Higgs production via vector-boson fusion

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Introduction – overview
Cross sections and significance of the Higgs signal at the LHC

(not only) Spira et al. '98

Higgs production via VBF ("qqH")
represents second largest cross section in entire \( M_H \) range
Significance of the Higgs signal at the LHC

Higgs production via VBF ("qqH") is cornerstone in Higgs search in entire $M_H$ range

$\rightarrow$ calculate / control higher orders to reduce theoretical uncertainty

down to the level of PDF ($\sim 3-4\%$) and experimental uncertainties ($\sim 5-10\%$)
Process topology of Higgs production via VBF

$$\begin{align*}
\text{colour exchange between quark lines suppressed} \\
\Rightarrow \text{small QCD corrections} \\
\leftrightarrow \text{“DIS-like approximation” (vertex corrections)}
\end{align*}$$

VBF cuts and background suppression:

- 2 hard “tagging” jets demanded:
  $$p_T^{j} > 20 \text{ GeV}, \quad |y_{j}| < 4.5$$
- tagging jets forward–backward directed:
  $$\Delta y_{jj} > 4, \quad y_{j1} \cdot y_{j2} < 0$$

$$\leftrightarrow \text{Suppression of background}$$
- from other (non-Higgs) processes, such as $t\bar{t}$ or WW production
  Zeppenfeld et al. ’94-’99
- induced by Higgs production via gluon fusion, such as $gg \rightarrow ggH$
  Del Duca et al. ’06; Campbell et al. ’06
WWH and ZZH coupling analyses

• Higgs via VBF plays important role in global Higgs couplings analysis
  Dührssen et al. '04

• azimuthal angle difference $\Delta \phi_{jj}$ of tagging jets is sensitive to BSM effects:
  Hankele, Klämke, Zeppenfeld, Figy '06
  Ruwiedel, Schumacher, Wermes '07

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi_{jj}} \]

(Individual contributions without SM; plot from Hankele et al.)

\[
\begin{align*}
\text{CP-even:} & \quad \mathcal{L} \propto H W^{+}_{\mu\nu} W^{-}, \mu\nu, \\
\text{CP-odd:} & \quad \mathcal{L} \propto H W^{+}_{\mu\nu} W^{-}, \mu\nu, \\
\Gamma^{H W^{+} W^{-}}_{\mu\nu} & \propto g_{\mu\nu} (k_{+} k_{-}) - k_{+}, \nu k_{-}, \mu \\
\Gamma^{H W^{+} W^{-}}_{\mu\nu} & \propto \epsilon_{\mu\nu\rho\sigma} k^{\rho}_{+} k^{\sigma}_{-}
\end{align*}
\]
Work on radiative corrections to the production of Higgs+2jets

• NLO QCD corrections to VBF in DIS-like approximation
  
  ◦ total cross section  Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  ◦ distributions Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
  ◦ matching with parton shower (POWHEG) Nason, Oleari ’09

• (full) NLO QCD+EW corrections to VBF  Ciccolini, Denner, S.D. ’07
  \[ \text{NLO QCD} \sim \text{NLO EW} \sim 5\text{–}10\% \]

• NNLO QCD corrections to VBF in DIS-like approximation  Bolzoni, Maltoni, Moch, Zaro ’10
  \[ \text{NNLO QCD} \sim 1\text{–}2\% \]

• NLO QCD corrections to \( gg \rightarrow Hgg \), etc.  Campbell, R.K.Ellis, Zanderighi ’06
  \[ \text{contribution to VBF} \sim 5\% \text{ Nikitenko, Vazquez ’07 (NLO scale uncertainty} \sim 35\% \]

• QCD loop-induced interferences between VBF and \( Hgg \)-initiated channels  Andersen, Binoth, Heinrich, Smillie ’07
  \[ \text{impact} \lesssim 10^{-3}\% \text{ (negligible!)} \text{ Bredenstein, Hagiwara, Jäger ’08} \]

• loop-induced VBF in \( gg \) scattering  Harlander, Vollinga, Weber ’08
  \[ \text{impact} \sim 0.1\% \]

• SUSY QCD+EW corrections  Hollik, Plehn, Rauch, Rzehak ’08
  \[ |\text{MSSM} - \text{SM}| \lesssim 1\% \text{ for SPS points (2–4\% for low SUSY scales)} \]
Work on related processes:

- NLO QCD corrections to \( H + 3\text{jets} \) via VBF  
  Figy, Hankele, Zeppenfeld '07

- NLO QCD corrections to \( HH \) production via VBF  
  Figy '08

- NLO QCD corrections to \( H + \gamma \) production via VBF  
  Arnold, Figy, Jäger, Zeppenfeld '10
LHC-Higgs cross section group → mandate for theory update
Available tools

- **VV2H** Spira
  NLO QCD for inclusive cross section

- **VBF@NNLO** Bolzoni, Maltoni, Moch, Zaro
  NNLO QCD for inclusive cross section

- **PHANTOM** Ballestrero et al.
  LO MC with PS for VBF → H → WW/ZZ → 4f

- **VBFNLO** Zeppenfeld et al.
  MC with NLO QCD corrections, including Higgs decays

- **HAWK** Denner, S.D., Mück
  MC with NLO QCD and EW corrections, including s-channel

- **POWHEG** Frixione, Nason, Oleari, Ridolfi
  MC with matching of NLO QCD with PS
NLO QCD and EW corrections to VBF
Higgs production via VBF in LO

- $\sigma_{LO} \propto \alpha^3$, no $\alpha_s$ dependence
  - no $\mu_{ren}$ dependence, scale dependence not a good measure of uncertainties
- many subcontributions from $qq$, $q\bar{q}$, and $\bar{q}q$ channels
- each channel receives contributions from one or two topologies ("$t$, $u$, $s$"):

- $s$-channel involves $W/Z$ resonances

Size of specific contributions:

<table>
<thead>
<tr>
<th>$M_H$ [GeV]</th>
<th>no cuts</th>
<th>VBF cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>120−200</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>$\Delta_{s-channel}$ [%]</td>
<td>30−10</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta_{t/u-interference}$ [%]</td>
<td>&lt; 0.5</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$\Delta_{b-quarks}$ [%]</td>
<td>$\approx$ 4</td>
<td>1</td>
</tr>
</tbody>
</table>
Higgs production via VBF in NLO:

- **partonic channels**
  - one-loop diagrams: $qq, q\bar{q}, \bar{q}q$
  - real QCD corrections $qq, q\bar{q}, \bar{q}q$ (gluon emission), $qg, \bar{q}g$ (gluon induced)
  - real QED corrections $qq, q\bar{q}, \bar{q}q$ (photon emission), $q\gamma, \bar{q}\gamma$ (photon induced)

- **collinear initial-state singularities**
  $\rightarrow$ factorization and PDF redefinition for QCD and QED singularities

  **Note:**
  $\text{MRSTqed2004} = \text{the only PDF set including } O(\alpha) \text{ effects}$
  but: $O(\alpha)$ effects in PDFs $\lesssim 1\%$
  $\rightarrow$ better use up-to-date PDFs without $O(\alpha)$ effects than miss PDF updates

- **$W/Z$ resonances in $s$-channel**
  $\rightarrow$ respect gauge invariance when introducing $W/Z$ decay widths!

  **Possible solution:** “complex-mass scheme” Denner, S.D., Roth, Wieders ’05
  - i.e. consistent use of complex $W/Z$ masses
  - and complex weak mixing angle

- **EW input parameter scheme**
  define $\alpha$ in $G_\mu$ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2) / \pi$
  $\rightarrow$ absorbs running of $\alpha$ from $Q = 0$ to EW scale and $\Delta\rho$ in $W qq'$ coupling
Survey of Feynman diagrams for NLO corrections

Lowest order: (one or two diagrams per flavour channel)

Typical one-loop diagrams: 

# diagrams = $\mathcal{O}(200-400)$

- pentagons
- boxes
- vertices
- self-energies

+ tree graphs with real gluon or photons
Classification of NLO QCD corrections

Possible Born diagrams:

(1)
\[ H \rightarrow V V^* \]
\[ f_a \quad f_b \quad f_c \quad f_d \]

(2)
\[ H \rightarrow V' V' \]
\[ f_a \quad f_b \quad f_c \quad f_d \]

diagrams (2) only for \( q\bar{q}q\bar{q} \) and \( q\bar{q}q'\bar{q}' \) channels

\( q' = \) weak-isospin partner of \( q \)

Classification of QCD corrections into four categories: (typical diagrams shown)

(a)
\[ (a) \text{ defines DIS-like approximation} \]

(b,c,d) = corrections to interferences (only for \( q\bar{q}q\bar{q} \) and \( q\bar{q}q'\bar{q}' \) channels)
Results on integrated cross sections

\begin{itemize}
    \item QCD and EW corrections are of same generic size
    \item reasonable scale choice: \( \mu_{\text{ren/fact}} \sim M_W \sim W/Z \) virtuality (rather than \( M_H \))
    \item scale uncertainty \( \sim 3\% \) within \( M_W/2 < \mu_{\text{ren/fact}} < 2M_W \) in NLO (\( \sim 10\% \) in LO)
    \item sensitivity to cuts: large for QCD, small for EW corrections
\end{itemize}
Size of specific corrections to cross sections:

<table>
<thead>
<tr>
<th>$M_H$ [GeV]</th>
<th>no cuts</th>
<th>VBF cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{QCD(a)}}$ [%]</td>
<td>4−0.5</td>
<td>+1</td>
</tr>
<tr>
<td>$\delta_{\text{QCD(b+c+d)}}$ [%]</td>
<td>$\lesssim 0.2$</td>
<td>$−0.1$</td>
</tr>
<tr>
<td>$\delta_{\text{EW},qq}$ [%]</td>
<td>$\approx −6$</td>
<td>+6</td>
</tr>
<tr>
<td>$\delta_{\text{EW},q\gamma}$ [%]</td>
<td>$\approx +1$</td>
<td>+2</td>
</tr>
<tr>
<td>$\delta_{G^2_M H^4}$ [%]</td>
<td>$&lt; 0.1$</td>
<td>+4</td>
</tr>
</tbody>
</table>

Heavy-Higgs corrections at $M_H \sim 700$ GeV:

\[ \frac{G^2_M H^2}{m_H^2} \sim \left(\frac{G^2 M_H^2}{m_H^2}\right)^2 \sim 4\% \]

$\leftrightarrow$ breakdown of perturbation theory

↑ taken from Ghinculov '95; Frink et al. '96

e nugible for $M_H < 400$ GeV
Distribution in the Higgs transverse momentum $p_{T,H}$

\[ \frac{d\sigma}{dp_{T,H}} \left[ \frac{fb}{GeV} \right] \quad pp \to Hjj + X \]

\[ \frac{d\sigma}{d\sigma_{LO}} - 1 \% \quad pp \to Hjj + X \]

$M_H = 120$ GeV

\[ M_H = 120 \text{ GeV} \]

$M_H = 120$ GeV

QCD and EW corrections distort shapes

QCD+EW $\sim 20\%$ ($40\%$) at $p_{T,H} = 200$ GeV ($500$ GeV)
Distribution in the rapidity $y_{j_1}$ of the leading tagging jet

Ciccolini, Denner, S.D. '07

$\frac{d\sigma}{dy_{j_1}}$ [fb] \hspace{1cm} pp $\to$ Hjj + X

\begin{align*}
M_H = 120 \text{ GeV} \\
\text{EW+QCD} \\
\text{LO}
\end{align*}

$\frac{d\sigma}{d\sigma_{\text{LO}}} - 1 \text{ [%]}$ \hspace{1cm} pp $\to$ Hjj + X

\begin{align*}
M_H = 120 \text{ GeV} \\
\text{EW+QCD} \\
\text{EW} \\
\text{QCD}
\end{align*}

→ Significant shape distortions by QCD effects, but EW effects almost uniform
Distribution in the azimuthal angle difference $\Delta \phi_{jj}$ of the tagging jets

Ciccolini, Denner, S.D. ’07

$$\frac{d\sigma}{d\Delta \phi_{jj}} \text{[fb]} \quad pp \rightarrow H_{jj} + X$$

$$\frac{d\sigma}{d\sigma_{LO}} - 1 \% \quad pp \rightarrow H_{jj} + X$$

QCD+EW corrections induce small distortions similar to BSM effects
Effects beyond NLO
Matching fixed order with partons shower at NLO QCD

**POWHEG** matching of NLO with **HERWIG/PYTHIA**: Nason, Oleari ’09

- Hardest radiation is generated first (largest $p_T$) using exact matrix elements
- **POWHEG** output transferred to parton shower
- Concept independent of shower algorithm
- Unweighted events

Results on VBF:

Characteristic features not changed by parton shower
NNLO QCD corrections

DIS-like corrections $\rightarrow$ structure-function approach

Bolzoni, Maltoni, Moch, Zaro ’10

Non-DIS-like corrections:

loop-induced contributions with ext. gluons and HVV couplings

Harlander, Vollinga, Weber ’08

colour-exchange diagrams and Higgs radiation off quark loops
expected small $\rightarrow$ neglected

Stefan Dittmaier, Higgs production via vector-boson fusion

Higgs Hunting, Orsay, July 2010 – 24
DIS-like NNLO QCD corrections to the total VBF cross section

**Scale uncertainty:**

- Scale choice: $Q/4 \leq \mu_R, \mu_F \leq 4Q$

**PDF uncertainty:**

(68% C.L.)

Results for $\sigma_{tot}$ at the LHC:

- NNLO QCD corrections $\sim 1\%$ with scale $Q = W/Z$ virtuality $= \mathcal{O}(M_W)$
- Scale uncertainty $\sim$ PDF uncertainty $\sim 2\%$

Implementation of VBF cuts $\rightarrow$ work in progress
Loop-induced contributions with ext. gluons and HVV couplings

LO/NLO for VBF

“minimal” cuts \( (p_{T,j}>20 \text{ GeV}, |\eta_j|<5, R>0.6) \)

\[ \downarrow \]

WBF cuts = minimal cuts

\[ + (\eta_1 \cdot \eta_2<0, |\Delta \eta|>4.2, m_{jj}>600 \text{ GeV}) \]

\[ \leftarrow \] reduction of \( \sigma \) by factor 2–3

Loop-induced parts with ext. gluons:

\[ \begin{align*}
\text{minimal cuts} & \rightarrow \text{WBF cuts} \\
& \leftarrow \text{reduction of } \sigma \text{ by factor } \sim 30
\end{align*} \]

Impact \( \lesssim 0.1\% \) \( \rightarrow \) negligible
Cross-talk between HVV- and Hgg-initiated production

Interference at LO:

\[ = 0 \]

But at NLO QCD:

\[ \neq 0 \]

Explicit result:

- various suppression mechanisms at work (PDF weights, weak couplings, etc.)
- impact \( \lesssim 10^{-3}\% \rightarrow \text{negligible} \)
Conclusions
Higgs production via VBF is important at the LHC

• for Higgs discovery
• for Higgs coupling analyses

Status of VBF predictions – size of higher-order effects:

• **significant corrections**: \( \sim 5-10\% \)
  ◦ NLO QCD (DIS-like) and NLO EW
  ◦ gg fusion via effective \( H_{gg} \)

• **small corrections**: \( \sim 1-2\% \)
  ◦ NNLO QCD \((\sigma_{\text{tot}} \text{ available, VBF cuts in progress})\)
  ◦ initial states with \( b \)-quarks or photons

• **negligible effects**: \(< 1\% \) (after VBF cuts)
  \( s \)-channel contributions, interferences, non-DIS-like NLO QCD, QCD–EW interferences, loop-induced gg-fusion

• Heavy-Higgs effects negligible for \( M_H < 400 \text{ GeV} \)
  but 1-loop \( \sim 2\)-loop at \( M_H \sim 700 \text{ GeV} \) \( \to \) breakdown of perturbation theory

**Theoretical accuracy of cross section** \( \sim 2\% \) (for intermediate Higgs masses)
matches uncertainties from PDFs and expected experimental errors
Extra slides
Scale dependence of LO and NLO cross sections

$\sigma [fb] \quad pp \to Hjj + X$

<table>
<thead>
<tr>
<th>$\mu/M_W$</th>
<th>$\text{LO}$</th>
<th>$\text{NLO}$</th>
<th>$\text{NLO QCD}$</th>
<th>$\text{NLO QCD'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>3400</td>
<td>3200</td>
<td>3000</td>
<td>2800</td>
</tr>
<tr>
<td>0.25</td>
<td>3300</td>
<td>3100</td>
<td>2900</td>
<td>2700</td>
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<tr>
<td>0.5</td>
<td>3200</td>
<td>3000</td>
<td>2800</td>
<td>2600</td>
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<tr>
<td>1</td>
<td>3100</td>
<td>2900</td>
<td>2700</td>
<td>2500</td>
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<tr>
<td>2</td>
<td>3000</td>
<td>2800</td>
<td>2600</td>
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<td>4</td>
<td>2900</td>
<td>2700</td>
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<td>2300</td>
</tr>
<tr>
<td>8</td>
<td>2800</td>
<td>2600</td>
<td>2400</td>
<td>2200</td>
</tr>
</tbody>
</table>

$M_H = 200$ GeV

$\text{QCD: } \mu = \mu_{\text{fact}} = \mu_{\text{ren}}$

$\text{QCD': } \mu = \mu_{\text{fact}} = M_W^2/\mu_{\text{ren}}$

no cuts

$VBF$ cuts

$M_H = 200$ GeV
Higgs rapidity distribution at NLO

\[ \frac{d\sigma}{dy_H} \text{ [fb]} \quad pp \rightarrow Hjj + X \]

\[ \frac{d\sigma}{d\sigma_{LO}} - 1 \text{ [%]} \quad pp \rightarrow Hjj + X \]

\[ M_H = 120 \text{ GeV} \]

\[ \leftarrow \text{ Significant shape distortions by QCD effects, but EW effects almost uniform} \]
Distribution in the transverse momentum $p_{Tj_1}$ of the leading tagging jet at NLO

Ciccolini, Denner, S.D. '07

pp → Hjj + X

$\frac{d\sigma}{dp_{j_1,T}}$ [fb/GeV]

$M_H = 120$ GeV

$\frac{d\sigma}{d\sigma_{LO}} - 1 \%$

$M_H = 120$ GeV

→ QCD and EW corrections distort shapes

QCD+EW $\sim 25\% (40\%)$ at $p_{T,H} = 200$ GeV (500 GeV)