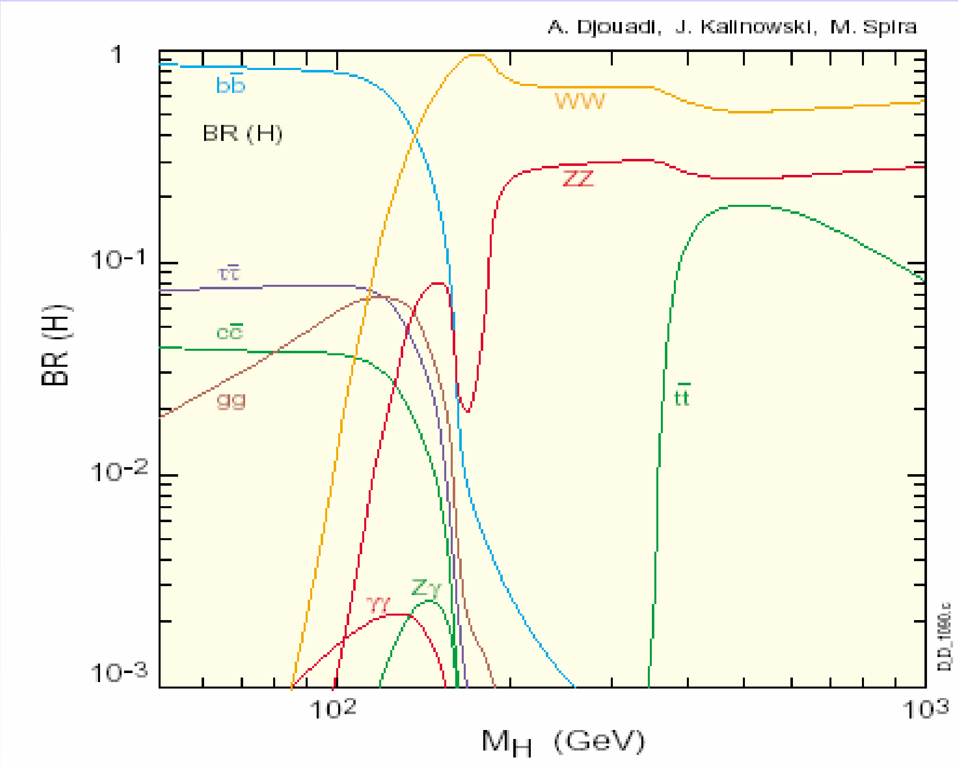
Higgs Boson Production cross sections





qq → W/Z + H   cross section   ~10 times larger at the LHC
gg → H   ~80 times larger at the LHC

Higgs Boson Decays at Hadron Colliders



at high mass:
Lepton final states
(via H → WW , ZZ)

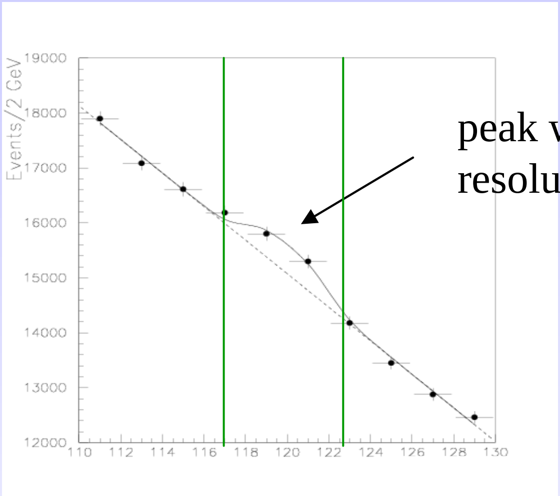
at low mass:
Lepton final states
(via H → WW*, ZZ*)
Photon final states

Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH) due to the huge QCD jet background

How can one claim a discovery ?

Suppose a new narrow particle $X \to \gamma\gamma$ is produced:



peak width due to detector resolution

$m_{\gamma\gamma}$

Signal significance:

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S = number of signal events
N_B = number of background events

} in peak region

$\sqrt{N_B} \equiv$ fluctuation in number of background events for large numbers
(otherwise use Poisson statistics)

S > 5 : signal is larger than a fluctuation of 5σ in background.
Gaussian probability that background fluctuates by more than 5σ : 10^{-7} $\to$ discovery

Critical parameters to maximize S

1. **Detector resolution** (σ_m)

If σ_m increases by e.g. a factor of two, then need to enlarge peak region by a factor of two to keep the same number of signal events

$\longrightarrow$ N_B increases by ~ 2 $\Rightarrow$ **$S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$**

$$\Rightarrow S \sim 1/\sqrt{\sigma_m}$$

Note: only valid if $\Gamma_H << \sigma_m$ otherwise resolution is not relevant.

m_H = 100 GeV $\rightarrow$ Γ_H ~0.001 GeV

m_H = 200 GeV $\rightarrow$ Γ_H ~ 1 GeV

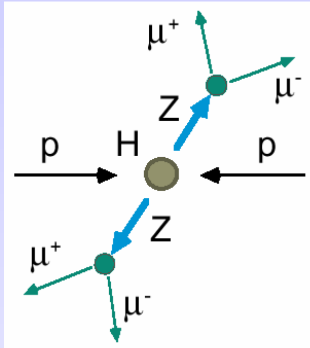
m_H = 600 GeV $\rightarrow$ Γ_H ~ 100 GeV **$\Gamma_H \sim m_H^3$**

2. **Integrated luminosity (L)**

$$\left.\begin{array}{l} N_S \sim L \\ N_B \sim L \end{array}\right\} \quad \Rightarrow S \sim \sqrt{L}$$

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

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

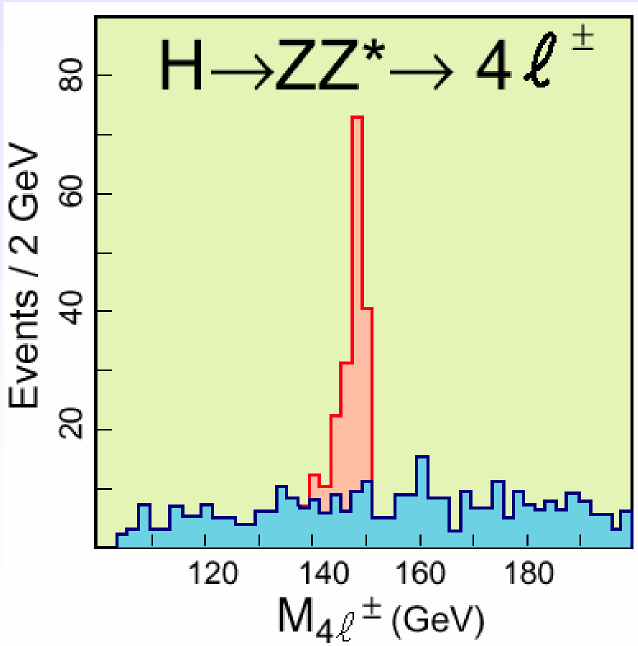
Background: Top production
$tt \rightarrow Wb\,Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$
Associated production Z bb

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

Background rejection: Leptons from b-quark decays are non isolated and do not originate from primary vertex

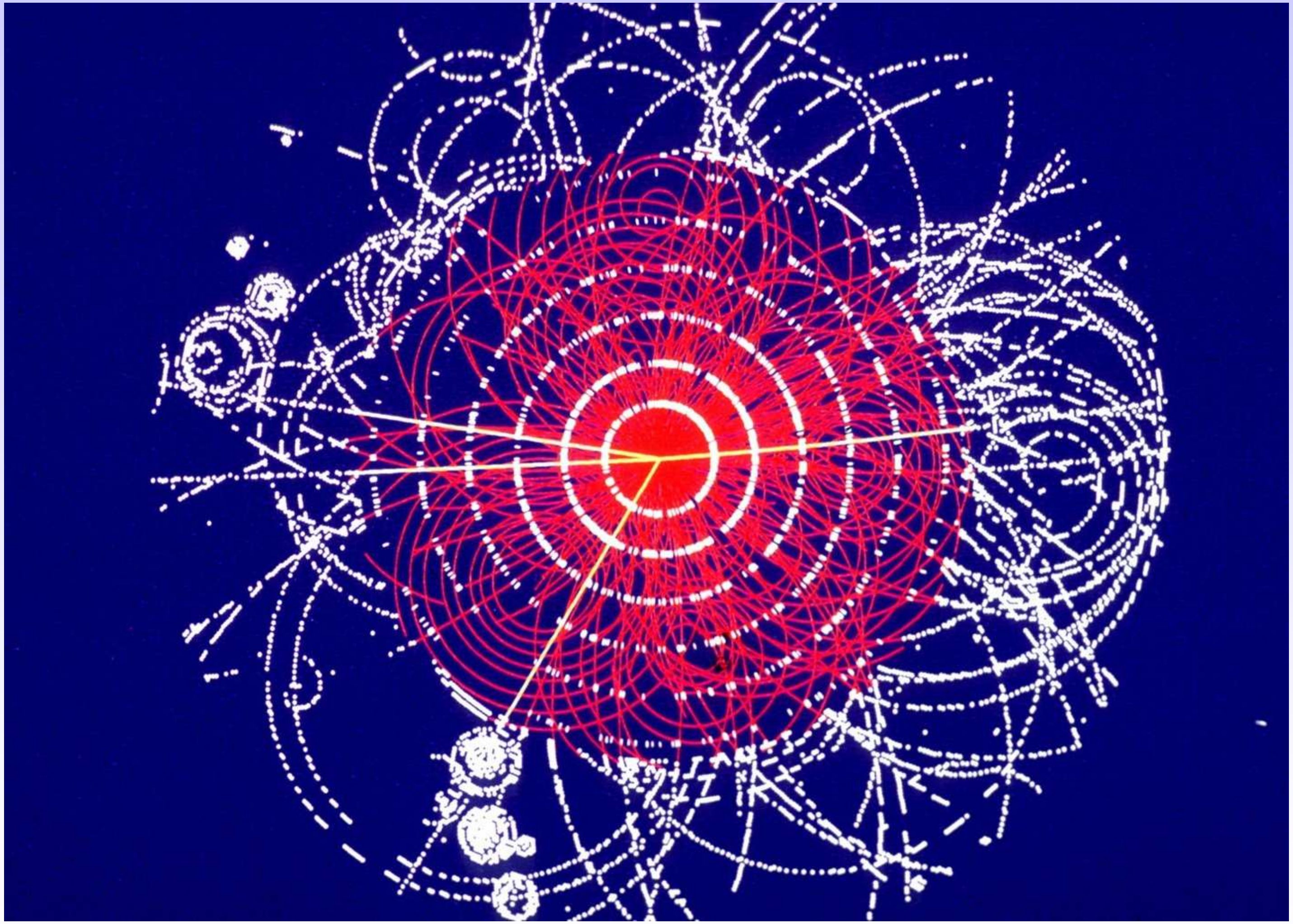
Dominant background after cuts: ZZ continuum

L = 100 fb^{-1}

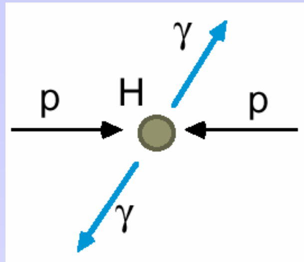


Discovery potential in mass range from ~130 to ~600 GeV/c^2

A simulated H → ZZ → ℓℓℓℓ event



$H \rightarrow \gamma\gamma$

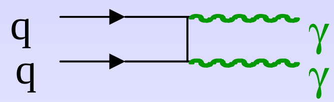


- Signal (mH ≤ 150 GeV)
  σ x BR ≈ 50 fb (BR ≈ 10^{-3})

- Backgrounds : - $\gamma\gamma$ (irreducible):

  $\sigma_{\gamma\gamma} \approx$ 2 pb / GeV

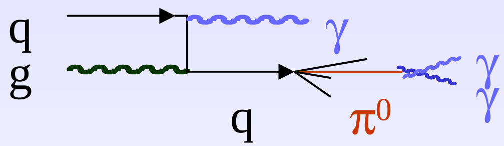
  → need $\sigma(m\ )/m \approx 1\%$



  – γj+ jj (reducible):

  $\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$

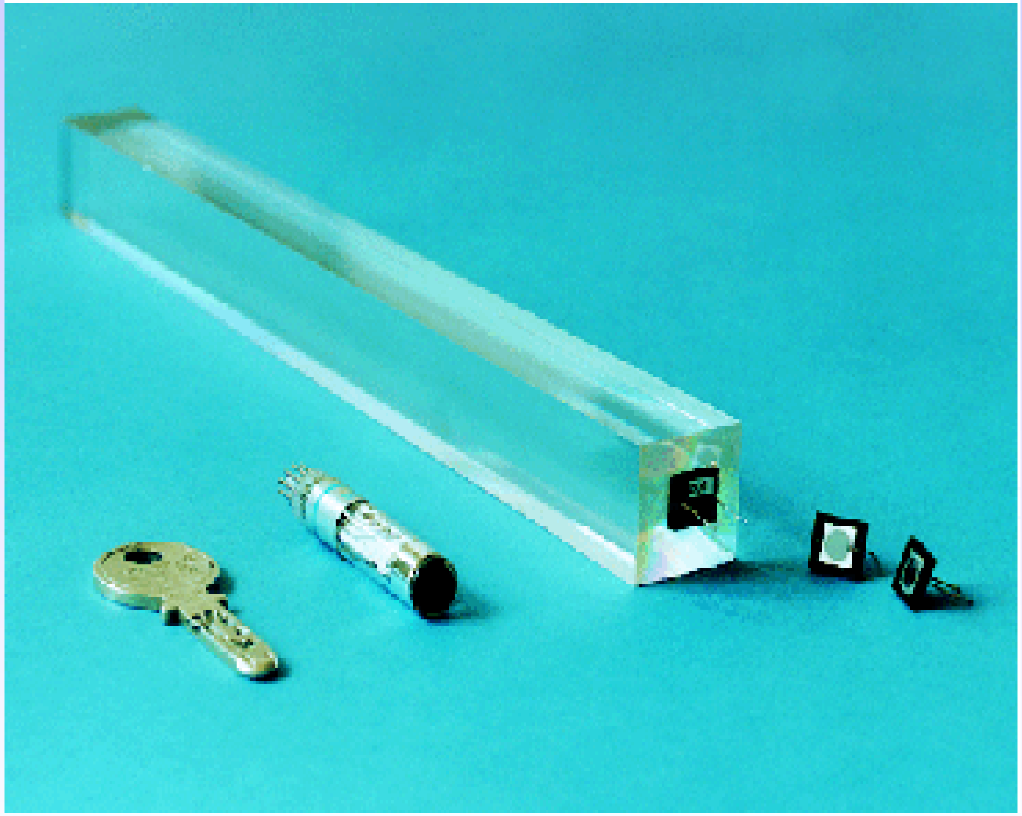
  → need $R_j > 10^3$



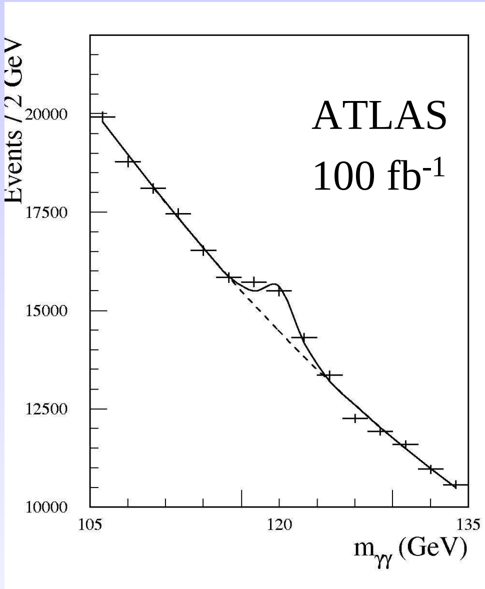
→ most demanding channel for EM calorimeter performance :
energy and angle resolution, acceptance, γ /jet and γ / π^0 separation

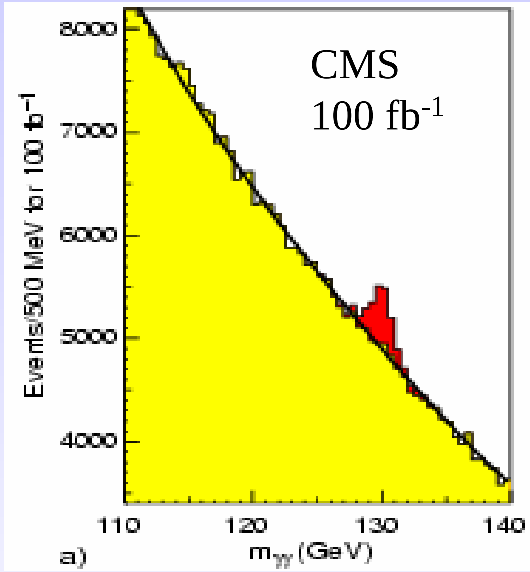
ATLAS and CMS: complementary performance

CMS crystal calorimeter



$H \rightarrow \gamma\gamma$ (cont.)





Two isolated photons:
$P_T(\gamma_1) > 40$ GeV
$P_T(\gamma_2) > 25$ GeV
$|\eta| < 2.5$

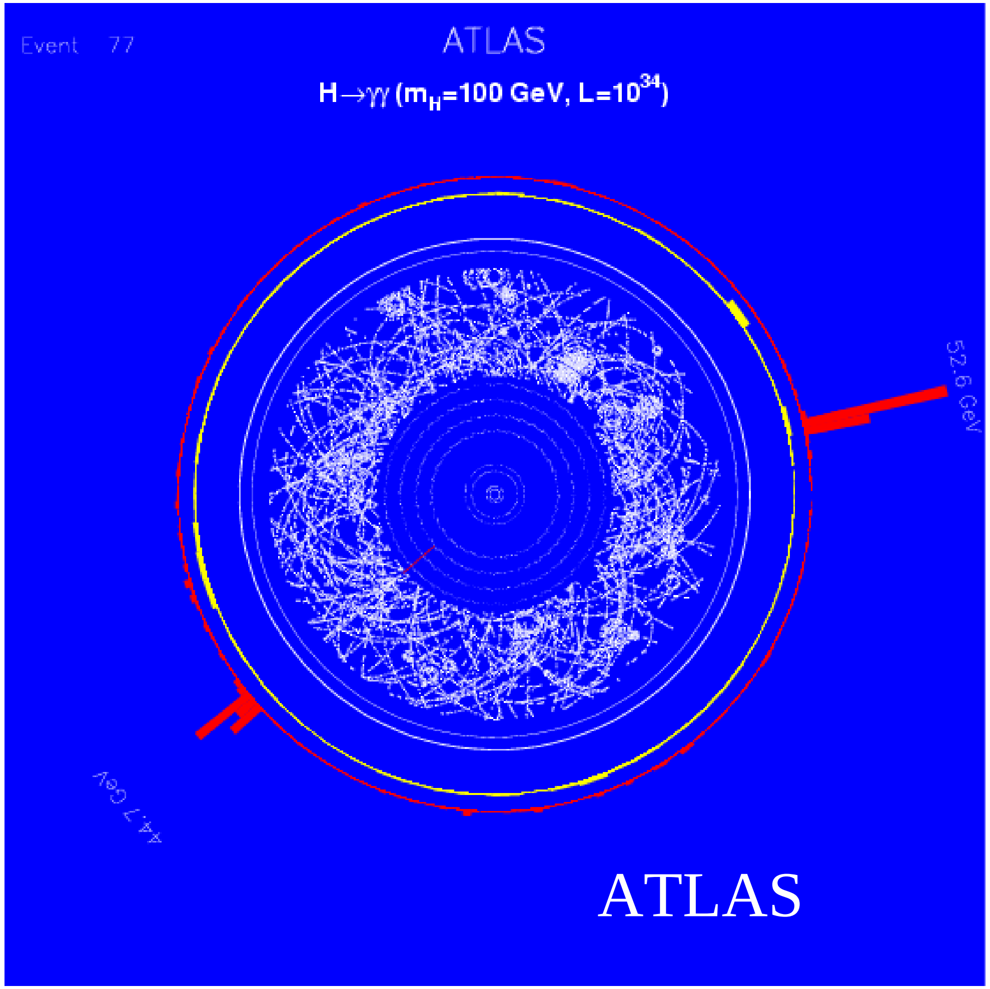
Mass resolution
for $m_H = 100$ GeV/c^2:

ATLAS : 1.1 GeV (LAr-Pb)
CMS : 0.6 GeV (crystals)

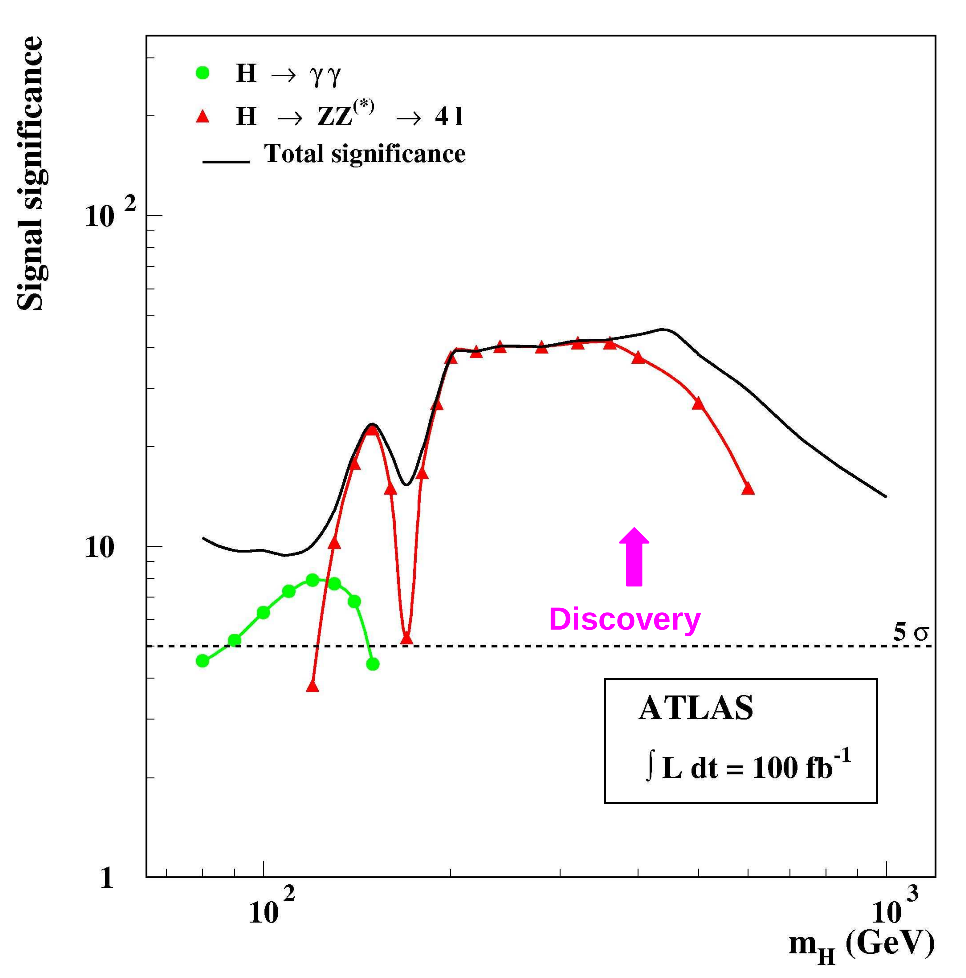
Signal / background ~ 4%
Background can be determined from side bands
important: $\gamma\gamma$-mass resolution in the calorimeters, γ / jet separation

Sensitivity in mass range 100 – 140 GeV/c2

A simulated $H \rightarrow \gamma\gamma$ event in ATLAS



If the Standard Model Higgs particle exists, it should be discovered at the LHC !



The full allowed mass range from the LEP limit (~114 GeV) up to the theoretical upper bound of ~1000 GeV can be covered after 1 year at high luminosity using the channels

$H \rightarrow ZZ \rightarrow \ell\ell\ \ell\ell$

and

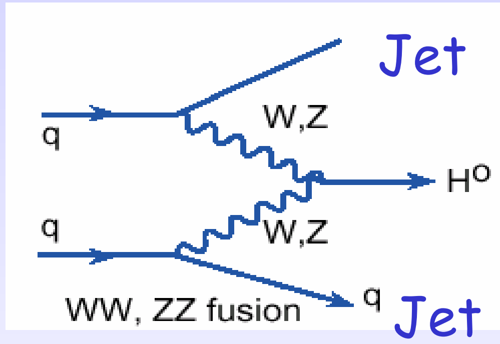
$H \rightarrow \gamma\gamma$

More difficult channels can also be used: Vector Boson Fusion
$qq\,H \rightarrow qq\,WW \rightarrow qq\,\ell\nu\,\ell\nu$

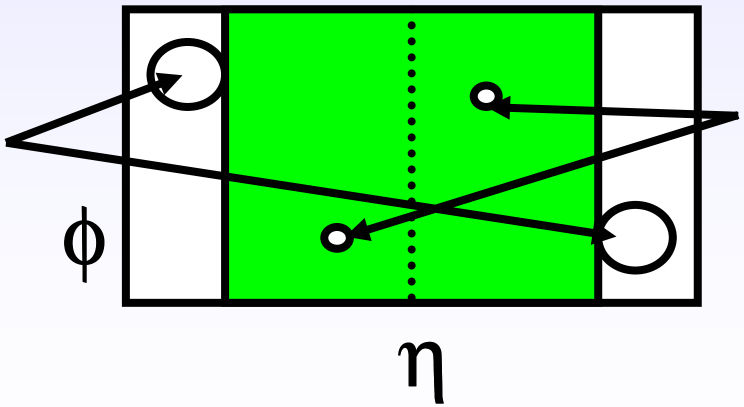
Motivation: Increase discovery potential at low mass
Improve measurement of Higgs boson parameters
(couplings to bosons, fermions)

Distinctive Signature of:

- **two forward tag jets**
- **little jet activity in the central region**
  $\Rightarrow$ **central jet Veto**



Tag jets

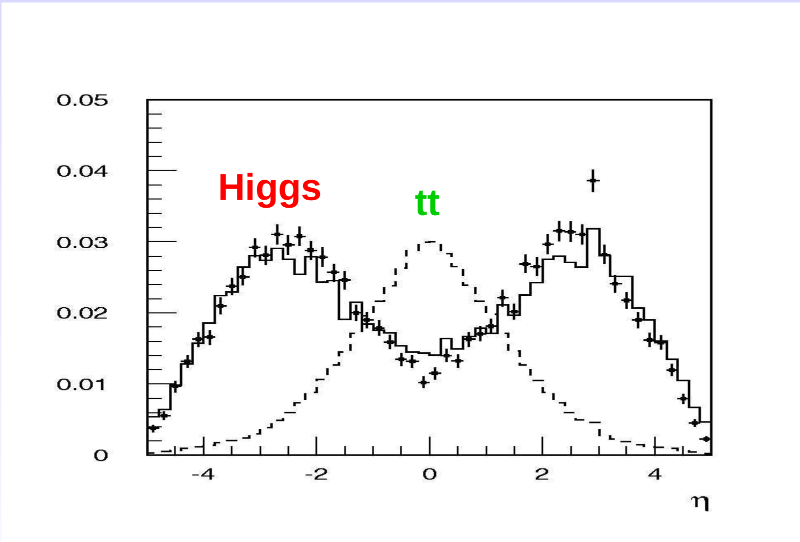


Higgs Decay

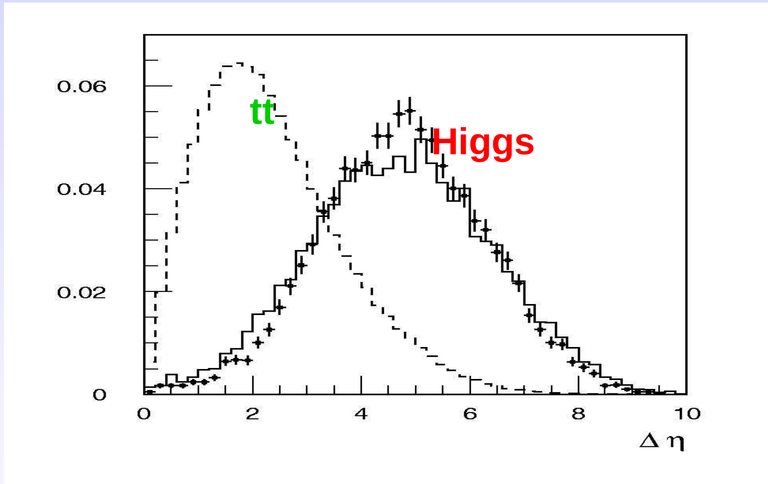
Forward jet tagging

Rapidity distribution of tag jets

VBF Higgs events vs. tt-background

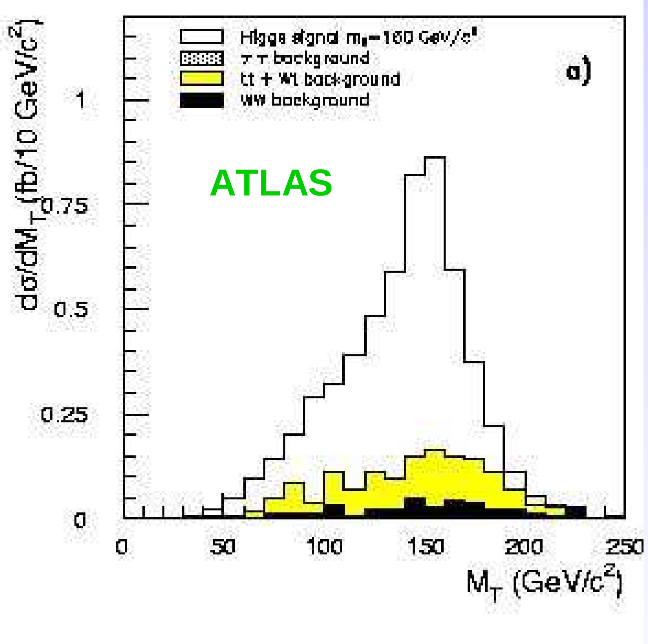


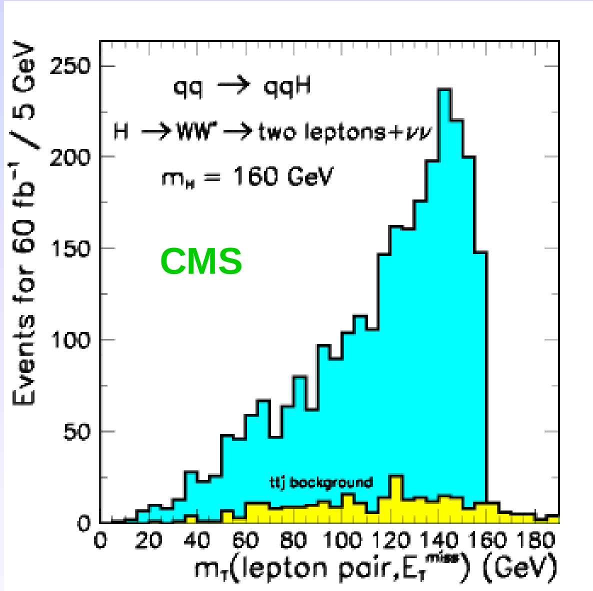
Rapidity separation



qq H $\rightarrow$ qq W W*
$\rightarrow$ qq $\ell\nu$ $\ell\nu$

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$

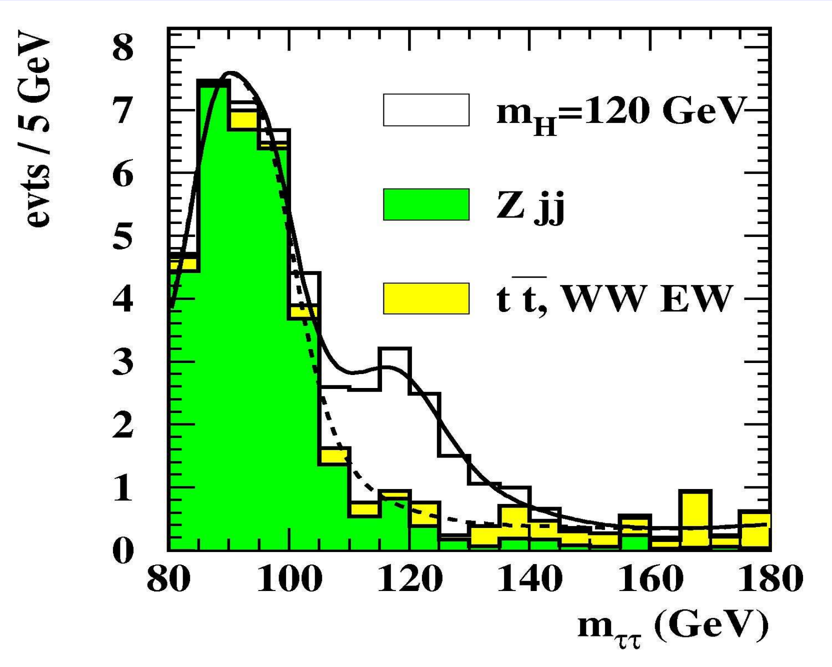




Transverse mass distributions: clear excess of events above the background from tt-production

H → τ τ decay modes for a SM Higgs boson are visible in vector boson fusion

qq H → qq τ τ
→ qq ℓνν ℓνν
→ qq ℓνν hν



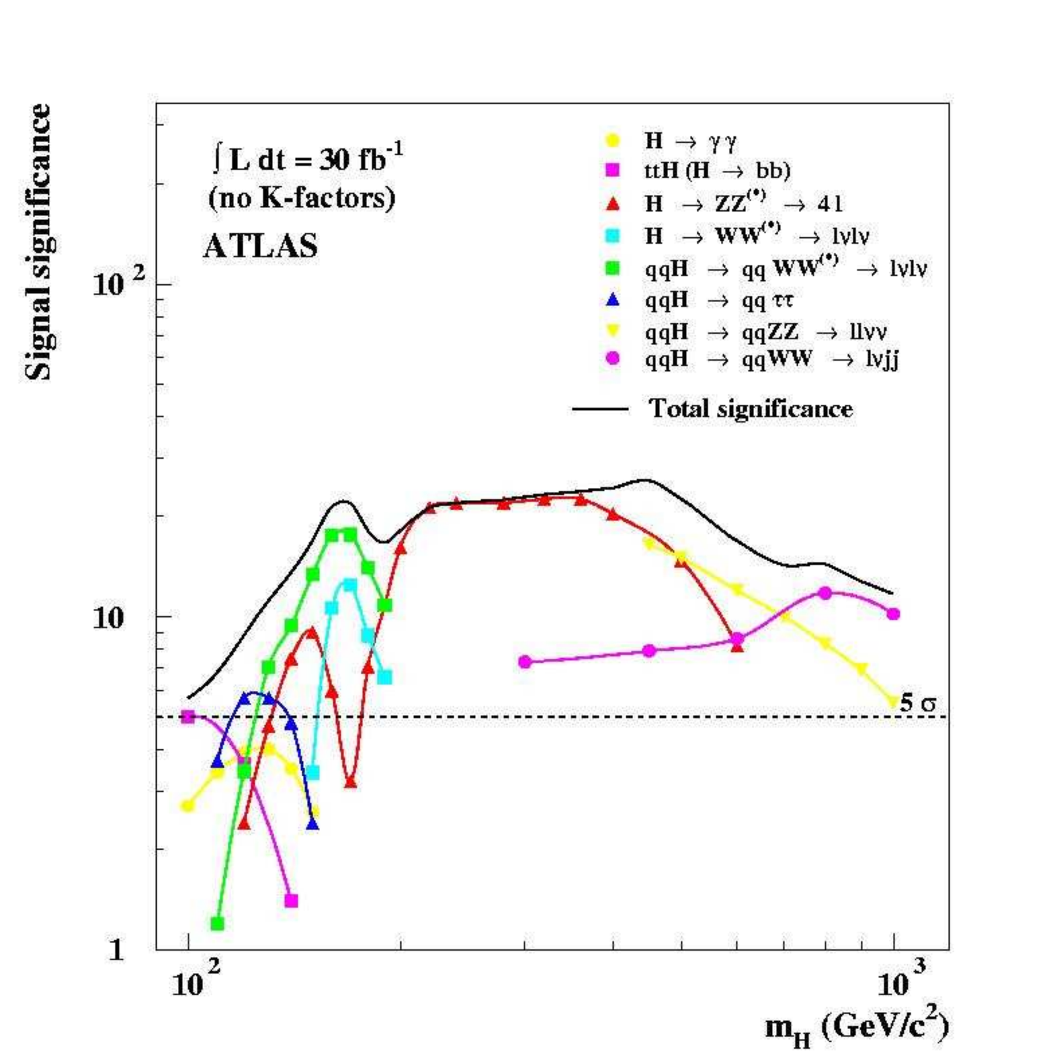
- τ momentum can be reconstructed

  → collinear approximation:
  assume neutrinos go in the direction of the visible decay products

  → Higgs mass can be reconstructed

- main background: Z jj, Z → ττ

ATLAS Higgs discovery potential for 30 fb^{-1}



- Full mass range can alreaday be covered after 3 years at low luminosity

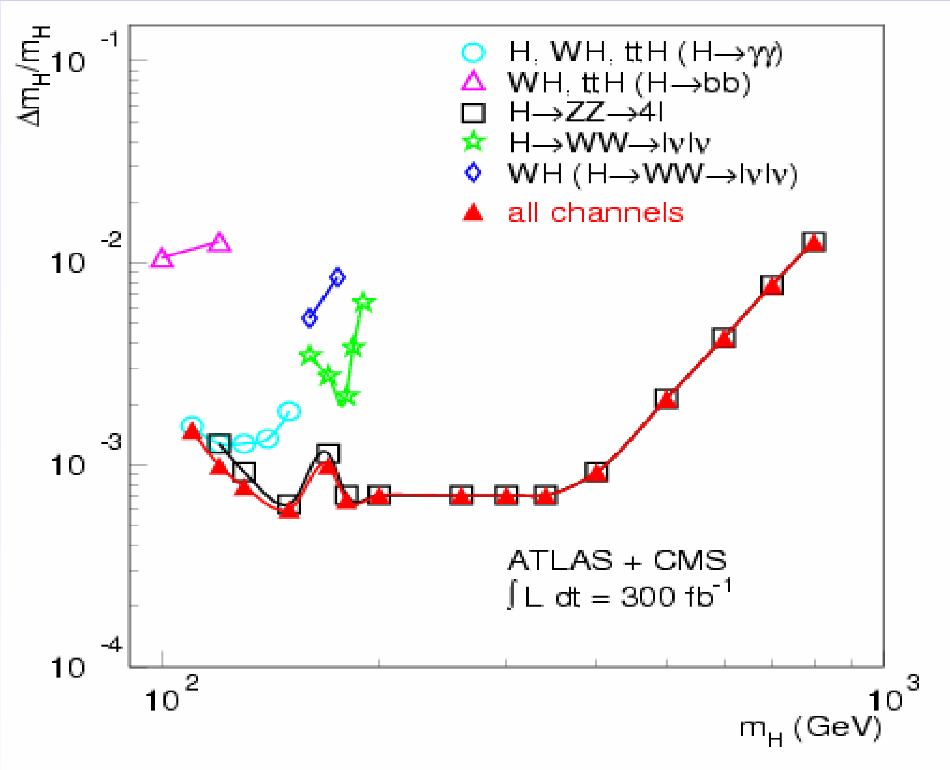
- Several channels available over a large range of masses

- Comparable situation for the CMS experiment

Determination of Higgs Boson Parameters

1. Mass
2. Spin (not covered)
3. Width (not covered)
4. Couplings to fermions and bosons

Measurement of the Higgs boson mass



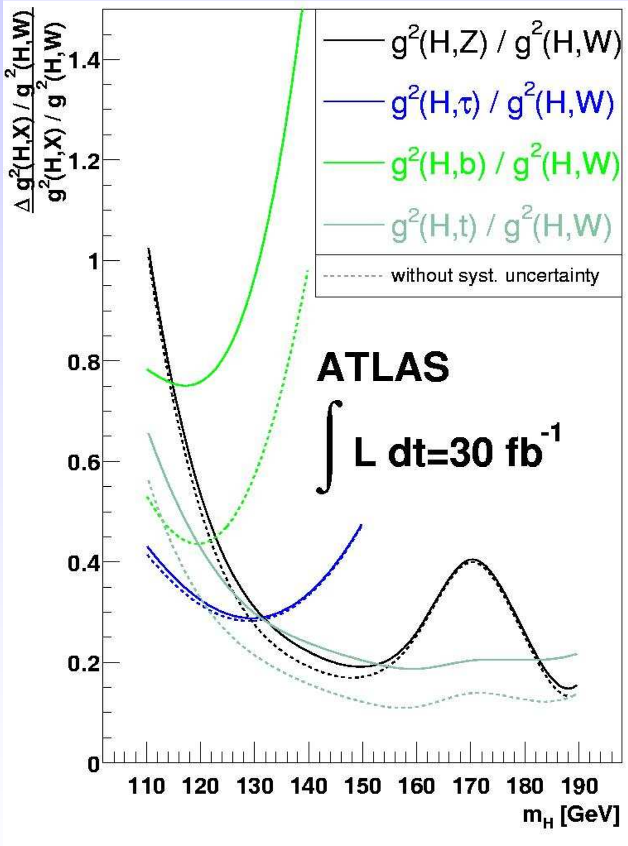
Dominated by γ/ℓ decays:
H→ ZZ→ 4ℓ and H→ γγ
good invariant mass resolution

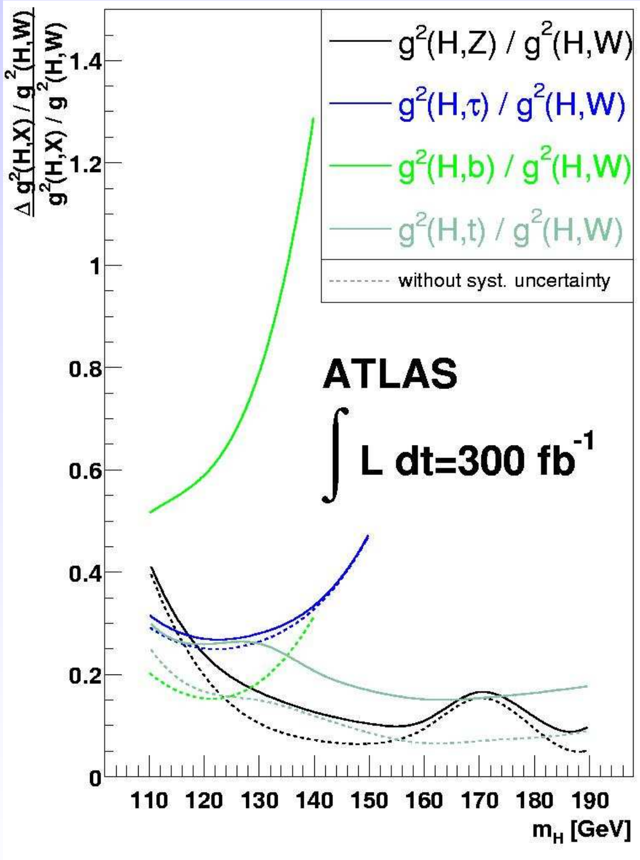
Main systematic uncertainty:
γ/ℓ Energy scale
assumed 0.1 % uncertainty
provided by Z → ℓℓ decays

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - 450 GeV / c^2)

Measurement of Higgs Boson Couplings

Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates for the various production modes





Relative couplings can be measured with 10-20% precision (for 300 fb^{-1})

Higgs searches at the Tevatron

- important modes: associated WH and ZH
  + gluon fusion with $H \to WW \to \ell\nu\ \ell\nu$
- hopeless modes: gluon fusion with $H \to \gamma\gamma$, 4 ℓ

Mass range 110 - 130 GeV:

- $WH \to l\nu\ bb$
- $ZH \to l^+l^-\ bb$
- $ZH \to \nu\nu\ bb$
- $ZH \to bb\ bb$
- $ttH \to l\nu\ b\ jjb\ bb$

Mass range 150 - 180 GeV:

- $H \to WW^{(*)} \to l\nu\ l\nu$
- $WH \to WWW^{(*)} \to l\nu\ l\nu\ l\nu$
- $WH \to WWW^{(*)} \to l^+\nu\ l^+\nu\ jj$

Signal:

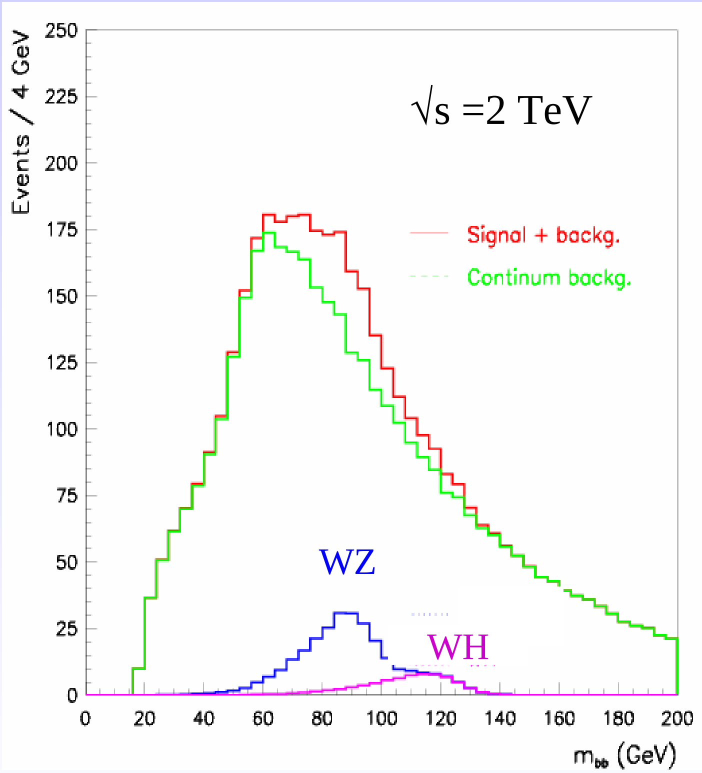
~10 -100 x larger at the LHC, depending on the channel

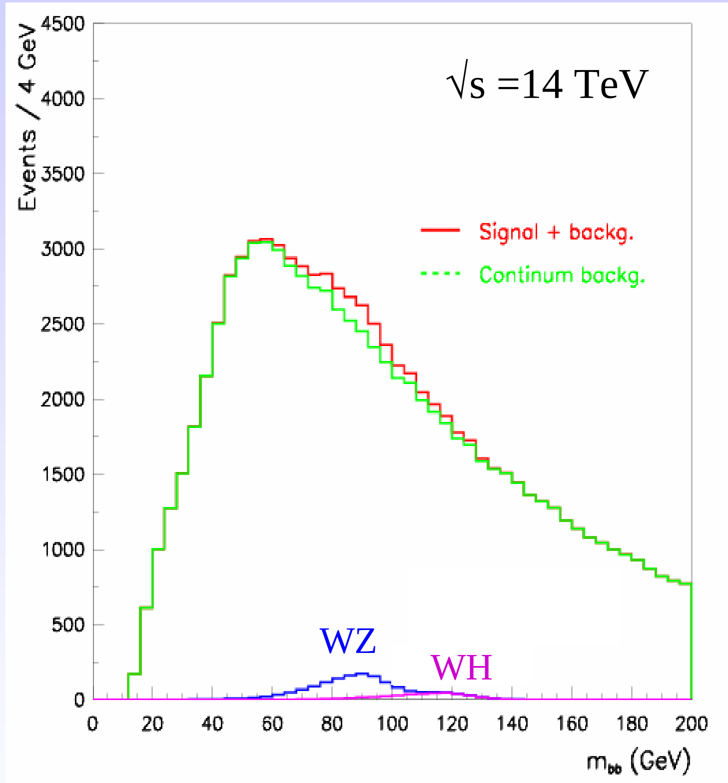
Background:

electroweak production:
~10 x larger at the LHC
QCD production (e.g, tt):
~ 100 x larger at the LHC

WH Signals at the LHC and the Tevatron

WH → lν bb (M_H = 120 GeV, 30 fb^{-1})

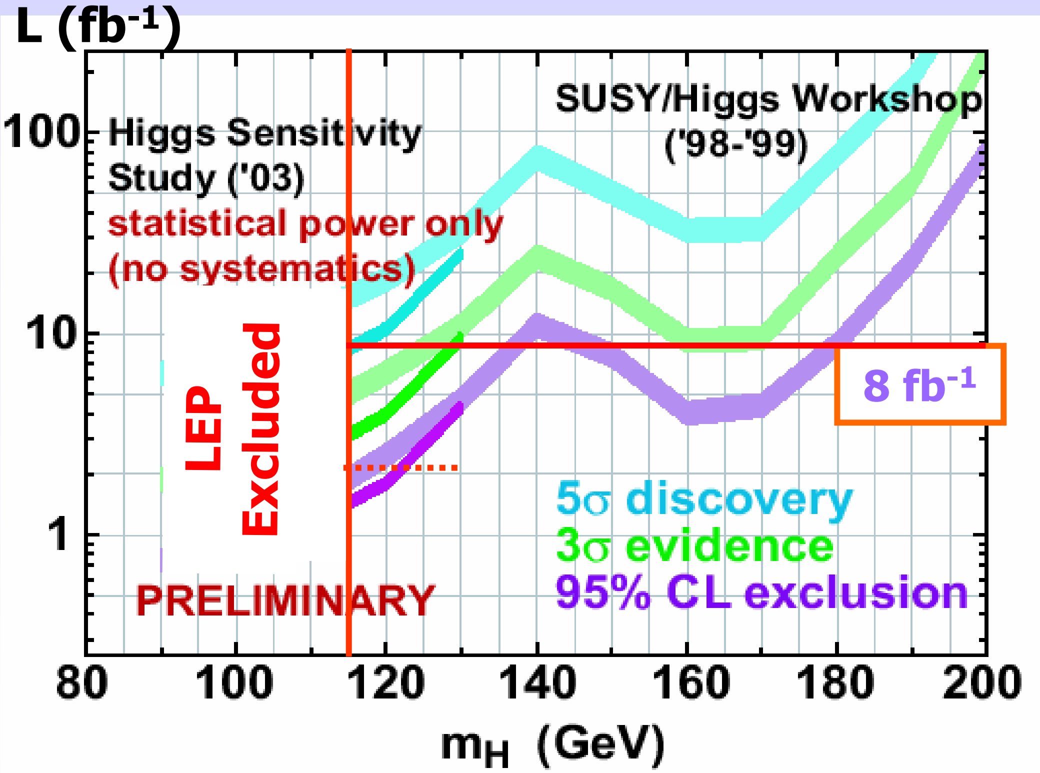




most important: control of the background shapes, very difficult!

Tevatron discovery potential for a light Higgs Boson

combination of both experiments and all channels
(discovery in a single channel not possible)



For 8 fb^{-1} :

(i) 95% CL exclusion of a SM Higgs boson is possible up to 135 GeV/c^2 and for 150 – 180 GeV/c^2

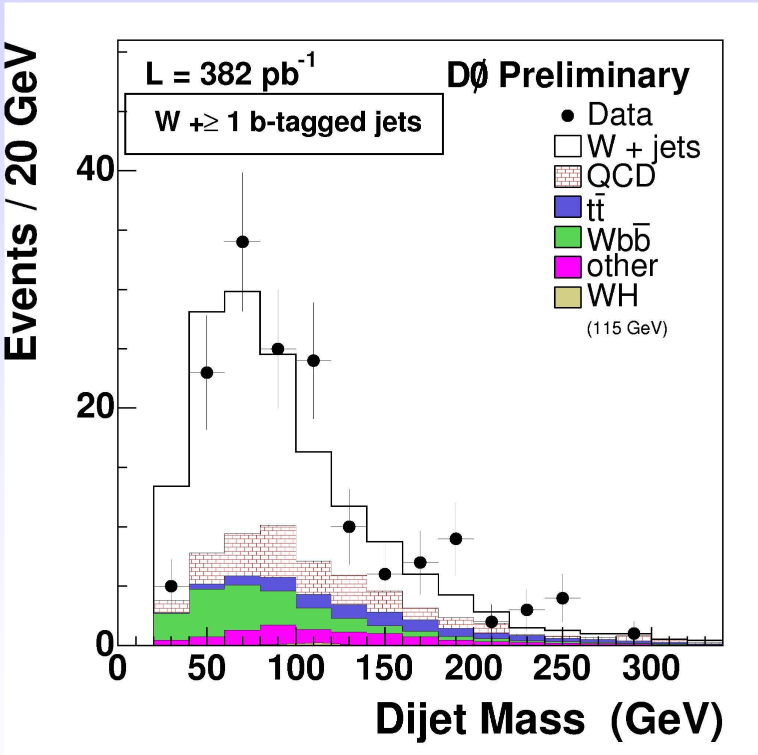
(ii) 3-σ evidence for M_H < 130 GeV/c^2

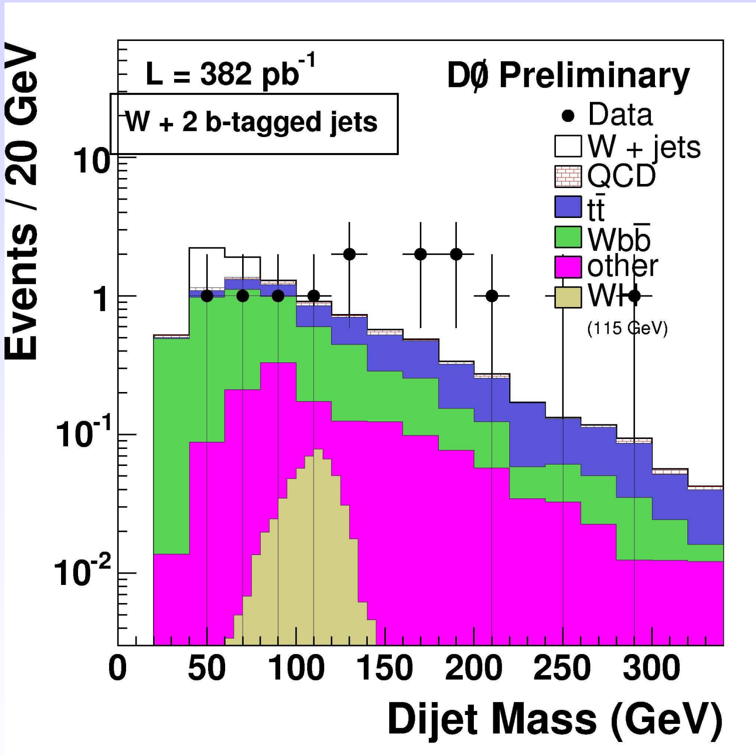
(iii) Sensitivity at low mass starts with an int. luminosity of 2 fb^{-1} (mid – end 2006)

Low Mass: WH → eν bb

Data sample: 382 pb^{-1}

Event selection: 1 e, (|η| < 1.1, E_T>20 GeV), E_T^{miss} > 20 GeV, 2 jets (E_T > 20 GeV) additional b-tags





Data:	**153**	**events**	**13**	**events**
Tot. expectation	**153.6**		**10.2**	
WH:	0.4		0.14	

Summary of the lecture

Electroweak precision data from LEP/SLC/Tevatron suggest a light Higgs boson

Should a SM Higgs boson exist, it cannot escape detection at the LHC

Tevatron might have a 3σ discovery potential at low mass, however, much depends on the detector and accelerator performance.