The Quest for the Origin of Mass: Hunting for the Higgs Particle

Doreen Wackeroth

University at Buffalo
The State University of New York

What is the physical world made of ?

or

"So that no more with bitter sweat
I need to talk of what I don't know yet,
So that I may perceive whatever holds
The world together in its inmost folds, ..."

Faust, Johann Wolfgang von Goethe

Outline

0. Prelude

I. Introduction

   1. The Standard Model of Particle Physics (SM)
   2. The Higgs mechanism
   3. Where is the Higgs particle ?

II. Supersymmetry: one of the most attractive extensions of the SM

III. Higgs production in association with heavy quarks at the Tevatron and the LHC

   1. The Need for Next-to-Leading order QCD calculations
   2. $t\bar{t}H$ production in the Standard Model
   3. $b\bar{b}h^0$ production in the Minimal Supersymmetric SM (MSSM)

IV. Conclusions

0. Prelude

In particle physics, the understanding of physical phenomena is based on identifying a few fundamental constituents and a few fundamental interactions.

Matter particles: Leptons and Quarks

Forces: Strong, Weak $\otimes$ Electromagnetic, (gravity)

The forces (or interactions) among the constituents of matter are interpreted in terms of the exchange of gauge bosons.

Gauge bosons: Gluon, $W^{\pm}$ and Z bosons, Photon, (graviton)

Particles

Leptons

	Electric Charge		Electric Charge
Tau	-1	Tau Neutrino	0
Muon	-1	Muon Neutrino	0
Electron	-1	Electron Neutrino	0

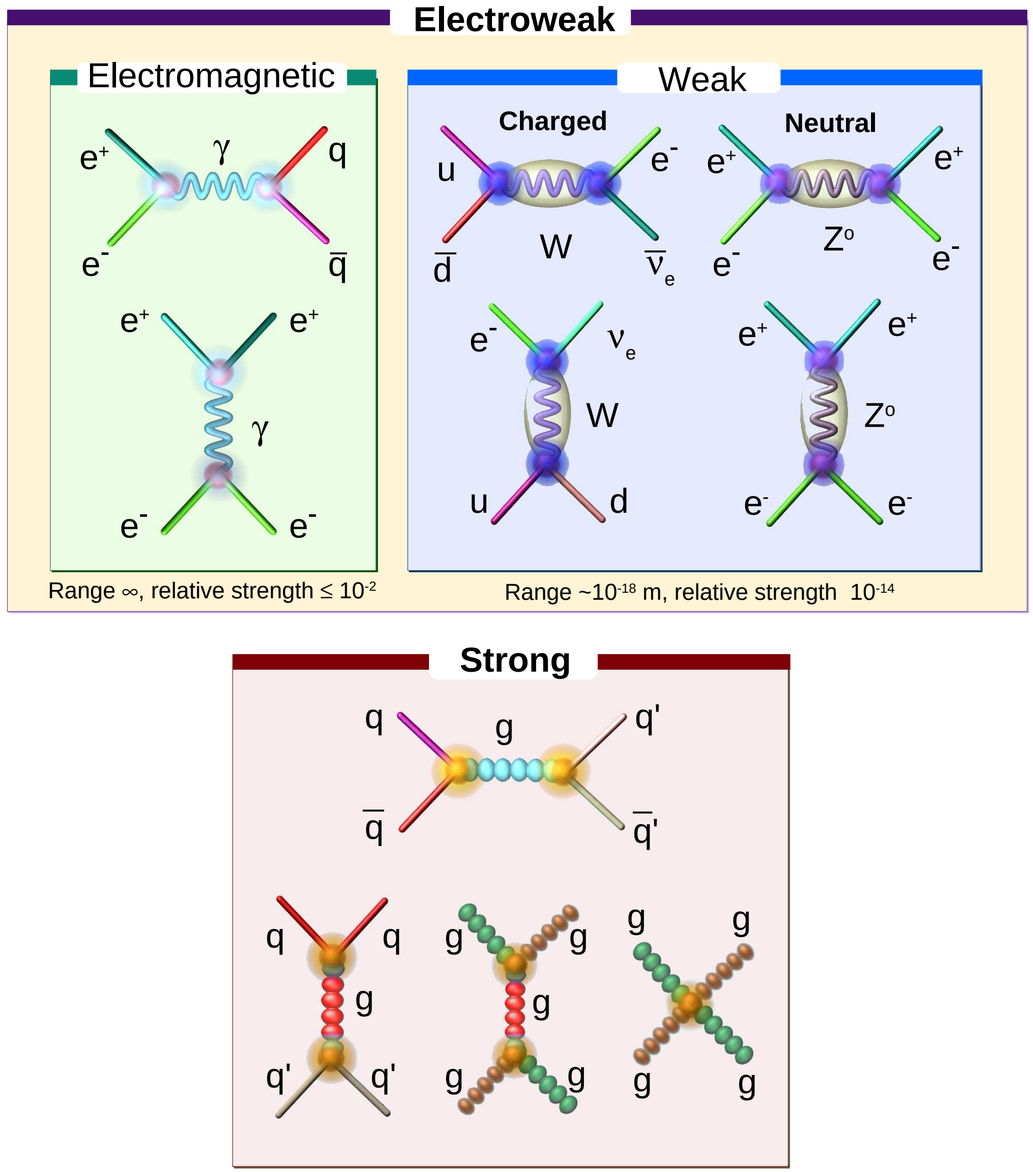
Quarks

	Electric Charge		Electric Charge
Bottom	-1/3	Top	2/3
Strange	-1/3	Charm	2/3
Down	-1/3	Up	2/3

each quark: ●R, ●B, ●G 3 colors

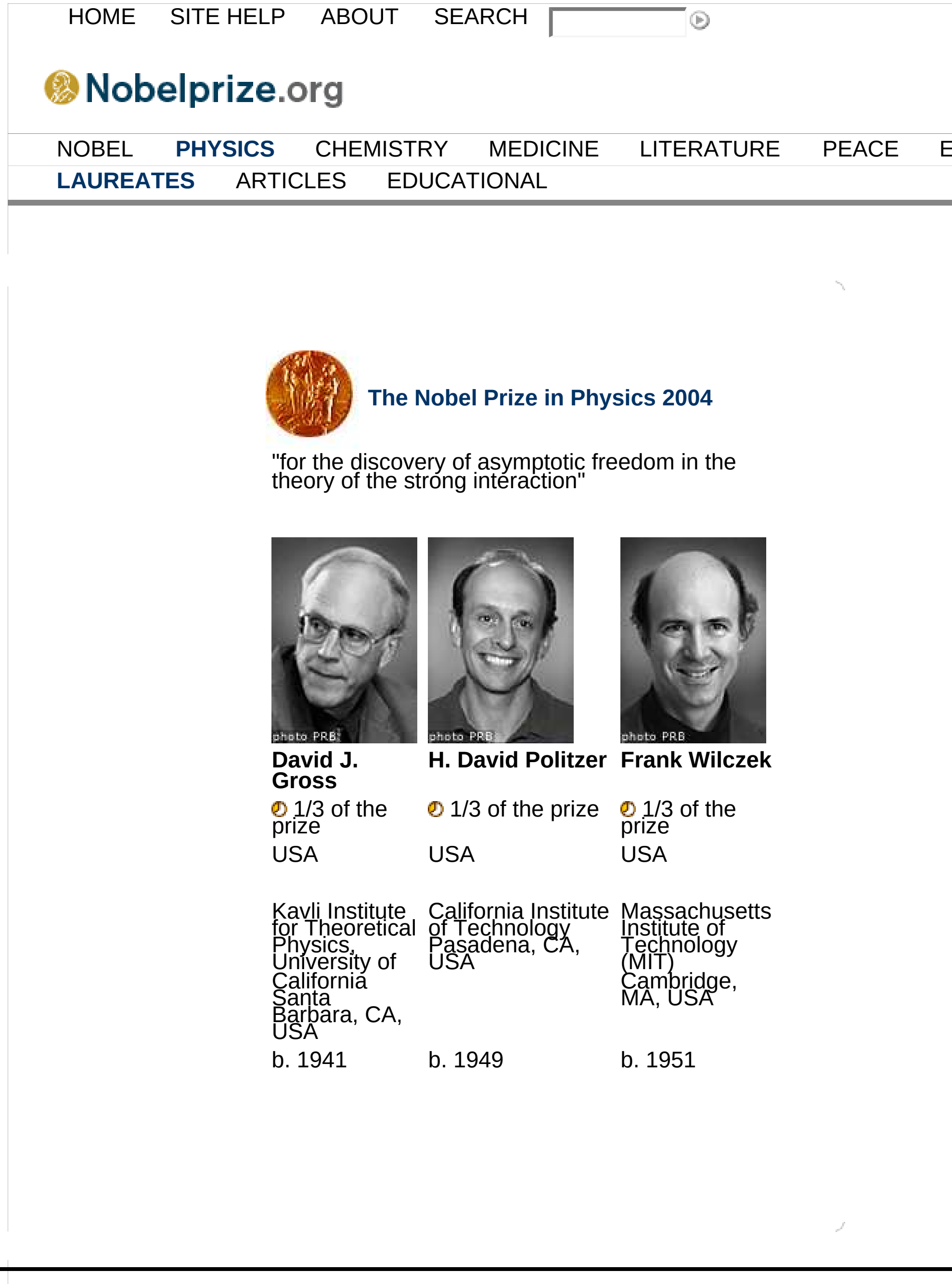
The particle drawings are simple artistic representations

Interactions: coupling of forces to matter

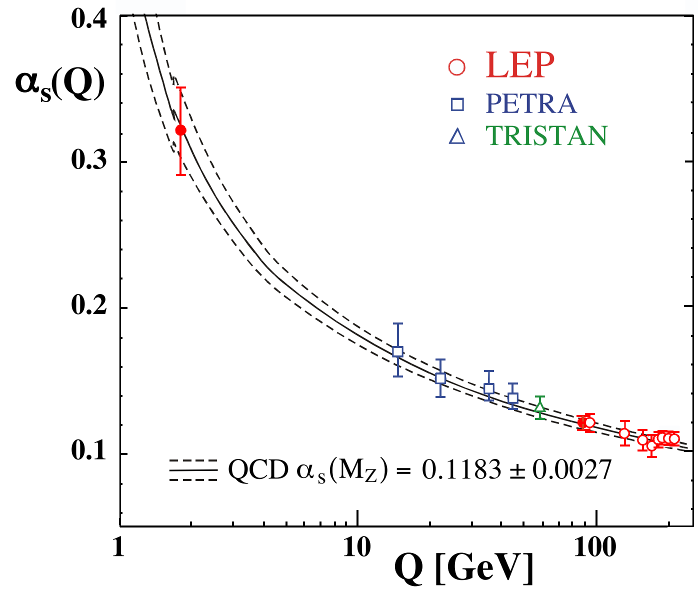


Range ~ 10^{-15} m, relative strength = 1

CMS March 98



The strong interaction is asymptotic free:



from S.Bethke, hep-ex/040702

The ultimate goal of elementary particle physics is to find the fundamental law(s) of nature, the final underlying theory, that determines the dynamics of matter.

Steven Weinberg: “*... to look for a simple set of physical principles, which have about them the greatest possible sense of inevitability and from which everything we know about physics can, in principle, be derived.*”

Elementary Particles and the Laws of Physics, The 1986 Dirac Memorial Lectures.

Steven Weinberg: One could imagine “... *that specifying the symmetry group of nature may be all we need to say about the physical world, beyond the principles of Quantum Mechanics.*”

Elementary Particles and the Laws of Physics, The 1986 Dirac Memorial Lectures

In the Standard Model of Particle Physics, gauge symmetries prescribe the dynamics of matter.

I. Introduction

I.1. The Standard Model of Particle Physics

To describe the fundamental interactions of quarks and leptons, a “new” fundamental symmetry principle has been identified:
local gauge invariance = laws of physics are invariant under a space-time dependent change of “scale”.

Electromagnetic interaction:

It does not matter, if we choose for the electromagnetic four-potential $A_\mu(x)$ in Iowa City and $A_\mu(x) + \partial_\mu \Lambda(x)$ in Buffalo, we will get the same $\vec{E}$ and $\vec{B}$ fields

or

the electromagnetic field strength tensor $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ is invariant under local phase transformations $A_\mu(x) \to A_\mu(x) + \partial_\mu \Lambda(x)$.

Local Gauge Invariance as Dynamical Principle

Starting with non-interacting electrons (and positrons) and photons and imposing local gauge invariance leads to electron-photon interaction in the form: $J^\mu_{em} A_\mu$ (J_{em} is the conserved electromagnetic current).

But: "naive" mass terms spoil local gauge invariance !

$$m_\lambda^2 A_\mu A^\mu \to m_\lambda^2 (A_\mu + \partial_\mu \Lambda(x))(A^\mu + \partial^\mu \Lambda(x)) \neq m_\lambda^2 A_\mu A^\mu$$

$\Rightarrow$ Masslessness of the photon as a consequence of gauge invariance of the electromagnetic interaction.

Symmetries of the Standard Model

Interaction	symmetry group	gauge theory
electromagnetic	local U(1): invariance under space-time dependent phase transitions generated by the electric charge	QED
strong	local SU(3): invariance under space-time dependent rotations in the 8-dimensional color space	QCD
electroweak	SU(2)$\otimes$U(1): invariance under space-time dependent rotations in the 3-dimensional (weak) isospin space and under phase transitions generated by the (weak) hypercharge Y ($Q = I_3 + Y/2$)	SM of electroweak interactions

Still far from Weinberg's one *symmetry group of nature* . . .

I.2. The Higgs mechanism

The origin of mass in the Standard Model (SM)

Experimental fact: the mediators of the weak force, the $W^\pm$ and Z bosons, are massive.

But: explicit mass terms break the electroweak gauge symmetry of the SM.

Solution: spontaneous symmetry breaking of the $SU(2)_I \otimes U(1)_Y$ gauge group: the symmetry is "hidden" in such a way that the W and Z bosons become massive and the photon remains massless.

Goldstone (1961); Goldstone, Salam and Weinberg (1962); Higgs (1964,1966); Kibble (1967); Brout and Englert (1964); Guralnik, Hagen and Kibble (1964)

Hidden symmetry:

A phenomenon that occurs when a system that is symmetric has critical points that are not, e.g., potential minima in classical theory, vacua in QFT.

Consequence: in the SM there exists one massive spin–0 (scalar) particle, the Higgs boson.

“Hiding” the electroweak gauge symmetry of the SM:

1. Introduce two complex scalar fields, $\Phi = (\Phi^+, \Phi^0)$, with gauge-invariant interactions among themselves and with the SM fermions and bosons

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi) + \mathcal{L}_{Yukawa}$$

with $D_\mu = \partial_\mu - i g_2 \frac{\vec{\tau}}{2} \vec{W}_\mu - i g_1 \frac{y_i}{2} B_\mu$.

2. Arrange self-interactions so that spontaneous symmety breaking can occurand choose the vacuum state so that it is not invariant under electroweak symmetry but still $U(1)_{em}$ symmetric:

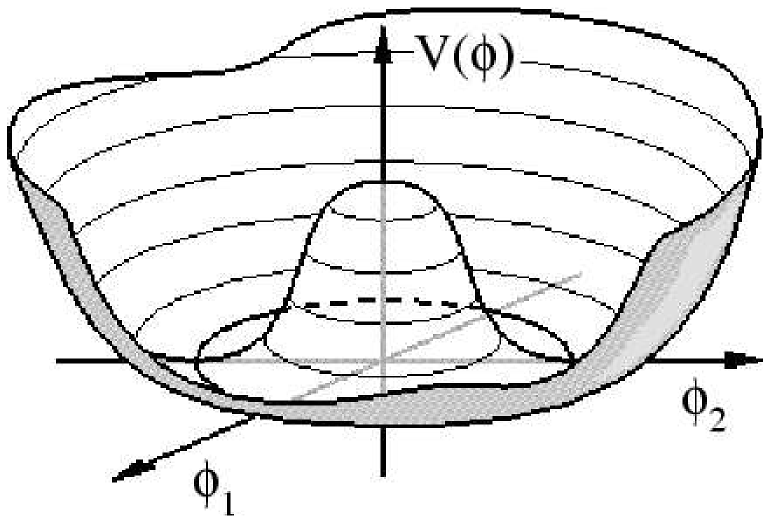
Higgs potential (“sombrero” potential):

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 ; \lambda > 0$$

$$\text{SSB:} \mu^2 > 0 : V(\Phi) \text{ is minimized by } |\Phi_0|^2 = \frac{\mu^2}{2\lambda} = \frac{v^2}{2} \neq 0$$

Orientation of Φ_0 in the SU(2) space is not fixed:

$\Phi_0 = exp(i\frac{\vec{\tau}}{2}\vec{\chi}(x))(0, \frac{v}{\sqrt{2}})$



The choice of one vacuum state (spontaneously) breaks the SU(2) symmetry, e.g., choose

$$\Phi_0 = (0, \frac{v}{\sqrt{2}})$$

but it is still invariant under $U(1)_{em} : Q\Phi^0 = 0.$

Spontaneous symmetry breakdown with $\Phi = \Phi_0 + (0, \frac{\eta(x)}{\sqrt{2}})$ (with $< 0|\eta|0 >= 0$) so that

$$\mathcal{L} = \frac{v^2 g_2^2}{4} W_\mu^+ W^{-\mu} + \frac{v^2(g_1^2 + g_2^2)}{8} Z_\mu Z^\mu - \frac{\lambda v^2}{4}\eta^2 - \sum_f \frac{v g_f}{\sqrt{2}} \bar{\Psi}_f \Psi_f - \sum_f \frac{g_f}{\sqrt{2}} \bar{\Psi}_f \Psi_f \eta + \cdots$$

$$= M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu - \frac{1}{2} M_H^2 \eta^2 - \sum_f M_f \bar{\Psi}_f \Psi_f - \sum_f \frac{g_2 M_f}{2 M_W} \bar{\Psi}_f \Psi_f \eta + \cdots$$

W and Z bosons and fermions acquire mass. The photon remains massless (residual symmetry $U(1)_{em}$). The Higgs-fermion coupling strength is proportional to the fermion mass.

One physical scalar particle emerges, the Higgs Boson (η), with mass $M_H = \sqrt{\lambda/2}v$.

The Higgs particle:
a necessary consequence of our understanding of the origin of mass in the SM.

The Higgs particle so far eluded direct observation.

We know from direct (LEP2) and indirect searches (fits to electroweak data) that the SM Higgs boson mass lies in the range

CERN-EP/2003-011, CERN-EP/2003-02 (update: LEPEWWG webpage)

$$114.4\,\mathrm{GeV} < M_H \lesssim 260\,\mathrm{GeV}\ (95\,\%\ \mathrm{C.L.})$$

$\Rightarrow$ the Higgs boson might be “just around the corner” . . .

I.3. Where is the Higgs particle ?

Status and prospects of (direct) Higgs searches at high-energy collider experiments:

• Past: Direct search at the CERN LEP2 e^+e^- collider operated above the W-pair production threshold up to $\sqrt{s} = 209$ GeV (shutdown in 2000):

$$M_H > 114.4\,\mathrm{GeV}\,(95\%\ \mathrm{CL})$$

• Present: Fermilab Tevatron $p\bar{p}$ collider operated at 1.96 TeV (status: 0.25 fb^{-1} of integrated luminosity on tape, $4 - 9\,\mathrm{fb}^{-1}$ by 2009):

Higgs discovery reach at the Tevatron with $7\,\mathrm{fb}^{-1}$ per experiment: $M_H \lesssim 115$ GeV

• Future: CERN LHC pp collider will be operated at 14 TeV, starts in $\sim$ 2007:

If it exists, the LHC will discover it.

And: LHC will measure the Higgs mass and ratios of its couplings, . . .

The LEP collider ring (27 km) at CERN, Geneva, Switzerland

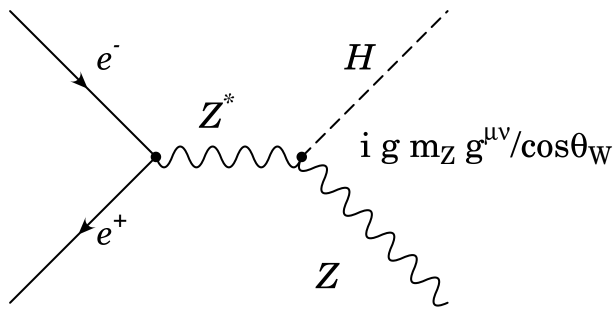
Future site of the Large Hadron Collider (LHC)

Movie

http://atlasexperiment.org/

The direct search for the Higgs boson is extremely challenging:

LEP-II and the Tevatron mainly look for the Higgs boson produced in association with a electroweak gauge boson, e.g., $e^+e^- \to Z \to HZ$:



and $H \to b\bar{b}$, $Z \to q\bar{q}$

Signature in the detector: 2 b-quark jets (identified via b-tagging) and two light quark jets.

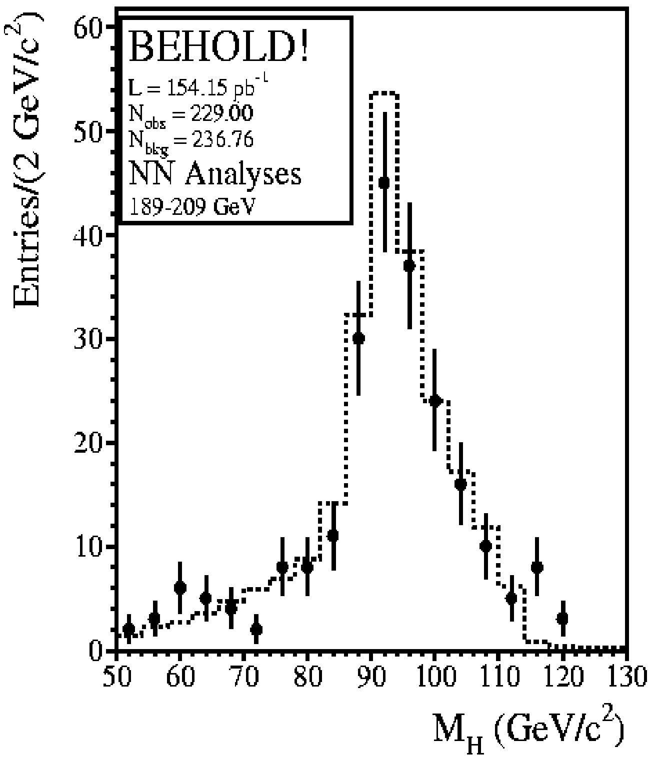
These events are extremely rare:

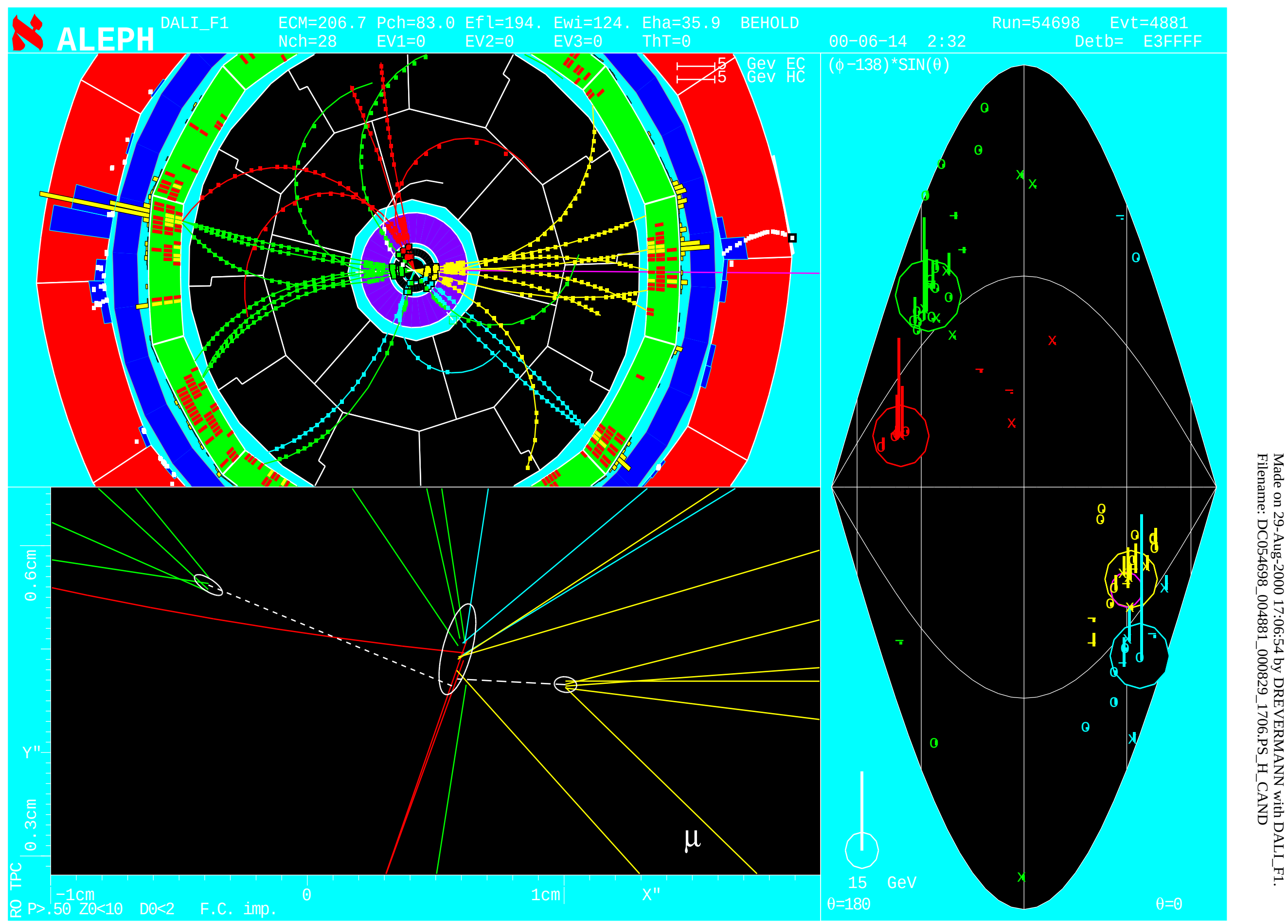
At LEP-II the background (=same signature in the detector but contains no Higgs) is up to two orders of magnitude larger than the Higgs signal.

At the Tevatron $\sigma(p\bar{p})/\sigma(p\bar{p} \to H) \approx 10^{10}$.

At the LHC, the background for the light Higgs search ($H \to b\bar{b}$) is of the order 10^7 times larger than the Higgs signal.

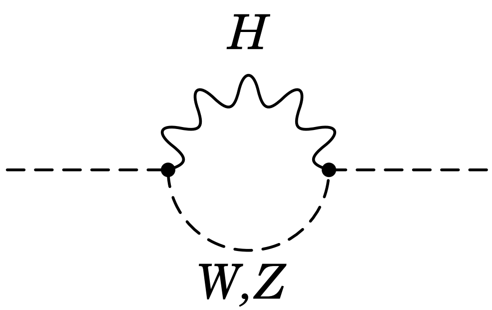
At LEP-II, a few spectacular SM Higgs candidates have been recorded (ALEPH, 4-jet events, $>$ 206 GeV) consistent with M_H around 116 GeV, but no discovery could be claimed.





from the ALEPH webpage at CERN

The indirect search for the Higgs boson:
the Higgs boson leaves a "trace" in measurements of W and Z boson properties through its virtual presence in quantum loops, e.g.,

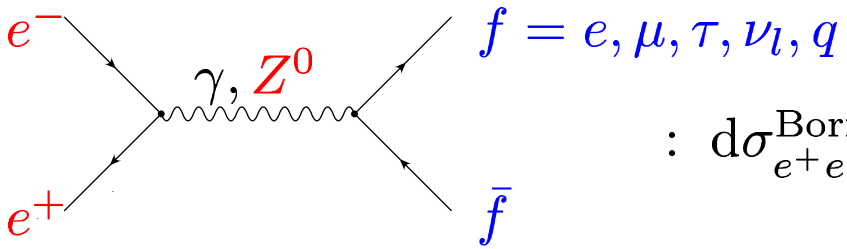


When comparing precise predictions with at least equally precise measurements information about unknown parameters of the SM such as the Higgs mass can be extracted.

How to make precise predictions for high-energy collider experiments ?

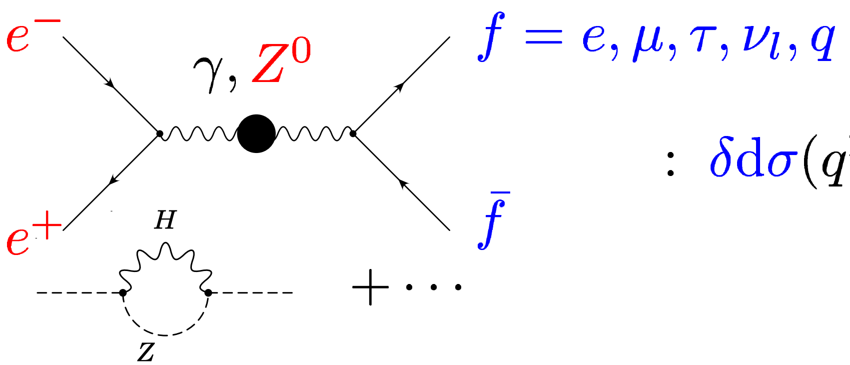
We rely on perturbation theory, e.g., a Feynman graph expansion in the coupling constant of the scattering amplitude:

lowest order: Born approximation, e.g., Z boson production at LEP/SLC



: $d\sigma^{\rm Born}_{e^+e^- \to f\bar{f}}(q^2, \alpha, m_f, m_e)$ is of $\mathcal{O}(\alpha^2)$

1-loop: in the 'quantum world' the photon and Z boson feel the virtual presence of all particles:



: $\delta d\sigma(q^2, \alpha, m_f, m_e, m_{top}, M_H, \ldots)$ is of $\mathcal{O}(\alpha^3)$

$$\Rightarrow d\sigma^{theory}_{e^+e^- \to f\bar{f}} = d\sigma^{Born}_{e^+e^- \to f\bar{f}} + \delta d\sigma(m_{top}, M_H) + \mathcal{O}(\alpha^4)$$

$\delta d\sigma$ are the quantum corrections (radiative corrections) of the theory.

By comparing predictions for electroweak observables including radiative corrections with measurements

- the electroweak sector of the SM is probed at the quantum-loop level,
- the consistency of the SM is checked by comparing direct with indirect determinations of input parameters, e.g., m_t, M_W,
- the SM Higgs boson mass can be predicted, and
- the parameters of models beyond the SM can be constrained.

The SM is successfully tested as a Quantum Field Theory at the permille level – no deviations found.

Note: We need to extend the SM to incorporate the experimental fact that neutrinos have mass.

Morever: Small descrepancies $(2-3\sigma)$ observed in the measurement of the weak mixing angle at NuTeV and the anomalous magnetic moment of the muon at BNL.

The global SM fi t to all electroweak data:

Two $\sim 3\sigma$ “anomalies”:

$A_{FB}^{0,b}$, $\sin^2\theta_W$ (NuTeV)

Possible sources:

statistical fluctuation

experimental systematics

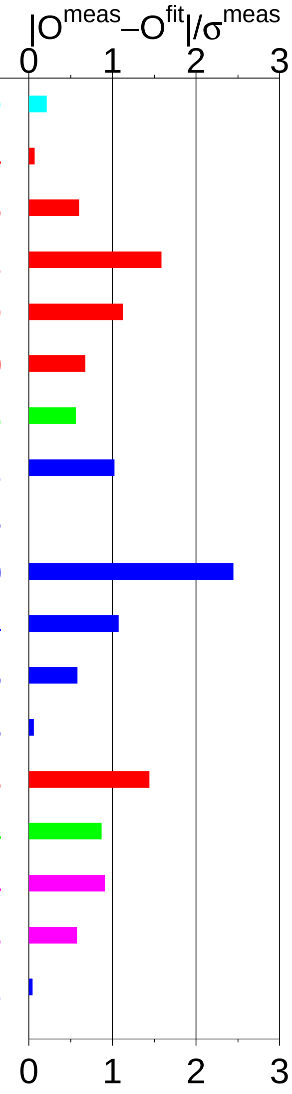
theoretical uncertainties

non-standard physics (“tough”,

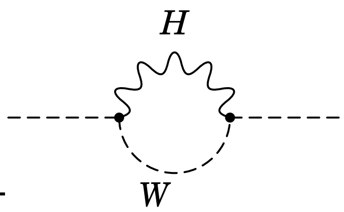
e.g., the MSSM does not help)

Summer 2004

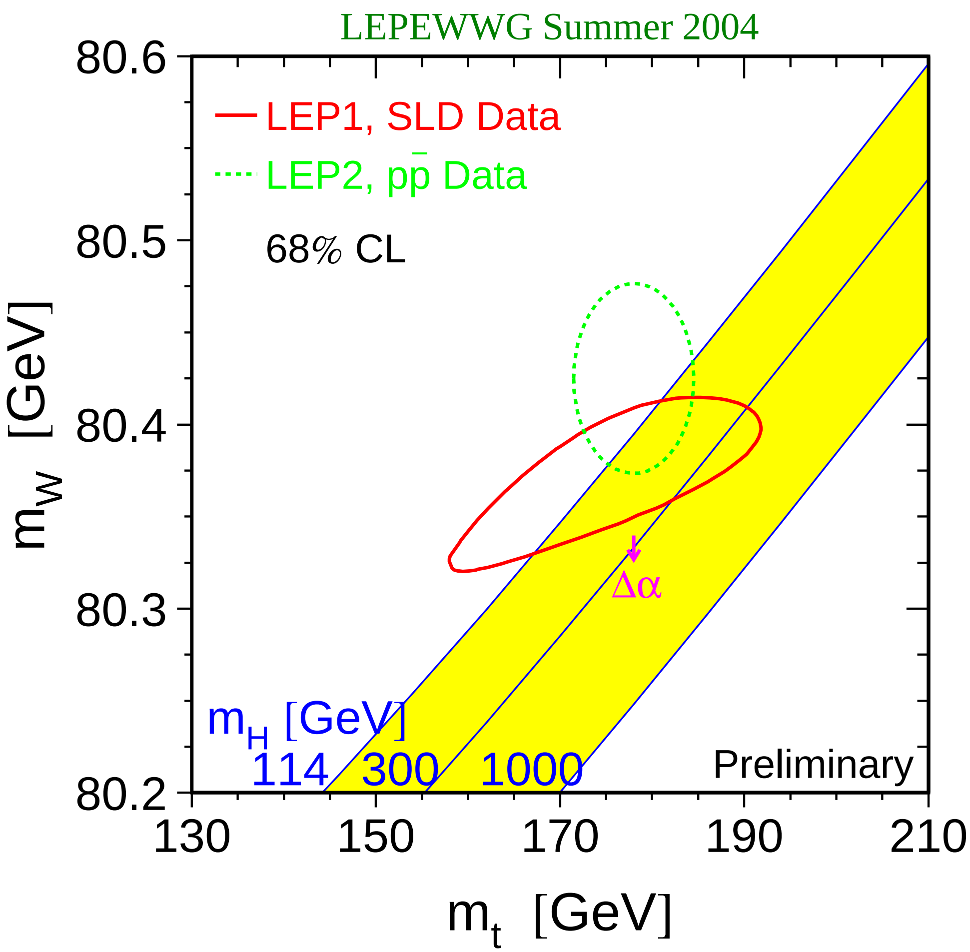
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



Indirect searches via presence in loops, M_W - M_Z correlation:



$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha(0)}{\sqrt{2}G_\mu(1-\Delta r(M_W,m_t,M_H,\ldots))}$$



Direct and indirect measurements of M_W are in good agreement:

$M_W(\mathrm{LEP},p\bar{p}) = 80.425 \pm 0.034$ GeV

$M_W(\mathrm{LEP/SLD}) = 80.368 \pm 0.032$ GeV

M_W(LEP,$p\bar{p}$) prefers a light Higgs

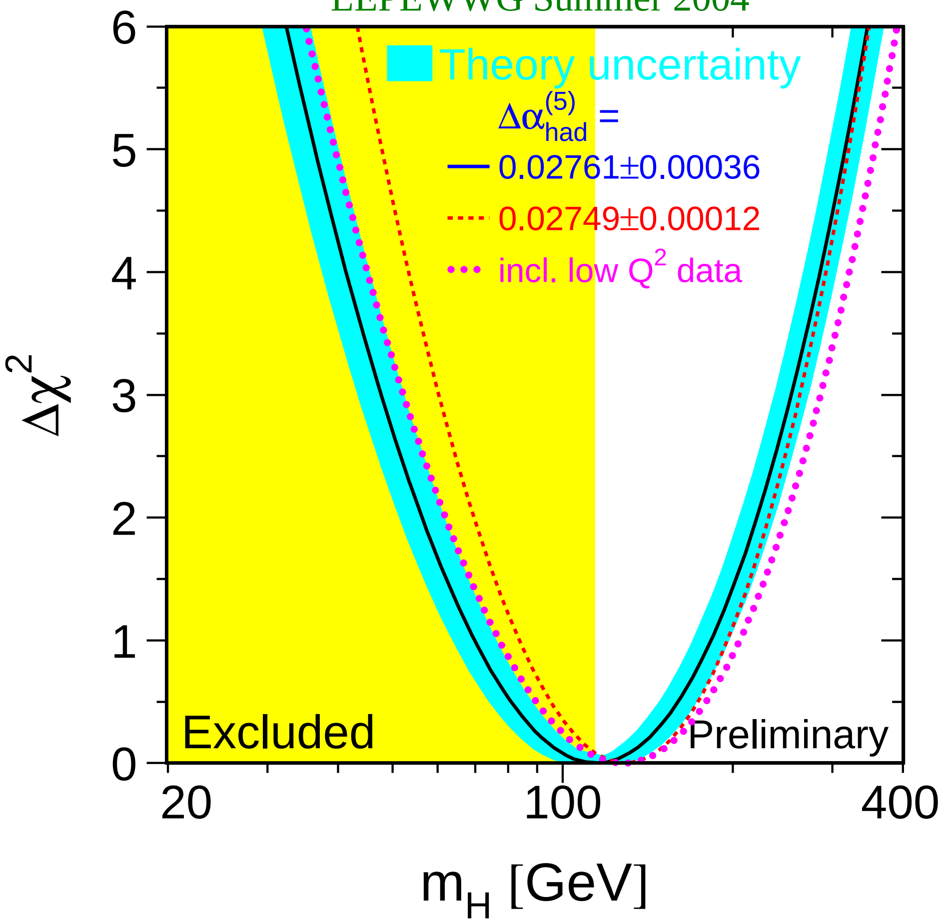
M_W(NuTeV)=80.136(84) GeV prefers a heavy Higgs

From global fit to all electroweak precision data:

CERN-EP/2003-091 (update Summer 2004)

$$M_H = 114^{+69}_{-45}\,\mathrm{GeV}(68\%)\quad ;\quad M_H < 260\ \mathrm{GeV}(95\%\mathrm{C.L.})$$

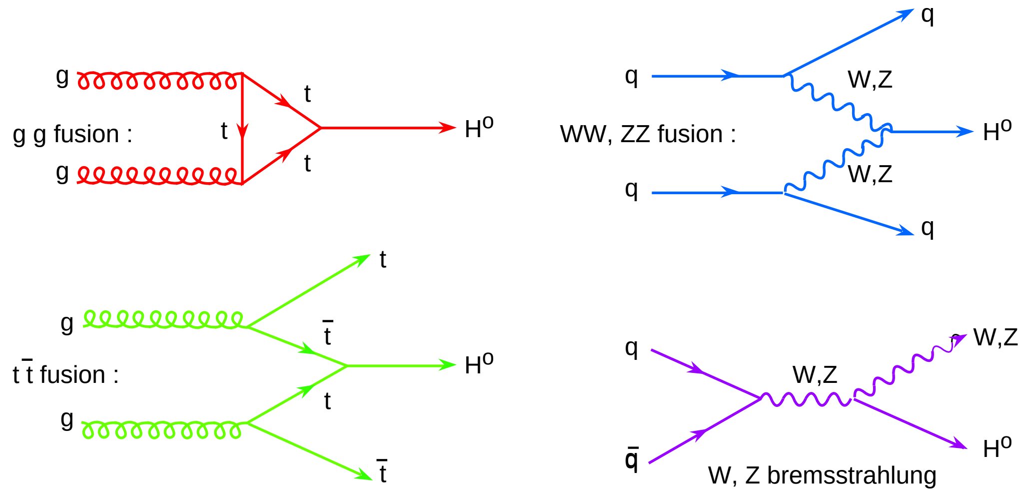
LEPEWWG Summer 2004

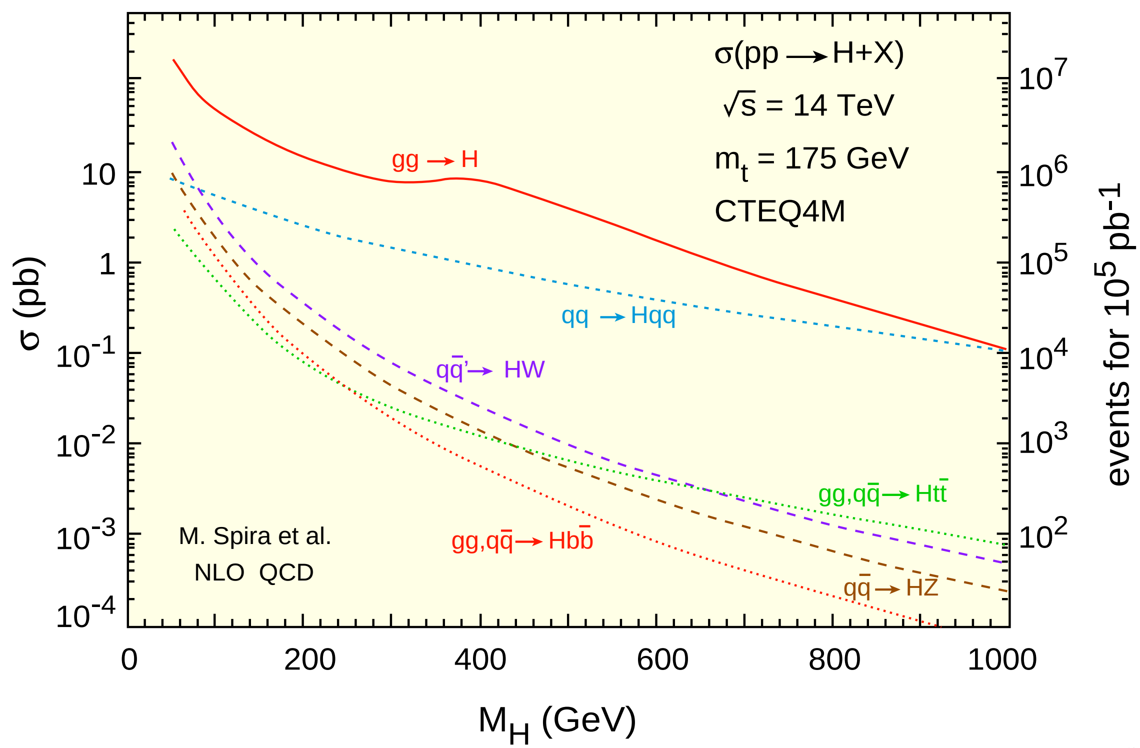


blue band: theoretical uncertainty due to missing higher order corrections

blue/red curves: uncertainty due to $\Delta\alpha^{(5)}_{had}$

H^o production at hadron colliders:





D_D_1186.c

from the CMS website at www.cern.ch

But : $BR(H \to Z_i Z_i \to 4l^-) = 1.4 \times 10^{-3}$

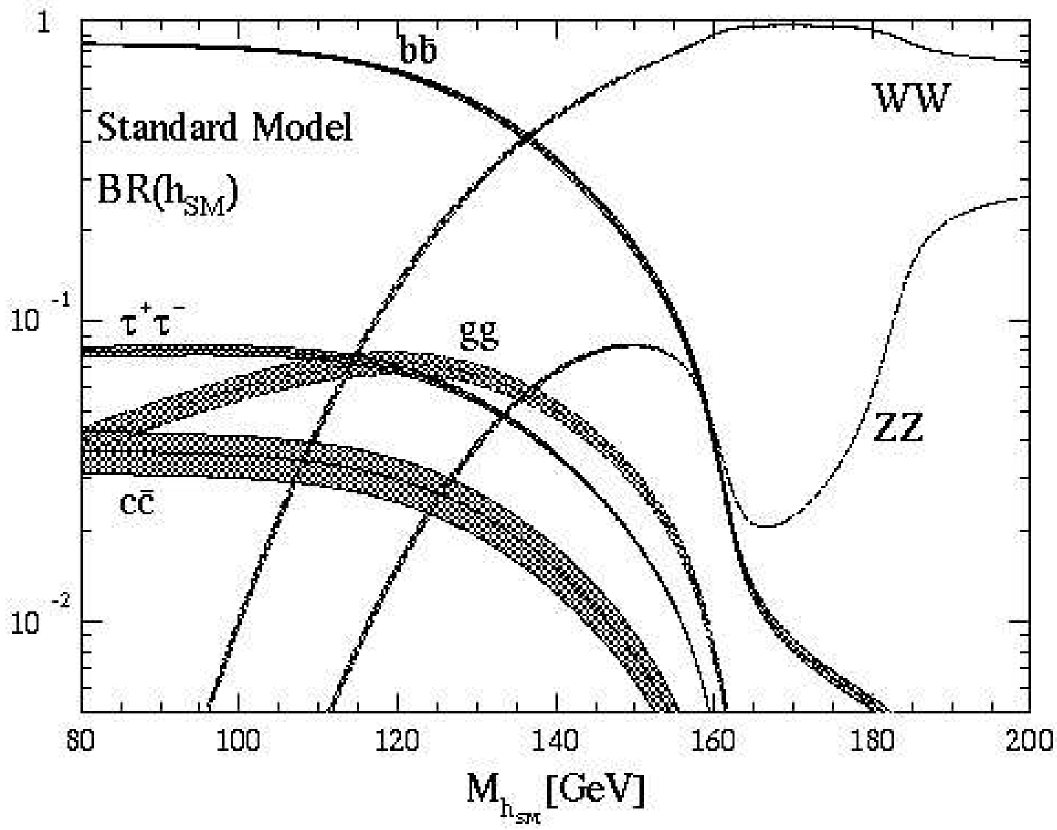
$BR(H \to Z_i Z_i \to 4\mu^-) = 3 \times 10^{-4}$

Dominant SM Higgs decay modes:

M_H <135 GeV: $H \to b\bar{b}$ with $BR = 43\%$,

M_H >135 GeV: $H \to W^+W^-$ with $BR = 40\%$

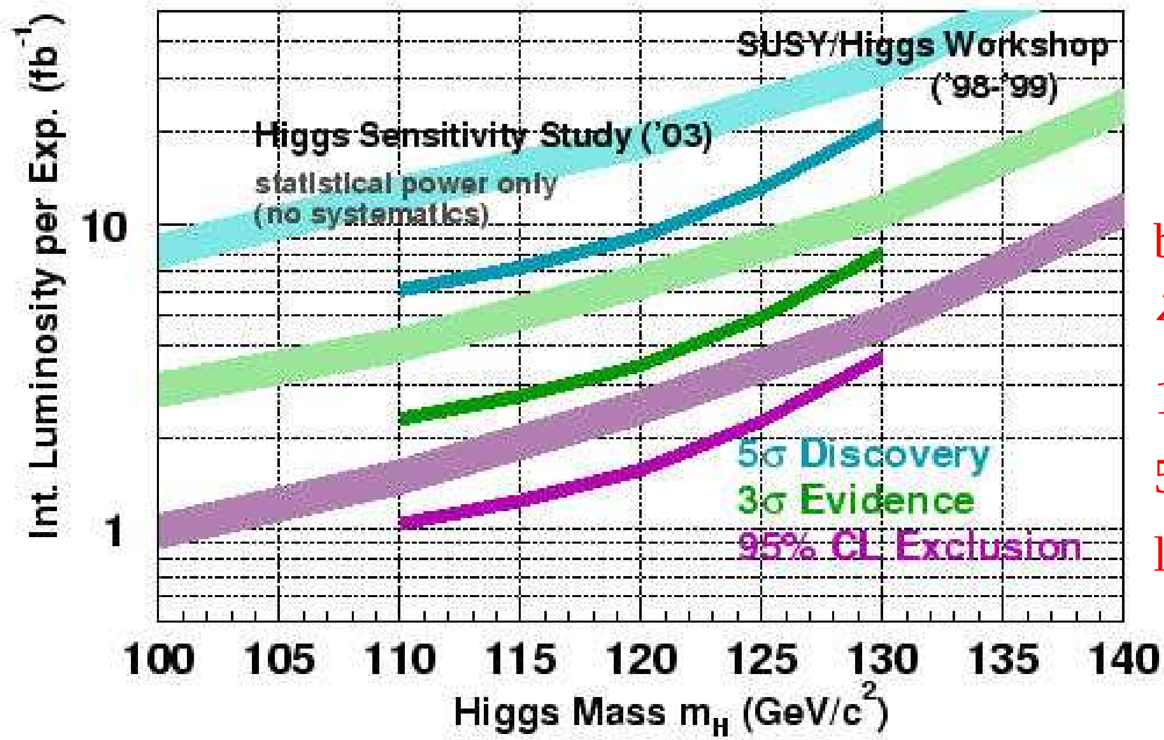
Branching ratios of the dominant SM Higgs decay modes:



from M.Carena and H.Haber, hep-ph/0208209
HDECAY (A.Djouadi *et al.*)
M.Spira, hep-ph/9810289

Tevatron SM Higgs discovery potential

Integrated luminosity per experiment for a 95% CL exclusion of a SM Higgs or a 3σ or a 5σ discovery:



Tevatron Higgs Sensitivity Study
FERMILAB-PUB-03/320E

based on Z/WH production only, $Z/W \to ll, l\nu, H \to b\bar{b}$

10% syst. uncertainty in S/B results in a 5,15,20 % increase in $95\%CL, 3\sigma, 5\sigma$ luminosity thresholds ($M_H = 120$ GeV)

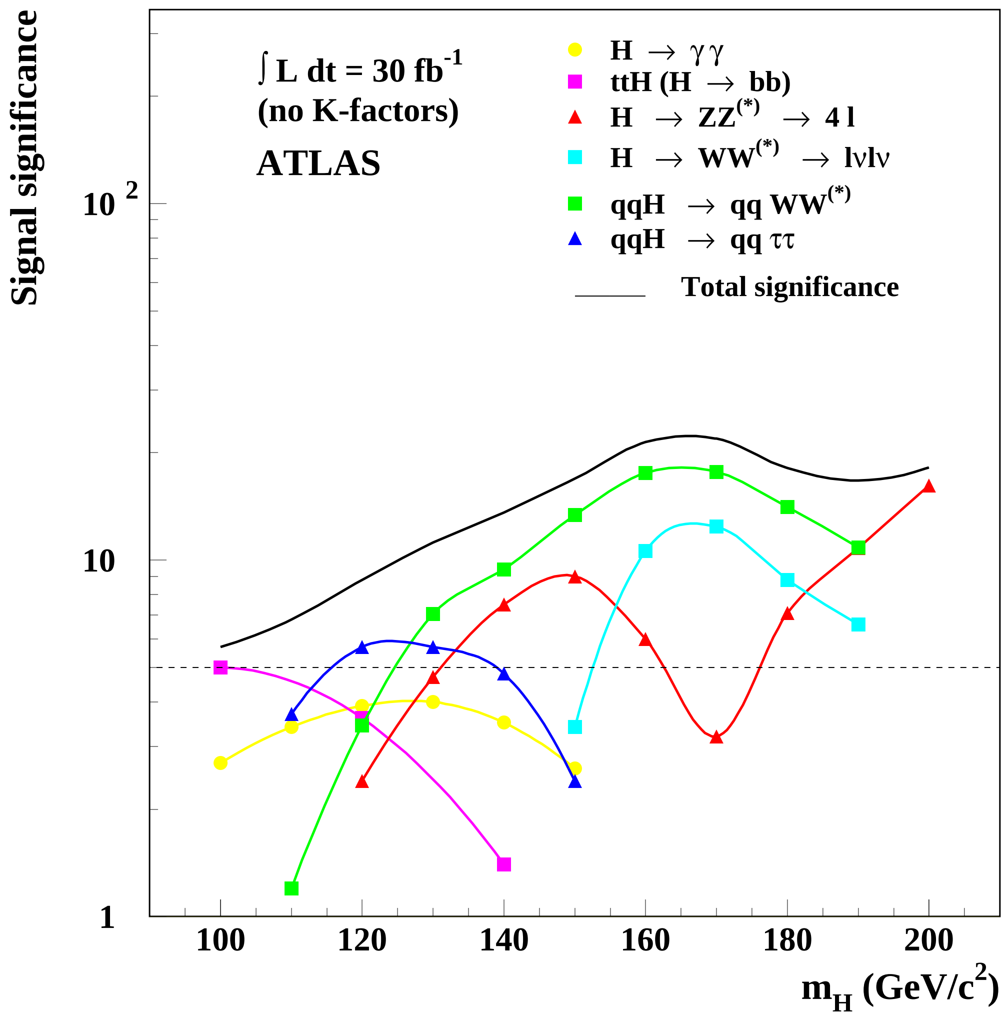
Can $t\bar{t}H$ help ?

SM Higgs discovery reach at the Tevatron Run II:

$M_H \lesssim 125$ GeV (95 % C.L. with 2 fb^{-1}, 3 σ evidence with 5 fb^{-1})

$M_H = 130$ GeV can be excluded with 4 fb^{-1}

LHC SM Higgs discovery potential



from S.Gentile
ATL-PHYS-2004-009 (and references therein)

For $M_H < 130$ GeV the SM Higgs search is mainly through $t\bar{t}H$.

After about 1 year of running at 10 fb^{-1} the full Higgs mass range can be covered !

II. Supersymmetry: one of the most attractive extensions of the SM

Supersymmetry (SUSY) introduces a higher symmetry into the SM. SUSY relates fermions (spin 1/2) and bosons (spin 0,1) and predicts new SUSY particles: Every SM particle gets a partner which only differs in spin.

- Nature has shown that it likes gauge theories - SUSY is the next logical gauge theory to try.

  Locally supersymmetric transformations are intimately tied up with space-time ones: possible path to unification of gravity with strong and electroweak forces

- *fine tuning* or the problem of fundamental scalars: In the SM the Higgs boson can be arbitrarily heavy due to the occurrence of quadratic divergences $\Rightarrow$ fine tuning is needed so that $M_H < 1$ TeV - not natural in a theory of everything

  SUSY partners cancel divergences - no fine tuning needed.

The Minimal Supersymmetric SM (MSSM) predicts the existence of 5 Higgs bosons, one of them (h^0) with a mass smaller than about 130 GeV.

III. Higgs production in association with heavy quarks at the Tevatron and the LHC

Both $t\bar{t}H$ and $b\bar{b}h^0$ production processes will play an important role in Higgs discovery and in the measurements of Higgs properties:

- discover/confirm the Higgs
- measurement of Top and Bottom Yukawa couplings
- SM? New Physics?

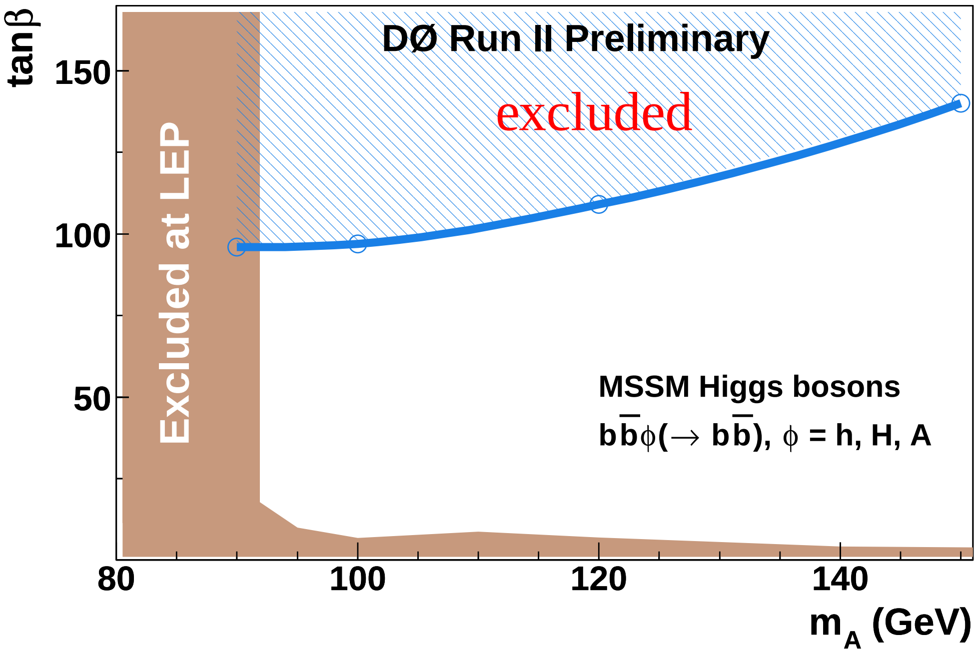
$b\bar{b}h^0$ is an important Higgs production mode in models with an enhanced b quark Yukawa coupling, e.g., for large values of $\tan\beta$ in the 2HDM, MSSM.

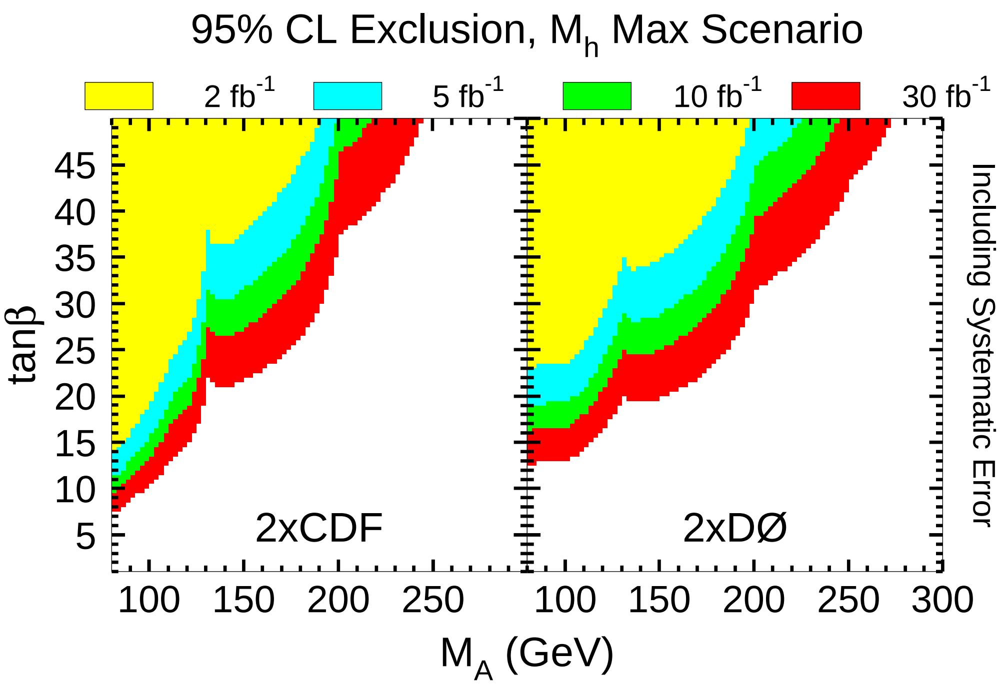
In the Standard Model, Higgs boson production in association with b quarks is suppressed by the small b Yukawa coupling, $g_{bbH} = \frac{m_b}{v} \approx 0.02$.

In the MSSM, however, the cross sections to $p\bar{p}, pp \to b\bar{b}h$, $h = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan\beta$:

$$g^{MSSM}_{bb(h^0,H^0)} = \frac{(-\sin\alpha, \cos\alpha)}{\cos\beta}\, g_{bbH} \quad \text{and} \quad g^{MSSM}_{bbA^0} = \tan\beta\, g_{bbH}$$

Search for MSSM $h = H^0, h^0, A^0$ in 3 b-tagged events using D0 Run II data (left) and Tevatron 95 % CL exclusion contours for $b\bar{b}h \to b\bar{b}b\bar{b}$ (right):



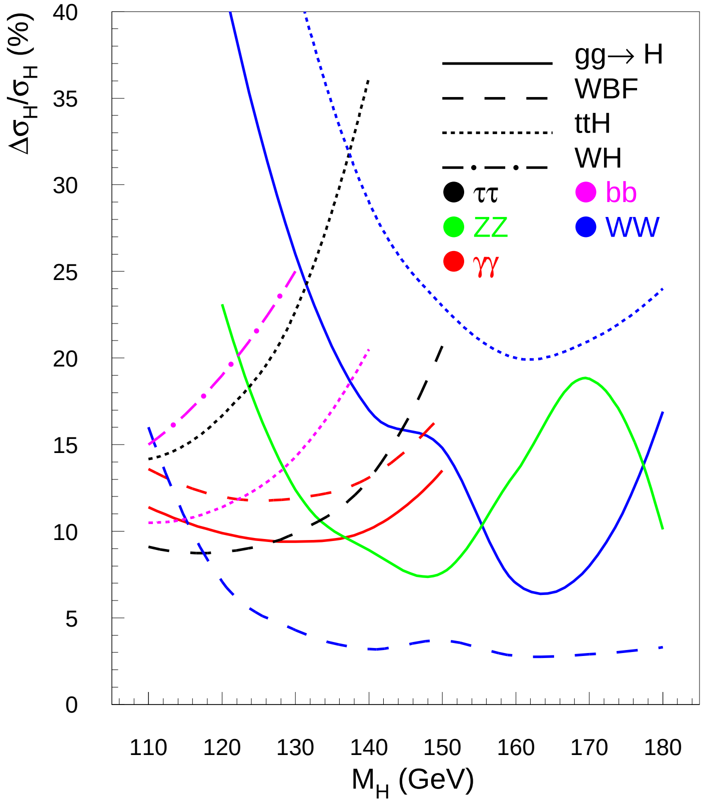


from The D0 collaboration, D0 Note 4366 - CONF

from the Report of the Tevatron Higgs WG, hep-ph/0010338

Systematic uncertainty in cross section measurement is about 25 %.

$\Rightarrow$ It is crucial to know the impact of QCD corrections.



from A.Belyaev and L.Reina, JHEP 0208 (2002)

see also review by D.Zeppenfeld, hep-ph/0203123
Based on studies by ATLAS, CMS, A.Belyaev, N.Kaur, F.Maltoni, T.Plehn, D.Rainwater, L.Reina, S.Willenbrock, D.Zeppenfeld

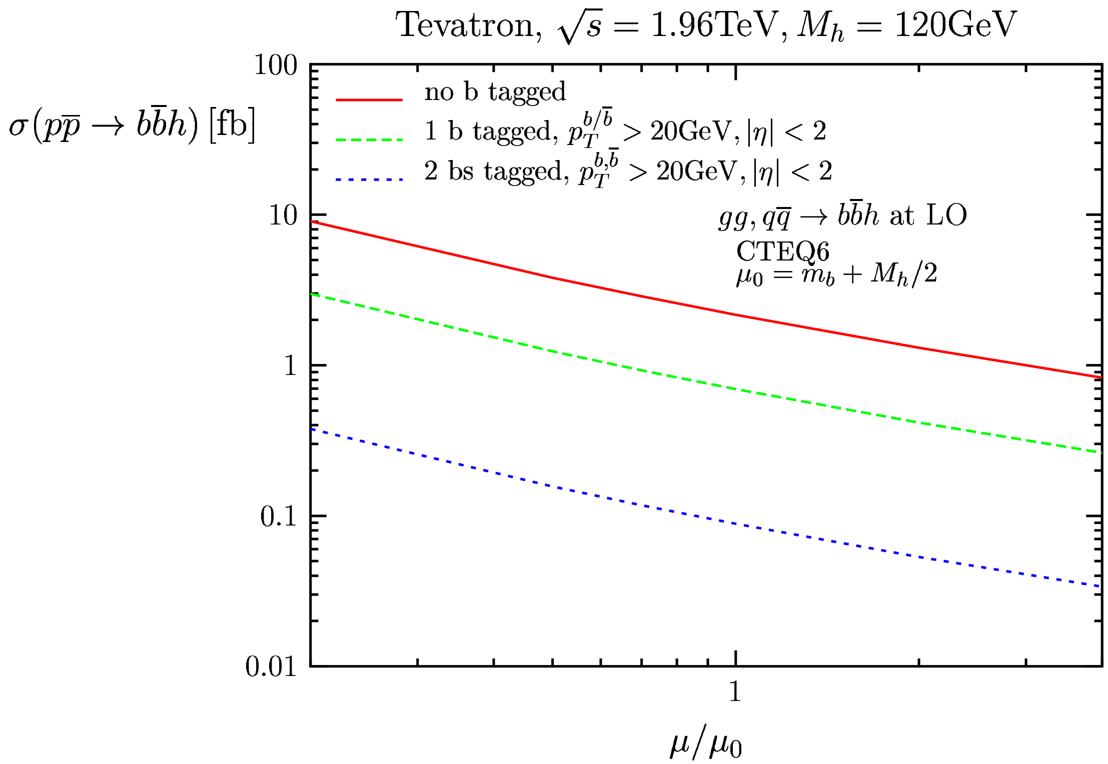
$t\bar{t}h$ directly probes the top quark Yukawa coupling:
at the LHC with 200 fb^{-1} and $M_H \lesssim 130$ GeV g_{ttH} can be measured with a precision of 15-20 %.

from D.Zeppenfeld, hep-ph/0203123 (and references therein)

$\Rightarrow$ It is crucial to know the impact of QCD corrections.

III.1. Need for next-to-leading order (NLO) QCD calculations

- Leading order (LO) calculations have very strong renormalization/factorization scale dependence:

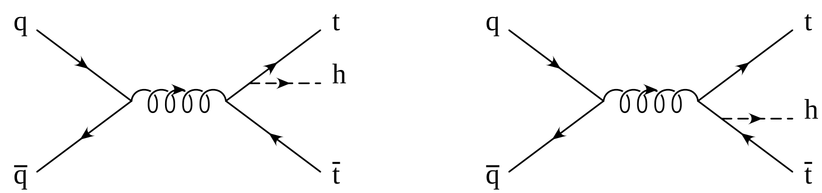


- $\mathcal{O}(\alpha_s)$ corrections can strongly increase/decrease the total production rate.

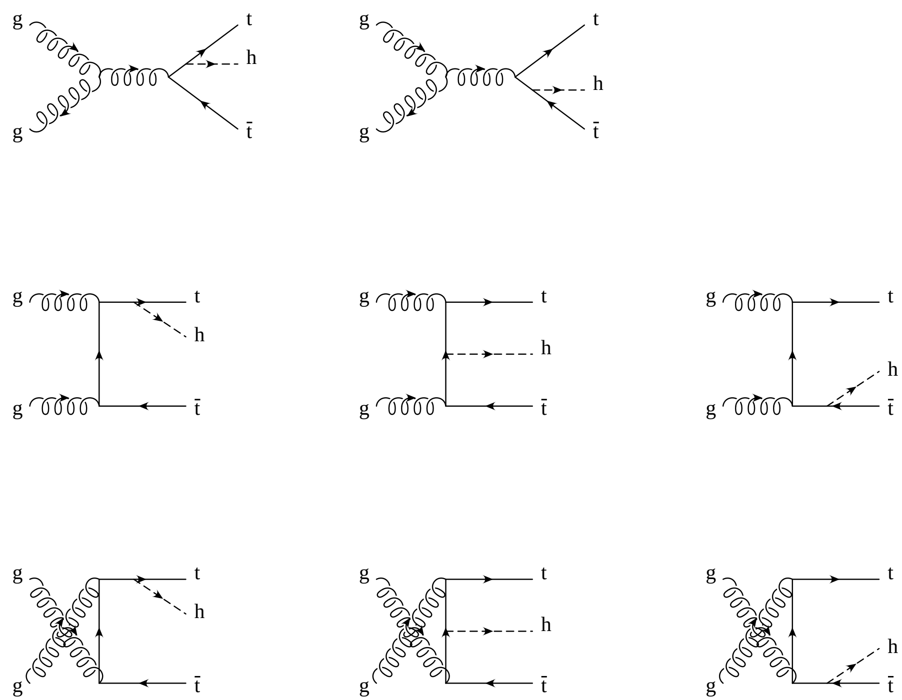
- $\mathcal{O}(\alpha_s)$ corrections may affect the shape of distributions.

III.2. $t\bar{t}H$ production in the Standard Model

$t\bar{t}H$ production at the Tevatron $p\bar{p}$ collider is dominated by the $q\bar{q}$ initiated process ($> 95\%$ of $\sigma_{\rm LO}$ at 1.96 TeV):



$t\bar{t}H$ production at the LHC pp collider is dominated by the gg initiated process (but all other production processes should be taken into account as well):



$O(\alpha_s)$ corrections to $p\bar{p}, pp \to t\bar{t}H$ production: A few technical details

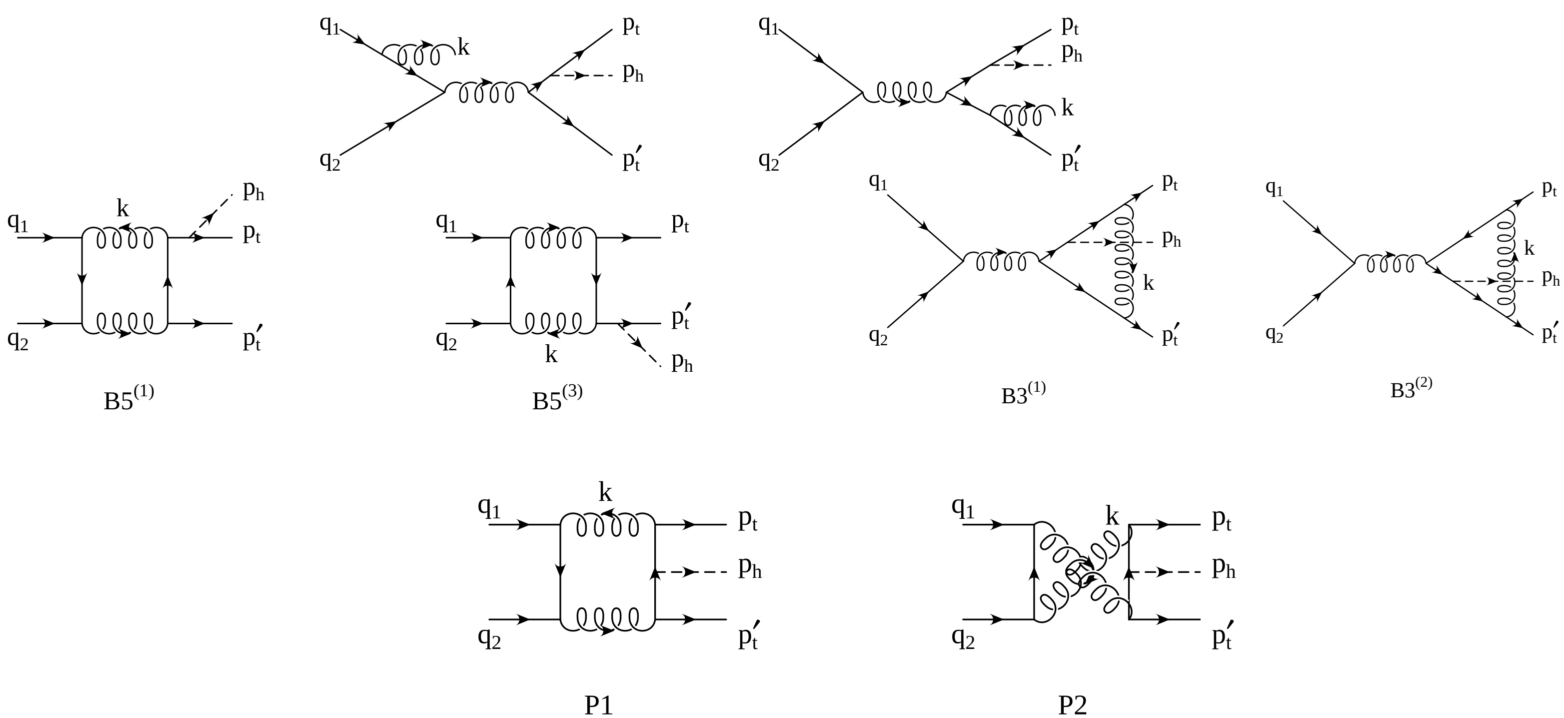
W.Beenakker, S.Dittmaier, M.Krämer, B.Plümber, M.Spira, P.M.Zerwas, PRL 87 (2001), NPB 653 (2003)

L.Reina, S.Dawson, PRL 87 (2001), L.Reina, S.Dawson, DW, PRD 65 (2002)

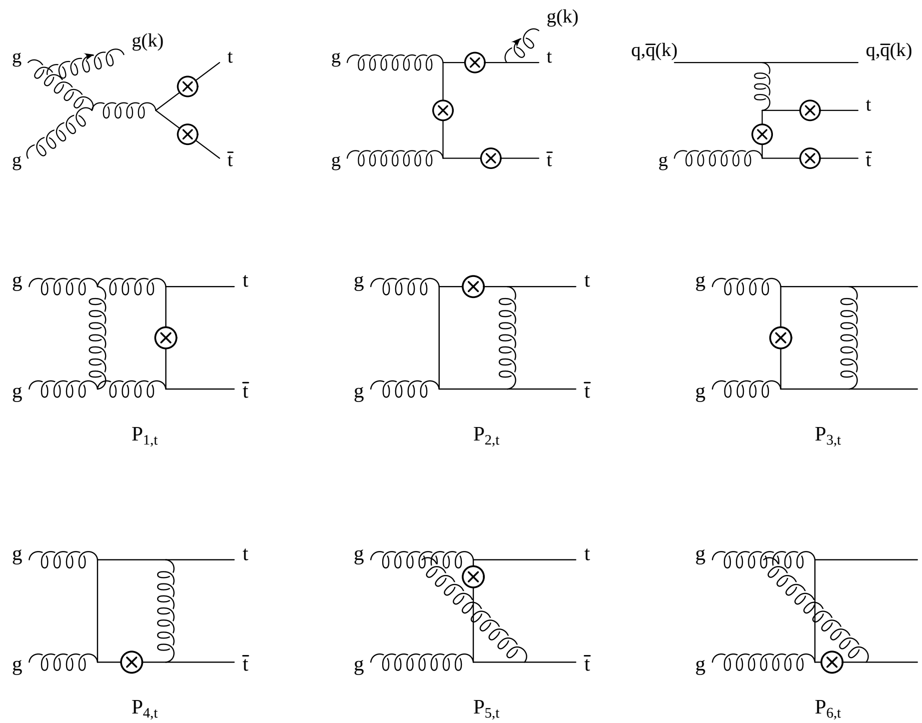
S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003)

At NLO QCD the cross section includes virtual and real gluon radiation:

Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $p\bar{p} \to t\bar{t}H$



Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $pp \to t\bar{t}H$



The calculations of the $\mathcal{O}(\alpha_s)$ corrections to $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ are technically similar.

However, in the case of $gg \to t\bar{t}H$ there are new challenges, e.g., spurious singularities arising in the reduction of pentagon tensor integrals.

NLO QCD total inclusive cross section to $p\bar{p}, pp \to t\bar{t}H$:

$$\sigma_{NLO} = \sum_{ij=q\bar{q},gg,qg} \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 [\mathcal{F}_i^p(x_1,\mu)\mathcal{F}_j^{\bar{p}}(x_2,\mu)\hat{\sigma}^{ij}_{\mathrm{NLO}}(x_1,x_2,\mu) + (1 \leftrightarrow 2)]$$

with the parton level cross sections

$$\hat{\sigma}^{ij}_{\mathrm{NLO}} = \hat{\sigma}^{ij}_{\mathrm{LO}} + \frac{\alpha_s}{4\pi}\delta\hat{\sigma}^{ij}_{\mathrm{NLO}} \text{ with } \delta\hat{\sigma}^{ij}_{\mathrm{NLO}} = \hat{\sigma}^{ij}_{\mathrm{virt}} + \hat{\sigma}^{ij}_{\mathrm{real}}$$

$\hat{\sigma}^{ij}_{\mathrm{virt}}$:

- UV divergences: renormalized in $d = 4 - 2\epsilon$ dimensions by suitable set of counterterms (modified $\overline{MS}$ scheme, on-shell subtraction for top)
- IR divergences: regularized in $d = 4 - 2\epsilon$ dimensions $\Rightarrow$ soft and collinear singularities appear as poles in $\frac{1}{\epsilon^2}, \frac{1}{\epsilon}$. IR singularities are completely canceled by corresponding IR poles in

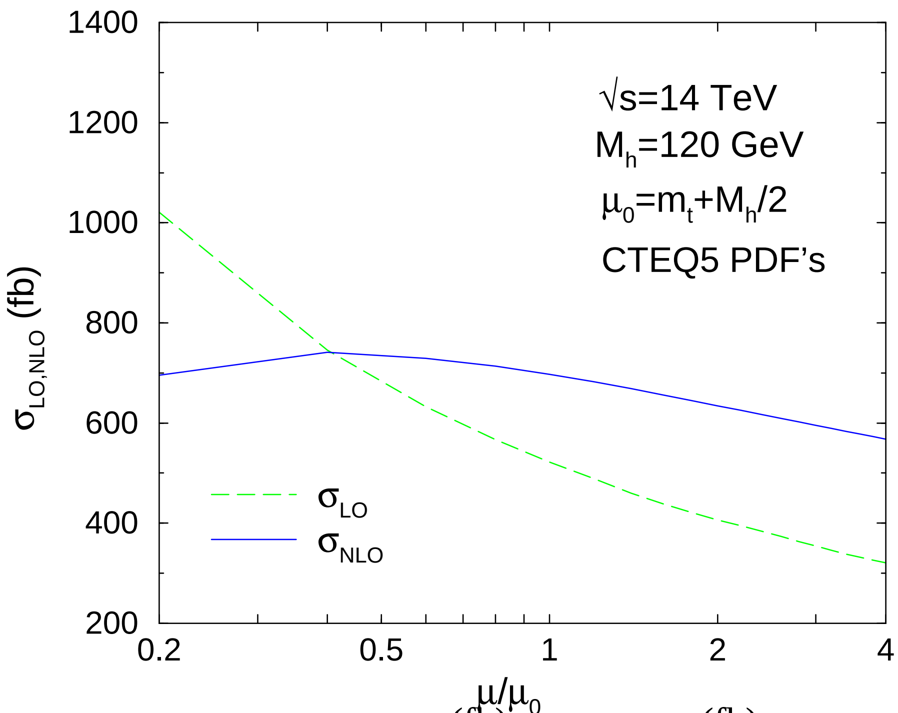
$\hat{\sigma}^{ij}_{\mathrm{real}}$:

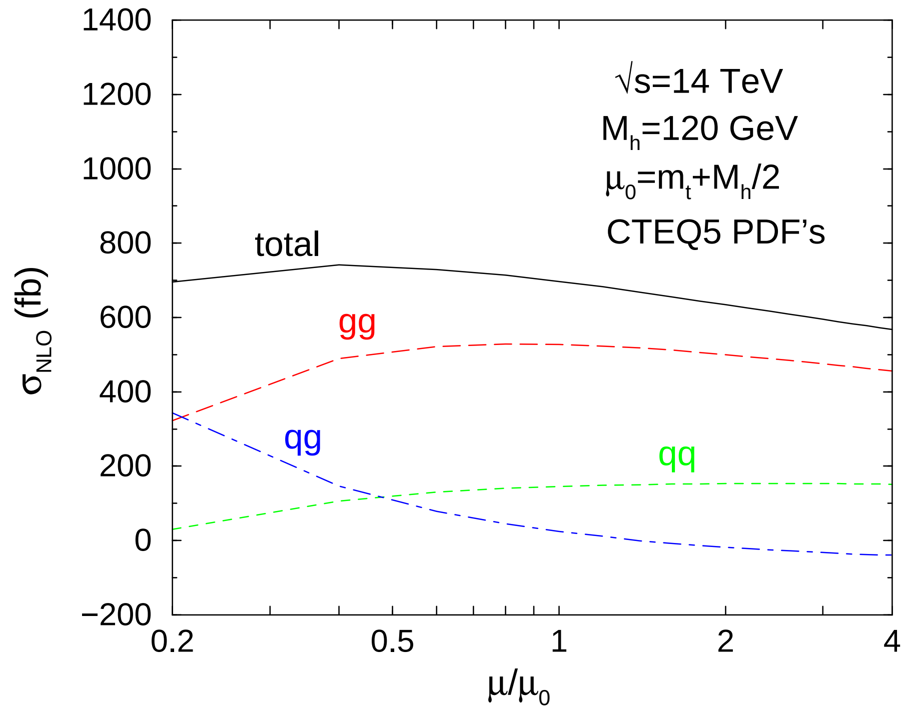
- IR divergences: extracted by suitable cuts on gluon phase space (phase space slicing): two and one cut-off PSS method using crossing symmetry and color ordered amplitudes. Remaining initial-state IR singularities are absorbed in PDFs (mass factorization).

Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

$pp \to t\bar{t}HX$ at the LHC





μ	σ_{LO} (fb)	σ_{NLO} (fb)
m_t	582.92(6)	719(4)
$m_t + M_h/2$	520.47(6)	697(3)
$2m_t$	450.09(5)	663(3)
$2m_t + M_h$	405.54(4)	634(2)

from S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003),

S.Dawson, C.Jackson, L.H.Orr, L.Reina, DW, PRD 68 (2003)

see also W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

- At NLO QCD the dependence on the arbitrary factorization/renormalization μ scale is strongly reduced.
- The residual theoretical uncertainty from μ variation is estimated to be about $10-15\%$(Tevatron) and $15-20\%$ (LHC).
- At the Tevatron the $\mathcal{O}(\alpha_s)$ corrections slightly reduce $\sigma_{\rm LO}$ for $m_t < \mu < 2m_t$ ($K = 0.7 - 0.95$).
- At the LHC the $\mathcal{O}(\alpha_s)$ corrections slightly enhance $\sigma_{\rm LO}$ for $m_t + M_H/2 < \mu < 4m_t + 2M_H$ ($K = 1.2 - 1.4$).
- Possible improvement: Resummation of large logarithmic corrections at the $t\bar{t}h$ threshold.

III.3. $b\bar{b}h^0$ production in the Minimal Supersymmetric SM

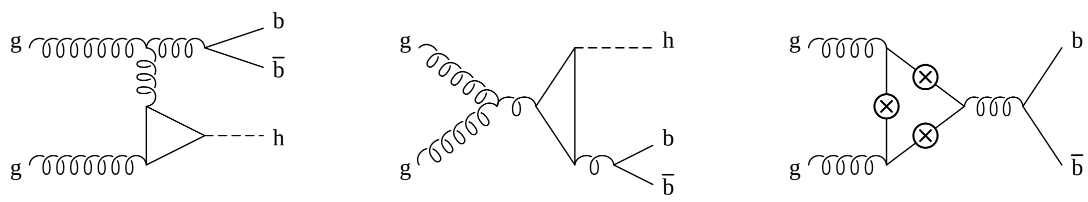
$gg, q\bar{q} \to b\bar{b}h$ at pp and $p\bar{p}$ colliders is dominated by the gg initiated process.

The calculation of the $\mathcal{O}(\alpha_s)$ corrections to $gg, q\bar{q} \to b\bar{b}h$ is technically similar to $t\bar{t}h$ production. We "simply" replace m_t by m_b.

However, there are differences:

→ We consider both the OS scheme and the $\overline{MS}$ scheme when renormalizing the b quark mass in the b Yukawa coupling:
OS: $g_{bbh} = m_b/v$ with m_b being the pole mass
$\overline{MS}$: $g_{bbh} = \overline{m}_b(\mu)/v$ with $\overline{m}_b(\mu)$ being the running mass ⇒ Possible improvement of perturpative calculation by resumming large logarithmic contributions to the $b\bar{b}h$ vertex.

→ The contribution from the closed top quark loops is included, e.g.:



The $b\bar{b}h$ processes are classified according to how many b quarks are identified: 2 b quarks tagged, 1 b quark tagged and the fully inclusive case.

In the 2(1) b-tag case we require two(one) high p_T b quark jets in the final state:

$$p_T^{b,\bar{b}} > 20 \text{ GeV} \text{ and } |\eta_{b,\bar{b}}| < 2(2.5) \text{ Tevatron (LHC)}$$

Moreover, we consider the radiated gluon and the $b/\bar{b}$ quarks as distinct particles only if

$$\Delta R = \sqrt{(\Phi_b - \Phi_g)^2 + (\eta_b - \eta_g)^2} > 0.4$$

Otherwise their 4-momentum vectors are combined into an effective $b/\bar{b}$ momentum vector.

Exclusive $b\bar{b}$ Higgs production at hadron colliders

→ Requiring two high p_T b quark jets in the final state reduces the signal, but also greatly reduces the background.

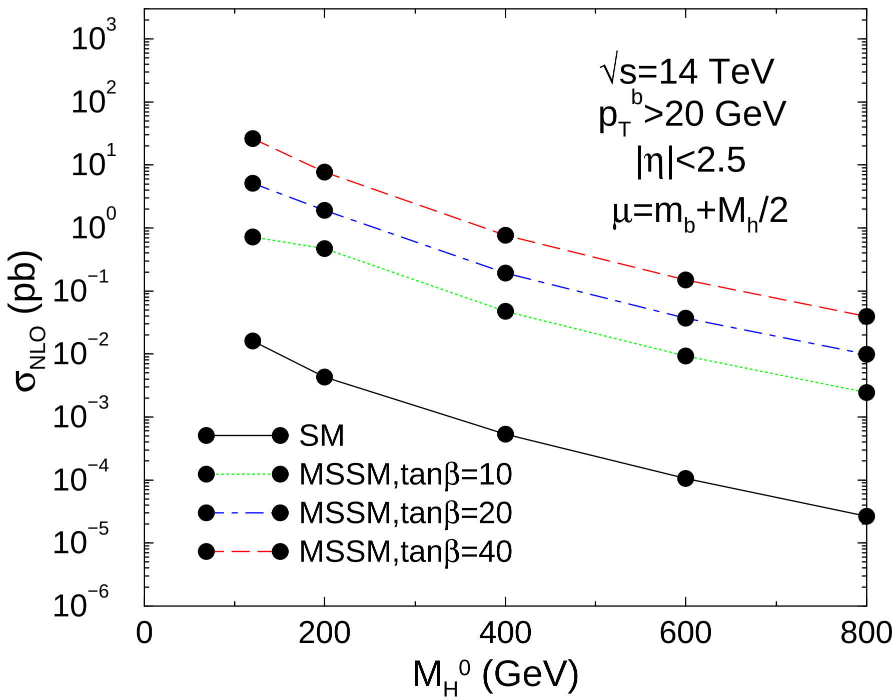
→ Unambiguously proportional to the b quark Yukawa coupling.

Status:

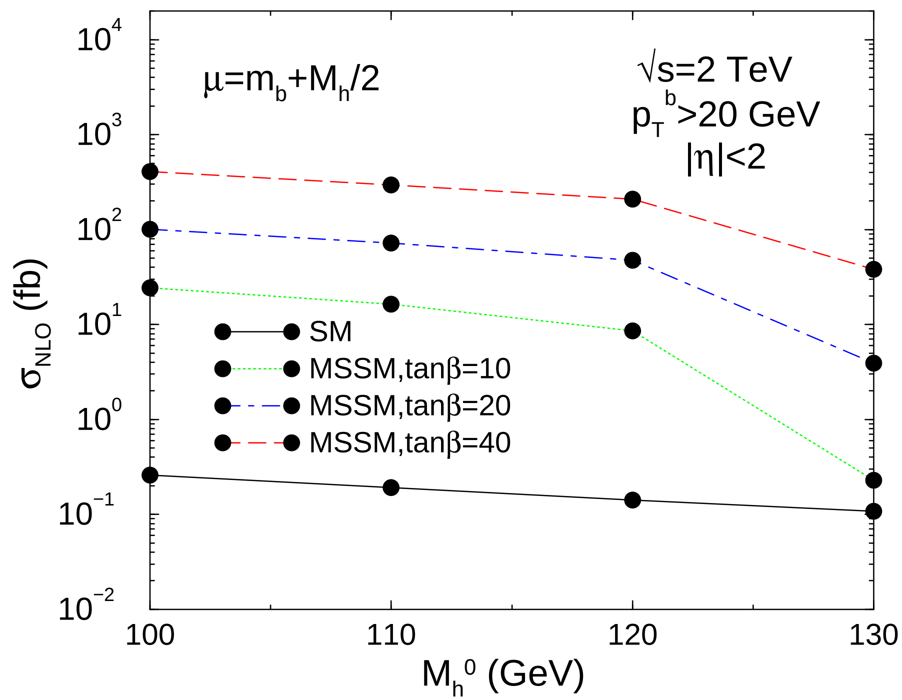
Two independent calculations based on $gg, q\bar{q} \to b\bar{b}h$ at NLO QCD by S.Dittmaier, M.Krämer, M.Spira (hep-ph/0309204) and S.Dawson, C.Jackson, L.Reina, D.W. (PRD 69 (2004)). They are in good agreement.

$M_{(h^0,H^0)}$, $\tan\beta$ dependence in the MSSM

$pp \to b\bar{b}H^0 + X$ at the LHC



$p\bar{p} \to b\bar{b}h^0 + X$ at the Tevatron



from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

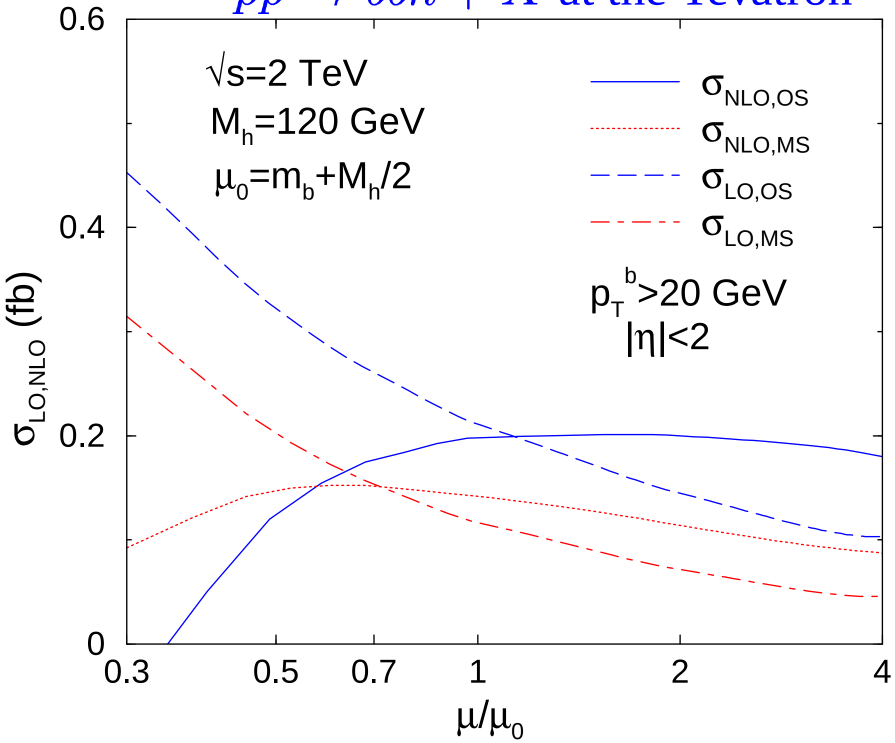
To a good approximation the MSSM result can be obtained from the SM result as follows:

$$\sigma_{\rm NLO}({\rm MSSM}) \sim \sigma_{\rm NLO}({\rm SM}) \left(\frac{g_{bbh}^{MSSM}}{g_{bbh}}\right)^2$$

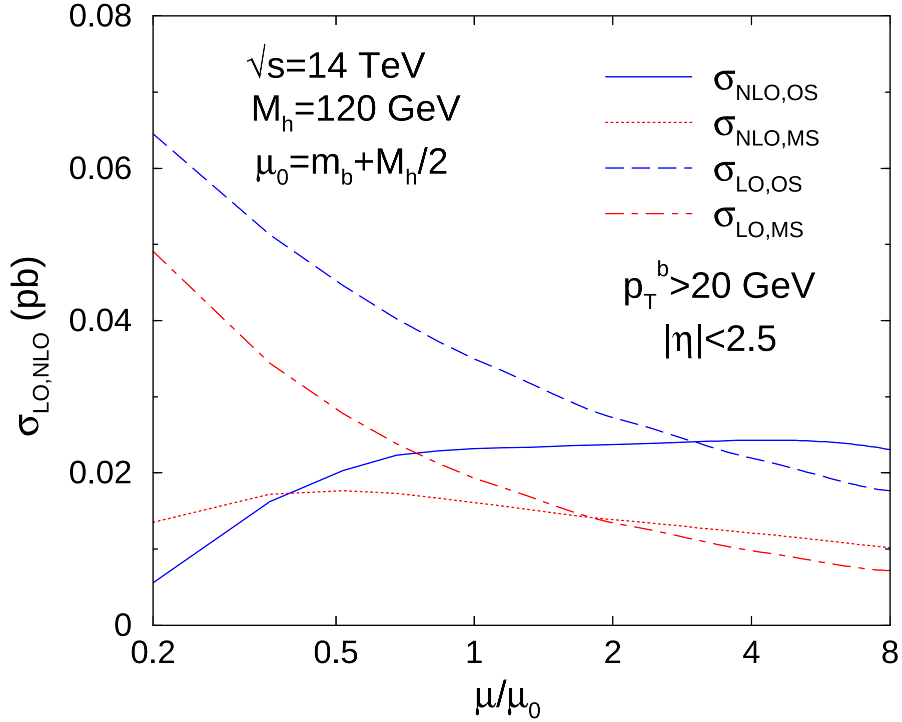
Main Result

Drastically reduced scale dependence of the NLO QCD cross sections:

$p\bar{p} \to b\bar{b}h + X$ at the Tevatron



$pp \to b\bar{b}h + X$ at the LHC



from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

$\Rightarrow$ the residual theoretical uncertainty is estimated to be about $15-20\%$ from μ dependence and about $15-20\%$ due to renormalization scheme dependence.

Inclusive and semi-inclusive $b\bar{b}$ Higgs production at hadron colliders

For a review see, e.g., J.Campbell *et al.*, LesHouches 2003 proceedings, hep-ph/0405302.

Status: There exist two approaches, dubbed *variable (or five) flavor number scheme* (VFS) and *fixed (or four) flavor number scheme* (FFS):

$\rightarrow$ FFS approach

Fixed order, explicit matrix element calculation based on the parton level processes $gg, q\bar{q} \rightarrow b\bar{b}h$.

Inclusive (no b tagged) and semi-inclusive (1 b tagged): known at NLO QCD

Two independent calculations by

S.Dittmaier, M.Krämer, M.Spira and S.Dawson, C.Jackson, L.Reina, D.W.

$\rightarrow$These two calculations are in good agreement.

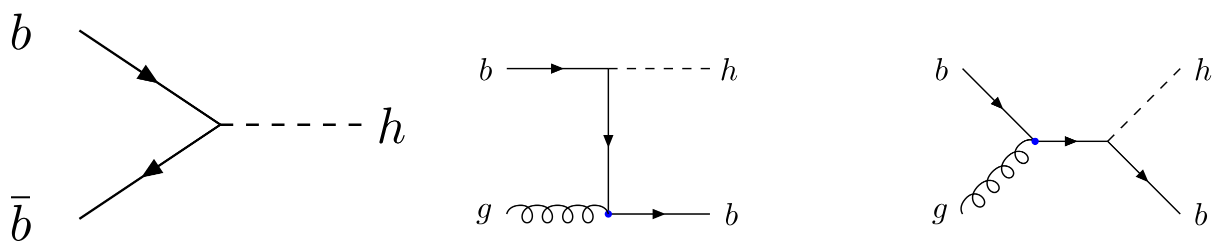
→ VFS approach

Use of b quark PDFs to sum to all orders large logs, $\alpha_s \ln(m_b^2/\mu_F^2)$ ($\mu_F \approx M_h$), which arise due to initial-state $g \to b\bar{b}$ splitting.

Inclusive (no b tagged): known at NNLO QCD

b quark fusion, $b\bar{b} \to h$, is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln^2(M_h/m_b))$ and $b(\bar{b})g \to b(\bar{b})h$ and $gg, q\bar{q} \to b\bar{b}h$ are identified as NLO contributions to $b\bar{b} \to h$ of $\mathcal{O}(1/\ln(M_h/m_b))$ and $\mathcal{O}(1/\ln^2(M_h/m_b))$, respectively.

D.Dicus, F.Maltoni, T.Stelzer, Z.Sullivan, S.Willenbrock



Inclusive $pp, p\bar{p} \to (b\bar{b})H + X$ production has been calculated at NNLO QCD by R.Harlander, W.Kilgore.

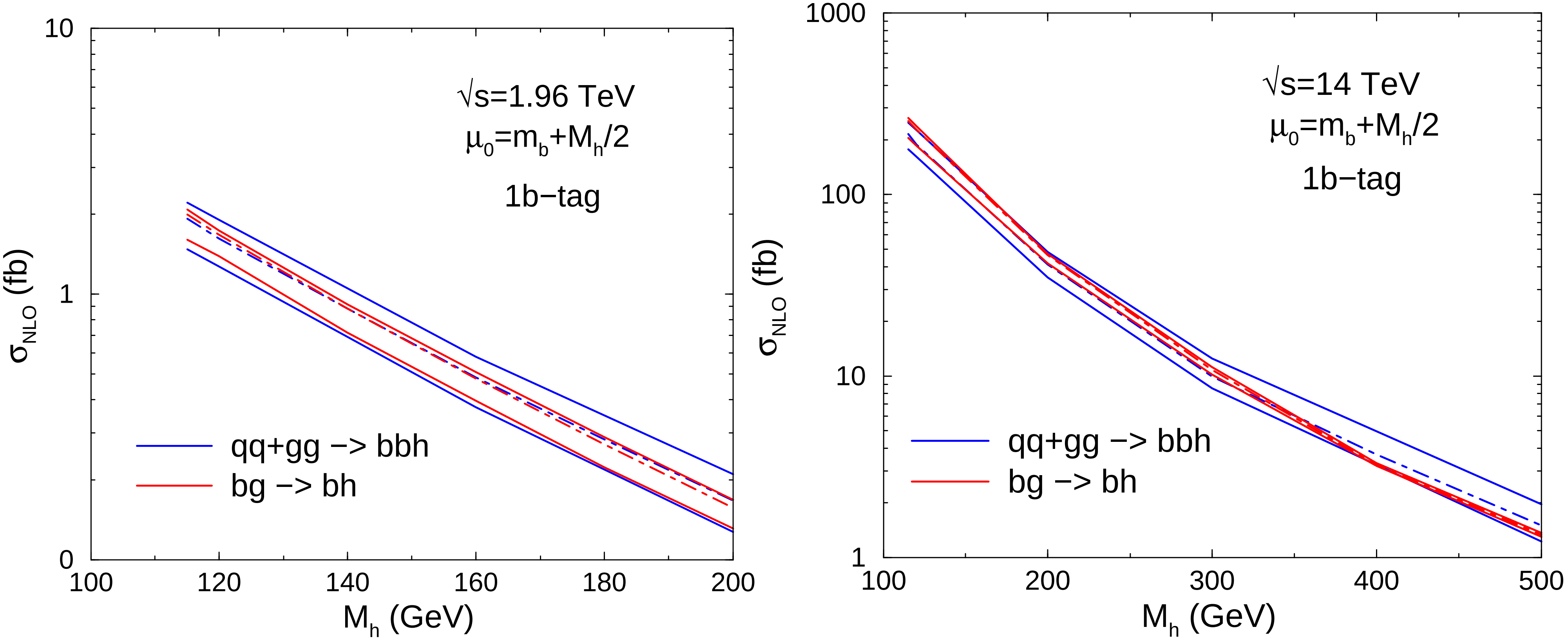
Semi-inclusive (1 b-tagged): known at NLO QCD

$b(\bar{b})g \to b(\bar{b})h$ is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln(M_h/m_b))$ and $gg, q\bar{q} \to b\bar{b}h$ are identified as NLO contributions of $\mathcal{O}(1/\ln(M_h/m_b))$.

J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock

M_h dependence – 1 b tagged

Comparison with b quark PDF approach by J.Campbell, R.K.Ellis, F.Maltoni, and S.Willenbrock:



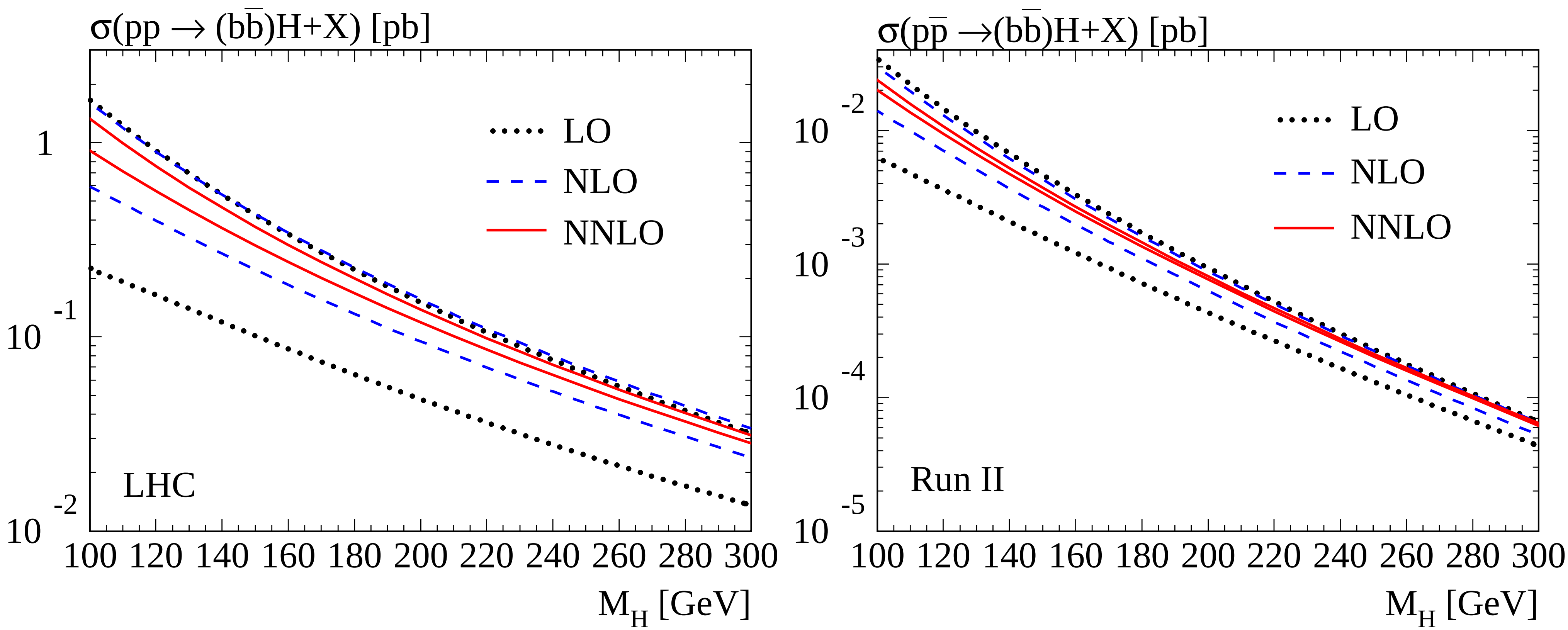
$gg, q\bar{q} \rightarrow b\bar{b}h$: from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077, see also S.Dittmaier *et al.*, hep-ph/0309204

$gb(\bar{b}) \rightarrow b(\bar{b})h$: from J.Campbell *et al.* in LesHouches 2003 procs. (hep-ph/0405302)

and closed top quark loop added to MCFM (J.Campbell *et al.*, PRD67 095002 (2003))

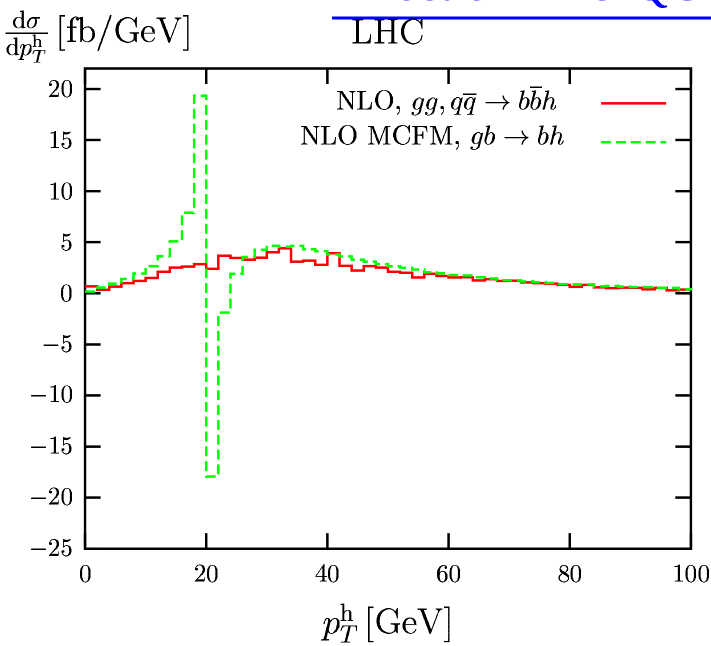
M_h dependence – 0 b tagged (VFS)

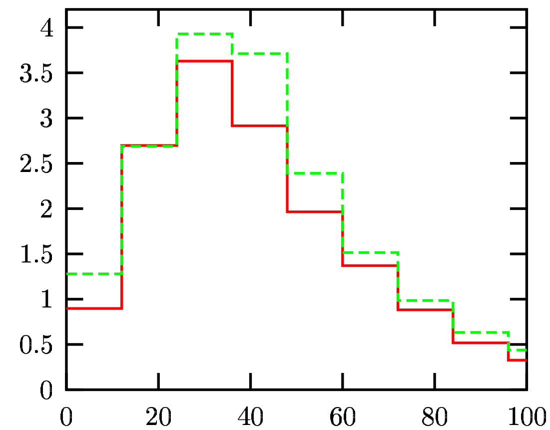
from R.Harlander, W.Kilgore, Phys.Rev. D68 (2003) 013001

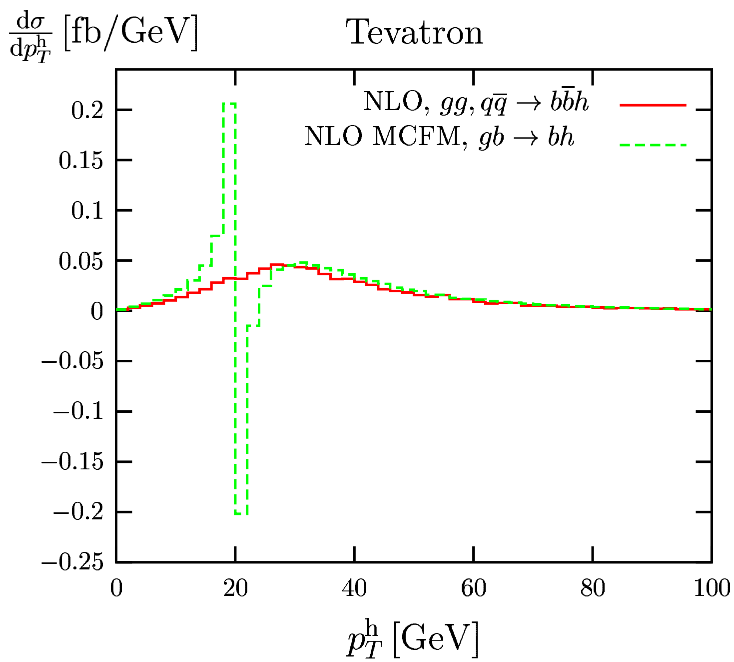


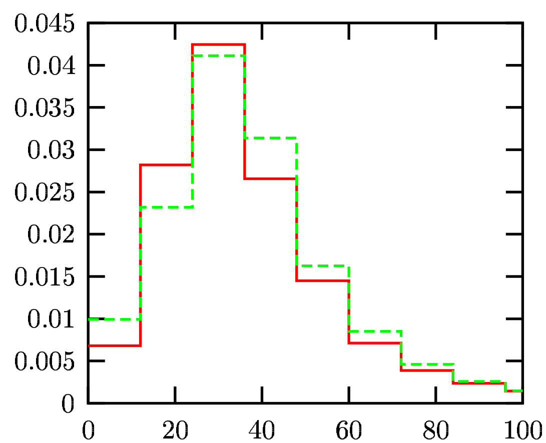
$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$

Effect of NLO QCD corrections on the Higgs p_T distribution:









from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

IV. Summary

- As a direct consequence of mass generation in the SM (Higgs-Kibble mechanism) the SM predicts the existence of a (fundamental) massive scalar particle, the Higgs boson.
- The Higgs boson so far eluded direct observation. The search for the Higgs boson in the SM (and its supersymmetric extensions) is one of the major tasks at the Tevatron $p\bar{p}$ and LHC pp collider.
- Both $t\bar{t}H$ and $b\bar{b}h^0$ production will play an important role in the discovery (and confirmation) of the Higgs boson at the Tevatron and the LHC.
- If the SM Higgs boson exists, it cannot escape detection at the LHC.
- If no Higgs boson is found, we expect to find signals of new physics, i.e. beyond the Standard Model.

Stay tuned . . .

The New York Times > Breaking News, World News & Multimedia - Microsoft Internet Explorer

The New York Times

ON THE WEB

UPDATED MONDAY, OCTOBER 18, 2010 4:50 PM ET | New York Mostly Cloudy 68°F

SEARCH · Go to Advanced Search/Archive

GO TO MEMBER CENTER

Welcome!

Spectacular discovery in Switzerland!

CERN - LHC finds Higgs-Bosons

(By Higgs, Kibble, Hagen, Guralnik)

Experiment confirms theory about the origin of mass.

Video: Hidden Symmetries

President commits additional funds to Particle Research.

By 2good2btrue

• Iowa resident wins super jackpot 3 times in a row.

By THE ASSOCIATED PRESS 4:50 PM ET

Probability was less than 1 in a trillion trillion.

Enlarge This Image

The vacuum

Symmetry of Lagrangian no longer reflected in ground state!

Even though the fundamental entity describing nature exhibits complex symmetries, nature herself hides them in massive vector gauge fields. Go to Article

• First Man on Mars. All red!

Markets

US | EUROPE

Dow Jones Industri

DJIA	10,002.33
NASDAQ	1,920.53
S&P 500	1,113.65
10-YR TRES.	

• Market Update: U.S

• View Your Personal

• Today's Earnings N

Stock Quotes:

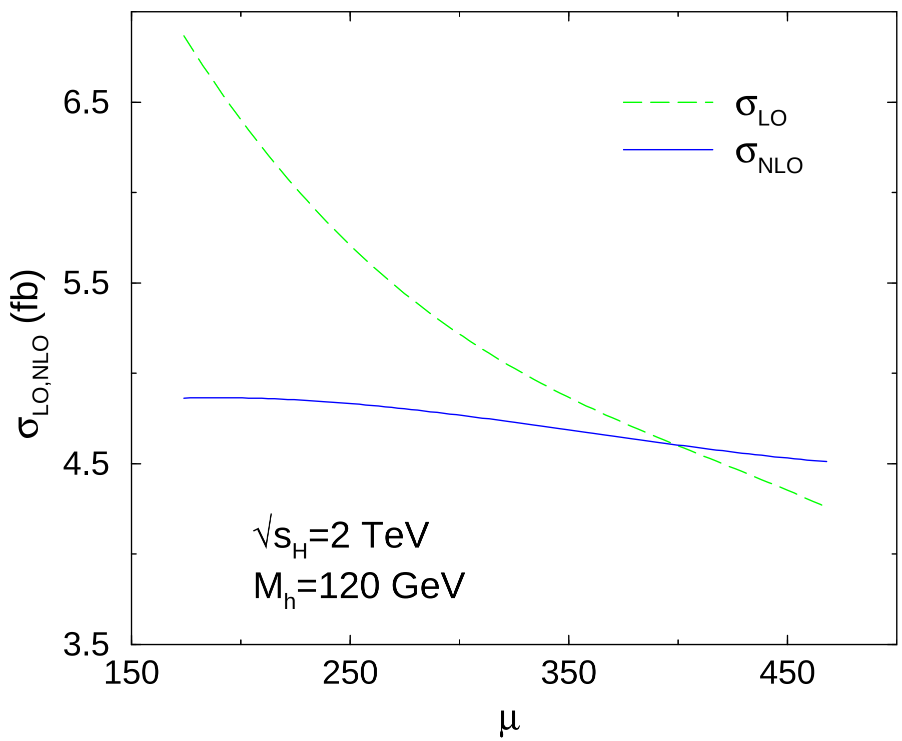
Mars Travel

Error on page. Internet

Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

$p\bar{p} \to t\bar{t}HX$ at the Tevatron



μ	σ_{LO} (fb)	σ_{NLO} (fb)
m_t	6.866(1)	4.86(3)
$m_t + M_h/2$	5.909(1)	4.85(2)
$2m_t$	4.879(1)	4.69(2)
$2m_t + M_h$	4.255(1)	4.51(2)

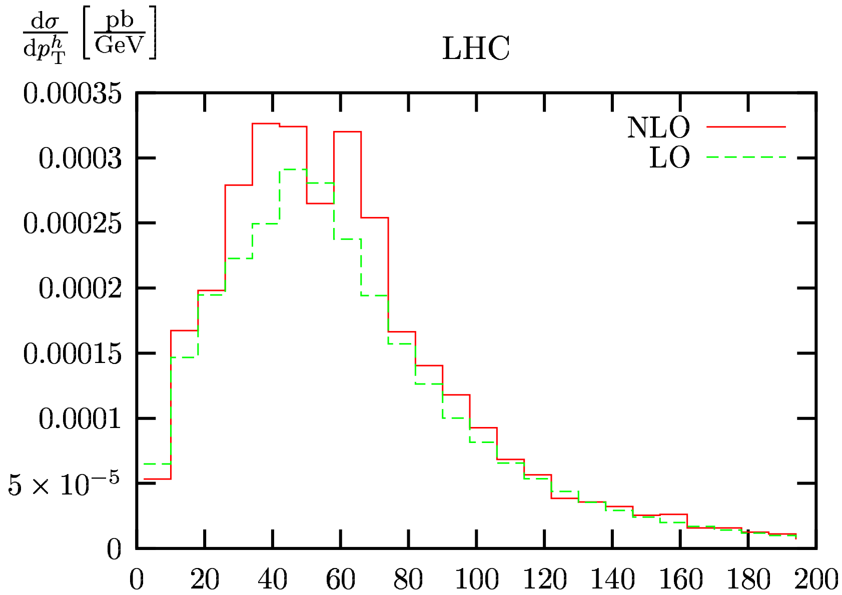
from L.Reina, S.Dawson, DW, PRD 65 (2002),

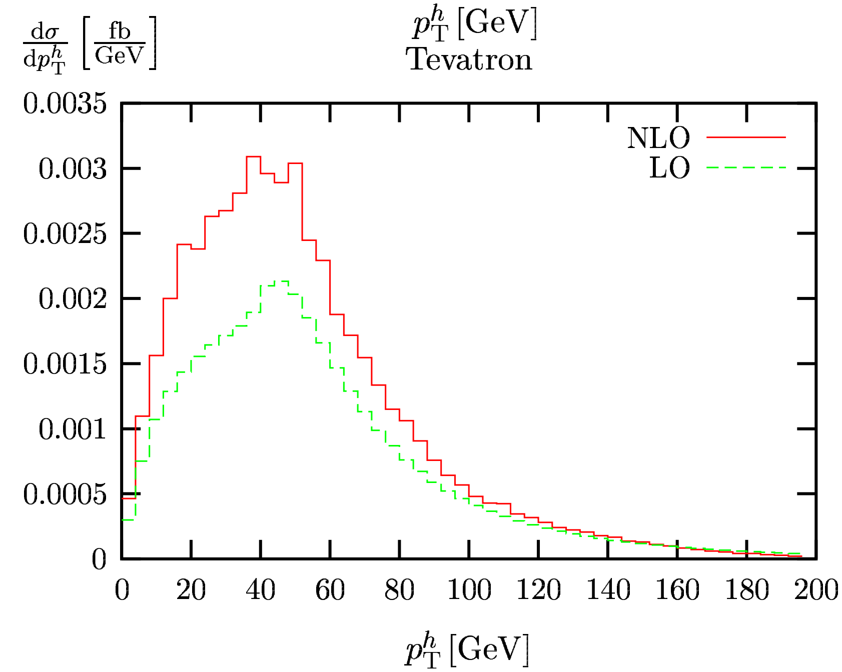
L.Reina, S.Dawson, PRL 87 (2001)

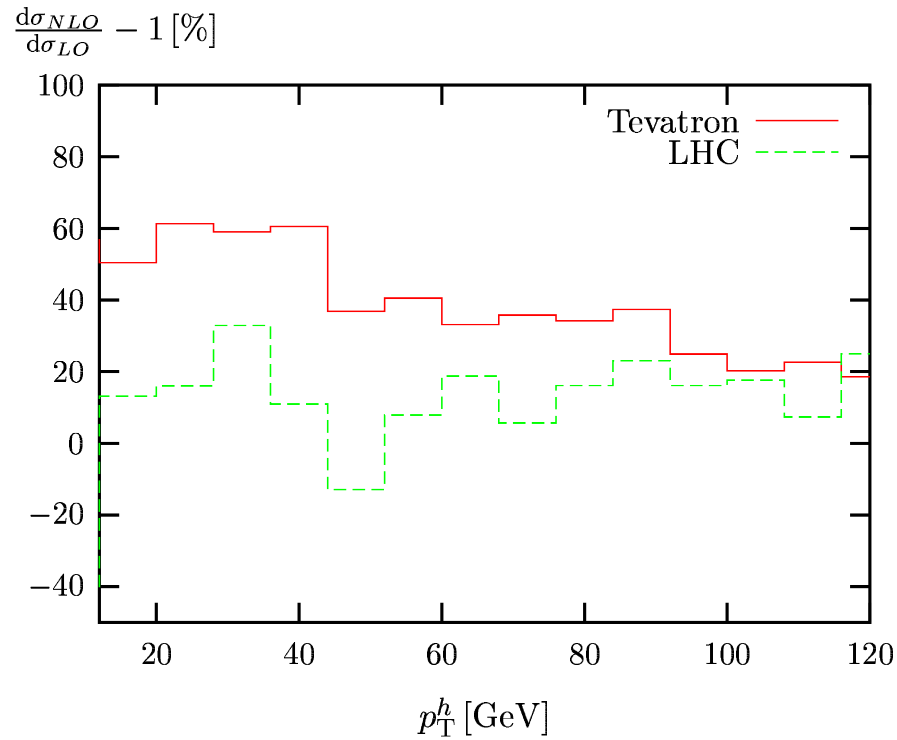
see also W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

More results . . .

Effect of NLO QCD corrections on the Higgs p_T distribution:

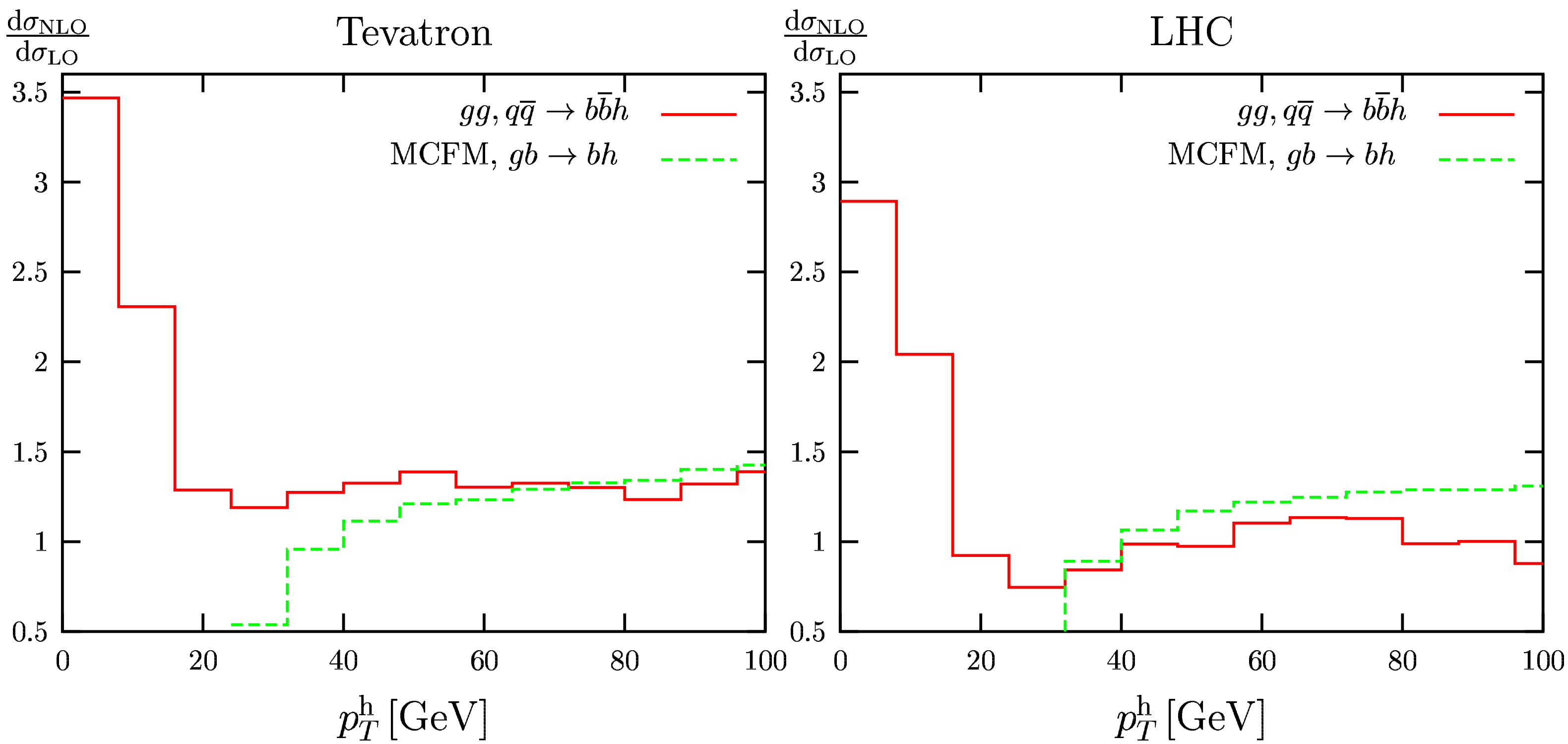






from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

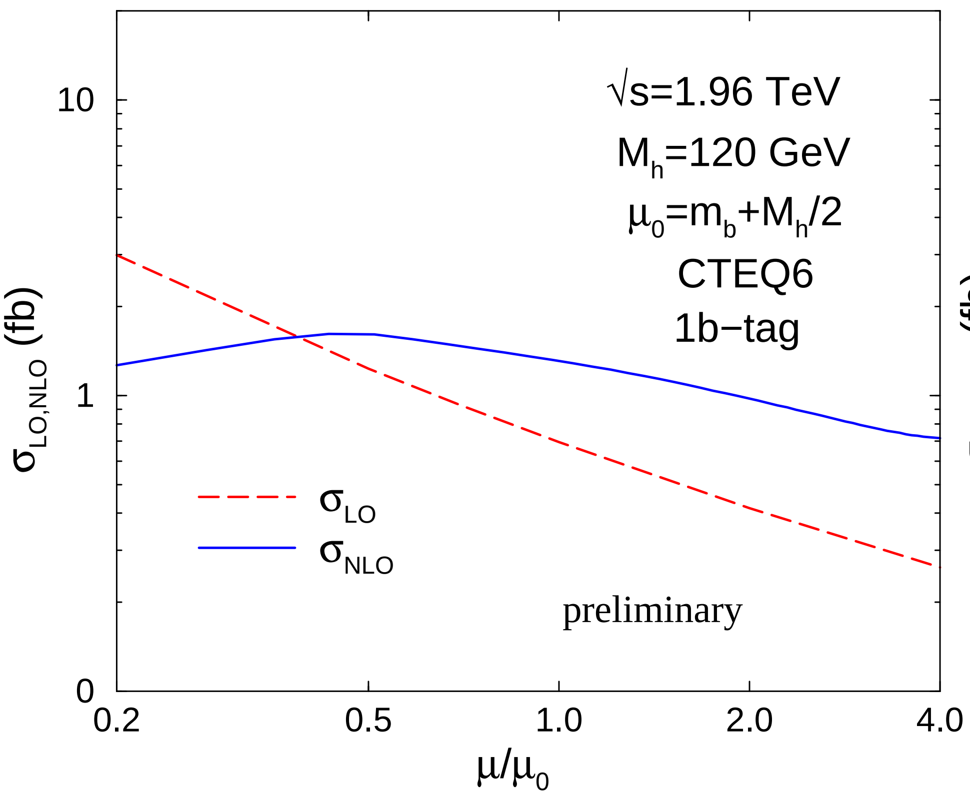
Effect of NLO QCD corrections on the Higgs p_T distribution:

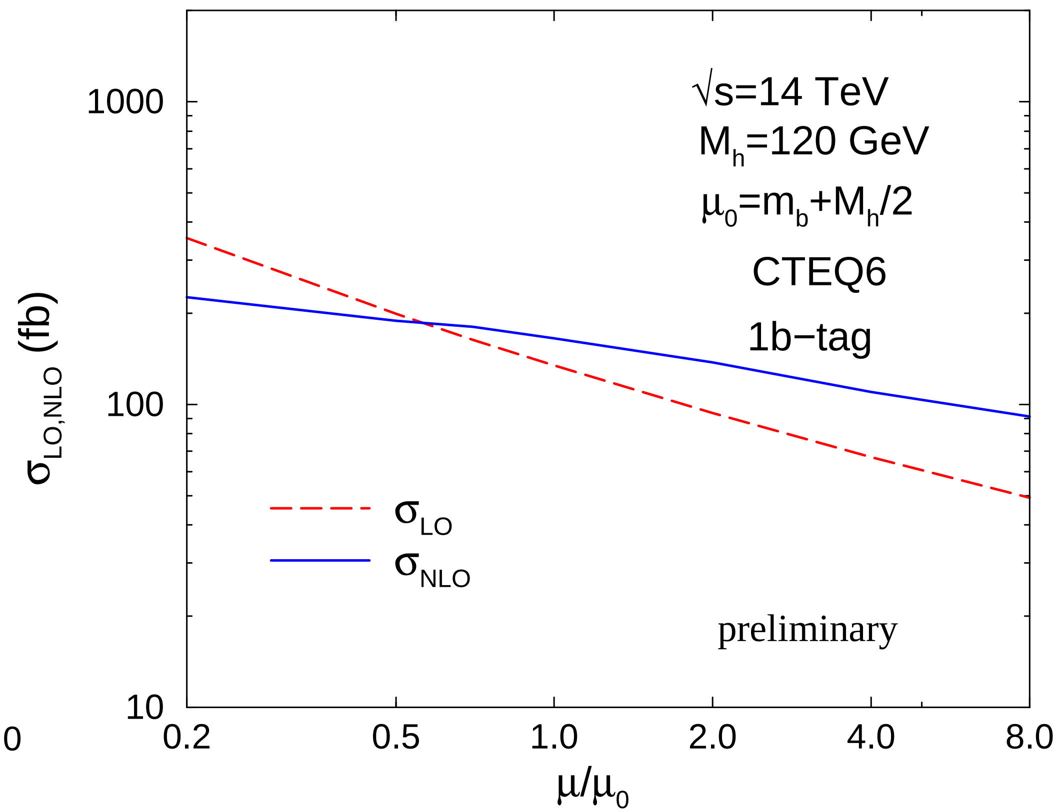


from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

Main Result

Drastically reduced scale dependence of the NLO QCD cross sections – 1 *b* tagged:



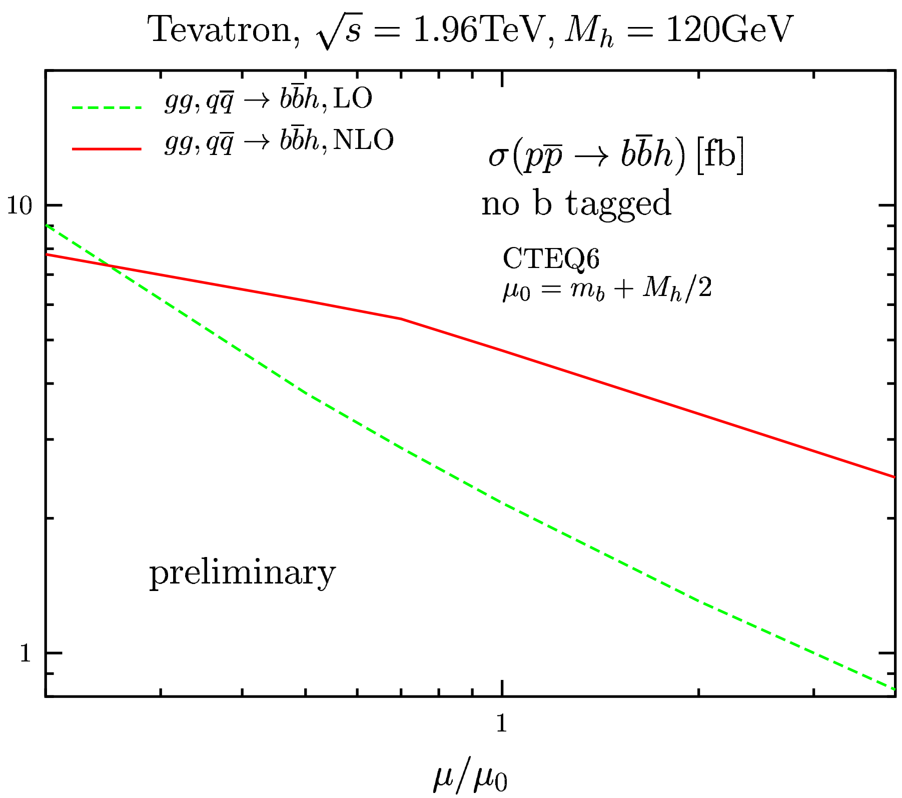


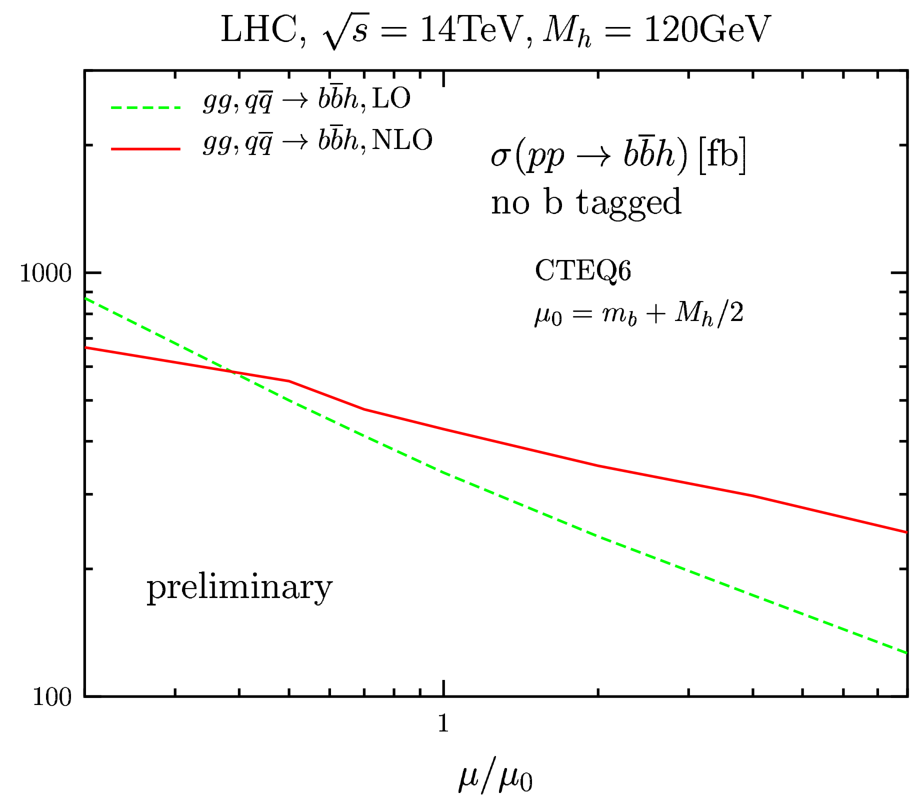
from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

Main Result

Drastically reduced scale dependence of the NLO QCD cross sections – no b tagged:





from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302