

# SusHi

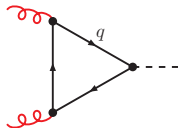
and more

Robert Harlander

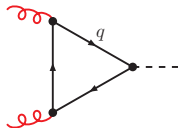
BU Wuppertal

SUSY Workshop 2013  
DESY Hamburg

# Motivation

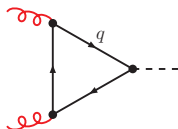


# Motivation

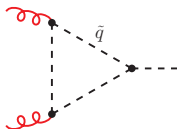


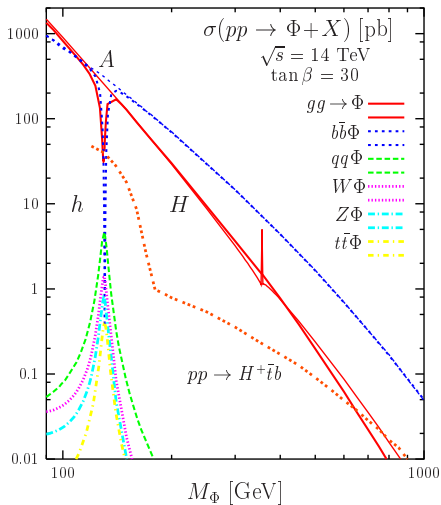
- studied in great detail in the Standard Model:  
NNLO + NNLL + EW + EW $\otimes$ QCD +  $\pi^2$  +  $\mathcal{O}(1/m_t^2)$   
+ *b*-loops + PDF-uncertainties + ...

# Motivation



- studied in great detail in the Standard Model:  
NNLO + NNLL + EW + EW $\otimes$ QCD +  $\pi^2$  +  $\mathcal{O}(1/m_t^2)$   
+  $b$ -loops + PDF-uncertainties + ...
- MSSM: NLO?  
e.g. LHXSWG YR2: without SUSY particles





[Djouadi '08]

# What is SusHi?

SusHi includes ...

Higgs production cross sections:

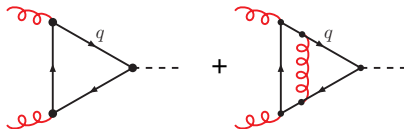
- $gg \rightarrow h, H, A$ 
  - quark, squark, gluino-loops through NLO
  - top loops through NNLO
  - EW effects
  - $\tan \beta$  resummation
  - various renormalization schemes
- $b\bar{b} \rightarrow h, H, A$ 
  - 5-flavor-scheme
  - NNLO
- SM, MSSM, 2HDM
- link to FeynHiggs (input parameters,  $M_{h,H,A}$ )
- link to 2HDMC (work in progress)
- **Authors: RH, Stefan Liebler, Hendrik Mantler**

# NLO amplitude

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$

# Top quark loops

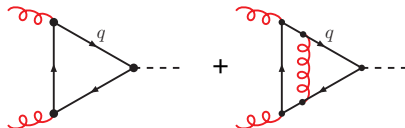
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- result for general  $m_q, M_h$  @ NLO

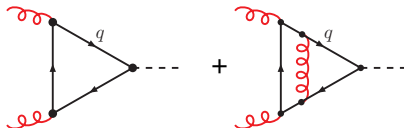
[Spira, Djouadi, Graudenz, Zerwas '95]

→ HIGLU

[RH, Kant '05], [Anastasiou *et al.* '07], [Aglietti *et al.* '07]

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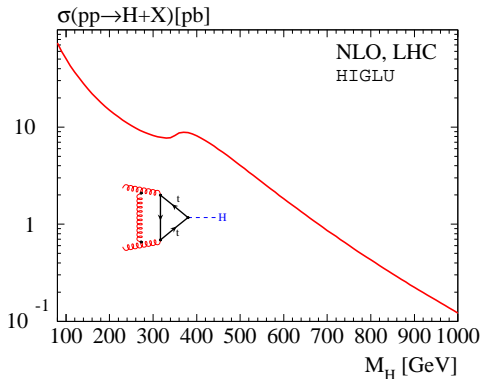
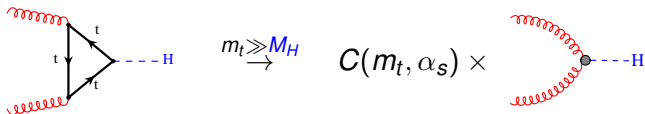
→ HIGLU

[RH, Kant '05], [Anastasiou *et al.* '07], [Aglietti *et al.* '07]

- lesson: heavy-top limit works!

# Heavy-top limit

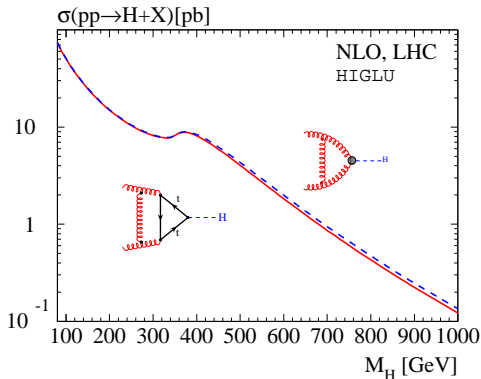
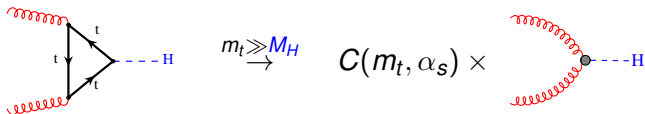
- effective theory for  $m_t \gg M_H$ :



$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left( \frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

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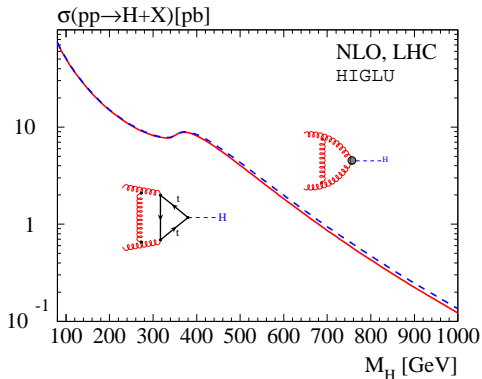
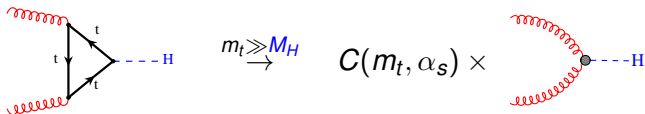
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[Dawson '91]

[Djouadi, Spira, Zerwas '91]

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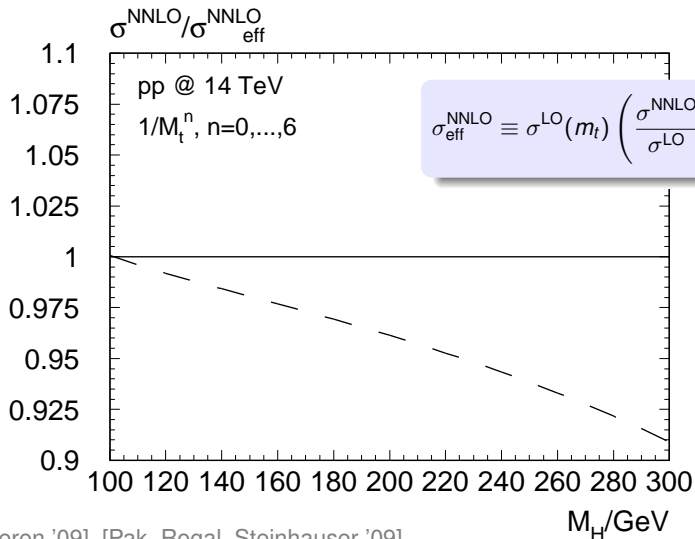
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**NNLO?**

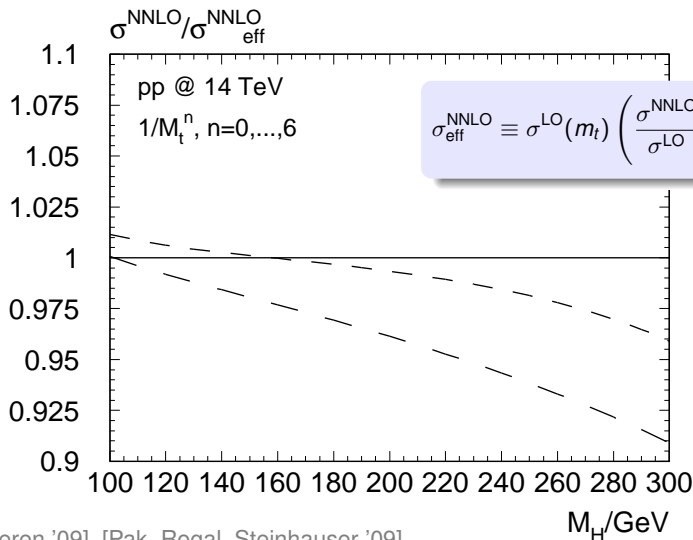
# Convergence of $1/m_t$ expansion at NNLO



[RH, Ozeren '09], [Pak, Rogal, Steinhauser '09]

[RH, Mantler, Marzani, Ozeren '09]

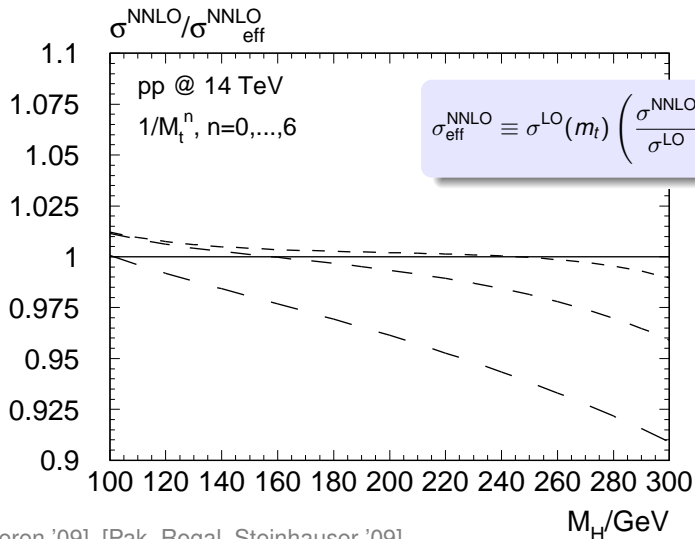
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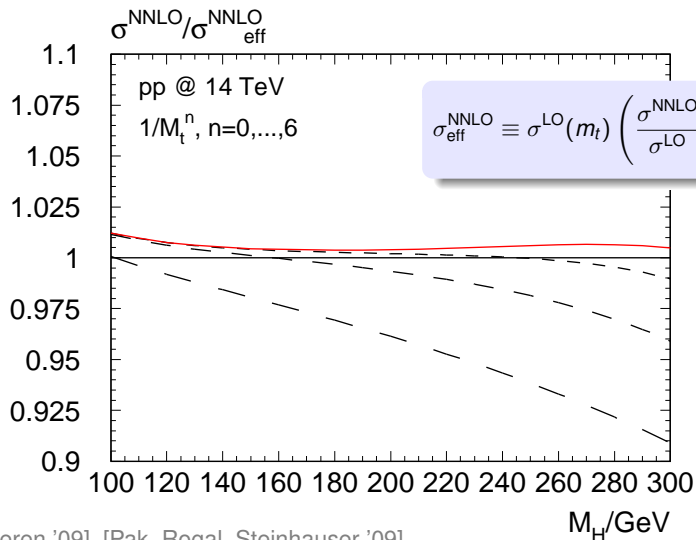


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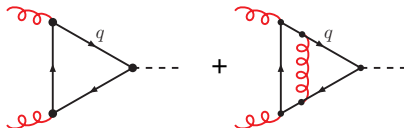


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- result for general  $m_q, M_h$  @ NLO

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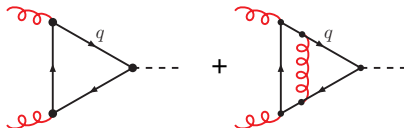
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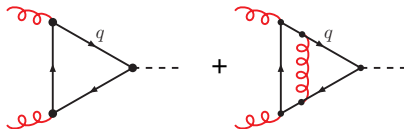
- lesson: heavy-top limit works!

- NNLO ✓

[RH, Kilgore '02], [Anastasiou, Melnikov '02], [Ravindran, Smith, v. Neerven '03]

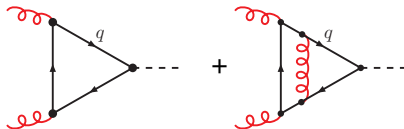
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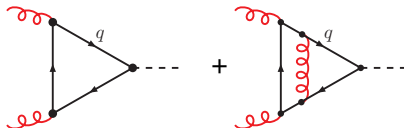
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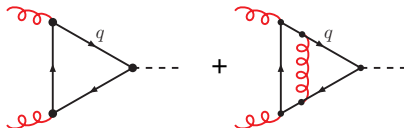
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[RH, Kant '05], [Anastasiou *et al.* '06], [Aglietti *et al.* '07]

- no heavy-bottom limit

⇒ no NNLO!

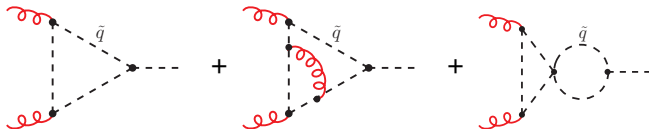
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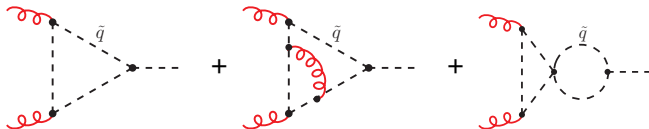
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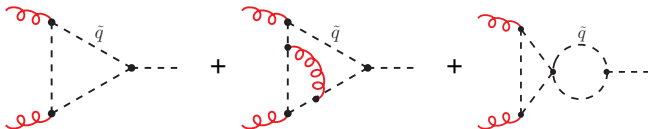


- exact result

[Anastasiou *et al.* '07], [Aglietti *et al.* '07], [Mühlleitner, Spira '08]

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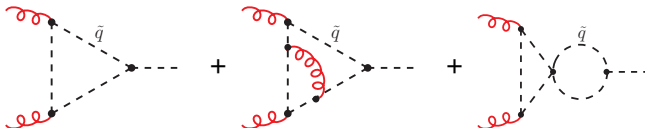
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- but: not SUSY!

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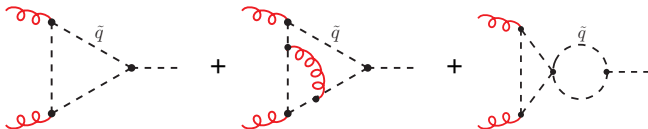
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- exact result

[Anastasiou *et al.* '07], [Aglietti *et al.* '07], [Mühlleitner, Spira '08]

- but: not SUSY!

- either: include gluino diagrams
- or: decouple gluino (see [Mühlleitner, Rzehak, Spira '09])

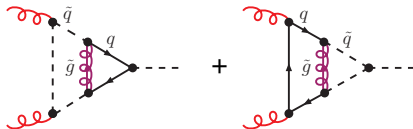
$$\Rightarrow \tilde{y}_q \sim m_q^2 \quad \tilde{m}_g \xrightarrow{\rightarrow} \infty \quad \tilde{y}_q^{\text{eff}} \sim \tilde{m}_q^2$$

# Quark/squark/gluino loops

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$

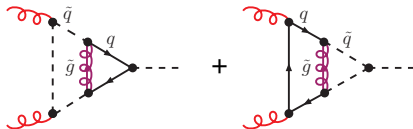
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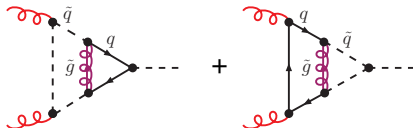
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[Anastasiou, Beerli, Daleo '08]



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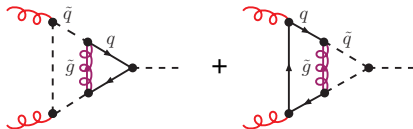
- exact result

[Anastasiou, Beerli, Daleo '08]

- but: only in fully numerical form  $\Rightarrow$  difficult to use

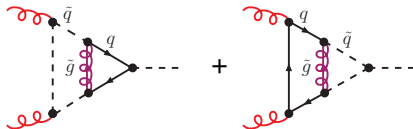
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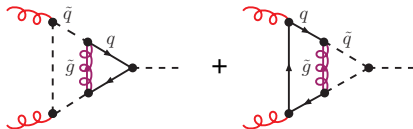
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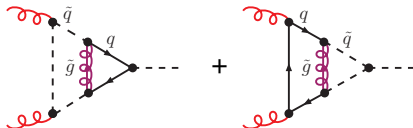
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● idea:  $\mathcal{L}_{\text{SM}} \xrightarrow{m_t \rightarrow \infty} \mathcal{L}_{\text{QCD}}^{(5)} + C(m_t, \alpha_s) H G_{\mu\nu} G^{\mu\nu} + \dots$

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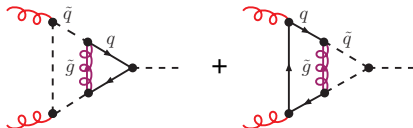
$$\mathcal{L}_{\text{SUSY}} \xrightarrow{\substack{\tilde{M} \rightarrow \infty \\ m_t \rightarrow \infty}} \mathcal{L}_{\text{QCD}}^{(5)} + \tilde{C}(m_t, \tilde{M}, \alpha_s) H G_{\mu\nu} G^{\mu\nu} + \dots$$

[RH, Steihauser '03]  $\rightarrow$  evalcsusy

[RH, Hofmann, '06] [Degrassi, Slavich '08] [Degrassi, Di Vita, Slavich '11]

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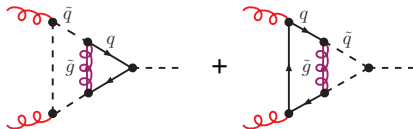
- Meanwhile NNLO [Pak, Steinhauser, Zerf '10/'12]  
(in SusHi: approximate NNLO [RH, Steinhauser '03])

# Bottom/sbottom/gluino

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$

# Bottom/sbottom/gluino

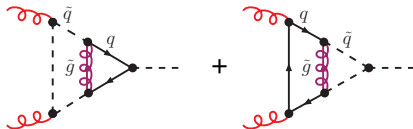
$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}} + a_{b\tilde{g}}$$





# Bottom/sbottom/gluino

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$

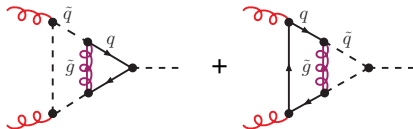


$$\begin{matrix} \tilde{M} \rightarrow \infty \\ \rightarrow \end{matrix} C_1(\tilde{M}, \alpha_S) \otimes \text{Diagram}$$

A diagram showing a red wavy line (gluon) loop with a grey circle representing a vertex correction, connected to a dashed line.

# Bottom/sbottom/gluino

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$

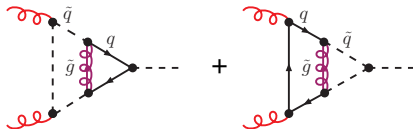


$$\xrightarrow{\tilde{M} \rightarrow \infty} C_1(\tilde{M}, \alpha_s) \otimes \text{Diagram}$$

$$+ C_2(\tilde{M}, \alpha_s) \otimes \text{Diagram}$$

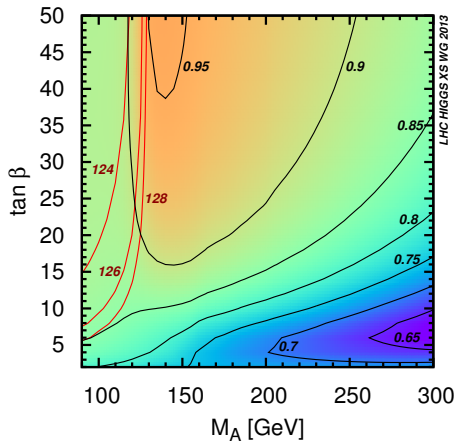
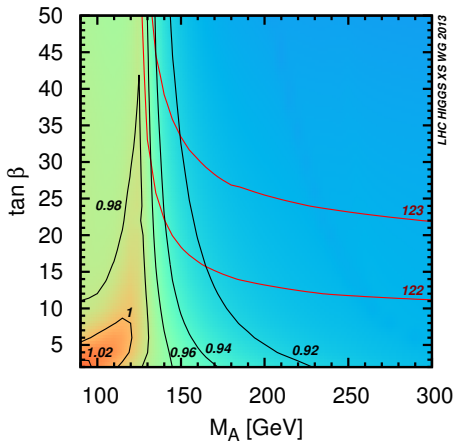
# Bottom/sbottom/gluino

$$\mathcal{A} = a_t^{(0)} + a_b^{(0)} + a_{\tilde{t}}^{(0)} + a_{\tilde{b}}^{(0)} + a_t^{(1)} + a_b^{(1)} + a_{\tilde{t}}^{(1)} + a_{\tilde{b}}^{(1)} + a_{t\tilde{g}}^{(1)} + a_{b\tilde{g}}^{(1)}$$



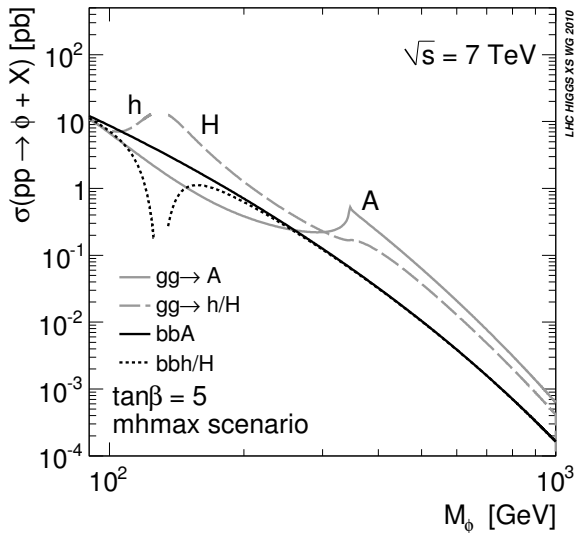
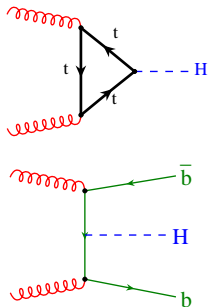
$$\begin{aligned} & \xrightarrow[\rightarrow]{\tilde{M} \rightarrow \infty} C_1(\tilde{M}, \alpha_s) \otimes \text{[Diagram: gluon self-energy loop]} \\ & + C_2(\tilde{M}, \alpha_s) \otimes \text{[Diagram: quark self-energy loop]} \end{aligned}$$

[Hofmann (diss) '09], [Degrassi, Slavich '10/'12], [RH, Hofmann, Mantler '11]

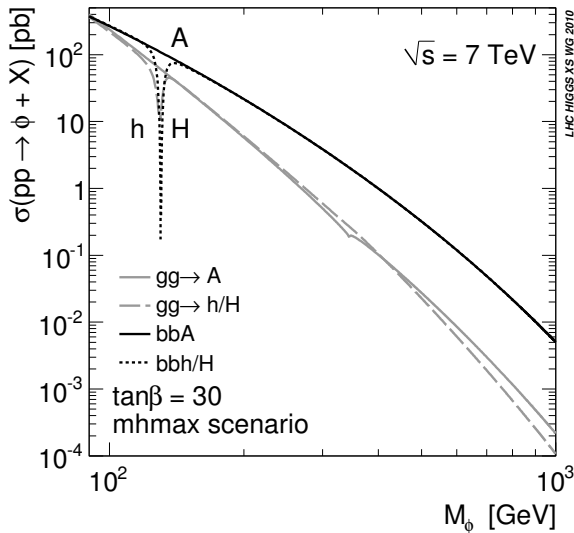
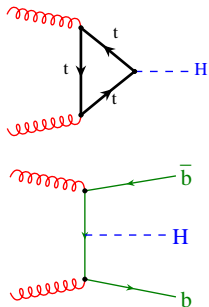


- ratio MSSM vs. MSSM w/o squarks
- “light stop” scenario [Carena, Heinemeyer, Stål, Wagner, Weiglein '13]

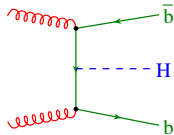
# Higgs XS, $\tan\beta = 5$

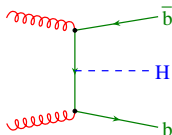


# Higgs XS, $\tan\beta = 30$



# $H/A + b\bar{b}$

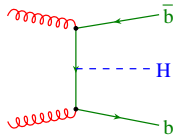




- collinear logarithms:

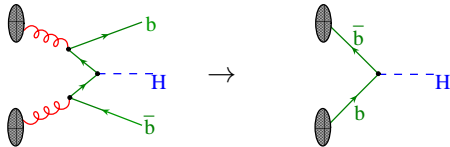
$$\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(4/100)$$



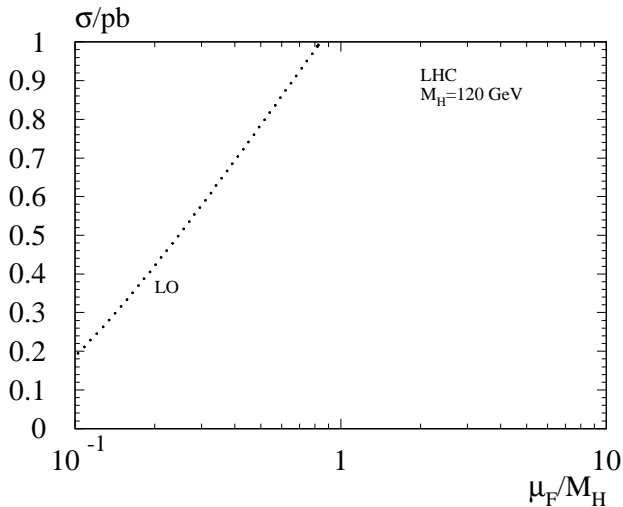


• collinear logarithms:  $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(4/100)$

• resummation: bottom quarks as partons

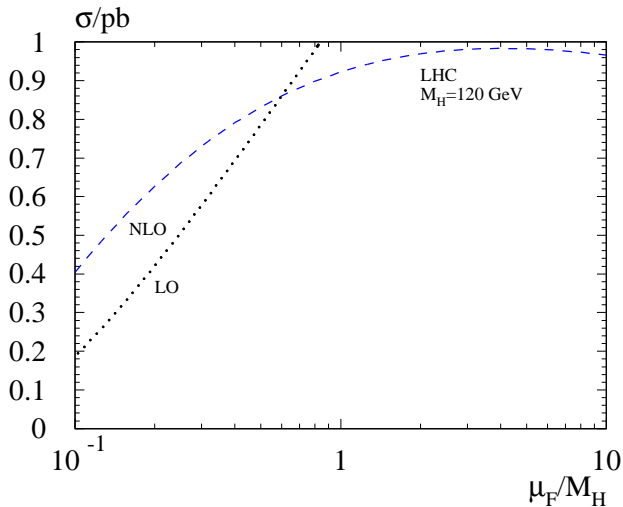


# $b\bar{b} \rightarrow H$ at NLO



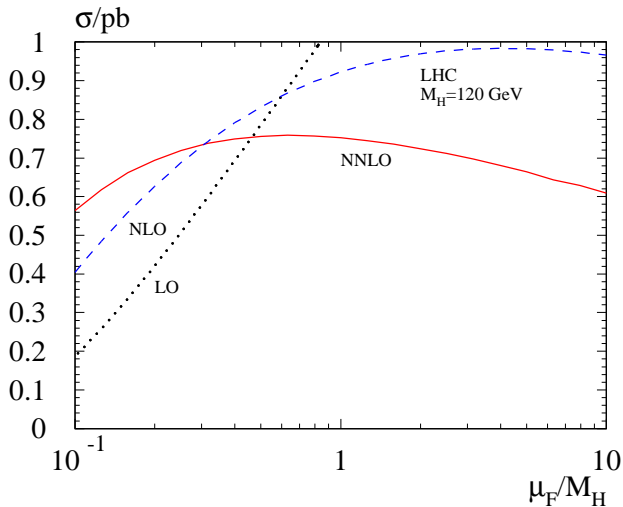
bbh@nnlo: [RH, Kilgore '03]

# $b\bar{b} \rightarrow H$ at NLO



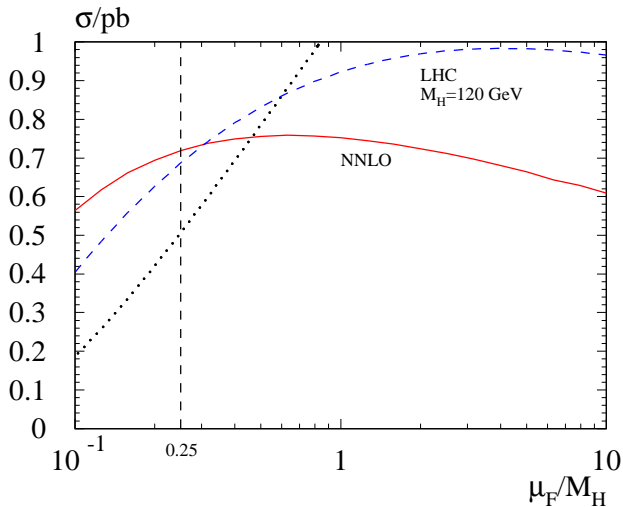
bbh@nnlo: [RH, Kilgore '03]

# $b\bar{b} \rightarrow H$ at NLO



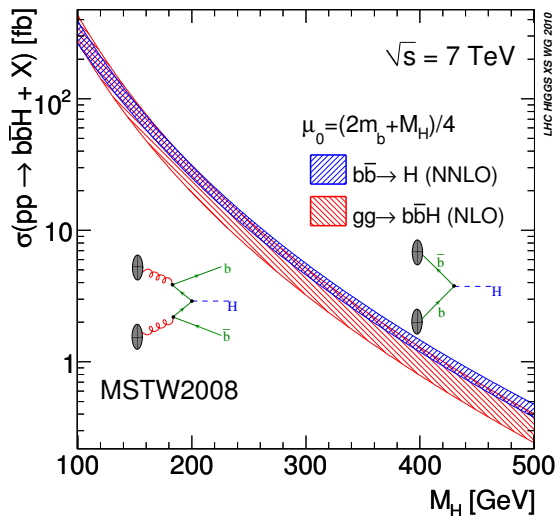
bbh@nnlo: [RH, Kilgore '03]

# $b\bar{b} \rightarrow H$ at NLO



bbh@nnlo: [RH, Kilgore '03]

$$pp \rightarrow H + b\bar{b}$$



[RH, Kilgore '03]

[Dittmaier, Krämer, Spira '04]

[Dawson, Jackson, Reina,  
Wackerath '04]

electro-weak:

[Dittmaier, Krämer, Mück,  
Schlüter '06]

Block SUSHI

```
1 1 # Chosen model: 0=SM, 1=MSSM, 2=2HDM
2 0 # Chosen Higgs particle: 0=h, 1=A, 2=H
3 0 # Particle collider: 0=pp, 1=ppbar
4 8.00000000E+03 # center-of-mass energy in GeV
5 2 # Order for ggh
6 2 # Order for bbh
7 1 # Electroweak contributions to ggh
```

Block SMINPUTS

```
1 1.27670000E+02 # 1/alpha_em(MZ) SM MSbar
2 1.16637000E-05 # G_F
3 1.19000000E-01 # alpha_s(m_Z)
4 9.11876000E+01 # m_Z(pole)
5 4.16000000E+00 # m_b(m_b)
6 1.72500000E+02 # m_t(pole)
```

Block MINPAR

```
3 2.00000000E+01 # tan(beta)
```

Block EXTPAR

```
3 1.50000000E+03 # Gluino mass
11 1.01750000E+03 # A_t
12 1.01750000E+03 # A_b
23 3.50000000E+02 # mu
26 2.90000000E+02 # mA
43 5.00000000E+02 # M3SQ
46 5.00000000E+02 # M3SU
49 5.00000000E+02 # M3SD
```

Block FEYNHIGGS

```
1 0.00000000E+00 # M1
2 3.50000000E+02 # M2
13 1.01750000E+03 # A_tau
14 0.00000000E+00 # A_c
15 0.00000000E+00 # A_s
```

```

#-----#
# SusHi: Supersymmetric Higgs production through #
# -- -- gluon fusion and bottom-quark #
# [- | | [- |_ | | annihilation #
# --] |_ | --] | | | #
# Version 1.1.0, April 2013 #
#-----#
# Date: 05.05.2013 at 08:17:51 #
# For the reconstructed input file, check below. #
#-----#
# Please cite the following papers (for this run):

```



```

#-----#
Block SUSHIgh # Bon appetit
    1    1.59402180E+01 # ggh XS in pb
Block SUSHIbbh # Bon appetit
    1    3.98148358E-01 # bbh XS in pb
Block XSGGH # ggh MSSM-Cross sec. in pb (w/o EW)
    2    1.13320858E+01 # NLO
    21   1.13716432E+01 # NLO gg
    22   -5.97876857E-02 # NLO qq
    23   2.02302270E-02 # NLO qq
Block XSGGHEFF # ggh MSSM-Cross sec.
    1    1.50277354E+01 # ggh@NLO MSSM
    2    1.89713141E+01 # ggh@NNLO MSSM
    3    5.86435287E-02 # electroweak factor
Block XSBBH # bbh MSSM-Cross sec. in pb
    1    5.53881751E-01 # LO
    2    4.98551721E-01 # NLO
    3    3.98148358E-01 # NNLO

```

# Conclusions

- SUSY Higgs production theory lags behind Standard Model
- SusHi: consistent implementation of
  - gluon fusion through NLO (partly NNLO and EW)
  - bottom quark annihilation through NNLO
- inclusive cross sections
- $p_T, y$  distributions (not covered here)
- download from `sushi.hepforge.org`