QCD Corrections to Vector Boson Fusion
Higgs Production Channels

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Outline

1. Introduction

2. Higgs plus two jets via VBF at NLO
   - The NLO Calculation
   - Results for the LHC
   - Including Anomalous Higgs Couplings

3. Higgs plus three jets via VBF at NLO
   - The NLO Calculation
   - NLO Results

4. Conclusions
SM Higgs boson

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

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

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

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

\[ \Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}, \quad Y = 1 \]

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

**Is the neutral scalar the SM Higgs?**

- Mass determination
- CP quantum numbers
- Couplings to gauge bosons and fermions
Fermion masses arise from Yukawa couplings via
\[ \Phi^\dagger \rightarrow \left(0, \frac{\nu + H}{\sqrt{2}}\right). \]

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

- Test SM prediction: \( \bar{f} f H \) Higgs coupling strength = \( m_f / \nu \)
- Observation of \( Hf \bar{f} \) 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:

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

- \(W, Z\) mass generation: \(m^2_W = \left( \frac{g v}{2} \right)^2, m^2_Z = \frac{(g^2 + g'^2) v^2}{4}\)
- \(WWH\) and \(ZZH\) couplings are generated: coupling strength = \(2m^2_V/v \approx g^2 v\) within SM
Total SM Higgs cross sections at the LHC
Total SM Higgs cross sections at the LHC
Total SM Higgs cross sections at the LHC
Total SM Higgs cross sections at the LHC

![Graph showing SM Higgs production cross sections](image)

- $gg \to h$
- $qq \to qh$
- $qq \to Wh$
- $bb \to h$
- $qq, gg \to tth$
- $qb \to qth$
- $qq \to Zh$

**Legend:**
- **$H$**
- **$W, Z$**

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**Notes:**
- TeV@LHC Higgs working group
- QCD Corrections to VBF $H^0$ Production

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**References:**
- [TeV@LHC Higgs working group](#)
Total SM Higgs cross sections at the LHC

- gg \rightarrow h
- pp \rightarrow qh
- bb \rightarrow h
- gg,qq \rightarrow thh
- qq \rightarrow Zh

Production

QCD Corrections to VBF $H^0$ Production

T. Figy
Decay of the SM Higgs

**Decay width**

\[ \Gamma(H) \text{ [GeV]} \]

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

**Branching ratios**

\[ \text{Br} \text{[}\text{Higgs Mass (GeV)}\text{]} \]

Decay of the SM Higgs

- Decay width
- Branching ratios

**Conclusions**

- T. Figy
- QCD Corrections to VBF \( H^0 \) Production
Discovery potential

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

**ATLAS**

![Graph showing signal significance vs. mass for H -> gamma gamma, H -> ZZ, H -> WW, etc.]

**2003**

**CMS, 30 fb^{-1}**

![Graph showing significance vs. mass for H -> gamma gamma, H -> ZZ, H -> WW, etc., with K factors included.]

![K factors included label]

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T. Figy

QCD Corrections to VBF \( H^0 \) Production

University of Durham
Vector Boson Fusion

Leading Order: $qQ \rightarrow HqQ$

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

Higgs search channels:
- $H \rightarrow W^+W^-$, $m_H > 120$ GeV
- $H \rightarrow \tau^+\tau^-$, $m_H < 140$ GeV
- $H \rightarrow \gamma\gamma$, $m_H < 150$ GeV

Eboli, Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld, . . .
**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 \( (p_T > 20 \text{ GeV}) \)
- Higgs decay products between tagging jets
**Vector Boson Fusion**

**Event Characteristics**

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

Vector Boson Fusion

NLO Corrections

- Total cross section at NLO: Han, Willenbrock (1991)
- 1-loop EW corrections: Ciccolini, Denner, Dittmaier (2007)
- approx. NLO QCD to $H_{jjjj}$: 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

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

\[
\sigma_{ab}^{NLO\{4\}}(p, \bar{p}) = \int_4 [d\sigma_{ab}^R(p, \bar{p})_{\epsilon=0} - d\sigma_{ab}^A(p, \bar{p})_{\epsilon=0}]
\]
Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Catani and Seymour, hep-ph/9605323

Dipole subtraction method

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

\[
\sigma_{ab}^{NLO\{3\}}(p, \bar{p}) = \int_3 \left[ d\sigma^V_{ab}(p, \bar{p}) + d\sigma^B_{ab}(p, \bar{p}) \otimes I \right]_{\epsilon=0}
\]
Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Catani and Seymour, hep-ph/9605323

Dipole subtraction method

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

\[
\int_0^1 dx \hat{\sigma}_{ab}^{\text{NLO}\{3\}}(x, xp, \bar{p}) = \sum a' \int_0^1 dx \int_3 d\sigma_{a'b}(xp, \bar{p}) \\
\otimes [P(x) + K(x)]^{aa'} \epsilon = 0
\]
Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Virtual Corrections

(a) 
\begin{align*}
\overline{q} & \rightarrow \mu \\
q_1 & \rightarrow V \\
q_2 & \rightarrow V \\
Q & \rightarrow \nu \rightarrow Q
\end{align*}

(b) 
\begin{align*}
\overline{q} & \rightarrow \mu \\
g & \\
q_1 & \rightarrow V \\
q_2 & \rightarrow V \\
Q & \rightarrow \nu \rightarrow Q
\end{align*}
Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

Real Corrections

\[ \begin{align*}
\bar{q}(p_a) & \rightarrow g(p_1) \rightarrow \bar{q}(p_2) \\
Q & \rightarrow V(q) \rightarrow H \\
Q & \rightarrow \bar{q}(p_2) \\
Q & \rightarrow g(p_a) \rightarrow q(p_1) \\
Q & \rightarrow V(q) \rightarrow H \\
Q & \rightarrow g(p_a) \rightarrow q(p_2) \\
Q & \rightarrow \bar{q} \rightarrow H \\
Q & \rightarrow g \rightarrow q
\end{align*} \]

Applied Cuts

- Require two hard jets with $p_T j \geq 20 \text{ GeV}, \ |y_j| \leq 4.5$
- Higgs decay: $p_T \ell \geq 20 \text{ GeV}, \ |\eta_\ell| \leq 2.5, \ \Delta R_{j\ell} \geq 0.6$
  
  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.

  $$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$$
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.
\[ K = \frac{\sigma(\mu_R, \mu_F)}{\sigma_{LO}(\mu_F = Q_i)} \]

- **$p_T$ method**: 3-5 % higher than LO
- **$E$ method**: 6-9 % higher than LO
Tagging jet rapidity separation

Tagging jets are slightly more forward at NLO than at LO

\[ \Delta y_{jj} > 4 \text{ cut} \] works well at NLO.
QCD and Electroweak Corrections

Anomalous Higgs Couplings

General Tensor Structure for the $HVV$ vertex

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] + a_3(q_1, q_2)\varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma$$
Anomalous Higgs Couplings

General Tensor Structure for the $HVV$ vertex

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma$$

1. SM-like: $a_1$
2. CP even: $a_2$
3. CP odd: $a_3$
Anomalous Higgs Couplings

General Tensor Structure for the $HVV$ vertex

\[
T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} \\
+ a_2(q_1, q_2) [q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}] \\
+ a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma
\]

Anomalous Higgs Couplings

General Tensor Structure for the $HVV$ vertex

\[
T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma
\]

Form factor dependence

\[
a_i(q_1, q_2) = a_i(0, 0) \left( \frac{M^2}{|q_1^2| + M^2} \right) \left( \frac{M^2}{|q_2^2| + M^2} \right)
\]
Anomalous Higgs Couplings

$p_{T_j}$ distributions

$m_h = 120$ GeV

SM

M=100 GeV

M=200 GeV

M=400 GeV

M→∞
Anomalous Higgs Couplings

\[ \phi_{jj} = |\phi_{j1} - \phi_{j2}| \] distributions

Form factor dependence is small.
Anomalous Higgs Couplings

The case: $a_2 = a_3$

But, it doesn’t work!
Redefinition of $\phi_{jj}$

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

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

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

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

$\implies$ Maxima at $\alpha$ and $\alpha + \pi$

- Mixed CP case: $a_2 = a_3$, $a_1 = 0$
- Pure CP–even case: $a_2$ only
- Pure CP–odd case: $a_3$ only
Anomalous Higgs Couplings
Pollution from the SM ?


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.


Events are discarded if any additional jet satisfies the criteria:

\[ p_{T_j}^{veto} > p_{T,veto}, \quad y_j^{veto} \in (y_{j,1}^{tag}, y_{j,2}^{tag}) \]
Higgs plus three jets via VBF at LO

Example: Gluon fusion vs vector boson fusion

\[ y_{\text{rel}} = y_j^{\text{veto}} - \left( y_j^{\text{tag} 1} + y_j^{\text{tag} 2} \right)/2 \]

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Higgs plus three jets via VBF at LO
Central Jet Veto at LO

Veto Probability:

\[
\text{Prob}_{\text{veto}} = \frac{1}{\sigma_{\text{NLO}}^2} \int_{p_{T,j}}^{\infty} dp_{T,j}^v \frac{d\sigma_{3}^{\text{LO}}}{dp_{T,j}^v}
\]

- red: LO $\mu_R=\mu_F=20$ GeV
- magenta: LO $\mu_R=\mu_F=40$ GeV
- blue: LO $\mu_R=\mu_F=80$ GeV
Higgs plus three jets via VBF at LO

Central Jet Veto at LO

- Scale variation at LO for $\sigma_3$: $+33\%$ to $-17\%$ for $p_{T,veto} = 15$ GeV
- Theoretical uncertainty in $\text{Prob}_{veto}$ feeds into the uncertainty in determining couplings.
- In order to constrain couplings more precisely, compute the NLO QCD corrections to $Hjjj$

Higgs plus three jets via VBF at NLO
Born amplitude

\[ \mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \begin{bmatrix} \mathcal{M}_{B,1a} : \\
\mathcal{M}_{B,2b} : \end{bmatrix} \]

\[ + \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \begin{bmatrix} \mathcal{M}_{B,1a} : \\
\mathcal{M}_{B,2b} : \end{bmatrix} \]
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

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

\[
\text{Box} = \delta_{i_2 i_b} t_{i_1 i_a}^{a_3} \left[ \begin{array}{c} \text{Box}(1a) : \end{array} \right]
\]

\[
+ \delta_{i_1 i_a} t_{i_2 i_b}^{a_3} \left[ \begin{array}{c} \text{Box}(2b) : \end{array} \right]
\]
Neglected hexagons and pentagons

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

$$\text{Hex}(1a) + \text{Pent}(1a) = \{ \text{diagram images} \}$$
Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Neglected hexagons and pentagons

\[ 2 \text{ Re} \left[ \mathcal{M}_V \mathcal{M}_B^* \right] = d_F^2 C_F^2 \left( \text{Re} \left[ (\text{Box}(1a)) \mathcal{M}_B^{*,1a} \right] + \frac{d_F^2 C_F^2}{d_G} \text{Re} \left[ (\text{Hex}(1a) + \text{Pent}(1a)) \mathcal{M}_B^{*,2b} \right] + \frac{d_F^2 C_F^2}{d_G} \text{Re} \left[ (\text{Hex}(2b) + \text{Pent}(2b)) \mathcal{M}_B^{*,1a} \right] \]
Higgs plus three jets via VBF at NLO
Virtual and Real Corrections

\[ M_4 = \]
Introduction

Virtual and Real Corrections

Treat Real Corrections Consistently!

\[ |\mathcal{M}_4|^2 = d_F^2 C_F^2 \left\{ \left| \begin{array}{cc} \text{hexagon} & \text{pentagon} \\ \end{array} \right|^2 + \left| \begin{array}{cc} \text{hexagon} & \text{pentagon} \\ \end{array} \right|^2 + \cdots \right\} \]

\[ + \frac{d_F^2 C_F^2}{d_G} 2 \text{ Re } \left\{ \left( \begin{array}{cc} \text{hexagon} & \text{pentagon} \\ \end{array} \right) \left( \begin{array}{cc} \text{hexagon} & \text{pentagon} \\ \end{array} \right)^* + \cdots \right\} \]

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

\[ \Delta_{NLO} \propto 2 \Re \left[ (M_{B,1a})(M_{B,2b})^* \right] \]

Left: \( \Delta \sigma_{3}^{NLO} \) (solid) and \( \sigma_{3}^{LO} \) (dashes).
Right: \( R(y_{rel}) = \Delta_{NLO}/LO \)
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

- $\alpha$ cut on the PS of the dipoles
  

- 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.
VBF H + 2 jets at NLO

VBF H + 3 jets at NLO

Conclusions

NLO vs LO

VBF Selection Cuts

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

\[
p_{T\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.5, \quad \triangle R_{j\ell} \geq 0.6
\]

\[
y_{j,\text{min}}^{\text{tag}} + 0.6 < \eta_{\ell_{1,2}}^{\text{tag}} < y_{j,\text{max}}^{\text{tag}} - 0.6.
\]
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:
  \[ m_{jj} = (p_j^{\text{tag} 1} + p_j^{\text{tag} 2})^2 > 600 \text{ GeV} \]
**NLO vs LO**

**Total Cross section**

\[ \mu_0 = 40 \text{ GeV} \]
\[ \xi = 2^{\pm 1} \text{ scale variations:} \]
- **LO:** +26\% to −19\%
- **NLO:** less than 5\%

- **solid:** NLO $\mu_R = \mu_F = \xi \mu_0$
- **dashes:** NLO $\mu_R = \xi \mu_0$
- **dotdash:** NLO $\mu_F = \xi \mu_0$
- **dots:** LO $\mu_R = \mu_F = \xi \mu_0$

**Total Cross section**

\[ \sigma_{\text{cuts}} [\text{fb}] \]

- $\mu_0 = 40 \text{ GeV}$
- $\xi = 2^{\pm 1}$
- Scale variations:
  - **LO:** +26\% to −19\%
  - **NLO:** less than 5\%

**Introduction**

- VBF $H + 2$ jets at NLO
- VBF $H + 3$ jets at NLO

**Conclusions**

NLO vs LO

Total Cross section
NLO vs LO

K-factor and relative change

\[ K(x) = \frac{d\sigma_{3\text{NLO}}^{\text{NLO}}(\mu_R = \mu_F = \xi \mu_0)/dx}{d\sigma_{3\text{LO}}^{\text{LO}}(\mu_R = \mu_F = \mu_0)/dx} \]

relative change = \[ \frac{d\sigma_{3}(\mu_R = \mu_F = \xi \mu_0)/dx}{d\sigma_{3}(\mu_R = \mu_F = \mu_0)/dx} \]
Tagging Jet Distributions

Tagging Jet Rapidity Separation

\[ \frac{d\sigma}{d\Delta y_{jj}} \text{ [fb]} \]

\[ \Delta y_{jj} \]

Relative change

\[ \xi = 0.5 \]

\[ \xi = 2 \]
Tagging Jet Invariant mass

$d\sigma/dm_{jj}[fb/GeV]$ vs $m_{jj}[GeV]$ for different values of $\xi$. The plots show the relative change between LO and NLO predictions for different $\xi$ values.

- Solid line: K-factor
- Dots: LO
- Dashes: NLO
NLO vs LO
Veto Jet Distributions

Veto Jet Rapidity: \( y_{\text{rel}} = y_{j_{\text{veto}}} - \frac{(y_{j_{\text{tag} \ 1}} + y_{j_{\text{tag} \ 2}})}{2} \)

\[ p_{Tj} > 20 \ \text{GeV}, \quad y_{j_{\text{veto}}} \in (y_{j_{\text{tag} \ 1}}, y_{j_{\text{tag} \ 2}}) \]
**Veto Jet $P_T$**

\[
p_{T_j}^{\text{veto}} > 20 \text{ GeV}, \quad y_j^{\text{veto}} \in (y_j^{\text{tag } 1}, y_j^{\text{tag } 2})
\]
NLO vs LO
Veto Jet Distributions

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

\[ \text{red: } \mu_R=\mu_T=20 \text{ GeV} \]
\[ \text{magenta: } \mu_R=\mu_F=40 \text{ GeV} \]
\[ \text{blue: } \mu_R=\mu_F=80 \text{ GeV} \]
\[ \text{dashes: LO} \]
\[ \text{solid: NLO} \]
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%
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.
Conclusions

VBFNLO

VBFNLO is a parton level Monte Carlo program for Vector Boson Fusion processes.


Project members:


The program can be downloaded from

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