

SuSHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM

Hendrik Mantler

Bergische Universität Wuppertal

in collaboration with Stefan Liebler, Robert Harlander
and Marius Wiesemann

25th Rencontres de Blois
May 29, 2013

1 SusHi

2 Transverse momentum resummation

What can you calculate with SusHi?

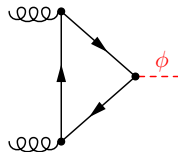
- Gluon fusion cross section within the standard model (SM), the 2 Higgs doublet model (2HDM) and the minimal supersymmetric standard model (MSSM) at NLO
- Different renormalization schemes for the bottom/sbottom sector
- Bottom quark annihilation at NLO within the SM
[Harlander, Ozeren, Wieseemann '10]
→ can be reweighted with MSSM couplings
- Not only inclusive, but also differential cross sections:
 - Transverse momentum distribution
- SusHi includes the codes `ggh@nnlo` [Harlander, Kilgore '02] and `bbh@nnlo` [Harlander, Kilgore '03] for the calculation of the NNLO inclusive cross section
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for the MSSM: take only dominant contribution [Aglietti, Bonciani, Degrandi, Vicini '04 '10] and reweight with MSSM coupling

LO partonic cross section:

$$\sigma_0^\phi = \frac{G_F \alpha_s^2}{288 \sqrt{2} \pi} |\mathcal{A}^\phi|^2$$

$$\mathcal{A}^\phi = \sum_{q \in \{t, b\}} \left(a_q^{\phi, (0)} \right)$$

with $a_q^{\phi, (0)} = \frac{3\tau_q}{2} (1 + (1 - \tau_q^\phi) f(\tau_q^\phi))$



$$\tau_q^\phi = 4m_q^2/m_\phi^2$$

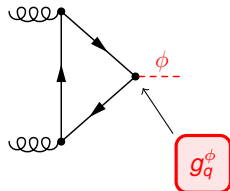
$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4} \left(\log \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right)^2 & \tau < 1 \end{cases}$$

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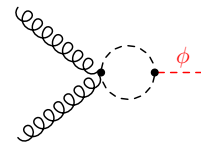
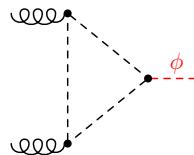
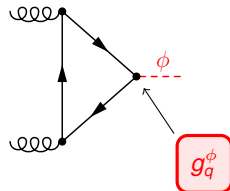
$$\mathcal{A}^\phi = \sum_{q \in \{t, b\}} \left(a_q^{\phi, (0)} + \tilde{a}_q^{\phi, (0)} \right)$$

with $a_q^{\phi, (0)} = g_q^\phi \frac{3\tau_q}{2} (1 + (1 - \tau_q^\phi) f(\tau_q^\phi))$

$$\tilde{a}_q^{\phi, (0)} = -\frac{3\tau_q^\phi}{8} \sum_{i=1}^2 g_{\tilde{q}ii}^\phi (1 - \tau_{\tilde{q}i}^\phi f(\tau_{\tilde{q}i}^\phi))$$

$$\tau_q^\phi = 4m_q^2/m_\phi^2, \quad \tau_{\tilde{q}i}^\phi = 4m_{\tilde{q}i}^2/m_\phi^2$$

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- **Quark-gluon** known analytically
(at higher orders)

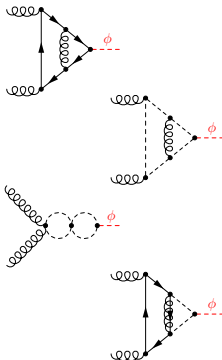
[Spira, Djouadi, Graudenz, Zerwas '95; Harlander, Kant '05]

- **Squark-gluon/squark**
known analytically

[Anastasiou, Beerli, Bucherer, Daleo, Kunstz '06;
Aglietti, Bonciani, Degrassi, Vicini '06; Mühlleitner, Spira '06]

- **Quark-squark-gluino**
semi-analytically known,
but no public code

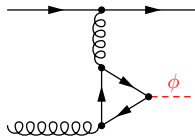
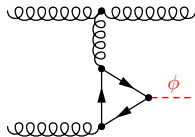
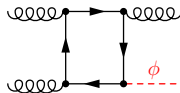
[Anastasiou, Beerli, Daleo '08; Mühlleitner, Rzehak, Spira '10]



- Taylor expansion in the Higgs mass: $m_\phi \ll m_q, m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
[Harlander, Steinhauser '03 '04 + Hofmann '05; Degrassi, Slavich '08]
→ top-stop-gluino
- Expansion in SUSY masses: $m_\phi, m_q \ll m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
for $m_{\tilde{q}_1} = m_{\tilde{q}_2} = m_{\tilde{g}}$ [Harlander, Hofmann, HM '10]
for arbitrary SUSY masses [Degrassi, Slavich '10 + Di Vita '11 '12]
→ bottom-sbottom-gluino

- **Quark**
known analytically
[Spira, Djouadi, Graudenz, Zerwas '95]

- **Squark**
known analytically
[Mühlleitner, Spira '06; Bonciani, Degrossi, Vicini '07]



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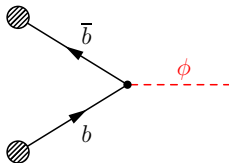
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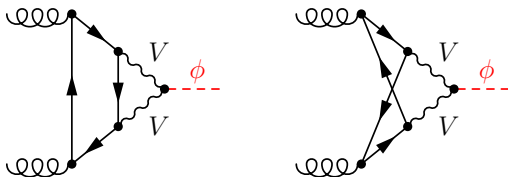
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Diagrams including only light quarks:



- Electro-weak corrections at NLO in the SM from `EWgint`
[\[Actis, Passarino, Sturm, Uccirati '08 '09\]](#)
 for the MSSM: take only dominant contribution [\[Aglietti, Bonciani, Degrassi, Vicini '04 '10\]](#) and reweight with MSSM coupling

SUSY Les Houches (SLHA) input- and outputfiles

Link to FeynHiggs:

[Hahn, Heinemeyer, Hollik, Rzehak,
Weiglein]

let FeynHiggs calculate the
Higgs mass
or
give Higgs mass in input file

We provide input files for the
latest benchmark scenarios

```
Block SUSHI
  1 1 # model: 0 = SM, 1 = MSSM, 2 = 2HDM
[.....]
  3 0 # collider: 0 = p-p, 1 = p-pbar
  4 8000.d0 # center-of-mass energy in GeV
Block MINPAR
  3 5.d0 # tanb
Block EXTPAR
  3 800.d0 # M_3
  11 2000.d0 # A_t
  12 2000.d0 # A_b
  23 200.d0 # mu in GeV
  26 130.d0 # M_A0
  43 1000.d0 # M_Q3
  46 1000.d0 # M_TR
  49 1000.d0 # M_BR
Block FEYNHIGGS # FeynHiggs specific input
  1 0.d0 # M_1
  2 200.d0 # M_2
  3 2000.d0 # A in GeV (except from A_t, A_b)
  4 1000.d0 # M_SUSY in GeV (except from M_Q3, M_TR, M_BR)
Block PDFSPEC
  1 MSTW2008lo68cl.LHgrid # name of pdf (lo)
  2 MSTW2008nlo68cl.LHgrid # name of pdf (nlo)
  3 MSTW2008nnlo_asmzrange.LHgrid # name of pdf (nnlo)
  4 0 # set number
Block FACTORS
  1 0.d0 # factor for yukawa-couplings: c
  2 1.d0 # t
  3 1.d0 # b
  4 1.d0 # st
  5 1.d0 # sb
```


New benchmark scenarios based on fits to the Higgs signal:

[M. Carena, S. Heinemeyer, O. Staål, C.E.M. Wagner, G. Weiglein]

Light stop scenario:

$$\begin{aligned}m_t &= 173.2 \text{ GeV} \\M_{SUSY} &= 500 \text{ GeV} \\ \mu &= 350 \text{ GeV} \\ X_t^{OS} &= 2M_{SUSY} \\ A_b &= A_t \\ m_{\tilde{g}} &= 1500 \text{ GeV} \\ M_{\tilde{t}_3} &= 1000 \text{ GeV}\end{aligned}$$

Vary $\tan \beta$ in the range $2 < \tan \beta < 50$
and M_A in the range $90 \text{ GeV} < M_A < 500 \text{ GeV}$

Stop quark masses are about 325 GeV and 670 GeV, respectively.

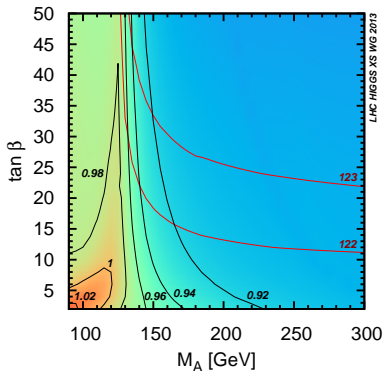
Results

Comparing $S_{\text{US}}\text{Hi}$ to previous LHCHSWG result:

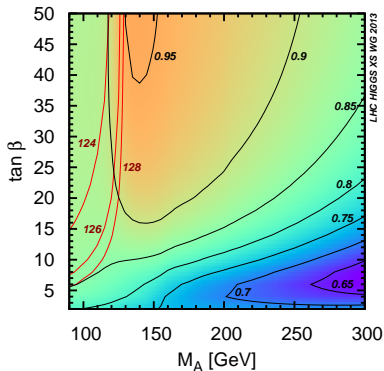
$$\frac{\sigma_{\text{new}}}{\sigma_{\text{old}}}$$

checked against private code [Bagnaschi, Degrassi, Slavich, Vicini]

light Higgs h



heavy Higgs H



Differences mainly due to squark-effects and inclusion of electro-weak corrections.

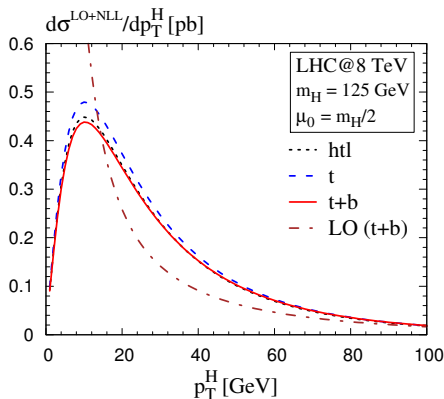
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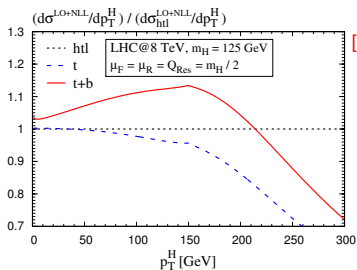
p_T distribution at LO+NLL:

[HM, Wiesemann '12]

$$\left(\frac{d\sigma}{dp_T}\right)^{LO+NLL} = \frac{d\sigma^{LO}}{dp_T} - \left[\frac{d\sigma^{logs}}{dp_T}\right]_{LO} + \left[\frac{d\sigma^{res}}{dp_T}\right]_{NLL}$$



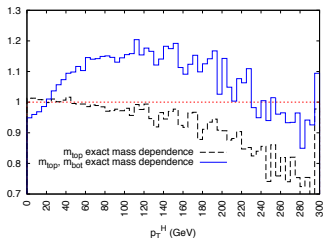
Mass effects:



[HM, Wiesemann '12]

POWHEG

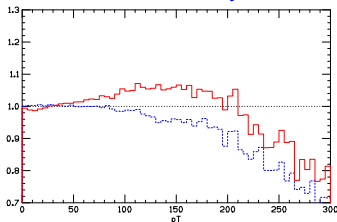
[Bagnaschi, Degrassi, Slavich, Vicini '12]



MC@NLO

[Frederix, Fixione, Maltoni]

Preliminary



- There are some differences regarding the mass effects of the p_T distribution between POWHEG, MC@NLO and the analytic resummation that are not yet understood.
- SusHi can calculate the Higgs production cross section within the MSSM including the squark diagrams in gluon fusion.
- The squark diagrams and the electro-weak corrections contribute up to 35%.
- We have produced new numbers with SusHi for the YR 3.
- SusHi is publicly available.

→ <http://sushi.hepforge.org>

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ATLAS NOTE

ATLAS-CONF-2013-027

March 10, 2013



**Search for Higgs bosons in Two-Higgs-Doublet models in the
 $H \rightarrow WW \rightarrow e\nu\mu\nu$ channel with the ATLAS detector**

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Thanks for your attention!

Backup

Relative couplings g_f^ϕ with respect to the SM Yukawa coupling for the four 2HDM types:

| Model | Type I | Type II | Lepton-specific | Flipped |
|---------|----------------------------|-----------------------------|----------------------------|-----------------------------|
| g_u^h | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ | $\cos \alpha / \sin \beta$ |
| g_d^h | $\cos \alpha / \sin \beta$ | $-\sin \alpha / \cos \beta$ | $\cos \alpha / \sin \beta$ | $-\sin \alpha / \cos \beta$ |
| g_u^H | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ | $\sin \alpha / \sin \beta$ |
| g_d^H | $\sin \alpha / \sin \beta$ | $\cos \alpha / \cos \beta$ | $\sin \alpha / \sin \beta$ | $\cos \alpha / \cos \beta$ |
| g_u^A | $\cot \beta$ | $\cot \beta$ | $\cot \beta$ | $\cot \beta$ |
| g_d^A | $-\cot \beta$ | $\tan \beta$ | $-\cot \beta$ | $\tan \beta$ |

α is the mixing angle in the Higgs sector and $\tan \beta = v_u/v_d$ the ratio of the vacuum expectation values.

The couplings within the MSSM coincide with the ones from Type II of the 2HDM.

- NLO+NNLL in heavy-top limit (htl), H_{QT} [Bozzi, Catani, de Florian, Grazzini '05]
- mass effects? \rightarrow reweighted with Born: $d\sigma_{\text{approx}} = d\sigma_{\text{htl}} \cdot \sigma_{\text{t+b}}^{(0)} / \sigma_{\text{htl}}^{(0)}$

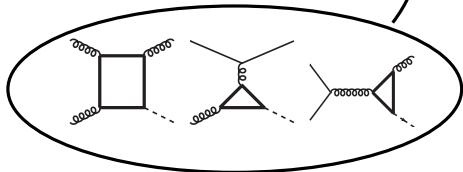
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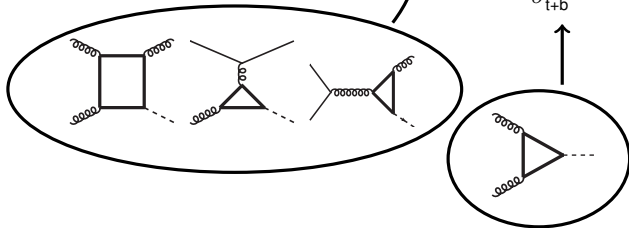
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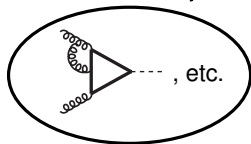
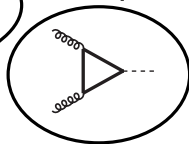
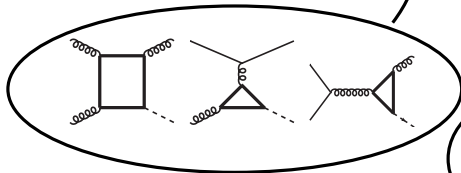
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$$\sigma_{gg\phi}^{\text{SM,(MSSM)}} = \sigma_{gg\phi,\text{NLO}}^{\text{SM,(MSSM)}} + (g_t^\phi)^2 \left[(1 + \delta_{\text{EW}}) \hat{\sigma}_{gg\varphi,\text{NNLO}}^{\text{SM},t} - \hat{\sigma}_{gg\varphi,\text{NLO}}^{\text{SM},t} \right] \quad (1)$$

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$$g_V^h = \sin(\beta - \alpha), \quad g_V^A = 0, \quad g_V^H = \cos(\beta - \alpha) \quad (3)$$

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