

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

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# Outline

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- Asymmetries in Top Quark Pair Production
- Top Quark Pair Production at LO QCD
- 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:

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

- 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:

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

# Asymmetries in Top Quark Pair Production

Asymmetries can be sensitive probes of new physics:

- **Forward Backward Asymmetry:**

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

where  $N_F$  and  $N_B$  are the number of forward ( $\Delta y > 0$ ) and backward events ( $\Delta y < 0$ ), respectively. SUSY one loop corrections may have a small impact.

V. M. Abazov et al., D0 Collaboration, Phys. Rev. Lett. 100, 142002 (2008).

T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 101, 202001 (2008).

S. Berge, D. Wackerth and M. Wiebusch, arXiv:1202.4762v1 [hep-ph]

- **Parity Violating Asymmetry:**

$$A_{PV} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

SUSY EW corrections can introduce a  $A_{PV} \sim 2 - 3\%$  at the LHC.

C. Kao and D. Wackerth, Phys. Rev. D61, 055009 (2000).

- **CP Violating Observables:**

$$\mathcal{A}_{LR} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{total}}$$

A difference in the production of  $t_L \bar{t}_L$  and  $t_R \bar{t}_R$  generates a charge asymmetry in the energy distribution of their decay products.

C. R. Schmidt and M. E. Peskin, Phys. Rev. Lett. 69, 410 (1992).

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

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

$A, b_1, b_2, c_1, c_2$  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.

# Top Quark Pair Production at LO QCD

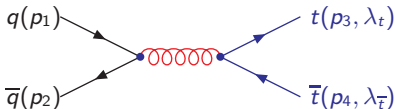
At **leading order (LO)** the **partonic cross section** for  $t\bar{t}$  production is of order  $\mathcal{O}(\alpha_s^2)$ . The subprocesses that contribute to the cross section at this level are

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

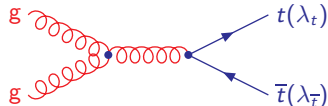
J. Babcock, D. Silvers and S. Wolfram, Phys. Rev. D18, 162 (1978);

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

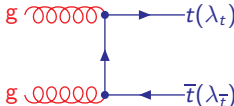
## $q\bar{q}$ Annihilation



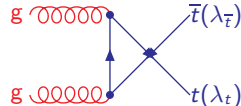
## Gluon Fusion



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

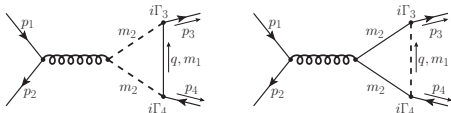
$$\begin{aligned}
 d\hat{\sigma}_{q\bar{q},gg}^{NLO}(\hat{t}, \hat{s}, \lambda_t, \lambda_{\bar{t}}) &= d\hat{\sigma}_{q\bar{q},gg}^{LO}(\hat{t}, \hat{s}, \lambda_t, \lambda_{\bar{t}}) + \delta d\hat{\sigma}_{q\bar{q},gg}(\hat{t}, \hat{s}, \lambda_t, \lambda_{\bar{t}}) \\
 &= \frac{d\Phi_{2\rightarrow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

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.

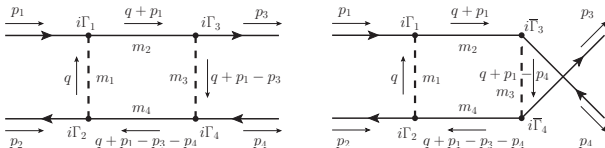
S. Berge, W. Hollik, W. M. Mosle and D. Wackerroth, Phys. Rev. D76, 034016 (2007).

# 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:

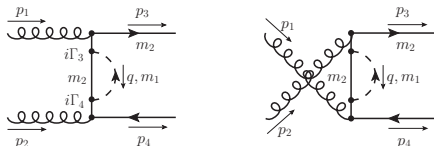


Momentum and mass assignments for the direct and crossed box diagrams:

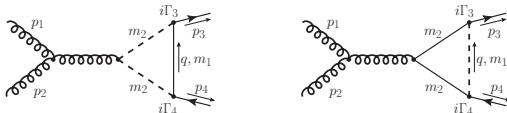


# CP Violation in Top Quark Pair Production in the Complex MFV-MSSM: Gluon Fusion

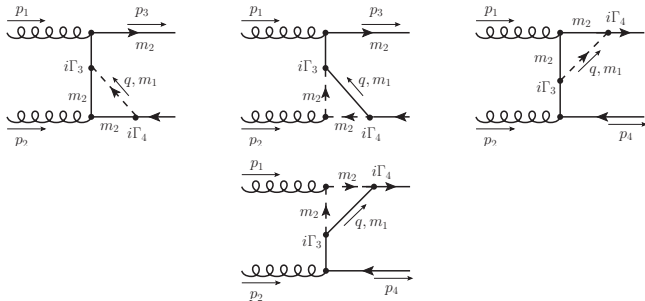
Momentum and mass assignments for the top self energy diagrams:



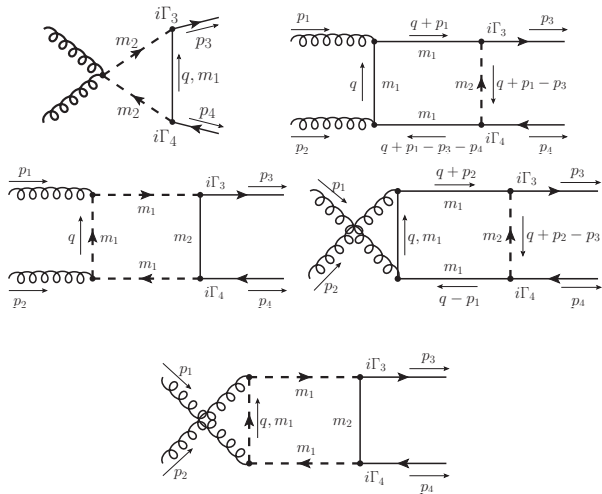
Momentum and mass assignments for the vertex diagrams:



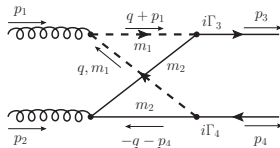
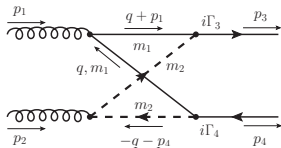
Momentum and mass assignments for the t-channel vertex diagrams of the gluon channel:



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

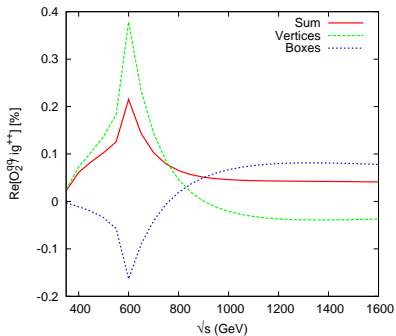
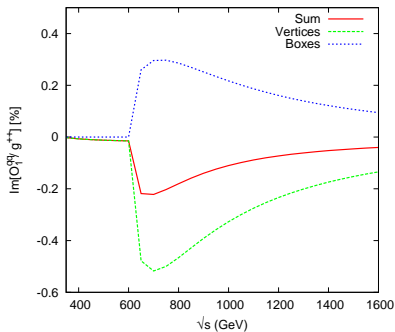


Momentum and mass assignments for the two additional SQCD box diagrams of the gluon channel:



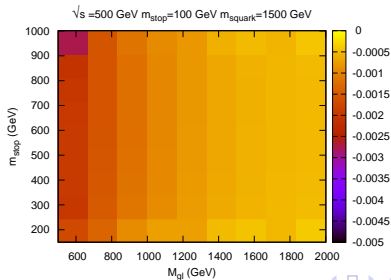
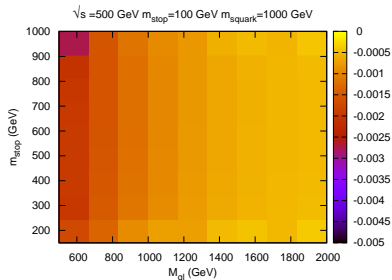
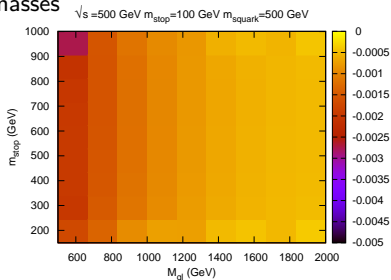
# Numerical Results: SQCD Corrections to $q\bar{q}$ Annihilation

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



# Numerical Results: SQCD

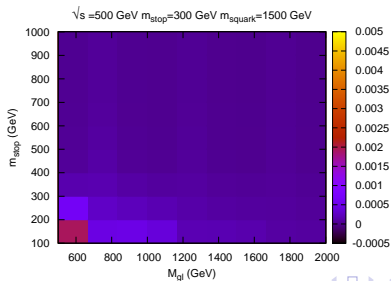
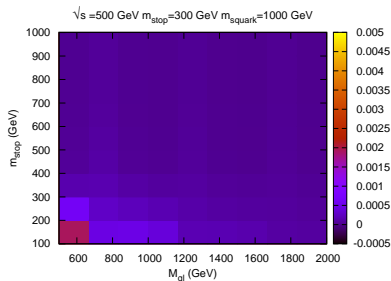
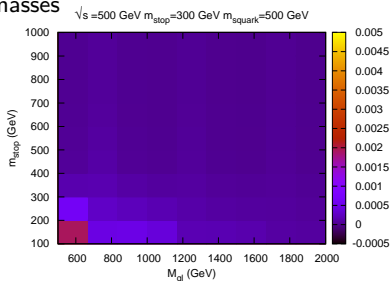
$q\bar{q} \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{O}_1$  in function of the gluino and stop masses





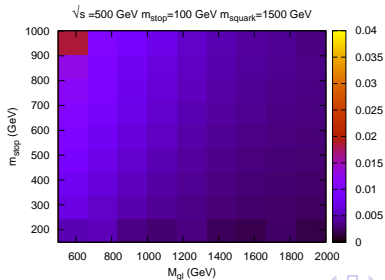
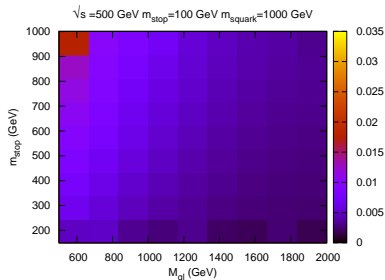
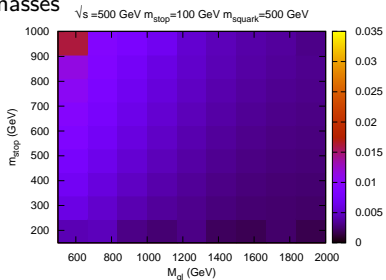
# Numerical Results: SQCD

$q\bar{q} \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{O}_1$  in function of the gluino and stop masses



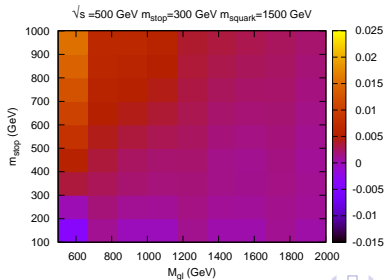
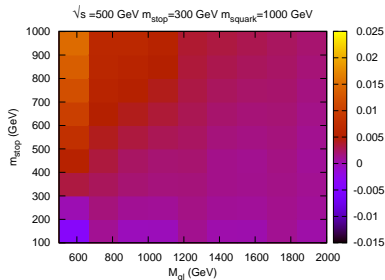
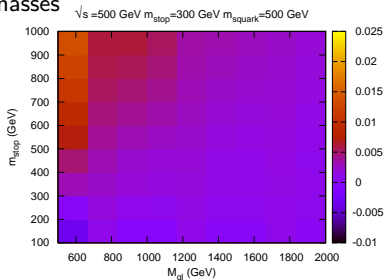
# Numerical Results: SQCD

$q\bar{q} \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{O}_2$  in function of the gluino and stop masses



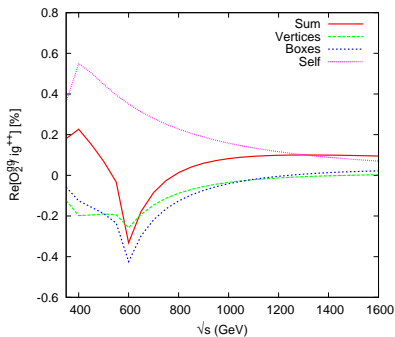
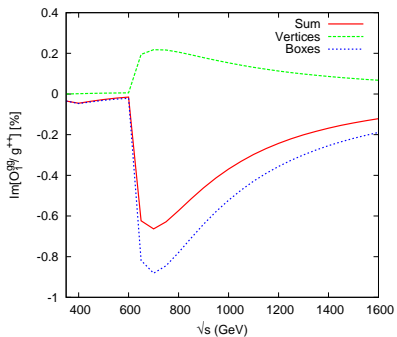
# Numerical Results: SQCD

$q\bar{q} \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{O}_2$  in function of the gluino and stop masses



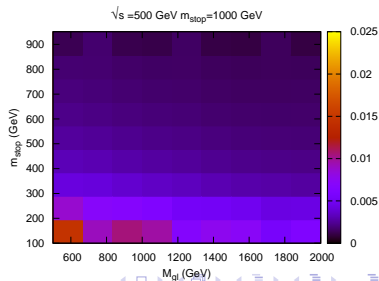
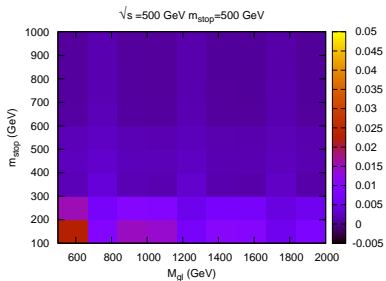
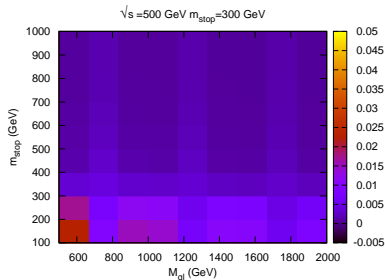
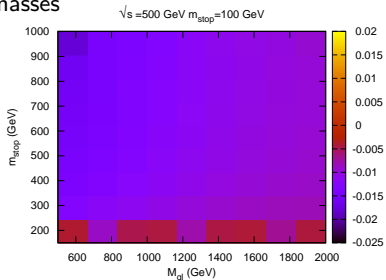
# Numerical Results: SQCD Corrections to Gluon Fusion

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



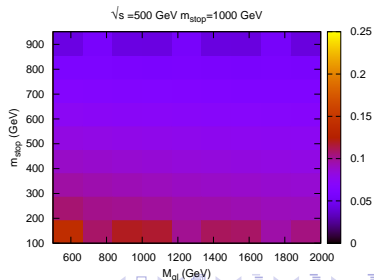
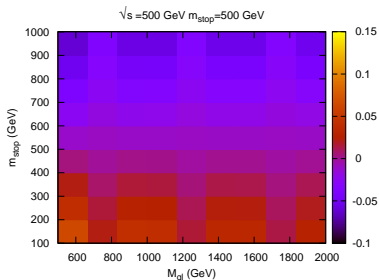
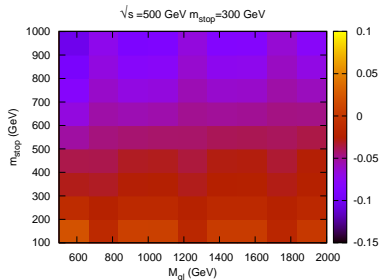
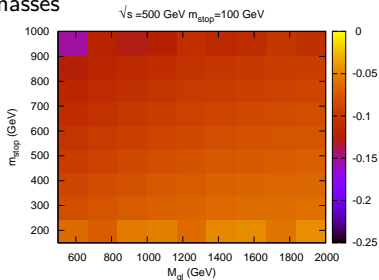
# Numerical Results: SQCD

$gg \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{O}_1$  in function of the gluino and stop masses



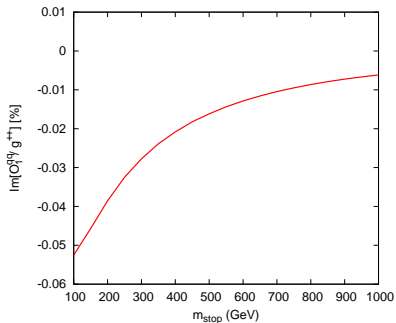
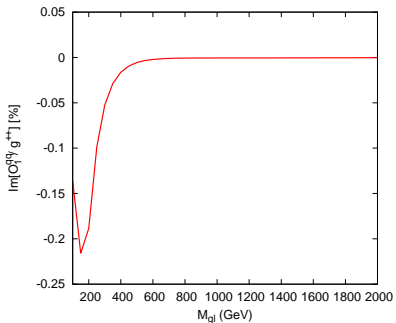
# Numerical Results: SQCD

$gg \rightarrow t\bar{t}$ , partonic contributions in % to  $\hat{\mathcal{O}}_2$  in function of the gluino and stop masses



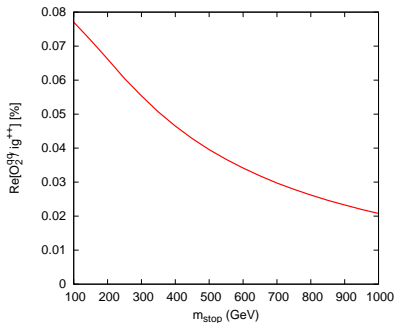
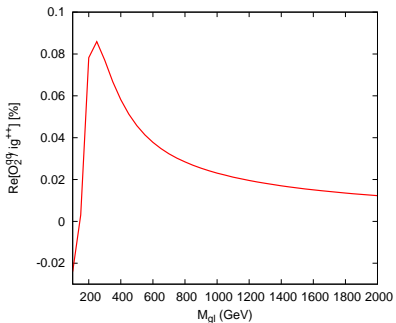
# SQCD Corrections to $q\bar{q}$ Annihilation at Hadron Level

Contributions in % to  $O_1$  at 14 TeV



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

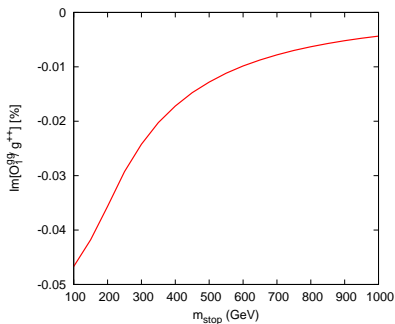
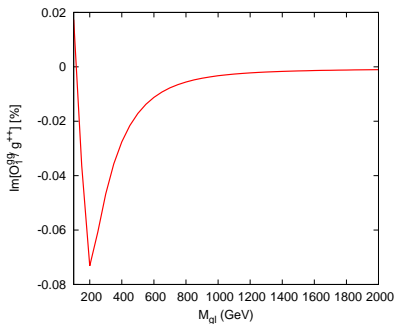
Contributions in % to  $O_2$  at 14 TeV





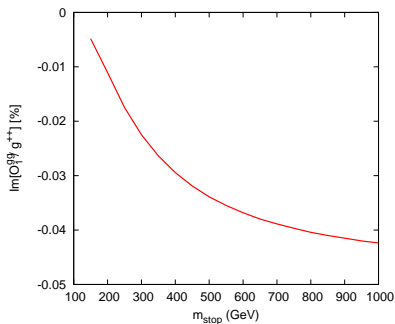
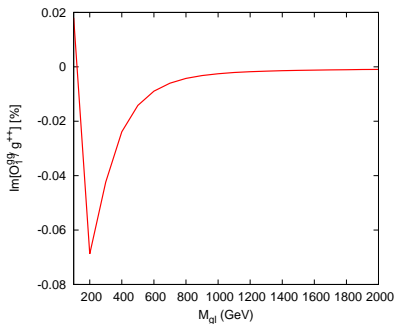
# SQCD Corrections to Gluon Fusion at Hadron Level

Contributions in % to  $O_1$  at 14 TeV



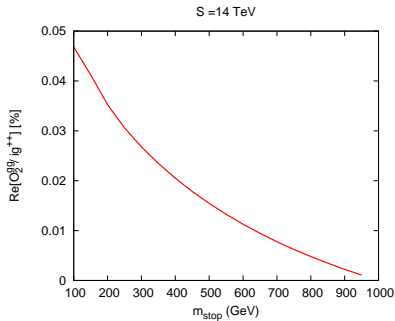
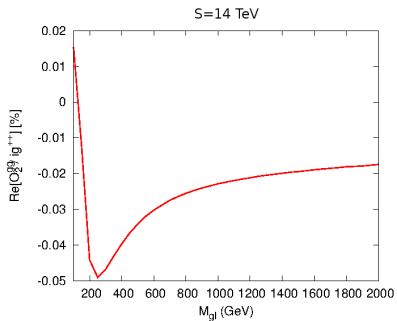
# SQCD Corrections to Gluon Fusion at Hadron Level

Contributions in % to  $O_1$  at 14 TeV



# SQCD Corrections to Gluon Fusion at Hadron Level

Contributions in % to  $O_2$



# 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.