Higgs + 2 Jet Production at the LHC

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- LHC goals
- Vector boson fusion
- Measurement of Higgs couplings
- Hjj production via gluon fusion
- $H \rightarrow WW$ study
- $H \rightarrow \tau \tau$ study
- Probing CP properties
- Summary
Goals of Higgs Physics

Higgs Search = search for dynamics of \( SU(2) \times U(1) \) breaking

- Discover the Higgs boson
- Measure its couplings and probe mass generation for gauge bosons and fermions

Fermion masses arise from Yukawa couplings via

\[
\Phi^\dagger \to (0, \frac{v + H}{\sqrt{2}})
\]

\[
\mathcal{L}_{\text{Yukawa}} = -\Gamma_{d}^{ij} \bar{Q}_{L}^{i} \Phi_{d}^{j} - \Gamma_{d}^{ij\ast} \bar{d}_{R}^{i} \Phi^\dagger Q_{L}^{j} + \ldots = -\Gamma_{d}^{ij} \frac{v + H}{\sqrt{2}} \bar{d}_{L}^{i} d_{R}^{j} + \ldots
\]

\[
= -\sum_{f} m_{f} \bar{f} f \left(1 + \frac{H}{v}\right)
\]

- Test SM prediction: \( \bar{f} f H \) Higgs coupling strength = \( m_{f} / v \)
- Observation of \( Hf\bar{f} \) Yukawa coupling is no proof that v.e.v exists
Higgs coupling to gauge bosons

Kinetic energy term of Higgs doublet field:

\[(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2} \partial^\mu H \partial_\mu H + \left[ \left( \frac{g v}{2} \right)^2 W^\mu W^-_\mu + \frac{1}{2} \frac{(g^2 + g'^2)v^2}{4} Z^\mu Z_\mu \right] \left( 1 + \frac{H}{v} \right)^2 \]

- $W, Z$ mass generation: $m_W^2 = \left( \frac{g v}{2} \right)^2, m_Z^2 = \frac{(g^2 + g'^2)v^2}{4}$

- $WWH$ and $ZZH$ couplings are generated

- Higgs couples proportional to mass: coupling strength $= 2 m^2\nu / v \sim g^2v$ within SM

Measurement of $WWH$ and $ZZH$ couplings is essential for identification of $H$ as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level
Verify tensor structure of $HVV$ couplings. Loop induced couplings lead to $HV_{\mu\nu} V^{\mu\nu}$ effective coupling and different tensor structure: 

$$g_{\mu\nu} \rightarrow q_1 \cdot q_2 g_{\mu\nu} - q_1 \nu q_2 \mu$$
Total cross sections at the LHC

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

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

NLO / NNLO

[Krämer ('02)]
Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times \text{BR}$, of order 10% (sometimes even better).
VBF signature

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 between tagging jets)
Example: Parton level analysis of $H \to WW$

Near threshold: $W$ and $W^*$ almost at rest in Higgs rest frame $\implies$ use $m_{ll} \approx m_{\nu\nu}$ for improved transverse mass calculation:

$$E_{T,ll} = \sqrt{p_{T,ll}^2 + m_{ll}^2}$$

$$E_T = \sqrt{\not{p}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{p}_T^2 + m_{ll}^2}$$

$$M_T = \sqrt{(E_T + E_{T,ll})^2 - (\not{p}_{T,ll} + \not{p}_T)^2}$$

Observe Jacobian peak below $M_T = m_H$

Transverse mass distribution for $m_H = 115$ GeV and $H \to WW^* \to e^\pm \mu^\mp \not{p}_T$
in collinear approximation, the decay lepton has the same direction as the $\tau$, i.e. $p_{\ell,i}^\mu = x_i \cdot p_{\tau,i}^\mu$

$\Rightarrow$ the energy fractions $x_1$, $x_2$ of the decay leptons can be reconstructed by solving the equation:

$$\vec{p}_T = \left(\frac{1}{x_1} - 1\right) \vec{p}_{1,T} + \left(\frac{1}{x_2} - 1\right) \vec{p}_{2,T}$$

the invariant tau pair mass is then given by

$$m_{\tau\tau}^2 = \frac{2 p_{\ell,1} \cdot p_{\ell,2}}{x_1 x_2} = \frac{m_{\ell\ell}^2}{x_1 x_2}$$
Weak Boson Fusion: $H \rightarrow \tau \tau$

Mass can be reconstructed in collinear approximation

$x^{\tau} = \text{momentum fraction carried by tau decay products}$

$\sigma_M = \text{11 to 12 GeV}$

$\star \text{significance} > 5 \text{ for } 30 \text{ fb}^{-1}$ and $M_H = 110 \text{ to } 140 \text{ GeV (} \tau \tau \rightarrow e\mu, \tau \tau \rightarrow l l, \tau \tau \rightarrow l \text{ had)}}$

$\star \text{background estimate: } \sim 10\%$

for $M_H > 125 \text{ GeV}$ from side bands

for $M_H > 125 \text{ GeV}$ from normalisation of $Z \rightarrow \tau \tau$ peak
$\int L \, dt = 30 \text{ fb}^{-1}$
(no K-factors)

**ATLAS**

$\begin{align*}
&\text{Signal significance} \\
&\frac{S}{\sqrt{B}}
\end{align*}$

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

**Total significance**
Assumed errors in fits to couplings:

- **QCD/PDF uncertainties**
  - $\pm 5\%$ for VBF
  - $\pm 20\%$ for gluon fusion

- **Luminosity/acceptance uncertainties**
  - $\pm 5\%$
LHC rates for partonic process \( pp \rightarrow H \rightarrow xx \) given by \( \sigma(pp \rightarrow H) \cdot BR(H \rightarrow xx) \)

\[
\sigma(H) \times BR(H \rightarrow xx) = \frac{\sigma(H)^{SM}}{\Gamma_p^{SM}} \times \frac{\Gamma_p \Gamma_x}{\Gamma},
\]

Measure products \( \Gamma_p \Gamma_x / \Gamma \) for combination of processes (\( \Gamma_p = \Gamma(H \rightarrow pp) \))

**Problem:** rescaling fit results by common factor \( f \)

\[
\Gamma_i \rightarrow f \cdot \Gamma_i, \quad \Gamma \rightarrow f^2 \Gamma = \sum_{obs} f \Gamma_i + \Gamma_{rest}
\]

leaves observable rate invariant \( \implies \) no model independent results at LHC

Loose bounds on scaling factor:

\[
f^2 \Gamma > \sum_{obs} f \Gamma_x \quad \implies \quad f > \sum_{obs} \frac{\Gamma_x}{\Gamma} = \sum_{obs} BR(H \rightarrow xx)(= \mathcal{O}(1))
\]

Total width below experimental resolution of Higgs mass peak (\( \Delta m = 1 \ldots 20 \text{ GeV} \))

\[
f^2 \Gamma < \Delta m \quad \implies \quad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10 - 40)
\]
Fit LHC data within constrained models

- $\frac{g_{H\tau\tau}}{g_{Hbb}} = \text{SM value}$
- $\frac{g_{HWW}}{g_{HZZ}} = \text{SM value}$
- no exotic channels

With 200 fb$^{-1}$ measure partial width with 10–30% errors, couplings with 5–15% errors
Distinguishing the MSSM Higgs sector from the SM

Alternative: compare data to predictions of specific models
Example: \(m_H^{\text{max}}\) scenario of LEP analyses

Consider modest \(m_A\):

- decoupling almost complete for \(hWW\) and \(h\gamma\gamma\) (effective) vertices
- enhanced \(hbb\) and \(h\tau\tau\) couplings compared to SM increases total width of \(h\)

\[\Rightarrow\]

- \(\approx\) SM rates for \(h\to\tau\tau\) in VBF
- suppressed \(h\to\gamma\gamma\) and \(h\to WW\) rates in VBF

3σ-effects or more at small \(m_A\)
How to distinguish VBF and gluon fusion?

Double real corrections to $gg \to H$ 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 $HWW$ and $HZZ$ coupling

- derive cuts to be applied to enhance gluon fusion with respect to VBF.
  - Measure effective $Hgg$ coupling or $Htt$ coupling

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Diagrams for gg fusion with finite $m_t$ effects

\[ q Q \rightarrow q Q H \quad q g \rightarrow q g H \quad g g \rightarrow g g H \]

plus crossed processes. In total 61 independent diagrams. [DelDuca, Kilgore, Oleari, Schmidt, DZ (2001)]
Applied cuts for LHC predictions

The cross section diverges in **collinear** and **soft** regions

- **INCLUSIVE cuts** to define $H + 2$ jets

  \[ p_{Tj} > 20 \text{ GeV} \quad |\eta_j| < 5 \quad R_{jj} = \sqrt{(\eta_{j_1} - \eta_{j_2})^2 + (\phi_{j_1} - \phi_{j_2})^2} > 0.6 \]

- **VBF cuts** to enhance VBF over gluon fusion

  In addition to the previous ones, we impose

  \[ |\eta_{j_1} - \eta_{j_2}| > 4.2 \quad \eta_{j_1} \cdot \eta_{j_2} < 0 \quad m_{jj} > 600 \text{ GeV} \]

  - the two tagging jets must be well separated in rapidity
  - they must reside in opposite detector hemispheres
  - they must possess a large dijet invariant mass.

LHC cross sections below calculated with CTEQ6L1 pdfs and fixed $\alpha_s = 0.12$

Expect factor $\approx 1.5$ to $2$ scale uncertainty due to $\sigma \sim \alpha_s^4$
Total cross section with cuts as function of $m_H$

**INCLUSIVE cuts**

- solid $m_t=175$ GeV
- dots $m_t \to \infty$
- dashes WBF

**WBF cuts**

- solid $m_t=175$ GeV
- dots $m_t \to \infty$
- dashes WBF

Large top mass limit ok for total cross section provided $m_H \lesssim m_t$
Transverse momentum: Large top mass limit ok provided $p_{T,j} \lesssim m_t$
Dijet invariant mass: Large top mass limit ok throughout
New calculation: pseudoscalar Higgs production

$pp \rightarrow AjjX$ including top and bottom loops + interference [Michael Kubocz, diploma thesis]
New elements in the calculation

- \( AQQ \) vertices given by \( -\frac{m_b}{\nu} \gamma_5 \tan \beta \) and \( -\frac{m_t}{\nu} \gamma_5 \frac{1}{\tan \beta} \)
- Interference of top and bottom loops
- Can simulate CP violation in the Higgs sector: \( a + ib \gamma_5 \) coupling to top and bottom

**Inclusive cuts**

- \( m_t = 175 \) GeV
- \( m_b \tan \beta = 4.4 \) GeV

**VBF cuts**

- \( m_t = 175 \) GeV
- \( m_b \tan \beta = 4.4 \) GeV

\( \sigma \) vs \( m_A \) [GeV]
Gluon Fusion as a signal channel

Heavy quark loop induces effective $Hgg$ vertex:

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

- **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 (hep-ph/0703202)
Gluon fusion signal and backgrounds

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

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

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
  \[ \Delta \eta_{jj} > 1.0, \quad R_{jl} > 0.7 \]

\begin{tabular}{|c|c|}
\hline
process & \( \sigma \) [fb] \\
\hline
GF \( pp \rightarrow H + jj \) & 115.2 \\
VBF \( pp \rightarrow W^+W^- + jj \) & 75.2 \\
\quad \( pp \rightarrow t\bar{t} \) & 6832 \\
\quad \( pp \rightarrow t\bar{t} + j \) & 9518 \\
\quad \( pp \rightarrow t\bar{t} + jj \) & 1676 \\
QCD \( pp \rightarrow W^+W^- + jj \) & 363 \\
\hline
\end{tabular}
Separation of VBF $Hjj$ signal from QCD background is much easier than separation of gluon fusion $Hjj$ signal.
• **b-tagging** for reduction of top-backgrounds.  
  - \((\eta, p_T)\) - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

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

  \[ M_{TWW} = \sqrt{(E_T + E_{Tll})^2 - (\vec{p}_{Tll} + \vec{p}_T)^2} \]

![Graphs showing distributions of various observables for signal, VBF, tt+Jets, and QCD-WW](image_url)
## Results

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$ [fb]</th>
<th>events/ 30 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF $pp \to H + jj$</td>
<td>31.5</td>
<td>944</td>
</tr>
<tr>
<td>VBF $pp \to W^+W^- + jj$</td>
<td>16.5</td>
<td>495</td>
</tr>
<tr>
<td>$pp \to t\bar{t}$</td>
<td>23.3</td>
<td>699</td>
</tr>
<tr>
<td>$pp \to t\bar{t} + j$</td>
<td>51.1</td>
<td>1533</td>
</tr>
<tr>
<td>$pp \to t\bar{t} + jj$</td>
<td>11.2</td>
<td>336</td>
</tr>
<tr>
<td>QCD $pp \to W^+W^- + jj$</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$^{-1}$
Higgs + 2 Jets in Gluon Fusion, $H \rightarrow \tau \tau \rightarrow \ell^+ \ell^- \nu \bar{\nu}$

- this channel has not been studied so far
- interesting for SM Higgs ($\approx 120$ GeV) and SUSY scenario with large $\tan \beta$ ($m_H \approx m_A \gtrsim 150$ GeV)
- $\sigma \times BR$ of $\approx 50$ fb looks promising (SM)
- has potential for study of Higgs CP-properties

Studied so far (by Gunnar Klämke):
- Study of signal and SM backgrounds for $m_H = 120$ GeV case (simple cut based analysis)
- same for one MSSM scenario $m_A = 200$ GeV, $\tan \beta = 50$

Questions:
- How many signal and background events are there after cuts (what’s the statistical significance)
- What are the prospects of CP-measurements via jet-jet azimuthal angle correlation
The detector has a finite resolution. The measured jet energy and missing transverse energy have large uncertainties. Parameterization (from CMS NOTE 2006/035, CMS NOTE 2006/036):

**Jets:**

\[
\frac{\Delta E_j}{E_j} = \left( \frac{a}{E_{Tj}} \oplus \frac{b}{\sqrt{E_{Tj}}} \oplus c \right)
\]

<table>
<thead>
<tr>
<th>( \eta_j )</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_j &lt; 1.4 )</td>
<td>5.6</td>
<td>1.25</td>
<td>0.033</td>
</tr>
<tr>
<td>( 1.4 &lt; \eta_j &lt; 3 )</td>
<td>4.8</td>
<td>0.89</td>
<td>0.043</td>
</tr>
<tr>
<td>( \eta_j &gt; 3 )</td>
<td>3.8</td>
<td>0</td>
<td>0.085</td>
</tr>
</tbody>
</table>

**Leptons:**

\[
\frac{\Delta E_\ell}{E_\ell} = 2\%
\]

**Missing \( p_T \):**

\[
\Delta \not{p}_x = 0.46 \cdot \sqrt{\sum E_{Tj}}
\]
### SM Higgs with 120 GeV mass

**inclusive cuts**

\[ p_{T,\text{jets}} > 30 \text{ GeV}, \quad p_{T,\ell} > 10 \text{ GeV}, \quad |\eta_j| < 4.5, \quad |\eta_\ell| < 2.5, \quad \Delta\eta_{jj} > 1.0, \quad \Delta R_{j\ell} > 0.7, \]

**cross sections for inclusive cuts for signal and background**

<table>
<thead>
<tr>
<th>process</th>
<th>( \sigma ) [fb]</th>
<th>events / 600 fb(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF ( pp \rightarrow H + jj \rightarrow \tau\tau jj )</td>
<td>11.283</td>
<td>6770</td>
</tr>
<tr>
<td>GF ( pp \rightarrow A + jj \rightarrow \tau\tau jj )</td>
<td>25.00</td>
<td>15002</td>
</tr>
<tr>
<td>VBF ( pp \rightarrow H + jj \rightarrow \tau\tau jj )</td>
<td>5.527</td>
<td>3316</td>
</tr>
<tr>
<td>QCD ( pp \rightarrow Z + jj \rightarrow \tau\tau jj )</td>
<td>1652.8</td>
<td>991700</td>
</tr>
<tr>
<td>VBF ( pp \rightarrow Z + jj \rightarrow \tau\tau jj )</td>
<td>15.70</td>
<td>9418</td>
</tr>
<tr>
<td>( pp \rightarrow t\bar{t} )</td>
<td>6490</td>
<td>3893900</td>
</tr>
<tr>
<td>( pp \rightarrow t\bar{t} + j )</td>
<td>9268</td>
<td>5560890</td>
</tr>
<tr>
<td>( pp \rightarrow t\bar{t} + jj )</td>
<td>1629</td>
<td>977263</td>
</tr>
<tr>
<td>QCD ( pp \rightarrow W^+W^- + jj )</td>
<td>334.2</td>
<td>200540</td>
</tr>
<tr>
<td>VBF ( pp \rightarrow W^+W^- + jj )</td>
<td>24.78</td>
<td>14871</td>
</tr>
</tbody>
</table>
Distributions

dilepton invariant mass

reconstructed $\tau\tau$ invariant mass

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a b-veto was applied to reduce the top backgrounds.

\[ R_{\ell\ell} < 2.4, \quad \not{p}_T > 30 \text{ GeV}, \quad m_{\ell\ell} < 80 \text{ GeV}, \quad 110 \text{ GeV} < m_{\tau\tau} < 135 \text{ GeV}, \quad 0 < x_i < 1 \]

<table>
<thead>
<tr>
<th>process</th>
<th>$\sigma$ [fb]</th>
<th>events / 600 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF $pp \rightarrow H + jj \rightarrow \tau\tau jj$</td>
<td>4.927</td>
<td>2956</td>
</tr>
<tr>
<td>GF $pp \rightarrow A + jj \rightarrow \tau\tau jj$</td>
<td>11.43</td>
<td>6860</td>
</tr>
<tr>
<td>VBF $pp \rightarrow H + jj \rightarrow \tau\tau jj$</td>
<td>2.523</td>
<td>1514</td>
</tr>
<tr>
<td>QCD $pp \rightarrow Z + jj \rightarrow \tau\tau jj$</td>
<td>27.62</td>
<td>16573</td>
</tr>
<tr>
<td>VBF $pp \rightarrow Z + jj \rightarrow \tau\tau jj$</td>
<td>0.475</td>
<td>285</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}$</td>
<td>3.86</td>
<td>2316</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + j$</td>
<td>8.84</td>
<td>5306</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} + jj$</td>
<td>3.8</td>
<td>2283</td>
</tr>
<tr>
<td>QCD $pp \rightarrow W^+W^- + jj$</td>
<td>1.48</td>
<td>887</td>
</tr>
<tr>
<td>VBF $pp \rightarrow W^+W^- + jj$</td>
<td>0.147</td>
<td>88</td>
</tr>
<tr>
<td>$\Sigma$ backgrounds</td>
<td>48.84</td>
<td>29300</td>
</tr>
</tbody>
</table>

for cp-even higgs: \( S/\sqrt{B} \approx 17 \) (600 fb$^{-1}$) 
for cp-odd higgs: \( S/\sqrt{B} \approx 40 \) (600 fb$^{-1}$)

this corresponds to: \( S/\sqrt{B} \approx 5 \) (50 fb$^{-1}$) 
this corresponds to: \( S/\sqrt{B} \approx 5 \) (10 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}_{eff} \sim HV_{\mu\nu} V^{\mu\nu} \rightarrow a_2$

CP odd $ \mathcal{L}_{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
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets

Dip structure at $90^\circ$ (CP even) or $0/180^\circ$ (CP odd) only depends on tensor structure of $HVV$ vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.
Azimuthal angle distribution and Higgs CP properties

Kinematics of $Hjj$ event:

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

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

- $\Delta \phi_{jj}$ 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
Signals for CP violation in the Higgs Sector

Position of minimum of $\Delta \phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

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

$\Rightarrow$ 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
**ΔΦ_{jj}-Distribution in gluon fusion: WW case**

Fit to Φ_{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)

**Signal**
- VBF
- t\bar{t}+Jets
- QCD-WW

$L = 300 \text{ fb}^{-1}$

$(\Delta \eta_{jj} > 3.0)$
$\Delta \Phi_{jj}$-Distribution: CP violating case

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

$A = 0.153 \pm 0.037$

$\Delta \Phi_{max} = 45.6 \pm 7.3$
$H \rightarrow \tau \tau$ case: $\Delta \Phi_{jj}$-distribution with backgrounds

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

Fit of the background only: $-0.043 \pm 0.016$

$\Rightarrow$ significance for CP-even vs. CP-odd $\approx 8$

$A = 0.004 \pm 0.015$

$A = -0.161 \pm 0.014$

$L = 600 \text{ fb}^{-1}$

($\Delta \eta_{jj} > 3.0$)
Summary

- Higgs + 2 Jet events at the LHC provide very useful information on Higgs couplings
- Order 200 fb$^{-1}$ of LHC data allow to probe Higgs couplings at the 10% level
- Beside VBF, gluon fusion is a second copious source of $Φjj$ events at the LHC
- Full one-loop calculations are available for quark-loop induced $Hjj$ and $Ajj$ production, including CP-even CP-odd interference and finite quark mass effects
- For $m_H = 160$ GeV and dominant decay $H → WW$ the gluon fusion induced signal at the LHC is visible above backgrounds. $H → ττ$ is somewhat more challenging
- CP-violation in the Higgs sector is observable via the shape of the azimuthal angle distribution $dσ/dΔφ_{jj}$