# 1-loop MSSM corrections to Higgs production in WBF

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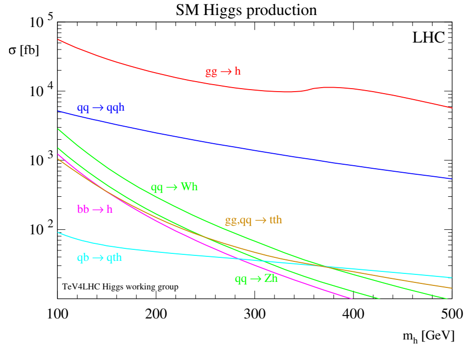
*Work in collaboration with G Weiglein and T Figy*

Karlsruher Institut für Technologie

# Outline

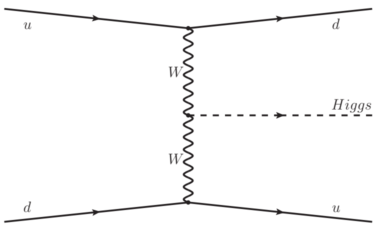
# Weak Boson Fusion

Weak boson fusion is expected to be the second largest contributor to Higgs boson production at the LHC




From: **hep-ph/0607308**, T Hahn, S Heinemeyer, F Maltoni, G Weiglein, S Willenbrock

$$q + q \rightarrow q + Higgs + q$$



# WBF - Status

- NLO QCD corrections in the SM have been implemented in public Monte Carlo codes, and are relatively small
(see, for instance, **hep-ph/0407066**, T Figy, C Oleari, D Zeppenfeld)
- Full SM one-loop corrections have been obtained and implemented in a Monte Carlo program
(**hep-ph/0710.4749, hep-ph/0806.3624**, M Ciccolini, A Denner, S Dittmaier)
- An estimation of $\mathcal{O}(\alpha^3\alpha_s^2)$ contributions has been published
(**hep-ph/0801.3355**, R Harlander, J Vollinga, M Weber; **hep-ph/0809.3693**, J Vollinga)
- Loop level interference effects have been investigated
(**hep-ph/0709.3513**, J Andersen, T Binoth, G Heinrich, J Smillie; **hep-ph/0801.4231**, A Bredenstein, K Hagiwara, B Jäger)
- The pure SUSY-loop corrections to the total cross section have been studied
(**hep-ph/0804.2676**, W Hollik, T Plehn, M Rauch, H Rzehak)

# VBFNLO

VBFNLO* is a public Monte Carlo program that provides predictions and distributions for WBF in the Standard Model and includes NLO SM QCD corrections.

- Arbitrary cuts can be implemented
- Various scales and PDF sets can be chosen
- Several relevant processes are included:
  - Higgs production
  - Single W/Z boson production with leptonic decay
  - WW/ZZ pair production with subsequent leptonic decays

*__hep-ph/0811.4559__, K. Arnold, M. Bahr, G. Bozzi, F. Campanario, C. Englert, T. Figy, N. Greiner, C. Hackstein, V. Hankele, B. Jager, G. Klamke, M. Kubocz, C. Oleari, S. Platzer, S. Prestel, M. Worek, D. Zeppenfeld

*Available at **http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb/***

# The New Corrections

We have modified VBFNLO such that

- The full 1-loop SM electroweak corrections are included (the QCD corrections were already present)
- In the MSSM, all SM-type corrections, together with the dominant SUSY corrections have been implemented for production of the 3 neutral Higgs bosons – the remaining SUSY boxes and pentagons are expected to be sub-dominant
- The full MSSM corrections are in progress

# The MSSM Higgs Sector

- In the MSSM, the Higgs sector needs to contain two Higgs doublets, which leads to 5 physical Higgs states:

$$h, H, A, H^+, H^-$$

- At tree level the Higgs sector is described by tan$\beta$ and $M_A$
- The tree level masses $m_h$ and $m_H$ are found by diagonalising the Higgs mass matrix

$$M_H^{2,tree} = \begin{pmatrix} M_A^2 sin^2\beta + M_Z^2 cos^2\beta & -\left(M_A^2 + M_Z^2\right) sin\beta cos\beta \\ -\left(M_A^2 + M_Z^2\right) sin\beta cos\beta & M_A^2 cos^2\beta + M_Z^2 sin^2\beta \end{pmatrix}$$

$\downarrow$ diagonalisation, $\alpha$

$$M_H^{2,tree} = \begin{pmatrix} m_H^{2,tree} & 0 \\ 0 & m_h^{2,tree} \end{pmatrix}$$

# The Complex MSSM

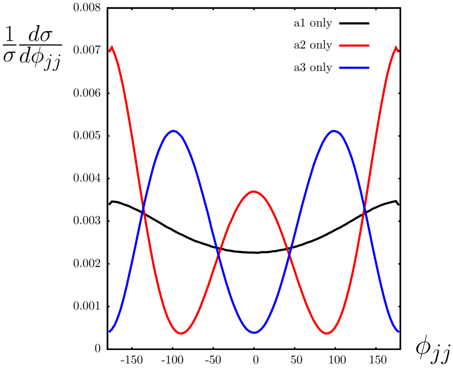
- In general, some of the parameters of the MSSM can be complex. For instance,
  - gluino mass parameter $M_3$
  - trilinear coupling parameter A
- When complex phases are included, interesting (non-excluded) phenomenology can result
- Complex phases allow mixing between all three neutral Higgs bosons

$$M(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & \hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

# The Higgs vertex

The most general *HVV* coupling is:

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)\, g^{\mu\nu} + a_2(q_1, q_2)\left(q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}\right) + a_3(q_1, q_2)\, \epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}$$



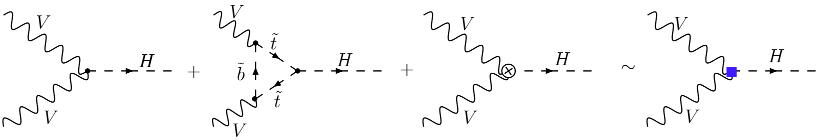
# Effective Couplings

The general form of the coupling, $T^{\mu\nu}$, can be used to incorporate higher order corrections

- At tree level

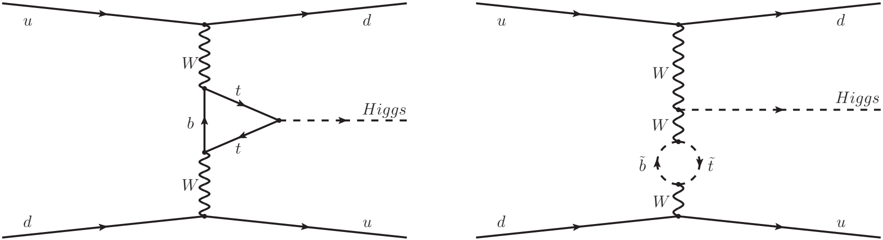
$$a_1^{SM} = \frac{ieM_W}{sin(\theta_W)}; \quad a_1^{MSSM} = \frac{ieM_W}{sin(\theta_W)} sin(\beta - \alpha); \quad a_2 = 0; \quad a_3 = 0;$$

- New physics (e.g. a heavy particle loop) can be represented by an effective coupling $T^{\mu\nu}$



# Virtual corrections

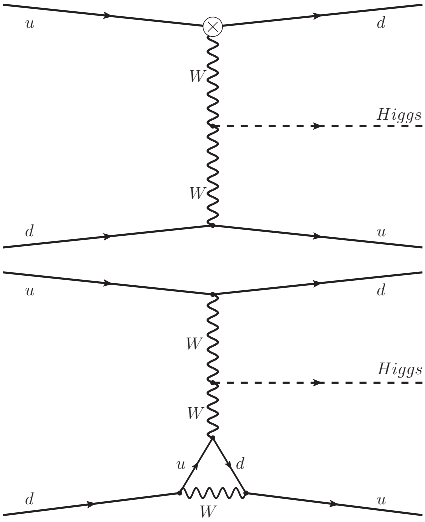
- Higgs vertex contributions and weak boson self energies are incorporated into an effective coupling $T^{\mu\nu}$
- For these diagrams, the full SM and MSSM corrections are included




- The programs* `FeynArts`, `FormCalc`, `LoopTools` and `FeynHiggs` have been used

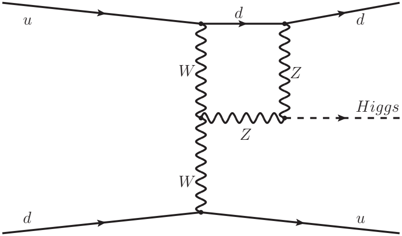
*Programs available at **www.feynarts.de** and **www.feynhiggs.de**

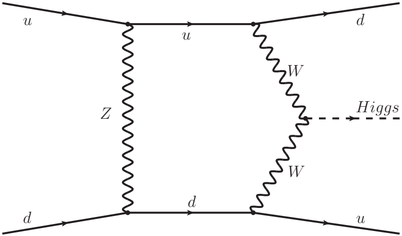
# Details of the Calculation

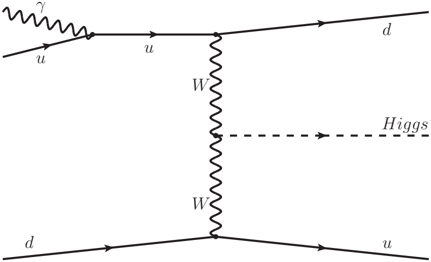



- When only (s)fermion loops are considered, the corrections to the *qqV* vertex arise from the counterterm only
- When all particles are included, the full matrix element is calculated
- *qqV* vertex corrections are included for the full SM and for (s)fermions in the MSSM

# Details of the Calculation



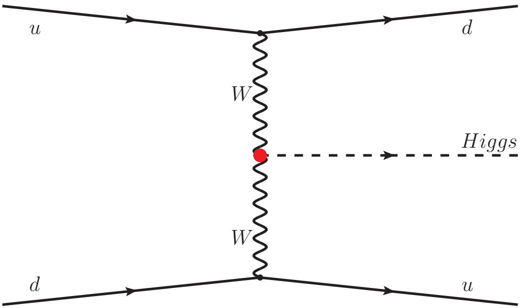




- All bosonic corrections have been implemented in the SM
- The SUSY boxes and pentagons are being implemented

# Higgs propagator corrections

- Finite wavefunction normalisation factors have been used to give outgoing particles the correct on-shell properties to take Higgs mixing into account




- FeynHiggs* is used to calculate the Z factors

$$\begin{pmatrix} \hat{\Gamma}_1 \\ \hat{\Gamma}_2 \\ \hat{\Gamma}_3 \end{pmatrix} = \hat{Z} \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}$$

**Available at **www.feynhiggs.de***

# Comparison: Standard Model

The new VBFNLO code, with our corrections implemented, compares well with the previously published full Standard Model calculations*.

| $M_H$ [GeV] | 120 | 150 | 200 |
|---|---|---|---|
| $\sigma_{LO}$, **hep-ph/0710.4749** [fb] | 1876 | 1590 | 1221 |
| $\sigma_{LO}$, new result [fb] | 1872 | 1587 | 1219 |
| $\sigma_{NLO}$, **hep-ph/0710.4749** [fb] | 1656 | 1402 | 1088 |
| $\sigma_{NLO}$, new result [fb] | 1654 | 1408 | 1092 |

* **hep-ph/0710.4749**, M Ciccolini, A Denner, S Dittmaier

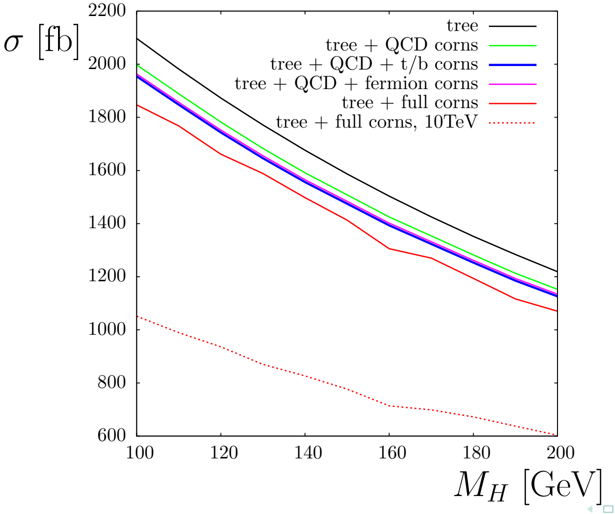
# Comparison: the real MSSM

| SPS point | $\frac{\Delta\sigma}{\sigma}$ [%] new result | $\frac{\Delta\sigma}{\sigma}$ [%] tuned result | $\frac{\Delta\sigma}{\sigma}$ [%] hep-ph/0804.2676* |
|---|---|---|---|
| **1a** | -0.184 | -0.362 | **-0.329** |
| **1b** | -0.057 | -0.202 | **-0.162** |
| **2** | -0.026 | -0.220 | **-0.147** |
| **3** | -0.004 | -0.211 | **-0.146** |
| **4** | -0.074 | -0.271 | **-0.258** |
| **5** | -0.526 | -0.612 | **-0.606** |
| **6** | -0.087 | -0.277 | **-0.226** |
| **7** | -0.058 | -0.244 | **-0.206** |
| **8** | -0.010 | -0.214 | **-0.157** |
| **9** | -0.051 | -0.189 | **-0.094** |

- To compare with published results*, the SM boson contributions were subtracted from the full MSSM corrections to the *HVV* vertex
- Reasonable agreement is found with our tuned results

* **hep-ph/0804.2676**, W Hollik, T Plehn, M Rauch, and H Rzehak

# SM: Total cross section

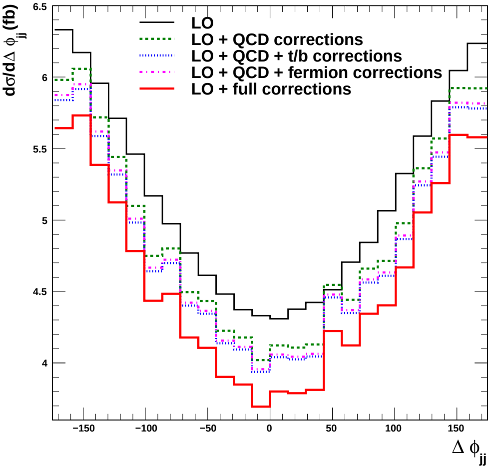



Electroweak corrections are of approximately the same size as QCD corrections – $\mathcal{O}(5\%)$

# SM: Azimuthal angle distribution

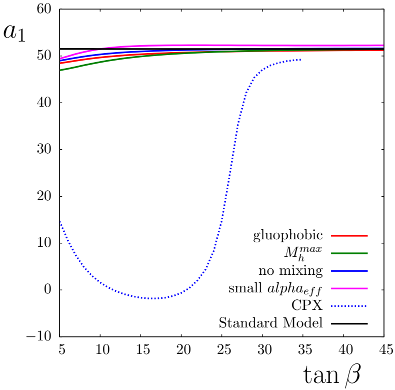
$M_H = 120$ GeV

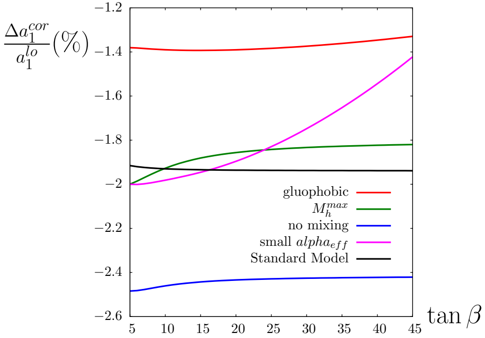
- The effect of higher order corrections on the distribution is moderate



# MSSM: Formfactor calculations

$M_A = 150$ GeV

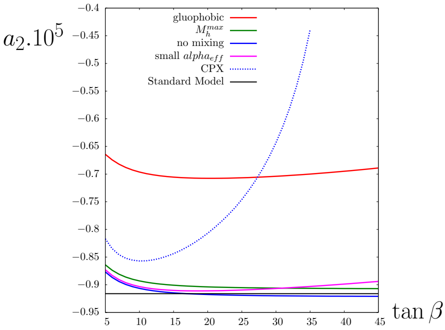



MSSM corrections are typically of the same order of magnitude as in the SM, but can deviate greatly in certain scenarios

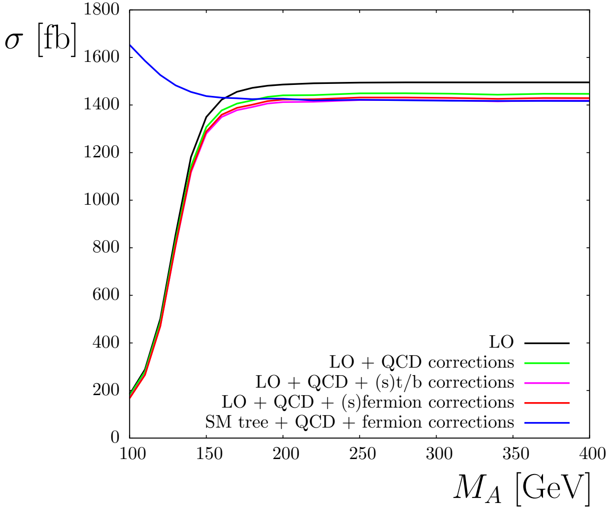
# MSSM: Formfactor calculations

$M_A = 150$ GeV




The loop-induced formfactors $a_2$ and $a_3$ are small.

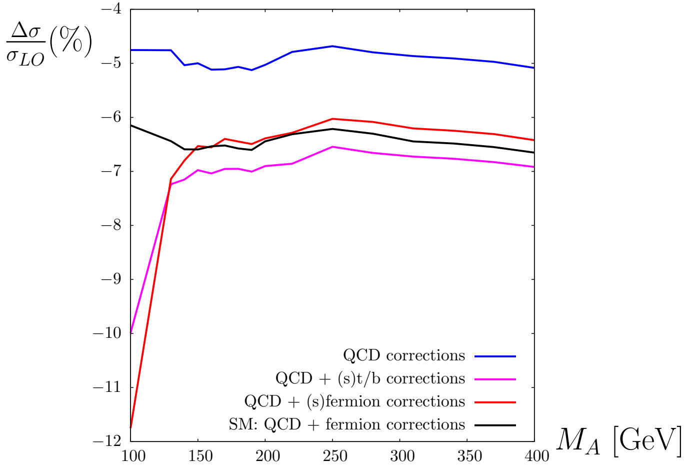
# Total cross section: the light CP-even Higgs




$M_h^{max}$ scenario
$\tan\beta = 10$

Large deviations from the SM are seen in the non-decoupling regime.

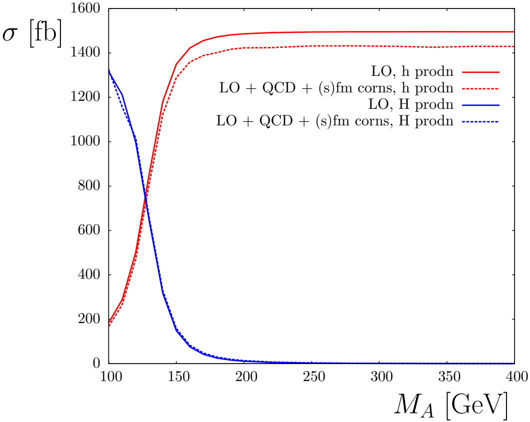
# Total cross section: the light CP-even Higgs




$M_h^{max}$ scenario
$\tan\beta = 10$

Large corrections ($\mathcal{O}(10\%)$) are seen in the non-decoupling regime.

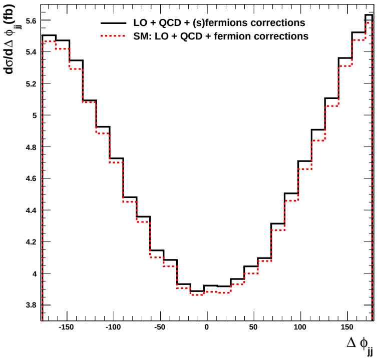
# Total cross section: the heavy CP-even Higgs



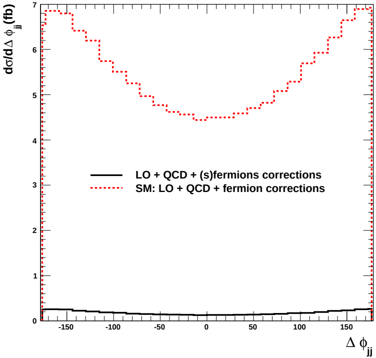

$M_h^{max}$ scenario
$\tan\beta = 10$

In the non-decoupling regime, the heavy Higgs has a larger cross section than the light Higgs.

# Azimuthal angle distribution: $M_h^{max}$ scenario



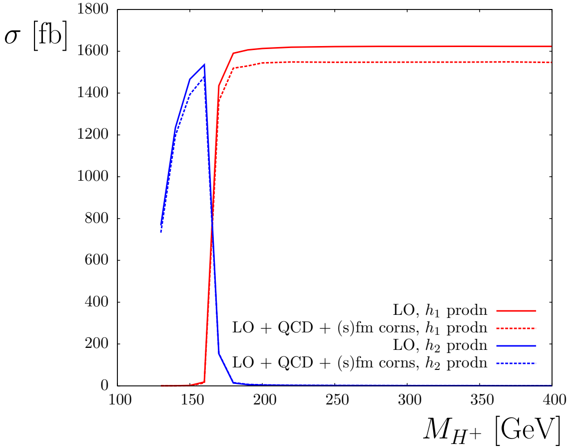

$\tan\beta = 10$, $M_A = 400$ GeV




$\tan\beta = 10$, $M_A = 100$ GeV

In the non-decoupling regime, deviations from the SM are large

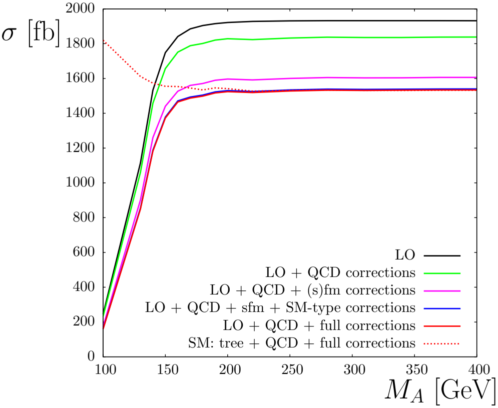
# Total cross section: complex MSSM




CPX scenario
$\tan\beta = 10$

At low $M_A$, the lightest Higgs decouples from the weak bosons

# Total cross section




- All SM-type corrections are included, as well as chargino/neutralino contributions to the *HVV* vertex and *VV* self energy corrections
- Charginos and neutralinos account for $\approx 1.5 - 3\%$ of the total correction

$M_h^{max}$ scenario, $\tan\beta = 10$

# Summary

- Weak boson fusion provides
  - Higgs discovery channel
  - Study of electroweak symmetry breaking and BSM
- Complete 1 loop corrections in the SM, and all SM-type corrections and dominant SUSY corrections in the (complex) MSSM have been calculated and implemented in VBFNLO
- There is good agreement with the literature
- Electroweak corrections are typically $\mathcal{O}(5\%)$, but can be greater than $\mathcal{O}(10\%)$ in the non-decoupling regime of the MSSM
- The code, including the complete SM and dominant SUSY 1-loop corrections, will be made publically available