HJJ PRODUCTION: SIGNALS AND CP MEASUREMENTS

Dieter Zeppenfeld
Universität Karlsruhe, Germany

Rencontres de Moriond: QCD and Hadronic interactions
La Thuile, March 17 - 24, 2007

- Hjj and Ajj production
- $H \rightarrow WW$ study
- Probing CP properties
- Summary
Total cross sections at the LHC

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

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

NLO / NNLO

- \( gg \rightarrow H \) (NNLO)
- \( q\bar{q} \rightarrow HW \)
- \( qq \rightarrow Hqq \)
- \( gg/\bar{q}\bar{q} \rightarrow t\bar{t}H \) (NLO)
- \( q\bar{q} \rightarrow HZ \)

\[ M_H \text{ [GeV]} \]

[Krämer ('02)]
How to distinguish VBF and gluon fusion?

Double real corrections to $gg \rightarrow H$ can “fake” VBF

⇒ we need to investigate the phenomenology of these two processes and understand the differences that can be exploited to distinguish between gluon fusion and VBF

⇒ derive cuts to be applied to enhance VBF with respect to gluon fusion.
  Measure $H_{WW}$ and $H_{ZZ}$ coupling

⇒ derive cuts to be applied to enhance gluon fusion with respect to VBF.
  Measure effective $H_{gg}$ coupling or $H_{tt}$ coupling
Characteristics:

- energetic jets in the **forward** and **backward** directions ($p_T > 20$ GeV)
- large **rapidity separation** and large **invariant mass** of the two tagging jets
- **Higgs decay products** between tagging jets
- Little gluon radiation in the central-rapidity region, due to **colorless** $W/Z$ exchange
  (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)
Diagrams for gg fusion with finite $m_t, m_b$ effects

\[ qQ \rightarrow qQ H/A \quad qg \rightarrow qg H/A \quad gg \rightarrow gg H/A \]

plus crossed processes. [DelDuca, Kilgore, Oleari, Schmidt, DZ (2001); Kubocz, DZ (2006)]
Gluon Fusion as a signal channel

Heavy quark loop induces effective $Hgg$ vertex:

\[ \text{CP – even : } i \frac{m_Q}{v} \rightarrow \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{\mu\nu,a} \]

\[ \text{CP – odd : } - \frac{m_Q}{v} \gamma_5 \rightarrow \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi v} A G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} = \frac{\alpha_s}{16\pi v} A G^a_{\mu\nu} G^a_{\alpha\beta} \varepsilon^{\mu\nu\alpha\beta} \]

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced $\Phi jj$ signal to probe structure of $Hgg$ vertex
- Measure size of coupling (requires NLO corrections for precision)
- Find cuts to enhance gluon fusion over VBF and other backgrounds

Study by Gunnar Klämke in $m_Q \rightarrow \infty$ limit
Gluon fusion signal and backgrounds

Signal channel (LO):
- \( pp \to Hjj \) in gluon fusion with \( H \to W^+W^- \to l^+l^-\nu\bar{\nu}, (l = e, \mu) \)
- \( m_H = 160 \text{ GeV} \)

dominant backgrounds:
- \( W^+W^- \)-production via VBF (including Higgs-channel): \( pp \to W^+W^-jj \)
- top-pair production: \( pp \to t\bar{t}, t\bar{t}j, t\bar{t}jj \) (N. Kauer)
- QCD induced \( W^+W^- \)-production: \( pp \to W^+W^-jj \)

applied inclusive cuts (minimal cuts):
- 2 tagging-jets
  \[ p_{Tj} > 30 \text{ GeV}, \quad |\eta_j| < 4.5 \]
- 2 identified leptons
  \[ p_{Tl} > 10 \text{ GeV}, \quad |\eta_l| < 2.5 \]
- separation of jets and leptons
  \[ \Delta\eta_{jj} > 1.0, \quad R_{jl} > 0.7 \]

<table>
<thead>
<tr>
<th>process</th>
<th>( \sigma ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF ( pp \to H + jj )</td>
<td>115.2</td>
</tr>
<tr>
<td>VBF ( pp \to W^+W^- + jj )</td>
<td>75.2</td>
</tr>
<tr>
<td>( pp \to t\bar{t} )</td>
<td>6832</td>
</tr>
<tr>
<td>( pp \to t\bar{t} + j )</td>
<td>9518</td>
</tr>
<tr>
<td>( pp \to t\bar{t} + jj )</td>
<td>1676</td>
</tr>
<tr>
<td>QCD ( pp \to W^+W^- + jj )</td>
<td>363</td>
</tr>
</tbody>
</table>
Characteristic distributions

Separation of VBF $Hjj$ signal from QCD background is much easier than separation of gluon fusion $Hjj$ signal

- **tagging jet rapidity separation**
- **dijet invariant mass**
• **b-jet veto** for reduction of top-backgrounds.  
  - \((\eta, p_T)\) - dependent tagging-efficiencies (60\% - 75\%) with 10\% mistagging - probability

• **selection cuts:**
  \[ p_{Tl} > 30 \text{ GeV}, \quad M_{ll} < 75 \text{ GeV}, \quad M_{ll} < 0.44 \cdot M_{WW}^{T}, \quad R_{ll} < 1.1, \]
  \[ M_{WW}^{T} < 170 \text{ GeV}, \quad p_{T} > 30 \text{ GeV} \]

\[ M_{WW}^{T} = \sqrt{(E_{T} + E_{Tll})^{2} - (\vec{p}_{Tll} + \vec{p}_{T})^{2}} \]

- **signal**
- **VBF**
- **tt+Jets**
- **QCD-WW**
Characteristic distributions: contn’d

Distributions for the Higgs decay products provide for best handle on background suppression. They do not distinguish between VBF $Hjj$ signal and gluon fusion $Hjj$ signal.

$m_{ll}$ to transverse mass ratio

minimal lepton $p_T$ after $m_{ll}$ and $R_{ll}$ cut
### Results

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$ [fb]</th>
<th>events/ 30 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF $pp \rightarrow H + jj$</td>
<td>31.5</td>
<td>944</td>
</tr>
<tr>
<td>VBF $pp \rightarrow W^+W^- + jj$</td>
<td>16.5</td>
<td>495</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}$</td>
<td>23.3</td>
<td>699</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + j$</td>
<td>51.1</td>
<td>1533</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + jj$</td>
<td>11.2</td>
<td>336</td>
</tr>
<tr>
<td>QCD $pp \rightarrow W^+W^- + jj$</td>
<td>11.4</td>
<td>342</td>
</tr>
<tr>
<td>$\Sigma$ backgrounds</td>
<td>113.5</td>
<td>3405</td>
</tr>
</tbody>
</table>

$\Rightarrow S/\sqrt{B} \approx 16.2$ for 30 fb$^{-1}$
Tensor structure of the $HVV$ coupling

Most general $HVV$ vertex $T_{\mu\nu}(q_1, q_2)$

Physical interpretation of terms:

- **SM Higgs** \( \mathcal{L}_I \sim HV_\mu V^\mu \rightarrow a_1 \)
  - loop induced couplings for neutral scalar
- **CP even** \( \mathcal{L}_{\text{eff}} \sim HV_{\mu\nu} V^{\mu\nu} \rightarrow a_2 \)
- **CP odd** \( \mathcal{L}_{\text{eff}} \sim HV_{\mu\nu} \tilde{V}^{\mu\nu} \rightarrow a_3 \)

Must distinguish $a_1, a_2, a_3$ experimentally

The $a_i = a_i(q_1, q_2)$ are scalar form factors
Azimuthal angle distribution and Higgs CP properties

Kinematics of $Hjj$ event:

Define azimuthal angle between jet momenta $j_+$ and $j_-$ via

$$\epsilon_{\mu\nu\rho\sigma} b_+^\mu j_+^\nu b_-^\rho j_-^\sigma = 2p_{T,+} p_{T,-} \sin(\phi_+ - \phi_-) = 2p_{T,+} p_{T,-} \sin\Delta\phi_{jj}$$

- $\Delta\phi_{jj}$ is a parity odd observable
- $\Delta\phi_{jj}$ is invariant under interchange of beam directions $(b_+, j_+) \leftrightarrow (b_-, j_-)$

Work with Vera Hankele, Gunnar Klämke and Terrance Figy: hep-ph/0609075
Position of minimum of $\Delta \phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

$$a_1 = 0, \quad a_2 = d \sin \alpha, \quad a_3 = d \cos \alpha,$$

$\implies$ Minimum at $-\alpha$ and $\pi - \alpha$

mixed CP case: $a_2 = a_3, a_1 = 0$

pure CP-even case: $a_2$ only

pure CP odd case: $a_3$ only
Gluon fusion: structure of $H_{gg}$ vertex

Sensitivity of the $\Delta \phi_{jj}$ distribution to the structure of the effective $H_{gg}$ coupling increases with the rapidity separation of the two tagging jets.

**CP-even coupling**

**CP-odd coupling**
Fit to $\Phi_{jj}$-distribution with function $f(\Delta \Phi) = N(1 + A \cos[2(\Delta \Phi - \Delta \Phi_{max})] - B \cos(\Delta \Phi))$

**CP-even**
- $A = 0.100 \pm 0.039$
- $\Delta \Phi_{max} = 5.8 \pm 15.3$

**CP-odd**
- $A = 0.199 \pm 0.034$
- $\Delta \Phi_{max} = 93.7 \pm 5.1$

fit of the background only: $A = 0.069 \pm 0.044$ and $\Delta \Phi_{max} = 64 \pm 25$

(mean values of 10 independent fits of data for $L = 30 \text{fb}^{-1}$ each)
$\Delta \Phi_{jj}$-Distribution: CP violating case

CP-mixture: equal CP-even and CP-odd contributions

$A = 0.153 \pm 0.037$

$\Delta \Phi_{\text{max}} = 45.6 \pm 7.3$
Conclusions

• Hjj events at LHC provide valuable information on Higgs couplings

• Separation of gluon fusion from vector boson fusion is possible with rapidity gap and central jet veto techniques. Gluon fusion behaves largely like QCD backgrounds.

• Higgs boson CP properties and structure of the $\text{HVV}$ and $\text{Hgg}$ vertices can be obtained from jet-angular correlations in VBF and gluon fusion

• For a Higgs mass around 160 GeV and SM-like coupling the CP structure of the effective $\text{Hgg}$ vertex (and thereby the $\text{Htt}$ coupling) is accessible at LHC via $H \rightarrow \text{WW}$ with about $30 \text{ fb}^{-1}$

• Results are based on parton level study. Full detector simulations needed.