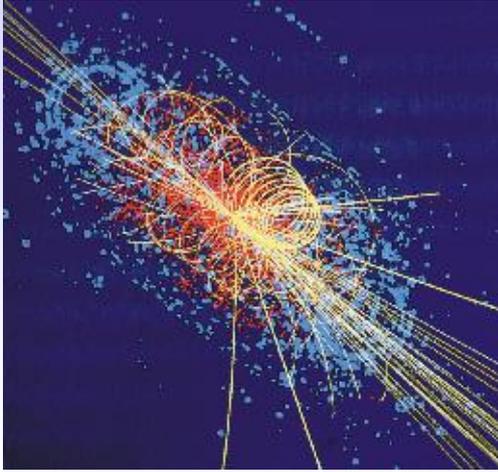


Physics at Hadron Colliders

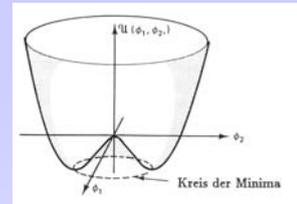
Lecture 3



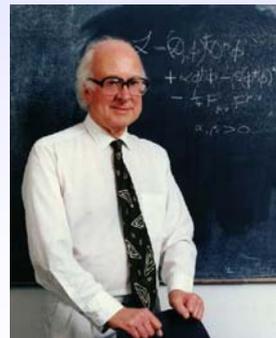
Search for the Higgs boson

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

The Search for the Higgs Boson

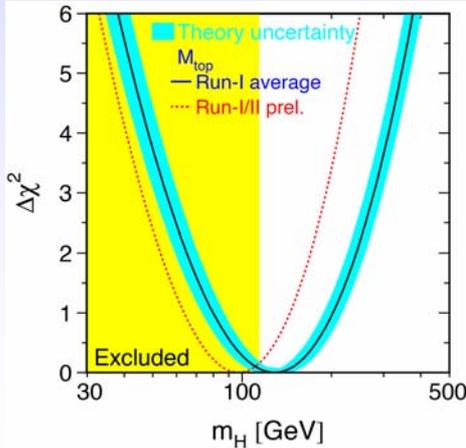


- „Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is **one of the key problems in particle physics**”
- „A new collider, such as the LHC must have the potential to detect this particle, should it exist.”



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 $m_H < 1000 \text{ GeV}$
- $m_H > 114.4 \text{ GeV}$ 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, July 2005):

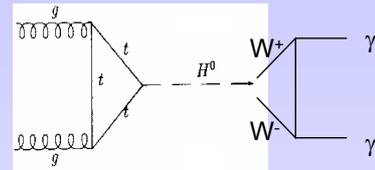
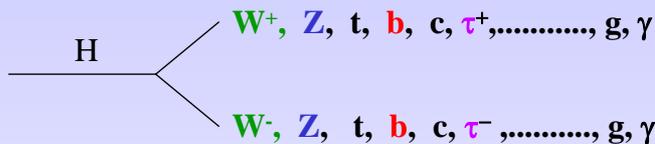
$$M_H = 91 (+45) (-32) \text{ GeV}/c^2$$

$$M_H < 186 \text{ GeV}/c^2 \quad (95 \% \text{ CL})$$

→ 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:**



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

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

where: $\delta_Z = 1, \delta_W = 2, x = M_V^2/M_H^2, \beta = \text{velocity}$

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

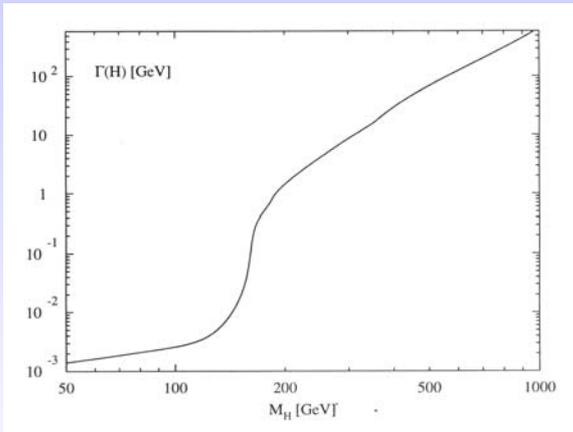
$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7 \right]^2$$

Higgs boson likes mass:

It couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

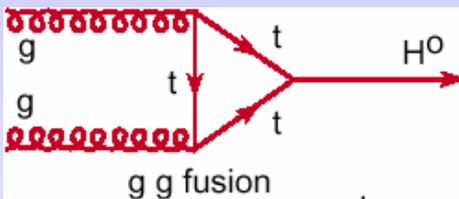
Properties of the Higgs Boson



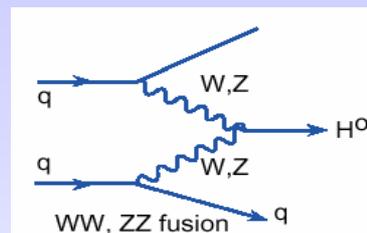
Upper limit on Higgs boson mass: from unitarity of WW scattering $M_H < 1 \text{ TeV}/c^2$

Higgs Boson Production at Hadron Colliders

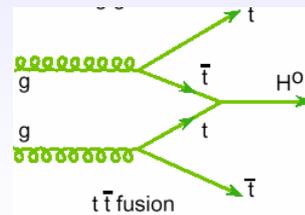
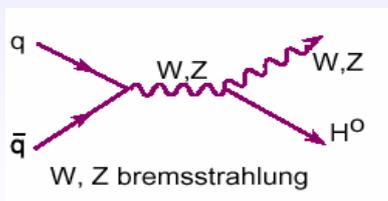
(i) Gluon fusion



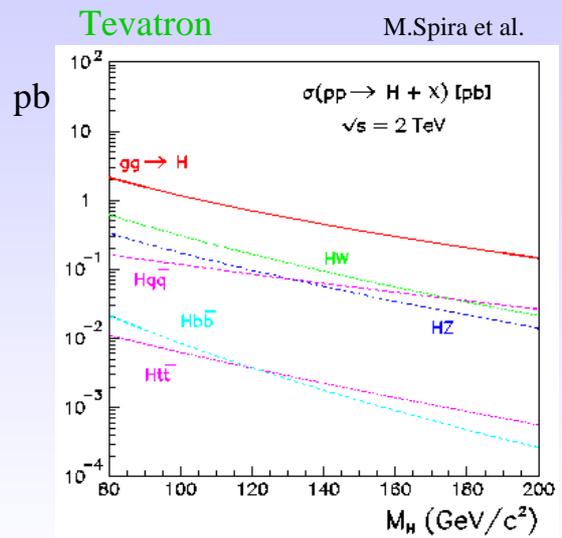
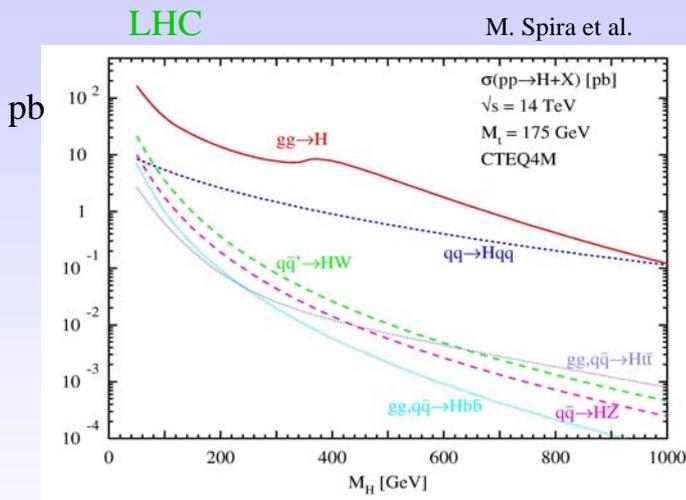
(ii) Vector boson fusion



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



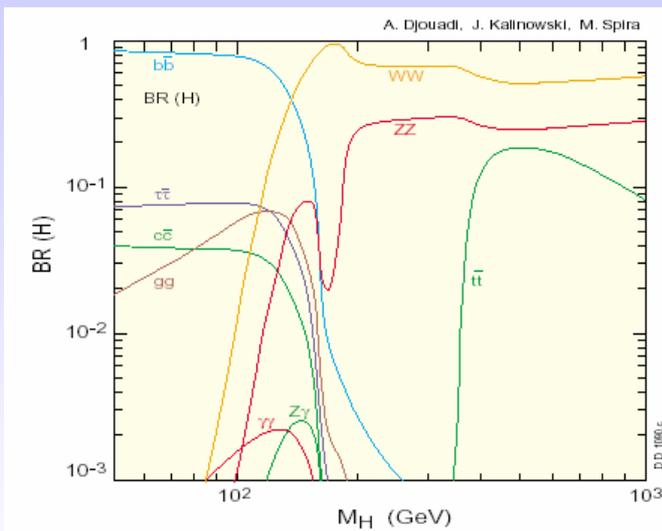
Higgs Boson Production cross sections



$qq \rightarrow W/Z + H$ cross sections
 $gg \rightarrow H$

~ 10 x larger at the LHC
 $\sim 70-80$ x larger at the LHC

Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states are essential
 (via $H \rightarrow WW, ZZ$)

at low mass:

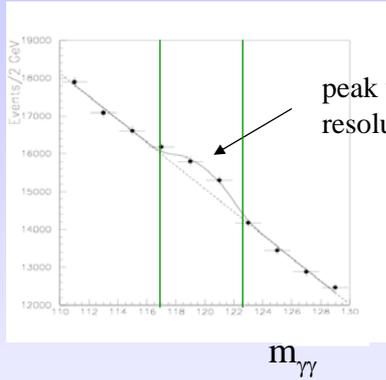
Lepton and Photon final states
 (via $H \rightarrow WW^*, ZZ^*$)

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

$\rightarrow N_B$ 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 $\Gamma_H \ll \sigma_m$. If Higgs is broad detector resolution is not relevant.

$m_H = 100 \text{ GeV} \rightarrow \Gamma_H \sim 0.001 \text{ GeV}$
 $m_H = 200 \text{ GeV} \rightarrow \Gamma_H \sim 1 \text{ GeV}$
 $m_H = 600 \text{ GeV} \rightarrow \Gamma_H \sim 100 \text{ GeV} \quad \Gamma_H \sim m_H^3$

2. Integrated luminosity :

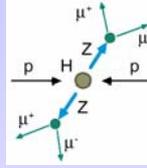
$$\left. \begin{array}{l} N_S \sim L \\ N_B \sim L \end{array} \right\}$$

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

H → ZZ(*) → eeee

Signal:

$\sigma \text{ BR} = 5.7 \text{ fb}$ ($m_H = 100 \text{ GeV}$)



Background:

Top production

$tt \rightarrow Wb \quad Wb \rightarrow \ell\nu \quad c\ell\nu \quad \ell\nu \quad c\ell\nu$
 $\sigma \text{ BR} \approx 1300 \text{ fb}$

Associated production Z bb

$Z \text{ bb} \rightarrow \ell\ell \quad c\ell\nu \quad c\ell\nu$

$P_T(1,2) > 20 \text{ GeV}$

$P_T(3,4) > 7 \text{ GeV}$

$|\eta| < 2.5$

Isolated leptons

$M(l\bar{l}) \sim M_Z$

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

$L = 100 \text{ fb}^{-1}$

Background rejection:

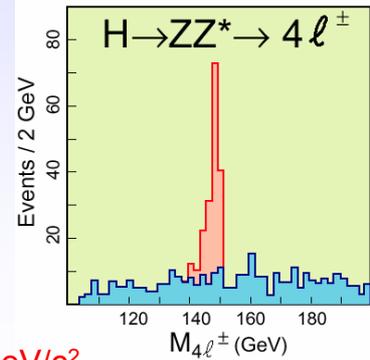
Leptons from b-quark decays

→ non isolated

→ do not originate from primary vertex

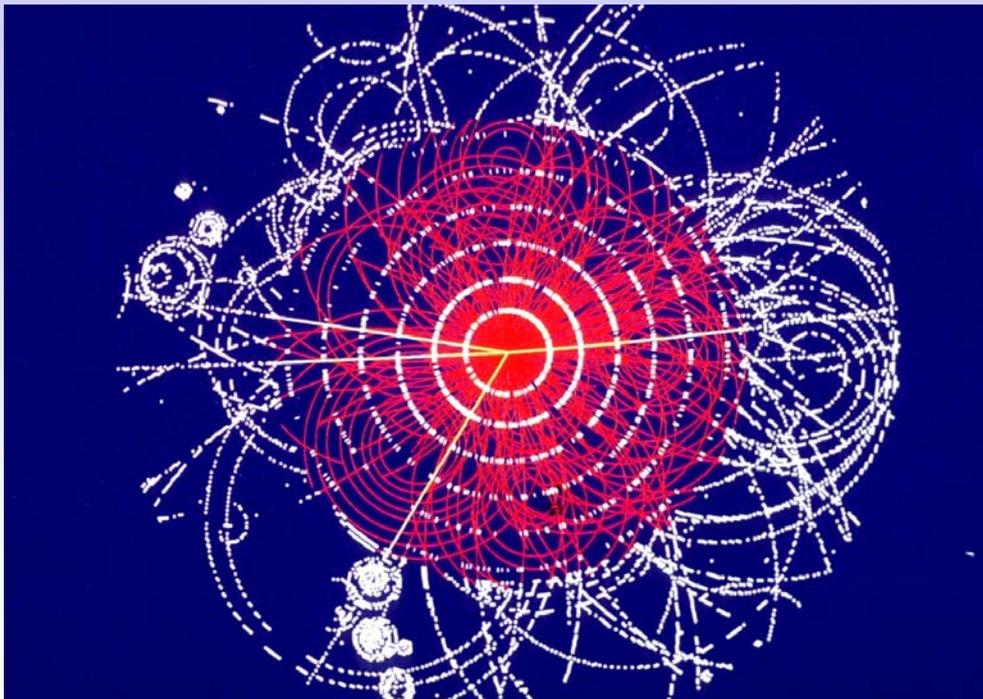
(B-meson lifetime: $\sim 1.5 \text{ ps}$)

Dominant background after isolation cuts: ZZ continuum

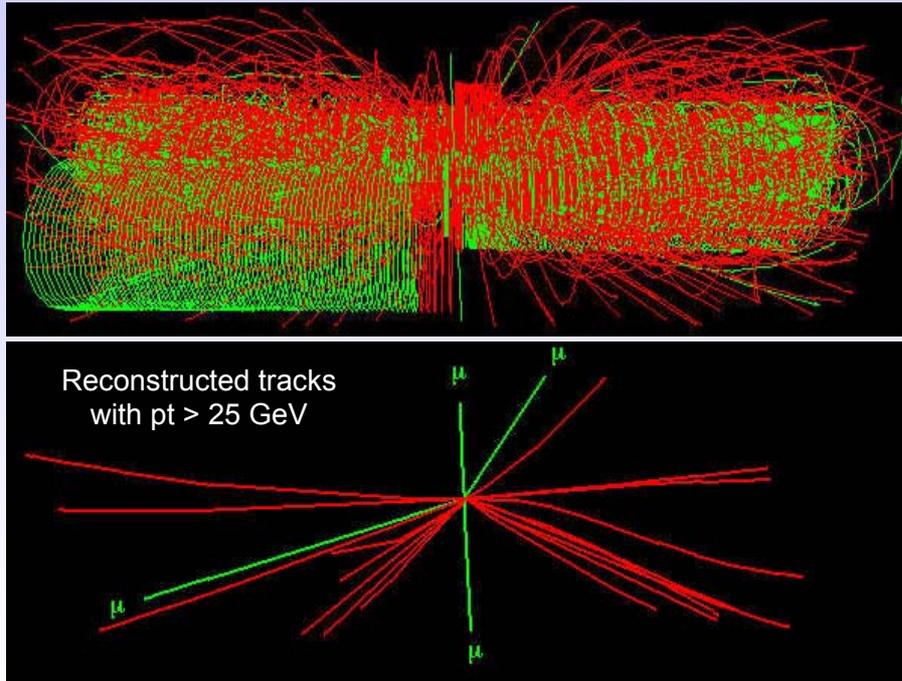


Discovery potential in mass range from ~ 130 to $\sim 600 \text{ GeV}/c^2$

A simulated H → ZZ → eeee event

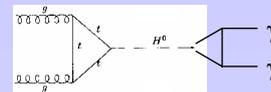


A simulated $H \rightarrow ZZ \rightarrow eeee$ event at high luminosity (pile-up)



$m_H \leq 150 \text{ GeV}$

$$H \rightarrow \gamma\gamma$$



• $\sigma \times \text{BR} \approx 50 \text{ fb}$ (BR $\approx 10^{-3}$)

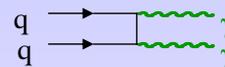
• Backgrounds :

- $\gamma\gamma$ (irreducible):

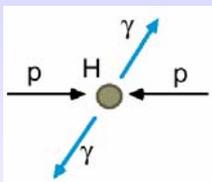
$$\sigma_{\gamma\gamma} \approx 2 \text{ pb / GeV}$$

$$\Gamma_H \approx \text{MeV}$$

e.g.



→ need $\sigma(m)/m \approx 1\%$

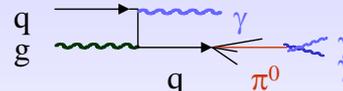


- $\gamma j + jj$ (reducible):

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

with large uncertainties

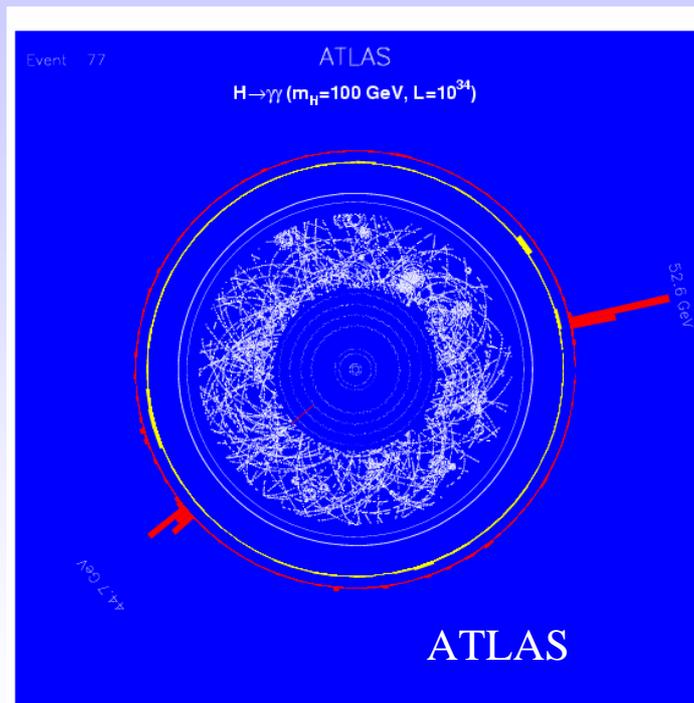
→ need $R_j > 10^3$ for $\epsilon_\gamma \approx 80\%$ to get $\sigma_{\gamma j + jj} \ll \sigma_{\gamma\gamma}$



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

ATLAS and CMS: complementary performance

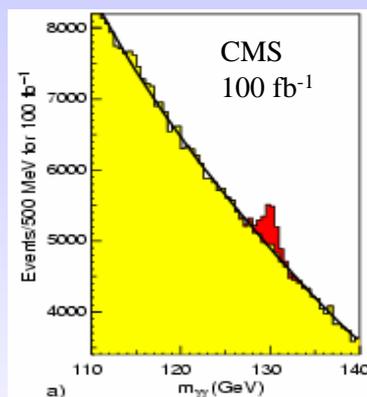
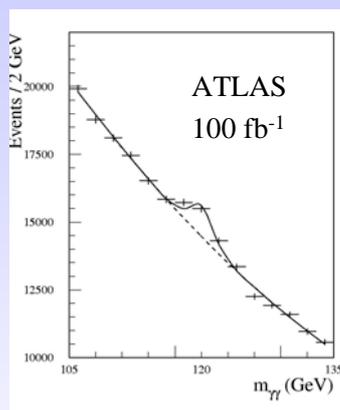
A simulated $H \rightarrow \gamma\gamma$ event in ATLAS



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



Two **isolated** photons:

$$P_T(\gamma_1) > 40 \text{ GeV}$$

$$P_T(\gamma_2) > 25 \text{ GeV}$$

$$|\eta| < 2.5$$

Mass resolution: $m_H = 100 \text{ GeV}/c^2$

ATLAS : 1.1 GeV (LAr-Pb)

CMS : 0.6 GeV (crystals)

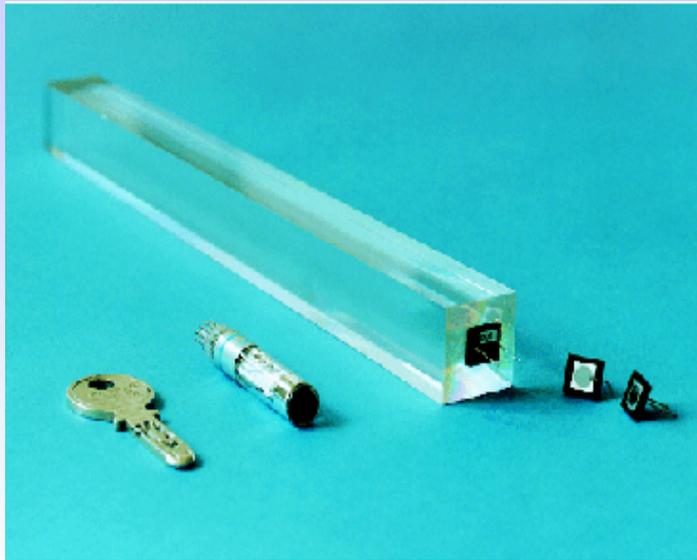
Signal / background $\sim 4\%$ (Sensitivity in mass range 100 – 140 GeV/c^2)
 background (dominated by $\gamma\gamma$ events *) can be determined from side bands
 important: $\gamma\gamma$ -mass resolution in the calorimeters, γ / jet separation

*) 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

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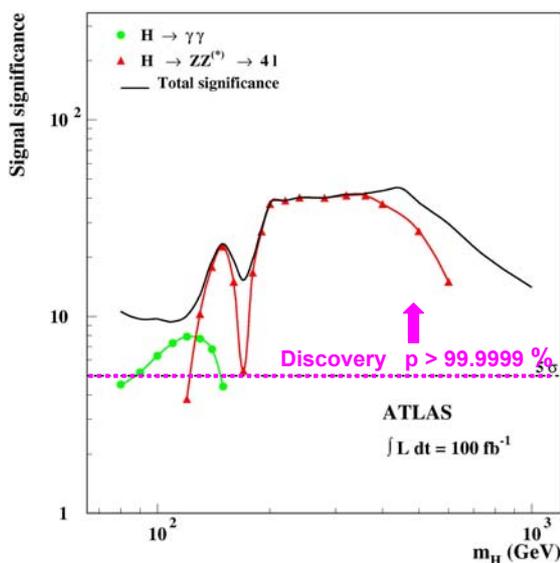
CMS crystal calorimeter



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



The full allowed mass range

from the LEP limit ($\sim 114 \text{ GeV}$)
up to
theoretical upper bound of $\sim 1000 \text{ GeV}$

can be covered using the two “safe” channels

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

$H \rightarrow \gamma\gamma$

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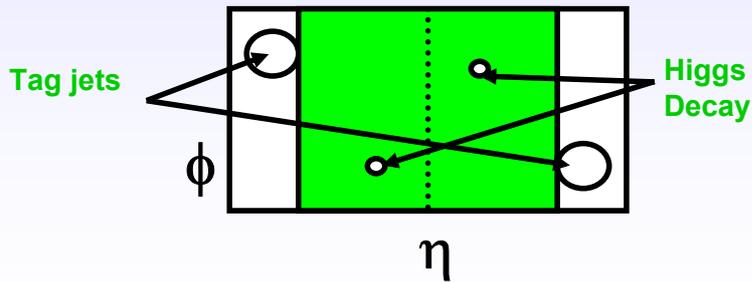
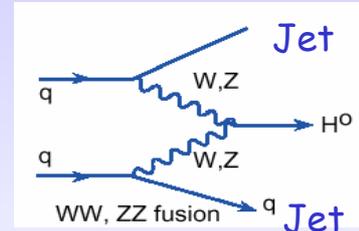
More difficult channels can also be used: **Vector Boson Fusion**

$$qq H \rightarrow qq WW \rightarrow qq \ell\nu \ell\nu$$

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

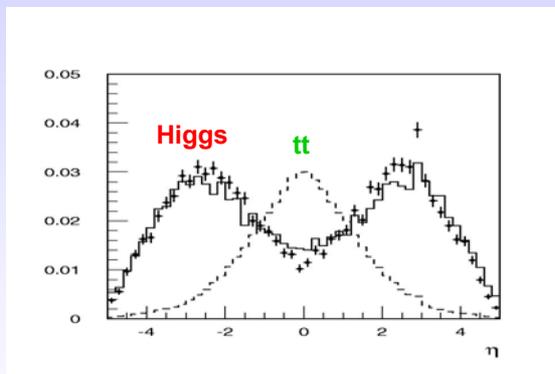
Distinctive Signature of:

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

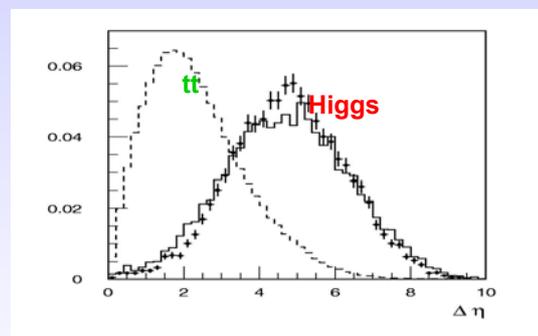


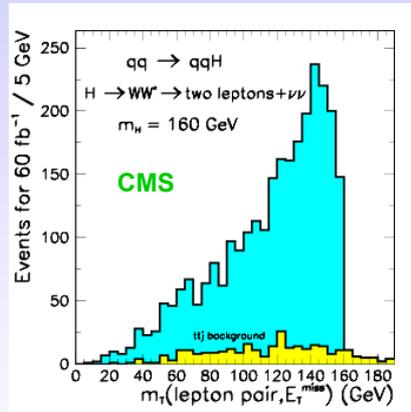
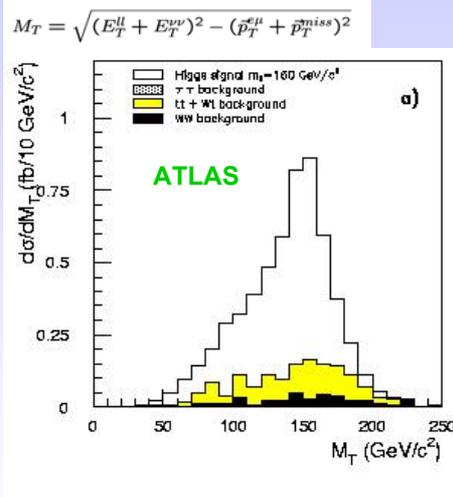
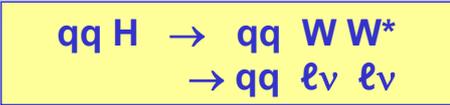
Forward jet tagging

Rapidity distribution of tag jets
VBF Higgs events vs. $t\bar{t}$ -background



Rapidity separation

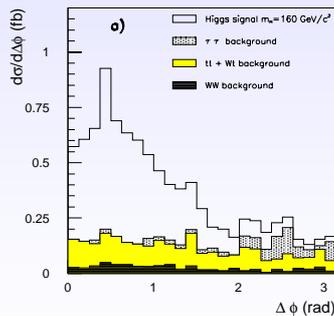
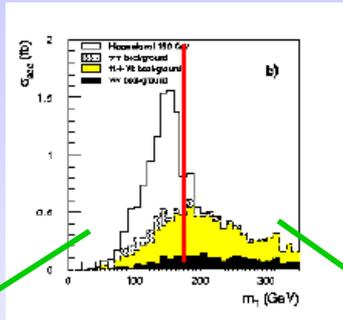




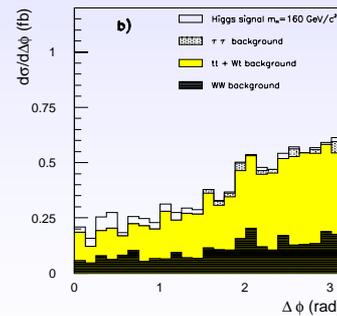
Transverse mass distributions: clear excess of events above the background from tt-production

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 $\rightarrow WW \rightarrow \ell\nu\ell\nu$ expect leptons to be close by in space

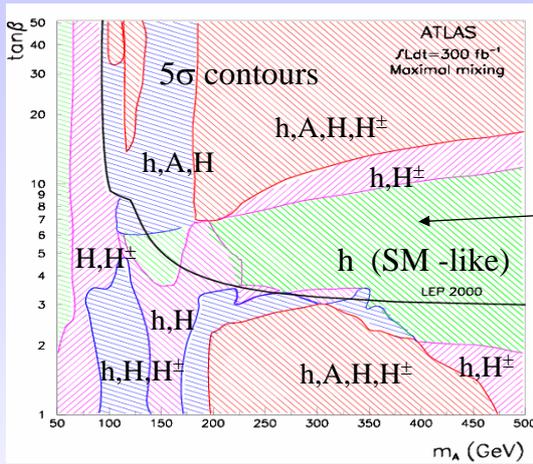


signal region



background region

LHC discovery potential for SUSY Higgs bosons



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

Parameter space is fully covered:

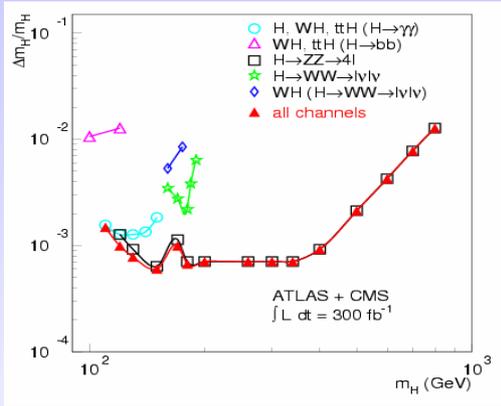
→

„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 $ZZ \rightarrow 4\ell$ 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 $Z \rightarrow \ell\ell$ (close to light Higgs)

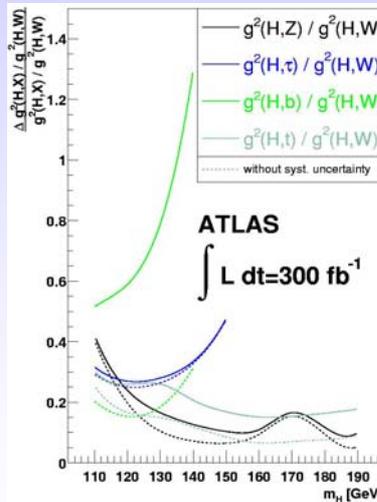
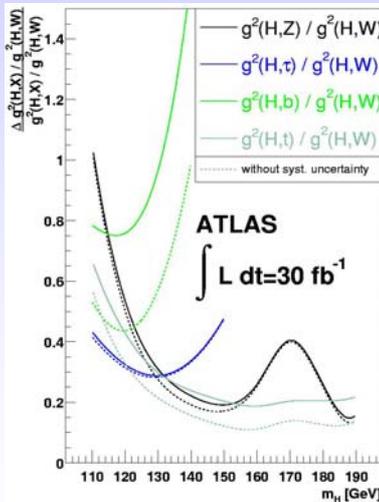
Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV / c^2)

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

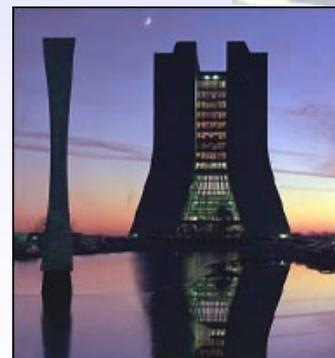
at Fermilab



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Impressions from Fermilab



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Impressions from Fermilab (cont.)



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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 $H \rightarrow \gamma\gamma, 4\ell$ (rate limited)
 $\sigma \text{BR}(H \rightarrow ZZ \rightarrow 4\ell) = 0.07 \text{ fb}$ ($M_H=150 \text{ GeV}$)

Mass range 110 - 130 GeV:

	LHC
* WH $\rightarrow \ell\nu \text{ bb}$	(✓) weak
* ZH $\rightarrow \ell^+\ell^- \text{ bb}$	weak
* ZH $\rightarrow \nu\nu \text{ bb}$	∅ (trigger)
* ZH $\rightarrow \text{bb bb}$	∅ (trigger)
* ttH $\rightarrow \ell\nu \text{ b jjb bb}$	✓

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 $\rightarrow WW^{(*)} \rightarrow \ell\nu \ell\nu$	✓
* WH $\rightarrow WWW^{(*)} \rightarrow \ell\nu \ell\nu \ell\nu$	✓
* WH $\rightarrow WWW^{(*)} \rightarrow \ell^+\nu \ell^+\nu \text{ jj}$	✓

Background:

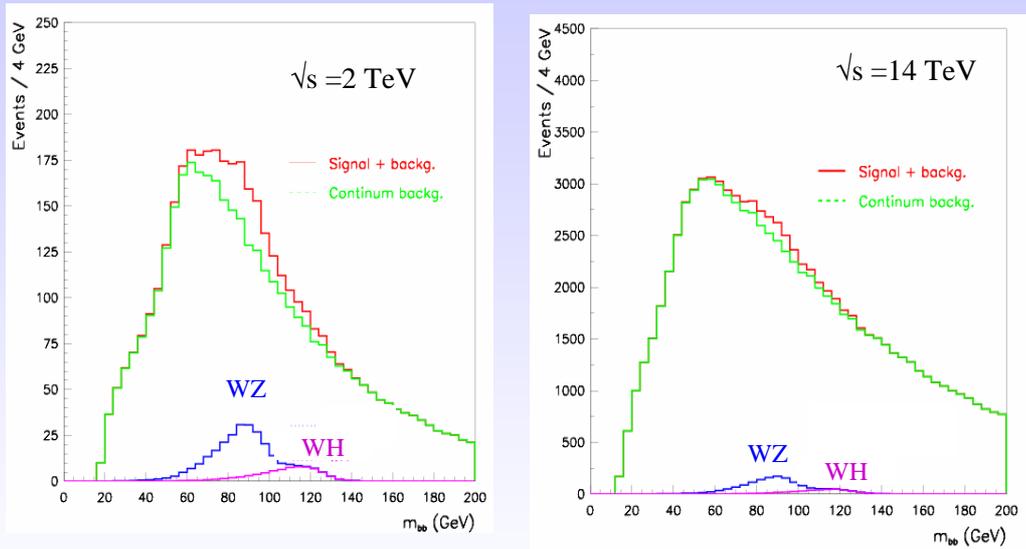
electroweak production:
~10 x larger at the LHC
QCD production (e.g. tt):
~100 x larger at the LHC

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WH Signals at the LHC and the Tevatron

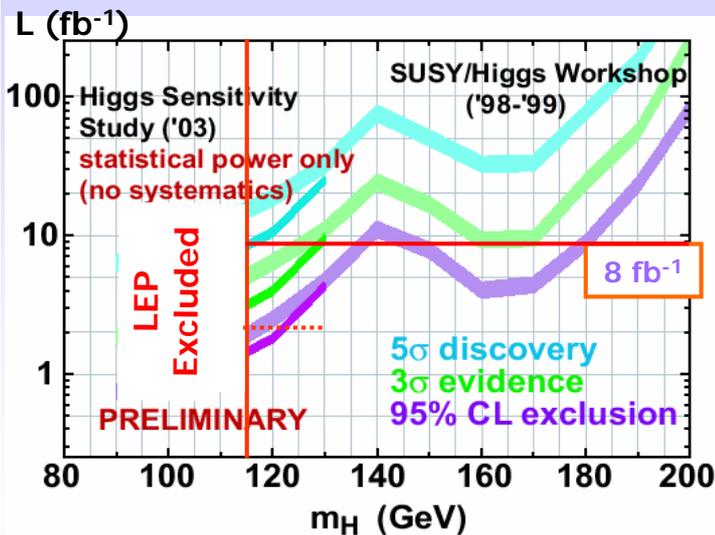
$M_H = 120 \text{ GeV}$, 30 fb^{-1}



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} :

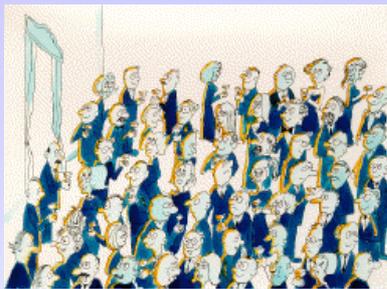
- (i) 95% CL exclusion of a SM Higgs boson is possible up to $135 \text{ GeV}/c^2$ and for $150 - 180 \text{ GeV}/c^2$
- (ii) $3\text{-}\sigma$ evidence for $M_H < 130 \text{ GeV}/c^2$
- (iii) Sensitivity at low mass starts with an int. luminosity of 2 fb^{-1} (mid - end 2006)

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 $3\text{-}\sigma$ 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 \leftrightarrow **Masse**