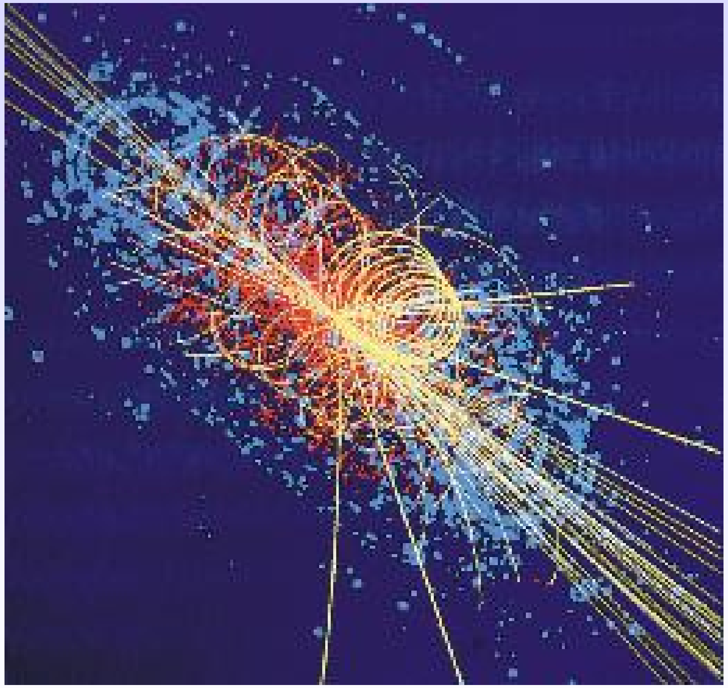
Physics at Hadron Colliders

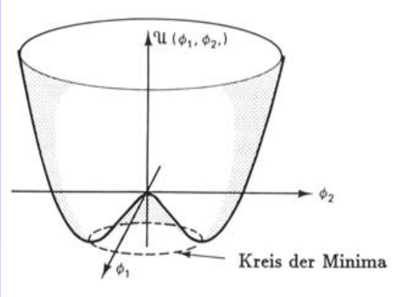
Lecture 3



Search for the Higgs boson

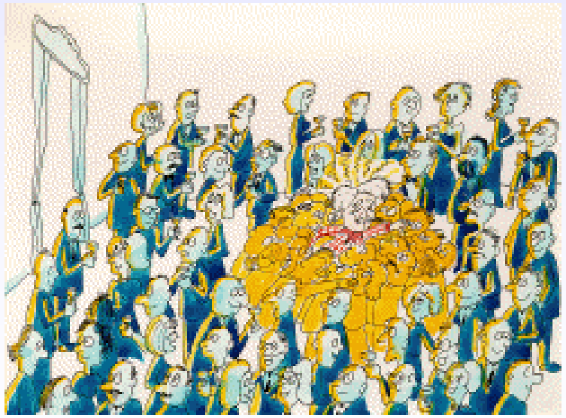
- **Higgs boson production and decays**
- **LHC discovery potential**
- **What can be covered at the Tevatron?**

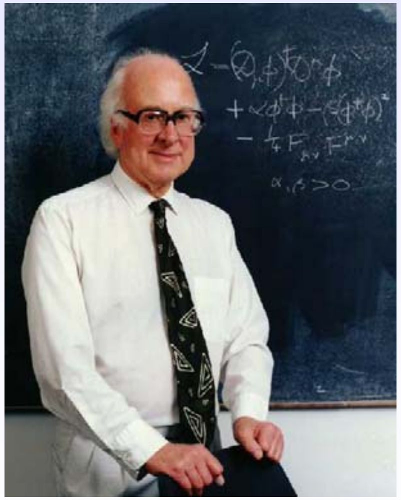
The Search for the Higgs Boson



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

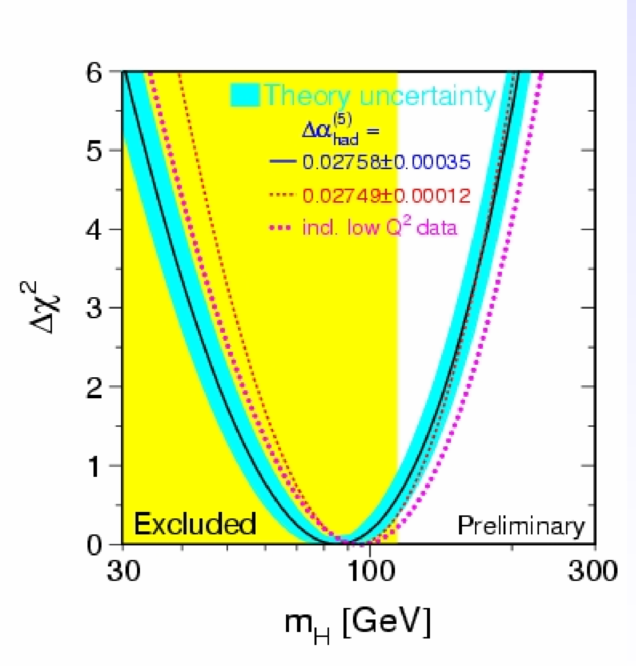
- „A new collider, such as the LHC must have the potential to detect this particle, should it exist."





What do we know about the Higgs Boson today

- 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):

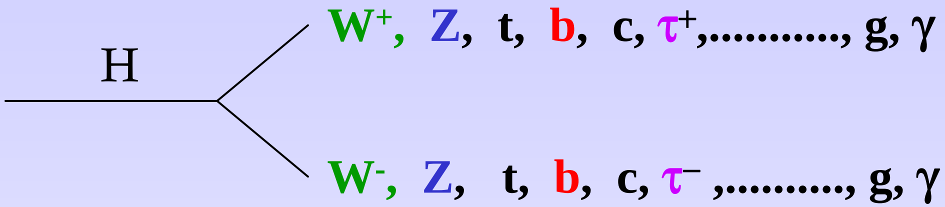
M_H = 85 (+39) (-28) GeV/c²

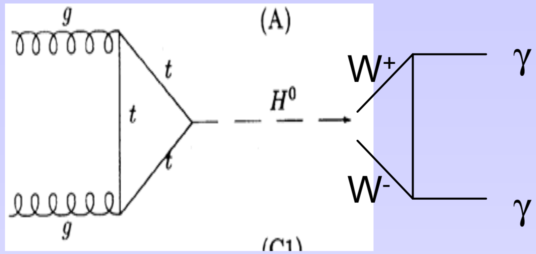
M_H < 166 GeV/c² (95 % CL)

→ 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:





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

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

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

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

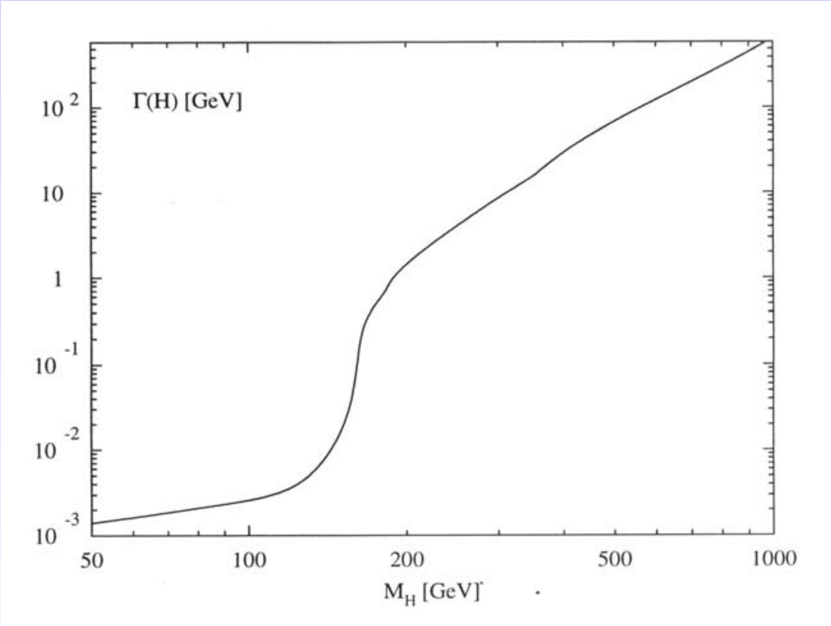
$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs boson likes mass:

It couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

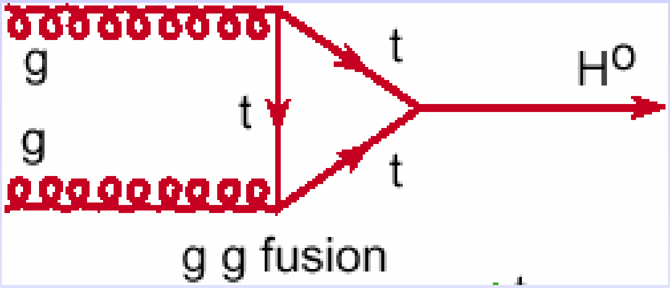
Properties of the Higgs Boson



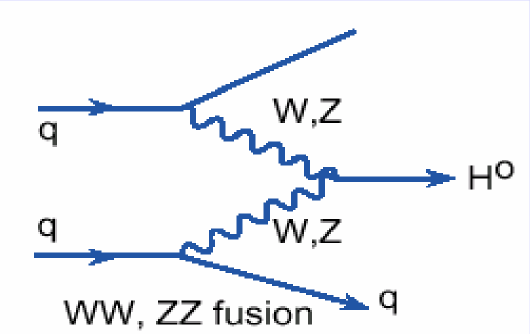
Upper limit on Higgs boson mass: from unitarity of WW scattering **$M_H < 1$ TeV/c^2**

Higgs Boson Production at Hadron Colliders

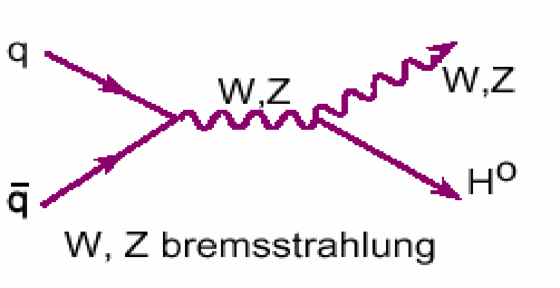
(i) Gluon fusion

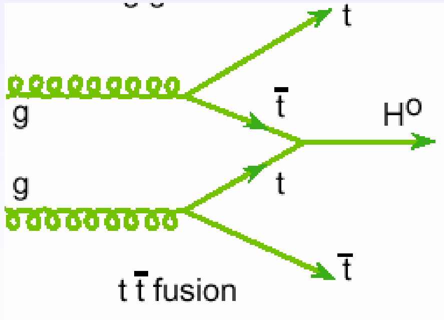


(ii) Vector boson fusion



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

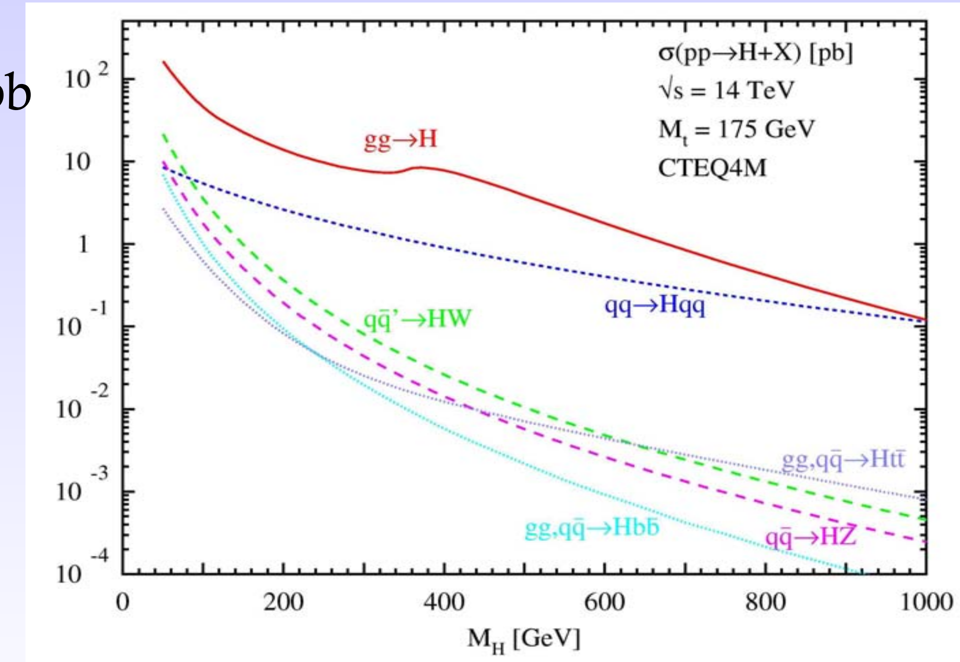




Higgs Boson Production cross sections

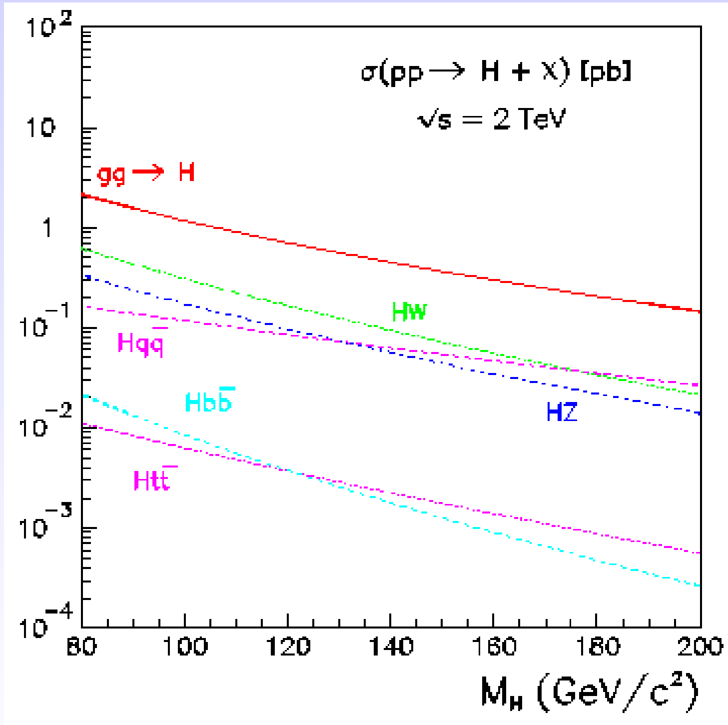
LHC M. Spira et al.

pb



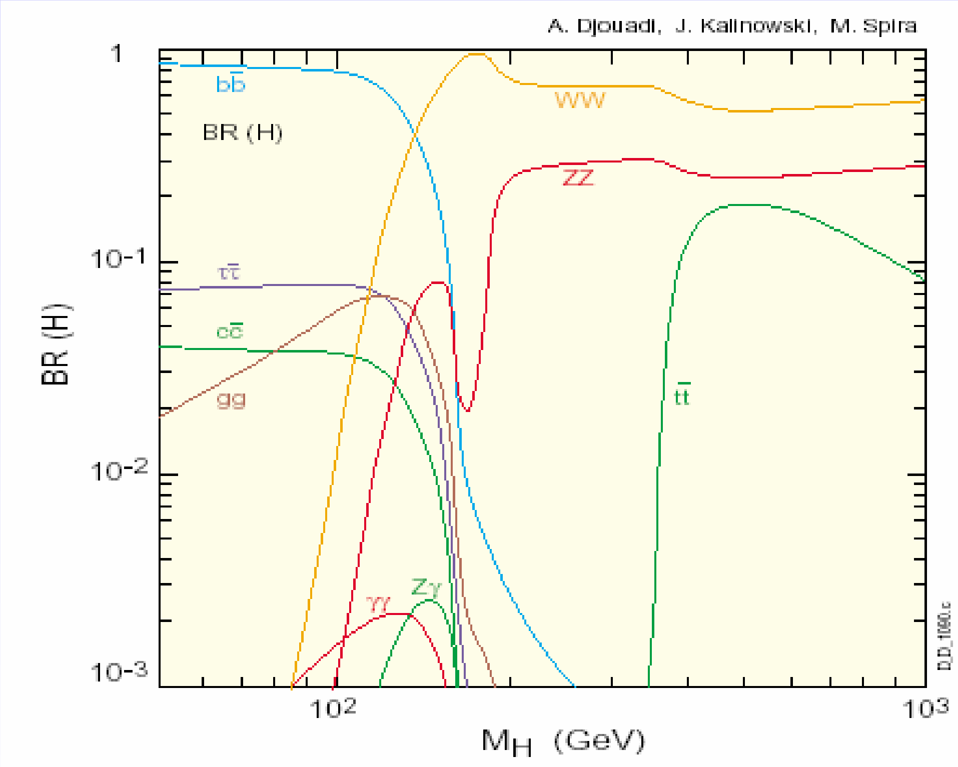
Tevatron M.Spira et al.

pb



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

Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states are essential
(via H → WW , ZZ)

at low mass:

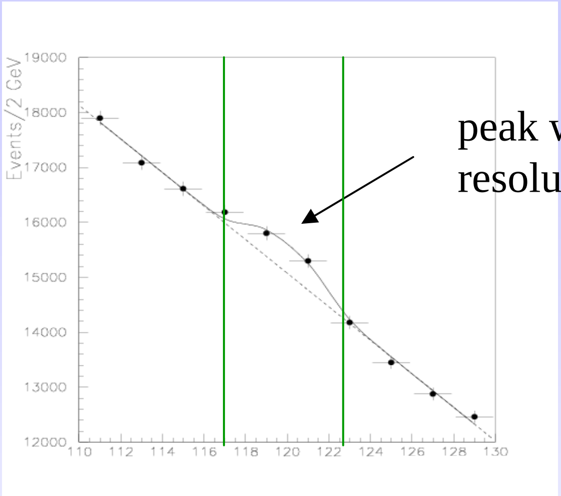
Lepton and Photon final states
(via H → WW*, ZZ*)

Tau final states

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

How can one claim a discovery ?

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



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} $\rightarrow$ discovery

Two critical parameters to maximize S

1. **Detector resolution:**

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 (assuming background flat)

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

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

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

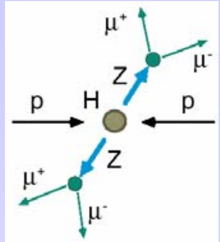
2. **Integrated luminosity** :

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

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

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

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

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

L = 100 fb^{-1}

Background: Top production

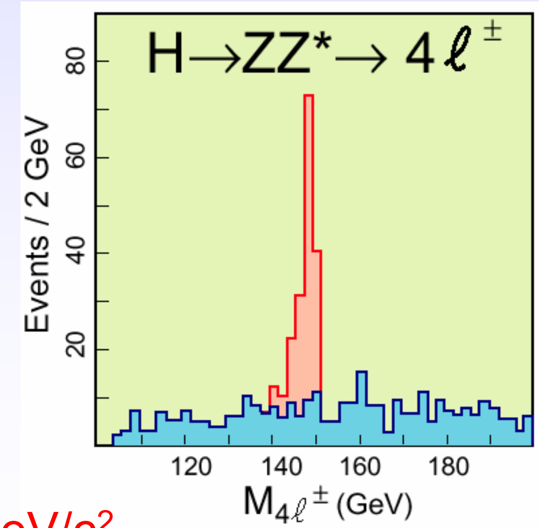
$tt \rightarrow Wb\, Wb \rightarrow \ell\nu\, c\ell\nu\, \ell\nu\, c\ell\nu$
σ BR ≈ 1300 fb

Associated production Z bb

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

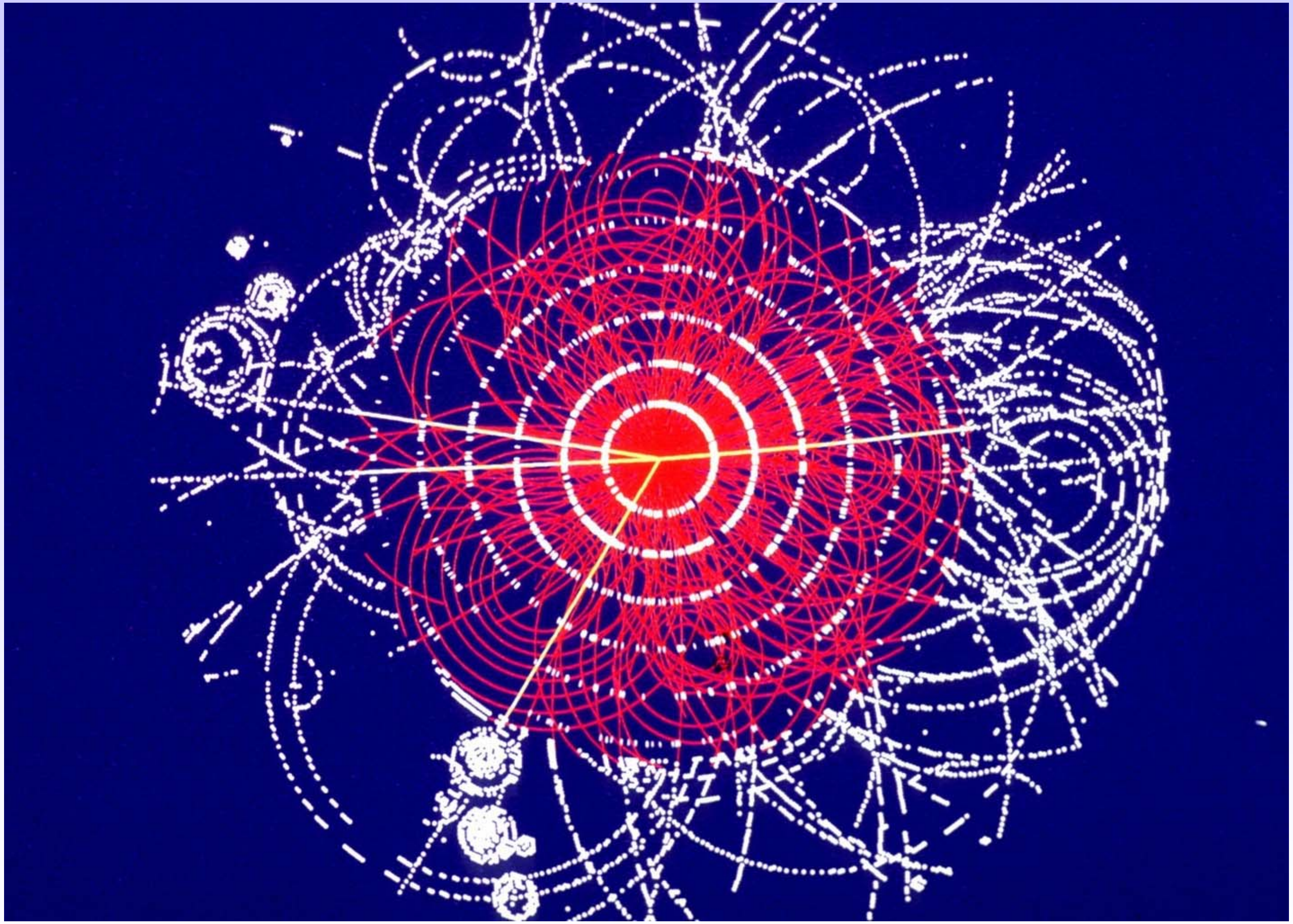
Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum

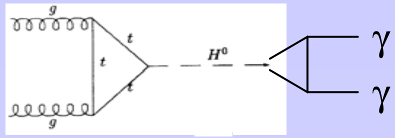


Discovery potential in mass range from ~130 to ~600 GeV/c^2

A simulated H → ZZ → ℓℓℓℓ event



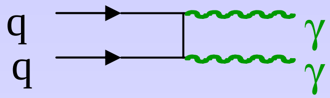
$H \rightarrow \gamma\gamma$



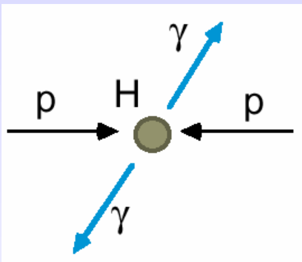
$m_H \leq 150$ GeV

- σ x BR ≈ 50 fb   (BR ≈ 10^{-3})

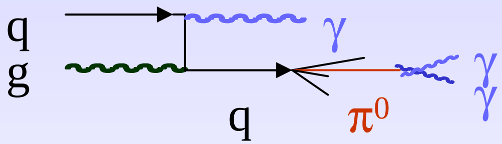
- Backgrounds :   - $\gamma\gamma$ (irreducible):   e.g.



$\sigma_{\gamma\gamma} \approx$ 2 pb / GeV
$\Gamma_H \approx$ MeV
$\rightarrow$ need $\sigma(m)/m \approx 1\%$



– γj+ jj (reducible):



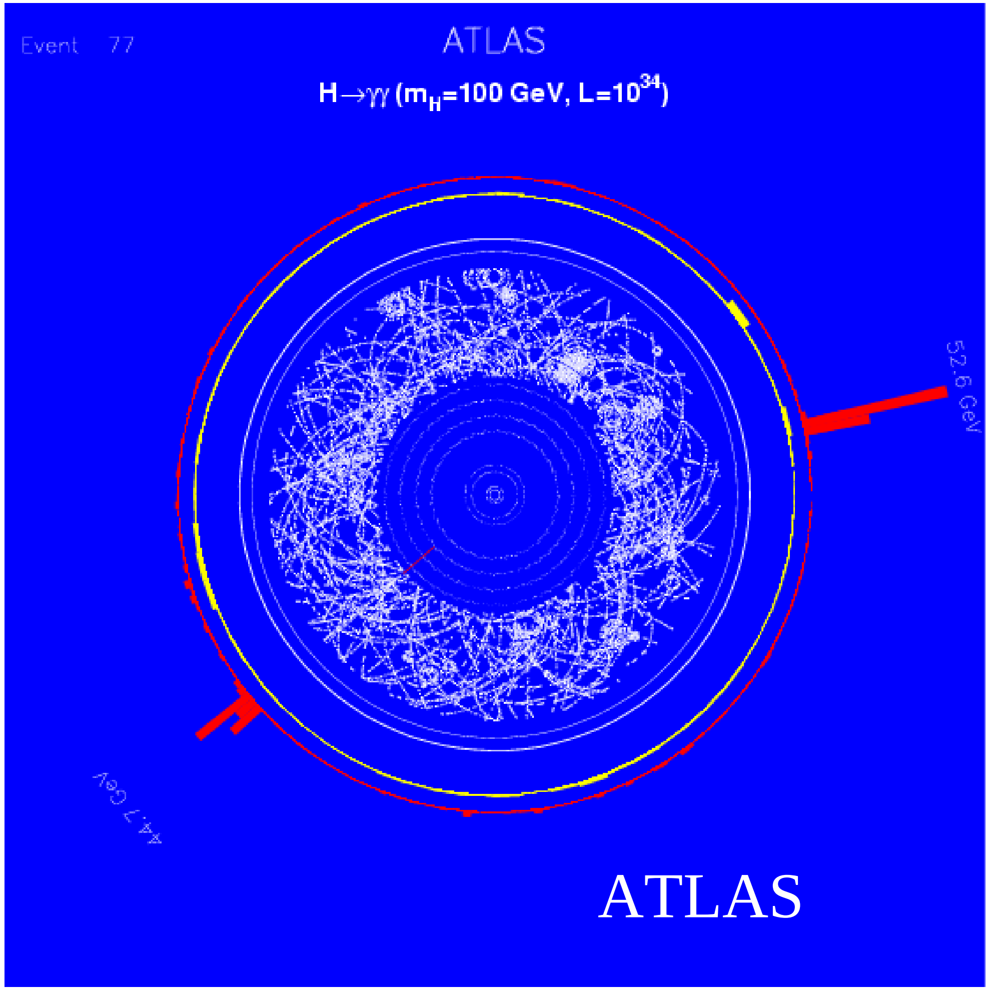
$\sigma_{\gamma j+jj} \sim 10^6 \sigma_{\gamma\gamma}$ with large uncertainties

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

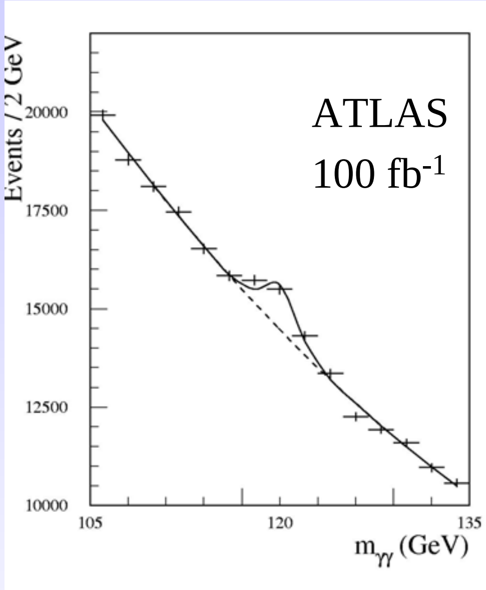
$\rightarrow$ most demanding channel for EM calorimeter performance :
energy and angle resolution, acceptance, γ/jet and γ / π^0 separation

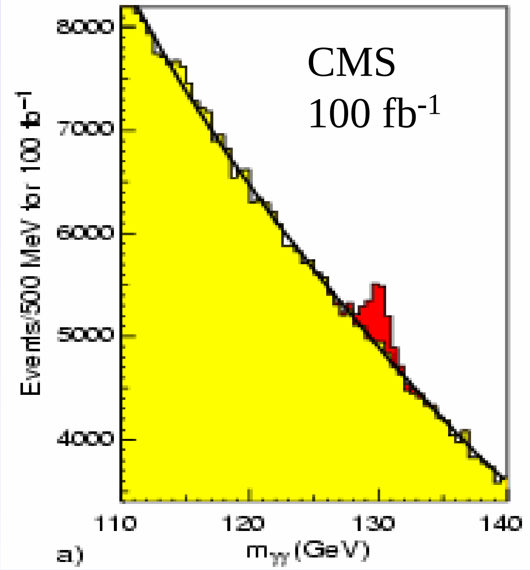
ATLAS and CMS: complementary performance

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



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





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

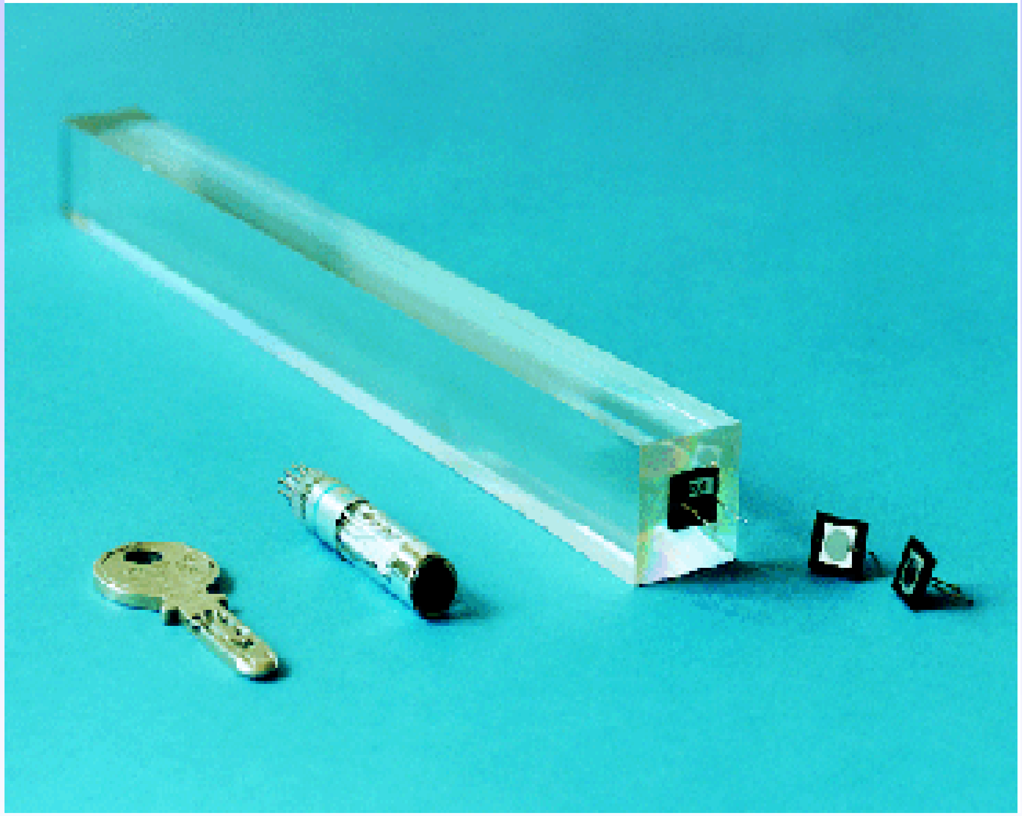
Mass resolution for m_H = 100 GeV/c^2:

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

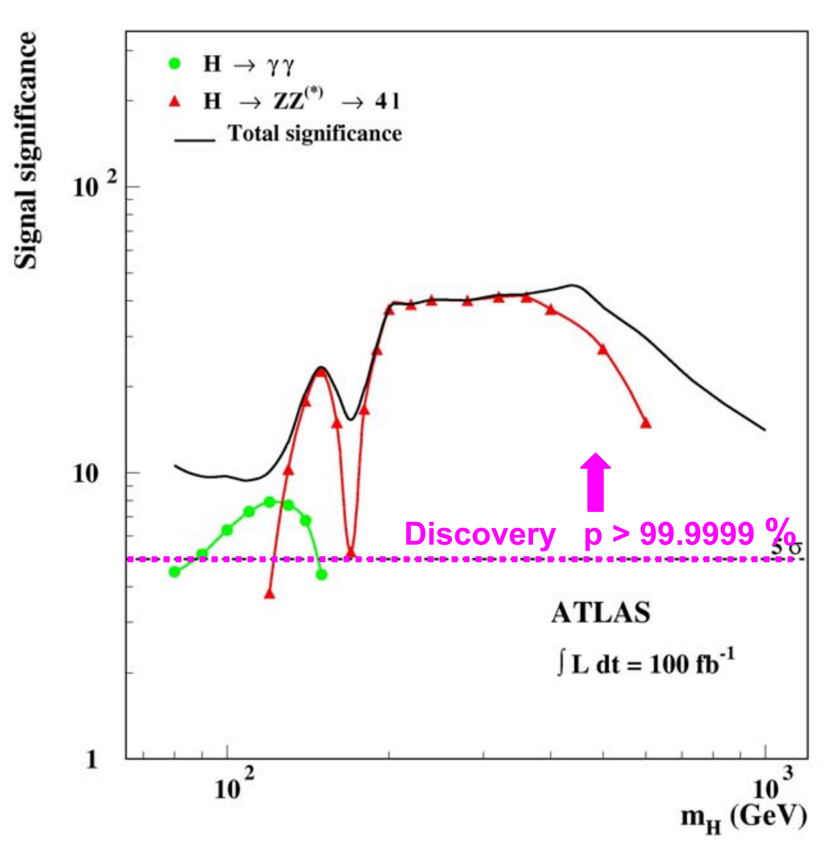
Signal / background ~ 4% (Sensitivity in mass range 100 – 140 GeV/c^2)
background (dominated by $\gamma\gamma$ events *) can be determined from side bands
important: $\gamma\gamma$-mass resolution in the calorimeters, γ / jet separation

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

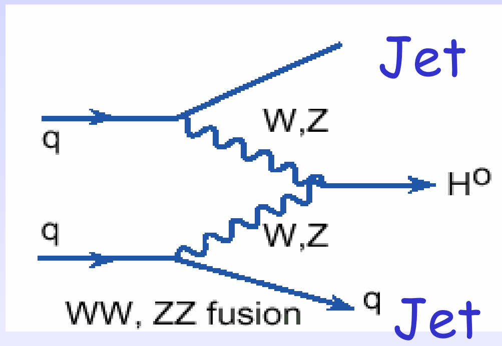
can be covered using the two "safe" channels

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

$H \rightarrow \gamma\gamma$

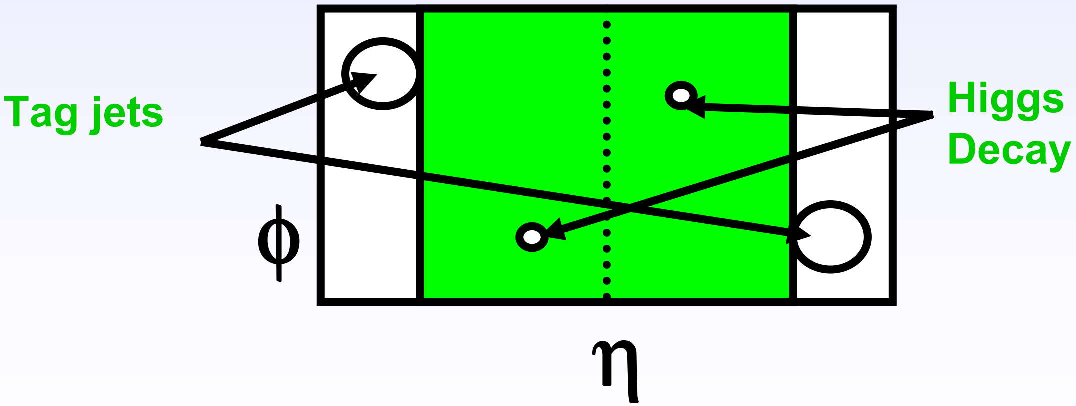
More difficult channels can also be used: Vector Boson Fusion
$qq\,H \rightarrow qq\,WW \rightarrow qq\,\ell\nu\,\ell\nu$

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



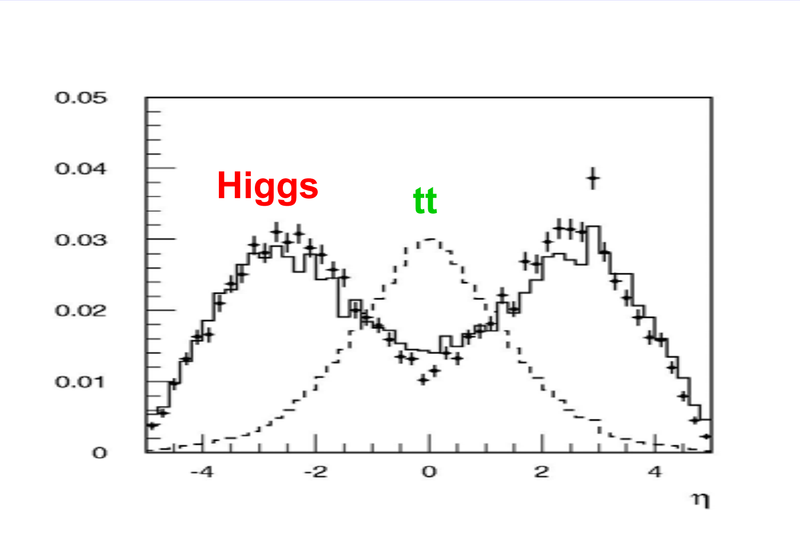
Distinctive Signature of:

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

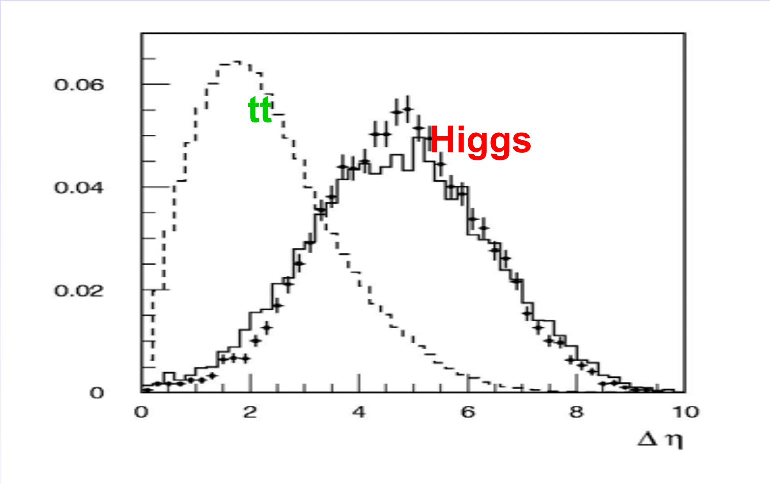


Forward jet tagging

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

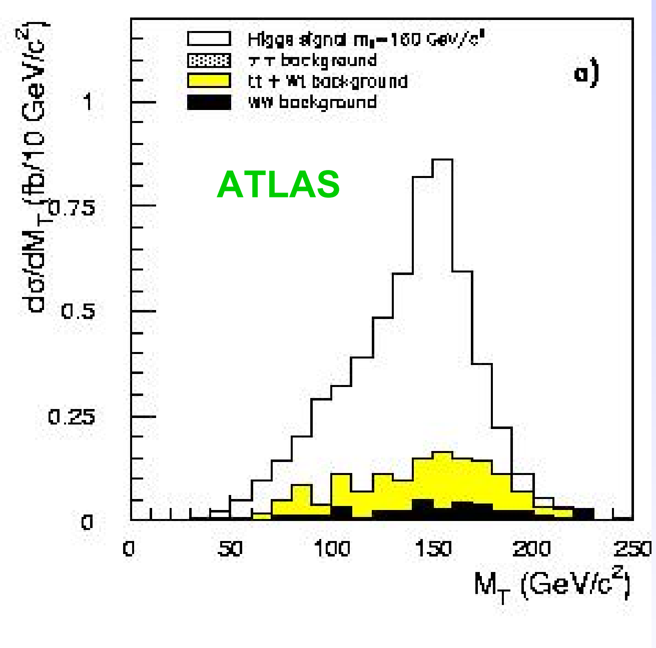


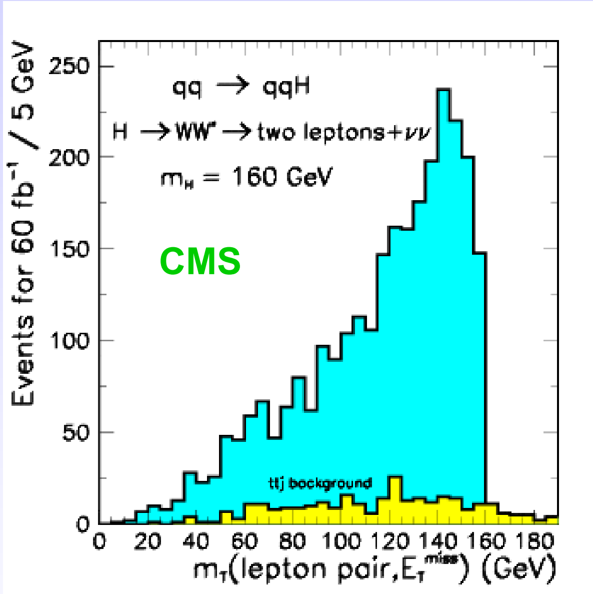
Rapidity separation



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

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



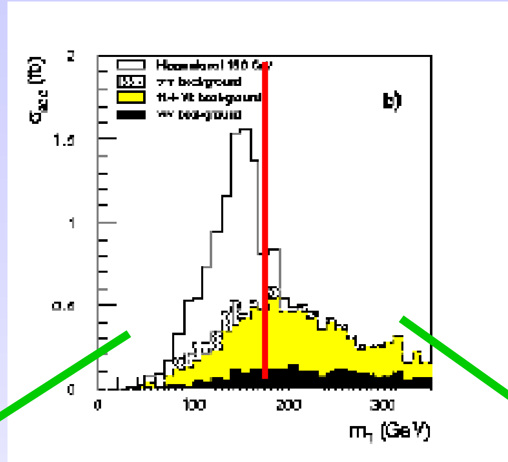


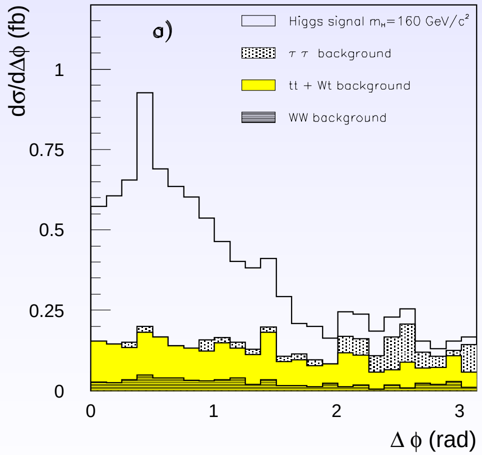
Transverse mass distributions: clear excess of events above the background from tt-production

Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution
(i.e. azimuthal difference between the two leptons)

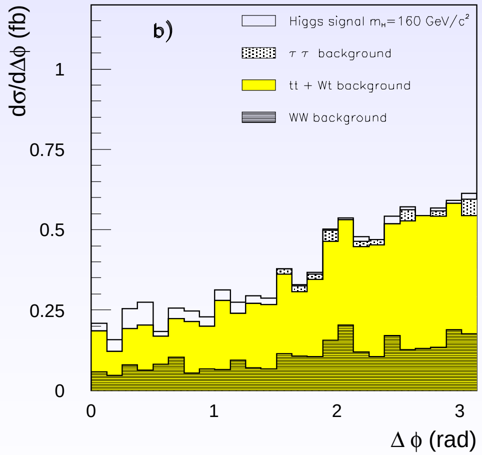
Evidence for spin-0 of the Higgs boson

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





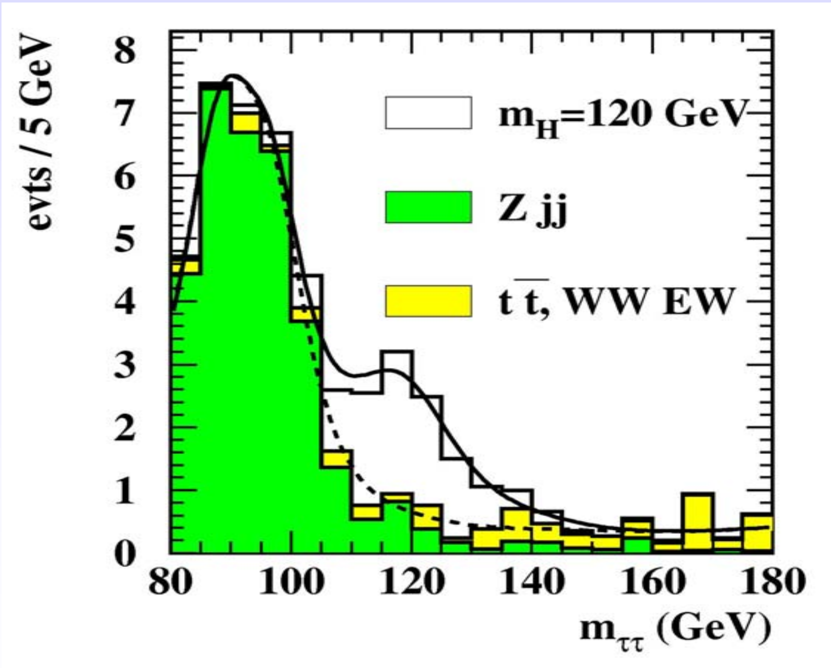
signal region



background region

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

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



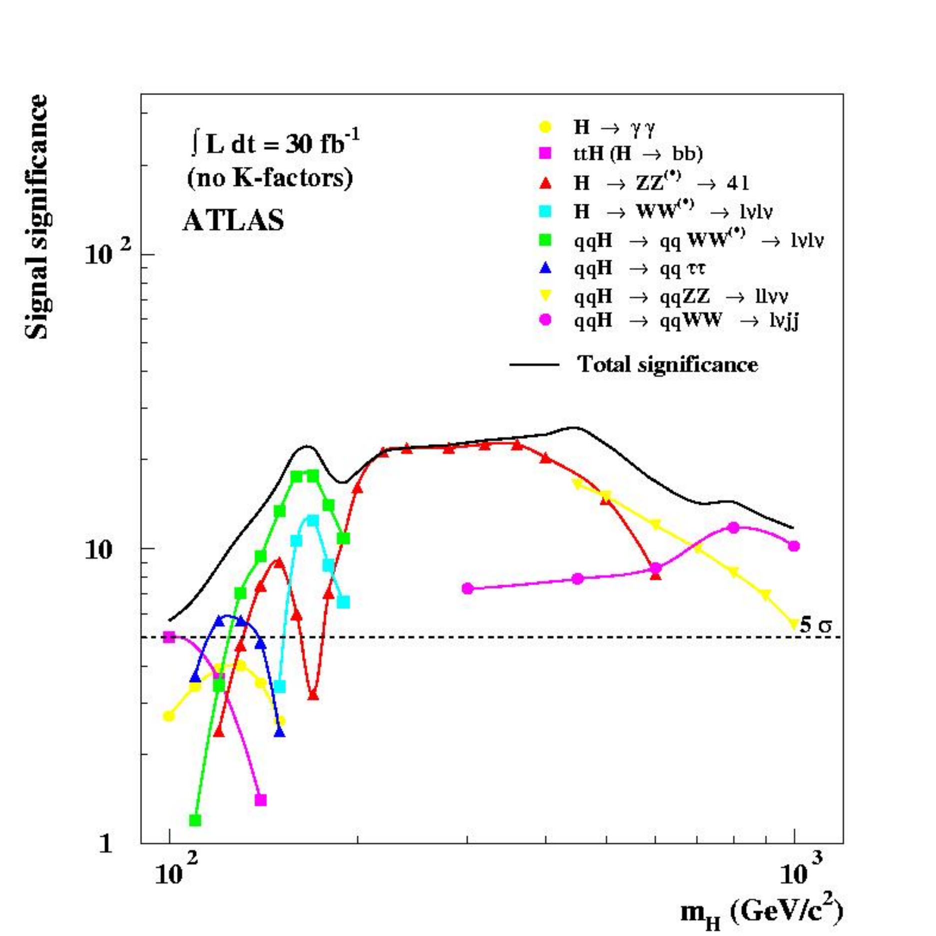
- large boost (high-P_T Higgs)

  → 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 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^-

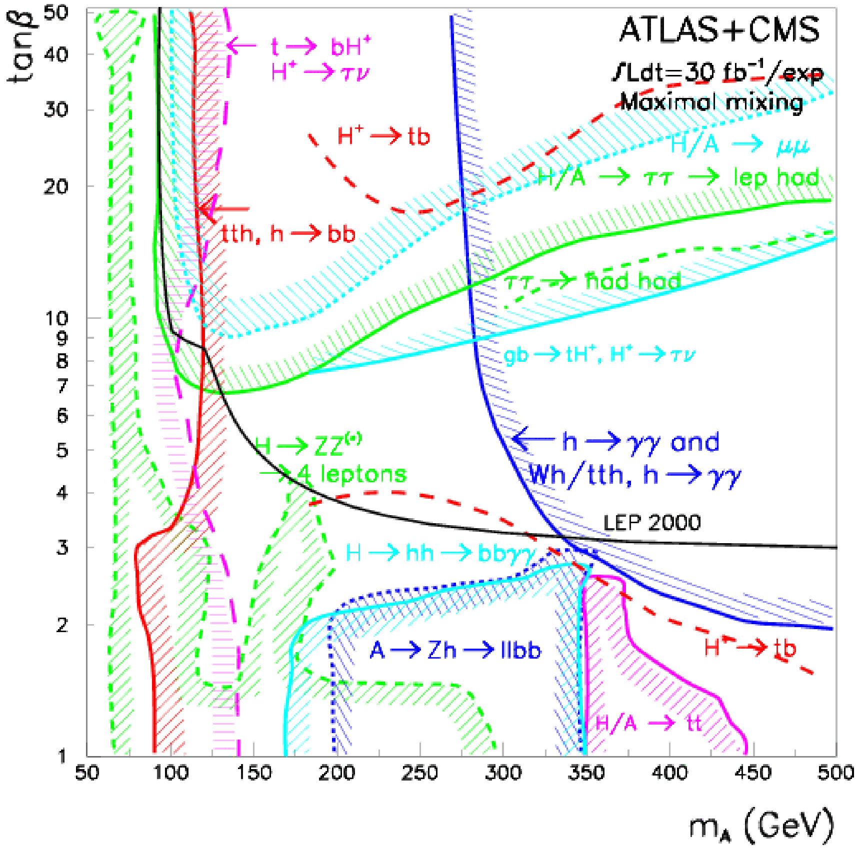
determined by two SUSY model parameters: m_A, $\tan \beta$

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

The others will most likely be heavy !

LHC discovery potential for MSSM Higgs bosons

5σ discovery in m_A – tan β plane

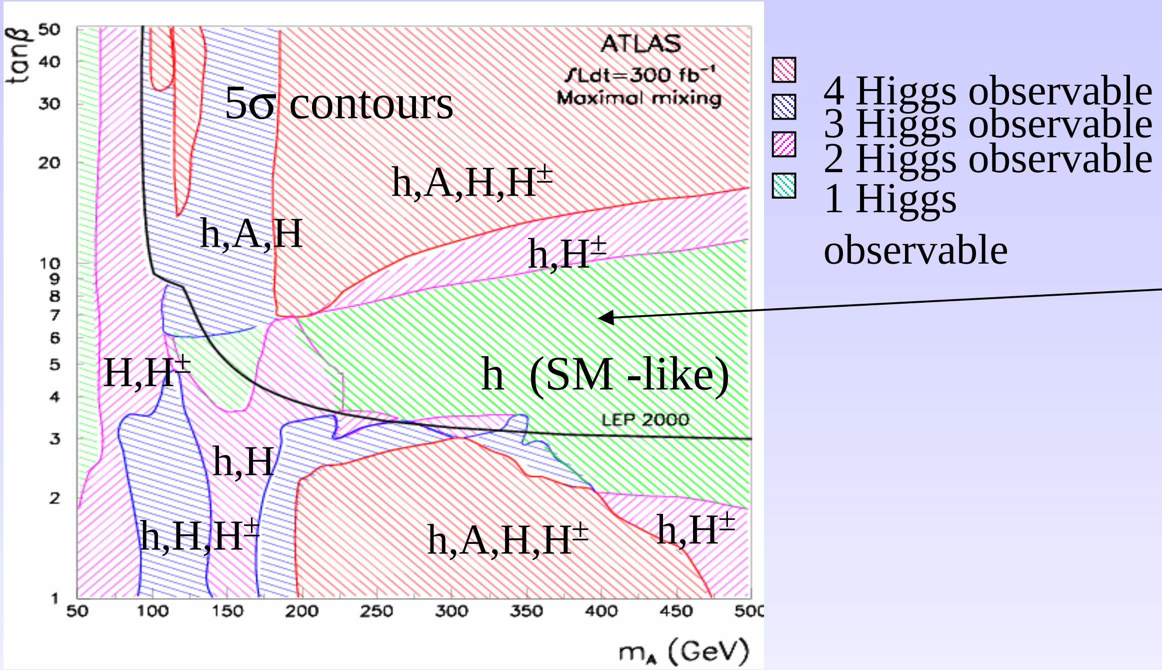


m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2

Two or more Higgs can be observed over most of the parameter space $\rightarrow$ disentangle SM / MSSM

- Plane fully covered (no holes) at low L (30 fb^{-1})
- **Main channels : h $\rightarrow \gamma\gamma$, tth h $\rightarrow$ bb, A/H $\rightarrow \mu\mu$, $\tau\tau$, $H^{\pm} \rightarrow \tau\nu$**

LHC discovery potential for SUSY Higgs bosons



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

Parameter space is fully covered:

→

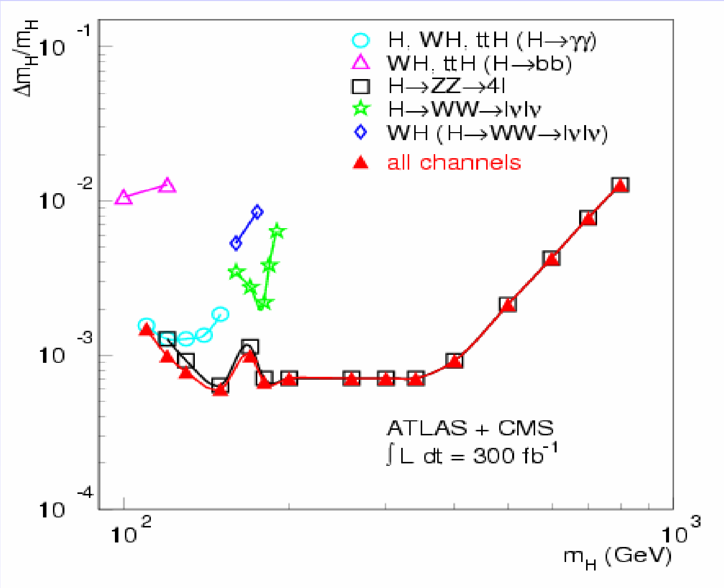
„Also in a SUSY world, Higgs bosons will be discovered at the LHC“

Determination of Higgs Boson Parameters

1. Mass

2. Couplings to bosons and fermions

Measurement of the Higgs boson mass



Dominated by ZZ→ 4ℓ and γγ resonances !

well identified, measured with a good resolution

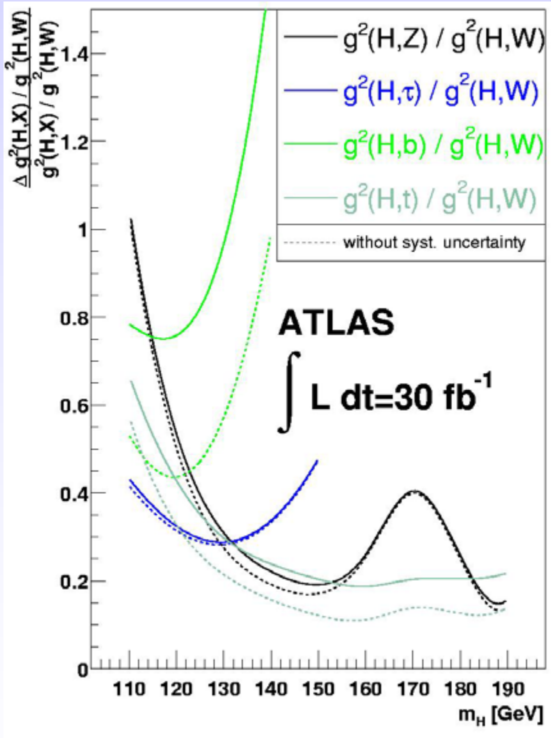
Dominant systematic uncertainty: γ / ℓ E scale.
Assumed 0.1 %
Goal 0.02 %
Scale from $Z \to \ell\ell$ (close to light Higgs)

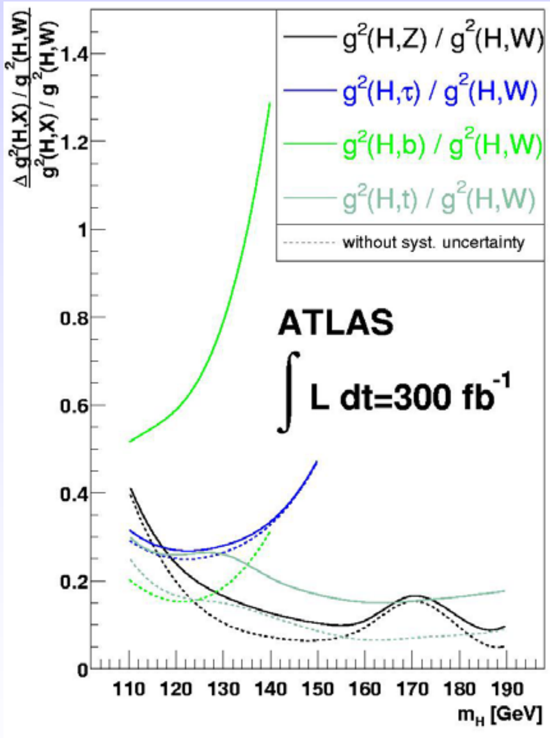
Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV / c^2)

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

Search channels at the Tevatron

- important production/decay modes: associated WH and ZH
  + gluon fusion with $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

- hopeless: gluon fusion in $H \rightarrow \gamma\gamma$, 4 ℓ (rate limited)
  σ BR ($H \rightarrow ZZ \rightarrow 4\ \ell$) = 0.07 fb ($M_H$=150 GeV)

Mass range 110 - 130 GeV:	LHC
* $WH \rightarrow l\nu\ bb$	(✓) weak
* $ZH \rightarrow l^+l^-\ bb$	weak
* $ZH \rightarrow \nu\nu\ bb$	∅ (trigger)
* $ZH \rightarrow bb\ bb$	∅ (trigger)
* $ttH \rightarrow l\nu\ b\ jjb\ bb$	✓

Triggering:

slightly easier at the Tevatron:

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

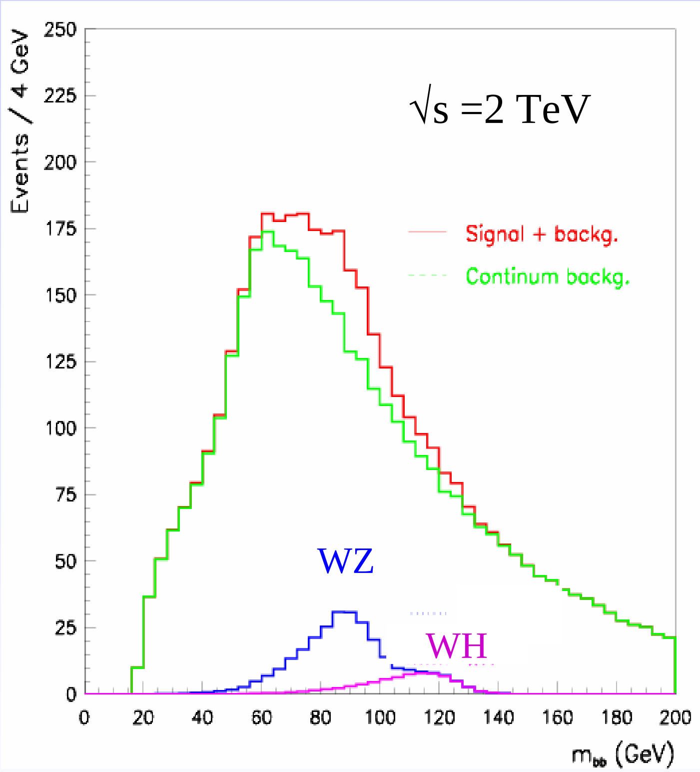
Mass range 150 - 180 GeV:	LHC
* $H \rightarrow WW^{(*)} \rightarrow l\nu\ l\nu$	✓
* $WH \rightarrow WWW^{(*)} \rightarrow l\nu\ l\nu\ l\nu$	✓
* $WH \rightarrow WWW^{(*)} \rightarrow l^+\nu\ l^+\nu\ jj$	✓

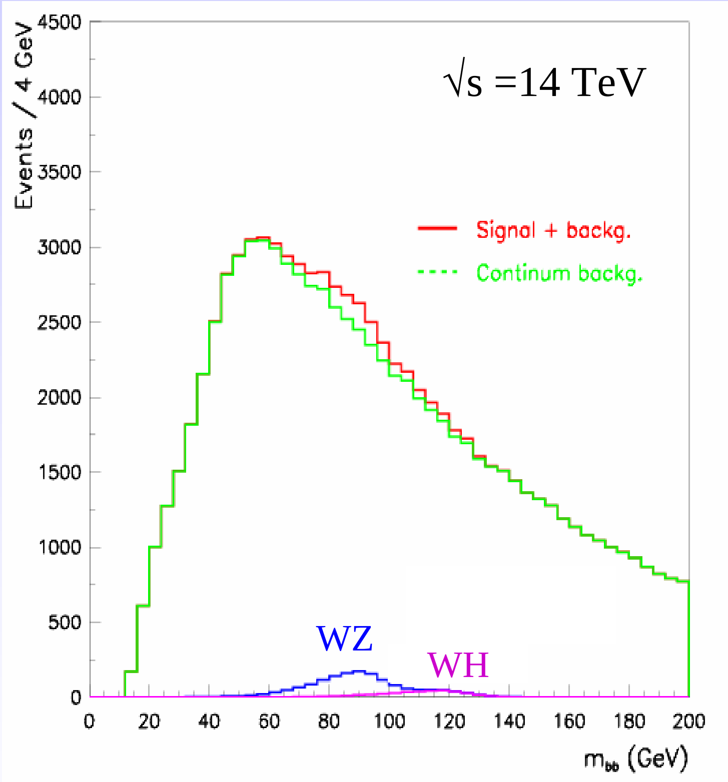
Background:

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}

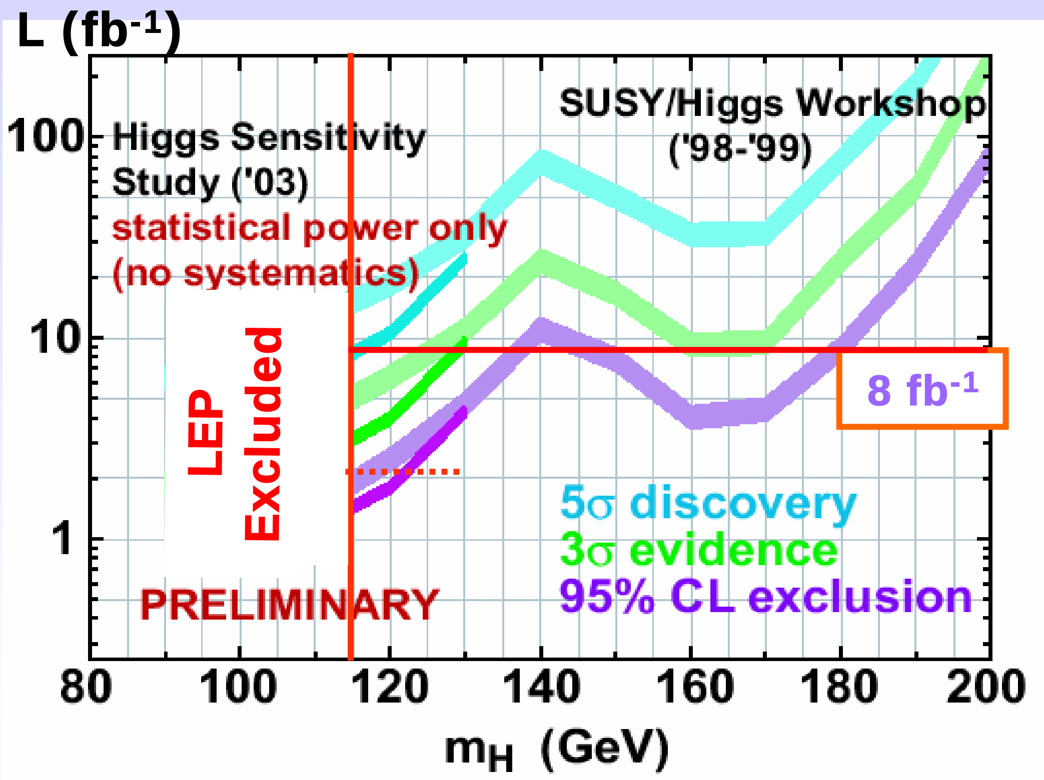




most important: control of the background shapes, very difficult!

Tevatron discovery potential for a light Higgs Boson

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



For 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)

Results from the

present

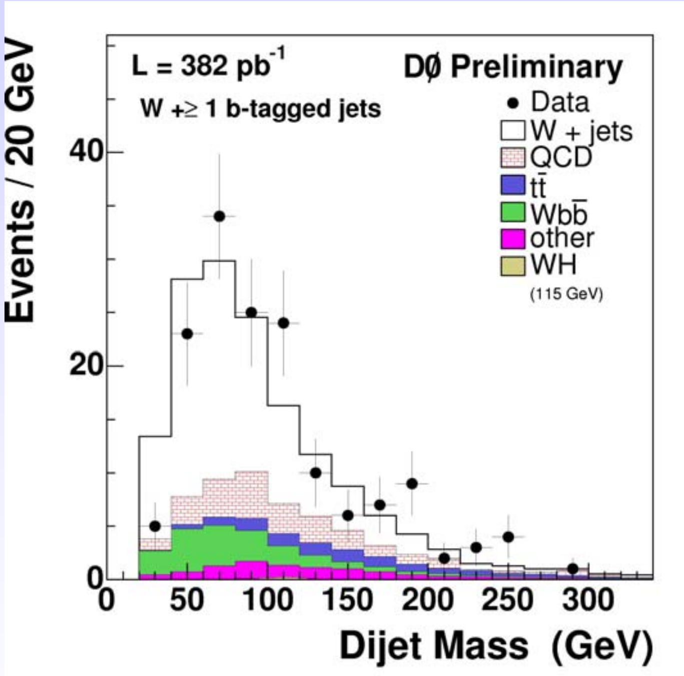
Run II data

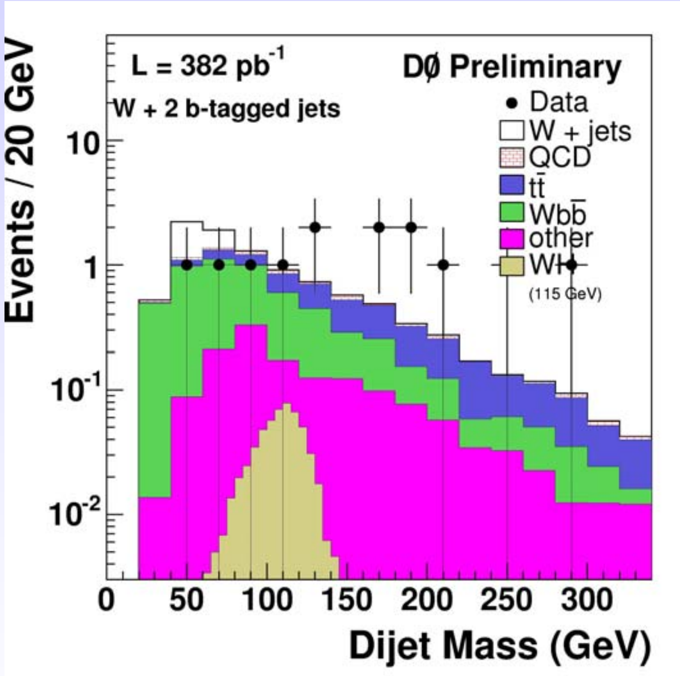
typically, data corresponding to 300 – 350 pb^{-1} analyzed

Low Mass: WH → eν bb

Data sample: 382 pb^{-1}

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

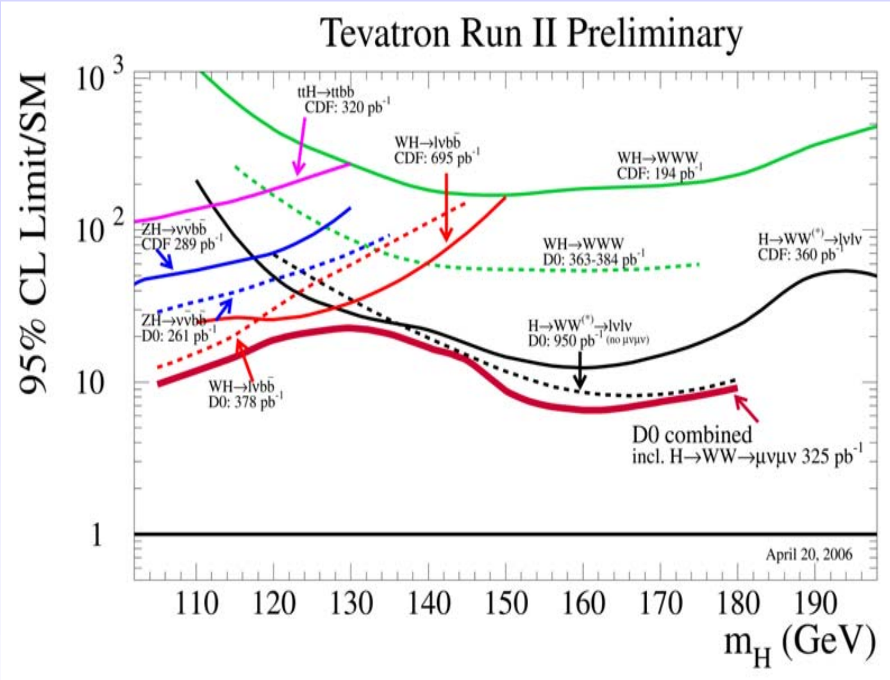




Data:	**153**	**events**	**13**	**events**
Tot. expectation	**153.6**		**10.2**	
Wbb:	18.1		4.29	
WH:	0.4		0.14	
Backgrounds:	135.5		5.73	

Higgs boson searches at the Tevatron

- Many analyses (in many different channels) presented
- No excess above SM background $\Rightarrow$ Limits extracted



Combination of current analyses (DØ): for ~325 pb^{-1}

→ upper limit about 15 times larger than Standard Model prediction at 115 GeV/c^2

Summary on Higgs Boson Searches

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

- Should a SM Higgs boson or MSSM Higgs bosons exist, they cannot escape detection at the LHC

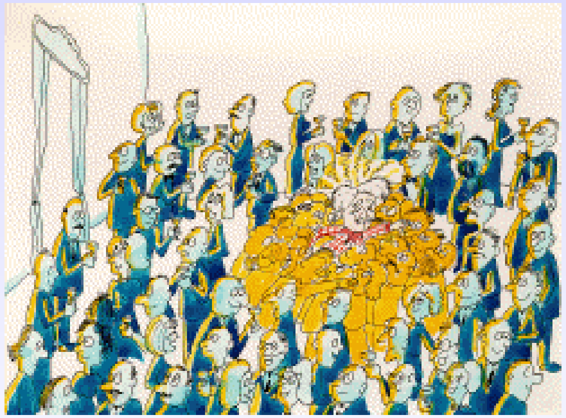
- Tevatron might have a 3-σ discovery windows at low mass, however, much depends on the detector and accelerator performance.

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