SUSY-QCD Corrections to Pseudoscalar Higgs Production via Gluon Fusion

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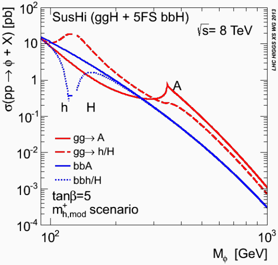
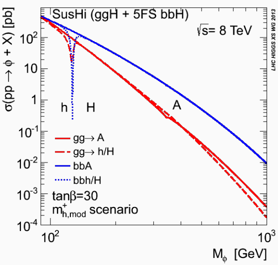
Introduction

Motivation





- gluon fusion important production channel, together with $gg \to b\bar{b}A$
- (pure) QCD corrections are large (10 - 100%)

  [Spira '93] [Harlander et al. '05] [Anastasiou, Melnikov '02] [Ravindran et al. '03]
- Can be reused for decay channels $A \to \gamma\gamma$ and $A \to gg$

Related work

- $gg \to H$
  - QCD corrections up to N^{3}LO in the heavy top limit [Djouadi eal,91;Dawson,91;Dawson,Kauffmann,94;Harlander,Kilgore,01,02;Anastasiou,Melnikov,02;Ravindran eal,03; Marzani eal,08;Gehrmann eal,12;Anastasiou eal,13;Ball, Bonvini, Forte, Marzani, Ridolfi,'13 ;Kilgore,14; Florian, Mazzitelli, Moch, Vogt eal, '14; Li eal,15; Anastasiou eal,15; Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger, eal '16; Moch, Vogt eal,'16]
  - Full quark mass dependence at NLO [Graudenz eal,93;Spira eal,95;Harlander,Kant,05;Aglietti eal,07;Anastasiou eal,07]
  - Subleading NNLO terms in the heavy top expansion [Harlander,Ozeren,09; Pak,Rogal,Steinhauser,09,10]
  - Mass effects at NNLO [Czakon, Harlander, Klappert, Niggetiedt,'21]
  - Finite quark mass effects in resummation [de Florian,Grazzini,12;Bonvini,Marzani,14;Schmidt,Spira,16]
  - Electroweak corrections [Degrassi,Maltoni,04, 05;Aglietti eal,04;Actis,Passarino,Sturm,Uccirati,08,09]
  - QCD corrections in quark/squark loops [Djouadi eal,91;Graudenz eal,93;Spira eal,93,95;Dawson eal,96;Kramer eal,98;Schmidt,Spira,16/ Mühlleitner,Spira,06;Aglietti eal,07]
  - SUSY-QCD corrections in heavy loop mass limit [Harlander,Steinhauser,03,Degrassi,Slavich,08;Harlander,Hofmann,Mantler,11]
- $gg \to A$ QCD
  - QCD corrections up to NNLO in the heavy top quark mass limit [Harlander, Kilgore '02;Anastasiou,Melnikov '02;Ravindran eal '03; Pak, Rogal, Steinhauser '11;]
  - QCD corrections at NLO with full mass dependence [Spira eal, '93, Spira eal, '95]

Previous Results

- $gg \to A$ SQCD
  - Top quarks & squarks integrated out [Harlander, Hofmann '05]
  - Expansions to $\mathcal{O}\left(\frac{M_A^2}{M_{\text{SUSY}}^2}\right) \& \mathcal{O}\left(\frac{m_t^2}{M_{\text{SUSY}}^2}\right)$ and $\mathcal{O}\left(\frac{m_b^2}{M_A^2}\right) \& \mathcal{O}\left(\frac{m_b}{M_{\text{SUSY}}}\right)$ [Degrassi, Di Vita, Slavich '11]

This work: Numerical integration with full mass dependence

$$F^Q = \frac{2}{M_A^4} q_{1\alpha} q_{2\beta} \epsilon^{\alpha\beta\mu\nu} \mathcal{M}_{\mu\nu}$$

$$F^Q = \frac{\alpha_s}{4\pi} \frac{2}{v} g_A^Q \tau_Q f(\tau_Q) \left(1 + \frac{\alpha_s}{\pi} C_{\text{SUSY}}^Q\right)$$

$$g_{Abb} = r_b = \tan\beta \qquad g_{Att} = r_t = \frac{1}{\tan\beta} \qquad \tau_Q = \frac{4m_Q^2}{M_A^2}$$

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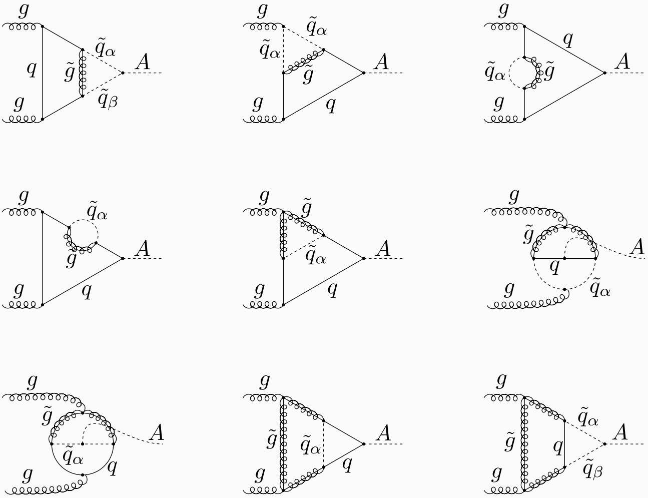
scheme choices: m_Q: on-shell α_s: 5-flavor scheme



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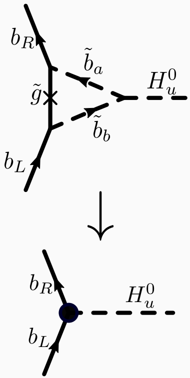
$\Delta_{b/t}$

$\Delta_{b/t}$

- Non decoupling for $M_{\text{SUSY}} \to \infty$
- Absorb into effective Yukawa coupling
- Resums large $\tan\beta$ contributions
- includes all leading powers of $\alpha_s \mu \tan\beta$ [Carena, Garcia, Nierste, Wagner '00][Guasch, Häflinger, Spira '03]



$$\Delta_q = \frac{C_F}{2} \frac{\alpha_s}{\pi} m_{\tilde{g}} \mu \, r_q \, I(m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}) + \Delta_q^{\text{elw.}}$$

$$r_b = \tan\beta \qquad r_t = \cot\beta$$

$\Delta_{b/t}$

effective couplings ($g_{AQQ} = r_Q$)

$$\tilde{g}_{Abb} = \frac{1 - \frac{\Delta_b}{\tan^2\beta}}{1 + \Delta_b} g_{Abb} \qquad \tilde{g}_{Att} = \frac{1 - \Delta_t \tan^2\beta}{1 + \Delta_t} g_{Att}$$

Avoid double counting

$$C^Q_{\mathsf{SUSY}} \to C^Q_{\mathsf{SUSY}} - C^Q_{\mathsf{LE}}$$

$$C^b_{\mathsf{LE}} = -\Delta_b^{\mathsf{QCD}} \left(1 + \frac{1}{\tan^2\beta}\right)$$

$$C^t_{\mathsf{LE}} = -\Delta_t^{\mathsf{QCD}} (1 + \tan^2\beta)$$

$$\Delta\hat{\sigma} = \frac{G_f \alpha_s^3}{128\sqrt{2}\pi^2} 2\,\mathrm{Re}\left[(\tilde{g}_{Abb} A_b + \tilde{g}_{Att} A_t) \left((g_{Abb} A_b (C^b_{\mathsf{SUSY}} - C^b_{\mathsf{LE}}) + g_{Att} A_t (C^t_{\mathsf{SUSY}} - C^t_{\mathsf{LE}}))\right)\right]$$

Adler Bardeen Theorem

Peccei Quinn Symmetry

- Chiral symmetry broken beyond mass terms
- Use $U(1)_{\mathrm{PQ}}$ instead
- broken by μ term

ϕ	H_u	t_L	$\tilde{t}_L$	t_R	$\tilde{t}_R$
Q_{PQ}	-2	-1	-1	1	1

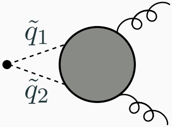
ϕ	H_d	b_L	$\tilde{b}_L$	b_R	$\tilde{b}_R$
Q_{PQ}	-2	-1	-1	1	1

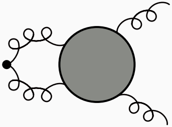
Adler Bardeen theorem

Adler Bardeen Theorem: no anomalous corrections at NLO

Peccei Quinn symmetry: $\partial_\mu j^\mu_{PQ} = -\delta\mathcal{L} + \frac{\alpha_s}{2\pi} F^{\mu\nu}\tilde{F}_{\mu\nu}$

$$\underbrace{\mathcal{M}_{p\to 0} = \frac{1+r_Q^2}{v}\, m_Q \mu \quad [\text{diagram}]}_{\to \Delta_Q} + \frac{\alpha_s}{8\pi v} \quad [\text{diagram}]$$





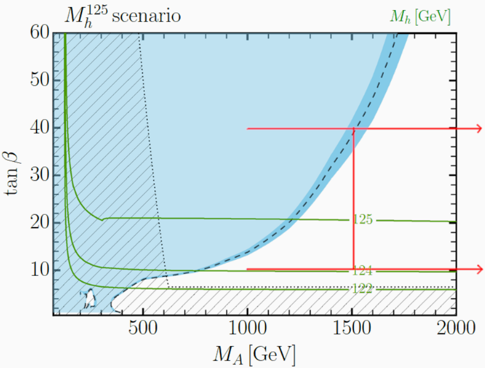
$\Rightarrow$ No corrections beyond Δ_b and Δ_t for $m_A^2 \ll m_Q^2 \ll M^2_{\mathrm{SUSY}}$

Scenario

M_h^{125} Scenario

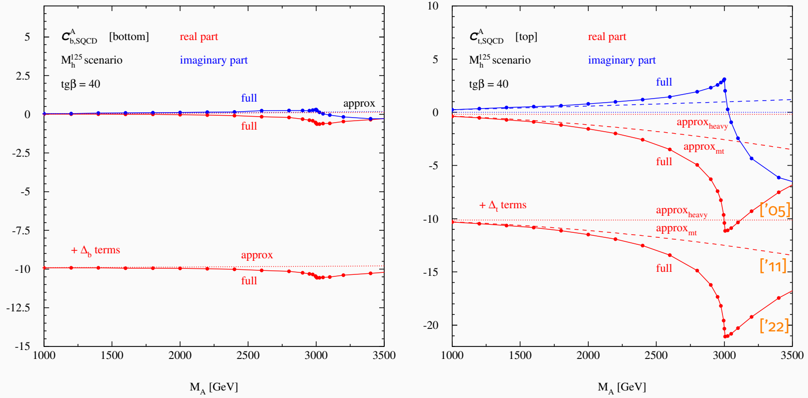
- $M_A, \tan\beta$ free
- $A_{b/t}, M^2_{Q_3}, M^2_{U_3}, M^2_{D_3}$ on-shell in stop sector
- On-shell scheme in sbottom sector: $A_q^{\overline{\mathsf{MS}}}(Q_0), M^{2\,\overline{\mathsf{MS}}}_{\tilde{q}_{L/R}}(Q_0)$ iteratively
- m_b, A_b renormalized through Higgs-squark coupling

M_h^{125} Scenario



Results

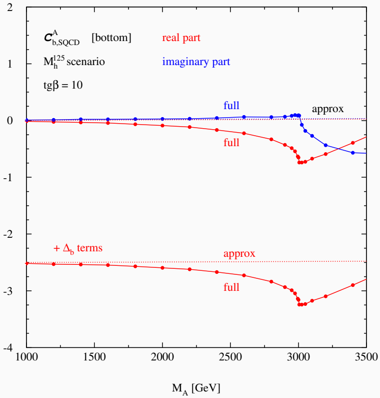
$\mathcal{C}_{\mathrm{Q,SQCD}}, \tan\beta = 40$

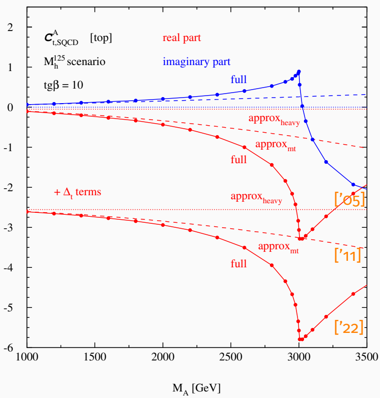


$$m_{\tilde{b}_1} = 1459\,\text{GeV} \qquad m_{\tilde{t}_1} = 1353\,\text{GeV}$$

$$m_{\tilde{b}_2} = 1531\,\text{GeV} \qquad m_{\tilde{t}_2} = 1650\,\text{GeV}$$

$\mathcal{C}_{\mathrm{Q,SQCD}}, \tan\beta = 10$





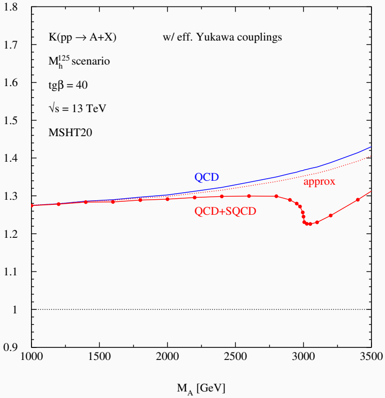
$m_{\tilde{b}_1} = 1466$ GeV

$m_{\tilde{b}_2} = 1504$ GeV

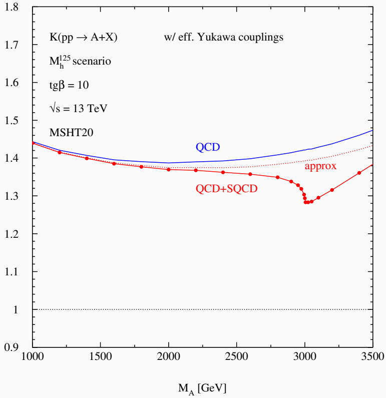
$m_{\tilde{t}_1} = 1353$ GeV

$m_{\tilde{t}_2} = 1650$ GeV

K-factors

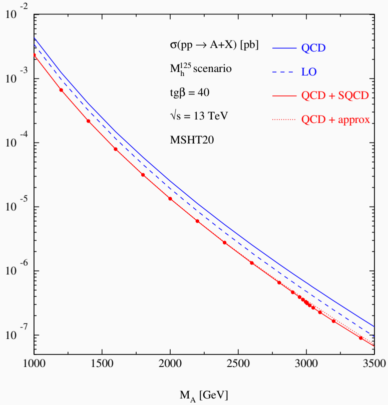


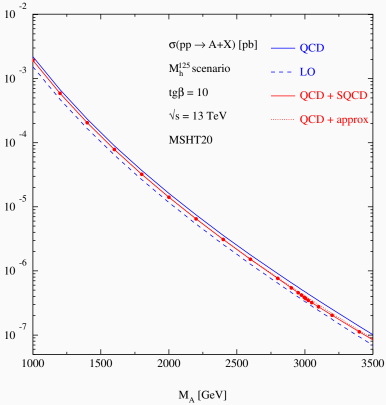
K(pp → A+X)
w/ eff. Yukawa couplings
M_h^{125} scenario
tgβ = 40
√s = 13 TeV
MSHT20
QCD
approx
QCD+SQCD
M_A [GeV]



K(pp → A+X)
w/ eff. Yukawa couplings
M_h^{125} scenario
tgβ = 10
√s = 13 TeV
MSHT20
QCD
approx
QCD+SQCD
M_A [GeV]

Crosssections





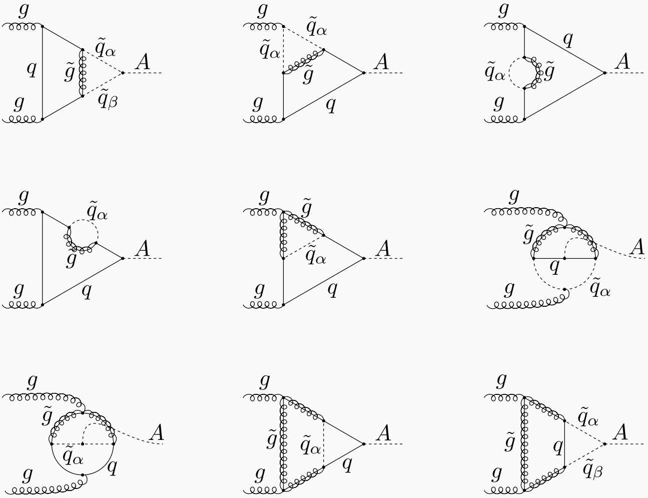
Conclusion

- Existing approximations valid for M_A well below the virtual squark thresholds
- Dominant contributions can be absorbed in effective coupling ($\rightsquigarrow$ electroweak and NNLO corrections)
- SUSY-QCD remainders significant for large M_A

$\diamond$ THANK YOU FOR YOUR ATTENTION $\diamond$

Backup slides

Diagrams



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Sum rules

$$\tilde{M}^2_{\tilde{q}_L} = M^2_{\tilde{q}_L} + D_{\tilde{q}} = \cos^2\theta_q m^2_{\tilde{q}_1} + \sin^2\theta_q m^2_{\tilde{q}_2} - m^2_Q$$

$$\tilde{M}^2_{\tilde{q}_R} = M^2_{\tilde{q}_R} + D_{\tilde{q}} = \sin^2\theta_q m^2_{\tilde{q}_1} + \cos^2\theta_q m^2_{\tilde{q}_2} - m^2_Q$$

$$\sin 2\theta_q = \frac{2m_Q(A_q - \mu r_q)}{m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2}}$$