MSSM corrections to top-quark pair observables at hadron colliders

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Content

1) The minimal supersymmetric extension of the SM

- Number of Standard Model particles is doubled

- Two Higgs doublets and superpartners required:

$$H_u = (H_u^+, H_u^0) \quad \text{and} \quad H_d = (H_d^0, H_d^-)$$

$$\tilde{H}_u = \left(\tilde{H}_u^+, \tilde{H}_u^0\right) \quad \text{and} \quad \tilde{H}_d = \left(\tilde{H}_d^0, \tilde{H}_d^-\right)$$

- The MSSM consists of the SM particles and its superpartners:

$[u, d, c, s, t, b]_{L,R}$	$[e, \mu, \tau]_{L,R}$	$[\nu_{e,\mu,\tau}]_L$	Spin $\frac{1}{2}$
$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R}$	$[\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R}$	$[\tilde{\nu}_{e,\mu,\tau}]_L$	Spin 0

g	$\underbrace{W^\pm H^\pm}$	$\underbrace{\gamma,\ Z^0,\ H_u^0,\ H_d^0}$	Spin1 / Spin 0
$\tilde{g}$	$\chi^\pm_{1,2}$	$\chi^0_{1,2,3,4}$	Spin $\frac{1}{2}$

- 2 Higgs doublets: $\longrightarrow$ 5 physical Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

1) The minimal supersymmetric extension of the SM

- Example, Squark/Gluino sector:

$$\mathcal{L}_m = -\left(\tilde{q}_L^\dagger, \tilde{q}_R^\dagger\right) M_{\tilde{q}}^2 \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$$

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_{\tilde{Q}}^2 + M_Z^2 \cos 2\beta \, (I_3^u - Q_u s_w^2) + m_u^2 & m_u(A_u^* - \mu \cot \beta) \\ m_u(A_u - \mu^* \cot \beta) & M_{\tilde{U}}^2 + M_Z^2 \cos 2\beta \, Q_u s_w^2 + m_u^2 \end{pmatrix}$$

$$m_{\tilde{g}} = |M_3|$$

- with $|M_3|$ soft Susy breaking parameter
- A_u, M_3, μ can in general be complex - possible source of CP violation
- Other sources in electroweak Susy sector

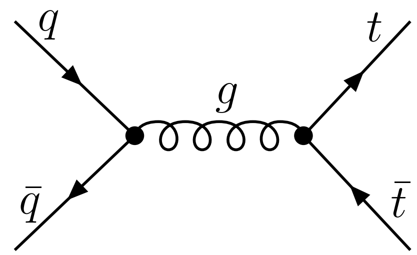
Supersymmetric Corrections to ttbar production at hadron colliders

- Corrections to total cross section and distributions
- Tevatron Forward-Backward Asymmetry
- Spin Correlations

(S.B., W. Hollik, W. Mosle, D.Wackeroth, Phys.Rev. D76 (2007) 034016,
C. Kao and D.Wackeroth, Phys. Rev. D61, 055009 (2000),
S.B., D.Wackeroth, M.Wiebusch, arXiv:1202.4762 [hep-ph],
S.B., D.Wackeroth, M.Wiebusch, Alexander Moreno Briceno, Muehlleitner, A. Schanz, in preparation)

2) MSSM corrections to ttbar production

$q\bar{q}$-annihilation:



NLO supersymmetric EW corrections:

Hollik, Mösle, Wackeroth (1998) (unpolarized)

Kao, Wackeroth (1999) (polarized top quarks)

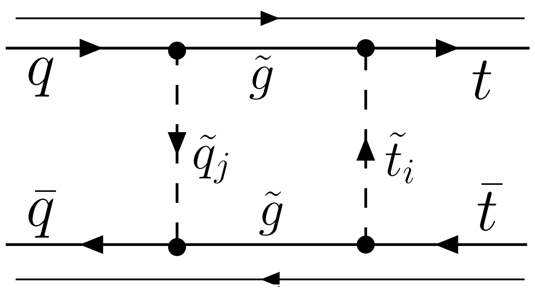
NLO supersymmetric QCD corrections (unpolarized):

C. Li et al. (1995), S. Alam et al. (1996), Z. Sullivan (1996),

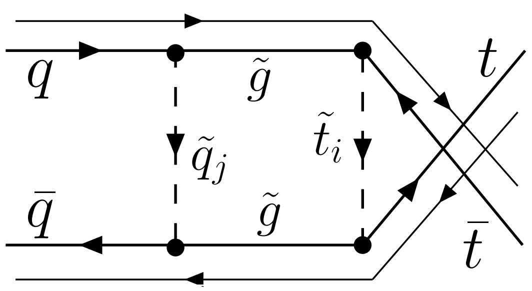
D. Wackeroth (1998), S. B. et al. (2007)

Denner, Eck, Hahn, Küblbeck (1992)
"Feynman rules for fermion-number-violating interactions"

Direct Box:



Crossed Box:



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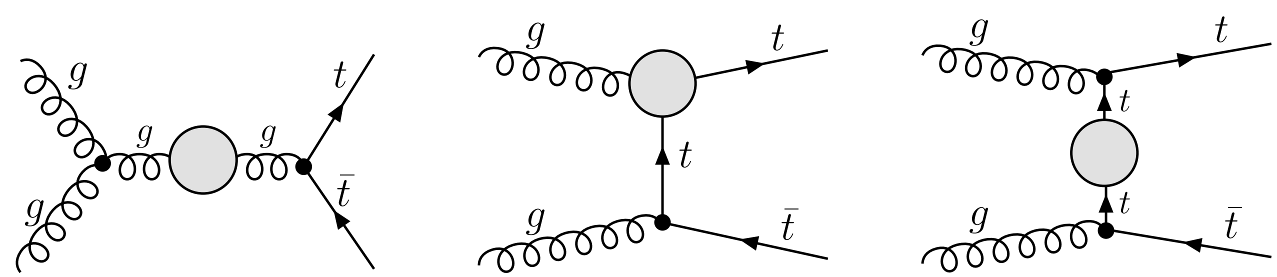
2) MSSM corrections to ttbar production

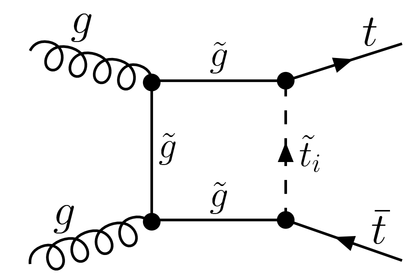
gg-fusion:



NLO supersymmetric EW corrections:

Hollik, Mösle, Wackeroth (1998) (unpolarized)

Kao, Wackeroth (1999) (polarized top quarks)



NLO supersymmetric QCD corrections:

Zhou, Li (1997) (unpolarized)

Zeng-Hui, Pietschmann, Wen-Gan, Liang, Yi (1999) (polarized gluons)

We examine the SQCD and SEW NLO corrections for the combined $q\bar{q}$ and gg channels at Tevatron and LHC for unpolarized and polarized top quark pairs in the complex MSSM.

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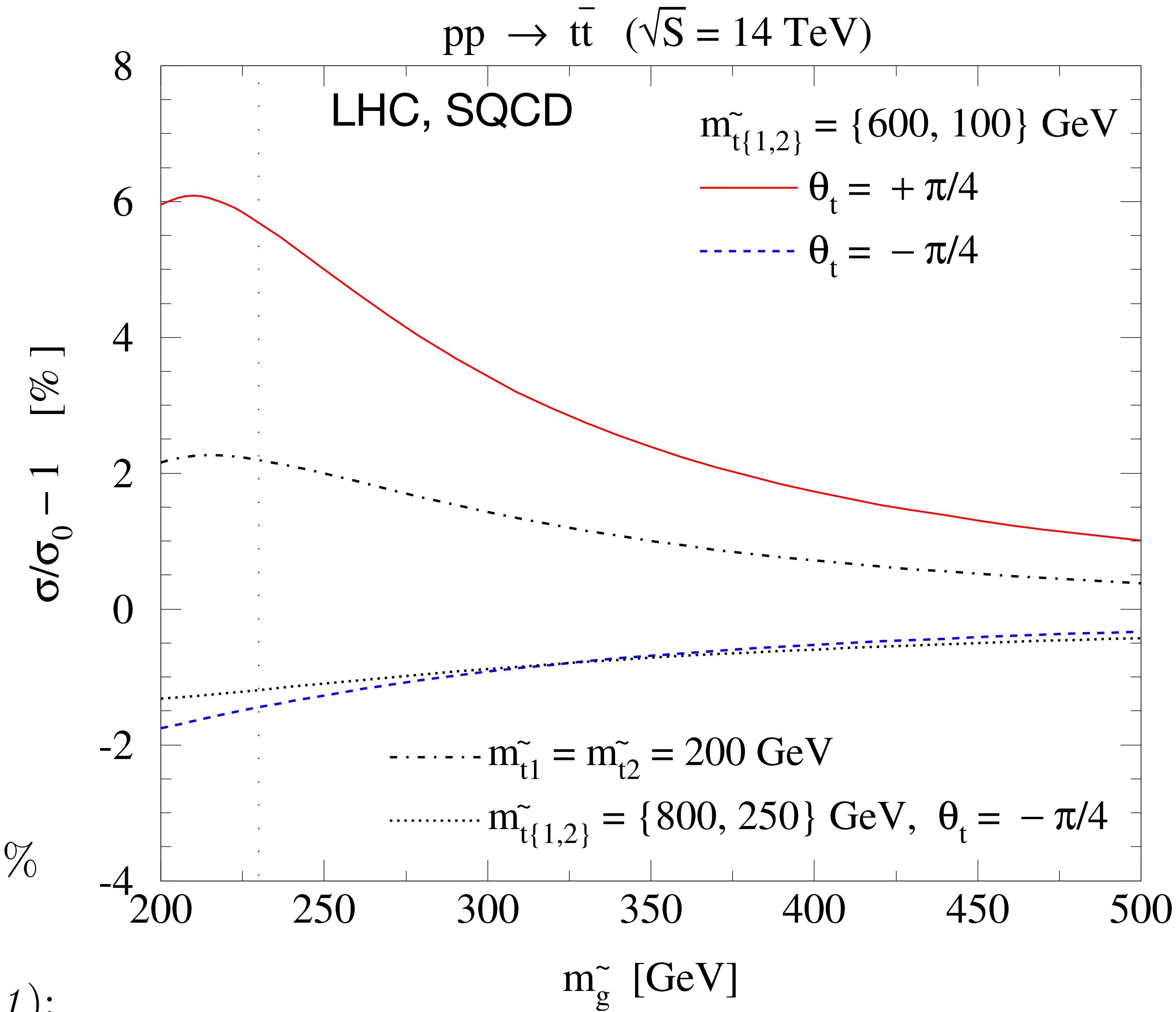
2) MSSM corrections: Total cross section

Total cross section:

- Large $\theta_{\tilde{t}}$ dependence for large $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$ splitting
- Large positive for $\theta_{\tilde{t}} = \pi/2$ negative for $\theta_{\tilde{t}} = -\pi/2$
- To obtain large corrections to $\sigma(S)$, need large corrections at $\sqrt{\hat{s}} = 350 - 550$ GeV
- NLO MSSM EW corrections: -4% to $+1\%$
- QCD cross section ($m_t = 173.1$ GeV, *Ahrens et al. Phys.Lett. B703 (2011) 135-141*):
  Tevatron: $\sigma(S = 1960 \text{ GeV}) = 6.91$ pb
  LHC: $\sigma(S = 14 \text{ TeV}) = 842$ pb



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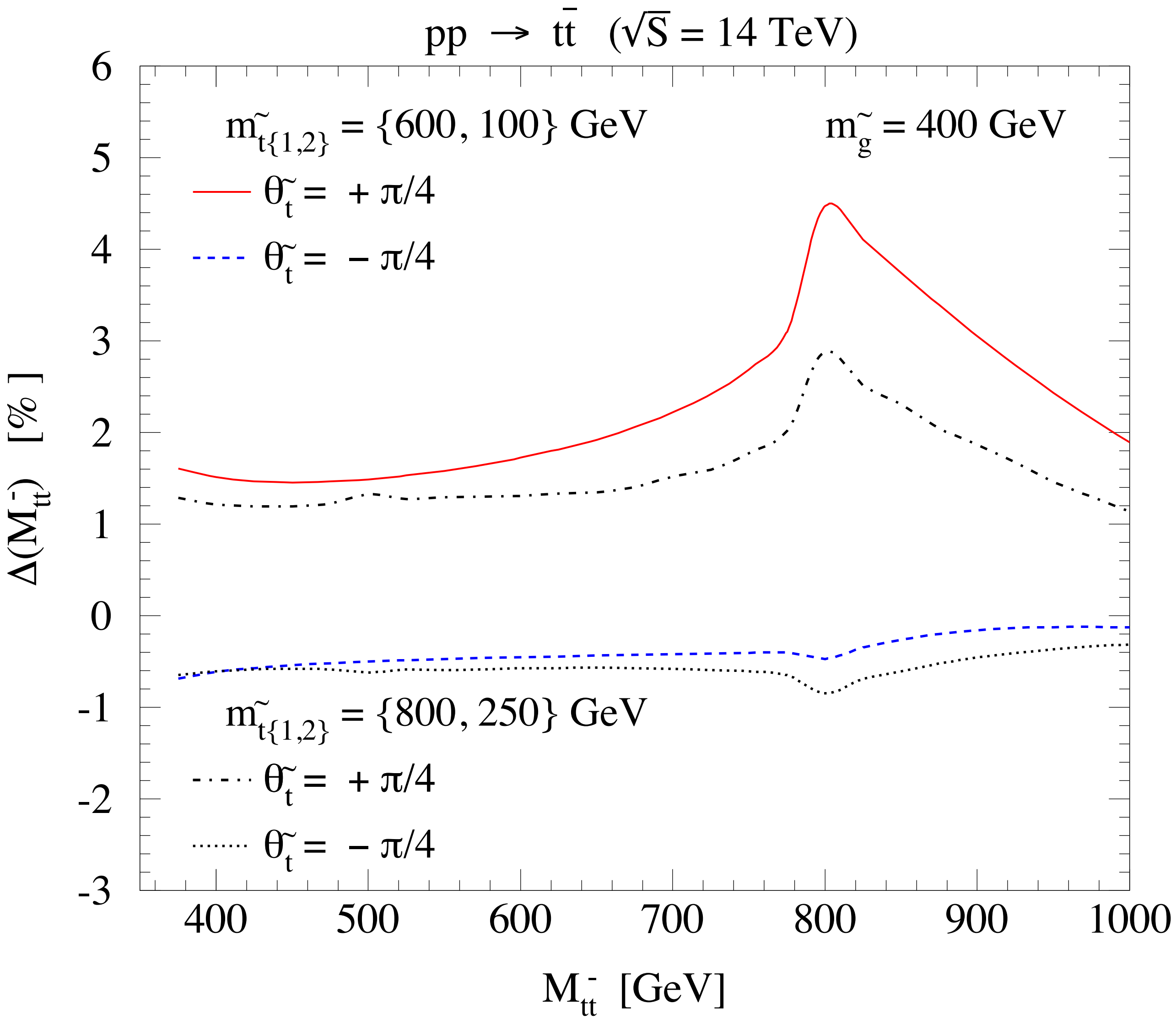
2) MSSM corrections: Mtt distribution

- Threshold at $\sqrt{\hat{s}} = 2 \cdot m_{\tilde{g}}$
- Large $\theta_{\tilde{t}}$ dependence for large $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$ splitting
- Large positive for $\theta_{\tilde{t}} = \pi/2$ negative for $\theta_{\tilde{t}} = -\pi/2$
- $\Delta(M_{t\bar{t}}) = \frac{d\sigma_{NLO}/dM_{t\bar{t}} - d\sigma_{LO}/dM_{t\bar{t}}}{d\sigma_{LO}/dM_{t\bar{t}}}$
- To obtain large corrections to $\sigma(S)$, need large corrections at $\sqrt{\hat{s}} = 350 - 550$ GeV

LHC

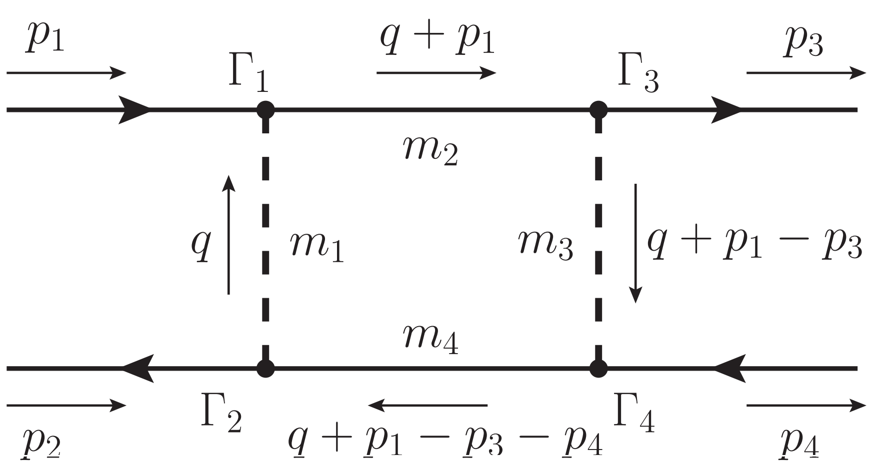


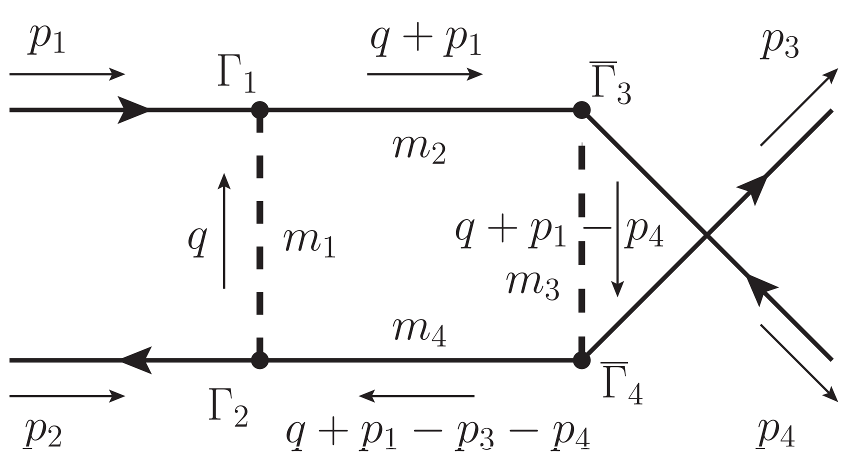
Supersymmetric Corrections to ttbar production at hadron colliders

- Corrections to total cross section and distributions
- Tevatron Forward-Backward Asymmetry
- Spin Correlations

3) Forward-Backward Asymmetry at Tevatron

- Asymmetry in gg-channel is zero
- Only box diagrams contribute
- SQCD: Direct and crossed diagrams with gluinos and squarks in the loop
- SEW: Direct and crossed diagrams with neutralinos, gluinos and squarks in the loop
- Motivation: provide upper and lower limits for possible contributions to fwba asymmetry
- For the stated limits, we don't include limits from other measurements
- We can provide a fast computer code for the calculation

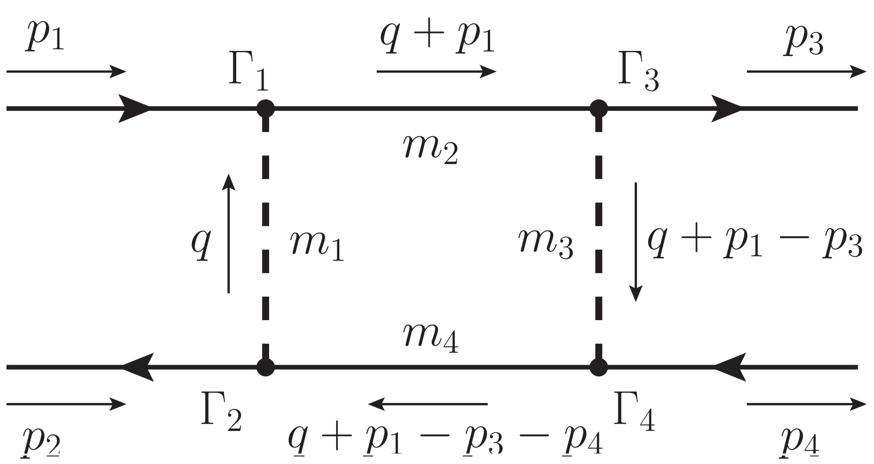




3) Forward-Backward Asymmetry at Tevatron

Write the couplings as

$$\Gamma_n = g_n^+ P^+ + g_n^- P^- \,, \qquad P^\pm = \frac{1 \pm \gamma_5}{2}$$



The 1-loop squared matrix element can be written as

$$\sum_{\text{spins}} 2Re\left\{\mathcal{M}^{(a)}\mathcal{M}^{(0)*}\right\} = N_a \sum_{\lambda=\pm} 2\,Re\Big[\; g_1^{+\lambda} g_2^{-\lambda} g_3^{+\lambda} g_4^{+\lambda} D^{+-++}(\hat{s}, \cos\theta)$$
$$+ g_1^{-\lambda} g_2^{+\lambda} g_3^{+\lambda} g_4^{+\lambda} D^{-+++}(\hat{s}, \cos\theta)$$
$$+ g_1^{-\lambda} g_2^{+\lambda} g_3^{+\lambda} g_4^{-\lambda} D^{-++-}(\hat{s}, \cos\theta)$$
$$+ g_1^{-\lambda} g_2^{+\lambda} g_3^{-\lambda} g_4^{+\lambda} D^{-+-+}(\hat{s}, \cos\theta)\Big]$$

3) Forward-Backward Asymmetry at Tevatron

To calculate the forward-backward asymmetry, we only need the difference of the interferences evaluated at $+\cos\theta$ and $-\cos\theta$.

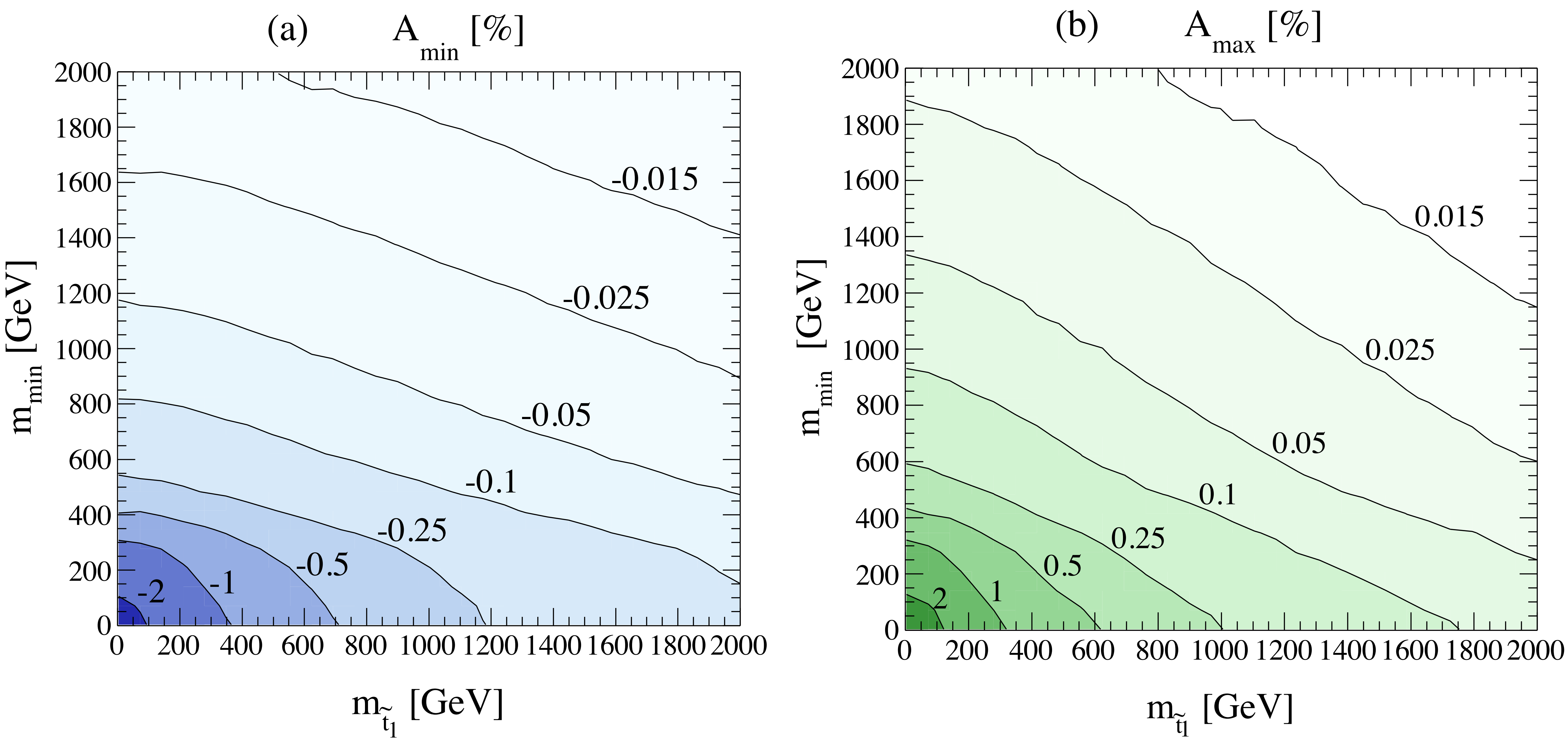
$$\begin{aligned} \hat{A}(s,\cos\theta) &= d\hat{\sigma}(\hat{s},\cos\theta) - d\hat{\sigma}(\hat{s},-\cos\theta) \\ &= Re\Big\{ \, G^{+-++}\hat{A}^{+-++} + G^{-+++}\hat{A}^{-+++} \\ &\quad + G^{-++-}\hat{A}^{-++-} + G^{-+-+}\hat{A}^{-+-+}\Big\} \end{aligned}$$

with

$$\hat{A}^{a}(\hat{s},\cos\theta) = \frac{\beta}{32\pi\hat{s}} \cdot \frac{1}{4} \cdot [2\,D^{a}(\hat{s},\cos\theta) - 2\,D^{a}(\hat{s},-\cos\theta)]$$

and some coupling combinations G^{a}, $a \in \{+-++,-+++,-++-,-+-+\}$

3) Forward-Backward Asymmetry at Tevatron



- First generate 4 Grids for A^a
- Scan over relevant MFV-MSSM parameter space

- $M_{t\bar{t}} \geq 450$ GeV
- $m_{min} = \mathrm{Min}\{\mathrm{m}_{\tilde{g}}, \mathrm{m}_{\tilde{\chi}_{1,2,3,4}}, \mathrm{m}_{\tilde{u}_{1,2}}, \mathrm{m}_{\tilde{d}_{1,2}}\}$
- dominated by $u\bar{u}$ channel

Supersymmetric Corrections to ttbar production at hadron colliders

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(S.B., D.Wackeroth, M.Wiebusch, A. Moreno Briceno, Muehlleitner, A. Schanz)

4) MSSM corrections: Parity violating asymmetries

Polarized Top quarks:

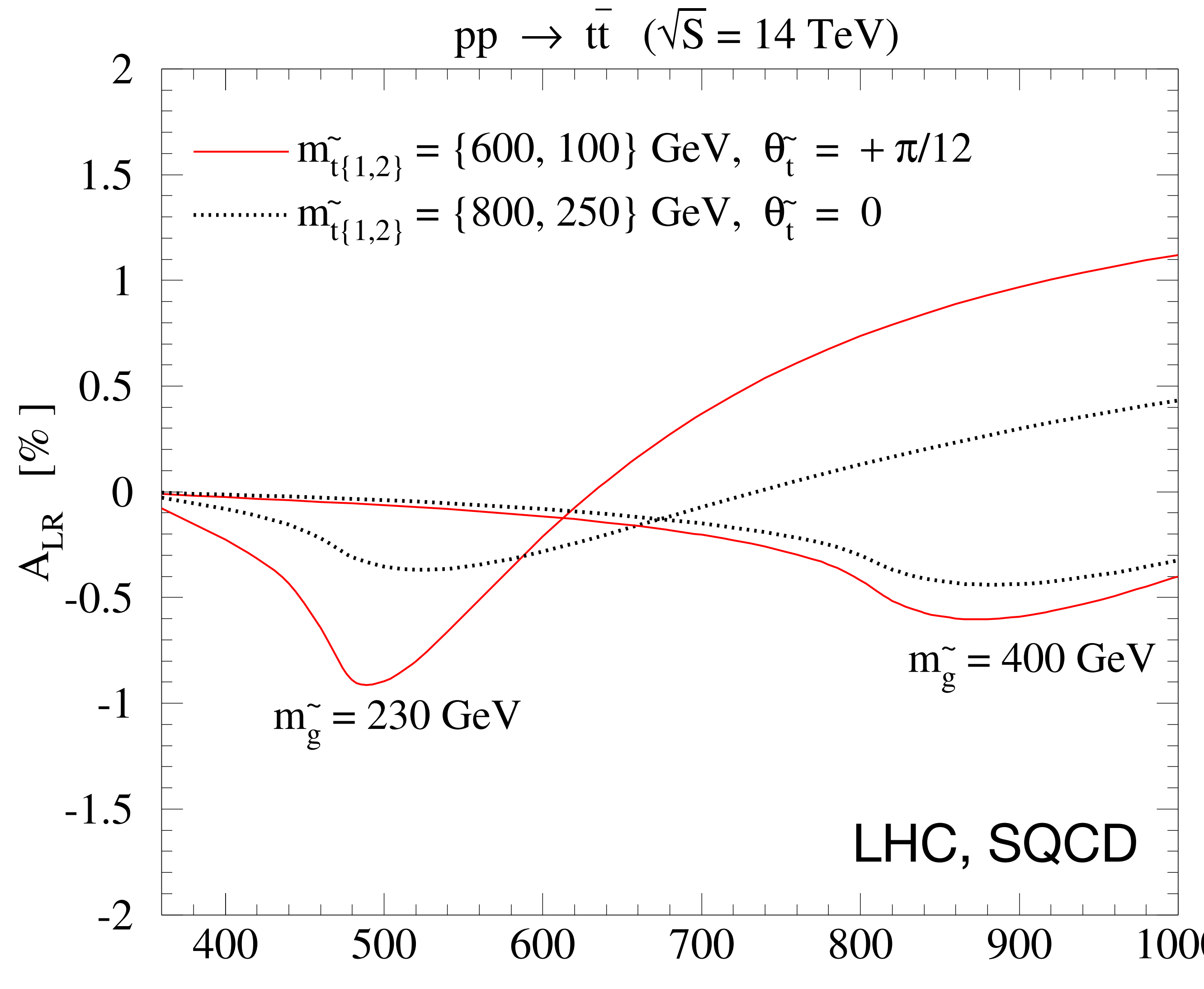
- $q\bar{q} \longrightarrow t(\lambda_1)\bar{t}(\lambda_2)$
- $gg \longrightarrow t(\lambda_1)\bar{t}(\lambda_2)$

- Using helicity basis with $\lambda = \{L, R\}$

$$\mathcal{A}_{LR}(M_{t\bar{t}}) = \frac{d\sigma_{RL}/dM_{t\bar{t}} - d\sigma_{LR}/dM_{t\bar{t}}}{d\sigma_{RL}/dM_{t\bar{t}} + d\sigma_{LR}/dM_{t\bar{t}}}$$

$A_{LR} = 0$:

- Tree level, because QCD preserves parity



Preliminary

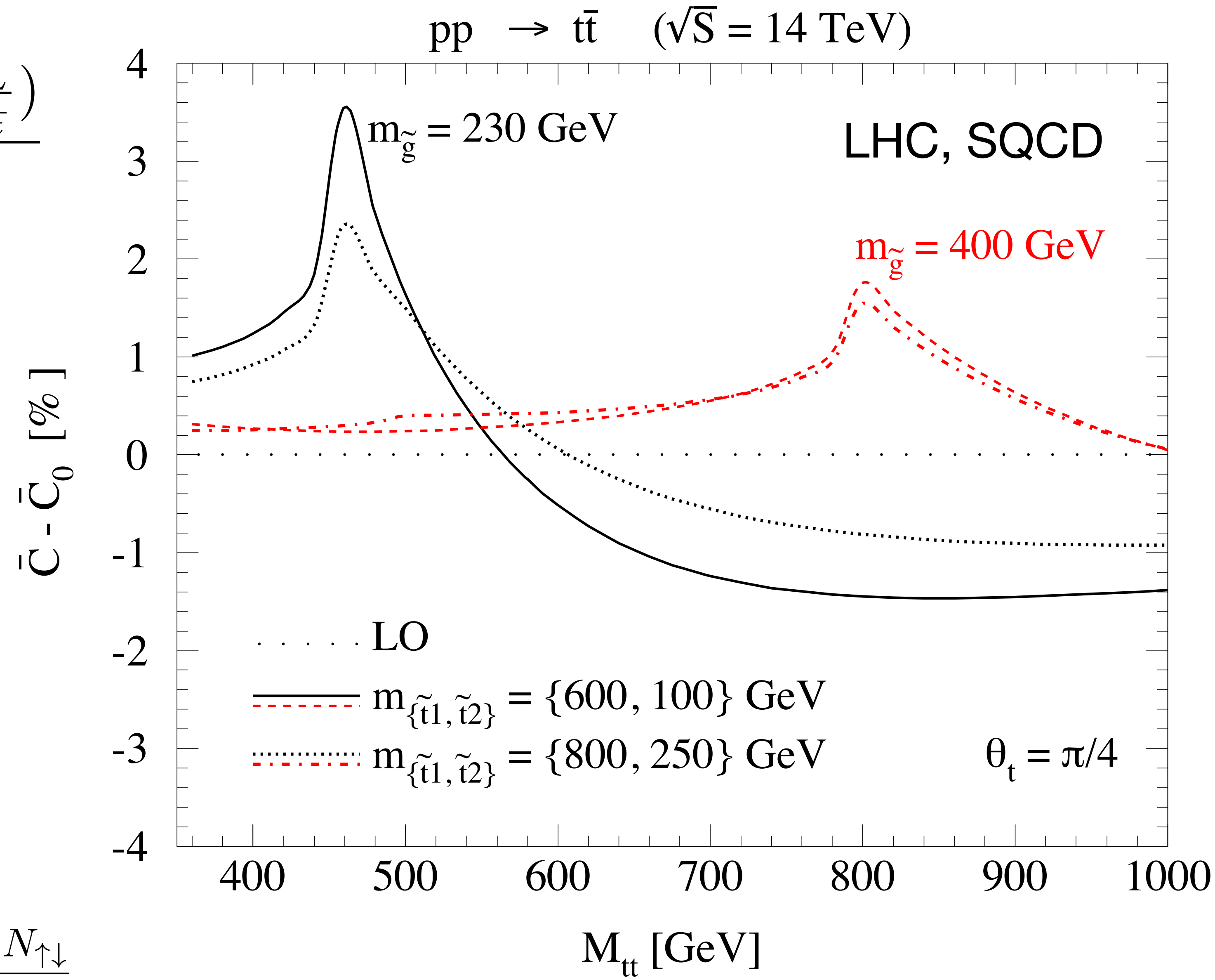
- LHC: Box correction dominant

  $A_{LR} \geq 0.1\%$ expected to be observable (hep-ph/9902202)

4) MSSM corrections: Correlation function

$$\overline{C} = \frac{\left(\frac{d\sigma_{RR}}{dM_{t\bar{t}}} + \frac{d\sigma_{LL}}{dM_{t\bar{t}}}\right) - \left(\frac{d\sigma_{LR}}{dM_{t\bar{t}}} + \frac{d\sigma_{RL}}{dM_{t\bar{t}}}\right)}{d\sigma_{NLO}/dM_{t\bar{t}}}$$

- $\overline{C}_0 \ldots$ SM value



Tevatron:

$$\text{Correlation function}: \quad \kappa = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

$$\kappa^{SM}_{beam} = 0.78^{+0.03}_{-0.04}$$ *(Nucl. Phys. B 690, 81 (2004))*

$$D0 : \kappa^{Combo(Dil,Lep+Jet)}_{beam} = 0.66 \pm 0.23$$ *(PRL 108, 032004 (2012))*

4) MSSM corrections: CP violating asymmetries

Using the top production density matrix one can define spin correlation observables on the level of the top quark pair production. The expectation value of an observable is defined as *(Bernreuther, Brandenburg Phys.Rev.D49 (1994), 4481)*

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

$$\langle \mathscr{O} \rangle = \frac{\int_{-1}^{1} dz\, Tr(R\,\mathscr{O})}{4\int_{-1}^{1} dz A}$$

with z the cosine of the top quark and an incomming parton.

E.g.:

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

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

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

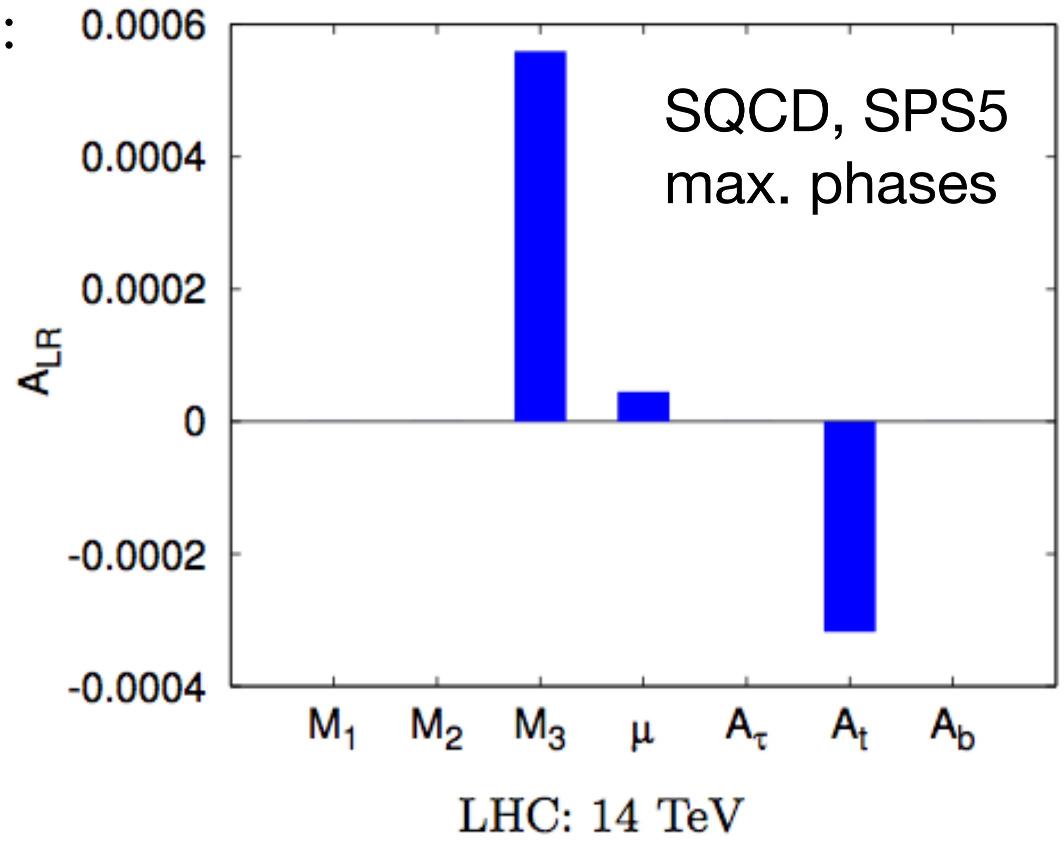
4) MSSM corrections: CP violating asymmetries

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

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

- O1 needs complex couplings and absorptive part (complex part of loop integral)
- O2 needs only complex couplings

$< \mathcal{O}_1 >$:



φ_i	$\mathcal{A}_{LR}$	σ_{tot} [pb]
M_1	-	684.69 ± 1.58
M_2	-	684.69 ± 1.58
M_3	$(5.59 \pm 0.03) \cdot 10^{-4}$	685.06 ± 1.44
μ	$(4.48 \pm 0.03) \cdot 10^{-5}$	685.72 ± 1.77
A_τ	-	684.69 ± 1.58
A_t	$-(3.18 \pm 0.02) \cdot 10^{-4}$	685.82 ± 1.54
A_b	$(4.71 \pm 0.34) \cdot 10^{-14}$	684.69 ± 1.59

(A. Schanz, 2011)

5) Concluding remarks

- MSSM corrections to ttbar cross sections and distributions do not exceed current measurement uncertainties
  - MSSM effects could e.g. be seen at LHC in Mtt distribution for high statistics
- Upper and lower limits of the MSSM contribution to forward-backward asymmetry at the Tevatron are roughly:
  - Susy-QCD contributions: smaller than 1 %
  - Susy-EW contributions: smaller than 0.3 %
- It is possible to measure parity violating and CP-violating effects at the LHC with the large luminosity run if the Susy scale is not to heavy