SUSY-QCD Corrections to Pseudoscalar Higgs Production via Gluon Fusion

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Outline i

Introduction

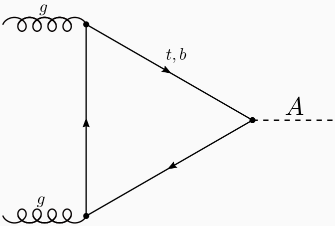
Motivation

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

- (pure) QCD corrections are large

  [Spira '93]

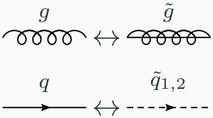
  [Harlander et al. '09]

  [Anastasiou, Melnikov '02]

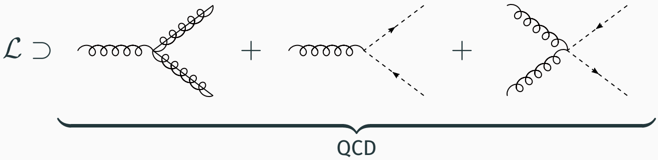
- Can be reused for decay $A \to \gamma\gamma$, an important decay channel

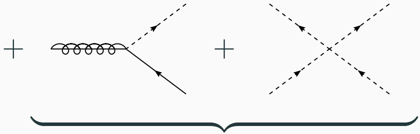
Susy QCD

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



New Interactions:

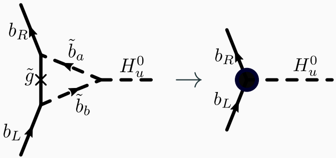




Existing Results

Δ_b Approximation

- Low energy effective Theory



- $\Delta_b \sim \frac{\alpha_s}{\pi} \tan\beta$
- $\tilde{g}_b^A = g_b^A \frac{1-\frac{\Delta_b}{\tan^2\beta}}{1+\Delta_b}$
- One-loop exact, resums large $\tan\beta$ effects

[Carena, Garcia, Nierste, Wagner ’00]

[Guasch, Häfliger, Spira ’03]

Existing Two-Loop Results

Analytic results exist as asymptotic expansion valid upto

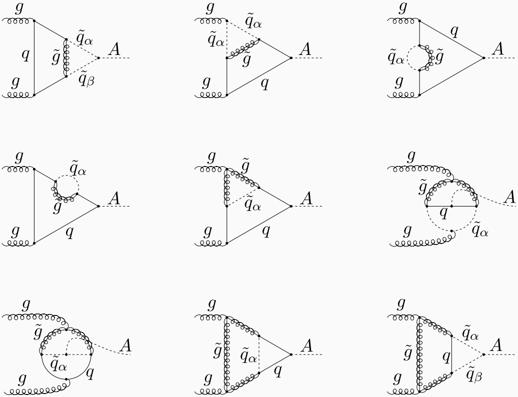
$$\mathcal{O}\left(\frac{M_A^2}{M^2}\right) \quad \& \quad \mathcal{O}(\frac{m_t^2}{M^2}) \qquad\qquad \mathcal{O}\left(\frac{m_b^2}{M_A^2}\right) \quad \& \quad \mathcal{O}\left(\frac{m_b}{M}\right)$$

[Harlander, Hofmann ’06]

[Degrassi, Vita, Slavich ’11]

Calculation

Diagrams



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

γ_5 in Dimensional Regularization

We use Larin scheme

- Only D-dimensional objects
- $\epsilon^{\mu_1\nu_1\rho_1\sigma_1}\epsilon_{\mu_2\nu_2\rho_2\sigma_2} = -\det \begin{vmatrix} g^{\mu_1}_{\mu_2} & g^{\mu_1}_{\nu_2} & g^{\mu_1}_{\rho_2} & g^{\mu_1}_{\sigma_2} \\ g^{\nu_1}_{\mu_2} & g^{\nu_1}_{\nu_2} & g^{\nu_1}_{\rho_2} & g^{\nu_1}_{\sigma_2} \\ g^{\rho_1}_{\mu_2} & g^{\rho_1}_{\nu_2} & g^{\rho_1}_{\rho_2} & g^{\rho_1}_{\sigma_2} \\ g^{\sigma_1}_{\mu_2} & g^{\sigma_1}_{\nu_2} & g^{\sigma_1}_{\rho_2} & g^{\sigma_1}_{\sigma_2} \end{vmatrix}$
- $\{\gamma_5, \gamma^\mu\} = 0$

[Larin '93]

Other schemes are being investigated:

- Breitenlohner Maison scheme $\{\gamma_5, \gamma^\mu\} \neq 0$

  [Breitenlohner, Maison '77]
- Pauli-Villars regularization to avoid the problem

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:

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

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

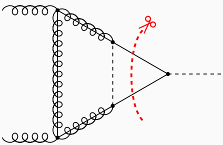
after expansion in ε

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

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

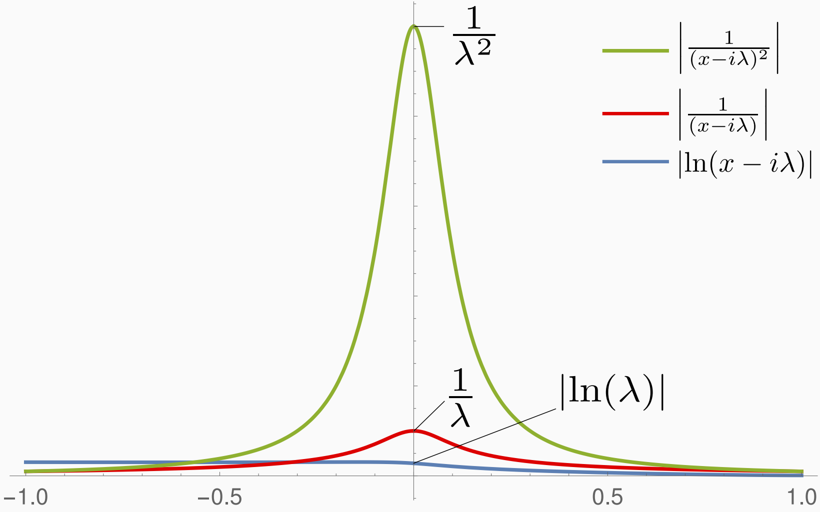
Microcausality: Masses from propagators are given small imaginary part

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



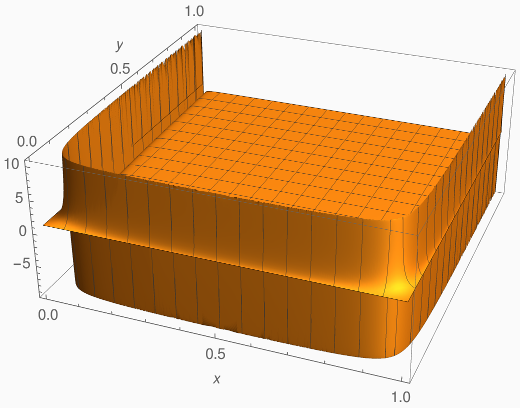
Usually $\lambda \to 0$, but for numerical integration we set λ sufficiently small but finite.

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

Thresholds



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:

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

```
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)
```

Adler Bardeen theorem

Matrix element of $gg \to A$ for vanishing momenta is ABJ-anomaly

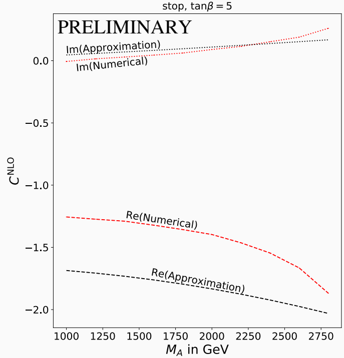
Adler Bardeen Theorem $\to$ no corrections at higher orders
Requires correct LE EFT $\Rightarrow$ Include Δ_b and Δ_t

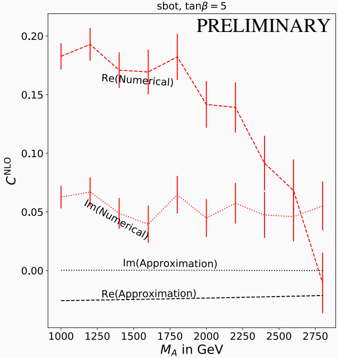
Results

C^{NLO}

$$F_q = F_q^{LO} \cdot \left(1 + \frac{\alpha_s}{\pi}\mathbf{C}_{\mathbf{q}}^{\mathsf{NLO}}\right) \qquad\qquad q = t, b$$

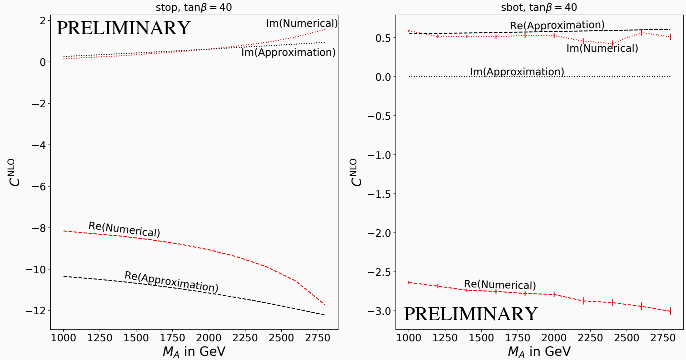
M_A scan, low $\tan\beta$





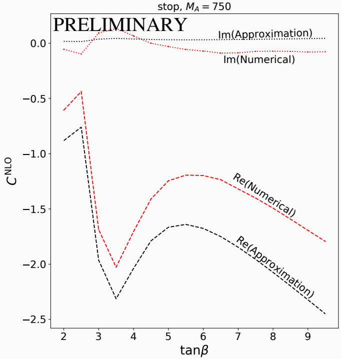
$\Delta_b -$ term ~ 1.5

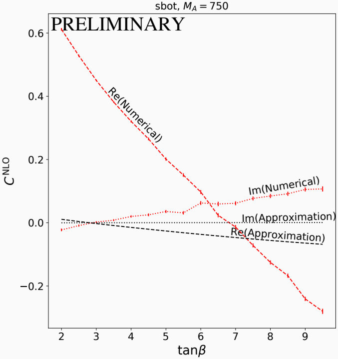
M_A scan, high $\tan\beta$



$\Delta_b -$ term ~ 10

$\tan\beta$ scan for $M_A = 750\,$GeV





$\Delta_b -$ term ~ 1.5

Conclusion

- Full mass dependence shows significant differences compared to existing approximations
- Threshold singularities can be controlled
- Outlook: Inclusion into hadronic codes