Higgs production in association with jets at the LHC

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Moriond ``QCD and Hadronic Interactions”  La Thuile  21 March 2007
Feynman x's for the production of a particle of mass M

\[ x_{1,2} = \frac{M}{14 \text{ TeV}} e^{\pm y} \]
In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

1. **gluon fusion** $gg \rightarrow H$
   - largest rate for all $M_H$
   - proportional to the top Yukawa coupling $y_t$

2. **weak-boson fusion (WBF)** $qq \rightarrow qqH$
   - second largest rate (mostly $u \bar{d}$ initial state)
   - proportional to the $WWH$ coupling

3. **Higgs-strahlung** $q\bar{q} \rightarrow W(Z)H$
   - third largest rate
   - same coupling as in WBF

4. **$t\bar{t}(b\bar{b})H$ associated production**
   - same initial state as in gluon fusion, but higher $x$ range
   - proportional to the heavy-quark Yukawa coupling $y_Q$
in the intermediate Higgs mass range \( M_H \sim 100 - 200 \text{ GeV} \)

- gluon fusion cross section is \( \sim 20 - 60 \text{ pb} \)
- WBF cross section is \( \sim 3 - 5 \text{ pb} \)
- \( WH, ZH, t\bar{t}H \) yield cross sections of \( \sim 0.2 - 3 \text{ pb} \)
**Weak Boson Fusion: \( qq \rightarrow qqH \)**

**A WBF event**

**Lego plot**

**WBF features**

- Energetic jets in the *forward* and *backward* directions
- Higgs decay products between the tagging jets
- Sparse gluon radiation in the central-rapidity region, due to colourless \( W/Z \) exchange
- NLO corrections increase the WBF production rate by about 10%, and thus are small and under control
- WBF can be measured with good statistical accuracy: \( \sigma \times \text{BR} \approx \mathcal{O}(10\%) \)

\[
\eta = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta}
\]
**Signal significance and (stat + syst) error**

\[ \Delta \sigma_H / \sigma_H = \sqrt{N_S + N_B} / N_S \]

\[ \text{lum} = 30 \text{ fb}^{-1} \]

(no K-factors)

ATLAS

**Statistical significance:**

\[ \frac{N_S}{\sqrt{N_S + N_B}} \]

**QCD/p.d.f. uncertainties:**

\( \mathcal{O}(5\%) \) for WBF

\( \mathcal{O}(20\%) \) for gluon fusion

**Luminosity uncertainties:**

\( \mathcal{O}(5\%) \)
Cross sections at high $Q^2$

separate the short- and the long-range interactions through factorisation

$$
\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \frac{f_a/A(x_1, \mu^2_F)}{f_b/B(x_2, \mu^2_F)} \times \hat{\sigma}_{ab \to X} \left( x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu^2_R), \alpha(\mu^2_F), \frac{Q^2}{\mu^2_R}, \frac{Q^2}{\mu^2_F} \right)
$$

$X = W, Z, H, Q\bar{Q}, \text{high}-E_T\text{jets, ...}$

$\hat{\sigma}$ is known as a fixed-order expansion in $\alpha_S$

$$
\hat{\sigma} = C \alpha^n_S \left( 1 + c_1 \alpha_S + c_2 \alpha^2_S + \ldots \right)
$$

$c_1 = \text{NLO} \quad c_2 = \text{NNLO}$

or as an all-order resummation

$$
\hat{\sigma} = C \alpha^n_S \left[ 1 + (c_{11} L + c_{10}) \alpha_S + (c_{22} L^2 + c_{21} L + c_{20}) \alpha^2_S + \ldots \right]
$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

$c_{11}, c_{22} = \text{LL} \quad c_{10}, c_{21} = \text{NLL} \quad c_{20} = \text{NNLL}$
**Leading Order**

\[ O(\alpha_s^2) \quad gg \rightarrow H \]

energy scales: \( \hat{s} = M_H^2 \) and \( M_t^2 \)
Higgs Production via Gluon Fusion

**Leading Order**

\[ \mathcal{O}(\alpha_s^2) \quad gg \rightarrow H \]

- energy scales: \( \hat{s} = M_H^2 \) and \( M_t^2 \)

**NLO Corrections**

\[ \mathcal{O}(\alpha_s^3) \]
- 2-loop \( gg \rightarrow H \)
- 1-loop \( gg \rightarrow gH \quad qg \rightarrow qH \quad + \quad \text{crossings} \)

Djouadi, Graudenz, Spira, Zerwas, ’93–’95

- large \( K \) factor: \( \sigma^{NLO} = K^{NLO} \sigma^{LO} \quad \mathcal{O}(40 – 100\%) \)
THE LARGE TOP-MASS LIMIT

\[ M_H \ll 2M_t \]
**The Large Top-mass Limit**

\[ M_H \ll 2M_t \]

**NLO Corrections**

- \[ K \text{ factor in the large } M_t \text{ limit} \]
  \[ K_\infty = \lim_{M_t \to \infty} K \]

- \[ \text{NLO rate in the large } M_t \text{ limit} \]
  \[ \sigma_{\infty}^{\text{NLO}} = K_\infty^{\text{NLO}} \sigma_{\infty}^{\text{LO}} \]

\[ \sigma_{\infty}^{\text{NLO}} \text{ is within } 10\% \text{ of } \sigma_{\infty}^{\text{NLO}} \text{ for } M_H \lesssim 1 \text{ TeV} \]
$gg \rightarrow H$ \textbf{IN THE LARGE $M_t$ LIMIT}

**NNLO CORRECTIONS**

\[ O(\alpha_S^4) \]

<table>
<thead>
<tr>
<th>2-loop</th>
<th>1-loop</th>
<th>tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>$gg \rightarrow gH$</td>
<td>$gg \rightarrow ggH$</td>
</tr>
<tr>
<td>$qg \rightarrow qH$</td>
<td>$qg \rightarrow qgH$</td>
<td>$qQ \rightarrow qQH$</td>
</tr>
<tr>
<td>+ crossings</td>
<td>+ crossings</td>
<td>+ crossings</td>
</tr>
</tbody>
</table>

R. Harlander \ hep-ph/0007289

**total cross section for inclusive Higgs production at LHC**

Harlander Kilgore 02
Anastasiou Melnikov 02
Ravindran Smith van Neerven 03

The band contours are

- lower: $\mu_R = 2M_H$, $\mu_F = M_H/2$
- upper: $\mu_R = M_H/2$, $\mu_F = 2M_H$
The properties of the Higgs-like resonance are its couplings: gauge, Yukawa, self-couplings.

quantum numbers: charge, colour, spin, CP

The gauge coupling has also CP properties and a tensor structure. Info on that can be obtained by analysing the final-state topology of Higgs + 2 jet events.
**H + 2 JETS RATE** as a function of $M_H$

\[ \mu_F = \sqrt{p_{j1}^\perp p_{j2}^\perp}, \mu_R = M_Z \]

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0105129

![Graphs showing the rate as a function of $M_H$](image)

- **Inclusive cuts:**
  \[ \begin{align*}
  p_{j}^\perp &> 20 \text{ GeV} \\
  |\eta_j| &< 5 \\
  R_{jj} &> 0.6
  \end{align*} \]

- **WBF cuts:**
  \[ \begin{align*}
  |\eta_{j_1} - \eta_{j_2}| &> 4.2 \\
  \eta_{j_1} \cdot \eta_{j_2} &< 0 \\
  \sqrt{s_{j_1j_2}} &> 600 \text{ GeV}
  \end{align*} \]

- WBF cuts enhance WBF wrt gluon fusion by a factor 10
**Scale Dependence**

renormalisation $\mu_R$ & factorisation $\mu_F$ scales

Kilgore, Oleari, Schmidt, Zeppenfeld, VDD hep-ph/0108030

\[
\mu_R = \xi \mu_0, \quad \mu_F = \sqrt{p_{j1 \perp} p_{j2 \perp}}
\]

\[
\mu_F = \xi \mu_0, \quad \mu_R = M_Z
\]

Strong $\mu_R$ dependence: the calculation is LO and $O(\alpha_S^4)$

A natural scale for $\alpha_S$?

High energy limit suggests $\alpha_S^4 \to \alpha_S(p_{j1 \perp}) \alpha_S(p_{j1 \perp}) \alpha_S^2(M_H)$

\[\sigma\] varies by a factor 2.5 for $\mu_0/2 < \mu_R < 2\mu_0$

Mild $\mu_F$ dependence: $O(10\%)$ over the $\mu_0/5 < \mu_R < 5\mu_0$ range
**NLO corrections**

NLO corrections increase the WBF production rate by about 10%, with a few % change under $\mu_R$ scale variation.

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003
Berger Campbell 2004

NLO corrections in the large $M_{top}$ limit increase the gluon fusion production rate by about 15--25%, but the change under $\mu_R$ scale variation is sizeable.

Campbell, Ellis, Zanderighi 2006
**RAPIDITY DISTRIBUTIONS**

\[ \Delta \eta_{jj} : \text{rapidity difference between the two jets} \]

\[ \frac{d\sigma}{d\Delta \eta_{jj}} (\text{pb}) \]

- **Solid:** gluon fusion
- **Dashes:** WBF

\[ m_H = 120 \text{ GeV} \]
\[ m_t = 175 \text{ GeV} \]

**Inclusive cuts:**

\[
\begin{align*}
\Delta \eta_{jj} & > 20 \text{ GeV} \\
|\eta_j| & < 5 \\
R_{jj} & > 0.6
\end{align*}
\]

**WBF cuts:** incl. +

\[
\begin{align*}
\eta_{j1} \cdot \eta_{j2} & < 0 \\
\sqrt{s_{jj}} & > 600 \text{ GeV}
\end{align*}
\]

- WBF events spontaneously have a large \( \Delta \eta_{jj} \)
- Dip in gluon fusion at low \( \Delta \eta_{jj} \) is unphysical: 
  \[ R_{jj} = \sqrt{\Delta \eta_{jj} + \Delta \phi_{jj}} > 0.6 \]
$\Delta \phi_{jj} \equiv$ the azimuthal angle between the two jets

\begin{align*}
A_{WB} & \sim \frac{1}{2p_1 \cdot p_4 - M_W^2} \frac{1}{2p_2 \cdot p_3 - M_W^2} \hat{s} m_{jj}^2 \\
\implies \text{a flat } \Delta \phi_{jj} \text{ distribution}
\end{align*}

gluon fusion in the large $M_t$ limit

$\mathcal{L}_{\text{eff}} = \frac{1}{4} A H G_{\mu \nu}^a G^{a \mu \nu} \quad A = \frac{\alpha_s}{3\pi v}$

$A_{\text{gluon}} \sim J_1^\mu (q_1^\nu q_2^\mu - g^{\mu \nu} q_1 \cdot q_2) J_2^\nu$

$J^\mu \equiv$ quark-gluon current

for $|p_i^z| \gg |p_i^{x,y}| \quad i = 3, 4$: forward jets

$A_{\text{gluon}} \sim (J_1^0 J_2^0 - J_1^3 J_2^3) \frac{p_3 \cdot p_4}{\pi}$

$\implies$ zero at $\Delta \phi_{jj} = \frac{\pi}{2}$
the azimuthal angle distribution discriminates between WBF and gluon fusion

note that the large $M_t$ limit curve approximates very well the exact curve
### 3 complementary approaches to $\hat{\sigma}$

<table>
<thead>
<tr>
<th></th>
<th>matrix-elem MC’s</th>
<th>fixed-order x-sect</th>
<th>shower MC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>final-state description</strong></td>
<td>hard-parton jets. Describes geometry, correlations, ...</td>
<td>limited access to final-state structure</td>
<td>full information available at the hadron level</td>
</tr>
<tr>
<td><strong>higher-order effects: loop corrections</strong></td>
<td>hard to implement: must introduce negative probabilities</td>
<td>straightforward to implement (when available)</td>
<td>included as vertex corrections (Sudakov FF’s)</td>
</tr>
<tr>
<td><strong>higher-order effects: hard emissions</strong></td>
<td>included, up to high orders (multijets)</td>
<td>straightforward to implement (when available)</td>
<td>approximate, incomplete phase space at large angles</td>
</tr>
<tr>
<td><strong>resummation of large logs</strong></td>
<td>?</td>
<td>feasible (when available)</td>
<td>unitarity implementation (i.e. correct shapes but not total rates)</td>
</tr>
</tbody>
</table>

M.L. Mangano KITP collider conf 2004
Parton showering and hadronisation are modelled through shower Monte Carlos (HERWIG or PYTHIA)
Including parton showers and hadronisation through HERWIG, Odagiri finds much less correlation between the jets.

Caveat!

the plot has been obtained by generating also the jets through the showers
Matrix-element MonteCarlo generators

multi-parton generation: processes with many jets (or W/Z/H bosons)

COMPHEP  A. Pukhov et al. 1999
GRACE/GR@PPA  T. Ishikawa et al.  K. Sato et al. 1992/2001
HELAC  C. Papadopoulos et al.  2000

processes with 6 final-state fermions

PHASE  E. Accomando A. Ballestrero E. Maina 2004

merged with parton showers

all of the above, merged with HERWIG or PYTHIA

SHERPA  F. Krauss et al. 2003
Azimuthal angle distribution

**ALPGEN:** $H + 2$ jets at parton level + parton shower by HERWIG

**VBF cuts**

- $p_T^{tag} > 30 \text{ GeV}$
- $|\eta_j| < 5$
- $R_{jj} > 0.6$
- $|\eta_{j1} - \eta_{j2}| < 4.2$
- $\eta_{j1} \cdot \eta_{j2} < 0$
- $m_{jj} > 600 \text{ GeV}$

$A_\phi$: a quantity that characterises how deep the dip is

<table>
<thead>
<tr>
<th>$A_\phi$</th>
<th>parton level</th>
<th>shower level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH + 2$ jets</td>
<td>0.474(3)</td>
<td>0.357(3)</td>
</tr>
<tr>
<td>$VBF + 2$ jets</td>
<td>0.017(1)</td>
<td>0.018(1)</td>
</tr>
</tbody>
</table>

$$A_\phi = \frac{\sigma(\Delta\phi < \pi/4) - \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}{\sigma(\Delta\phi < \pi/4) + \sigma(\pi/4 < \Delta\phi < 3\pi/4) + \sigma(\Delta\phi > 3\pi/4)}$$

$\Delta\Phi$ is the azimuthal angle between the tagging jets
Normalised jet multiplicity after parton shower for H + 2 (solid) and 3 (dashes) partons. Solid curve is normalised to the total x-sect for H + 2 jets. Note the log scale on the rhs panel.

**VBF cuts**

\[ p_{Tj}^{\text{tag}} > 30 \text{ GeV} \quad p_{Tj} > 20 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} > 0.6 \]

\[ |\eta_{j1} - \eta_{j2}| < 4.2 \quad \eta_{j1} \cdot \eta_{j2} < 0 \quad m_{jj} > 600 \text{ GeV} \]
the azimuthal angle $\Delta \phi_{jj}$ between the jets can be used as a tool to investigate the tensor structure of the WWH coupling.

Plehn, Rainwater, Zeppenfeld hep-ph/0105325

take a gauge-invariant effective Lagrangian with dim. 6 operators (CP even and CP odd) describing an anomalous WWH coupling

$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_{e,6}^2} (\Phi^\dagger \Phi) V_{\mu\nu} V^{\mu\nu} + \frac{g^2}{2\Lambda_{o,6}^2} (\Phi^\dagger \Phi) \tilde{V}_{\mu\nu} V^{\mu\nu}$$

expand $\Phi$ about the vev (get dim. 5 (D5) operators)

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H W^+_{\mu\nu} W^{-\mu\nu} + \frac{1}{\Lambda_{o,5}} H \tilde{W}^+_{\mu\nu} W^{-\mu\nu} \quad \text{with} \quad \frac{1}{\Lambda_5} = \frac{g^2 v}{\Lambda_6^2}$$

CP odd D5 operator: $\epsilon^{\mu\nu\alpha\beta}$ tensor in the coupling

zero at $\Delta \phi_{jj} = 0, \pi$

CP even D5 operator is like the effective $ggH$ coupling

$$\mathcal{A}_\text{CP even} \sim \frac{1}{\Lambda_{e,5}} J_1^\mu (q_1^\nu q_2^\mu - g^{\mu\nu} q_1 \cdot q_2) J_2^\nu \quad \Rightarrow \quad \text{zero at } \Delta \phi_{jj} = \frac{\pi}{2}$$
AZIMUTHAL ANGLE DISTRIBUTION FOR WWH COUPLINGS

- assume a Higgs-like scalar signal is found at LHC at the SM rate (for D5 operators: $\Lambda_5 \sim 500$ GeV)

![Azimuthal Angle Distribution for WWH Couplings](image_url)

- the $\Delta\phi_{jj}$ distribution
  - discriminates between different WWH couplings
  - is independent of the particular decay channel and the Higgs mass range

WBF cuts:
- $p_{j\perp} > 20$ GeV
- $|\eta_j| < 5$
- $R_{jj} > 0.6$
- $\eta_{j1} \cdot \eta_{j2} < 0$
- $|\eta_{j1} - \eta_{j2}| > 4.2$
**Interference effects in the $\Delta \phi_{jj}$ distribution**

- assume a Higgs candidate is found at LHC with a predominantly SM $g^{\mu\nu}$ coupling. How sensitive are experiments to any D5 terms?
- no interference between SM and CP odd D5 operator

\[\frac{d\sigma}{d\Delta \phi_{jj}} (H \rightarrow \tau\tau) \text{ [fb]}\]
\[m_H = 120 \text{ GeV}\]

$\Delta \phi_{jj}$ distribution for the SM and interference with a CP even D5 coupling. The two curves for each sign of the operator correspond to values $\sigma/\sigma_{SM} = 0.04, 1.0$. Error bars correspond to an integrated luminosity of 100 fb$^{-1}$ per experiment, distributed over 6 bins, and are statistical only.

- interference between SM and CP even D5 operator: $|A|^2 = |A_{SM} + A_{e,5}|^2$
  - all terms, but $|A_{SM}|^2$, have an approximate zero at $\Delta \phi_{jj} = \pi/2$
  - systematic uncertainty induced by $H + 2$ jet rate from gluon fusion
  - $HG_{\mu\nu}G^{\mu\nu}$ is a CP even D5 operator
In WBF no colour is exchanged in the $t$ channel.

The central-jet veto is based on the different radiation pattern expected for WBF versus its major backgrounds, i.e. $tt$ production and $WW + 2\ jet$ production. (Barger, Phillips & Zeppenfeld hep-ph/9412276)

The central-jet veto can also be used to distinguish between Higgs production via gluon fusion and via WBF.
Distribution in **rapidity** of the **third jet** wrt to the rapidity average of the tagging jets

**Ratio of Higgs + 3 jet to Higgs + 2 jet production as a function of \( p_T^{\min} \)**

Frizzo, Maltoni, VDD  hep-ph/0404013
Once a Higgs-like resonance is found at the LHC, we shall want to study its couplings and quantum numbers.

In Higgs + 2 jets, the azimuthal angle correlation between the two jets can be used as a tool to distinguish between WBF and gluon fusion, and to investigate the tensor structure of the WWH coupling.

Because of the characteristic final-state topology induced by WBF production large-rapidity cuts can be used to deplete gluon fusion wrt WBF.

We examined Higgs + 2 jet-production through matrix-element MC's, which include shower effects. The analysis confirms the one at the parton level, however, in gluon fusion large fraction of events with 3 or more jets need a CKKW-type analysis, need NLO overall normalisation. → MC@NLO