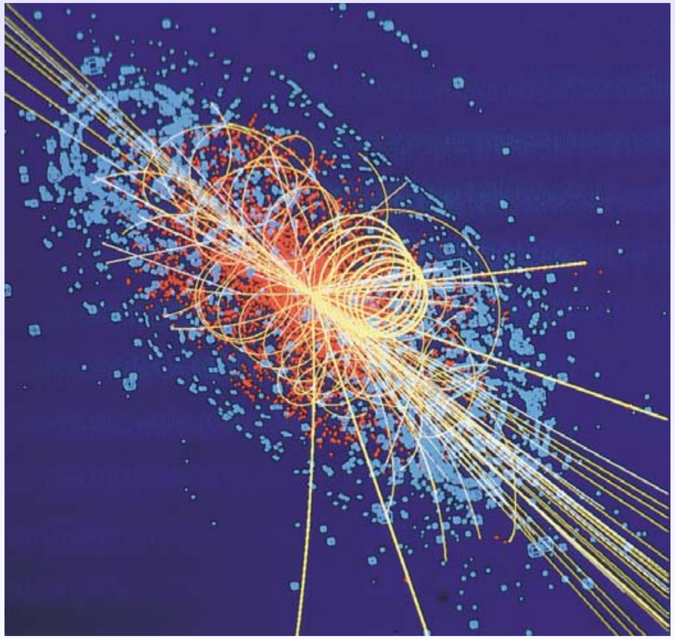
Physics at Hadron Colliders

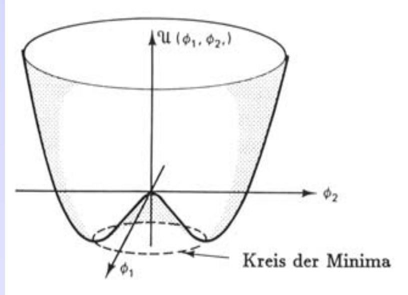
Lecture 3



Search for the Higgs boson

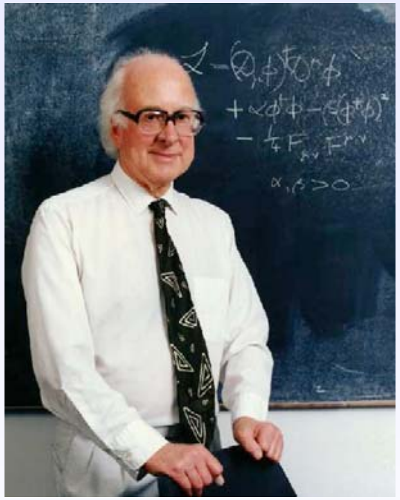
- **Higgs boson production and decays**
- **LHC discovery potential**
- **What can be covered at the Tevatron?**

The Search for the Higgs Boson



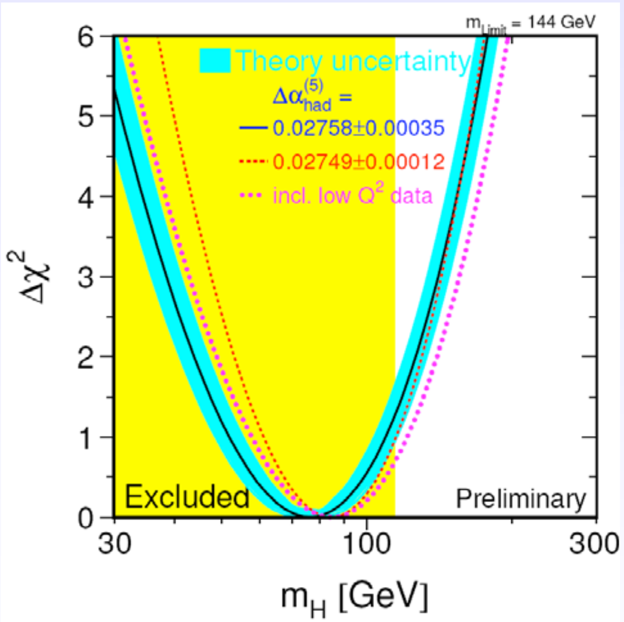
- „Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics”

- „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 2007):

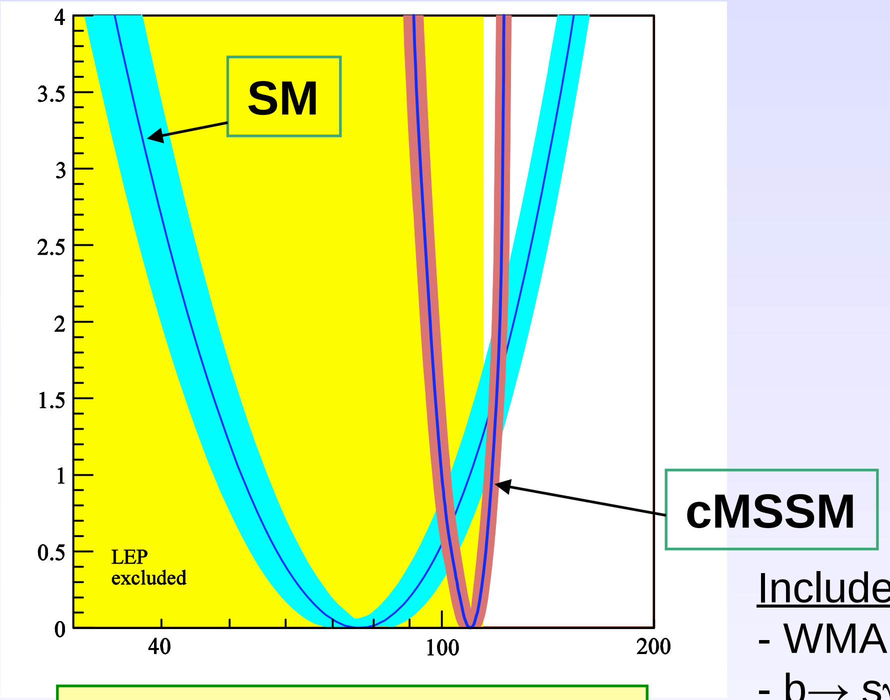
M_H = 80 (+36) (-26) GeV/c²

M_H < 144 GeV/c² (95 % CL)

→ Higgs boson could be around the corner !

How do the constraints look like in a supersymmetric theory ?

O. Buchmüller et al., arXiv:0707.3447



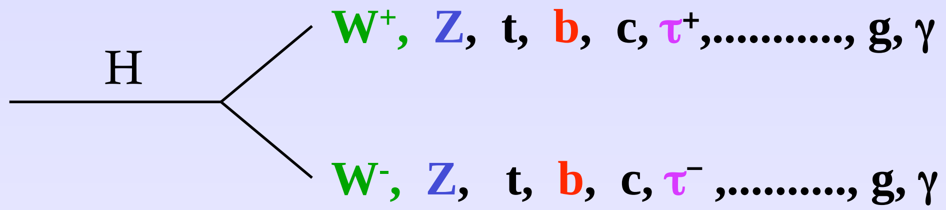
m_h = 110 (+8) (-10) ± 3 (theo) GeV/c^2

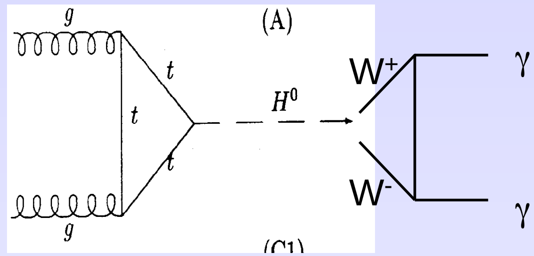
….watch the low mass region !

Includes:
- WMAP
- $b \to s\gamma$
- a_μ

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

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

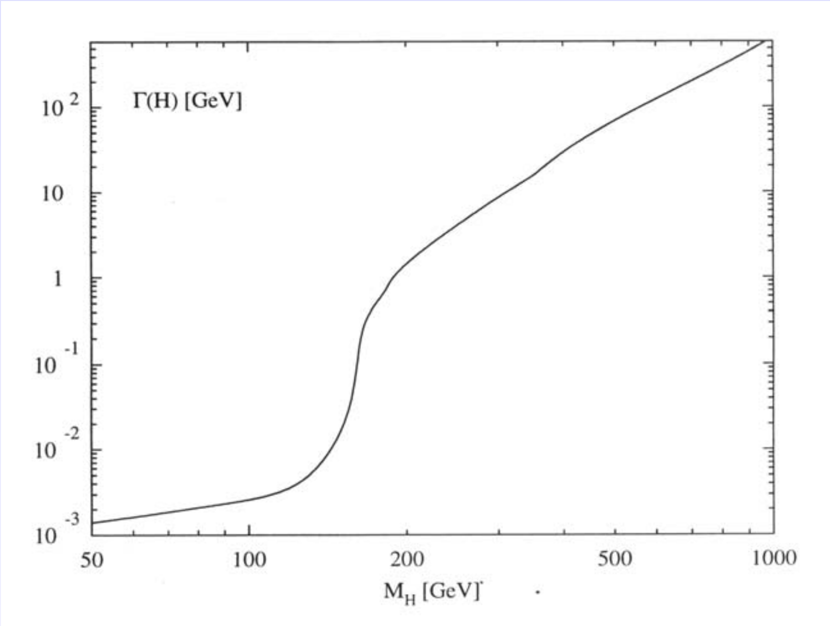
$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs boson likes mass:

It couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

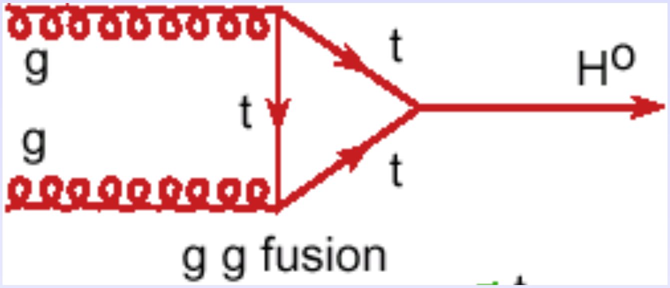
Properties of the Higgs Boson



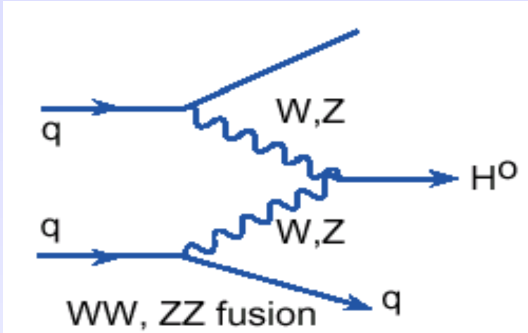
Upper limit on Higgs boson mass: from unitarity of WW scattering **M_H < 1 TeV/c^2**

Higgs Boson Production at Hadron Colliders

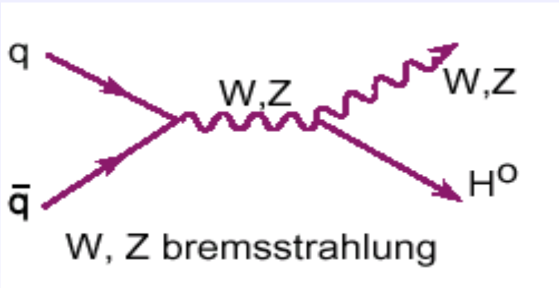
(i) Gluon fusion

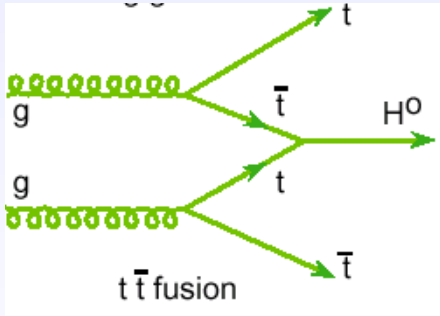


(ii) Vector boson fusion



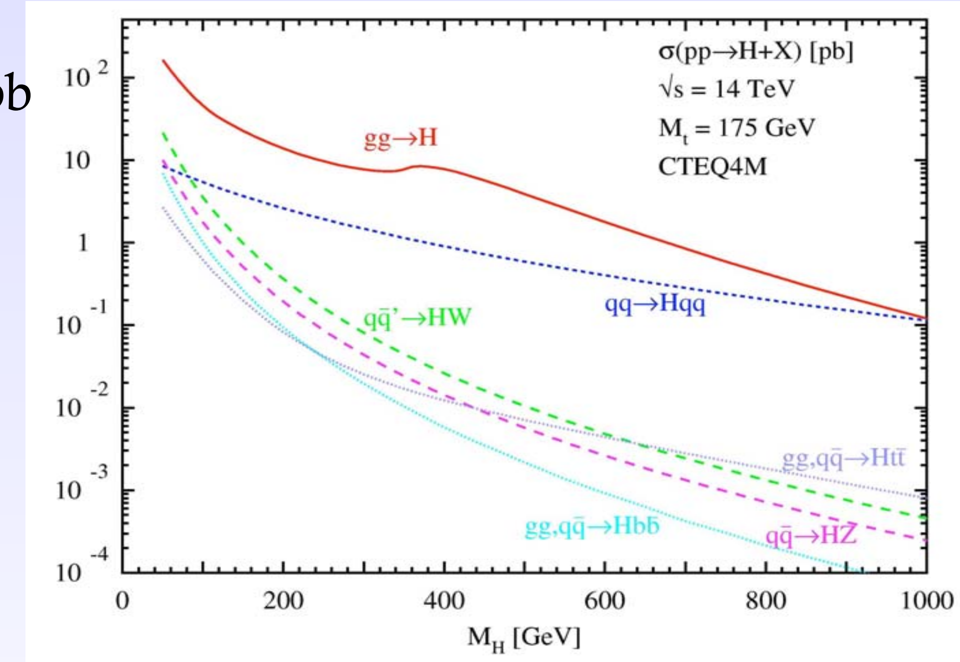
(iii) Associated production (W/Z, tt)



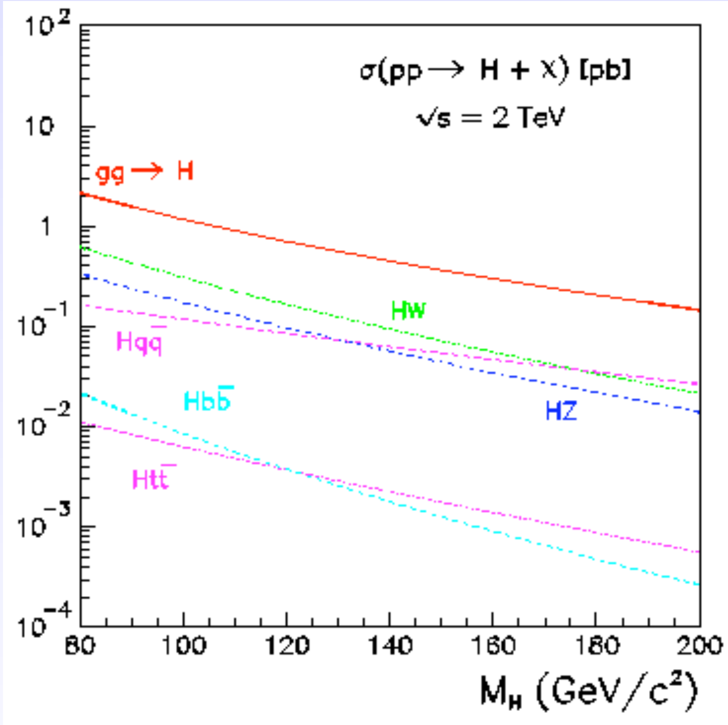


Higgs Boson Production cross sections

LHC — M. Spira et al.

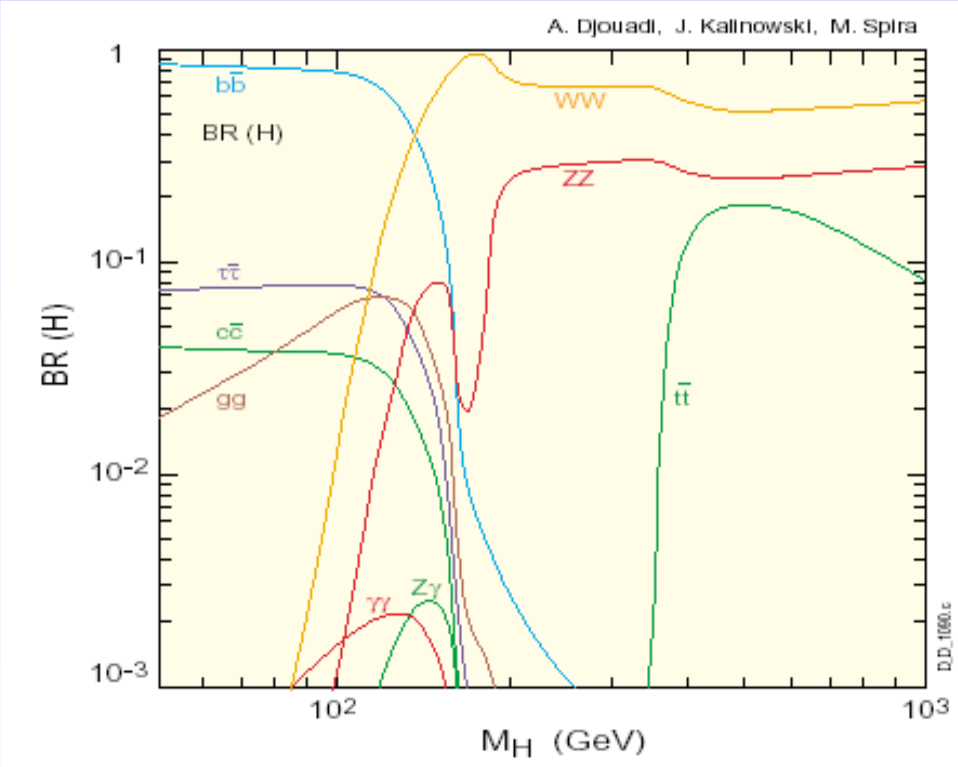


Tevatron — M.Spira et al.



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

Higgs Boson Decays at Hadron Colliders



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

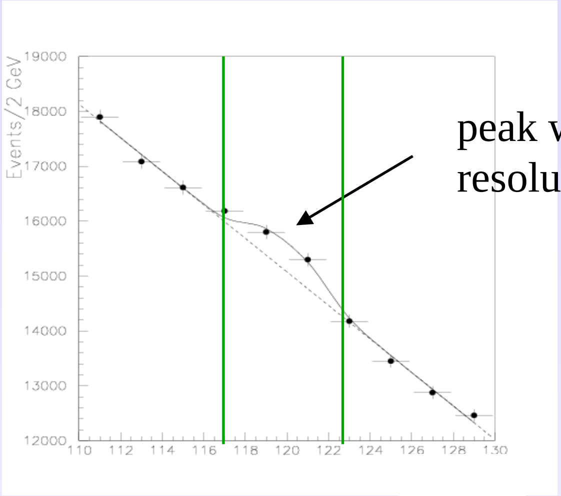
at low mass:
Lepton and Photon final states
(via H → WW*, ZZ*)

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:



$m_{\gamma\gamma}$

Signal significance:

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

N_S= number of signal events
N_B= number of background events
} in peak region

$\sqrt{N_B} \equiv$ 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

⟶ 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.

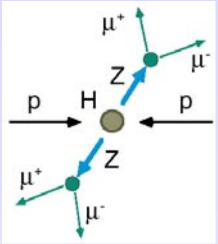
$m_H = 100$ GeV → $\Gamma_H \sim 0.001$ GeV
$m_H = 200$ GeV → $\Gamma_H \sim 1$ GeV
$m_H = 600$ GeV → $\Gamma_H \sim 100$ GeV **$\Gamma_H \sim m_H^3$**

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

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

Background: Top production

$tt \rightarrow Wb\, Wb \rightarrow \ell\nu\, c\ell\nu\, \ell\nu\, c\ell\nu$

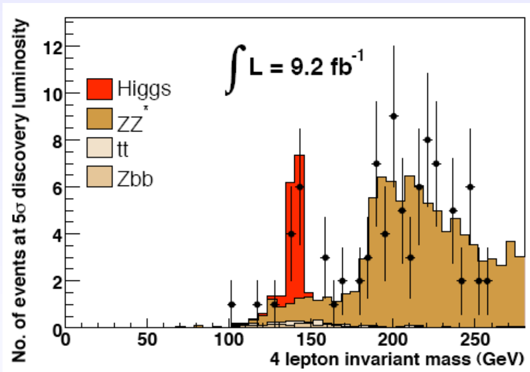
σ BR ≈ 1300 fb

Associated production Z bb

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

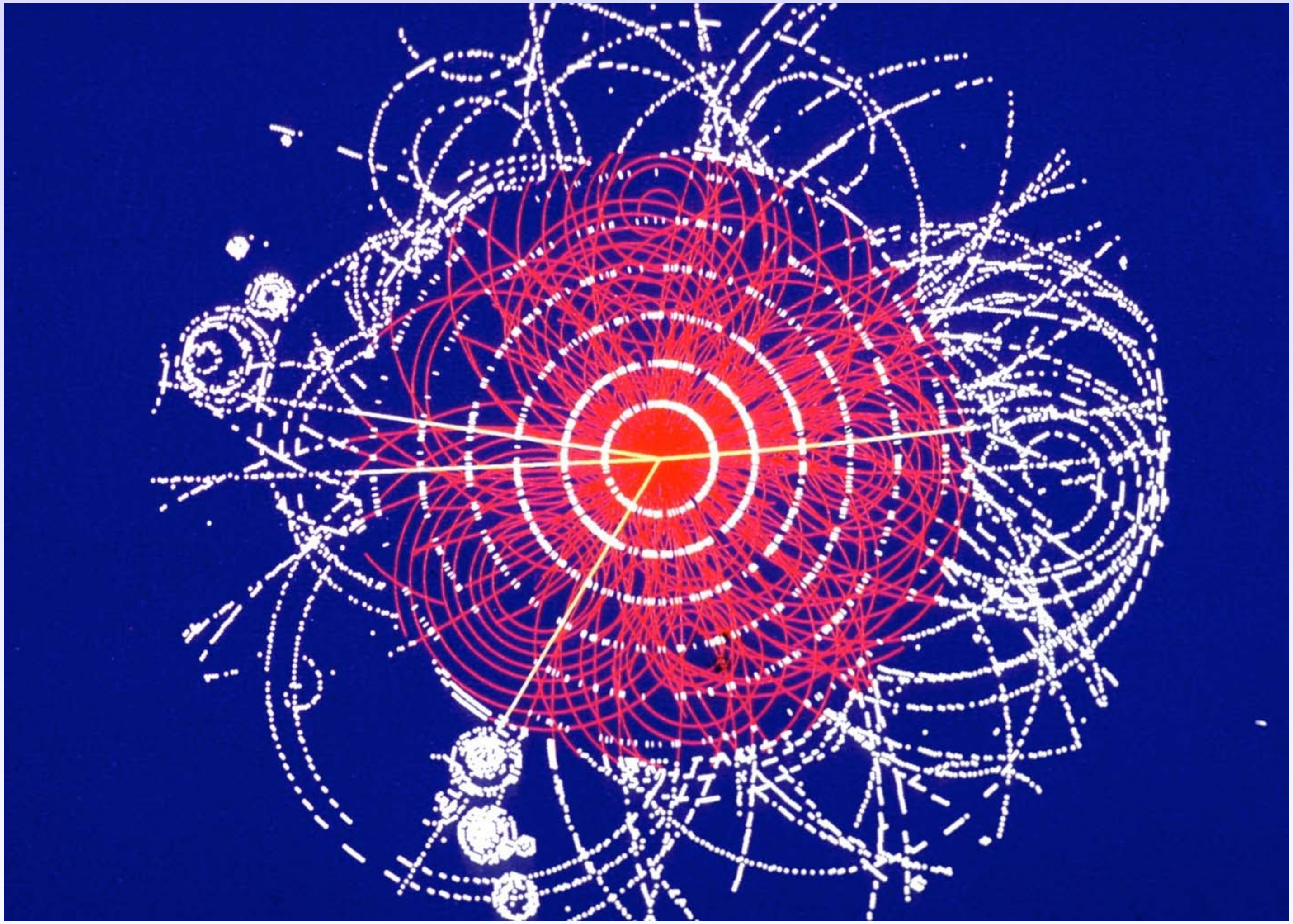
Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum



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

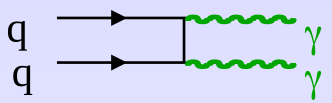
A simulated H → ZZ → ℓℓℓℓ event



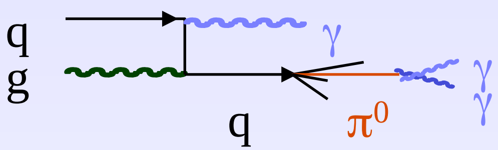
$H \rightarrow \gamma\gamma$

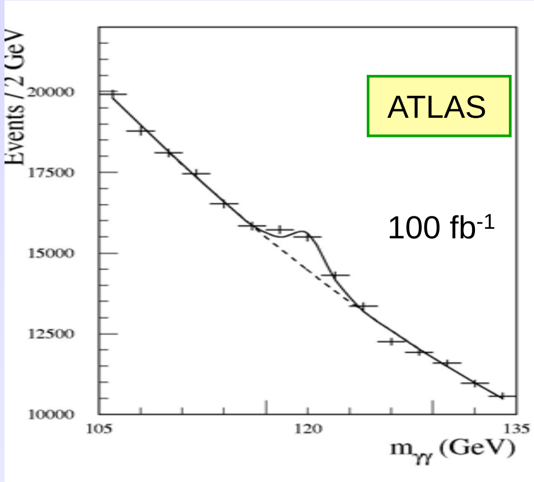
Main backgrounds:

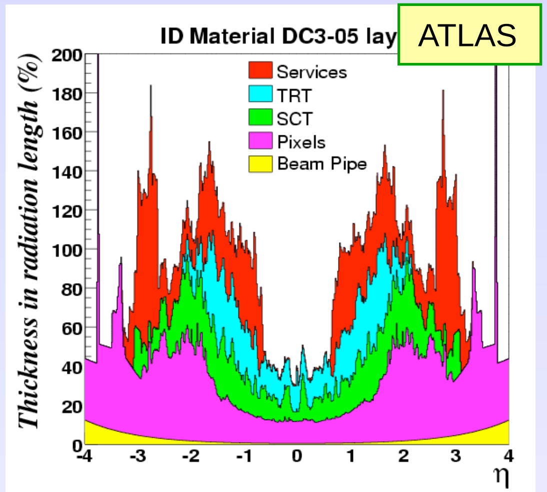
γγ irreducible background

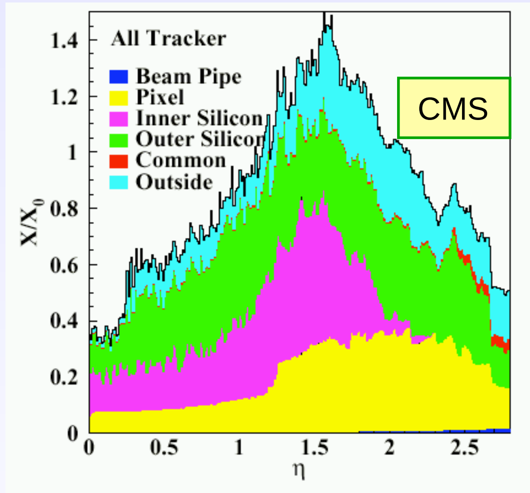


γ-jet and jet-jet (reducible)









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

→ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

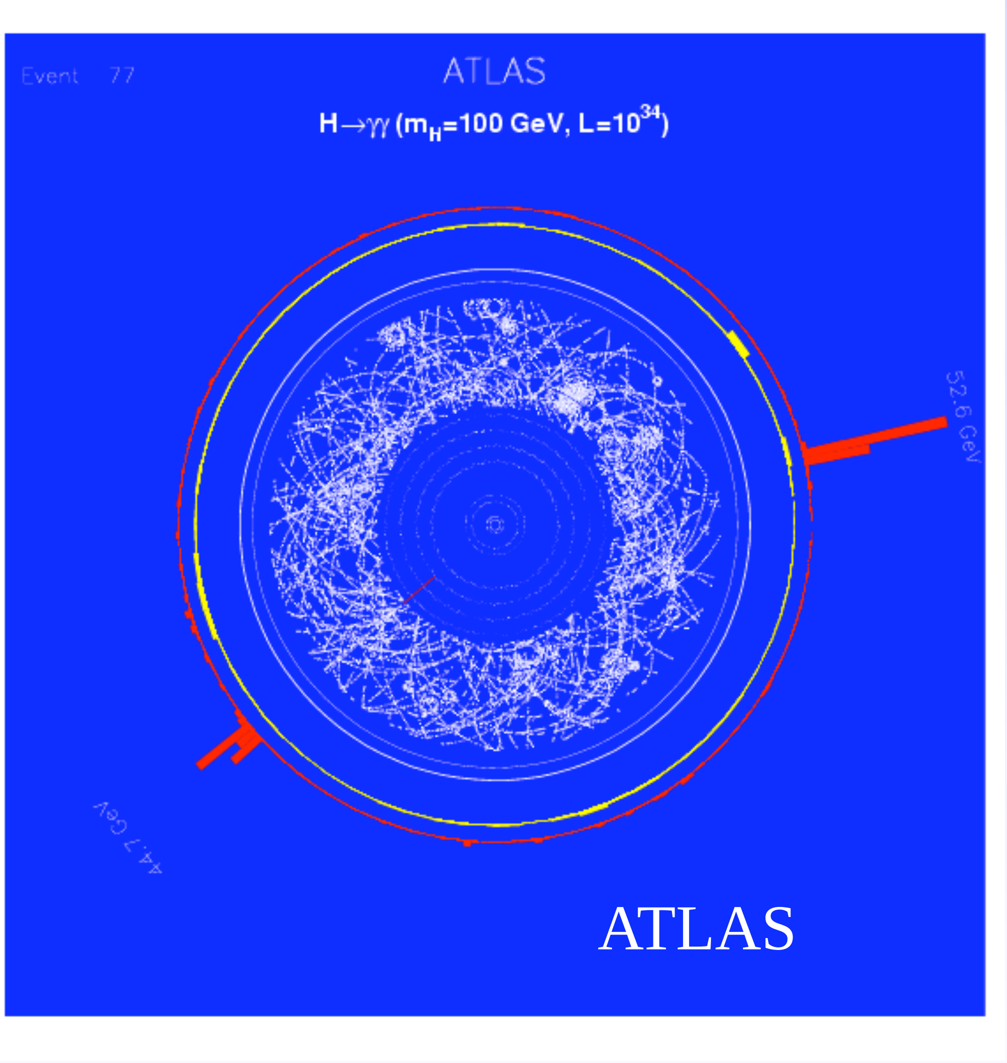
- Main exp. tools for background suppression:
  - photon identification
  - γ / jet separation (calorimeter + tracker)
  - note: also converted photons need to be reconstructed (large material in LHC silicon trackers)

CMS: fraction of converted γs

Barrel region:	42.0 %
Endcap region:	59.5 %

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

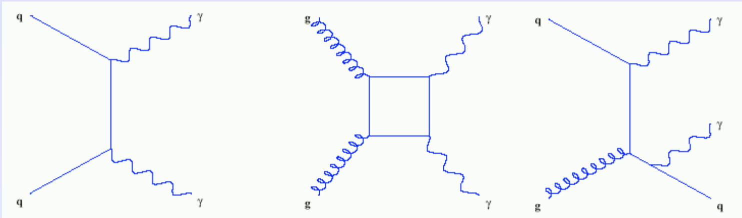
A simulated H → γγ event in ATLAS



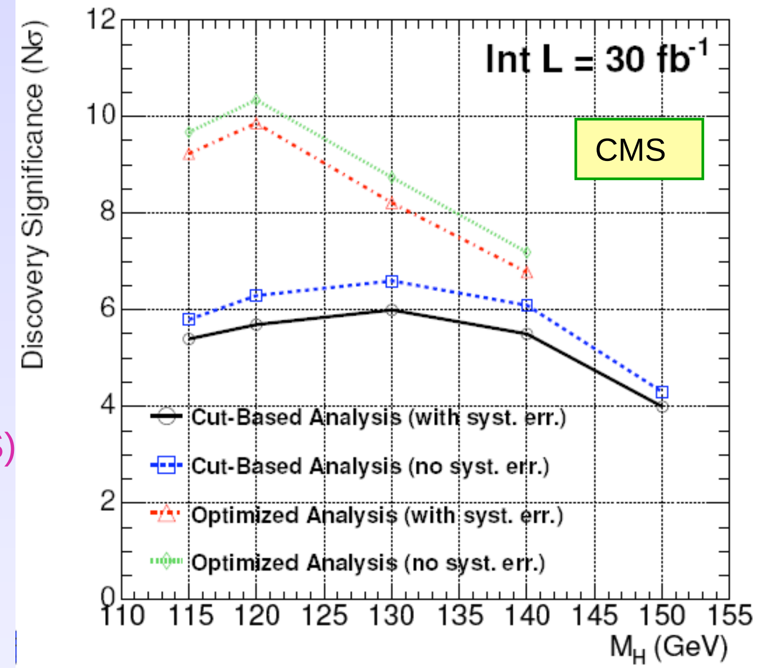
Updated Studies from ATLAS and CMS

New elements of the analysis:

- more contributions to the γγ background



- NLO calculations available (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)

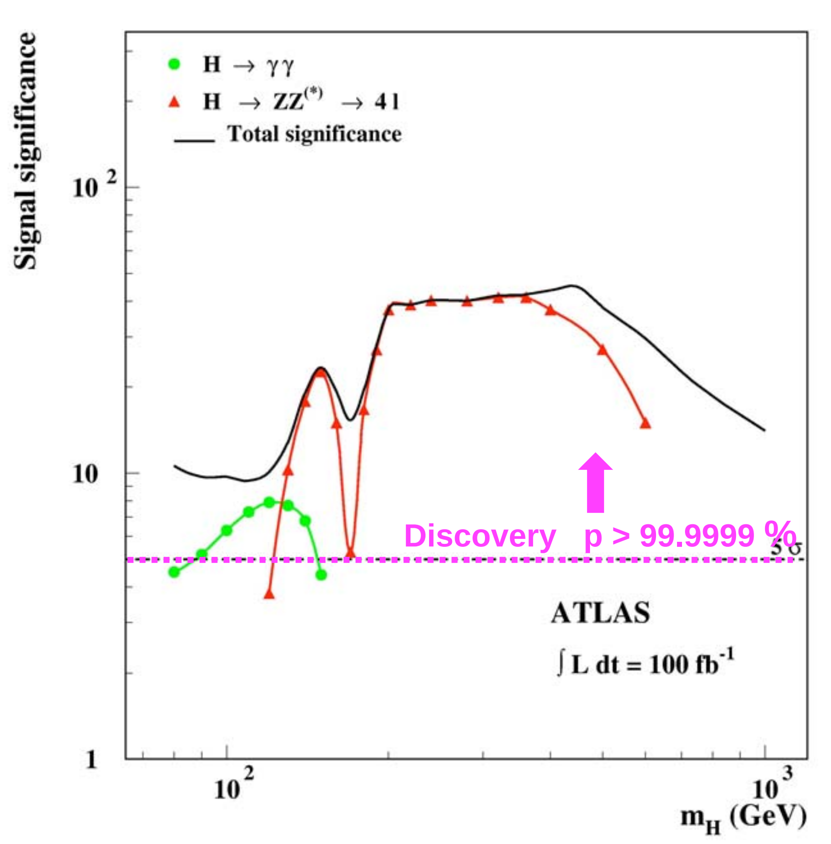


Signal significance for m_H = 130 GeV/c^2 and 30 fb^{-1}

ATLAS	LO (TDR, 1999)	3.9 σ
	NLO (update, cut based)	6.3 σ
	NLO (likelihood methods)	8.7 σ
CMS	NLO (cut based, TDR-2006)	6.0 σ
	NLO (neural net optimization, TDR-2006)	8.2 σ

Comparable results for ATLAS and CMS

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



The full allowed mass range

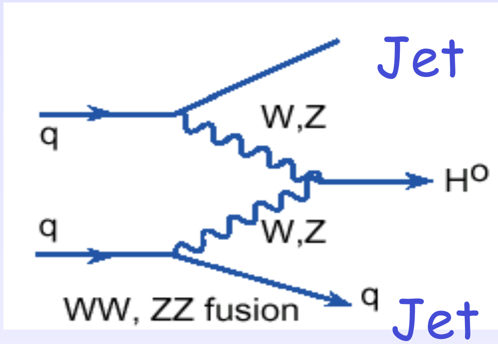
from the LEP limit (~114 GeV)
up to
theoretical upper bound of ~1000 GeV

can be covered using the two "safe" channels

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

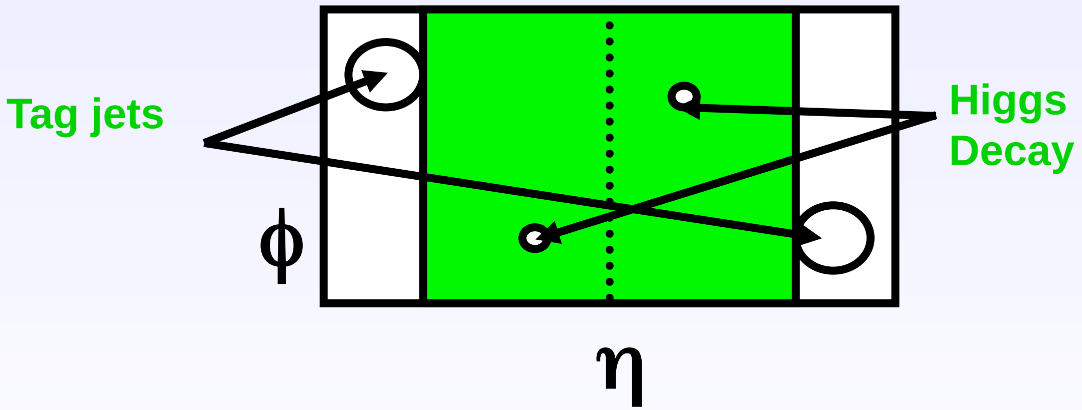
More difficult channels can also be used: Vector Boson Fusion
qq H → qq WW → qq ℓν ℓν

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



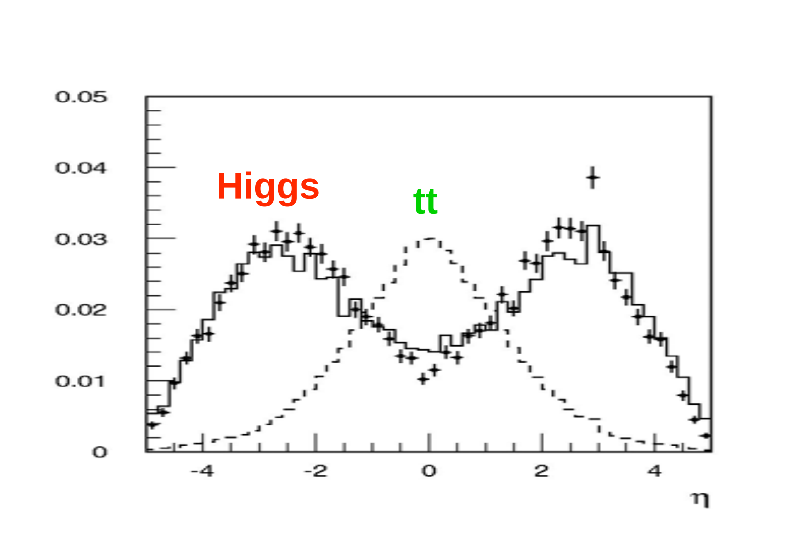
Distinctive Signature of:

- **two forward tag jets**
- **little jet activity in the central region**
  ⇒ **central jet Veto**

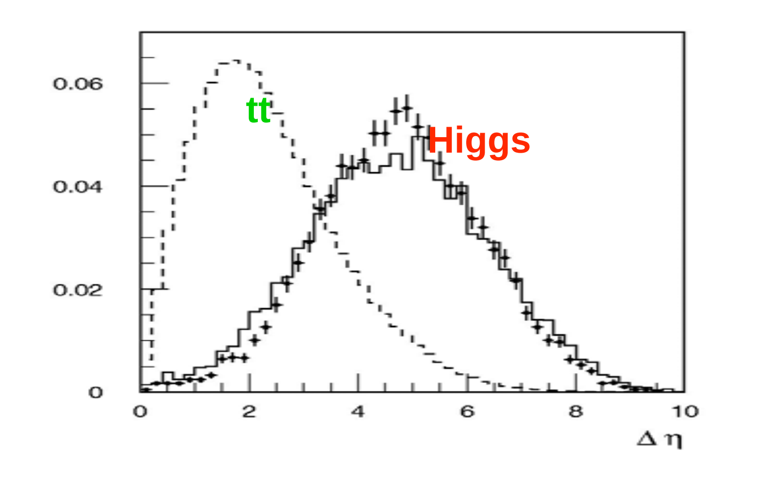


Forward jet tagging

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

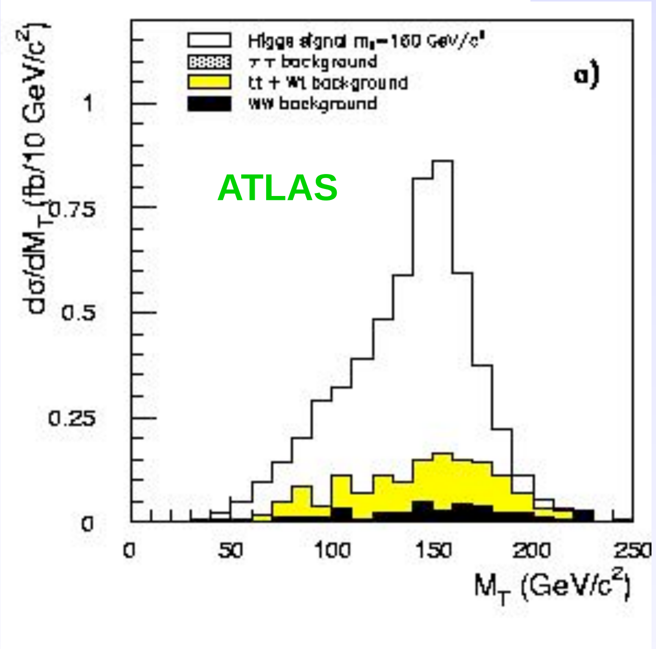


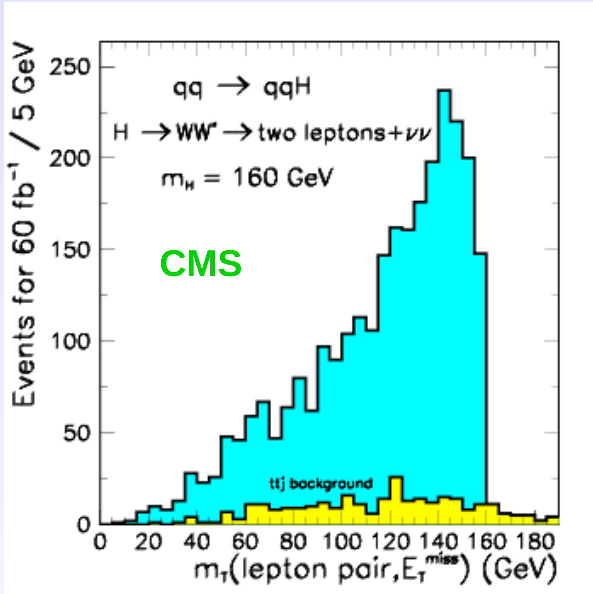
Rapidity separation



$$qq\,H \rightarrow qq\;W\,W^{*}$$
$$\rightarrow qq\;\ell\nu\;\;\ell\nu$$

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



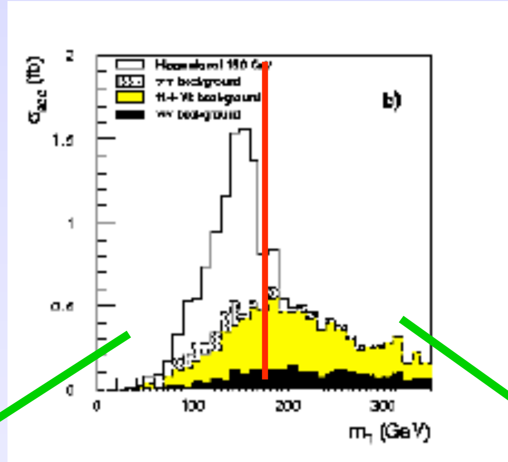


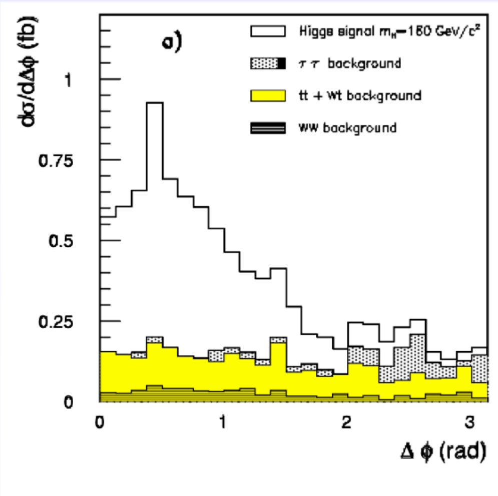
Transverse mass distributions: clear excess of events above the background from tt-production

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

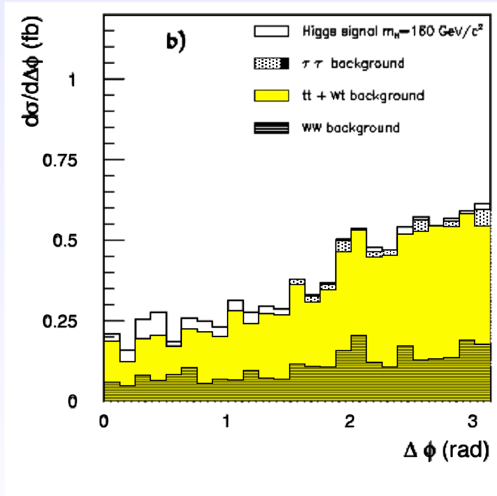
Evidence for spin-0 of the Higgs boson

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





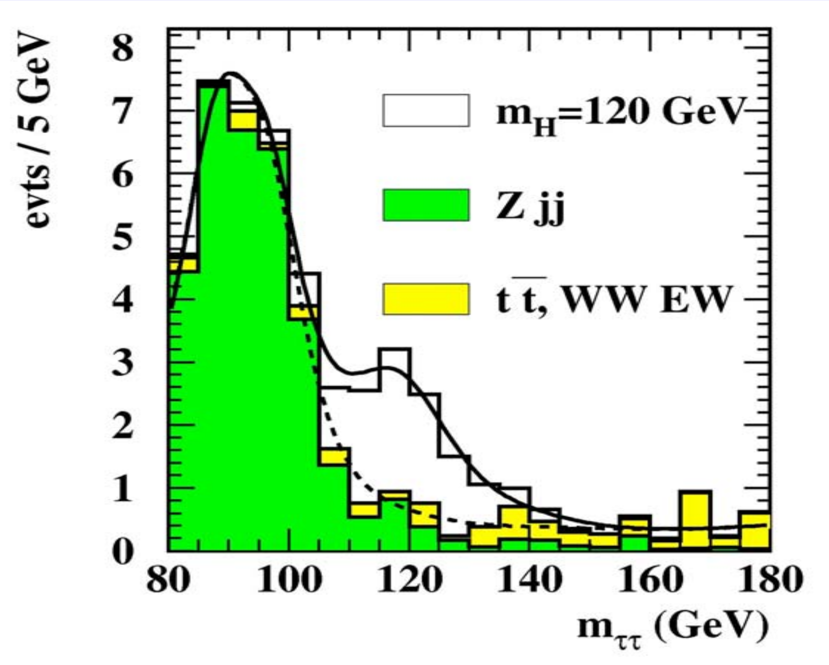
signal region



background region

$H \to \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion

$qq H \to qq \tau\tau$
$\to qq\ \ell\nu\nu\ \ell\nu\nu$
$\to qq\ \ell\nu\nu\ h\nu$



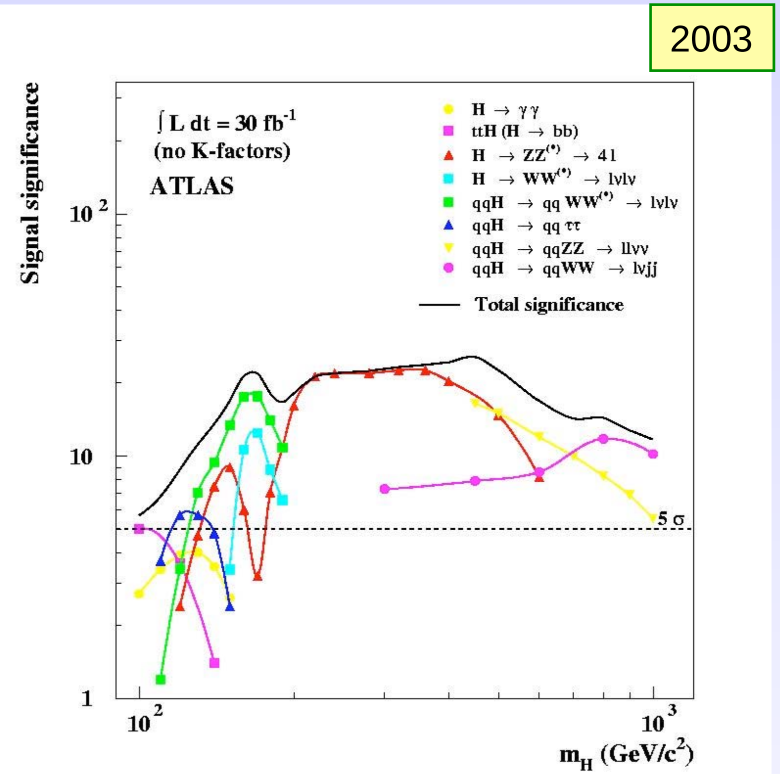
- large boost (high-P_T Higgs)

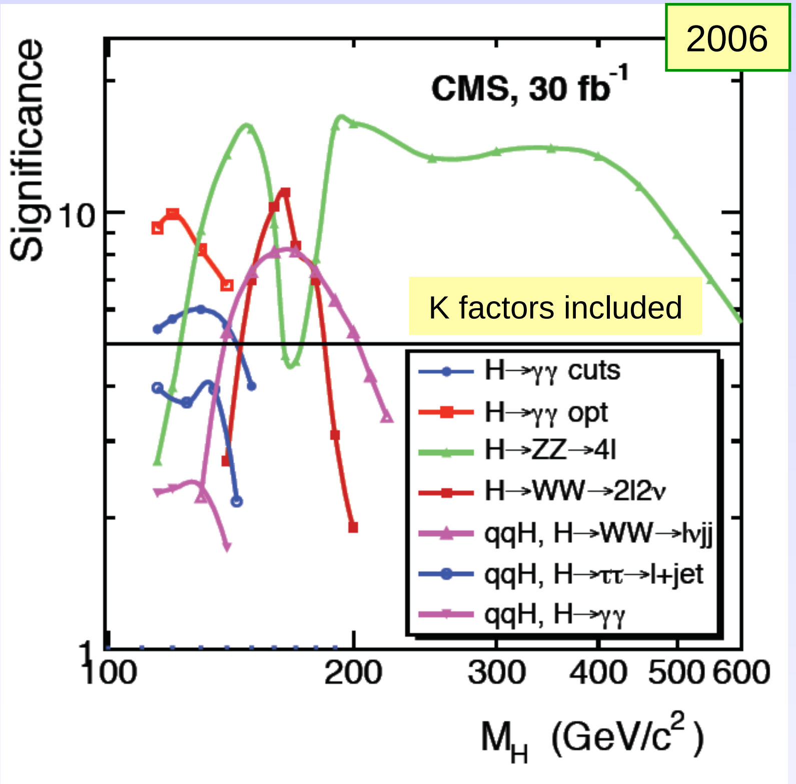
  → collinear approximation:
  assume neutrinos go in the direction of the visible decay products

  → Higgs mass can be reconstructed

- main background: Z jj, $Z \to \tau\tau$

LHC discovery potential for 30 fb^{-1}



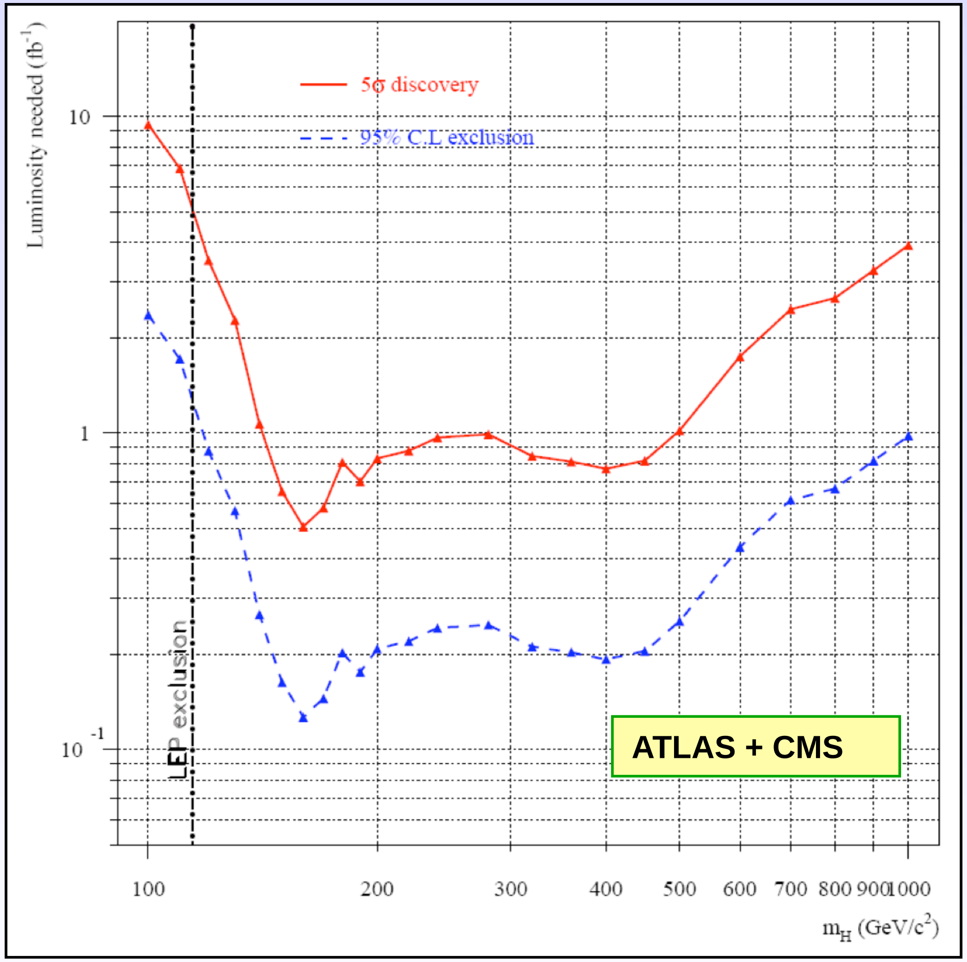


- Full mass range can already be covered after a few years at low luminosity
- Several channels available over a large range of masses

  Vector boson fusion channels play an important role at low mass !

Combined ATLAS + CMS discovery potential

- Luminosity required for a 5σ discovery or a 95% CL exclusion -



~ 5 fb^{-1} needed to achieve a 5σ discovery

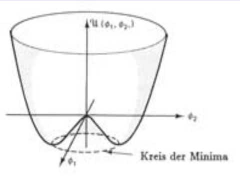
(well understood and calibrated detector)

~ < 1 fb^{-1} needed to set a 95% CL limit

(low mass ~ 115 GeV/c^2 more difficult)

comments:

- systematic uncertainties assumed to be luminosity dependent (no simple scaling, σ ~ √L, possible)



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

(→ see next slide)

3. Spin and CP

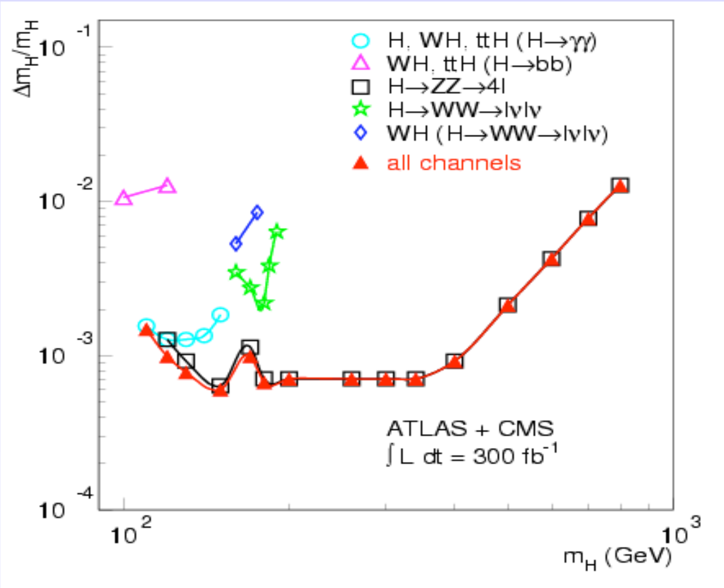
Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

4. Higgs self coupling

Possible channel: **gg → HH → WW WW → ℓν jj ℓν jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2

Measurement of the Higgs boson mass

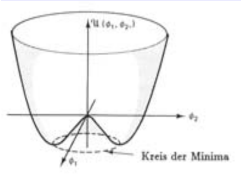


Dominated by ZZ→ 4ℓ and γγ resonances !

well identified, measured with a good resolution

Dominant systematic uncertainty: γ /ℓ E scale.
Assumed 0.1 %
Goal 0.02 %
Scale from Z → ℓℓ (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)



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($\rightarrow$ see next slide)

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$\Rightarrow$ no significant measurement possible at the LHC
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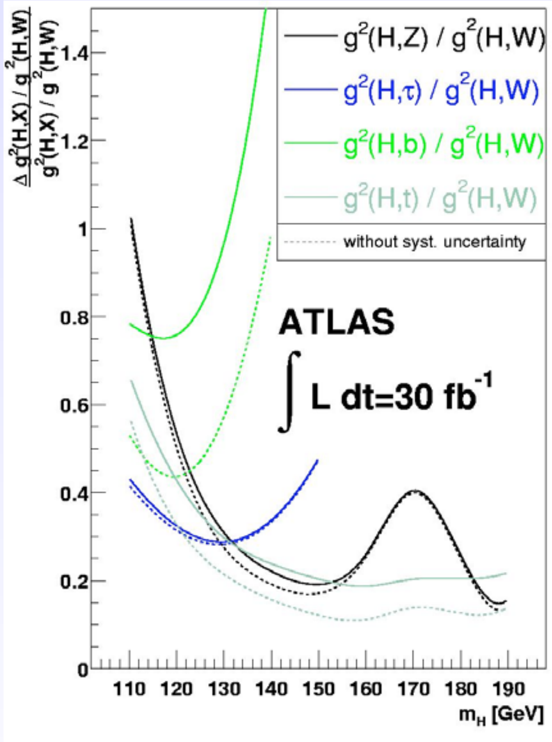
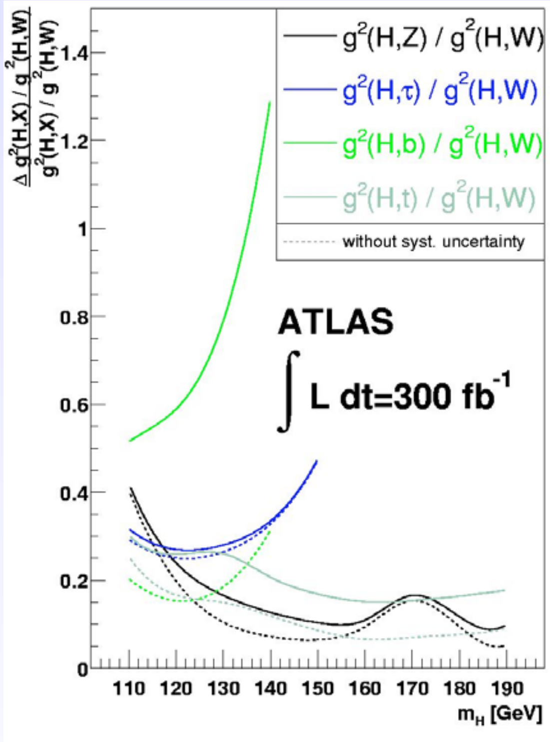
Measurement of Higgs Boson Couplings

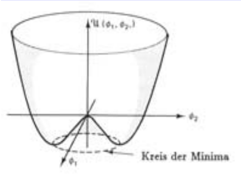
Global likelihood-fit   (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

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





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



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

1. Mass

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV/c^2)
($\gamma\gamma$ and ZZ$\rightarrow$ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

(→ see next slide)

3. Spin and CP

Angular distributions in the decay channel H → ZZ(*) → 4 ℓ are sensitive to spin and CP eigenvalue

4. Higgs self coupling

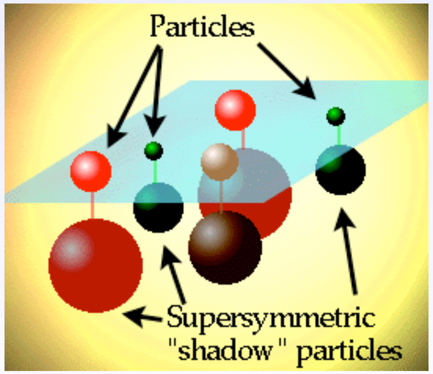
Possible channel: **gg → HH → WW WW → $\ell\nu$ jj $\ell\nu$ jj** (like sign leptons)
Small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
very difficult at a possible SLHC (6000 fb^{-1})
limited to mass region around 160 GeV/c^2

The Higgs Sector

in the MSSM

(the Minimal Supersymmetric Standard Model)



Can LHC also discover Higgs bosons in a supersymmetric world ?

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

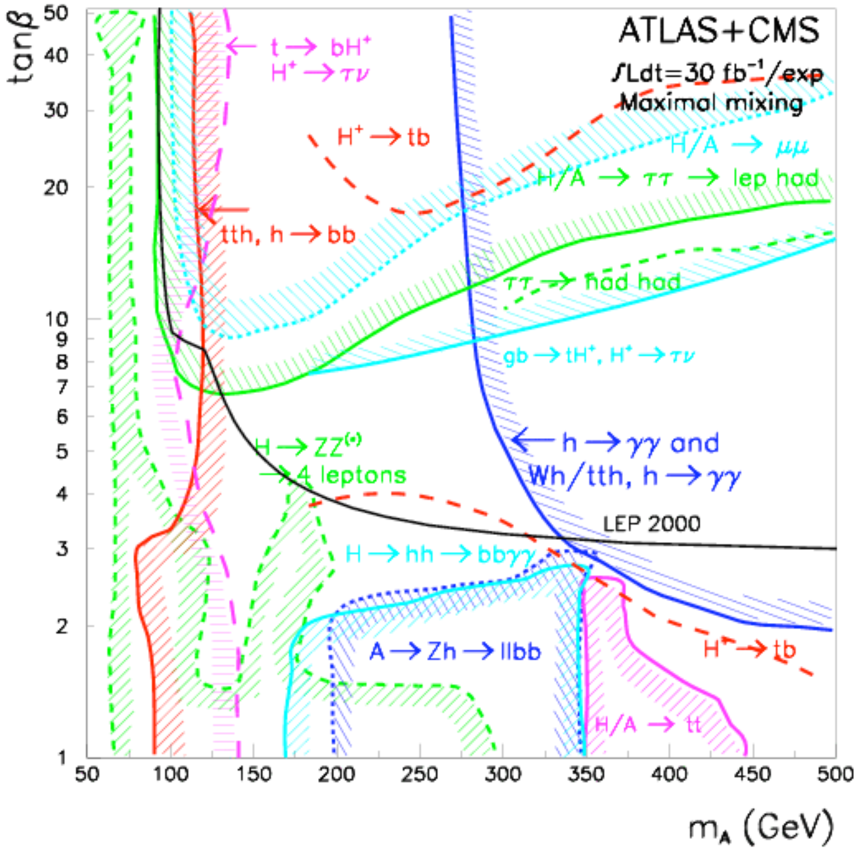
determined by two SUSY model parameters: m_A, $\tan\beta$

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

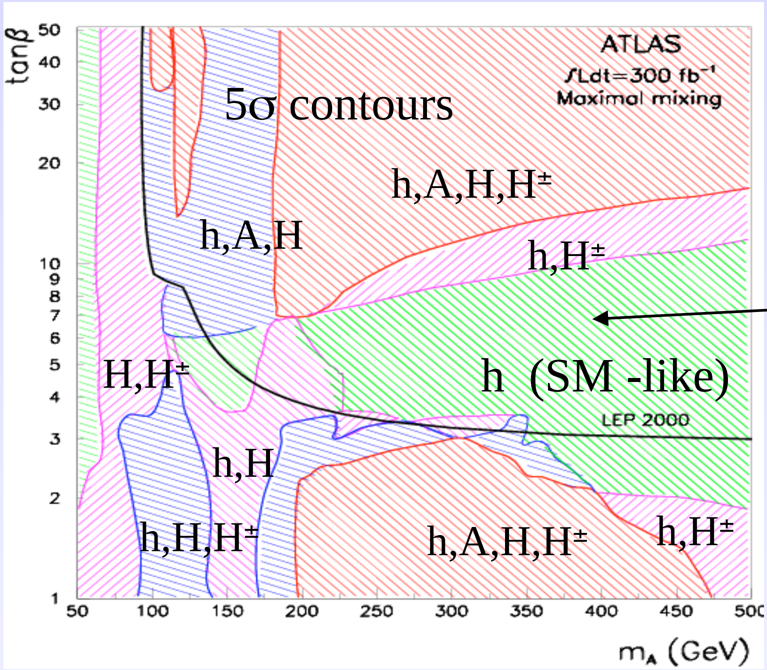


m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2

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

- Plane fully covered (no holes) at low L (30 fb^{-1})
- **Main channels : h → γγ , tth h → bb, A/H → μμ, ττ , H± → τ ν**

LHC discovery potential for SUSY Higgs bosons



4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

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“

Can the Higgs boson already

be discovered

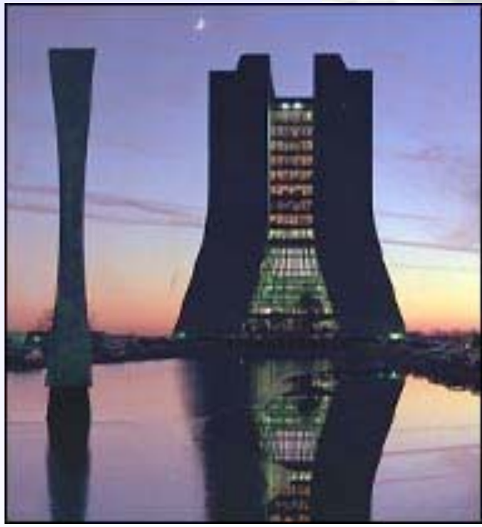
at Fermilab

Impressions from Fermilab







Search channels at the Tevatron

- important production/decay modes: **associated WH and ZH**
  + gluon fusion with H → 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)

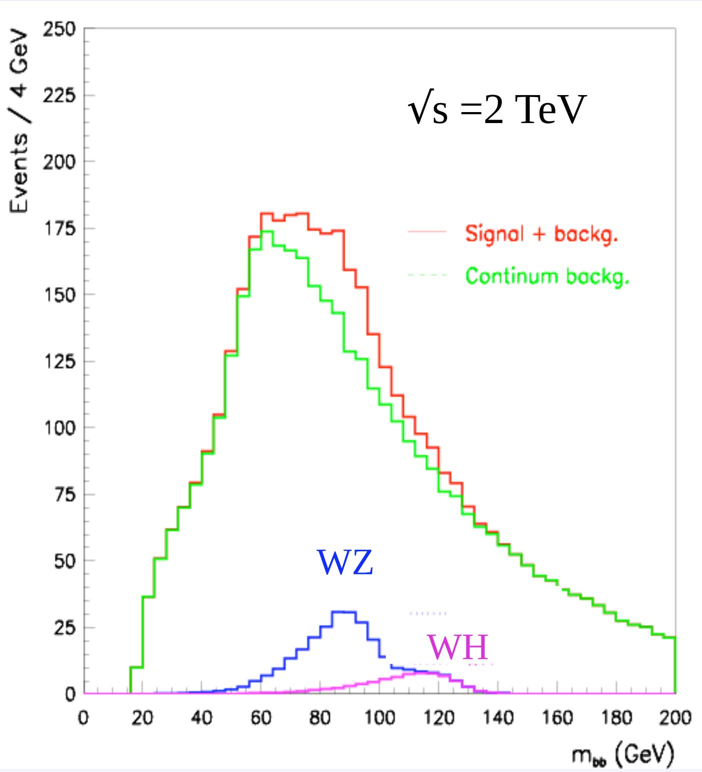
Mass range 150 - 180 GeV:	**LHC**
H → $WW^{(*)}$ → lν lν	✓
WH → $WWW^{(*)}$ → lν lν lν	✓
WH → $WWW^{(*)}$ → $l^+ν$ $l^+ν$ jj	✓

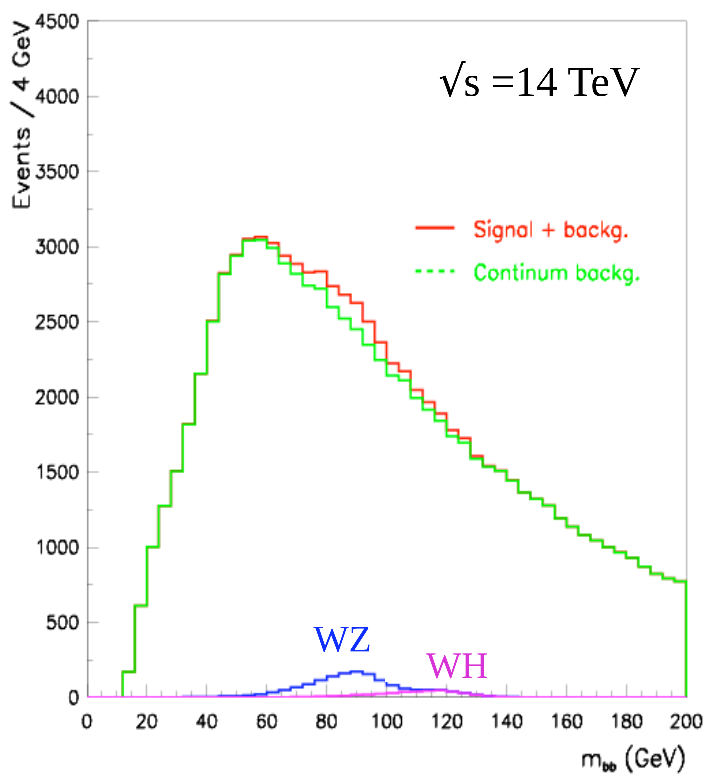
Background:

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!

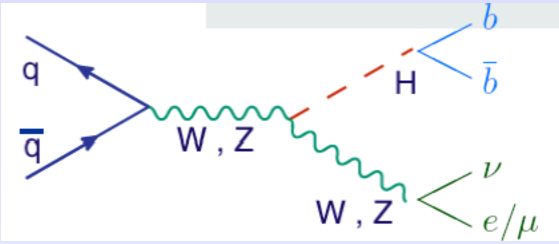
Results from the

present

Run II data

typically, data corresponding to
~ 1 fb^{-1} analyzed

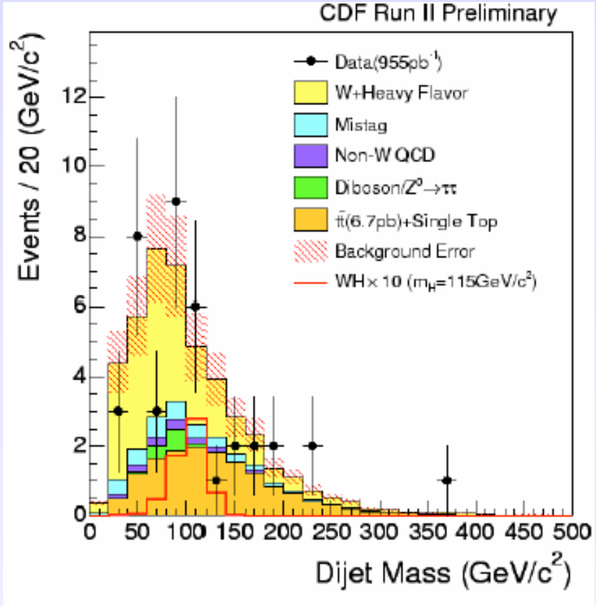
Low mass range: WH → e/μ ν bb

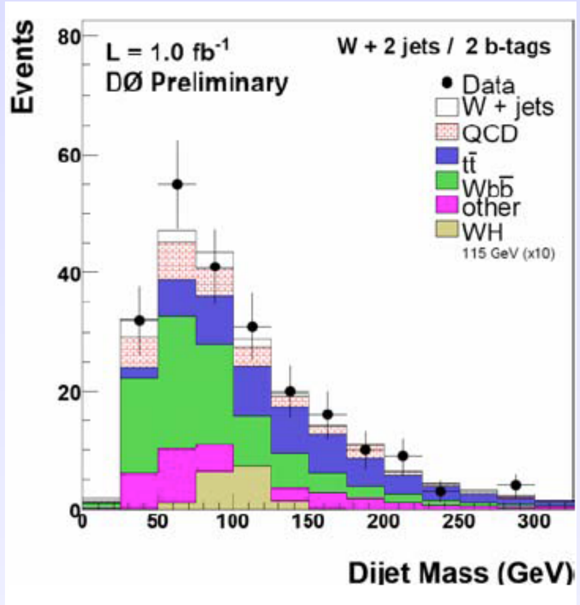


Run II data: ~ 1 fb^{-1}

Event selection:

- 1 e or μ with large P_T
- P_T^{miss} > 20 GeV/c
- 2 jets, b-tagged





Background:

- Wbb, Wcc, Wjj
- WW, WZ, ZZ, Z→ ττ
- tt, t
- Jet production
  (from QCD processes)

Data are consistent with background from Standard Model processes:

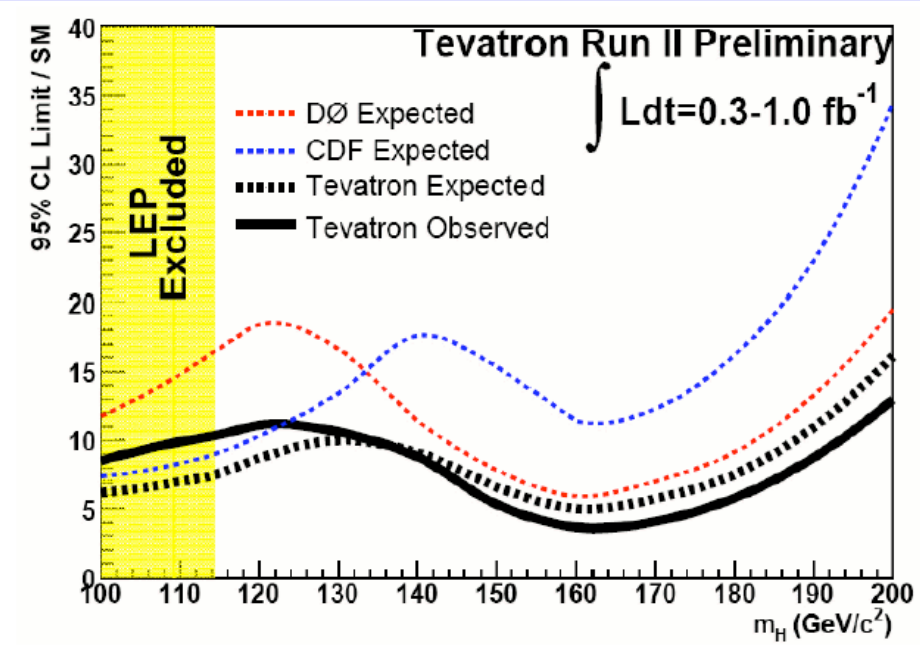
Limits on the Higgs boson production cross section:

CDF: σ(H) < 3.4 pb (95 % CL)
DØ: σ(H) < 1.3 pb (95 % CL)

Standard Model value: σ(H) ~ 0.13 pb

Combination of several search channels and both experiments

95% CL Limit / SM value



WH → ℓ ν bb
ZH → ℓ ℓ bb
ZH → νν bb

H → WW → ℓν ℓν
WH → WWW → ℓν ℓν + …

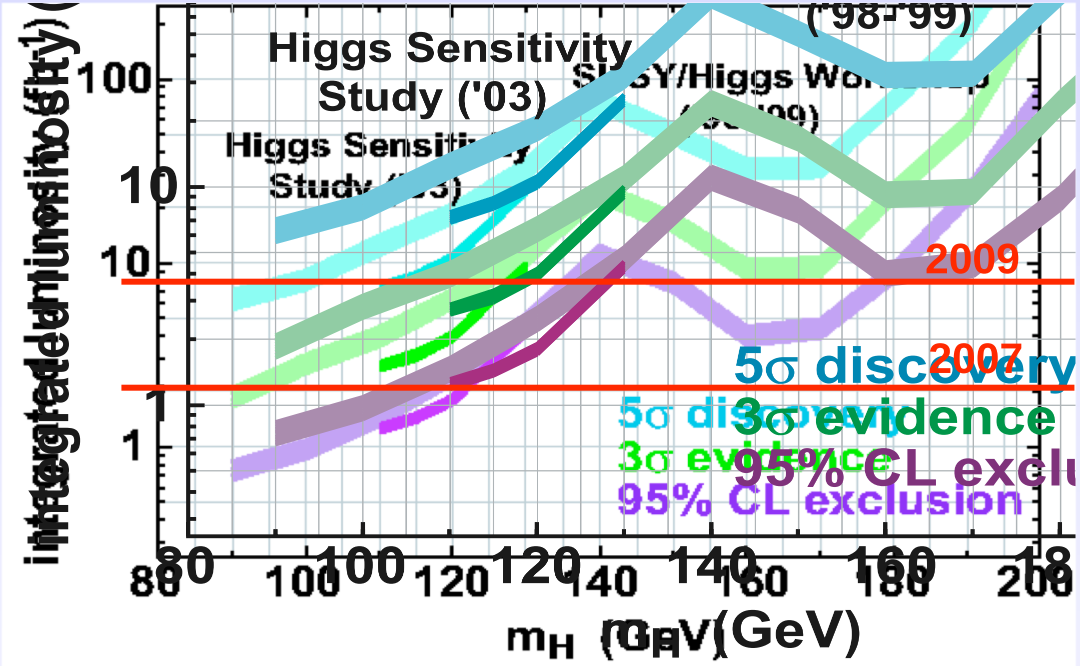
- The expected combined limits are still a factor of 7.5 (m_H=115 GeV/c^2) and 4 (m_H=160 GeV/c^2) away from the Standard Model expectation

- However, not all results included yet (CDF 1fb^{-1} results at high mass and DØ 1fb^{-1} result at low mass are missing)

- Many improvements have been made during the past year

Expectations for higher integrated luminosities

Combination of two experiments and all channels (no sensitivity in a single channel alone)



95% CL exclusion:	**~ 2 fb^{-1}:**	**115 GeV/c^2**
	8 fb^{-1}:	**115 - 135 GeV/c^2 and 150 – 180 GeV/c^2**
3 σ evidence:	**8 fb^{-1}:**	**115 - 125 GeV/c^2**

In order to achieve this, some additional improvements are still needed

(increased acceptance (forward leptons), improvements in b-tagging (forward b-tags, neural network), improved di-jet mass resolution......)

Not demonstrated yet, but there is a chance….

In reserve: improved multivariate techniques (already used in Single Top analyses)

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