Stefan Liebler

Report on the work of the MSSM subgroup: Neutral Higgs production

on behalf of the MSSM subgroup

Meeting of the LHC Higgs XS WG

Geneva - 13 June 2014

University of Hamburg

Universität Hamburg
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Particles, Strings,
and the Early Universe
Collaborative Research Center SFB 676

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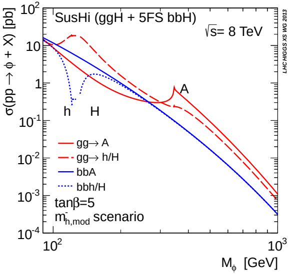
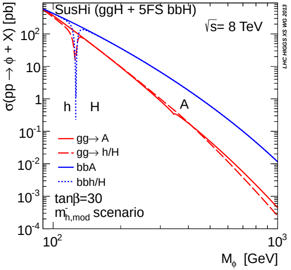
Outline

1. Status of neutral Higgs production in YR3
2. New developments since YR3
3. Transverse momentum distributions
4. Conclusions

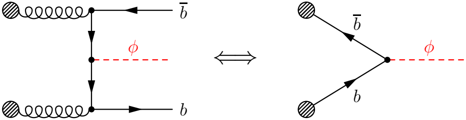
Neutral Higgs production in the real MSSM:



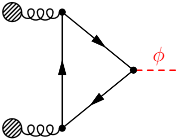


Production cross sections according to YR3 [arXiv:1307.1347]

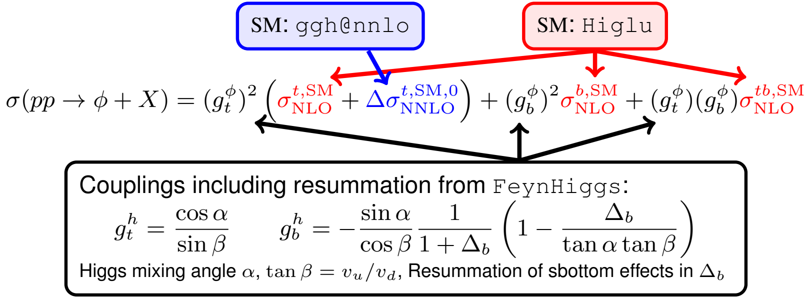
Bottom-quark annihilation:



Gluon fusion:



Gluon fusion: Calculation of MSSM Higgs cross sections in YR1:



SM: `ggh@nnlo`

SM: `Higlu`

$$\sigma(pp\to\phi+X) = (g_t^\phi)^2\left(\sigma_{\text{NLO}}^{t,\text{SM}} + \Delta\sigma_{\text{NNLO}}^{t,\text{SM},0}\right) + (g_b^\phi)^2\sigma_{\text{NLO}}^{b,\text{SM}} + (g_t^\phi)(g_b^\phi)\sigma_{\text{NLO}}^{tb,\text{SM}}$$

Couplings including resummation from `FeynHiggs`:

$$g_t^h = \frac{\cos\alpha}{\sin\beta} \qquad g_b^h = -\frac{\sin\alpha}{\cos\beta}\frac{1}{1+\Delta_b}\left(1-\frac{\Delta_b}{\tan\alpha\tan\beta}\right)$$

Higgs mixing angle α, $\tan\beta = v_u/v_d$, Resummation of sbottom effects in Δ_b

Improvements in YR3:

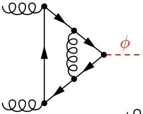
- ✓ Inclusion of NLO third generation squark contributions (on top of Δ_b)
- ✓ Inclusion of electroweak contributions by light quarks

$$\sigma(pp\to\phi+X) = \sigma_{\text{NLO}}^{\text{MSSM}}(1+\delta_{\text{EW}}^{lq}) + (g_t^\phi)^2\left(\Delta\sigma_{\text{NNLO}}^{t,\text{SM},0}\right)$$

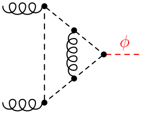
$\Longrightarrow$ XS for $\phi\in\{h,H,A\}$ with `SusHi` (linked to `FeynHiggs` for m_ϕ and α)
(`SusHi` also provides the $bb\phi$ XS in 5FS!)

`Higlu` [Spira '95], `ggh@nnlo` [Harlander Kilgore '02], `SusHi` [Harlander Liebler Mantler '12]
`FeynHiggs` [Hahn Heinemeyer Hollik Rzehak Weiglein]

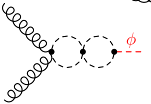
✓ Inclusion of NLO squark contributions:



- gluon-quark: known analytically (higher orders)
  [Spira Djouadi Graudenz Zerwas '95; Harlander Kant '05; . . .]

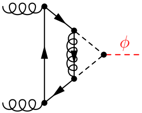


- gluon-squark: known analytically/numerically
  [Anastasiou Beerli Bucherer Daleo Kunszt '06;
  Aglietti Bonciani Degrassi Vicini '06; Mühlleitner Spira '06;
  Bonciani Degrassi Vicini '07]



- gluino-squark-quark contributions:
  semi-analytically known
  [Anastasiou Beerli Daleo '08; Mühlleitner Spira Rzehak '10]

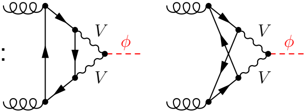
Challenge for gluino-quark-squark contributions:
Five different masses: $m_q, m_{\tilde{q}1}, m_{\tilde{q}2}, m_{\tilde{g}}, p^2 = m_\phi^2$



- Taylor expansion in small Higgs mass:
  $\longrightarrow$ top-stop-gluino contribution $m_\phi \ll m_t, m_{\tilde{t}1}, m_{\tilde{t}2}, m_{\tilde{g}}$
  [Harlander Steinhauser '03 '04 + Hofmann '05; Degrassi Slavich '08]
  (NNLO top-stop-gluino contr. [Pak Steinhauser Zerf '10 '12])
- Expansion in heavy SUSY masses: $m_\phi, m_q \ll m_{\tilde{q}1}, m_{\tilde{q}2}, m_{\tilde{g}}$
  $\longrightarrow$ quark-squark-gluino [Harlander Hofmann Mantler '10; Degrassi Slavich '10 + Di Vita '11 '12]

✓ **Inclusion of elw. contributions by light quarks:** [Aglietti Bonciani Degrassi Vicini '04 '10]

Relevant diagrams with $V \in \{W, Z\}$:



Definition of SUSY electroweak correction factor:

$$\delta_{\mathrm{EW}}^{lq} = \frac{\alpha_{\mathrm{EW}}}{\pi} 2\mathrm{Re}(\mathcal{A}^{\phi} \mathcal{A}^{\phi,\mathrm{EW}})/|\mathcal{A}^{\phi}|^2$$

$$\mathcal{A}^{\phi,\mathrm{EW}} = -\frac{3}{8}\frac{x_W}{s_W^2}\left[\frac{2}{c_W^2}\left(\tfrac{5}{4} - \tfrac{7}{3}s_W^2 + \tfrac{22}{9}s_W^4\right) A[x_Z] + 4A[x_W]\right] g_V^{\phi}$$

Complex mass scheme: $x_V = (m_V - i\frac{\Gamma_V}{2})^2/m_\phi^2$

Supersymmetry enters g_V^{ϕ}:
$g_V^h = \sin(\beta - \alpha), \quad g_V^A = 0, \quad g_V^H = \cos(\beta - \alpha)$

For moderate masses of SM-like Higgs results in similiar correction as SM electroweak correction factor [Actis Passarino Sturm Uccirati '08].

Usage of YR3 setup for new benchmark scenarios (compatible with Run 1):

Scenario	M_{SUSY} [GeV]	X_t [GeV]	μ [GeV]	M_2 [GeV]
m_h^{max}	1000	2000	200	200
$m_h^{\text{mod}+}$	1000	1500	200	200
$m_h^{\text{mod}-}$	1000	-1900	200	200
light stop	500	1000	400	400
light stau	1000	1600	500	200
tau-phobic	1500	3675	2000	200
(low MH)	1500	3675	$m_A = 110$ GeV	200

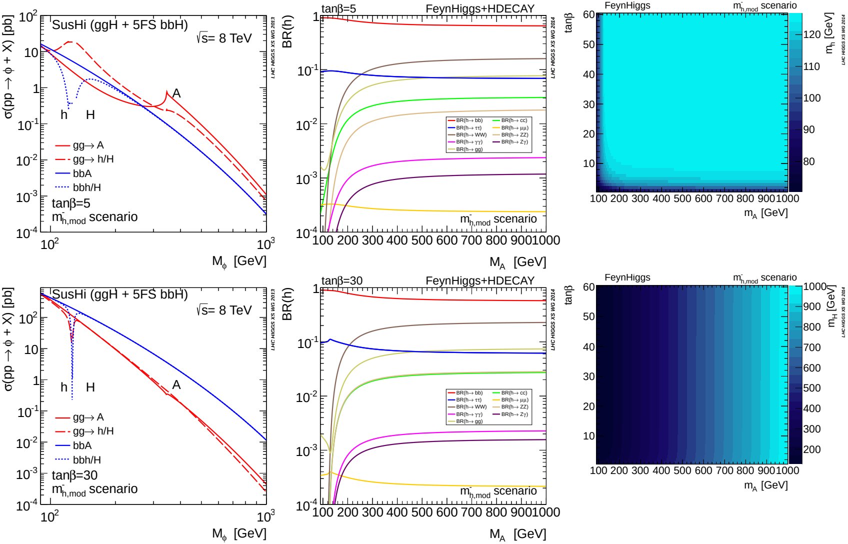
[Carena Heinemeyer Stål Wagner Weiglein '13]

Root files provided on the webpage of the LHC Higgs XS WG as a function of m_A and $\tan\beta$ for $\phi \in \{h, H, A\}$: [Vazquez Acosta Frensch]

- ✓ Higgs masses m_ϕ (h mostly compatible with SM Higgs ~ 125 GeV)
- ✓ Gluon fusion XS (in accordance to YR3)
- ✓ Bottom-quark annihilation XS in 4FS/5FS and Santander-matched XS
- ✓ Branching ratios (with `FeynHiggs` and `HDECAY` - see A. Mück's talk)
- ✓ Scale and PDF$+\alpha_s$ uncertainties

For other scenarios: Easy to use setup. Get in contact!

Plots for the new benchmark scenarios on the webpage (Picture Gallery), e.g.:



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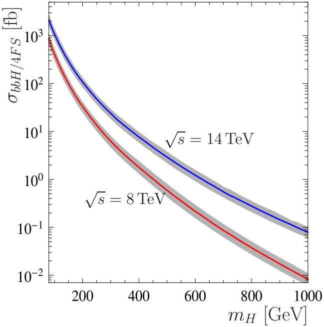
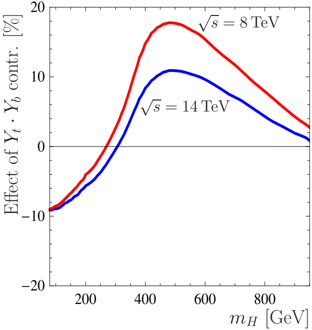
Bottom-quark annihilation in 4FS: [Dittmaier Krämer Spira]

- ✓ Completion of grids for $\sqrt{s} = 7, 8, 13$ and 14 TeV for H/A
- ✓ Addition of complete grids for the $Y_b \cdot Y_t$ interference terms (interferences of bbH/A in 4FS and ggH/A production)
- ✓ Update of Santander-matched XS for SM Higgs on webpage





Detailed uncertainty estimation for gluon fusion:

[Bagnaschi Harlander Liebler Mantler Slavich Vicini '14]

Study includes approx. NNLO stop contributions (incl. in `SusHi`).
Adopt vanishing-Higgs-mass limit (VHML) for top-stop sector to obtain NNLO:

$$\mathcal{L}_{ggH} = -\frac{1}{4v}\,C(\alpha_s)\,HG_{\mu\nu}G^{\mu\nu} \Rightarrow C(\alpha_s) = C^{(0)} + \frac{\alpha_s}{\pi}\,C^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 C^{(2)}$$

$$\sigma^{\rm NNLO} = |\mathcal{A}^{1\ell}_{t\tilde{t}}|^2\,\Sigma^{(0)} + \frac{\alpha_s}{\pi}\left(|\mathcal{A}^{1\ell}_{t\tilde{t}}|^2\,\Sigma^{(1)} + 2\,C^{(1)}\,\Sigma^{(0)}\,{\rm Re}\,\mathcal{A}^{1\ell}_{t\tilde{t}}\right)$$

$$+ \left(\frac{\alpha_s}{\pi}\right)^2 \left[|\mathcal{A}^{1\ell}_{t\tilde{t}}|^2\,\Sigma^{(2)} + 2\left(C^{(1)}\,\Sigma^{(1)} + C^{(2)}\,\Sigma^{(0)}\right){\rm Re}\,\mathcal{A}^{1\ell}_{t\tilde{t}} + (C^{(1)})^2\,\Sigma^{(0)}\right]$$

Approximation: $C^{(2)} = C^{(2)}_t \leftrightarrow$ Uncertainty $[0, 2C^{(2)}_t]$

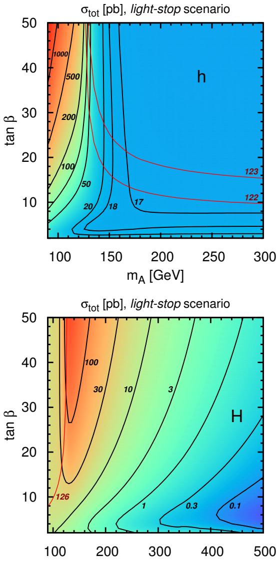
Discussion of XS and uncertainties for the *light stop* scenario:

$m_{\tilde{t}_1} = 324$ GeV and $m_{\tilde{t}_2} = 672$ GeV
$m_{\tilde{b}_1} > 450$ GeV and $m_{\tilde{b}_2} < 550$ GeV

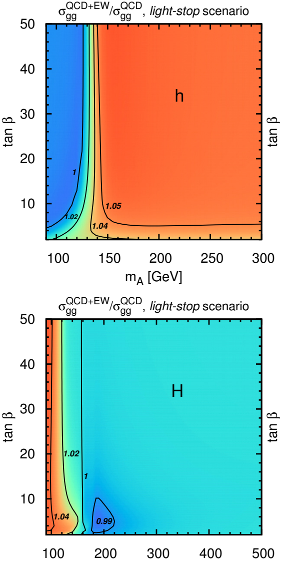
New developments since YR3

Detailed uncertainty estimation for gluon fusion

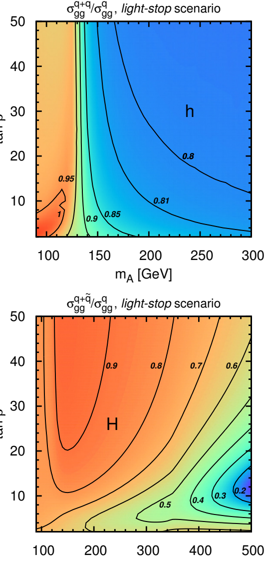
Cross section predictions:



Electroweak contr.



Squark contr.



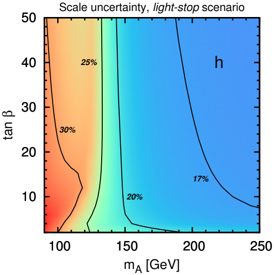
Uncertainties in the gluon fusion XS prediction:

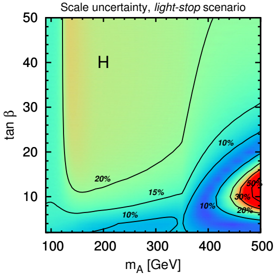
- ✓ Renormalization and factorization scale uncertainties ✓ $\sim \pm(5-25)\%$

  Consider sets C_μ of pairs $(\mu_\mathrm{R}, \mu_\mathrm{F})$ with
  $\mu_\mathrm{R} = \{m_\phi/4,\, m_\phi/2,\, m_\phi\}$, $\mu_\mathrm{F} = \{m_\phi/4,\, m_\phi/2,\, m_\phi\}$,
  with the additional constraint $1/2 \leq \mu_\mathrm{R}/\mu_\mathrm{F} \leq 2$

$$\sigma^- \equiv \min_{(\mu_\mathrm{R},\mu_\mathrm{F})\in C_\mu} \{\sigma(\mu_\mathrm{R},\mu_\mathrm{F})\},\; \sigma^+ \equiv \max_{(\mu_\mathrm{R},\mu_\mathrm{F})\in C_\mu} \{\sigma(\mu_\mathrm{R},\mu_\mathrm{F})\}$$

$$\Delta_\mu \equiv \Delta_\mu^+ - \Delta_\mu^- \quad \text{with} \quad \Delta_\mu^\pm \equiv \frac{\sigma^\pm - \sigma(\mu_\mathrm{R}^0,\mu_\mathrm{F}^0)}{\sigma(\mu_\mathrm{R}^0,\mu_\mathrm{F}^0)}$$





Uncertainties in the gluon fusion XS prediction:

- ✓ Renormalization and factorization scale uncertainties ✓ $\sim \pm(5-25)$%
- ✓ PDF+α_s uncertainties ✓ $\sim \pm(2-5)$%

Performed study according to PDF4LHC recipe:
Outcome: main dependence on the Higgs mass m_ϕ
$\leftrightarrow$ can be taken from SM uncertainty

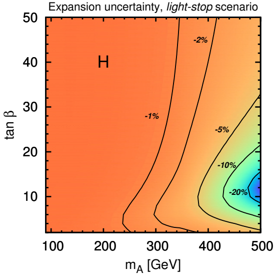
New developments since YR3

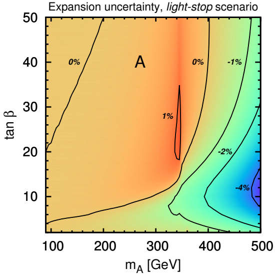
Detailed uncertainty estimation for gluon fusion

Uncertainties in the gluon fusion XS prediction:

- ✓ Renormalization and factorization scale uncertainties ✓ $\sim \pm(5-25)\%$
- ✓ PDF+α_s uncertainties ✓ $\sim \pm(2-5)\%$
- ✓ Uncertainty from heavy SUSY masses expansion + of approximate NNLO stop contributions ✓ $\sim \pm(5-20)\%^{(*)}$

Multiply the two-loop $\tilde{t}+\tilde{b}$ contributions by test factors $\mathcal{A}^{1\ell}_{\tilde{q}_1}/\mathcal{A}^{1\ell,\,\mathrm{exp}}_{\tilde{q}_1}$ with $\tilde{q}=\{\tilde{t},\tilde{b}\}$, $\mathcal{A}^{1\ell,\,\mathrm{exp}}_{\tilde{q}_1}$ includes only $\mathcal{O}(m_{\tilde{q}_1}^{-2})$





Approximative NNLO stop contributions uncertainty: $< 1\%$

$(*)$ for m_ϕ close to the SUSY threshold, i.e. $2m_{\tilde{t}_1}$

New developments since YR3

Detailed uncertainty estimation for gluon fusion

Uncertainties in the gluon fusion XS prediction:

✓	Renormalization and factorization scale uncertainties	✓	$\sim \pm(5-25)\%$
✓	PDF+α_s uncertainties	✓	$\sim \pm(2-5)\%$
✓	Uncertainty from heavy SUSY masses expansion + of approximate NNLO stop contributions	✓	$\sim \pm(5-20)\%^{(*)}$
✓	Uncertainty from missing contributions to Δ_b	✓	$\sim \pm10(25)\%^{(**)}$

Variation of Δ_b by $\pm10\%$
→ for positive μ: Uncertainty $< 10\%$
→ for negative μ: Uncertainty up to $\sim 25\%$
Future work: Inclusion of NNLO contributions [Noth Spira '08 '10, Mihaila Reisser '10]

$(*)$ for m_ϕ close to the SUSY threshold, i.e. $2m_{\tilde{t}_1}$

$(**)$ in case of large coupling $b\bar{b}\phi$ / large $\tan\beta$

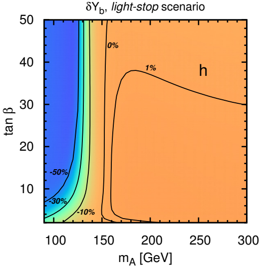
New developments since YR3

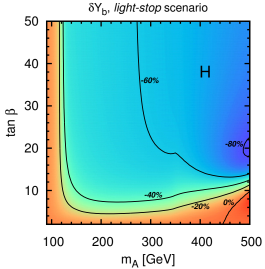
Detailed uncertainty estimation for gluon fusion

Uncertainties in the gluon fusion XS prediction:

- ✓ Renormalization and factorization scale uncertainties ✓ $\sim \pm(5-25)\%$
- ✓ PDF+α_s uncertainties ✓ $\sim \pm(2-5)\%$
- ✓ Uncertainty from heavy SUSY masses expansion + of approximate NNLO stop contributions ✓ $\sim \pm(5-20)\%^{(*)}$
- ✓ Uncertainty from missing contributions to Δ_b ✓ $\sim \pm 10(25)\%^{(**)}$
- ✓ Uncertainty in renormalization of Y_b ✓ $\sim -(0-80)\%^{(**)}$

  Choose $Y_b \propto m_b^{\text{pole}}$ or $m_b^{\overline{\text{MS}}}(\mu_\text{R} \sim m_\phi/2)$





↔ large, where $bb\phi$ dominates

$(*)$ for m_ϕ close to the SUSY threshold, i.e. $2m_{\tilde{t}_1}$

$(**)$ in case of large coupling $b\bar{b}\phi$ / large $\tan\beta$

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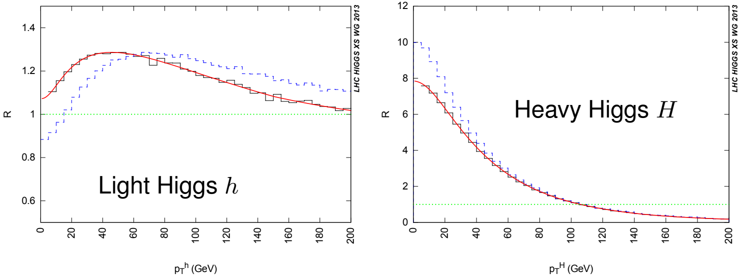
Gluon fusion: Status in YR3

Example: *light stop* scenario with $m_A = 130\,\text{GeV}$, $\tan\beta = 40$

Red: `SusHi` fixed order, Black: `POWHEG` fixed order,
Blue: `POWHEG` method (Resummation of $\log(p_T/m_\phi)$ via Sudakov form factor and PS)
[Bagnaschi Degrassi Slavich Vicini '11]

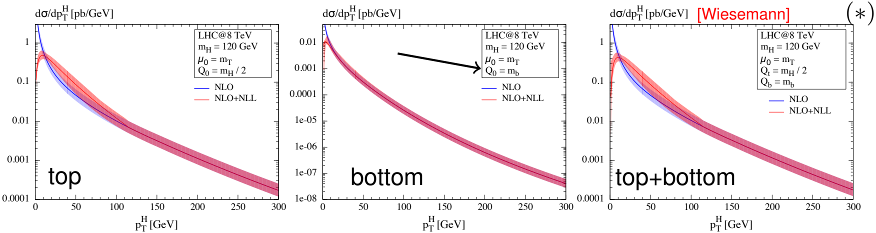
$$R = \frac{d\sigma^{\text{SUSY}}/dp_T}{d\sigma^{\text{SM}}/dp_T}$$



Gluon fusion: Analytic resummation

Treatment of heavy-quark masses in SM

[Mantler Wiesemann '12, Grazzini Sargsyan '13, Banfi Monni Zanderighi '13]



[Wiesemann] $(*)$

for top in VHML: NNLO+NNLL [Bozzi Catani de Florian Grazzini '06]

Ongoing: Translation to MSSM/2HDM - Detailed comparison [Nikitenko]

Public: `POWHEG-BOX` (gg_H_MSSM, gg_H_2HDM) [Bagnaschi Vicini]

On the way: `SusHi` version with analytic resummation [Harlander Mantler Wiesemann]

`SusHi`-amplitudes to `POWHEG-BOX/MG5_aMC@NLO` [Mantler Wiesemann]

Bottom-quark annihilation: p_T resummation in 5FS at NNLO+NNLL [Harlander Tripathi Wiesemann '14]

(NLO+NLL [Belyaev Nadolsky Yuan '06])

$(*)$ SM recommendation: Scale choices: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \mu_0 = m_T = \sqrt{m_H^2 + p_T^2}, Q_t = m_H/2, Q_b = m_b$

Uncertainties: $m_T/2 < \mu_{\mathrm{F}}/\mu_{\mathrm{R}} < 2m_T$ (excluding $\mu_{\mathrm{R}}/\mu_{\mathrm{F}} = 4, 1/4$), $m_H/4 < Q_t < m_H, m_b/3 < Q_b < 3m_b$

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Conclusions

The MSSM subgroup was a **success**,
similar to the whole LHC Higgs cross section working group.

Recently (2013-2014) the MSSM subgroup

- ✓ improved precision in Higgs production cross sections by including squark and electroweak contributions to $gg\phi$, adding more contributions to $bb\phi$.
- ✓ provided root files/figures for benchmark scenarios compatible with Run 1. (Check the webpage!)

Are we done? Never ever!

- ✓ We can improve the theoretical uncertainty estimation and/or work harder to calculate higher orders.
- ✓ Work on transverse momentum distributions is appreciated.
- ✓ Inclusion of bottom-quark annihilation to `POWHEG`.

Thank you for your attention!

The neutral components of the Higgs doublets $H_u = (H_u^+, H_u^0)^T$ and $H_d = (H_d^0, H_d^-)^T$ mix as follows

CP-even Higgs CP-odd Higgs

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G \\ A \end{pmatrix} \quad .$$

The mixing matrix is expressed in terms of the “Higgs mixing angle α”

$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \quad .$$

The Higgs sector at LO is determined by fixing $\tan\beta = \frac{v_u}{v_d}$ and m_A^2:

$$m_{h,H} = \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_Z^2 m_A^2 \sin^2(2\beta)} \right)$$

$$\tan(2\alpha) = \tan(2\beta) \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}$$

The lightest Higgs h mass obtains large corrections at higher orders:
`FeynHiggs` [Frank Degrassi Hahn Heinemeyer Hollik Rzehak Slavich Weiglein Williams]
3-loop [Martin ’07; Kant Harlander Mihaila Steinhauser ’08 ’10].

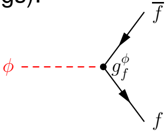
Appendix

MSSM Higgs sector

In the MSSM, Higgs couplings to the b-quark can be enhanced by $\tan\beta$:
Relative strength of the Higgs boson couplings g_f^ϕ with $\phi \in \{h, H, A\}$ to the SM fermions (with respect to the SM Higgs boson couplings):

$$g_u^h = \frac{\cos\alpha}{\sin\beta} \qquad g_u^H = \frac{\sin\alpha}{\sin\beta} \qquad g_u^A = \frac{1}{\tan\beta}$$

$$g_d^h = -\frac{\sin\alpha}{\cos\beta} \qquad g_d^H = \frac{\cos\alpha}{\cos\beta} \qquad g_d^A = \tan\beta$$

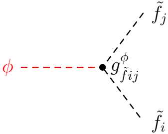


In addition, the superpartners of the quarks, the squarks, are relevant

$$\mathcal{L} \supset -(\tilde{q}_L^\dagger, \tilde{q}_R^\dagger)\mathcal{M}_{\tilde{q}}^2 \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$$

with the mass matrix:

$$\mathcal{M}_{\tilde{q}}^2 = \begin{pmatrix} M_{qL}^2 + m_q^2 + m_{E1}^2 & m_q(A_q - \mu\kappa) \\ m_q(A_q - \mu\kappa) & M_{qR}^2 + m_q^2 + m_{E2}^2 \end{pmatrix}$$



They form two mass eigenstates:

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{q}} & \sin\theta_{\tilde{q}} \\ -\sin\theta_{\tilde{q}} & \cos\theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$$

$m_{E1}^2 = m_z^2 \cos(2\beta)(T_q^3 - Q_q \sin^2\theta_W)$; $m_{E2}^2 = m_Z^2 \cos(2\beta) Q_q \sin^2\theta_W$; $\kappa = \tan\beta(d), \cot\beta(u)$

Appendix

Gluon fusion

Gluon fusion at LO using $\tau_\phi = m_\phi^2/s$:

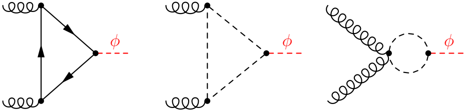
$$\sigma(pp \to \phi + X) = \sigma_0^\phi \tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}$$

Partonic → Hadronic XS:

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x) g(\tau/x)$$

LO partonic cross section (XS):

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



$$\mathcal{A}^\phi = \sum_{q\in\{t,b\}} \left(a_q^{\phi,(0)} + a_{\tilde{q}}^{\phi,(0)} \right)$$ with $$a_q^{\phi,(0)} = g_q^\phi \frac{3\tau_q}{2}(1 + (1 - \tau_q^\phi) f(\tau_q^\phi))$$

Quark contributions

Squark contributions

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

$$\tau_q^\phi = 4m_q^2/m_\phi^2, \quad \tau_{\tilde{q}i}^\phi = 4m_{\tilde{q}i}^2/m_\phi^2, \quad f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left(\log \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right)^2 & \tau < 1 \end{cases}$$

Cancellation of logs - Bottom 2-loop contributions:

[Spira Djouadi Graudenz Zerwas '95] in the notation of [Degrassi Slavich '10]

$$G_b^{2\ell} = C_F\, G_b^{(g,C_F)} + C_A\, G_b^{(g,C_A)}$$

$$2\, m_b^2\, G_b^{(g,C_F)} = \mathcal{F}_{1/2}^{(2\ell,a)}(\tau_b) + \mathcal{F}_{1/2}^{(2\ell,b)}(\tau_b) \left(\ln \frac{m_b^2}{Q^2} - \frac{1}{3} \right)$$

$$2\, m_b^2\, G_b^{(g,C_A)} = \mathcal{G}_{1/2}^{(2\ell,C_A)}(\tau_b)$$

In the limit $\tau_b = 4m_b^2/m_\phi^2 \ll 1$ the above expressions reduce to:

$$\mathcal{F}_{1/2}^{(2\ell,a)}(\tau) = -\tau \left[9 + \frac{9}{5}\,\zeta_2^2 - \zeta_3 - (1+\zeta_2+4\,\zeta_3)\,\ln(\frac{-4}{\tau}) - (1-\zeta_2)\,\ln^2(\frac{-4}{\tau}) + \frac{1}{4}\,\ln^3(\frac{-4}{\tau}) + \frac{1}{48}\,\ln^4(\frac{-4}{\tau}) \right] + \mathcal{O}(\tau^2)$$

$$\mathcal{F}_{1/2}^{(2\ell,b)}(\tau) = 3\,\tau \left[1 + \frac{1}{2}\,\ln(\frac{-4}{\tau}) - \frac{1}{4}\,\ln^2(\frac{-4}{\tau}) \right] + \mathcal{O}(\tau^2)$$

$$\mathcal{G}_{1/2}^{(2\ell,C_A)}(\tau) = -\tau \left[3 - \frac{8}{5}\,\zeta_2^2 - 3\,\zeta_3 + 3\,\zeta_3\,\ln(\frac{-4}{\tau}) - \frac{1}{4}\,(1+2\,\zeta_2)\,\ln^2(\frac{-4}{\tau}) - \frac{1}{48}\,\ln^4(\frac{-4}{\tau}) \right] + \mathcal{O}(\tau^2)$$

For $Q = m_b$ the various logarithms accidentally cancel in case of gluon fusion.

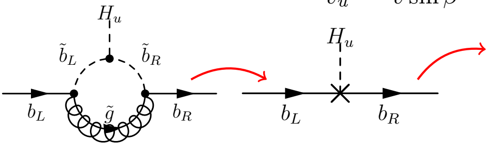
Choice of Y_b

Resummation of large $\tan\beta$-enhanced terms in the MSSM

$$\mathcal{L} \supset -Y_t H_u Q t_R + Y_b H_d Q b_R$$

Using $\langle H_u\rangle = v_u, \langle H_d\rangle = v_d$ and $v_d^2 + v_u^2 = v^2, \tan\beta = v_u/v_d$ we define

$$Y_t = \frac{m_t}{v_u} = \frac{m_t}{v\sin\beta}, \qquad Y_b = \frac{m_b}{v_d} = \frac{m_b}{v\cos\beta}$$



$$\mathcal{L}^{\text{eff}} \supset Y_b H_d Q b_R - \tilde{Y}_b H_u^* Q b_R$$

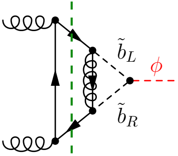
$$\Delta_b = \frac{\tilde{Y}_b v_u}{Y_b v_d} =: \epsilon\tan\beta$$

The effective Lagrangian motivates:

$$m_b = Y_b v_d + \tilde{Y}_b v_u = Y_b v_d(1+\epsilon\tan\beta)$$

$$\Rightarrow \quad Y_b = \frac{m_b}{v_d(1+\Delta_b)}$$

This replacement implies a resummation of large $\tan\beta$-enhanced terms:

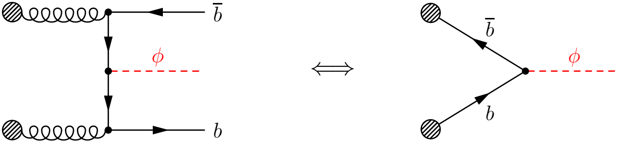


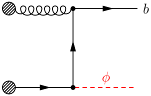
[Hall Rattazzi Sarid '93, Hempfling '94, Carena Garcia Nierste Wagner '99, Guasch Häfliger Spira '03]

Bottom-quark annihilation:
$pp \to (b\bar{b})\phi + X$ for enhanced couplings to b-quarks relevant → MSSM!

4 flavour scheme (4FS)
Collinear logarithms $\propto \log(m_b/m_\phi)$

5 flavour scheme (5FS)
Resummmation of logarithms
b quarks as partons





Calculation of inclusive cross section at NNLO in the 5FS:
`bbh@nnlo` [Harlander Kilgore '03]

Distributions for Higgs+jet(s) production in the 5FS
[Harlander Ozeren Wiesemann '10, Buehler Herzog Lazopoulos Mueller '12]