PITHA 01/11 Nov. 2001
DESY 01-199
TTP01-31

Top Quark Pair Production and Decay including Spin Effects at Hadron Colliders: Predictions at NLO QCD

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Abstract:
Top quark-antiquark ($t\bar{t}$) pairs will be produced copiously at the Tevatron collider and in huge numbers at the LHC. This will make possible detailed investigations of the properties and interactions of this quark flavor. The analysis and interpretation of future data requires precise predictions of the hadronic production of $t\bar{t}$ pairs and of their subsequent decays. In this talk the reactions $p\bar{p}, pp \to t\bar{t} + X \to \ell^+\ell'^- + X$ are considered and results are presented of our calculation[6] of the dilepton angular distribution at next-to-leading order QCD, keeping the full dependence on the spins of the intermediate $t\bar{t}$ state. The angular distribution is determined for different choices of reference axes that can be identified with the t and $\bar{t}$ spin axes. While the QCD corrections to the leading-order distribution turn out to be small in the case of the LHC, we find them to be sizeable in the case of the Tevatron and find, moreover, the angular distribution to be sensitive to the parton content of the proton.

PACS number(s): 12.38.Bx, 13.88.+e, 14.65.Ha
Keywords: hadron collider physics, top quarks, spin correlations, QCD corrections

[1] Speaker at the conference

So far the top quark, which was discovered six years ago[1] is still a relatively unexplored particle, as compared with other quark flavors. This will change once the upgraded Tevatron collider and, in several years, the LHC will be in full operation. It is expected that about 10^4 top quark-antiquark ($t\bar{t}$) pairs per year will be produced at the Tevatron and more than 10^7 $t\bar{t}$ pairs per year at the LHC. These large data sample will make feasible precise investigations of the properties and interactions of top quarks.

An important aspect of top quark physics will then come into play, namely, spin physics with top quarks. It is well-known by now that the t quark is unique among the quark flavors in that it allows to study effects associated with its spin in a direct and unambiguous way. This is due to its extremely short lifetime that prevents the top quark from forming hadronic bound states. It behaves like a highly instable "bare" quark. Therefore phenomena associated with the spins of the top quark and antiquark are reflected directly in the distributions and in the corresponding angular correlations of the jets, W bosons, or leptons into which the t and $\bar{t}$ decay. These distributions and correlations reflect the t and $\bar{t}$ polarizations and spin correlations which in turn characterize the t and $\bar{t}$ production and decay mechanism(s).

On the theoretical side the spin correlations of hadronically produced $t\bar{t}$ pairs were studied some time ago[2, 3] to leading order in the coupling α_s of Quantum Chromodynamics (QCD). There exists also an extensive literature, for example refs.[4] and references therein, on how to exploit top-quark spin phenomena at hadron colliders in the search for new interactions. For instance the spin and parity of a new heavy resonance that strongly couples to $t\bar{t}$ in the s channel could be pinned down with spin correlations. With appropriate observables that reflect the t and/or $\bar{t}$ spins one can, for instance, check whether or not the $V-A$ law is valid also for top decay, $t \to Wb$, or search for non-standard CP violation in $t\bar{t}$ production and/or decay. A prerequisite of this kind of experimental analysis is that these spin effects must be known as precisely as possible within the standard model (SM) of particle physics. Therefore we have determined the production of $t\bar{t}$ pairs by $q\bar{q}$ annihilation, gluon-gluon fusion and gluon-$q(\bar{q})$ scattering at next-to-leading order (NLO) in the QCD coupling for arbitrary t and $\bar{t}$ spins[5]. Moreover, we have analyzed the hadronic production of $t\bar{t}$ pairs and their subsequent decays to order α_s^3, keeping the full information on the spins of the intermediate $t\bar{t}$ state. Within the SM, where the main top-quark decay modes are $t \to bW \to bq\bar{q}', b\ell\nu_\ell$, the most powerful analyzers of the polarization of the top quark are the charged leptons, or the jets that originate from quarks of weak isospin $-1/2$ produced by the decay of the W boson. Here we restrict ourselves to the channels where both t and $\bar{t}$ decay semileptonically,

$$p\bar{p}, pp \to \bar{t}t + X \to \ell^+\ell'^- + X, \tag{1}$$

($\ell = e, \mu, \tau$), and we present our predictions of the dileptonic angular distribution[6] that encodes the $t\bar{t}$ spin correlations.

At the parton level the NLO analysis involves the following subprocesses:

$$gg, q\bar{q} \quad \xrightarrow{t\bar{t}} \quad b\bar{b}\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}, \tag{2}$$

$$gg, q\bar{q} \quad \xrightarrow{t\bar{t}} \quad b\bar{b}\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'} + g, \tag{3}$$

$$g+q(\bar{q}) \quad \xrightarrow{t\bar{t}} \quad b\bar{b}\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}+q(\bar{q}). \tag{4}$$

At the Tevatron $t\bar{t}$ production is dominated by quark-antiquark annihilation while at the LHC it is mainly due to gluon-gluon fusion.

Because the total width Γ_t of the top quark is much smaller than its mass m_t ($\Gamma_t/m_t = O(1\%)$), we can expand the amplitudes of the parton reactions (2) - (4) around the poles of the unstable t and $\bar{t}$ quarks and keep only the leading term of this expansion, i.e., the residue of the double poles. The radiative corrections to the respective lowest-order amplitudes can be classified into so-called factorizable and non-factorizable corrections. We take into account the factorizable corrections to the above reactions for which the squared matrix element $\mathcal{M}^{(\lambda)}$ is of the form $|\mathcal{M}^{(\lambda)}|^2 \propto \mathrm{Tr}[\rho^{(f)}R^{(a,i)}\bar{\rho}^{(\bar{f}')}]$. Here $\lambda = 1,...,6$ labels the 6 amplitudes of (2) - (4), and $R^{(a,i)}$ denotes the respective spin density matrix for the production of on-shell $t\bar{t}$ pairs. The superscript a labels the initial state and i lables the intermediate state, i.e., $i = t\bar{t}, t\bar{t}g, t\bar{t}q, t\bar{t}\bar{q}$ state. The decay density matrix $\rho^{(f)}(\bar{\rho}^{(\bar{f}')})$ describes the normalized angular distribution of the decay of a polarized $t(\bar{t})$ quark into $\ell^+(\ell^-) + \textit{anything}$ in the rest frame of the $t(\bar{t})$ quark. Note that for the reactions (3) the squared matrix elements $|\mathcal{M}^{(\lambda)}|^2$ have, for each λ, three different contributions of the form $\mathrm{Tr}[\rho^{(f)}R^{(a,i)}\bar{\rho}^{(\bar{f}')}]$ because the final-state gluon is either associated with the $t\bar{t}$ production, the t, or $\bar{t}$ decay amplitude.

Let us first discuss the production density matrices $R^{(a,i)}$ and the QCD-induced spin correlation effects at the level of the $t\bar{t}$ states. The spin density matrix $R^{(a,i)}$ is defined in terms of the respective transition matrix element $\mathcal{T}(a \to i)$. For instance, for $gg \to t\bar{t}$ we have

$$R^{(gg,t\bar{t})}_{\alpha\alpha',\beta\beta'} = \frac{1}{N_{gg}} \sum_{\substack{\text{colors} \\ \text{initial spins}}} \langle t_\alpha \bar{t}_\beta | \mathcal{T} | gg \rangle \, \langle gg | \mathcal{T}^\dagger | t_{\alpha'} \bar{t}_{\beta'} \rangle \, , \tag{5}$$

where the factor N_{gg} averages over the spins and colours of the initial pair of partons. The matrix structure of the $R^{(a,i)}$ is (for ease of notation we drop the superscripts)

$$\begin{aligned} R_{\alpha\alpha',\beta\beta'} &= A\delta_{\alpha\alpha'}\delta_{\beta\beta'} + B_i(\sigma^i)_{\alpha\alpha'}\delta_{\beta\beta'} + \bar{B}_i\delta_{\alpha\alpha'}(\sigma^i)_{\beta\beta'} \\ &\quad + C_{kl}(\sigma^k)_{\alpha\alpha'}(\sigma^l)_{\beta\beta'} \, , \end{aligned} \tag{6}$$

The function $A = \mathrm{Tr}(R)/4$ determines the differential cross section with $t\bar{t}$ spins summed over. Because of parity invariance the vectors $\mathbf{B}, \bar{\mathbf{B}}$ can have, within QCD, only a component normal to the scattering plane. This component, which amounts to a normal polarization of the t and $\bar{t}$ quarks, is induced by the absorptive part of the scattering amplitude which, for the $i = t\bar{t}$ intermediate state, is non-zero to order α_s^3. The normal polarization is quite small, both for $t\bar{t}$ production at the Tevatron and at the LHC [8]. The functions C_{kl} encode the correlation between the t and $\bar{t}$ spins.

In the computation of the $R^{(a,i)}$ to order α_s^3 we used dimensional regularization to treat both the ultraviolet and the infrared/collinear singularities. Renormalization was performed using the $\overline{\mathrm{MS}}$ prescription for the QCD coupling α_s and the on-shell definition of the top mass m_t. For $a = q\bar{q}, gg$ the soft and collinear singularities in $R^{(a,t\bar{t})}$, which appear as single and double poles in $\varepsilon = (4-D)/2$, are cancelled after including the contributions from $R^{(a,t\bar{t}g)}$ in the soft and collinear limits and after mass factorization. For the latter we used the $\overline{\text{MS}}$ factorization scheme. The order α_s^3 production density matrices of (4) contain initial state collinear singularities which are also removed by mass factorization. The soft and collinear singularities were extracted by employing a simplified version of the phase-space slicing technique.

From these density matrices one can obtain, in particular, the total parton cross sections $\hat{\sigma}_a(\hat{s})$ for the reactions gg,$q\bar{q}$, $q/(\bar{q})g \to t\bar{t}+X$ at NLO. We have computed these cross sections[5] and found excellent agreement with previous results[10, 11].

In order to study the $t\bar{t}$ spin correlations at the parton level we consider the following class of observables

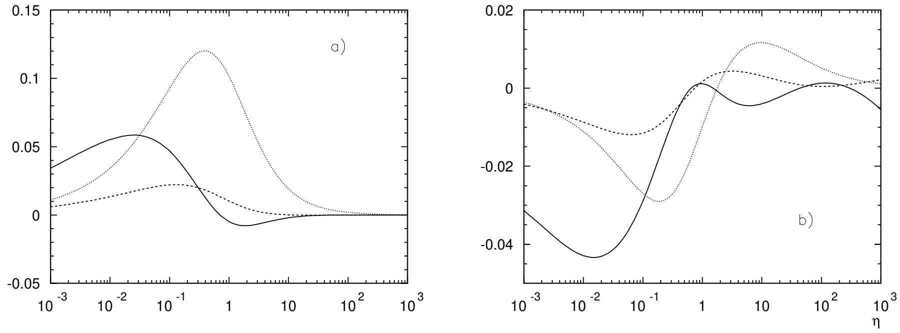
$$O = 4\,(\hat{\mathbf{a}}\cdot\mathbf{s}_t)(\hat{\mathbf{b}}\cdot\mathbf{s}_{\bar{t}}) \tag{7}$$

where $\mathbf{s}_t, \mathbf{s}_{\bar{t}}$ denote the t and $\bar{t}$ spin operators, and $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$ are reference directions that serve as spin axes. We choose the following vectors:

$$\begin{aligned}
\hat{\mathbf{a}} = \hat{\mathbf{k}}_t, \hat{\mathbf{b}} = \hat{\mathbf{k}}_{\bar{t}}, &\qquad \text{(helicity basis)},\\
\hat{\mathbf{a}} = \hat{\mathbf{p}},\ \hat{\mathbf{b}} = \hat{\mathbf{p}} &\qquad \text{(beam basis)},\\
\hat{\mathbf{a}} = \hat{\mathbf{d}}_t, \hat{\mathbf{b}} = \hat{\mathbf{d}}_{\bar{t}}, &\qquad \text{(off-diagonal basis)}.
\end{aligned} \tag{8}$$

Here $\hat{\mathbf{k}}_t(\hat{\mathbf{k}}_{\bar{t}})$ denotes the direction of flight of the $t(\bar{t})$ quark in the parton center-of-mass frame, and $\hat{\mathbf{p}}$ is the unit vector along one of the hadronic beams in the laboratory frame. Furthermore $\hat{\mathbf{d}}_t$ is the axis with respect to which the spins of t and $\bar{t}$ produced by $q\bar{q}$ annihilation are 100 % correlated[3, 12] to leading order in α_s. (For $gg \to t\bar{t}$ one can show that no spin basis with this property exists.)

Figure 1: The unnormalized expectation value of the spin correlation observable (7) in the beam basis. The plots show $g_a^{(0)}(\eta)$(dotted line), $g_a^{(1)}(\eta)$(full line) and $\tilde{g}_a^{(1)}(\eta)$(dashed line) as a function of η for the $q\bar{q}$ (a), and gg (b) initial state.



The expectation values of the above observables O signify the degree of correlations among the $t\bar{t}$ spins when using the above spin quantization axes. If one identifies the $\overline{\text{MS}}$

renormalization scale μ_R with the mass factorization scale μ_F, $\mu_R = \mu_F = \mu$, and neglects all quark masses except for m_t, then one can express the unnormalized expectation value of a spin-correlation observable O in terms of dimensionless scaling functions as follows:

$$\hat{\sigma}_a \langle O \rangle_a = \frac{\alpha_s^2}{m_t^2} [g_a^{(0)}(\eta) + 4\pi\alpha_s (g_a^{(1)}(\eta) + \tilde{g}_a^{(1)}(\eta) \ln(\mu^2/m_t^2))] \,, \tag{9}$$

where $a = gg, q\bar{q}, q/(\bar{q})g$, $\hat{s}$ is the parton center-of-mass energy squared, and $\eta = \frac{\hat{s}}{4m_t^2} - 1$. As an example the functions $g_a^{(0)}(\eta)$, $g_a^{(1)}(\eta)$ and $\tilde{g}_a^{(1)}(\eta)$ are shown in Fig.1 for ($a = q\bar{q}, gg$) and the observable in the beam basis. The contributions of the $q/(\bar{q})g$ initial states to the spin correlations at the hadron level are very small. The results for the other spin observables are given in ref.[5].

The QCD corrections to the unnormalized spin correlations are large close to threshold. This behaviour is due to the factor $\hat{\sigma}_a$ which, in this order of perturbation theory, is non-zero at threshold due to Coulomb attraction. For hadronic observables these effects are damped by the parton distribution functions and integration over the momenta of the partons in the initial state.

Next we discuss t and $\bar{t}$ decay. Here only the semileptonic decays of a polarized $t(\bar{t})$ into $\ell^+(\ell'^-)$ + *anything* are considered. The decay density matrix $\rho^{(f)}(\bar{\rho}^{(\bar{f}')})$ has the form $2\rho^{(f)}_{\alpha'\alpha} = (1\!\mathrm{l} + \kappa_+ \sigma \cdot \hat{\mathbf{q}}_+)_{\alpha'\alpha}$ where $\hat{\mathbf{q}}_+$ describes the direction of flight of ℓ^+ in the rest frame of the t quark and σ_i denote the Pauli matrices. The decay matrix $\bar{\rho}^{(\bar{f}')}$ is obtained from $\rho^{(f)}$ by replacing $\hat{\mathbf{q}}_+$ by $-\hat{\mathbf{q}}_-$ and κ_+ by κ_-. The factor κ_+ (κ_-) signifies the top-spin analyzing power of the charged lepton. It is equal to one to lowest order in the SM, that is, for $V - A$ charged currents. Its value including the order α_s corrections can be extracted from the results of [13] and turns out to be very close to one: $\kappa_+ = \kappa_- = 1 - 0.015\alpha_s$.

So far to the building blocks with which the factorizable contributions (which are gauge-invariant) to the squared matrix elements of the above reactions are determined at NLO. As far as the non-factorizable NLO QCD corrections are concerned which were calculated in ref.[7], we expect that their contribution to the spin effects is considerably smaller than those of the factorizable corrections given below.

Now we consider the hadronic reactions (1) and analyze the following double leptonic distribution,

$$\frac{1}{\sigma_t} \frac{d^2\sigma_t}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}(1 - \mathrm{C}\cos\theta_+ \cos\theta_-) \,, \tag{10}$$

with σ_t being the cross section for the channel under consideration. In Eq. (10) θ_+ (θ_-) denotes the angle between the direction of flight of the lepton ℓ^+ (ℓ'^-) in the t ($\bar{t}$) rest frame and a reference direction $\hat{\mathbf{a}}$ ($\hat{\mathbf{b}}$). Different choices will yield different values for the coefficient C. Using the general expressions for ρ, $\bar{\rho}$ and the fact that the factorizable contributions are of the form $\mathrm{Tr}[\rho R \bar{\rho}]$ we have obtained the following formula for the correlation coefficient C in Eq. (10):

$$\mathrm{C} = 4\kappa_+\kappa_- \langle (\hat{\mathbf{a}} \cdot \mathbf{s}_t)(\hat{\mathbf{b}} \cdot \mathbf{s}_{\bar{t}}) \rangle . \tag{11}$$

The expectation value in Eq. (11) is defined with respect to the matrix elements for the hadronic production of $t\bar{t}X$. It can be expressed in terms of the more familiar double spin asymmetry

$$4\langle(\hat{\mathbf{a}}\cdot\mathbf{s}_t)(\hat{\mathbf{b}}\cdot\mathbf{s}_{\bar{t}})\rangle = \frac{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)-\mathrm{N}(\uparrow\downarrow)-\mathrm{N}(\downarrow\uparrow)}{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)+\mathrm{N}(\uparrow\downarrow)+\mathrm{N}(\downarrow\uparrow)}, \tag{12}$$

where $N(\uparrow\uparrow)$ etc. denote the number of $t\bar{t}$ pairs with t and $\bar{t}$ spin parallel – or anti-parallel – to $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$, respectively. From Eq. (12) one can see that the axes $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$ introduced in Eq. (10) through the angles $\theta_\pm$ can be interpreted, as in Eq. (7), to be the spin axes of the intermediate $t\bar{t}$ state within our approximation. This means that the coefficient C in Eq. (10) reflects spin correlations of the $t\bar{t}$ intermediate state. Eq. (11) holds for factorizable contributions to all orders in α_s.

Table 1: Coefficient C of Eq. (11) to leading (LO) and next-to-leading order (NLO) in α_s for the spin bases of Eq. (8). The CTEQ parton distribution functions[14] were used and we have chosen $\mu_R = \mu_F = m_t = 175$ GeV.

	$p\bar{p}$ at $\sqrt{s} = 2$ TeV		pp at $\sqrt{s} = 14$ TeV	
	LO	NLO	LO	NLO
$\mathrm{C_{hel.}}$	-0.456	-0.389	0.305	0.311
$\mathrm{C_{beam}}$	0.910	0.806	-0.005	-0.072
$\mathrm{C_{off.}}$	0.918	0.813	-0.027	-0.089

Table 1 contains our results for C at leading and next-to-leading order in α_s using the parton distribution functions[14] CTEQ5L (LO) and CTEQ5M (NLO). These numbers and the results given below were obtained by integrating over the full phase phase. A further technical comment is in order here. In order to match with the definition of the QCD coupling used in the evolution of the PDF, we have expressed the $\overline{\mathrm{MS}}$ coupling α_s of 6 flavor QCD by the $\overline{\mathrm{MS}}$ coupling whose evolution is governed by the beta function that depends only on the 5 light quark flavors.

For $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV the helicity basis is not the best choice because the t, $\bar{t}$ quarks are only moderately relativistic in this case. Table 1 shows that the dilepton spin correlations at the Tevatron are large both in the off-diagonal and in the beam basis. These two spin bases yield almost identical results. The QCD corrections decrease the LO results for these correlations by about 10%. Since the gg initial state dominates $t\bar{t}$ production with pp collisions at $\sqrt{s} = 14$ TeV the beam and off-diagonal bases are no longer useful. Here the helicity basis is a good choice and gives a spin correlation of about 30%. In this case the QCD corrections are small. The large difference between the LO and NLO results for the correlation in the beam basis at the LHC is due to an almost complete cancellation of the contributions from the $q\bar{q}$ and gg initial state at LO.

As usual, there are several sources of theoretical errors at fixed order in perturbation theory. As to the scale uncertainty, the inclusion of the QCD corrections reduces the dependence of the $t\bar{t}$ cross section σ_t on the renormalization and factorization scales significantly. The same is true for the product σ_tC – see ref.[6] for details. To leading

Table 2: Upper part: Dependence of the correlation coefficients, computed with the PDF of ref.[14], and $\mu = \mu_R = \mu_F$ at NLO. Lower part: Correlation coefficients $C_{\text{hel.}}$, C_{beam}, and $C_{\text{off.}}$ at NLO for $\mu_R = \mu_F = m_t$ and different sets of parton distribution functions: GRV98[15], CTEQ5[14], and MRST98 (c-g)[16].

	$p\bar{p}$ at $\sqrt{s} = 2$ TeV			pp at $\sqrt{s} = 14$ TeV
$\mu_R = \mu_F$	$C_{\text{hel.}}$	C_{beam}	$C_{\text{off.}}$	$C_{\text{hel.}}$
$m_t/2$	-0.364	0.774	0.779	0.278
m_t	-0.389	0.806	0.813	0.311
$2m_t$	-0.407	0.829	0.836	0.331
PDF	$C_{\text{hel.}}$	C_{beam}	$C_{\text{off.}}$	$C_{\text{hel.}}$
GRV98	-0.325	0.734	0.739	0.332
CTEQ5	-0.389	0.806	0.813	0.311
MRST98	-0.417	0.838	0.846	0.315

order in α_s the coefficient C depends only on the factorization scale μ_F, while at NLO it depends on both scales μ_R and μ_F. Table 2 shows our NLO results for the three choices $\mu_R = \mu_F = m_t/2, m_t, 2m_t$, again using the PDF of ref.[14].

In Table 2 we also compare our results for C obtained with different sets of PDF. For $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV, the spread of the results is larger than the scale uncertainty given in the upper part of Table 2. To a considerable extent this is due to an important property of C, namely the $q\bar{q}$ and gg initial states contribute to C with opposite signs. Therefore the spin correlations are quite sensitive to the relative weights of $q\bar{q}$ and gg initiated $t\bar{t}$ events. These weights depend in particular on the chosen set of PDF. For example, we find the following individual NLO contributions for the helicity, beam, and off-diagonal correlation at the upgraded Tevatron: for the GRV98 (MRST98) PDF $C^{q\bar{q}}_{\text{hel.}} = -0.443$ (-0.486), $C^{gg}_{\text{hel.}} = +0.124$ $(+0.075)$, $C^{q\bar{q}}_{\text{beam}} = +0.802$ $(+0.879)$, $C^{gg}_{\text{beam}} = -0.068$ (-0.042), and $C^{q\bar{q}}_{\text{off.}} = +0.810$ $(+0.889)$, $C^{gg}_{\text{off.}} = -0.073$ (-0.044). This suggests that accurate measurements of the dilepton distribution (10), using different spin bases, at the upgraded Tevatron could be a useful tool in the effort to improve the knowledge of the PDF.

The above analysis can be extended to the "lepton+jets" and "all jets" decay channels in a straightforward fashion[17]. The "lepton+jets" channels should be particularly useful for detecting $t\bar{t}$ spin correlations: although one looses top-spin analyzing power one gains in statistics and the experimental reconstruction of the t and $\bar{t}$ rest frames may also be facilitated.

To conclude: we have determined, at NLO in the QCD coupling, the dileptonic angular distribution (10) that reflects the degree of correlation between the t and $\bar{t}$ spins. Our results for the Tevatron show that the scale and in particular the PDF uncertainties in the prediction of this distribution must be reduced before $t\bar{t}$ spin correlations can be used in a meaningful way to search for relatively small effects of new interactions affecting $t\bar{t}$ production and/or decay, but respect, like QCD, parity and CP. For example, the effect of a small anomalous chromomagnetic $t\bar{t}g$ coupling that would lead to deviation from the SM predictions at the, say, few percent level would be swamped by these uncertainties. On the other hand our Tevatron results should be useful to learn more about the parton distributions in the proton at high energies. For pp collisions at $\sqrt{s} = 14$ TeV the theoretical uncertainties in the prediction of this distribution are, fortunately, smaller. This gives rise to expectations that top quark spin correlations will play an important role in the precision analysis of $t\bar{t}$ events at the LHC.

Acknowledgements

This work is supported by BMBF, contract 05 HT1 PAA 4. A.B. is supported by a Heisenberg grant of the D.F.G.

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