$t\bar{t}$ Spin Correlations: NLO Standard Model Predictions

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SM top spin effects in hadronic $t\bar{t}$ events

- polarization of $t, \bar{t}$ in hadronic $t\bar{t}$ production **(very) small,** $\sim 1\%$**:**

t polarization in production plane (parity-violating) due to weak interactions, e.g., $< \mathbf{s_t} \cdot \hat{\mathbf{k}}_\mathbf{t} >$
"normal" polarization $< \mathbf{s_t} \cdot (\hat{\mathbf{k}}_\mathbf{t} \times \hat{\mathbf{p}}) >$ (P-even, T-odd) due to QCD absorptive parts

- $t\bar{t}$ spin correlations: **large effect** in the SM, dominated by QCD.

$$< (\hat{\mathbf{a}} \cdot \mathbf{s_t})(\hat{\mathbf{b}} \cdot \mathbf{s_{\bar{t}}}) > = \mathcal{A}/4, \quad \text{where } \mathcal{A} = \frac{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)-\mathrm{N}(\uparrow\downarrow)-\mathrm{N}(\downarrow\uparrow)}{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)+\mathrm{N}(\uparrow\downarrow)+\mathrm{N}(\downarrow\uparrow)}$$

Strength depends on the choice of reference axes $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$. Choices:

$$\hat{\mathbf{a}} = \hat{\mathbf{k}}_\mathbf{t}, \quad \hat{\mathbf{b}} = \hat{\mathbf{k}}_{\bar{\mathbf{t}}} \qquad \text{(helicity basis; good for LHC)}$$
$$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{p}} \qquad \text{(beam basis; good for Tevatron)}$$

Top polarization, $t\bar{t}$ spin correlations $\longrightarrow$ at level of final states:
non-isotropic angular distributions, non-zero angular correlations with resp. to $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$.

Suitable analysis channels:

$$t\bar{t} \longrightarrow \ell^+\ell'^- + \cdots \qquad (\ell = e, \mu)$$

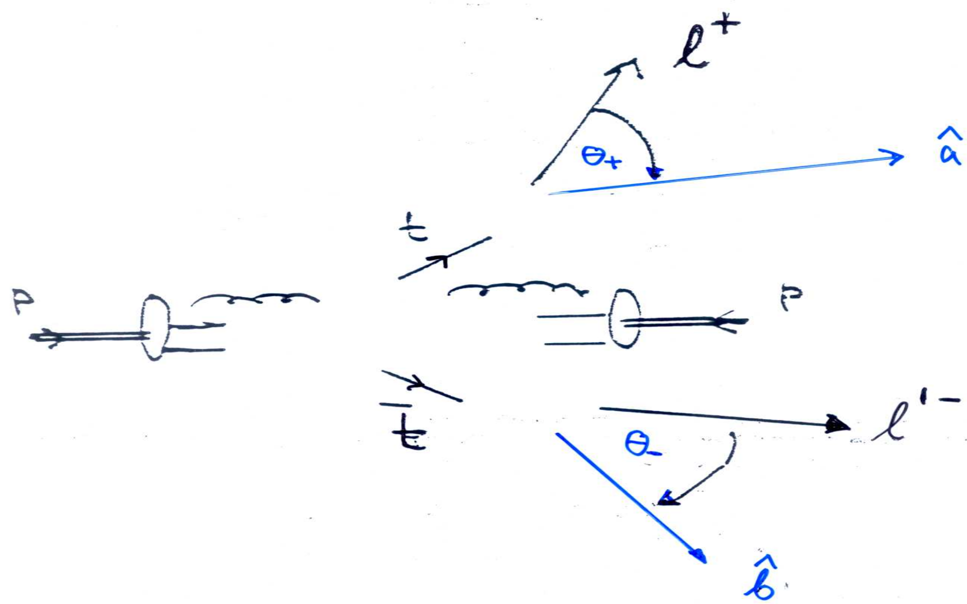
and lepton + jets channels:

$$t\bar{t} \longrightarrow \ell^+ j + \cdots$$

where $j = j_{\bar{b}}$ or $j_<$.

$$p\bar{p},\ pp \to t\bar{t}X \to 2\ell + j_b + j_{\bar{b}} + ... + E_T^{miss}$$

Angular correlations with respect to reference axes $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$:



Spin correlations observables for Tevatron and LHC:

angular correlations designed to trace $t\bar{t}$ spin correlations (W.B., Brandenburg, Si, Uwer 2001, 2004)

- Double distributions: (shapes hold if no cuts are applied:)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1\cos\theta_1 + B_2\cos\theta_2 - C\cos\theta_1\cos\theta_2)$$

where $\theta_1 = \angle(\hat{\mathbf{p}}^+, \hat{\mathbf{a}})$, $\theta_1 = \angle(\hat{\mathbf{p}}^-, \hat{\mathbf{b}})$, $\hat{\mathbf{p}}^+$ $(\hat{\mathbf{p}}^-)$ in t $(\bar{t})$ rest frame

- Opening angle distribution:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

where $\varphi = \angle(\hat{\mathbf{p}}^+, \hat{\mathbf{p}}^-)$ in t $(\bar{t})$ rest frame

If no acceptance cuts are applied:

$$C = \kappa_1\kappa_2\langle 4\mathbf{S}_t\cdot\hat{\mathbf{a}})(\mathbf{S}_{\bar{t}}\cdot\hat{\mathbf{b}})\rangle\ , \qquad D = \kappa_1\kappa_2\langle\frac{4}{3}\mathbf{S}_t\cdot\mathbf{S}_{\bar{t}}\rangle$$

If particles 1,2 $= \ell^+, \ell'^-$: $\longrightarrow \kappa_{1,2} = 0.999$

distributions are flat if t and $\bar{t}$ are uncorrelated

With acceptance cuts, use instead the estimators (esp. for double dist.):

$$\hat{C} = -9\langle \cos\theta_1 \cos\theta_2 \rangle$$

$$\hat{D} = -3\langle \cos\varphi \rangle$$

$\hat{C} = C$, $\hat{D} = D$ when no cuts are applied

compute also $\frac{\Delta \hat{C}}{\Delta M_{t\bar{t}}}$, $\frac{\Delta \hat{D}}{\Delta M_{t\bar{t}}}$

(notation below: $\hat{C} \to C$, $\hat{C} \to C$)

W.B. , Z.G. Si (2010): updates – NLO QCD in production & decay, mixed QCD-weak corrections included, with acceptance cuts "NLOW predictions"

Results for dilepton final states

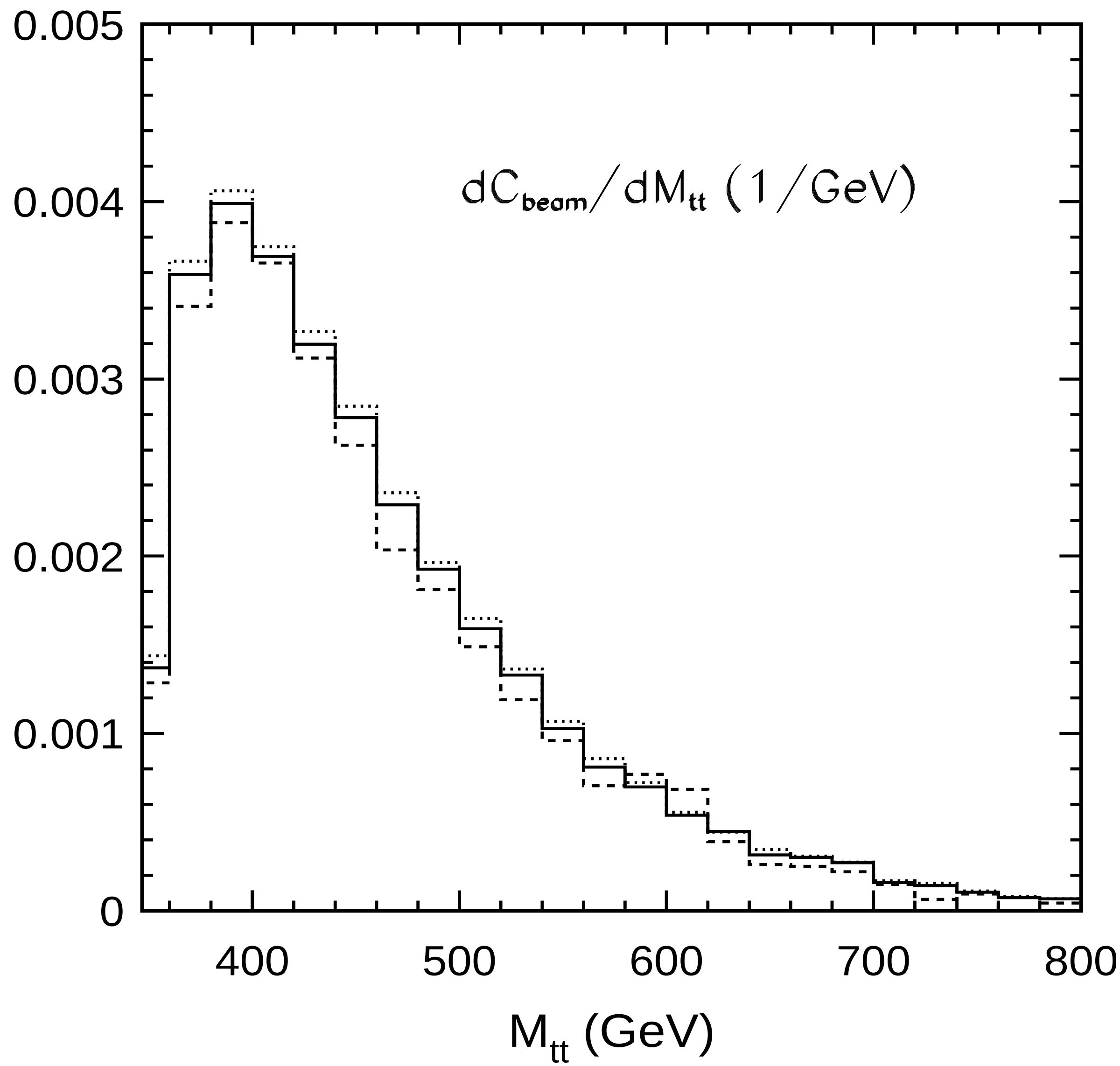
$$p\bar{p},\ pp \to t\bar{t}X \to 2\ell + j_b + j_{\bar{b}} + \ldots + E_T^{miss}$$

use acceptance cuts:

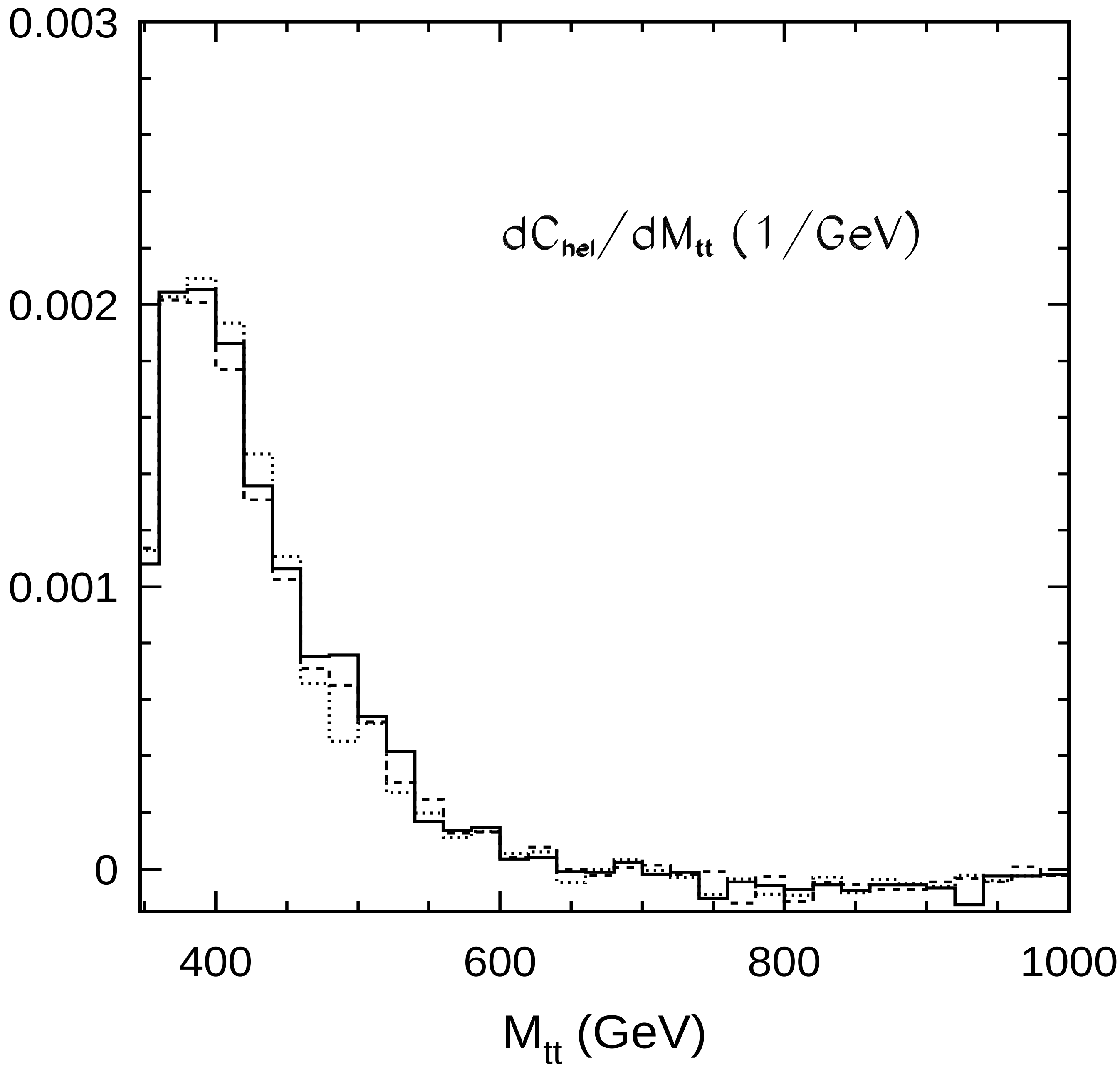
$$\begin{aligned} \text{Tevatron}: &\quad p_T^\ell \geq 20\,\text{GeV}, \quad |\eta_\ell| \leq 2.0, \quad p_T^j \geq 20\,\text{GeV}, \quad |\eta_j| \leq 2.0, \quad \not{E}_T \geq 25\,\text{GeV}, \\ \text{LHC}: &\quad p_T^\ell \geq 20\,\text{GeV}, \quad |\eta_\ell| \leq 2.5, \quad p_T^j \geq 20\,\text{GeV}, \quad |\eta_j| \leq 2.4, \quad \not{E}_T \geq 40\,\text{GeV}. \end{aligned}$$

Some examples:

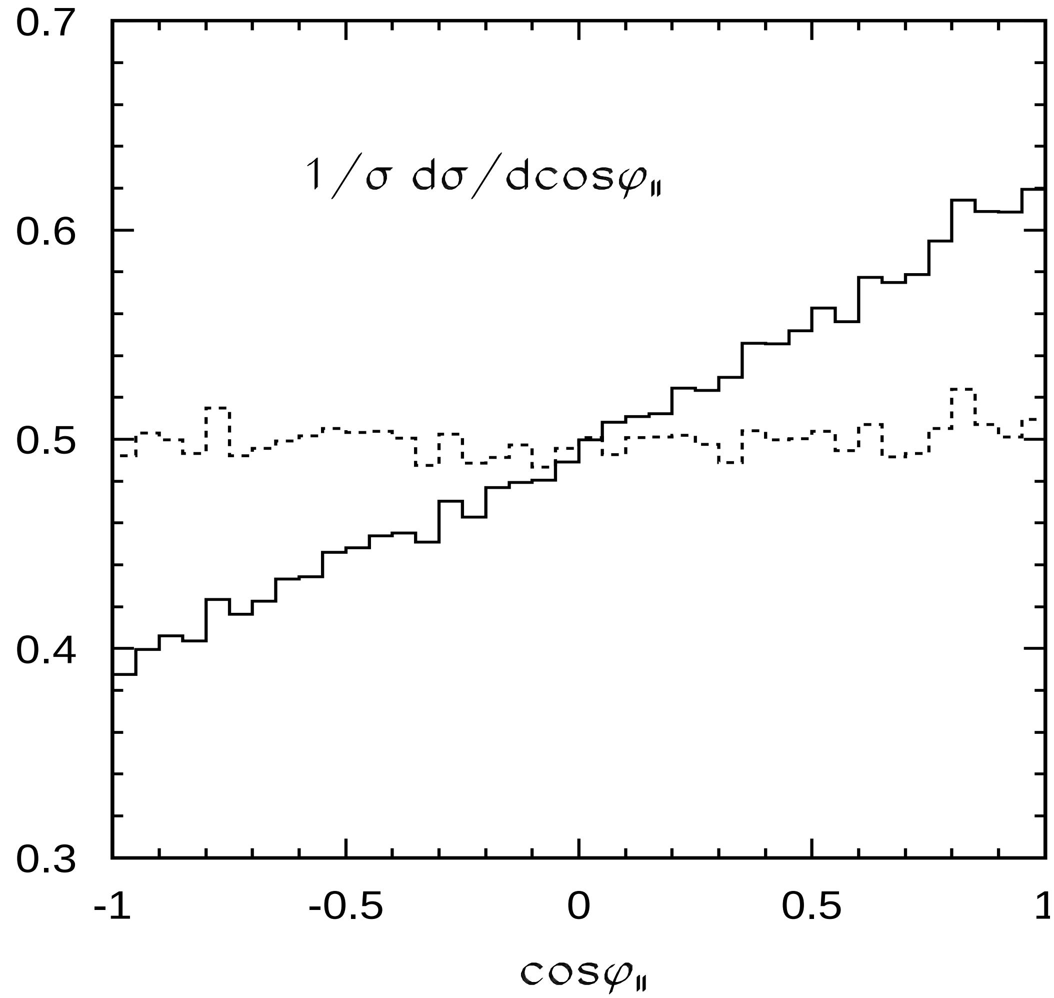
correlation with resp. to beam axis @ Tevatron
$\mu = m_t$ (solid), $m_t/2$ (dashed), $2m_t$ (dotted)



helicity correl. @ LHC (14 TeV)



Opening angle distribution @ LHC (14 TeV)



solid = $t\bar{t}$ correlated, dashed = $t\bar{t}$ uncorrelated

Comparison with Tevatron results (2009/2010):

	D0, $\ell\ell'$	**CDF**, $\ell +$ jets	**CDF**, $\ell +$ jets
	$C_{\rm beam} = -0.17^{+0.64}_{-0.53}$	$\kappa_{\rm beam} = 0.72 \pm 0.64 \pm 0.26$	$\kappa_{\rm hel} = 0.48 \pm 0.48 \pm 0.20$
NLOW:	$C_{\rm beam} =$ 0.791(5)	$\kappa_{\rm beam} = \mathcal{A}_{\rm beam} =$ 0.791(5)	$\kappa_{\rm hel} = -\mathcal{A}_{\rm hel} =$ 0.368(10)
with cuts:	0.614(10)	0.614(10)	$+$0.300(6)

Expectations @ LHC (14 TeV): Hubaut et al., (ATLAS 2005):

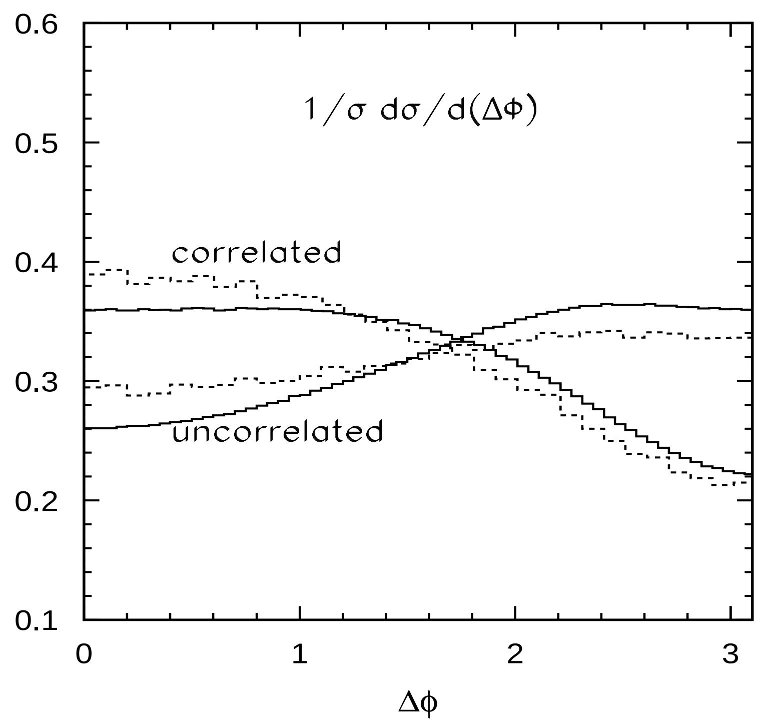
$\delta C_{\rm hel} = 7\%$, $\delta D = 5\%$ in $\ell\ell$ and $\ell +$ jets events with 10 $\rm fb^{-1}$

Dilepton azimuthal angle correlation $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ @ LHC (14 TeV)

where $\Delta\phi = \phi^+ - \phi^-$ measured in lab frame

Cut $M_{t\bar{t}} < 400$ GeV leads to discrimination between correlated and uncorrelated events

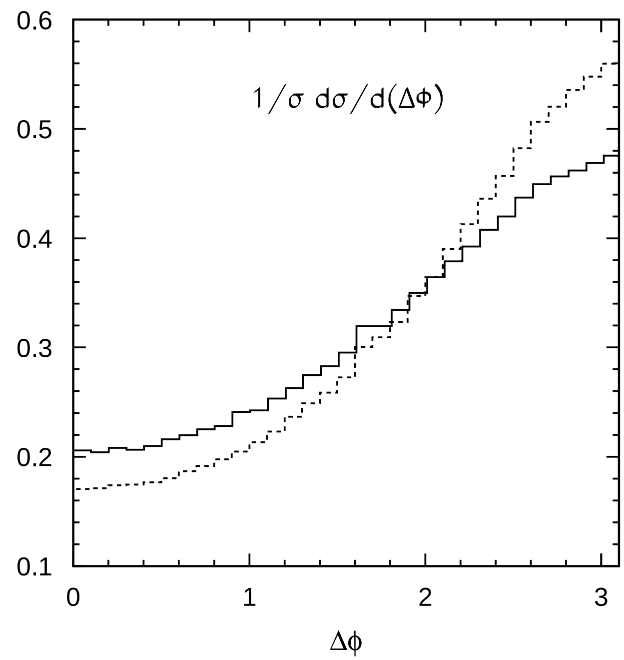
W.B., Z.G. Si: shapes @ NLOW (LO by Mahlon, Parke (2010))



event nr.: $\sigma_{\ell\ell'}(M_{t\bar{t}} < 400\,\mathrm{GeV})/\sigma_{\ell\ell'} \simeq 18.6\%$ $\Rightarrow$ $\sim$ 32000 dilepton events with 10 fb^{-1}

- shapes depend sensitively on how precisely ${M_{t\bar{t}}}^{\rm cut}$ can be determined by exp.
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ looses dicriminating power rapidly for ${M_{t\bar{t}}}^{\rm cut} > 400$ GeV

$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ with no cut on $M_{t\bar{t}}$: (NLOW)

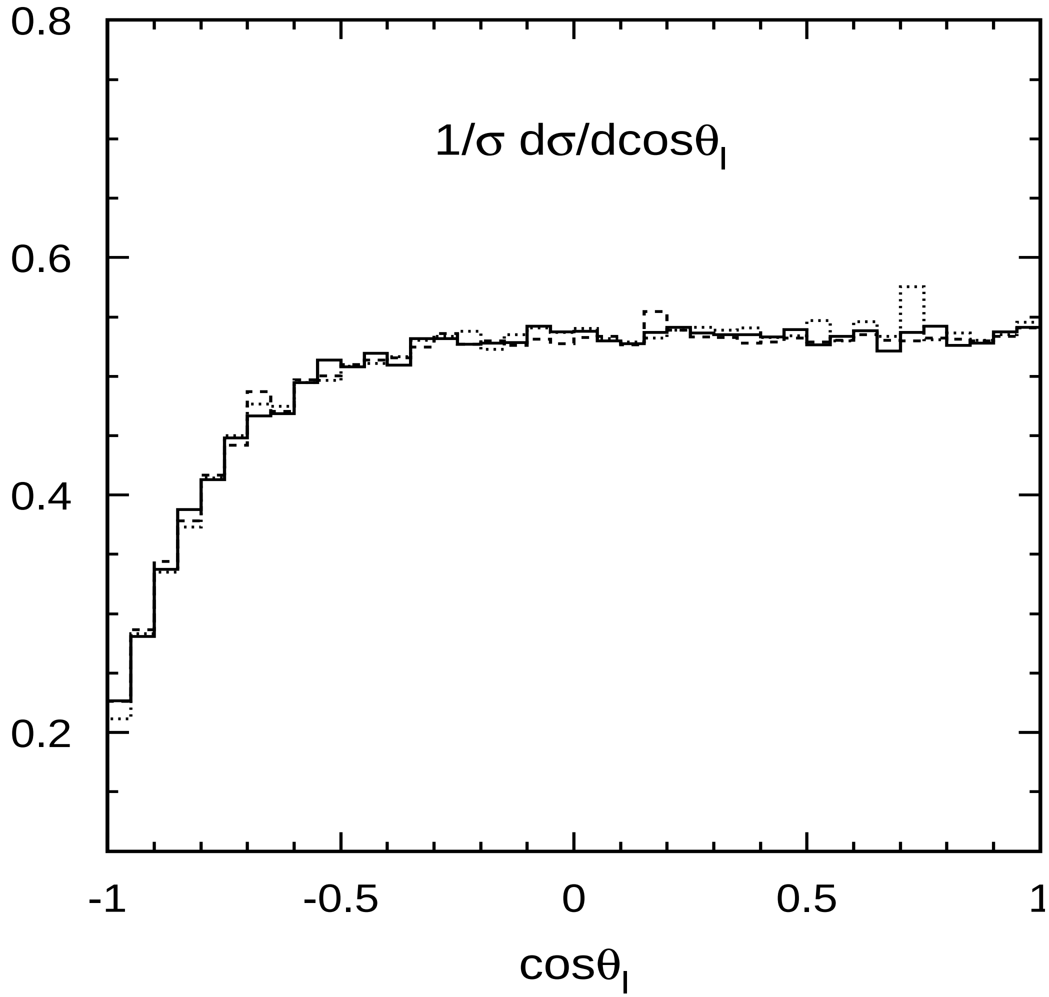


LHC (14 TeV) solid = correlated, dashed = uncorrelated

Check for longitudinal top polarization in $t\bar{t} \to \ell + \mathrm{jets}$

distribution $G_{\ell+} = \sigma^{-1} d\sigma / d\cos\theta_{\ell+}$ where $\theta_{\ell+}$ is lepton helicity angle in t rest frame

SM prediction to NLOW:



CP invariance $\Rightarrow$ $G_{\ell+}(\cos\theta_+) = G_{\ell-}(\cos\theta_-)$

Conclusions

- A number of observables are available that trace $t\bar{t}$ spin correlations
  & respective SM predictions at NLOW
- NLO QCD corrections for LHC energies moderate/small
  weak-int. corrections typically lead to depletion of $\sim$ few %.

- In the long run: use also appropriate distributions to probe for
  non-SM **P** and **CP** violation in $t\bar{t}$ production & decay
  A number of **CP** observables can be identified
  that receive no SM contributions at few per mille level.

- Usefulness of top spin observables as probes of the dynamics of $t\bar{t}$
  depends on exp. sensitivity
  Exp. precision on helicitiy & opening angle dist. @ LHC (7 TeV) with 1 fb^{-1} ?
  How precise can $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$ eventually be measured
  – in view of shape uncertainty due to $\delta M_{t\bar{t}}{}^{exp}$?

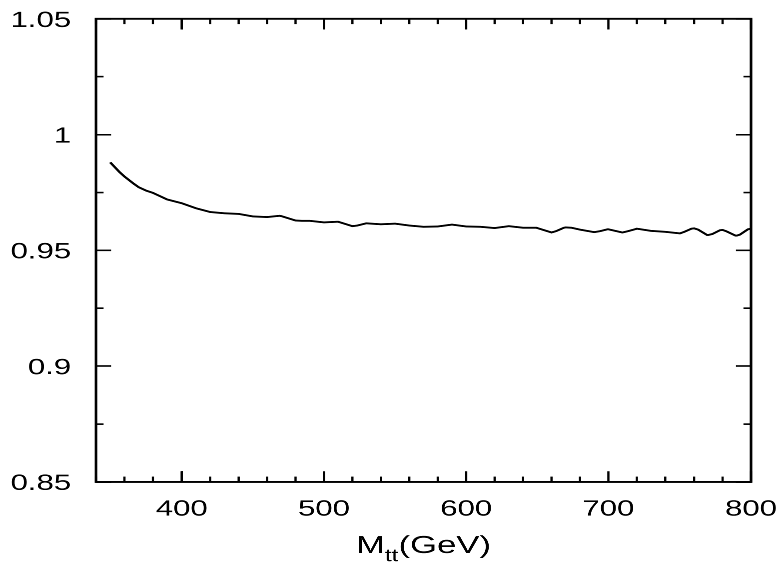
backup slides

NLOW predictions of correlation coefficients for dileptonic final states ($\ell\ell' = e, \mu$) with cuts

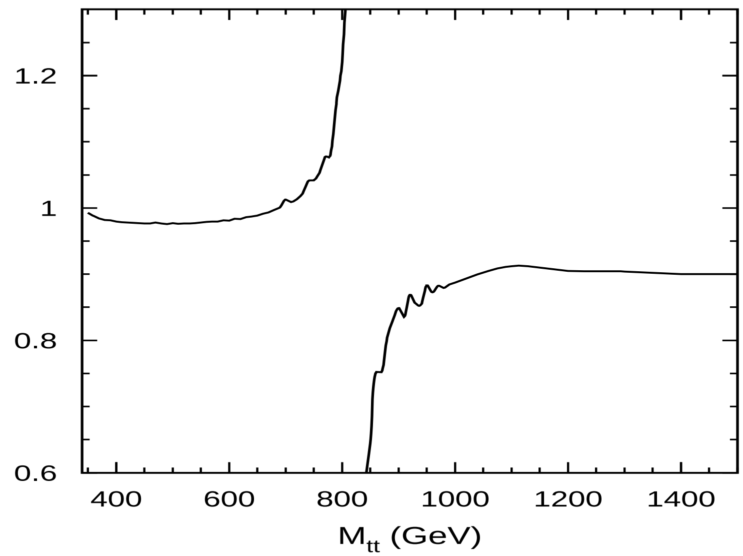
cut on $M_{t\bar{t}}$ enhances correl. coeff. @ LHC.
here $M_{t\bar{t}} < M_{\max} = 550$ GeV   (not optimized)

	Tevatron			LHC (10 TeV)			LHC (14 TeV)		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$	$m_t/2$	m	$2m$
$\sigma_{\ell\ell}$ (pb)	0.043	0.042	0.038	2.31	2.03	1.76	5.00	4.38	3.82
D	0.139	0.145	0.151	-0.257	-0.252	-0.257	-0.240	**-0.247**	-0.230
$D(M_{\max})$	0.125	0.132	0.138	-0.344	-0.340	-0.347	-0.340	**-0.353**	-0.338
C_{hel}	-0.294	**-0.299**	-0.306	0.249	0.247	0.252	0.225	**0.237**	0.229
$C_{\text{hel}}(M_{\max})$	-0.256	-0.262	-0.269	0.350	0.351	0.362	0.336	**0.360**	0.345
C_{beam}	0.605	**0.614**	0.624						
$C_{\text{beam}}(M_{\max})$	0.577	0.586	0.596						
C_{off}	0.612	**0.621**	0.631						
$C_{\text{off}}(M_{\max})$	0.582	0.591	0.601						

Ratio NLOW/NLO for correlation coeff. D (opening angle dist.) @ LHC (14 TeV)



Ratio NLOW/NLO for helicity correl.



Semileptonic final states:

$$pp,\ p\bar{p} \longrightarrow t\bar{t}X \longrightarrow \ell + 4j + \ldots + E_T^{miss}$$

use acceptance cuts:

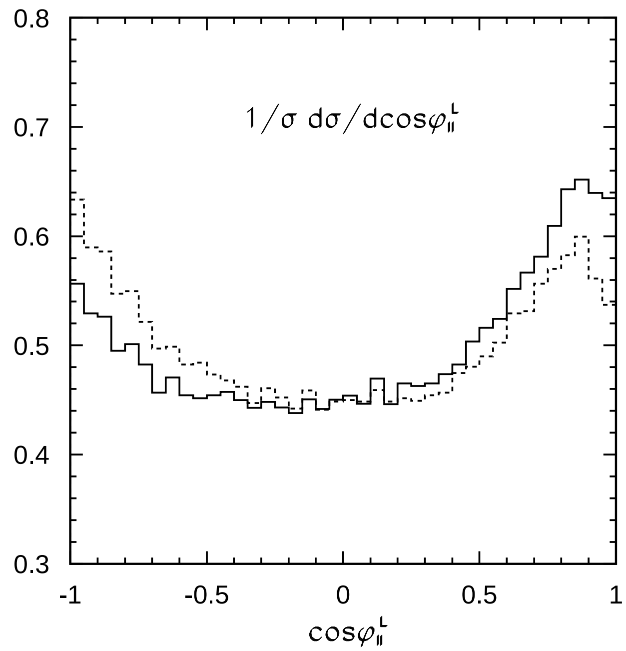
$$\text{Tevatron}: \quad p_T^\ell \geq 20\,\text{GeV}, \quad |\eta_\ell| \leq 2.0, \quad p_T^j \geq 20\,\text{GeV}, \quad |\eta_j| \leq 2.0, \quad \not{E}_T \geq 20\,\text{GeV},$$

$$\text{LHC}: \quad p_T^\ell \geq 20\,\text{GeV}, \quad |\eta_\ell| \leq 2.5, \quad p_T^j \geq 20\,\text{GeV}, \quad |\eta_j| \leq 2.4, \quad \not{E}_T \geq 20\,\text{GeV}.$$

Dileptonic angular correlation defined in lab frame:

1) $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_L}$, where $\varphi_L = \angle(\hat{\mathbf{p}}_{\mathbf{L}}^{+}, \hat{\mathbf{p}}_{\mathbf{L}}^{-})$

does not discriminate efficiently between correlated vs. uncorrelated events



LHC (14 TeV) solid = correlated, dashed = uncorrelated