

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

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# Outline

- Introduction
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- Top Quark Pair Production Density Matrix
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- CP Violation in Top Quark Pair Production in the Complex MFV-MSSM
- Numerical Results
- Conclusions and Outlook

# 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).

- The most general superpotential is

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

- Soft SUSY-breaking terms

- Mass terms for the gluinos, winos and binos:

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

- Mass terms for the scalar fermions:

$$-\mathcal{L}_{sfermions} = \sum_{i=gen} m_{\bar{Q}_i}^2 \bar{Q}_i^\dagger \bar{Q}_i + m_{\bar{L}_i}^2 \bar{L}_i^\dagger \bar{L}_i + m_{\bar{u}_i}^2 |\bar{u}_{Ri}|^2 + m_{\bar{d}_i}^2 |\bar{d}_{Ri}|^2 + m_{\bar{l}_i}^2 |\bar{l}_{Ri}|^2$$

- Mass and bilinear terms for the Higgs bosons:

$$-\mathcal{L}_{Higgs} = m_{H_2}^2 H_2^\dagger H_2 + m_{H_1}^2 H_1^\dagger H_1 + B\mu(H_2 \cdot H_1 + \text{h.c.})$$

- Trilinear couplings between sfermions and Higgs bosons:

$$-\mathcal{L}_{tril.} = \sum_{i,j=gen} \left[ A_{ij}^u \bar{u}_{Ri}^* H_2 \cdot \bar{Q}_j + A_{ij}^d \bar{d}_{Ri}^* H_1 \cdot \bar{Q}_j + A_{ij}^l \bar{l}_{Ri}^* H_1 \cdot \bar{L}_j + \text{h.c.} \right]$$

# Top Quark Pair Production at LO QCD

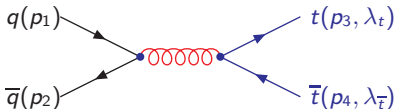
At **leading order (LO)** the **partonic cross section** for  $t\bar{t}$  production is of order  $\mathcal{O}(\alpha_s^2)$ . The subprocesses that contribute to the cross section at this level are

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

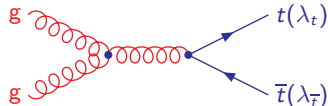
J. Babcock, D. Silvers and S. Wolfram, Phys. Rev. D18, 162 (1978);

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

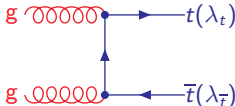
## $q\bar{q}$ Annihilation



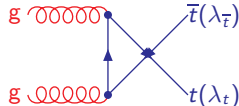
## Gluon Fusion



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

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

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  $\theta$  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. Wackerroth, Phys. Rev. D76, 034016 (2007).

# Top Quark Pair Production Density Matrix

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

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

with the top spin index  $\alpha$  and the anti-top spin index  $\beta$ .

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  $2 \times 2$  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:

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

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

$$R_{CP\text{-odd}} = (\mathbf{b}_1^{CP\text{-odd}} \hat{\mathbf{p}}_i + \mathbf{b}_2^{CP\text{-odd}} \hat{\mathbf{k}}_i + b_3^{CP\text{-odd}} \hat{n}_i)(\sigma^i \otimes \mathbf{1} - \mathbf{1} \otimes \sigma^i) + \epsilon_{ijk} (c_1 \hat{\mathbf{p}}_i + c_2 \hat{\mathbf{k}}_i + c_3 \hat{n}_i) \sigma_j \otimes \sigma_k.$$

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

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

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

where  $\rho_1$  ( $\rho_2$ ) 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

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

# CP Violating Observables

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

$$\textcircled{2} \langle \mathcal{O}_2 \rangle := \left\langle \hat{k} \cdot (\vec{s}_1 \times \vec{s}_2) \right\rangle = \frac{2 \int_{-1}^1 dz (z \cdot c_1 + c_2)}{4 \int_{-1}^1 dz A}$$

$A, b_1, b_2, c_1, c_2$  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:

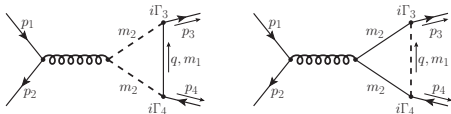
- complex couplings and
- non-zero imaginary part of loop integrals.

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

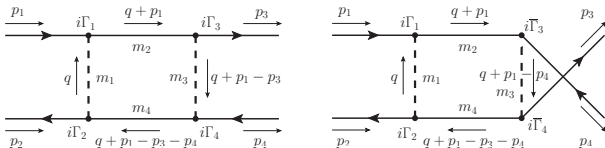
- $M_3$ ,
- complex squark mixing matrix elements,
- complex chargino mixing matrix elements,
- complex neutralino mixing matrix elements.

# 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:

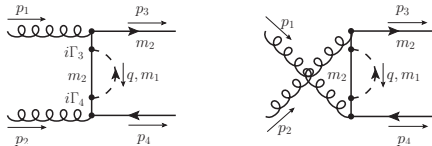


Momentum and mass assignments for the direct and crossed box diagrams:

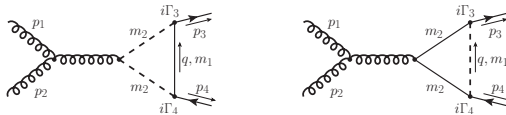


# CP Violation in Top Quark Pair Production in the Complex MFV-MSSM: Gluon Fusion

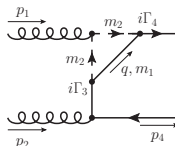
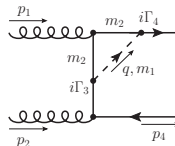
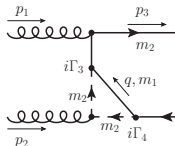
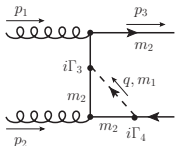
Momentum and mass assignments for the top self energy diagrams:



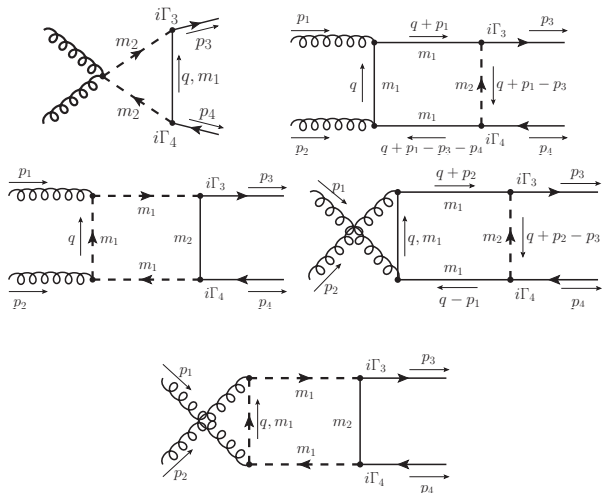
Momentum and mass assignments for the vertex diagrams:



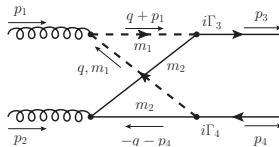
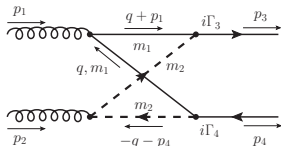
Momentum and mass assignments for the t-channel vertex diagrams of the gluon channel:



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



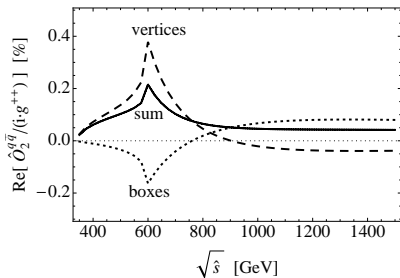
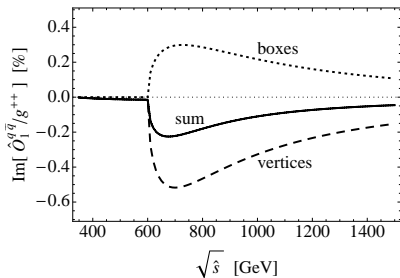
Momentum and mass assignments for the two additional SQCD box diagrams of the gluon channel:





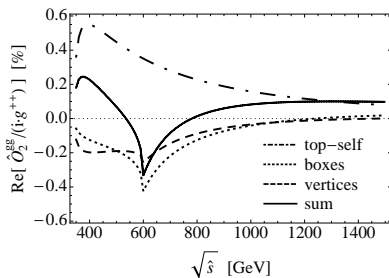
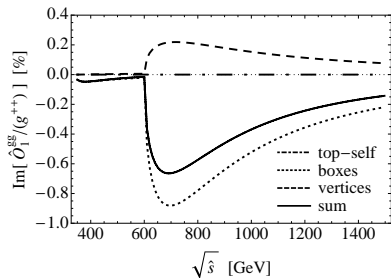
# Numerical Results: SQCD Corrections to $q\bar{q}$ Annihilation

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



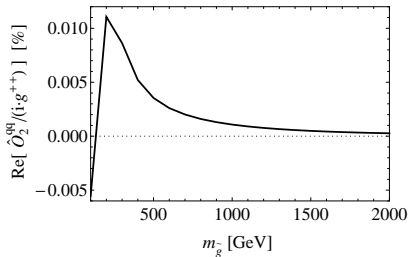
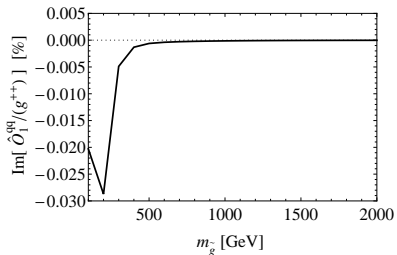
# Numerical Results: SQCD Corrections to Gluon Fusion

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



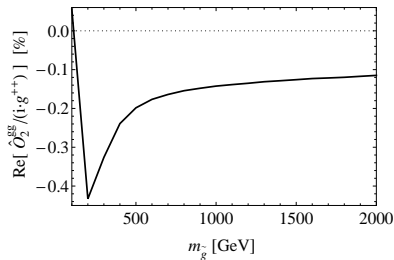
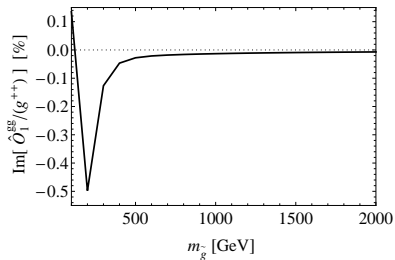
# SQCD Corrections to $q\bar{q}$ Annihilation at Hadron Level

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



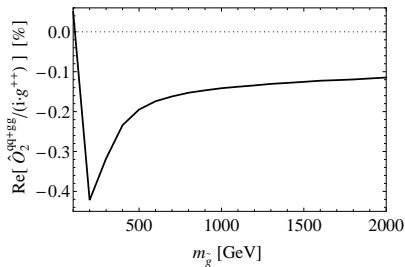
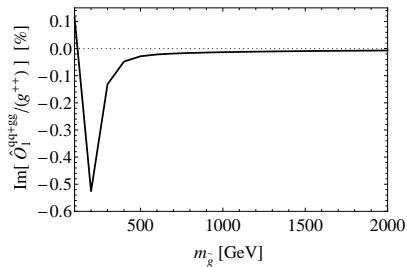
# SQCD Corrections to Gluon Fusion at Hadron Level

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.