Top quark spin correlations at hadron colliders: Predictions at NLO QCD

Arnd Brandenburg, RWTH Aachen

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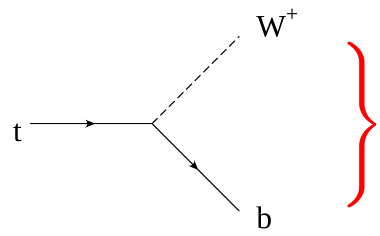
Based on

- 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 fundamental particle observed

- **Extremely unstable**: Lifetime $\sim 4 \times 10^{-25}$s



Length scale of decay $\ll$ hadronization scale $\sim$ 1 fm

- Decays too fast to form hadronic bound states $\Rightarrow$ properties of a **naked quark** can be studied.
- Strong interactions involved in dynamics of top quark production and decay described by **perturbative QCD**.
- Standard Model decay mode $t \to Wb$ is **parity violating** $\Rightarrow$

Spin properties of top quarks transferred to decay products, not diluted by hadronization, become additional observables to study top quark interactions.

Physics questions

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

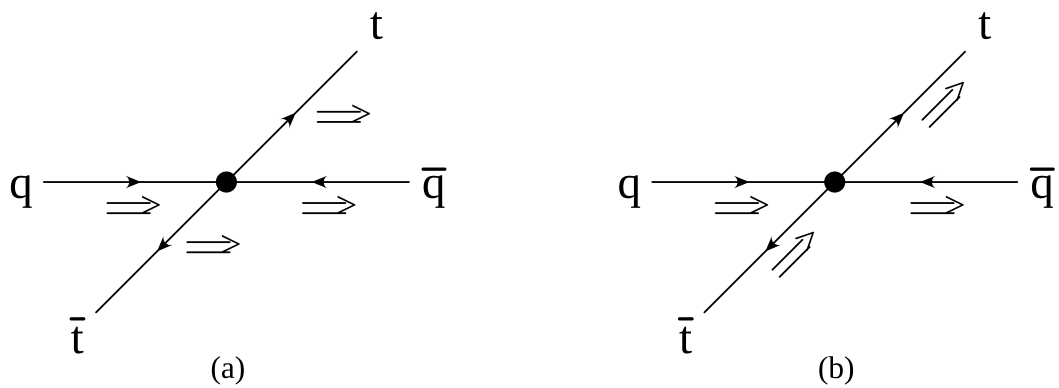
- top still **point-like**?
- m_t due to usual **Higgs mechanism**?
- **Production:** new mechanisms, e.g. new heavy spin 0 resonances that are strongly coupled to $t\bar{t}$?
- **Decay:** deviation from **V-A** structure?
- top quark **couplings and quantum numbers** as expected (e.g. V_{tb})?
- **Discrete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

Spin observables will help to answer these questions.

- Single top production: **polarization** of top quarks
- $t\bar{t}$ production: also **spin correlations**, which can be of order 1!

LO spin correlations at the parton level

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



- At threshold, $t\bar{t}$ in $^3\mathbf{S}_1$ state (a) $\Rightarrow$ 100% spin correlation along the beam line $\Rightarrow$ at the Tevatron, **beam line basis** (or off-diagonal basis Mahlon, Parke) for $t\bar{t}$ spins is a good choice
- Helicity conservation at high energies (b):
  Top polarization parallel to direction of flight.

LHC Due to dominance of $gg \longrightarrow t\bar{t}$, beam line and off-diagonal basis are **bad**. Better choice: **Helicity basis.**

Theoretical framework

Precise predictions for spin correlations requires:

- inclusion of **QCD corrections**
- cross section that is **fully differential** in top quark decay products

We need differential cross section in NLO QCD for

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

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 to $d\sigma(\mathbf{s}_t, \mathbf{s}_{\bar{t}})$.
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.

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

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, $-1 \le \mathbf{C} \le +1$.

In the following we consider three spin quantization axes:

(a) Helicity basis ($\theta_\pm = \hat{\ell}_\pm \cdot \hat{\mathbf{k}}_{t,\bar{t}}$)

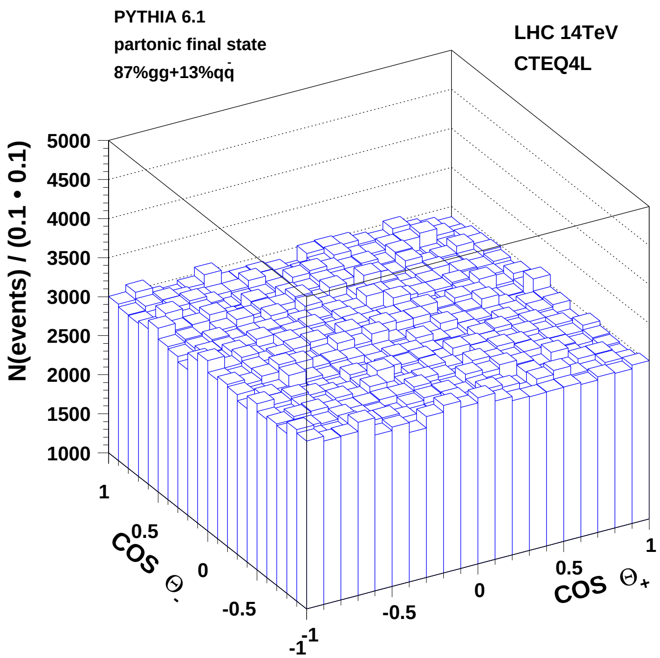
(b) Beam basis

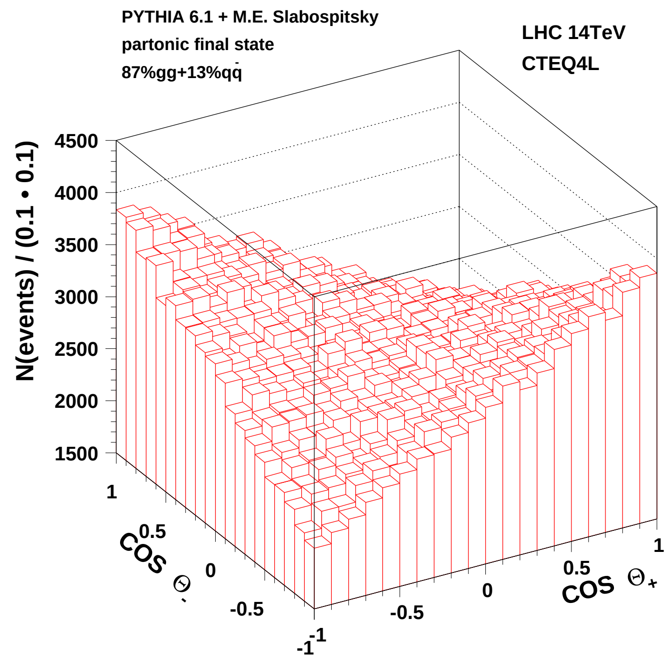
(c) Off-diagonal basis

Simulation of spin correlations

Simulation of **helicity correlation** at the LHC

A.B., W. Bernreuther, V. Simak, L. Sonnenschein, hep-ph/0003033; S.R. Slabospitsky, L. Sonnenschein, hep-ph/0201292





Left: Distribution $d^2N/d\cos\theta_+ d\cos\theta_-$ at LHC generated **without** spin correlations.

Right: Same distribution, but including the Standard Model $t\bar{t}$ spin correlations.

Result of the fit: $\mathbf{C_{fit} = 0.33 \pm 0.02}$. Detector response simulated with CMSJET.

Computing spin correlations at NLO QCD

$\mathbf{C}$ factorizes:

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

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

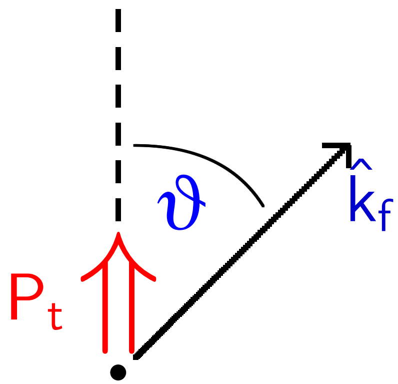
$$\mathbf{D} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

$\kappa_\pm$: **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



Final state particle f

analyses top polarization P_t

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 $t \longrightarrow bq\bar{q}'$:

Suitable spin analyser is **least energetic non-b-quark jet**.

QCD corrected spin analysing power A.B., Si, Uwer '02

$$\kappa_j = +0.51(1 - 0.65\alpha_s) = +0.47.$$

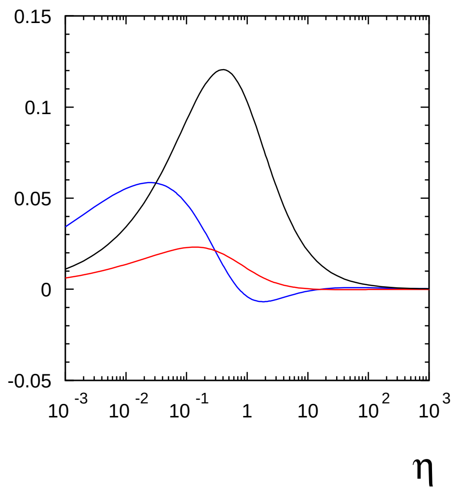
Double spin asymmetry at parton level

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

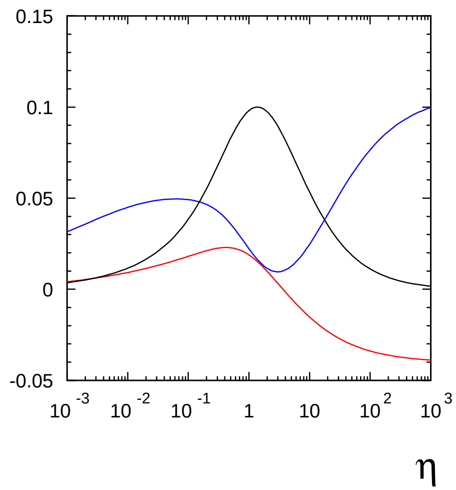
$$\hat{\sigma}(\hat{s}, m_t^2) = \frac{\alpha_s^2}{m_t^2}\left\{f^{(0)}(\eta) + 4\pi\alpha_s\left[f^{(1)}(\eta) + \tilde{f}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

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

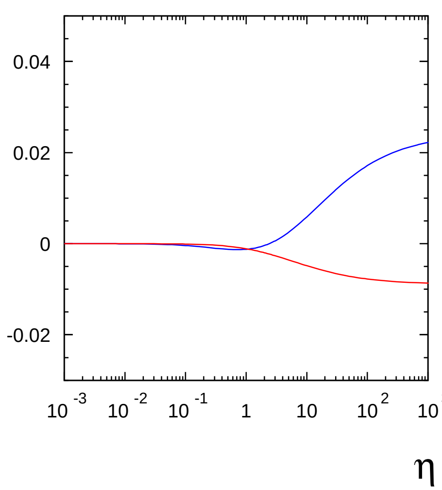
$q\bar{q} \longrightarrow t\bar{t}(g)$



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



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



Double spin asymmetry at parton level

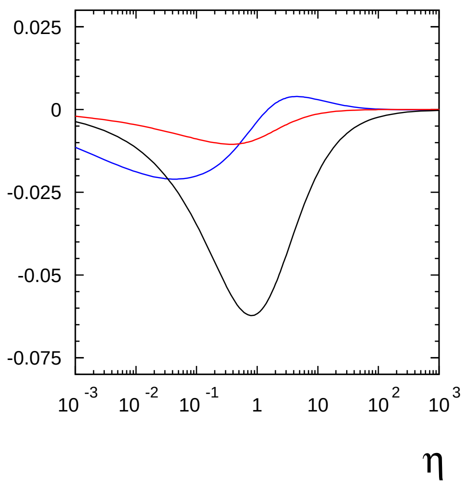
Analogous decomposition for

$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$

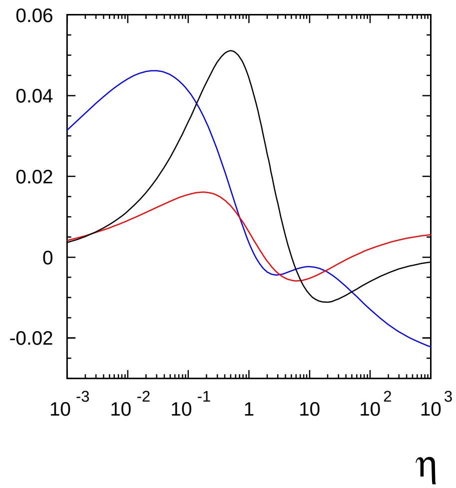
$$= \frac{\alpha_s^2}{m_t^2} \left\{ g^{(0)}(\eta) + 4\pi\alpha_s \left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta) \ln(\mu^2/m_t^2) \right] \right\},$$

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

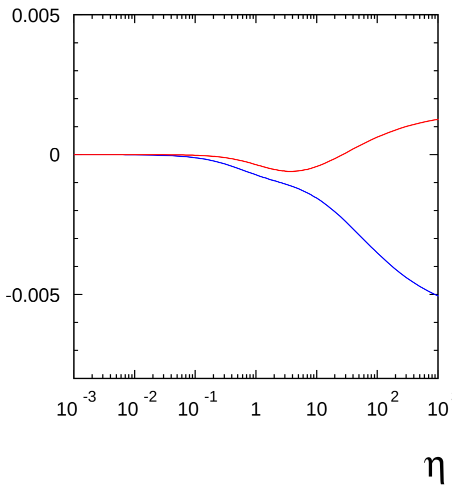
$q\bar{q} \to t\bar{t}(g)$



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



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

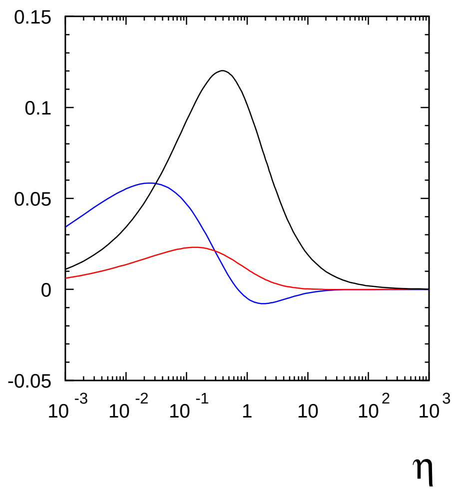


Double spin asymmetry at parton level

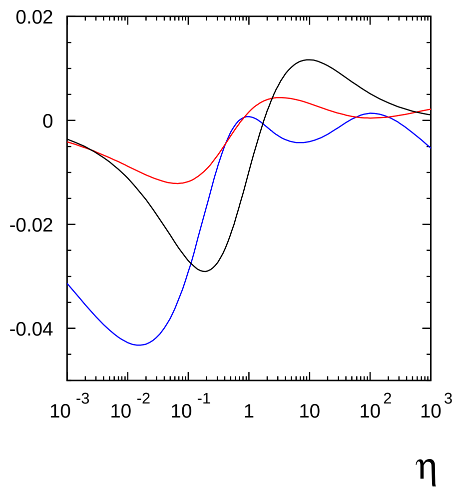
$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$
$$= \frac{\alpha_s^2}{m_t^2}\left\{g^{(0)}(\eta) + 4\pi\alpha_s\left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

Beam basis: Spin quantization axis is proton beam.

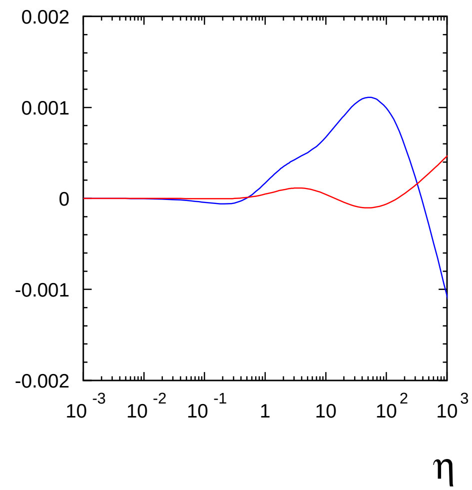
$q\bar{q} \rightarrow t\bar{t}(g)$



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



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

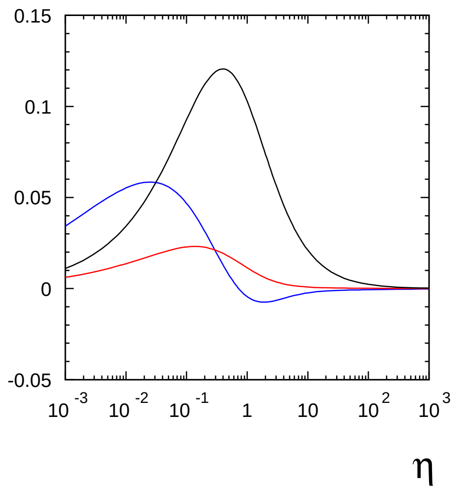


Double spin asymmetry at parton level

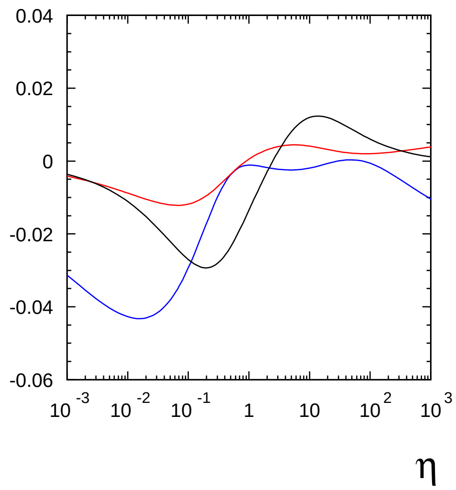
$$\hat{\sigma}\mathbf{D} = \hat{\sigma}(\uparrow\uparrow) + \hat{\sigma}(\downarrow\downarrow) - \hat{\sigma}(\uparrow\downarrow) - \hat{\sigma}(\downarrow\uparrow)$$
$$= \frac{\alpha_s^2}{m_t^2}\left\{ g^{(0)}(\eta) + 4\pi\alpha_s \left[g^{(1)}(\eta) + \tilde{g}^{(1)}(\eta)\ln(\mu^2/m_t^2)\right]\right\},$$

'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

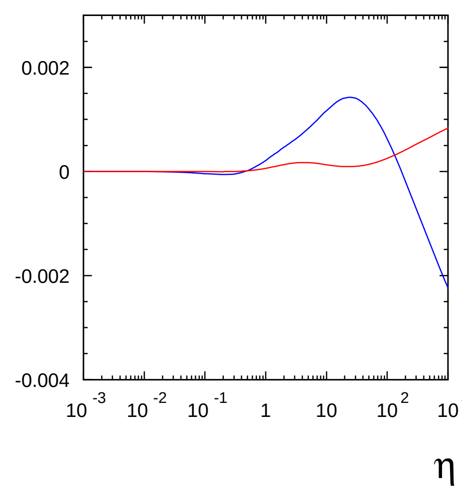
$q\bar{q} \to t\bar{t}(g)$



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



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



Double angular distributions: Dilepton channel

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

For $\mu_F = \mu_R = m_t = 175$ GeV and CTEQ6L (LO), CTEQ6M (NLO) we obtain:

	$p\bar{p}$ at $\sqrt{s} = 1.96$ TeV		pp at $\sqrt{s} = 14$ TeV	
	LO	NLO	LO	NLO
$\mathbf{C}_{\text{hel.}}$	-0.469	-0.402	0.296	0.299
$\mathbf{C}_{\text{beam}}$	0.934	0.823	-0.005	-0.072
$\mathbf{C}_{\text{off.}}$	0.945	0.829	-0.027	-0.089

- **Tevatron**: **Large** dilepton spin correlations in **beam** and **off-diagonal basis**. QCD corrections $\sim -15\%$
- **LHC**: beam and off-diagonal basis bad (due to dominance of $gg \to t\bar{t}$). **Helicity basis** good choice, QCD corrections **small**.

PDF dependence

Dependence on choice of parton distribution functions:

PDF	$p\bar{p}$ at $\sqrt{s} = 1.96$ TeV			pp at $\sqrt{s} = 14$ TeV
	$C_{\text{hel.}}$	C_{beam}	$C_{\text{off.}}$	$C_{\text{hel.}}$
GRV98	-0.328	0.735	0.740	0.333
CTEQ6	-0.402	0.823	0.829	0.299
MRST02	-0.384	0.800	0.804	0.315

- CTEQ6 and MRST02 agree up to a few percent
- difference between GRV98 and CTEQ6 at Tevatron $\sim 10 - 20\%$

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

Double angular distributions: Lepton+jets/all jets channel

Use least energetic non-b-quark jet as spin analyzer.
($\mu_F = \mu_R = m_t = 175$ GeV, CTEQ6)

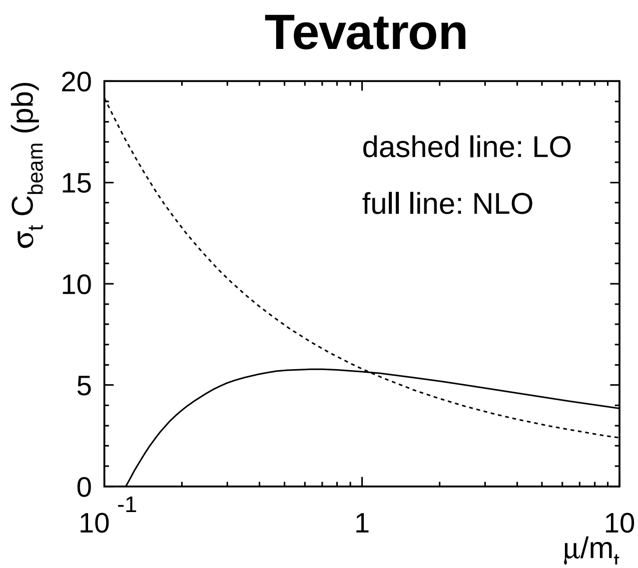
decay	$p\bar{p}$ at $\sqrt{s} = 1.96$ TeV			pp at $\sqrt{s} = 14$ TeV
	$C_{hel.}$	C_{beam}	$C_{off.}$	$C_{hel.}$
lepton+jet	-0.192	0.392	0.395	0.145
all jets	-0.091	0.187	0.188	0.070

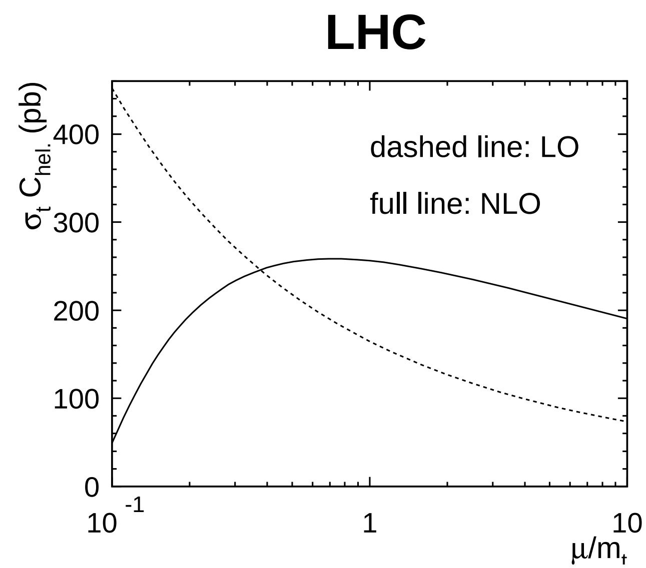
Conclusions

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

Scale dependence





Scale dependence of **C** at NLO: (CTEQ5)

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