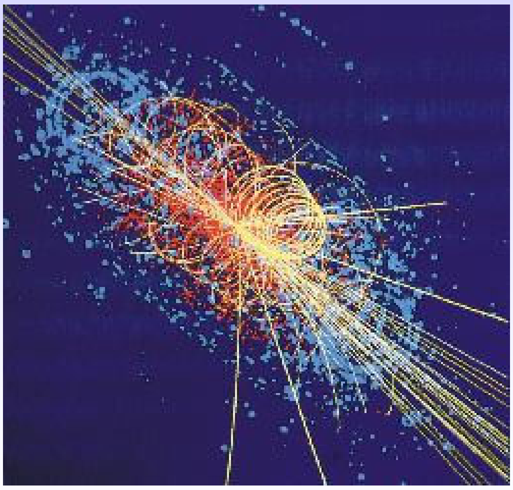
Physics at Hadron Colliders

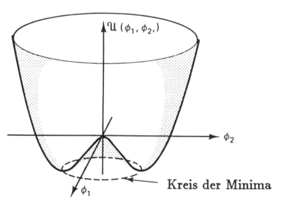
Lecture 3



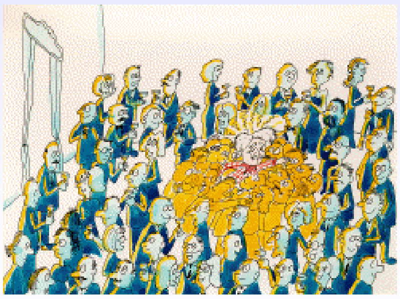
Search for the Higgs boson

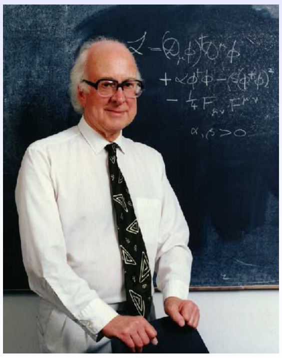
- Higgs boson production and decays
- LHC discovery potential
- What can be covered at the Tevatron?

The Search for the Higgs Boson



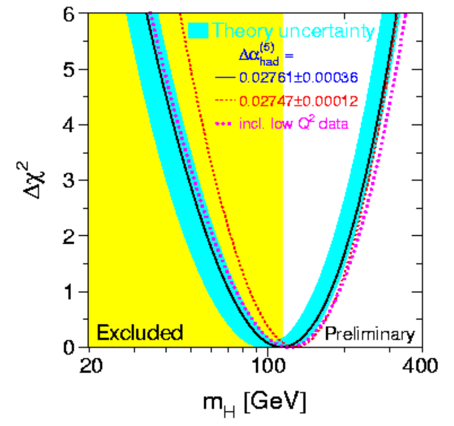
- „Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics"
- „A new collider, such as the LHC must have the potential to detect this particle, should it exist."





What do we know today 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 (→Lecture by P. Wells)
- Indirect limits from electroweak precision measurements
  (LEP, Tevatron and other experiments….)



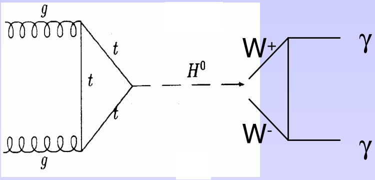
Results of the precision el.weak measurements:
(all experiments, April 2004):

M_H = 113 (+62) (-42) GeV/c^2
M_H < 237 GeV/c^2 (95 % CL)

→ Higgs boson could be around the corner !

Properties of the Higgs Boson

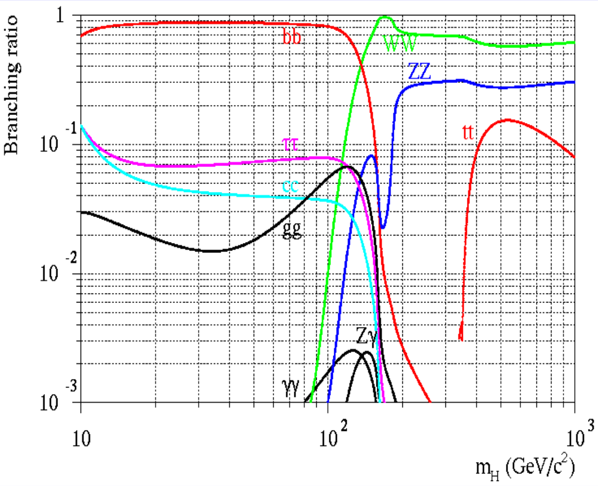
- The decay properties of the Higgs boson are fixed, if the **mass** is known:



H

W⁺, Z, t, b, c, τ⁺,..........., g, γ

W⁻, Z, t, b, c, τ⁻ ,.........., g, γ

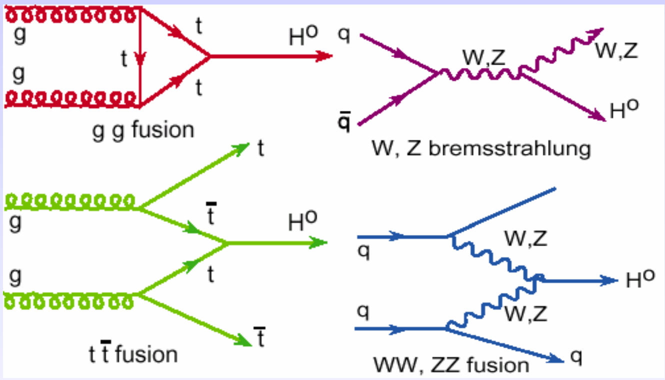


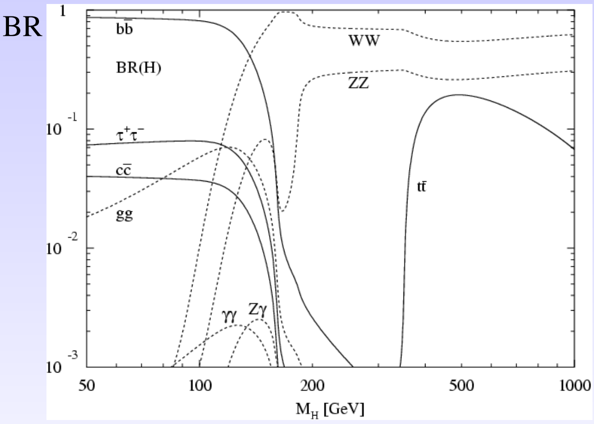
Higgs boson likes mass:

It couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

Higgs Boson Production at Hadron Colliders



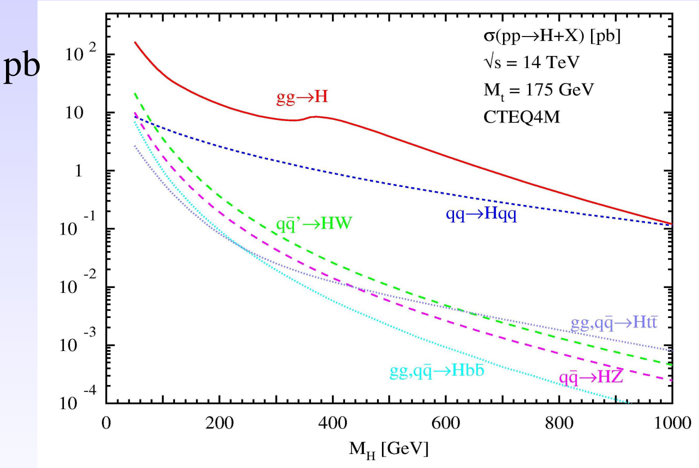


Lepton and Photon final states are essential (**via H → WW , ZZ, (ττ), γγ**)
(QCD jet background)

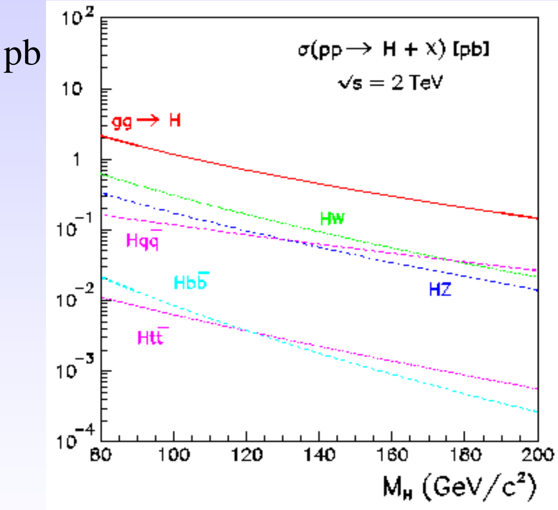
bb decay mode only possible in associated production (W/Z,   tt)

Higgs Boson Production cross sections

LHC M. Spira et al.



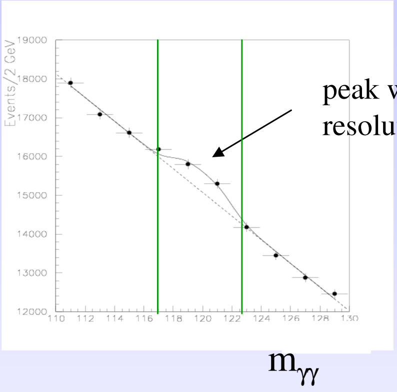
Tevatron M.Spira et al.



qq → W/Z + H cross sections ~10 x larger at the LHC
gg → H ~70-80 x larger at the LHC

How can one claim a discovery ?

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



peak width due to detector resolution

Signal significance:

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

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

} in peak region

$\sqrt{N_B} \equiv$ error on number of background events, for large numbers
otherwise: use Poisson statistics

S > 5 : signal is larger than 5 times error on background.
Gaussian probability that background fluctuates up by more than 5σ : 10^{-7} → discovery

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Two critical parameters to maximize S

1. Detector resolution:

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

→ N_B increases by ~ 2 (assuming background flat)

$\Rightarrow$ S = $N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$

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

"A detector with better resolution has larger probability to find a signal"

Note: only valid if $\Gamma_H << \sigma_m$. If Higgs is broad detector resolution is not relevant.

m_H = 100 GeV → Γ_H ~0.001 GeV
m_H = 200 GeV → Γ_H ~ 1 GeV
m_H = 600 GeV → Γ_H ~ 100 GeV **$\Gamma_H \sim m_H^3$**

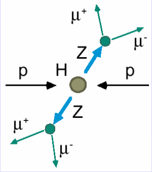
2. Integrated luminosity :

$$\left.\begin{array}{l} N_S \sim L \\ N_B \sim L \end{array}\right\}$$

$$\boxed{\Rightarrow S \sim \sqrt{L}}$$

H → ZZ$^{(*)}$ → ℓℓℓℓ

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

$M(ll) \sim M_Z$
$M(l'l') \sim < M_Z$

Background: Top production

$t\bar{t} \to Wb\,Wb \to \ell\nu\; c\ell\nu\; \ell\nu\; c\ell\nu$
σ BR ≈ 1300 fb

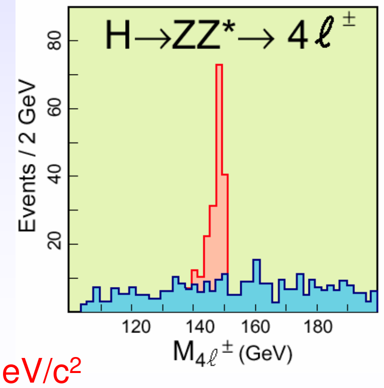
Associated production Z bb

Z bb → ℓℓ cℓν cℓν

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

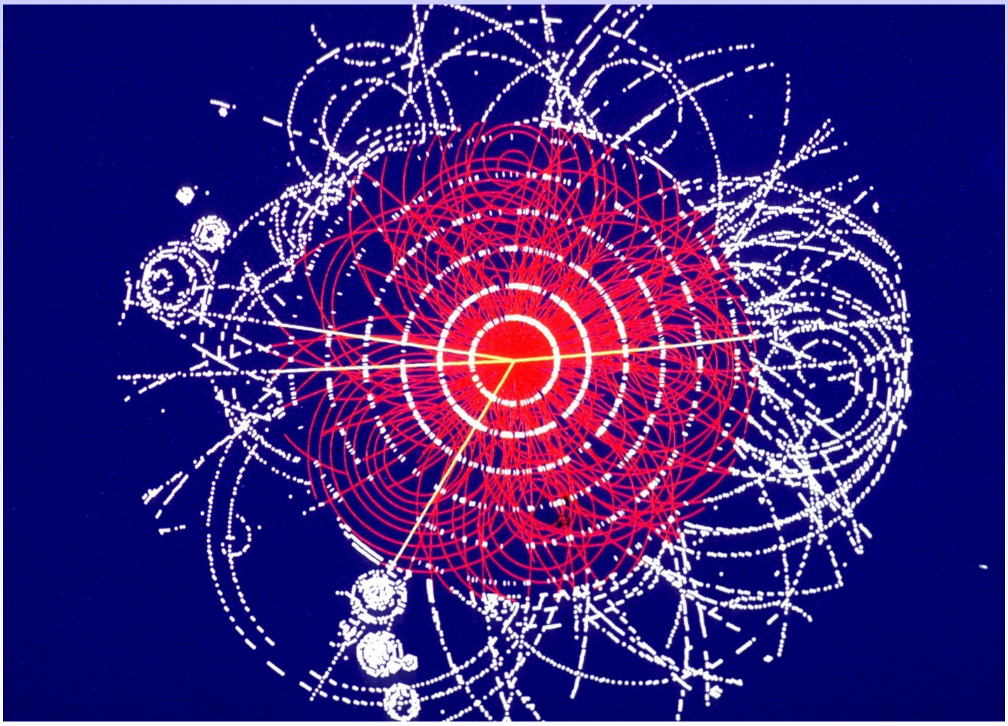
Dominant background after isolation cuts: ZZ continuum

L = 100 fb^{-1}

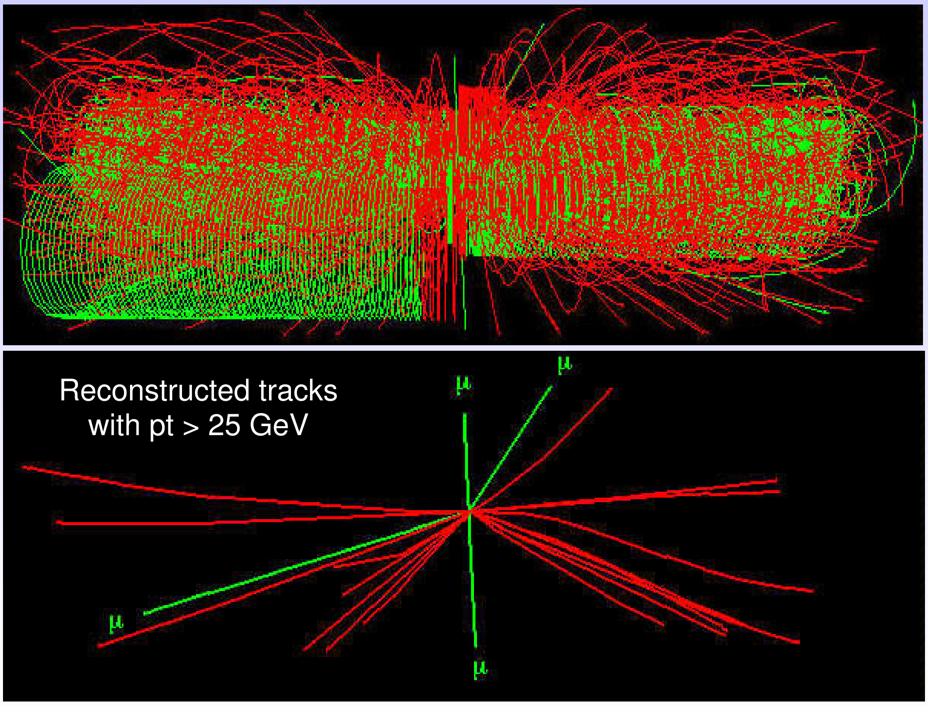


Discovery potential in mass range from ~130 to ~600 GeV/c^2

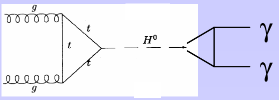
A simulated H → ZZ → ℓℓℓℓ event



A simulated H → ZZ → ℓℓℓℓ event at high luminosity (pile-up)

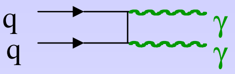


$H \rightarrow \gamma\gamma$

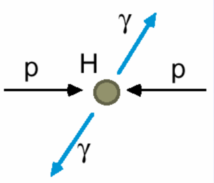


$m_H \leq 150$ GeV

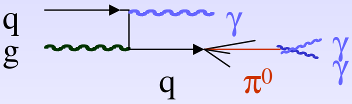
- σ x BR ≈ 50 fb (BR ≈ 10^{-3})
- Backgrounds : - $\gamma\gamma$ (irreducible): e.g.



$$\left.\begin{array}{l}\sigma_{\gamma\gamma} \approx 2 \text{ pb / GeV} \\ \Gamma_H \approx \text{MeV}\end{array}\right\} \rightarrow \text{need } \sigma(m\ )/m \approx 1\%$$



– γj+ jj (reducible):



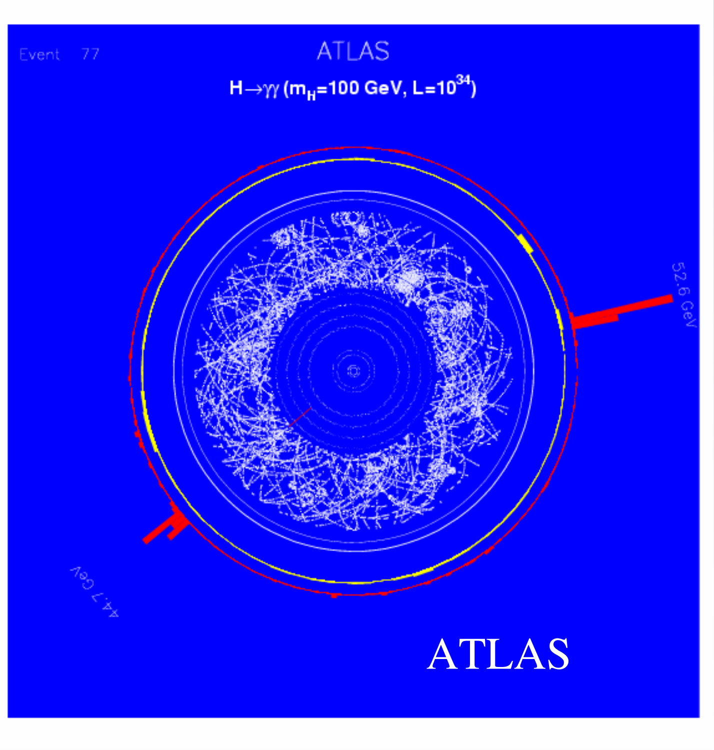
$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

→ need $R_j > 10^3$ for $\varepsilon_\gamma \approx$ 80% to get $\sigma_{\gamma j+jj} << \sigma_{\gamma\gamma}$

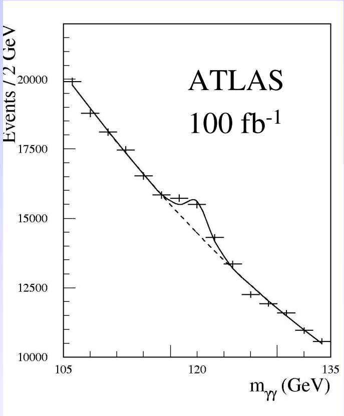
→ most demanding channel for EM calorimeter performance :
energy and angle resolution, acceptance, γ /jet and γ / π^0 separation

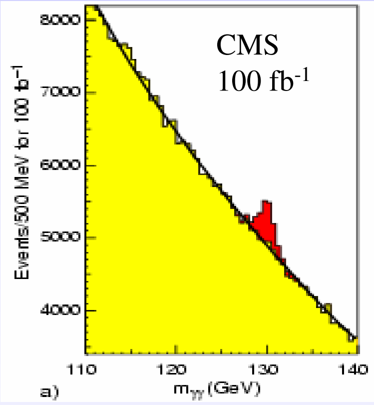
ATLAS and CMS: complementary performance

A simulated H → γγ event in ATLAS



H→ γγ (cont.)





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

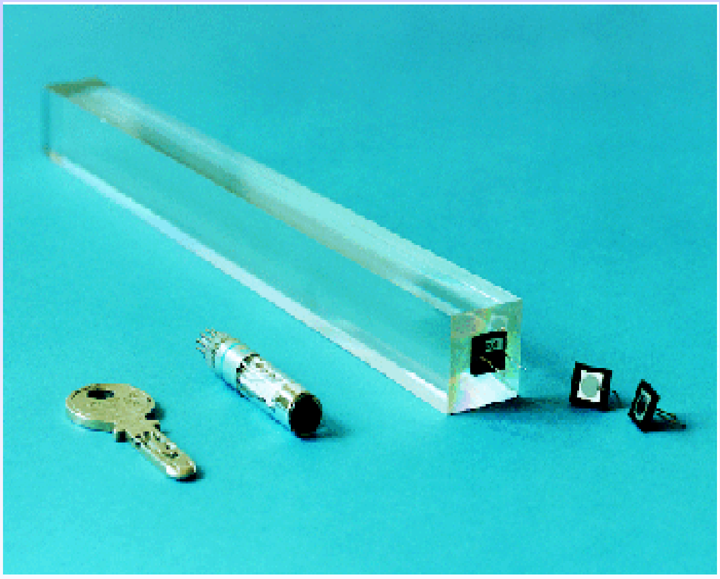
Mass resolution: $m_H = 100$ GeV/c^2

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

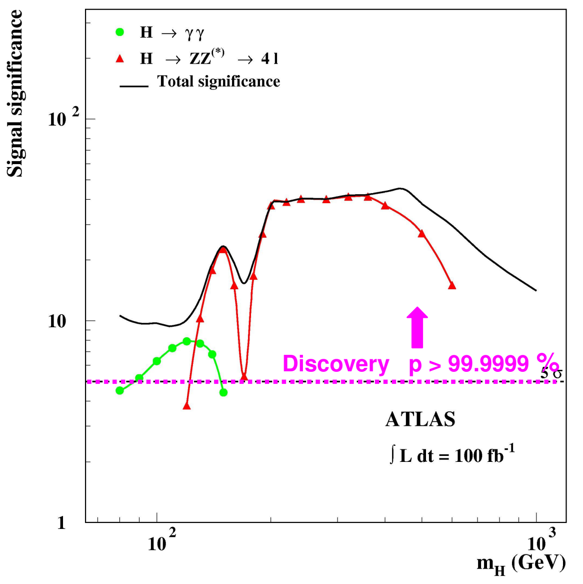
Signal / background ~ 4% (Sensitivity in mass range 100 – 140 GeV/c^2)
background (dominated by γγ events *) can be determined from side bands
important: γγ-mass resolution in the calorimeters, γ / jet separation

*) detailed simulations indicate that the γ-jet and jet-jet background can be suppressed to the level of 10-20% of the irreducible γγ-background

CMS crystal calorimeter



„If the Standard Model Higgs particle exists, it will be discovered at the LHC ! “



The full allowed mass range

from the LEP limit (~114 GeV)
up to
theoretical upper bound of ~1000 GeV

can be covered using the two “safe” channels

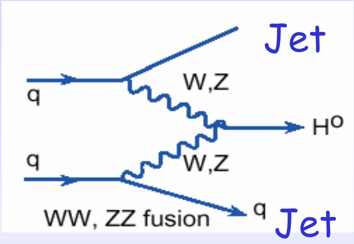
$H \rightarrow ZZ \rightarrow \ell\ell\ \ell\ell$ and
$H \rightarrow \gamma\gamma$

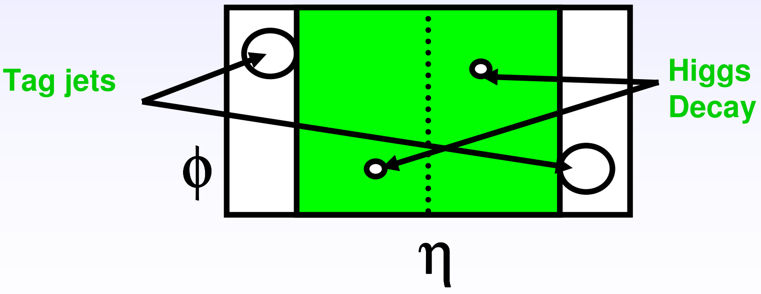
More difficult channels can also be used: $qq\,H \to qq\,WW \to qq\,\ell\nu\,\ell\nu$

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

Distinctive Signature of:

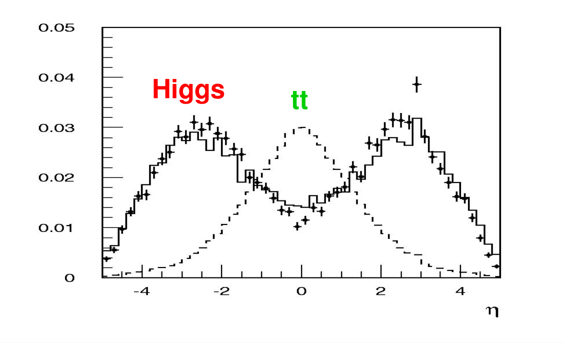
- **two high P_T leptons**
- **missing transverse momentum**
- **two high P_T forward tag jets**
- **little jet activity in the central region**
  ⇒ **central jet Veto**



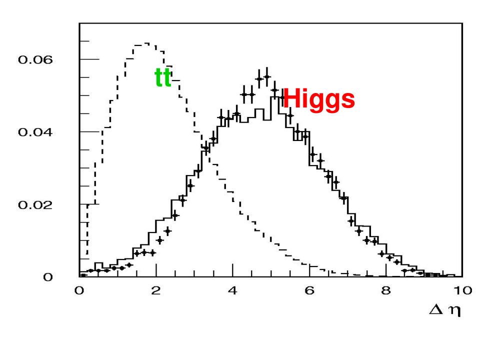


Forward jet tagging

Rapidity distribution of tag jets
VBF Higgs events vs. tt-background

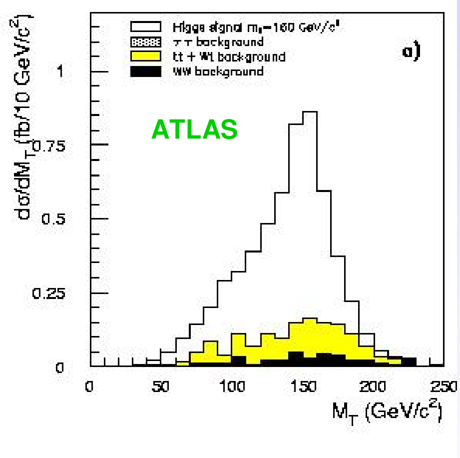


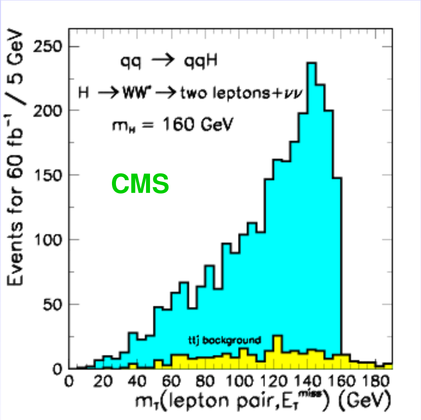
Rapidity separation



$qq\,H \to qq\;W\,W^*$
$\to qq\;\ell\nu\;\ell\nu$

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





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

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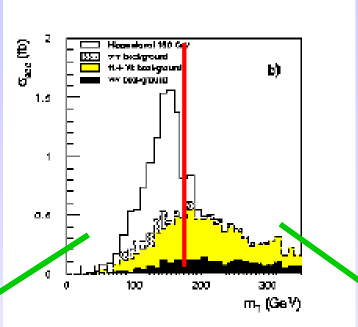
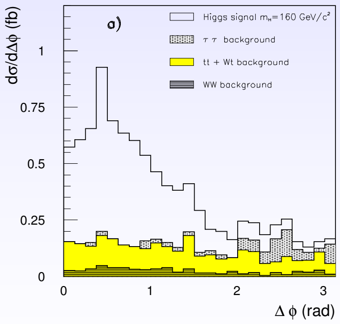
Presence of a signal can also be demonstrated in the Δ φ distribution (i.e. azimuthal difference between the two leptons)

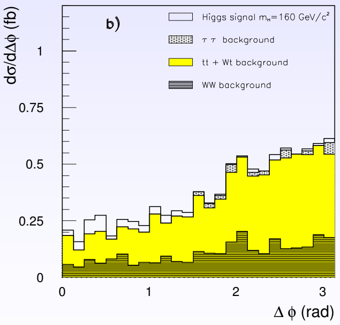
Evidence for spin-0 of the Higgs boson

Spin-0 → WW → ℓνℓν expect leptons to be close by in space



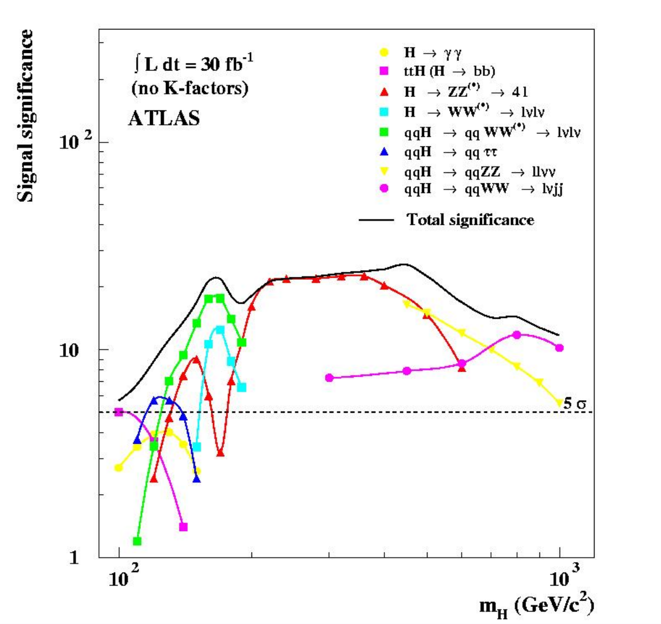


signal region



background region

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



- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses
- Comparable situation for the CMS experiment

Can LHC also discover Higgs bosons in a supersymmetric world ?

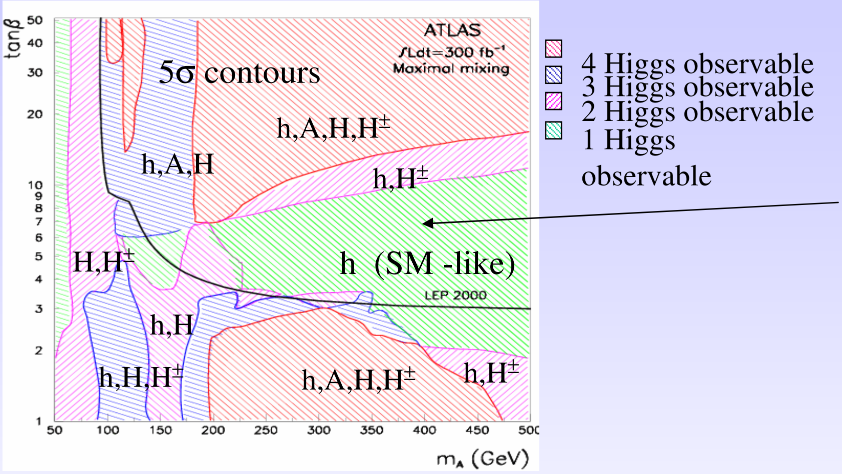
SUSY: 5 Higgs particles **H, h, A**
H^+, H^-

determined by two SUSY model parameters: m_A, $\tan\beta$

One of the Higgs bosons is light: $m_h < 135$ GeV

The others will most likely be heavy !

LHC discovery potential for SUSY Higgs bosons



Here only SM-like h observable if SUSY particles neglected.

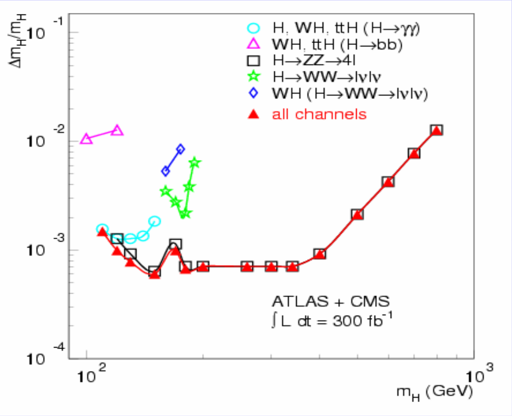
Parameter space is fully covered:
→

„Also in a SUSY world, Higgs bosons will be discovered at the LHC“

Determination of Higgs Boson Parameters

1. Mass
2. Couplings to bosons and fermions

Measurement of the Higgs boson mass



Dominated by $ZZ \to 4\ell$ and $\gamma\gamma$ resonances !

well identified, measured with a good resolution

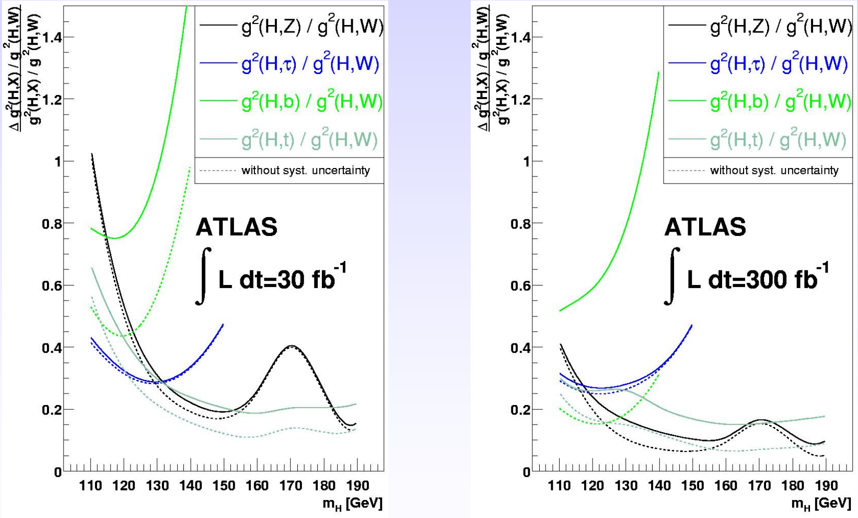
Dominant systematic uncertainty: γ / ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \to \ell\ell$ (close to light Higgs)

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, separated for the various production modes

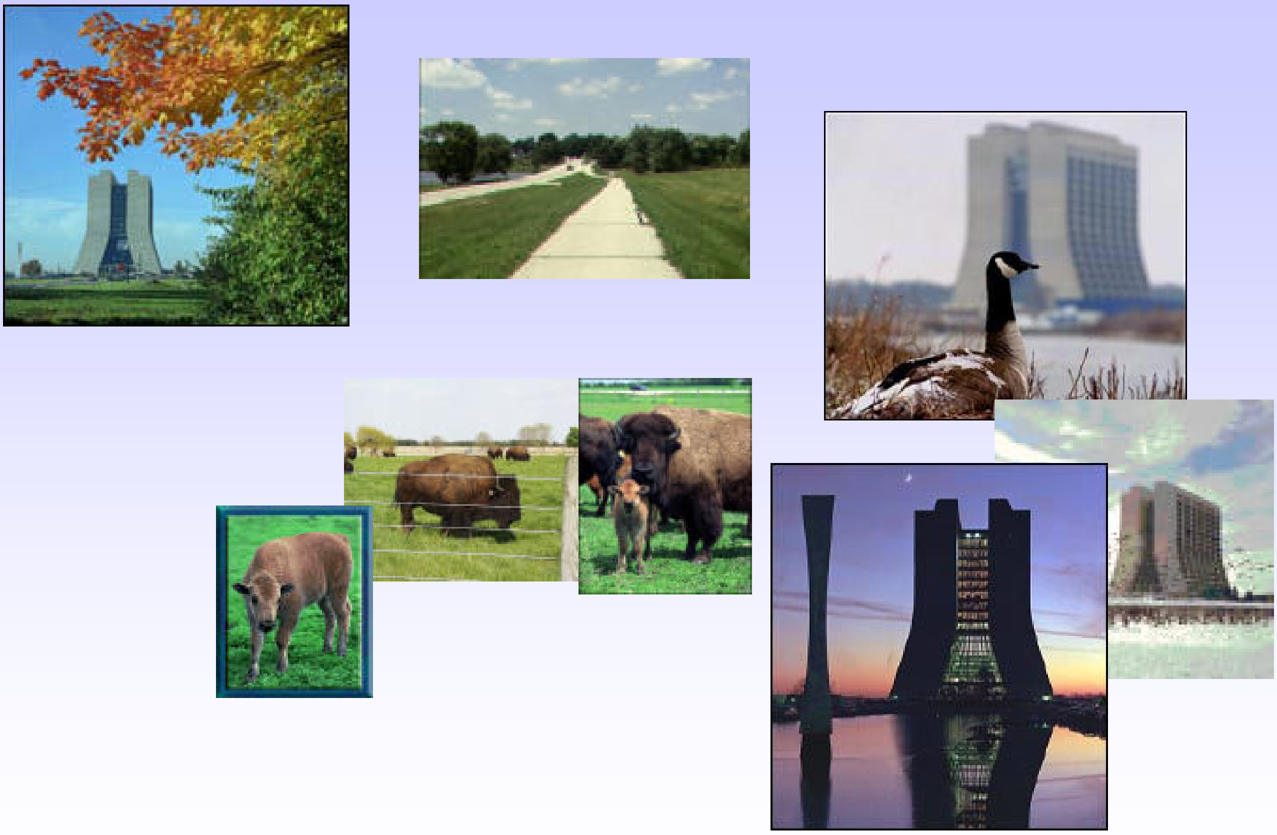
Output: Higgs boson couplings, normalized to the WW-coupling



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

Can the Higgs boson already be discovered at Fermilab

Impressions from Fermilab



Impressions from Fermilab (cont.)

Search channels at the Tevatron

- important production modes: associated WH and ZH
  gluon fusion with H → WW → ℓν ℓν

- hopeless: gluon fusion in H → γγ, 4 ℓ (rate limited)
  σ BR (H → ZZ → 4 ℓ) = 0.07 fb (M_H=150 GeV)

Mass range 110 - 130 GeV:	**LHC**
* **WH → lν bb**	**(✓) weak**
* **ZH → l^+l^- bb**	**weak**
* **ZH → νν bb**	**∅ (trigger)**
* **ZH → bb bb**	**∅ (trigger)**
* **ttH → lν b jjb bb**	✓

Triggering:

slightly easier at the Tevatron:

- better P_T^{miss}-resolution
- track trigger at level-1
  (seems to work)

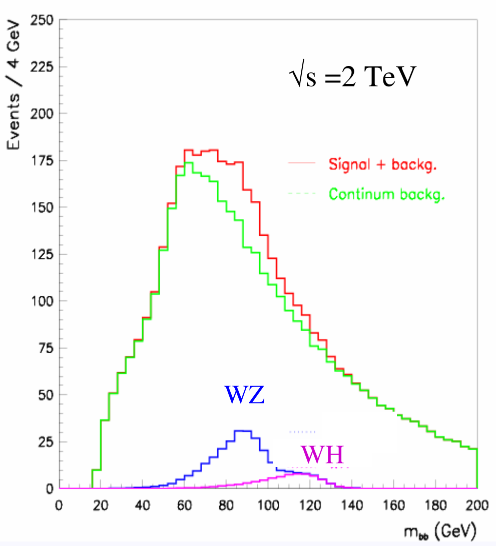
Mass range 150 - 180 GeV:	**LHC**
* **H → WW$^{(*)}$ → lν lν**	✓
* **WH → WWW$^{(*)}$ → lν lν lν**	✓
* **WH → WWW$^{(*)}$ → l^+ν l^+ν jj**	✓

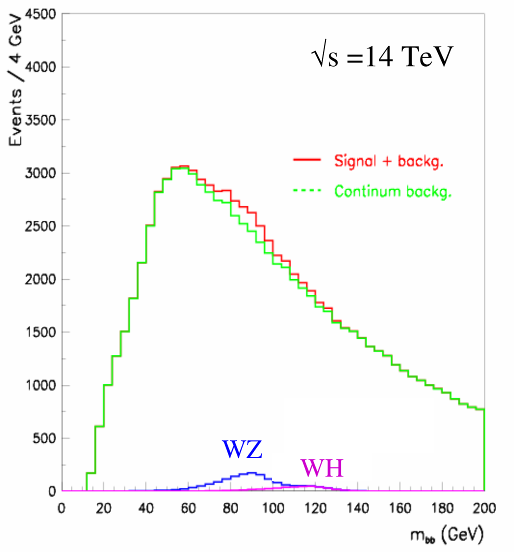
Background:

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

M_H = 120 GeV, 30 fb^{-1}

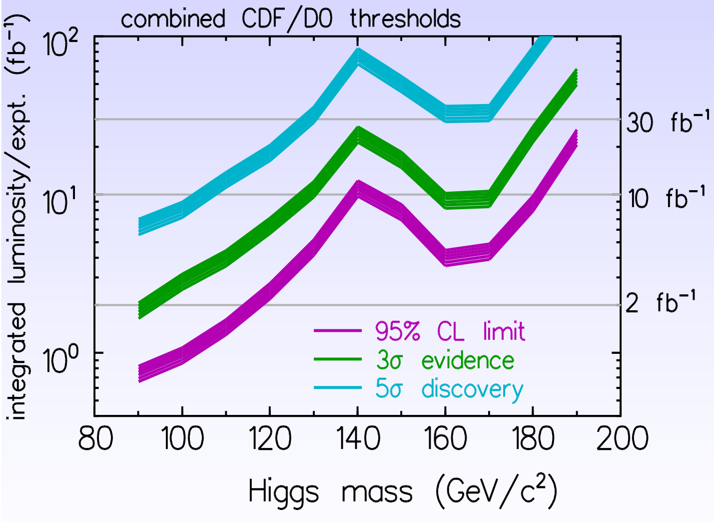




most important: control of the background shapes, very difficult!

Tevatron discovery potential for a light Higgs Boson

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



For 10 fb^{-1} :

(i) 95% CL exclusion of a SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

(ii) 3-σ evidence for M_H < 130 GeV and 155 GeV < M_H < 175 GeV

Für 30 fb^{-1} (optimistic) :

(i) 3-σ evidence for the SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

Summary on Higgs Boson Searches

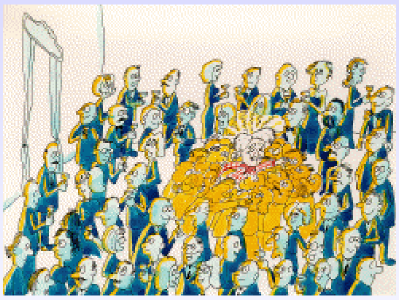
- Electroweak precision data from LEP/SLC suggest a light Higgs boson
- Should a SM Higgs boson or MSSM Higgs bosons exist, they can not escape detection at the LHC
- Tevatron might have a 3-σ discovery windows, however, much depends on the detector and accelerator performance.

Der Higgs Mechanismus, eine Analogie:

Prof. D. Miller
UC London

Higgs-Hintergrundfeld
erfüllt den Raum

Ein Teilchen
im Higgs-Feld...



... Widerstand gegen
Bewegung ...
Trägheit ↔ Masse