Higher order corrections to Higgs production in Weak Boson Fusion

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The MSSM Higgs Sector

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

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

- At tree level the Higgs sector is described by tanβ 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, α

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

The Complex MSSM

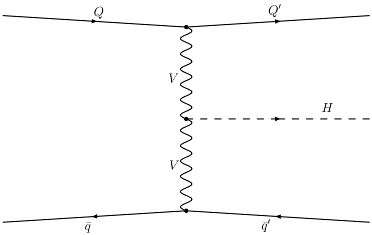
- In general, some of the parameters of the MSSM can be complex. For instance,
  - gluino mass parameter M_3
  - trilinear coupling parameter A
- When complex phases are included, interesting (non-excluded) phenomenology can result
- Complex phases allow mixing between all three neutral Higgs bosons

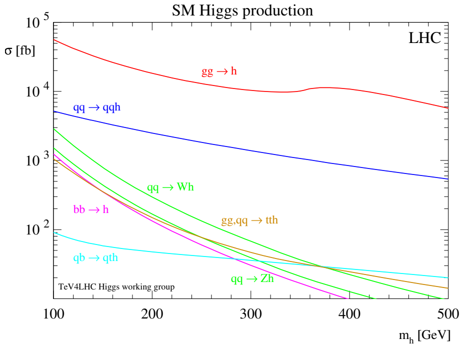
$$M(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & \hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

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

WBF - Status

- NLO QCD corrections in the SM have been implemented in public 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
- 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/0809.3693**, J Vollinga)
- The pure SUSY-loop corrections to the total cross section have been investigated
(**hep-ph/0804.2676**, W Hollik, T Plehn, M Rauch, H Rzehak)
- Loop level 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)

vbfnlo

By using Monte Carlo programs, cross section distributions can be calculated, providing a useful tool for experimentalists. **`vbfnlo`*** is a public parton level Monte Carlo program that provides predictions for weak boson fusion in the Standard Model and includes NLO 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 of W/Z bosons

* **hep-ph/0306109**, T Figy, C Oleari, D Zeppenfeld

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

Effective Couplings

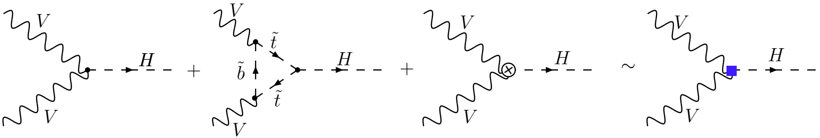
- The most general HVV coupling is:

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

- 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

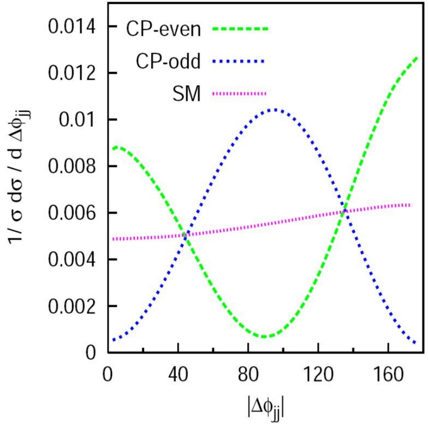


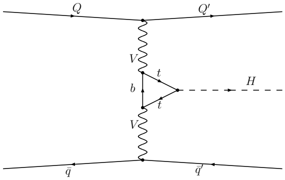
Figure from: **hep-ph/0609075**, T Figy, V Hankele, G Klamke, D Zeppenfeld

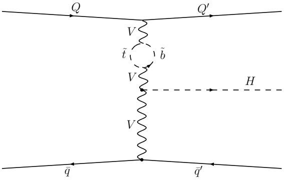
The LHC will (hopefully) provide information about

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

Calculation of Higher Order Corrections to WBF

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

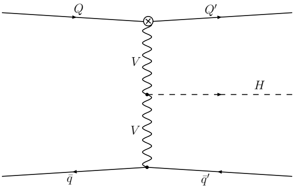




- Higgs vertex couplings and weak boson self energies are incorporated into an effective coupling $T^{\mu\nu}$
- For these diagram-types, the full Standard Model corrections and all fermion/sfermion corrections in the MSSM are included

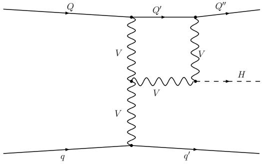
Programs available at **www.feynarts.de and **www.feynhiggs.de***

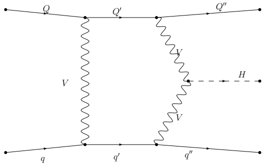
Calculation of Higher Order Corrections to WBF



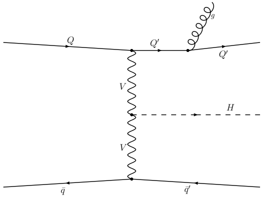
- When only (s)fermionic corrections are being considered, the corrections to qqV are calculated using the counterterm coupling
- When bosons are included too, the full matrix element is calculated
- qqV vertex corrections are included for the full Standard Model and for fermions and sfermions in the MSSM

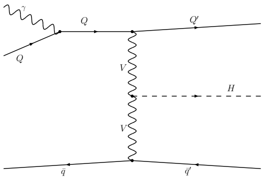
Bosonic Corrections to WBF





- All bosonic corrections have been implemented in the Standard Model
- Outlook: Implementing these diagram-types in the MSSM



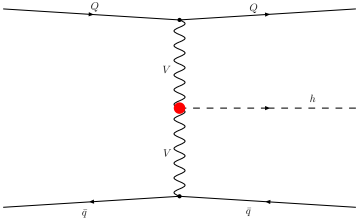


Boxes and pentagons

- The boxes and pentagons are included by calculating the full matrix element squared, using code generated by a modified version of `FormCalc`
- In order to check this procedure, the Born amplitude and the corrections to the Higgs vertex were calculated using this method, and the results cross checked against the simpler formfactor calculation

Higgs propagator corrections in the MSSM

- Radiative corrections lead to further mixing between Higgs bosons
- Finite wavefunction normalisation factors have been used to give outgoing particles the correct on-shell properties to take this mixing into account



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

Higgs propagator corrections in the MSSM

- The non-unitary $\hat{Z}$ matrix is given by

$$\hat{Z} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h}Z_{hH} & \sqrt{Z_h}Z_{hA} \\ \sqrt{Z_H}Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_h}Z_{HA} \\ \sqrt{Z_h}Z_{Ah} & \sqrt{Z_A}Z_{AH} & \sqrt{Z_A} \end{pmatrix}$$

- When producing a Higgs i, $\sqrt{Z_i}$ is a normalisation factor (dependent on the ii propagator), and Z_{ij} involves the ij propagator and takes account of diagrams where there is a tree level Higgs j connected directly to the vertex.
- These corrections can be very important numerically. They are calculated using `FeynHiggs`, which includes the dominant two-loop contributions as well as the full one-loop corrections.

Δm_b corrections

- Higher order corrections can significantly affect the relation between the bottom quark mass and the Yukawa coupling λ_b

$$\lambda_b = \frac{m_b}{v_1} \rightarrow \frac{m_b}{v_1} \frac{1}{1 + \Delta m_b}$$

- Δm_b is output by `FeynHiggs`
- These corrections can potentially be large, especially for the heavy Higgs

The Higgs vertex

- In the Standard Model, the HWW counterterm coupling is simply

$$\Gamma^{CT}_{HWW} = \frac{ieM_W}{sin(\theta_w)}\left(\delta\tilde{Z}_e + \frac{1}{2}\frac{\delta M^2_W}{M^2_W} + \delta Z_W - \frac{\delta sin(\theta_w)}{sin(\theta w)} + \frac{1}{2}\delta Z_H\right)$$

- In the MSSM, however, this counterterm is more complicated

$$\Gamma^{CT}_{hWW} = \frac{ieM_W}{sin(\theta_w)} sin(\beta-\alpha)\left(\delta\tilde{Z}_e + \frac{1}{2}\frac{\delta M^2_W}{M^2_W} + \delta Z_W + \frac{\delta sin(\theta_w)}{sin(\theta w)} + \frac{1}{2}\delta Z_h + sin(\beta)cos(\beta)\frac{cos(\beta-\alpha)}{sin(\beta-\alpha)}\delta tan(\beta)\right) + \frac{1}{2}\frac{ieM_W}{sin(\theta_w)}cos(\beta-\alpha)\delta Z_{Hh}$$

- We work in a scheme where α is not renormalised

Renormalisation constants

- The Higgs field renormalisation terms are calculated in the $\overline{DR}$ scheme

$$\delta Z_h = -\left[Re\Sigma'_{hh}(m_h^2)\right]^{div} \qquad \delta Z_H = -\left[Re\Sigma'_{HH}(m_H^2)\right]^{div}$$

$$\delta Z_{hH} = \frac{sin(\alpha)cos(\alpha)}{cos(2\alpha)}\left(\delta Z_h - \delta Z_H\right) \qquad \delta tan\beta = \frac{1}{2cos(2\alpha)}\left(\delta Z_h - \delta Z_H\right)$$

- The lowest order electromagnetic coupling α_{em} is parametrised either by the coupling at the scale M_Z or by the Fermi constant

$$\alpha_{em}(M_Z) = \frac{\alpha_{em}(0)}{1-\Delta\alpha} \qquad \alpha_{em} = \frac{\sqrt{2}G_F M_W^2 \cos^2(\theta_w)}{\pi\,(1+\Delta r)}$$

Charge Renormalisation

- The constant $\delta\tilde{Z}_e$ incorporates both charge renormalisation and the $\Delta\alpha$ or Δr contributions

$$\delta\tilde{Z}_e = \delta Z_e - \frac{1}{2}\Delta\alpha \qquad \delta\tilde{Z}_e = \delta Z_e - \frac{1}{2}\Delta r$$

- Charge renormalisation has the form

$$\delta Z_e = \frac{1}{2}\Pi^{\gamma}(0) - \frac{\sin(\theta_w)}{\cos(\theta_w)}\frac{\Sigma_{\gamma Z}(0)}{M_Z^2}$$

- In the fermion / sfermion sector, $\delta\tilde{Z}_e$ can be written as

$$\delta\tilde{Z}_e = \frac{\delta\sin(\theta_w)}{\sin\theta_w} - \frac{1}{2}\left(\frac{\Sigma_W(0) - \delta M_W^2}{M_W^2}\right)$$

Soft and collinear divergences

- We work in the limit of zero quark mass for the external (1st and 2nd generation) quarks
- The IR and collinear divergences are regularised by a small photon mass and small quark masses respectively
- We use the dipole subtraction formalism described in **hep-ph/9904440***
- As an additional check on the IR divergences, we have also used the soft photon approximation as an alternative to dipole subtraction

*__hep-ph/9904440__, S Dittmaier

Renormalisation checks

Several checks have been performed to ensure that the final answer is finite:

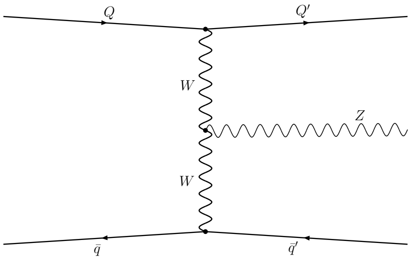
- The UV divergences are checked analytically in the 3rd generation quark (and squark) sector and checked numerically in the other sectors
- In the fermion / sfermion sector, the Standard Model and MSSM corrections are separately finite
- In the fermion / sfermion sector, the Higgs vertex, the quark vertex and the weak boson self energy contributions are all separately finite
- The result is independent of all renormalisation parameters (the UV divergence, the regulator quark mass and the photon mass)

Calibration Process

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

The search for (and understanding of) Higgs production via weak boson fusion at the LHC depends on understanding the detector response

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



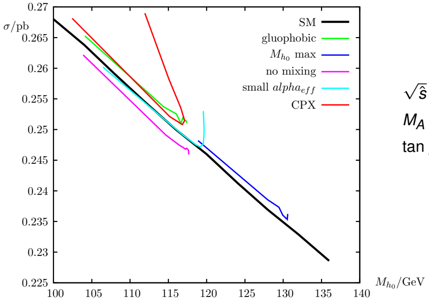
See **hep-ex/0502009, D Green**

MSSM benchmark scenarios

- In the MSSM M_A / M_{H^+} and tan β are taken to be free parameters
- Other parameters are fixed according to a benchmark prescription
- The benchmarks used here are
  - Gluophobic Higgs scenario
  - No-mixing scenario
  - M_h-max scenario
  - Small α_{eff} scenario
  - CPX scenario

Partonic Cross Sections - h_0

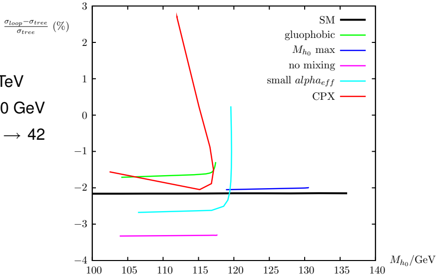
- Partonic cross sections have been calculated for the process: u + c $\longrightarrow$ u + h_0 + c



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

M_A = 500 GeV

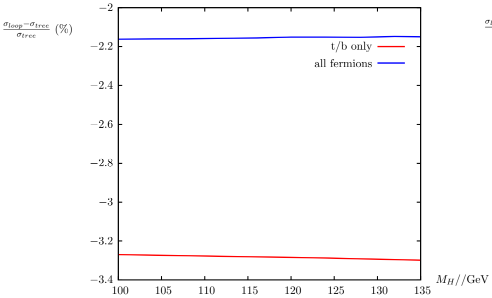
tan β : 3 $\longrightarrow$ 42



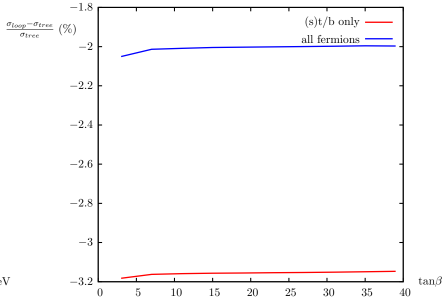
- The partonic cross section is $\sim$ 0.25 pb, with loop corrections at the % level

Partonic Cross Section - h_0

For the partonic process: u + c $\longrightarrow$ u + h_0 + c



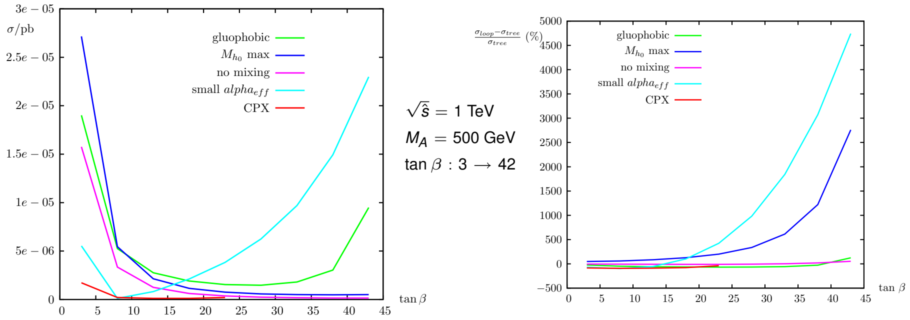
Standard Model



CPX scenario, M_A = 500GeV

Partonic Cross Sections - H_0

- Partonic cross sections have been calculated for the process: u + c $\longrightarrow$ u + H_0 + c



- The loop corrections are extremely large, but the total cross section is still very small

Experimental cuts

- We use the PDF set MRST2004qed
- Cuts are implemented*
  - $p_t > 20$ GeV
  - $|\eta_{ij}| \leq 4.5$
  - $|\eta_{j_1} - \eta_{j_2}| > 4$
- A range of distributions are output

Cuts from* ***hep-ph/0403297**: T Figy, D Zeppenfeld*

Comparison: Standard Model

The adapted `vbfnlo` code compares well with the previously published full Standard Model calculations*.

M_H [GeV]	120	150	200
σ_{LO}, **hep-ph/0710.4749** [fb]	1876	1590	1221
σ_{LO}, `vbfnlo` [fb]	1874	1588	1220
$\Delta\sigma_{NLO}$, **hep-ph/0710.4749** [fb]	-220	-188	-132
$\Delta\sigma_{NLO}$, `vbfnlo` [fb]	-217	-190	-128

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

Comparison: Standard Model

- Numerical inputs, cuts and PDF sets are the same
- The results presented in **hep-ph/0710.4749** include more corrections than the adapted `vbfnlo`
- `vbfnlo` assumes the Higgs decays into two massless particles
- These `vbfnlo` cross sections have numerical errors of $\sim \pm 0.5$pb at LO and $\sim \pm 5$pb at NLO

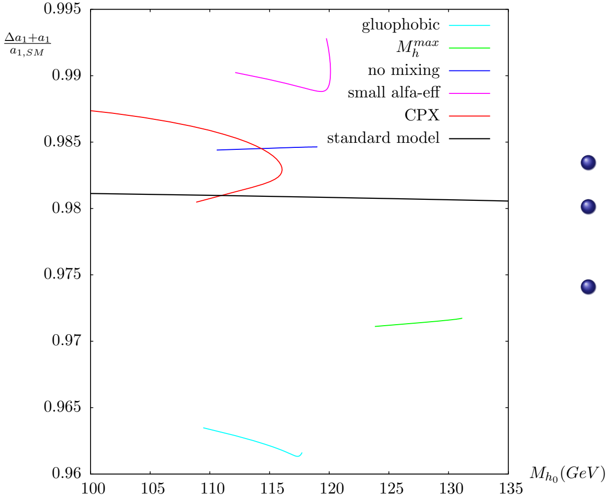
Comparison: the real MSSM

SPS point	$\frac{\Delta\sigma}{\sigma}$ [%] **hep-ph/0804.2676**	$\frac{\Delta\sigma}{\sigma}$ [%] `vbfnlo`
1a	-0.469	-0.44
1b	-0.229	-0.21
2	0.129	0.17
3	-0.216	-0.31
4	-0.355	0.01
5	-0.912	-2.01
6	-0.309	-0.32
7	-0.317	-0.07
8	-0.206	-0.01
9	-0.071	-0.03

- The pure SUSY-loop contributions have been published*
- The adapted `vbfnlo` can study weak boson fusion calculating loops with only fermions, loops with only sfermions or both contributions
- Different corrections are included in the published and the adapted `vbfnlo` results - a more detailed comparison is in progress

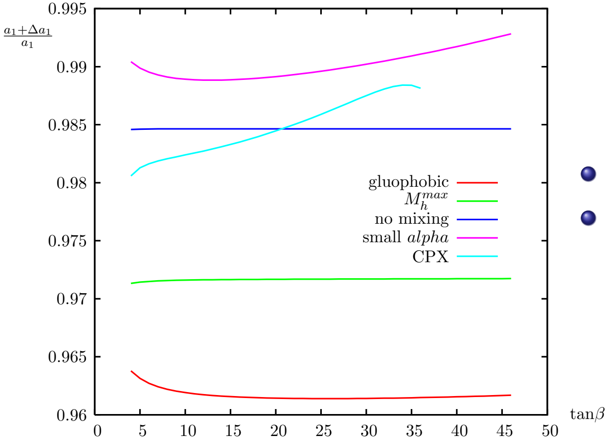
* **hep-ph/0804.2676**, W Hollik, T Plehn, M Rauch, and H Rzehak

Decoupling regime: h_1 formfactor a_1



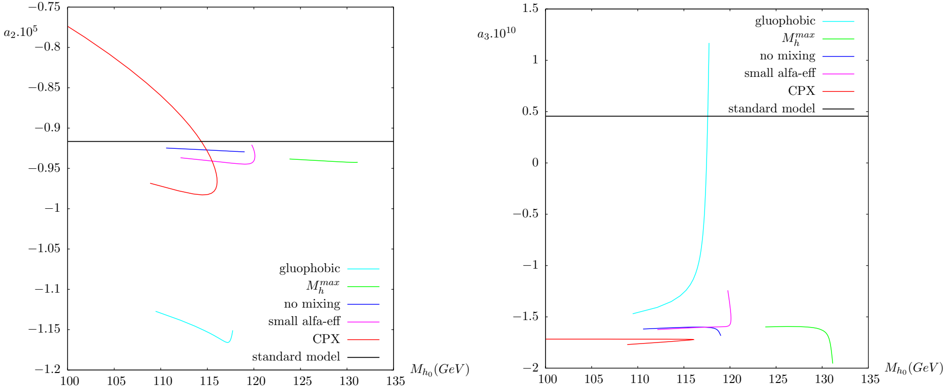
- $M_A/M_{H^+} = 500$ GeV
- In the MSSM, tanβ is varied between 3 and 53
- In the decoupling regime, we expect the SUSY effects to be small

Decoupling regime: h_1 formfactor a_1



- $M_A/M_{H^+} = 500$ GeV
- The loop effects in the decoupling regime are at the % level

Decoupling regime: h_1 formfactors a_2 and a_3

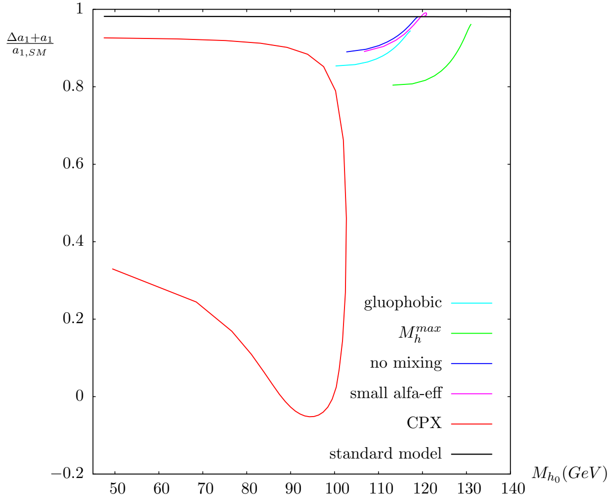


$$M_A/M_{H^+} = 500\text{GeV}$$

- These values are almost certainly too small to be experimentally visible*

*EPJC 51, 386, C Ruwiedel, M Schumacher, N Wermes

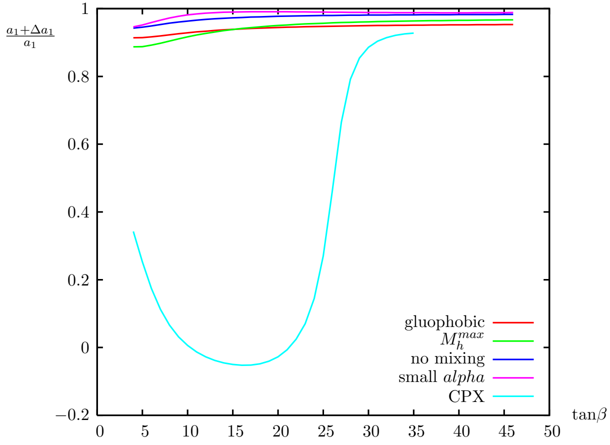
Non-decoupling regime: h_1 formfactor a_1



$M_A/M_{H^+} = 150 GeV$

- In the MSSM, tanβ is varied between 3 and 53
- Away from the decoupling regime, deviations from the Standard Model are pronounced

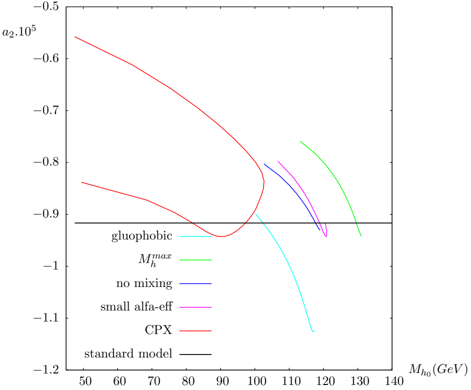
Non-decoupling regime: h_1 formfactor a_1

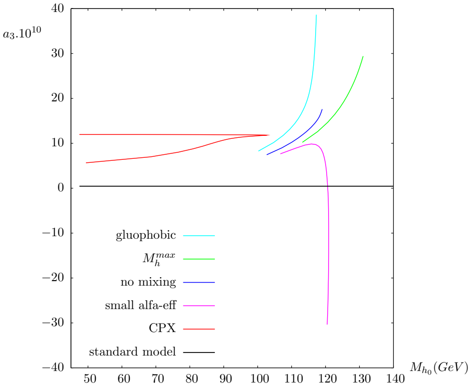


$M_A/M_{H^+} = 150 GeV$

The loop (and, more importantly, Higgs propagator) corrections are extremely significant

Non-decoupling regime: h_1 formfactors a_2 and a_3

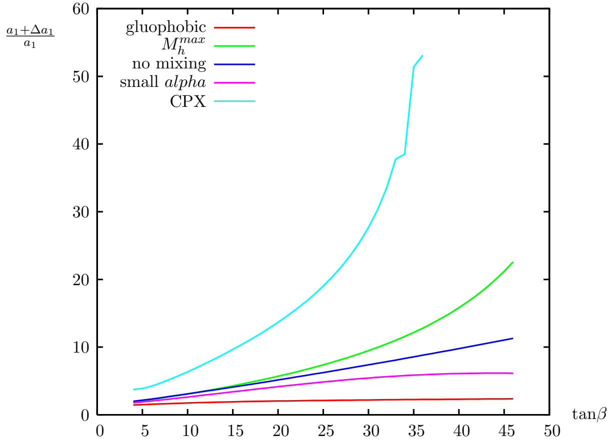




In the MSSM, tanβ is varied between 3 and 53

M_A/M_{H^+} = 150GeV

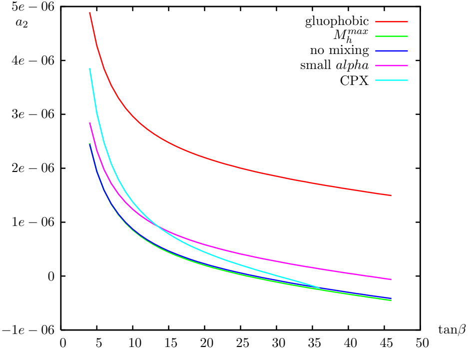
h_2 formfactor a_1

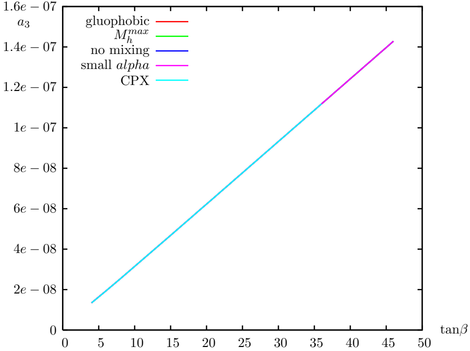


$M_A/M_{H^+} = 500 GeV$

In the MSSM, $\tan\beta$ is varied between 3 and 53

h_2 formfactors a_2 and a_3

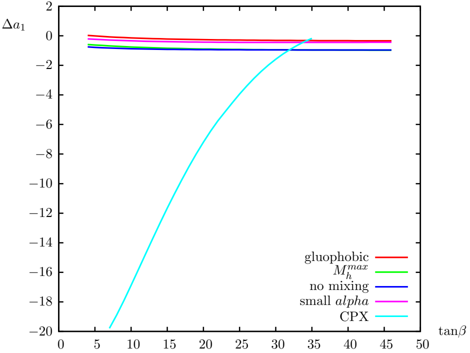


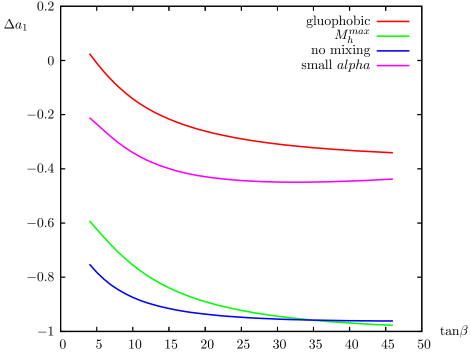


In the MSSM, tanβ is varied between 3 and 53

M_A / M_{H^+} = 500GeV

h_3 formfactors

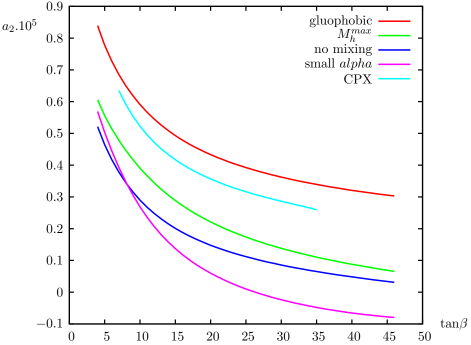


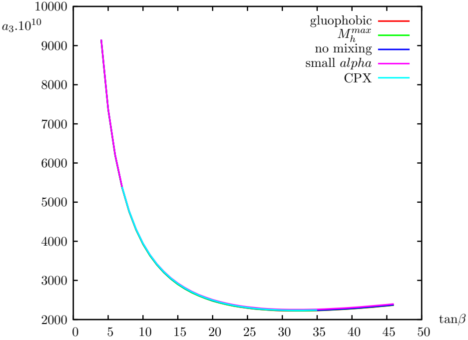


In the MSSM, tanβ is varied between 3 and 53

M_A/M_{H^+} = 150GeV

h_3 formfactors



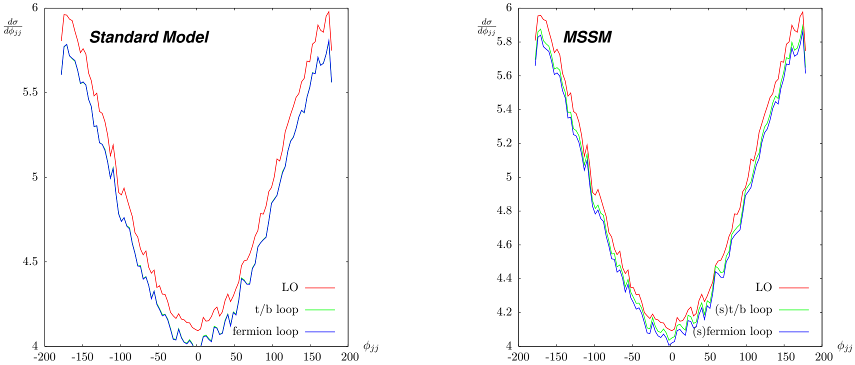


In the MSSM, tanβ is varied between 3 and 53

M_A/M_{H^+} = 150GeV

Monte Carlo Results

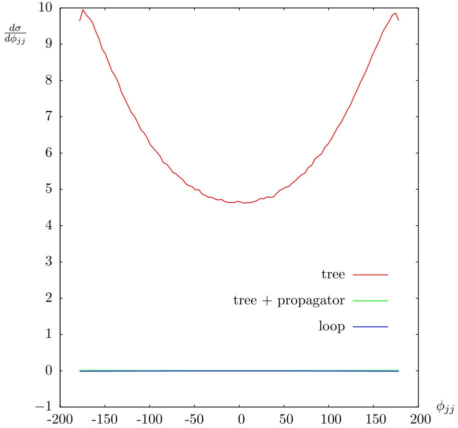
Producing the light CP-even Higgs in the real MSSM



M_h-max scenario, $M_A = 500$ GeV (decoupling regime)
$\tan\beta = 8$, $M_h = 129.8$ GeV

Monte Carlo Results

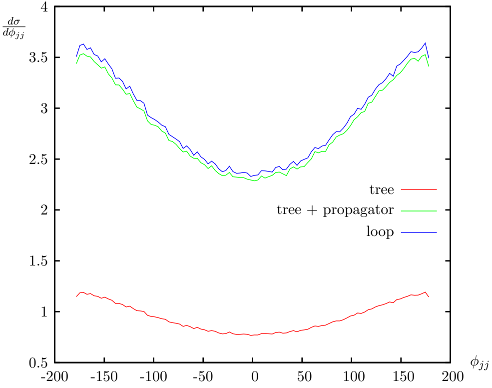
Producing the lightest Higgs in the complex MSSM



CPX scenario, $M_{H^+} = 127$ GeV
tan β = 10, $M_h = 45$ GeV

Monte Carlo Results

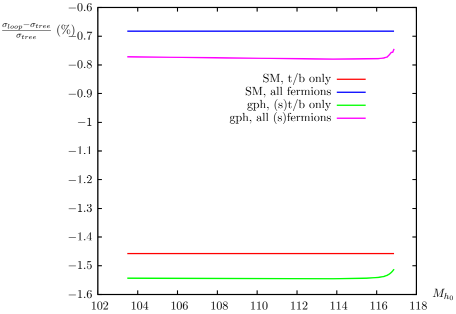
Producing the second lightest Higgs in the complex MSSM

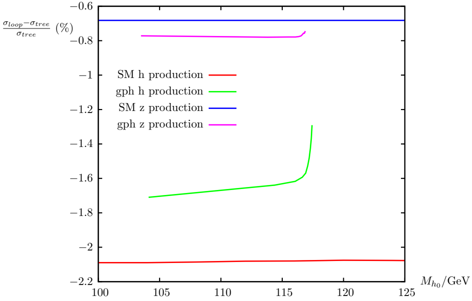


CPX scenario, $M_{H^+} = 127$ GeV
tan β = 10, $M_H = 104$ GeV

Z production - Partonic Cross Sections

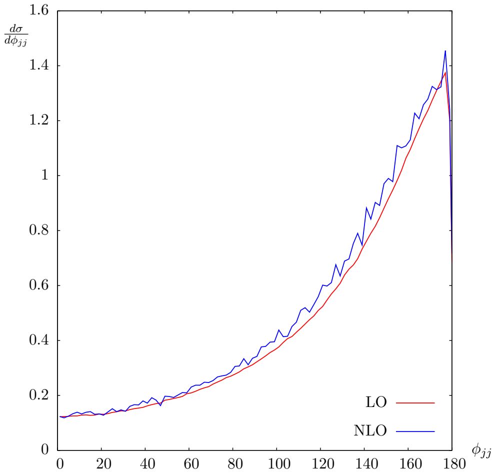
For the partonic process: u + s → d + Z + c





Gluophobic scenario, M_A = 500 GeV

Z Production - MC Results



Summary

- Weak boson fusion provides
  - Higgs discovery channel
  - Study of electroweak symmetry breaking and BSM
- Complete corrections in the SM have been calculated and implemented in a modified `vbfnlo`
- The fermion/sfermion loop corrections in the MSSM have been implemented
- There is reasonable agreement with the literature
- Fermion/sfermion corrections are typically $\sim$ 3-4% for the production of the lightest Higgs in the decoupling regime
- Corrections for the heavier Higgs bosons are generally large
- A possible calibration process is being studied
- **Outlook:** Remaining SUSY corrections