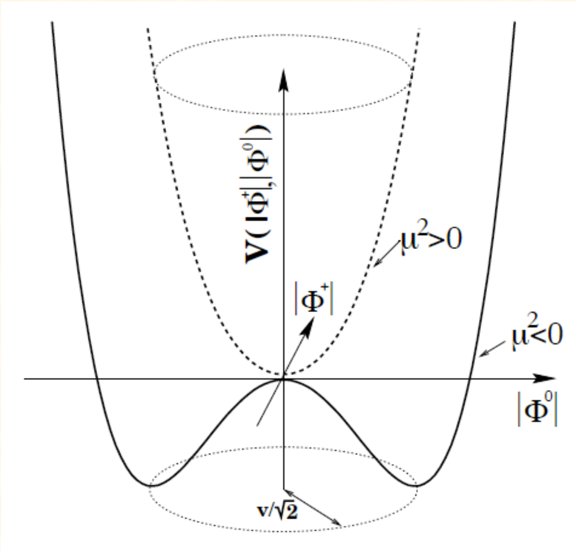
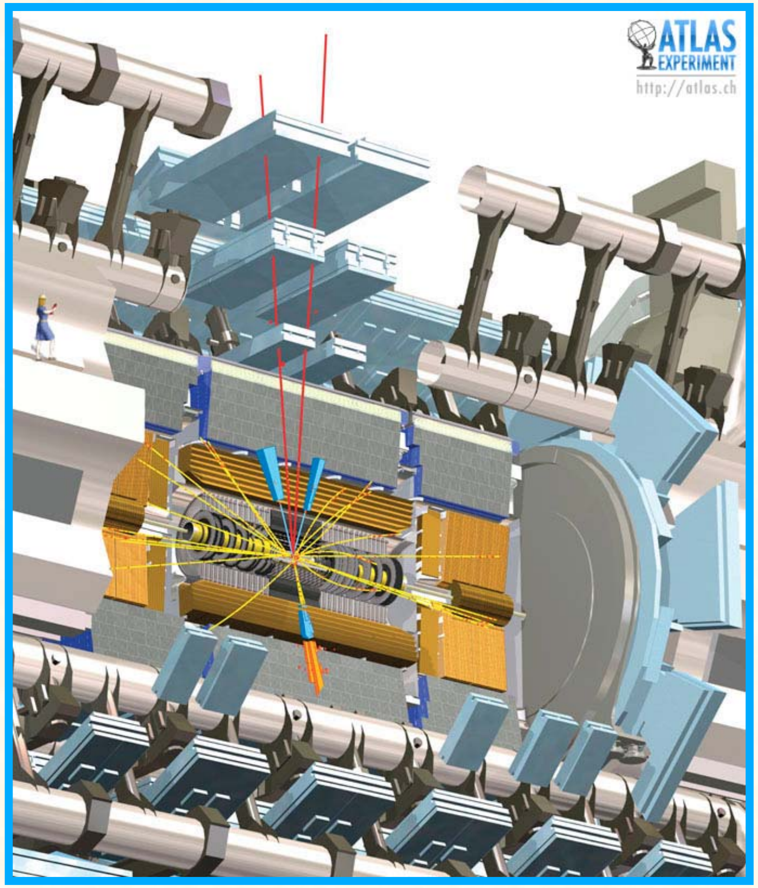
Higgs Boson Searches at Hadron Colliders





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Outline of the four lectures:

1. Introduction, Higgs Mechanism, Cross sections
   - The Higgs boson in the Standard Model
   - Properties of the Higgs boson
   - Current limits on the Higgs boson mass
   - Higgs boson production at Hadron Colliders

2. Search for the Standard Model Higgs Boson
   - Experimental aspects of Higgs boson searches at Hadron Colliders
   - Searches for the Standard Model Higgs boson at the Tevatron
   - The potential for Higgs boson searches at the LHC, part I (14 TeV, 7 TeV)

3. SM Higgs Boson Searches and Higgs Boson Parameters
   - The potential for Higgs boson searches at the LHC, part II (14 TeV, 7 TeV)
   - How well can Higgs boson parameters be determined at the LHC

4. Non-Standard Higgs Boson scenarios
   - MSSM Higgs boson
   - Invisibly decaying Higgs bosons
   - Strongly coupled scenarios, composite Higgs

Preface / Disclaimer:

- The subject I am talking about is "an old topic"
  - Many talks about this subject, extensively discussed in the literature
  - Many theorists and experimentalists working on it, overwhelming wealth of material

    → selection of material, will not be complete

    → tutorial

- LHC is running at $\sqrt{s}$ = 7 TeV

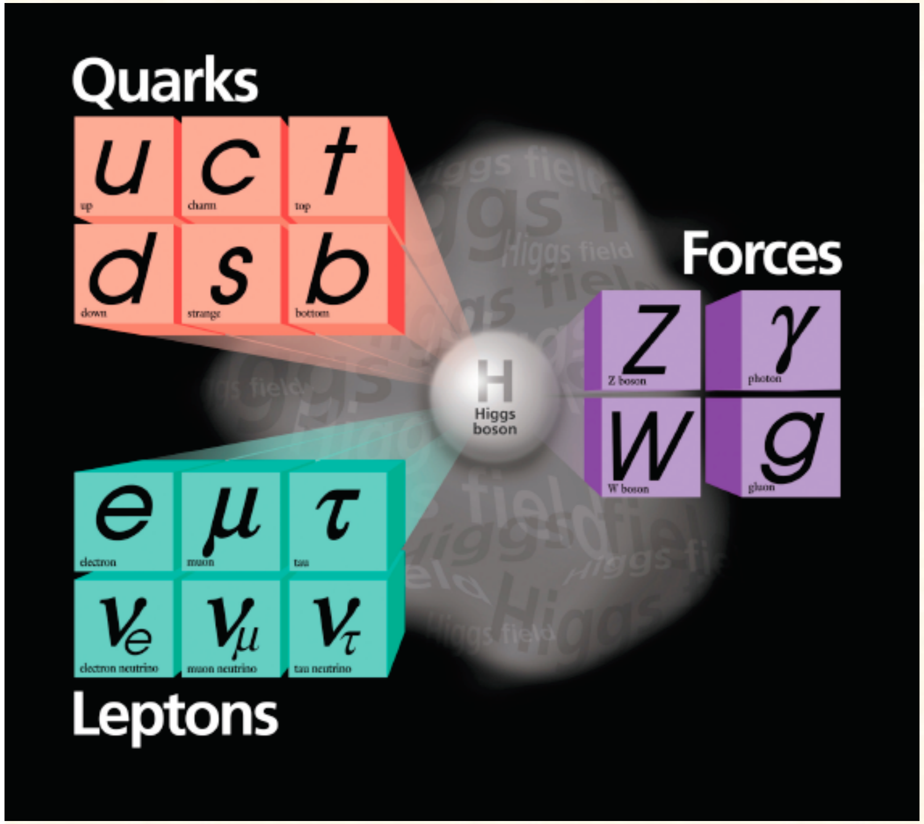
  - Many studies have been performed by the experimental collaborations for $\sqrt{s}$ = 14 (10) TeV during the past years

    → difficult to give a consistent picture for the present LHC energy; main intention is **the discussion of methods to detect the Higgs bosons**, and not so much to give the precise values of the discovery significance

  - 7 TeV results are quoted wherever available and relevant

  - First results of LHC detector performance relevant for Higgs boson searches are presented as well

Building blocks of the Standard Model



- **Matter**

  Made out of fermions

  (Quarks and Leptons)

- **Forces**

  Electromagnetism, weak and strong force

  + gravity

  (mediated by bosons)

- **Higgs field**

  Needed to break (hide) the electroweak symmetry and to give mass to weak gauge bosons and fermions

  → Higgs particle

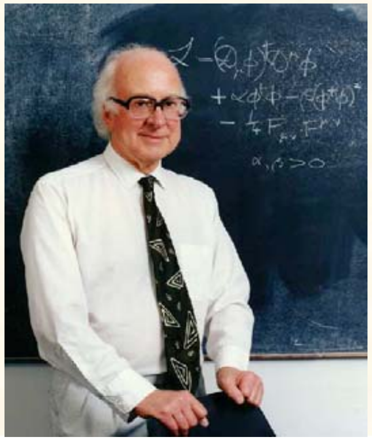
Where do we stand today?

e^+e^- colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider
+ HERA at DESY + many other experiments (fixed target…….)
have explored the energy range up to **~100 GeV** with incredible precision

- The Standard Model is consistent with all experimental data !

- No Physics Beyond the SM observed
  (except clear evidence for neutrino masses)
- No Higgs seen (yet)

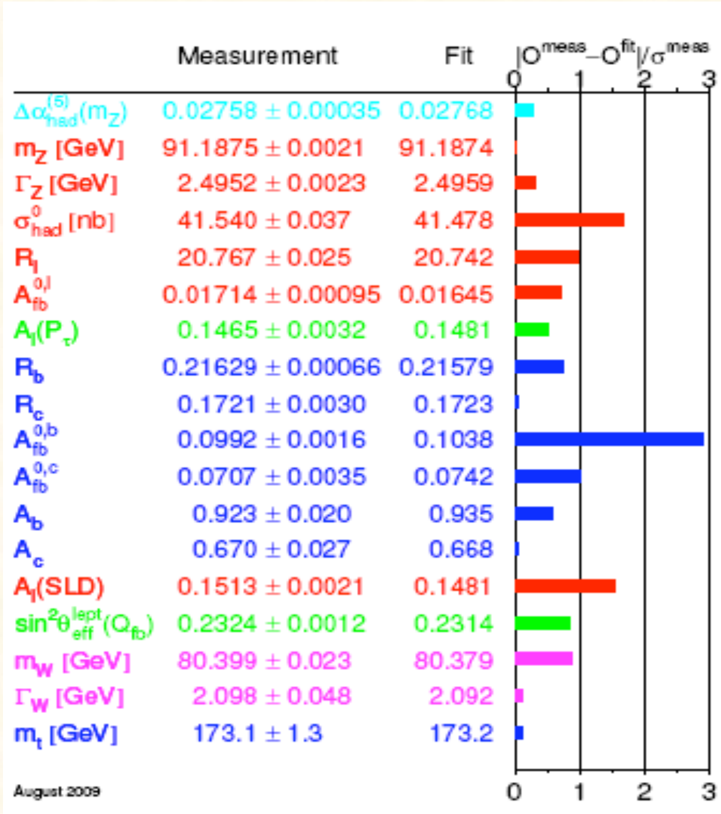
Direct searches: (95% CL limits)
$m_H > 114.4$ GeV
$m_H < 162$ GeV or $m_H > 166$ GeV



Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

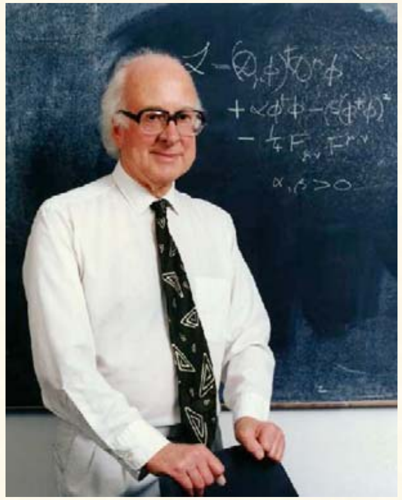
Summer 2009



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."



Why do we need the Higgs Boson?

- How does it enter the Standard Model ?
- What is its role?

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: $$\psi(x) \to e^{i\alpha(x)}\psi(x)$$

(derivative: $\partial_\mu \psi \to e^{i\alpha(x)}\partial_\mu \psi + ie^{i\alpha(x)}\psi\partial_\mu \alpha$,

$\delta_\mu \alpha$ 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:

$$A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha$$ where $e = g_e/4\pi$ = coupling strength

Can be formally achieved by the construction of a "modified" derivative

$$\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$$ (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):

$$D_\mu = \partial_\mu + igT_a G^a_\mu$$

$$G^a_\mu \rightarrow G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G^c_\mu$$

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):

$SU(2)_L$ x $U(1)_Y$ transformations,
4 gauge fields, (W_μ^1, W_μ^2, W_μ^3, B_μ)

Physical states:

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right)$$

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

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

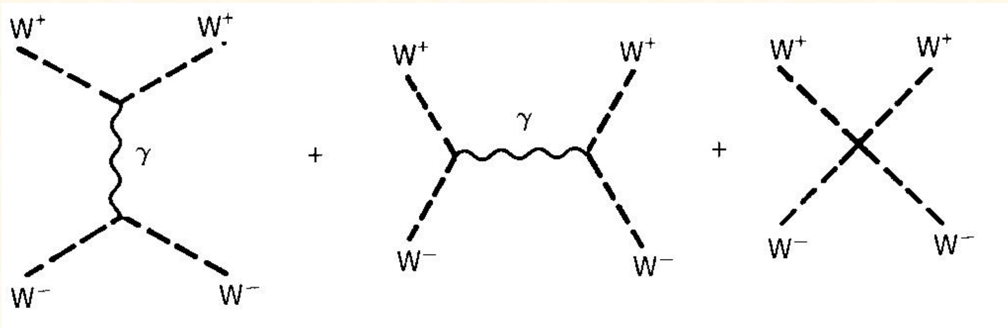
Problems at that stage:

- **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)**



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

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

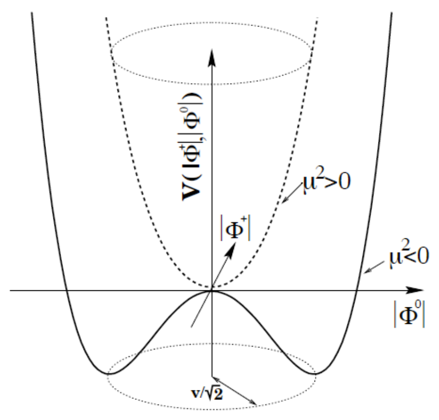
Spontaneous breaking of the SU(2) x U(1) gauge symmetry

- 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:

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

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:

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

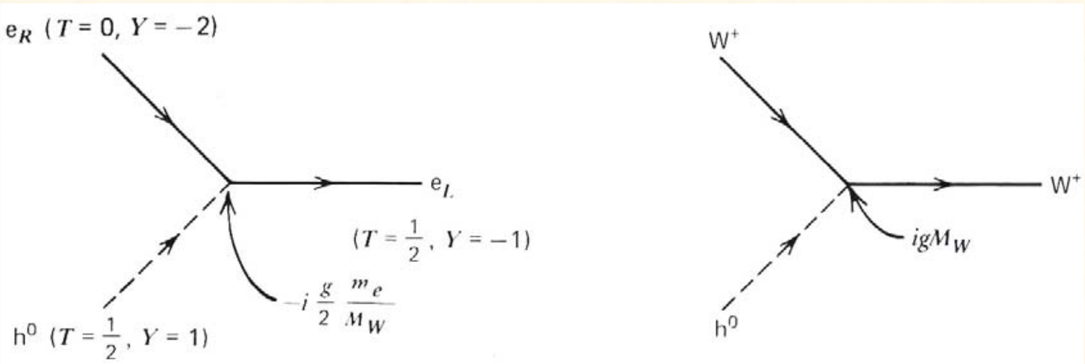
$$L_3 = -\frac{G_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) h$$

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**:

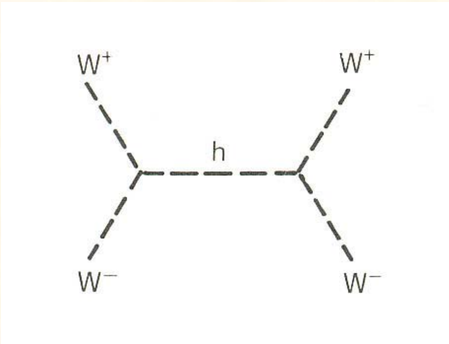
• Mass: $\boxed{m_h^2 = 2v^2\lambda}$

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

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

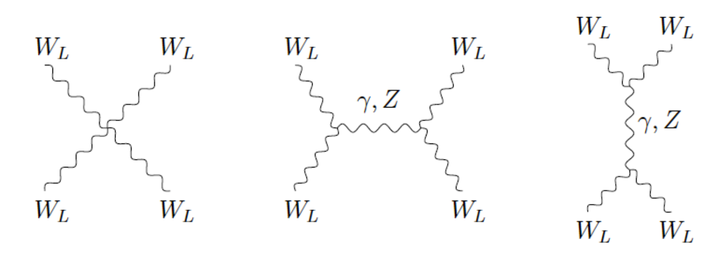
….. and:

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



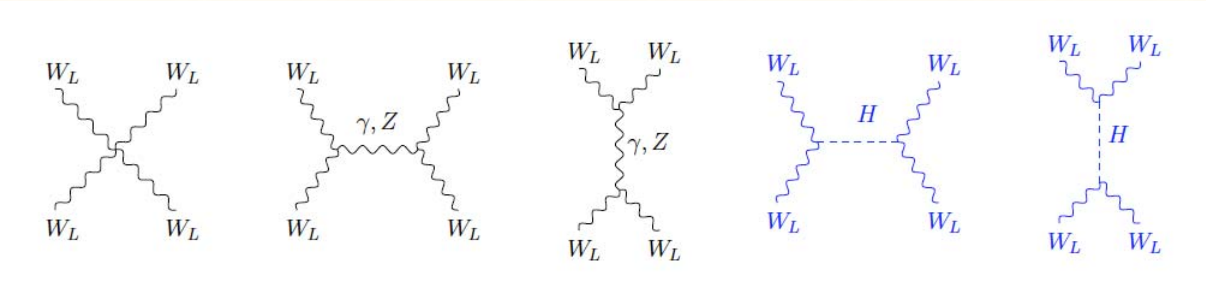
The Higgs boson as a UV regulator

Scattering of longitudinally polarized W bosons



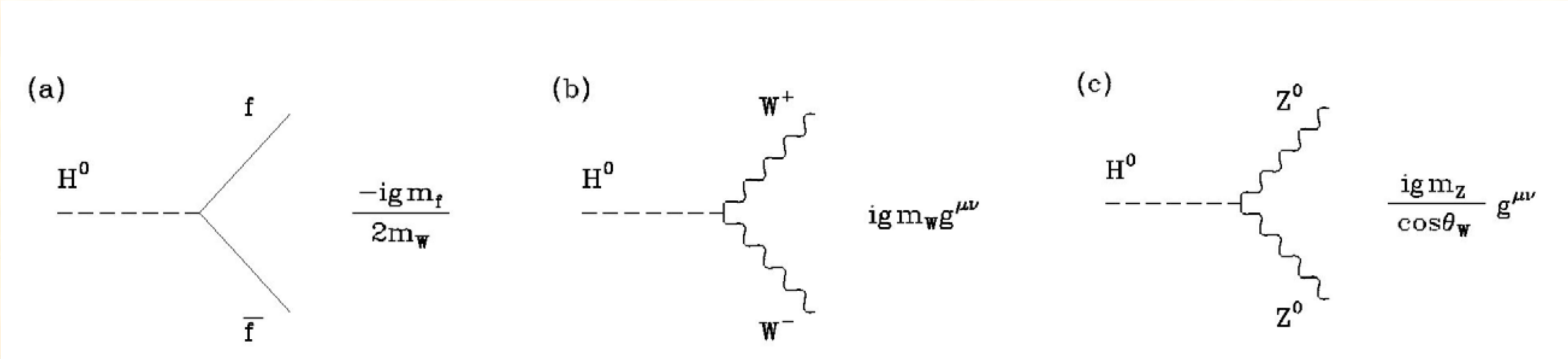
$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{m_W^2} \quad \text{for} \quad s \rightarrow \infty$$

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



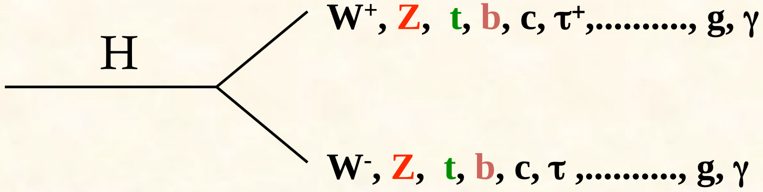
$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$

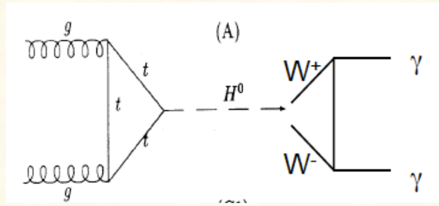
Higgs boson properties



Higgs Boson Decays

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





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

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

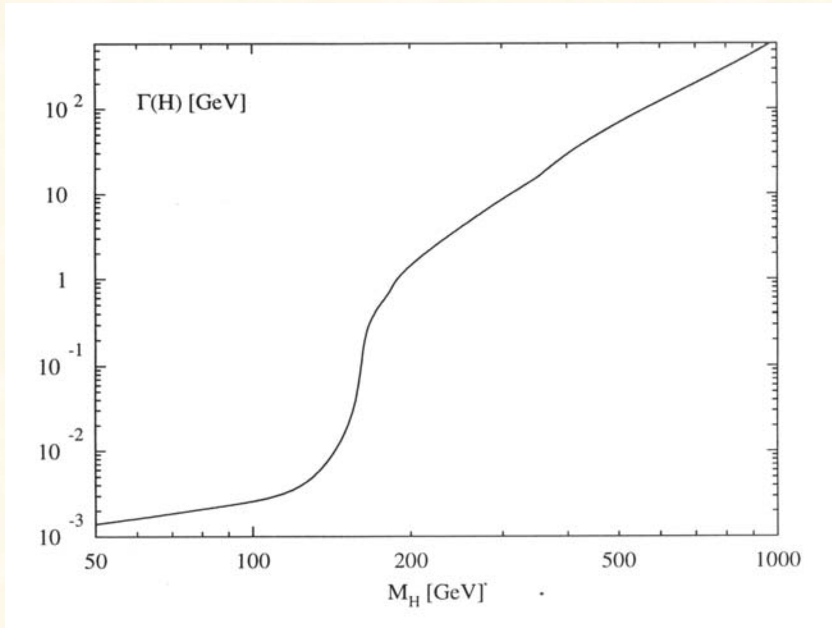
$$\text{where:} \quad \delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_V^2, \quad \beta = \text{velocity}$$

(+ 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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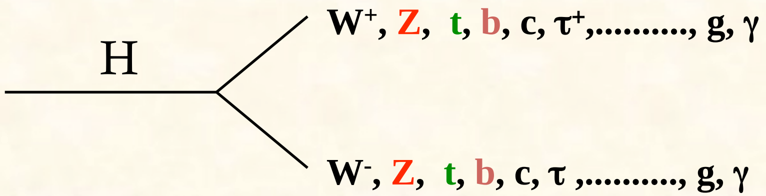
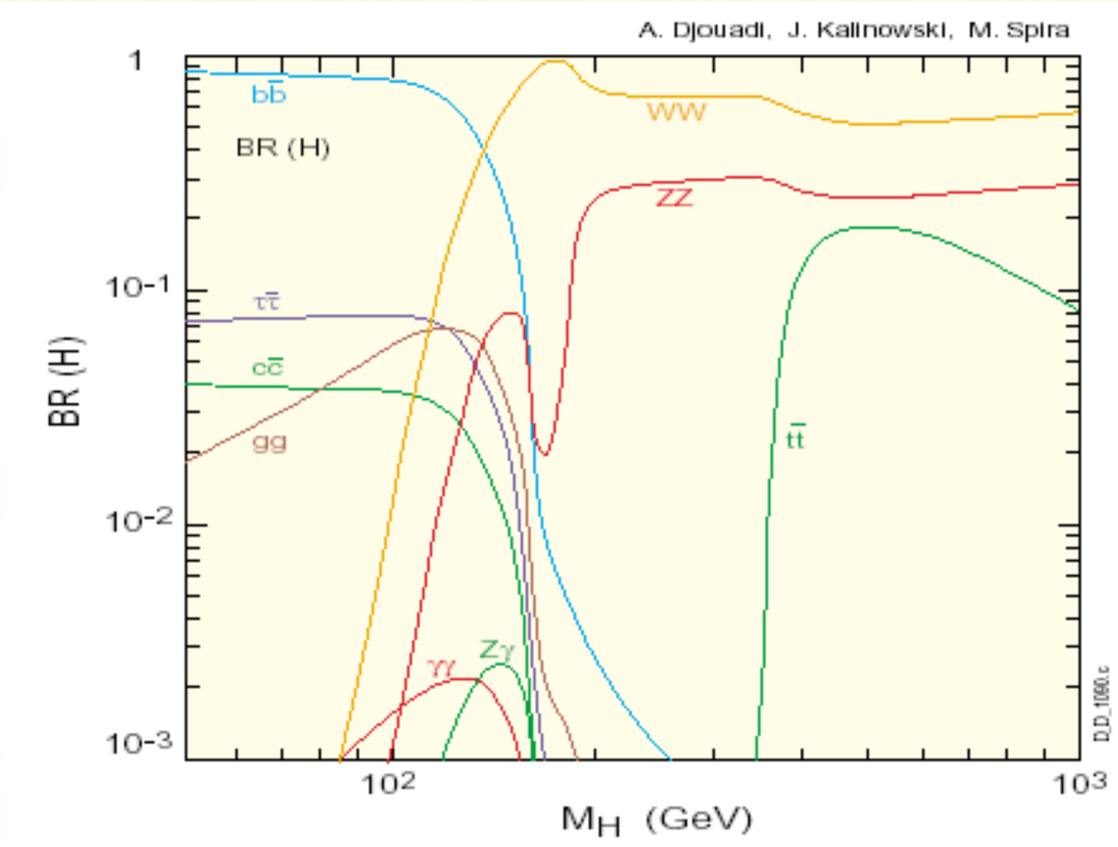




Constraints on the Higgs boson mass

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:

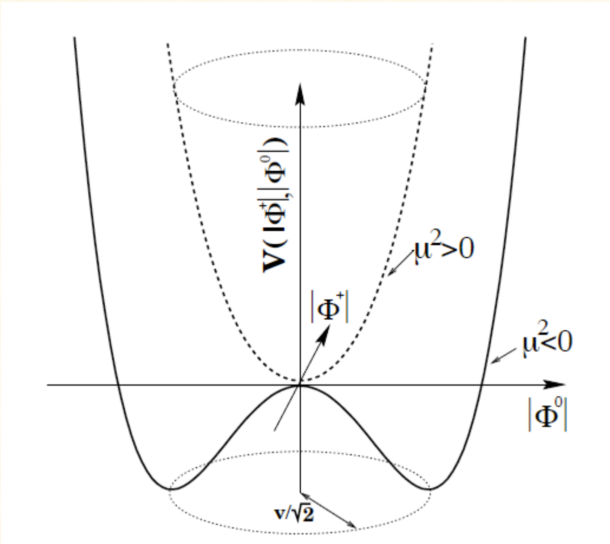
  If Higgs boson too heavy, the regulation of the WW cross section is less effective and unitarity is violated again

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

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

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

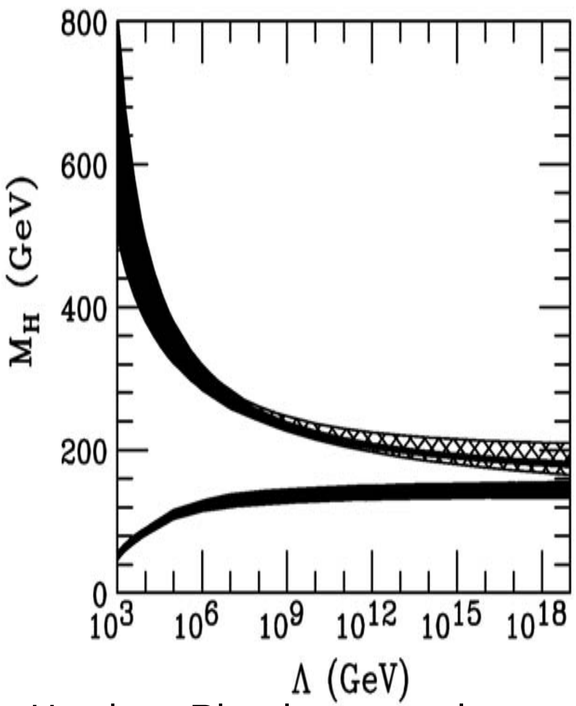
  → next slides



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

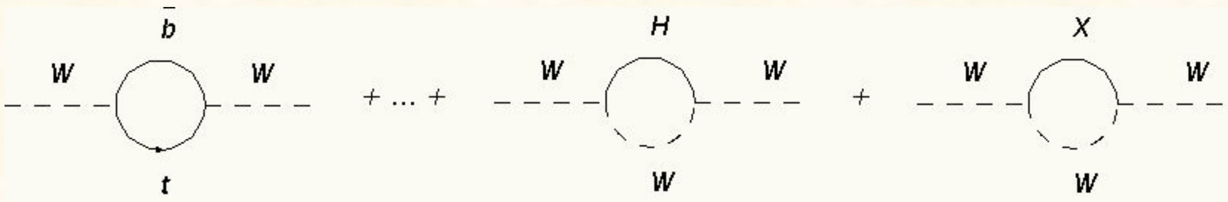
weak mixing angle
measured at
LEP/SLC

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

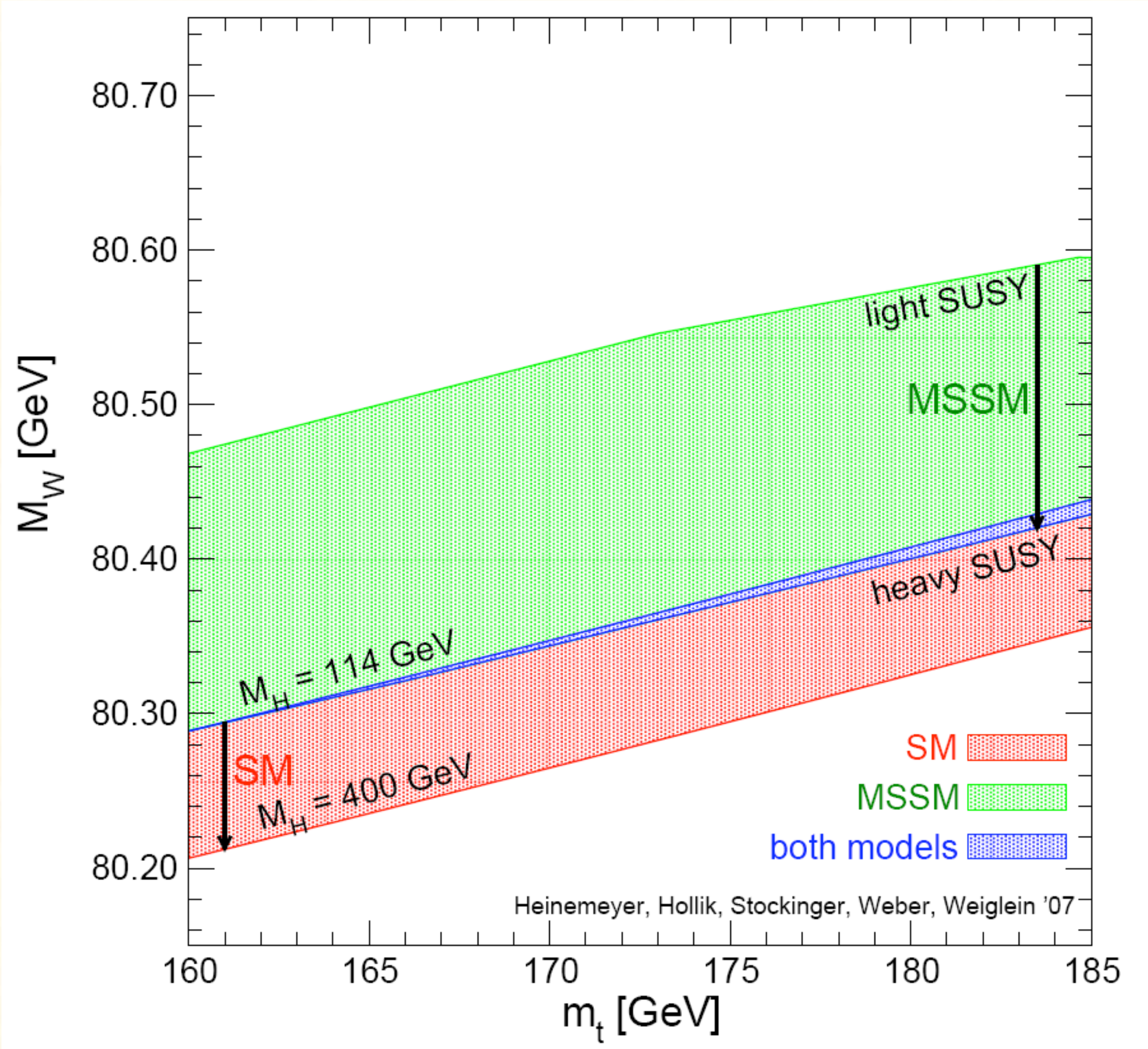
G_F, α_{EM}, $\sin\theta_W$

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)



Relation between m_W, m_t, and m_H



The W and top mass measurements

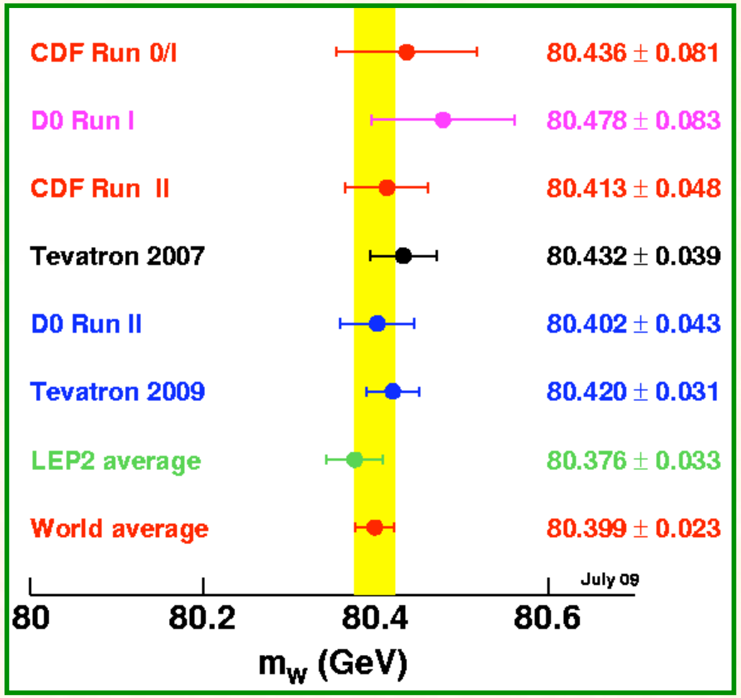
$$m_W = \left(\frac{\pi\, \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

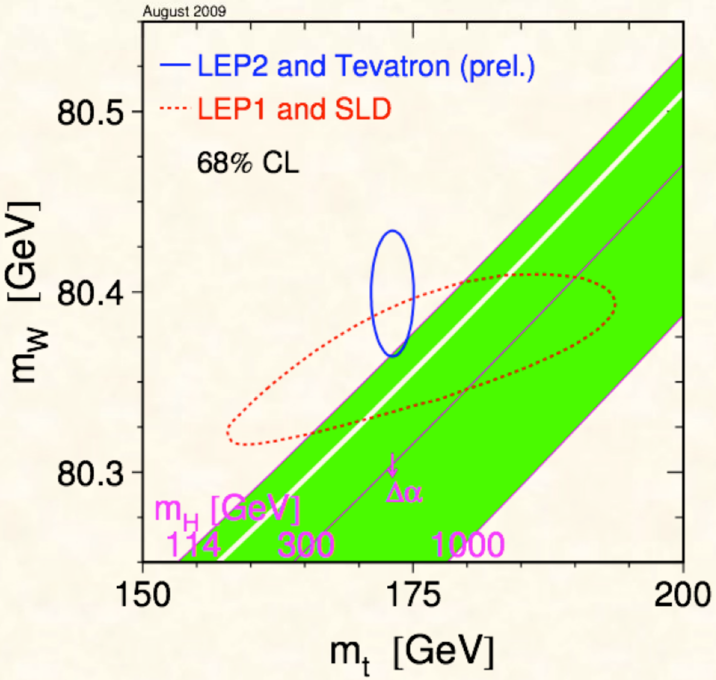
3·10^{-4}

m_W (from LEP2 + Tevatron) = 80.399 ± 0.023 GeV

m_{top} (from Tevatron) = 173.1 ± 1.3 GeV

0.8%



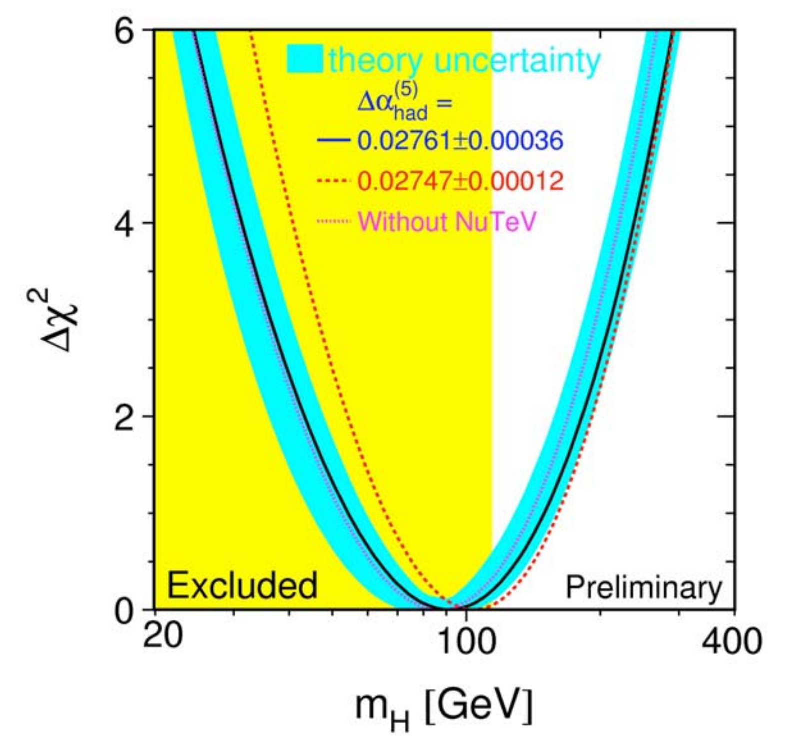


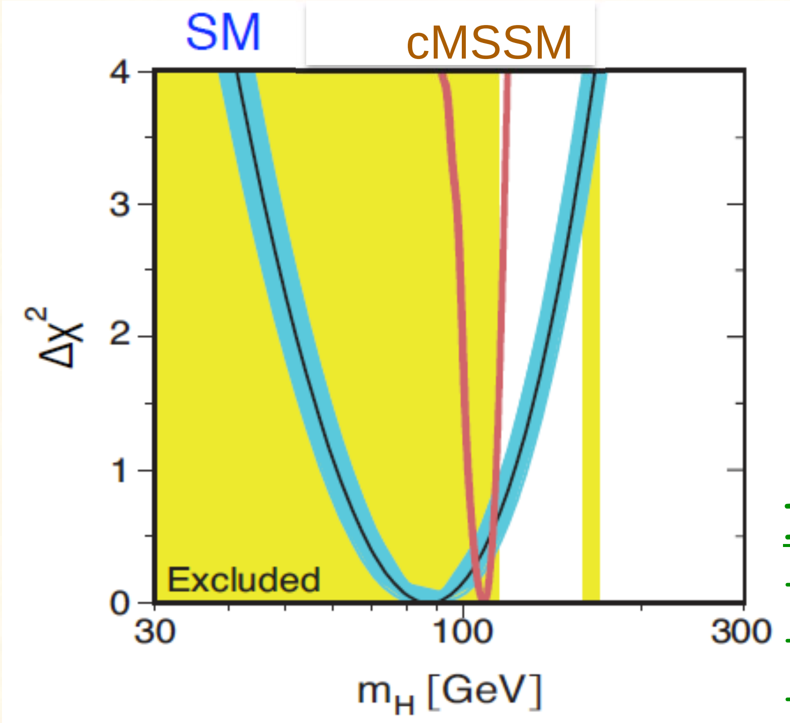
A light Higgs boson is favoured by present measurements

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass and predictions from 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

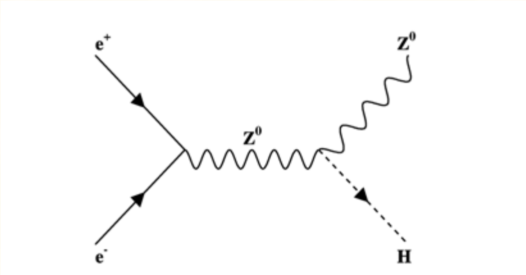
direct searches at

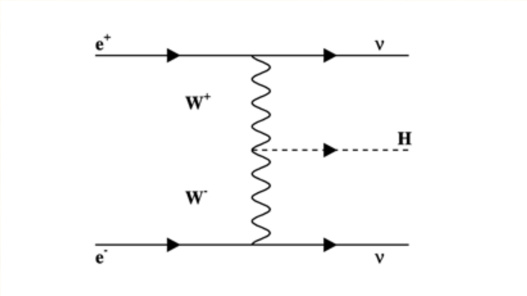
LEP and Tevatron

Higgs bosons searches at LEP

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

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





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

Decay modes searched for:

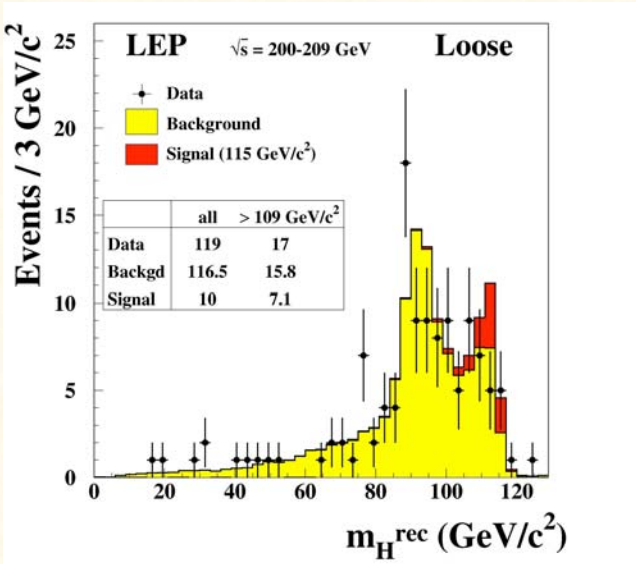
- Four Jet channel: $HZ \rightarrow bb\ qq$
- Missing energy channel: $\rightarrow bb\ \nu\nu$
- Leptonic channel: $\rightarrow bb\ ee$, $bb\ \mu\mu$
- Tau channels: $\rightarrow bb\ \tau\tau$, and $\tau\tau\ qq$

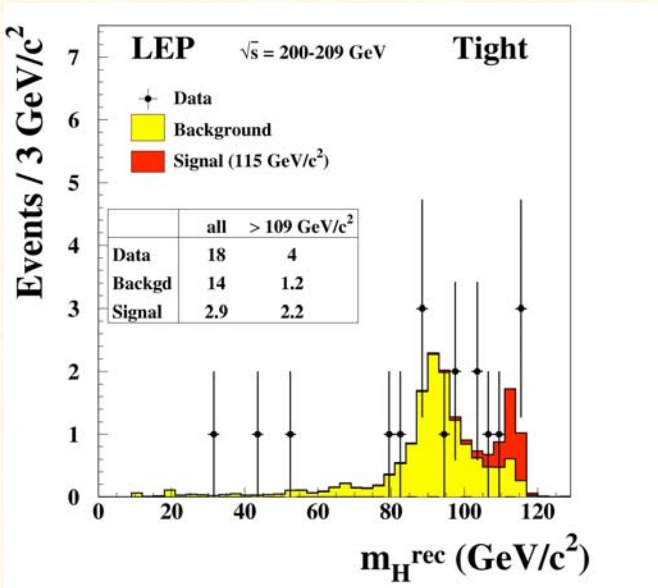
Results of the final LEP analysis:

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.

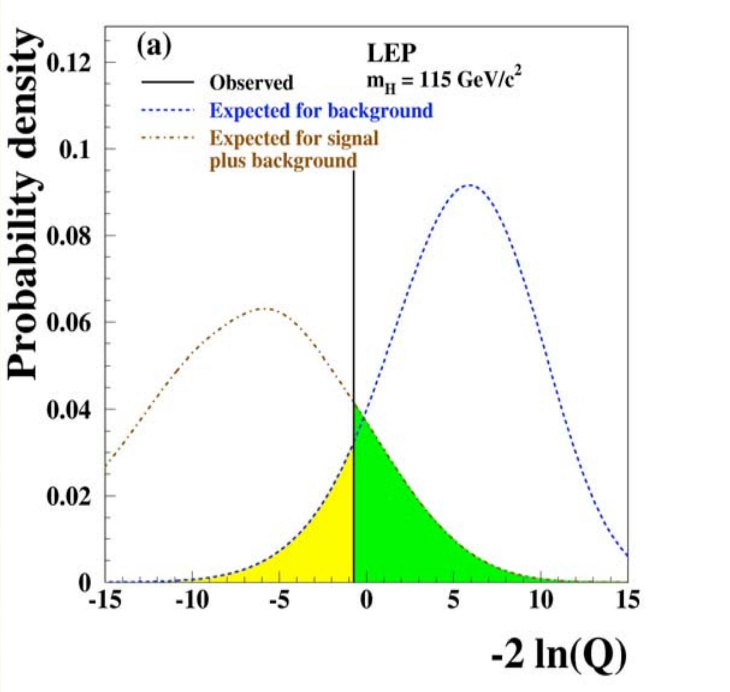
The reconstructed bb mass for two levels of signal purity (loose and tight cuts):





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

$1\text{-}\ CL_B = 0.09$ ↔

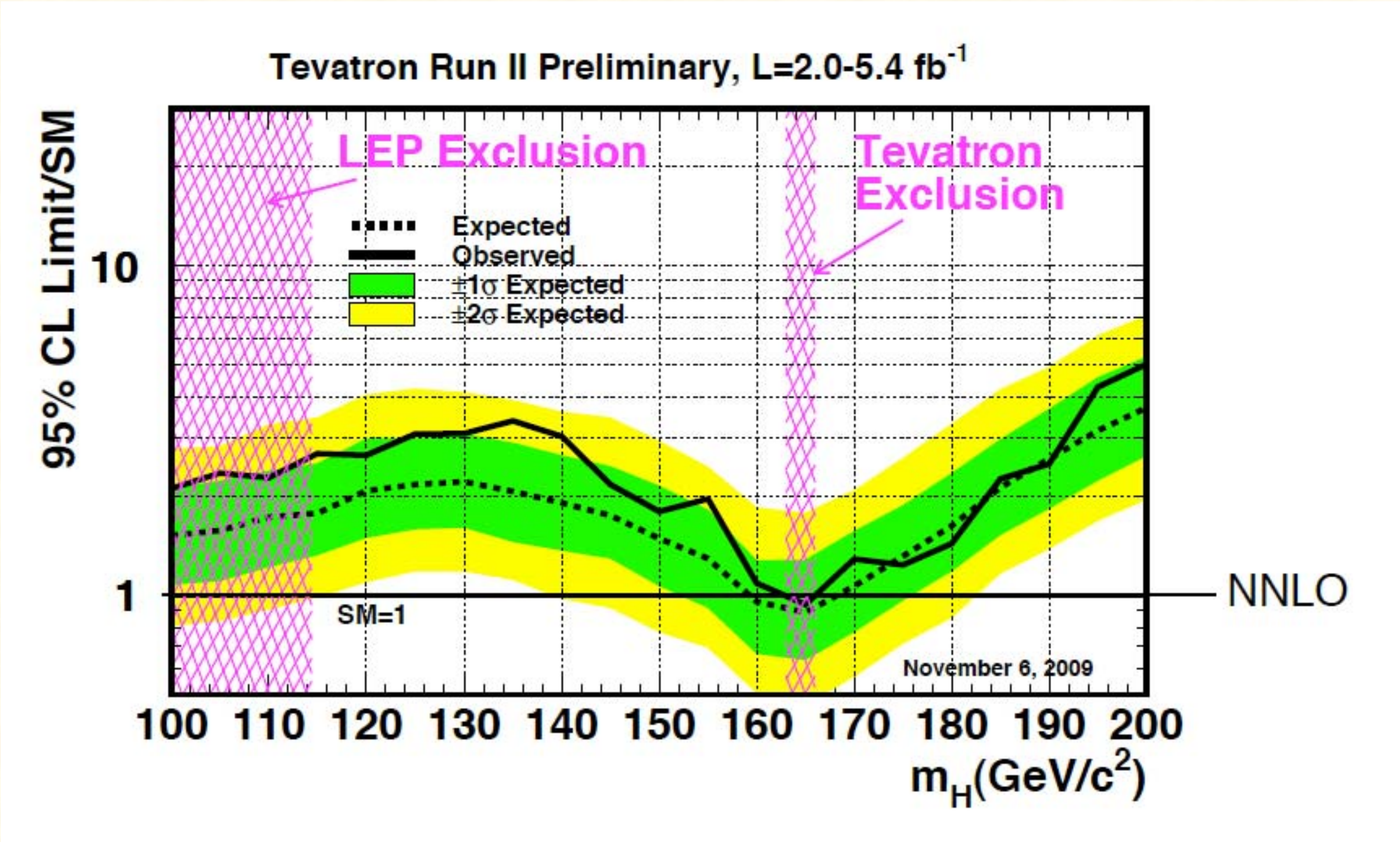
Signal significance = 1.7 σ

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)

Direct limits from searches at the Tevatron



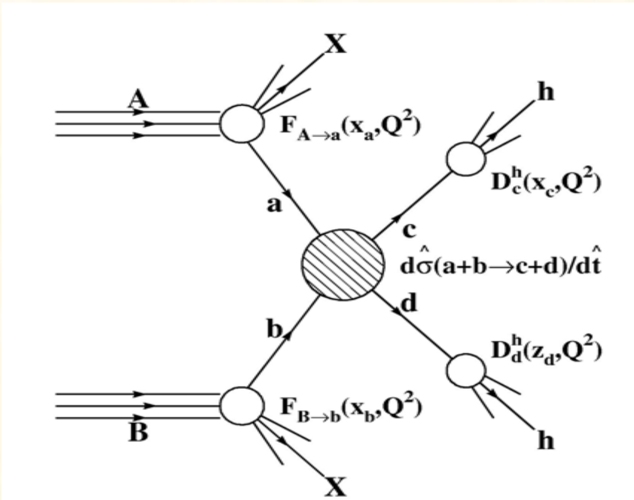
Exclude mass region between 162 and 166 GeV (95% C.L.)

(First exclusion since LEP, detailed discussion tomorrow)

Higgs boson production

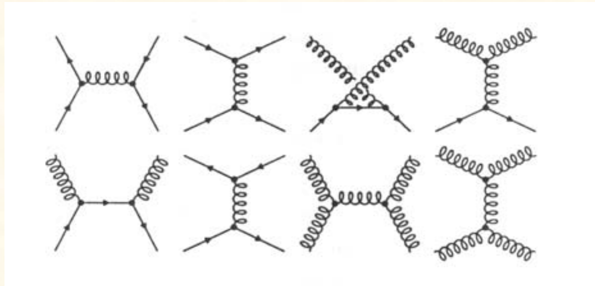
at Hadron Colliders

Phenomenology of pp collisions



Dominant hard scattering cross section:

„QCD Jet Production“
quark/gluon scattering



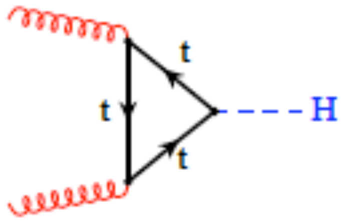
$$\sigma = \sum_{ij} \int dx_1 dx_2\, f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states — *Parton Distributions* — *Factorization Scale* — *Point Cross Section* — *Order α_s* — *Renormalization Scale*

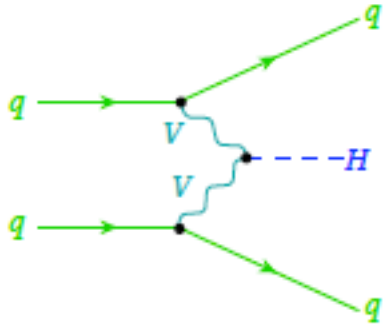
Detection of Higgs boson decays into qq (bb) final states (without associated signatures) is hopeless !!

Higgs Boson production processes at Hadron Colliders

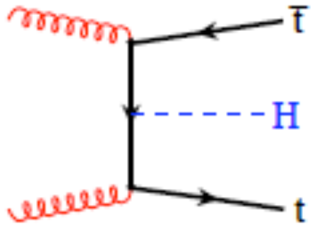
Relative importance of
the various processes
is different at the
LHC and at the Tevatron



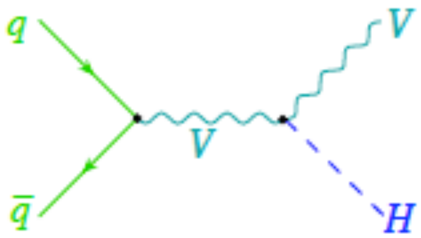
Gluon Fusion



Vector boson fusion

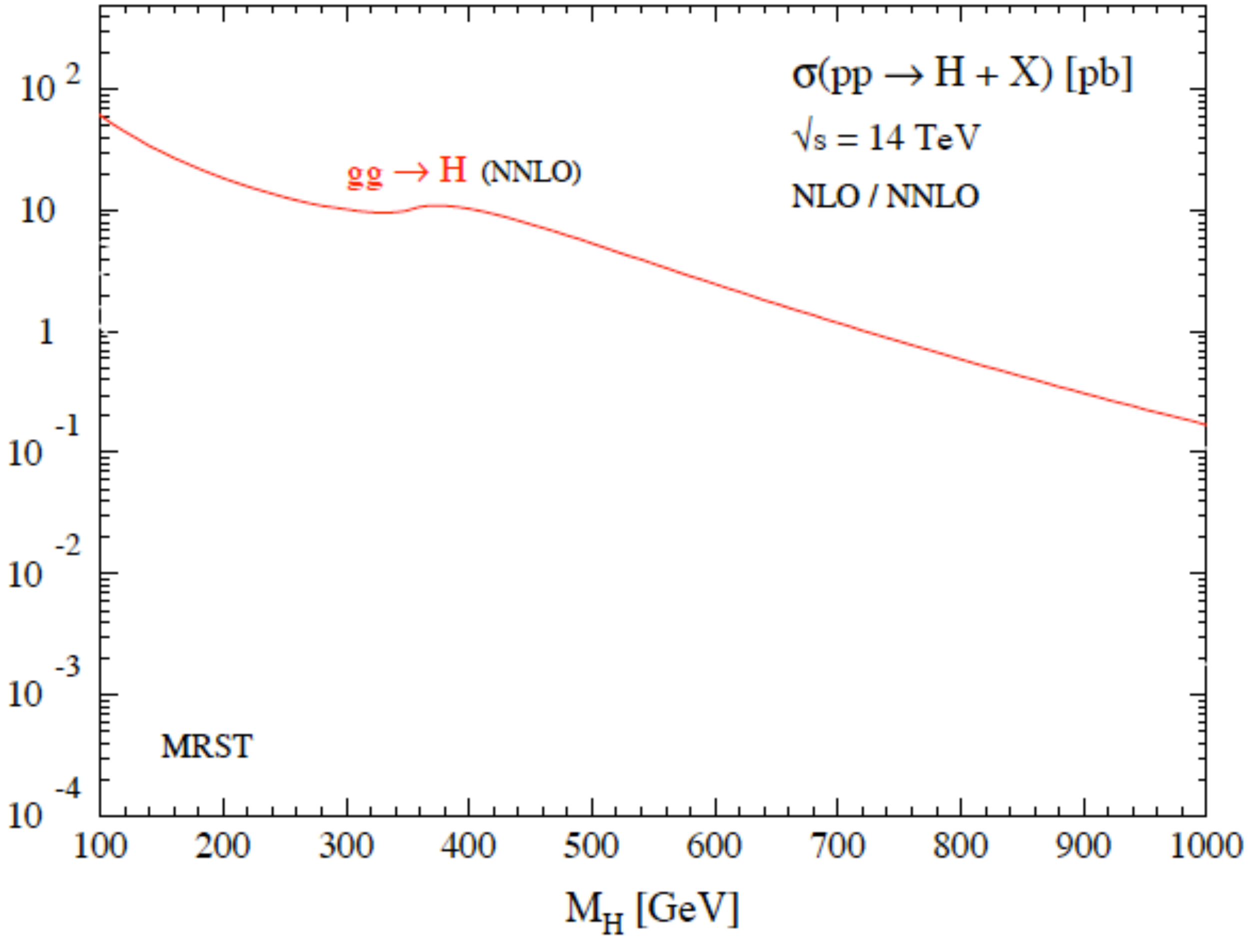


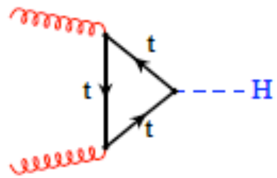
tt associated production



WH/ZH associated production

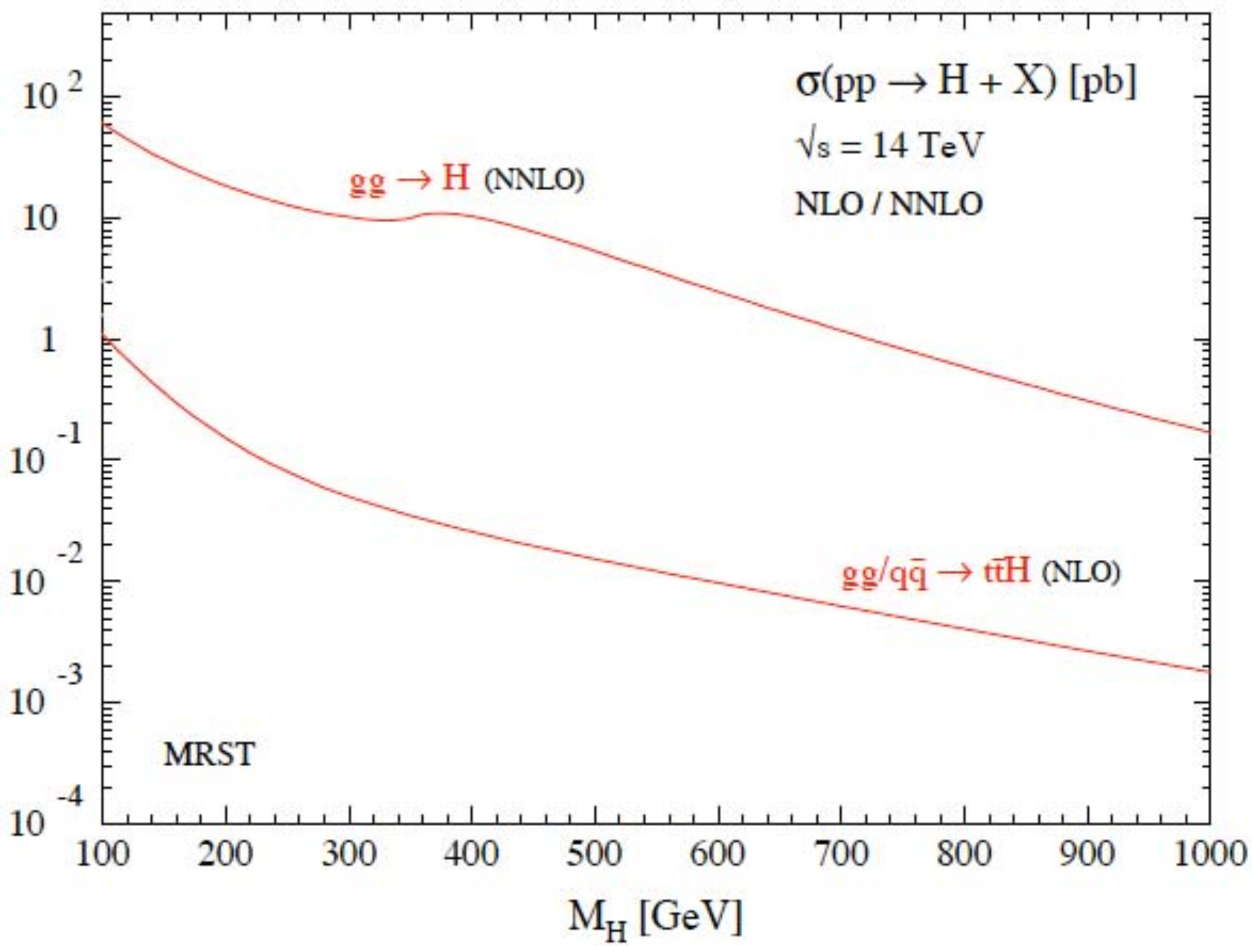
Production cross sections at the LHC

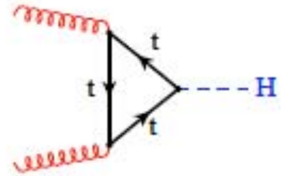


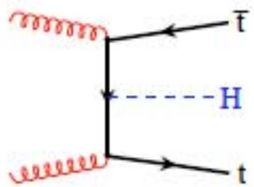


(for √s = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

Production cross sections at the LHC

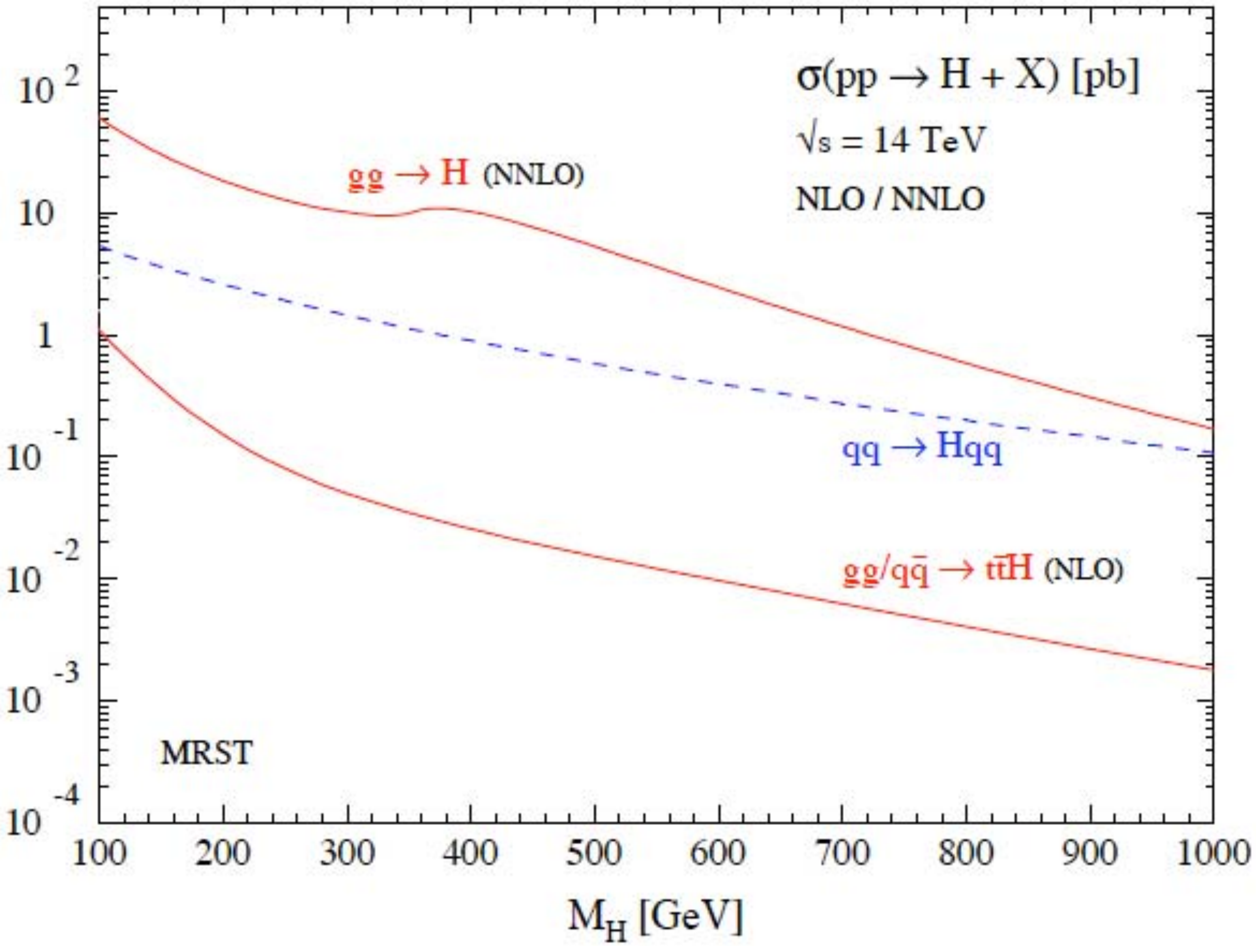


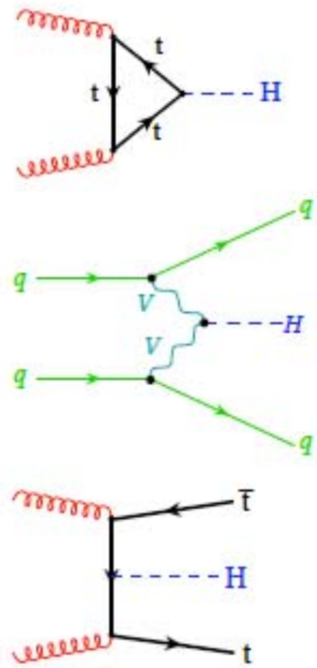




(for √s = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

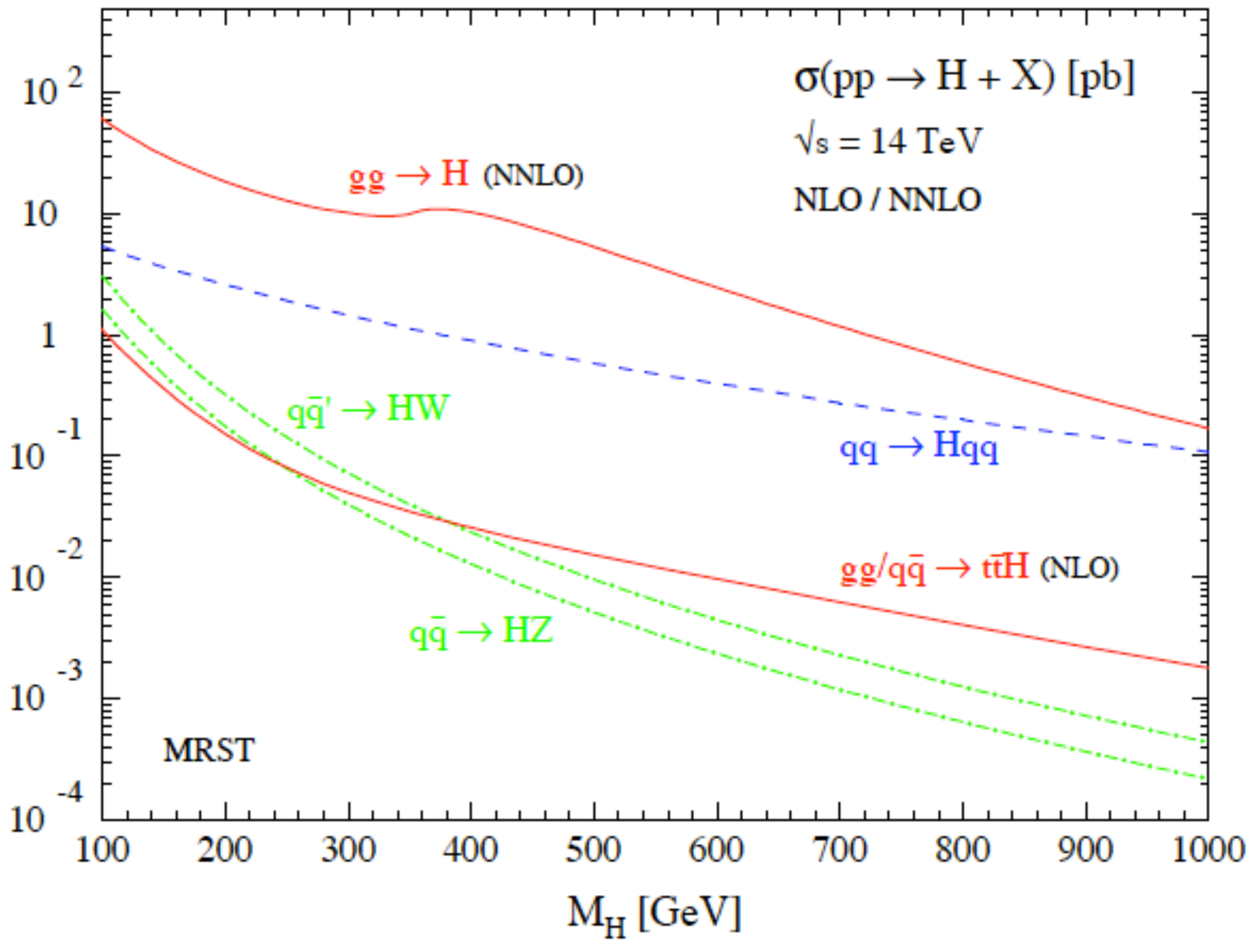
Production cross sections at the LHC

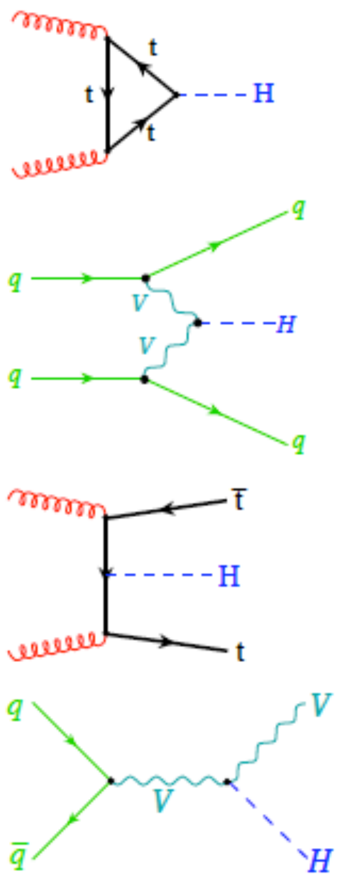




(for $\sqrt{s}$ = 14 TeV, difference between 14 and 7 TeV to be discussed tomorrow)

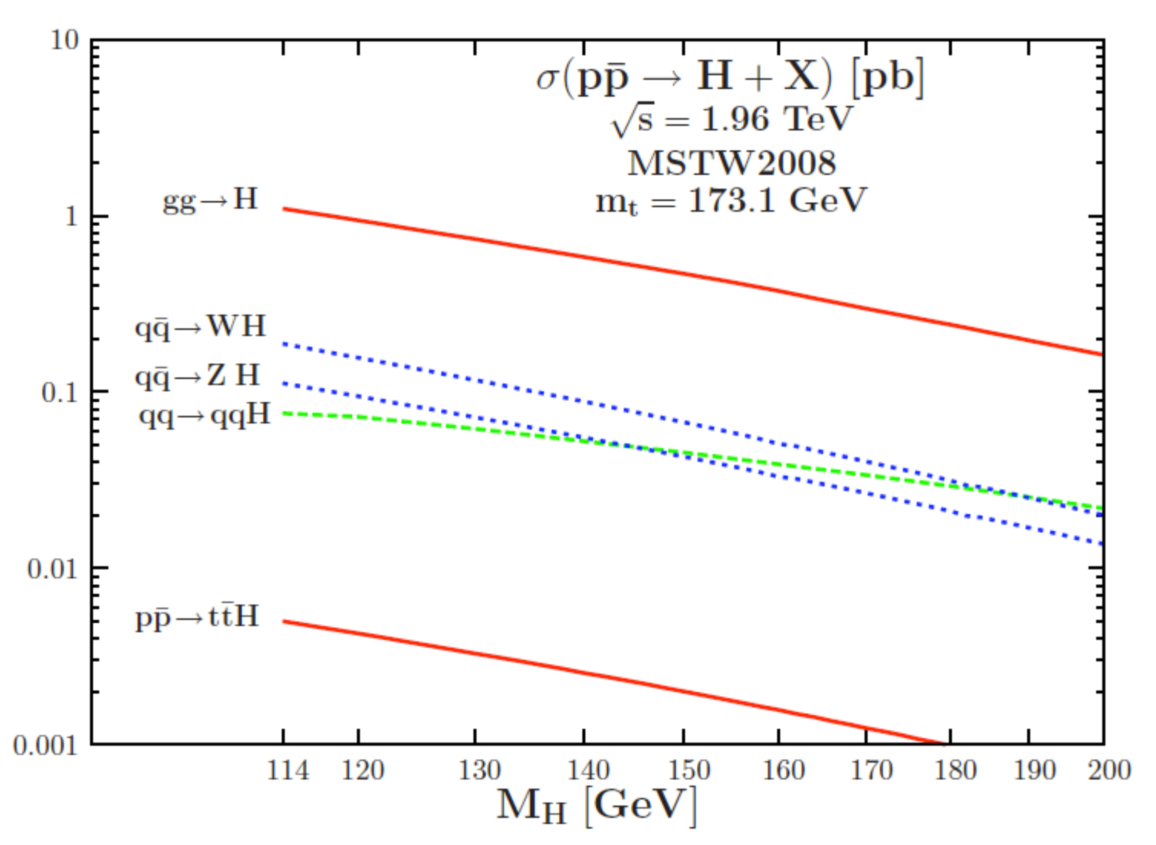
Production cross sections at the LHC





(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

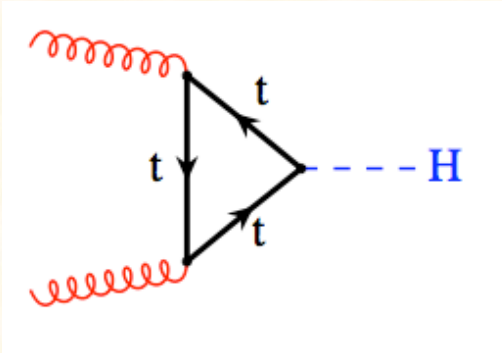
1. Gluon fusion

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:

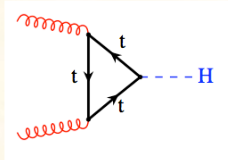


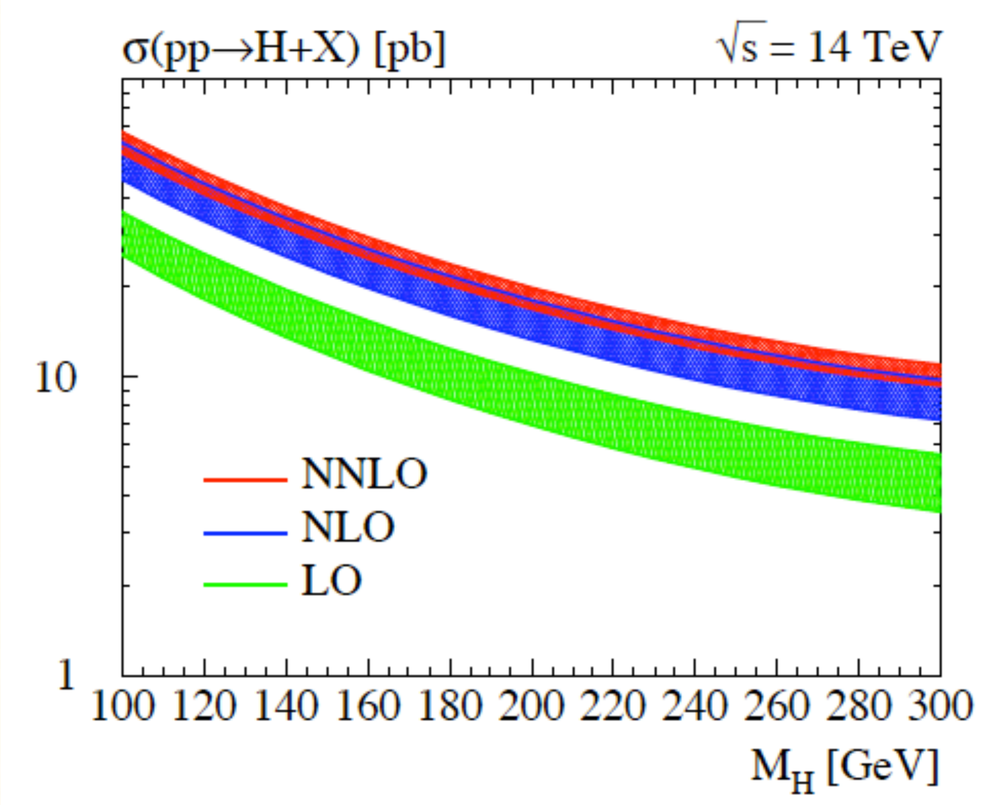
- Dominant production mode

- 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:





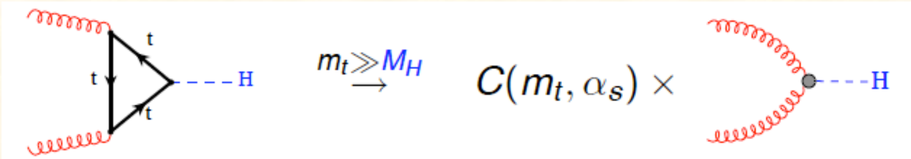
- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

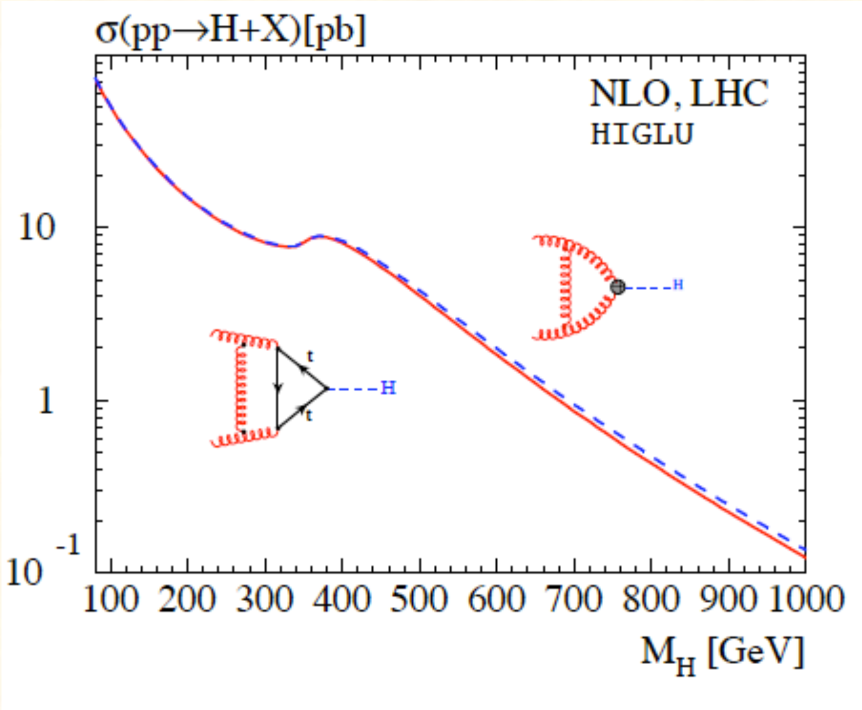
- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)

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

Effects of the finite top quark mass

(Effective theory for $m_t >> m_H$)

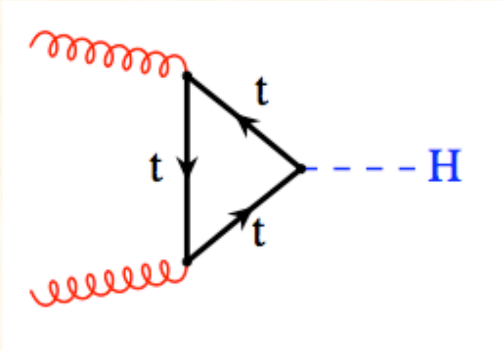




- Krämer, Laenen, Spira (1996)

Large m_t approximation works extremely well up to m_H ~ 300 GeV

Gluon fusion:



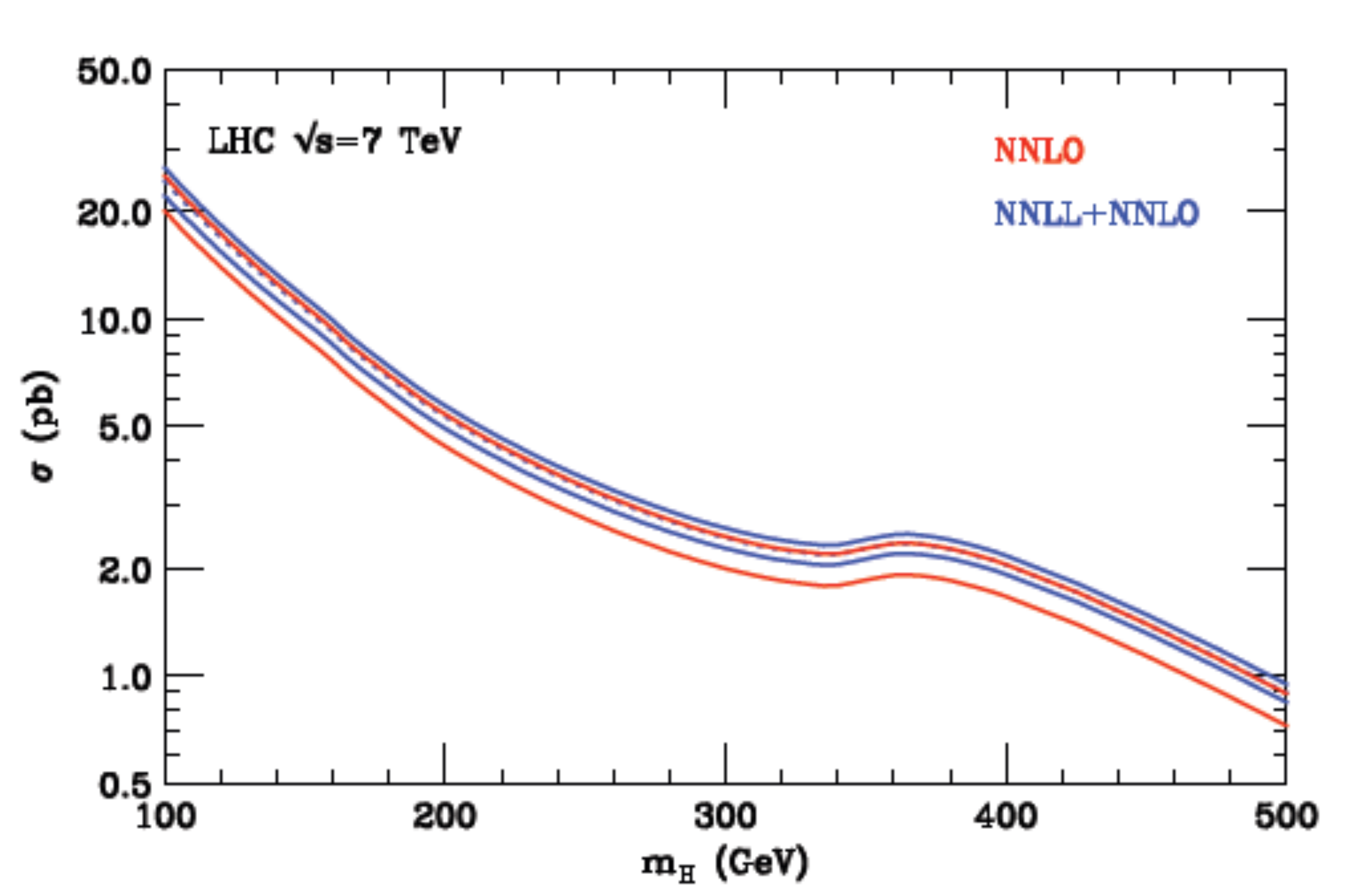
- Dominant production mode

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

- 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

- Effects of soft-gluon resummation at next-to-next-to leading logarithmic (NNLL) accuracy

Results for LHC at 7 TeV:

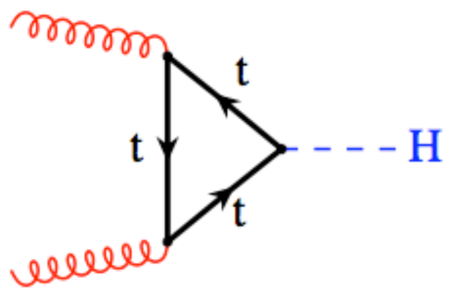


9-10% increase at 7 TeV

- M. Grazzini, D. de Florian (Higgs cross section working group, Freiburg, April 2010)
- S. Catani, D. de Florian, M. Grazzini, P. Nason (2003)

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

Gluon fusion:



- Dominant production mode

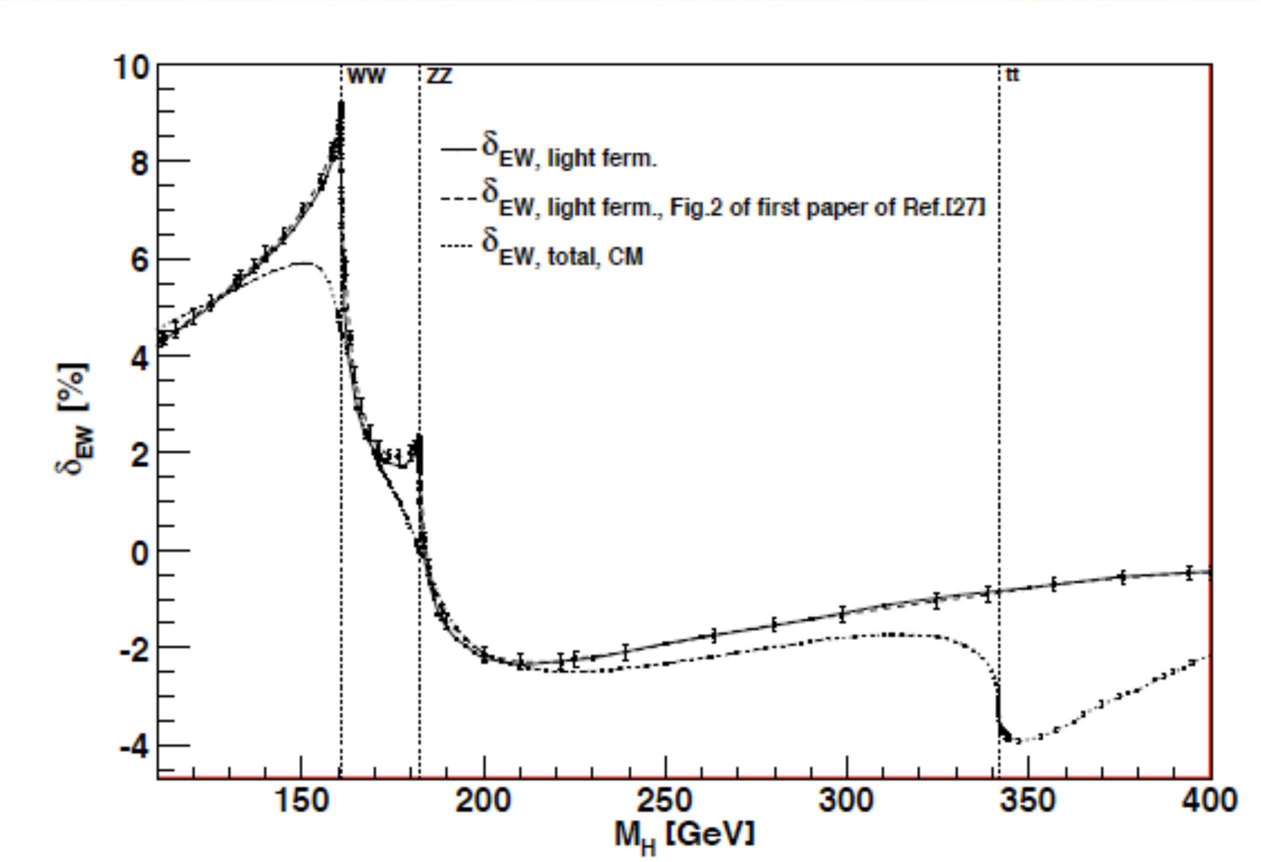
- Sensitive to heavy particle spectrum …
  (e.g. 4th generation quarks)
  …and the corresponding Yukawa couplings
  (important for coupling measurements)

- 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

- Effects of soft-gluon resummation at next-to-next-to leading logarithmic (NNLL) accuracy

- Two-loop el.weak corrections

Electroweak corrections:

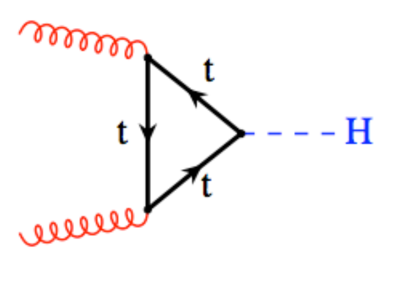


normalized to LO

- Actis, Passarino, Sturm, Uccirati (2008)

Partial:
- Aglietti, Bonciani, Degrassi, Vicini (2004)
- Degrassi, Maltoni (2004)
- Djouadi, Gambino (1994)

Gluon fusion:



- Results of the calculations:

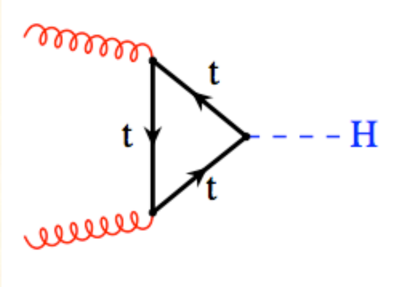
Calculation	LHC, $\sqrt{s}$ = 14 TeV m_H = 160 GeV
NLO	+110% of LO
NNLO	+ 30% of NLO
Soft gluon resummation (NNLO + NNLL)*	+ 11% of LO
Electroweak	+ 6% of LO

- Dependence on parton density functions
(gluon distribution, α_s)

Calculation	LHC, $\sqrt{s}$ = 14 TeV m_H = 160 GeV
MRST 2006 → MSTW2008	-13% of LO

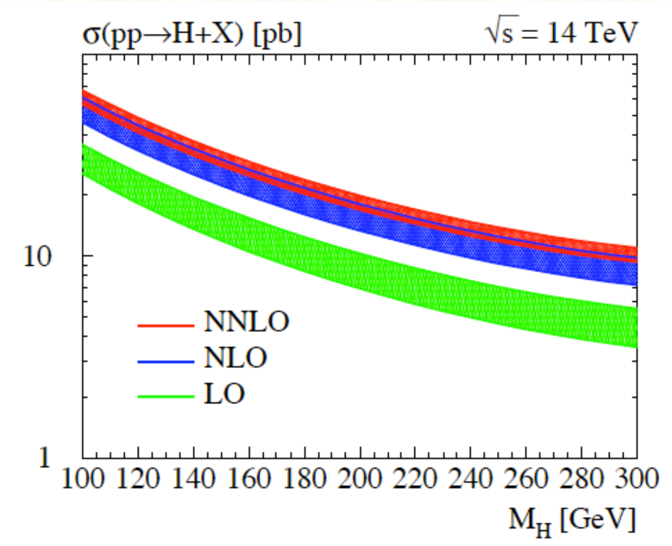
*) Includes full NNLO result plus all-order resummation of logarithmically enhanced terms

Gluon fusion:



- How large are the uncertainties on the cross section?

  - Uncertainties from renormalization and factorization scale



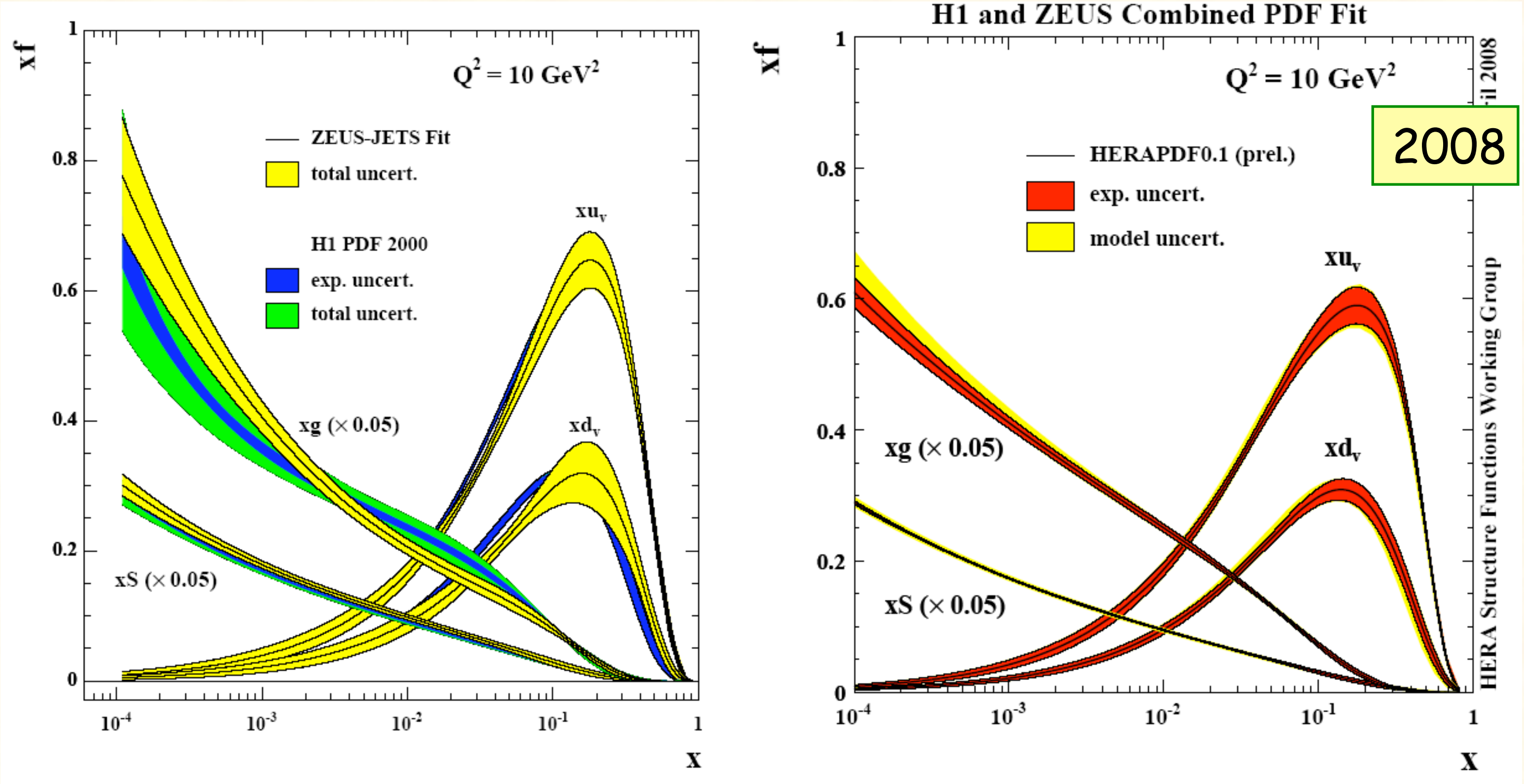
For each order: bands correspond to a variation of the renormalization and factorization scale by factors of 2:
$m_R = m_F = m_H/2 \leftrightarrow m_R = m_F = 2\ m_H$

Typical uncertainty: 10 – 15%
(depends on scale factor, which is not well defined)

  - Uncertainties from structure function and α_s
    (→ next slides)

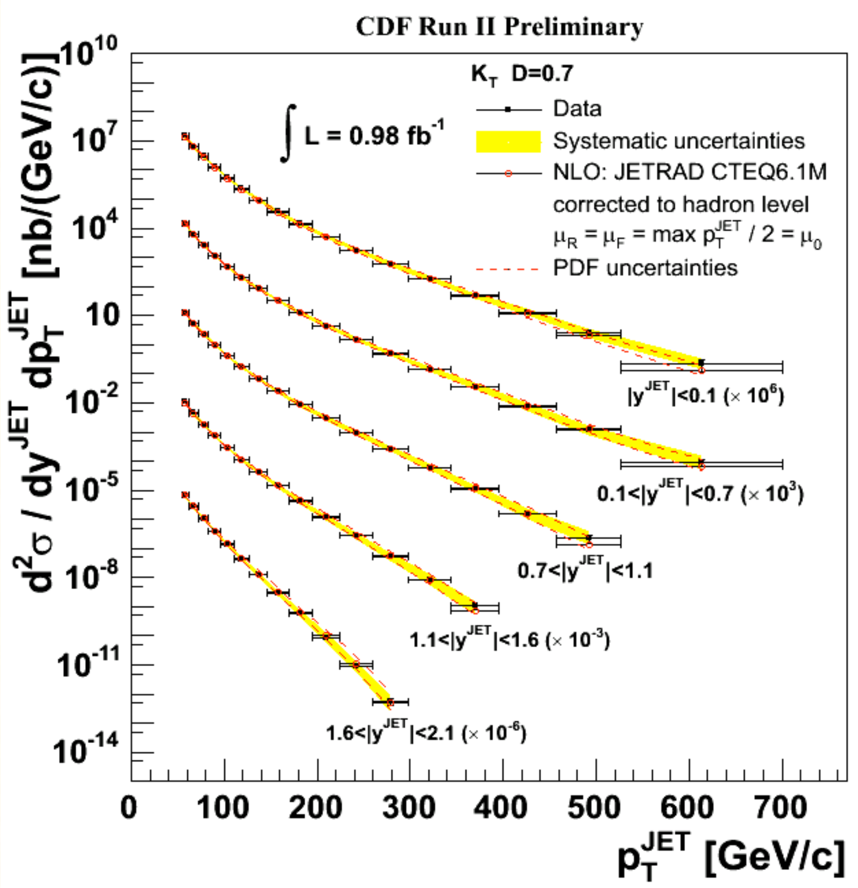
Results from HERA on the proton structure

- Large data sets and combination of the two HERA experiments (H1 and ZEUS) improve the precision on the parton distribution functions

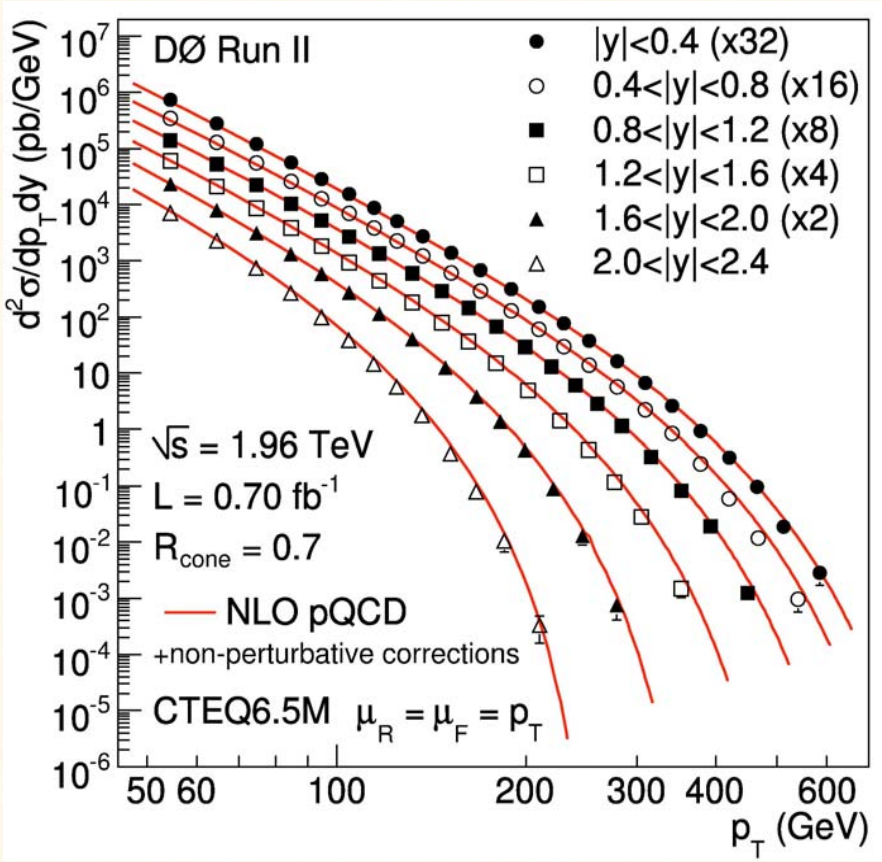


- Important to reduce cross section uncertainties at hadron colliders;

Tevatron jet production vs. p_T and η



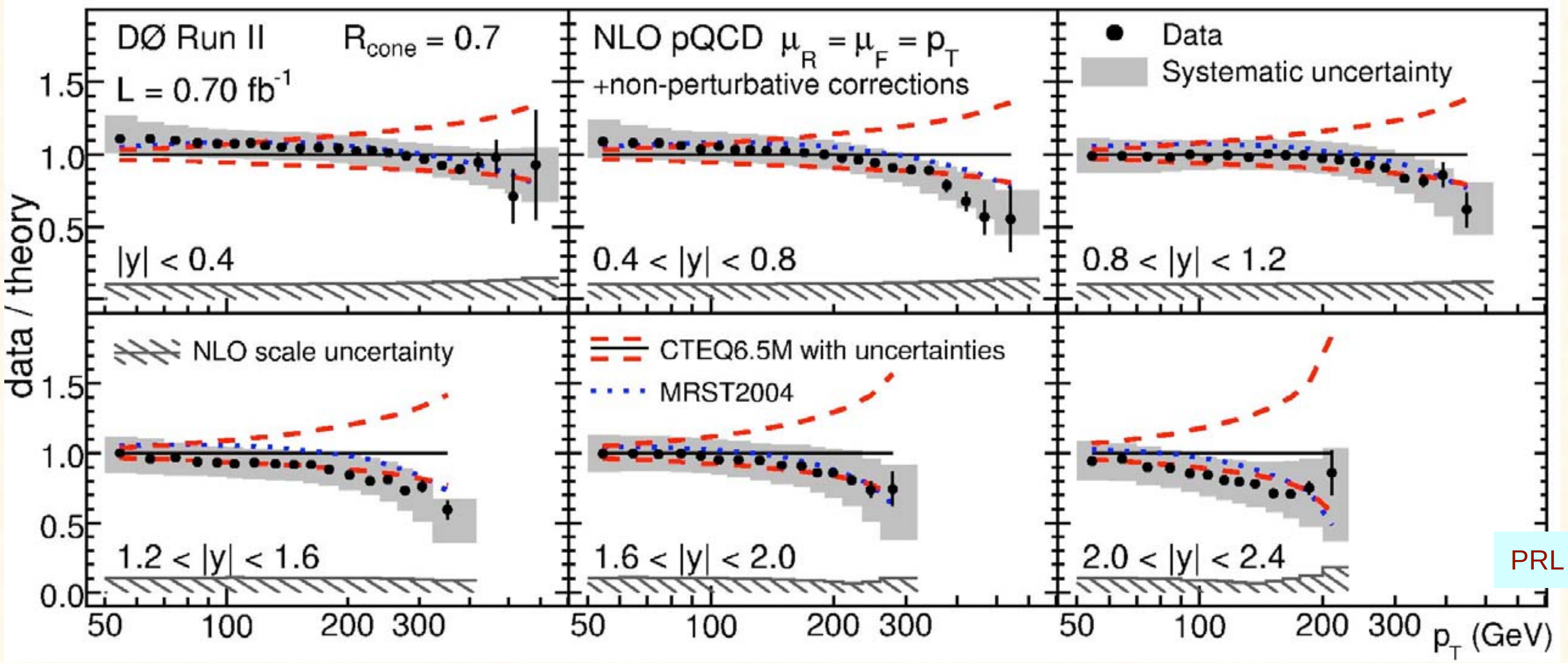
PRD 78 052006 ('08)



PRL 101 062001 ('08)

- Measurement in 5-6 different rapidity bins, over 9 orders of magnitude, up to p_T ~650 GeV
- Data corresponding to ~ 1 fb^{-1} (CDF) and 0.7 fb^{-1} (DØ)

Comparison between data and theory

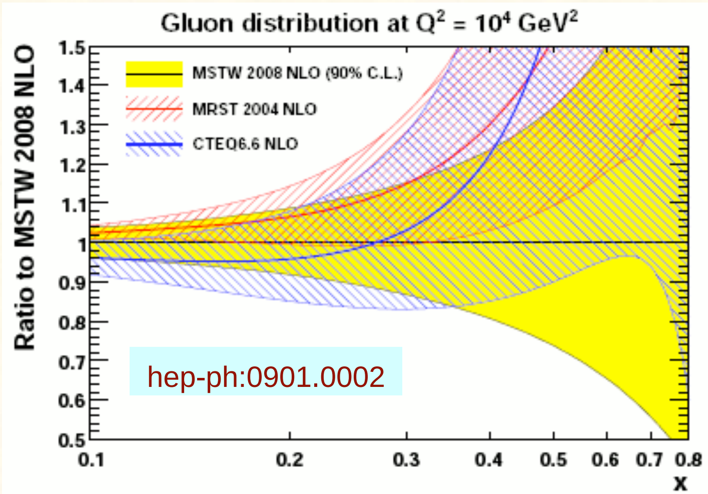


PRL 101 062001 ('08)

- CDF and DØ agree within uncertainties

- Experimental uncertainties are smaller than the pdf uncertainties
  (in particular large for large x, gluon distribution)

- Updated (2009) parametrizations include these data



hep-ph:0901.0002

Structure function parametrizations

R. Thorne, Higgs cross section meeting, Freiburg, April 2010

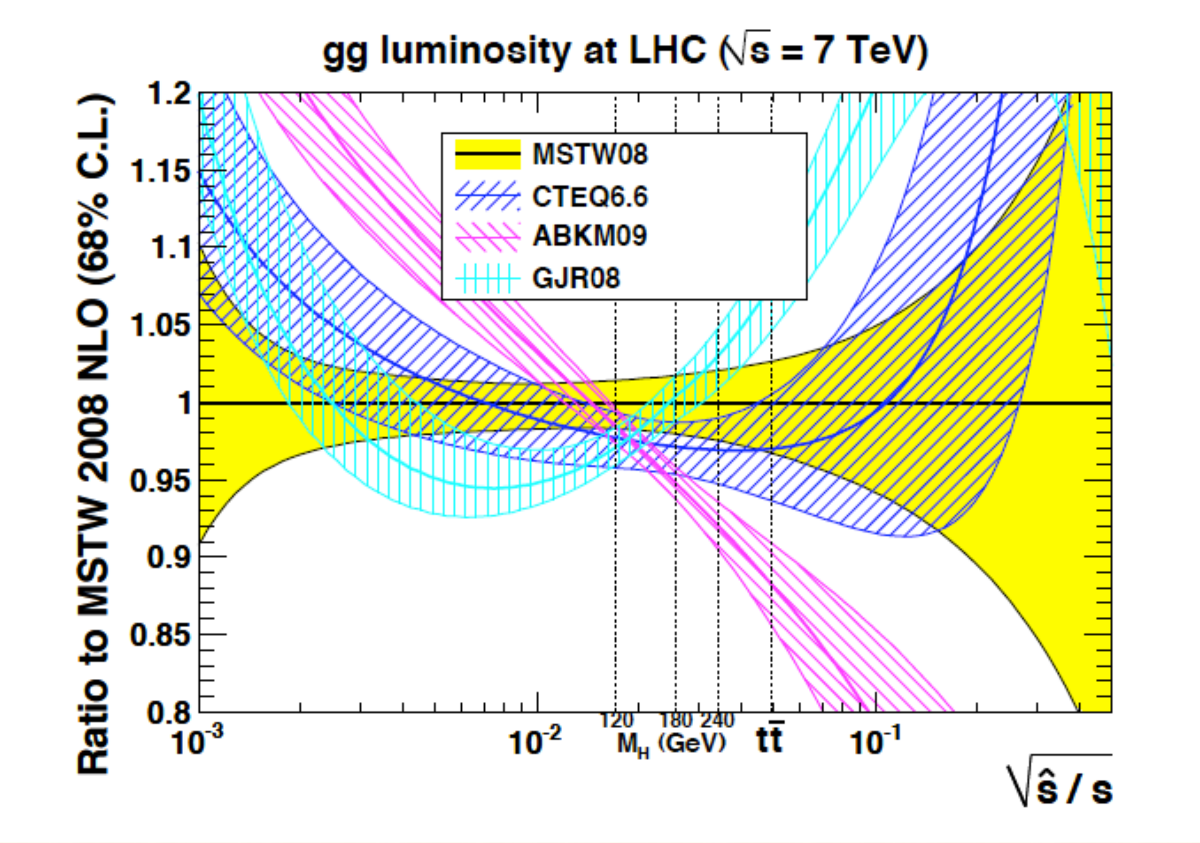
Different PDF sets

- MSTW08 – fit all previous types of data. Most up-to-date Tevatron jet data. Not most recent HERA combination of data. PDFs at LO, NLO and NNLO.
- CTEQ6.6 – very similar. Not quite as up-to-date on Tevatron data. PDFs at NLO.
- NNPDF2.0 – include all above except HERA jet data (not strongest constraint) and heavy flavour structure functions. Include HERA combined data. PDFs at NLO.
- HERAPDF2.0 – based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at LO, NLO.
- ABKM09 – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO.
- GJR08 – fit to DIS, fixed target Drell-Yan and Tevatron jet data. PDFs at NLO and NNLO.

Use of HERA combined data instead of original data $\rightarrow 1-2.5\%$ increase in quarks at low x (depending on procedure), similar on $\alpha_S(M_Z^2)$ if free (MSTW prelim.), and somewhat less on gluon. More stable at NNLO (MSTW prelim.).

Structure function parametrizations

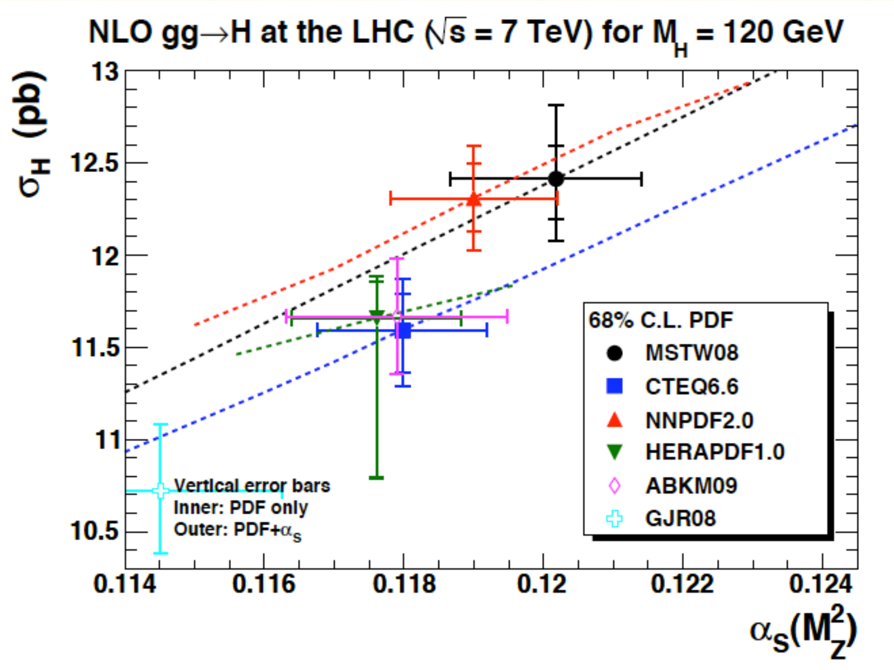
R. Thorne, Higgs cross section meeting, Freiburg, April 2010



Clearly some distinct variations between the various groups

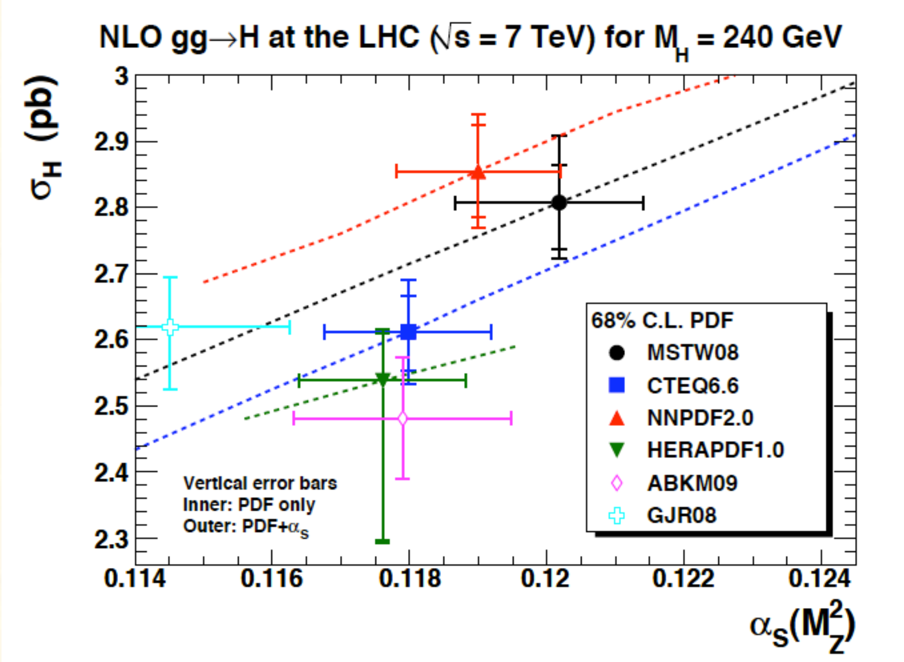
Higgs gg-cross section for various SF parametrizations

R. Thorne, Higgs cross section meeting, Freiburg, April 2010

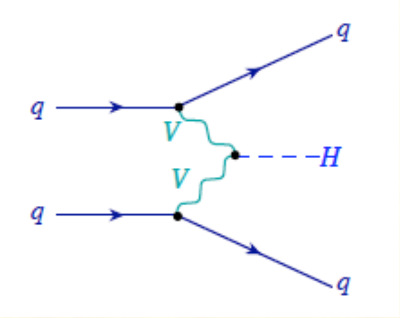


Significant effects, resulting from both α_s and parametrizations of parton distributions (correlated)

Working group in place (theory + expt.) to address these issues and to come up with LHC cross section values and estimates of the uncertainties



Vector boson fusion:



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

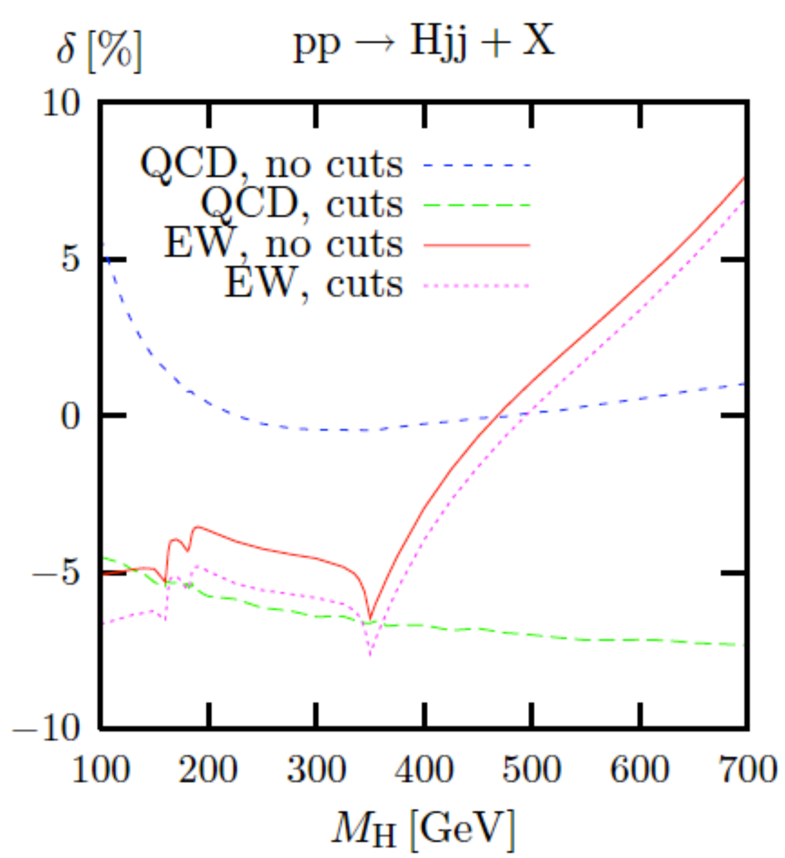
- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

  Both NLO QCD and el.weak have been calculated

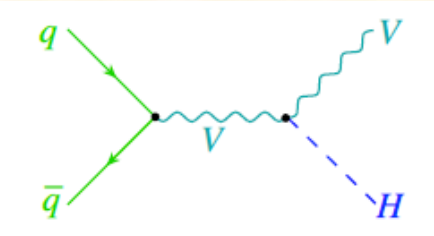
- Effective K-factor depends on experimental cuts

  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:



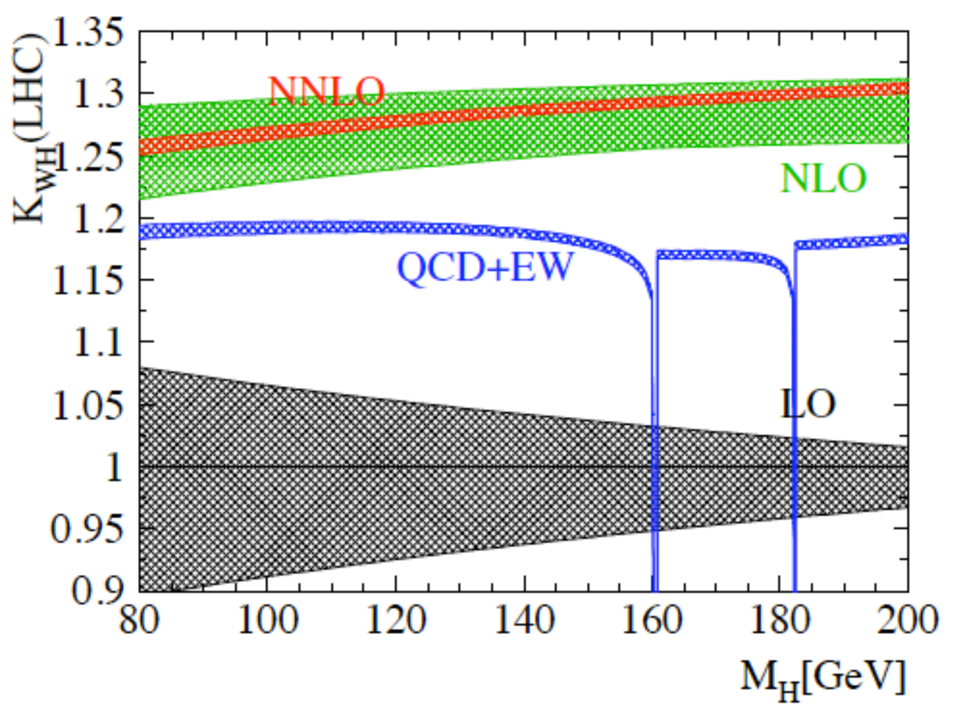
- Weak at the LHC,
  Relatively stronger at the Tevatron

- Allows for a Higgs-decay-independent trigger
  $W \to l\nu$, $Z \to ll$

- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

  Both NLO QCD and el.weak
  corrections available

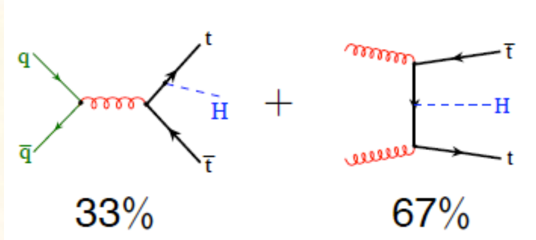


Brein, Djouadi, Harlander, (2003)

Han, Willenbrock (1990)

Ciccolini, Dittmaier, Krämer (2003)

ttH associated production:



- Weak and difficult at the LHC

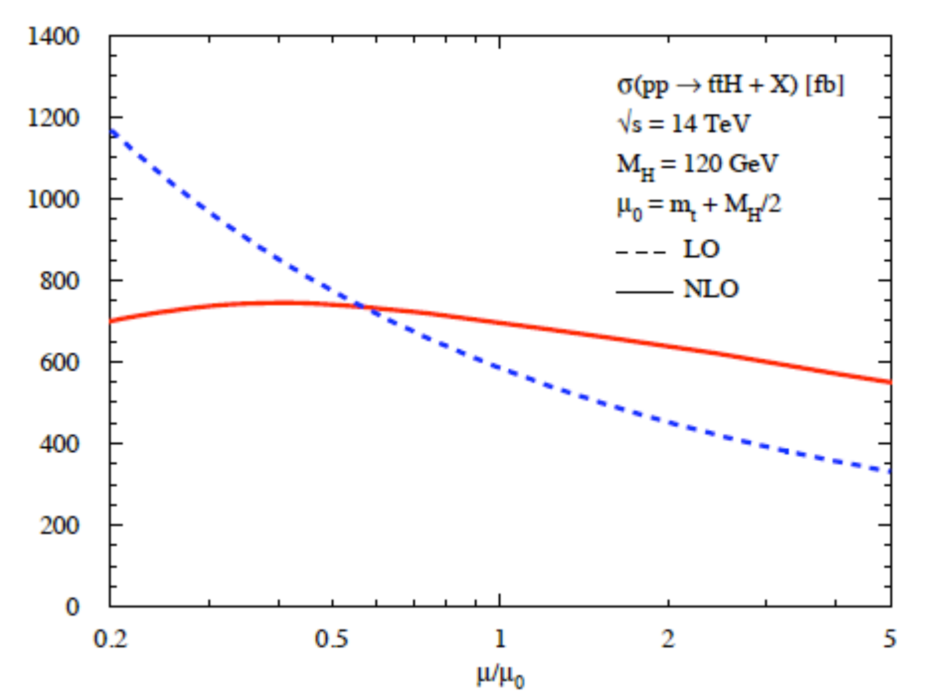
- Sensitivity to top-Yukawa coupling

- 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)

Some important comments:

- Huge theoretical effort !!
  (N)NLO corrections calculated for many signal and background processes during the past years

- New Tools → Experimentalists have started to use and validate them:

(i) 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/webber/MCatNLO
- T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
- E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
- FEHIP, C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130 (differential cross sections through NNLO)
- HNNLO, S. Catani and M. Grazzini (2007, 2008)

(ii) New approaches to match parton showers and matrix elements:
(based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)

- ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
- PYTHIA, adapted by S. Mrenna
- SHERPA Monte Carlo, F. Krauss et al., www.physik.tu-dresden.de/~krauss/hep/index.html

Data are extremely important for validation,
(some examples tomorrow)

*) S. Catani, F. Krauss, R. Kuhn, B. R. Webber, JHEP 0111 (2001) 063.

PAUL SCHERRER INSTITUT PSI

Background processes: Les Houches '05 wishlist

Reaction	background for	existing calculations
$\mathrm{pp} \to VVj$	$\mathrm{t\bar{t}H}$, new physics	$\mathrm{WW}j$: Dittmaier, Kallweit, Uwer '07 $\mathrm{WW}j$: Campbell, R.K.Ellis, Zanderighi '07 $\mathrm{WW}j$: Binoth, Guillet, Karg, Kauer, Sanguinetti (in progress)
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}H}$	this talk
$\mathrm{pp} \to \mathrm{t\bar{t}}jj$	$\mathrm{t\bar{t}H}$	–
$\mathrm{pp} \to VV\mathrm{b\bar{b}}$	VBF$\to \mathrm{H} \to VV$, $\mathrm{t\bar{t}}$, NP	–
$\mathrm{pp} \to VVjj$	VBF$\to \mathrm{H} \to VV$	VBF: Jäger, Oleari, Zeppenfeld '06 + Bozzi '07
$\mathrm{pp} \to Vjjj$	new physics	amplitudes: Berger et al. '08, R.K.Ellis et al. '08
$\mathrm{pp} \to VVV$	SUSY trilepton signal	ZZZ: Lazopoulos, Melnikov, Petriello '07 WWZ: Hankele, Zeppenfeld '07 VVV: Binoth, Ossola, Papadopoulos, Pittau '08

- NLO for $2 \to 3$ processes established
- very few calculations for $2 \to 4$, no complete calculation for pp process

  $\mathrm{e^+e^+} \to 4f$ (EW) Denner et al. '05 , $\mathrm{e^+e^+} \to \mathrm{HH}\nu\bar{\nu}$ (EW) Boudjema et al. '05

  $\gamma\gamma \to \mathrm{t\bar{t}b\bar{b}}$ (QCD) Lei et al. '07, $\mathrm{u\bar{u}} \to \mathrm{s\bar{s}b\bar{b}}$ (QCD) Binoth et al. '08

Summary on cross section calculations:

- Large progress on the theoretical side: (N)NLO calculations available for all production processes

- Gluon fusion is the dominant production channel;
  NNLO and NNLO + NNLL calculations available

  Current uncertainties: ± 10-15 % (scale)
  ± 5 % (pdfs and α_s)

- Large progress also on Monte Carlo simulation programs
  - NLO and NNLO generators
  - Matrix element + parton shower matching approaches