Higgs Physics and QCD
(part 2)

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CTEQ Summer School
June, 2004
Outline

• The Standard Model & the Higgs Mechanism
• Agents of Electro-weak Symmetry Breaking
• The Higgs Boson
• QCD and the Higgs - Hadronic Production
• Impact of Radiative Corrections
• Elements of Precision Higgs Studies
Higgs Production in QCD

How can the Higgs be produced at hadron colliders?

- Quark annihilation?
- Higgs-strahlung?
- Weak boson fusion?
- In association with heavy quarks?
- Through heavy quark loops?

Each process plays a role.
Quark Annihilation

The Higgs couples to mass. The quarks in the proton are much heavier than the electron, but are they heavy enough to produce a viable cross section?

\[ \sigma_{\text{LO}}(q\bar{q} \rightarrow H) = \frac{\pi G_F \overline{m}_q^2}{3 \sqrt{2} M_H^2} \delta \left(1 - \frac{M_H^2}{\hat{s}}\right) \]

\(\overline{m}_q\) is the running mass, evaluated at \(\mu \sim M_H\).
Quark Annihilation (cont.)

u and d quarks have much larger parton luminosities than s, c or b quarks.

But it’s not enough. $m_d^2/m_b^2 \sim 10^{-5}$, even if running is neglected!
Higgs-strahlung $qq \rightarrow W^+H$

Similar to $e^+e^- \rightarrow ZH$ Higgs-strahlung. The problem at hadron colliders is that it is a weak process with QCD backgrounds. This is the discovery mode at the Tevatron, where it is near the end of the kinematic reach, but it is swamped by gluon induced backgrounds at LHC.
Weak Boson Fusion

Originally used for heavy Higgs studies. Identifiable signal makes it important for lower mass regions as both a discovery channel and a for measuring couplings.
In Association with Heavy Quarks

- $pp \rightarrow t\bar{t}H$
  Spectacular signal. C.M. Energy $> 450$ GeV! Only viable for low mass region.
- $pp \rightarrow b\bar{b}H$
  Closely related to $b\bar{b} \rightarrow H$. More later.
Heavy Quark Loops

Somewhat surprisingly, gluon fusion via a virtual top-quark loop dominates Higgs production at hadron colliders.

\[ \sigma_{\text{LO}}(gg \rightarrow H) = \frac{\pi G_F}{128\sqrt{2}} \left( \frac{\alpha_s(\mu)}{\pi} \right)^2 \tau^2 |1 + (1 - \tau)f(\tau)|^2 \delta \left( 1 - \frac{M_H^2}{\hat{s}} \right) \]

\[ f(\tau) = \begin{cases} 
\arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\
-\frac{1}{4} \left[ \ln \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right]^2, & \tau < 1,
\end{cases} \]

\[ \tau = \frac{4M_t^2}{M_H^2}, \]
Comparing $b\bar{b}\to H$ to $gg\to H$:

\[
\lim_{t\to\infty} \sigma_{LO}(gg \to H) = \frac{\pi G_F}{288\sqrt{2}} \left( \frac{\alpha_s(\mu)}{\pi} \right)^2 \delta \left( 1 - \frac{M_H^2}{\hat{s}} \right)
\]

\[
\sigma_{LO}(b\bar{b} \to H) = \frac{\pi G_F}{3\sqrt{2}} \frac{m_b^2}{M_H^2} \delta \left( 1 - \frac{M_H^2}{\hat{s}} \right)
\]

For $M_H \sim 120$ GeV, $\sigma_{b\bar{b}}/\sigma_{gg} \sim 50$,

For $M_H \sim 900$ GeV, $\sigma_{b\bar{b}}/\sigma_{gg} \sim 1$. 
The Gluon Luminosity is Huge

The large gluon luminosity more than makes up for any suppression from the loop factor!
SM Higgs Production at the LHC

The most important channels are gluon fusion, WBF and \( t\bar{t}H \).
Higgs Discovery requires that you detect the decay products.

Inclusive production with decay to $b\bar{b}$ is swamped by $\text{QCD}$ production, so we must use rare decays or associated production below the $W^+W^-$ threshold.
Higgs Branching Ratios

The diagram shows the branching ratios of the Higgs boson as a function of its mass. The x-axis represents the Higgs mass in GeV, and the y-axis represents the branching ratio on a logarithmic scale. Different decay modes are indicated by different colored lines:

- $W^+W^-$
- $Z^0Z^0$
- $c\bar{c}$
- $\gamma\gamma$
- $Z\gamma$
- $s\bar{s}$
- $\mu^+\mu^-$
- $\tau^+\tau^-$
- $t\bar{t}$
- $b\bar{b}$

The graph illustrates how the branching ratios vary with the Higgs mass, with peaks and valleys indicating the dominance of certain decay modes at different mass values.
The Impact of Radiative Corrections

Most processes in QCD must be computed to Next-to-Leading Order (NLO) to get an accurate description of rate and distributions. This is particularly true of Higgs production. Many of the most important signals have substantial radiative corrections.

In addition to the total rate, differential distributions are needed at higher order and often need resummation.
Gluon Fusion Dominates Higgs Production

The reason: top loops.

The problem for theorists, however, is top loops.

\[
\sigma_{\text{LO}}(gg \rightarrow H) = \frac{\pi G_F}{128\sqrt{2}} \left( \frac{\alpha_s(\mu)}{\pi} \right)^2 \tau^2 |1 + (1 - \tau)f(\tau)|^2 \delta \left( 1 - \frac{M_H^2}{s} \right)
\]

\[
f(\tau) = \begin{cases} 
\arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\
-\frac{1}{4} \left[ \ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2, & \tau < 1,
\end{cases} 
\]

\[\tau = \frac{4M_t^2}{M_H^2},\]
Effective Lagrangian

In the limit that the top quark is very heavy, we can integrate it out and formulate an effective Lagrangian coupling the Higgs to Gluons.

\[ \mathcal{L} = C_1 H \ G^{a,\mu\nu} \ G^a_{\mu\nu} \]

\( C_1 \) has been computed to order \( \alpha_s^4 \) ![Chetyrkin, Kniehl, Steinhauser]

Using the effective Lagrangian greatly simplifies the calculation of radiative corrections.
Higher Order Corrections

NLO Corrections have been computed in both the effective Lagrangian and in the full theory.

[Dawson; Djouadi, Spira, Graudenz, Zerwas]

[Djouadi, Spira, Graudenz, Zerwas]
They agree extremely well
But we need NNLO!
NNLO Corrections

For NNLO corrections, we assume that the Effective Lagrangian provides a good description of Higgs Production, especially in the most interesting mass range (< 200 GeV).

NNLO Corrections combine three components

- Virtual corrections to two loops
- Single Real Emission corrections to one loop
- Double Real Emission corrections
Virtual Corrections:
One-Loop Single Real Emission:
Double Real Emission:
In recent years, the Higgs production cross section has been computed to NNLO in the effective theory by three groups using very different methods.

[Harrlander, WK; Ravindran, Smith, van Neerven]

[Anastasiou & Melnikov]
All groups agree exactly

\[ \sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{6} \]
Higgs Cross Section at NNLO

\[ \sigma(pp \rightarrow H + X) \, [\text{pb}] \]

\[ \sqrt{s} = 14 \, \text{TeV} \]

Harlander, Kilgore (02)
Anastasiou, Melnikov (02)
Ravindran, Smith, van Neven (03)
Threshold resummation

[Catani, de Florian, Grazzini, Nason]
Higgs Distributions at NNLO

Using the cutting method, NNLO distributions can be computed.

[Distributions for Drell-Yan exist at NNLO. For Higgs, they are known only to NLO so far.]

\[ \text{pp} \rightarrow \text{H+X Rapidity distribution at LHC} \]

\[ M_H/4 < \mu_R, \mu_F < M_H \]

MRST2001 pdfs

\[ M_H = 115 \text{ GeV} \]
Signal identification as well as the signal to background ratio can be improved by looking at Higgs production at finite $Q_T$. In the effective theory, this is known at NLO. [de Florian, Grazzini, Kunszt; Ravindran, Smith, van Neerven; Glosser, Schmidt]

The background, $\gamma\gamma + \text{jet}$, is also known at NLO. [Del Duca, Maltoni, Nagy, Trócsányi]

The Higgs $Q_T$ can be resummed alone [Balázs, Yuan; Berger, Qiu; Bozzi, Catani, de Florian, Grazzini] or in conjunction with threshold resummation. [Kulesza, Sterman, Vogelsang]
QT Resummation

![Graph showing the relationship between qT and dσ/dqT with different QCD corrections and initial conditions.]
Joint Threshold and $Q_T$ Resummation

$sqrt(s)=14$ TeV, $M_H=125$ GeV, CTEQ5M

- recoil
- joint, $\eta=1$
ttH production at NLO

This process serves as a discovery mode for a light Higgs and gives information on the top Yukawa coupling. [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth]
Weak Boson Fusion

Recently implemented in multi-purpose Monte-Carlo calculation. [Figy, Oleari, Zeppenfeld]

Offers discovery potential in the low to intermediate mass range and allows one to measure Higgs couplings. [Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld]

\[ gg \rightarrow H + 2j \] background computed with \( m_\tau \) dependence. [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld]

NLO corrections have been known for some time. [Han, Willenbrock]
Higgs Discovery through Weak Boson Fusion

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

ATLAS

Signal significance vs. \( m_H \) (GeV/c^2)

- \( \gamma\gamma \)
- \( t\bar{t}H (H \rightarrow bb) \)
- \( H \rightarrow ZZ^{(*)} \rightarrow 4l \)
- \( H \rightarrow WW^{(*)} \rightarrow l\nu l\nu \)
- \( qqH \rightarrow qq WW^{(*)} \)
- \( qqH \rightarrow qq \tau\tau \)

Total significance
Expected precision in $\sigma \cdot BR$
Expected Precision of Absolute couplings

ATLAS

\[ \int L \, dt = 30 \text{ fb}^{-1} \]

ATLAS

\[ \int L \, dt = 300 \text{ fb}^{-1} \]
In the Minimal Supersymmetric Standard Model (MSSM) there are two Higgs doublets, with vacuum expectation values $v_u$, $v_d$. After symmetry breaking, there are 5 physical Higgs Scalars:

$$h^0, H^0, A^0, H^\pm$$

In the “decoupling” limit, the light neutral scalar, $h^0$, has properties almost identical to the Standard Model Higgs. The heavy scalar, $H^0$, and the pseudoscalar, $A^0$, have very different interactions.
Gluon fusion is also very important to pseudoscalar production and can also be described by an effective Lagrangian in which the top quark is integrated out. This effective Lagrangian coupling the pseudoscalar to gluons is:

\[ \mathcal{L} = C_1 A \varepsilon_{\mu\nu\alpha\beta} G^{a,\mu\nu} G^{a,\alpha\beta} + \ldots \]
SUSY Higgs Production

SUSY Higgs production has also been computed using massive fermions to NLO.

[Spira, Djouadi, Graudenz, Zerwas]

NNLO Pseudoscalar production is computed in the same way as scalar production. But the effective Lagrangians are only valid for top quark loops! The same three groups again obtained exact analytic agreement.

[Harlander, WK; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]

For scalar Higgs production in SUSY, you can also add squark gluino effects.

[Harlander, Steinhauser; Dawson, Djouadi, Spira]
Pseudoscalar Production in Gluon Fusion

\[ \sigma(pp \rightarrow A + X) \quad (\sqrt{s} = 14 \text{ TeV}) \]

- **g_t=1**
  - **NNLO**
  - **NLO**
  - **LO**

![Graph showing the production cross section of pseudoscalar particles in gluon fusion](graph.png)

- **M_A [GeV]**
  - **100 120 140 160 180 200 220 240 260 280 300**
H/A Couplings

For the pseudoscalar (and for $H^0$ in the decoupling limit) the couplings to "up-type" fermions are suppressed by $\tan \beta = v_u/v_d$ while those to "down-type" fermions are enhanced by $\tan \beta$. This presents a problem for gluon fusion calculations: For $\tan \beta$ much larger than 1, b-quark interactions are important. But an effective Lagrangian from integrating out the b-quark to produce $\sim$100 GeV Higgs bosons is unjustifiable! An NNLO calculation would require massive 3-loop diagrams.
A new production mode at large \( \tan \beta \)

The importance of b-quark couplings at large \( \tan \beta \) suggests a new inclusive production mechanism:

\[
b\bar{b} \rightarrow H
\]

Since b-quark distributions are generated by gluon splitting the true parent process is

\[
gg \rightarrow b\bar{b}H
\]

The b-quark distribution resums large logs associated with the gluon splitting, but is fully consistent only if calculated to high enough order to include the parent process.

In this case, one must compute to NNLO.
Fixed vs. Variable Flavor Number

The question arises whether one should work in the Fixed Flavor Number Scheme (FFNS) or a Variable Flavor Number Scheme (VFNS).

A FFNS has a fixed number (say 3) of “active” flavors. Heavy flavor production only occurs through gluon splitting. While well-defined, FFNS seems forced if $Q^2 \gg m_q$. In addition, $\ln(Q/m_q)$ terms become problematic.

A VFNS recognizes thresholds and changes the number of “active” flavors with $Q^2$. 
Parton Distributions in VFNS

Logarithmic terms arise from forward emission of on-shell $b$-quarks.

In VFNS, the lowest order terms are $b\bar{b} \rightarrow H$. Parton evolution resums the logarithmic terms.
Worries about the VFNS

At leading order, the inclusive cross section for \( bb \rightarrow H \) is much bigger than \( gg \rightarrow b\bar{b}H \).
Power Counting in the VFNS

[Dicus, Steltzer, Sullivan, Willenbrock]

The key to obtaining a consistent calculation is to properly count the powers of $\alpha_s$ and $\ln(M_H/m_b)$. The leading contribution in $b\bar{b}\to H$ is not order 1 but order $\alpha_s^2 \ln^2(M_H/m_b)$. To all orders in perturbation theory, the inclusive Higgs production cross section is: ($\mu_F \sim M_H$)

$$\sigma_{b\bar{b}} = \sum_{n=0}^{\infty} (\alpha_s \ln(M_H/m_b))^n \{ $$

$$\alpha_s^2 [c_{n0} \ln^2(M_H/m_b) + c_{n1} \ln(M_H/m_b) + c_{n2}] $$

$$+ \alpha_s^3 c_{n3} + \alpha_s^4 c_{n4} + \alpha_s^5 c_{n5} + \ldots \}$$
The lowest order calculation to include all terms at order $\alpha_s^2$ and the resummed collinear logs is NNLO. Since all collinear logs are resummed in the PDFs, the b-quark mass is ignored, except in Yukawa couplings. Other b-quark mass effects are suppressed by factors of $m_b^2/M_H^2$.

$b\bar{b}\to H/A$ can dominate at large $\tan \beta$ because

$$\sigma_{b\bar{b}} \sim m_b^2/M_H^2 \tan^2 \beta$$

while

$$\sigma_{gg} \sim A \cot^2 \beta + B m_b^2/M_H^2 + C m_b^4/M_H^4 \tan^2 \beta$$
\( \bar{b}b \rightarrow A \) versus \( gg \rightarrow A \)

At small \( \tan \beta \), \( b \) quark fusion is tiny.

At large \( \tan \beta \), it dominates.
Scale Dependence of $b\bar{b} \rightarrow H/A$ at LHC
Results for $gg \rightarrow b\bar{b}H @ NLO$

This calculation goes to order $\alpha_s^3$ and includes more of the log-enhanced terms.

This result is flexible in that it can be applied to the

- Double tag mode
- Single tag mode
- Inclusive mode

But it still suffers from un-resummed log-enhanced terms in (semi-)inclusive modes.

[Dittmaier, Krämer, Spira; Dawson, Jackson, Reina, Wackeroth]
The good behavior of $\bar{b}b \rightarrow H$ and the favorable comparison to $gg \rightarrow bbH$ largely settles the controversy over $b$ parton distributions.
Results for inclusive $gg \rightarrow b\bar{b}H$

- Preliminary
- $\sqrt{s} = 14$ TeV
- $M_h = 120$ GeV
- $\mu_0 = m_b + M_h / 2$
- CTEQ6
- No b-tag

Graph showing:
- $\sigma_{LO,MS}$ (dashed green line)
- $\sigma_{NLO,MS}$ (solid purple line)

Y-axis: $\sigma_{LO,NLO}$ (pb)
X-axis: $\mu / \mu_0$
Compare $b\bar{b} \rightarrow H$ to $gg \rightarrow b\bar{b}H$
Higgs + b quark Production

H+b production may be more promising. The b tag and the Higgs $Q_T$ greatly improve detection efficiency.

With only one b quark in the initial state, NLO is sufficient to obtain a reliable result.

$pp \rightarrow hb$ @ LHC

$\mu/m_h\rightarrow 0$

$m_h=120$ GeV
$p_T(b)>15$ GeV
$|\eta(b)|<2.5$

[Campbell, Ellis, Maltoni, Willenbrock]
Compare $bg \rightarrow bH$ to $gg \rightarrow b\bar{b}H$
$gg \rightarrow b\bar{b}H$ with two tagged $b$ quarks

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

$p_T^b > 20 \text{ GeV} \]
\[ |\eta| < 2.5 \]
$gg \rightarrow b\bar{b}H$ with two tagged $b$ quarks

$\sigma(pp \rightarrow b\bar{b}h + X)$ [fb]
$\sqrt{s} = 14$ TeV
$\mu = (2m_b + M_h)/4$
$p_T^{b/\bar{b}} > 20$ GeV
$|\eta_{b/\bar{b}}| < 2.5$

- --- LO
- --- NLO

[Campbell et al., hep-ph/0405302]
Finding SUSY Higgs at LHC
Higgs Bosons at a Linear Collider:

We want to measure all we can at the LHC, but we should remember the importance of the Linear Collider to the program of Higgs studies.

The Linear Collider will be able to measure Higgs properties with phenomenal precision and will allow us to fully understand those components of the symmetry breaking sector that are within its kinematic reach.
Higgs Couplings at a Linear Collider

If the Higgs mass is below ~160 GeV, many branching ratios can be precisely measured.
Spin and CP at a Linear Collider

The spin and CP quantum numbers can also be definitively measured at a linear collider.
Conclusions

The nature of electroweak symmetry breaking is the most important question in particle physics.

This has been true for ~ 20 years. It is still true.

The discovery of the agent of electroweak symmetry will likely be made at the LHC.

The Tevatron can find evidence and perhaps set important limits, but it will be difficult to make a definitive observation.
Conclusions (continued)

Radiative corrections and resummations will play an essential role in the discovery and exploration of the symmetry breaking sector of the Standard Model.

Higher order corrections can do more than provide a more accurate calculation. They can also clarify difficult issues.