Higgs plus three jets via vector boson fusion at NLO QCD

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In collaboration with V. Hankele and D. Zeppenfeld
JHEP **0802** (2008) 076 [arXiv:0710.5621]

Outline

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SM Higgs boson

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Is the neutral scalar-like resonance a SM Higgs?

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

SM Higgs boson

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

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

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

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SM Higgs boson

Higgs couplings to fermions

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

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

- 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 (maybe a scalar singlet)

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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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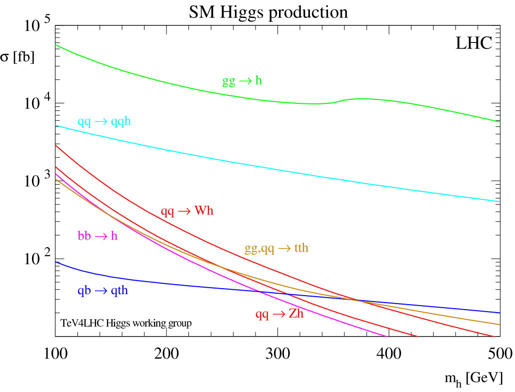
Total SM Higgs cross sections at the LHC



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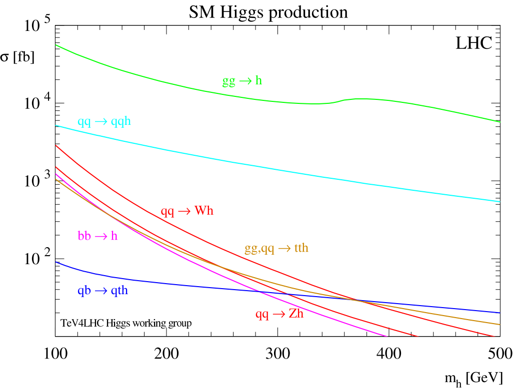

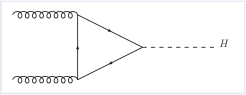

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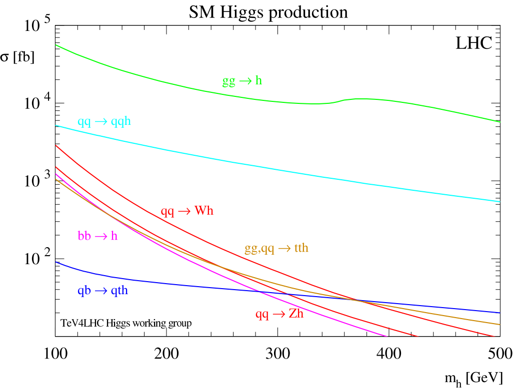

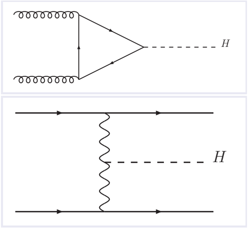

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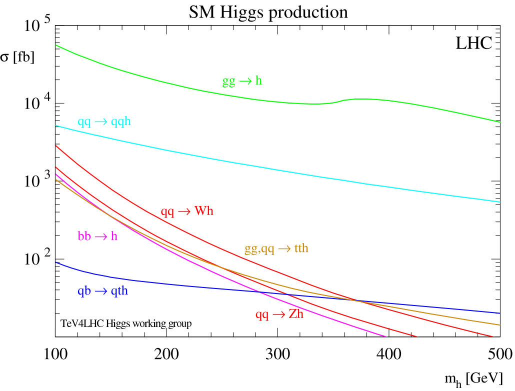

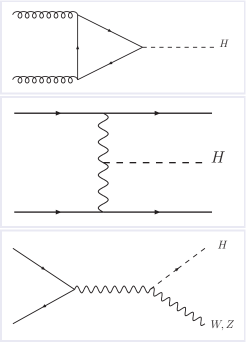

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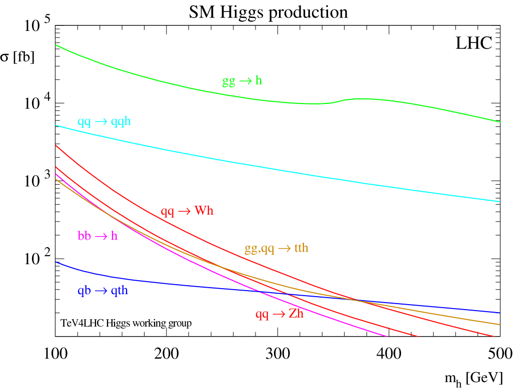
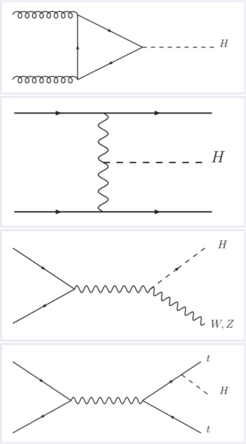
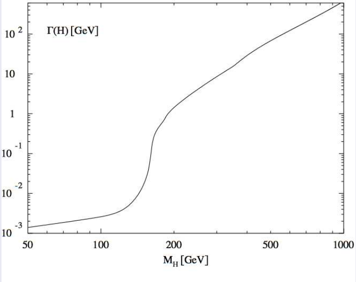
Total SM Higgs cross sections at the LHC



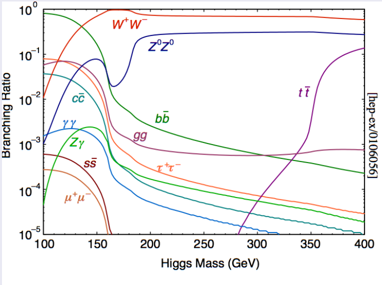


Decay of the SM Higgs

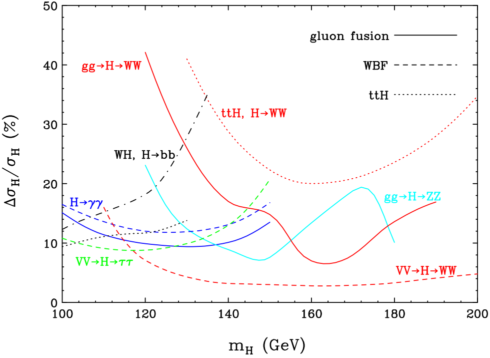
Decay width



Branching ratios



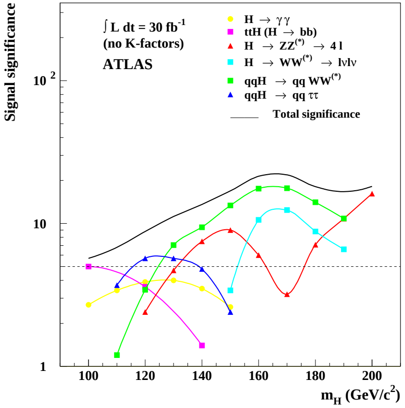
Statistical and systematic errors at the LHC



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

hep-ph/0203187

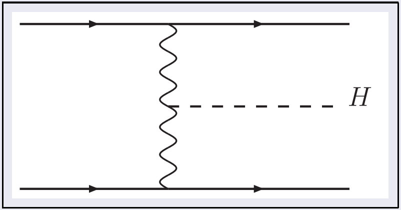
Discovery potential



hep-ph/0402254

Vector Boson Fusion

Leading Order: $qQ \to HqQ$



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, . . .

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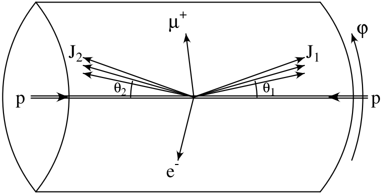
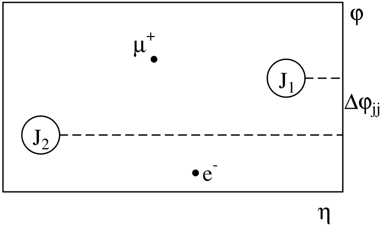
Vector Boson Fusion

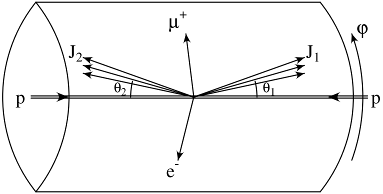


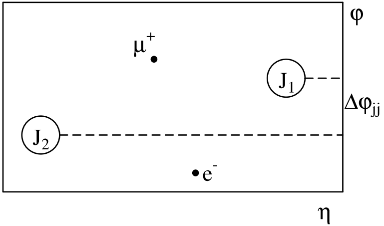


Event Characteristics

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

Vector Boson Fusion

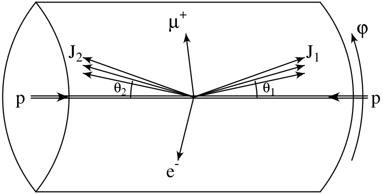


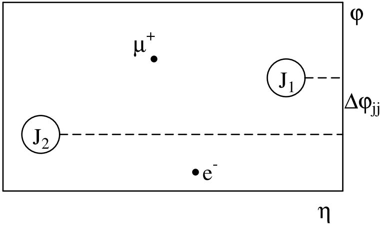


Event Characteristics

- 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

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

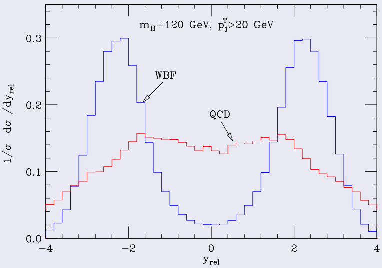
hep-ph/9412276, hep-ph/0012351

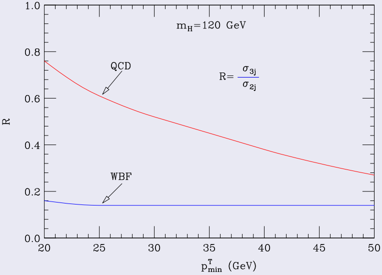
Events are discarded if any additional jet satisfies the criteria:

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

Vector Boson Fusion

Gluon fusion vs vector boson fusion





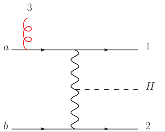
JHEP 05 (2004) 064

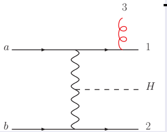
$$y_{\rm rel} = y_j^{\rm veto} - (y_j^{\rm tag\ 1} + y_j^{\rm tag\ 2})/2$$

Higgs plus three jets via VBF at LO

Born amplitude

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





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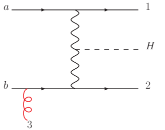
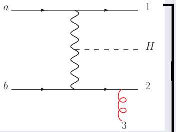
$$+ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} :$$





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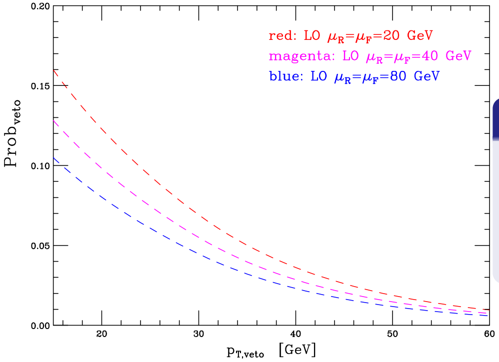
Higgs plus three jets via VBF at LO

Veto Probability



Veto Probability

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

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

Higgs plus three jets via VBF at LO

Veto Probability

- 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*

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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Higgs plus three jets via VBF at NLO
Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

Higgs plus three jets via VBF at NLO
Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

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.

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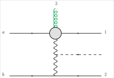
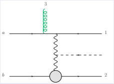
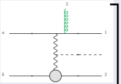
Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Box+Vertex+Propagator corrections

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

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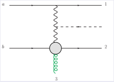
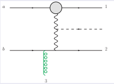
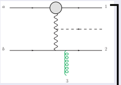
$$+ \; \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\textbf{Box(2b)} :$$

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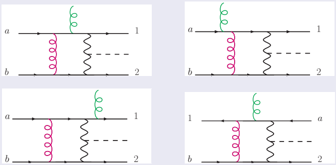
Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Neglected hexagons and pentagons

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

$$\textbf{Hex(1a)} + \textbf{Pent(1a)} = \left\{ \right.$$



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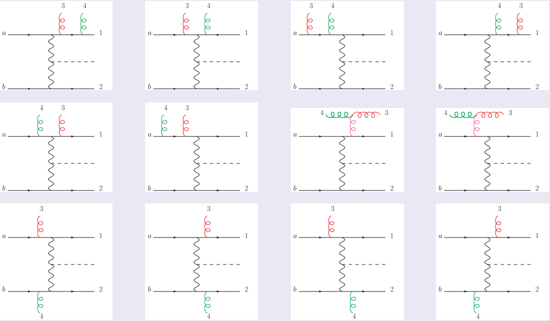
Higgs plus three jets via VBF at NLO
Virtual and Real Corrections

Real Corrections

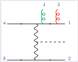
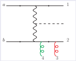
$$\mathcal{M}_4 = \left\{ \quad \right\}$$

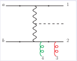
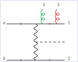


Higgs plus three jets via VBF at NLO

Virtual and Real Corrections

Treat Real Corrections Consistently!

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

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

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.

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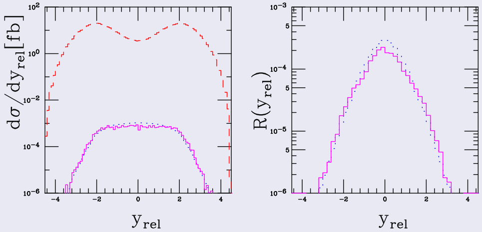
Higgs plus three jets via VBF at NLO
Virtual and Real Corrections

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 ($VHj \to Hjjj$) 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 $p_{Tj} \geq 20$ 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:

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

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

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NLO vs LO

VBF Selection Cuts

- Rapidity gap and opposite detector hemispheres:

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

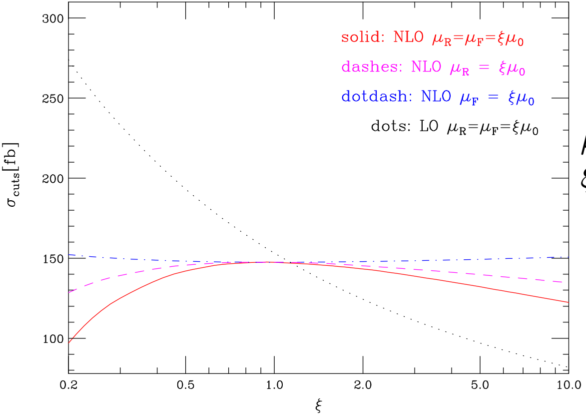
$$\Delta y_{jj} = |y_j^{\text{tag } 1} - y_j^{\text{tag } 2}| > 4$$

- 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

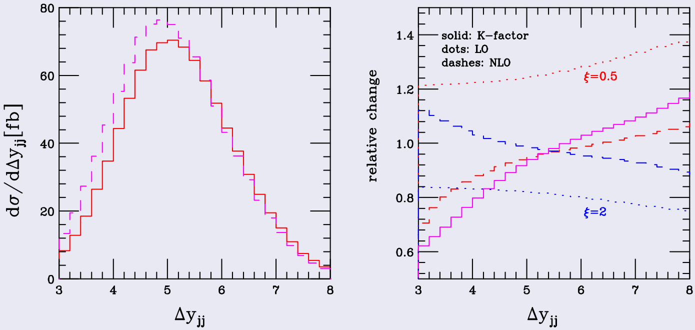
$$K(x) = \frac{d\sigma_3^{NLO}(\mu_R = \mu_F = \xi\mu_0)/dx}{d\sigma_3^{LO}(\mu_R = \mu_F = \mu_0)/dx}$$

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

NLO vs LO

Tagging Jet Distributions

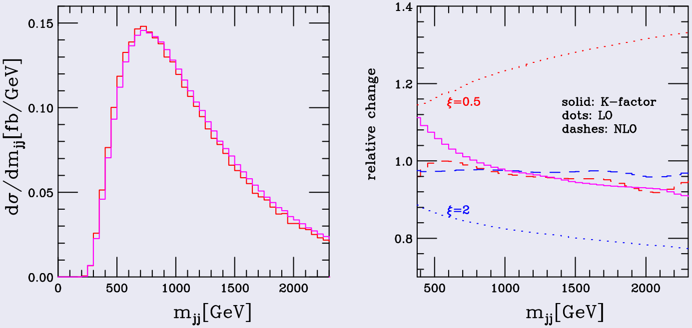
Tagging Jet Rapidity Separation



NLO vs LO

Tagging Jet Distributions

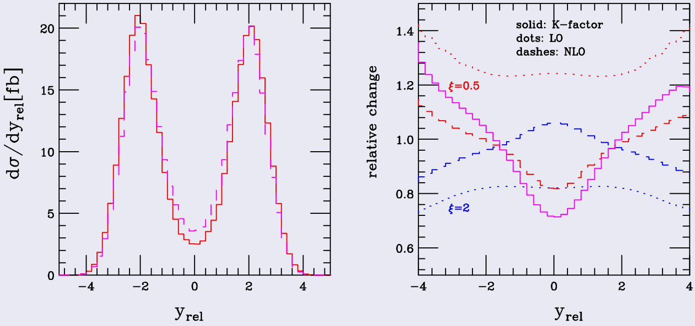
Tagging Jet Invariant mass



NLO vs LO

Veto Jet Distributions

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

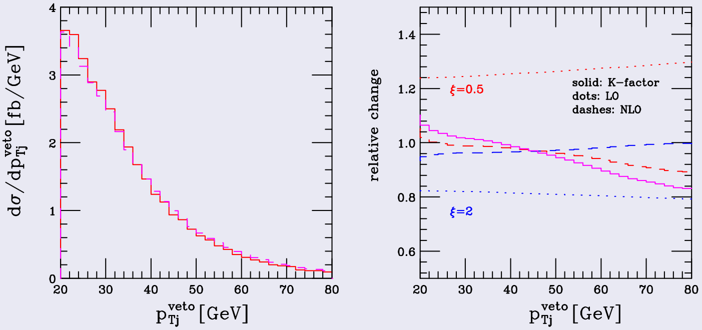


$$p_{Tj}^{\rm veto} > 20\ {\rm GeV}, \qquad y_j^{\rm veto} \in (y_j^{\rm tag\ 1}, y_j^{\rm tag\ 2})$$

NLO vs LO

Veto Jet Distributions

Veto Jet P_T



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

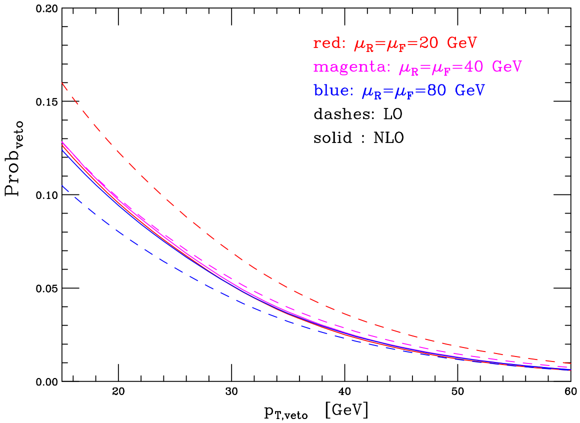
NLO vs LO

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 $y_{rel} = 0$.

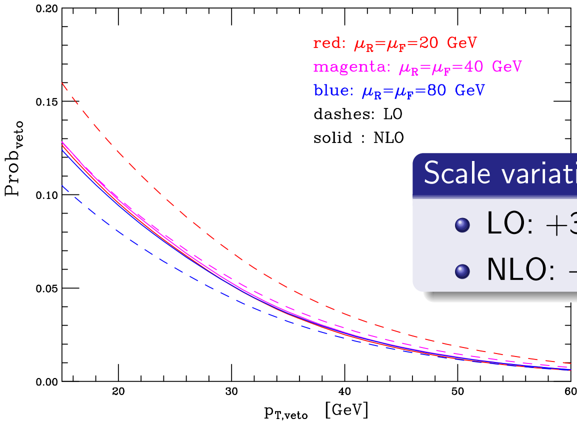
NLO vs LO

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%

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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.