Standard Model: QCD

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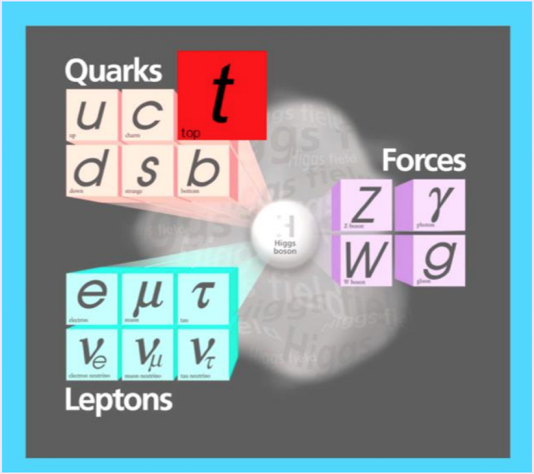
2014.8.21

- **Lecture 2: Heavy Quark and QCD**

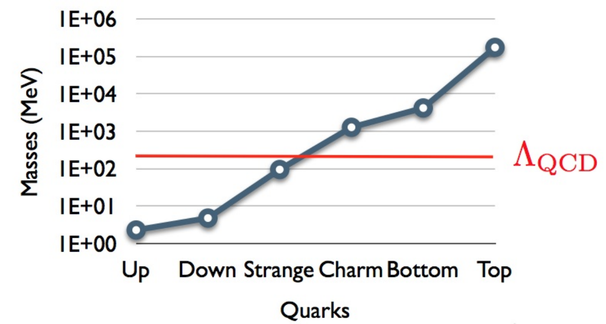
➢ **Top quark physics and QCD**



- What is heavy quark?
- Why study heavy quark?
- Why study top quark?

What is Heavy Quark

- Quarks are heavy if $M_Q >> \Lambda_{QCD} \sim$ *hundred MeV*
- Heavy Quarks: c, b, t

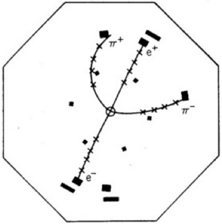


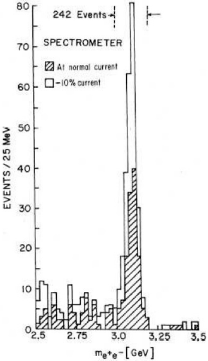
Charm Quark discovered in 1974!

- Charm Quark mass: $M_c \sim 1.5 GeV$

The first heavy quark, charm was discovered in 1974 in $p\bar{p}$ collisions at BNL and e^+e^- at SLAC

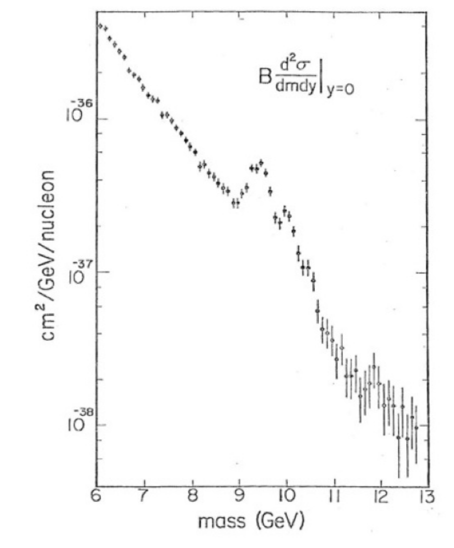
The J/ψ was recognized as a $c\bar{c}$ bound state $\Rightarrow m_c \sim 1.5$ GeV





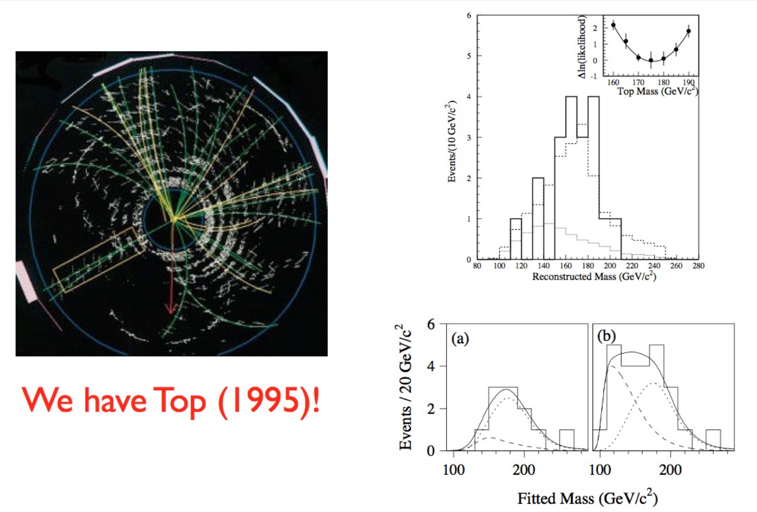
Bottom Quark discovered in 1977!

- Bottom Quark mass: $M_b \sim 5GeV \Rightarrow$ We must have top Quark!



Top Quark discovered in 1995!

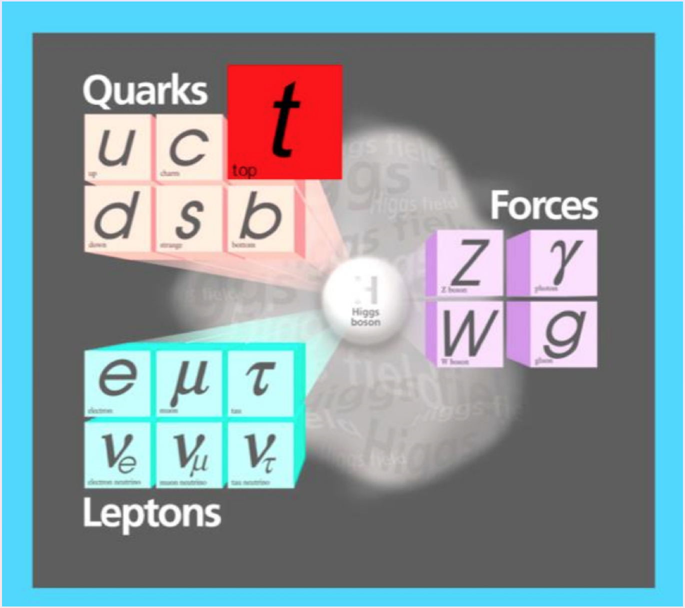
- Top Quark mass: $M_t = 173.07 \pm 0.52 \pm 0.72 GeV$



Why Study Heavy Quarks?

Why study heavy quarks?

- Measure and tests of SM parameters
- Important to understand for backgrounds
- Search for new physics beyond SM
- . . . .

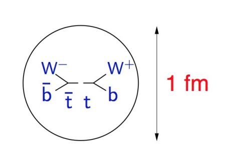

Quarks
u
c
t
top
d
s
b
Forces
Z
γ
W
g
Higgs boson
e
μ
τ
ν_e
ν_μ
ν_τ
Leptons

- Properties of Top Quark
- Theoretical Framework
- Top Quark Physics within SM
  - Top Quark Decay
  - Cross Section for Hadronic $t\bar{t}$ Production
  - Charge Asymmetry in Hadronic $t\bar{t}$ Production
  - Top Quark Spin Effects in Hadronic $t\bar{t}$ Production
- Top Quark Physics BSM
  - Top Quark Spin and Anomalous Top Quark Coupling
  - Top Quark Spin and W' Chiral Coupling
- Outlook

Why Study Top Quark

Top Quark Mass: $m_t \sim 173.07 \pm 0.52 \pm 0.72$

- Spin: $\frac{1}{2}$ Color: $SU(3)_C$ Triplet Electric Charge: $\frac{2}{3}e$
- The heavist elementary particle
- Decay Width: $\Gamma_t^{SM} \sim 1.3$ GeV , PDG 2013: $\Gamma_t = 2.0 \pm 0.5$ GeV
- Lifetime $\tau_t \sim 4 \times 10^{-25}$sec $<<$ Characteristic Hadronization time $\sim 3 \times 10^{-24}$sec



$\Rightarrow$ **Unique opportunity to investigate interactions of a bare quark !**

$\Rightarrow$ **Interactions are governed by short distance dynamics!!**

$\Rightarrow$ **Theoretical predictions related to top quark are reliable!!**

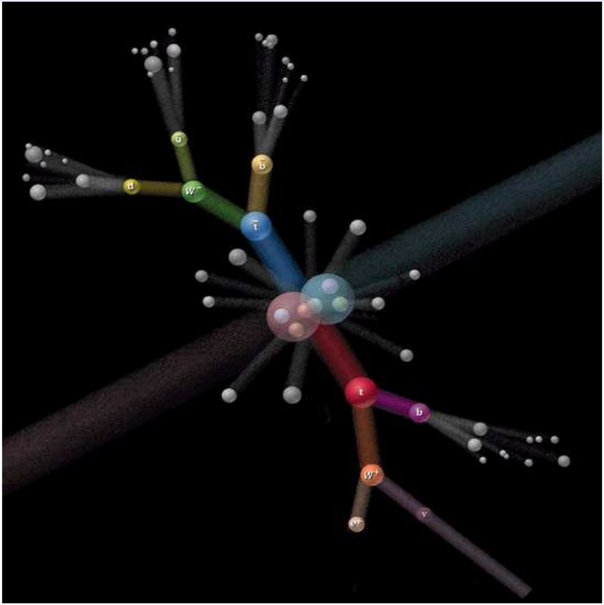
Top Quark Physics

- **Dynamics of top production and decay is not known very precisely so far:**
  Is $t \to b$ decay vertex really (V-A) ? New decay modes, eg., $t \to c + \cdots$?
  Exp. analyses require precise SM predictions.
- **Excellent probe of mechanism of EWSB**
  Higgs boson H has been found
  within SM, the Yukawa coupling(s) $y_t \, t\bar{t}H$
  $y_t = m_t/(246 GeV) \simeq 0.7$
  Search for heavy resonances, e.g. heavy non-standard Higgs bosons, that couple strongly to $t\bar{t}$
- **Good probe for non-SM parity and/or non-SM CP violation**:
  effects could be induced, e.g., by non-standard Higgs bosons

$\Longrightarrow$ **Important tool to precisely test SM and search for new physics BSM**

Theoretical Framework

Theoretical Framework



Theoretical Framework

Top-Quark Production and Decay: eg.

$$p\bar{p} \rightarrow t\bar{t}X \rightarrow bW^{+}\bar{b}W^{-} + X \rightarrow b\ell^{+}\nu\bar{b}\ell^{-}\bar{\nu} + X \rightarrow B_1\ell^{+}B_2\ell^{-} + p_T^{miss} + X$$

The distance between Top Quark Production- and Decay-verrtex is only $\sim 10^{-16}$m

$\Rightarrow$ Reconstruct Top Quark from its Decay Product!

Dilepton Channel:

$W^{+} \rightarrow \ell^{+}\nu,\ W^{-} \rightarrow \ell^{-}\bar{\nu}$

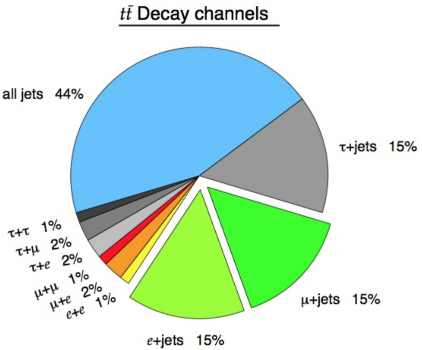
Single Lepton Channel:

$W^{+} \rightarrow \ell^{+}\nu,\ W^{-} \rightarrow d_i\bar{u}_j$

$W^{+} \rightarrow u_i\bar{d}_j,\ W^{-} \rightarrow \ell^{-}\bar{\nu}$

Hadronic Channel:

$W^{+} \rightarrow u_i\bar{d}_j,\ W^{-} \rightarrow d_i\bar{u}_j$



Calculation of $d\sigma(h_1 h_2 \to t\bar{t}X \to 6f + X$ at NLO QCD)

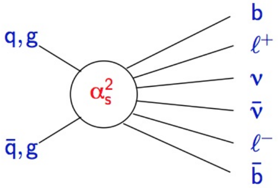
Within SM

$$q\bar{q}, gg \to t\bar{t} \to b\bar{b} + 4f(+g), \qquad f = q, \ell, \nu$$

QCD Correction: Amplitude to Order $\alpha_s^2(\times\alpha_W^2)$ Bernreuther, Brandenburg, Si, Uwer '00,'01,'02,'04

Amplitude $\mathcal{M}_{2\to 6}$:

(Analog $\mathcal{M}_{2\to 7}$)

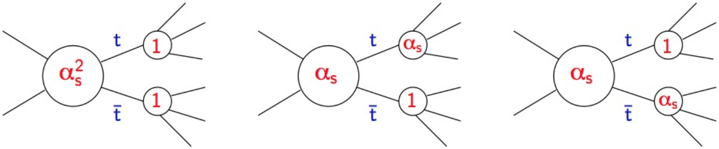


- $t, \bar{t}$ **instable** Particle with $\Gamma_t \approx 1.5$ GeV $\ll m_t$
  $\Rightarrow$ Expand the Amplitude at Complex Pole of the $t, \bar{t}$-Propagator

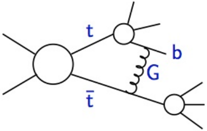
Calculation of $d\sigma(h_1 h_2 \to t\bar{t}X \to 6f(+g) + X$ at NLO QCD)

Factorizble and **non-factorizable** Corr.

In factorizable QCD Correction: **on-shell** Approximation: $|\frac{1}{k^2 - m^2 + im\Gamma}|^2 \to \frac{\pi}{m\Gamma}\delta(k^2 - m^2)$



Example for Non-factorizable Corr.

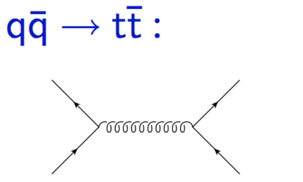


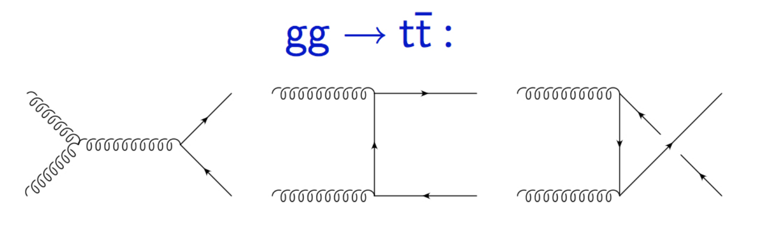
C at NLO QCD: **only factorizable** Corr.!

$$|\mathcal{M}_{\text{fakt.}}|^2 \sim \text{Tr}\{R\rho_t\rho_{\bar{t}}\}$$

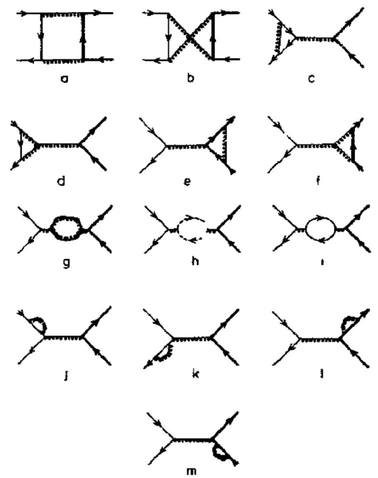
- R **Spin-Density Matrix** for all Process $i \to t\bar{t}X$ to Order α_s^3
- $\rho, \rho_{\bar{t}}$ **Decay Density Matrix** for $t \to f_t X$ and $\bar{t} \to f_{\bar{t}} X$ to Order α_s

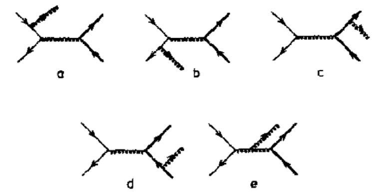
Feyman Diagram for $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$ at LO QCD



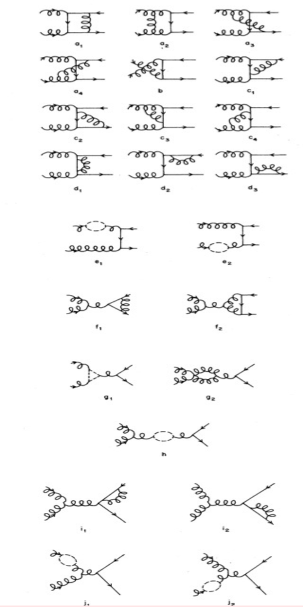


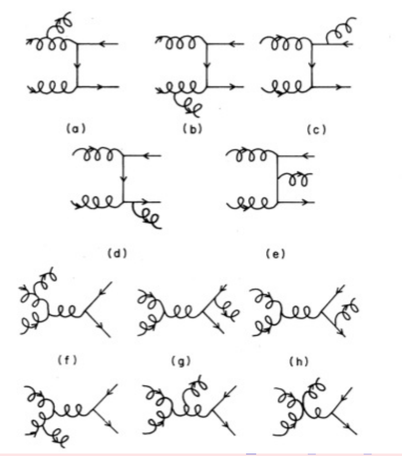
Feyman Diagram for $q\bar{q} \to t\bar{t}$ at NLO QCD





Feyman Diagram for $gg \to t\bar{t}$ at NLO QCD

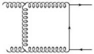




Technical Method

1. Feynman-Diagram virtual and real Correction: Computer-Algebra

- Regularize all **Divergences** in **$d=4-2\varepsilon$** Dimensions
- "Box-integrale": Calculated in **$d=6$** Dimensions
  $\Rightarrow$ Box-integral finite



- Real Correction: **Helicity amplitude for massive particle**
- UV-Divergence is removed by **Renormalization**
  α_s: $\overline{MS}$-Scheme by Scale μ_R; m_t: on-shell-Scheme

2. Definition and Calculation for "collinear safe" Spin-Observable

- **Factorization** of **infrared Singularities** (Gluon-energy $\rightarrow 0$) and **collinear Singularity** (Gluon $||$ masseless Parton):
- Remove the Divergences by **Renormalize the Parton-Distribution-Function** by Factorization-scale μ_F

3. Numerical Calculations: Monte-Carlo Integration

The contribution from $gq(\bar{q} \rightarrow t\bar{t}q(\bar{q})$ is small.

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

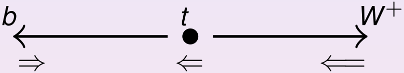
- $$\Gamma_t \simeq \frac{G_F m_t^3 |V_{tb}|^2}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

Top Quark Decays

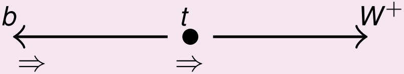
W-boson Helicity

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

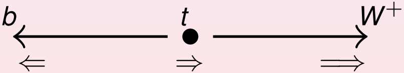
1. $t \rightarrow bW^{+}(h_W = -1)$ Allowed: *Prob.* $\sim 30\%$.



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



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



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

Top Quark Decays

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

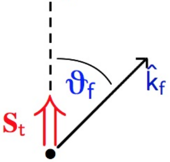
$$F_0 + F_- + F_+ = 1$$

	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 Decay

- Within SM, $t \to Wb$ **parity-violating** ($V-A$ Structure as well as μ-Decay)

  ⇒ **Top-Polarization** is transfered to its decay-products



Top-Quark Spin-Density-matrix $\rho = [1\!\!1 + \mathbf{P}_t \cdot \sigma]/2$

Decay-product f “analyze”

Top-Quark Polarization $\mathbf{P}_t$

Within SM, $t \to W^+ b \to f + X$: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta_f} = \frac{1}{2}(1 + \kappa_f |\mathbf{P}_t| \cos\vartheta_f)$

$-1 \leq \kappa_f \leq 1$ **Important Top-Spin-Analyser** (incl. QCD Corrections)

Czarnecki, Jezabek, Kühn ’91

Brandenburg, Si, Uwer ’02

⇒ **Top Quark Spin Effects can be measured**

Useful observables:

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

Cross Section for Hadronic $t\bar{t}$ Production

Present Status: top quark pair production at hadron colliders

- NLO QCD corrections to $t\bar{t}$ production
  Nason, Dawson, Ellis; Beenakker, et al.; Mangano, Nason, Ridolfi
- NLO QCD+ Threshold resummation
  Boncani, et al.; Moch, Uwer; Cacciari et al.; Kidonakis, Vogt; Banfi, Lanenen
- Mixed weak-QCD corrections
  Beenakker, et al.; Kao, Ladinsky, Yuan; Bernreuther, Fücker, Si; Kühn, Scharf, Uwer; Moretti, et al.
- Mixed QED-QCD corrections — Hollik, Pagani
- P_T resummation for $t\bar{t}$ production — C. S. Li, et al
- NLO QCD corrections to $t\bar{t} + jet$ production
  Dittmaier, Uwer, Weinzierl; Melnikov, Schulze
- NNLO QCD corrections to $t\bar{t}$ production
  M. Czakon, et al

$t\bar{t}$ production cross section at parton level

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

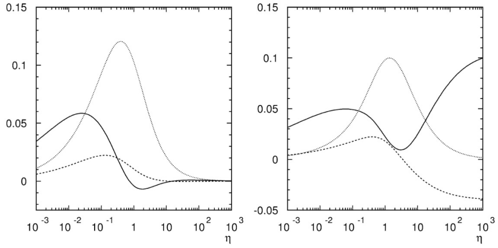


Fig. 1. Left: scaling functions $f_{q\bar{q}}^{(0)}(\eta)$ (dotted), $f_{q\bar{q}}^{(1)}(\eta)$ (full), and $\tilde{f}_{q\bar{q}}^{(1)}(\eta)$ (dashed). Right: the same for the process $gg \to t\bar{t}(g)$.

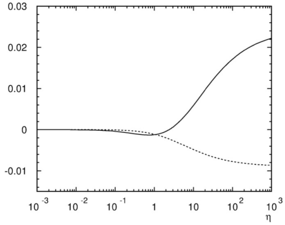


Fig. 2. Dimensionless scaling functions $f_{gq}^{(1)}(\eta)$ (full) and $\tilde{f}_{gq}^{(1)}(\eta)$ (dashed) that determine $\hat{\sigma}_{gq}$.

$t\bar{t}$ production cross section at parton level

- NLO QCD contributions are important near threshold region for $q\bar{q} \to t\bar{t}(g)$ and $gg \to t\bar{t}(g)$

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 (pb)	NLO QCD	868.150	850.385	793.543
	Weak	-14.127	-10.790	-8.368

- NLO QCD and Weak corrections: CTEQ6.1M
- Weak contributions $\sim -1.3\%$ at LHC, $\sim 0.5\%$ at Tevatron
- Weak/(NLO QED) corrections smaller than the scale uncertainties of the fixed-order NLO QCD corrections

- Non-factorizable Contributions are small

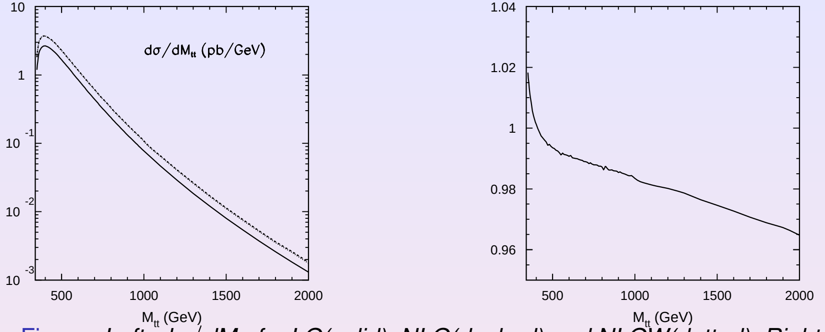


Figure: *Left: $d\sigma/dM_{tt}$ for LO(solid), NLO(dashed) and NLOW(dotted), Right: the ratio of $d\sigma^{NLOW}/dM_{tt}$ and $d\sigma^{NLO}/dM_{tt}$ at LHC*

Weak Corrections

- Weak corrections to total cross section is tiny.
- Weak corrections to M_{tt} distributions are negative except close to $2m_t$ and become larger than $\sim 2\%$ when $M_{tt} > 1.2$TeV

Top Quark Pair Production within SM: Total Cross Section

$t\bar{t}$ production cross section at LHC

LHC	SM prediction	LHC measurement
7TeV (pb)	172 ± 7	173 ± 10 (LHC comb)
8TeV (pb)	246 ± 10	241 ± 32 (ATLAS) 227 ± 15 (CMS)

- **SM predictions agree with data quite well!**

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

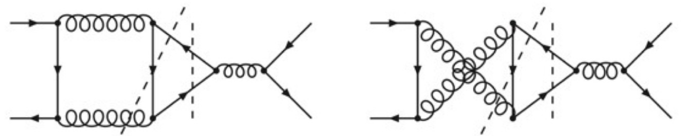
Charge Asymmetry

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

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

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

$t\bar{t}$ Charge Asymmetry comes from the Interference between initial and final state gluon radiation for $q\bar{q} \to t\bar{t}$



$t\bar{t}$ Charge Asymmetry also comes from $gq(\bar{q}) \to t\bar{t}q(\bar{q})$

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

Ratio of Charge Asymmetry from mixed QED-QCD and pure QCD

$$f_q = \frac{\mathcal{O}(\alpha_s^2 \alpha_{QED})}{\mathcal{O}(\alpha_s^3)} = \frac{4\alpha e_q e_t}{\alpha_s d_{abc}^2/4} = \frac{24\alpha e_q e_t}{5\alpha_s} \sim \mathcal{O}(0.1)$$

$\Longrightarrow$ **Mixed QCD-QED and QED-weak contributions are important!**

Within SM, Charge Asymmetry comes from:

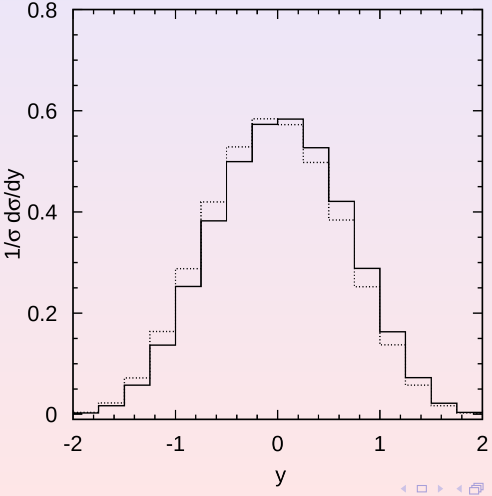
- $q\bar{q} \to t\bar{t}(g), \quad gq(\bar{q}) \to t\bar{t}q(\bar{q})$

Present status:

1. QCD at $\mathcal{O}(\alpha_s^3)$: Kühn, Rodrigo ’98, ’08; Bowen, Ellis, Rainwater ’06
2. + mixed QCD-weak at $\mathcal{O}(\alpha_s^2\alpha)$ and $\mathcal{O}(\alpha^2)$: Bernreuther, Si ’10, ’12; Hollik, Pagani ’11
3. + mixed QCD-QED at $\mathcal{O}(\alpha_s^2\alpha)$: Hollik, Pagani ’11; Bernreuther, Si ’12

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: $A^t_{FB} = \frac{N_t(y_t>0) - N_t(y_t<0)}{N_t(y_t>0) + N_t(y_t<0)}$ and $A^{\bar{t}}_{FB} = -A^t_{FB}$
- 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		$N^i_t/N^{tot}_t(\%)$	$N^i_{t\bar{t}}/N^{tot}_{t\bar{t}}$
$O(\alpha_s^3)$	$u\bar{u}$	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	$0.206^{+0.011}_{-0.010}$
$A^{t\bar{t}}(M_{t\bar{t}} \leq 450 \text{ GeV})$	-0.116 ± 0.153	0.078 ± 0.054	$0.062^{+0.004}_{-0.003}$
$A^{t\bar{t}}(M_{t\bar{t}} > 450 \text{ GeV})$	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 $< 3\sigma$.

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

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

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 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 '13(%):	0.6 ± 1.0		
$A_C^{\Delta\|\eta\|}$	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

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

1. **Production Threshold ($\beta_t \rightarrow 0$):** $t\bar{t}$ in $^3\mathbf{S_1}$ State
   $\Rightarrow$ $t\bar{t}$-Spins **100% correlated** w. r. t. Beam Basis
2. **High Energy Limit ($\beta_t \rightarrow 1$):** 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)

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

$gg \rightarrow t\bar{t}$

Production Threshold: $t\bar{t}$ in $^1\mathbf{S_0}$ State
No Off-Diagonal Basis exists to produce 100% $t\bar{t}$ correlations!!!

$t\bar{t}$ 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:

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

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

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

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

Spin Axes

- At Tevatron, $q\bar{q} \to t\bar{t} + X$ is the dominant process
  beam basis essentially as good as off-diagonal basis
- at LHC, $gg \to t\bar{t} + X$ is the dominant process
  helicity basis is the best choice

Consider, e.g., dilepton channels

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

$$\int d\sigma = \sum_{ij} \int dx_1 dx_2 f_i^{h_1}(x_1, \mu_F) f_j^{h_2}(x_2, \mu_F) \times [d\Phi_6 |M_6|^2_{LO+NLO} + d\Phi_7 |M_7|^2_{NLO}]$$

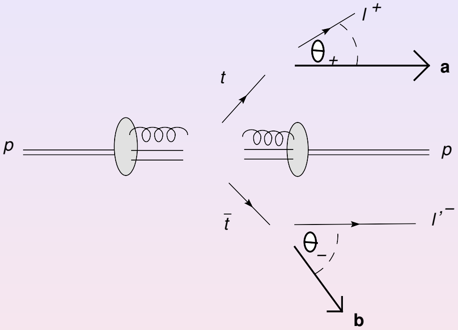
Double Distribution

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

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

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



l +
Θ+
a
t
p
p
t̄
l'−
Θ−
b

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

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

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

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

	Tevatron, $\sqrt{s} = 1.96$ GeV		LHC, $\sqrt{s} = 14$ GeV	
$l + l$	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

Bernreuther, Brandenburg, Si, Uwer, 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
   Yet results almost unchanged when CTEQ6.1M $\rightarrow$ MRST2003

- For the di-leptonic events at LHC: $pp \rightarrow t\bar{t} + X \rightarrow l^+ l^- + X$, 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

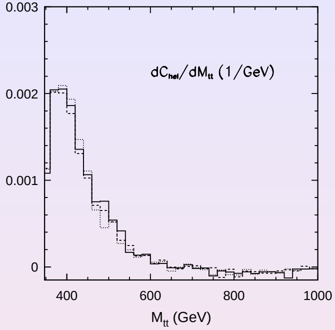


Figure: LHC(14TeV): $\mu = m_t/2$(dashed), m_t(solid) and $2m_t$(dotted)

- 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 (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(2010): $-0.17^{+0.65}_{-0.53}$

CDF off-diagonal basis(2010): $0.32^{+0.55}_{-0.78}$

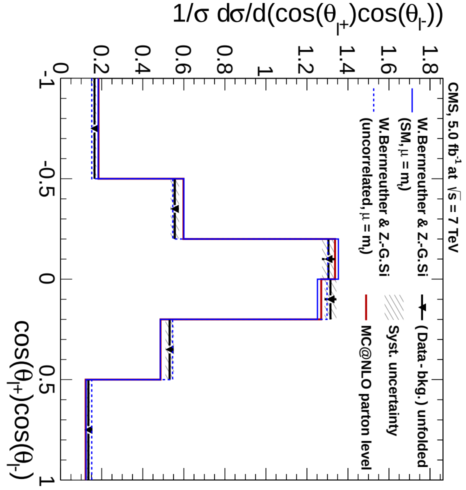
Comments

- Correlation coefficients can be affected significantly by cuts
- Proper choice of M_{tt}^{max} can enlarge the $t\bar{t}$ spin correlations
- Within large experimental unsetainties, SM predictions agree with data atTevatron
- MC simulation at ATLAS show that D and C_{hel} can be measured at percent level: $\delta D \sim 5\%$ and $\delta C_{hel} \sim 7\%$

7 TeV@LHC

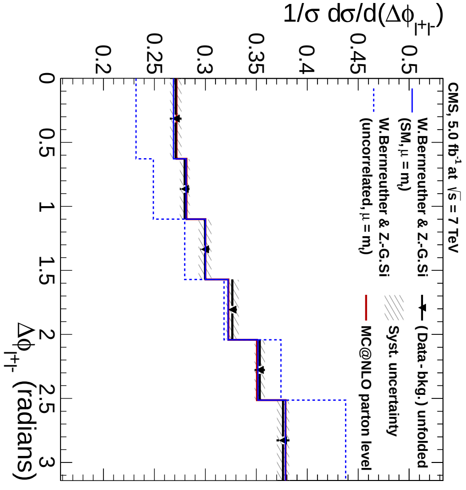
- ATLAS '13:$C_{hel} = 0.23 \pm 0.06 \pm 0.10$,
  SM prediction: $C_{hel} = 0.310 \pm 0.02$
- ATLAS '13: $C_{hel}^{maximal} = 0.36 \pm 0.06 \pm 0.09$
  SM prediction: 0.44 ± 0.03

Top spin induced distributions and correlations



- SM predictions agree with LHC data quite well.

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



- $t\bar{t}$ pairs produced at LHC are spin correlated.

Top Quark Physics BSM

Top quark spin and top quark coupling

- **Observables related to top quark spin can be used to trace top quark coupling**

Two examples

- **Top Quark Spin and Anomalous Top Quark Coupling**
- **Top Quark Spin and W' Chiral Coupling**

Top quark spin and anomalous top quark coupling

- Consider the process

$$pp \to t\bar{t} + X \to l^+ l^- + X$$

Assume:

- New physics is induced by new heavy pariticle exchanges
- Consider the interaction of mass dimension 5, Construct $\mathcal{L}_{eff}$ w.r.t $t\bar{t}g$

$$\begin{aligned} \mathcal{L}_{eff} \quad \sim \quad & \mathcal{L}_{SM} - (Re[\hat{\mu}_t] + i\, Im[\hat{\mu}_t])\, \bar{t}\sigma^{\mu\nu} T^a t G^a_{\mu\nu} \\ & - (Re[\hat{d}_t] + i\, Im[\hat{d}_t])\; i\, \bar{t}\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu} + \cdots \end{aligned}$$

- Our aim: to find suitable observables to trace the coupling

Bernreuther, Si, '13

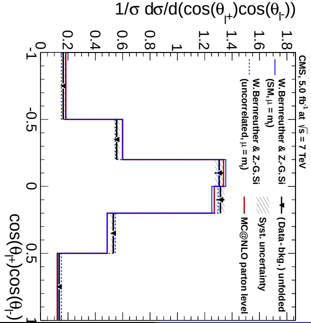
Tracing $Re[\hat{\mu}_t]$

For the process $pp \to t\bar{t} \to l^+ l^- + X$

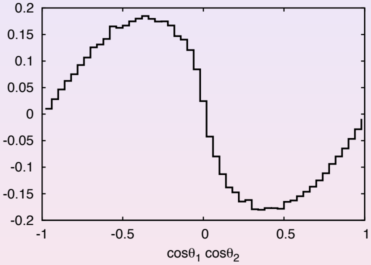
$$\frac{1}{\sigma}\frac{d\sigma}{dO_l} = \left(\frac{1}{\sigma}\frac{d\sigma}{dO_l}\right)_{SM} + \left(\frac{1}{\sigma}\frac{d\sigma}{dO_l}\right)_{NP} Re[\hat{\mu}_t]$$

- $O_l = \cos\theta_{l^+}\cos\theta_{l^-}$
- $O_l = |\Delta\phi_{ll}|$

can be used to trace $Re[\hat{\mu}_t]$



Tracing $Re[\hat{\mu}_t]$



Tracing $Re[\hat{\mu}_t]$

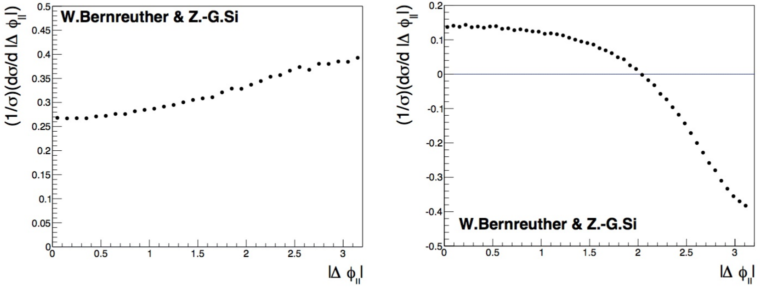


Figure 1: NLOW SM (left) and NP (right) contributions to $(1/\sigma)(d\sigma/d|\Delta\phi_{ll}|)$ at the LHC ($\sqrt{s} =$ 7 TeV), from [11]. NP is the CP-conserving part of the leading new physics effects of Eq. 1.

Tracing $Re[\hat{\mu}_t]$

mailto:cms-pag-conveners-top@cern.ch?subject=TOP-14-005 CDS information server

CMS PAS TOP-14-005

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch 2014/07/23

Limits on the top-quark chromomagnetic dipole moment from angular distributions in $t\bar{t}$ events at $\sqrt{s} = 7$ with the CMS detector

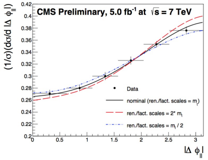


Figure 2: $(1/\sigma)(d\sigma/d|\Delta\phi_{ll}|)$ observed in data [4], and for SM NLOW predictions [11]. The black lines correspond to the nominal calculation, while the blue and red lines correspond to up and down variations of the renormalization and factorization scales, respectively.

CMS results

- $Re(\hat{\mu}_t) = 0.037 \pm 0.041$, and no sign of new physics observed
- Limits on $Re(\hat{\mu}_t)$: $-0.043 < Re(\hat{\mu}_t) < 0.117$ @95%C.L.

Top quark spin and W' chiral coupling

- New heavy gauge bosons in many extensions of the Standard Model,eg, W'

$$\mathcal{L} \sim \bar{\Psi}_u^i \gamma_\mu \sum_{\tau=L,R} g_\tau V_\tau^{\prime ij} P_\tau \Psi_d^j W_\tau^{\prime\mu+} + h.c.$$

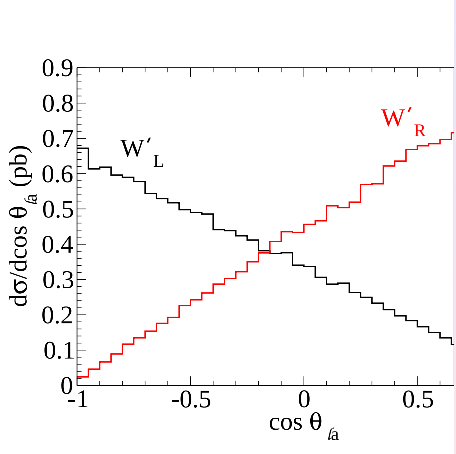
1. $g_L = 1$, $g_R = 0$ for pure left-handed theory W'_L
2. $g_L = 0$, $g_R = 1$ for pure right-handed theory W'_R
3. $g_L = 1$, $g_R = 1$ for pure left-right symmetric theory W'

- W' is observed $\Rightarrow$ distinguish the W' chiral interaction
- for $pp \to W' \to t\bar{b} \to b\bar{b}l\nu_l$, the leptonic angular distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}\left\{1 + A\cos\theta\right\},\ A = \frac{\sigma(\cos\theta \geq 0) - \sigma(\cos\theta \leq 0)}{\sigma(\cos\theta \geq 0) + \sigma(\cos\theta \leq 0)}$$

is a good diagnostic for the top quark spin.

Top quark spin and W' chiral coupling



- **Clearly distinguish between the left-handed and righthanded cases.**

Top quark spin and W' chiral coupling

Table: Forward-backward asymmetry A at the LHC for $M_{W'} = 1$TeV.

A	$W + W'_L$	$W + W'_R$	W'_L	W'_R
No Cuts or smearing	-0.42	0.17	-0.48	0.48
No Cuts	-0.42	0.15	-0.49	0.45
Cuts 1	-0.48	0.24	-0.51	0.37
+2	-0.49	0.39	-0.49	0.40
+3	-0.53	0.36	-0.53	0.37
+4 & tagging 1 b-jet	-0.48	0.40	-0.48	0.40

Gopalakrishna, Han, Lewis, Si, Zhou, '10

1. $p_T^l > 20GeV$, $\eta_l < 2.5$, $P_T^j > 50GeV$, $\eta_j < 3.0$, $\not{E}_T > 25GeV$.
2. $\Delta R_{lb} > 0.3$, $\Delta R_{bb} > 0.4$.
3. $|M_{W'} - M_{t\bar{b}}| \leq 100GeV$, $|m_t^{rec} - m_t| < 20GeV$.
4. $P^j_{T,max} > 300GeV$.

Outlook

1. Test SM predictions as precisely as possible
2. Top quark mass close to the scale of EWSB, $Y_t \sim 1$
   $\Rightarrow$ Probe the Mechanism of EWSB
3. Observables w.r.t. Top quark spin can be predicted perturbatively and measured
   - Good Probe for non-SM Parity and/or CP Violation
   - Study top quark couplings
4. Dynamics of Top Production and Decay is not fully explored so far
   - New Decay Modes, e.g., $t \to Z\,q\,,\ \cdots$?
   - New Resonance Production ? $\cdots\cdots$
5. Is top quark still point-like?
6. $\ldots\ldots\ldots$

Thanks a lot for your attention!