Higgs boson production via vector boson fusion

Dr. Terrance Figy

NAFUM Research Fellow
The University of Manchester

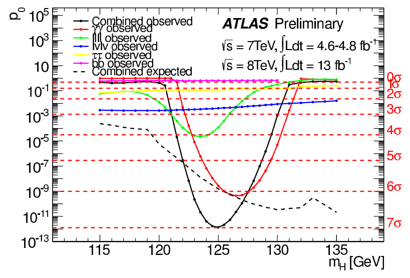
8th LNF Mini-workshop series:
Challenges in Higgs Phenomenology
24 January 2013 INFN - Laboratori Nazionali di Frascati

Outline

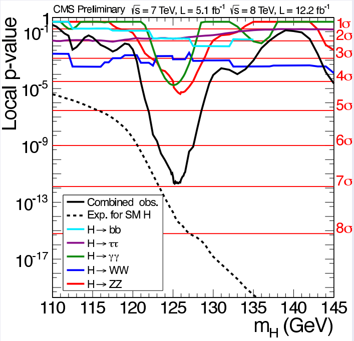
1. Overview
    - Standard Model Higgs Boson
    - Higgs Boson Production and Decay
2. Higgs Boson Production via Vector Boson Fusion
3. Results
    - Hjj via VBF at NLO
    - Anomalous Higgs Boson Couplings
    - $Hjjj$ via VBF at NLO
4. Concluding Remarks

Happy Higgsdependence Day!

"I think we have it" -Rolf-Dieter Heuer, 4 July 2012



ATLAS-CONF-2012-170



CMS-PAS-HIG-12-045

SM Higgs boson

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

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

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

- 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

SM Higgs boson

Higgs couplings to gauge bosons

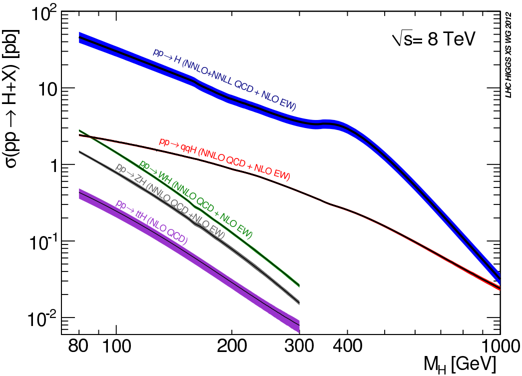
Kinetic energy term of the Higgs doublet field:

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2}\partial^\mu H \partial_\mu H \quad + \quad \left[\left(\frac{gv}{2}\right)^2 W^{\mu +} W^-_\mu \right.$$

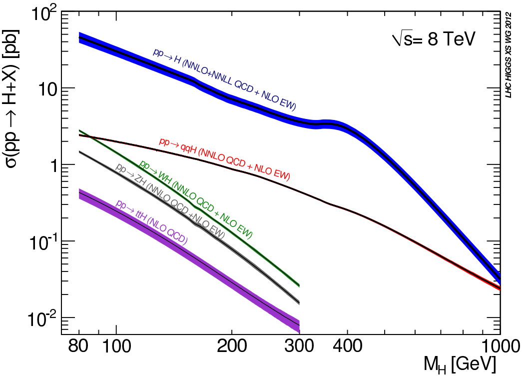
$$\left. + \quad \frac{1}{2} \frac{(g^2 + g'^2)v^2}{4} Z^\mu Z_\mu \right] \left(1 + \frac{H}{v}\right)^2$$

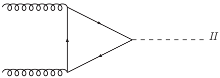
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated:coupling strength $= 2m_V^2/v \approx g^2 v$ within SM

Total SM Higgs cross sections at the LHC

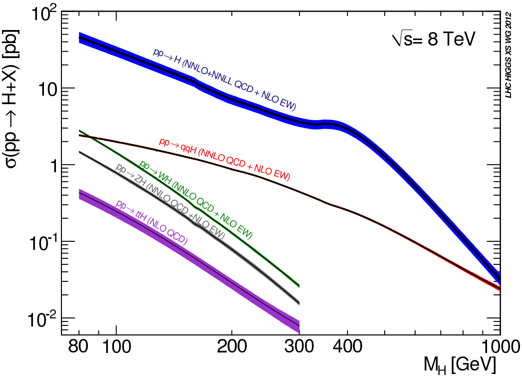


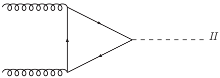
Total SM Higgs cross sections at the LHC

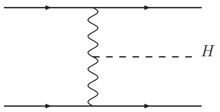




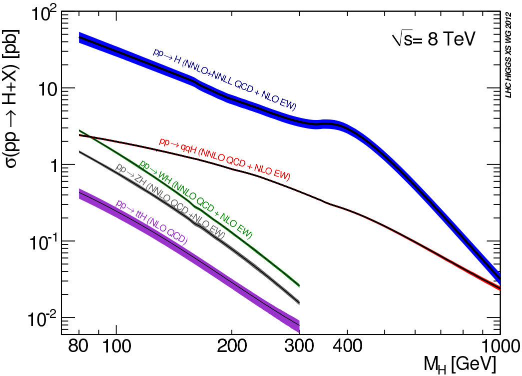
Total SM Higgs cross sections at the LHC

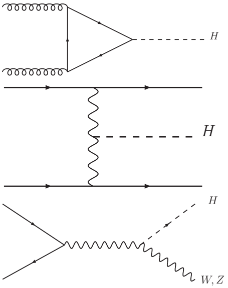




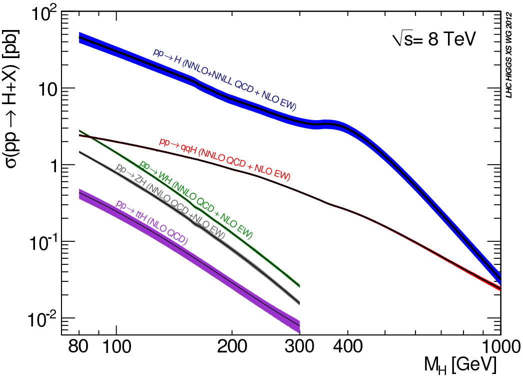


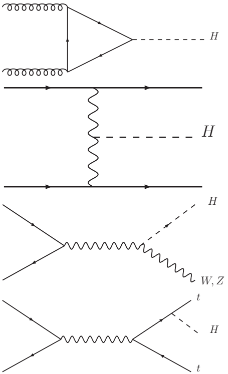
Total SM Higgs cross sections at the LHC





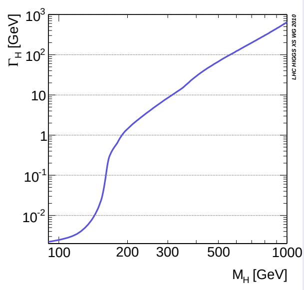
Total SM Higgs cross sections at the LHC



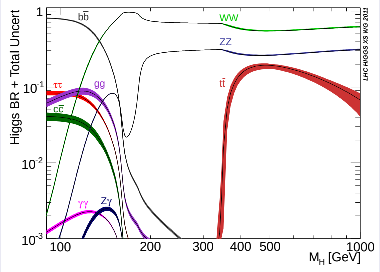


Decay of the SM Higgs

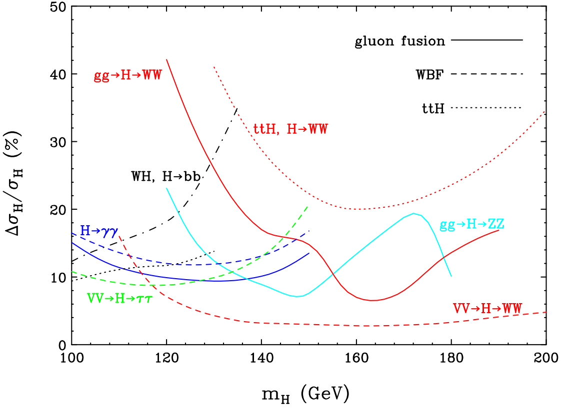
Decay width



Branching ratios



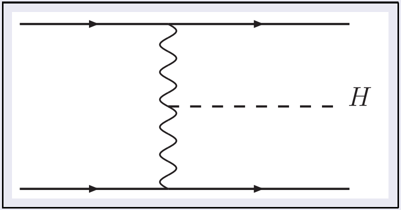
Statistical and systematic errors at the LHC



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

Vector Boson Fusion

Leading Order: $qQ \to HqQ$



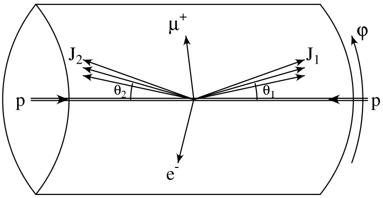
Higgs search channels:

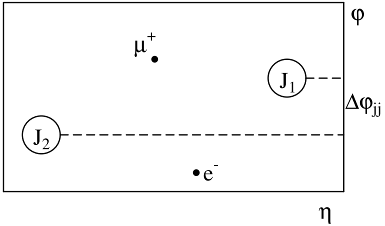
- $H \to W^+W^-$, $m_H > 120$ GeV
- $H \to \tau^+\tau^-$, $m_H < 140$ GeV
- $H \to \gamma\gamma$, $m_H < 150$ GeV

Eboli,Hagiwara,Kauer,Plehn,

Rainwater,Zeppenfeld,. . .

Vector Boson Fusion





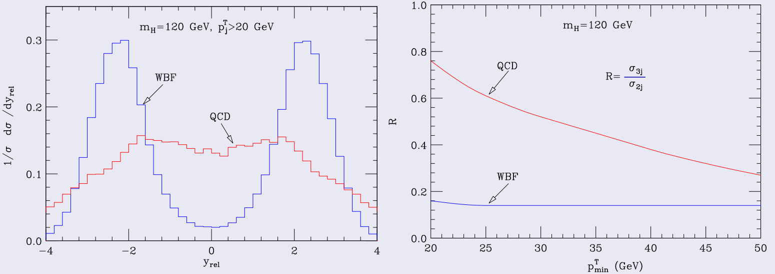
Event Characteristics

- 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



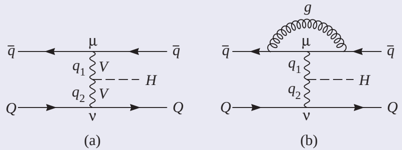
JHEP 05 (2004) 064

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

Higgs Production via Vector Boson Fusion at NLO

The NLO Calculation

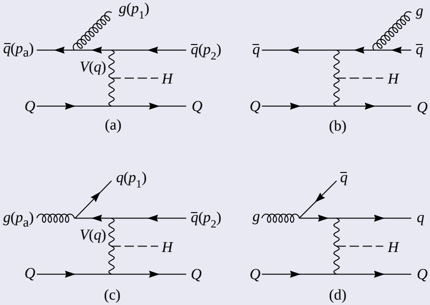
Virtual Corrections



(a) (b)

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

Real Corrections



(a) (b) (c) (d)

Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

Higgs Production via Vector Boson Fusion at NLO

Dipole subtraction method

Catani and Seymour, hep-ph/9605323

NLO cross section:

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

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

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.

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

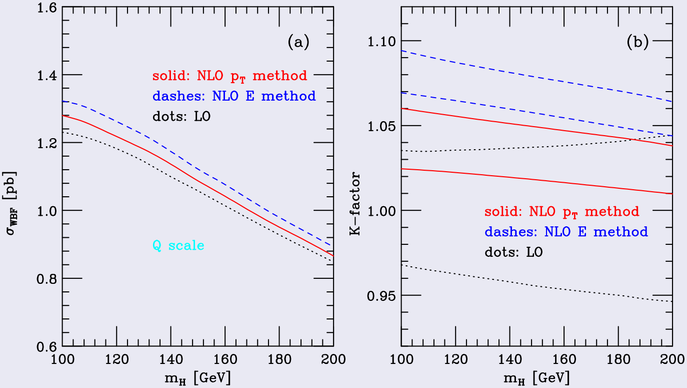
- Backgrounds to VBF are significantly suppressed by requiring a large rapidity separation of the two tagging jets.

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

Tagging Jet Selection

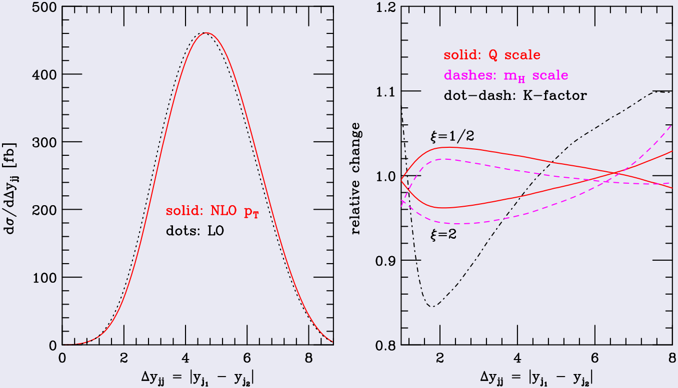
- p_T **-method**: Define the tagging jets at the two highest p_T jets in the event.
- E **-method**: Define the tagging jets as the two highest energy jets in the event.

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



- 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

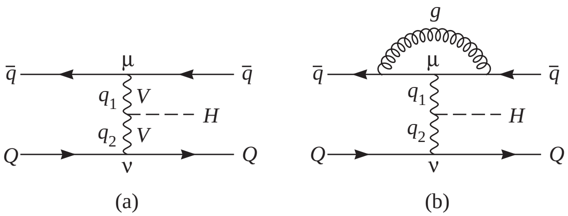
$\Downarrow$

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

Anomalous Higgs Couplings

General Tensor Structure for the HVV vertex

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



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

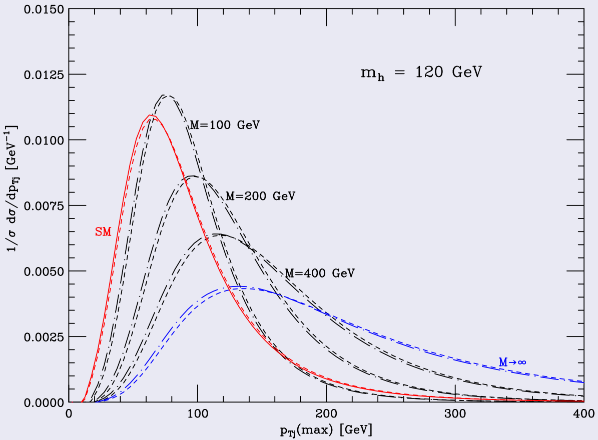
$$\begin{aligned} T^{\mu\nu}(q_1,q_2) &= a_1(q_1,q_2)g^{\mu\nu} \\ &+ a_2(q_1,q_2)[q_1\cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu] \\ &+ a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma} \end{aligned}$$

Form factor dependence

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

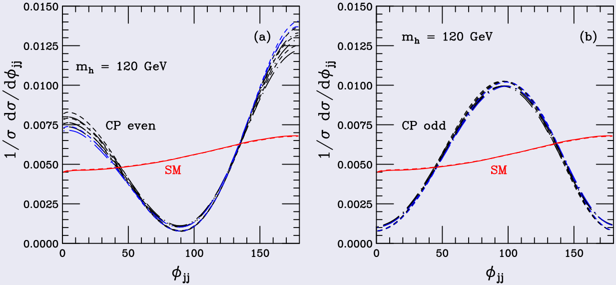
Anomalous Higgs Couplings

p_{T_j} distributions



Anomalous Higgs Couplings

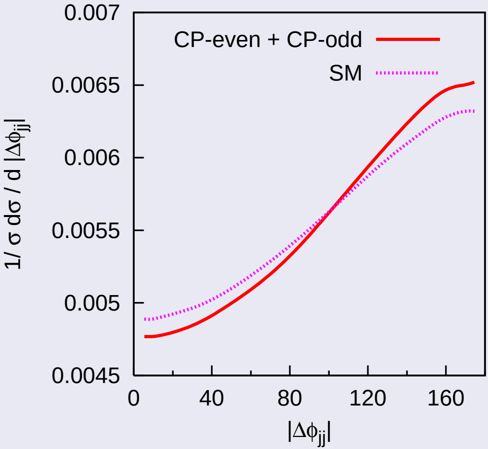
$\phi_{jj} = |\phi_{j_1} - \phi_{j_2}|$ distributions



Form factor dependence is small.

Anomalous Higgs Couplings

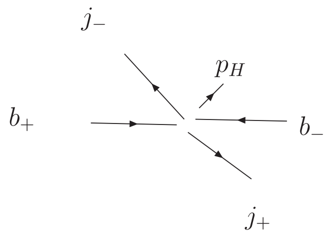
The case: $a_2 = a_3$



But, it doesn't work!

Anomalous Higgs Couplings

Redefinition of ϕ_{jj}



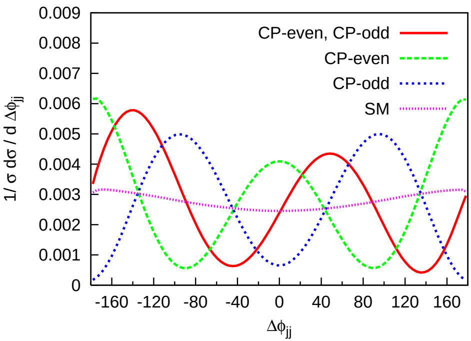
- Invariant under $(b_+, p_+) \leftrightarrow (b_-, p_-)$
- Parity odd variable

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:

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

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.

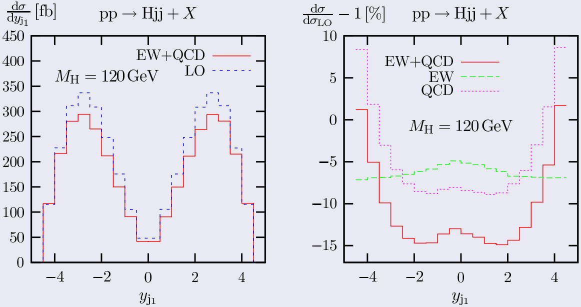
$$a_1 = 0\,, \quad a_2 = d\cos\alpha\,, \quad a_3 = d\sin\alpha$$

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

Electroweak Corrections

Rapidity distribution of leading jet

Ciccolini, Denner, Dittmaier, 0710.4749 Figy, Palmer, Weiglein arXiv:1012.4789



Stong shape changes by QCD corrections, EW corrections affect mostly the normalization.

Electroweak Corrections

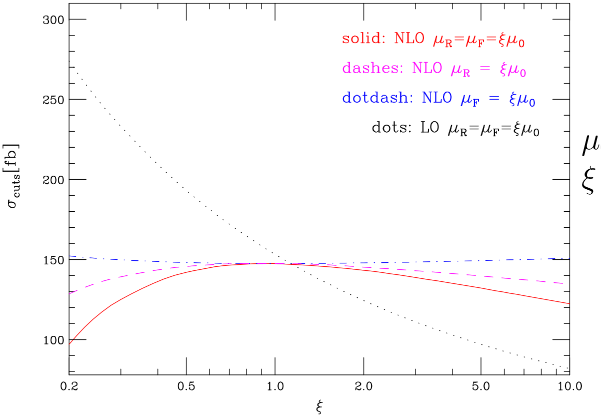
VBFNLO vs HAWK for $\sqrt{S} = 14$ TeV

M_H [GeV]	120	150
σ_{LO}, HAWK [fb]	1876.96 ± 1.59	1589.87 ± 1.25
σ_{LO}, VBFNLO [fb]	1876.66 ± 1.32	1590.19 ± 1.10
σ_{NLO}, HAWK [fb]	1637.85 ± 3.22	1387.36 ± 2.40
σ_{NLO}, VBFNLO [fb]	1634.54 ± 2.39	1387.37 ± 2.09

Here we have used the typical VBF cuts

Hjjj via VBF at NLO (only *t*-channels)

Total Cross section



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

$\mu_0 = 40$ GeV

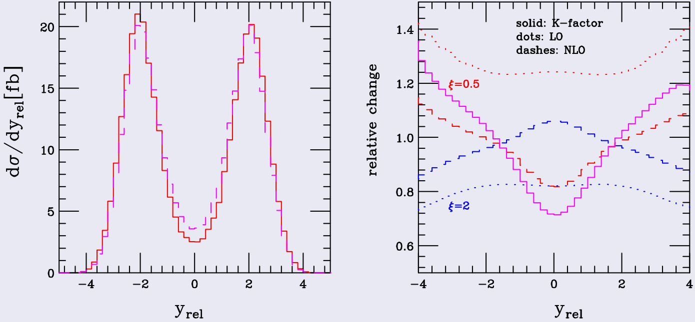
$\xi = 2^{\mp 1}$ scale variations:

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

Hjjj via VBF at NLO

Veto Jet Distributions

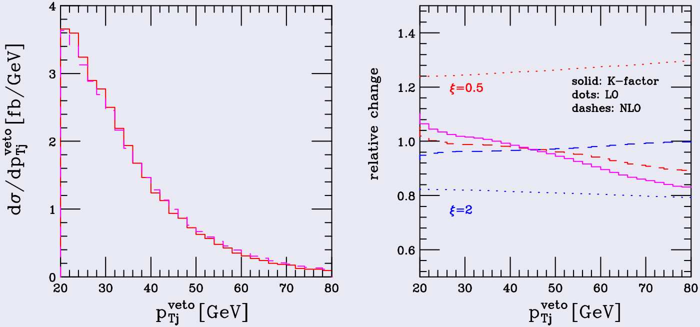
Veto Jet Rapidity



Hjjj via VBF at NLO

Veto Jet Distributions

Veto Jet P_T



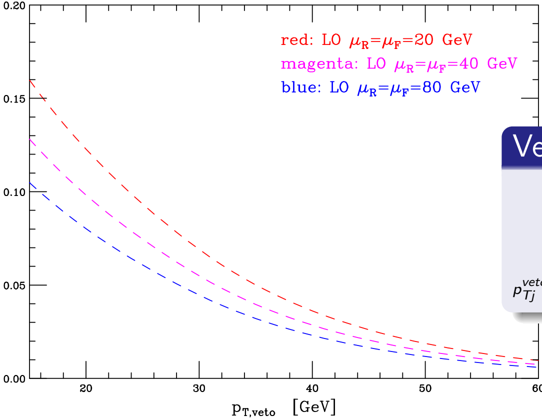
Hjjj via VBF at NLO

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



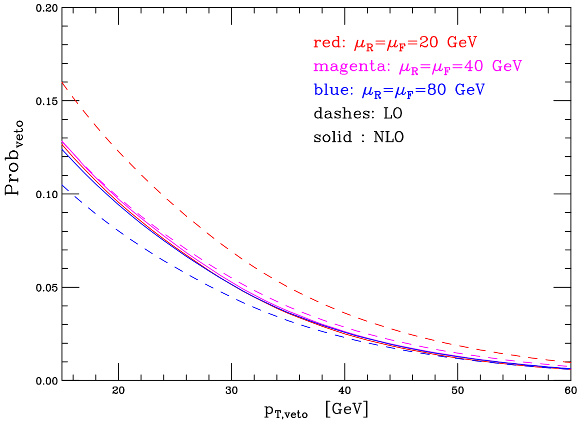
Veto Probability

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

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

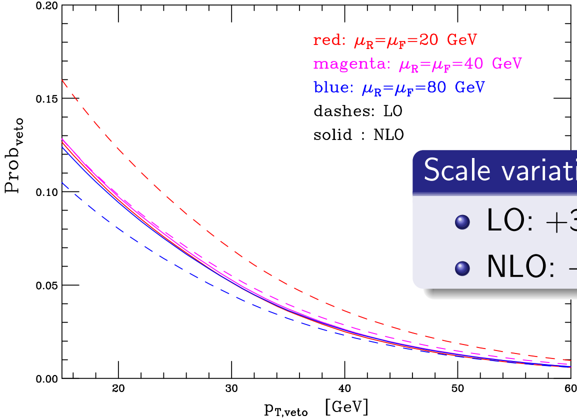
Hjjj via VBF at NLO

Veto Probability for the VBF Signal



Hjjj via VBF at NLO

Veto Probability for the VBF Signal

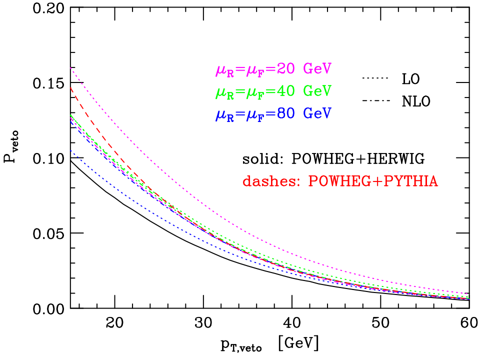


Scale variations, $p_{T,veto} = 15$ GeV:

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

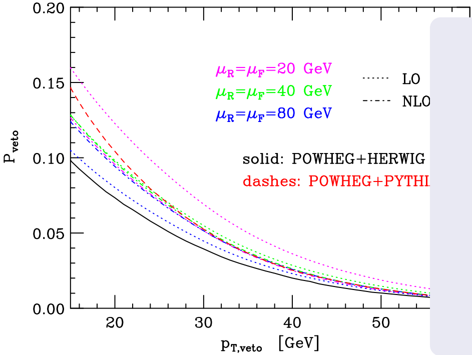
Hjjj via VBF at NLO

VBF H+2 jet POWHEG vs. NLO H+3 jet



Hjjj via VBF at NLO

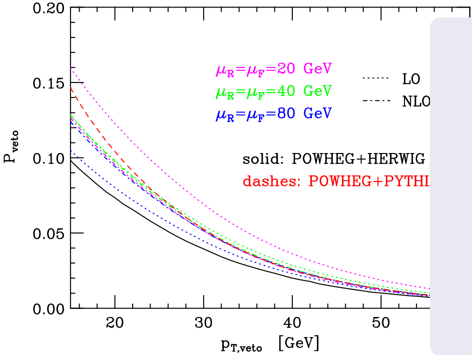
VBF H+2 jet POWHEG vs. NLO H+3 jet



- The result from the POWHEG is nothing more than the LO matched a shower.

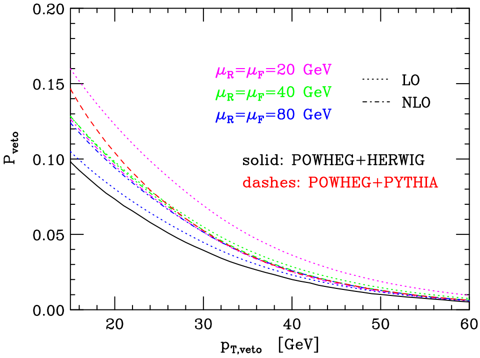
Hjjj via VBF at NLO

VBF H+2 jet POWHEG vs. NLO H+3 jet

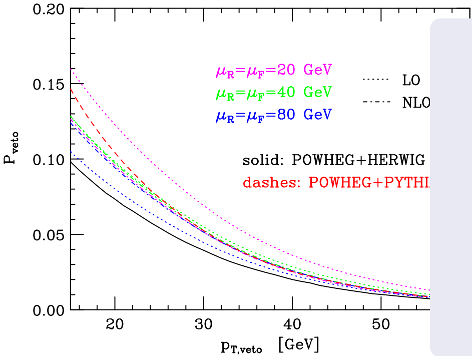


- The result from the POWHEG is nothing more than the LO matched a shower.
- Clearly, what is needed is an NLO H+3 jet computation matched to a parton shower.

Hjjj via VBF at NLO

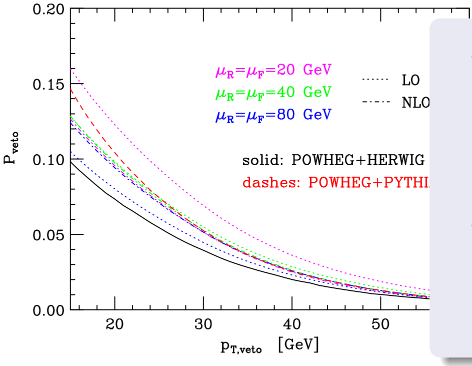


Hjjj via VBF at NLO



- The result from the POWHEG is nothing more than the LO matched a shower.

Hjjj via VBF at NLO



- The result from the POWHEG is nothing more than the LO matched a shower.
- Clearly, what is needed is an NLO H+3 jet computation matched to a parton shower.

Electroweak H+ 3 jets at NLO in `Matchbox`

In collaboration with Ken Arnold, Francisco Campanario, Simon Plätzer, and Malin Sjödahl

Coming Soon!

- `Matchbox` is `Herwig++`module which provides the necessary functionality to perform hard process generation at the level of NLO QCD accuracy and eases the setup of runtime interfaces to external codes for the hard process. S. Plätzer, S. Gieske
- `ColorFull` is used to compute the color correlations such as $< T_i \cdot T_j >$. M. Sjödahl
- Tensor reduction routines developed by F. Campanario are used for the one-loop computations.

Concluding Remarks

- In order for make full use of LHC data improved tools are required.
- The program VBFNLO is available at http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb.
- Improvements to *Hjj*: Electroweak and Susy corrections have been included in VBFNLO.
- H+3 jets in `Matchbox` is coming soon!