HIGGS BOSON PHYSICS AT THE LHC

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Les Houches 2009, Physics at TeV Colliders

- Introduction
- Search channels at the LHC
- Higgs coupling measurements
- QCD and EW corrections
- Hjj events: VBF vs gluon fusion
- Higgs CP measurements
- Conclusions
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

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

$$L_{\text{Yukawa}} = -\Gamma_{d}^{ij} \bar{Q}_{L}^{i} d_{R}^{j} - \Gamma_{d}^{ij*} \bar{d}_{R}^{i} \Phi^{\dagger} Q_{L}^{j} + \ldots = -\Gamma_{d}^{ij} \frac{v + H}{\sqrt{2}} \bar{d}_{L}^{i} d_{R}^{j} + \ldots$$

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

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

Kinetic energy term of Higgs doublet field:

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

- $W, Z$ 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 $= 2 \frac{m_v^2}{v} \sim g^2 v$ 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
Feynman rules for SM Higgs couplings

Verify tensor structure of $HVV$ couplings. Loop induced couplings lead to $HV_{\mu\nu}V^{\mu\nu}$ effective coupling and different tensor structure:

$$g_{\mu\nu} \rightarrow q_1 \cdot q_2 g_{\mu\nu} - q_1 \nu q_2 \mu$$

Distinguish scalar from pseudoscalar Higgs couplings to fermions.
The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = \sigma_2 \Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.}$$
$$-\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}$$

Two complex Higgs doublet fields $\Phi_1$ and $\Phi_2$ receive mass and $v.e.v.s \; v_1, v_2$ from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

**Neutral sector:**
- 2 CP even Higgs bosons: $h$ and $H$
- 1 CP odd Higgs boson: $A$
- 1 Goldstone boson: $\chi_0$

**Charged sector:**
- charged Higgs bosons: $H^\pm$
- charged Goldstone boson: $\chi^\pm$

Goldstone bosons absorbed as longitudinal degrees of freedom of $Z, W^\pm$
Fermions

Two doublet fields mix, two v.e.v’s \( v_1 = v \cos \beta, \quad v_2 = v \sin \beta: \)

\[
\mathcal{L}_{\text{Yuk.}} = -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.} \\
= -\Gamma_b \bar{b}_L v_1 + H \cos \alpha - h \sin \alpha + iA \sin \beta \sqrt{2} b_R - \Gamma_t \bar{t}_L v_2 + H \sin \alpha + h \cos \alpha + iA \cos \beta \sqrt{2} t_R + \ldots
\]

Expressed in terms of masses the Yukawa Lagrangian is

\[
\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v} \bar{b} \left( v + \frac{H \cos \alpha}{\cos \beta} - h \frac{\sin \alpha}{\cos \beta} - i\gamma_5 A \tan \beta \right) b - \frac{m_t}{v} \bar{t} \left( v + \frac{H \sin \alpha}{\sin \beta} + h \frac{\cos \alpha}{\sin \beta} - i\gamma_5 A \cot \beta \right) t
\]

\( \Rightarrow \) coupling factors compared to SM \( hff \) coupling \( -i \frac{m_f}{v} \)

Gauge Bosons

extra coupling factors for \( hVV \) and \( HVV \) couplings as compared to SM

\[
hVV \sim \sin(\beta - \alpha) \quad \quad \quad HVV \sim \cos(\beta - \alpha)
\]
Total cross sections at the LHC

$\sigma(pp \rightarrow H + X)$ [pb]

$\sqrt{s} = 14$ TeV

NLO / NNLO

$gg \rightarrow H$ (NNLO)

$qq \rightarrow Hqq$

$gg/\bar{q}\bar{q} \rightarrow t\bar{t}H$ (NLO)

$qq \rightarrow HZ$

$M_H$ [GeV]

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$

$100$ $200$ $300$ $400$ $500$ $600$ $700$ $800$ $900$ $1000$

MRST

[Krämer ('02)]
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

![Graph showing SM Higgs decay width and branching ratios vs. Higgs mass](image-url)
Inclusive search channels

- inclusive search for
  \[ H \rightarrow \gamma\gamma \]
  invariant-mass peak, for \( m_H < 150 \text{ GeV} \)

- inclusive search for
  \[ H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^- \]
  for \( m_H \geq 130 \text{ GeV} \) and \( m_H \neq 2m_W \).

- inclusive search for
  \[ H \rightarrow W^+W^- \rightarrow \ell^+\bar{\nu}\ell^-\nu \]
  for \( 140 \text{ GeV} \leq m_H \leq 200 \text{ GeV} \)

Inclusive searches dominated by gluon fusion production
probe \( ttH \) coupling (or \( ggH \) effective vertex)
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)
Central jet veto

$tt'$ + jets background for $qq \rightarrow H, H \rightarrow WW^*$

$\nu \rightarrow b$-jets from $t \rightarrow bW$

$t$-channel color singlet exchange

"Synchrotron radiation between initial and final quark direction" central jets suppressed

$\Rightarrow$ central jets suppressed

$\Rightarrow$ central jets suppressed

Major QCD backgrounds: $t$-channel color octet exchange
deflection of color charge by $180^\circ$ by strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

central jet veto suppresses QCD backgrounds
to weak boson fusion
Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

- Angular distribution of third (softest) jet follows classically expected radiation pattern.
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events).
- Central jet veto can be used to distinguish Higgs production via GF from VBF.

[ Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]


- Scale variation at LO for $\sigma_{3j}$: $+33\%$ to $-17\%$ for $p_{T,veto} = 15$ GeV
- The uncertainty in $P_{veto}$ feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)
$Hjjj$ Cross Section within VBF cuts: NLO vs LO

$\mu_0 = 40$ GeV
$\xi = 2^{\pm 1}$ scale variations:
- LO: +26% to −19%
- NLO: less than 5%
Veto Probability for the VBF Signal

\[ P_{\text{veto}} = \frac{1}{\sigma_{NLO}^2} \int_{p_{T,veto}}^{\infty} dp_{T,j} \frac{d\sigma_3}{dp_{T,j}} \]

Scale variations, \( p_{T,veto} = 15 \text{ GeV} \):

- LO: +33\% to −17\%
- NLO: −1.4\% to −3.4\%

Reliable prediction for perturbative part of veto probability at NLO

Dieter Zeppenfeld  Gauge Boson Fusion  16
Higgs discovery potential

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

ATLAS

\[ \frac{S}{\sqrt{B}} \]

Signal significance

\[ m_H \text{ (GeV/c}^2) \]

\[ \text{Total significance} \]
Associated production search channels

- $pp \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$
  for $m_H < 120–130$ GeV

- $q\bar{q} \rightarrow WH, ZH$  
  trigger on leptonic decay of $W$ or $Z$, look for $H \rightarrow b\bar{b}$

New idea for $WH$ and $ZH$ associated production: concentrate on high $p_T(H) \gtrsim 200$ GeV:

- $\Rightarrow$ fat Higgs jet with $b\bar{b}(g)$ subjet structure
- small separation of $b$-quark jets from $H \rightarrow bb$ decay $\Rightarrow$ better $b\bar{b}(g)$ invariant mass resolution
- lower background fraction than at low $p_T(H)$
Example: $m_H = 120$ GeV, $\int Ldt = 30$ fb$^{-1}$

- Need excellent $b$ tagging and non-$b$ rejection efficiencies (assumed: 60% and 2% respectively)
- Search in
  (a) $HZ$ with $Z \rightarrow ll$
  (b) $HZ$ with $Z \rightarrow \nu\nu$ and
  (c) $WH \rightarrow \ell\nu b\bar{b}$ samples
- Promising signal with 30 fb$^{-1}$ when combining all 3 channels

Detailed studies with full detector simulation on the way
Measuring Higgs couplings at LHC

LHC rates for partonic process $pp \rightarrow H \rightarrow xx$ given by $\sigma(pp \rightarrow H) \cdot BR(H \rightarrow xx)$

$$\sigma(H) \times BR(H \rightarrow xx) = \frac{\sigma(H)^{\text{SM}}}{\Gamma_p^{\text{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma_x}$$

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

**Problem:** rescaling fit results by common factor $f$

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

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

Loose bounds on scaling factor:

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

Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 20$ 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
New analysis: Lafaye et al., arXiv:0904:3866

Correlations \( m_H = 120 \text{ GeV} \) and 300 fb\(^{-1}\)

- theoretical and experimental errors including correlations. Study relative errors

\[
g_{Hxx} = g_{Hxx}^{SM}(1 + \Delta_{Hxx})
\]

- sophisticated statistical analysis in SFitter framework

- Results for \( m_H = 120 \text{ GeV} \) and 30 fb\(^{-1}\)

<table>
<thead>
<tr>
<th></th>
<th>RMS</th>
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<th>(\sigma_{\text{neg}})</th>
<th>(\sigma_{\text{pos}})</th>
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<tbody>
<tr>
<td>(\Delta_{WWW})</td>
<td>± 0.31</td>
<td>± 0.23</td>
<td>− 0.21</td>
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<tr>
<td>(\Delta_{ZZH})</td>
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<td>± 0.36</td>
<td>− 0.40</td>
<td>+ 0.35</td>
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<td>(\Delta_{t\bar{t}H})</td>
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<td>(\Delta_{b\bar{b}H})</td>
<td>± 0.53</td>
<td>± 0.45</td>
<td>− 0.33</td>
<td>+ 0.56</td>
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<tr>
<td>(\Delta_{\tau\bar{\tau}H})</td>
<td>± 0.47</td>
<td>± 0.33</td>
<td>− 0.21</td>
<td>+ 0.46</td>
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</table>
Corrections for Higgs production cross sections

Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

⇒ need QCD corrections to production cross sections. Much progress in recent years

- $gg \rightarrow H$ (all but NLO in $m_t \rightarrow \infty$ limit)

- $Hjj$ by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2006)

- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - 1-loop EW corrections: Ciccolini, Denner, Dittmaier (2007)

- $\bar{t}tH$ associated production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)

- $\bar{b}bH$ associated production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)
Cross sections without and with VBF cuts: $p_T(j) > 20 \text{ GeV}$  
$|y_{j_1} - y_{j_2}| > 4$, $y_{j_1} \cdot y_{j_2} < 0$

Ciccolini, Denner, Dittmaier, arXiv:0710.4749
Statistical and systematic errors at LHC: snapshot from 2003 for expected SM Higgs rate

- Expected experimental errors on rates
  - $\pm 10 - 20\%$ is typical
  - Perhaps $\pm 5\%$ achievable for VBF if measurable at high lumi

- QCD/PDF uncertainties
  - $\pm 5\%$ for VBF
  - $\pm 10\%$ for gluon fusion

$\Delta \sigma_H/\sigma_H = \sqrt{(N_S+N_B)/N_S}$ for $200$ fb$^{-1}$ of data
How to distinguish VBF and gluon fusion?

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

$\implies$ 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

$\implies$ derive cuts to be applied to enhance VBF with respect to gluon fusion. Measure $HWW$ and $HZZ$ coupling

$\implies$ derive cuts to be applied to enhance gluon fusion with respect to VBF. Measure effective $Hgg$ coupling or $Htt$ coupling
Tensor structure of the $HVV$ coupling

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

$$T^{\mu\nu} = a_1 g^{\mu\nu} +$$
$$a_2 \left( q_1 \cdot q_2 g^{\mu\nu} - q_1^\gamma q_2^\mu \right) +$$
$$a_3 \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

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
Azimuthal angle correlations

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

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

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

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

$$\implies$$  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
From VBF to gluon fusion

- Loop induced $HVV$ couplings are almost certainly too small to give observable azimuthal angle modulation at the LHC in VBF. Interest for VBF is in experimentally confirming the structure of the tree level $HVV$ coupling as coming from $(D^\mu \Phi)^\dagger (D_\mu \Phi)$

- The $a_2$ and $a_3$ terms naturally arise for $\Phi gg$ couplings from top quark triangles and lead to effective Lagrangians

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

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

- Study gluon fusion induced $\Phi jj$ events to distinguish CP-even and CP-odd couplings

Effective Lagrangian and full top and bottom loops implemented in VBFNLO:
parton level Monte Carlo for $Hjj$, $Wjj$, $Zjj$, $W^+W^-jj$, $ZZjj$, $VVV$ production by Bozzi, Figy, Hankele, Jäger, Klämke, Kubocz, Oleari, Worek, DZ, ...

Available at http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/
Feynman graphs for (pseudo)scalar Higgs production

$p p \rightarrow \Phi jjX$ including top and bottom loops + interference
Gluon Fusion as a signal channel

Heavy quark loop induces effective $Hgg$ vertex:

- **CP – even**:\[ i \frac{m_Q}{v} \rightarrow \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi v} H G_{\mu\nu}^a G^{\mu\nu,a} \]
- **CP – odd**:\[ -m_Q \frac{\gamma_5}{v} \rightarrow \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi v} A G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} = \frac{\alpha_s}{16\pi v} A G_{\mu\nu}^a G_{\alpha\beta}^a \varepsilon^{\mu\nu\alpha\beta} \]

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced $\Phi jj$ signal to probe structure of $Hgg$ vertex
- 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 $H \rightarrow W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$, $(l = e, \mu)$
- $m_H = 160$ 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
  - $p_Tj > 30$ GeV, $|\eta_j| < 4.5$
- 2 identified leptons
  - $p_Tl > 10$ GeV, $|\eta_l| < 2.5$
- separation of jets and leptons
  - $\Delta\eta_{jj} > 1.0$, $R_{jl} > 0.7$

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

  (CMS Note 06/014)

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

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

**Graphs:**
- $1/\sigma \, d\sigma/\Delta R_{ll}$
- $1/\sigma \, d\sigma/dm_{WW}^T$
### Results

<table>
<thead>
<tr>
<th>process</th>
<th>(\sigma) [fb]</th>
<th>events/ 30 fb(^{-1})</th>
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<tr>
<td>GF (pp \to H + jj)</td>
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<td>VBF (pp \to W^+W^- + jj)</td>
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<tr>
<td>(pp \to t\bar{t})</td>
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<td>(pp \to t\bar{t} + j)</td>
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<td>QCD (pp \to W^+W^- + jj)</td>
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<tr>
<td>(\Sigma) backgrounds</td>
<td>113.5</td>
<td>3405</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \frac{S}{\sqrt{B}} \approx 16.2 \text{ for } 30 \text{ fb}^{-1} \]
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)
- $\sigma \times B$ 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
a b-veto was applied to reduce the top backgrounds.

\[ R_{\ell\ell} < 2.4, \quad p_T > 30 \text{ GeV}, \quad m_{\ell\ell} < 80 \text{ GeV}, \quad 110 \text{ GeV} < m_{\tau\tau} < 135 \text{ GeV}, \quad 0 < x_i < 1 \]

<table>
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<th>process</th>
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<th>events / 600 fb(^{-1} )</th>
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<td>GF ( pp \to H +jj \to \tau\tau jj )</td>
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</tr>
<tr>
<td>QCD ( pp \to W^+W^- + jj )</td>
<td>1.48</td>
<td>887</td>
</tr>
<tr>
<td>VBF ( pp \to 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: \( S/\sqrt{B} \approx 17 \ (600 \text{ fb}^{-1}) \)
this corresponds to: \( S/\sqrt{B} \approx 5 \ (50 \text{ fb}^{-1}) \)

for cp-odd higgs: \( S/\sqrt{B} \approx 40 \ (600 \text{ fb}^{-1}) \)
this corresponds to: \( S/\sqrt{B} \approx 5 \ (10 \text{ fb}^{-1}) \)
Sensitivity of gluon fusion to 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)
Fit to $\Phi_{jj}$-distribution with function $f(\Delta \Phi) = N(1 + A \cos[2(\Delta \Phi)] - B \cos(\Delta \Phi))$

CP-even

$A = 0.004 \pm 0.015$

CP-odd

$A = -0.161 \pm 0.014$

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

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

- LHC will observe a SM-like Higgs boson in multiple channels, with 5\ldots20\% statistical errors
  \[\Rightarrow\] great source of information on Higgs couplings

- Gauge boson fusion processes provide important facets of this information, both on absolute values of couplings but also on their tensor structure.

- Loop corrections on signal processes provide SM predictions with 10\% accuracy or better.

- Beside weak boson fusion also the gluon fusion process \( pp \rightarrow H jj \) is an interesting analysis channel which deserves more work.

- Higgs boson CP properties and structure of the \( HVV \) and \( Hgg \) vertices from jet-angular correlations in VBF and gluon fusion