Top quark pair production and decay at hadron colliders: Predictions at NLO QCD including spin correlations

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ICHEP02, 26.7.2002

Based on

- W. Bernreuther, A.B., Z.G. Si, Phys. Lett. **B 483** (2000) 99 [hep-ph/0004184]
- W. Bernreuther, A.B., Z.G. Si, P. Uwer, Phys. Lett. **B 509** (2001) 53 [hep-ph/0104096]; Phys. Rev. Lett. **87** (2001) 242002 [hep-ph/0107086]
- A.B., Z.G. Si, P. Uwer, Phys. Lett. **B 539** (2002) 235 [hep-ph/0205023]

Motivation

- Top Quark: **heaviest** known fundamental particle
$\Rightarrow$ Production and decay of top quarks involve very **high energy scales**
- $\Gamma_t \approx 1.4\ \mathrm{GeV} \gg \Lambda_{QCD} \Rightarrow$ **no hadronization effects in top decays**
$\Rightarrow$ in particular, **information on top spin not diluted**, can be analysed using the decay products
- Perturbation theory gives **reliable description** of top quark production and decay
- Large number of top quarks will be produced at the upgraded Tevatron ($\sim 10^4\ t\bar{t}$/year) and the LHC ($\sim 10^7\ t\bar{t}$/year)

Top quark: Optimal laboratory
to search for new physics

Motivation

So far, top quark interactions not precisely known. Questions to be answered:

- top still **point-like**?
- m_t due to usual **Higgs mechanism**?
- **Production:** new mechanisms, e.g. new heavy spin 0 resonances that are strongly coupled to $t\bar{t}$?
- **Decay:** deviation from **V-A** structure?
- top quark **couplings and quantum numbers** as expected (e.g. V_{tb})?

Spin observables will help to answer these (and other) questions.

- Single top production: **polarization** of top quarks
- $t\bar{t}$ production: also **spin correlations**

$\Rightarrow$ more **precise** investigations of top quark interactions possible.

$\Rightarrow$ probe ‘quasi-free’ quark

Theoretical framework

Studying the above questions in top quark pair production at hadron colliders requires:

- precise SM prediction including **QCD corrections**
- cross section that is **fully differential** in top quark decay products

We need differential cross section in NLO QCD for

$$p\bar{p}, pp \to t\bar{t}X \to \begin{cases} 2\ell + n \geq 2 \text{ jets} + P_T^{\text{miss}} \\ \ell + n \geq 4 \text{ jets} + P_T^{\text{miss}} \\ n \geq 6 \text{ jets} \end{cases}$$

Theoretical framework: **leading pole approximation** (LPA)

- expand amplitude around complex poles of unstable particle propagators
- keep only the **leading pole** terms
- within LPA: **factorizable** and **non-factorizable** contributions

Theoretical framework

Here we will consider only the **factorizable** radiative corrections. Further we apply the **on-shell approximation** for t and $\bar{t}$ propagator:

$$\lim_{\Gamma/m\to 0}\left|\frac{1}{k^2-m^2+im\Gamma}\right|^2 \to \frac{\pi}{m\Gamma}\delta(k^2-m^2)$$

Associated error is of order Γ/m.
Necessary ingredients at NLO QCD within this approximation:
Differential cross sections keeping full information on t and $\bar{t}$ spin for parton processes:

- $q\bar{q}\to t\bar{t},\ gg\to t\bar{t}$ to order α_s^3
- $q\bar{q}\to t\bar{t}g,\ gg\to t\bar{t}g,\ q(\bar{q})\to t\bar{t}q(\bar{q})$ to order α_s^3
- $t\to b\ell\nu, bq\bar{q}'$ to order α_s

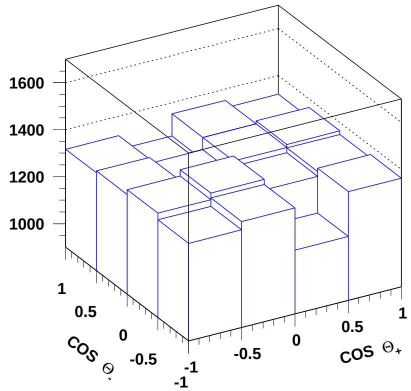
Observing spin correlations

Spin correlations show up in in angular distributions of top decay products, e.g.

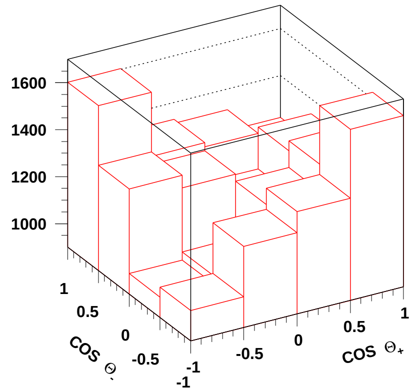
$$\frac{1}{\sigma}\frac{d^2\sigma(h_1h_2 \longrightarrow t\bar{t} \longrightarrow \ell^+\ell^- X)}{d\cos\theta_+\cos\theta_-} = \frac{1}{4}(1 - \mathbf{C}\cos\theta_+\cos\theta_-)$$

θ_+, θ_-: angles of $\ell^\pm$ in the t ($\bar{t}$) rest frame with respect to **arbitrary** axes ('spin quantization axes'). $\mathbf{C}$ reflects strength of $t\bar{t}$ spin correlations for the chosen quantization axes, $-1 \leq \mathbf{C} \leq +1$.

Example: Helicity correlation at the LHC A.B., Bernreuther, Simak, Sonnenschein '00



no spin correlations



$C = 0.33$

Observing spin correlations

$\mathbf{C}$ **factorizes**:

$$\mathbf{C} = \kappa_+ \kappa_- \mathbf{D}$$

with $t\bar{t}$ **double spin asymmetry** $\mathbf{D}$

$$\mathbf{D} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

$\kappa_\pm$: **spin analysing power** of charged lepton in decays $t(\bar{t}) \longrightarrow b(\bar{b})\ell^\pm \nu(\bar{\nu})$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta_\pm} = \frac{1 \pm \kappa_\pm \cos\vartheta_\pm}{2}$$

$\cos\vartheta_\pm$ angles of $\ell^\pm$ w.r.t. t $(\bar{t})$ spin.

Spin analysing power of top decay products

Leptonic decays $t \longrightarrow b\ell\nu$

$$\kappa_+ = \kappa_- = 1 - 0.015\alpha_s$$

Czarnecki, Jezabek, Kühn '91

$\Rightarrow$ Charged lepton perfect analyser of top quark spin.

Hadronic decays $t \longrightarrow bq\bar{q}'$: Analogous decay distribution.
QCD corrected spin analysing power A.B., Si, Uwer '02

$$\kappa_b = -0.41(1 - 0.39\alpha_s) = -0.39,$$

$$\kappa_j = +0.51(1 - 0.67\alpha_s) = +0.47.$$

κ_j: Analysing power of **least energetic non-b-quark jet**.

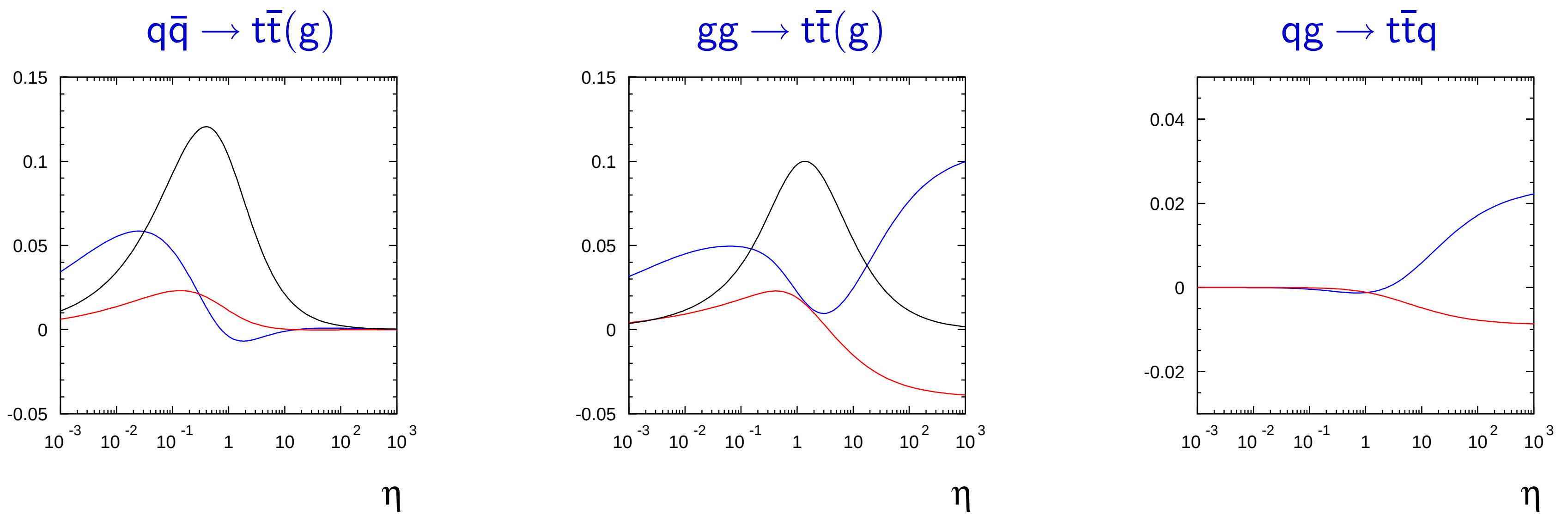
NLO results for $\mathbf{C}$ that will be shown are for **double lepton channel** of $t\bar{t}$ decays.
NLO results for **single lepton channel** diluted by $\kappa_{j,b}$.
(Over-)compensated by higher statistics!

Double spin asymmetry at parton level

NLO QCD results for $\overline{\mathrm{MS}}$ subtracted parton cross sections $q\bar{q} \to t\bar{t}(g)$, $gg \to t\bar{t}(g)$, $q(\bar{q})g \to t\bar{t}q(\bar{q})$ with $t\bar{t}$ spins summed over: Nason, Dawson, Ellis '88; Beenakker, Kuijf, van Neerven, Smith '89

$$\hat{\sigma}(\hat{s}, m_t^2) = \frac{\alpha_s^2}{m_t^2} \left\{ f^{(0)}(\eta) + 4\pi\alpha_s \left[f^{(1)}(\eta) + \tilde{f}^{(1)}(\eta) \ln(\mu^2/m_t^2) \right] \right\},$$

where $\eta = \frac{\hat{s}}{4m_t^2} - 1$ and $\mu = \mu_F = \mu_R$.



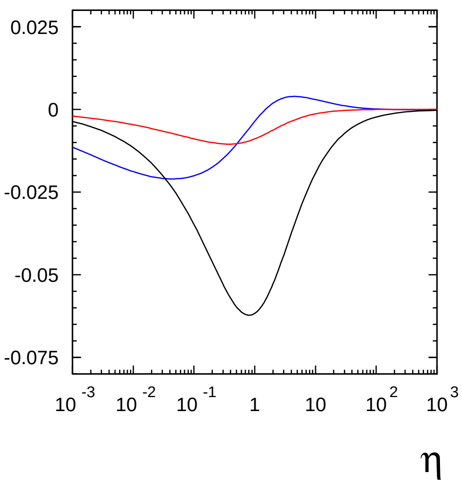
Double spin asymmetry at parton level

Analogous decomposition for

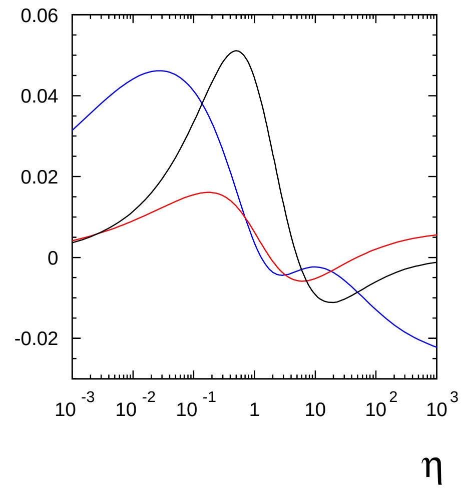
$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$
$$= \frac{\alpha_s^2}{m_t^2}\left\{g^{(0)}(\eta) + 4\pi\alpha_s\left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

Helicity basis: Spin quantization axis is $t(\bar{t})$ direction of flight.

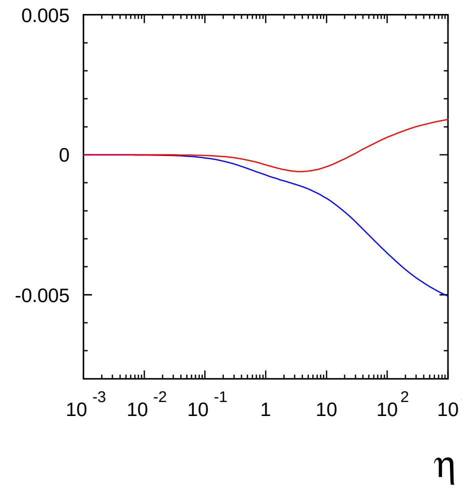
$q\bar{q} \longrightarrow t\bar{t}(g)$



$gg \longrightarrow t\bar{t}(g)$



$qg \longrightarrow t\bar{t}q$

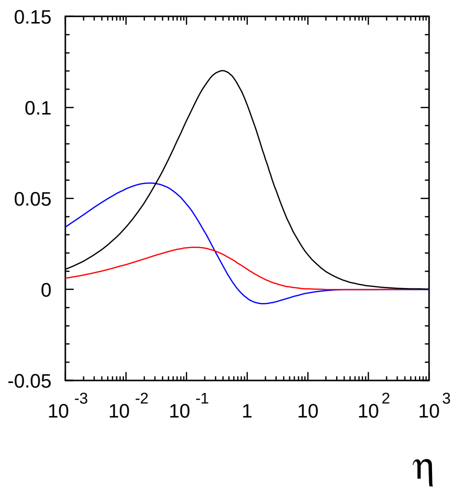


Double spin asymmetry at parton level

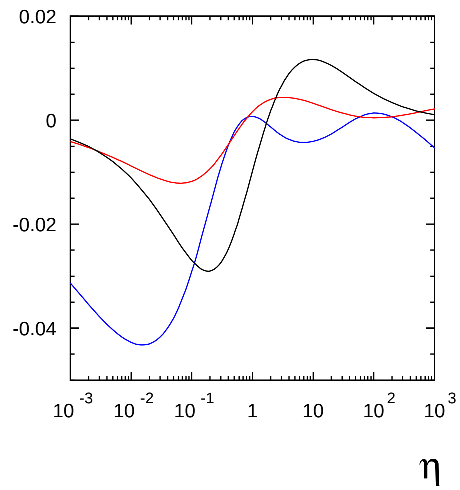
$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$
$$= \frac{\alpha_s^2}{m_t^2}\left\{g^{(0)}(\eta) + 4\pi\alpha_s\left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

Beam basis: Spin quantization axis is proton beam.

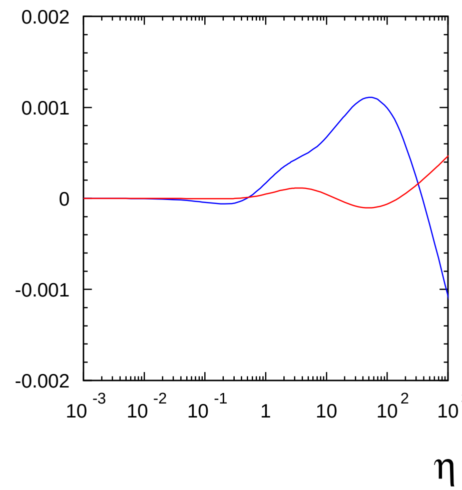
$q\bar{q} \to t\bar{t}(g)$



$gg \to t\bar{t}(g)$



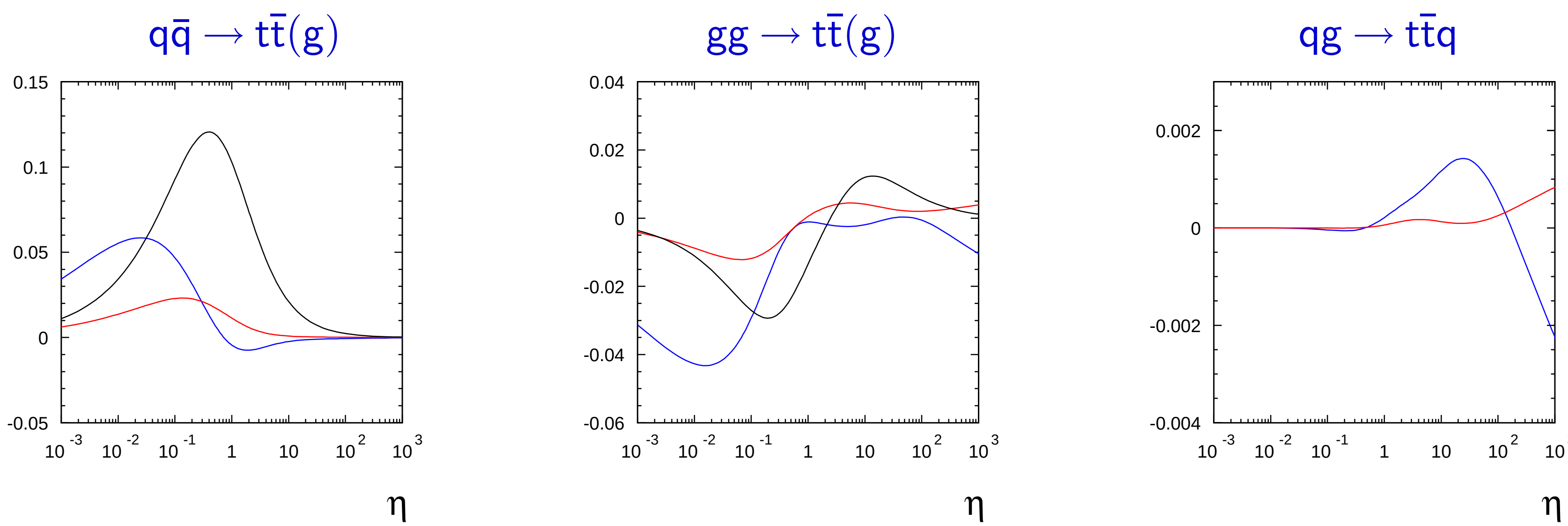
$qg \to t\bar{t}q$



Double spin asymmetry at parton level

$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$
$$= \frac{\alpha_s^2}{m_t^2}\left\{g^{(0)}(\eta) + 4\pi\alpha_s\left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

'Off-diagonal' basis: Spin quantization axis defined by $\hat{\sigma}(\uparrow\downarrow) = \hat{\sigma}(\downarrow\uparrow) = 0$ ($\Rightarrow \mathbf{D} = \mathbf{1}$) for $q\bar{q} \to t\bar{t}$ at tree level Parke, Shadmi '96; Mahlon, Parke '97



Double angular distributions

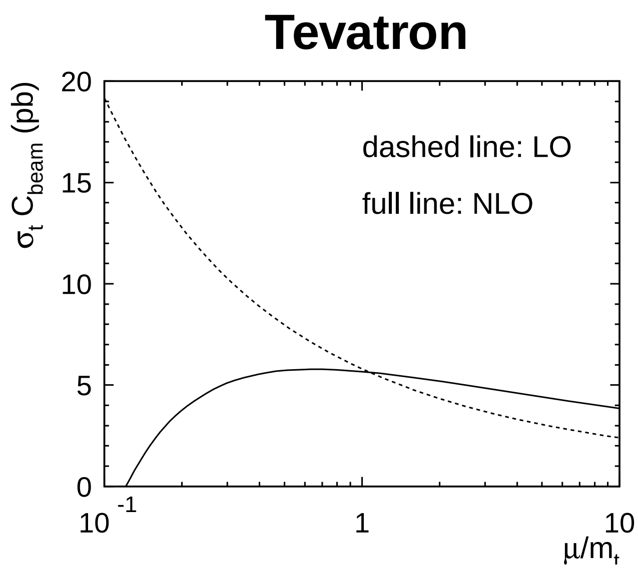
$$\frac{1}{\sigma}\frac{d^2\sigma(h_1 h_2 \longrightarrow t\bar{t} \longrightarrow \ell^+\ell^- X)}{d\cos\theta_+ \cos\theta_-} = \frac{1}{4}(1 - \mathbf{C}\cos\theta_+ \cos\theta_-)$$

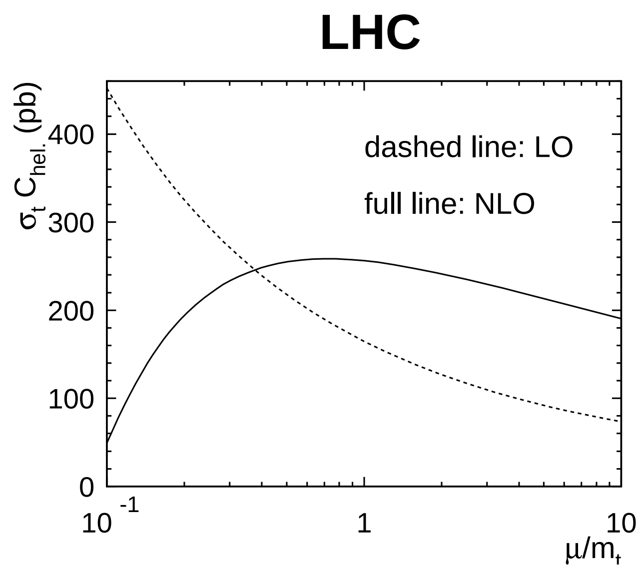
For $\mu_F = \mu_R = m_t = 175$ GeV and CTEQ5L (LO), CTEQ5M (NLO) we obtain:

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

- **Tevatron**: **Large** dilepton spin correlations in **beam** and **off-diagonal basis**. QCD corrections $\sim -10\%$
- **LHC**: beam and off-diagonal basis bad (due to dominance of $gg \longrightarrow t\bar{t}$). **Helicity basis** good choice, QCD corrections **small**.

Scale dependence





Scale dependence of **C** at NLO:

μ	$p\bar{p}$ at $\sqrt{s} = 2$ TeV $C_{hel.}$	C_{beam}	$C_{off.}$	pp at $\sqrt{s} = 14$ TeV $C_{hel.}$
$m_t/2$	-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 dependence

Dependence on choice of parton distribution functions:

PDF	$p\bar{p}$ at $\sqrt{s} = 2$ TeV $C_{hel.}$	C_{beam}	$C_{off.}$	pp at $\sqrt{s} = 14$ TeV $C_{hel.}$
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

- CTEQ5 and MRST98 agree up to a few percent
- difference between GRV98 and MRST98 at Tevatron $\sim 10\%$

Note: **gluon** and **quark** contributions enter with different sign.
$\Rightarrow$ **Constraining PDFs** by measuring spin correlations?

Dependence on top mass and kinematic cuts

Changing m_t from 170 $\longrightarrow$ 180 GeV implies:
Tevatron:

$$C_{hel.} = -0.378 \longrightarrow C_{hel.} = -0.397$$

$$C_{beam} = 0.790 \longrightarrow C_{beam} = 0.817$$

$$C_{off.} = 0.797 \longrightarrow C_{hel.} = 0.822$$

LHC: Change is less than 1%.

Kinematic cuts: **Tevatron**: $|\mathbf{k}_t^T| > 15$ GeV, $|r_t| < 2$; **LHC**: $|\mathbf{k}_t^T| > 20$ GeV, $|r_t| < 3$

	$p\bar{p}$ at $\sqrt{s} = 2$ TeV			pp at $\sqrt{s} = 14$ TeV
	$C_{hel.}$	C_{beam}	$C_{off.}$	$C_{hel.}$
no cuts	-0.389	0.806	0.813	0.311
with cuts	-0.386	0.815	0.823	0.295

Conclusions and Outlook

Conclusions

- $t\bar{t}$ spin correlations are **large** effects, can be studied at Tevatron and LHC
- QCD corrections are under control
- spin correlations are suited to study in detail top quark interactions, search for new effects, and may help to constrain PDFs

Outlook

- Implementation of NLO matrix elements in an event generator
- Study of non-factorizable corrections
- Resummation