Spin Effects in Hadronic Top-Quark Pair Production

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- Polarized t decay
- SM $t\bar{t}$ spin effects
- Heavy (Higgs) resonances $\to t\bar{t}$

Physics Issues:

• Unique opportunity to investigate interactions of a bare quark at energies $\sim$ a few 100 GeV
• Dynamics of top production and decay is not explored very precisely so far

- Top quark is as heavy as gold atom $\leftrightarrow$ yet pointlike particle?
- Excellent probe of mechanism of EWSB
- Good probe also for non-SM parity and/or non-SM CP violation (induced, e.g., by non-standard Higgs bosons)
- New decay modes $t \to \tilde{t}$, ... ?
  Is $t \to b$ decay vertex really (V-A) ?
  ....

Exp. analyses require precise SM predictions.

• Strong (and electroweak) interactions of top quarks can be reliably predicted – asset!

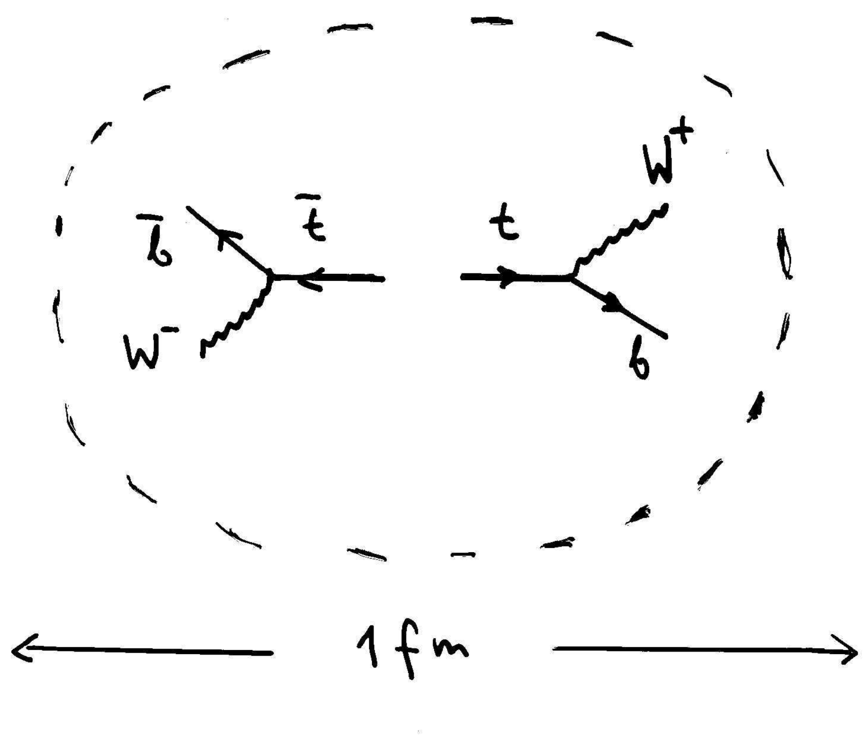
Properties of the top quark

$m_t \simeq 173$ GeV
t quark decays mainly into

$$t \to b + W^+$$

Top decay width in SM: $\Gamma_t = 1.4$ GeV
$\to$ lifetime $\tau_t \simeq 4 \times 10^{-25}$ sec

$\to$ t and $\bar{t}$ decay before they can form hadronic bound states $(t\bar{q})$, (tqq')



top quark $\sim$ quasi-free, instable particle
$\longrightarrow$ top-quark spin phenomena are measurable

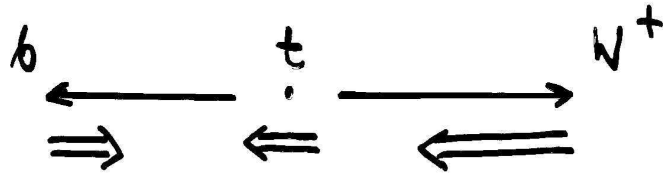
t, $\bar{t}$ quarks or pairs of $\bar{t}t$ are produced in a specific spin configuration (which depends on the production dynamics).
In the decays of t, $\bar{t}$, e.g.
$t \to b + W^+$, $\bar{t} \to \bar{b} + W^-$, $W \to \ell\nu_\ell, q\bar{q}'$
this spin information is transfered to the decay products

$\longrightarrow$ polarization of t, $\bar{t}$ quarks and $\bar{t}t$ spin correlations are "good" observables

- **reliably calculable**
- **well suited to experimentally check predictions of SM or of its extensions**

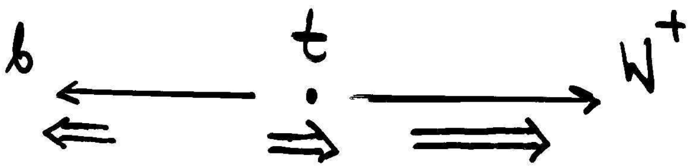
Decay of polarized $t \to b + W^+$ in SM:

$t \to W^+(h_W = -1)$ allowed:
$Prob(h_W = -1) \simeq 30\%$



$t \to W^+(h_W = 0)$ allowed: $Prob(h_W = 0) \simeq 70\%$

$t \to W^+(h_W = +1)$ forbidden for $m_b = 0$



$m_b \neq 0$ + QCD & EW corrections
$\longrightarrow Prob(h_W = +1) \simeq 0.1\%$. Do et al. (2003)

Important observables for determining the structure of tbW vertex

Ensemble of top quarks self-analyses its spin polarization via its parity-violating weak decays

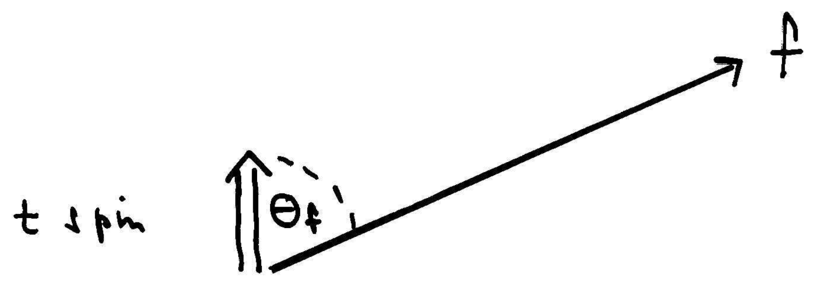
$$t \to W + b \to \begin{cases} \ell + \nu_\ell + b \\ q + \bar{q}' + b \end{cases}$$

Standard V-A charged current interaction → charged lepton $\ell = e, \mu, \tau$ is the best analyzer of the top spin.

Decay distribution of (100 %) polarized $t \to f + ...$

$$\frac{1}{\Gamma_t} \frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + c_f \cos\theta_f)$$

where $c_\ell = 1$ (maximal), while $c_b = - c_W =$ -0.41



Order α_s QCD corrections

semileptonic decays:
$t \longrightarrow b\,\ell^+\,\nu_\ell, \quad b\,\ell^+\,\nu_\ell + \text{gluon}$

non-leptonic decays:
$t \longrightarrow b\,\bar{q}_1\,q_2, \quad b\,\bar{q}_1\,q_2 + \text{gluon}$
respectively
$t \longrightarrow j_b\,j_1\,j_2, \quad j_b\,j_1\,j_2\,j_3$

consider decay distributions

$$\frac{1}{\Gamma_t}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + p\,c_f\,\cos\theta_f)$$

p = polarization degree of t quark ensemble.

Spin analyzer quality factor c_f:

	ℓ^+	$\bar{d}$	u	b	$j_<$	$j_>$
LO:	1	1	-0.32	-0.41	0.51	0.2
NLO:	0.999	0.966	-0.31	-0.39	0.47	

A.Brandenburg, Z.G. Si, P. Uwer (2002)
$j_<$ least energetic non-b jet (Durham algorithm)
$j_>$ most energetic non-b jet

Effects of non-SM interactions:

Examples:

- charged Higgs exchange:

$$t \xrightarrow{H^+} b\, f_1\, \bar{f}_2$$

here $c_b = -0.4 \longrightarrow c_b = 1$, neglecting interferences

- small $V + A$ admixture

$$(V - A) + \kappa(V + A)$$

neutrino energy-angle distribution most sensitive to $\kappa \neq 0$
decay distributions including QCD corrections available W.B., M. Fuecker, Y. Umeda (2004)

$t\bar{t}$ production at Tevatron and LHC

main reactions

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

within SM:

$t\bar{t}$ production dominated by strong interactions:
$q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}, \cdots$

weak decays of t and $\bar{t}$ into
semileptonic $t \to b\ell\nu_\ell$ and non-leptonic $t \to bq\bar{q}'$ channels

Status of theory:
spin-averaged cross sections $\sigma(pp, p\bar{p} \to t\bar{t}X)$ known to order α_s^3 + resummation of „infrared and threshold logarithms"
Nason et al.; Beenakker et al.
Bonciani et al.; Kidonakis, Vogt; Cacciari et al.
MC generators ⟶ see talk by S. Slabospitsky

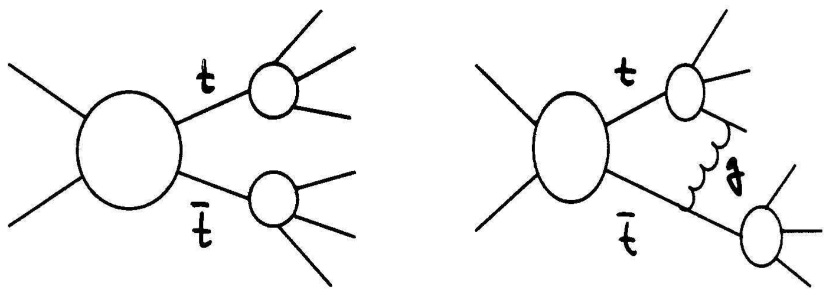
NLO predictions including $t, \bar{t}$ spin d.o.f.

- $2 \rightarrow 6$ and $2 \rightarrow 7$ reactions at NLO QCD:

$$q\bar{q} \xrightarrow{t\bar{t}} b + \bar{b} + 4\ f\ \ (+\text{gluon}),$$
$$gg \xrightarrow{t\bar{t}} b + \bar{b} + 4\ f\ \ (+\text{gluon}),$$
$$g\,q\ (\bar{q}) \xrightarrow{t\bar{t}} b + \bar{b} + 4\ f\ \ + q\ (\bar{q}), \quad f = q, \ell, \nu$$

unstable $t, \bar{t}$ are narrow resonances: $\Gamma_t \ll m_t$
→ leading pole approximation appropriate (consider top as signal)

→ 2 types of radiative corrections:
factorizable and nonfactorizable corr.



Differential parton cross sections

$$d\sigma_i = d\sigma_i^0 + d\sigma_{i,fact} + d\sigma_{i,nf}$$
$$i = q\bar{q}, gg, gq, g\bar{q}$$

Factorizable corrections: **may apply narrow width approximation for t, $\bar{t}$:**

$$d\sigma_{i,fact} \propto \mathrm{Tr}\left\{R^{(i)} \rho_t \rho_{\bar{t}}\right\}$$

R, ρ_t, $\rho_{\bar{t}}$ **: production and decay density matrices.**
$d\sigma_{i,fact}$ **known for all** $i \xrightarrow{t\bar{t}}$ **final states to order** α_s^3
W.B., Brandenburg, Si, Uwer (2004)

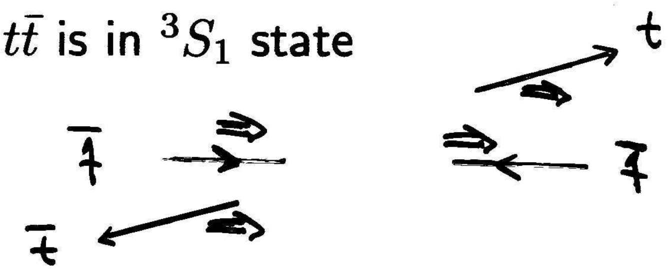
Nonfactorizable corrections: Beenakker, Berends, Chapovsky
dominant contributions to $d\sigma_{i,nf}$ **from semi-soft gluons,** $E_g \lesssim \mathcal{O}(\Gamma_t)$**; important for** $t, \bar{t}$ **momentum distributions,** $t, \bar{t}$ **and** $t\bar{t}$ **invariant mass distributions**

$t, \bar{t}$ polarization and spin correlations

- $t, \bar{t}$ polarization in hadronic $t\bar{t}$ production very small, i.e., polarization in production plane due to weak interactions, "normal" polarization due to QCD absorptive parts

- $t\bar{t}$ spin correlations induced by the production dynamics – i.e., QCD within SM. Strength depends on the choice of reference axes $\rightarrow t, \bar{t}$ spin quantization axes in on-shell approximation

Consider $q\bar{q} \rightarrow t\bar{t}$.
At threshold $t\bar{t}$ is in $^3S_1$ state



$\beta_t = v_t/c \rightarrow 0$, then 100% correlation of $t\bar{t}$ with respect to "beam basis" $\hat{\mathrm{p}}$ (relevant for Tevatron).

If $\beta_t \rightarrow 1$, then 100% correlation with respect to helicity basis (because of helicity conservation of quark-gluon interactions)

• For $q\bar{q} \to t\bar{t}$,
choosing "off-diagonal basis" (Mahlone, Parke),

$$\hat{\mathbf{d}} = \frac{-\hat{\mathbf{p}}+(1-\gamma)(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}_t)\hat{\mathbf{k}}_t}{\sqrt{1-(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}_t)^2(1-\gamma^2)}}, \quad \gamma = E_t/m_t,$$

there is 100% correlation (at LO) for any β_t:

$$< 4(\hat{\mathbf{d}}\cdot\mathbf{s_t})(\hat{\mathbf{d}}\cdot\mathbf{s_{\bar{t}}}) > = 1$$

• For $gg \to t\bar{t}$ no axis
exists that yields 100 % correlation.

At Tevatron ($\sim 85\%\, q\bar{q}$, $\sim 15\%\, gg$), beam basis $\hat{\mathbf{p}}$ essentially as good as off-diagonal basis $\hat{\mathbf{d}}$

$t\bar{t}$ spin correlations
with respect to arbitrary reference axes $\hat{\text{a}}$, $\hat{\text{b}}$:

$$< 4(\hat{\mathbf{a}} \cdot \mathbf{s_t})(\hat{\mathbf{b}} \cdot \mathbf{s_{\bar{t}}}) > = \mathcal{A}$$

where $\mathcal{A}$ is the $t\bar{t}$ double spin asymmetry

$$\mathcal{A} = \frac{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)-\mathrm{N}(\uparrow\downarrow)-\mathrm{N}(\downarrow\uparrow)}{\mathrm{N}(\uparrow\uparrow)+\mathrm{N}(\downarrow\downarrow)+\mathrm{N}(\uparrow\downarrow)+\mathrm{N}(\downarrow\uparrow)}$$

For on-shell $t, \bar{t}$: $\hat{\mathbf{a}}$, $\hat{\mathbf{b}} \leftrightarrow$ spin axes.

Choose in the following:

$\hat{\mathbf{a}} = \hat{\mathbf{k}}_{\mathbf{t}}$, $\hat{\mathbf{b}} = \hat{\mathbf{k}}_{\bar{\mathbf{t}}}$ (helicity basis),
$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{p}}$ (beam basis),
$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{d}}$ (off-diagonal basis).

Predictions at level of $t, \bar{t}$ decay products

Consider, e.g., dilepton channels

$$pp, p\bar{p} \longrightarrow t\bar{t}X \longrightarrow \ell^+\ell'^-X.$$

$$\int d\sigma = \sum_{ij} \int dx_1 dx_2 f_i^{h_1}(x_1, \mu_F) f_j^{h_2}(x_2, \mu_F)$$
$$\times\{d\Phi_6|\mathcal{M}_6|^2_{LO+NLO} + d\Phi_7|\mathcal{M}_7|^2_{NLO}\}$$

- **double distribution:**

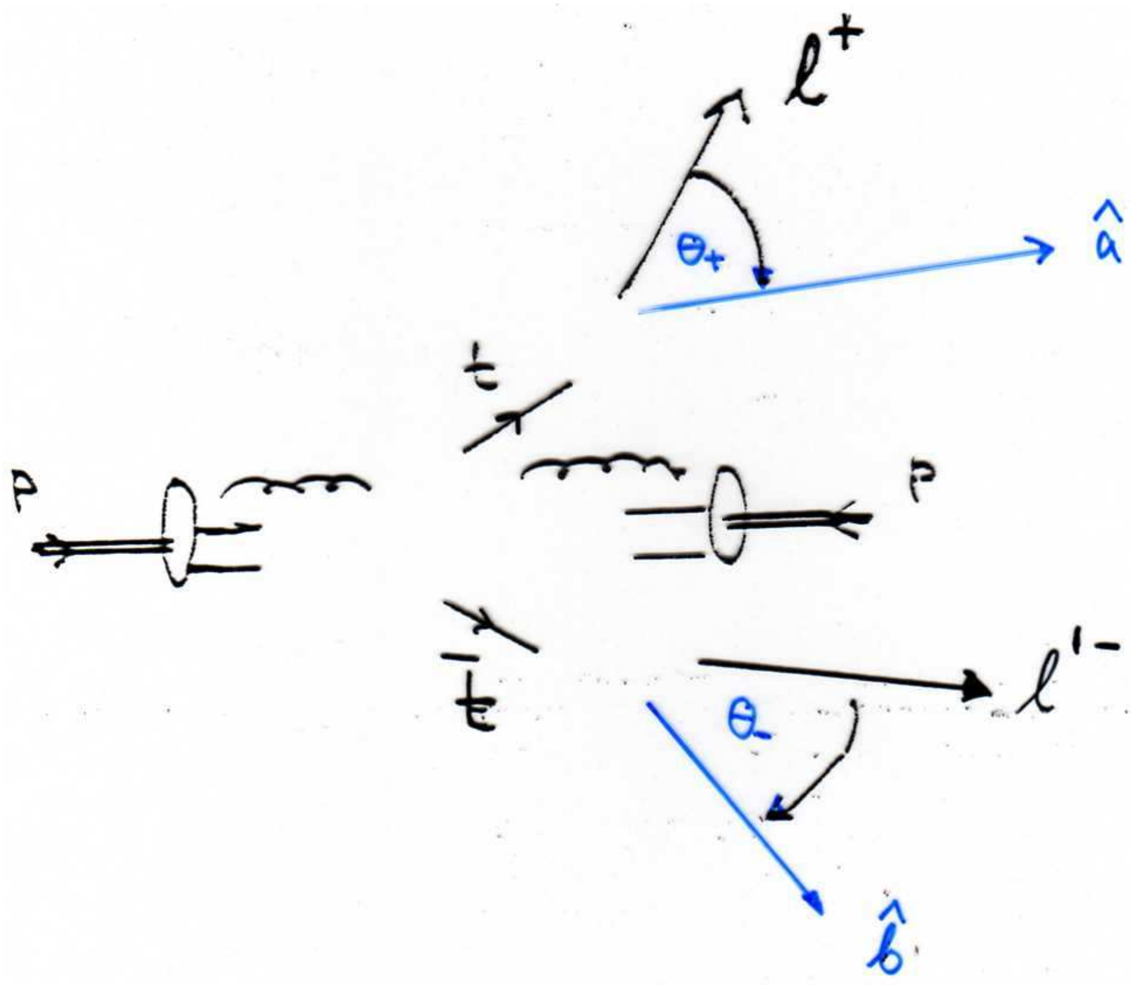
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} =$$

$$\frac{1}{4}\{1 + B_1\cos\theta_+ + B_2\cos\theta_- - C\cos\theta_+\cos\theta_-\}$$

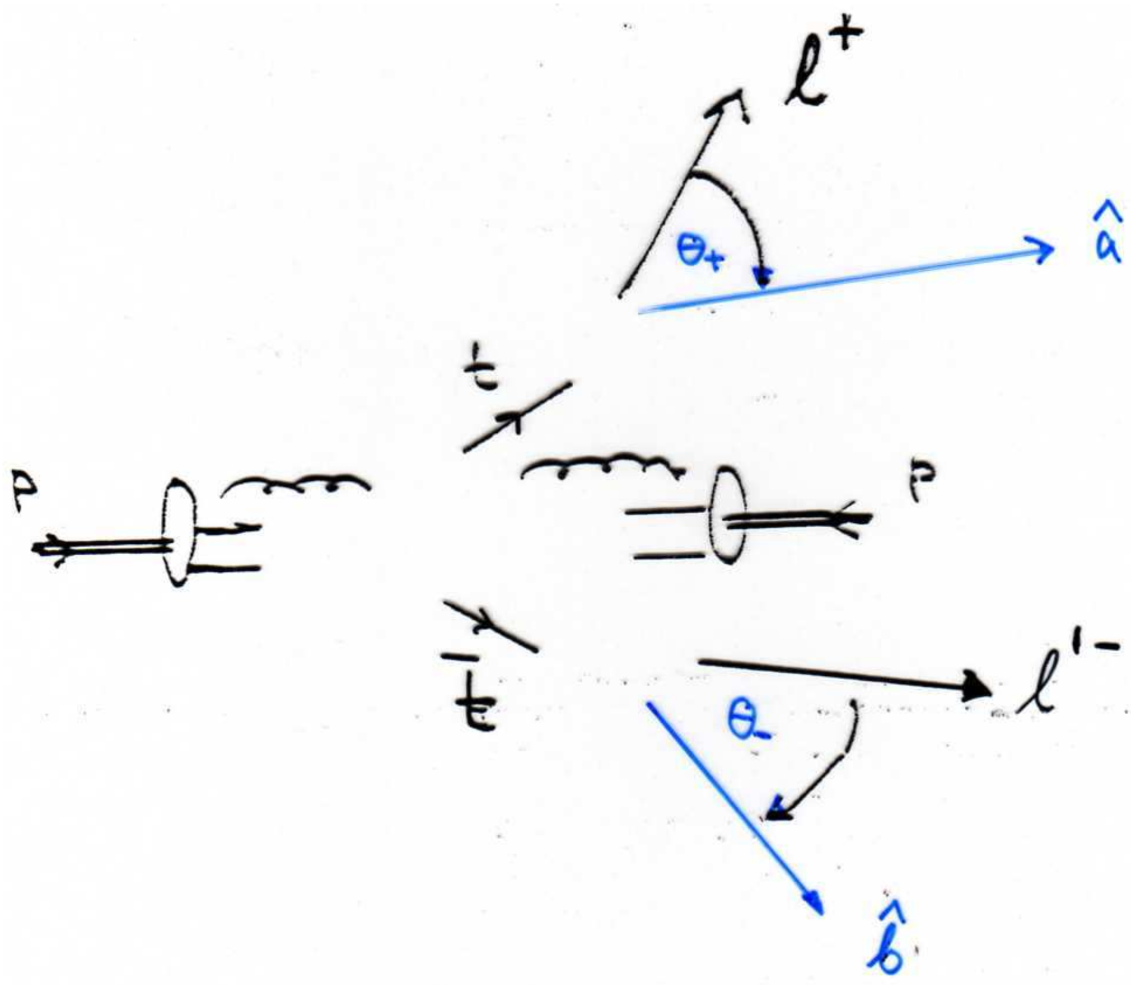
θ_+ (θ_-) is angle between direction of flight of $\ell^+(\ell^-)$ in t ($\bar{t}$) rest frame and the reference axis $\hat{\mathbf{a}}$ ($\hat{\mathbf{b}}$).

$B_{1,2} \leftrightarrow$ polarization of $t, \bar{t}$. In SM: $|B_1|, |B_2| < 1\%$
$C \leftrightarrow t\bar{t}$ spin correlations.
All-order formula (factorizable corrections):

$$C = c_+ c_- \mathcal{A}$$



ℓ+
θ+
â
t
p
p
t̄
ℓ'−
θ−
b̂



ℓ^+
$\hat{a}$
θ_+
t
p
p
$\bar{t}$
ℓ'^-
θ_-
$\hat{b}$

Another useful observable for detecting $t\bar{t}$ spin correlations:

- opening angle distribution (W.B. et al.)

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

e.g., for dilepton channels

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

$\varphi = \angle(\ell^+, \ell'^-)$ in resp. t, $\bar{t}$ rest frames.

Above distributions apply also to lepton + jets (& all-jets) channels
For these channels, $j_<$ is used, in the following, as top-spin analyzer in non-leptonic t decays

$$c_{j_<} > |c_b|, \ldots.$$

Predictions

PDF input: CTEQ6L and CTEQ6.1M

	Tevatron, $\sqrt{s}=1.96$ TeV		LHC, $\sqrt{s}=14$ TeV	
$\ell\ell$	LO	NLO	LO	NLO
$C_{\rm hel}$	-0.471	-0.352	0.319	0.326
$C_{\rm beam}$	0.928	0.777	-0.005	-0.072
$C_{\rm off}$	0.937	0.782	-0.027	-0.089
D	0.297	0.213	-0.217	-0.237
$\ell+j$				
$C_{\rm hel}$	-0.240	-0.168	0.163	0.158
$C_{\rm beam}$	0.474	0.370		
$C_{\rm off}$	0.478	0.372		
D	0.151	0.101	-0.111	-0.115

W.B., A. Brandenburg, Z.G. Si, P.Uwer, NPB690 (2004)81

- results available also for all-jets channels
- good choices: beam basis for Tevatron, helicity basis and D for LHC (somewhat better basis exists, Uwer (2005))
- effects enhanced by suitable cuts on $M_{t\bar{t}}$
- dependence on PDFs, as $q\bar{q}$ and gg contributions enter with different sign.

Yet results almost unchanged when CTEQ6.1M $\longrightarrow$ MRST2003

- recent LHC study of dilepton and lepton + jets events at the detector level:

F. Hubaut et al. (2005): $\delta D \simeq 4\%$, $\delta C_{hel} \simeq 6\%$

EW corrections, single spin asymmetries

electroweak corrections to hadronic $t\bar{t}$ production:

$$\text{LO: } q\bar{q} \to \gamma^*, Z^* \to t\bar{t}$$

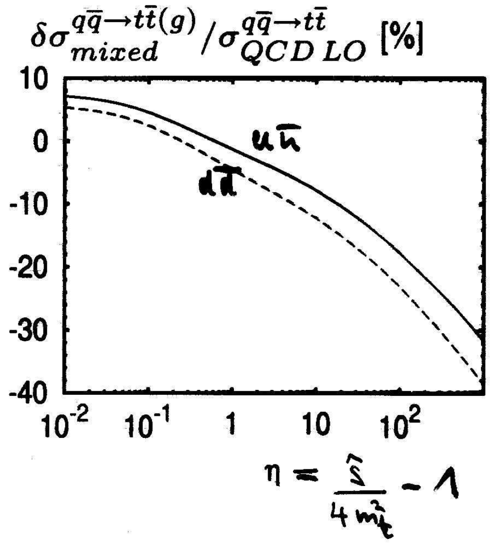
NLO: mixed QCD-EW $\mathcal{O}(\alpha\alpha_s^2)$ corrections to $q\bar{q}$, $gg \to t\bar{t}$

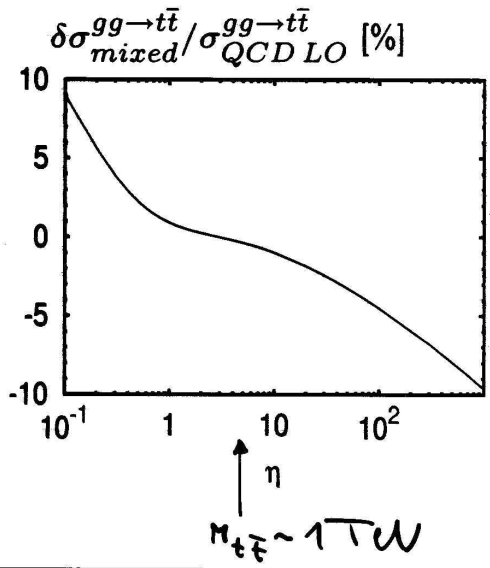
Beenakker et al., Kao, Ladinsky, Yuan

recent addition: box contributions + real gluon radiation

W.B., Fuecker, Si (2005); Kühn, Scharf, Uwer (2005)

EW contributions to $\sigma_{t\bar{t}}$ swamped by QCD uncertainties might be visible in $\frac{1}{\sigma}\frac{d\sigma}{dM_{t\bar{t}}}$ for $M_{t\bar{t}} > 1$ TeV (large EW Sudakov logs)





EW corrections $\longrightarrow$ P-violating single spin asymmetries, i.e., t, $\bar{t}$ polarization in production plane

$$< \mathbf{s}_t \cdot \hat{\mathbf{p}} >, \qquad < \mathbf{s}_t \cdot \hat{\mathbf{k}}_t >$$

and likewise for $\bar{t}$

$\rightarrow$ **leptonic asymmetries in $\ell\ell$ and $\ell + j$ channels:**

$$pp, p\bar{p} \rightarrow t\bar{t}X \rightarrow \ell^+ + X$$

Angular distributions:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+} = \frac{1}{2}(1 + B\cos\theta_+)$$

$$\theta_+ = \angle(\ell^+, \hat{\mathbf{a}})$$

e.g., $\hat{\mathbf{a}}$ = **beam axis (Tevatron), helicity axis (LHC)**

small effect: $|B| < 1\%$

Kao, Wackeroth; W.B., Fuecker, Si

may be enhanced somewhat by choosing suitable inv. mass bins

definite SM prediction $\longrightarrow$ good observables to search for non-SM parity violation in $t\bar{t}$ production

Heavy resonances

Extensions of SM, e.g. supersymmetric extensions, top-condensation models, ...
$\rightarrow$ heavy resonances φ_J that strongly couple to top quarks
φ_J: could be a Higgs boson, a bound state,...
E.g., 2HDMs or minimal supersymmetric extension of SM:

3 neutral Higgs bosons $h_1, h_2,$ $\quad J^{PC} = 0^{++}$
$A,$ $\quad J^{PC} = 0^{-+}$

h_2, A may be heavy, $m > 300$ GeV
$A \not\rightarrow W^+W^-, ZZ$ in lowest order,
but A (like $h_{1,2}$) can strongly couple to top quarks

Consider $\varphi_J = h_2, A$:

$$\mathrm{gg} \longrightarrow \mathrm{t\bar{t}} \longrightarrow \text{final state}$$
$$\mathrm{gg} \longrightarrow \varphi_J \longrightarrow \mathrm{t\bar{t}} \longrightarrow \text{final state}$$

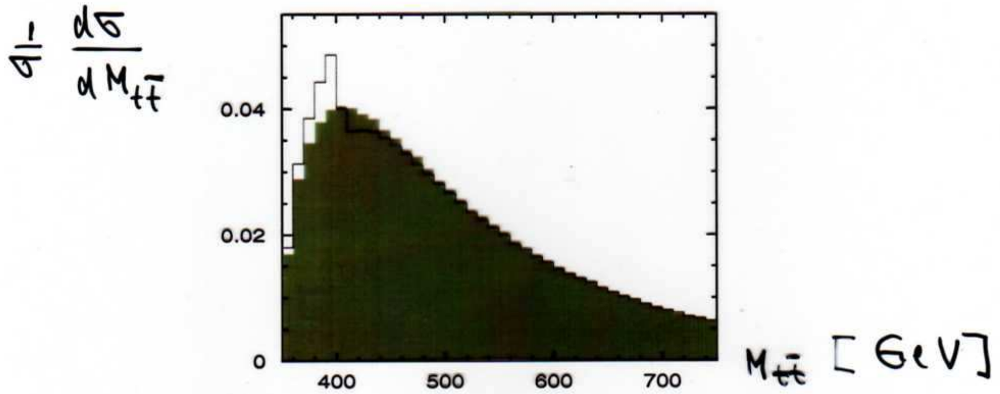
interference of amplitudes leads to typical peak-dip resonance structure

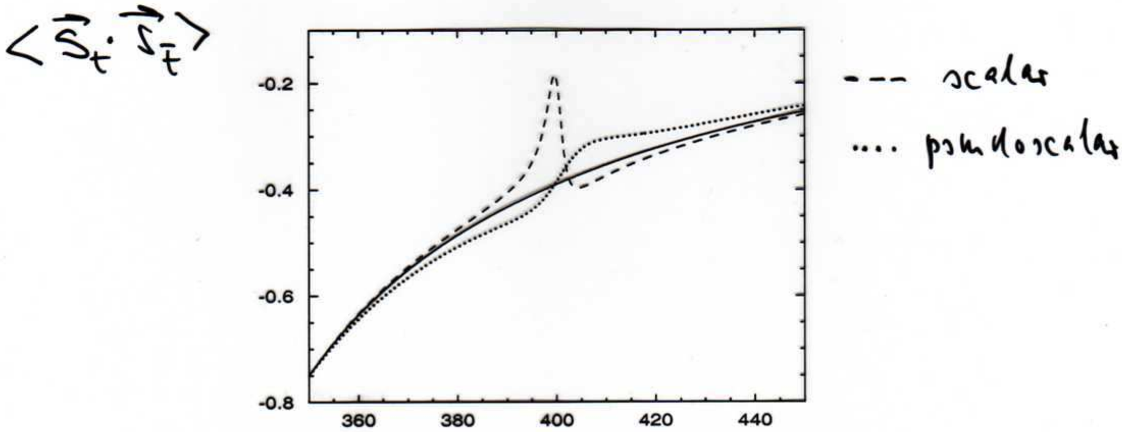
LHC: $pp \to A + X \to t\bar{t} + X \to \ell +$ Jets

Example: $m_A = 400$ GeV, $\Gamma_A = 12$ GeV

$t\bar{t}$ invariant mass distribution

$M_{t\bar{t}} = \sqrt{(p_t + p_{\bar{t}})^2}$





W.B., Flesch, Haberl

If resonance φ will be found in $M_{t\bar{t}}$ distribution $\rightarrow t\bar{t}$ spin correlations will be useful tool for determining properties of φ

scalar $\leftrightarrow$ pseudoscalar

consider reaction $gg \rightarrow \varphi \rightarrow t\bar{t}$

- if φ scalar, $J^{PC} = 0^{++}$
$\rightarrow t\bar{t}$ in ${}^3P_0$ state
$\rightarrow < \mathbf{s}_t \cdot \mathbf{s}_{\bar{t}} >= 1/4$

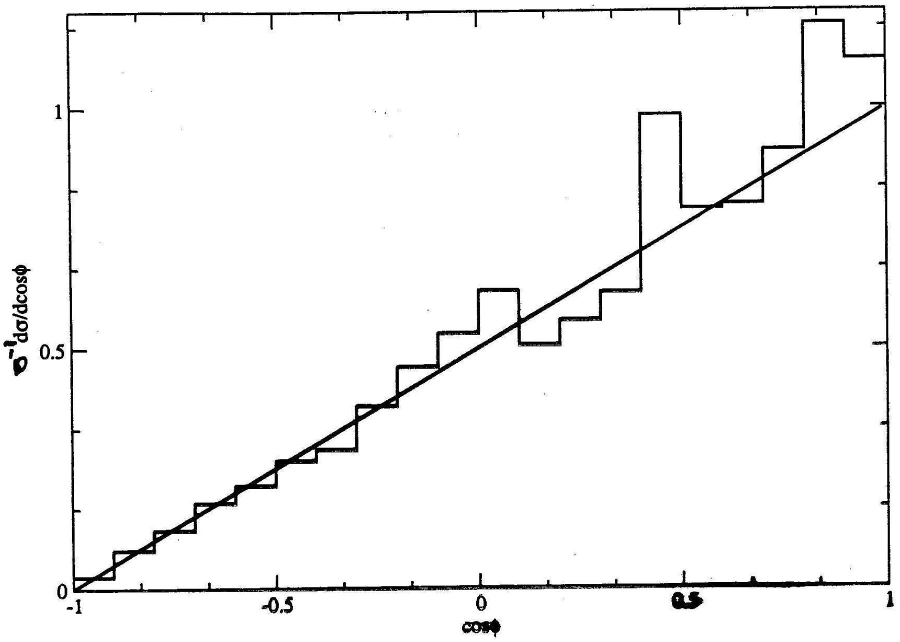
- if φ pseudoscalar, $J^{PC} = 0^{-+}$
$\rightarrow t\bar{t}$ in ${}^1S_0$ state
$\rightarrow < \mathbf{s}_t \cdot \mathbf{s}_{\bar{t}} >= -3/4$

only valid if non-resonant $t\bar{t}$ background is neglected. With $t\bar{t}$ background $\rightarrow$ Fig.

observable for dilepton channels:

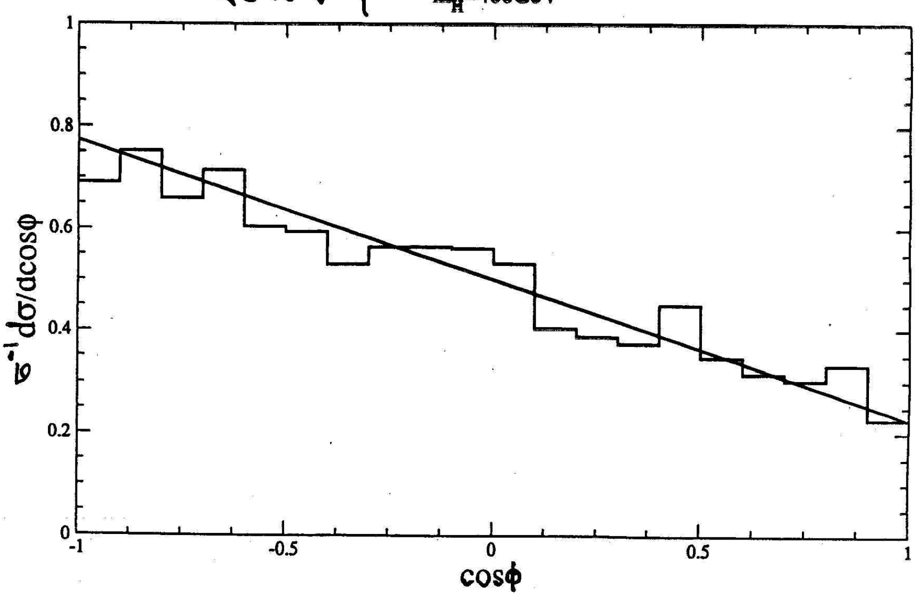
$< \mathbf{s}_t \cdot \mathbf{s}_{\bar{t}} > \quad \rightarrow \quad \hat{\ell}_+ \cdot \hat{\ell}_- = \cos\varphi$
$\rightarrow \quad \frac{1}{\sigma}\frac{d\,\sigma}{d\cos\varphi}$ sensitive to scalar $\leftrightarrow$ pseudoscalar

Opening angle distrib. for pseudoscalar $m_A = 400\,GeV$



$380\,GeV \leq M_{t\bar{t}} \leq 420\,GeV$

scalar



CP-violating Higgs boson interactions

In extensions of SM, Higgs boson self-interactions are in general not CP-invariant $\rightarrow$ neutral spin-zero mass eigenstates do not have a definite CP parity

e.g. 2HDM or minimal SUSY: mixing of $h_1, h_2 \leftrightarrow A$ $\rightarrow$ 3 neutral mass eigenstates φ with CP-violating Yukawa couplings;
e.g. couplings to top quark:

$$\mathcal{H}_Y = (\sqrt{2}G_F)^{1/2} m_t (a_t \bar{t}t + b_t \bar{t} i\gamma_5 t)\, \varphi$$

If $\quad \gamma_{CP} \equiv -a_t b_t \neq 0$

then $\quad H_Y = \int d^3x\, \mathcal{H}_Y$

violates CP

Consequences for $gg \to \varphi \to t\bar{t}$:

if $\gamma_{CP} \neq 0$, then CPV spin correlation

$$< \hat{\mathbf{k}}_t \cdot (\mathbf{s}_t \times \mathbf{s}_{\bar{t}}) >= \gamma_{CP}\, \beta_t/(b_t^2 + a_t^2\beta_t^2)$$

and CPV asymmetry in longitudinal polarization

$$< \hat{\mathbf{k}}_t \cdot (\mathbf{s}_t - \mathbf{s}_{\bar{t}}) > \neq 0$$

These spin corr./asymmetry induce CPV angular correlations/asymmetries among the $t\bar{t}$ decay products. Consider, e.g., the channels

$$\mathrm{pp} \to \varphi\mathrm{X} \to \mathrm{t\bar{t}X} \to \begin{cases} \ell^+ + \text{jets} \\ \ell^- + \text{jets} \end{cases}$$

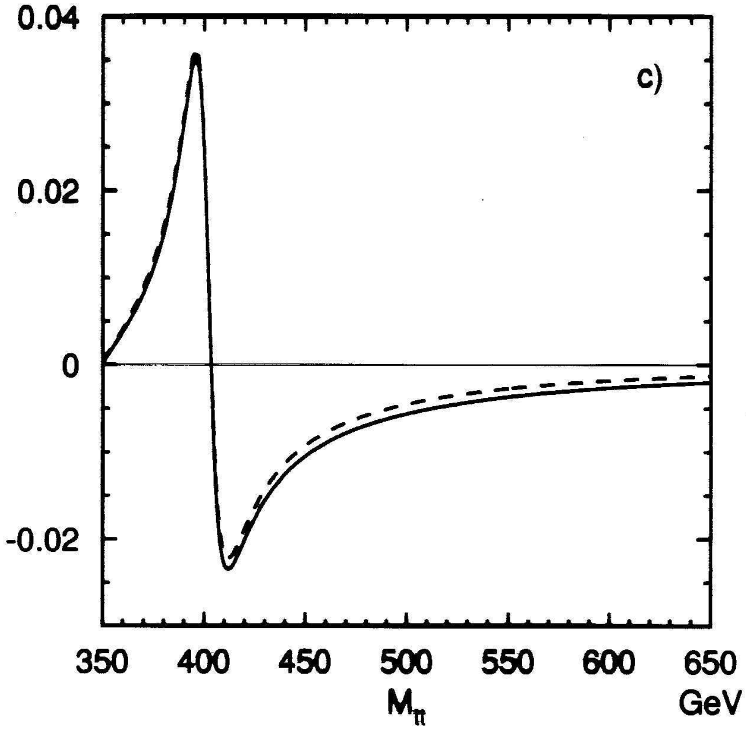
then

$$\hat{\mathbf{k}}_t \cdot (\mathbf{s}_t - \mathbf{s}_{\bar{t}}) \quad \to \quad \mathcal{O} = \cos\theta_+ \; - \; \cos\theta_-$$

with angles $\theta_+ = \angle(t, \ell^+)$, $\theta_- = \angle(\bar{t}, \ell^-)$

W.B., A. Brandenburg

$< \mathcal{O} >$ als a function of $t\bar{t}$ invariant mass,
Example: $m_\varphi = 400$ GeV, $\Gamma_\varphi = 20$ GeV and $\gamma_{CP} = 1$



Observables which are more robust experimentally:

e.g. for dilepton channels

$t\bar{t} \to \ell^+ \ell'^- \; + \; ....$

observable

$\mathcal{O} = \cos\theta_+ \; - \; \cos\theta_-$

corresponds to asymmetry

$$A \;=\; \frac{N_{\ell\ell}(\mathcal{O} > 0) - N_{\ell\ell}(\mathcal{O} < 0)}{N_{\ell\ell}}$$

Results at the level partonic final states:
if Yukawa couplings are such that
$|\gamma_{CP}| = |a_t b_t| > 0.2$ and $m_\varphi \sim$ 300 - 500 GeV
$\to$ statistically significant effects (5σ)

Conclusions

• Top-quark spin physics ↔ physics of a bare quark
remains to be fully explored
both in $t\bar{t}$ and in single top production & decay

• $t\bar{t}$ production: spin correlations, t and $\bar{t}$ polarization:
SM predictions at NLO (QCD and EW)
precision measurements at LHC feasible
→ important tools to explore the dynamics of top quarks

Open issues (theory):

• efficient NLO MC generator
with t, $\bar{t}$ spin d.o.f. included

• effect of gluon resummation on spin correlations

• more systematic studies of non-SM top-spin effects