# SUSY Effects in $t\bar{t}$ Production in the CP-Violating MSSM at the LHC

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**SUSY 2011**
**Fermilab**

September 1, 2011

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- Numerical Results (Preliminary)
- Conclusions and Outlook

# Introduction

- CP Violation plays an important role in the study of weak interactions and the determination 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 mechanism of EWSB.
- Physics beyond the SM connected to EWSB may be found first through precision studies of top quark observables and deviations of experimental measures from the SM predictions, including EW and QCD corrections, could show non-standard top quark production or decay mechanisms.
- Searches of non-SM signals in $t\bar{t}$ production asymmetries, such as the forward-backward asymmetry, parity violating asymmetries in polarized $t\bar{t}$ production and spin correlations between $t$ and $\bar{t}$, require the inclusion of radiative corrections to top quark production and decay within the SM and beyond the SM.

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

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

# CP Violating MSSM

- **The most general superpotential is**

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

- **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).

At the unification scale $M_X$

- $M_1 = M_2 = M_3 = M_\lambda$
- $A_{ij} = A$

Then, we have four complex parameters: $\{\mu, m_{12}^2 = B\mu, M_\lambda, A\}$.

Two phases may be absorbed $\Rightarrow m_{12}^2, M_\lambda$ become Real $\Rightarrow arg\{\mu\}$ and $\arg\{A\}$ are the physical CP-violating phases in the MSSM imposing universality.


A. Pilaftsis, Phys. Lett. B435, 88 (1998);

A. Pilaftsis and C E. M. Wagner, Nucl. Phys. B553, 3 (1999);

# MSSM Higgs Sector

In the MSSM we need two doublets of complex scalar fields of opposite hyperchage

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ with } Y_{H_1} = -1, \; H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \text{ with } Y_{H_2} = +1$$

to break the EWS.

5 Physical States:
2 CP-even h, H with mixing angle $\alpha$
a CP-odd A and a charged pair $H^\pm$

Higgs masses and couplings are given in terms of two parameters:
$m_A$ and $\tan\beta = v_2/v_1$

Neutral Higgs bosons couplings to fermions and gauge bosons

| $\Phi$ | $g_{\Phi\bar{u}u}$ | $g_{\Phi\bar{d}d}$ | $g_{\Phi VV}$ | $g_{\Phi AZ}$ | $g_{\Phi H^\pm W^\pm}$ |
|---|---|---|---|---|---|
| $h_{SM}$ | 1 | 1 | 1 | 0 | 0 |
| h | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\sin(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | $\mp\cos(\beta-\alpha)$ |
| H | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $\cos(\beta-\alpha)$ | $-\sin(\beta-\alpha)$ | $\pm\sin(\beta-\alpha)$ |
| A | $\cot\beta$ | $\tan\beta$ | 0 | 0 | 1 |

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

# Phenomenological Consequences of the CP-Violating Mixing

- The neutral Higgs bosons do not have to carry any definite CP parities. The Higgs mass eigenstates are no longer CP eigenstates.
- The neutral Higgs boson mixing is described by the $3 \times 3$ mixing matrix $O_{\alpha i}$ as

$$\begin{pmatrix} h & H & A \end{pmatrix}^T = O_{\alpha i} \begin{pmatrix} h_1 & h_2 & h_3 \end{pmatrix}_i^T$$

  with $m_{h_1} \leq m_{h_2} \leq m_{h_3}$.
- The couplings of the Higgs bosons to the SM and MSSM particles, and their decays, are significantly modified.


A. Pilaftsis, Phys. Lett. B435, 88 (1998);

A. Pilaftsis, Phys. Rev. D58, 096010 (1998);

A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B553, 3 (1999);


Input parameters:The charged Higgs mass $m_{H^\pm}$, $|\mu|$, $|A|$, $|m_{\tilde{g}}|$, $\arg(A)$, $\arg(\mu)$.

# Interactions of the Higgs Fields: Higgs-Fermion-Antifermion Interactions

Interactions of the neutral Higgs bosons with quarks and charged leptons are described by the Lagrangian

$$\mathcal{L}_{H_i \bar{f} f} = - \sum_{f=u,d,l} \frac{g m_f}{2 M_W} \sum_{i=1}^{3} H_i \bar{f} (g^S_{H_i \bar{f} f} + i g^P_{H_i \bar{f} f} \gamma_5) f \, .$$

with $(g^S, g^P) = (O_{\phi_1 i}/c_\beta, -O_{ai} \tan\beta)$ for $f = (l, d)$ and $(g^S, g^P) = (O_{\phi_2 i}/s_\beta, -O_{ai} \cot\beta)$ for $f = u$.

Interactions of the charged Higgs bosons with quarks and leptons are described by the Lagrangian:

$$\mathcal{L}_{H^\pm f_\uparrow f_\downarrow} = \frac{g}{\sqrt{2} M_W} \sum_{(f_\uparrow f_\downarrow)=(u,d),(\nu,l)} H^+ \bar{f}_\uparrow (m_{f_\uparrow} g^L_{H^+ \bar{f}_\uparrow f_\downarrow} P_L + m_{f_\downarrow} g^R_{H^+ \bar{f}_\uparrow f_\downarrow} P_R) f_\downarrow + \text{h. c.}$$

where $P_{L/R} \equiv (1 \mp \gamma_5)/2$ and with $g^L = \cot\beta$ and $g^R = \tan\beta$.

J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis and C. E. M. Wagner, Comput. Phys. Commun. 156, 283 (2004).

# Interactions of the Higgs Fields: Higgs-Sfermion-Sfermion Interactions

These interactions can be written in terms of the sfermion mass eigenstates as

$$\mathcal{L}_{H_i \tilde{f}\tilde{f}} = v \sum_{f=u,d} g_{H_i \tilde{f}_j^\star \tilde{f}_k} (H_i \tilde{f}_j^\star \tilde{f}_k),$$

where

$$v g_{H_i \tilde{f}_j^\star \tilde{f}_k} = (\Gamma^{\alpha \tilde{f}^\star \tilde{f}})_{\beta\gamma} O_{\alpha i} U^{\tilde{f}\star}_{\beta j} U^{\tilde{f}}_{\gamma k},$$

with $\alpha = (h, H, A) = (1, 2, 3)$; $\beta, \gamma = L, R$; $i = (h_1, h_2, h_3)$ and j, k=1, 2.

$\Gamma^{\alpha \tilde{f}^\star \tilde{f}}$ is the Higgs-sfermion-sfermion couplings in the weak interaction basis and

$$U^{\tilde{f}} = \begin{pmatrix} \cos\theta_{\tilde{f}} & -\sin\theta_{\tilde{f}} e^{-i\phi_{\tilde{f}}} \\ \sin\theta_{\tilde{f}} e^{+i\phi_{\tilde{f}}} & \cos\theta_{\tilde{f}} \end{pmatrix}$$

is the squark mixing matrix.

J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis and C. E. M. Wagner, Comput. Phys. Commun. 156, 283 (2004).

# Top Pair Production at LO

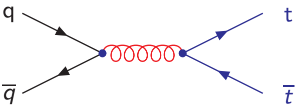
At leading order (LO) the partonic cross section for $t\bar{t}$ production is of order $\mathcal{O}(\alpha_s^2)$. The subprocesses that contribute to the cross section at this level are

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

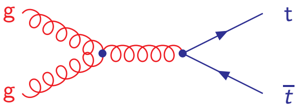
J. Babcock, D. Silvers and S. Wolfram, Phys. Rev. D18, 162 (1978);

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

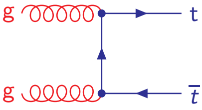
**$q\bar{q}$ Annihilation**



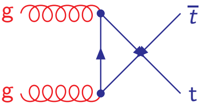

**Gluon Fusion**




**s-channel**




**t-channel**




**u-channel**

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

$$d\hat{\sigma}^{NLO}_{q\overline{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\overline{t}}) = d\hat{\sigma}^{LO}_{q\overline{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\overline{t}}) + \delta d\hat{\sigma}_{q\overline{q},gg}(\hat{t},\hat{s},\lambda_t,\lambda_{\overline{t}})$$
$$= \frac{d\Phi_{2\to2}}{8\pi^2\hat{s}}\Big[\overline{\sum}|\mathcal{M}_B^{q\overline{q},gg}|^2 + 2Re\overline{\sum}(\delta\mathcal{M}^{SUSYEW}_{q\overline{q},gg}\times\mathcal{M}_B^{q\overline{q},gg}) + 2Re\overline{\sum}(\delta\mathcal{M}^{SQCD}_{q\overline{q},gg}\times\mathcal{M}_B^{q\overline{q},gg})\Big]$$

where $\lambda_t(\lambda_{\overline{t}}) = \pm 1/2$ 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.

The phase space of the $2\to2$ scattering process, $d\Phi_{2\to2}$, as usual reads

$$\int d\Phi_{2\to2} = \int \frac{d^3\mathbf{p_1}}{2p_1^0}\frac{d^3\mathbf{p_2}}{2p_2^0}\delta^4(p_3+p_4-p_1-p_2) = \frac{\beta_t}{8}\int_0^{2\pi}d\phi^\star\int_{-1}^{1}d\cos\theta$$

W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998);

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

The observable hadronic differential cross sections are obtained by convoluting the partonic cross sections with PDFs

$$d\sigma_{LO,NLO}(S,\lambda_t,\lambda_{\bar{t}}) = \sum_{i,j=q\bar{q},gg} \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 \times \left[ f_i(x_1,\mu_F) f_j(x_2,\mu_F) d\hat{\sigma}_{ij}^{LO,NLO}(\alpha_s(\mu_R)\hat{s},\hat{t},\lambda_t,\lambda_{\bar{t}}) + i \leftrightarrow j \right]$$

with $S = \hat{s}/(x_1 x_2)$.

W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998);

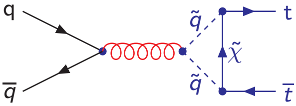
S. Berge, W. Hollik, W. M. Mosle and D. Wackeroth, Phys. Rev. D76, 034016 (2007).

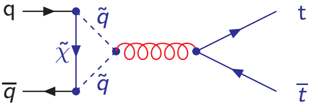
# Top Pair Production at NLO SUSY EW

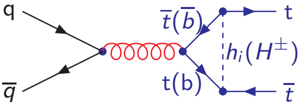
At one loop level the $gt\bar{t}$-vertex is modified due to the exchange of two charginos $\hat{\chi}^{\pm}_{i=1,2}$, four neutralinos $\hat{\chi}^{0}_{i=1,2,3,4}$ and five Higgs Bosons, $h_i$ and $H^{\pm}$. The SUSY EW one loop corrections to $q\overline{q}$ annihilation are

W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998).

D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



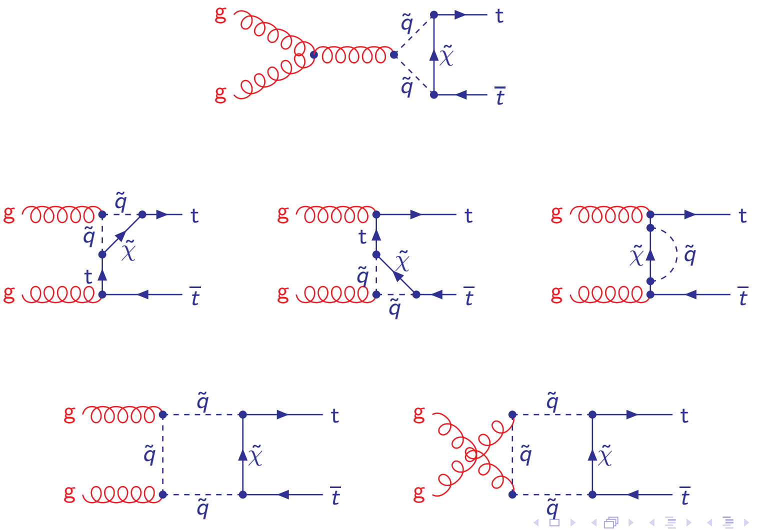



The SUSY EW one loop corrections to gluon fusion are

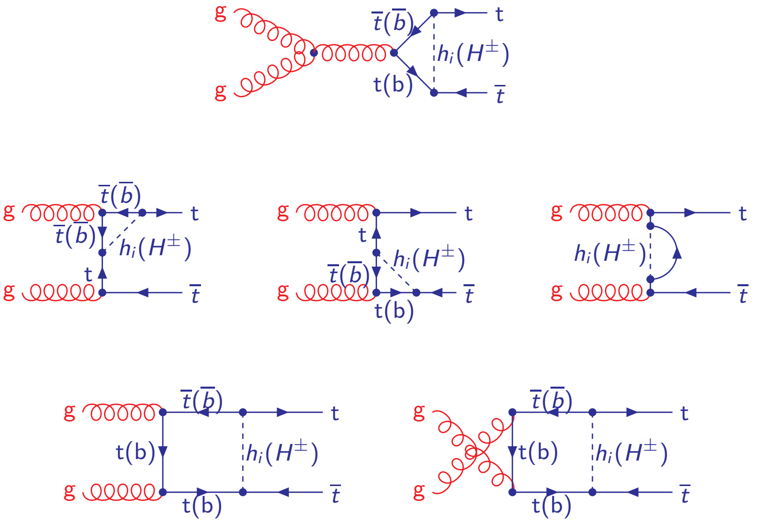
W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998).

D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



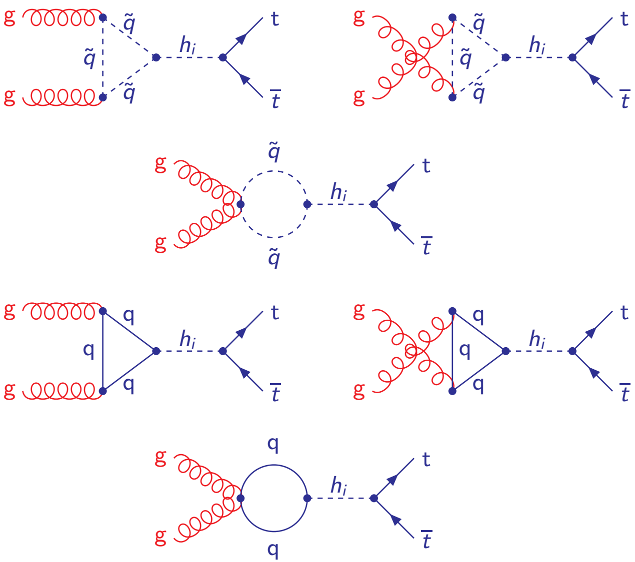
W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998).

D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



W. Hollik, W. M. Mosle and D. Wackeroth, Nucl. Phys B516, 29 (1998).

D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



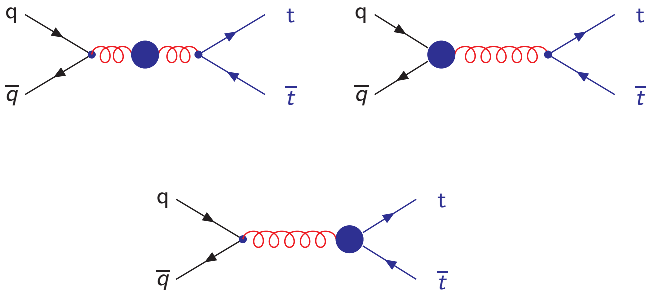
# Top Pair Production at NLO SQCD

The SQCD $\mathcal{O}(\alpha_s)$ corrections modify the tree level $gg\bar{t}$, $ggg$ and $gq\bar{q}$ vertices and the gluon propagator through the virtual presence of gluinos ($\tilde{g}$), squarks ($\tilde{q}_{L,R}$), stops ($\tilde{t}_{L,R}$) and sbottoms ($\tilde{b}_{L,R}$).

Generic self-energy and vertex corrections to $q\bar{q} \rightarrow t\bar{t}$ at NLO SQCD:

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

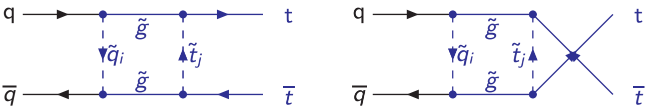
D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



## Direct box diagrams and cross box diagrams contributions to $q\overline{q} \rightarrow t\overline{t}$ at NLO SQCD

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

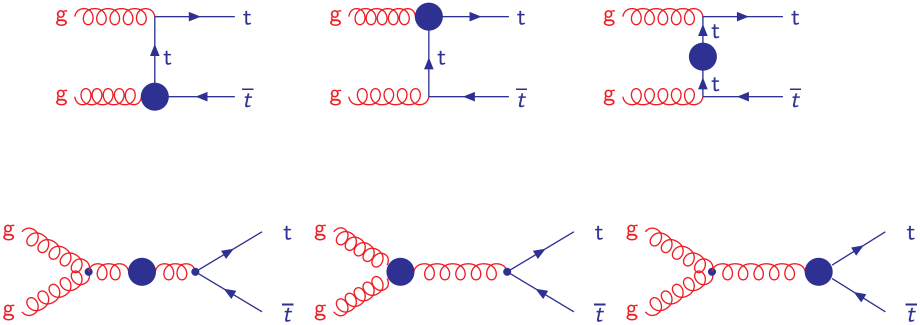
D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



Generic vertex and self-energy corrections to the t, u and s channel of the $gg \to t\bar{t}$ subprocess at NLO SQCD

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

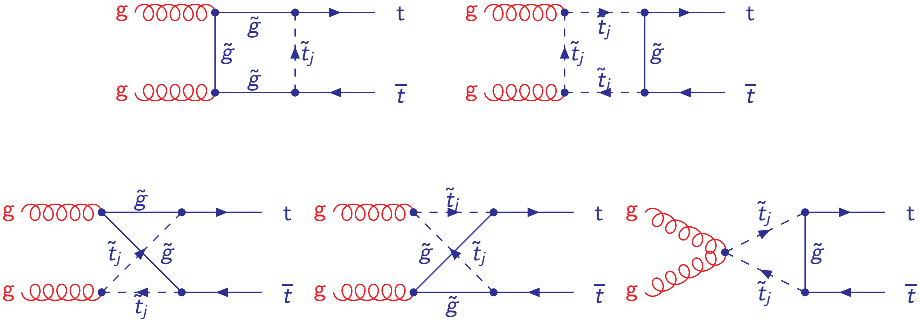
D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



# Box corrections to $gg \to t\bar{t}$ at NLO SQCD

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

D. A. Ross and M. Wiebusch, JHEP 0711, 041 (2007).



# Asymmetries in Top 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 are not expected to have a significant impact.

- **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. Wackeroth, Phys. Rev. D61, 055009 (2000).

- **CP Violating Asymmetry**:

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

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).

In the SM and CP conserving MSSM $A_{LR} = 0$. For $A_{LR} \neq 0$ 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 CP violating MSSM exhibit CP violating couplings due to

- complex top and bottom Yukawa couplings (radiative corrections),
- stop mixing matrix,
- complex neutralino and chargino mixing matrix elements.

# Numerical Results (Preliminary): 2HDM (with MSSM Couplings)

Input parameters and Higgs couplings have been calculated from CPsuperH2.2:

J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis and C. E. M. Wagner, Comput. Phys. Commun. 180, 312 (2009).

Real SUSY Parameters
0.5000E+01 : tan(beta)
0.1961E+00 : cos(beta)
0.9806E+00 : sin(beta)

Complex SUSY Parameters
0.2000E+04:Mag. of MU parameter in GeV
0.5000E+02:Mag. of M1 parameter in GeV
0.1000E+03:Mag. of M2 parameter in GeV
0.1000E+04:Mag. of M3 parameter in GeV
0.1000E+04:Mag. of AT parameter in GeV
0.1000E+04:Mag. of AB parameter in GeV
0.1000E+04:Mag. of ATAU parameter in GeV
0.0000E+00:Arg. of MU parameter in Degree
0.0000E+00:Arg. of M1 parameter in Degree
0.0000E+00:Arg. of M2 parameter in Degree
0.9000E+02:Arg. of M3 parameter in Degree
0.9000E+02:Arg. of AT parameter in Degree
0.9000E+02:Arg. of AB parameter in Degree
0.9000E+02:Arg. of ATAU parameter in Degree

Charged Higgs boson pole mass : 0.3000E+03 GeV

Masses of Higgs bosons :
H1 Pole Mass = 0.1197E+03 GeV
H2 Pole Mass = 0.2718E+03 GeV
H3 Pole Mass = 0.2982E+03 GeV

# Numerical Results (Preliminary): 2HDM (with MSSM Couplings)

- In this scenario (**CPX scenario**):

  SUSY EW corrections (only Higgs contribution): $\mathcal{A}_{LR} \approx 1 \cdot 10^{-5}$ (14 TeV)

# Numerical Results (Preliminary): SQCD

- **SPS1a with Complex Phases**

B. Allanach et al, Eur. Phys. J. C25, 113 (2002).

$$SPS1a: \; m_0 = 100 \; \text{GeV}, \; m_{1/2} = 250 \; \text{GeV}, \; A_0 = -100 \; \text{GeV}, \; \tan\beta = 10, \; \mu > 0$$

FeynHiggs

SUSY QCD corrections (SPS1a): $\mathcal{A}_{LR} \approx 7 \cdot 10^{-5}$ (14 Tev)

- **SPS5 with Complex Phases**

$$SPS5: \; m_0 = 150 \; \text{GeV}, \; m_{1/2} = 300 \; \text{GeV}, \; A_0 = -1000 \; \text{GeV}, \; \tan\beta = 5, \; \mu > 0, \; m_{\tilde{t}_1} = 203 \; \text{GeV}$$

FeynHiggs

SUSY QCD corrections (SPS5): $\mathcal{A}_{LR} \approx 6 \cdot 10^{-4}$ (14 TeV)

- **VLS with Complex Phases**

$$VLS: \; m_0 = 200 \; \text{GeV}, \; m_{1/2} = 200 \; \text{GeV}, \; A_0 = -750 \; \text{GeV}, \; \tan\beta = 22, \; \mu > 0, \; m_{\tilde{t}_1} = 135.3 \; \text{GeV}$$

FeynHiggs, SoftSusy

SUSY QCD corrections (VLS): $\mathcal{A}_{LR} \approx -1 \cdot 10^{-3}$ (14 TeV)

# Conclusions and Outlook

- We extended earlier work on SUSY EW and SUSY QCD corrections to top pair production to include CP violating interactions.
- The CP violating asymmetry may be a sensitive probe of loop-induced SUSY effects in top pair production in the CP violating MSSM.
- A first, preliminary study found small asymmetries induced by Higgs and SUSY EW corrections but interesting CP violating effects may arise due to SQCD corrections, i.e. asymmetries of $O(10^{-3})$.
- A detailed survey of the MSSM parameter space and a study of the impact of both SUSY EW and SUSY QCD corrections on $A_{LR}$ at the LHC is in progress.