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

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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

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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

<table>
<thead>
<tr>
<th>Particle</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau</td>
<td>-1</td>
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<tr>
<td>Muon</td>
<td>-1</td>
</tr>
<tr>
<td>Electron</td>
<td>-1</td>
</tr>
<tr>
<td>Tau Neutrino</td>
<td>0</td>
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<tr>
<td>Muon Neutrino</td>
<td>0</td>
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<tr>
<td>Electron Neutrino</td>
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Quarks

<table>
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<tr>
<th>Quark</th>
<th>Electric Charge</th>
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<tr>
<td>Bottom</td>
<td>-1/3</td>
</tr>
<tr>
<td>Strange</td>
<td>-1/3</td>
</tr>
<tr>
<td>Down</td>
<td>-1/3</td>
</tr>
<tr>
<td>Top</td>
<td>2/3</td>
</tr>
<tr>
<td>Charm</td>
<td>2/3</td>
</tr>
<tr>
<td>Up</td>
<td>2/3</td>
</tr>
</tbody>
</table>

*each quark: \( R, B, G \) 3 colors*

*The particle drawings are simple artistic representations*
Interactions: coupling of forces to matter

Electromagnetic

- \( \gamma \)
- \( e^+ \)
- \( e^- \)
- \( q \)
- \( q' \)

Range \( \infty \), relative strength \( \leq 10^{-2} \)

Strong

- \( g \)
- \( q \)
- \( \bar{q} \)
- \( q' \)
- \( g \)

Range \( \sim 10^{-15} \) m, relative strength \( = 1 \)

Electroweak

Charged

- \( W \)
- \( u \)
- \( \bar{d} \)
- \( e^- \)
- \( e^+ \)
- \( \nu_e \)

Range \( \sim 10^{-18} \) m, relative strength \( 10^{-14} \)

Neutral

- \( Z^0 \)
- \( e^- \)
- \( e^+ \)

Range \( \sim 10^{-15} \) m, relative strength \( = 1 \)
The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

The strong interaction is asymptotic free:

\[
\alpha_s(Q) = 0.1183 \pm 0.0027
\]

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.”


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 \( A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \Lambda(x) \).
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:  $J_{em}^\mu A_\mu$ ($J_{em}$ is the conserved electromagnetic current).

But: “naive” mass terms spoil local gauge invariance!

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

⇒ Masslessness of the photon as a consequence of gauge invariance of the electromagnetic interaction.
## Symmetries of the Standard Model

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Symmetry Group</th>
<th>Gauge Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>electromagnetic</td>
<td>local U(1): invariance under space-time dependent phase transitions generated by the electric charge</td>
<td>QED</td>
</tr>
<tr>
<td>strong</td>
<td>local SU(3): invariance under space-time dependent rotations in the 8-dimensional color space</td>
<td>QCD</td>
</tr>
<tr>
<td>electroweak</td>
<td>SU(2)⊗U(1): invariance under space-time dependent rotations in the 3-dimensional (weak) isospin space and under phase transitions generated by the (weak) hypercharge $Y (Q = I_3 + Y/2)$</td>
<td>SM of electroweak interactions</td>
</tr>
</tbody>
</table>

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 \( D_\mu = \partial_\mu - ig_2 \frac{\tau}{2} \vec{W}_\mu - ig_1 \frac{\nu}{2} B_\mu \).

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

Higgs potential (“sombrero” potential):

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

SSB: \( \mu^2 > 0 \): \( V(\Phi) \) is minimized by \( |\Phi_0|^2 = \frac{\mu^2}{2\lambda} = \frac{v^2}{2} \neq 0 \)
Orientation of $\Phi_0$ in the SU(2) space is not fixed:

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

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 \( \eta \), with mass \( M_H = \sqrt{\lambda/2v} \).
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


\[
114.4 \text{ GeV} < M_H \lesssim 260 \text{ GeV (95 \% C.L.)}
\]

⇒ 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):

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

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

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

- **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., \( e^+e^- \rightarrow Z \rightarrow HZ \):

\[
e^+ e^- \rightarrow Z \rightarrow HZ
\]

and \( H \rightarrow b\bar{b}, \ Z \rightarrow q\bar{q} \)

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 \( \sigma(p\bar{p})/\sigma(p\bar{p} \rightarrow H) \approx 10^{10} \).

At the LHC, the background for the light Higgs search (\( H \rightarrow b\bar{b} \)) 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

\[ f = e, \mu, \tau, \nu_l, q \]

\[ \text{d}\sigma^\text{Born}_{e^+e^- \to ff}(q^2, \alpha, m_f, m_e) \text{ is of } \mathcal{O}(\alpha^2) \]

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

\[ f = e, \mu, \tau, \nu_l, q \]

\[ \text{d}\sigma(q^2, \alpha, m_f, m_e, m_{top}, M_H, \ldots) \text{ is of } \mathcal{O}(\alpha^3) \]

\[ \Rightarrow \text{d}\sigma^\text{theory}_{e^+e^- \to ff} = \text{d}\sigma^\text{Born}_{e^+e^- \to ff} + \delta\text{d}\sigma(m_{top}, M_H) + \mathcal{O}(\alpha^4) \]

$\delta\text{d}\sigma$ 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.

Moreover: Small discrepancies (2 – 3σ) observed in the measurement of the weak mixing angle at NuTeV and the anomalous magnetic moment of the muon at BNL.
The global SM fit 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)
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:

- $M_W (\text{LEP}, p\bar{p}) = 80.425 \pm 0.034 \text{ GeV}$
- $M_W (\text{LEP}/\text{SLD}) = 80.368 \pm 0.032 \text{ GeV}$

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

$M_W (\text{NuTeV})=80.136(84) \text{ GeV}$ prefers a heavy Higgs
From global fit to all electroweak precision data:


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

- blue band: theoretical uncertainty due to missing higher order corrections
- blue/red curves: uncertainty due to \( \Delta \alpha_{\text{had}}^{(5)} \)

D.Wackeroth, SUNY Buffalo
Colloquium at the University of Iowa
10/18/04
$H^0$ production at hadron colliders:

\[ \sigma(pp \rightarrow H + X) \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ m_t = 175 \text{ GeV} \]
CTEQ4M

But:
\[ \text{BR}(H \rightarrow Z\bar{Z} \rightarrow 4\ell^-) = 1.4 \times 10^{-3} \]
\[ \text{BR}(H \rightarrow Z\bar{Z} \rightarrow \mu^+\mu^-) = 3 \times 10^{-4} \]

from the CMS website at www.cern.ch

D.Wackeroth, SUNY Buffalo

Conference at the University of Iowa

10/18/04
Dominant SM Higgs decay modes:

\[ M_H < 135 \text{ GeV}: \ H \rightarrow b\bar{b} \text{ with } BR = 43\%, \]
\[ M_H > 135 \text{ GeV}: \ H \rightarrow W^+W^- \text{ with } BR = 40\% \]

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 $3\sigma$ or a $5\sigma$ discovery:

![Graph showing Tevatron Higgs Sensitivity Study](image)

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

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

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:

\[ M_H \lesssim 125 \text{ GeV} \] (95 % C.L. with 2 fb$^{-1}$, $3\sigma$ evidence with 5 fb$^{-1}$)  
\[ M_H = 130 \text{ GeV} \] can be excluded with 4 fb$^{-1}$
LHC SM Higgs discovery potential

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
(no K-factors)

ATLAS

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

For \( M_H < 130 \text{ GeV} \) 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 ⇒ **fine tuning is needed so that** $M_H < 1 \text{ TeV}$ - **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 $p\bar{p}, pp \rightarrow b\bar{b}h, h = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan\beta$:

$$g_{bb(h^0,H^0)}^{MSSM} = \left(\frac{\sin\alpha, \cos\alpha}{\cos\beta}\right) g_{bbH} \quad \text{and} \quad g_{bbA^0}^{MSSM} = \tan\beta g_{bbH}$$
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 $b\bar{b}h \rightarrow b\bar{b}b\bar{b}$ (right):

from The D0 collaboration, D0 Note 4366 - CONF

Systematic uncertainty in cross section measurement is about 25 %.

⇒ It is crucial to know the impact of QCD corrections.
Expected relative error on the determination of $\sigma_{\text{Higgs}}$ at the LHC:

$t\bar{t}h$ directly probes the top quark Yukawa coupling:
at the LHC with 200 $\text{fb}^{-1}$ 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)

⇒ 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 $\sigma_{LO}$ 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 $p\bar{p}, pp \rightarrow t\bar{t}H$ production: A few technical details


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

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

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

However, in the case of $gg \rightarrow t\bar{t}H$ there are new challenges, e.g., spurious singularities arising in the reduction of pentagon tensor integrals.
NLO QCD total inclusive cross section to $p\bar{p}, pp \to t\bar{t}H$:

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

with the parton level cross sections

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

- $\hat{\sigma}_{\text{virt}}^{ij}$:
  - **UV divergences**: renormalized in $d = 4 - 2\epsilon$ dimensions by suitable set of counterterms (modified $\overline{\text{MS}}$ scheme, on-shell subtraction for top)

- $\hat{\sigma}_{\text{real}}^{ij}$:
  - **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 $\hat{\sigma}_{\text{real}}^{ij}$.

- **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

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_h = 120 \text{ GeV} \]
\[ \mu_0 = m_t + M_h / 2 \]

CTEQ5 PDF's

<table>
<thead>
<tr>
<th>( \mu / \mu_0 )</th>
<th>( \sigma_{LO} ) (fb)</th>
<th>( \sigma_{NLO} ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_t )</td>
<td>582.92(6)</td>
<td>719(4)</td>
</tr>
<tr>
<td>( m_t + M_h / 2 )</td>
<td>520.47(6)</td>
<td>697(3)</td>
</tr>
<tr>
<td>( 2m_t )</td>
<td>450.09(5)</td>
<td>663(3)</td>
</tr>
<tr>
<td>( 2m_t + M_h )</td>
<td>405.54(4)</td>
<td>634(2)</td>
</tr>
</tbody>
</table>

from S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003),
see also W.Beenakker et al., PRL 87 (2001), NPB 653 (2003)
• At NLO QCD the dependence on the arbitrary factorization/renormalization \( \mu \) scale is strongly reduced.

• The residual theoretical uncertainty from \( \mu \) variation is estimated to be about 10 – 15\% (Tevatron) and 15 – 20\% (LHC).

• At the Tevatron the \( \mathcal{O}(\alpha_s) \) corrections slightly reduce \( \sigma_{\text{LO}} \) for \( m_t < \mu < 2m_t \) \( (K = 0.7 - 0.95) \).

• At the LHC the \( \mathcal{O}(\alpha_s) \) corrections slightly enhance \( \sigma_{\text{LO}} \) 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

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

The calculation of the $\mathcal{O}(\alpha_s)$ corrections to $gg, q\bar{q} \rightarrow b\bar{b}h$ 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 perturbative 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 $2(1)$ tag case we require two(one) high $p_T$ $b$ quark jets in the final state:

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

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 $gg, q\bar{q} \rightarrow b\bar{b}h$ 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.
dependence in the MSSM

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

\[ pp \rightarrow b\bar{b}H^0 + X \text{ at the LHC} \]

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ p_T^b > 20 \text{ GeV} \]
\[ |\eta| < 2.5 \]
\[ \mu = m_b + M_{h^0} / 2 \]

\[ \sigma_{NLO}(\text{MSSM}) \sim \sigma_{NLO}(\text{SM}) \left( \frac{g_{bbh}^{MSSM}}{g_{bbh}} \right)^2 \]

\[ pp \rightarrow b\bar{b}h^0 + X \text{ at the Tevatron} \]

\[ \sqrt{s} = 2 \text{ TeV} \]
\[ p_T^b > 20 \text{ GeV} \]
\[ |\eta| < 2 \]


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

Drastically reduced scale dependence of the NLO QCD cross sections:

\[ p\bar{p} \rightarrow b\bar{b}h + X \text{ at the Tevatron} \]

\[ pp \rightarrow b\bar{b}h + X \text{ at the LHC} \]

\[ \sqrt{s}=2 \text{ TeV} \]
\[ M_h=120 \text{ GeV} \]
\[ \mu_0=m_b+M_h/2 \]
\[ p_T^b>20 \text{ GeV} \]
\[ |\eta|<2 \]

\[ \sqrt{s}=14 \text{ TeV} \]
\[ M_h=120 \text{ GeV} \]
\[ \mu_0=m_b+M_h/2 \]
\[ p_T^b>20 \text{ GeV} \]
\[ |\eta|<2.5 \]


⇒ the residual theoretical uncertainty is estimated to be about 15 — 20% from \( \mu \) 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):

→ 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.
→These two calculations are in good agreement.
\rightarrow \text{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 $g \rightarrow b\bar{b}$ splitting.

**Inclusive (no $b$ tagged):** known at NNLO QCD

$b$ quark fusion, $b\bar{b} \rightarrow h$, is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln^2(M_h/m_b))$ and $b(\bar{b})g \rightarrow b(\bar{b})h$ and $gg, q\bar{q} \rightarrow b\bar{b}h$ are identified as NLO contributions to $b\bar{b} \rightarrow h$ 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 $pp, p\bar{p} \rightarrow (b\bar{b})H + X$ production has been calculated at NNLO QCD by R.Harlander, W.Kilgore.

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

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

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


$$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$$
Effect of NLO QCD corrections on the Higgs $p_T$ distribution:

LHC

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 …
Spectacular discovery in Switzerland!
CERN - LHC finds Higgs-Bosons

(By Higgs, Kibble, Hagen, Guralnik)
Experiment confirms theory about the origin of mass.

President commits additional funds to Particle Research.

By 2good2true

- 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.

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 right!
- NASA: Red Planet

The vacuum
Main Result

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

\[ p\bar{p} \to t\bar{t}H X \text{ at the Tevatron} \]

<table>
<thead>
<tr>
<th>( \mu )</th>
<th>( \sigma_{LO} ) (fb)</th>
<th>( \sigma_{NLO} ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_t )</td>
<td>6.866(1)</td>
<td>4.86(3)</td>
</tr>
<tr>
<td>( m_t + M_h/2 )</td>
<td>5.909(1)</td>
<td>4.85(2)</td>
</tr>
<tr>
<td>( 2m_t )</td>
<td>4.879(1)</td>
<td>4.69(2)</td>
</tr>
<tr>
<td>( 2m_t + M_h )</td>
<td>4.255(1)</td>
<td>4.51(2)</td>
</tr>
</tbody>
</table>

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:

![Graphs showing the effect of NLO QCD corrections on the Higgs $p_T$ distribution.](image)

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:

\[
\sigma_{\text{LO},\text{NLO}} \quad (\text{fb})
\]

\[
\begin{array}{c}
\sqrt{s}=1.96 \text{ TeV} \\
M_h=120 \text{ GeV} \\
\mu_0=m_b+M_h/2 \\
\text{CTEQ6} \\
1b-\text{tag}
\end{array}
\]

\[
\begin{array}{c}
\sqrt{s}=14 \text{ TeV} \\
M_h=120 \text{ GeV} \\
\mu_0=m_b+M_h/2 \\
\text{CTEQ6} \\
1b-\text{tag}
\end{array}
\]

preliminary

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

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