Weak Boson Fusion

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Work in collaboration with G Weiglein and T Figy

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Outline

The MSSM Higgs Sector

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

$$h_0, H_0, A_0, H^+, H^-$$

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

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

$$\downarrow \textit{diagonalization}, \alpha$$

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

The Complex MSSM

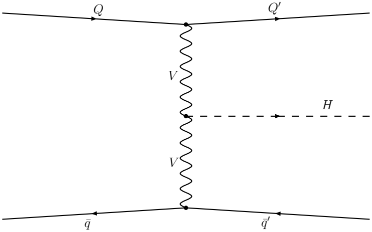
- In general, some of the parameters of the MSSM can be complex. For instance,
  - gluino mass parameter M_3
  - trilinear coupling parameter A
- When complex phases are included, interesting (non-excluded) phenomenology can result
- Complex phases allow mixing between all three neutral Higgs bosons

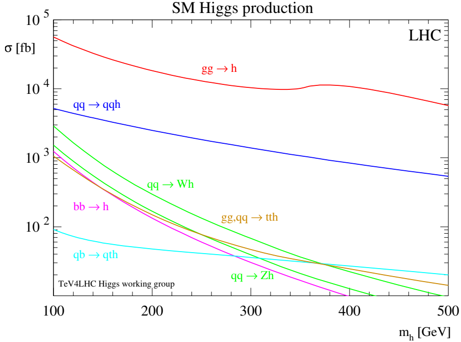
$$M(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & \hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

Weak Boson Fusion

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

$$Q + \bar{q} \rightarrow Q' + h/H + \bar{q}'$$





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

Effective Couplings

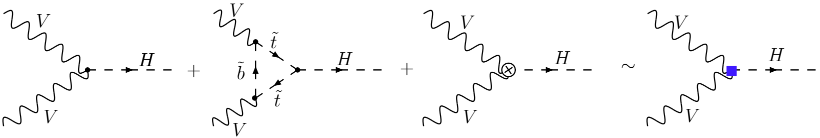
- The most general HVV coupling is:

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

- 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 the effective coupling $T^{\mu\nu}$



VVH Coupling and Azimuthal Angles

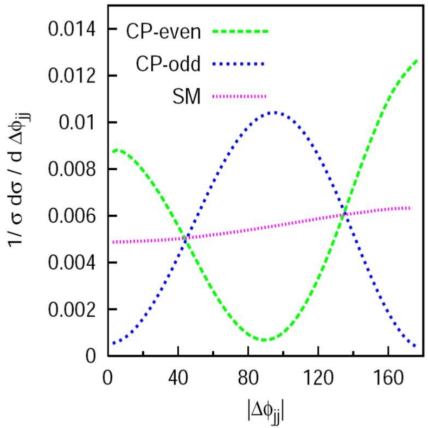


Figure from: **hep-ph/0609075**, Hankele, G Klamke, D Zeppenfeld, T Figy

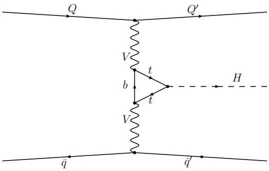
The LHC will (hopefully) provide information about

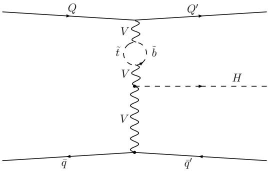
- Strength of the HVV coupling
- Tensor structure of the HVV coupling

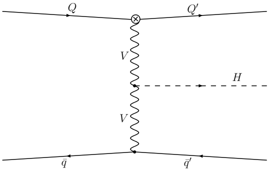
WBF - Status

- In the Standard Model, next to leading order QCD corrections have been implemented in Monte Carlo codes
  (see, for instance **hep-ph/0407066**, T Figy, C Oleari, D Zeppenfeld)
- The QCD corrections to weak boson fusion are relatively small, so electroweak corrections could be important
- Full one-loop corrections in the Standard Model have been calculated
  (**hep-ph/0710.4749, hep-ph/0806.3624**, M Ciccolini, A Denner, S Dittmaier)
- In the MSSM, the NLO corrections to the total cross section have been investigated
  (**hep-ph/0804.2676**, W Hollik, T Plehn, M Rauch, H Rzehak)
- Interference effects have been calculated
  (**hep-ph/0709.3513**, J Andersen, T Binoth, G Heinrich, J Smillie; **hep-ph/0801.4231**, A Bredenstein, K Hagiwara, B Jäger)

Fermion/Sfermion Corrections to WBF



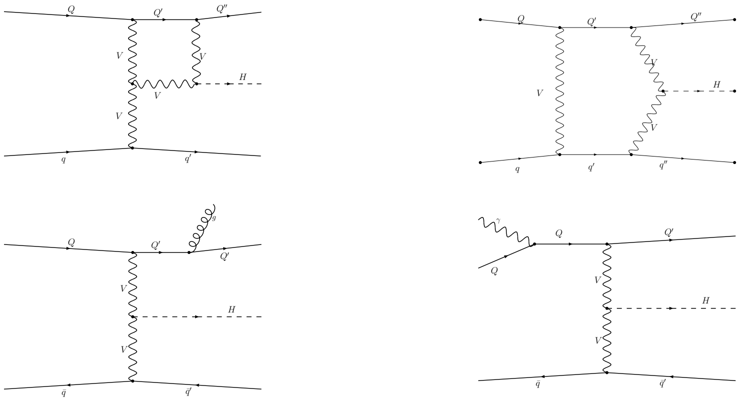




- The programs FeynArts, FormCalc, LoopTools and FeynHiggs have been used

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

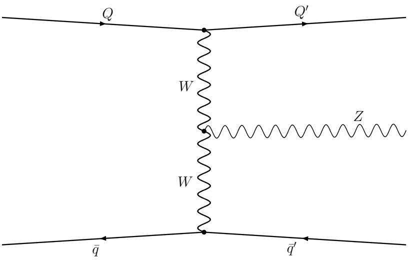
Bosonic Corrections to WBF



Calibration Process

$$\boxed{Q + \bar{q} \to Q' + Z + \bar{q}'}$$

The search for Higgs via WBF at LHC depends on understanding the detector response

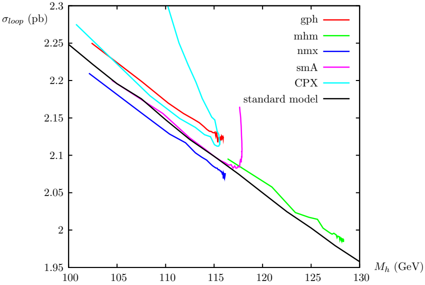


- Feynman diagrams are the same for Z / H production
- $M_Z \sim M_H$, so the kinematics of the tag jets are similar

See **hep-ex/0502009, D Green**

Partonic Cross Section

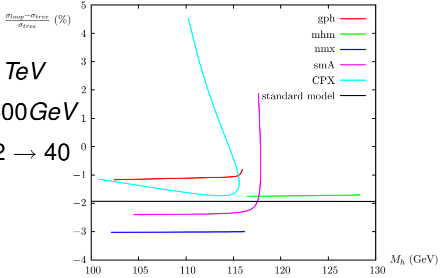
- Partonic cross sections have been calculated for the process: u + d $\longrightarrow$ d + H + u



$\sqrt{\hat{s}} = 1\,TeV$

$M_A = 500\,GeV$

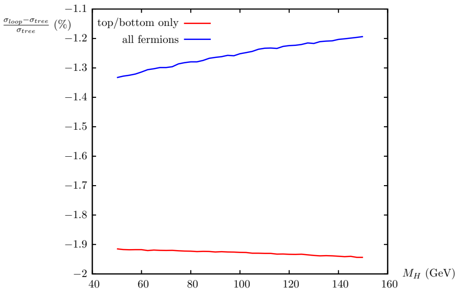
$tan\beta : 2 \longrightarrow 40$



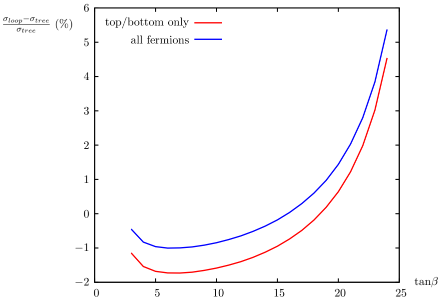
- The partonic cross section is $\sim$ 2 - 2.5 pb, with loop corrections at the percent level for certain benchmarks

Partonic Cross Section

For the partonic process: u + d → d + H + u



Standard Model



CPX scenario
M_A = 500GeV

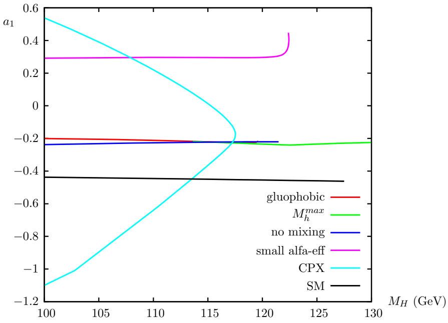
vbfnlo

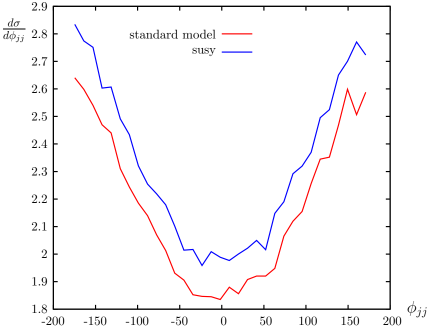
These corrections have been implemented into a Monte Carlo code: vbfnlo

- Results are integrated over PDF's
    - CTEQ4L is used here
- Cuts are implemented
    - $p_t > 20$ GeV
    - $|\eta_{ij}| \leq 5$, $|\eta_{j_1} - \eta_{j_2}| > 4.2$
    - $R_{jj} > 0.6$
    - $S_{jj} > 600$ GeV
- A range of distributions are output
- Loop corrections are included for:
    - Standard Model, t/b only OR all fermions
    - (complex) MSSM, t/b $\tilde{t}/\tilde{b}$ only OR all fermions / sfermions

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

Monte Carlo Results



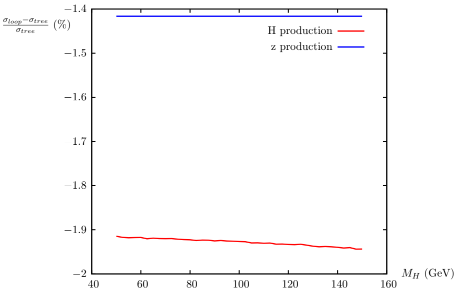


For the MSSM, M_A = 500 GeV and tan β is varied between 2 and 42

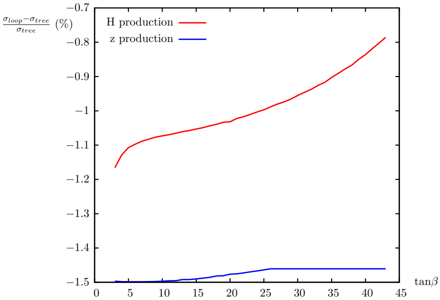
NLO result, small α_{eff} scenario
tan β = 5
M_A = 500 GeV, M_h = 115 GeV

Z production

For the partonic process: u + d → d + Z + u



Standard Model



Gluophobic scenario
M_A = 500 GeV

Summary

- Weak boson fusion provides
  - Higgs discovery channel
  - Study of electroweak symmetry breaking and BSM
- The fermion/sfermion loop corrections in the SM and MSSM have been calculated and implemented in vbfnlo
- Fermion/sfermion corrections can be $\sim$ 3-4%
- vbfnlo is a general tool to investigate weak boson fusion in the SM, MSSM and other models
- The QED corrections and bosonic electroweak corrections are being finalised
- A possible calibration process has been studied