QCD Corrections to Vector Boson Fusion Higgs Production Channels

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Outline

SM Higgs boson

$SU(2)_L$ doublet of scalar Higgs fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} , \qquad Y = 1$$

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$$

SM Higgs boson

$SU(2)_L$ doublet of scalar Higgs fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad Y = 1$$

$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

Is the neutral scalar the SM Higgs?

- Mass determination
- CP quantum numbers
- Couplings to gauge bosons and fermions

SM Higgs boson
Higgs couplings to fermions

Fermion masses arise from Yukawa couplings via $\Phi^\dagger \to \left(0, \frac{v+H}{\sqrt{2}}\right)$.

$$\mathcal{L}_{\text{Yukawa}} = -\sum_f m_f \bar{f} f \left(1 + \frac{H}{v}\right)$$

- 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 a v.e.v exists (maybe a scalar singlet)

SM Higgs boson

Higgs couplings to gauge bosons

Kinetic energy term of the Higgs doublet field:

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

- W,Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{\left(g^2+g'^2\right)v^2}{4}$
- WWH and ZZH couplings are generated:coupling strength $= 2m_V^2/v \approx g^2 v$ within SM

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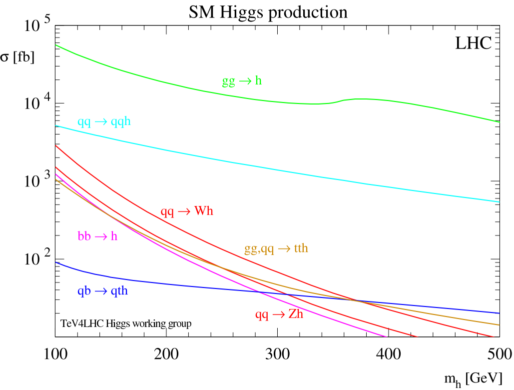
Total SM Higgs cross sections at the LHC



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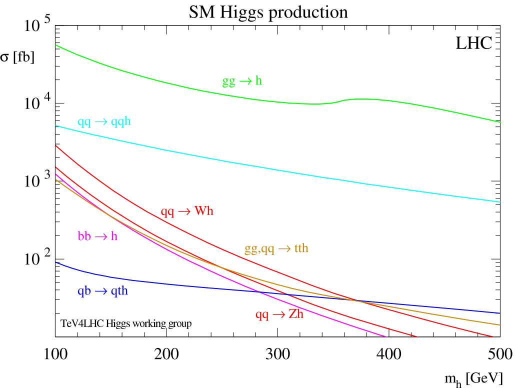

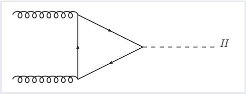

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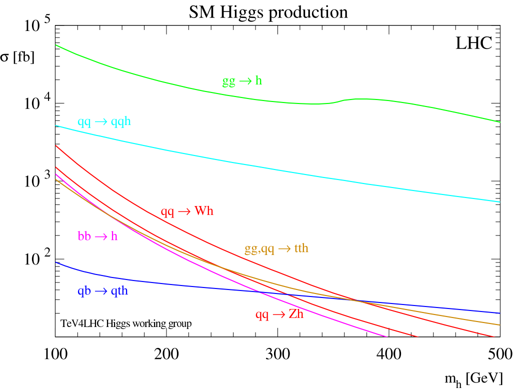

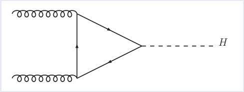

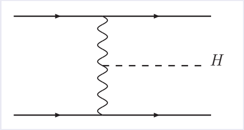

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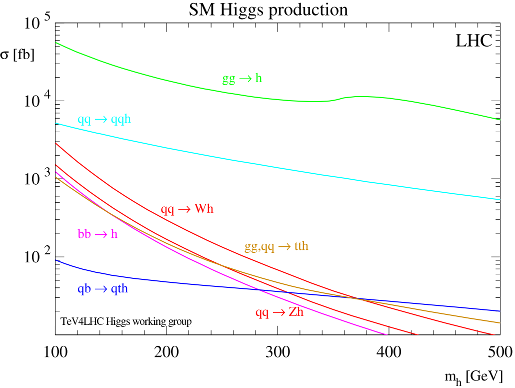

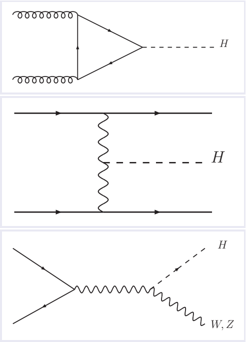

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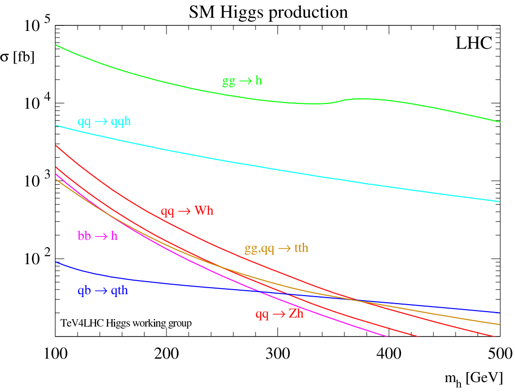
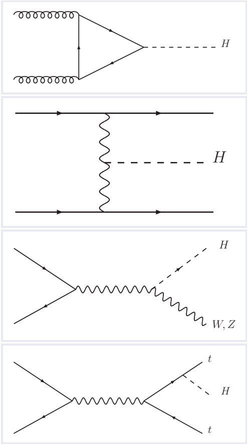
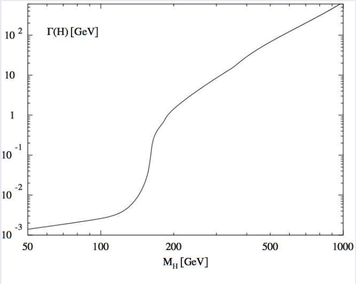
Total SM Higgs cross sections at the LHC



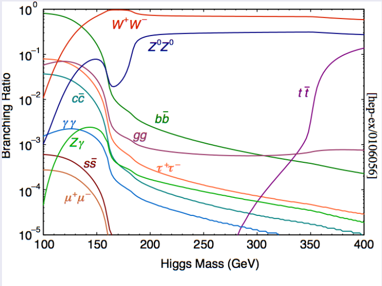


Decay of the SM Higgs

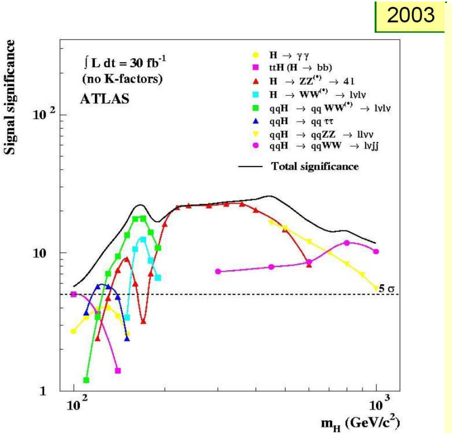
Decay width

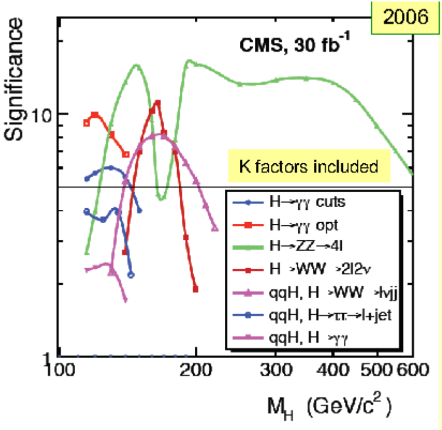


Branching ratios



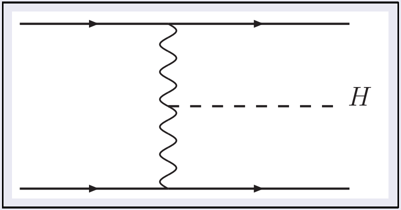
Discovery potential





Vector Boson Fusion

Leading Order: $qQ \to HqQ$



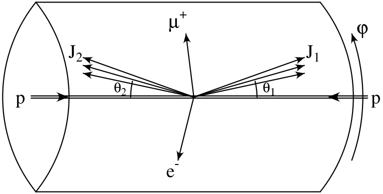
Statistical accuracies at the LHC: $\sigma \times \mathrm{BR} \sim 10\%$

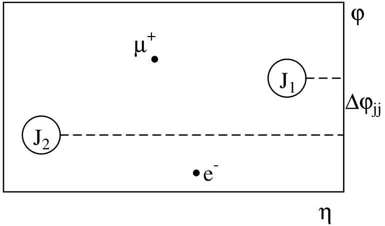
Higgs search channels:

- $H \to W^+W^-$, $m_H > 120$ GeV
- $H \to \tau^+\tau^-$, $m_H < 140$ GeV
- $H \to \gamma\gamma$, $m_H < 150$ GeV

Eboli,Hagiwara,Kauer,Plehn, Rainwater,Zeppenfeld,. . .

Vector Boson Fusion

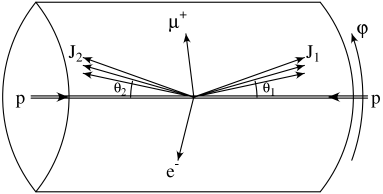


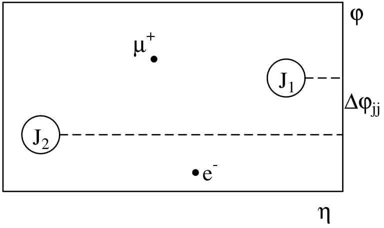


Event Characteristics

- Energetic jets in the forward and backward directions ($p_T > 20$ GeV)

Vector Boson Fusion

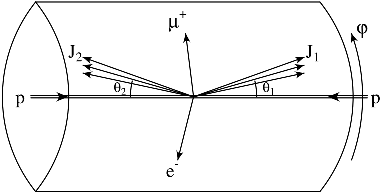


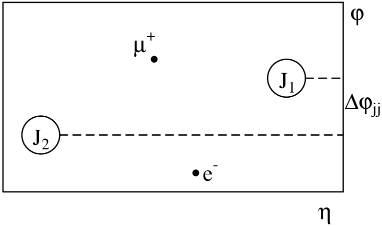


Event Characteristics

- Energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets

Vector Boson Fusion





Event Characteristics

- Energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region (colorless W/Z exchange)

Vector Boson Fusion

NLO Corrections

- Total cross section at NLO: Han,Willenbrock (1991)
- Distributions at NLO: T.F., Oleari, Zeppenfeld (2003); Campbell,Ellis,Berger (2004)
- 1-loop EW corrections: Ciccolini,Denner,Dittmaier (2007)
- approx. NLO QCD to *Hjjj*: T.F.,Hankele,Zeppenfeld (2007)

Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Catani and Seymour, hep-ph/9605323

Dipole subtraction method

$$\sigma_{ab}^{NLO}(p,\bar{p}) = \sigma_{ab}^{NLO\{4\}}(p,\bar{p}) + \sigma_{ab}^{NLO\{3\}}(p,\bar{p}) + \int_0^1 dx[\hat{\sigma}_{ab}^{NLO\{3\}}(x,xp,\bar{p}) + \hat{\sigma}_{ab}^{NLO\{3\}}(x,p,x\bar{p})]$$

$$\sigma_{ab}^{NLO\{4\}}(p,\bar{p}) = \int_4 [d\sigma_{ab}^{R}(p,\bar{p})_{\epsilon=0} - d\sigma_{ab}^{A}(p,\bar{p})_{\epsilon=0}]$$

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Higgs Production via Vector Boson Fusion at NLO

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$$\sigma_{ab}^{NLO\{3\}}(p,\bar{p}) = \int_3 [d\sigma_{ab}^{V}(p,\bar{p}) + d\sigma_{ab}^{B}(p,\bar{p}) \otimes \mathbf{I}]_{\epsilon=0}$$

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Higgs Production via Vector Boson Fusion at NLO

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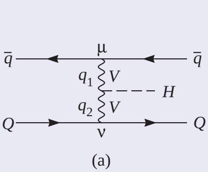
$$\sigma_{ab}^{NLO}(p,\bar{p}) = \sigma_{ab}^{NLO\{4\}}(p,\bar{p}) + \sigma_{ab}^{NLO\{3\}}(p,\bar{p}) + \int_0^1 dx[\hat{\sigma}_{ab}^{NLO\{3\}}(x,xp,\bar{p}) + \hat{\sigma}_{ab}^{NLO\{3\}}(x,p,x\bar{p})]$$

$$\int_0^1 dx\hat{\sigma}_{ab}^{NLO\{3\}}(x,xp,\bar{p}) = \sum_{a'}\int_0^1 dx \int_3 \{d\sigma^B_{a'b}(xp,\bar{p}) \otimes [\mathbf{P}(x)+\mathbf{K}(x)]^{aa'}\}_{\epsilon=0}$$

Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Virtual Corrections



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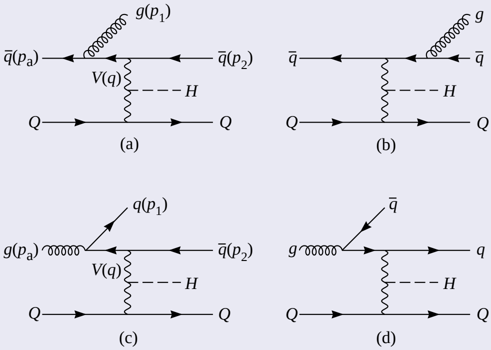
Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Real Corrections



T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D **68**, 073005 (2003)

NLO vs LO

Applied Cuts

- Require two hard jets with $p_{Tj} \geq 20\ \mathrm{GeV}$, $|y_j| \leq 4.5$
- Higgs decay: $p_{T\ell} \geq 20\ \mathrm{GeV}$, $|\eta_\ell| \leq 2.5$, $\Delta R_{j\ell} \geq 0.6$ Additionally, the Higgs decay products are required to fall between the tagging jets.

$$y_{j,min} < \eta_{\ell_{1,2}} < y_{j,max}$$

- Backgrounds to VBF are significantly suppressed by requiring a large rapidity separation of the two tagging jets.

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$$

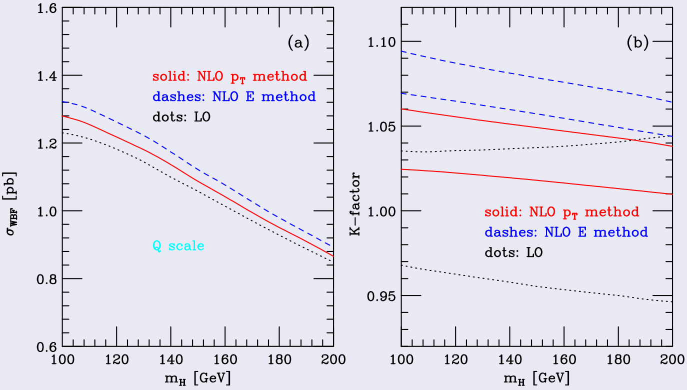
NLO vs LO

Tagging Jet Selection

- p_T **-method**: Define the tagging jets at the two highest p_T jets in the event.
- E **-method**: Define the tagging jets as the two highest energy jets in the event.

NLO vs LO

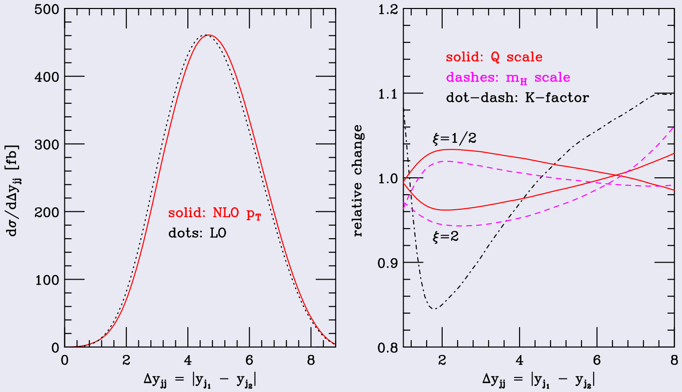
$K = \frac{\sigma(\mu_R, \mu_F)}{\sigma^{LO}(\mu_F = Q_i)}$



- p_T method: 3-5 % higher than LO
- E method: 6-9 % higher than LO

NLO vs LO

Tagging jet rapidity separation

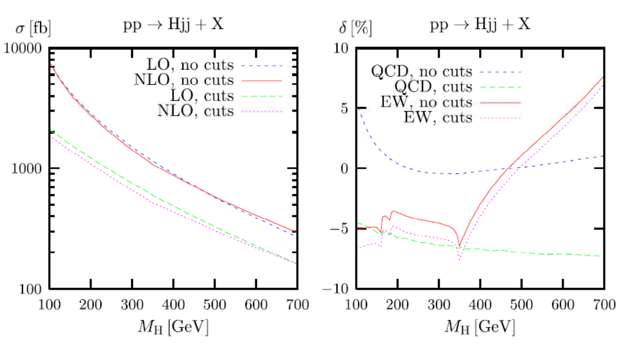


Tagging jets are slightly more forward at NLO than at LO

$\Downarrow$

$\Delta y_{jj} > 4$ cut works well at NLO.

QCD and Electroweak Corrections



M. Ciccolini, A. Denner and S. Dittmaier, Phys. Rev. D **77** (2008) 013002 [arXiv:0710.4749 [hep-ph]].

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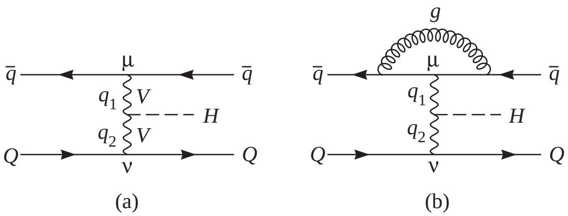
Anomalous Higgs Couplings

General Tensor Structure for the *HVV* vertex

$$
\begin{aligned}
T^{\mu\nu}(q_1, q_2) &= a_1(q_1, q_2) g^{\mu\nu} \\
&+ a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] \\
&+ a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}
\end{aligned}
$$



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Anomalous Higgs Couplings

General Tensor Structure for the HVV vertex

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&+ a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}
\end{aligned}
$$

1. SM-like: a_1
2. CP even: a_2
3. CP odd: a_3

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Anomalous Higgs Couplings

General Tensor Structure for the *HVV* vertex

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\end{aligned}
$$

The QCD corrections to Higgs production via VBF are computed in the presence of anomalous *HVV* couplings using VBFNLO. T. Figy and D. Zeppenfeld, Phys. Lett. B **591**, 297 (2004)

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Anomalous Higgs Couplings

General Tensor Structure for the *HVV* vertex

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&+ a_3(q_1, q_2)\varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}
\end{aligned}
$$

Form factor dependence

$$
a_i(q_1, q_2) = a_i(0,0) \frac{M^2}{|q_1^2| + M^2} \frac{M^2}{|q_2^2| + M^2}
$$

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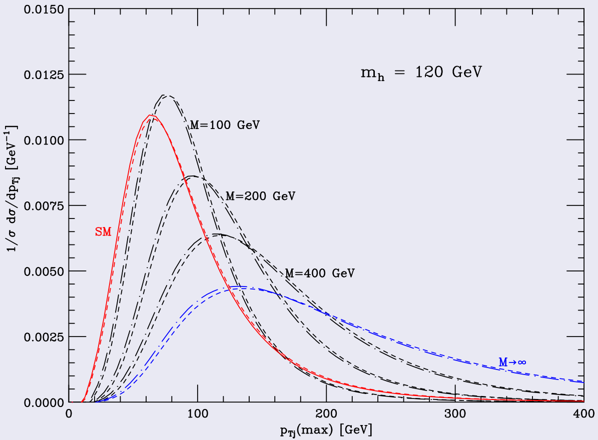
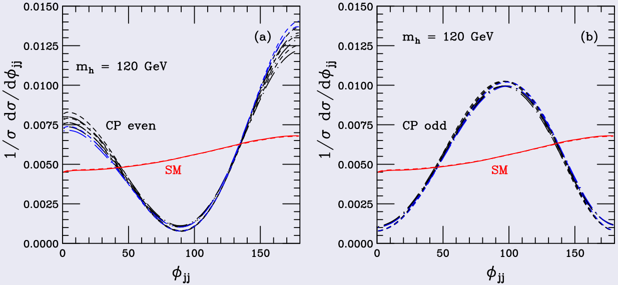
Anomalous Higgs Couplings

p_{T_j} distributions



Anomalous Higgs Couplings

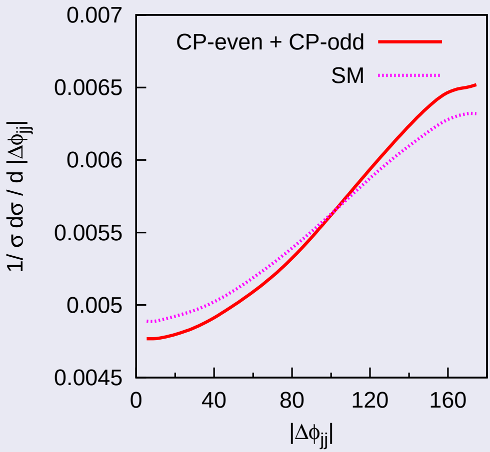
$\phi_{jj} = |\phi_{j_1} - \phi_{j_2}|$ distributions



Form factor dependence is small.

Anomalous Higgs Couplings

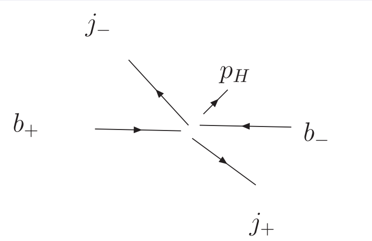
The case: $a_2 = a_3$



But, it doesn't work!

Anomalous Higgs Couplings

Redefinition of ϕ_{jj}



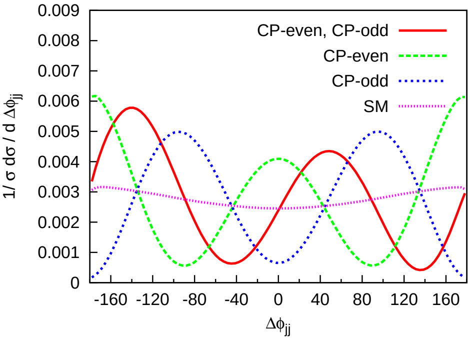
- Invariant under $(b_+, p_+) \leftrightarrow (b_-, p_-)$
- Parity odd variable

V. Hankele, G. Klamke, D. Zeppenfeld and T. Figy, Phys. Rev D74 (2006) 095001 [hep-ph/0609075]

Define the azimuthal angle between j_+ and j_- as:

$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2p_{T,1}p_{T,2}\sin(\phi_+ - \phi_-) = 2p_{T,1}p_{T,2}\sin\Delta\phi_{jj}$$

Anomalous Higgs Couplings



- Mixed CP case: $a_2 = a_3$, $a_1 = 0$
- Pure CP–even case: a_2 only
- Pure CP–odd case: a_3 only

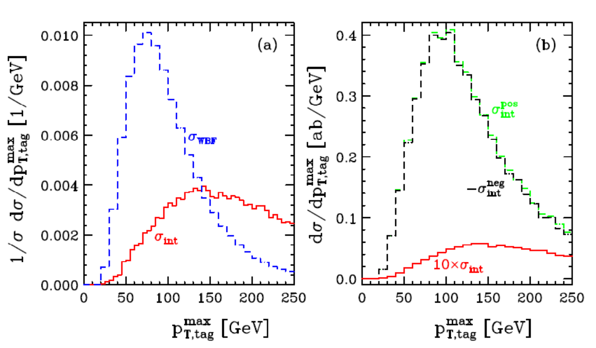
Position of minimum of the $\Delta\phi_{jj}$ distribution measures the relative size of the CP–even and CP–odd couplings.

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

$\Longrightarrow$ Maxima at α and $\alpha + \pi$

Anomalous Higgs Couplings

Pollution from the SM ?



A. Bredenstein, K. Hagiwara and B. Jager, Phys. Rev. D **77** (2008) 073004 [arXiv:0801.4231 [hep-ph]].

J. R. Andersen, T. Binoth, G. Heinrich and J. M. Smillie, JHEP **0802** (2008) 057 [arXiv:0709.3513 [hep-ph]]

Higgs plus three jets via VBF at LO

The Central Jet Veto Proposal

- Distinguishing feature of VBF: at LO no color is exchanged in the t-channel.
- The central-jet veto is based on the different radiation pattern expected for VBF versus its major backgrounds

hep-ph/9412276, hep-ph/0012351

Events are discarded if any additional jet satisfies the criteria:

$$p_{Tj}^{veto} > p_{T,veto}, \quad y_j^{veto} \in (y_j^{\mathrm{tag}\ 1}, y_j^{\mathrm{tag}\ 2})$$

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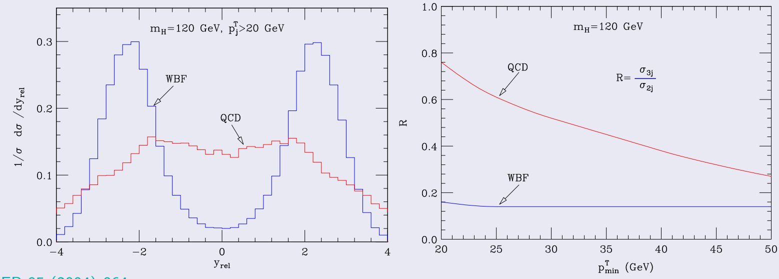
Higgs plus three jets via VBF at LO

Example: Gluon fusion vs vector boson fusion

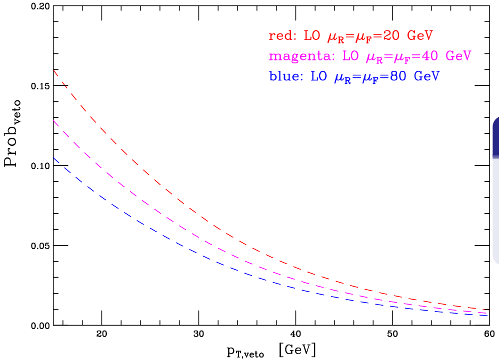


JHEP 05 (2004) 064

$$y_{\rm rel} = y_j^{\rm veto} - (y_j^{\rm tag\ 1} + y_j^{\rm tag\ 2})/2$$

Higgs plus three jets via VBF at LO

Central Jet Veto at LO



Veto Probability:

$$\text{Prob}_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

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Higgs plus three jets via VBF at LO

Central Jet Veto at LO

- Scale variation at LO for σ_3: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- Theoretical uncertainty in Prob_{veto} feeds into the uncertainty in determining couplings.
- In order to constrain couplings more precisely, compute the NLO QCD corrections to *Hjjj*

TF,V. Hankele and D. Zeppenfeld JHEP **0802** (2008) 076 [arXiv:0710.5621]

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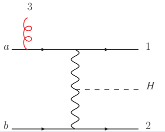
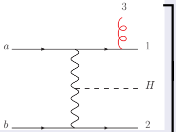
Higgs plus three jets via VBF at NLO

Born amplitude

Color structure

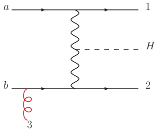
$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \left[\mathcal{M}_{B,1a} : \right.$$

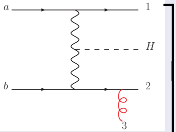




$$\left. \right]$$

$$+ \ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \left[\mathcal{M}_{B,2b} : \right.$$





$$\left. \right]$$

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Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

- Virtual: Two gauge invariant subsets
  - Vertex + Propagator + Box
  - Pentagon + Hexagon
- Real: 4 final state partons + Higgs via VBF

T. M. Figy, Ph.D. Thesis, UMI-32-34582.

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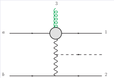
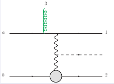
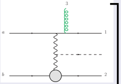
Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

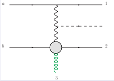
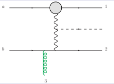
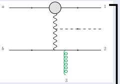
Box+Vertex+Propagator corrections

$$\textbf{Box} = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\textbf{Box(1a)} :$$

$$\Big]$$

$$+ \ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\textbf{Box(2b)} :$$

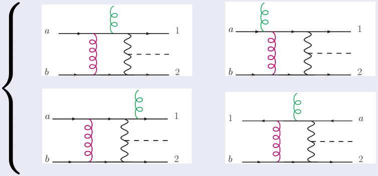
$$\Big]$$

Higgs plus three jets via VBF at NLO
Virtual and Real Corrections

Neglected hexagons and pentagons

These graphs contribute to the virtual corrections for $qQ \rightarrow qQgH$ and are color suppressed $(d_F = 3,\ d_G = 8)$.

Hex(1a) + **Pent(1a)** =



Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Neglected hexagons and pentagons

$$
\begin{aligned}
2\,\mathrm{Re}\left[\mathcal{M}_V \mathcal{M}_B^*\right] &= d_F^2 C_F^2 \; 2\,\mathrm{Re}\left[(\mathbf{Box(1a)})\mathcal{M}_{B,1a}^*\right] \\
&+ d_F^2 C_F^2 \; 2\,\mathrm{Re}\left[(\mathbf{Box(2b)})\mathcal{M}_{B,2b}^*\right] \\
&+ \frac{d_F^2 C_F^2}{d_G} \; 2\,\mathrm{Re}\left[(\mathbf{Hex(1a)} + \mathbf{Pent(1a)})\mathcal{M}_{B,2b}^*\right] \\
&+ \frac{d_F^2 C_F^2}{d_G} \; 2\,\mathrm{Re}\left[(\mathbf{Hex(2b)} + \mathbf{Pent(2b)})\mathcal{M}_{B,1a}^*\right]
\end{aligned}
$$

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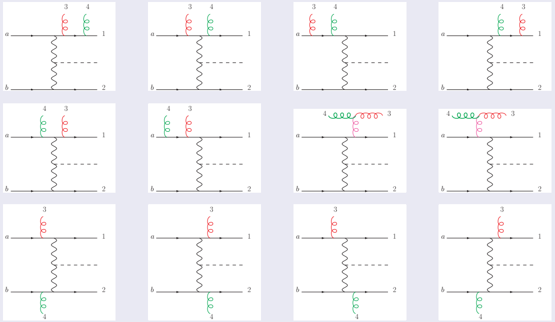
Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Real Corrections

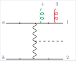
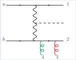
$$\mathcal{M}_4 = \left\{ \quad \right\}$$

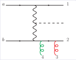
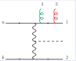


Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Treat Real Corrections Consistently!

$$|\mathcal{M}_4|^2 = d_F^2 C_F^2 \Big\{ \Big|$$  $$\Big|^2 + \Big|$$  $$\Big|^2 + \cdots \Big\}$$

$$+ \frac{d_F^2 C_F^2}{d_G} \, 2\,\mathrm{Re} \Big\{ \Big($$  $$\Big) \Big($$  $$\Big)^* + \cdots \Big\}$$

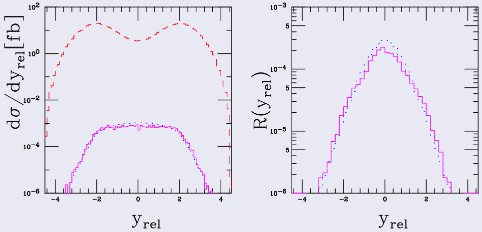
The term $\propto 1/d_G$ when integrated over PS gives rise to a soft divergence. This soft divergence is cancelled against the soft divergence arising from the hexagons and pentagons. For consistency, this term is also neglected.

Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Error Estimate on the Approximation

$$\Delta\textbf{NLO} \propto 2\,\mathrm{Re}\left[\left(\mathcal{M}_{B,1a}\right)\left(\mathcal{M}_{B,2b}\right)^{*}\right]$$



Left: $\Delta\sigma_3^{NLO}$ (solid) and σ_3^{LO} (dashes).
Right: $R(y_{\mathrm{rel}}) = \Delta\textbf{NLO}/\textbf{LO}$

Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Other approximations

- s–channel weak boson exchange ($VHj \rightarrow Hjjj$) is explicitly excluded at NLO and LO.
  - The interference between VBF and Higgsstrulung is very small in the VBF PS region. C. Georg; Smillie, Anderson, Binoth, Heinrich; Ciccolini, Denner, Dittmaier
  - Hence, Higgsstrulung is viewed as separate process.
- Gluon fusion contributions are viewed a separate process. The interference between GF and VBF is at the level 10^{-3} fb.
- Pauli interference has been systematically neglected in the real corrections as it is negligible.

Higgs plus three jets via VBF at NLO

NLO parton level Monte Carlo Program

- The dipole subtraction method of Catani and Seymour hep-ph/9605323
- α cut on the PS of the dipoles hep-ph/0307268.
- Real amplitudes with MADGRAPH.
- b-quarks for neutral current processes.
- The Monte Carlo integration –VEGAS.
- CTEQ6M PDFs at NLO with $\alpha_s(M_Z) = 0.118$ and CTEQ6L1 PDFs at LO with $\alpha_s(M_Z) = 0.130$.
- SM parameters: LO electroweak relations with M_Z, M_W, and G_F as inputs

NLO vs LO

VBF Selection Cuts

- k_T algorithm: Require at least 3 hard jets with $p_{Tj} \geq 20\ \mathrm{GeV}$ and $|y_j| \leq 4.5$.
- Tagging jets: 2 jets of $p_{Tj}^{\mathrm{tag}} \geq 30\ \mathrm{GeV}$ and $|y_j^{\mathrm{tag}}| \leq 4.5$.
- Higgs decay products:

$$p_{T\ell} \geq 20\ \mathrm{GeV}\,, \qquad |\eta_\ell| \leq 2.5\,, \qquad \triangle R_{j\ell} \geq 0.6$$

$$y_{j,min}^{\mathrm{tag}} + 0.6 < \eta_{\ell_{1,2}} < y_{j,max}^{\mathrm{tag}} - 0.6.$$

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NLO vs LO

VBF Selection Cuts

- Rapidity gap and opposite detector hemispheres:

$$y_j^{\text{tag }1} \cdot y_j^{\text{tag }2} < 0$$

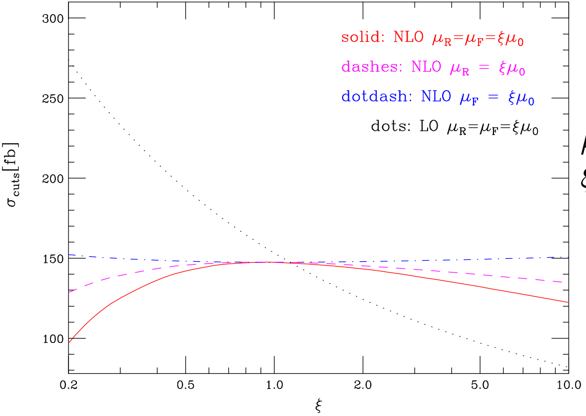
$$\Delta y_{jj} = |y_j^{\text{tag }1} - y_j^{\text{tag }2}| > 4$$

- Invariant mass of tagging jets:

$$m_{jj} = \left(p_j^{\text{tag }1} + p_j^{\text{tag }2}\right)^2 > 600 \text{ GeV}$$

NLO vs LO

Total Cross section



$\mu_0 = 40$ GeV

$\xi = 2^{\mp 1}$ scale variations:

- LO: +26% to −19%
- NLO: less than 5%

NLO vs LO

K-factor and relative change

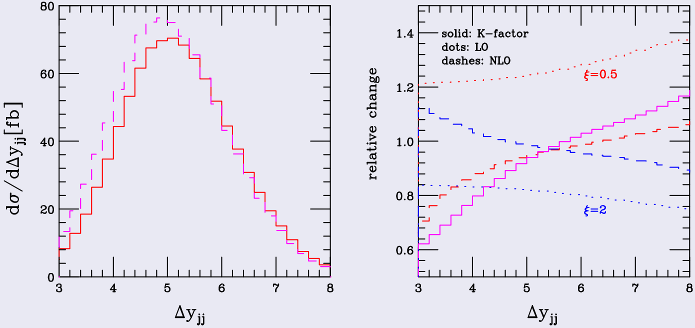
$$K(x) = \frac{d\sigma_3^{NLO}(\mu_R = \mu_F = \xi\mu_0)/dx}{d\sigma_3^{LO}(\mu_R = \mu_F = \mu_0)/dx}$$

$$\text{relative change} = \frac{d\sigma_3(\mu_R = \mu_F = \xi\mu_0)/dx}{d\sigma_3(\mu_R = \mu_F = \mu_0)/dx}$$

NLO vs LO

Tagging Jet Distributions

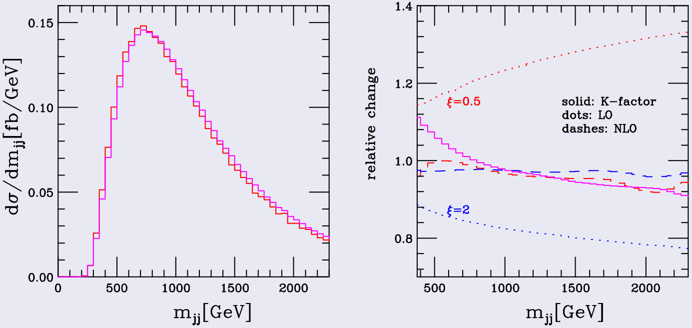
Tagging Jet Rapidity Separation



NLO vs LO

Tagging Jet Distributions

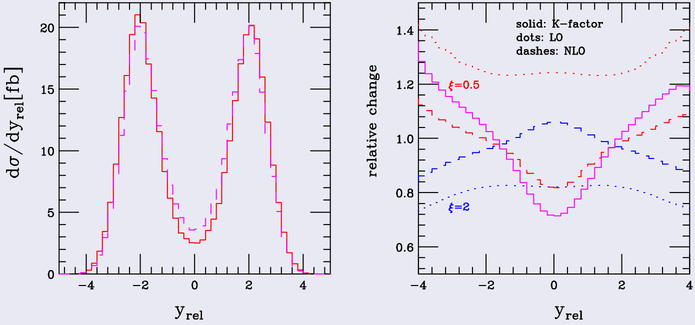
Tagging Jet Invariant mass



NLO vs LO

Veto Jet Distributions

Veto Jet Rapidity: $y_{\rm rel} = y_j^{\rm veto} - (y_j^{\rm tag\ 1} + y_j^{\rm tag\ 2})/2$

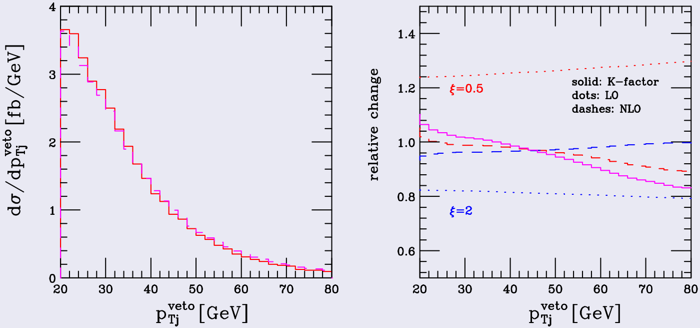


$$p_{Tj}^{\rm veto} > 20\ {\rm GeV}, \qquad y_j^{\rm veto} \in (y_j^{\rm tag\ 1}, y_j^{\rm tag\ 2})$$

NLO vs LO

Veto Jet Distributions

Veto Jet P_T



$$p_{Tj}^{\rm veto} > 20 \text{ GeV}, \qquad y_j^{\rm veto} \in (y_j^{\rm tag\ 1}, y_j^{\rm tag\ 2})$$

NLO vs LO

Veto Jet Distributions

- Veto is slightly softer at NLO.
- $\xi = 2^{\mp 1}$ scale variations at y_{rel}=0:
  - LO: −27% to +42%
  - NLO: −20% to +7%
- Suppressed radiation in the vicinity of $y_{rel} = 0$.

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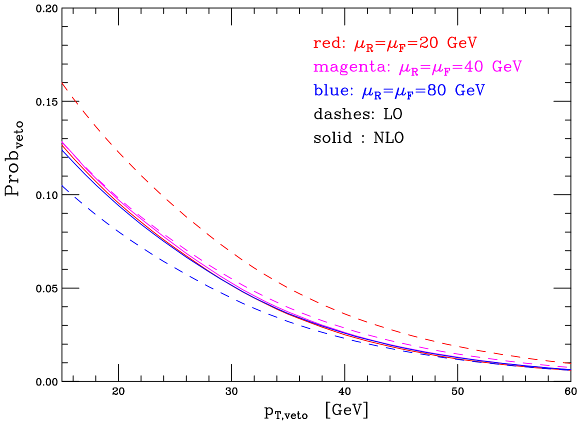
NLO vs LO

Veto Probability for the VBF Signal



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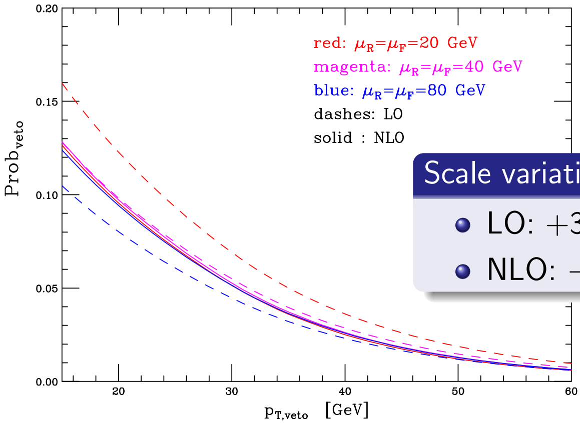
NLO vs LO

Veto Probability for the VBF Signal



Scale variations, $p_{T,veto} = 15$ GeV:

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

Conclusions

- QCD corrections for VBF Hjj (in VBFNLO) and the dominant QCD corrections for VBF $Hjjj$ have been computed in the form of NLO parton–level Monte Carlos using the dipole subtraction method.
- Scale dependence is reduced for the total cross section and distributions at NLO.
- QCD corrections are small while K factors are phase space dependent.

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Conclusions

VBFNLO

- VBFNLO is a parton level Monte Carlo program for Vector Boson Fusion processes.
  - Vjj, $V = Z, W^{\pm}$: C. Oleari, D. Zeppenfeld. Phys. Rev. **D68** (2003) 073005
  - W^+W^-jj: B. Jager, C. Oleari, D. Zeppenfeld. JHEP **0607** (2006) 015
  - $ZZjj$: B. Jager, C. Oleari, D. Zeppenfeld. Phys. Rev. **D74** (2006) 1113006
  - Hjj : T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D **68**, 073005 (2003)
    T. Figy and D. Zeppenfeld, Phys. Lett. B **591**, 297 (2004)
    V. Hankele, G. Klamke, D. Zeppenfeld and T. Figy, Phys. Rev **D74** (2006) 095001
- Project members:

  M. Bähr, G. Bozzi, C. Englert, T. Figy, J. Germer, N. Greiner, K. Hackstein, V. Hankele, B. Jäger, G. Klämke, M. Kubocz, P. Konar, C. Oleari, M. Werner, M. Worek, D. Zeppenfeld
- The program can be downloaded from

  http://www-itp.physik.uni-karlsruhe.de/∼vbfnloweb/VBFNLO.