CP-Violation in Top Quark Pair Production at Hadron Colliders in the Complex MFV-MSSM

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- CP Violation in Top Quark Pair Production in the Complex MFV-MSSM
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Introduction

- CP Violation plays an important role in the study of weak interactions and the understanding of the Baryon Asymmetry of the Universe.

  A. Sakharov, Pisma Zh. Eksp. Theor. Fiz. 5, 32 (1967).

- Extra CP-violating phases beyond the CKM ones, which are associated with complex SUSY breaking parameters. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963);

  M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973);

  M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B255, 413 (1985);

  S. Dimopoulos and S. D. Thomas, Nucl. Phys. B465, 23 (1996).

- The study of top quark properties and dynamics provides a unique window to the study of physics beyond the SM connected to CP violation which may be found first through precision studies of top quark observables.

  M. Beneke et al.,arXiv:hep-ph/0003033;

  W. Bernreuther, J. Phys. G 35, 083001 (2008).

Complex MFV-MSSM

- **The most general superpotential is**

$$W = \sum_{i,j=gen} -Y^u_{ij}\,\hat{u}_{Ri}\,\hat{H}_2 \cdot \hat{Q}_j + Y^d_{ij}\,\hat{d}_{Ri}\,\hat{H}_1 \cdot \hat{Q}_j + Y^l_{ij}\hat{l}_{Ri}\,\hat{H}_1 \cdot \hat{L}_j + \mu \mathbf{\hat{H}_2} \cdot \mathbf{\hat{H}_1}$$

- **Soft SUSY-breaking terms**
  - Mass terms for the gluinos, winos and binos:

$$-\mathcal{L}_{gaugino} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a + \text{h.c}\right]$$

  - Mass terms for the scalar fermions:

$$-\mathcal{L}_{sfermions} = \sum_{i=gen} m^2_{\tilde{Q}_i}\,\tilde{Q}^\dagger_i\,\tilde{Q}_i + m^2_{\tilde{L}_i}\,\tilde{L}^\dagger_i\,\tilde{L}_i + m^2_{\tilde{u}_i}|\tilde{u}_{Ri}|^2 + m^2_{\tilde{d}_i}|\tilde{d}_{Ri}|^2 + m^2_{\tilde{l}_i}|\tilde{l}_{Ri}|^2$$

  - Mass and bilinear terms for the Higgs bosons:

$$-\mathcal{L}_{Higgs} = m^2_{H_2}\,H^\dagger_2\,H_2 + m^2_{H_1}\,H^\dagger_1\,H_1 + B\mu(H_2 \cdot H_1 + \text{h.c.})$$

  - Trilinear couplings between sfermions and Higgs bosons:

$$-\mathcal{L}_{tril.} = \sum_{i,j=gen}\left[A^u_{ij}\tilde{u}^\star_{Ri}H_2 \cdot \tilde{Q}_j + A^d_{ij}\tilde{d}^\star_{Ri}H_1 \cdot \tilde{Q}_j + A^l_{ij}\tilde{l}^\star_{Ri}H_1 \cdot \tilde{L}_j + \text{h.c.}\right]$$

A. Djouadi, Phys. Rept. 459, 1 (2008).

Top Quark Pair Production at LO QCD

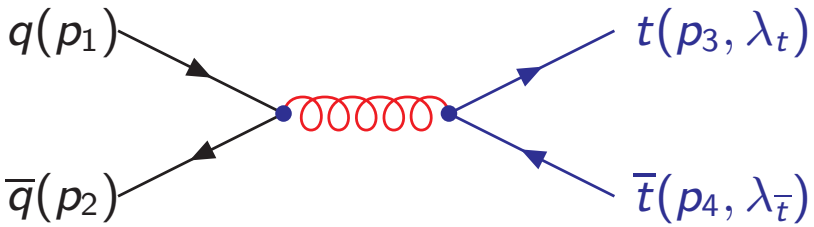
At leading order (LO) the partonic cross section for $t\bar{t}$ production is of order $\mathcal{O}(\alpha_s^2)$. The subprocesses that contribute to the cross section at this level are

M. Glück, J. F. Owens and E. Reya, Phys. Rev. D17, 2324 (1978);

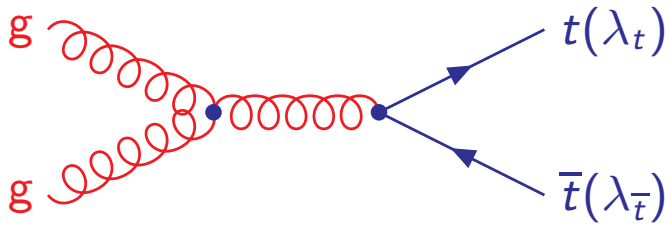
J. Babcock, D. Silvers and S. Wolfram, Phys. Rev. D18, 162 (1978);

H. Georgi et al., Ann. Phys. 114, 273 (1978).

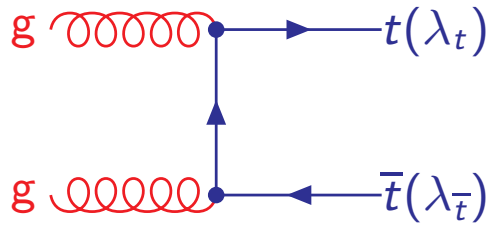
$q\bar{q}$ Annihilation



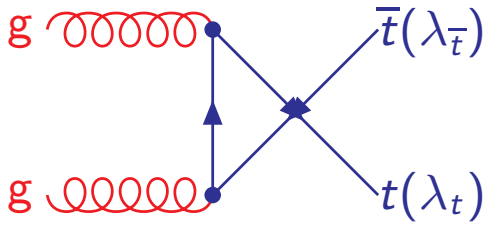
Gluon Fusion



s-channel



t-channel



u-channel

The partonic differential cross section to the $q\bar{q}$ **annihilation** and **gluon fusion** processes for polarized top quark pairs at NLO SUSY EW and SQCD can be written as

$$\begin{aligned} d\hat{\sigma}^{NLO}_{q\bar{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\bar{t}}) =& d\hat{\sigma}^{LO}_{q\bar{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\bar{t}}) + \delta d\hat{\sigma}_{q\bar{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\bar{t}}) \\ =& \frac{d\Phi_{2\to 2}}{8\pi^2\hat{s}}\left[\overline{\sum}|\mathcal{M}_B^{q\bar{q},gg}|^2 + 2Re\overline{\sum}(\delta\mathcal{M}^{SUSYEW}_{q\bar{q},gg} \times \mathcal{M}_B^{q\bar{q},gg}) + \right. \\ & \left. 2Re\overline{\sum}(\delta\mathcal{M}^{SQCD}_{q\bar{q},gg} \times \mathcal{M}_B^{q\bar{q},gg})\right] \end{aligned}$$

where $\lambda_t(\lambda_{\bar{t}}) = \pm 1/2$ denotes the top(antitop) helicity state,
$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2$ and
$\hat{t} = (p_3 - p_1)^2 = (p_4 - p_2)^2 = m_t^2 - \hat{s}(1 - \beta_t \cos\theta)/2$ are Mandelstam variables with θ denoting the scattering angle in the parton center of mass system (CMS) and $\beta_t = \sqrt{1 - 4m_t^2/\hat{s}}$ is the top quark velocity.

S. Berge, W. Hollik, W. M. Mosle and D. Wackeroth, Phys. Rev. D76, 034016 (2007).

Top Quark Pair Production Density Matrix

We can express the partonic cross section for $q\bar{q}, gg \to t\bar{t}$ in terms of a density matrix as follows:

$$R_{\alpha_1\alpha_2,\,\beta_1\beta_2}(\vec{p},\vec{k}) = \frac{1}{N}\sum_{a}\sum_{\text{color},\,\text{initial spins}} \langle t(k_1,\alpha_1),\bar{t}(k_2,\beta_1)\,|\,T\,|\,a(p_1)\bar{a}(p_2)\rangle^* \langle t(k_1,\alpha_2),\bar{t}(k_2,\beta_2)\,|\,T\,|\,a(p_1)\bar{a}(p_2)\rangle$$

with the top spin index α and the anti-top spin index β.

The density matrix R can be decomposed in the t and $\bar{t}$ spin space as

$$R = A\cdot\mathbf{1}\otimes\mathbf{1} + \vec{B}^{+}\cdot\vec{\sigma}\otimes\mathbf{1} + \mathbf{1}\otimes\vec{\sigma}\cdot\vec{B}^{-} + C_{ij}\,\sigma_i\otimes\sigma_j$$

W. Bernreuther and A. Brandenburg, Phys. Rev. D49, 4481 (1994).

with

$$
\begin{aligned}
B_i^{\pm} &= b_1^{\pm}\,\hat{p}_i + b_2^{\pm}\,\hat{k}_i + b_3^{\pm}\,\hat{n}_i \\
C_{ij} &= c_0\,\delta_{ij} + \epsilon_{ijl}\left(c_1\hat{p}_l + c_2\hat{k}_l + c_3\hat{n}_l\right) \\
&\quad + c_4\hat{p}_i\hat{p}_j + c_5\hat{k}_i\hat{k}_j + c_6\left(\hat{p}_i\hat{k}_j + \hat{p}_j\hat{k}_i\right) + \\
&\quad + c_7\left(\hat{p}_i\hat{n}_j + \hat{n}_i\hat{p}_j\right) + c_8\left(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j\right)
\end{aligned}
$$

where $\{i,j\} = 1,2,3$ and $\vec{n} = \vec{p} \times \vec{k}$.

The first factor of the tensor product of the 2×2 unit matrices $\mathbf{1}$ and the Pauli matrices $\vec{\sigma}$ refers to top spin space, the second factor of the tensor product refers to the anti-top spin space.

The structure functions A, $b_i^{\pm}$ and c_i depend only on the partonic center of mass energy $\hat{s}$ and on the cosine of the scattering angle:

$$
z = \cos\theta_t = \hat{p}\hat{k}.
$$

The contributions to the density matrix R can be decomposed into a CP-even and a CP-odd part:

$$R = R_{CP-even} + R_{CP-odd}$$

We have that the CP-odd part of the density matrix R is:

$$R_{CP-odd} = (\mathbf{b_1^{CP-odd}}\,\hat{\mathbf{p}}_\mathbf{i} + \mathbf{b_2^{CP-odd}}\,\hat{\mathbf{k}}_\mathbf{i} + b_3^{CP-odd}\,\hat{n}_i)(\sigma^i \otimes \mathbf{1} - \mathbf{1} \otimes \sigma^i) +$$
$$\epsilon_{ijk}\,(\mathbf{c_1}\hat{\mathbf{p}}_\mathbf{i} + \mathbf{c_2}\hat{\mathbf{k}}_\mathbf{i} + c_3\hat{n}_i)\sigma_j \otimes \sigma_k .$$

Interactions with CP violation, which are also parity violating, can give contributions to b_1^{CP-odd}, b_2^{CP-odd}, c_1, c_2. Nonzero b_1^{CP-odd}, b_2^{CP-odd} require in addition absorptive parts.

The density matrix R is related to the averaged squared matrix element by

$$\overline{\left|M\left(t(\vec{k}_1,\vec{s}_1)\bar{t}(\vec{k}_2,\vec{s}_2)\right)\right|}^2 := \overline{|M(\vec{s}_1,\vec{s}_2)|}^2 = Tr\left[R\left(\rho_1\otimes\rho_2\right)\right]$$
$$= Tr\left[R\cdot\frac{1}{2}\left(\mathbf{1}+\vec{s}_1\boldsymbol{\sigma}\right)\otimes\frac{1}{2}\left(\mathbf{1}+\vec{s}_2\boldsymbol{\sigma}\right)\right]$$

where ρ_1 (ρ_2) are the spin projection matrices of the top (anti-top) quark, $\vec{s}_1$ is the normalized top quark spin vector in the top quark's rest frame and $\vec{s}_2$ is the normalized anti-top quark spin vector in the anti-top rest frame.

We have that

$$\overline{|M(\vec{s}_1\vec{s}_2)|}^2 = A+\left(\vec{B}^+\cdot\vec{s}_1\right)+\left(\vec{B}^-\cdot\vec{s}_2\right)+C_{ij}\left(s_{1i}s_{2j}\right)$$

CP Violating Observables

1. $\langle \mathcal{O}_1 \rangle := \left\langle \hat{k} \cdot (\vec{s}_1 - \vec{s}_2) \right\rangle = \frac{4 \int_{-1}^{1} dz \left(z \cdot b_1^{CP} + b_2^{CP} \right)}{4 \int_{-1}^{1} dz\, A} \equiv \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{tot}}$
2. $\langle \mathcal{O}_2 \rangle := \left\langle \hat{k} \cdot (\vec{s}_1 \times \vec{s}_2) \right\rangle = \frac{2 \int_{-1}^{1} dz \left(z \cdot c_1 + c_2 \right)}{4 \int_{-1}^{1} dz\, A}$

A, b_1, b_2, c_1, c_2 are coefficients extracted from the top quark pair production density matrix only depending on z and $\hat{s}$.

W. Bernreuther and A. Brandenburg, Phys. Rev. D49, 4481 (1994).

In the SM and CP conserving MSSM these two CP violating observables are zero. For $\mathcal{O}_1 \neq 0$ and/or $\mathcal{O}_2 \neq 0$ one needs:

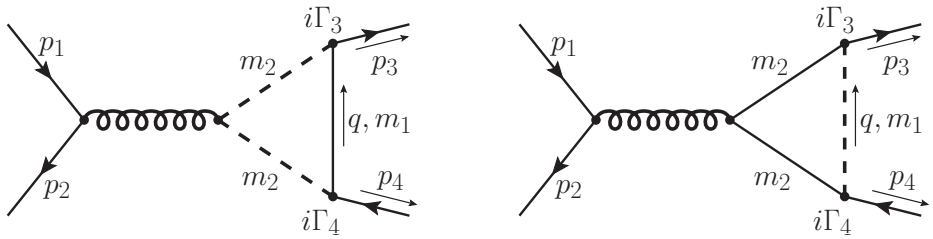
- complex couplings and
- non-zero imaginary part of loop integrals.

SUSY EW and SUSY QCD corrections to top pair quark production in the complex MFV-MSSM exhibit CP violating couplings due to

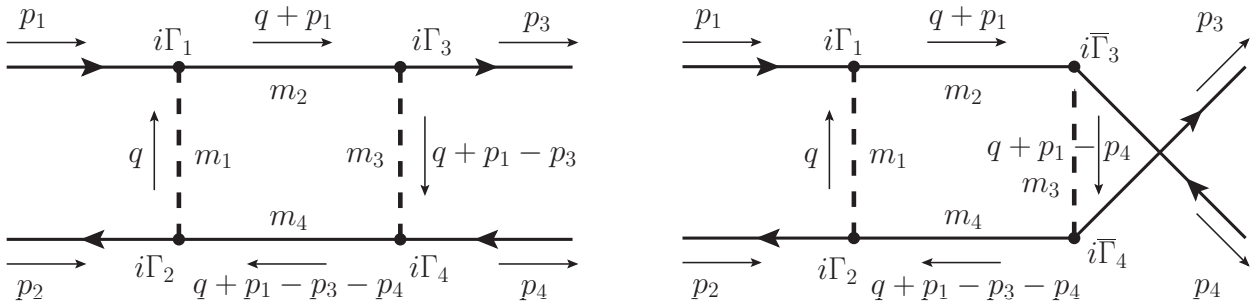
- M_3,
- complex squark mixing matrix elements,
- complex chargino mixing matrix elements,
- complex neutralino mixing matrix elements.

CP Violation in Top Quark Pair Production in the Complex MFV-MSSM: $q\bar{q}$ Annihilation

Momentum and mass assignments for the vertex diagrams of the $q\bar{q}$-channel:

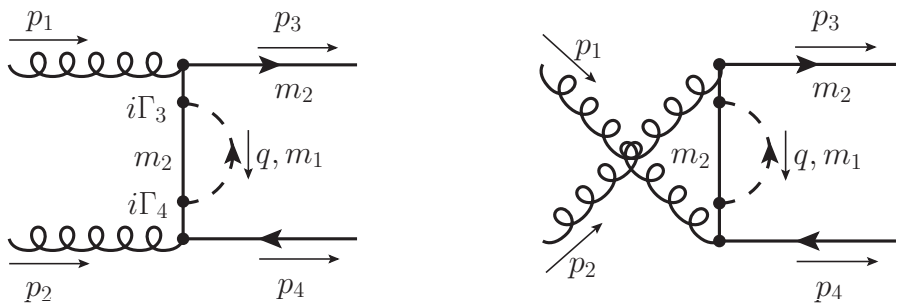


Momentum and mass assignments for the direct and crossed box diagrams:

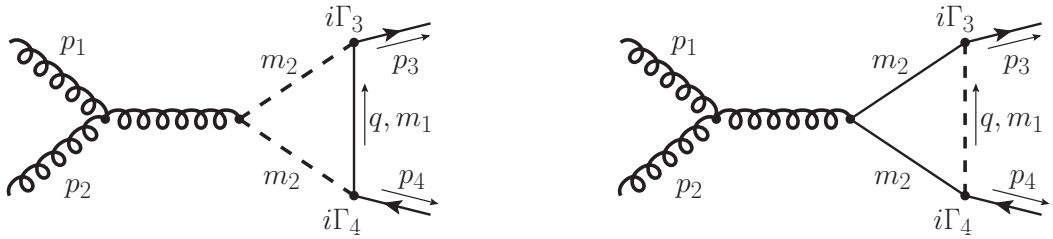


CP Violation in Top Quark Pair Production in the Complex MFV-MSSM: Gluon Fusion

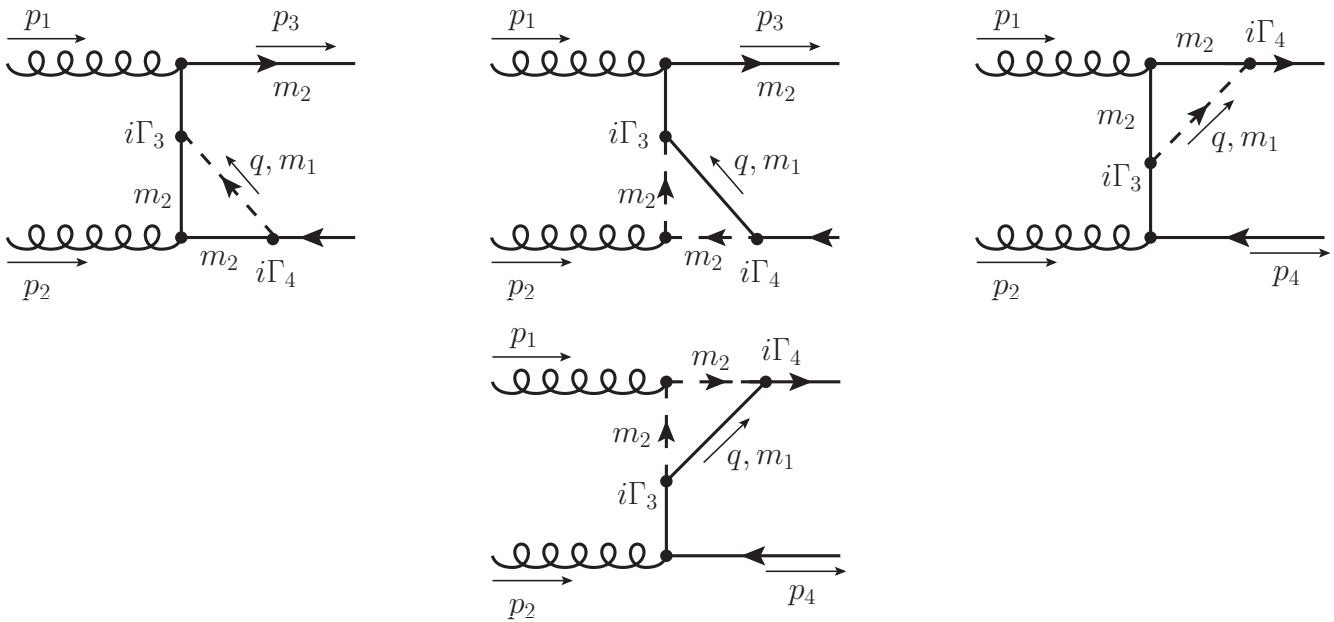
Momentum and mass assignments for the top self energy diagrams:



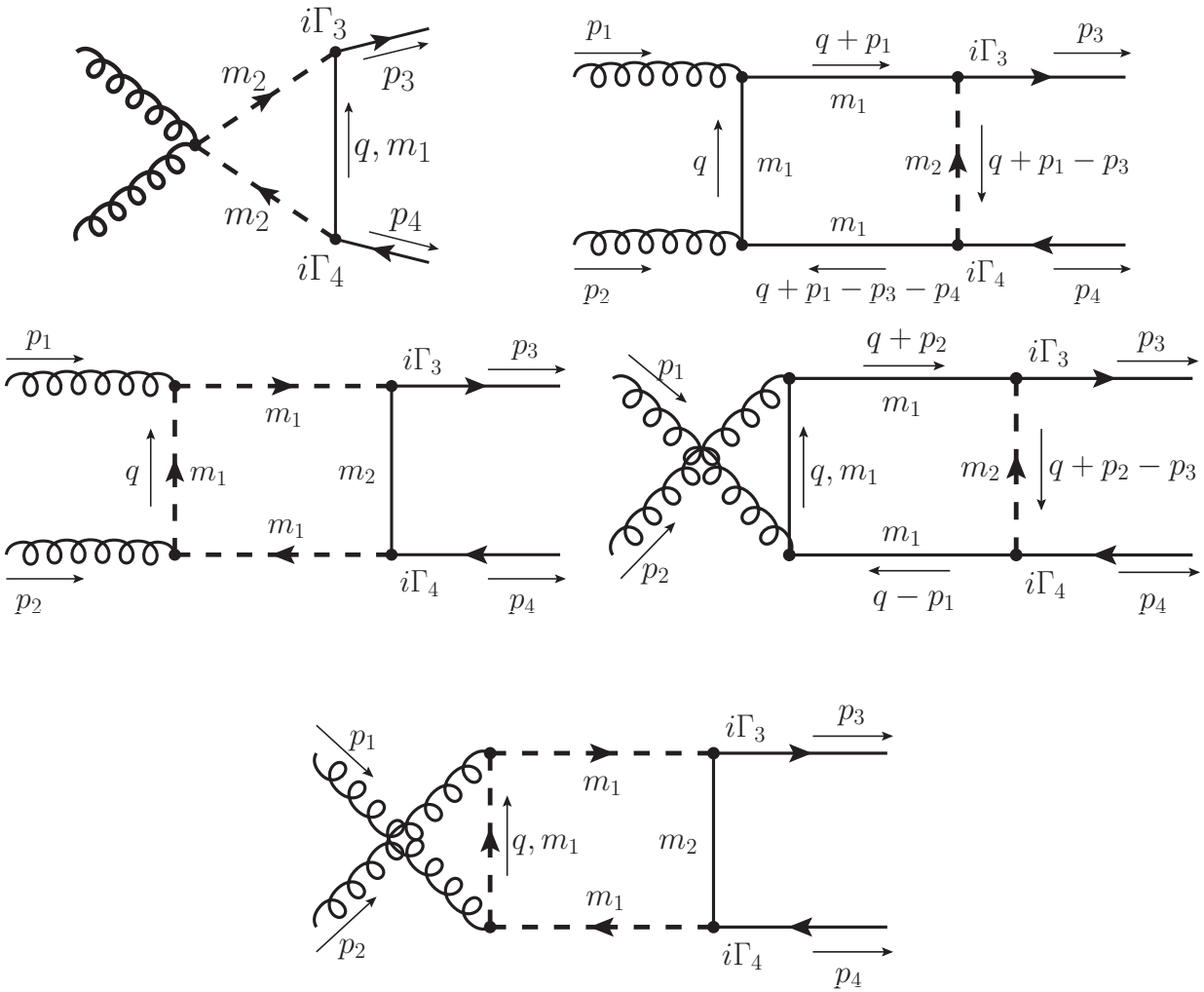
Momentum and mass assignments for the vertex diagrams:



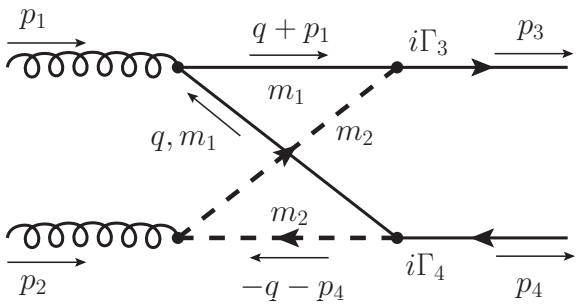
Momentum and mass assignments for the t-channel vertex diagrams of the gluon channel:

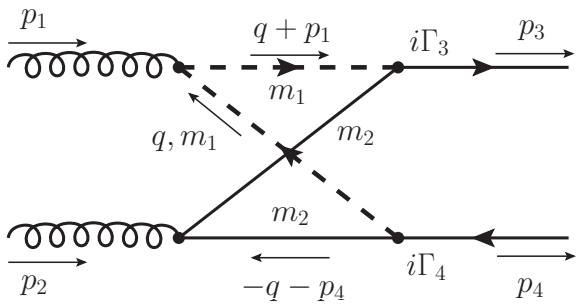


Momentum and mass assignments for the generic box diagrams of the gluon channel:



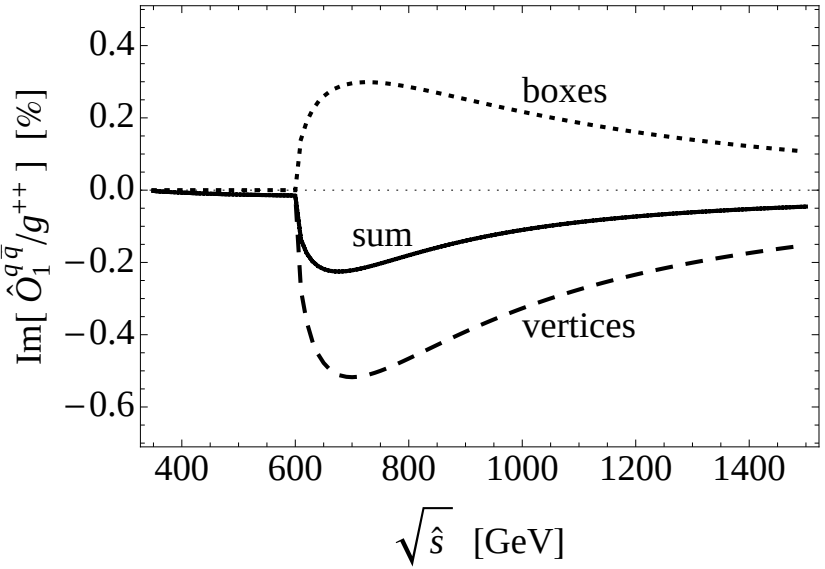
Momentum and mass assignments for the two additional SQCD box diagrams of the gluon channel:

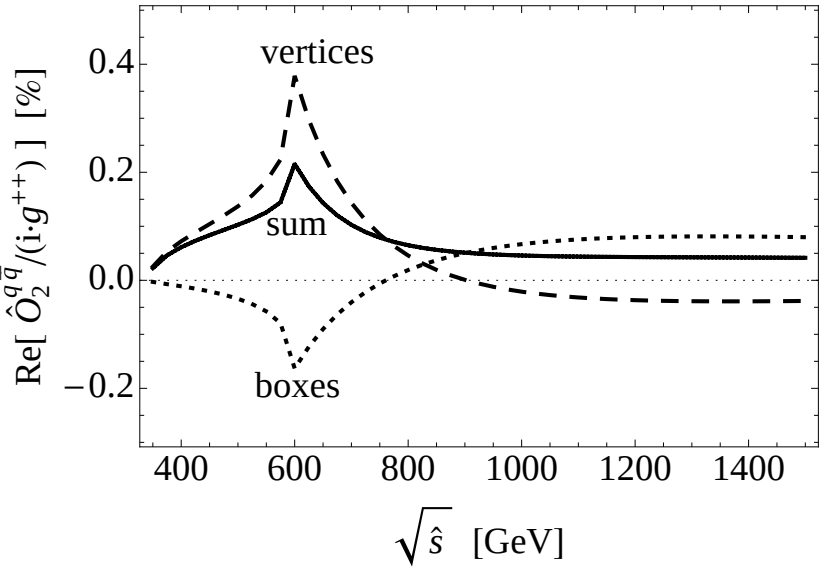




Numerical Results: SQCD Corrections to $q\bar{q}$ Annihilation

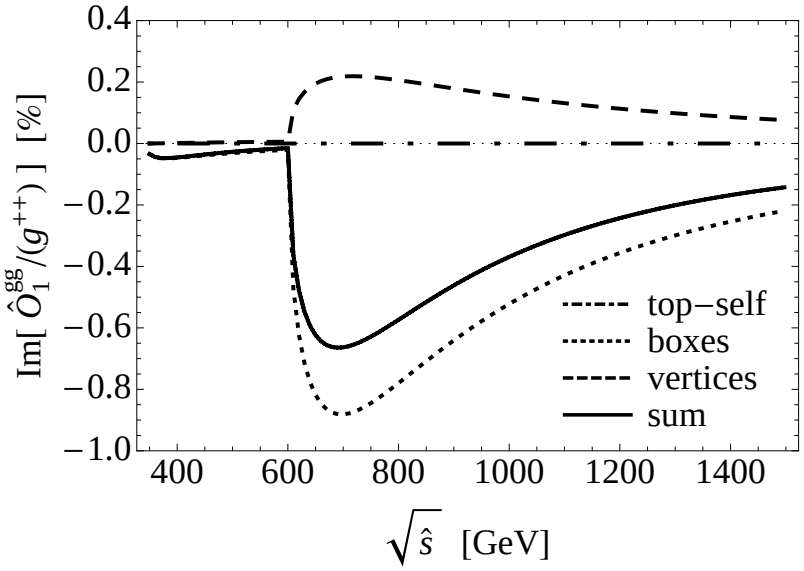
$q\bar{q} \to t\bar{t}$, partonic contributions in % to $\hat{O}_1$ (left) and $\hat{O}_2$ (right)

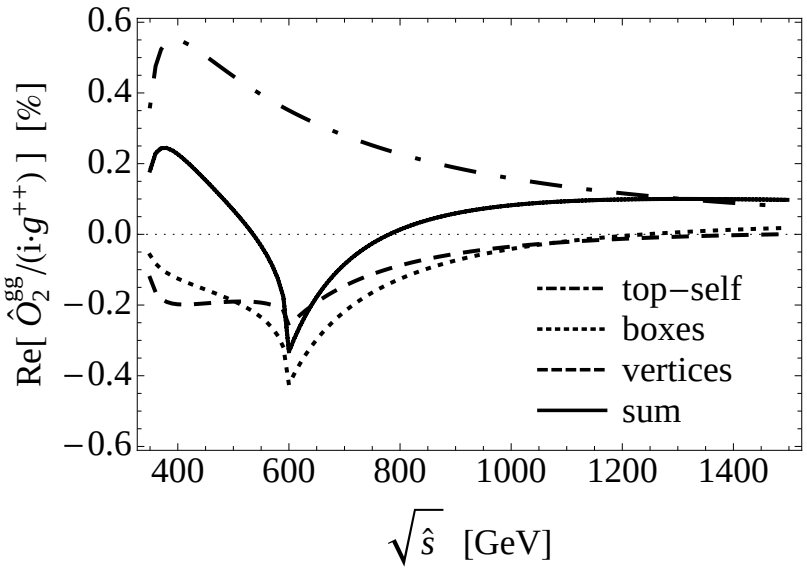




Numerical Results: SQCD Corrections to Gluon Fusion

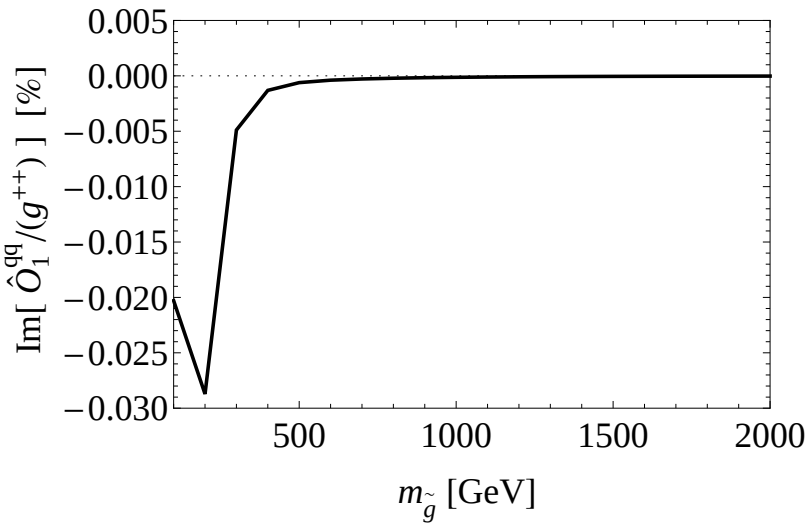
$gg \to t\bar{t}$, partonic contributions in % to $\hat{O}_1$ (left) and $\hat{O}_2$ (right)

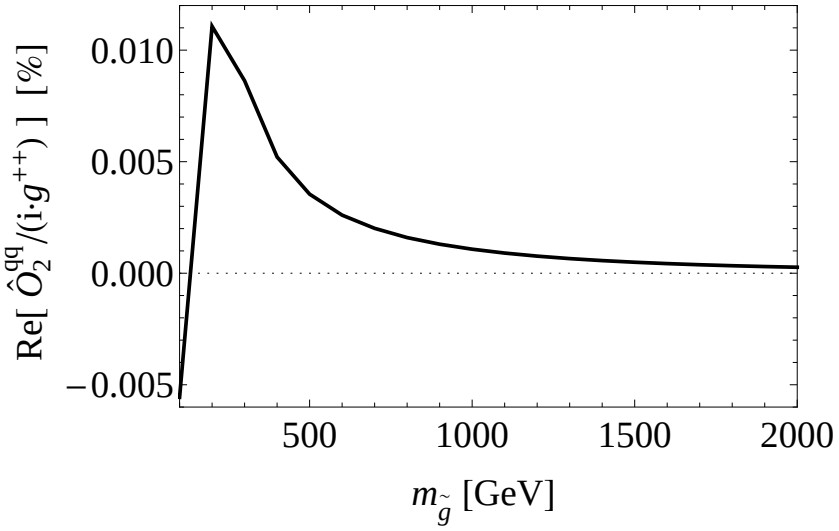




SQCD Corrections to $q\bar{q}$ Annihilation at Hadron Level

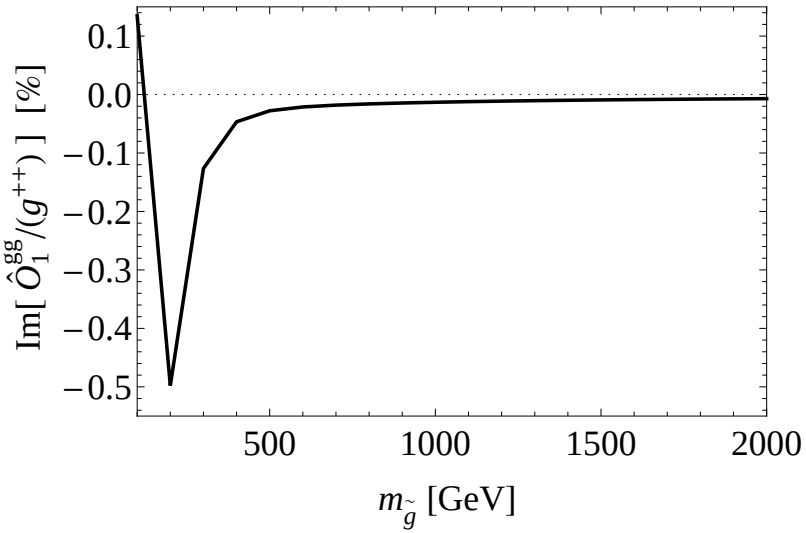
Contributions in % to O_1 (left) and O_2 (right) at 14 TeV

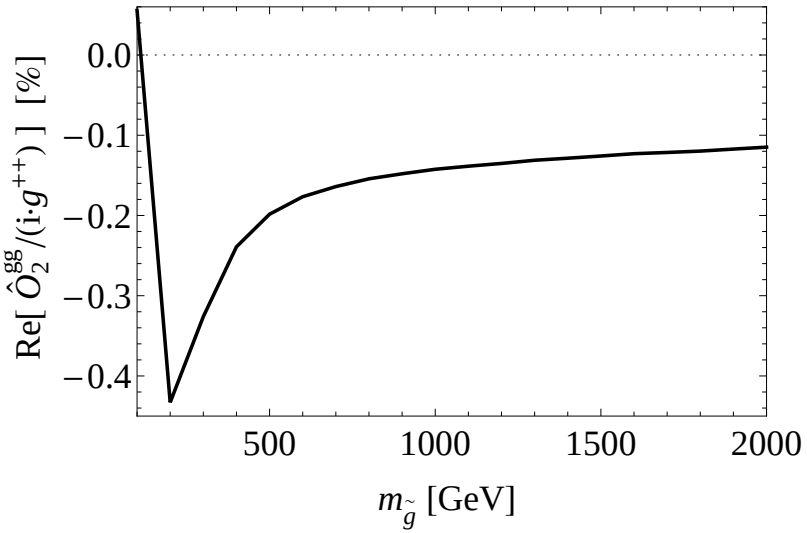




SQCD Corrections to Gluon Fusion at Hadron Level

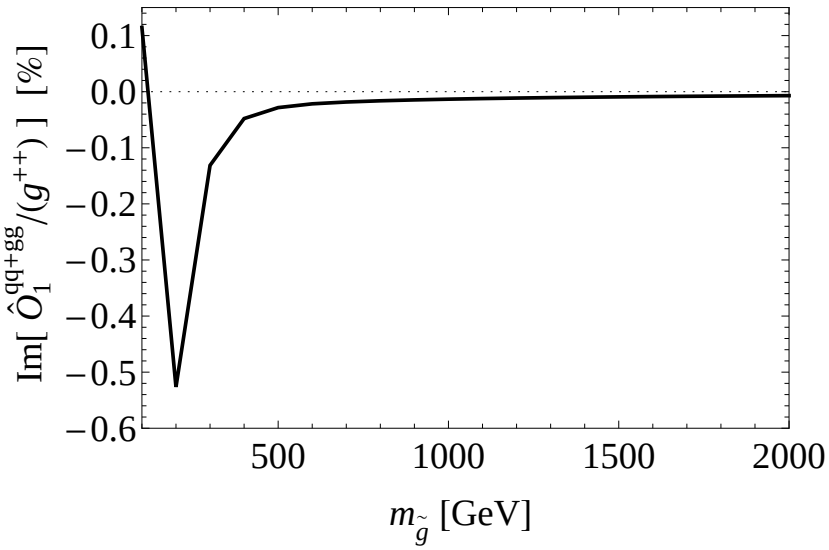
Contributions in % to O_1 (left) and O_2 (right) at 14 TeV

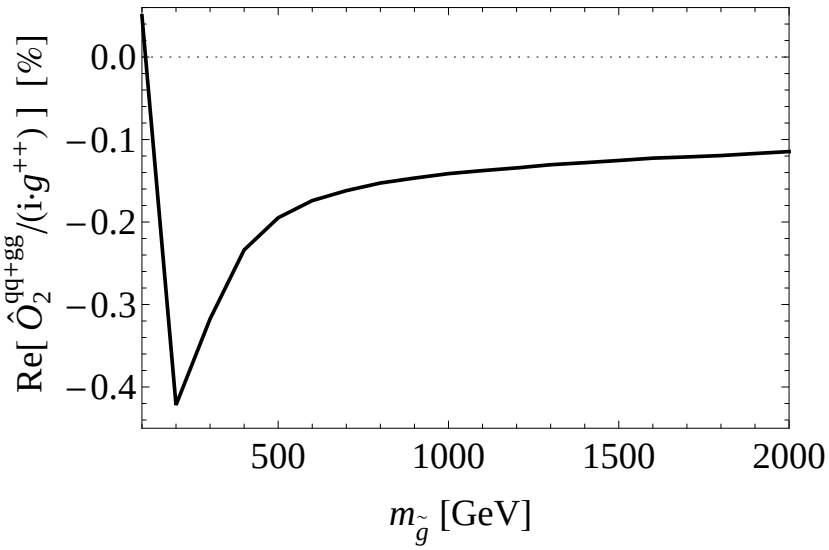




SQCD Corrections at Hadron Level

Contributions in % to O_1 (left) and O_2 (right) at 14 TeV





Conclusions and Outlook

- The CP violating asymmetries may be a sensitive probe of loop-induced SUSY effects in top pair production in the Complex MFV-MSSM.
- Interesting CP violating effects may arise due to SQCD corrections to gluon fusion, i.e. asymmetries of $O(10^{-3})$, which may be observable at the LHC. Contributions to O_2 with large gluino masses and large stop masses splitting.
- A detailed MC study is needed to determine if these effects are indeed observable.
- A detailed survey of the MSSM parameter space and a study of the impact of both SUSY EW and SUSY QCD corrections on O_1 and O_2 at the LHC is in progress.