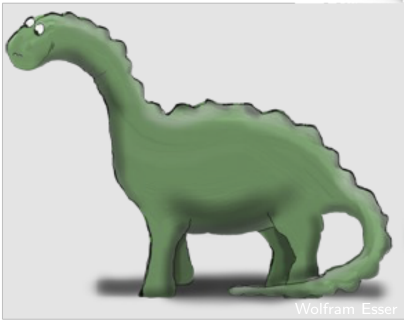
# MSSM Higgs Boson Production via Gluon Fusion:

# The Large Gluino Mass




Heidi Rzehak

in coll. with M. Mühlleitner and M. Spira

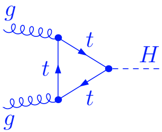
KIT-NEP '19, 7 October 2019

# Outline

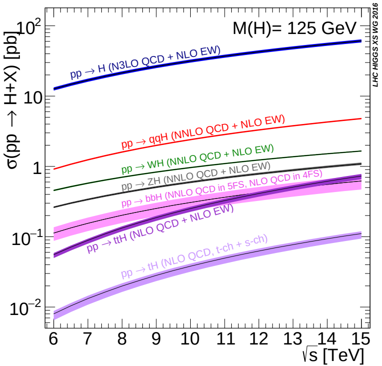
- Higgs boson production via gluon fusion
- Why heavy gluinos?
- Treatment of heavy gluinos

# Standard Model Higgs Boson Production

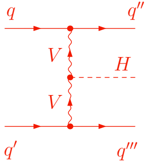
Gluon fusion:



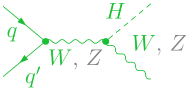

Largest cross section!



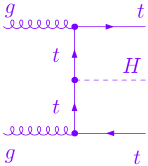

Weak boson fusion:




Higgs-strahlung:



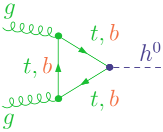

Heavy quark fusion:



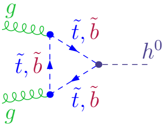
# MSSM Higgs Production via Gluon Fusion

- Higgs production via gluon fusion with subsequent decay

  ▷ into photons: $gg \to h^0 \to \gamma\gamma$
  Possible discovery channel for
  Higgs boson masses $M_{h^0} \sim 120$ GeV
  [CMS 06, ATLAS 09]

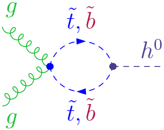



  ▷ into photons or other particles:
  Useful for coupling measurements




  $\Rightarrow$ Need to know the cross section of $gg \to h^0$

- Coupling of gluons, $g$, to the Higgs bosons is mediated via quarks and their superpartners squarks.
  (here: $h^0$, lightest MSSM Higgs boson)



# MSSM Higgs Production via Gluon Fusion

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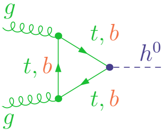
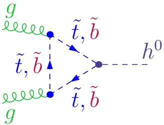



  - ▷ into photons: $gg \to h^0 \to \gamma\gamma$
    ~~Possible~~ discovery channel for
    Higgs boson masses $M_{h^0} \sim$ ~~120~~ 125 GeV
    [CMS ~~06~~ 12, ATLAS ~~09~~ 12]

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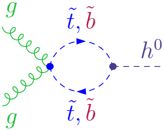


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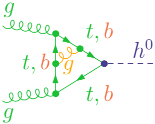
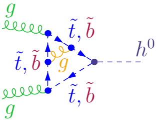
  (here: $h^0$, lightest MSSM Higgs boson)

# Pure QCD Corrections

- Pure QCD (only gluons) corrections to quark and squark loops with full mass dependence
  $\Rightarrow$ increase of the cross section of 100%.
  [Spira, Djouadi, Graudenz, Zerwas 92, 95; Graudenz, Spira, Zerwas 93; Anastasiou, Beerli, Bucherer, Daleo, Kunszt 07; Aglietti, Bonciani, Degrassi, Vicini 07; Bonciani, Degrassi, Vicini 07; Mühlleitner, Spira 08]




- Pure QCD corrections can be approximated by very heavy top quarks and squarks with 20 – 30 % accuracy for small $\tan\beta$ (large $\tan\beta$: bottom quark and squark contributions are important).
  $\tan\beta$ = ratio of Higgs vacuum expectation values
  [Djouadi, Spira, Zerwas 91; Dawson 91; Kauffman, Schaffer 94; Dawson, Kauffman 94; Dawson, Djouadi, Spira 96; Krämer, Laenen, Spira 98 ]

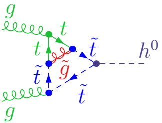


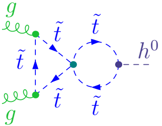
# SUSY QCD Contributions

- (SUSY) QCD (gluons and gluinos) contributions
  in the heavy top quark/squark and gluino limit:
  Next term in the mass expansion indicates:
  Approximation: Good for the lightest MSSM Higgs boson
  and small and moderate $\tan\beta$ values.
  [Harlander, Steinhauser 03,03, 04, Harlander, Hoffmann 06, Degrassi, Slavich 08]

- (SUSY) QCD contribution including the
  mass dependence of all particles
  (bottom quark/squark contributions included):
  - ▷ The heavy mass limit approximation:
    Good for small and moderate $\tan\beta$.
  - ▷ Contributions from squark quartic couplings and
    gluinos can be sizeable.

  [Anastasiou, Beerli, Daleo 08]



# Why consider a heavy gluino? Conceptual problem

On the one hand: Keeping supersymmetric relations between parameters intact

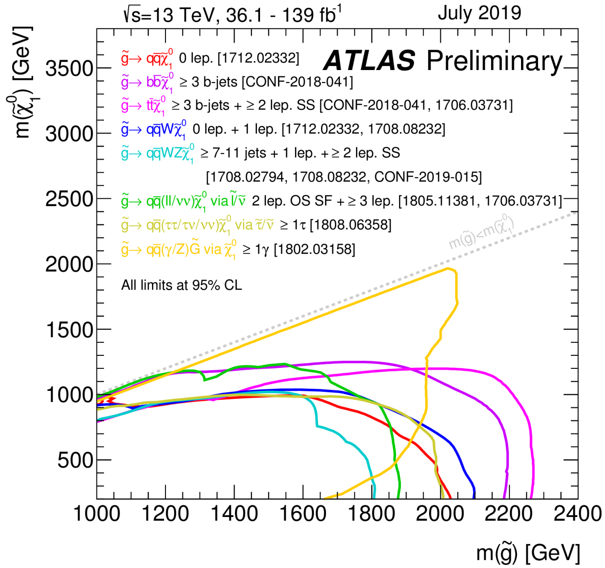
$\Rightarrow$ gluinos do not decouple

(For heavy gluinos: Result depends logarithmically on the gluino mass $M_{\tilde{g}}$.)

On the other hand: Decoupling theorem: [Appelquist, Carrazzone 75]

Heavy fields decouple at low momenta (except for renormalization effects).

# Why consider a heavy gluino? Viable scenarios




Neutralino vs gluino mass:

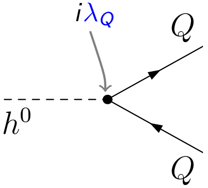
If $M_{\tilde{g}} < m(\tilde{\chi}^0)$,

then $M_{\tilde{g}} \gtrsim 2$ TeV.

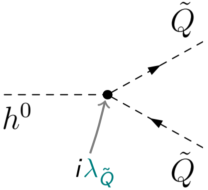
$m(\tilde{g}) \equiv M_{\tilde{g}}$

# Decoupling of the Gluinos

Simplified scenario: no mixing, degenerate squark masses:




$$\lambda_Q = g\,\frac{m_Q}{v}$$




$$\lambda_{\tilde{Q}} = 2\,g\,\frac{m_Q^2}{v} = 2\frac{v}{g}\lambda_Q{}^2$$

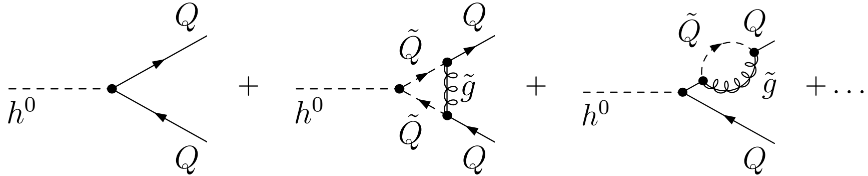
SUSY relation

$m_Q$ = quark mass;
$v = (v_1^2 + v_2^2)^{\frac{1}{2}} \approx 246$ GeV, $v_i$ = Higgs vacuum expectation value;
$g$ = norm. factor of the Higgs coupling to a quark pair with respect to the SM

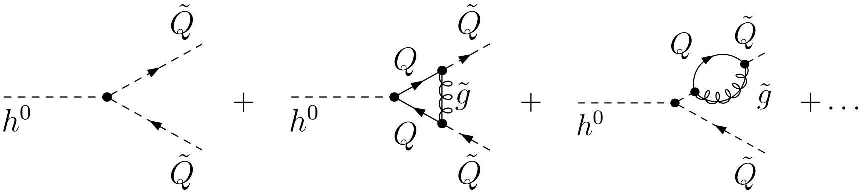
# Decoupling of the Gluinos

In higher oders (1-loop):

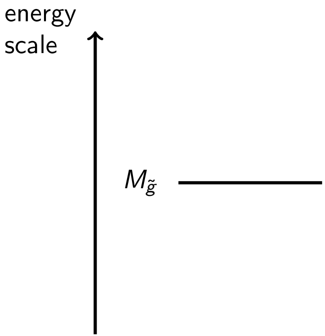
$\lambda_Q$:




$\lambda_{\tilde{Q}}$:



# Decoupling of the Gluinos




I: $\mu_R > M_{\tilde{g}}$: **gluino "active"**

II: $\mu_R = M_{\tilde{g}}$ **Matching of the "theories"**

III: $\mu_R < M_{\tilde{g}}$: **gluino "decoupled"**

# Decoupling of the Gluinos

| Scales above $M_{\tilde{g}}$: $\mu_R > M_{\tilde{g}}$ | Scales below $M_{\tilde{g}}$: $\mu_R < M_{\tilde{g}}$ |
|---|---|
| • Renormalization scheme:<br>$\overline{\text{MS}}$<br>(only divergent parts in counterterms) | • Renormalization scheme:<br>momentum subtraction (MO)<br>(for decoupling of the gluino) |
| • RGE: **(Renormalization group equations)**<br>same for $\lambda_{\tilde{Q}}$ and $2\frac{v}{g}\lambda_Q^2$ | • RGE:<br>differ for $\lambda_{\tilde{Q}}$ and $2\frac{v}{g}\lambda_Q^2$ |
| • Symmetry relation between<br>$\lambda_Q$ and $\lambda_{\tilde{Q}}$ intact | • Symmetry relation between<br>$\lambda_Q$ and $\lambda_{\tilde{Q}}$ broken |

Matching at scale $M_{\tilde{g}}$: $\mu_R = M_{\tilde{g}}$:

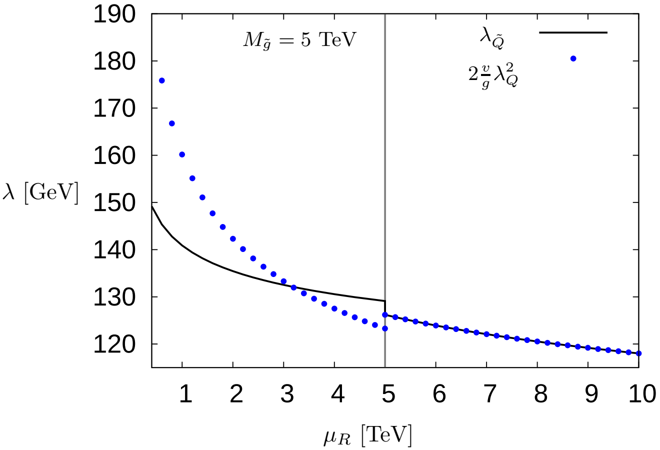
- Threshold contributions

Taking into account the mismatch of the couplings $\lambda_Q$ and $\lambda_{\tilde{Q}}$ for $\mu_R < M_{\tilde{g}}$:

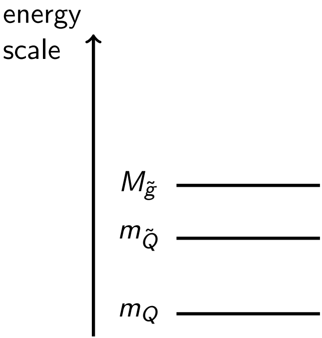
$\Rightarrow$ Gluino decouples from the theory [Mühlleitner, HR, Spira 08]

# Decoupling of the Gluinos

Scale dependence of $\lambda_{\tilde{Q}}$ and $2\frac{v}{g}\lambda_Q^2$:



# Further scales: Quark and squark masses

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III: $\mu_R < M_{\tilde{g}}$: **gluino "decoupled"**

# Relation between $m_Q$ and $\lambda_Q$

At scale $m_Q$: Clearly, III: $\mu_R < M_{\tilde{g}}$

$\Rightarrow$ Momentum-subtracted (MO) scheme at scale $\mu_R = m_Q$:

$$g_Q^\phi \frac{m_Q}{v} = \lambda_{Q,MO}(m_Q) \left(1 + \frac{4}{3}\frac{\alpha_s(m_Q)}{\pi}\right)$$ [Gray, Broadhurst, Grafe, Schilcher, 90]

$g_Q^\phi$ = mixing angle factor depending on mixing angles $\alpha$ and $\beta$

$\Rightarrow$ Relation between $m_Q$ and $\lambda_{\tilde{Q}}$:

At $m_Q$: $$2 g_Q^\phi \frac{m_Q^2}{v} = \lambda_{\tilde{Q},MO}(m_Q) \left[1 + \frac{4}{3}\frac{\alpha_s(m_Q)}{\pi}\left(\log\frac{M_{\tilde{g}}^2}{m_Q^2} + \frac{1}{2}\right)\right]$$

At $m_{\tilde{Q}}$: $$2 g_Q^\phi \frac{m_Q^2}{v} = \lambda_{\tilde{Q},MO}(m_{\tilde{Q}}) \left[1 + \frac{4}{3}\frac{\alpha_s(m_Q)}{\pi}\left(\log\frac{M_{\tilde{g}}^2}{m_{\tilde{Q}}^2} + \frac{3}{2}\log\frac{m_{\tilde{Q}}^2}{m_Q^2} + \frac{1}{2}\right)\right]$$

# Back to gluon fusion

Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi} G^{a,\mu\nu} G^a_{\mu\nu} \frac{H}{v} \left[ \cdots + \sum_{\tilde{Q}} \frac{v \lambda_{\tilde{Q},MO}}{4 m_{\tilde{Q}}} \left( 1 + C_{\text{SQCD}} \frac{\alpha_s}{\pi} \right) \ldots \right]$$

No decoupling (equal squark masses):

$$C^{\text{HS}}_{\text{SQCD}} = \frac{11}{2} - \frac{4}{3} \log \frac{M^2_{\tilde{g}}}{m^2_{\tilde{Q}}} - 2 \log \frac{m^2_{\tilde{Q}}}{m^2_Q}$$

Include decoupling contributions:

$$\Delta C_{\text{SQCD}} = \frac{4}{3} \log \frac{M^2_{\tilde{g}}}{m^2_{\tilde{Q}}} + 2 \log \frac{m^2_{\tilde{Q}}}{m^2_Q} + \frac{2}{3}$$

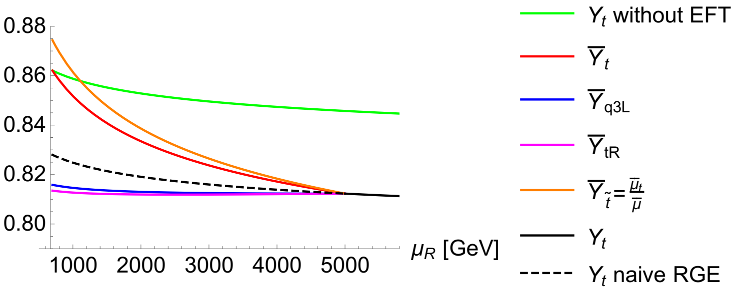
$\Rightarrow C^{\text{HS}}_{\text{SQCD}} + \Delta C_{\text{SQCD}} = \frac{37}{6} =$ finite

# Decoupling of gluinos and first-generations squarks

[Aebischer, Crivellin, Greub, Yamada, 17], see also [Krämer, Summ, Voigt 19]

Similar procedure for full MSSM (including mixing)

→ effective field theory for the stop sector




Below the decoupling scale of 5 TeV:

Yukawa couplings evolve differently

(Higgs-Quark-Quark, Higgsino-Quark-Squark)

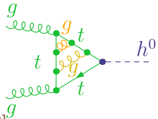
⇒ Supersymmetry relations are broken.

# Conclusions

- Gluon fusion:
  - ▷ A loop-induced Higgs boson production mechanism
  - ▷ Large cross section
- For scales below the gluino mass:
  - ▷ Symmetry relation between Higgs couplings to quarks and to squarks: Broken
  - ▷ Gluinos decouple
- Important: Respect large different scales in the theory

# Pure SM QCD Corrections: Status: $\sim$ 2010

- NNLO QCD corrections in the heavy top quark limit
  (no squarks included)
  $\Rightarrow$ increase of the cross section by 20 – 30 %.
  [Harlander, Kilgore 02, 02; Anastasiou, Melnikov 02, 03; Ravindran, Smith, van Neerven 03]




- Finite top quark mass effects at NNLO (no squarks)
  $\Rightarrow$ below the scale uncertainty.
  [Harlander, Ozeren 09, 09; Pak, Rogal, Steinhauser 09, 09; Harlander, Mantler, Marzani, Ozeren 09 ]

- Estimates of $N^3LO$ corrections (no squarks)
  $\Rightarrow$ improved convergence
  [Catani, de Florian, Grazzini, Nason 07; Moch, Vogt 05; Ravindran 06, 06 ]

- Soft gluon resummation: $\sim$ 10% effects
  [Catani, de Florian, Grazzini, Nason 07]

- Electroweak contributions: $\sim$ 5% effects
  [Degrassi, Maltoni 04, Aglietti, Bonciani, Degrassi, Vicini 06,
  Actis, Passarino, Sturm, Uccirati 08, Anastasiou, Boughezal, Petriello 09]