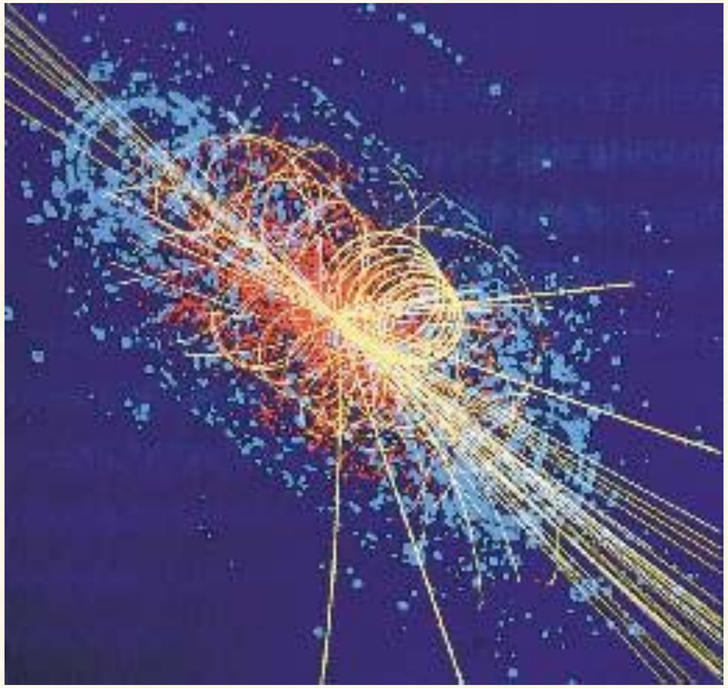
Physics at Hadron Colliders

Part 3



Search for the Higgs boson

- **Higgs Bosons at the Tevatron**
- **SM Higgs bosons at the LHC**
- **How well can the Higgs boson parameters be measured**
- **MSSM Higgs bosons**

Why do we need the Higgs Boson?

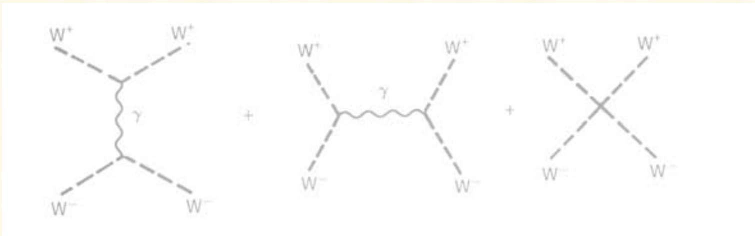
The Higgs boson enters the Standard Model to solve two fundamental problems:

- **Masses of the vector bosons W and Z:**

Experimental results: $M_W = 80.399 \pm 0.023$ GeV / c^2
$M_Z = 91.1875 \pm 0.0021$ GeV / c^2

A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory (scattering of W bosons)**



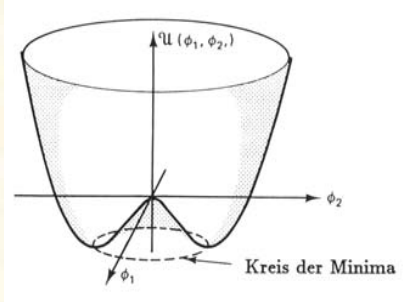
$$-i\, M\ (W^+W^- \rightarrow W^+W^-) \sim s / M_W^2$$

The Higgs mechanism

Spontaneous breaking of the SU(2) x U(1) gauge symmetry

- Scalar fields are introduced

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



Potential : $\mathcal{U}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$

- For $\mu^2 < 0$, $\lambda > 0$, minimum of potential: $\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v^2 = -\mu^2/\lambda$

- Perturbation theory around ground state:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad \Rightarrow$$

3 massive vector fields: $M_{W^\pm} = \frac{1}{2} v g$

$M_Z = \frac{1}{2} v g / \cos\theta_W = M_W / \cos\theta_W$

1 massless vector field: $M_\gamma = 0$

1 massive scalar field: **The Higgs boson H**

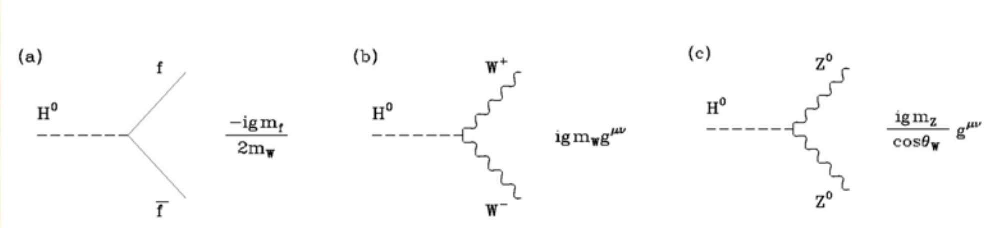
$M_H = \sqrt{\lambda v^2}$

v = vacuum expectation value $v = (\sqrt{2}\ G_F)^{-1/2} = 246$ GeV

Mass terms result from interaction of gauge bosons with Higgs field

The Higgs mechanism (cont.)

• Coupling terms of W- and Z-bosons and fermions to the Higgs field:



$$g_{ffH} = \left(\sqrt{2}G_F\right)^{1/2} m_f$$

$$g_{VVH} = 2\left(\sqrt{2}G_F\right)^{1/2} M_V^2$$

• The introduced scalar fields can also be used to generate fermion masses

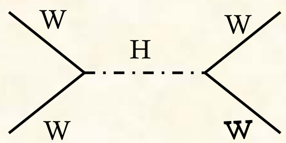
$$m_f = g_f\, v / \sqrt{2} \quad \Rightarrow \quad g_f = m_f \sqrt{2} / v$$

(where g_f is the coupling of the Higgs field to the fermion)

• Higgs boson self-coupling L = …… **- λ v h³ - ¼ λ h⁴**

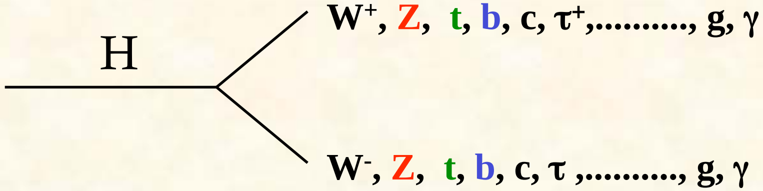
and finally:

• Higgs boson regulates divergences in the WW scattering cross section



Properties of the Higgs Boson

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



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

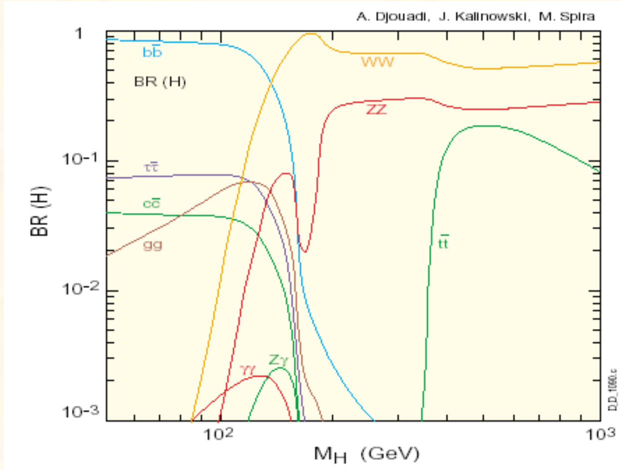
$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3\, (1 - 4x + 12x^2)\, \beta_V$$

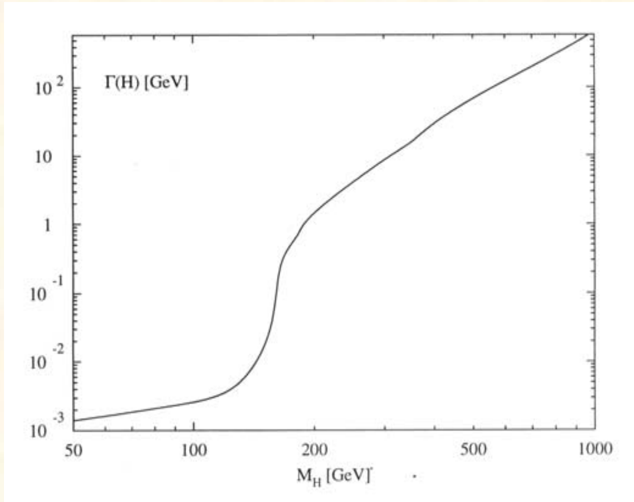
where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta =$ velocity

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

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

(+ W-loop contributions)





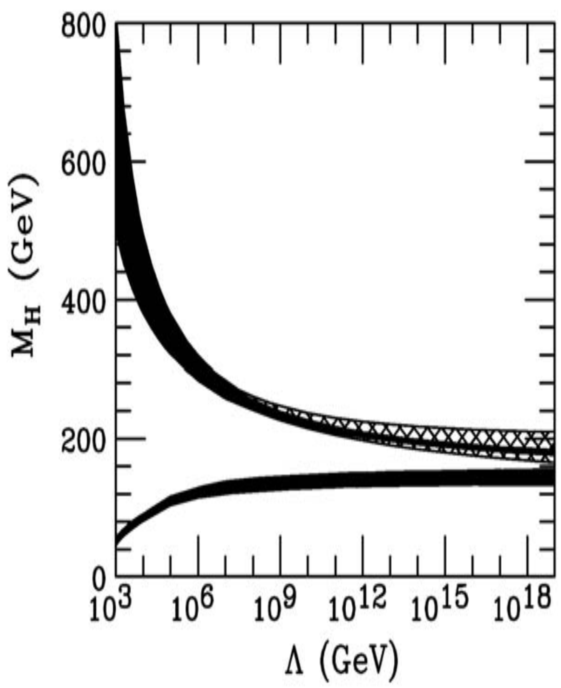
Upper limit on Higgs boson mass, from unitarity of WW scattering: $M_H < 1$ TeV/c^2

Higgs mass constraints (from theory):

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda\,(Q^2)$

(if the SM is assumed to be valid up to some scale Λ)

$\lambda\,(Q^2) = \lambda_0\,\{\,1 + 3\lambda_0/2\pi^2 \log\,(2\,Q^2/v^2) + \ldots. - 3g_t^4/32\pi^2 \log\,(2Q^2/v^2) + \ldots.\}$ $\lambda_0 = M_H^2/v^2$



Hambye, Risselmann et al.

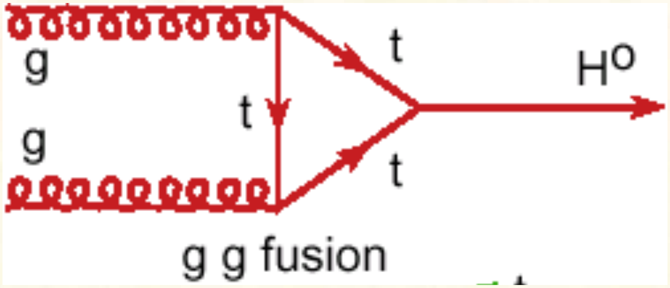
Upper bound: diverging coupling (Landau Pole)

Lower bound: stability of the vacuum (neg. contribution from top quark dominates)

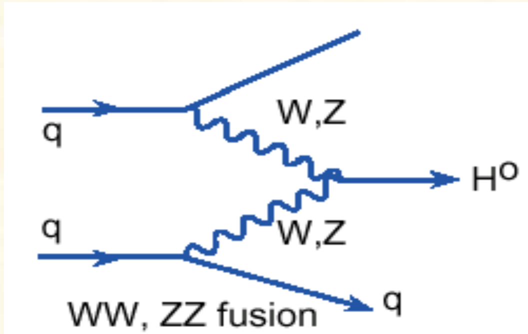
Mass bounds depend on scale Λ up to which the Standard Model should be valid

Higgs Boson Production at Hadron Colliders

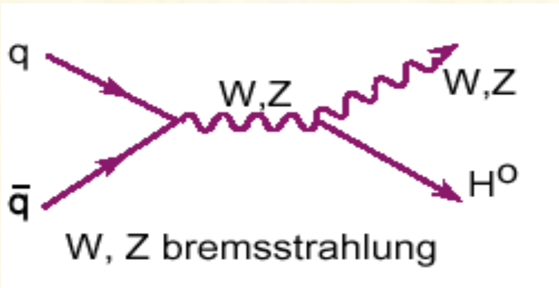
(i) Gluon fusion

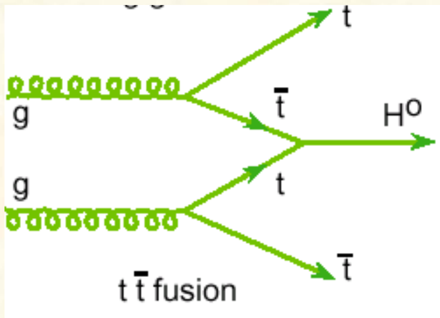


(ii) Vector boson fusion



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

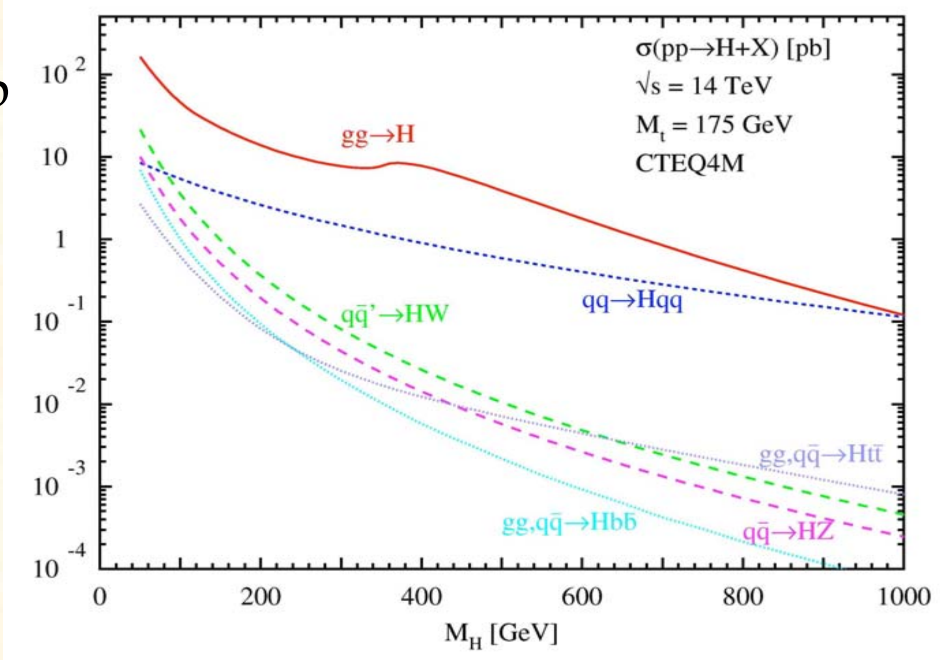




Higgs Boson Production cross sections

LHC M. Spira et al.

pb



Tevatron M.Spira et al.

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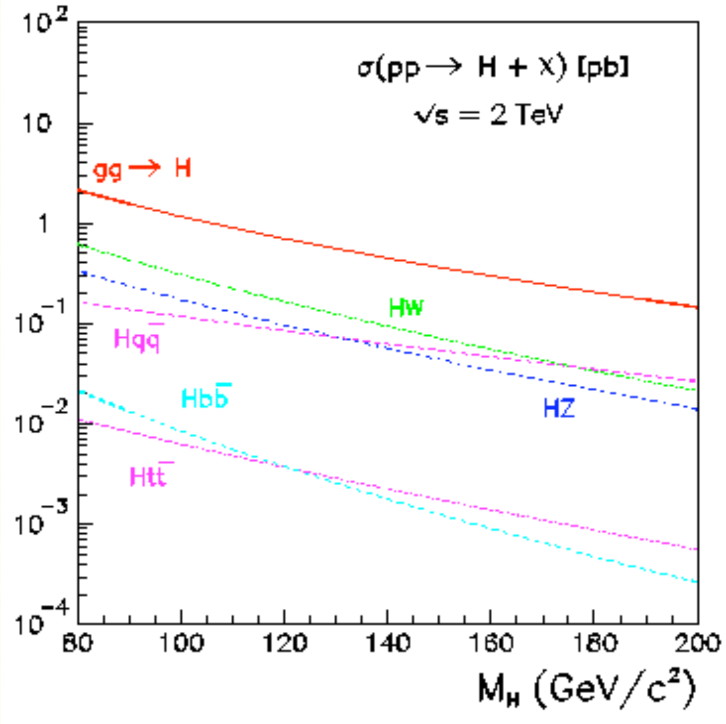


qq → W/Z + H cross sections ~10 x larger at the LHC

gg → H ~70-80 x larger at the LHC

Status of higher order corrections

NLO corrections (K-factors) have meanwhile been calculated for all Higgs production processes (huge theoretical effort !)

1. gg fusion:

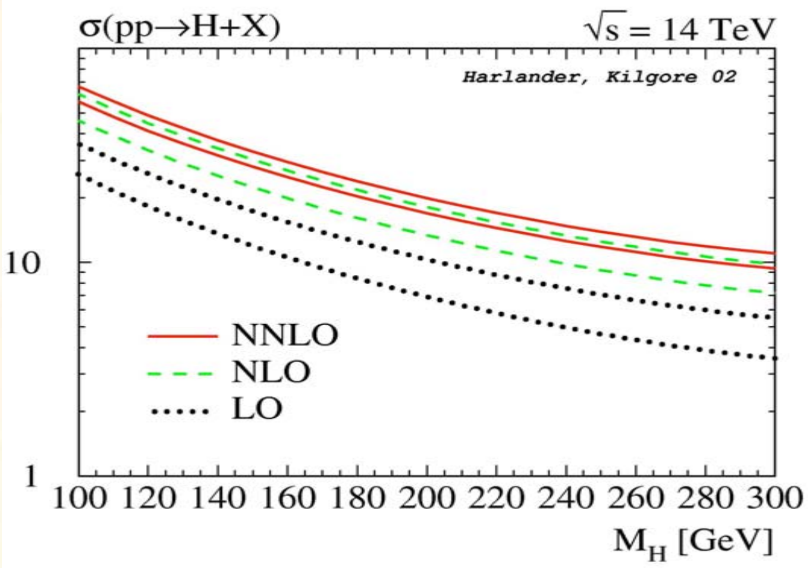
- large NLO QCD correction **K ~ 1.7 – 2.0**

  [Djouadi, Spira, Zerwas (91)] [Dawson (91)]

- complete NNLO calculation ⇒

  evidence for nicely converging pQCD series (infinite top mass limit)

  [Harlander, Kilgore (02)] [Anastasiou, Melnikov (02)]



2. Weak boson fusion: K ~1.1

[Han, Valencia, Willenbrock (92)] [Spira (98)]

(similar behaviour for the Tevatron)

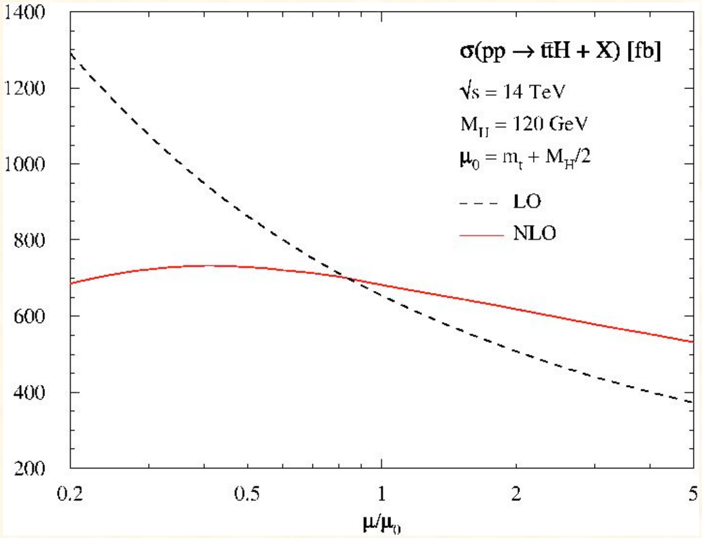
3. WH associated production: K ~ 1.3

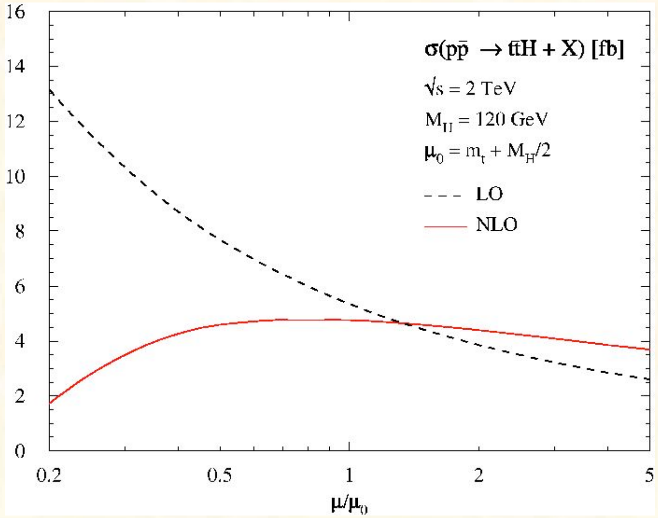
(QCD corrections from Drell-Yan process)

Status of higher order corrections (cont.)

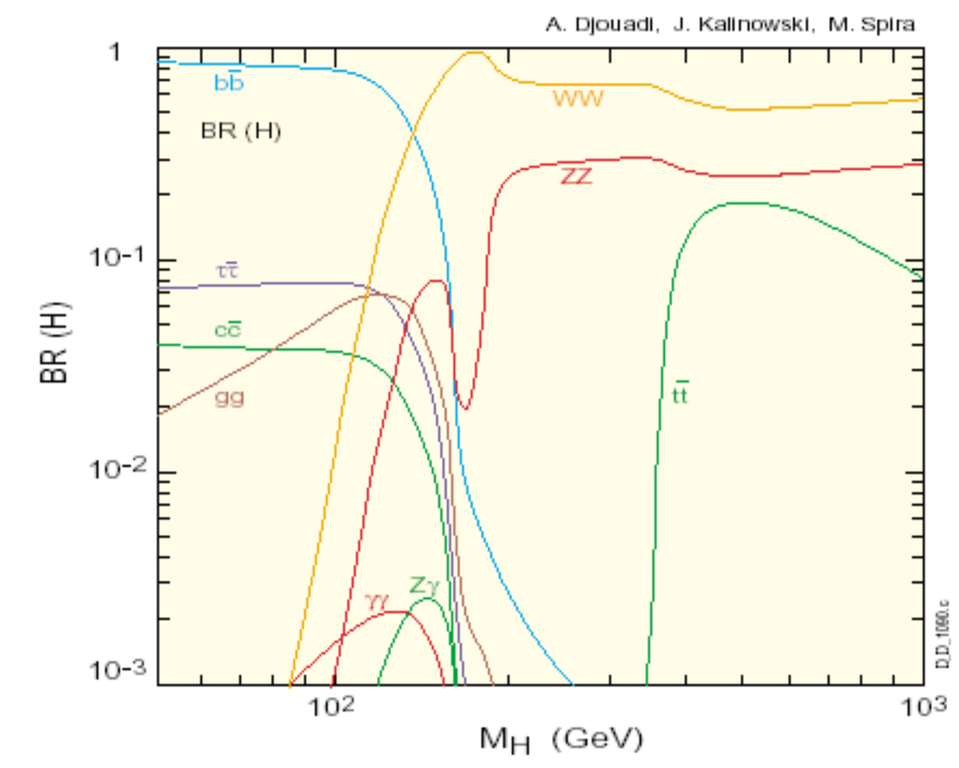
4. ttH associated production:

- full NLO calculation LHC: K ~ 1.2 scale: $\mu_0 = m_t + M_H/2$
  Tevatron: K ~ 0.8
- scale uncertainty drastically reduced
  [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (01)] [Dawson, Reina (01)]





Higgs Boson Decays at Hadron Colliders



at high mass:

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

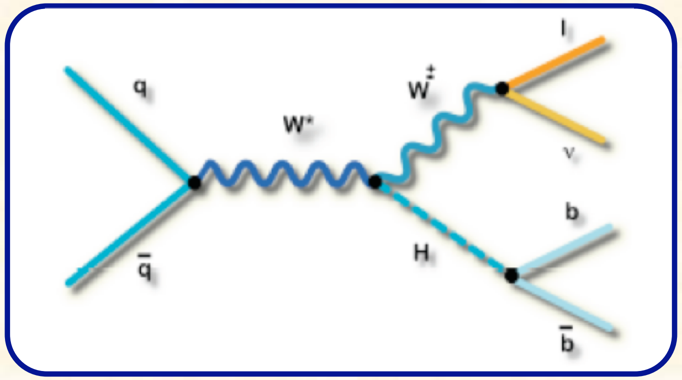
at low mass:

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, W/Z H)
(due to the huge QCD jet background)

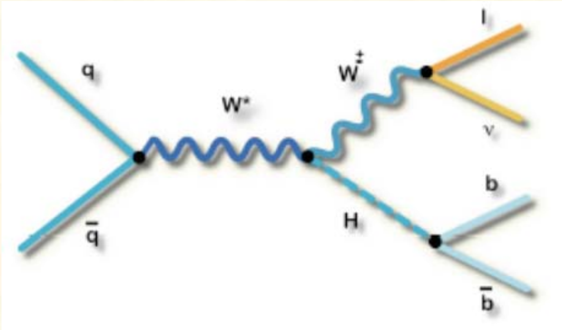
Searches for a low mass Higgs boson at the Tevatron



$m_H < 135$ GeV:

Associated production WH and ZH with H→bb decay

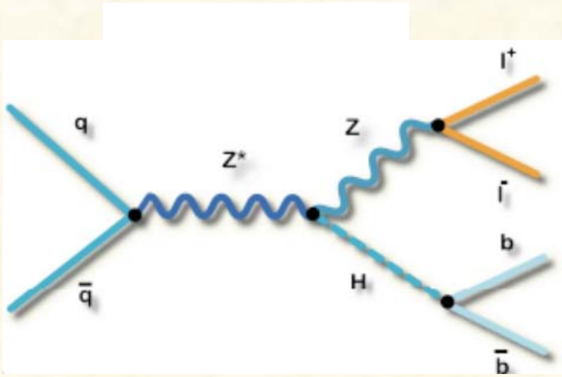
Main low mass search channels



ℓ + E_T^{miss} + bb: $WH \rightarrow \ell\nu bb$

Largest *VH* production cross section

More backgrounds than $ZH \rightarrow \ell\ell bb$

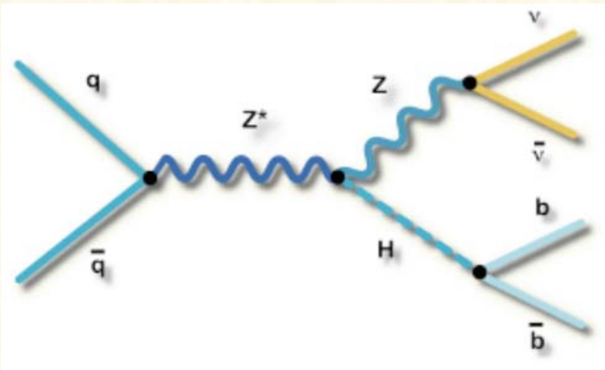


$\ell\ell$+bb: $ZH \rightarrow \ell\ell bb$

Less background than WH

Fully constrained

Smallest Higgs signal



E_T^{miss} + bb: $ZH \rightarrow \nu\nu bb$

3x more signal than $ZH \rightarrow \ell\ell\, bb$

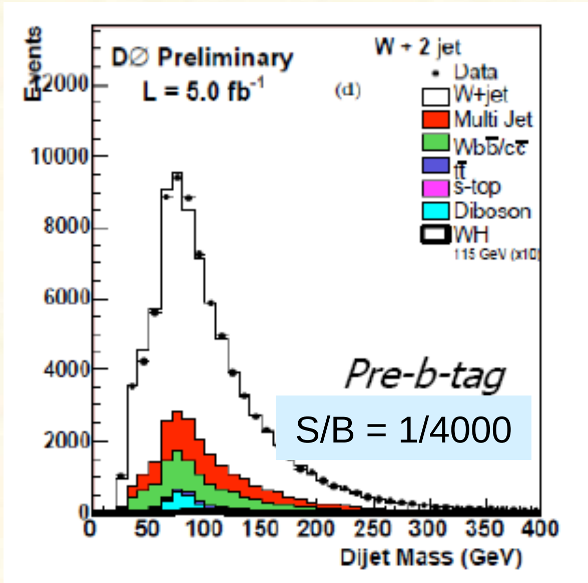
(+$WH \rightarrow \ell\nu\, bb$ when lepton non-identified)

Large backgrounds which are difficult to handle

General Search Strategy

Example: WH → ℓν bb

(i) Select events consistent with Z/W + 2 jets
(large W+jet and Z+jet backgrounds)

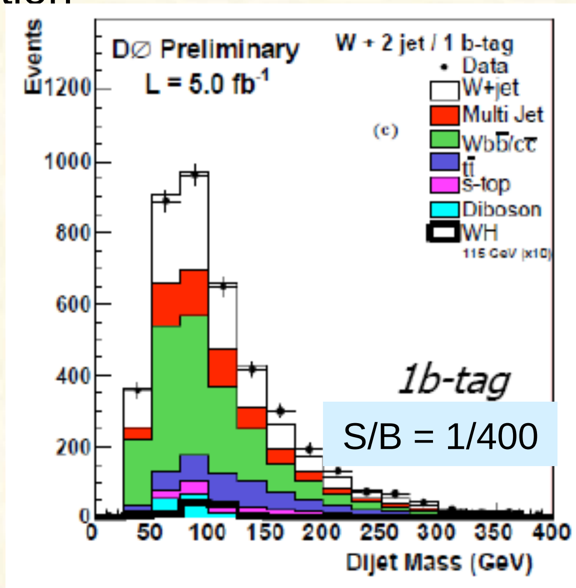


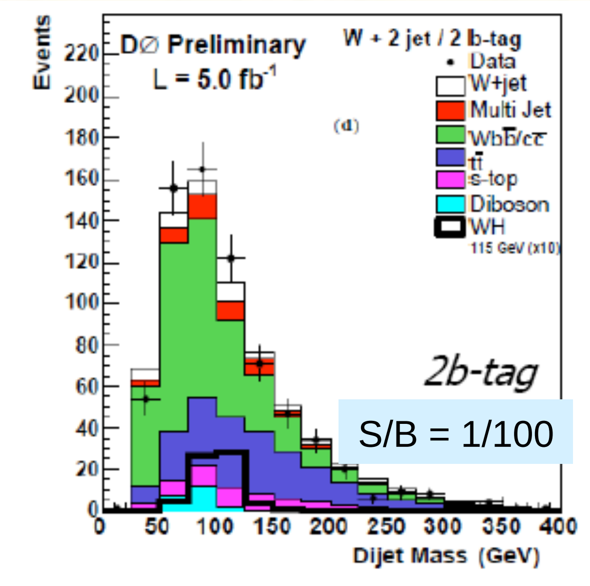
(ii) Apply b-tagging
(most discriminating variable: dijet inv. mass)

even after b-tagging S:B ratio remains small,
→ needs advanced (multivariate) analysis tools

(iii) Optimize separation power by multivariate discrimination (neutral networks, matrix elements, ….)

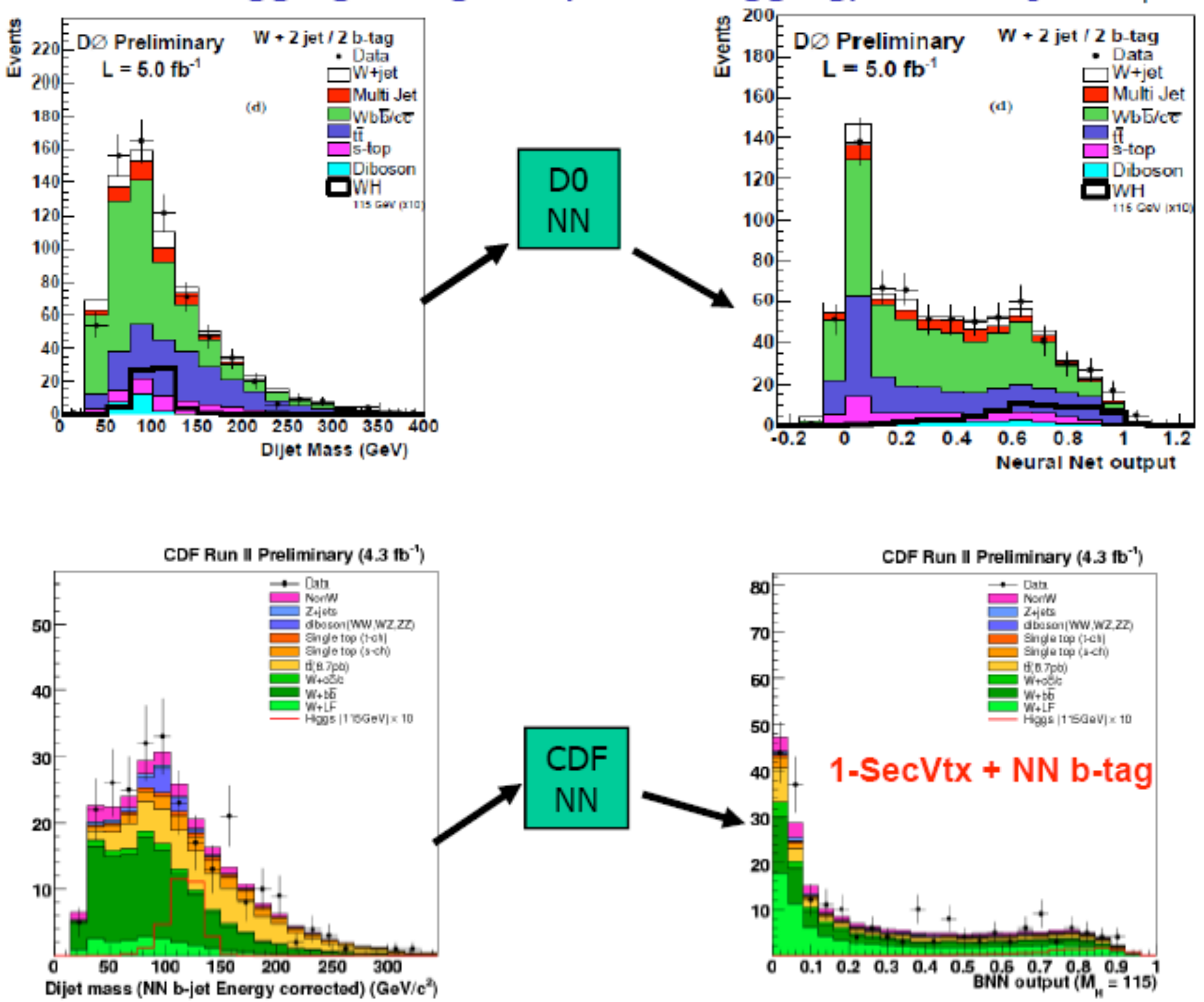
Major input variables:
- dijet mass
- P_T of the dijet system
- P_T of W/Z
- Sphericity
- ΔR_{jj}, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$





DØ: 2 b-tagging categories, NN b-tagging, 2 and 3 jet

Example: WH → ℓν bb

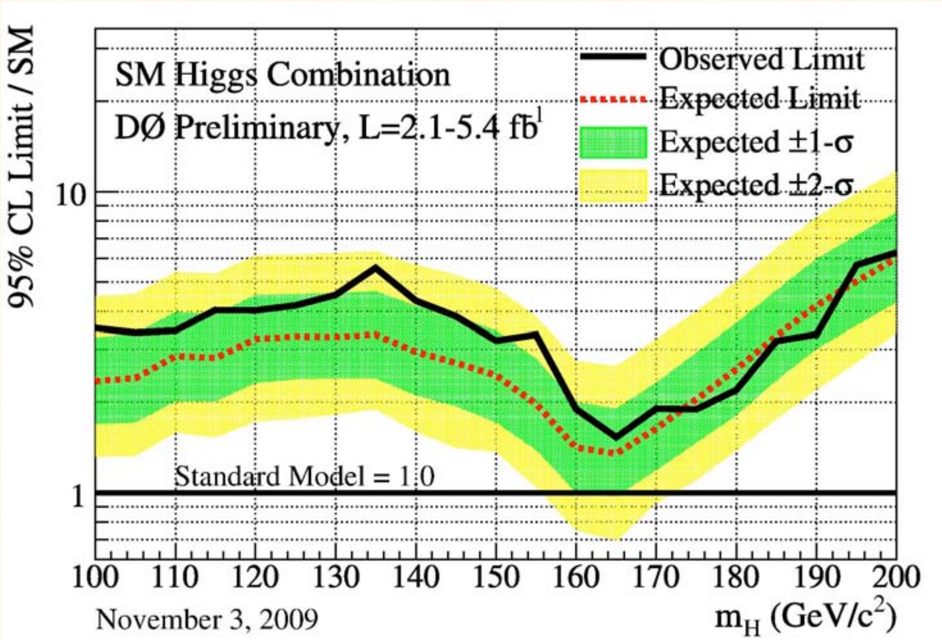


(iv) Split data into several sub-samples with different final state topologies

- maximize sensitivity due to S:B variations
- different background composition in the different classes

Sensitivity in individual channels

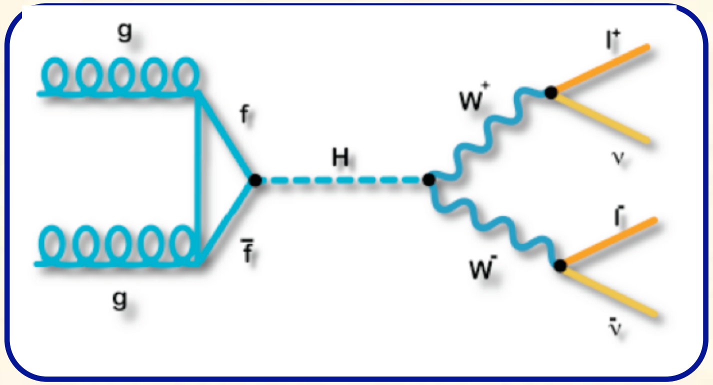
- Limits on individual channels a factor of 5-10 away from SM cross section at m_H = 115 GeV
- → The combination of all contributing channels is crucial



- Main systematic uncertainties for low mass channels:
  - Signal (total 15%): cross section, b-tagging, ID efficiencies
  - Background (total 25-30%): normalization of W/Z+jets heavy flavour samples, modelling of the multijet and W/Z+jet backgrounds, b-tagging

- At high values of the discriminant output, S:B is typically 1/10 - 1/20 for the most sensitive low mass channels

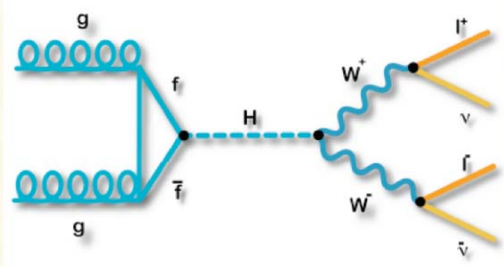
Searches for a high mass Higgs boson at the Tevatron



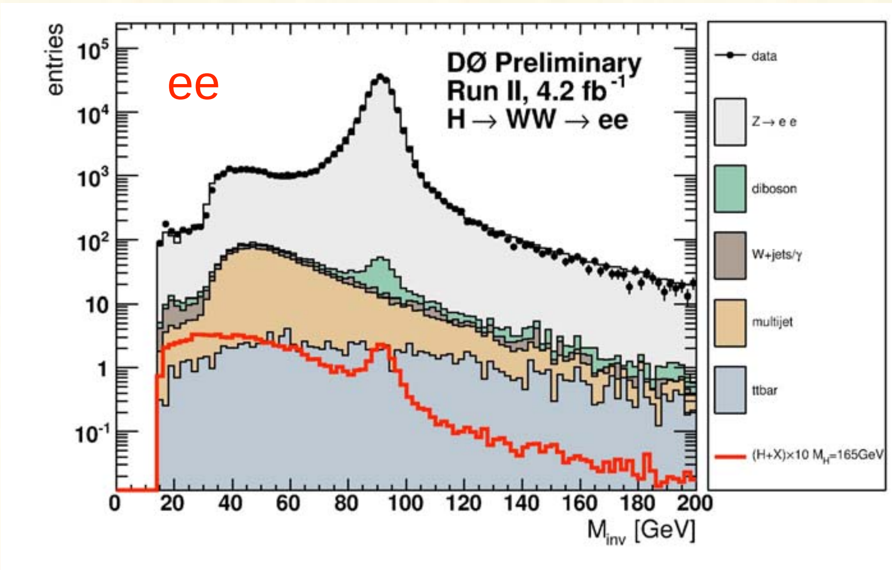
m_H > 135 GeV:

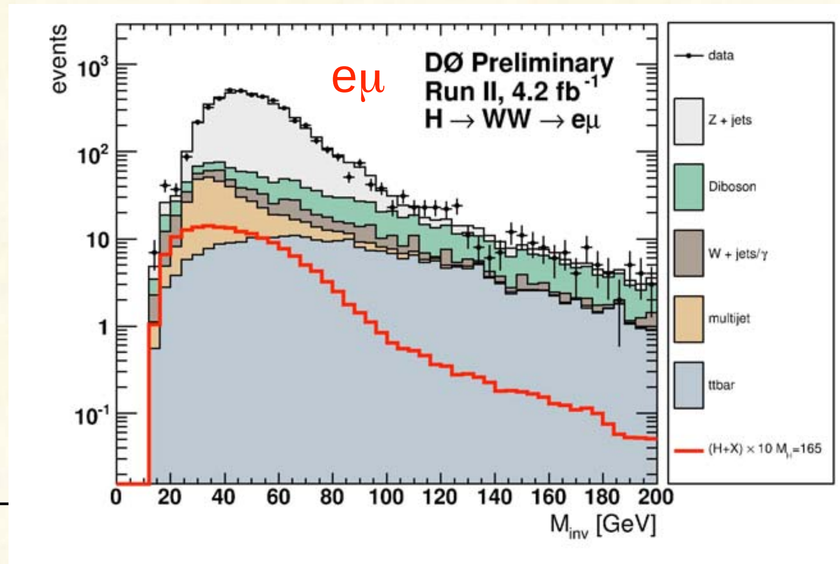
gg → H → WW → ℓν ℓν

$H \rightarrow \ell^+\ell^- \nu\nu$



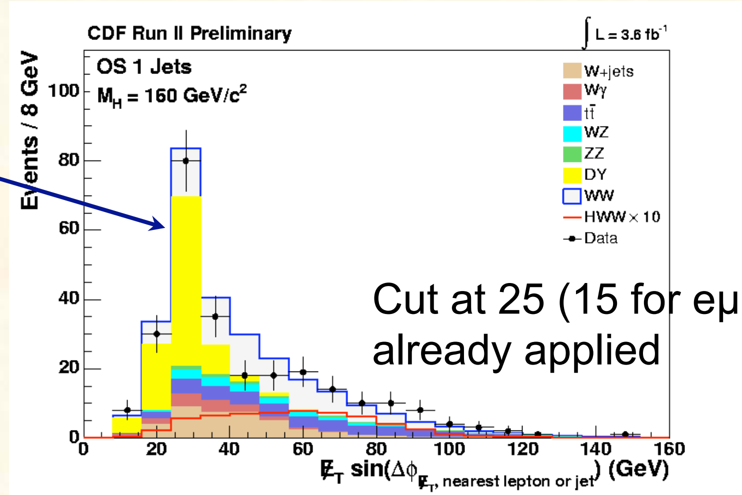
- Dominant decay for m_H >135 GeV: $H \rightarrow W^*W$
- Leptons in final state
  → exploitation of gg→H is possible
- Signal contribution also from $W/Z+H$ *and* qqH production
  → Consider all sources of opposite sign di-lepton + E_T^{miss}
  Split analysis in ee, μμ, and eμ final states
- Backgrounds: Drell-Yan, dibosons, tt, W+jet, multijet production

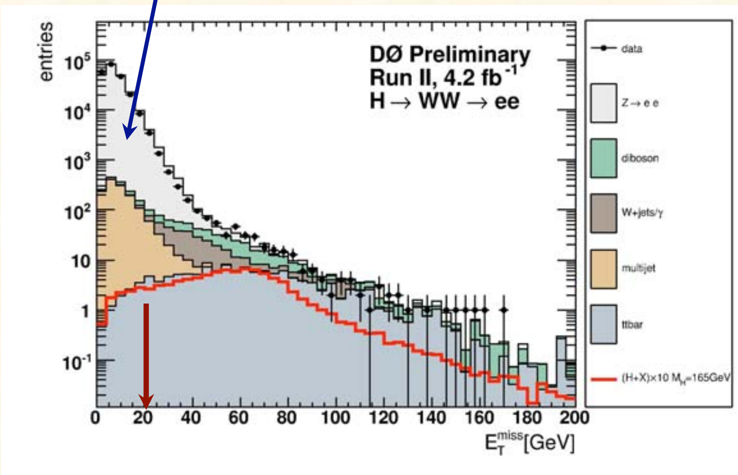




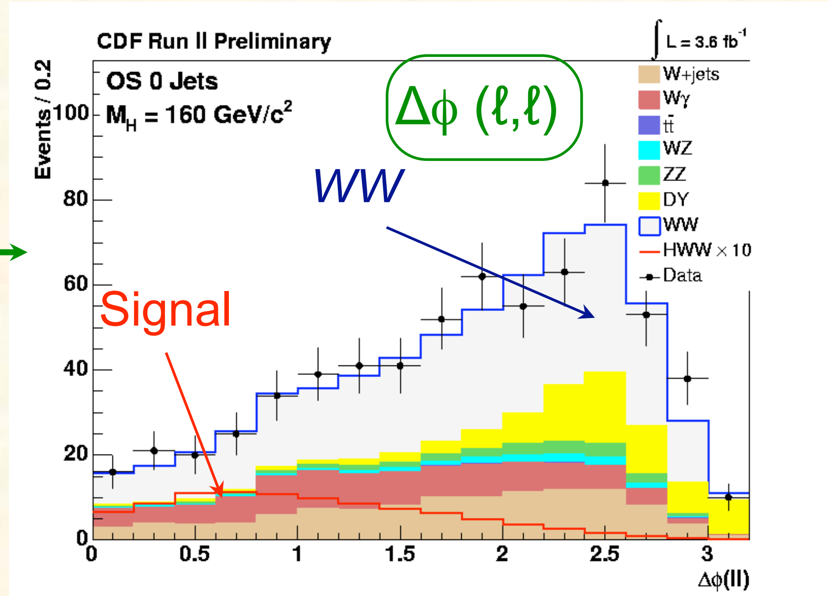
$H \to \ell^+\ell^- \nu\nu$

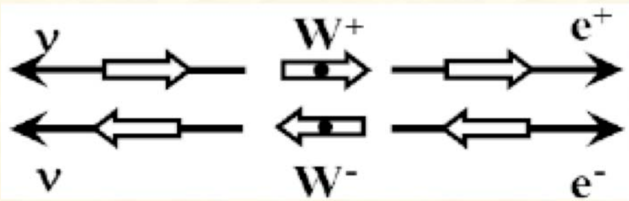
Dominant Drell-Yan background can be reduced with cuts on E_T^{miss} and its isolation (distance to nearest object)





Spin correlation gives main discrimination against irreducible background from non-resonant *WW* production



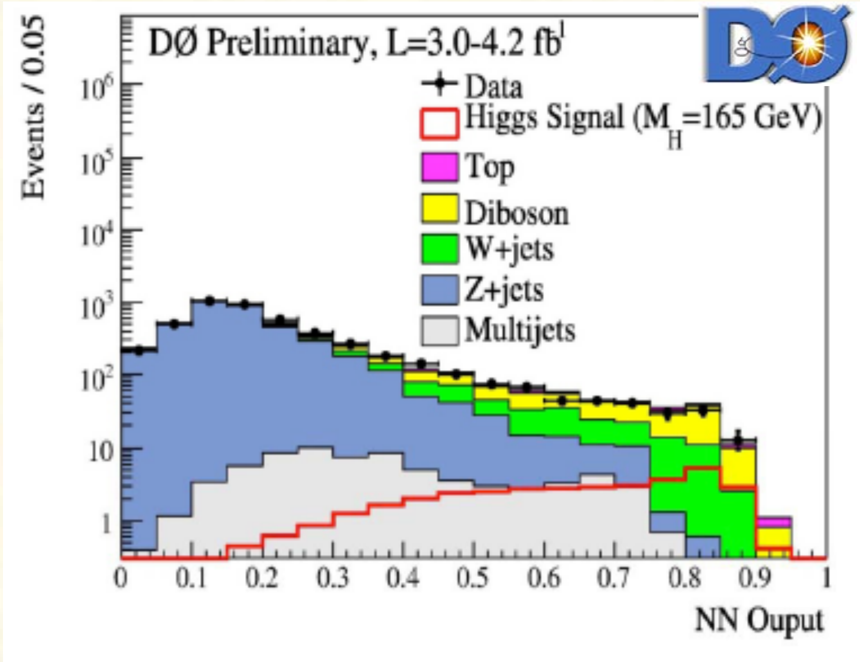


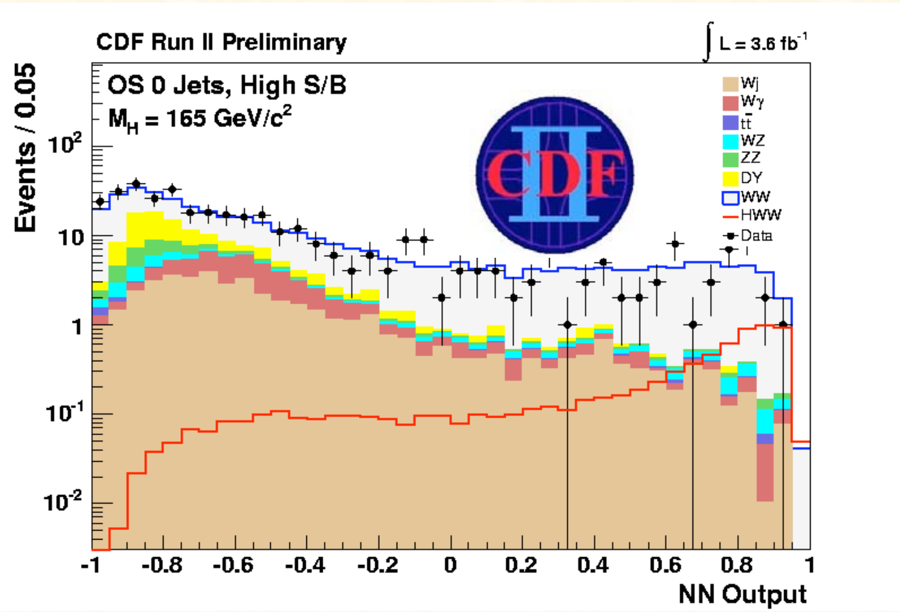
$H \rightarrow \ell^+\ell^- \nu\nu$

To increase sensitivity:

DØ: Split the samples according to lepton flavour and combines the result

Neural Network with 11 kinematic and topological input variables

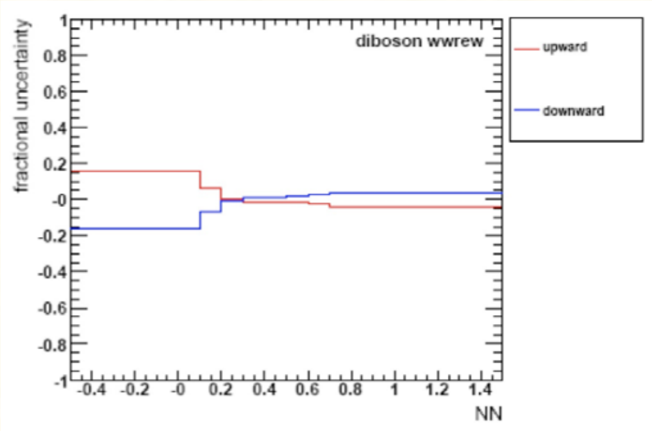




CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

Systematic uncertainties



Change of NN when $p_T(WW)$ changes

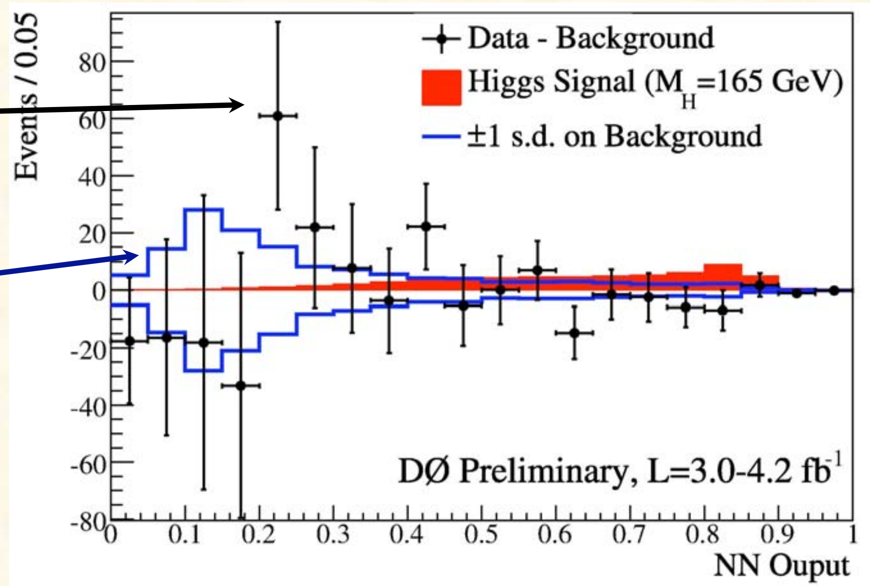
Main systematic uncertainties:

- Signal (total 10%): cross section, lepton ID/trigger
- Background (total 13%): cross sections, jet → lepton fake rate, jet ID/resolution/calibration

Systematic uncertainties change rate and shape of the signal and background predictions

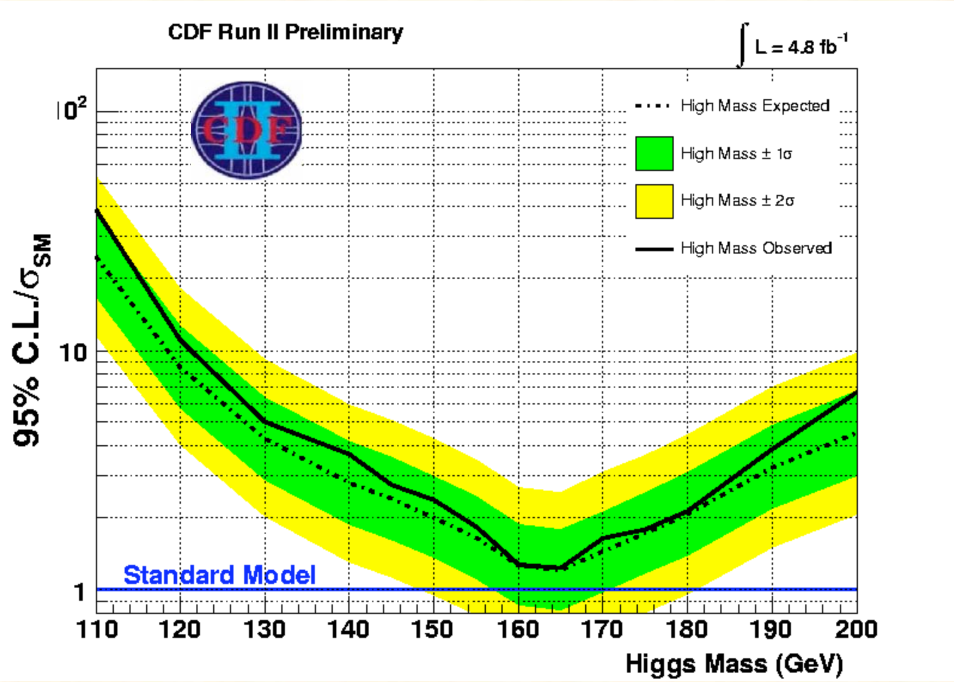
SM signal expectation and data after background subtraction

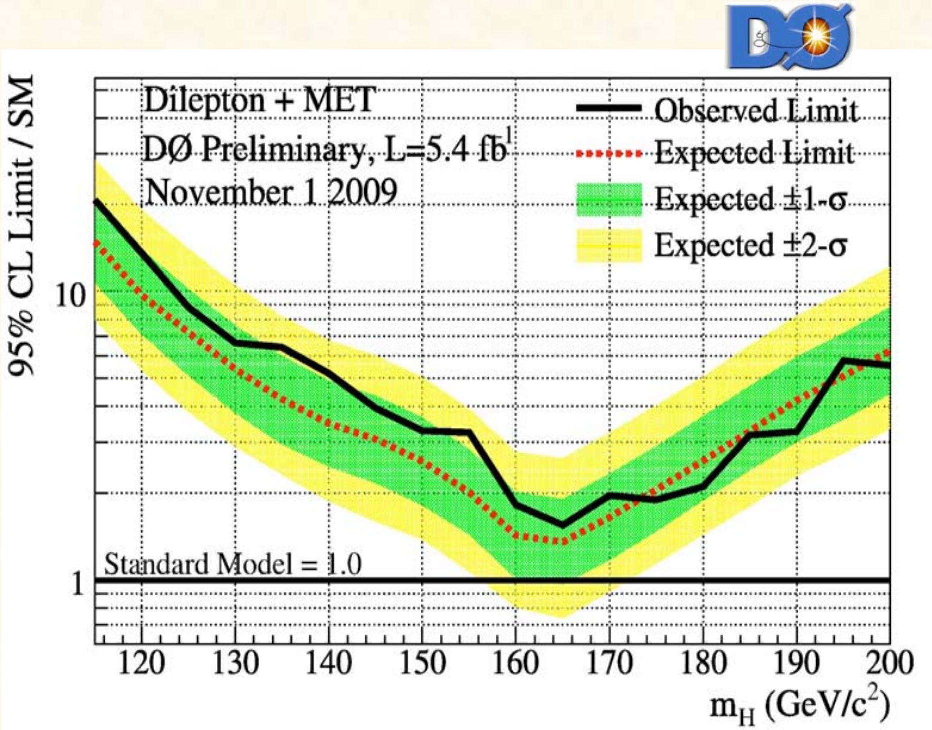
Constrained total systematic uncertainty



$H \rightarrow \ell^+\ell^- \nu\nu$

Exclusion limits per experiment:

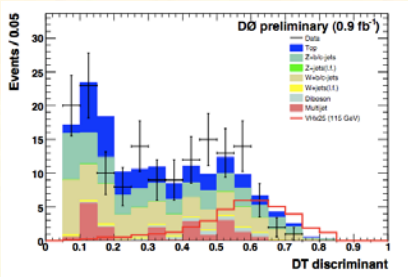


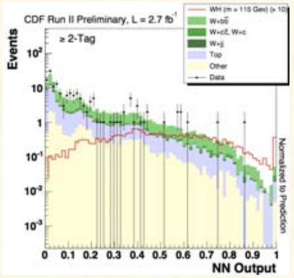


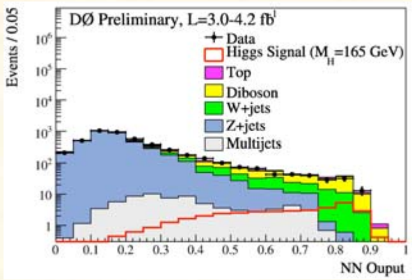
With additional luminosity expect single experiment exclusion around m_H = 165 GeV

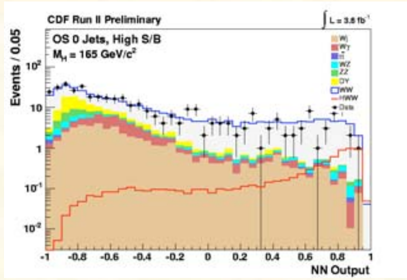
Combination → limit setting

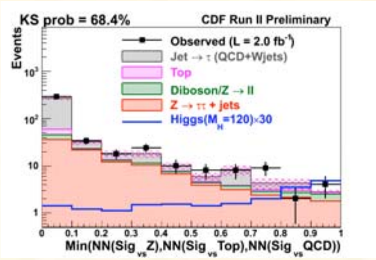
Combination of all channels and of the two experiments:
(note that exclusion is not possible in a single channel / experiment)

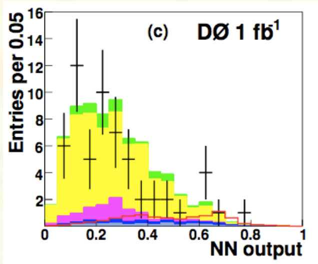


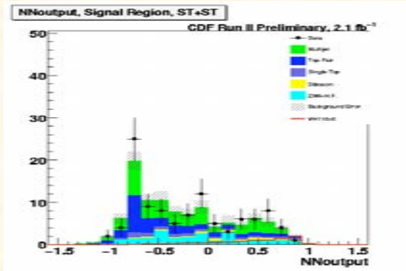












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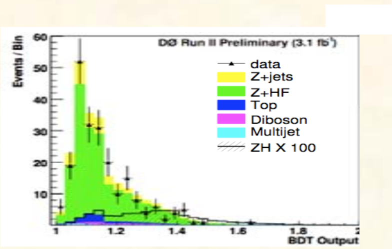
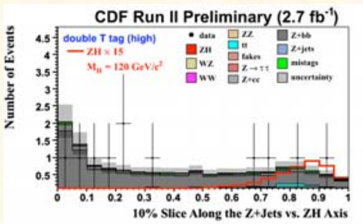
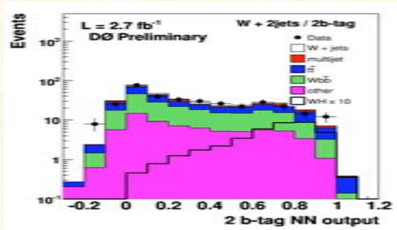
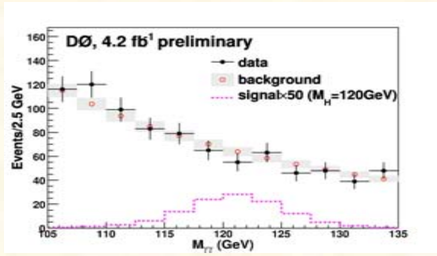
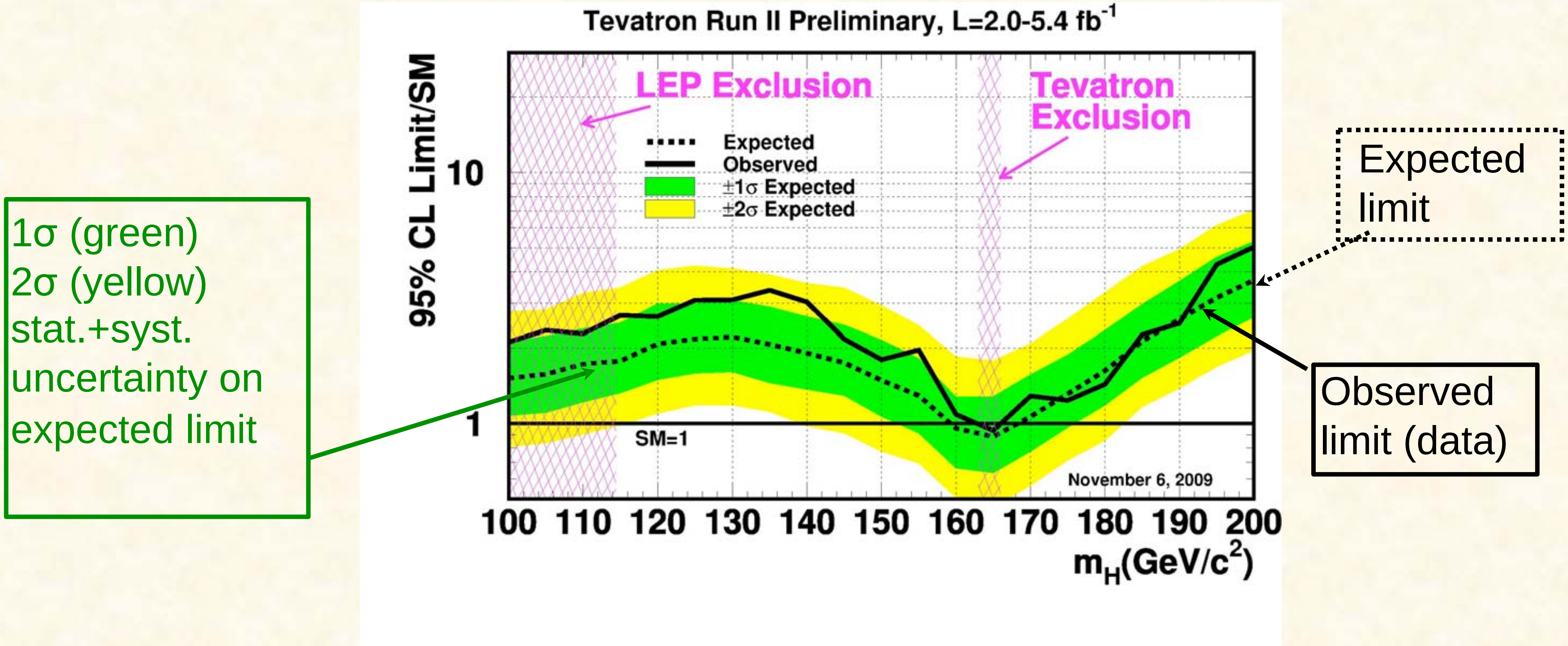








Combined Tevatron limits



Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 163−166 GeV (first direct exclusion since LEP)

At m_H = 115 GeV Expected limit: 1.8 x σ_{SM}

Observed limit: 2.7 x σ_{SM}

Conclusions on the Tevatron Higgs search

- The Tevatron experiments have reached sensitivity (expected limit) for the SM Higgs boson in the mass range around 160 GeV

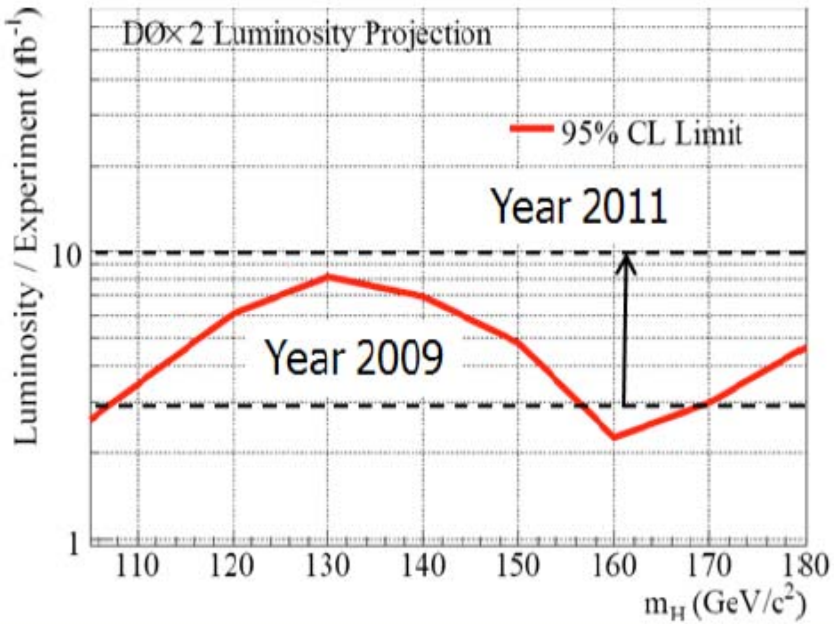
- With increased luminosity the sensitivity in this region is expected to reach the 3σ level
  → either a large mass region can be excluded with 95% C.L. or
  first evidence (3σ) for a SM Higgs boson can be found;

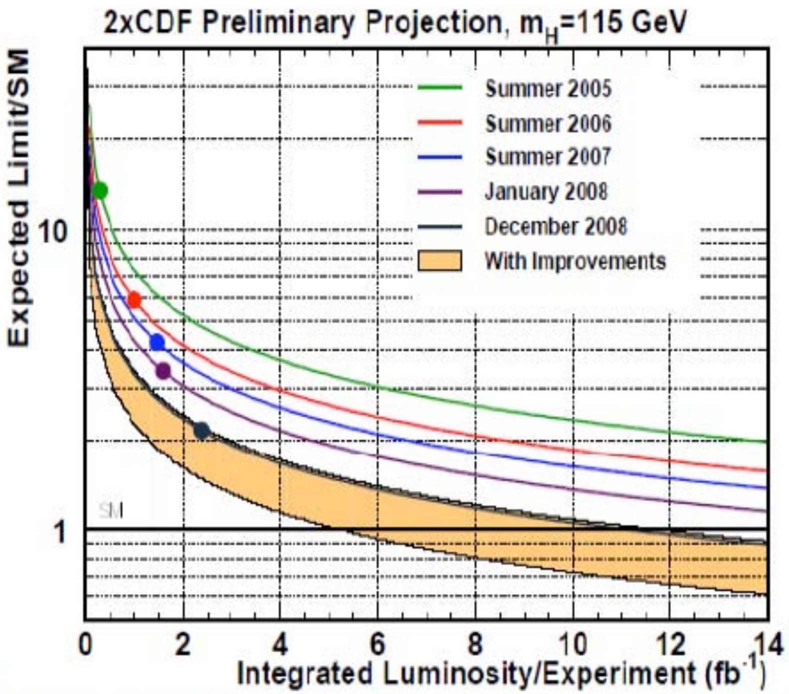
- The Higgs search in the mass range below ~130 GeV is difficult (also at the LHC);

  Search for the bb final state at the Tevatron will provide important complementary information to the LHC Higgs search in the $H \rightarrow \gamma\gamma$ and $qqH \rightarrow qq\ \tau\tau$ channels

Expected Higgs sensitivity

assume CDF+DØ, and projected improvements:





2009: precision EW measurements + Tevatron → SM Higgs 115 – 160 GeV
2010: with Tevatron luminosity, expects upper limit to go down to ~145 GeV
≥2011: @ Tevatron, direct exclusion from 115 to 185 GeV, or first evidence?

G. Bernardi, Lepton-Photon 2009 (Hamburg)

The Search for

The Higgs boson at the LHC

What is new on LHC Higgs studies ?

- Many studies have meanwhile been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration
  - ATLAS CSC book (Computing System Commissioning)

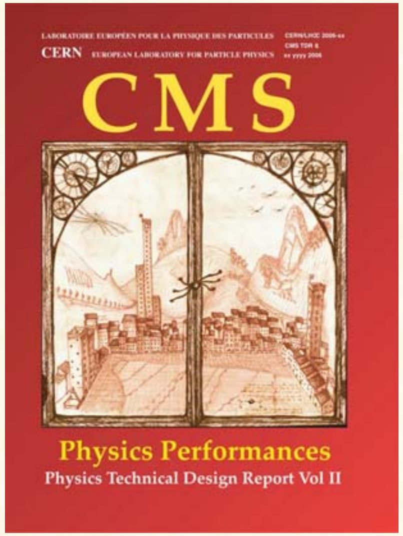
- New (N)NLO Monte Carlos (also for backgrounds)
  - MCFM Monte Carlo, J. Campbell and K. Ellis, http://mcfm.fnal.gov
  - MC@NLO Monte Carlo, S.Frixione and B. Webber, wwwweb.phy.cam.ar.uk/theory/
  - T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
  - E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
  - C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130
  - …..

- New approaches to match parton showers and matrix elements
  - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
  - SHERPA Monte Carlo, F. Krauss et al.
  - …

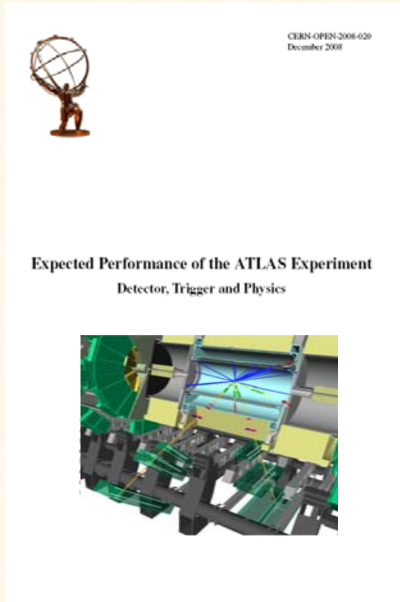
  Tevatron data are extremely valuable for validation (see yesterday's lecture)

- More detailed, better understood reconstruction methods
  (partially based on test beam results,…)

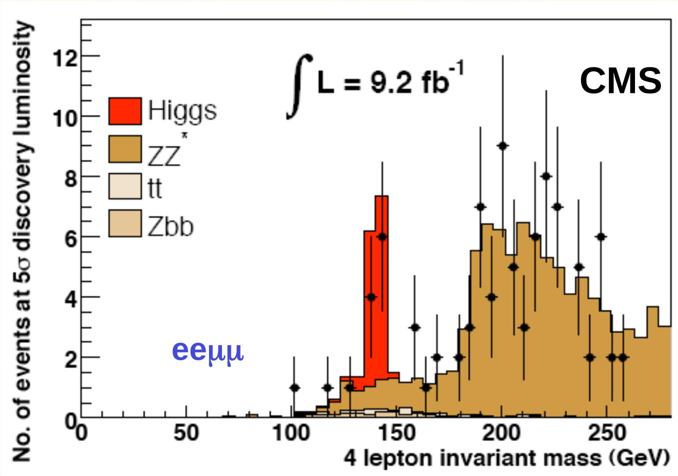
- Further studies of new Higgs boson scenarios
  (Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)



CMS: CERN / LHCC 2006-021
ATLAS: CERN-OPEN 2008-020



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

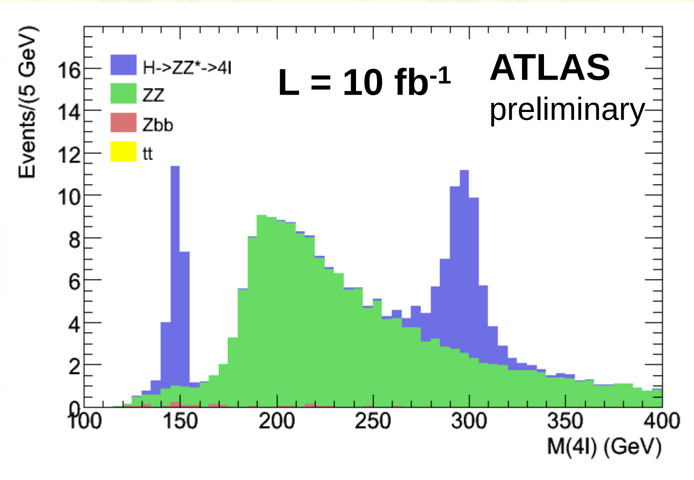


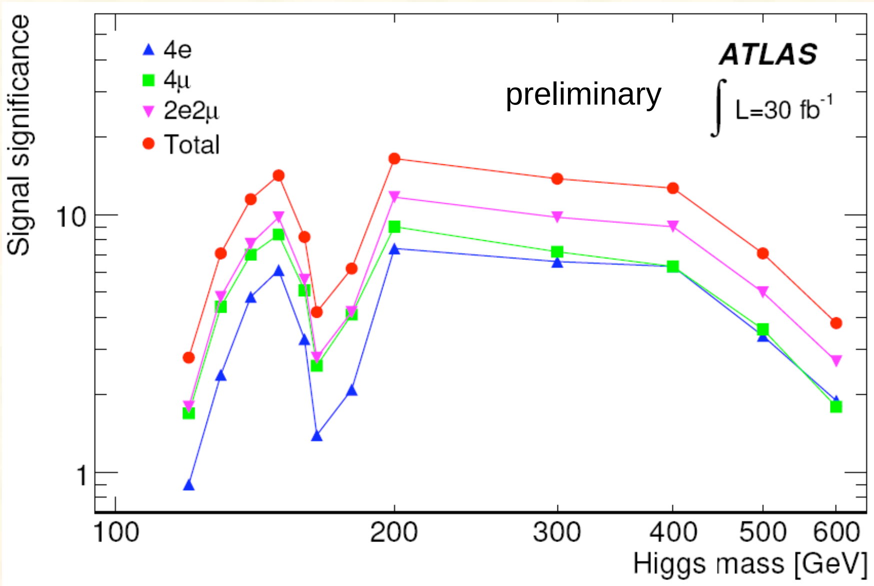
Main backgrounds: ZZ (irreducible),
tt, Zbb (reducible)

Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)

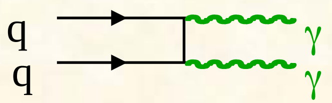




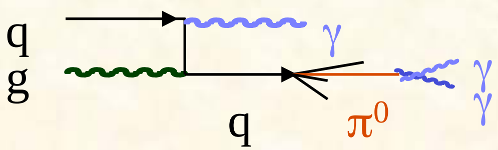
$H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



γ-jet and jet-jet (reducible)



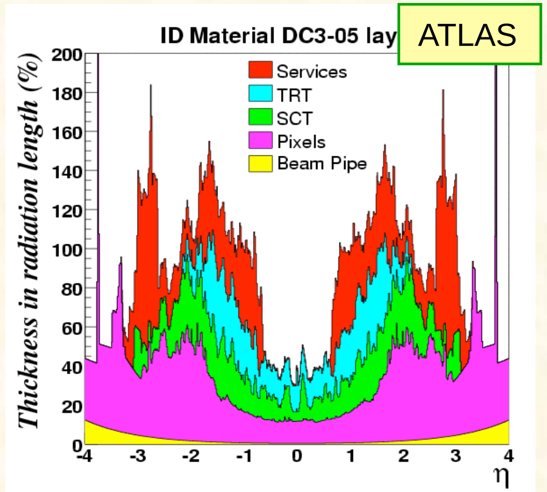
$\sigma_{\gamma j + jj} \sim 10^6\ \sigma_{\gamma\gamma}$ with large uncertainties

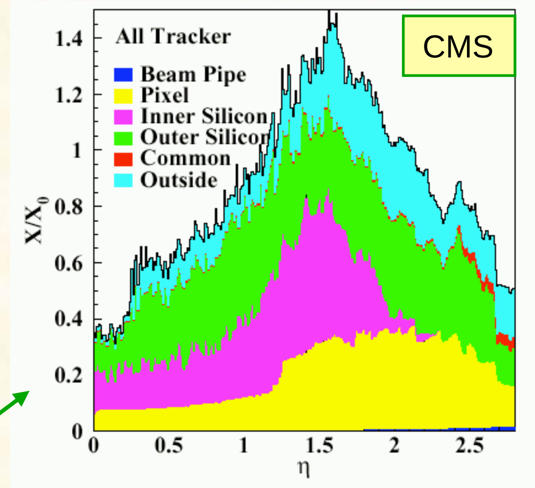
$\rightarrow$ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

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

- 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)





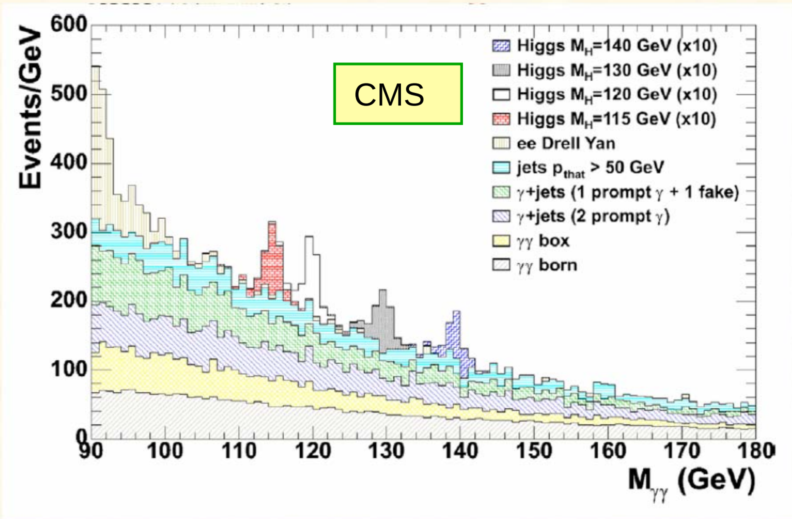
CMS: fraction of converted γs

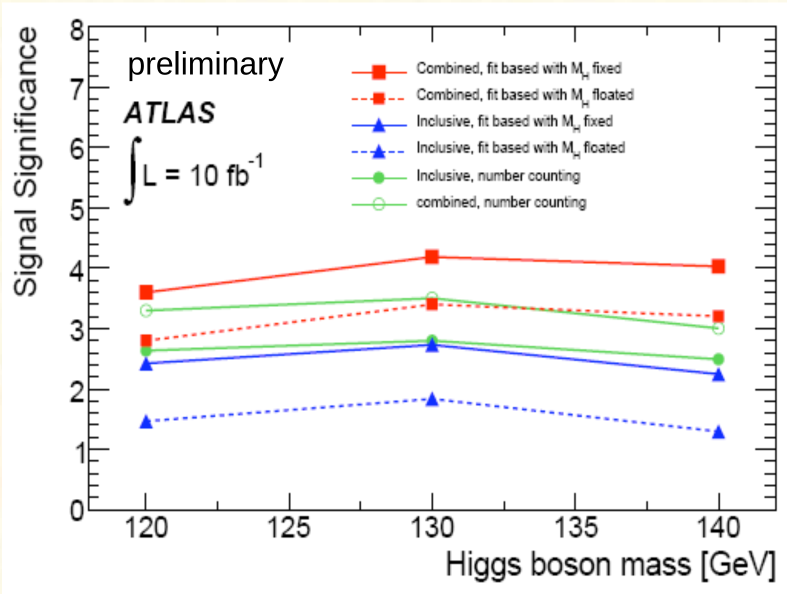
Barrel region: 42.0 %

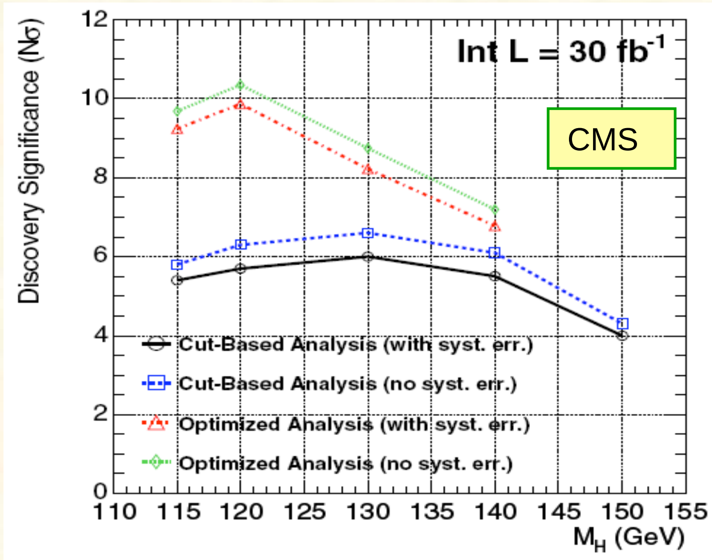
Endcap region: 59.5 %

New elements of the analyses:

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







- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies

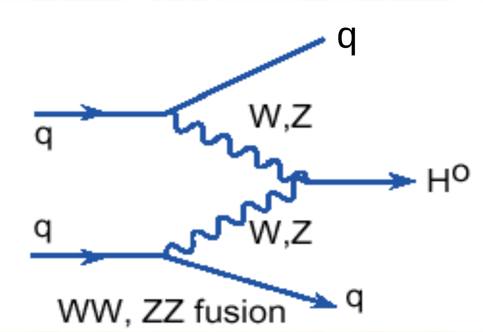
Vector Boson Fusion qq H

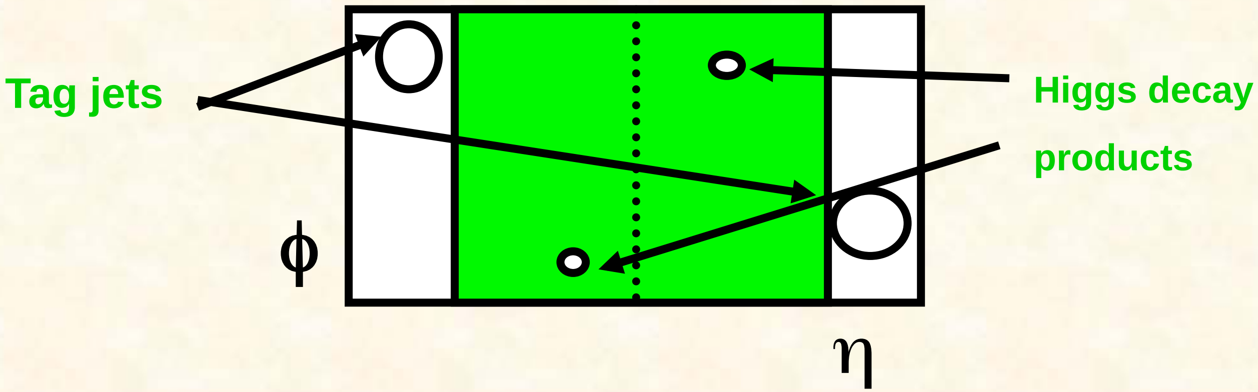
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.

Distinctive Signature of:

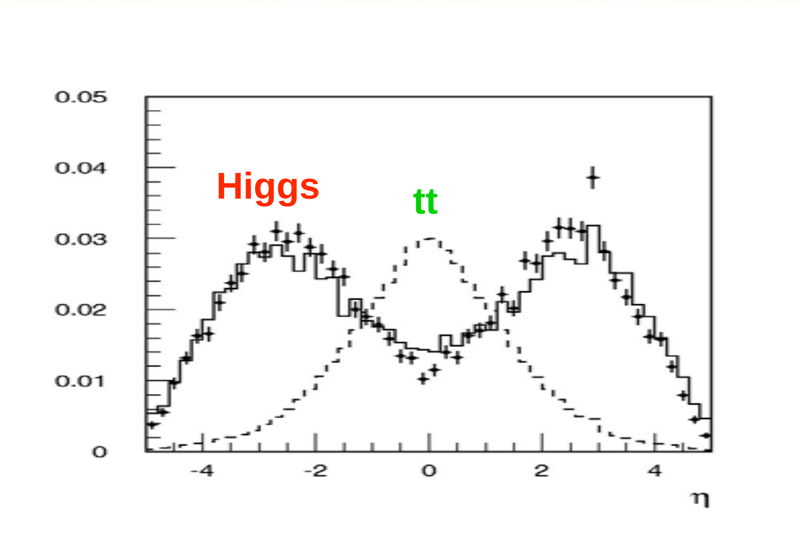
- two high p_T forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto



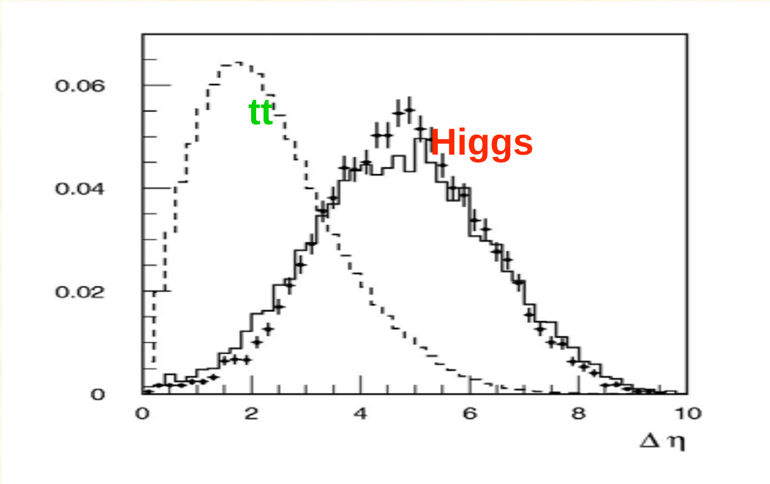


Forward jet tagging

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



Rapidity separation

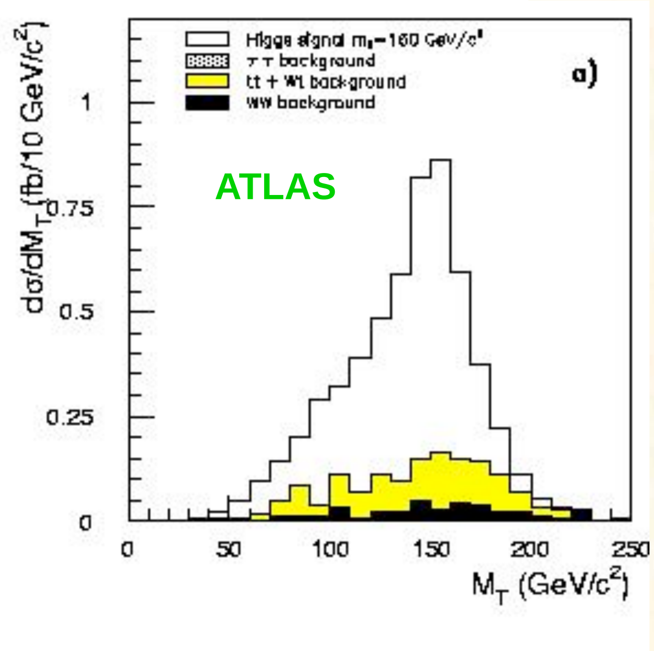


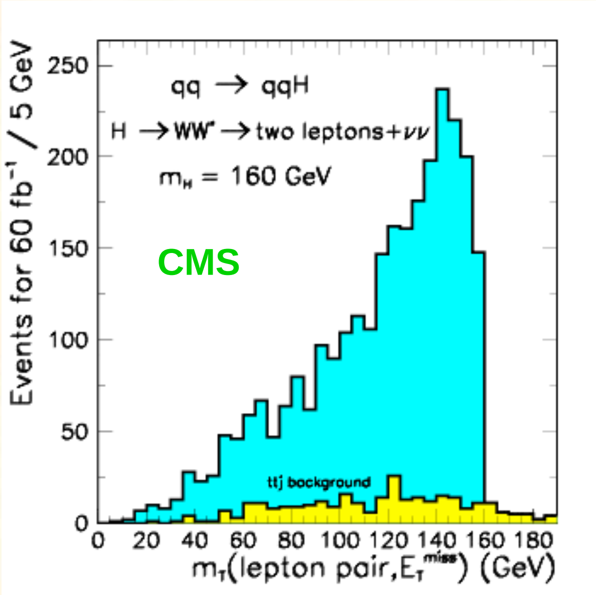
$$qq\,H \rightarrow qq\;W\,W^* \rightarrow qq\;\ell\nu\;\ell\nu$$

Selection criteria:

- Lepton P_T cuts and
- Tag jet requirements ($\Delta\eta$, P_T, large mass)
- Jet veto (important)
- Lepton angular and mass cuts

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



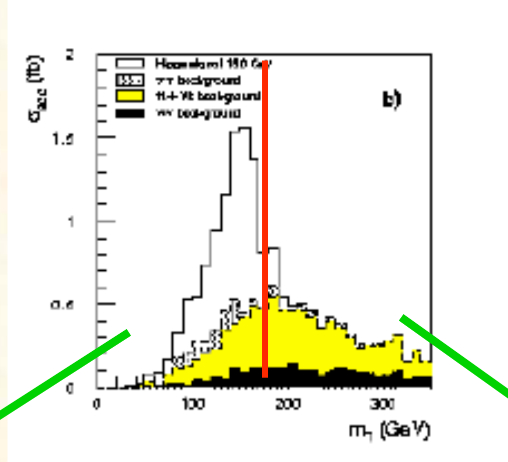


Transverse mass distributions: clear excess of events above the background from tt-production

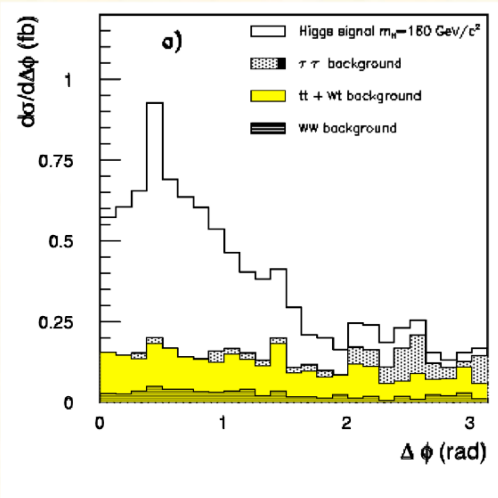
Presence of a signal can also be demonstrated in the $\Delta\phi$ distribution (i.e. azimuthal difference between the two leptons)

Evidence for spin-0 of the Higgs boson

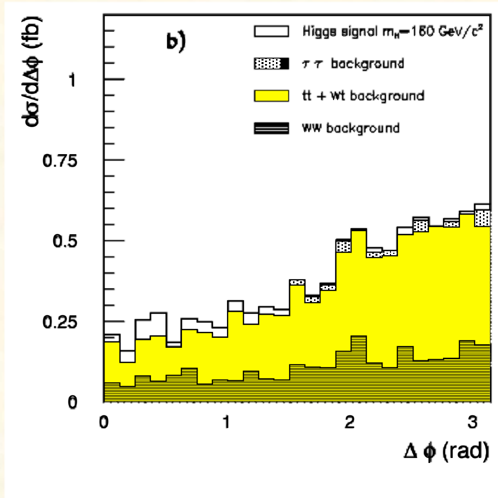
Spin-0 → WW → ℓνℓν expect leptons to be close by in space



relaxed cuts on the leptons (angular cuts not applied)



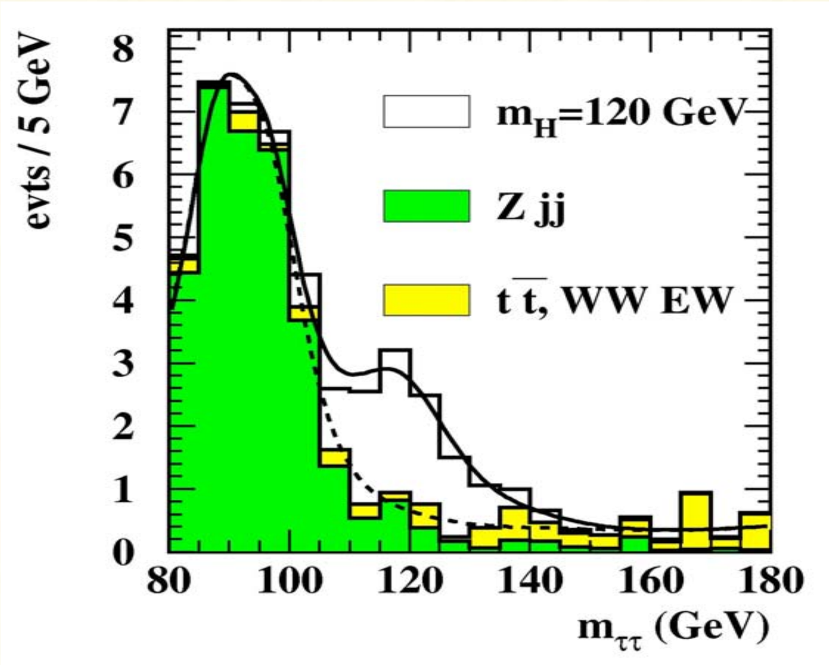
signal region



background region

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

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



Experimental challenge:

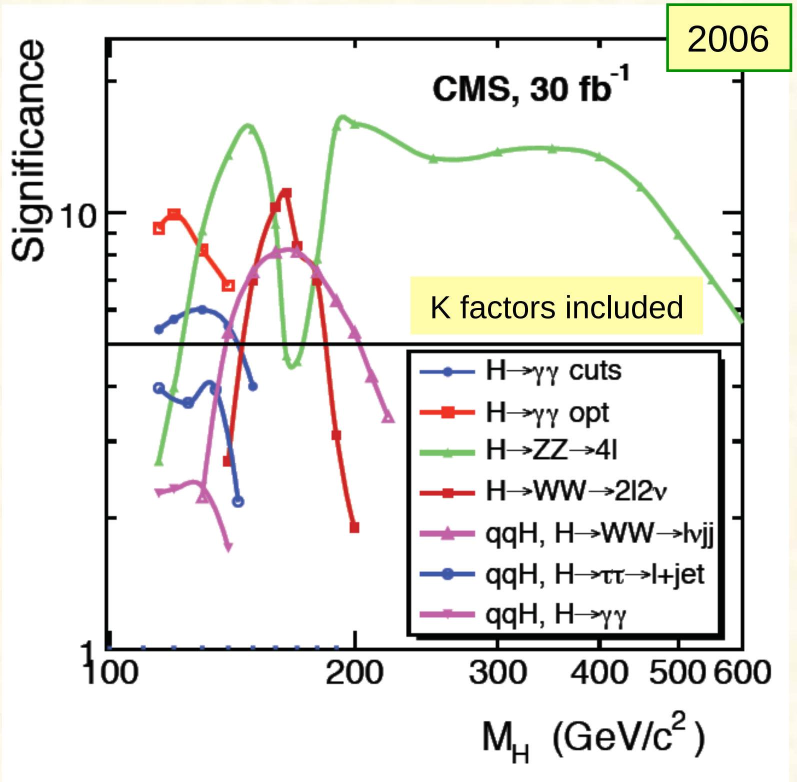
- Identification of hadronic taus
- Good E_T^{miss} resolution
  ($\tau\tau$ mass reconstruction in collinear approximation,
  i.e. assume that the neutrinos go in the direction of the visible decay products,
  good approximation for highly boosted taus)

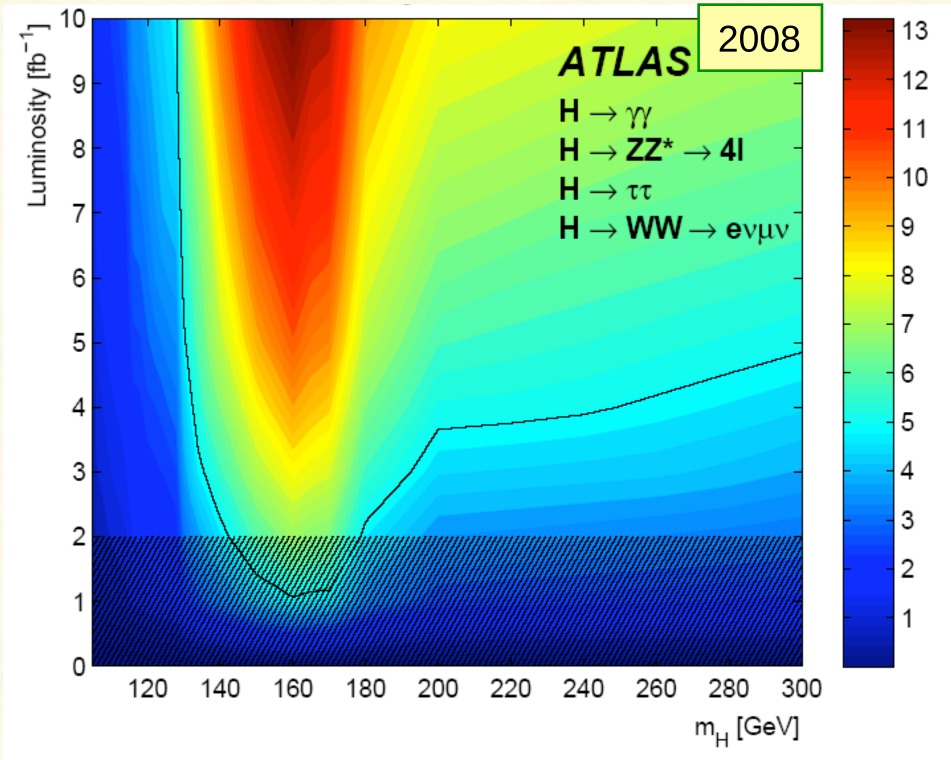
  → Higgs mass can be reconstructed

- Dominant background: $Z \to \tau\tau$

  the shape of this background must be controlled the high mass region
  → use data ($Z \to \mu\mu$) to constrain it

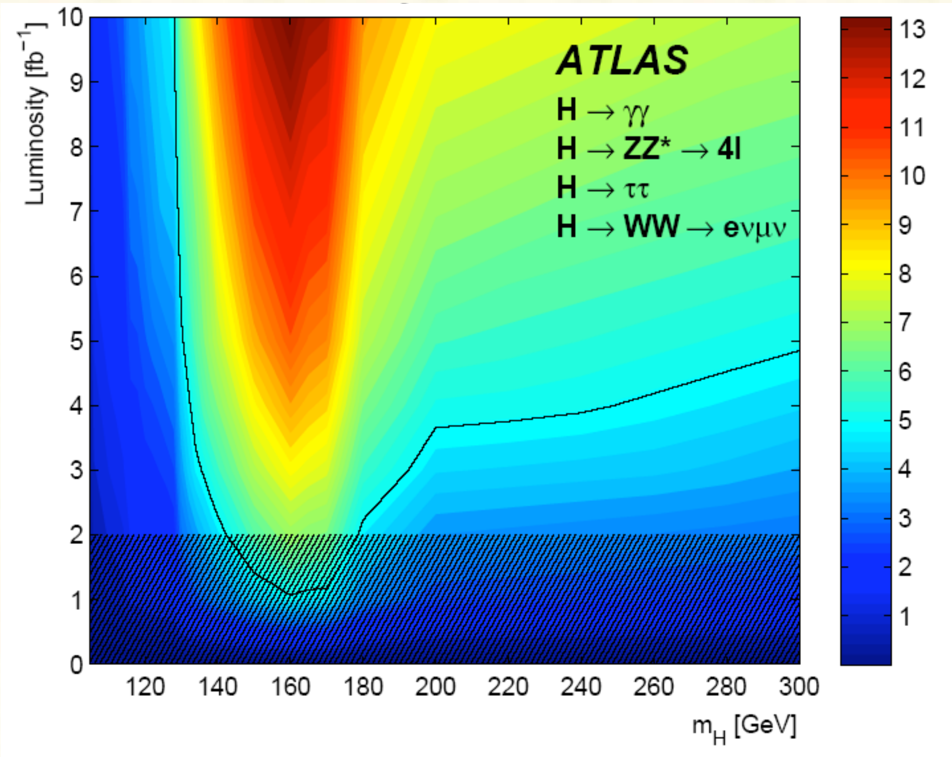
LHC Higgs boson discovery potential





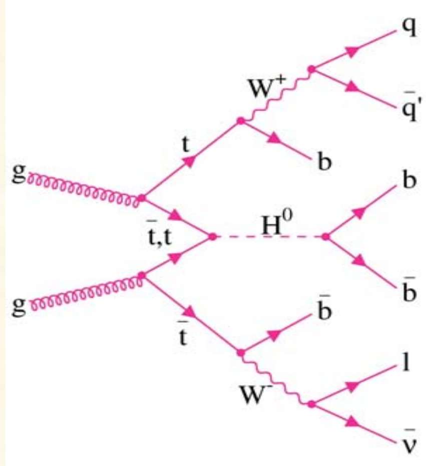
- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]

- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)



Can the situation at low mass be improved
by detecting the bb decay mode ?

$t\bar{t}\,H \rightarrow t\bar{t}\,b\bar{b}$

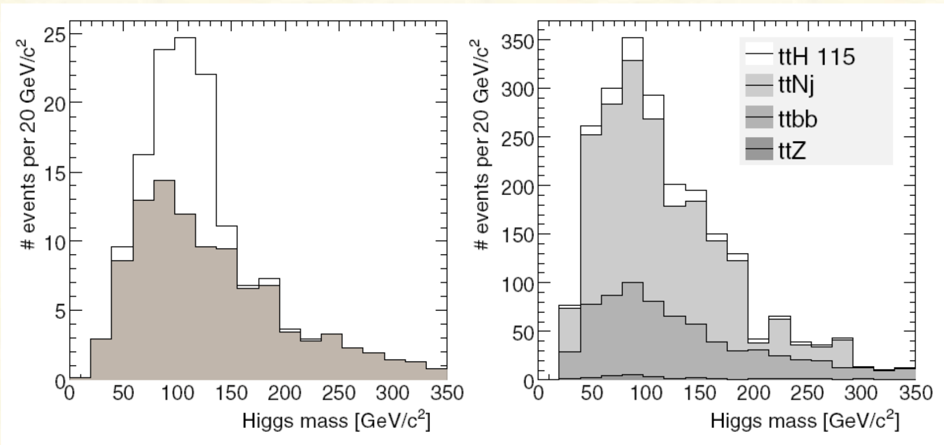


Complex final states: H→ bb, t → bjj, t → bℓν
t → bℓν, t → bℓν
t → bjj, t → bjj

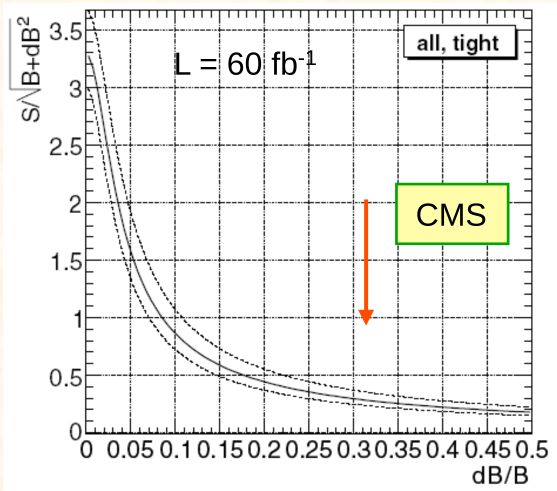
Main backgrounds:
- combinatorial background from signal (4b in final state)
- ttjj, ttbb, ttZ,…
- Wjjjjj, WWbbjj, etc. (excellent b-tag performance required)

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
→ larger backgrounds (ttjj dominant), experimental + theoretical uncertainties, e.g. ttbb, exp. norm. difficult…..

M (bb) after final cuts, 60 fb^{-1}



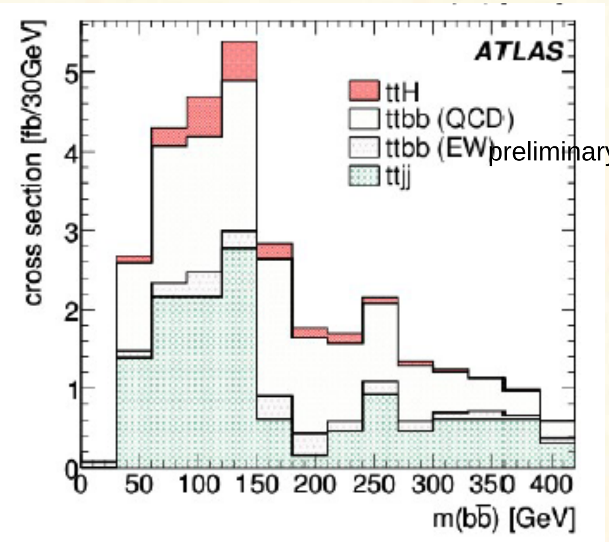
Signal events only …. backgrounds added

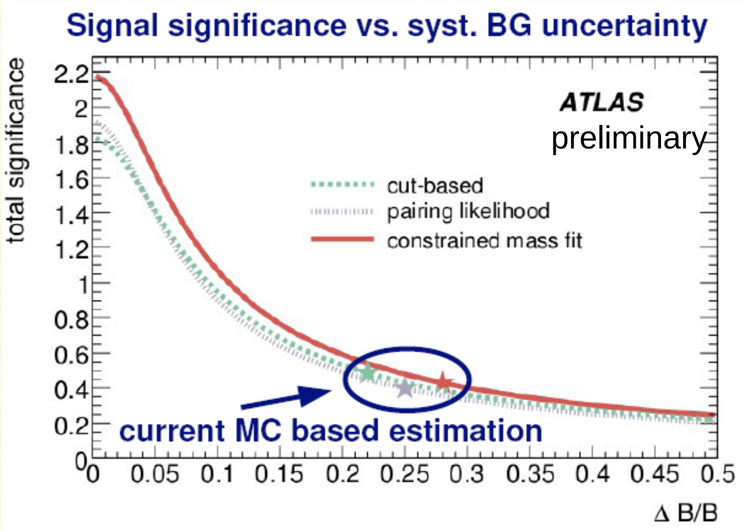


Signal significance as function of background uncertainty

…..comparable situation in ATLAS   (ttH cont.)

Preselection cut	$t\bar{t}H$(fb)	$t\bar{t}b\bar{b}$(EW) (fb)	$t\bar{t}b\bar{b}$(QCD) (fb)	$t\bar{t}X$ (fb)
lepton cuts (ID + p_T)	$57. \pm 0.2$	141 ± 1.0	1356 ± 6	63710 ± 99
+ $\geq$ 6 jets	36 ± 0.2	77 ± 0.9	665 ± 4	26214 ± 64
+ $\geq$ 4 loose b-tags	16.2 ± 0.2	23 ± 0.7	198 ± 3	2589 ± 25
+ $\geq$ 4 tight b-tags	3.8 ± 0.06	4.2 ± 0.2	30 ± 0.8	51 ± 2
	LO	LO	LO	NLO





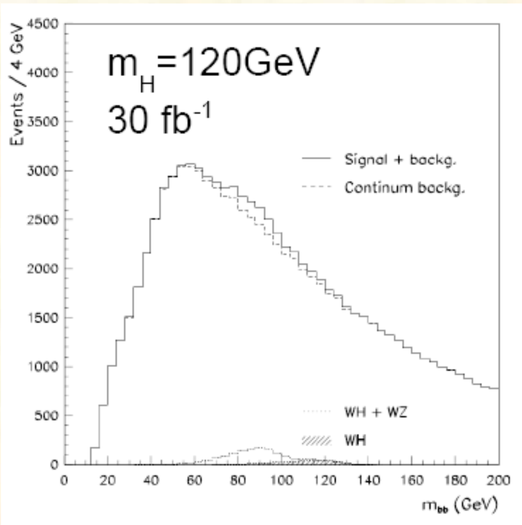
estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))
⇒ Normalization from data needed to reduce this (non trivial,…)

New hope for H→ bb decays at the LHC: W/Z H, H → bb

NEW!

The most important channels at the TEVATRON at low mass!

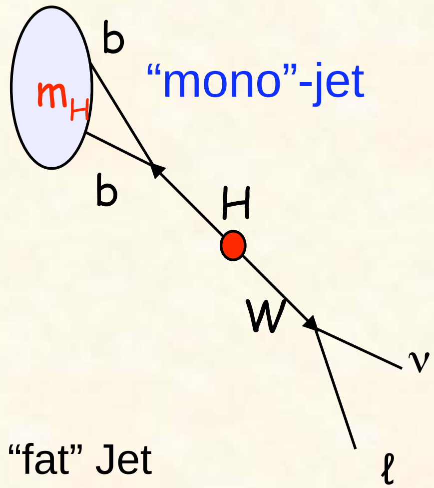
But: signal to background ratio less favourable at the LHC



$S/\sqrt{B}$	2.1
S/B	1.3%

Follow idea of J. Butterworth, et al.
[PRL 100 (2008) 242001]

Select events (≈5% of cross section), in which H und W bosons have large transverse momenta: p_T > 200 GeV



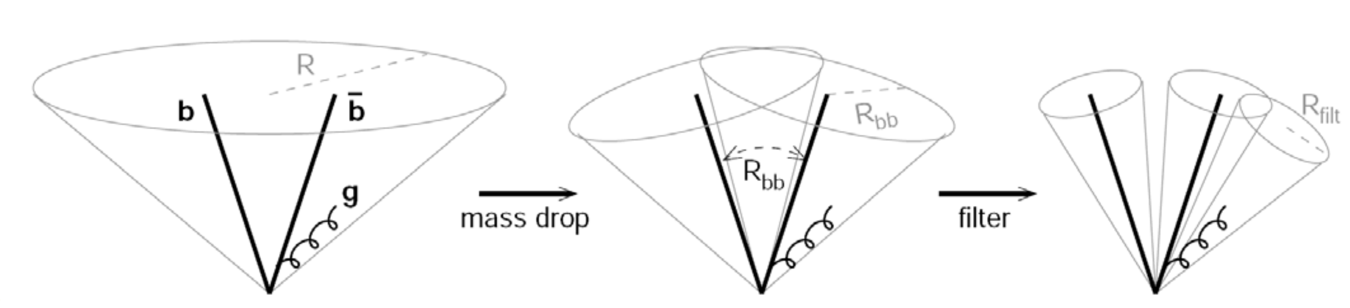
→ b-quarks in one “fat” Jet

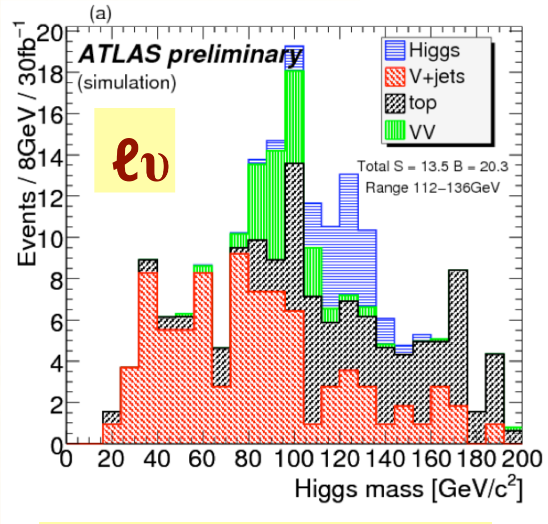
+ Acceptance (more central in detector)
+ Lepton identification, b-tagging

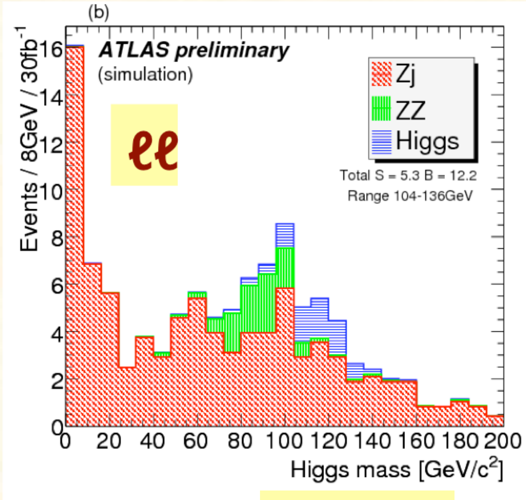
High p_T W/Z H, H → bb

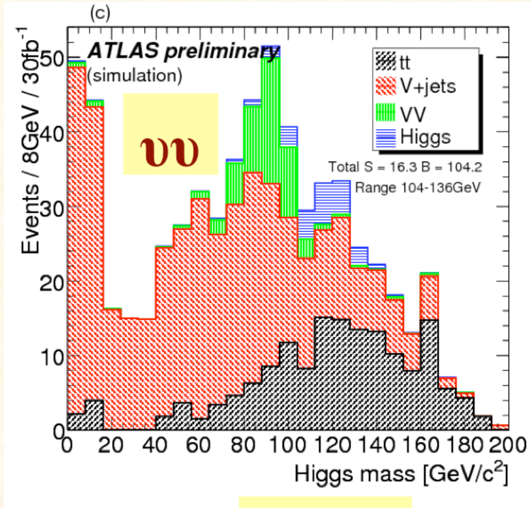
ATL-PHYS-PUB-2009-088

Analyze jet structure:









$L^{int.} = 30\, fb^{-1}: \frac{S}{\sqrt{B}} = \mathbf{3.0}$

M_H = 120 GeV

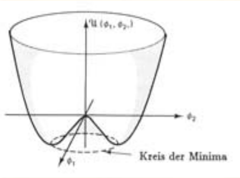
$\frac{S}{\sqrt{B}} = \mathbf{1.5}$

$\frac{S}{\sqrt{B}} = \mathbf{1.6}$

Combined: $\frac{S}{\sqrt{B}} = \mathbf{3.7}$

(Pileup not yet included)

- S/B much better than for ttH
- Different backgrounds for different channels
- Still good sensitivity including systematics
  (e.g. S/√B = 3.0 for 15% uncertainty on all backgrounds)



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 slides)

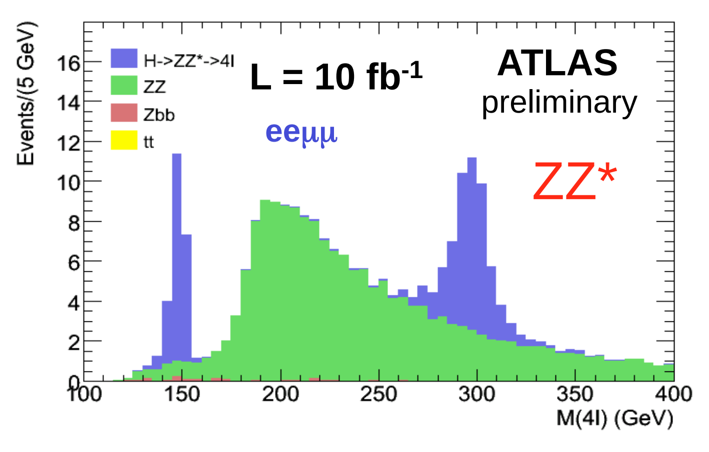
3. Spin and CP

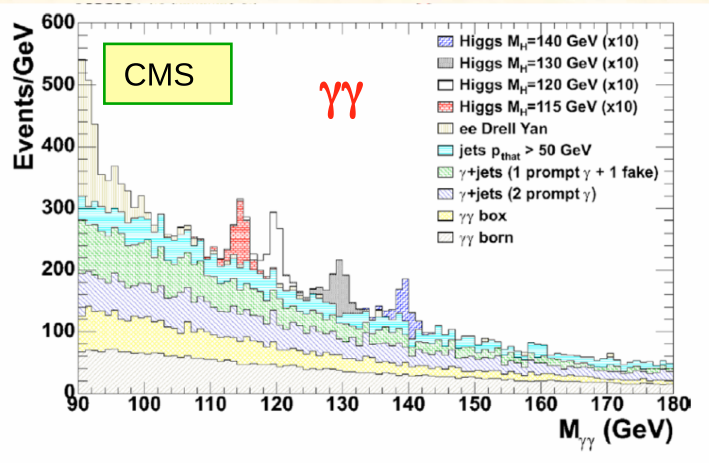
Angular correlations in H → ZZ(*) → 4 ℓ and $\Delta\phi_{jj}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling

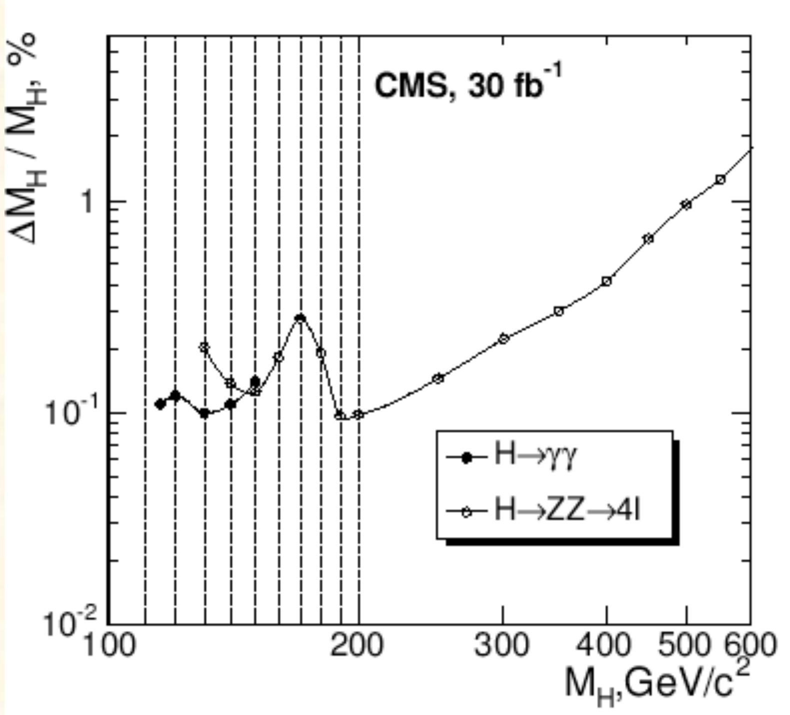
(→ see next slides)

(i) Precision on mass is achieved in el.magn. final states





Dominant systematic uncertainty:
γ / ℓ energy scale.
assumed: 1‰ (goal 0.2‰)
Scale from Z → ℓℓ (close to light Higgs)



Precision below 1% can be achieved over a large mass range for 30 fb^{-1};
syst. limit can be reached for higher integrated luminosities → 100 fb^{-1}

Note: no theoretical errors, e.g. mass shift for large Γ_H (interference resonant/non-resonant production) taken into account

(ii) Higgs boson couplings to fermions and bosons

The Higgs boson couplings can in principle be extracted from rate measurements,

$$\sigma_{yy \rightarrow H} \cdot BR(H \rightarrow xx) \sim \Gamma_y \cdot \Gamma_x / \Gamma_H$$

however, Γ_H is needed, which cannot be directly measured at the LHC for $m_H < 200$ GeV.

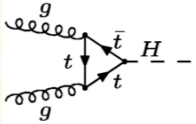
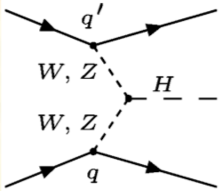
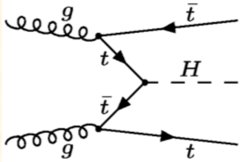
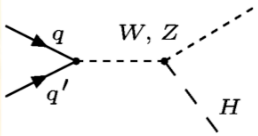
Two options:

(i) Measure ratios of couplings
Systematic uncertainties taken into account;
M. Dührssen, ATLAS-PHYS-2003-030.

(ii) Include more theoretical assumptions and measure absolute couplings
M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld, Phys. Rev. D70 (2004) 113009.

For both options, the information from all visible Higgs boson production and decay modes can be combined into one global maximum likelihood fit

Experimental input:

Production		Decay	mass range	
	Gluon-Fusion ($gg \to H$)	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 200 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	WBF ($qq\, H$)	$H \to ZZ \to 4l$	110 GeV - 200 GeV	
		$H \to WW \to l\nu\, l\nu$	110 GeV - 190 GeV	
		$H \to \tau\tau \to l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV	
		$H \to \tau\tau \to l\nu\nu\, \mathrm{had}\nu$	110 GeV - 150 GeV	
		$H \to \gamma\gamma$	110 GeV - 150 GeV	
	$t\bar{t}H$	$H \to WW \to l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV	optimistic assumptions
		$H \to b\bar{b}$	110 GeV - 140 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	WH	$H \to WW \to l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV	optimistic assumptions
		$H \to \gamma\gamma$	110 GeV - 120 GeV	
	ZH	$H \to \gamma\gamma$	110 GeV - 120 GeV	

Mass range is restricted to m_H < 200 GeV
Based on „old ATLAS studies“
Most significant differences: ttH channels with H → bb and H → WW

Higgs-Boson Couplings (cont.)

Global fit

(all channels at a given mass point)

Analysis is done with increasing level of theoretical assumptions

Fit parameters:

$$\frac{g_Z^2}{g_W^2} \quad \frac{g_\tau^2}{g_W^2} \quad \frac{g_b^2}{g_W^2} \quad \frac{g_t^2}{g_W^2} \quad \frac{g_W^2}{\sqrt{\Gamma_H}}$$

Production cross-sections

$$\sigma_{ggH} = \alpha_{ggH} \bullet g_t^2$$
$$\sigma_{VBF} = \alpha_{WF} \bullet g_W^2 + \alpha_{ZF} \bullet g_Z^2$$
$$\sigma_{ttH} = \alpha_{ttH} \bullet g_t^2$$
$$\sigma_{WH} = \alpha_{WH} \bullet g_W^2$$
$$\sigma_{ZH} = \alpha_{ZH} \bullet g_Z^2$$

(b loop neglected so far in ggH)

Branching ratios

$$BR(H \to WW) = \beta_W \frac{g_W^2}{\Gamma_H}$$
$$BR(H \to ZZ) = \beta_Z \frac{g_Z^2}{\Gamma_H}$$
$$BR(H \to \gamma\gamma) = \frac{\left(\beta_{\gamma(W)} g_W - \beta_{\gamma(t)} g_t\right)^2}{\Gamma_H}$$
$$BR(H \to \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H}$$
$$BR(H \to bb) = \beta_b \frac{g_b^2}{\Gamma_H}$$

α,β from theory with assumed Uncertainties:

$\Delta\alpha_{ggH} = 20\%$

$\Delta\alpha_{WF} = \alpha_{ZF} = 4\%$

$\Delta\alpha_{ttH} = 15\%$

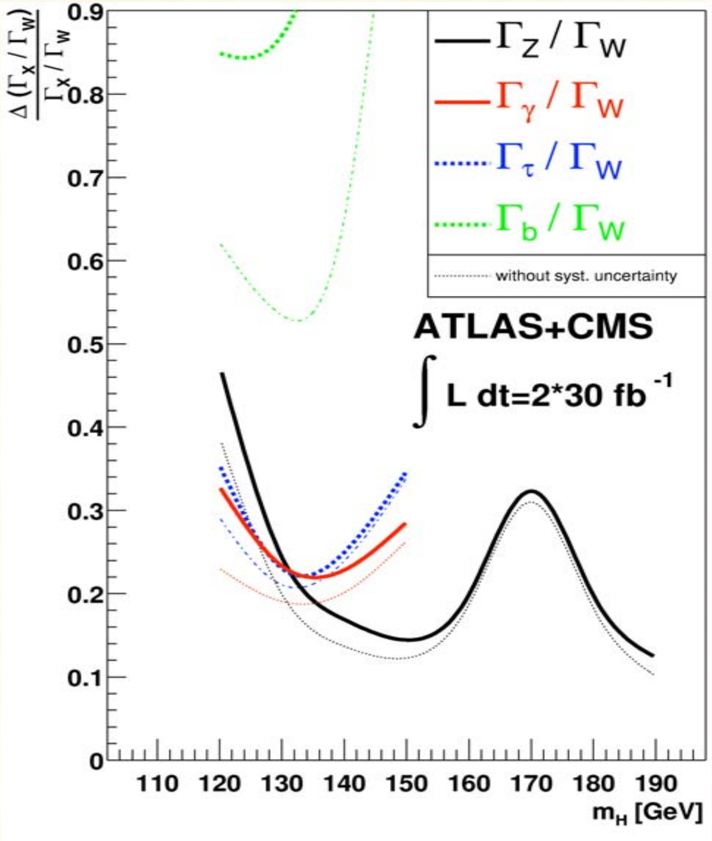
$\Delta\alpha_{WH} = \Delta\alpha_{ZH} = 7\%$

$\Delta\beta = 1\%$

Step 1: measurement of ratios of partial decay width:

Assumption: only one light Higgs boson

To cancel Γ_H, normalization to Γ_W is made
(suitable channel, measurable over a large mass range ~120–200 GeV)

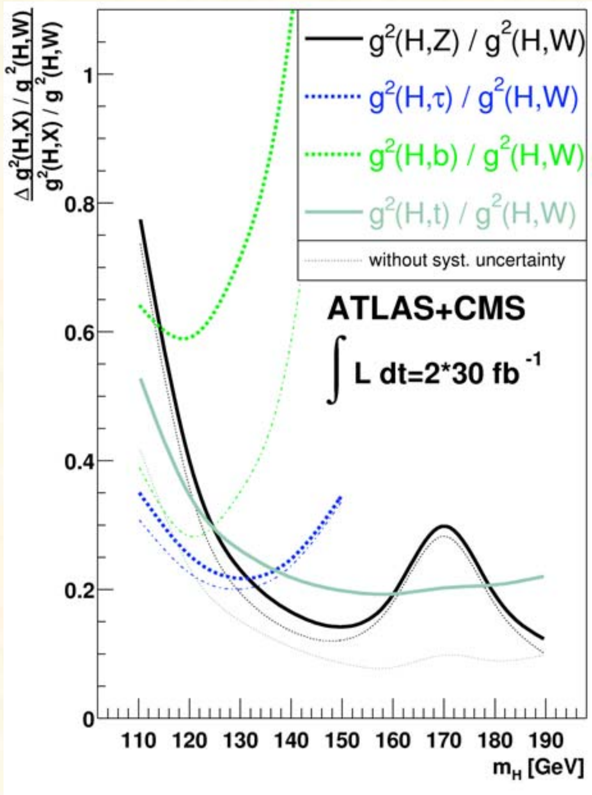


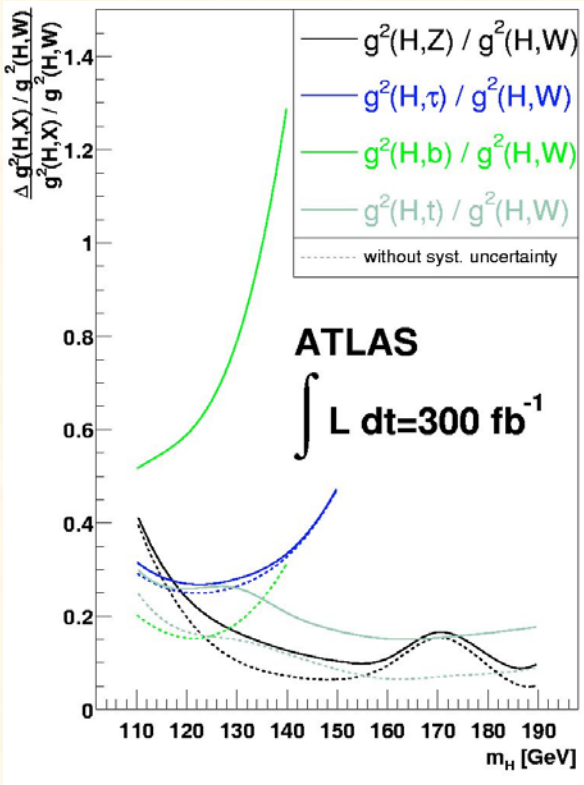
Note: optimistic assumptions for H → bb (based on old studies)

Step 2: measurement of ratios of couplings:

Additional assumption: particle content in the gg- and γγ-loops are known;

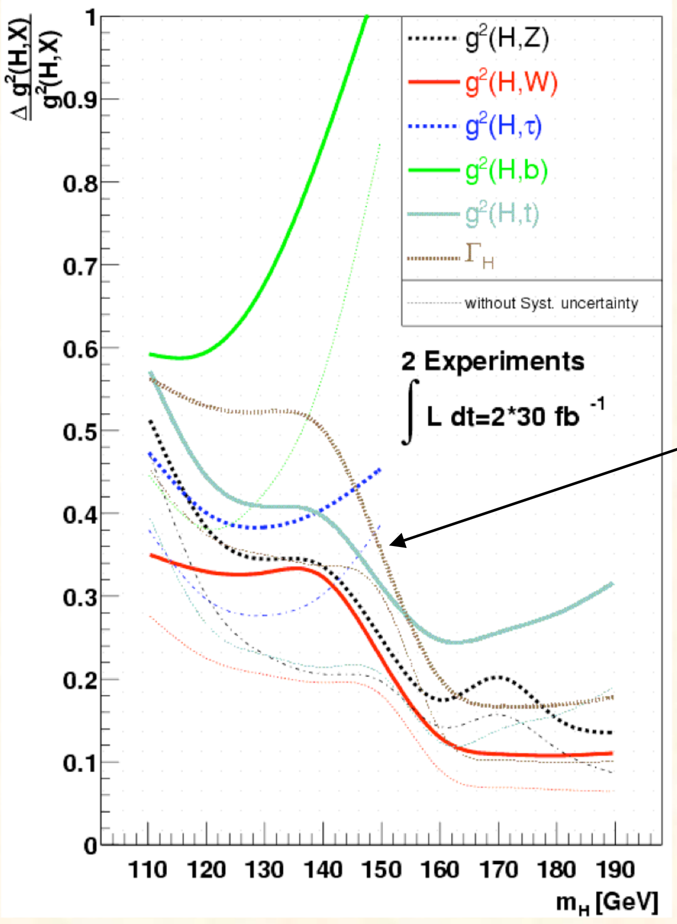
Information from Higgs production is now used as well;
Important for the determination of the top-Yukawa coupling



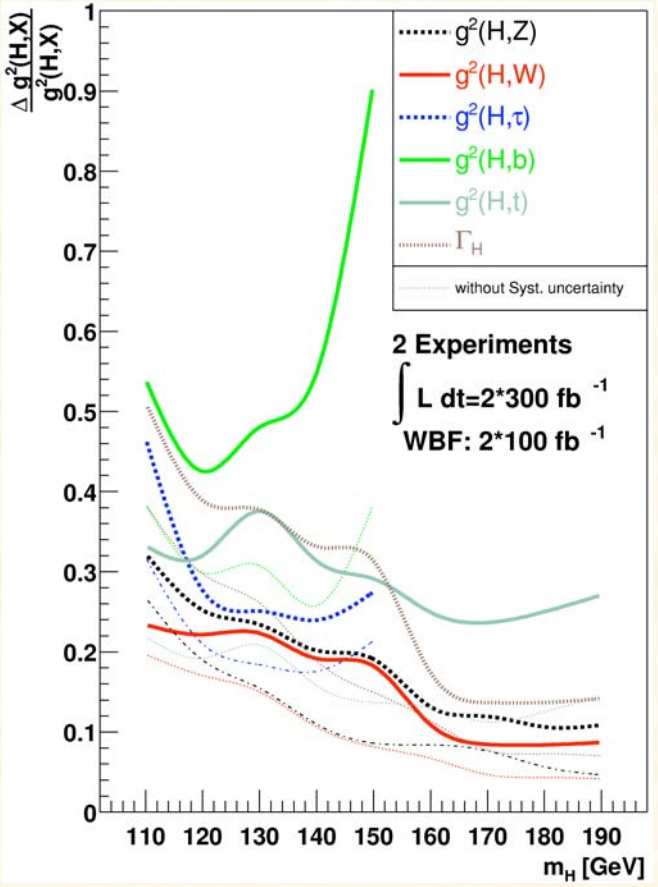


Step 3: measurement of couplings (absolute values):

Needs additional *("mild")* theoretical assumptions:
- use lower limit on Γ_H from visible decay modes
- assume that g (H,W) are bound from above by the Standard Model value:
  $g^2(H,W) \leq g^2(H,W,SM)$; (valid for any model that contains only Higgs doublets and singlets)
  (upper value is motivated from WW scattering unitarity arguments)



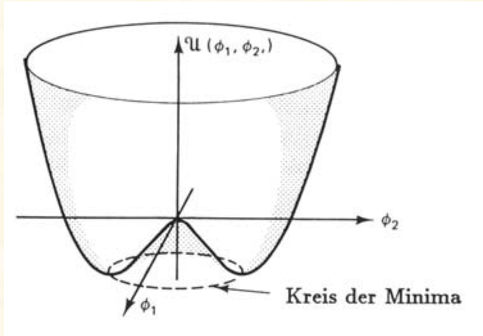
Total width is "measured" as well



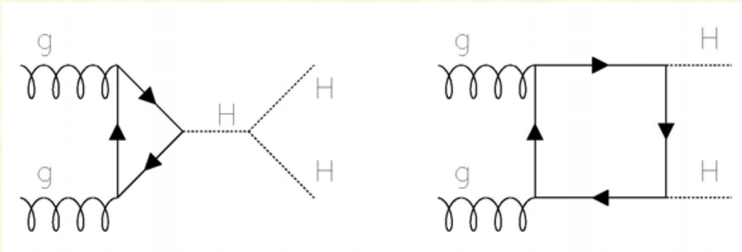
(iv) Higgs boson self-coupling ?

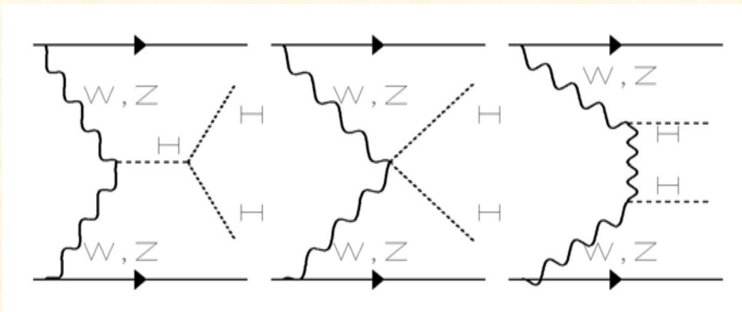
To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

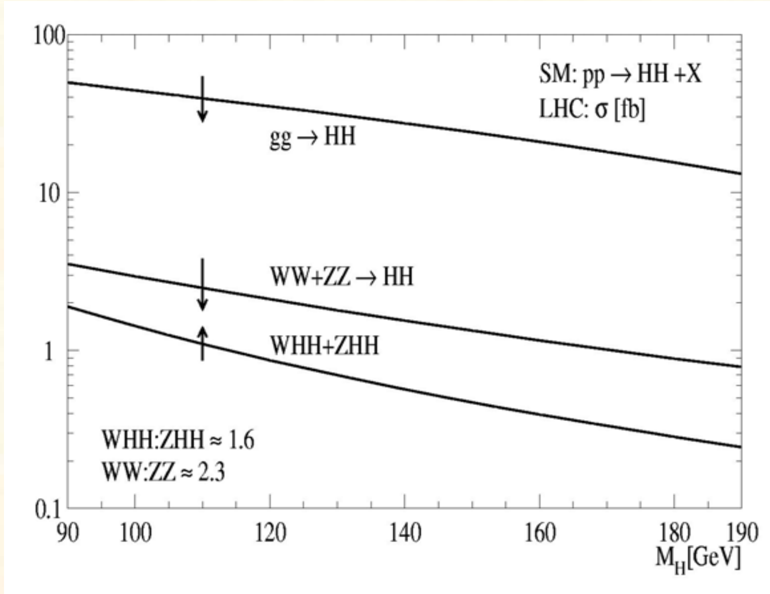
$$\lambda^{SM}_{HHH} = 3\,\frac{m_H^2}{v}\,, \qquad \lambda^{SM}_{HHHH} = 3\,\frac{m_H^2}{v^2}$$



Cross sections for HH production:





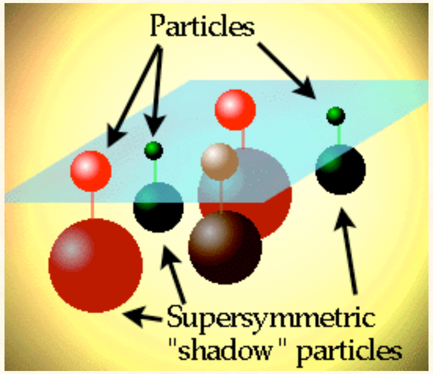


small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC
need Super LHC $L = 10^{35}$ cm^{-2} sec^{-1}, 6000 fb^{-1}
even there: a measurement is very difficult, needs more studies.

The Higgs Sector

in the MSSM



The Higgs Sector in the MSSM

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

Determined by two parameters: m_A, $\tan\beta$

Fixed mass relations at tree level:
(Higgs self coupling in MSSM fixed by gauge couplings)

$$m^2_{H,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_Z m^2_A \cos^2 2\beta}\right)$$

$$m^2_h \leq m^2_Z \cos^2 2\beta \leq m^2_Z$$

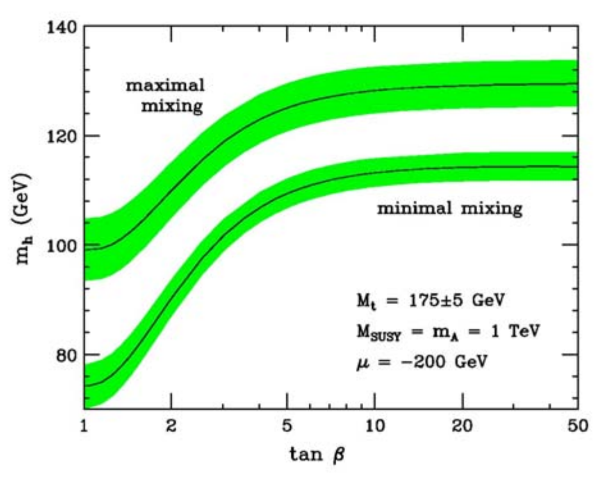
Important radiative corrections !! (tree level relations are significantly modified)
→ upper mass bound depends on top mass and mixing in the stop sector

$$m^2_h \leq m^2_Z + \frac{3g^2 m_t^4}{8\pi^2 m^2_W}\left[\ln\left(\frac{M^2_S}{m^2_t}\right) + x^2_t\left(1 - \frac{x^2_t}{12}\right)\right]$$

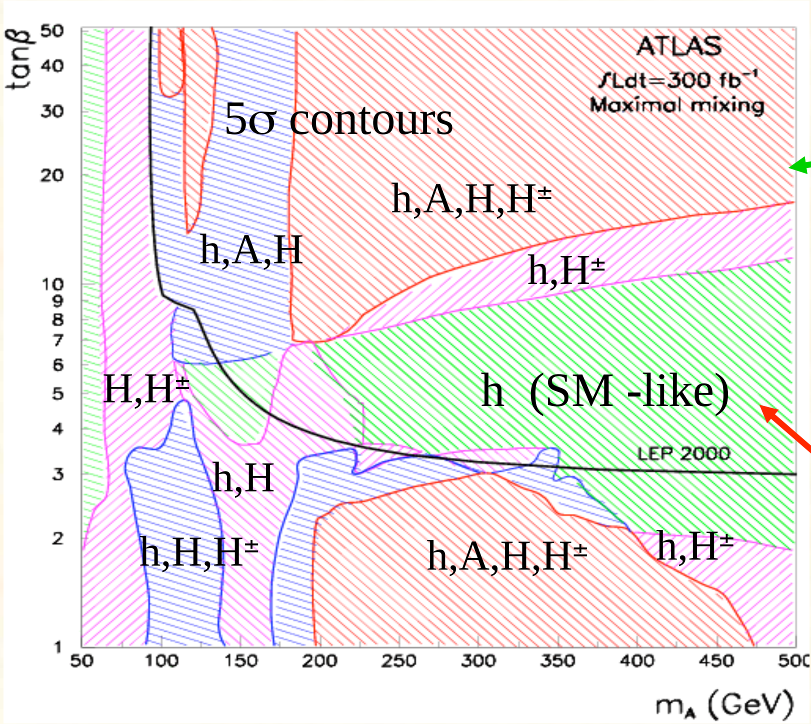
where: $M^2_S = \frac{1}{2}\left(M^2_{\tilde{t}_1} + M^2_{\tilde{t}_2}\right)$ and $x_t = (A_t - \mu \cot\beta) \,/\, M_S$

→ m_h < 115 GeV for no mixing
→ m_h < 135 GeV for maximal mixing

i.e., no mixing scenario: in LEP reach
max. mixing: easier to address at the LHC



LHC discovery potential for SUSY Higgs bosons



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

A, H, H± cross-sections ~ $\tan^2\beta$

- best sensitivity from A/H → ττ, H± → τν
  (not easy the first year ....)

- A/H → μμ experimentally easier
  (esp. at the beginning)

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

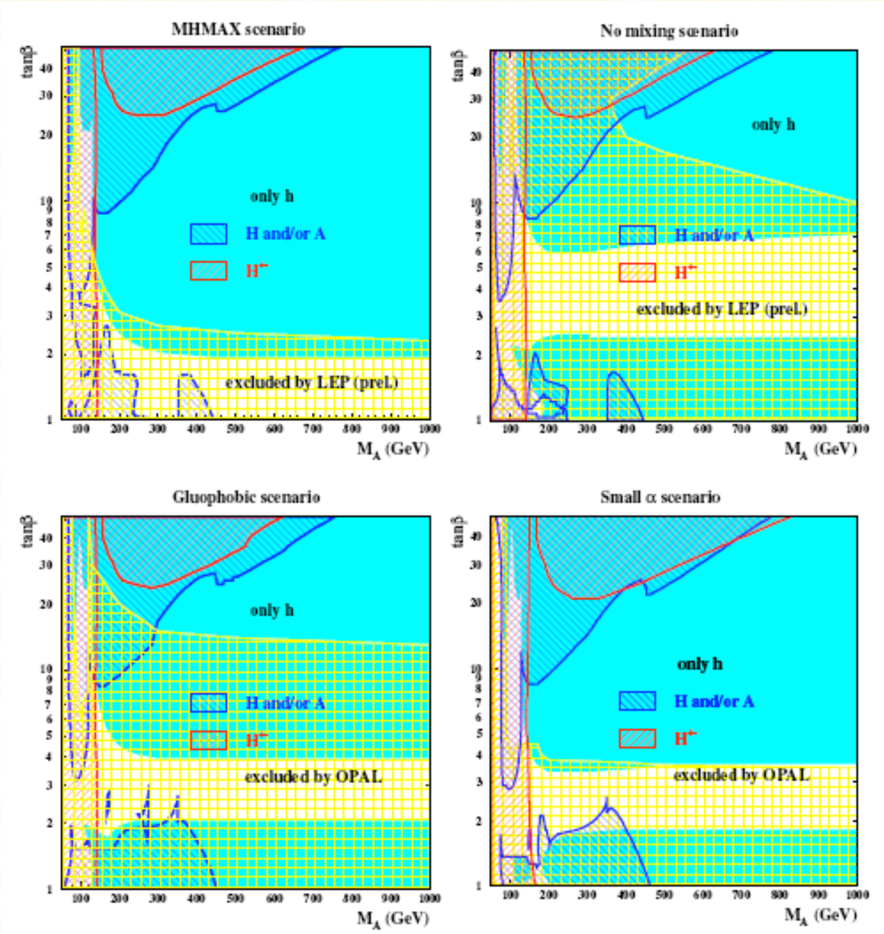
* Validated by recent ATLAS and CMS full simulation studies *

Coverage in the large m_A wedge region can be improved (slightly) by:
- Higher luminosity: sLHC
- Additional SUSY decay modes (however, model dependent)

Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ $\gamma\gamma$ and Z→4 ℓ

Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2