Top Quark Theory Review

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Top Quark Physics at Hadron Colliders

- Properties of Top Quark
- Top Quark Decays
- Cross Section for Hadronic Top Quark Production
- Charge Asymmetry in Hadronic $t\bar{t}$ Production
- Top Quark Spin Effects in Hadronic $t\bar{t}$ Production
- Summary

Properties of Top Quark

Top Quark

- Spin: $\frac{1}{2}$ Color: $SU(3)_C$ Triplet Electric Charge: $\frac{2}{3}e$
- mass: $m_t \sim 173.1 \pm 0.6 \pm 1.1$ (PDG '10)

  $\Rightarrow$the heavist elementary particle
- Top Decay Width: $\Gamma_t = 2.0^{+0.3}_{-0.6}$ GeV (PDG '10)
- Lifetime $\tau_t \sim 4 \times 10^{-25}$sec

  $<<$Characteristic Hadronization $\sim 3 \times 10^{-24}$sec

$\Rightarrow$ Top Quark Decays before Hadronization!

- Top quark physics: useful tool to test SM and search for new physics BSM

Properties of Top Quark

Physics Issuses

1. Top quark is an ideal laboratory to test predictions of perturbation theory w.r.t. heavy quark production
2. Unique Opportunity to Investigate Interactions of a **Bare Quark** at Energies $\sim$ a few 100 GeV
   - observables w.r.t. Top quark spin can be predicted perturbatively and measured at Tevatron and LHC
   - top quark mass close to the scale of EWSB, $Y_t \sim 1$
     $\Rightarrow$Excellent Probe of Mechanism of EWSB
   - Good Probe for non-SM Parity and/or CP Violation
3. Dynamics of Top Production and Decay is not fully explored so far
   - New Decay Mode of Top Quark, e.g., $t \to \tilde{t}, \cdots$?
   - New Resonance Production ? $\cdots\cdots$

- Top Quark Physics within SM

Top Quark Decays

$t \to q + W^+$ $(q = d, s, b)$

- $\Gamma(t \to qW^+) \propto |V_{tq}|^2$
  Unitarity Relation: $|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2 = 1$
  $|V_{td}| \sim 0.00874,\ |V_{ts}| \sim 0.0407,\ |V_{tb}| \sim 0.999133$

$$\Rightarrow \begin{cases} Br(t \to bW^+) \simeq 0.998 \\ Br(t \to sW^+) \simeq 0.0019 \\ Br(t \to dW^+) \simeq 0.0001 \end{cases}$$

Dominant Decay Channel: $t \to bW^+$

Top Quark Decay Width

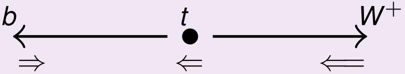
- $\Gamma_t \simeq \frac{G_F m_t^3 |V_{tb}|^2}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$

Jezabek, Kühn '89; Li, Oakes, Yuan, '91

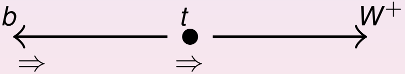
W-boson Helicity

Within SM, the structure of tbW vertex is the universal $(V - A)$ charged current interaction

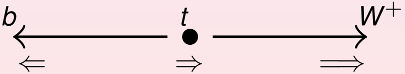
1. $t \to bW^+(h_W = -1)$ Allowed: *Prob.* $\sim 30\%$.



2. $t \to bW^+(h_W = 0)$ Allowed: *Prob.* $\sim 70\%$.



3. $t \to bW^+(h_W = +1)$ Forbidden for $m_b = 0$



non-zero m_b+QCD+EW Corr. $\to$ *Prob.* $\sim 0.1\%$. Do et al. '03

W-boson Helicity

Information on W polarization can be obtained from $W^+ \to l^+ \nu_l$:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\Psi^*} = \frac{3}{4}F_0 \sin^2\Psi^* + \frac{3}{4}F_-\left(1-\cos\Psi^*\right)^2 + \frac{3}{8}F_+\left(1+\cos\Psi^*\right)^2$$

- the decay functions: $F_{0,\pm} \sim B[t \to bW(\lambda_W = 0, \pm 1)]$

$$F_0 + F_- + F_+ = 1$$

	F_0	F_+	F_-
Tevatron: CDF	$0.85^{+0.16}_{-0.23}$	-0.02 ± 0.08	
D0	0.62 ± 0.10	-0.02 ± 0.07	
LHC: ATLAS	0.67 ± 0.07	0.01 ± 0.05	0.32 ± 0.04

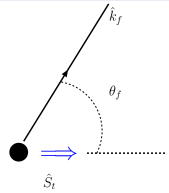
Top Quark Decays

Top Quark Spin Analyzer

Ensemble of Top Quarks Self-Analyses its Spin Polarization via its Parity-Violating Weak Decays

$$t \to W^+ + b \to \left[\begin{array}{l} l + \nu_l + b \\ q_1 + \bar{q}_2 + b \end{array} \right.$$

Standard V-A Charged Current Interaction $\to$ Charged Lepton $l = e, \mu, \tau$ or d-type quark: the Best Analyzer of Top Spin



Decay Distribution of (100%) Polarized $t \to f + \cdots$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta_f} = \frac{1}{2}\left(1 + \kappa_f cos\vartheta_f\right)$$

κ_f: the top quark spin analyzing power of f

$\kappa_l = 1$ (Maximal)

$\kappa_b = -\kappa_W = -0.41$

Top Quark Decays

NLO QCD Corrections to Top Quark Spin Analyzing Power

Semi-leptonic Decays: $t \to b l^+ \nu_l,\ b l^+ \nu_l + g$

Non-leptonic Decays: $t \to b q_1 \bar{q}_2,\ b q_1 \bar{q}_2 + g \Longrightarrow t \to j_b j_1 j_2,\ j_b j_1 j_2 j_3$

Spin Analyzer Quality Factor κ_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	

Czarnecki, Jezabek, Kühn '91 (semileptonic)

Brandenburg, Si, Uwer '02 (non-leptonic)

- a u-type jet cannot be distinguished from a d-type jet

  $j_<$: *Least energetic non-b-jet(Durham Algorithm)*

  $j_>$: *most energetic non-b-jet(Durham Algorithm)*

Cross Section for Hadronic Top Quark Production

Cross section for $t\bar{t}$ pair production

1. NLO QCD corrections to $t\bar{t}$ production
   Nason, Dawson, Ellis; Beenakker, et al.; Mangano, Nason, Ridolfi
2. NLO QCD+ NLL Threshold resummation
   Boncani, et al.; Moch, Uwer; Cacciari et al.; Kidonakis, Vogt; Banfi, Lanenen; Czakon, et al.; Beneke, et al.; ...
3. Mixed weak-QCD corrections
   Beenakker, et al.; Kao, Ladinsky, Yuan; Bernreuther, Fücker, Si; Kühn, Scharf, Uwer; Moretti, et al.
4. Mixed QED-QCD corrections Hollik, et al.
5. P_T resummation for $t\bar{t}$ production Huaxing Zhu's Talk
6. NLO QCD corrections to $t\bar{t} + jet$ production
   Dittmaier, Uwer, Weinzierl; Melnikov, Schulze
7. NNLO QCD corrections to hadronic $t\bar{t}$ production
   Czakon, Mitov, Moch; Bonciani, et al.

Top Quark Pair Production within SM: Total Cross Section

Cross section($\sigma_{t\bar{t}}$) from QCD and weak interactions

		$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
Tevatron (pb)	NLO QCD	7.493	7.105	6.314
	Weak	0.0339	0.0355	0.0346
LHC 7TeV (pb)	NLO QCD	162.636	146.018	127.523
	Weak	-0.950	-0.629	-0.440
LHC 14TeV (pb)	NLO QCD	868.150	850.385	793.543
	Weak	-14.127	-10.790	-8.368

- Weak corrections smaller than the scale uncertainties of the fixed-order NLO QCD corrections
- Weak corrections to large M_{tt} or P_T can and become larger due to the electroweak Sudokov logorithms

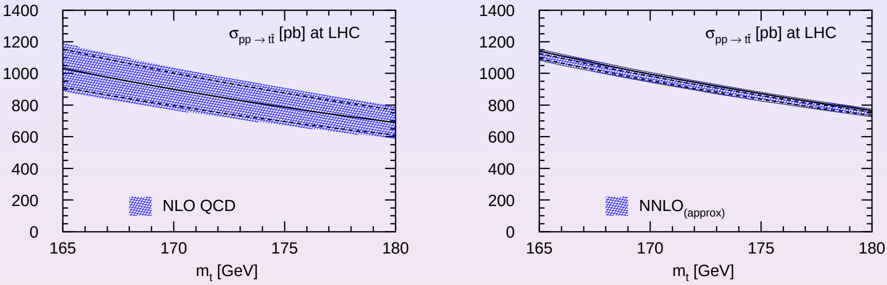


Figure: *The NNLO (approx) QCD prediction for the $t\bar{t}$ total cross section.*

Moch, Uwer '08

Cross Section for Hadronic Top Quark Production

Cross section for single top quark production

1. NLO QCD corrections
   Bordes, Eijk; Giele, Keller, Laenen; Stelzer, Sullivan, Willenbrock; Harris et al.; Campbell, Ellis, Tramontano; Cao, Yuan, et al.; White et al.
2. Threshold resummation — Kidonakis
3. Mixed weak-QCD corrections — Beccaria, et al.

Cross section(σ_t) at NNNLO approximation

σ_t(pb)	Teavtron	LHC
t-channel	1.15 ± 0.07	150 ± 6
s-channel	0.54 ± 0.04	$7.8^{+0.7}_{-0.6}$
tW channel	0.14 ± 0.03	43.5 ± 4.8

Kidonakis '06, '07

Charge Asymmetry in Hadronic $t\bar{t}$ production

Charge Asymmetry

$$A_{charge} = \frac{N_t(\cos\theta) - N_{\bar{t}}(\cos\theta)}{N_t(\cos\theta) + N_{\bar{t}}(\cos\theta)} \neq 0$$

generated from the interference of even and odd terms under $t \leftrightarrow \bar{t}$:

$$d\sigma(t,\bar{t}) = -d\sigma(\bar{t},t)$$

Within SM, Charge Asymmetry comes from:

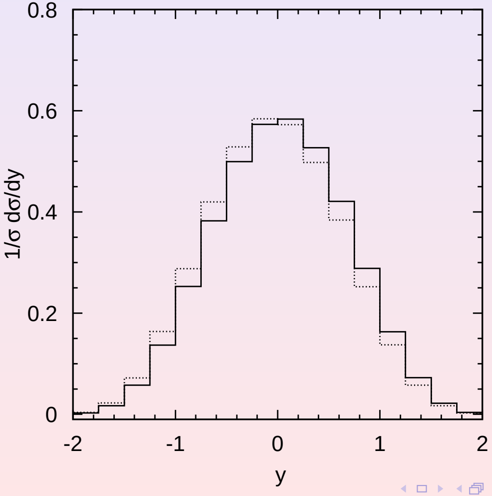
- $q\bar{q} \to t\bar{t}(g), \quad gq(\bar{q}) \to t\bar{t}q(\bar{q})$

Present status:

1. QCD at $\mathcal{O}(\alpha_s^3)$: Kühn, Rodrigo; Bowen, Ellis, Rainwater
2. + mixed QCD-weak at $\mathcal{O}(\alpha_s^2\alpha)$ and $\mathcal{O}(\alpha^2)$: Bernreuther, Si; Hollik, Pagani
3. + mixed QCD-QED at $\mathcal{O}(\alpha_s^2\alpha)$: Hollik, Pagani; Bernreuther, Si
4. QCD resummation: Langenfeld, Moch, Uwer; Almeida, Sterman

Top Quark Charge Asymmetry at Tevatron

Tevatron: $|p(\mathbf{p})\bar{p}(-\mathbf{p}) >$ is CP eigenstate:
CP invariance $\Rightarrow N_{\bar{t}}(y_{\bar{t}}) = N_t(-y_t)$



Top Quark Charge Asymmetry at Tevatron

- charge asymmetry: $A_{FB}^{t} = \frac{N_t(y_t>0) - N_t(y_t<0)}{N_t(y_t>0) + N_t(y_t<0)}$ and $A_{FB}^{\bar{t}} = -A_{FB}^{t}$
- pair asymmetry: $A^{t\bar{t}} = \frac{N_{t\bar{t}}(\Delta y>0) - N_{t\bar{t}}(\Delta y<0)}{N_{t\bar{t}}(\Delta y>0) + N_{t\bar{t}}(\Delta y<0)}$ with $\Delta y = y_t - y_{\bar{t}}$

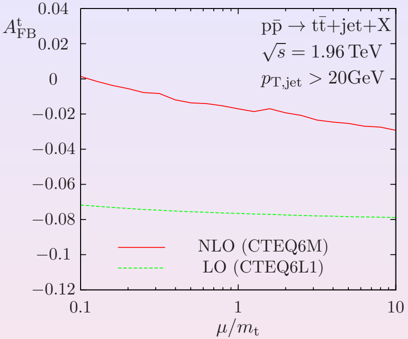
Tevatron		$N_t^i / N_t^{tot}(\%)$	$N_{t\bar{t}}^i / N_{t\bar{t}}^{tot}$
$O(\alpha_s^3)$	$u\bar{u}$	69.3	69.1
	$d\bar{d}$	12.1	12.2
	qg	0.01	0.01
$O(\alpha^2)_{weak}$	$u\bar{u}$	2.6	2.7
	$d\bar{d}$	0.4	0.3
$O(\alpha\alpha_s^2)_{weak}$	$u\bar{u}$	1.7	1.6
	$d\bar{d}$	-0.5	-0.5
$O(\alpha\alpha_s^2)_{QED}$	$u\bar{u}$	15.9	16.0
	$d\bar{d}$	-1.4	-1.4

Top Quark Charge Asymmetry at Tevatron

	CDF '11	CDF '12	SM Prediction
A^t_{FB}	0.150 ± 0.055		0.058 ± 0.004
$A^{t\bar{t}}$	0.158 ± 0.075	0.162 ± 0.047	0.088 ± 0.006
$A^{t\bar{t}}(\lvert\Delta y\rvert \leq 1)$	0.026 ± 0.118	0.088 ± 0.047	$0.061^{+0.004}_{-0.003}$
$A^{t\bar{t}}(\lvert\Delta y\rvert > 1)$	0.611 ± 0.256	0.433 ± 0.109	$0.206^{+0.011}_{-0.010}$
$A^{t\bar{t}}(M_{t\bar{t}} \leq 450\ \mathrm{GeV})$	-0.116 ± 0.153	0.078 ± 0.054	$0.062^{+0.004}_{-0.003}$
$A^{t\bar{t}}(M_{t\bar{t}} > 450\ \mathrm{GeV})$	0.475 ± 0.114	0.296 ± 0.067	$0.129^{+0.008}_{-0.006}$

- D0 '11 for $A^{t\bar{t}}$: 0.196 ± 0.065
- The largest deviation between data and SM prediction $< 3\sigma$.

Top Quark Charge Asymmetry at Tevatron



For $p\bar{p} \to t\bar{t} + jet + X$ with $P_T^{jet} > 20$ GeV

- Dittmaier, Uwer, Weinzierl: $A^t_{FB} = -0.015 \pm 0.015$ (-8% @ LO)
- Melnikov, Schulze: $A^t_{FB} \simeq 2\%$

Top Quark Charge Asymmetry at Tevatron

For the process $p\bar{p} \to t\bar{t}X \to l^+l^- + X$ define the charge asymmetry w.r.t. charged leptons Bernreuther, Si '10, '12

- $A^l(y) = \frac{N_{l^+}(y>0) - N_{l^-}(y>0)}{N_{l^+}(y>0) + N_{l^-}(y>0)}$, $A^{l^+l^-}(y) = \frac{N(\delta y>0) - N(\delta y<0)}{N(\delta y>0) + N(\delta y<0)}$

Tevatron		SM	data
A^l (%)	QCD:	3.1 (3)	D0 '11: 15.2 ± 4.0
	QCD + EW:	3.8 (3)	CDF '12: 6.6 ± 2.5
A^l (%)	QCD:	5.8 (5)	
($m_{t\bar{t}} \geq 450$ GeV)	QCD + EW:	7.0 (5)	CDF '12: 11.6 ± 4.2
A^l (%)	QCD:	1.5 (1)	
($m_{t\bar{t}} < 450$ GeV)	QCD + EW:	1.8 (1)	CDF '12: 3.7 ± 3.1
A^{ll} (%)	QCD:	4.0 (4)	
	QCD + EW:	4.8 (4)	D0 '12: $5.8 \pm 7.9 \pm 2.9$

Top Quark Charge Asymmetry at Tevatron

	Tevatron (($t\bar{t}$ correlated))			Tevatron ($t\bar{t}$ uncorrelated))		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m_t	$2m_t$
$A^{t\bar{t}}$ (NLO')	0.074	0.068	0.062	0.075	0.067	0.061
$A^{t\bar{t}}$ (NLOW')	0.078	0.071	0.066	0.077	0.070	0.065
A^{l} (NLO')	0.038	0.033	0.031	0.037	0.033	0.030
A^{l} (NLOW')	0.039	0.034	0.032	0.038	0.035	0.032
$A^{l^+l^-}$ (NLO')	0.047	0.042	0.038	0.050	0.045	0.041
$A^{l^+l^-}$ (NLOW')	0.048	0.044	0.040	0.052	0.047	0.043

Bernreuther, Si '10

- Charge asymmetry from top quark spin effects can be neglected.

Top Quark Charge Asymmetry at LHC

- LHC: $|p(\mathbf{p})p(-\mathbf{p}) >$ is Parity eigenstate
- in lab frame without asymmetric cuts:
  Parity invariance $\Rightarrow A^{t}_{FB} = A^{\bar{t}}_{FB} = 0$

Charge Asymmetry at LHC:

- no contribution from $gg \to t\bar{t}(g)$ due to Bose symmetry
- $q\bar{q} \to t\bar{t}, q = u, d$
  production dominated by q with large x_q and $\bar{q}$ with small $x_{\bar{q}}$
  1. **NLO QCD** $\Rightarrow t(\bar{t})$ emitted in the direction of $q(\bar{q})$ with large probabilty
  2. **Boost to lab frame**: t in the forward and backword region
     $\bar{t}$ in the central region

  $\Rightarrow$ differential charge asymmetry $A(y) \neq 0$, though $\int A(y)dy = 0$
- likewise: $qg \to t\bar{t}g$

$\Rightarrow$ **with suitable cuts, charge asymmetry can be non-zero in SM**

Top Quark Charge Asymmetry at LHC

Cut-dependent charge asymmetry

1. **Central Charge Asymmetry** — Antunano, Kühn, Rodrigo '08
   - $A_C = \frac{N(|y_t|<y_c)-N(|y_{\bar t}|<y_c|}{N(|y_t|<y_c)+N(|y_{\bar t}|<y_c|}$
2. **One-side FB asymmetry** — Wang, Xiao, Zhu '11
   - $A_O^{FB} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}\Big|_{P^z_{t\bar t}>P_c}^{M_{t\bar t}>M_c}$

Cut-independent charge asymmetry

1. $A_C^{\Delta|y|} = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$ with $\Delta|y| = |y_t| - |y_{\bar t}|$
2. $A_C^{\Delta|\eta|} = \frac{N(\Delta|\eta|>0)-N(\Delta|\eta|<0)}{N(\Delta|\eta|>0)+N(\Delta|\eta|<0)}$ with $\Delta|\eta| = |\eta_t| - |\eta_{\bar t}|$

kühn, Rordrigo '12

Top Quark Charge Asymmetry at LHC

Bernreuther, Si '12

	$\sqrt{s}$=7 TeV	$M_{t\bar{t}} \geq 2m_t$	$M_{t\bar{t}} \geq 0.5$TeV	$M_{t\bar{t}} \geq 1$TeV
$A_C^{\Delta\|y\|}$	QCD (%):	1.07(4)	1.27(4)	2.06(5)
	QCD+EW (%):	1.23(5)	1.48(4)	2.40(6)
	CMS '12(%):	$0.4 \pm 1.0 \pm 1.2$		
	ATLAS '12(%):	$-1.8 \pm 2.8 \pm 2.3$		
$A_C^{\Delta\|\eta\|}$	QCD (%):	1.36(6)	1.39(5)	2.15(5)
	QCD+EW (%):	1.56(7)	1.64(6)	2.52(5)
	CMS '12(%)	$-1.7 \pm 3.2^{+2.5}_{-3.6}$		

- **within the large experimental error, SM predictions agree with data**

Top Quark Charge Asymmetry at LHC

- Charge asymmetry w.r.t charged lepton for $pp \to t\bar{t}X \to l^+l^-X$

$$A^{\Delta|\eta_l|} = \frac{N_{ll}(\Delta|\eta_l| > 0) - N_{ll}(\Delta|\eta_l| < 0)}{N_{ll}(\Delta|\eta_l| > 0) + N_{ll}(\Delta|\eta_l| < 0)}, \quad \Delta|\eta_l| = |\eta_{l^+}| - |\eta_{l^-}|$$

	$\sqrt{s}$=7 TeV	$M_{t\bar{t}} \geq 2m_t$	$M_{t\bar{t}} \geq 0.5$TeV	$M_{t\bar{t}} \geq 1$TeV
$A_C^{\Delta|\eta_l|}$	QCD (%):	0.41(2)	0.94(4)	1.63(2)
	QCD+EW (%):	0.49(1)	1.13(2)	1.94(1)
	ATLAS '12(%):	$2.3 \pm 1.2 \pm 0.8$		

Bernreuther, Si '12

Possible Spin-Effects

1. **Polarization of t,$\bar{t}$: (very) Small**
   - Normal to Production Plane(P-even, T-odd) due to QCD Absorptive Parts (Bernreuther, Uwer)
   - Polarization in Production Plane(Parity-violation) due to Weak Interactions (Bernreuther, Fuecker, Si)

2. **$t\bar{t}$ Spin Correlations:**
   - Large Effect in SM, mainly due to QCD (Mahlon, Parke; Brandenburg; Bernreuther, Brandenburg, Si, Uwer)
   - Strength Depends on the Choice of Reference Axes $\longrightarrow$ t, $\bar{t}$ Spin Quantization Axes(Mahlon, Parke; Uwer)

Spin-Correlation: Qualitative Analyse

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

1. **Production Threshold ($\beta_t \to 0$):** $t\bar{t}$ in $^3\mathbf{S}_1$ State
   $\Rightarrow$ $t\bar{t}$-Spins **100% correlated** w. r. t. Beam Basis
2. **High Energy Limit ($\beta_t \to 1$):** Top-Polarization $||$ Flying-Direction
   $\Rightarrow$ $t\bar{t}$-Spins **100%correlated** w. r. t. Helicity basis
   (helicity conservation of quark gluon inter.)
3. "Off-Diagonal Basis" (Mahlon, Parke)

$$\hat{\mathbf{d}} = \frac{-\hat{\mathbf{p}}+(1-\gamma)(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}_t)\hat{\mathbf{k}}_t}{\sqrt{1-(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}_t)^2(1-\gamma^2)}}, \quad \gamma = E_t/m_t \quad \Rightarrow < 4(\hat{\mathbf{S}}_t\cdot\hat{\mathbf{d}})(\hat{\mathbf{S}}_{\bar{t}}\cdot\hat{\mathbf{d}}> = 1 \text{ (LO)}$$

$gg \to t\bar{t}$

Production Threshold: $t\bar{t}$ in $^1\mathbf{S}_0$ State
No Off-Diagonal Basis exists to produce 100% $t\bar{t}$ correlations!!!

Spin Effects in Hadronic $t\bar{t}$ Production

$t\bar{t}$ Spin Correlations

W.R.T Arbitrary Reference Axes $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$:

$$< 4(\hat{\mathbf{a}} \cdot \hat{\mathbf{s}}_t)(\hat{\mathbf{b}} \cdot \hat{\mathbf{s}}_{\bar{t}}) >= A$$

where A is the $t\bar{t}$ Double Spin Asymmetry

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

For on-shell t, $\bar{t}$: $\hat{\mathbf{a}}$, $\hat{\mathbf{b}} \leftrightarrow$ Spin Axes:

$$\hat{\mathbf{a}} = \hat{\mathbf{k}}_t, \quad \hat{\mathbf{b}} = \hat{\mathbf{k}}_{\bar{t}} \qquad (helicity\ basis)$$

$$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{p}} \qquad (beam\ basis)$$

$$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{d}} \qquad (off - diagonal\ basis)$$

Spin Effects in Hadronic $t\bar{t}$ Production

Double Distribution for $pp/p\bar{p} \to t\bar{t} + X \to a_1 a_2 + X$ process

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ \cos\theta_-} = \frac{1}{4}[1 + B_1 \cos\theta_+ + B_2 \cos\theta_- - C \cos\theta_+ \cos\theta_-]$$

$\theta_+ = \sphericalangle(\hat{\mathbf{a}}_1, \hat{\mathbf{a}})$, $\theta_- = \sphericalangle(\hat{\mathbf{a}}_2, \hat{\mathbf{b}})$, $\hat{\mathbf{a}}, \hat{\mathbf{b}}$: **Spin-Quantization Axes**

1. B_1 and B_2 reflects top quark spin polarization
   - pure QCD effects: component normal to scattering plane
   - Weak int. leads to a component parallel to scattering plane
2. C reflects spin-spin correlations between t and $\bar{t}$
   - contr. from initial $q\bar{q}$ and gg induced by pure QCD effects have different sign $\Longrightarrow$ C can be used as a tool to determine PDF
   - all-order formula(factorizable corrections):

$$C = \kappa_+ \kappa_- A, \qquad -1 \le C \le 1$$

Spin Effects in Hadronic $t\bar{t}$ Production

Opening Angle Distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\phi} = \frac{1}{2}[1 - D\cos\phi]$$

e.g., for the dilepton channels

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

$\phi = \sphericalangle(l^+, l'^-)$ in resp. t, $\bar{t}$ rest frames.
These distributions apply also to (lepton +jets) & (all-jets) channels.
For these channels, $j_<$ is used, since top-spin analyzer in non-leptonic t decays

$$\kappa_{j_<} > |\kappa_b|, \cdots$$

We use the estimators

$$C = -9 < cos\theta_1 cos\theta_2 >, \quad D = -3 < cos\phi >, B_1 = 3 < cos\theta_1 > .$$

PDF Input: CTEQ6L and CTEQ6.1M, No cuts adopted

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

BBSU, NPB690(2004)81.

Spin Effects in Hadronic $t\bar{t}$ Production

Remarks

1. good choices: beam basis for Tevatron, helicity basis and D for LHC(somewhat better basis exists, Uwer(2005))
2. dependence on PDFs, as $q\bar{q}$ and gg contributions enter with different sign

- For the di-leptonic events at LHC: $pp \to t\bar{t} + X \to l^+ l^- + X$, the following cuts for the final states are used

$$p_T^l \geq 20 GeV, \quad |\eta_l| \leq 2.5, \quad p_T^j \geq 20 GeV$$

$$|\eta_j| < 2.4, \not{E}_T \geq 40 GeV$$

Top spin induced distributions and correlations

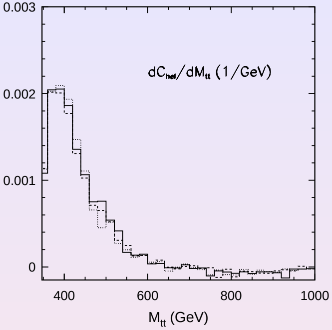


Figure: LHC(14TeV): $\mu = m_t/2$(dashed), m_t(solid) and $2m_t$(dotted)

- dC_{hel}/dM_{tt} change sign around $M_{tt} \sim 700$ GeV
- at LHC, proper choice of cut for M_{tt} can enlarge the spin correlations

Top Quark Spin Effects for dileptonic final states with cuts

	Tevatron			LHC $\sqrt{s} = 14 TeV$		
μ	$m_t/2$	m_t	$2m_t$	$m_t/2$	m	$2m$
$\sigma_{\ell\ell}$ (pb)	0.043	0.042	0.038	5.00	4.38	3.82
D	0.139	0.145	0.151	-0.240	-0.247	-0.230
$D(M_{\rm max})$	0.125	0.132	0.138	-0.340	-0.353	-0.338
$C_{\rm hel}$	-0.294	-0.299	-0.306	0.225	0.237	0.229
$C_{\rm hel}(M_{\rm max})$	-0.256	-0.262	-0.269	0.336	0.360	0.345
B_1				0.162	0.162	0.178
$C_{\rm beam}$	0.605	0.614	0.624			
$C_{\rm off}$	0.612	0.621	0.631			

Bernreuther, Si, '10 $M_{\rm max} = 550 GeV$

D0 beam basis(2011): 0.66 ± 0.23

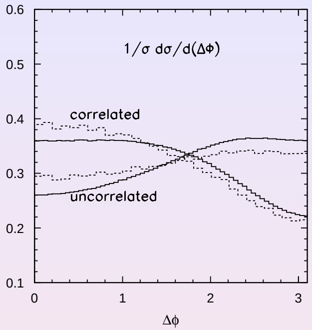
CDF off-diagonal basis(2011): $0.72 \pm 0.64 \pm 0.26$

ATLAS '11: $C_{hel} = 0.34^{+0.15}_{-0.11}$, SM prediction: $C_{hel} = 0.310 \pm 0.02$

Remarks

- Proper choice of M_{tt}^{max} can enlarge the $t\bar{t}$ spin correlations
- SM predictions agree with data at Tevatron and LHC

Di-lepton azimuthal opening angle($\Delta\phi$ Distribution)



- $\Delta\phi$ is the difference of the azimuzal angles between l^+ and l^- in the laboratory frame.
- For $M_{tt} < 400 GeV$, $\frac{1}{\sigma} d\sigma d\Delta\phi$ does discriminate between the correlated and uncorrelated $t\bar{t}$ events at
  - LO QCD Mahlon, Parke '10, Bernreuther, Si '10
  - NLO QCD Bernreuther, Si '10

Summary

- Predictions for $\sigma_{t\bar{t}}$ and σ_t contributed from NLO QCD, NLO EW and threshold resummation are available
- Some necessary building blocks for NNLO QCD calculations for $\sigma_{t\bar{t}}$ have been completed
- SM predictions for charge asymmetry agree with data
  $\Rightarrow$ precise measurements are important
  $\Rightarrow$ NNLO QCD computations for charge asymmetry are necessary
- NLO QCD and mixed QCD-weak corrections to $t\bar{t}$ production and decay including full top quark spin information are available

Detailed and precise studies on top quark physics are still necessary

Thanks a lot for your attention!