SUSY-QCD Corrections to Pseudoscalar Higgs Production via Gluon Fusion

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Introduction

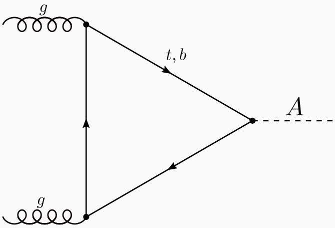
Motivation

MSSM has extended Higgs sector

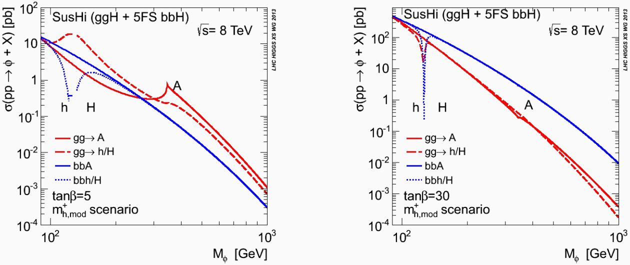
$$h, H, \mathbf{A}, H^{\pm}$$

$\rightarrow$ Find SUSY-QCD corrections to the production cross section numerically

Production at the LHC via



Motivation

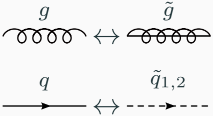


- gluon fusion important production channel at the LHC, together with $gg \to b\bar{b}A$
- (pure) QCD corrections are large (10 - 30%)

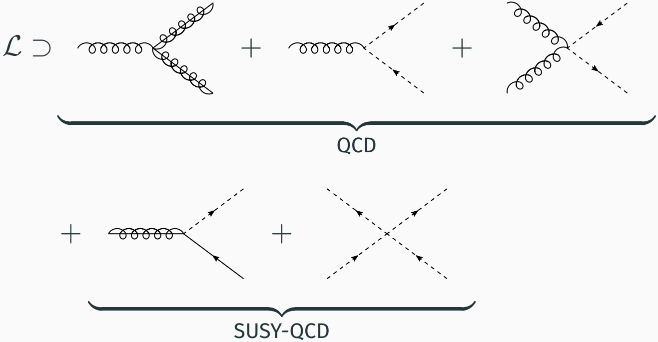
  [Spira '93] [Harlander et al. '09] [Anastasiou, Melnikov '02]
- Can be reused for relevant decay channels $A \to \gamma\gamma, gg$

Susy QCD

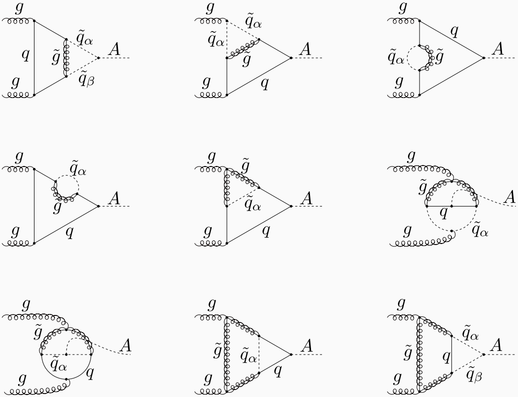
Supersymmetry $\rightarrow$ every particle gets a (heavy) super-partner



New Interactions:



Diagrams



g g q $\tilde{g}$ $\tilde{q}_\alpha$ $\tilde{q}_\beta$ A
g g $\tilde{q}_\alpha$ $\tilde{q}_\alpha$ $\tilde{g}$ q A
g g q $\tilde{q}_\alpha$ $\tilde{g}$ A
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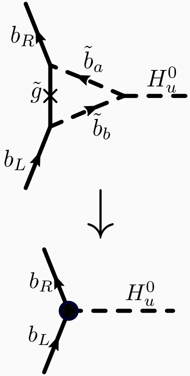
g g $\tilde{g}$ q $\tilde{q}_\alpha$ $\tilde{q}_\beta$ A

Existing Results

- 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]



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

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

Analytic results exist as asymptotic expansion valid upto

$$\mathcal{O}\left(\frac{M_A^2}{M^2}\right) \quad \& \quad \mathcal{O}\left(\frac{m_t^2}{M^2}\right) \qquad \mathcal{O}\left(\frac{m_b^2}{M_A^2}\right) \quad \& \quad \mathcal{O}\left(\frac{m_b}{M}\right)$$

[Harlander, Hofmann ’06]

[Degrassi, Vita, Slavich ’11]

Calculation

γ_5 in Dimensional Regularization

γ_5 inconsistent in $D-$dim:

$$2(D-4)\,\mathrm{tr}(\gamma_5\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma) = 0$$

- Larin scheme
  - $\overline{\psi}\gamma_5\psi = \frac{i}{4!}\epsilon_{\mu\nu\rho\sigma}\overline{\psi}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\psi$
  - $\epsilon^{\mu_1\nu_1\rho_1\sigma_1}\epsilon_{\mu_2\nu_2\rho_2\sigma_2} = -\det\begin{vmatrix} g^{\mu_1}_{\mu_2} & g^{\mu_1}_{\nu_2} & g^{\mu_1}_{\rho_2} & g^{\mu_1}_{\sigma_2} \\ g^{\nu_1}_{\mu_2} & g^{\nu_1}_{\nu_2} & g^{\nu_1}_{\rho_2} & g^{\nu_1}_{\sigma_2} \\ g^{\rho_1}_{\mu_2} & g^{\rho_1}_{\nu_2} & g^{\rho_1}_{\rho_2} & g^{\rho_1}_{\sigma_2} \\ g^{\sigma_1}_{\mu_2} & g^{\sigma_1}_{\nu_2} & g^{\sigma_1}_{\rho_2} & g^{\sigma_1}_{\sigma_2} \end{vmatrix}$
  - Only D-dimensional objects

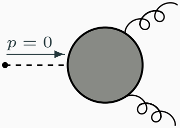
  [Larin ’93]
- Breitenlohner Maison scheme: $\{\gamma_5, \gamma^\mu\} \neq 0$

  [Breitenlohner, Maison ’77]
- Kreimer scheme: Noncyclic trace [Kreimer ’94]

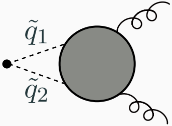
Adler Bardeen theorem

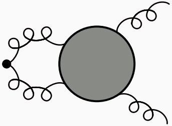
Adler Bardeen Theorem: no anomalous corrections at NLO

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

m_A^2 

$= \mathcal{M}_{p\to 0}$

$= \sum_{Q=t,b} \frac{m_Q(1+r_Q^2)}{v}\,\mu$ 

$+ \frac{r_t + r_b}{v}\frac{\alpha_s}{4\pi}$ 

$\rightarrow \Delta_Q$

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

Numerical Integration

After Feynman Parametrization:

$$I = \int_0^1 d^d x \quad \frac{f(x)}{N^{n+2\varepsilon}(x)}$$

upto 5 parameters

parametrized, such that $N(x)$ is quadratic polynomial in Feynmanparameters
Example:

$$\begin{aligned} N(x) = & M_A^2 \left(x_1 - 1\right) x_2 \left(1 - x_3\right) \left(x_3 + x_1 \left(x_3 + x_4 - 1\right) \left(x_5 - 1\right)\right) x_5 \\ & + M_{\tilde{g}}^2 x_1 x_5 + M_Q^2 \left(x_5 - x_1 x_5\right) + M_{\tilde{q}_\alpha}^2 \left(x_1 - 1\right) x_1 \left(x_5 - 1\right) \end{aligned}$$

UV singularities

To get finite and divergent part expand in ε

Divergent integrals can arise from factors $x^{-1+\varepsilon}$ $\Rightarrow$ Endpoint subtraction

$$\int_0^1 dx \quad x^{-1+\varepsilon} f(x) = \int_0^1 dx \quad \underbrace{x^{-1+\varepsilon}(f(x) - f(0))}_{\text{regular in x}} + \underbrace{\int_0^1 dx \quad x^{-1+\varepsilon} f(0)}_{=\frac{f(0)}{\varepsilon}}$$

```
Iteration 8:  80000000 integrand evaluations so far
[1] 107.257 +- 87.4996          chisq 2.60227 (7 df)
[2] 52.3746 +- 81.1029          chisq 4.40932 (7 df)
[3] 59011.6 +- 53836.4          chisq 7.80152 (7 df)
[4] 81290.5 +- 140535   chisq 5.79475 (7 df)

Iteration 9:  90000000 integrand evaluations so far
[1] 106.833 +- 82.401   chisq 2.60247 (8 df)
[2] 16.4968 +- 75.2997          chisq 5.82753 (8 df)
[3] 43936.9 +- 53032.7          chisq 10.4471 (8 df)
[4] 57839.8 +- 139436   chisq 7.58229 (8 df)

Iteration 10:  100000000 integrand evaluations so far
[1] 72.2666 +- 79.8743          chisq 5.51663 (9 df)
[2] 24.5327 +- 69.712   chisq 5.90723 (9 df)
[3] 37029.3 +- 52329.3          chisq 11.0909 (9 df)
[4] 34889.4 +- 118027   chisq 7.67784 (9 df)
```

Thresholds

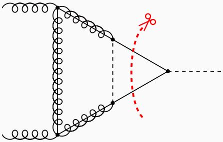
after expansion in ε

$$I = \int_0^1 d^d x \quad \frac{g(x) + h(x)\ln(N(x))}{N^n(x)}$$

What happens for $N(x) = 0$?

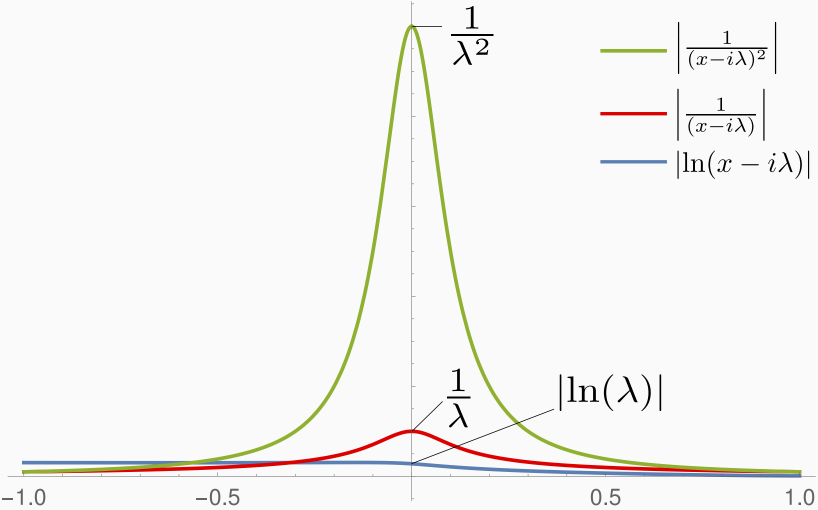
Microcausality: Masses from propagators are given small imaginary part

$$m^2 \to m^2(1 - i\lambda)$$



Usually $\lambda \to 0$, but for numerical integration we set λ sufficiently small but finite.

Thresholds


$\frac{1}{\lambda^2}$
$\left|\frac{1}{(x-i\lambda)^2}\right|$
$\left|\frac{1}{(x-i\lambda)}\right|$
$|\ln(x-i\lambda)|$
$\frac{1}{\lambda}$
$|\ln(\lambda)|$
−1.0
−0.5
0.5
1.0

Integration by parts

$$1 = \underbrace{\frac{1}{R}}_{\text{better zeros}} \Big(\underbrace{p_0 N}_{\text{Cancels one power of the denominator}} + \underbrace{\vec{p} \cdot \vec{\nabla} N}_{\text{Integration by parts}} \Big)$$

$$\frac{\vec{\nabla} N}{N^n} = \frac{1}{n-1} \vec{\nabla} \frac{1}{N^{n-1}}$$

Example in one dimension:

$$N(x) = ax^2 + bx + c$$

$$\Rightarrow 1 = \underbrace{\frac{1}{4ac - b^2}}_{\text{constant}} \left(\underbrace{4a}_{p_0} \cdot N(x) \underbrace{-(2ax+b)}_{p_1} \cdot \partial_x N(x) \right)$$

```
Iteration 8:  80000000 integrand evaluations so far
[1] -0.419694 +- 0.000978278    chisq 4.17753 (7 df)
[2] 0.0699153 +- 0.000950702    chisq 4.28112 (7 df)
[3] 1.972 +- 0.050616   chisq 5.16887 (7 df)
[4] -1.3137 +- 0.0504296        chisq 6.73128 (7 df)

Iteration 9:  90000000 integrand evaluations so far
[1] -0.420145 +- 0.00071454     chisq 4.63387 (8 df)
[2] 0.0696467 +- 0.000687736    chisq 4.44859 (8 df)
[3] 1.98024 +- 0.0339793        chisq 5.21711 (8 df)
[4] -1.3158 +- 0.0342964        chisq 6.73449 (8 df)

Iteration 10:  100000000 integrand evaluations so far
[1] -0.420004 +- 0.00057225     chisq 4.74287 (9 df)
[2] 0.0694324 +- 0.00054715     chisq 4.71313 (9 df)
[3] 1.97658 +- 0.02691          chisq 5.24823 (9 df)
[4] -1.33638 +- 0.0284265       chisq 7.88515 (9 df)
```

Richardson Extrapolation

- Stability for larger values of regulator λ
- Extrapolate from stable integration regions
- Assumes polynomial behavior for small λ

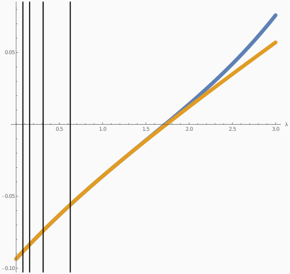
$$R_n(G)(\lambda) = \frac{t^n R_{n-1}(G)(\lambda) - R_{n-1}(G)(t^n\lambda)}{t^n - 1} = G(0) + \mathcal{O}(\lambda^n)$$

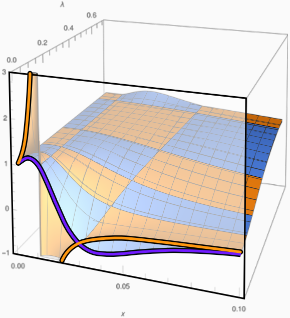
$$R_0(G)(\lambda) = G(\lambda)$$

e.g. $$R_3(G)(\lambda) = \frac{64G(\lambda)}{21} - \frac{8}{3}G(2\lambda) + \frac{2}{3}G(4\lambda) - \frac{1}{21}G(8\lambda) \approx G(0)$$

Richardson Extrapolation

$$\underbrace{G(\lambda)}_{\text{well approximated}} = \int dx \underbrace{g(x,\lambda)}_{\text{badly approximated}}$$



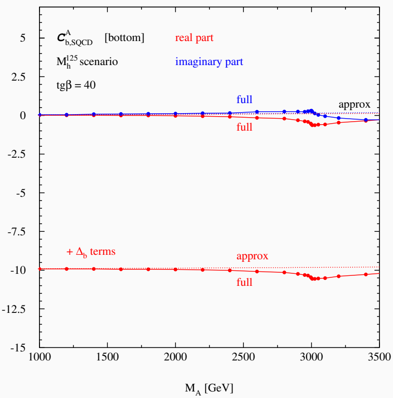


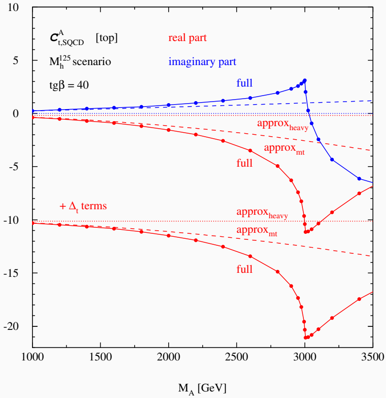
$\rightarrow$ can gain stability

Does not work near threshold, because $G(\lambda) \sim \sqrt{\lambda}$

Results

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





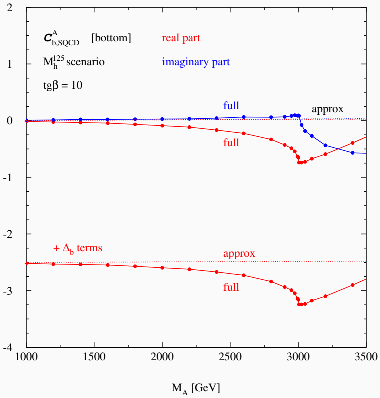
$m_{\tilde{b}_1} = 1459$ GeV

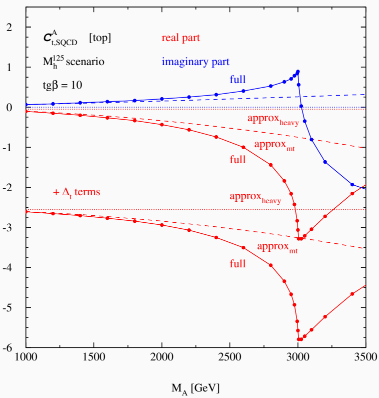
$m_{\tilde{b}_2} = 1531$ GeV

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

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

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

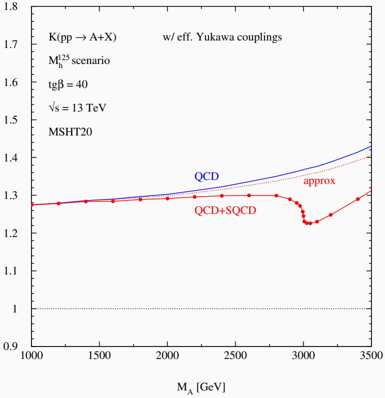


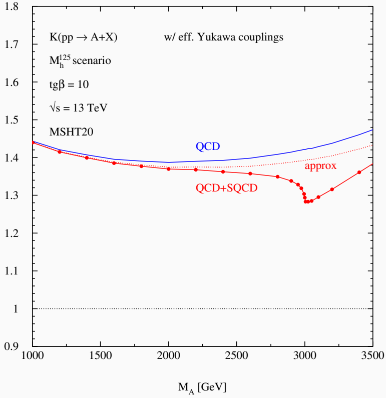


$m_{\tilde{b}_1} = 1466$ GeV $\qquad m_{\tilde{t}_1} = 1353$ GeV

$m_{\tilde{b}_2} = 1504$ GeV $\qquad m_{\tilde{t}_2} = 1650$ 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]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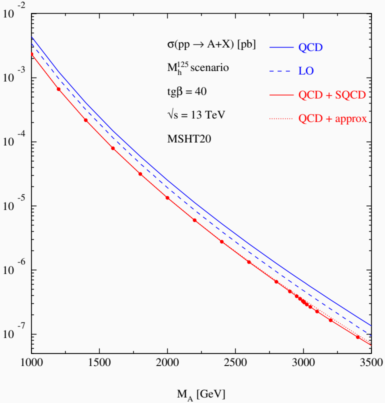
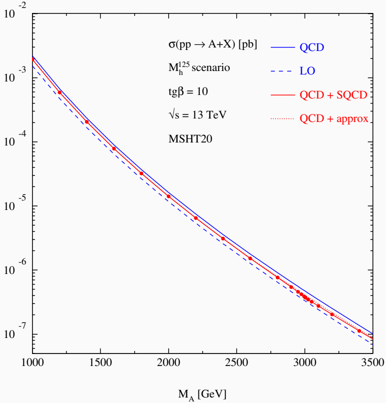
M_h^125 scenario
tgβ = 10
√s = 13 TeV
MSHT20
QCD
approx
QCD+SQCD
M_A [GeV]

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 $\diamond$