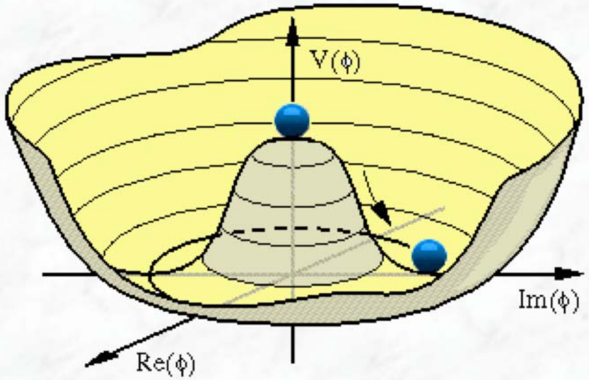
8. Physics of the Higgs Boson



8.1 The Higgs boson in the Standard Model

8.2 Properties of the Higgs boson

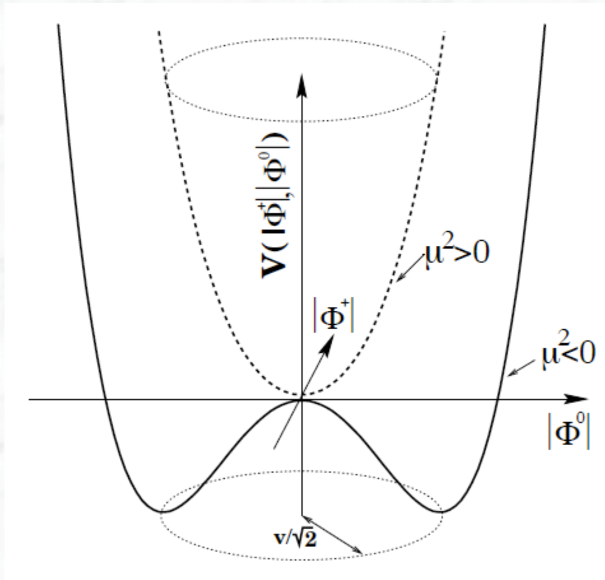
8.3 Higgs boson production at hadron colliders

8.4 The search for the Higgs boson at the Tevatron

8.5 Status and prospects for Higgs boson searches at the LHC

8.1 The Higgs boson in the Standard Model

(a brief summary, for more details, see lecture notes)



The structure of the Standard Model

Fundamental principle: **Local gauge invariance**
Prototype: **Quantum Electrodynamics (QED)**

Free Dirac equation: $i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$

Lagrangian formalism: $L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi$

Local gauge transformation: $\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$

(derivative: $\partial_{\mu}\psi \rightarrow e^{i\alpha(x)}\partial_{\mu}\psi + ie^{i\alpha(x)}\psi\partial_{\mu}\alpha$,
$\delta_{\mu}\alpha$ term breaks the invariance of L)

Invariance of L under local gauge transformations can be accomplished by introducing a gauge field A_{μ}, which transforms as:

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha$$

where $e = g_e/4\pi$ = coupling strength

Can be formally achieved by the construction of a “modified” derivative

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

(covariant derivative)

→ Lagrangian of QED:

$$L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi + \underbrace{e\overline{\psi}\gamma^{\mu}A_{\mu}\psi}_{\text{interaction term}} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where $F_{\mu\nu}$ is the usual field strength tensor: $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

Note:

(i) Imposing local gauge invariance leads to the interacting field theory of QED

(ii) A mass term ($\frac{1}{2}m^2 A_{\mu}A^{\mu}$) for the gauge field A_{μ} would violate gauge invariance

Similar for the Standard Model interactions:

Quantum Chromodynamics (QCD):

$$D_\mu = \partial_\mu + igT_a G_\mu^a$$

$$G_\mu^a \to G_\mu^a - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G_\mu^c$$

SU(3) transformations, 8 gauge fields,
8 massless gluons, Gluon self-coupling

- T_a (a = 1,…,8) generators of the SU(3) group (independent traceless 3x3 matrices)
- G_μ gluon fields
- g = coupling constant

Electroweak Interaction (Glashow, Salam, Weinberg):
$SU(2)_L \times U(1)_Y$ transformations,
4 gauge fields, (W_μ^1, W_μ^2, W_μ^3, B_μ)

Physical states:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right)$$

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3$$

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3$$

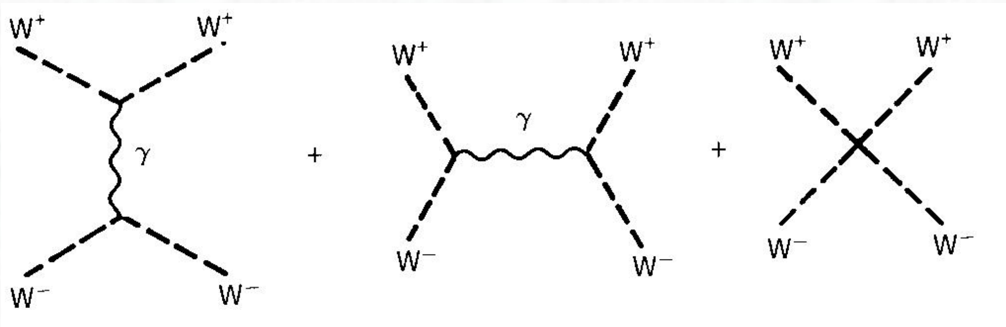
Problems at that stage:

- **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)**



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \qquad \text{for} \qquad s \rightarrow \infty$$

Solution to **both** problems:

- create mass via spontaneous breaking of electroweak symmetry

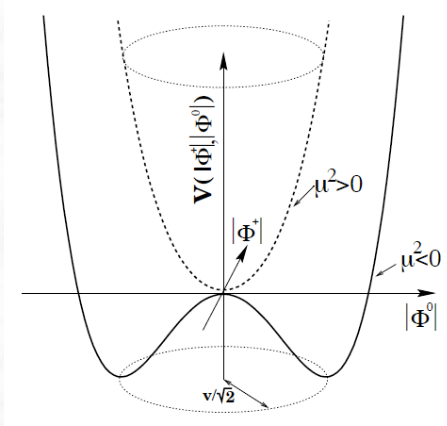
- introduce a scalar particle that regulates the WW scattering amplitude

➔ **Higgs Mechanism**

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 : $$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

- Lagrangian for the scalar fields:
  g, g' = SU(2), U(1) gauge couplings

$$L_2 = \left|\left(i\partial_\mu - g\mathbf{T}\cdot\mathbf{W}_\mu - g'\frac{Y}{2}B_\mu\right)\phi\right|^2 - V(\phi)$$

- 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:

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix} \Rightarrow$$

Particle content and masses

- Mass terms for the $W^{\pm}$ bosons:

$$\boxed{M_{W^{\pm}} = \frac{1}{2} v g}$$

- Remaining terms off-diagonal in W_μ^3 and B_μ:

$$\frac{1}{8} v^2 (W_\mu^3, B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} = \frac{1}{8} v^2 \left[g W_\mu^3 - g' B_\mu \right]^2 + 0 \left[g' W_\mu^3 + g B_\mu \right]^2$$

- Massless photon:

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} \quad with \quad \boxed{M_A = 0}$$

- Massive neutral vector boson:

$$Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \quad with \quad \boxed{M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}}$$

Masses of the gauge bosons:

$$\left|\left(-ig\frac{\tau}{2}\cdot\mathbf{w}_{\mu}-i\frac{g'}{2}B\right)\phi\right|^{2}$$

$$=\frac{1}{8}\left|\begin{pmatrix} gW_{\mu}^{3}+g'B_{\mu} & g(W_{\mu}^{1}-iW_{\mu}^{2}) \\ g(W_{\mu}^{1}+iW_{\mu}^{2}) & -gW_{\mu}^{3}+g'B_{\mu}\end{pmatrix}\begin{pmatrix}0\\ v\end{pmatrix}\right|^{2}$$

$$=\frac{1}{8}v^{2}g^{2}\left[(W_{\mu}^{1})^{2}+(W_{\mu}^{2})^{2}\right]+\frac{1}{8}v^{2}(g'B_{\mu}-gW_{\mu}^{3})(g'B^{\mu}-gW^{3\mu})$$

$$=\left(\frac{1}{2}vg\right)^{2}W_{\mu}^{+}W^{-\mu}+\frac{1}{8}v^{2}(W_{\mu}^{3},B_{\mu})\begin{pmatrix} g^{2} & -gg' \\ -gg' & g'^{2}\end{pmatrix}\begin{pmatrix}W^{3\mu}\\ B^{\mu}\end{pmatrix}$$

Important relations in the Glashow-Salam-Weinberg model:

• Relation between the gauge couplings:

$$\frac{g'}{g} = \tan\theta_W$$

→ Important prediction of the GSW with a Higgs doublet:

$$\frac{M_W}{M_Z} = \cos\theta_W$$

or expressed in terms of the ρ parameter:

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

• From the M_W relation the value of the vacuum expectation value of the Higgs field can be calculated:

$$\frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \qquad \rightarrow \quad v = 246\ GeV$$

where G_F = Fermi constant, know from low energy experiments (muon decay)

Masses of the Fermions:

- The same Higgs doublet which generates $W^{\pm}$ and Z masses is sufficient to give masses to the fermions (leptons and quarks):

  e.g. for electrons: use an arbitrary coupling G_e

$$L_3 = -G_e \left[(\bar{\nu}_e, \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \bar{e}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right]$$

- Spontaneous symmetry breaking:

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

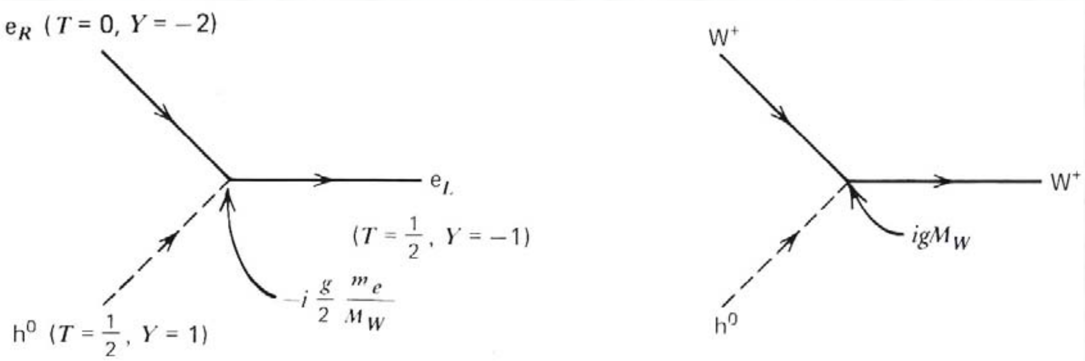
$$L_3 = -\frac{G_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) h$$

mass term

interaction term with the Higgs field

- Important relation: coupling of the Higgs boson to fermions is proportional to their mass

$$\boxed{G_f = \frac{\sqrt{2}\, m_f}{v}}$$



and finally...... a massive scalar with self-coupling, the **Higgs boson**:

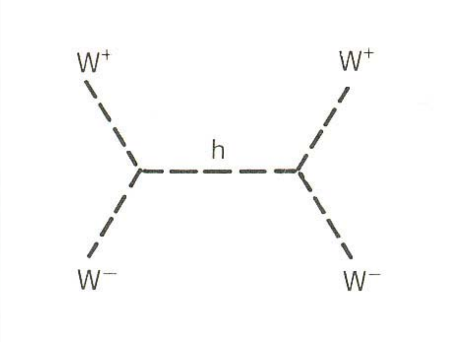
• Mass: $$\boxed{m_h^2 = 2v^2\lambda}$$

(since λ is not predicted by theory, the mass of the Higgs boson is unknown)

• Self-coupling: $$-\lambda v h^3 - \frac{1}{4}\lambda h^4$$

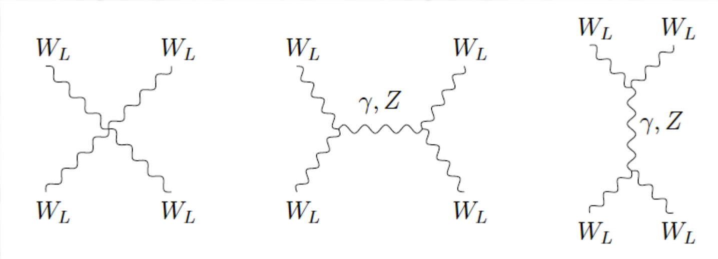
….. and:

• The additional diagram, with Higgs boson exchange, regulates the divergences in the longitudinal WW scattering



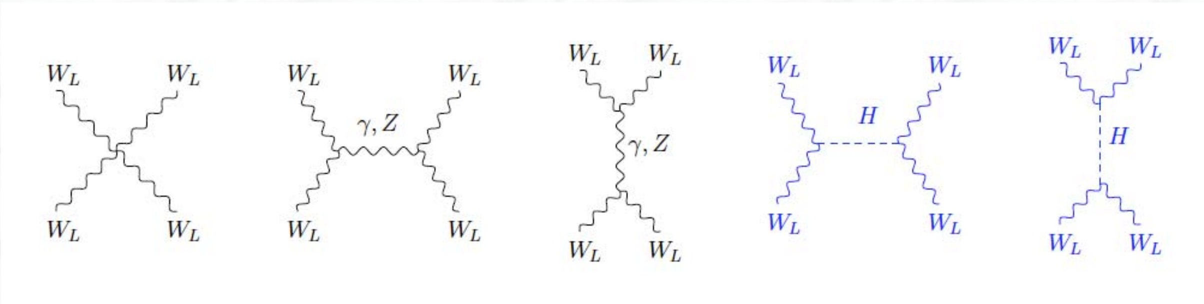
The Higgs boson as a UV regulator

Scattering of longitudinally polarized W bosons



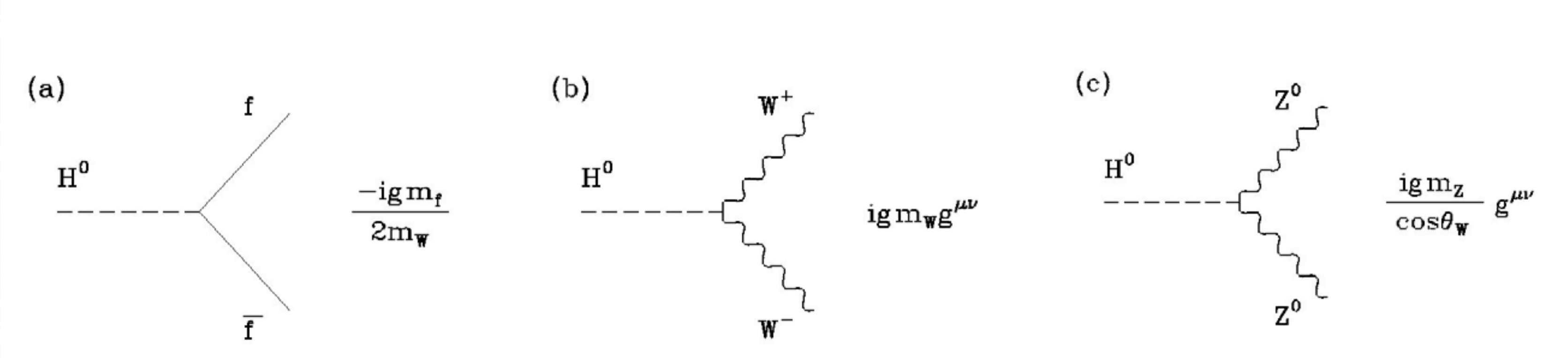
$$-iM(W^+W^- \to W^+W^-) \sim \frac{s}{m_W^2} \qquad \text{for} \qquad s \to \infty$$

Higgs boson guarantees unitarity (if its mass is < ~1 TeV)



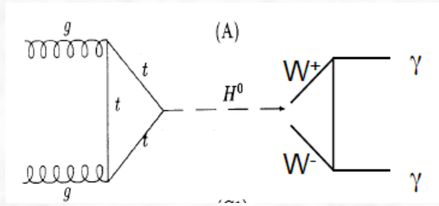
$$-iM(W^+W^- \to W^+W^-) \sim m_H^2 \qquad \text{for} \qquad s \to \infty$$

8.2 Higgs boson properties



Higgs Boson Decays

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



H

W⁺, Z, t, b, c, τ⁺,.........., g, γ

W⁻, Z, t, b, c, τ ,.........., g, γ

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

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

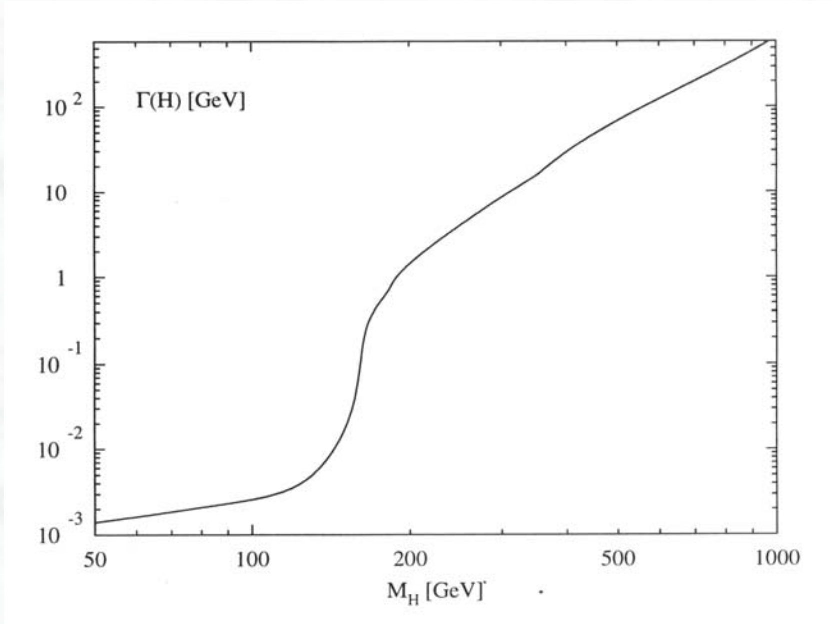
$$\text{where:}\quad \delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_V^2, \quad \beta = \text{velocity}$$

(+ W-loop contributions)

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

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

Total width



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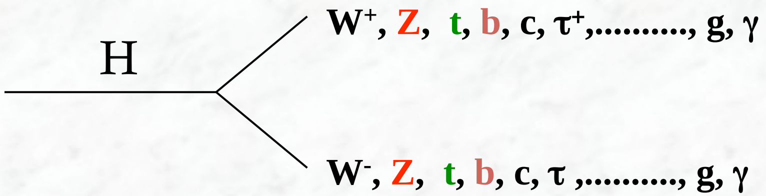
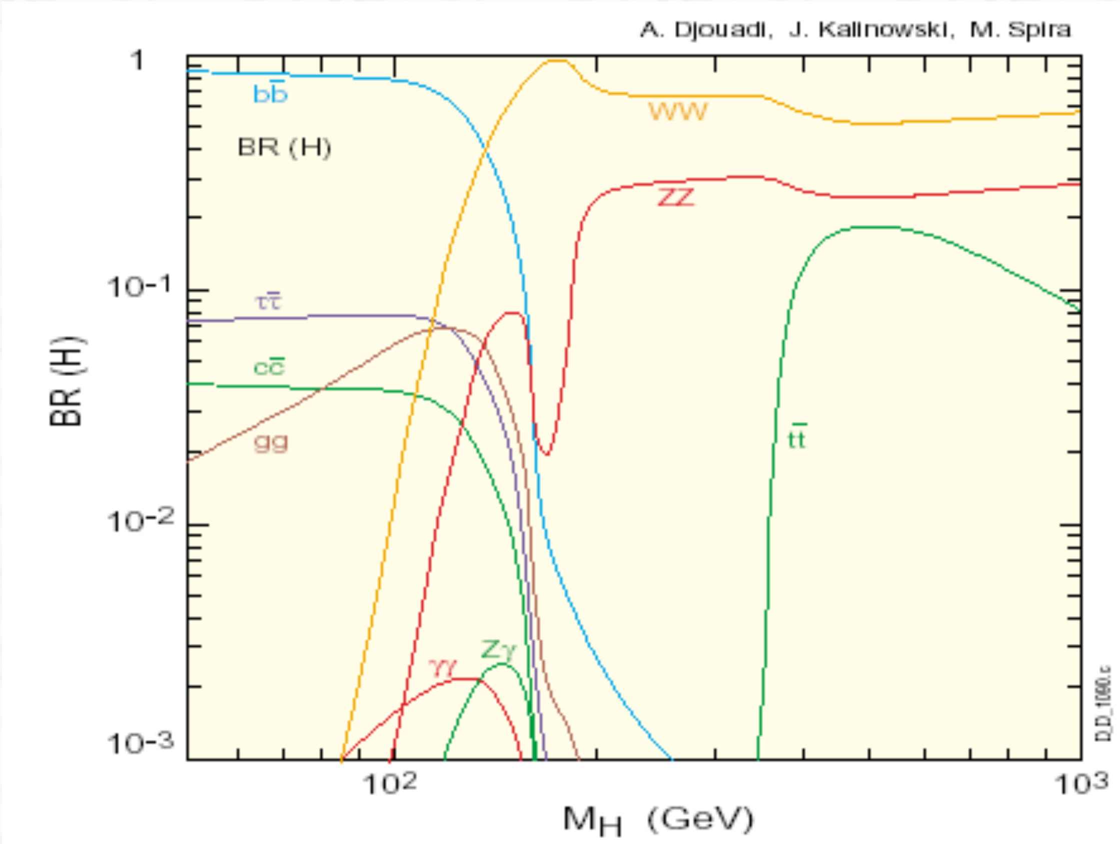




Constraints on the Higgs boson mass

1. Constraints from theory
2. Indirect limits from electroweak precision data (theory and experiment)
3. Limits from Direct Searches (LEP, Tevatron)

(i) Theory Constraints on the Higgs boson mass

- Unitarity limit:

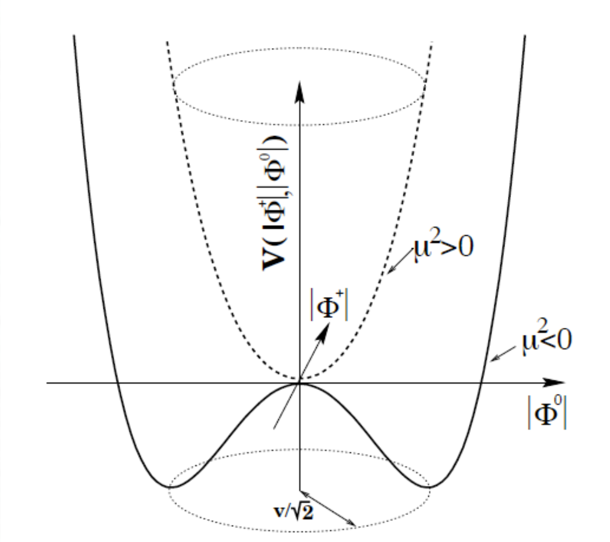
  If Higgs boson too heavy, the regulation of the WW cross section is less effective and unitarity is violated again

  → $m_H <$ ~1 TeV (as just discussed)

- Stricter limits from the energy dependence of the Higgs boson self coupling λ

  − Stability of the vacuum
  - Diverging coupling $\lambda(Q^2)$

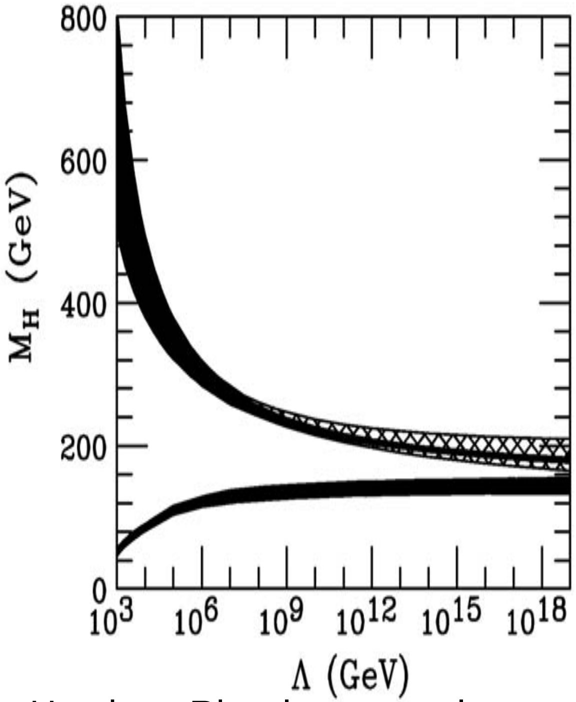
  → next slides



Tighter Higgs mass constraints:

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda(Q^2)$
(if the Standard Model is assumed to be valid up to some scale Λ)

$$\lambda(Q^2) = \lambda_0 \left\{ 1 + \frac{3\lambda_0}{2\pi^2} \log\left(2\frac{Q^2}{v^2}\right) + \ldots - \frac{3g_t^4}{32\pi^2} \log\left(2\frac{Q^2}{v^2}\right) + \ldots \right\} \qquad \text{where} \quad \lambda_0 = \frac{m_h^2}{v^2}$$



Hambye, Risselmann et al.

Upper bound: diverging coupling (Landau Pole)

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

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

(ii) Indirect limits from electroweak precision data   (m_W and m_t)

Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between m_W, m_t and m_H

Electromagnetic constant
measured in atomic transitions,
e^+e^- machines, etc.

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant
measured in muon
decay

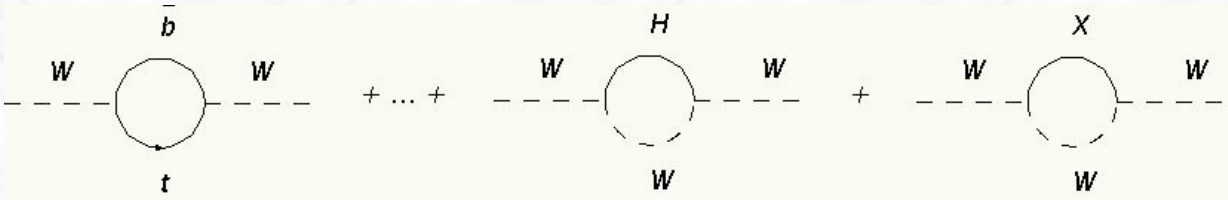
weak mixing angle
measured at
LEP/SLC

radiative corrections
$\Delta r \sim f(m_t^2, \log m_H)$
$\Delta r \approx 3\%$

G_F, α_{EM}, $\sin\theta_W$

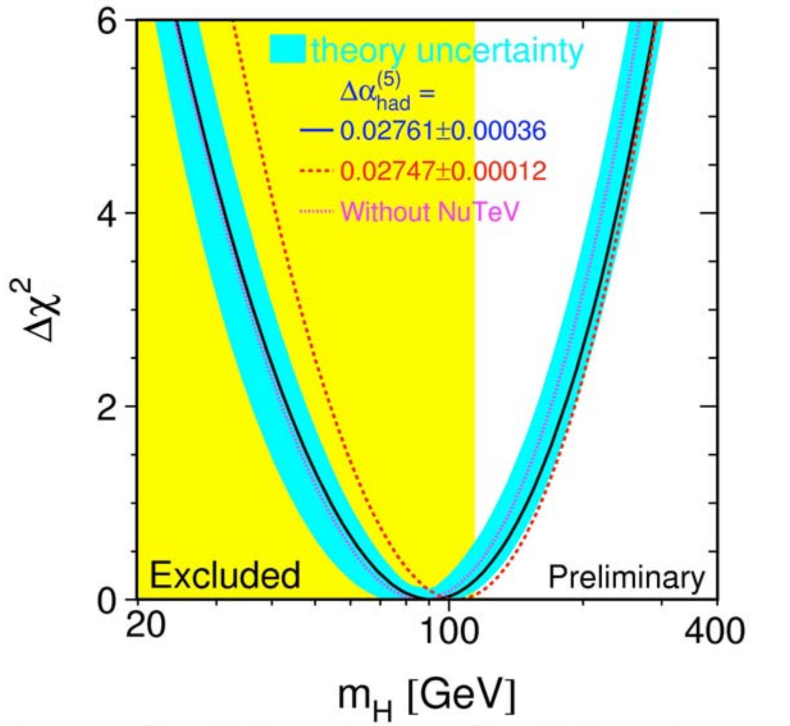
are known with high precision

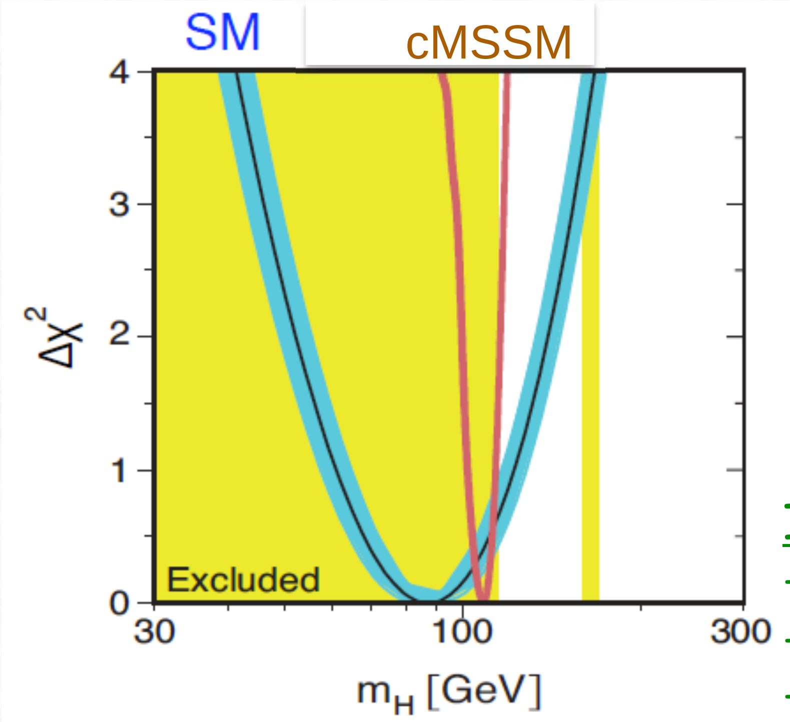
Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory,
radiative corrections)



Fit in the constrained MSSM

O. Buchmüller et al. (2010)





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

Results of the precision el.weak measurements: (LEWWG-2009):

$$m_H = 87^{+35}_{-26}\ GeV$$

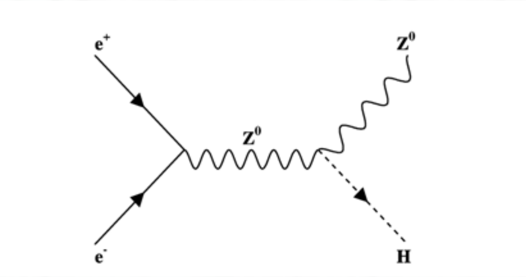
$$m_H = 108^{+6}_{-6}\ GeV$$

(iii) Constraints from

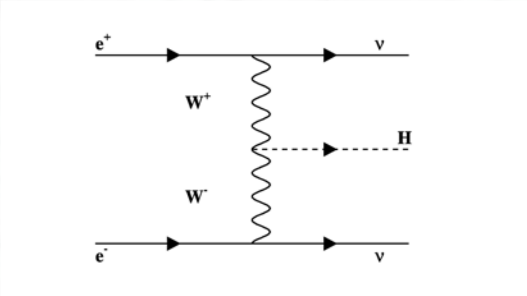
direct searches at LEP

Higgs bosons searches at LEP

Higgs-Strahlung: $e^+ e^- \to Z H$



WW-Fusion: $e^+ e^- \to \nu\nu H$



Higgs decay branching ratios for m_H=115 GeV/c^2:
BR ($H \to bb$) = 74%, BR ($H \to \tau\tau$, WW, gg) = 7% each, BR($H \to cc$) = 4%

Decay modes searched for:

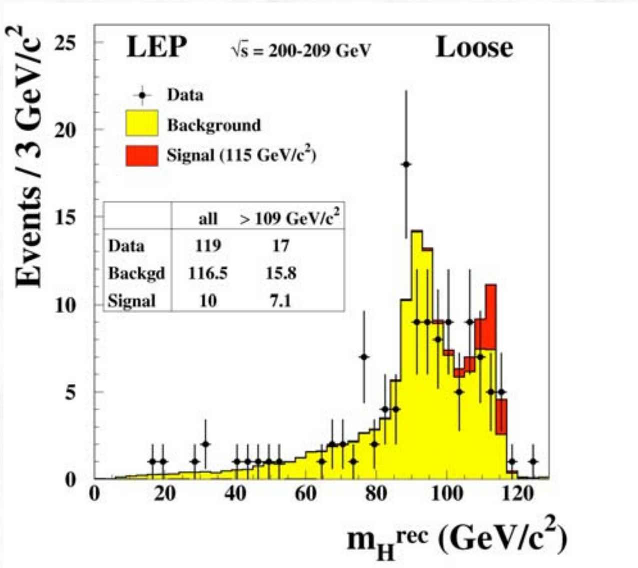
- Four Jet channel: $HZ \to bb\, qq$
- Missing energy channel: $\to bb\, \nu\nu$
- Leptonic channel: $\to bb\, ee$, $bb\, \mu\mu$
- Tau channels: $\to bb\, \tau\tau$, and $\tau\tau\, qq$

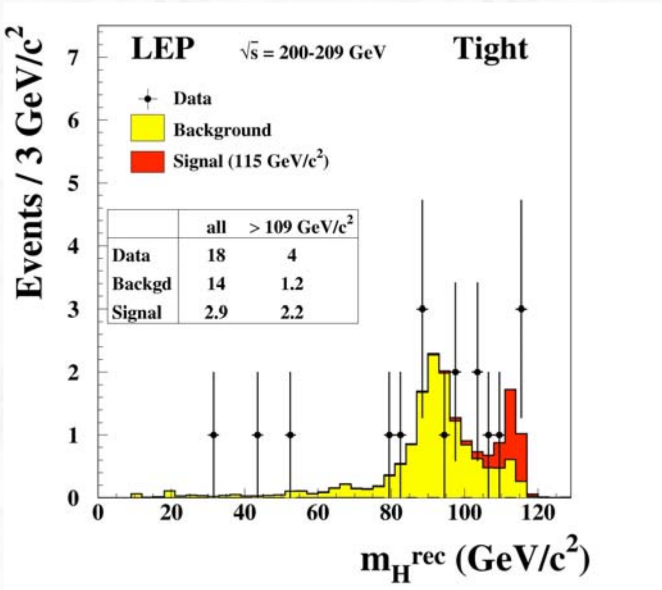
Results of the final LEP analysis:

Final results have been published: CERN-EP / 2003-011:

Based on final calibrations of the detectors, LEP-beam energies, final Monte Carlo simulations and analysis procedures.

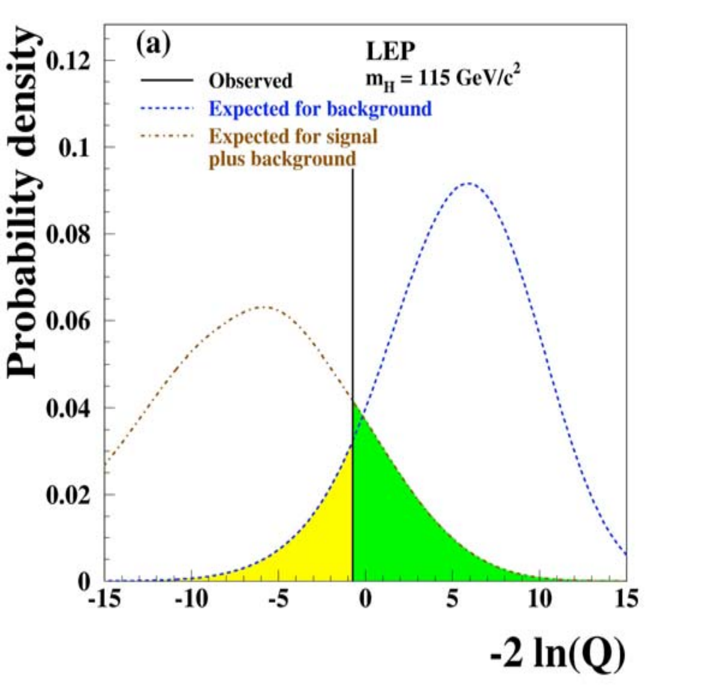
The reconstructed bb mass for two levels of signal purity (loose and tight cuts):





Clear peak in the background prediction in the vicinity of m_Z due to the $e^+e^- \rightarrow ZZ$ background, which is consistent with the data.

Final combined LEP result



	$1-CL_b$	CL_{s+b}
LEP	0.09	0.15
ALEPH	3.3×10^{-3}	0.87
DELPHI	0.79	0.03
L3	0.33	0.30
OPAL	0.50	0.14
Four-jet	0.05	0.44
All but four-jet	0.37	0.10

$1\text{-}\ CL_B = 0.09 \quad \leftrightarrow$

Signal significance = 1.7 σ

Likelihood ratio $Q := L_{S+B} / L_B$
Test statistics: $-2 \ln Q$

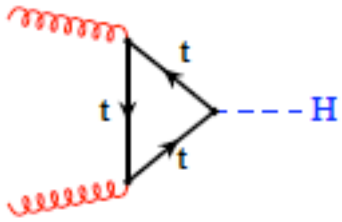
$M_H > 114.4$ GeV/c^2 (95% CL)

expected mass limit: 115.3 GeV/c^2
(sensitivity)

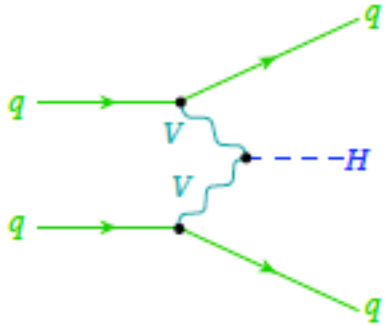
8.3 Higgs boson production at Hadron Colliders

Higgs Boson production processes at Hadron Colliders

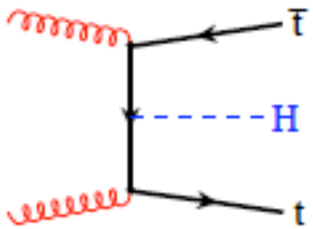
Relative importance of the various processes is different at the LHC and at the Tevatron



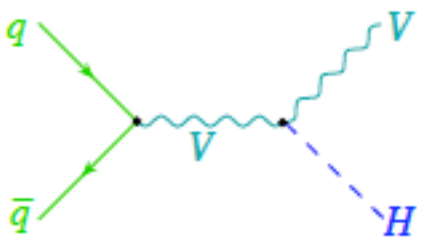
Gluon Fusion



Vector boson fusion

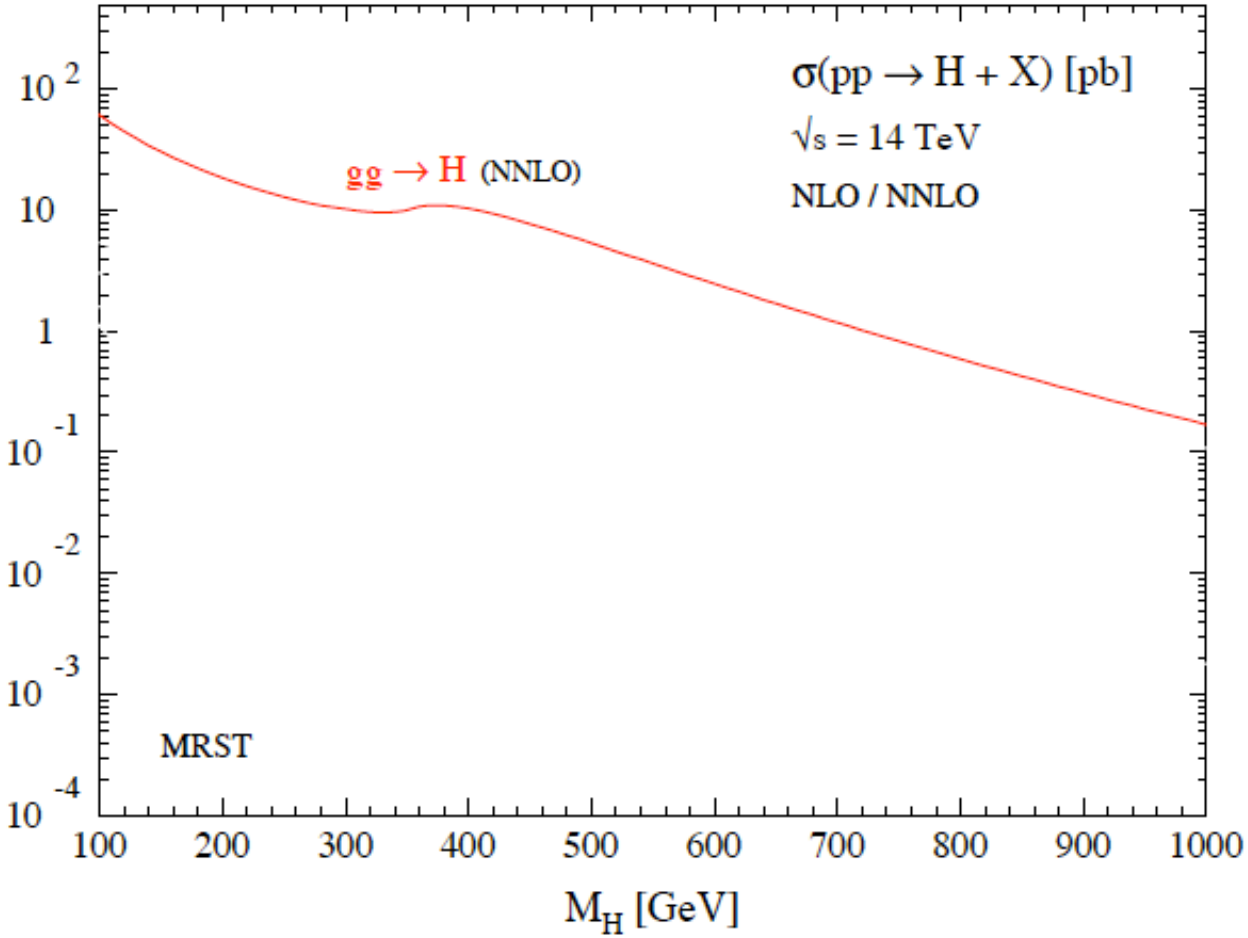


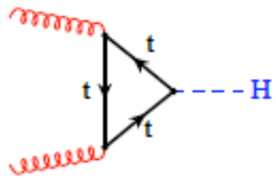
tt associated production



WH/ZH associated production

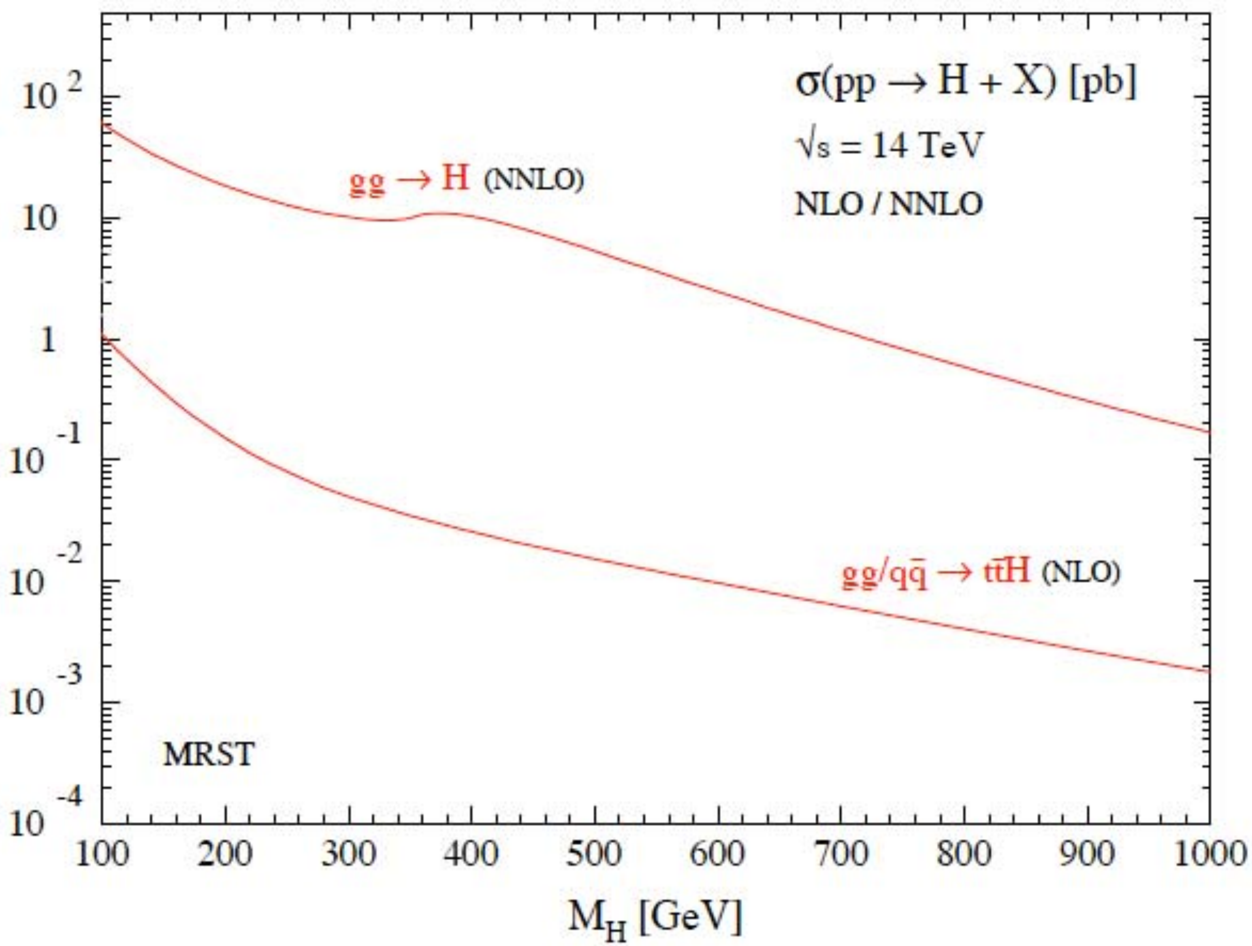
Production cross sections at the LHC

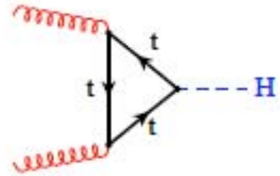


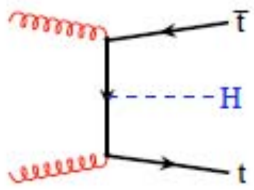


(for √s = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

Production cross sections at the LHC







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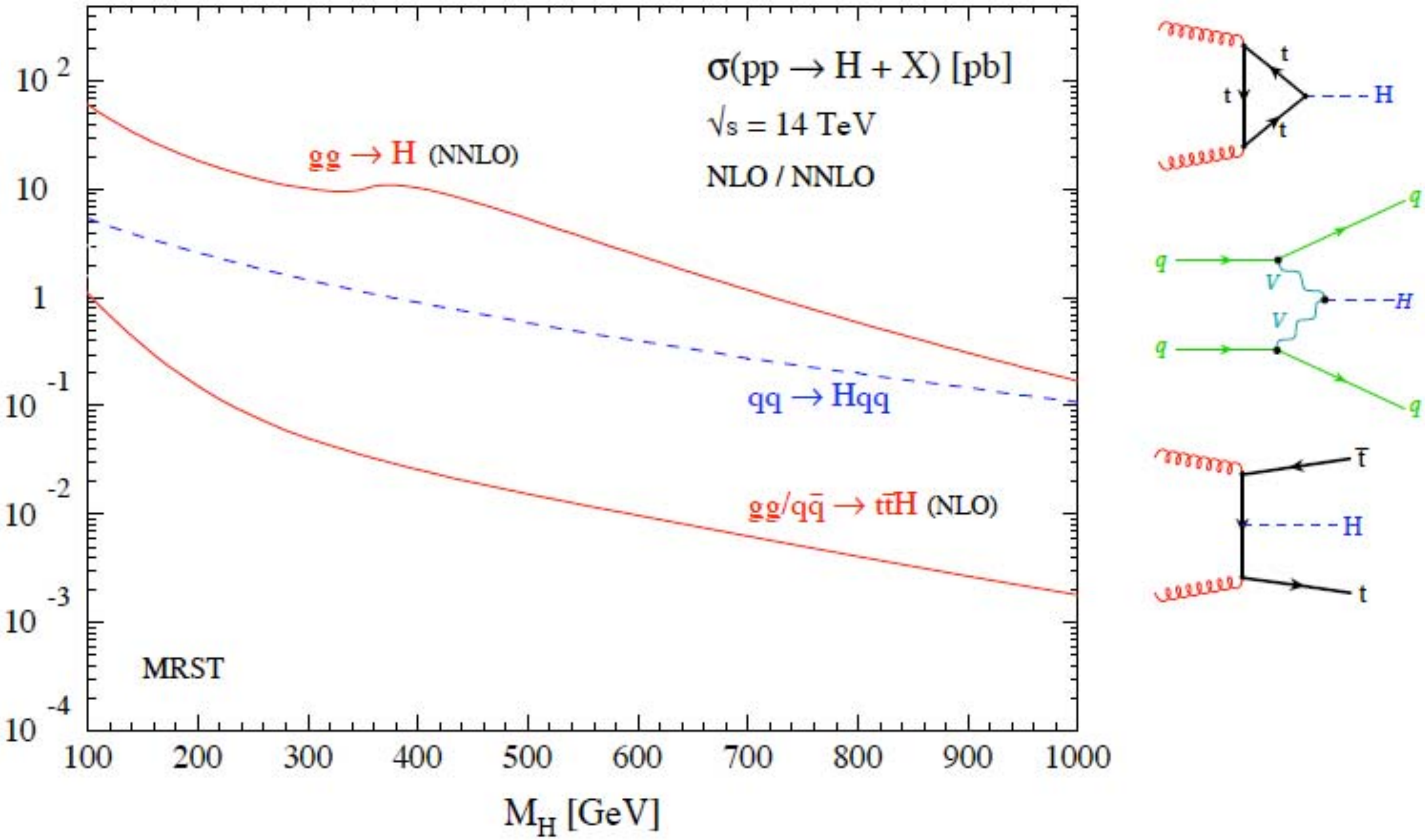
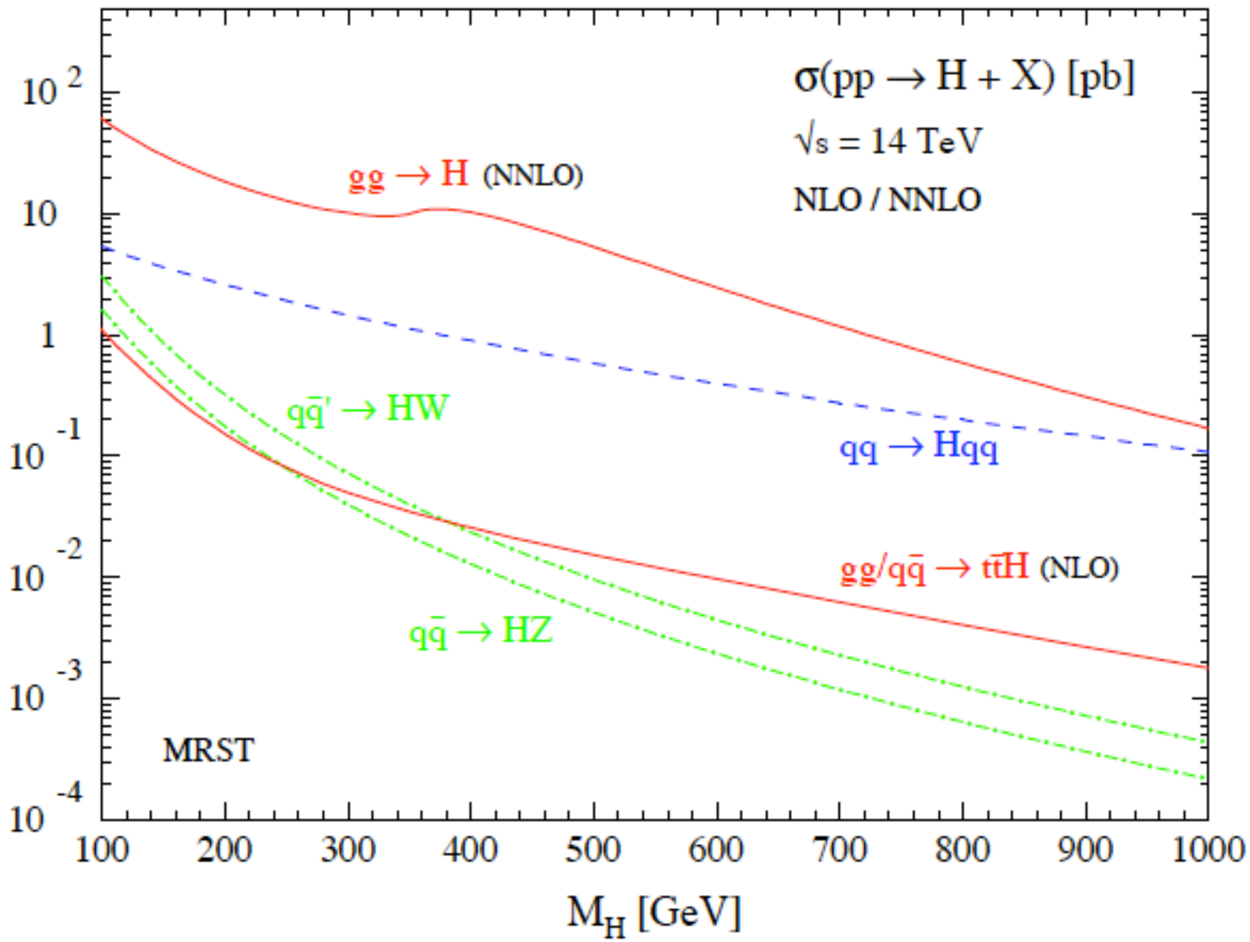
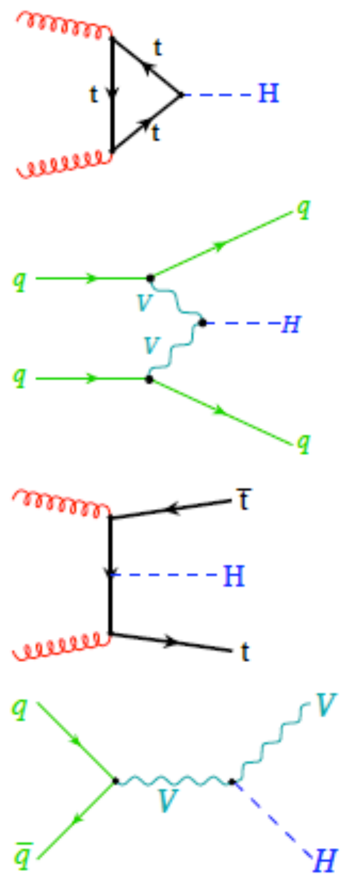
Production cross sections at the LHC



(for √s = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

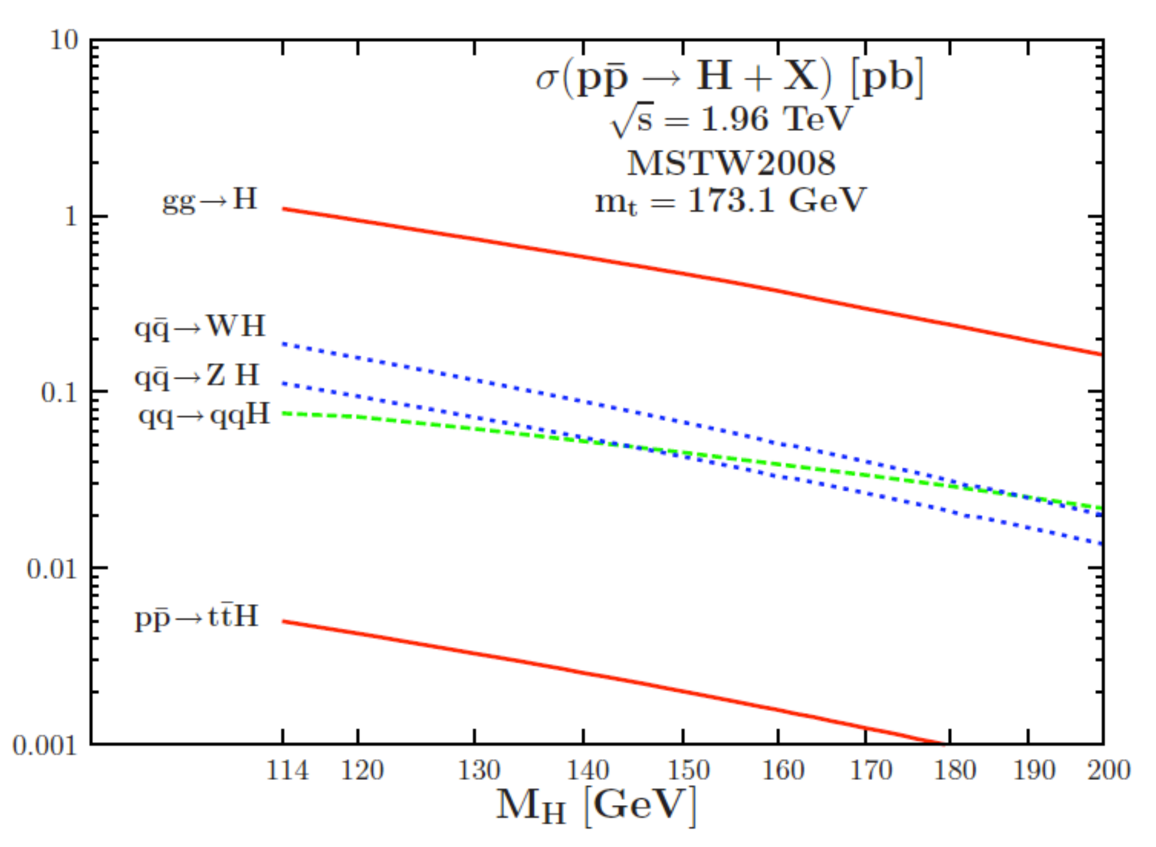
Production cross sections at the LHC





(for √s = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

Production cross sections at the Tevatron



J. Baglio, A. Djouadi, arXiv:1003.4266

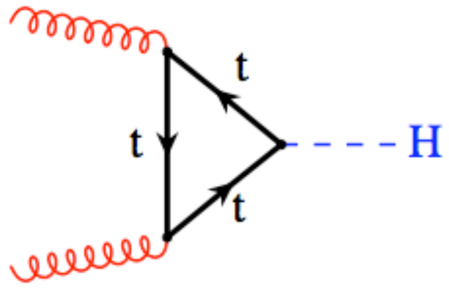
1. Gluon fusion

2./3. W/Z H associated production
Vector boson fusion

4. ttH (very small cross section)

qq → W/Z + H cross sections ~10 x larger at the LHC (√s = 14 TeV)
gg → H ~70-80 x larger at the LHC (√s = 14 TeV)

Gluon fusion:

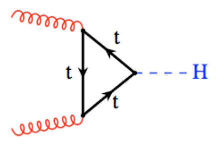


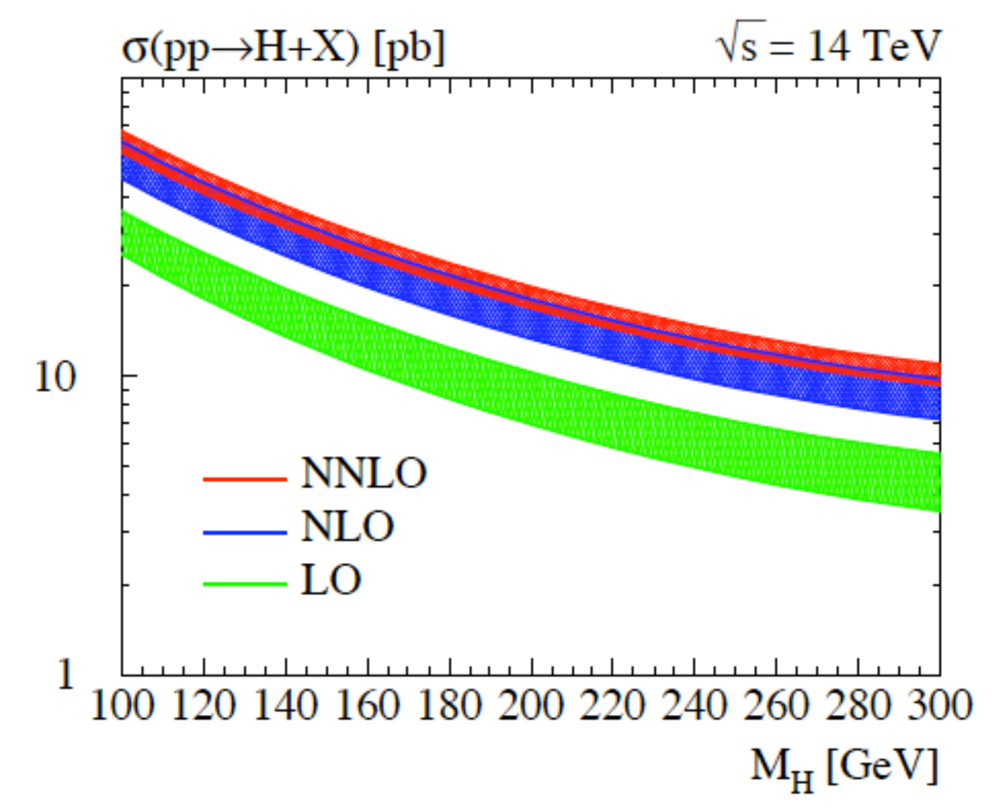
- Dominant production mode

- Sensitive to heavy particle spectrum …
  (e.g. 4th generation quarks)
  …and the corresponding Yukawa couplings
  (important for coupling measurements, top Yukawa coupling)

- Large K-factors (NLO, NNLO corrections)
  - Difficult to calculate, loop already at leading order
    (calculation with infinite top mass is used as an approximation, however, this seems to be a good approximation)
  - Nicely converging perturbative series

Higher order corrections:



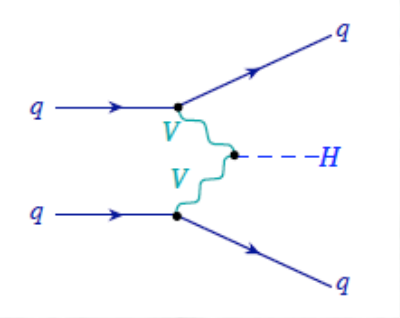


- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)

Independent variation of renormalization and factorization scales (with $0.5\ m_H < \mu_F, \mu_R < 2\ m_H$)

Vector boson fusion:



- Second largest production mode,
  Distinctive signature
  (forward jets, little jet activity in the central region)

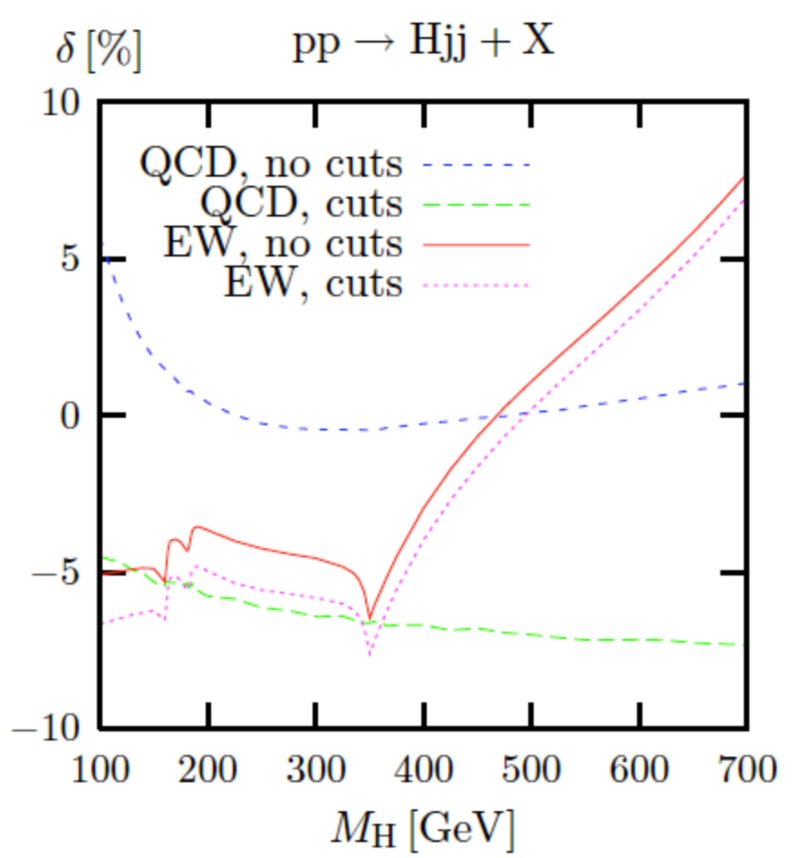
- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

  Both NLO QCD and el.weak have been calculated

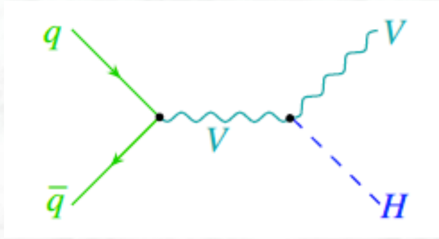
- Effective K-factor depends on experimental cuts

  Example: typical VBF cuts
  P_T(jet) > 20 GeV
  $\eta < 4.5$, $\Delta\eta > 4$, $\eta_1 \cdot \eta_2 < 0$



Ciccolini, Denner, Dittmaier (2008)

WH / ZH associated production:



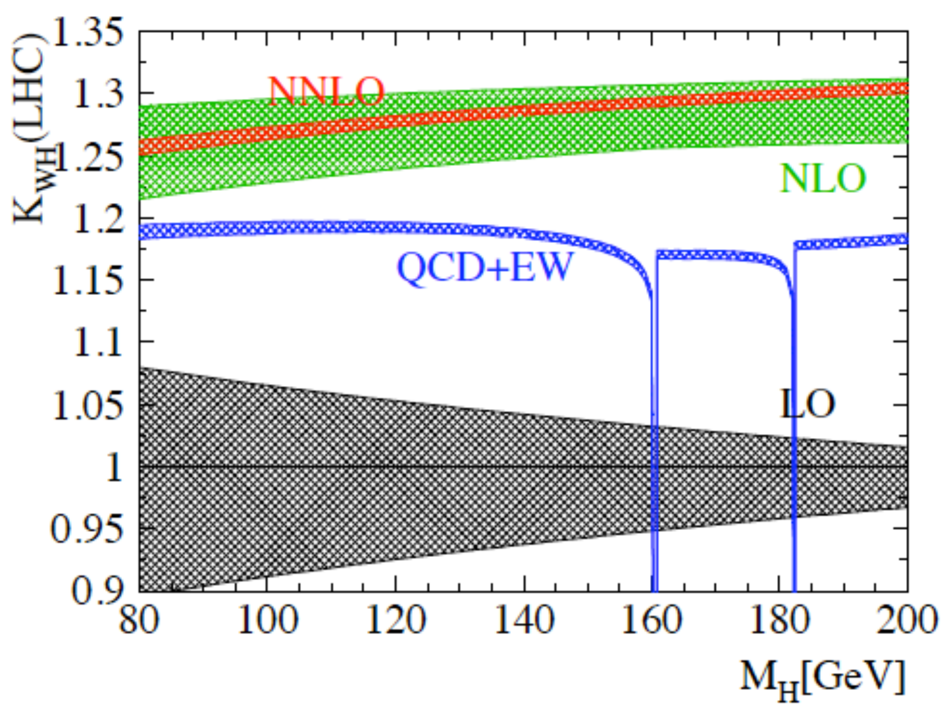
- Weak at the LHC,
  Relatively stronger at the Tevatron

- Allows for a Higgs-decay-independent trigger
  W → lν, Z → ll

- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

  Both NLO QCD and el.weak
  corrections available

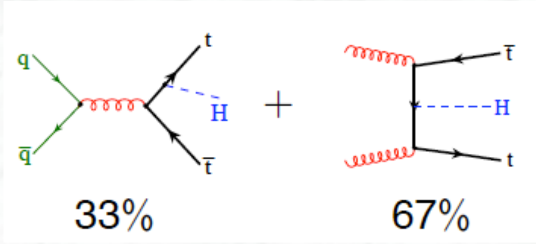


Brein, Djouadi, Harlander, (2003)

Han, Willenbrock (1990)

Ciccolini, Dittmaier, Krämer (2003)

ttH associated production:

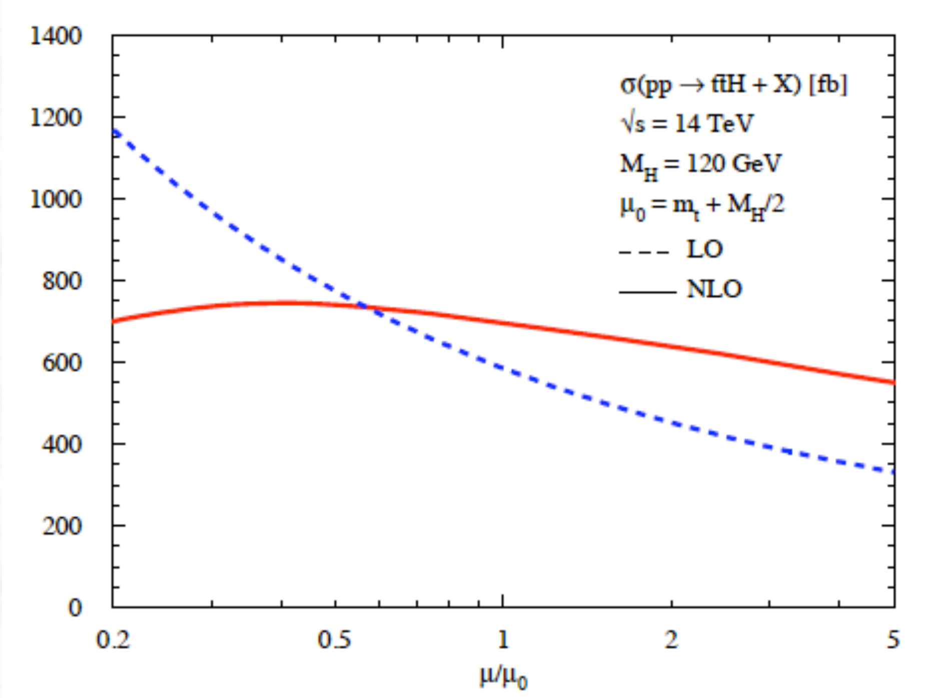


- Weak and difficult at the LHC
- Sensitivity to top-Yukawa coupling
- Moderate K-factors
  (NLO corrections)

NLO QCD corrections available,
scale uncertainty drastically reduced

scale: $\mu_0 = m_t + m_H/2$

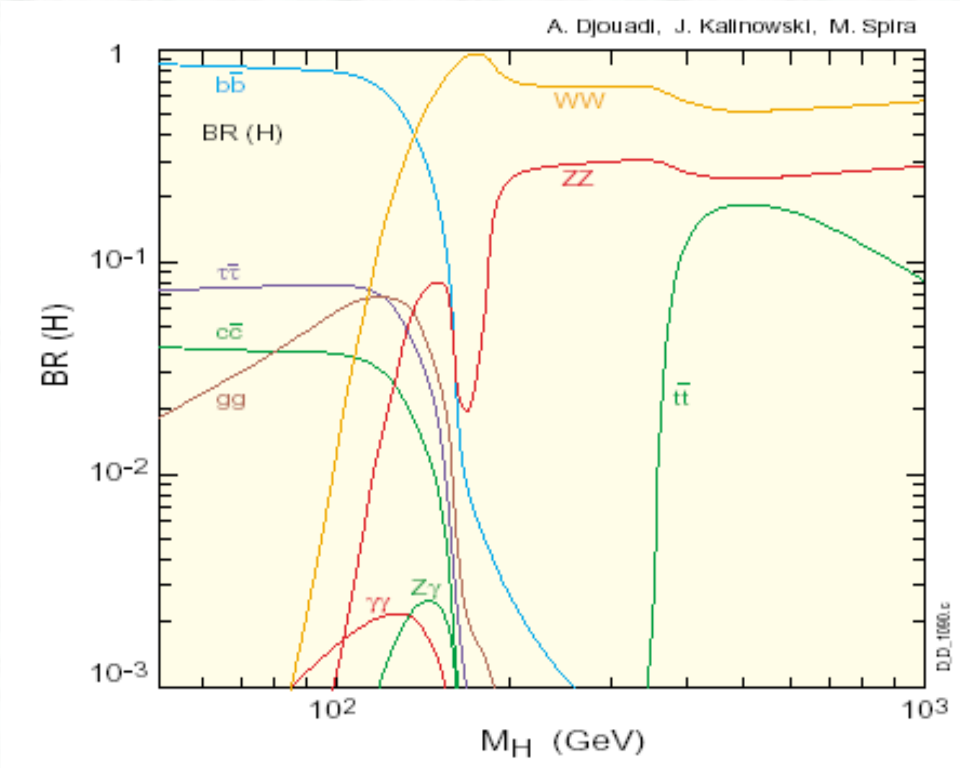
LHC: K ~ 1.2
Tevatron: K ~ 0.8



Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (2001)
Dawson, Reina, Wackeroth, Orr, Jackson (2001, 2003)

8.4 The Search for the Higgs Boson at the Tevatron

Useful Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states
(via H → WW , ZZ)

at low mass:

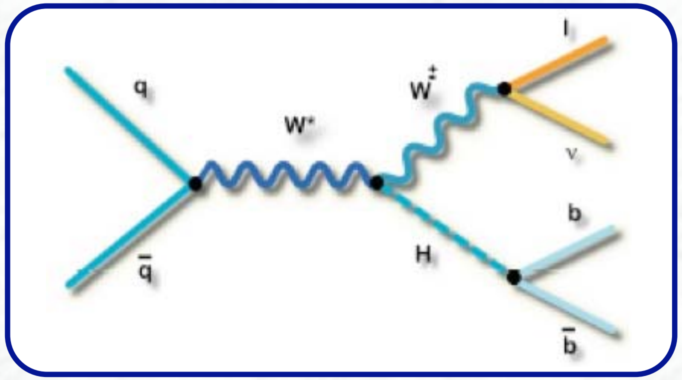
Lepton and Photon final states
(via H → WW*, ZZ*)

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, leptons from W/Z or tt decays)

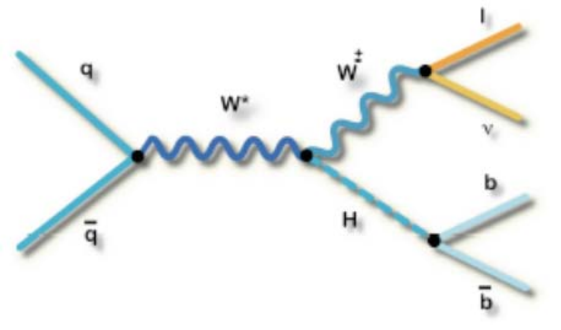
Searches for a low mass Higgs boson at the Tevatron



m_H < 135 GeV:

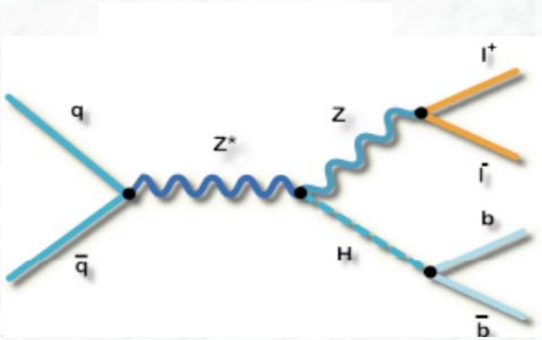
Associated production WH and ZH with H→bb decay

Main low mass search channels



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

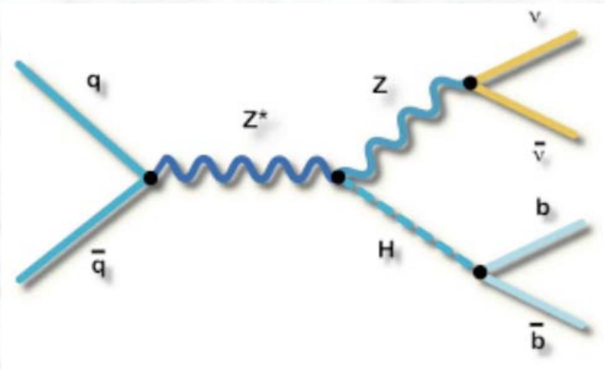
Largest *VH* production cross section, however, severe backgrounds



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

Less background than WH

Smallest Higgs signal



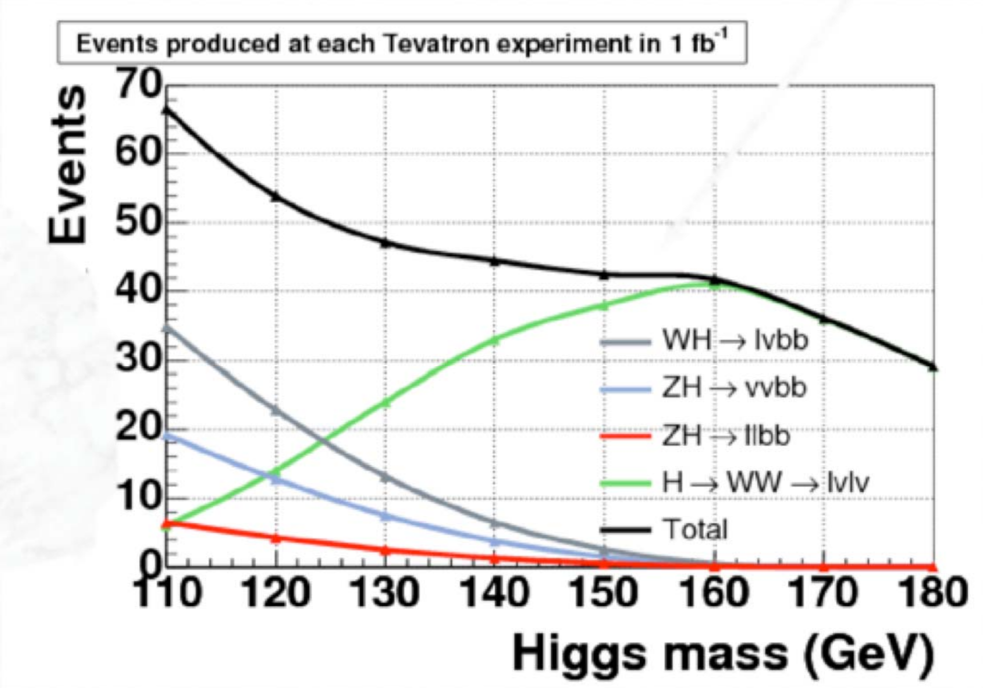
E_T^{miss} + bb: $ZH \rightarrow \nu\nu bb$

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

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

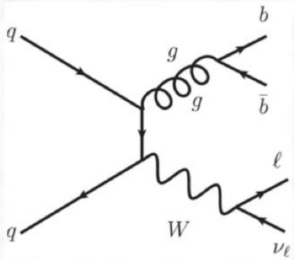
Large backgrounds which are difficult to handle

Number of produced events (incl. decays) per 1 fb^{-1}



WH ($H \to bb$) Signal, m_H = 115 GeV:
$\sigma \times BR$ = 14 fb (per lepton)

Large backgrounds: W+jet productio



W+bb: $\sigma \times BR = 4 \times 10^4$ fb
W+cc: $\sigma \times BR = 1 \times 10^5$ fb
W+qq: $\sigma \times BR = 2 \times 10^6$ fb

Additional backgrounds:

WW: $\sigma \times BR$ = 13 pb
tt: $\sigma \times BR$ = 7 pb
single top: $\sigma \times BR$ = 3 pb

+ multijet QCD background

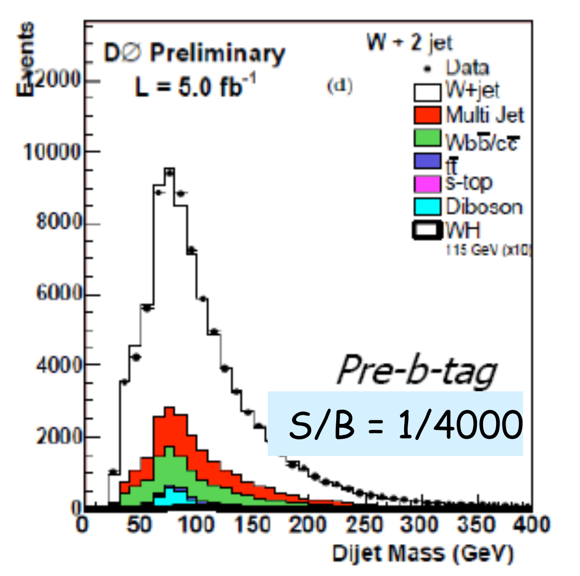
General Search Strategy

Example: $WH \to \ell\nu\, bb$

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

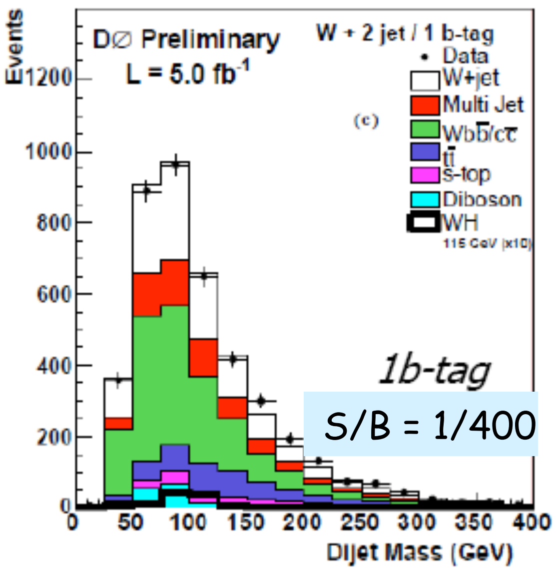
(ii) Apply b-tagging
(most discriminating variable: dijet inv. mass)

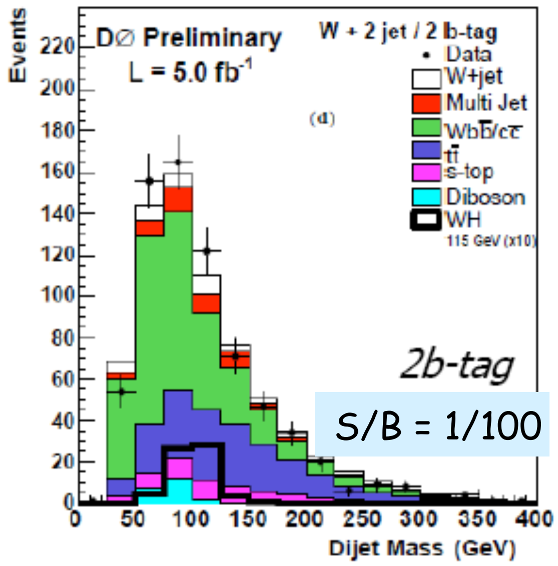
even after b-tagging S:B ratio remains small,
→ needs advanced (multivariate) analysis tools



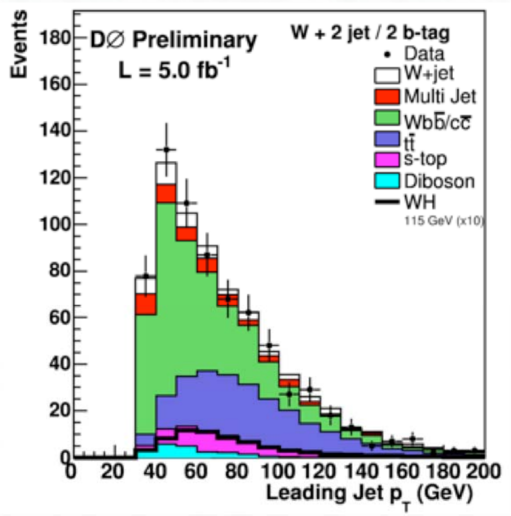
(iii) Optimize separation power by multivariate discrimination (neutral networks, matrix elements, ….)

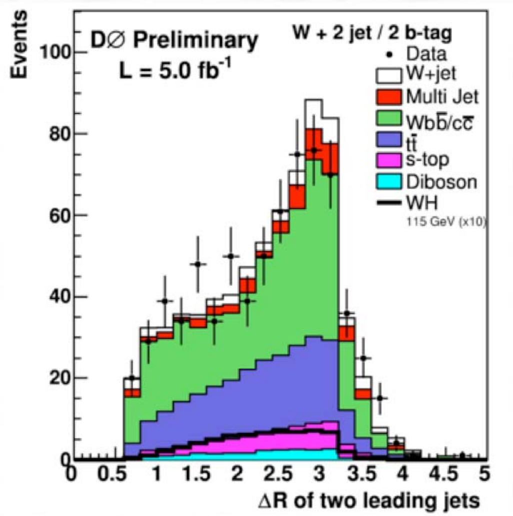
Major input variables:
- dijet mass
- P_T of the dijet system
- P_T of W/Z
- Sphericity
- ΔR_{jj}, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$

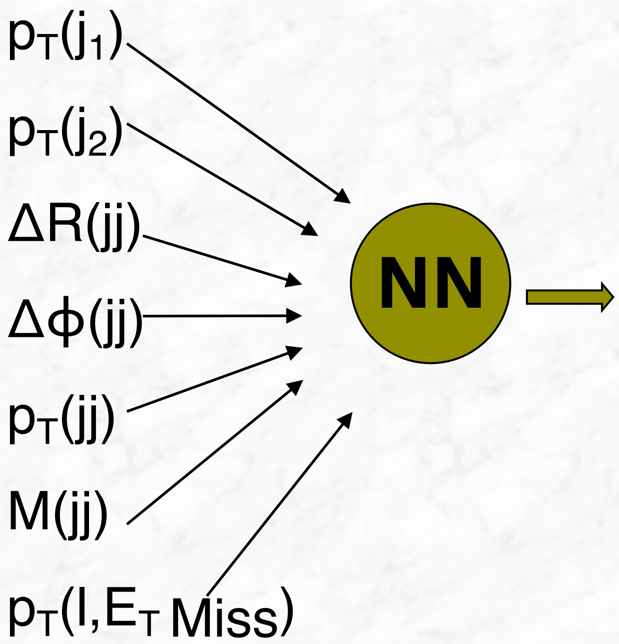


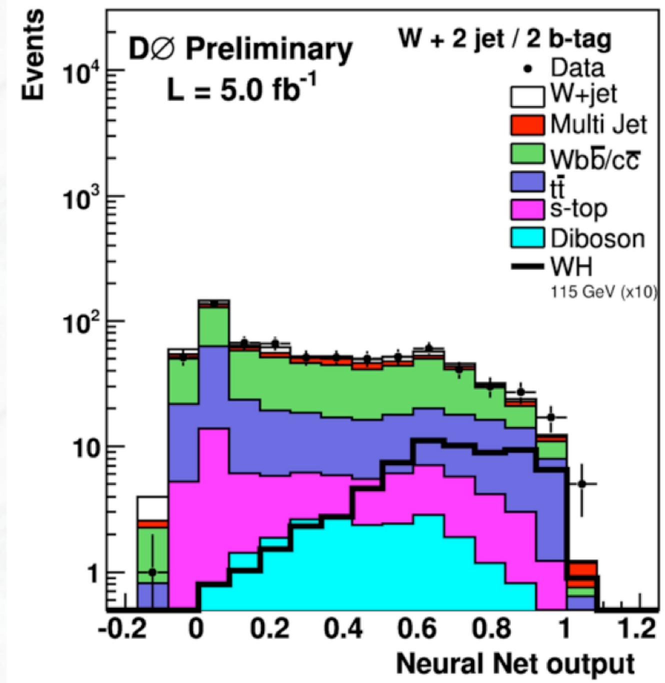


DØ: WH→lν bb (l=e,μ) neural net



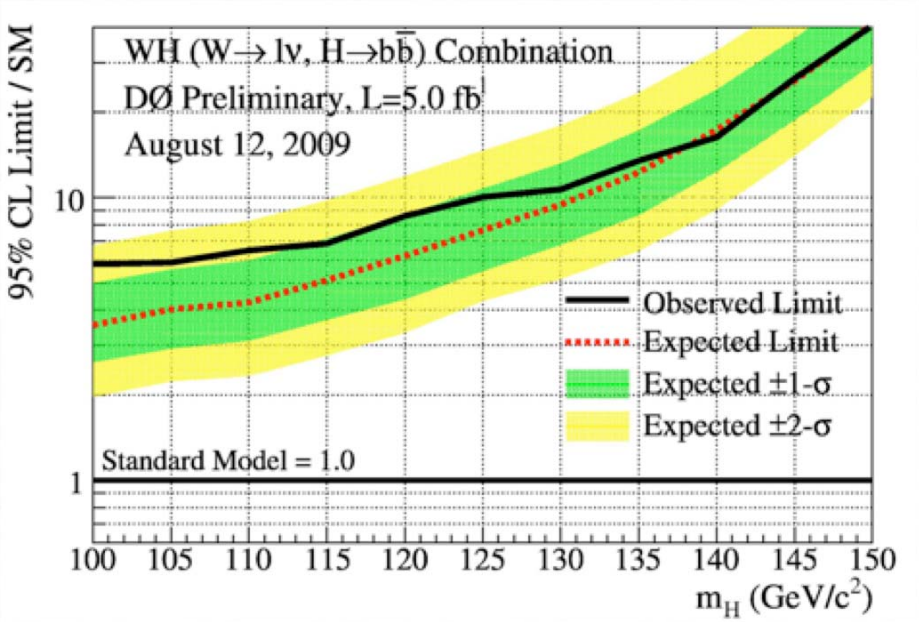






Sensitivity in the low mass region

- Limits for 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

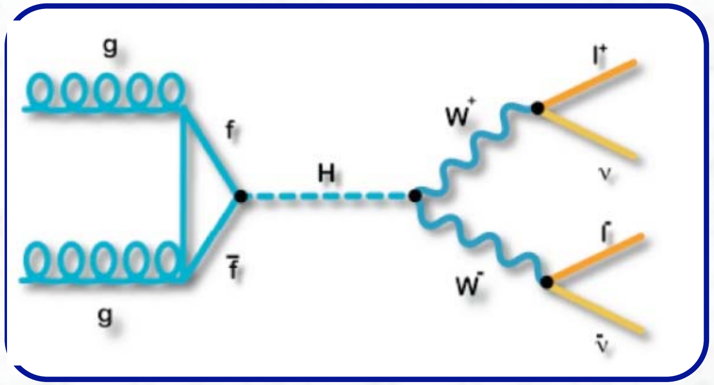


Excluded cross section:
(95% C.L., m_H = 115 GeV)

D0: $\sigma_{95} = 6.9 \cdot \sigma_{SM}$
CDF: $\sigma_{95} = 4.3 \cdot \sigma_{SM}$

- 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

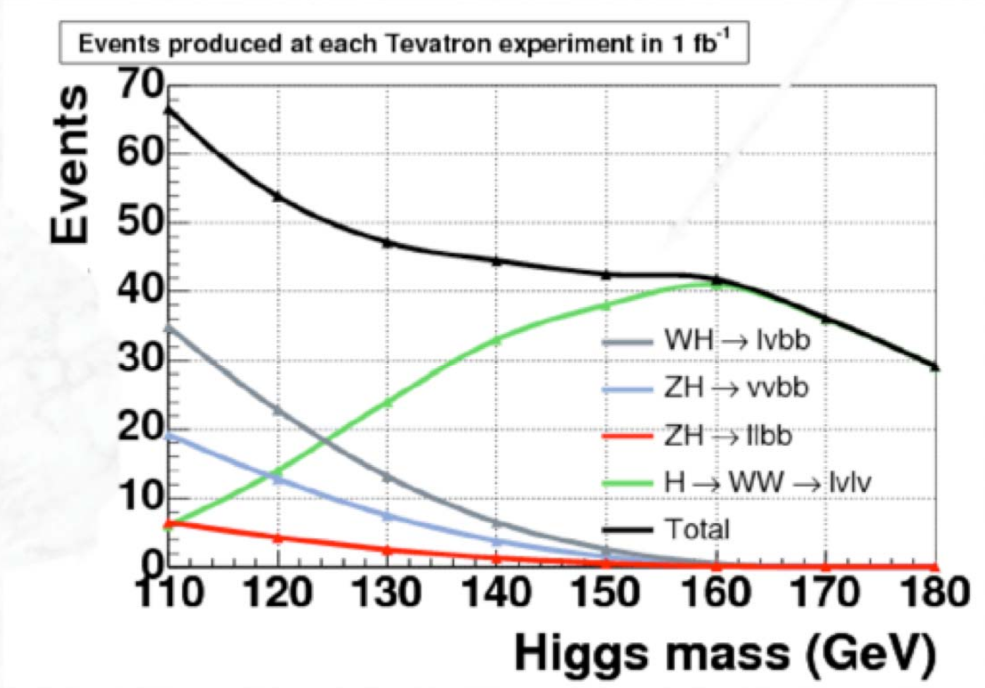
Searches for a high mass Higgs boson at the Tevatron



$m_H > 135$ GeV:

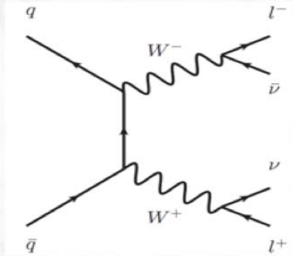
$gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$

Number of produced events (incl. decays) per 1 fb^{-1}



<u>$gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$) Signal, m_H = 160 GeV:</u>
σ×BR = 40 fb
Associated WH and qqH production increase signal by ~30%

Significant di-boson backgrounds:

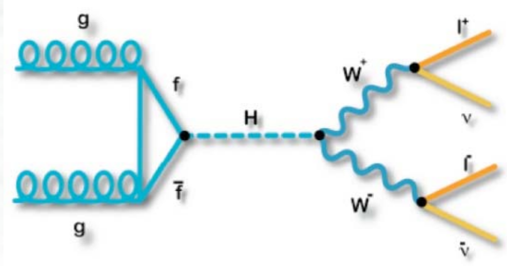


<u>Di-Boson</u>
WW: σ×BR = 13 pb
WZ: σ×BR = 4.0 pb
ZZ: σ×BR = 1.5 pb

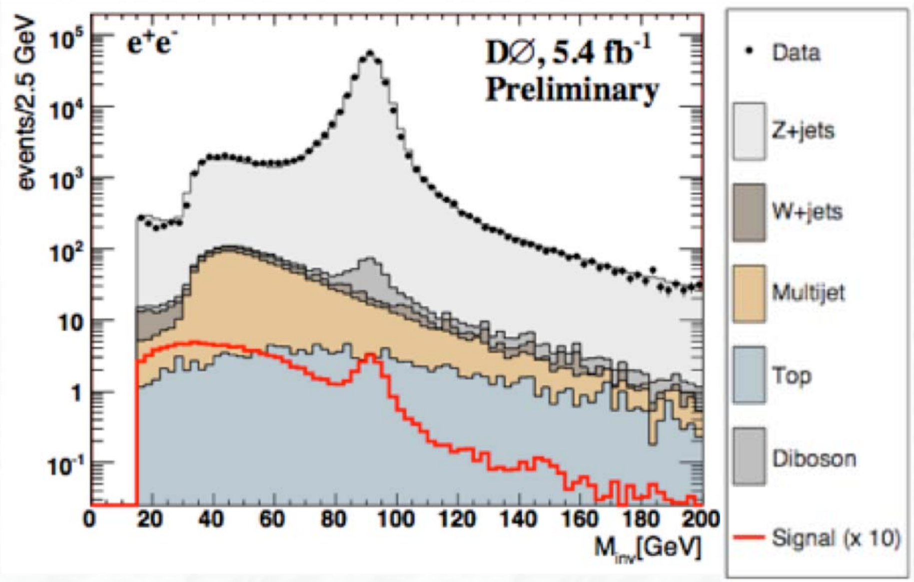
<u>Additional backgrounds:</u>
tt: σ×BR = 7 pb
single top: σ×BR = 3 pb

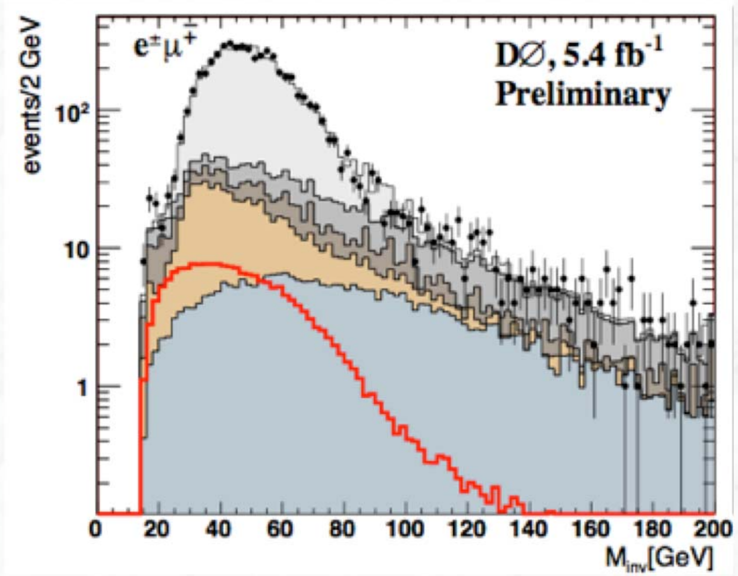
+ multijet QCD background

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



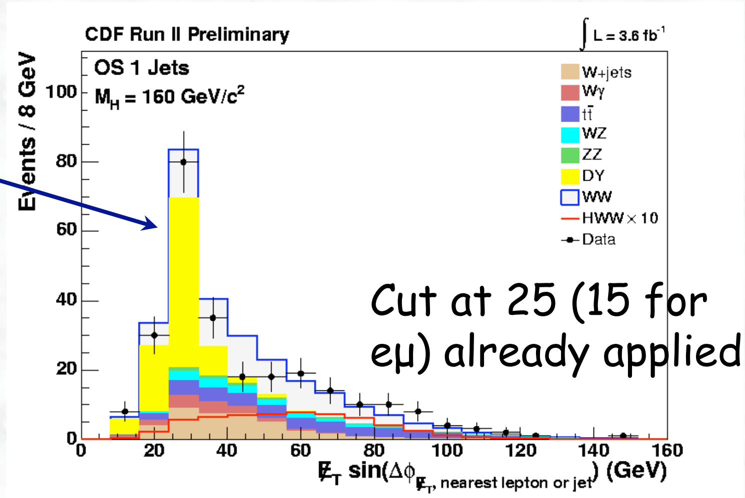
- Dominant decay for m_H >135 GeV: $H \to W^*W$
- Leptons in final state
  → exploitation of gg→H is possible
- Signal contribution also from $W/Z+H$ *and* qqH production
  → Consider all sources of opposite sign di-lepton + E_T^{miss}
  Split analysis in ee, μμ, and eμ final states
- Backgrounds: Drell-Yan,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



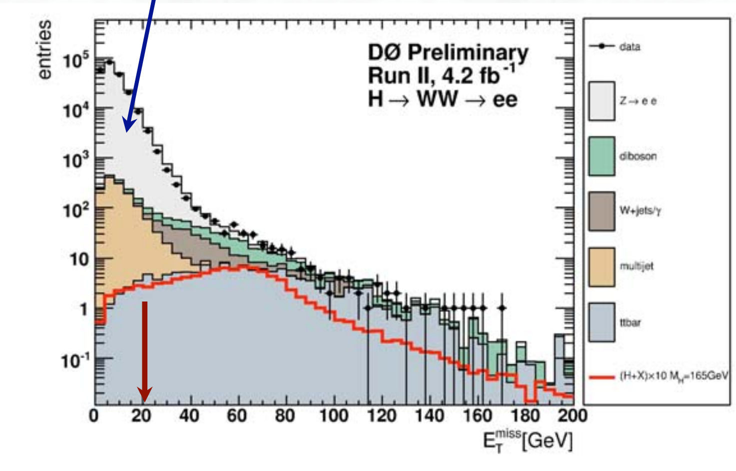


$H \rightarrow \ell^+\ell^- \nu\nu$

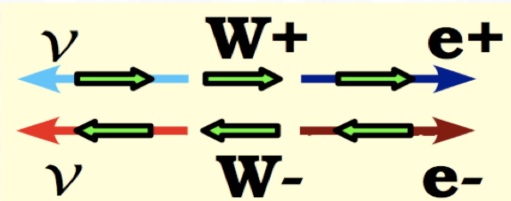
Dominant Drell-Yan background can be reduced with cuts on E_T^{miss} and its isolation (distance to nearest object)

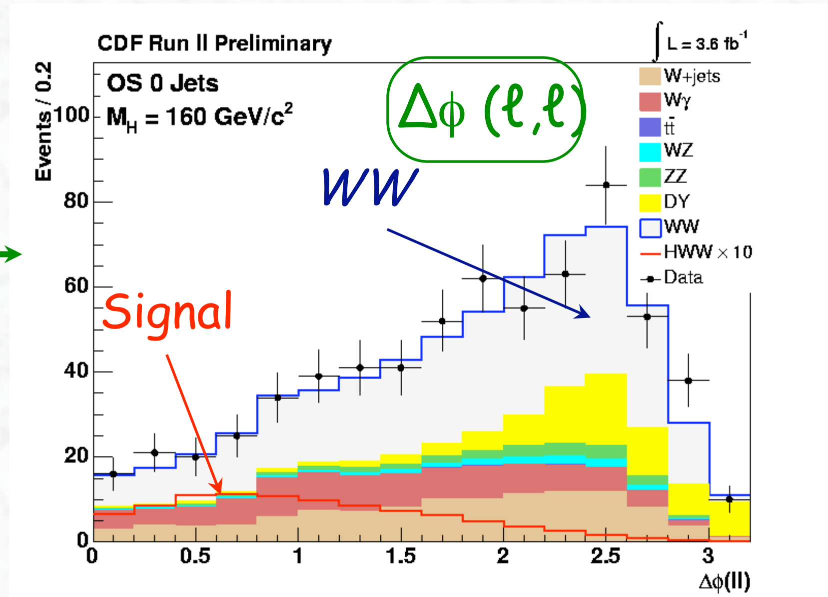


Cut at 25 (15 for eμ) already applied



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

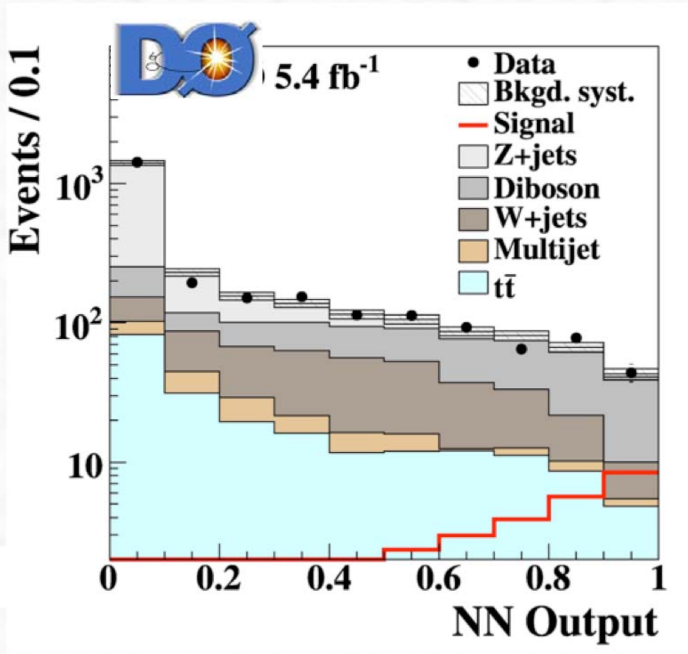


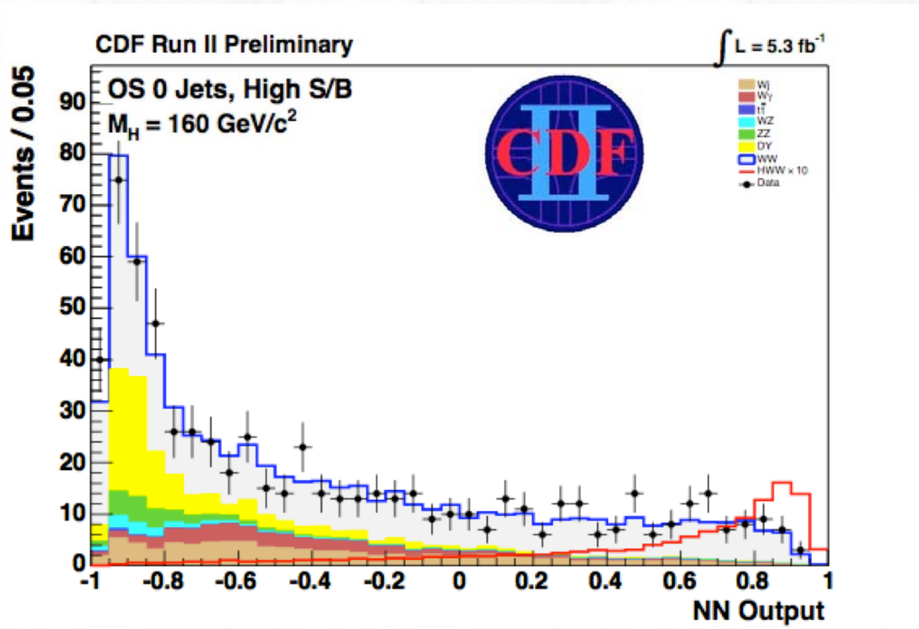


$H \rightarrow \ell^+\ell^- \nu\nu$

To increase sensitivity:

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

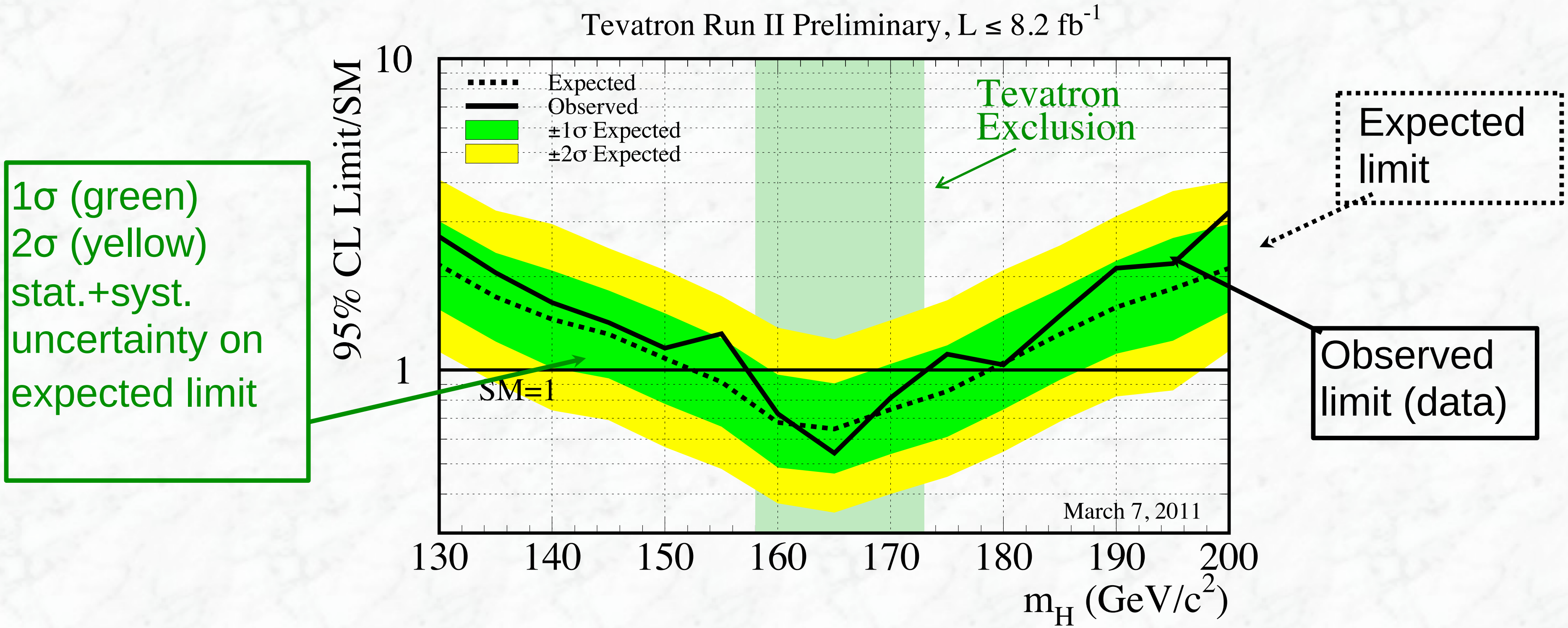




CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

Combined Tevatron limits



Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 158−173 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}

Systematic uncertainties

Analyses are affected by significant systematic uncertainties;

Example: The two most significant DØ analyses:

Source	$WH \rightarrow e\nu b\bar{b}$
Luminosity	6.1
Normalization	-
Jet Energy Scale	3.0
Jet ID	5.0
Jet Triggers	-
Electron ID/Trigger	4.0
Muon ID/Trigger	-
b-Jet Tagging	3-9
Background σ	7-20
Multijet	14
Shape-Dependent Bkgd Modeling	2-10

Source	$H \rightarrow W^+W^-$
Luminosity	6.1
Jet Energy Scale	3.0
Jet ID	1-2
Tau Energy Scale/ID	-
Electron ID/Trigger	3-10
Muon ID/Trigger	7.7-10
b-Jet Tagging	-
Background σ	7-10
Signal σ	11
Multijet	2-20
Shape-Dependent Bkgd Modeling	5-20

- Systematic uncertainties for background rates are generally several times larger than the signal expectation itself

- To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximizing a likelihood function
  Nuisance parameters allow for variations within errors

- Each systematic uncertainty (incl. uncertainty on signal cross section) is folded into the signal and background expectation via Gaussian distributions (correlations preserved)