Higgs boson production via vector boson fusion at next–to–leading order

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Outline

SM Higgs boson

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

SM Higgs Doublet

$$\Phi = U(x)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

The remormalizable Lagrangian

$$\mathcal{L} = |D_\mu \Phi|^2 + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

leads to the vacuum expectation value $v = \sqrt{\frac{\mu^2}{\lambda}}$ for the Higgs field H.

SM Higgs boson

Higgs couplings to fermions

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

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

- 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

SM Higgs boson

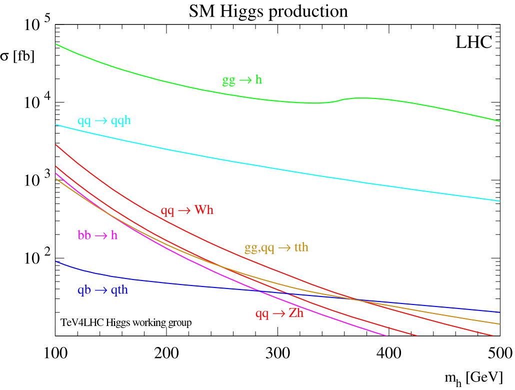
Higgs couplings to gauge bosons

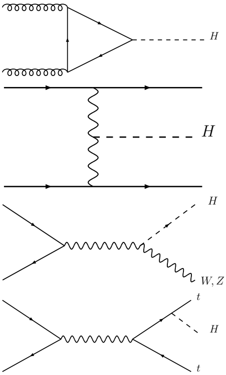
Kinetic energy term of the Higgs doublet field:

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

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

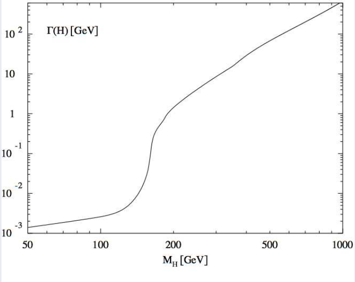
Total SM Higgs cross sections at the LHC



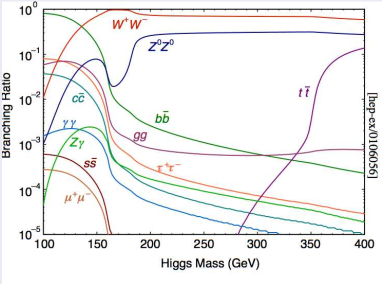


Decay of the SM Higgs

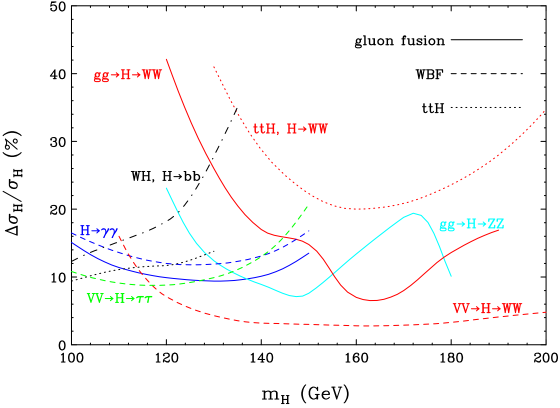
Decay width



Branching ratios



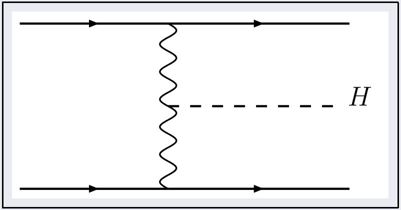
Statistical and systematic errors at the LHC



- QCD/PDF uncertainties: ±5% for VBF, ±20% for gluon fusion
- luminosity/acceptance uncertainties : ±5%

Vector Boson Fusion

Leading Order: $qQ \to HqQ$

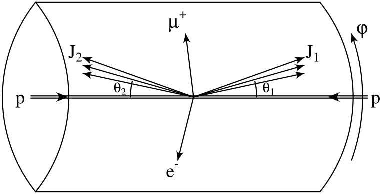


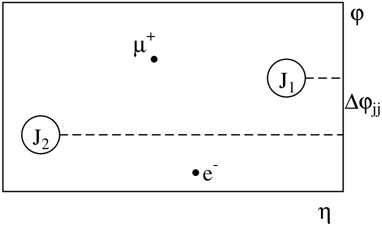
Higgs search channels:

- $H \to W^+W^-$, $m_H > 120$ 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





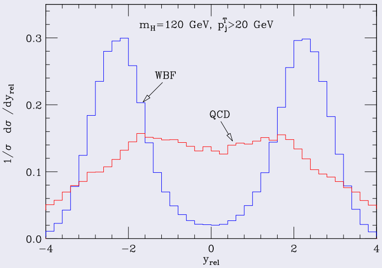
Event Characteristics

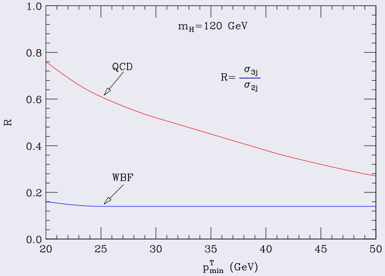
- Energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

Vector Boson Fusion

Central Jet Veto

Example: Gluon fusion vs vector boson fusion





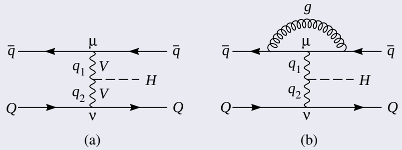
JHEP 05 (2004) 064

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

Higgs Production via Vector Boson Fusion at NLO

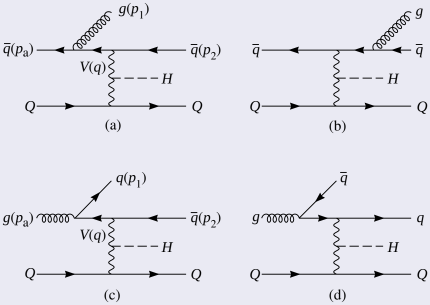
The NLO Calculation

Virtual Corrections



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

Real Corrections



Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

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

Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

Applied Cuts

- Require two hard jets with $p_{Tj} \geq 20$ GeV, $|y_j| \leq 4.5$
- Higgs decay: $p_{T\ell} \geq 20$ 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.

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

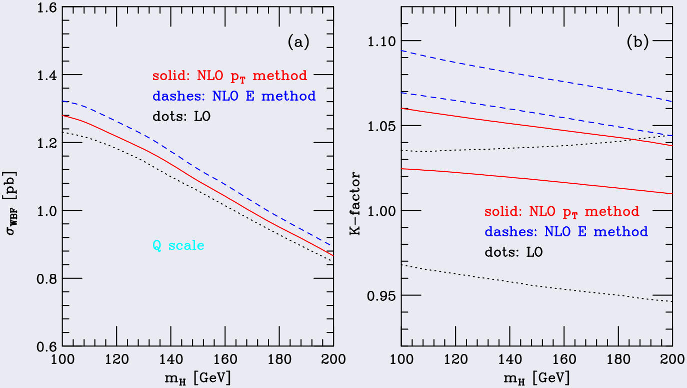
- Backgrounds to VBF are significantly suppressed by requiring a large rapidity separation of the two tagging jets.

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

Tagging Jet Selection

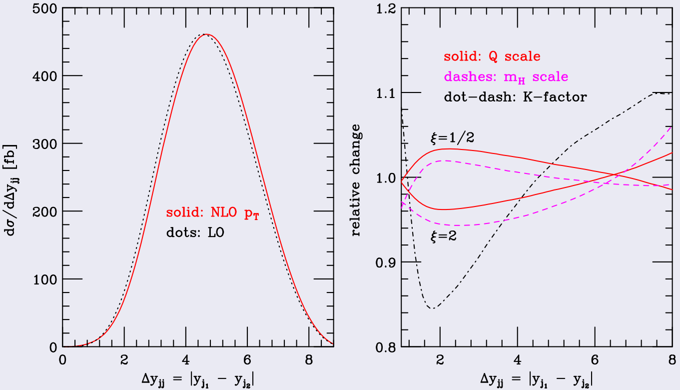
- p_T **-method**: Define the tagging jets at the two highest p_T jets in the event.
- E **-method**: Define the tagging jets as the two highest energy jets in the event.

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



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

Tagging jet rapidity separation



Tagging jets are slightly more forward at NLO than at LO

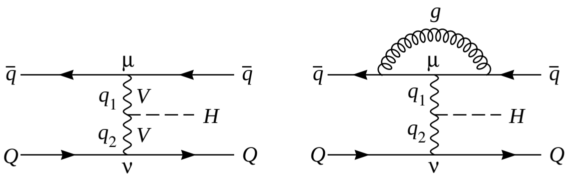
$\Downarrow$

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

Anomalous Higgs Couplings

General Tensor Structure for the *HVV* vertex

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



(a) (b)

Anomalous Higgs Couplings

General Tensor Structure for the HVV vertex

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

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

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

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)

Anomalous Higgs Couplings

General Tensor Structure for the HVV vertex

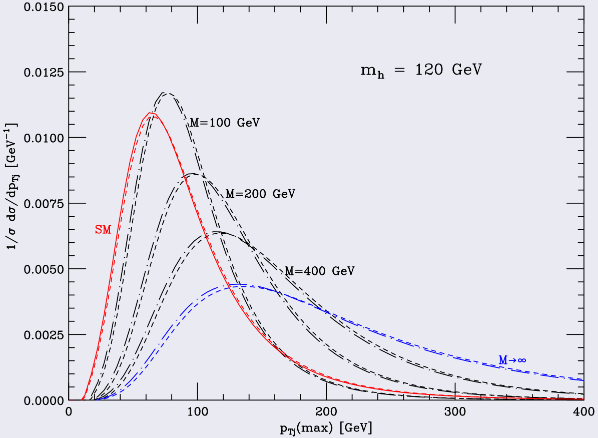
$$\begin{aligned} T^{\mu\nu}(q_1, q_2) &= a_1(q_1, q_2) g^{\mu\nu} \\ &+ a_2(q_1, q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] \\ &+ a_3(q_1, q_2)\varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma} \end{aligned}$$

Form factor dependence

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

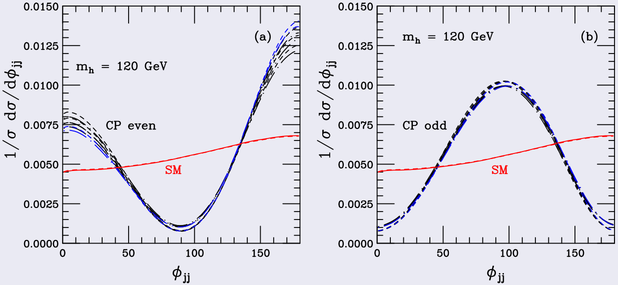
Anomalous Higgs Couplings

p_{T_j} distributions



Anomalous Higgs Couplings

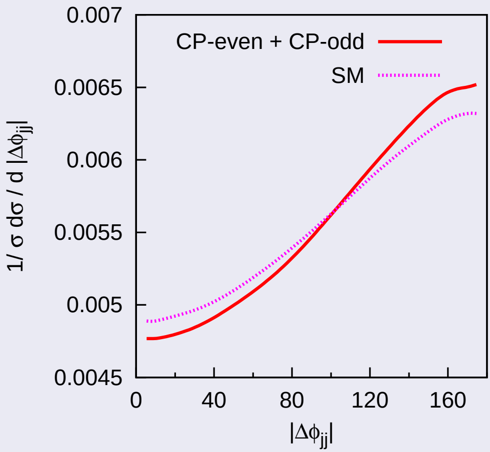
$\phi_{jj} = |\phi_{j_1} - \phi_{j_2}|$ distributions



Form factor dependence is small.

Anomalous Higgs Couplings

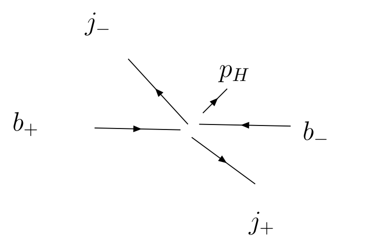
The case: $a_2 = a_3$



But, it doesn't work!

Anomalous Higgs Couplings

Redefinition of ϕ_{jj}



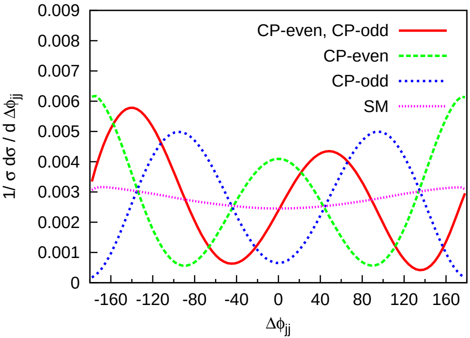
- Invariant under $(b_+, p_+) \leftrightarrow (b_-, p_-)$
- Parity odd variable

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



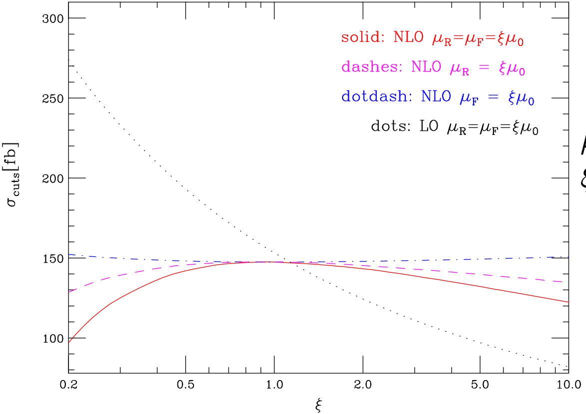
- Mixed CP case: $a_2 = a_3$, $a_1 = 0$
- Pure CP–even case: a_2 only
- Pure CP–odd case: a_3 only

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 $\alpha + \pi$

$Hjjj$ via VBF at NLO
Total Cross section



JHEP **0802** (2008) 076 [arXiv:0710.5621]

$\mu_0 = 40$ GeV

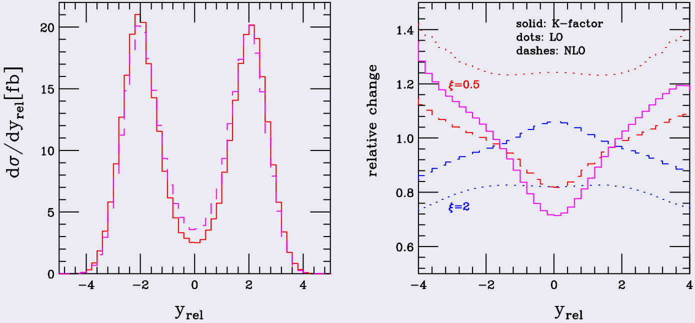
$\xi = 2^{\mp 1}$ scale variations:

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

Hjjj via VBF at NLO

Veto Jet Distributions

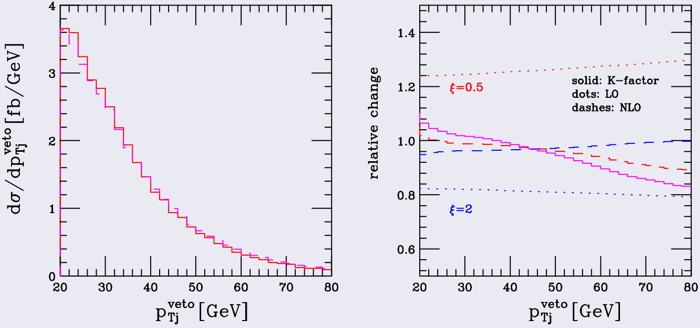
Veto Jet Rapadity



Hjjj via VBF at NLO

Veto Jet Distributions

Veto Jet P_T

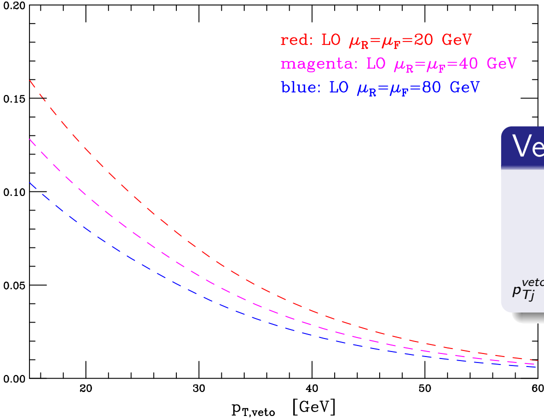


$Hjjj$ via VBF at NLO
Veto Jet Distributions

- 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 $y_{rel} = 0$.

Hjjj via VBF at NLO

Veto Probability for the VBF Signal



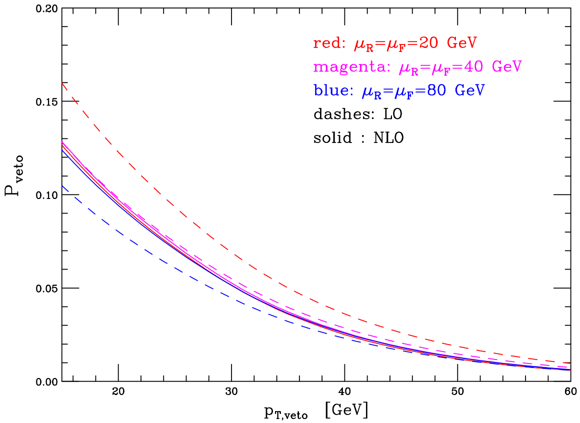
Veto Probability

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

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

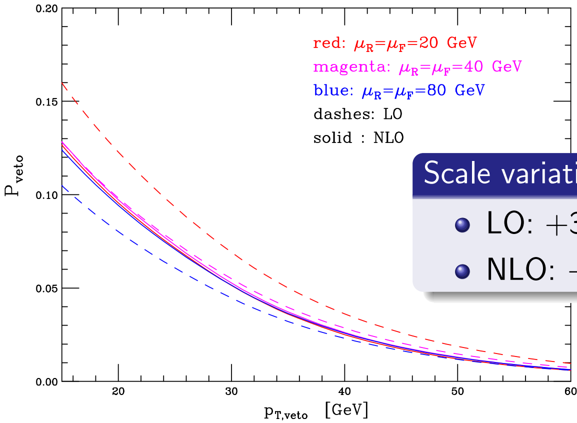
$Hjjj$ via VBF at NLO

Veto Probability for the VBF Signal



Hjjj via VBF at NLO

Veto Probability for the VBF Signal



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

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

Concluding Remarks

- In order for make full use of LHC data improved tools are required.
- The program VBFNLO is available at http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb.
- Improvements to *Hjj*: Electroweak and Susy corrections will be included in a future release of VBFNLO.
- Additional processes: Higgs boson production via VBF in association with a photon will be included in a future release of VBFNLO.