

# Higgs plus three jets via vector boson fusion at NLO QCD

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Loopfest VII, Buffalo, NY  
May 15, 2008

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



# Outline

- 1 Introduction
- 2 The NLO Calculation
- 3 NLO Results
- 4 Conclusions



# SM Higgs boson



# SM Higgs boson

Is the neutral scalar-like resonance a SM Higgs?

- CP quantum numbers ?
- Measure its couplings to gauge bosons and fermions



# SM Higgs boson

Is the neutral scalar-like resonance a SM Higgs?

- CP quantum numbers ?
- Measure its couplings to gauge bosons and fermions

$SU(2)_L$  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

## Higgs couplings to fermions

Fermion masses arise from Yukawa couplings via

$$\Phi^\dagger \rightarrow \left(0, \frac{v+H}{\sqrt{2}}\right).$$

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

- Test SM prediction:  $\bar{f}fH$  Higgs coupling strength =  $m_f/v$
- Observation of  $Hf\bar{f}$  Yukawa coupling is no proof that a v.e.v exists (maybe a scalar singlet)

# SM Higgs boson

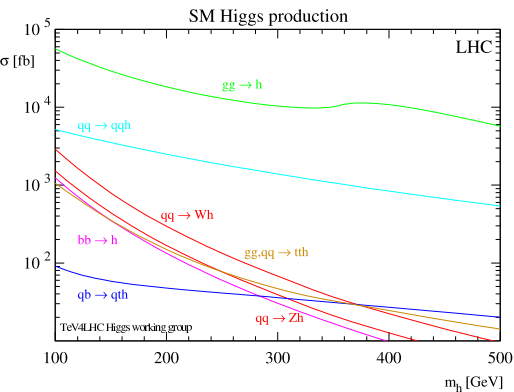
## Higgs couplings to gauge bosons

Kinetic energy term of the Higgs doublet field:

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

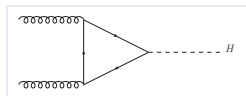
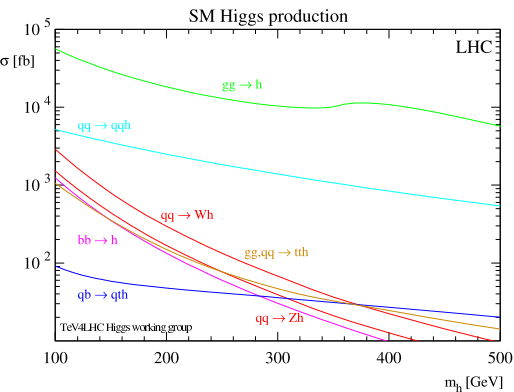
- $W, Z$  mass generation:  $m_W^2 = \left( \frac{gV}{2} \right)^2$ ,  $m_Z^2 = \frac{(g^2 + g'^2)v^2}{4}$
- $WWH$  and  $ZZH$  couplings are generated: coupling strength =  $2m_V^2/v \approx g^2 v$  within SM

# Total SM Higgs cross sections at the LHC

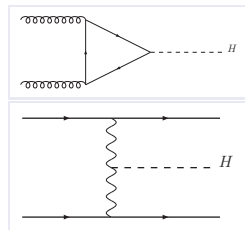
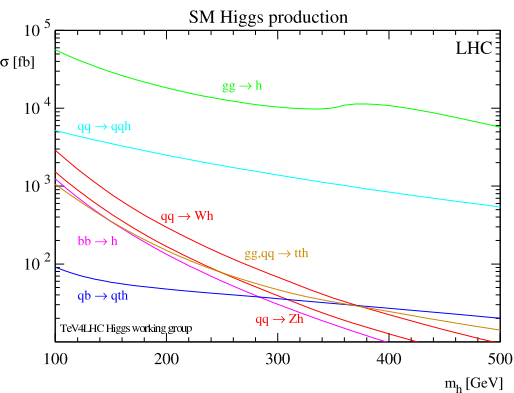




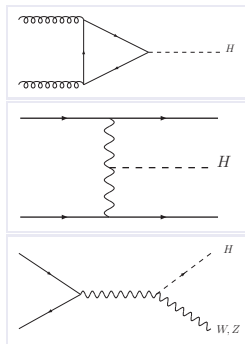
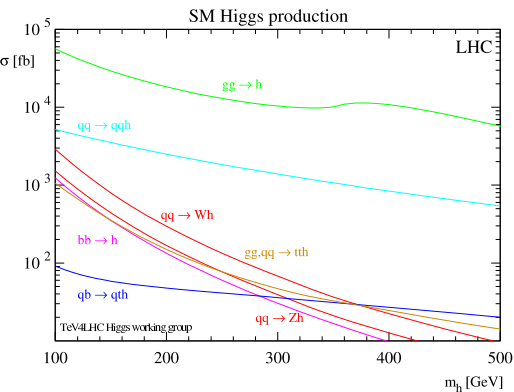
# Total SM Higgs cross sections at the LHC



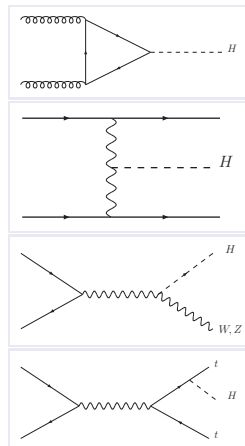
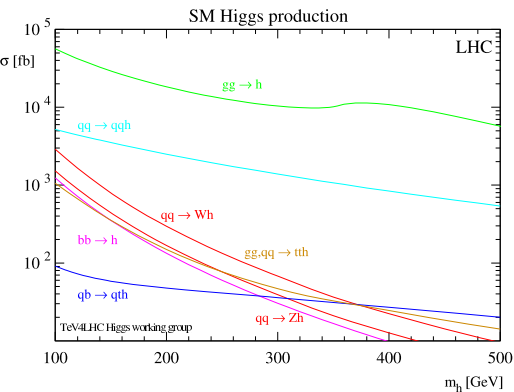
# Total SM Higgs cross sections at the LHC



# Total SM Higgs cross sections at the LHC

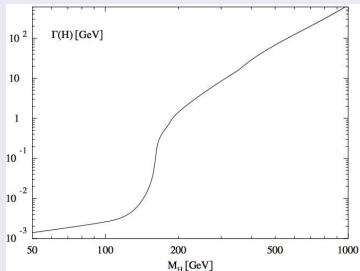


# Total SM Higgs cross sections at the LHC

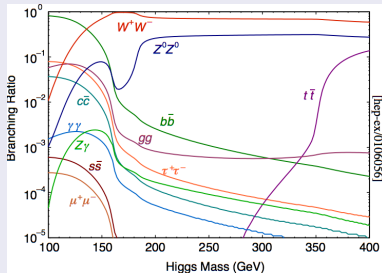


# Decay of the SM Higgs

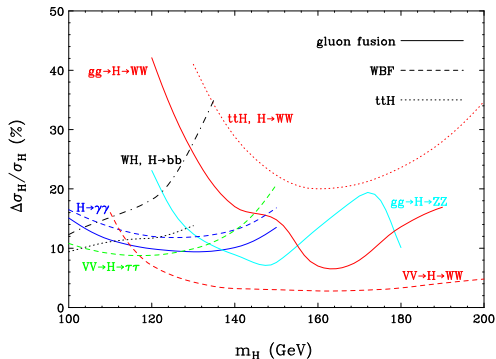
## Decay width



## Branching ratios



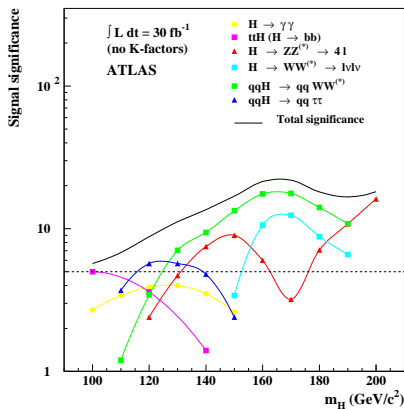
# Statistical and systematic errors at the LHC



- QCD/PDF uncertainties:
  - $\mathcal{O}(5\%)$  for WBF
  - $\mathcal{O}(20\%)$  for gluon fusion
- luminosity/acceptance uncertainties :  $\mathcal{O}(5\%)$

hep-ph/0203187

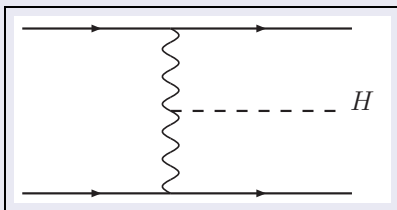
# Discovery potential



hep-ph/0402254

# Vector Boson Fusion

Leading Order:  $qQ \rightarrow HqQ$



Higgs search channels:

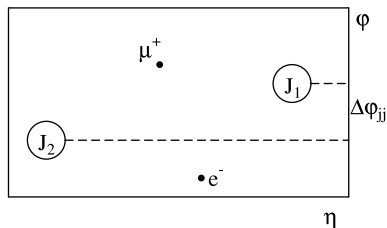
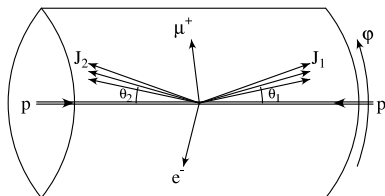
- $H \rightarrow W^+W^-$ ,  
 $m_H > 120 \text{ GeV}$
- $H \rightarrow \tau^+\tau^-$ ,  
 $m_H < 140 \text{ GeV}$
- $H \rightarrow \gamma\gamma$ ,  
 $m_H < 150 \text{ GeV}$

Eboli,Hagiwara,Kauer,Plehn,

Rainwater,Zeppenfeld,...



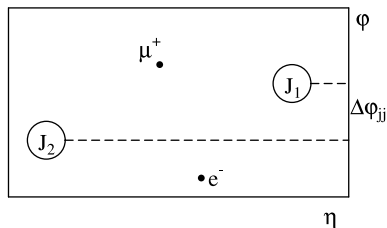
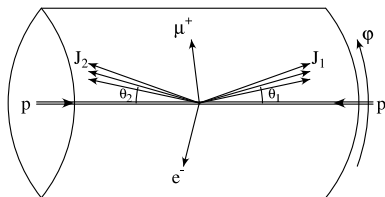
# Vector Boson Fusion



## Event Characteristics

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

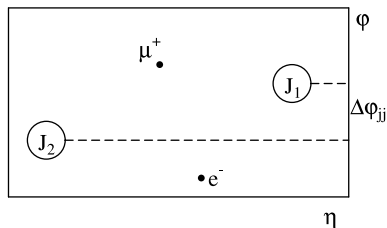
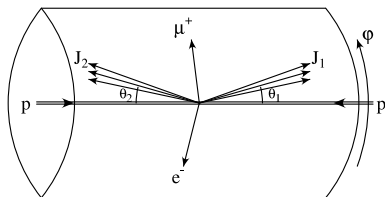
# Vector Boson Fusion



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- 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

## 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

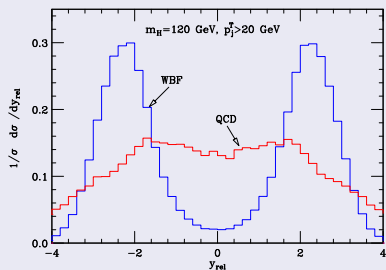
[hep-ph/9412276](#), [hep-ph/0012351](#)

Events are discarded if any additional jet satisfies the criteria:

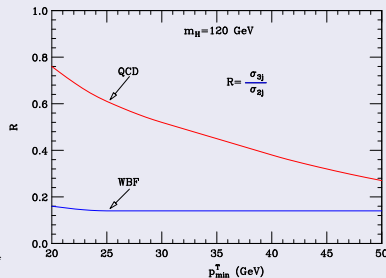
$$p_{Tj}^{\text{veto}} > p_{T,\text{veto}}, \quad y_j^{\text{veto}} \in (y_j^{\text{tag } 1}, y_j^{\text{tag } 2})$$

# Vector Boson Fusion

## Gluon fusion vs vector boson fusion



JHEP 05 (2004) 064



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

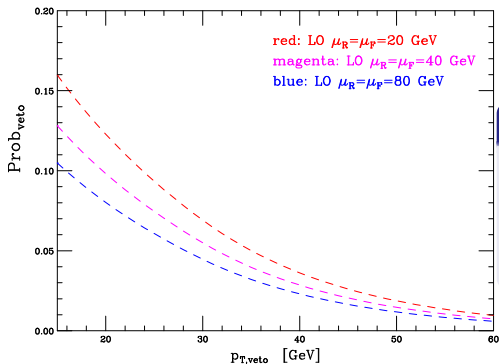
# Higgs plus three jets via VBF at LO

## Born amplitude

$$\mathcal{M}_B = \delta_{i_2 i_b} t_{i_1 i_a}^{a_3} \left[ \mathcal{M}_{B,1a} : \begin{array}{c} \text{3} \\ \text{a} \text{---} \text{1} \\ \text{---} \text{H} \\ \text{b} \text{---} \text{2} \end{array} \right] + \delta_{i_1 i_a} t_{i_2 i_b}^{a_3} \left[ \mathcal{M}_{B,2b} : \begin{array}{c} \text{a} \text{---} \text{1} \\ \text{---} \text{H} \\ \text{b} \text{---} \text{2} \end{array} \right]$$

# Higgs plus three jets via VBF at LO

## Veto Probability



### Veto Probability

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

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

# Higgs plus three jets via VBF at LO

## Veto Probability

- Scale variation at LO for  $\sigma_3$ :  $+33\%$  to  $-17\%$  for  $p_{T,veto} = 15 \text{ GeV}$
- 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  $H_{jjj}$**





# Higgs plus three jets via VBF at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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



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



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

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



# Higgs plus three jets via VBF at NLO

## Virtual and Real Corrections

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

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



# Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

## Box+Vertex+Propagator corrections

$$\begin{aligned}
 \mathbf{Box} &= \delta_{i_2 i_b} t_{i_1 i_a}^{a_3} \left[ \mathbf{Box(1a)} : \begin{array}{ccc} \text{Diagram 1} & \text{Diagram 2} & \text{Diagram 3} \end{array} \right] \\
 &+ \delta_{i_1 i_a} t_{i_2 i_b}^{a_3} \left[ \mathbf{Box(2b)} : \begin{array}{ccc} \text{Diagram 4} & \text{Diagram 5} & \text{Diagram 6} \end{array} \right]
 \end{aligned}$$

The diagrams show various box, vertex, and propagator corrections to the VBF process. Each diagram consists of two incoming quark lines (1 and 2) and two outgoing quark lines (1 and 2). A wavy line represents a Higgs boson, and a dashed line represents a gluon. The diagrams are arranged in two rows: Box(1a) and Box(2b). Each row contains three diagrams. In the first row, the Higgs boson is attached to the top quark line, and the gluon is attached to the bottom quark line. In the second row, the Higgs boson is attached to the bottom quark line, and the gluon is attached to the top quark line. The diagrams show different ways the Higgs and gluon lines can interact with the quark lines, including box diagrams, vertex corrections, and propagator corrections.

# 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 ( $d_F = 3$ ,  $d_G = 8$ ).

$$\mathbf{Hex}(1\mathbf{a}) + \mathbf{Pent}(1\mathbf{a}) = \left\{ \begin{array}{ll} \begin{array}{c} \text{Diagram 1: } a \text{ and } b \text{ lines, red gluon loop, green gluon emission from } a, \text{ wavy boson } 1, \text{ dashed } 2 \end{array} & \begin{array}{c} \text{Diagram 2: } a \text{ and } b \text{ lines, red gluon loop, green gluon emission from } b, \text{ wavy boson } 1, \text{ dashed } 2 \end{array} \\ \begin{array}{c} \text{Diagram 3: } a \text{ and } b \text{ lines, red gluon loop, green gluon emission from } a, \text{ wavy boson } 1, \text{ dashed } 2 \end{array} & \begin{array}{c} \text{Diagram 4: } a \text{ and } b \text{ lines, red gluon loop, green gluon emission from } b, \text{ wavy boson } 1, \text{ dashed } 2 \end{array} \end{array} \right.$$

# Higgs plus three jets via VBF at NLO

## Virtual and Real Corrections

### Neglected hexagons and pentagons

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

# Higgs plus three jets via VBF at NLO

## Virtual and Real Corrections

### Real Corrections

$$\mathcal{M}_4 = \left\{ \begin{array}{cccc} \text{Diagram 1} & \text{Diagram 2} & \text{Diagram 3} & \text{Diagram 4} \\ \text{Diagram 5} & \text{Diagram 6} & \text{Diagram 7} & \text{Diagram 8} \\ \text{Diagram 9} & \text{Diagram 10} & \text{Diagram 11} & \text{Diagram 12} \end{array} \right\}$$

The figure shows a set of 12 Feynman diagrams for real corrections to the Higgs plus three jets process via vector boson fusion (VBF). The diagrams are arranged in a 3x4 grid. Each diagram features a central wavy line representing a Higgs boson, with two external lines labeled 'a' and 'b' representing the incoming quarks. Three additional lines represent outgoing jets, labeled '1', '2', and '3'. The diagrams illustrate various real emission topologies, including gluon and quark emissions from the quark lines and from the Higgs boson itself. The diagrams are grouped by large curly braces on the left and right sides, indicating they contribute to the total amplitude  $\mathcal{M}_4$ .



# Higgs plus three jets via VBF at NLO

## Virtual and Real Corrections

Treat Real Corrections Consistently!

$$\begin{aligned}
 |\mathcal{M}_4|^2 &= d_F^2 C_F^2 \left\{ \left| \text{Diagram 1} \right|^2 + \left| \text{Diagram 2} \right|^2 + \dots \right\} \\
 &+ \frac{d_F^2 C_F^2}{d_G} 2 \operatorname{Re} \left\{ \left( \text{Diagram 1} \right) \left( \text{Diagram 2} \right)^* + \dots \right\}
 \end{aligned}$$

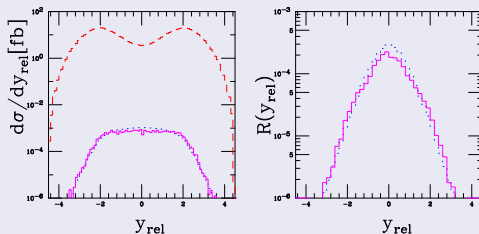
The term  $\propto 1/d_G$  when integrated over PS gives rise to a soft divergence. This soft divergence is cancelled against the soft divergence arising from the hexagons and pentagons. **For consistency, this term is also neglected.**

# Higgs plus three jets via VBF at NLO

## Virtual and Real Corrections

### Error Estimate on the Approximation

$$\Delta\text{NLO} \propto 2 \operatorname{Re} [(\mathcal{M}_{B,1a})(\mathcal{M}_{B,2b})^*]$$



Left:  $\Delta\sigma_3^{NLO}$  (solid) and  $\sigma_3^{LO}$  (dashes).

Right:  $R(y_{\text{rel}}) = \Delta\text{NLO}/\text{LO}$

# 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 Higgsstrahlung is very small in the VBF PS region. [C. Georg](#); [Smillie, Anderson, Binoth, Heinrich](#); [Ciccolini, Denner, Dittmaier](#)
  - Hence, Higgsstrahlung 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](https://arxiv.org/abs/hep-ph/9605323)
- $\alpha$  cut on the PS of the dipoles [hep-ph/0307268](https://arxiv.org/abs/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  $p_{Tj} \geq 20$  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:

$$p_{T\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.5, \quad \Delta R_{j\ell} \geq 0.6$$

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

# NLO vs LO

## VBF Selection Cuts

- Rapidity gap and opposite detector hemispheres:

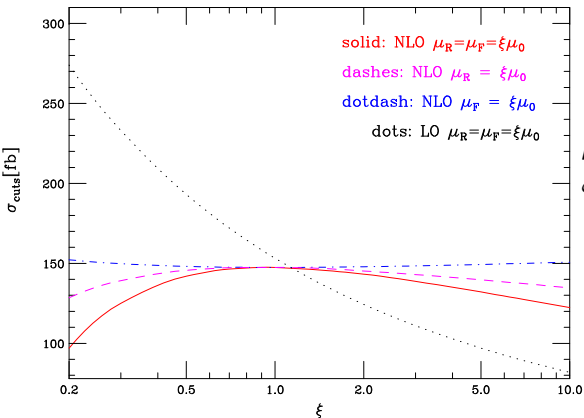
$$y_j^{\text{tag } 1} \cdot y_j^{\text{tag } 2} < 0$$
$$\Delta y_{jj} = |y_j^{\text{tag } 1} - y_j^{\text{tag } 2}| > 4$$

- 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



$\mu_0 = 40 \text{ GeV}$

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

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

# NLO vs LO

## K-factor and relative change

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

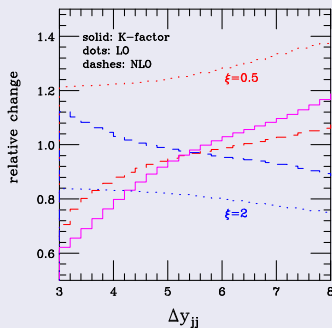
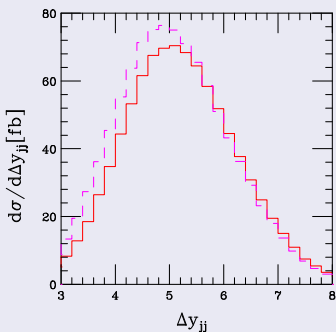
$$\text{relative change} = \frac{d\sigma_3(\mu_R = \mu_F = \xi\mu_0)/dx}{d\sigma_3(\mu_R = \mu_F = \mu_0)/dx}$$



# NLO vs LO

## Tagging Jet Distributions

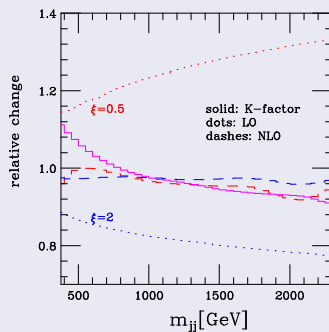
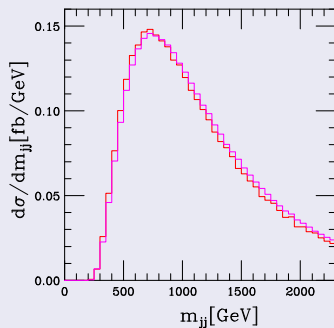
### Tagging Jet Rapidity Separation



# NLO vs LO

## Tagging Jet Distributions

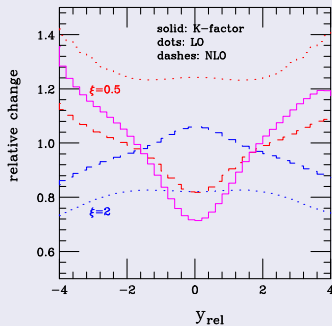
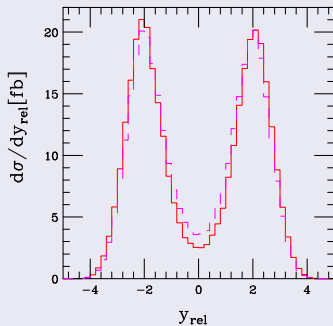
### Tagging Jet Invariant mass



# NLO vs LO

## Veto Jet Distributions

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



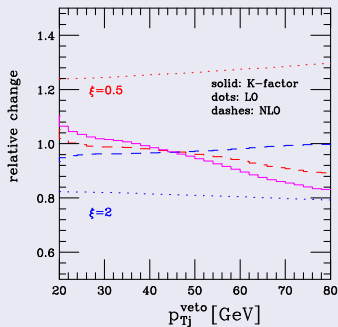
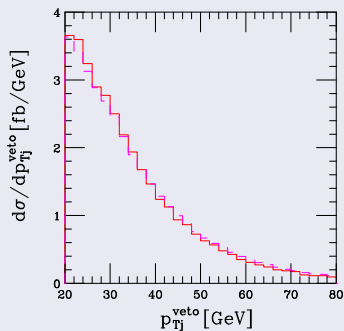
$$p_{Tj}^{\text{veto}} > 20 \text{ GeV},$$

$$y_j^{\text{veto}} \in (y_j^{\text{tag } 1}, y_j^{\text{tag } 2})$$

# NLO vs LO

## Veto Jet Distributions

### Veto Jet $P_T$



$$p_{Tj}^{\text{veto}} > 20 \text{ GeV},$$

$$y_j^{\text{veto}} \in (y_j^{\text{tag } 1}, y_j^{\text{tag } 2})$$

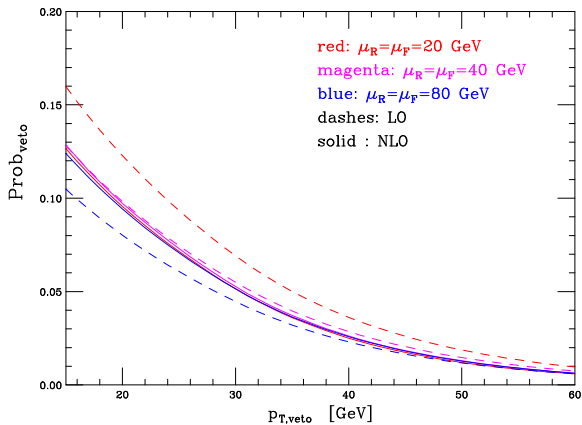
# NLO vs LO

## Veto Jet Distributions

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

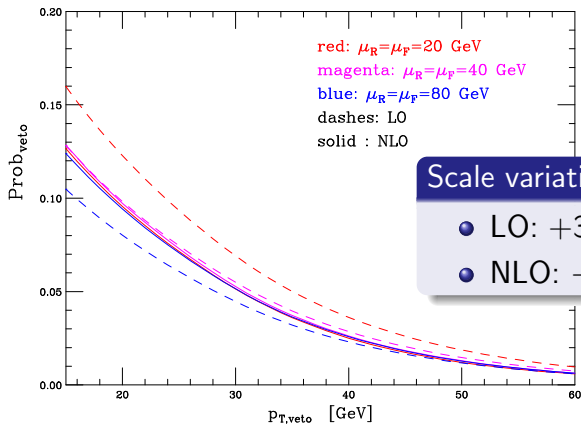
# NLO vs LO

## Veto Probability for the VBF Signal



# 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

- The dominant NLO QCD corrections have been computed for VBF  $Hjjj$  in the form of a fully flexible NLO partonic Monte Carlo program.
- Scale dependence is **reduced** for the total cross section and distributions at NLO.
- QCD corrections are small while  $K$  factors are **phase space dependent**.