Model independent analysis of the forward-backward asymmetry of top quark pair production at the Tevatron

Pyungwon Ko

Korea Institute for Advanced Study

in collaboration with Dr. J.-S. Lee, Dr. D.W. Jung and Dr. S.H. Nam

based on arXiv:0912.1105, PLB 2010.06.040

< ICHEP 2010, July 22-28, 2010 >

Outline

Introduction

- Top physics has began to enter a new era after its first discovery, due to the high luminosity achieved at the Tevatron, and precision study will be possible at the LHC in the coming years.
- Forward-backward asymmetry $A_{\rm FB}$ in $t\bar{t}$ production has been off the SM prediction ($\sim$ 0.078(9)) by 2σ in the $t\bar{t}$ rest frame (CDF2008):

$$A_{\rm FB}^t \equiv \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)} = 0.24 \pm 0.13 \pm 0.04$$

- This $\sim 2\sigma$ deviation stimulated some speculations on new physics scenarios
- We adopt a model independent approach using effective Lagrangian in order to accommodate the current measurement of $A_{\rm FB}^t$, since there is no clear evidence for any new particles coupling to top at the Tevatron

Introduction

- New CDF data with 5.6 fb^{-1} presented at Blois meeting

$$0.158 \pm 0.072 \pm 0.017$$

- Less deviation than before
  $\rightarrow$ Any new physics scale is probably too high to be explored directly at the Tevatron
- Still interesting to speculate what type of new physics can modify top physics at what level
- In fact, our approach based on the effective lagrangian could be more useful in this case,
- Also could be used to set substructure scale of top quark, as in the light quark system

Introduction

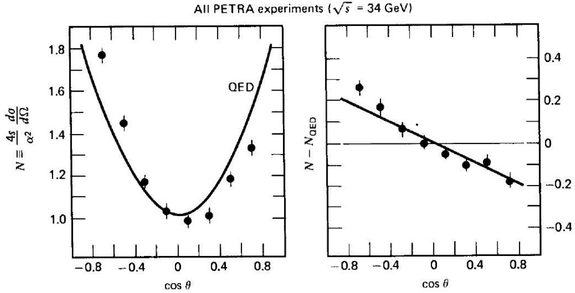
Related works

- SM predictions: Kühn and Rodrigo
  - Interference between tree (one gluon exchange) and one-loop (two gluon exchange)
  - (anti)quark-gluon scattering into $t\bar{t}g$
  - initial (final) gluon emission $q\bar{q} \to t\bar{t}g$
- Axigluon: Rodrigo et al.; Frampton, Shu, Wang; Chivukular, Simmons, CP Yuan
- Extra $Z^{'}$: Jung, Murayama, Pierce, Wells
- Extra $W^{'}$: Cheung, Keung, TC Yuan
- RS KK gluon: Djouadi et al.
- Color sextet or antitriplet: Tait et al.; CH Chen et al.; Berger et al.;
- RPV and LR model: Cao, Heng, Wu, Yang
- Comprehensive study: Cao, McKeen, Rosner, Shaughnessy, Wagner
- Effective Lagrangian Approach : this talk
- Apologies to those who are not listed

Introduction

Wisdom from EW sector

- The first evidence of asymmetry was found in angular distribution of muons from e^+e^- collisions at PETRA in the 80's ($\sqrt{s} \sim 30$ GeV , well below the Z^0 pole)



- Source of A_{FB} is a term linear in $\cos\theta$ from interference between γ or Z vector coupling and the axial vector Z coupling.

Effective Lagrangian Approach

Dim-6 Contact Interaction

- $t\bar{t}$ production at the Tevatron dominated by $q\bar{q}$ channel
- Enough to consider dimension-6 four-quark operators assuming new physics scale is high enough:

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} \left[C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A)(\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A)(\bar{t}_B T^a \gamma^\mu t_B) \right]$$

where

$$T^a = \lambda^a/2, \quad \{A, B\} = \{L, R\}, \quad L, R \equiv (1 \mp \gamma_5)/2 \quad (q = u, d, s, c, b)$$

- Other d=6 operators are all reducible to the above operators after Fierzing (Hill and Parke 1994)
- This contact term used to explore light quark substructures
- We ignore flavor changing dim-6 operators such as $\overline{d_R} \gamma^\mu s_R \overline{t_R} \gamma_\mu t_R$, since those contributions to the $t\bar{t}$ production cross section will be of a order $1/\Lambda^4$

Effective Lagrangian Approach

Helicity Amplitude Squared

- The squared helicity amplitude is given by

$$\overline{|\mathcal{M}(t_L\bar{t}_L + t_R\bar{t}_R)|^2} = \frac{4\,g_s^4}{9\,\hat{s}} m_t^2 \left[2 + \frac{\hat{s}}{\Lambda^2}(C_1 + C_2)\right] s_{\hat{\theta}}^2$$

$$\overline{|\mathcal{M} t_L\bar{t}_R + t_R\bar{t}_L)|^2} = \frac{2\,g_s^4}{9}\Big[\left(1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)\right)(1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2}(C_1 - C_2)\right) c_{\hat{\theta}}\Big]$$

where

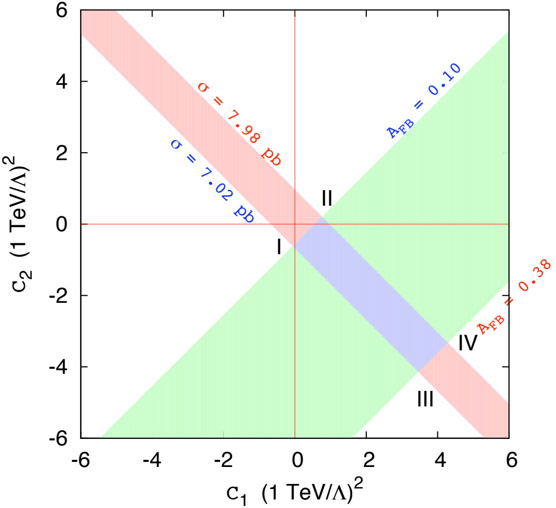
$$C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}, \quad C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$$

$$\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}, \quad s_{\hat{\theta}} \equiv \sin\hat{\theta}, \quad c_{\hat{\theta}} \equiv \cos\hat{\theta}$$

- The term linear in $\cos\hat{\theta}$ could generate the foreward-backward asymmetry which is propotional to $\Delta C \equiv C_1 - C_2$.

Effective Lagrangian Approach

Allowed region in the (C_1, C_2) plane



Effective Lagrangian Approach

Validity of our approach

- Our Validity Criteria:
  - $\sigma_{\rm int} < r\sigma_{\rm SM}$ (straight line)
  - $\sigma_{\rm NP} < r\sigma_{\rm int}$ (ellipses passing through the origin)
  - $\sigma_{\rm NP} < r^2\sigma_{\rm SM}$ (ellipses centered at the origin)
- Take $r = 0.3$, $r = 0.5$, and $r = 1.0$
- Our predictions pass these validity criteria even for $r = 0.3$, and could be considered reliable
- Another Issue: Violation of Unitarity by dim-6 op's Any nonrenormalizable interactions violate "unitarity" , which is very subtle issue at hadron colliders, since $\sqrt{\hat{s}}$ is not fixed
- Our criteria is hopefully stronger than unitarity constraint

Effective Lagrangian Approach

Validity of our approach

$\sigma_{\rm NP}$ is obtained using

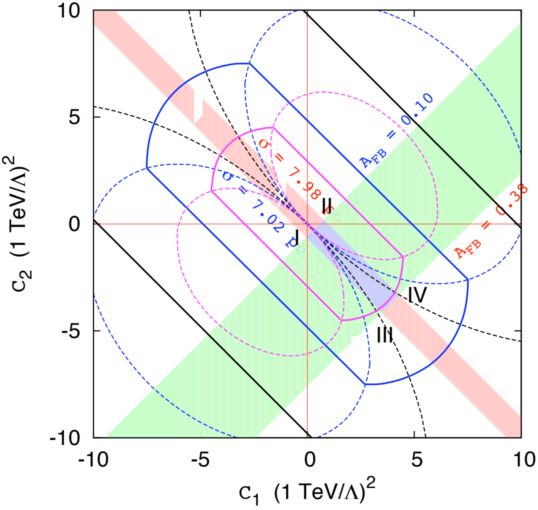
$$\begin{aligned}
\overline{|\mathcal{M}_{\rm NP}|^2} &= \frac{4g_s^4}{9\hat{s}^2}\frac{\hat{s}^2}{4\Lambda^4} \\
&\times \Big\{ \left[9\left((C_{1q}^{LL})^2 + (C_{1q}^{RR})^2\right) + 2\left((C_{8q}^{LL})^2 + (C_{8q}^{RR})^2\right)\right]\left(\hat{u} - m_t^2\right)^2 \\
&+ \left[9\left((C_{1q}^{RL})^2 + (C_{1q}^{LR})^2\right) + 2\left((C_{8q}^{RL})^2 + (C_{8q}^{LR})^2\right)\right]\left(\hat{t} - m_t^2\right)^2 \\
&+ \left[9\left(C_{1q}^{LL}C_{1q}^{LR} + C_{1q}^{RR}C_{1q}^{RL}\right) + 2\left(C_{8q}^{LL}C_{8q}^{LR} + C_{8q}^{RR}C_{8q}^{RL}\right)\right]\left(2\hat{s}m_t^2\right)\Big\} ,
\end{aligned}$$

where

$$\hat{u} - m_t^2 = -\hat{s}\,(1 + \hat{\beta}_t c_{\hat{\theta}})/2, \quad \hat{t} - m_t^2 = -\hat{s}\,(1 - \hat{\beta}_t c_{\hat{\theta}})/2$$

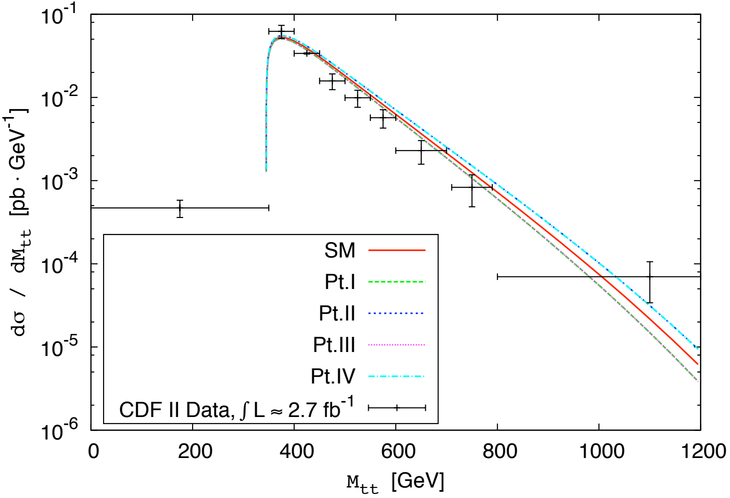
Effective Lagrangian Approach

Validity region



Effective Lagrangian Approach

$M_{t\bar{t}}$ distribution



Effective Lagrangian Approach

Spin-Spin Correlation

- chiral structure of new physics affecting $q\bar{q} \to t\bar{t}$ is also sensitive to the top quark spin-spin correlation (in the helicity basis):

$$-K = C = \frac{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) - \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) + \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}$$

- SM prediction for helicity basis: K = 0.47 (LO) and 0.352 (NLO) [Bernreuther et al., NPB (2004)]
- New CDF data:

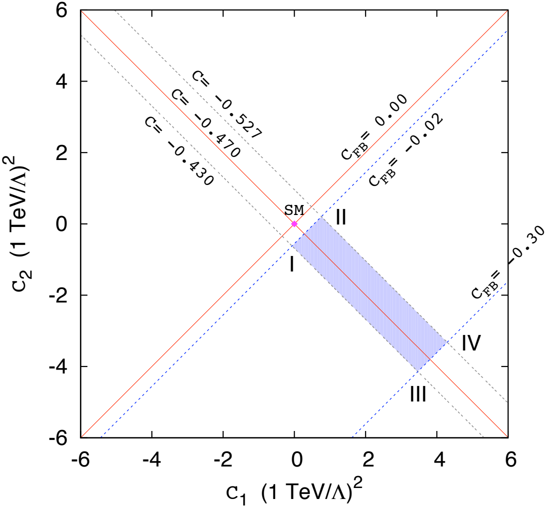
$$K = 0.48 \pm 0.48 \pm 0.22$$

- New physics should have chiral couplings both to light quarks and top quark $\longrightarrow$ P must be broken
- Any new observable ?

Top quark polarization (work in progress)

Effective Lagrangian Approach

New Spin-Spin Correlation C_{FB}



Effective Lagrangian Approach

Proposing a “NEW” Spin-Spin Correlation

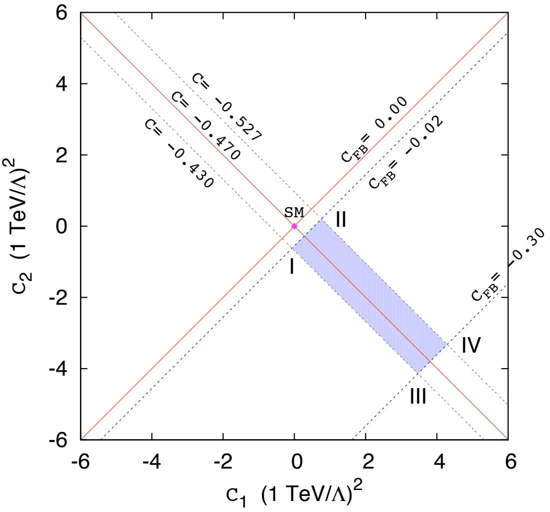
- The usual C is correlated with $\sigma_{t\bar{t}}$, and not to $A_{\rm FB}$
- We propose a new spin-spin correlation $C_{\rm FB}$: Separate the events in forward and backward directions, and form $C_{\rm FB}$

$$C_{FB} \equiv C(\cos\theta \geq 0) - C(\cos\theta \leq 0)$$

  $C(\cos\theta \geq 0(\leq 0))$ implies the cross sections in the numerator of C are obtained for the forward (backward) region: $\cos\theta \geq 0(\leq 0)$
- Advantages of the new $C_{\rm FB}$:
  - Larger spin-spin correlation
  - Stronger correlation with $A_{\rm FB}$
- This new $C_{\rm FB}$ could be also useful for testing the QCD in the top sector

Effective Lagrangian Approach

Spin-Spin Correlation



Spin-1 Resonances

- One can consider the following interactions of quarks with spin-1 flavor-conserving (changing) color-singlet $V_1(\tilde{V}_1)$ and color-octet $V_8^a(\tilde{V}_8^a)$ vectors $(A = L, R)$ relevant to A_{FB}^t:

$$\begin{aligned}
\mathcal{L}_V = & \, g_s V_1^\mu \sum_A \left[g_{1q}^A (\bar{q}_A \gamma_\mu q_A) + g_{1t}^A (\bar{t}_A \gamma_\mu t_A) \right] \\
& + g_s V_8^{a\mu} \sum_A \left[g_{8q}^A (\bar{q}_A \gamma_\mu T^a q_A) + g_{8t}^A (\bar{t}_A \gamma_\mu T^a t_A) \right] \\
& + g_s \left[\tilde{V}_1^\mu \sum_A \tilde{g}_{1q}^A (\bar{t}_A \gamma_\mu q_A) + \tilde{V}_8^{a\mu} \sum_A \tilde{g}_{8q}^A (\bar{t}_A \gamma_\mu T^a q_A) + \text{h.c.} \right]
\end{aligned}$$

Spin-0 Resonances

- Following interactions of quarks with spin-0 flavor-changing color-singlet $\tilde{S}_1$ and color-octet $\tilde{S}_8^a$ scalars could also contribute to A_{FB}^t:

$$\mathcal{L}_{\tilde{S}} = g_s \left[\tilde{S}_1 \sum_A \tilde{\eta}_{1q}^A (\bar{t} A q) + \tilde{S}_8^a \sum_A \tilde{\eta}_{8q}^A (\bar{t} A T^a q) + \text{h.c.} \right]$$

- One can also consider color-triplet S_k^γ and color-sextet scalars $S_{ij}^{\alpha\beta}$ with minimal flavor violating interactions with the SM quarks (Arnold, Pospelov, Trott, Wise):

$$\mathcal{L}_S = g_s \left[\frac{\eta_3}{2} \epsilon_{\alpha\beta\gamma} \epsilon^{ijk} u_{iR}^\alpha u_{jR}^\beta S_k^\gamma + \eta_6 u_{iR}^\alpha u_{jR}^\beta S_{ij}^{\alpha\beta} + h.c. \right]$$

Wilson Coefficients from Resonances

- After integrating out the heavy vectors and scalars, we obtain the Wilson coefficients as follows:

$$
\begin{aligned}
\frac{C_{8q}^{LL}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^L g_{8t}^L - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^L|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^L|^2\right] \\
\frac{C_{8q}^{RR}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^R g_{8t}^R - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^R|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^R|^2\right] - \frac{|\eta_3|^2}{m_{S_3}^2} + \frac{2|\eta_6|^2}{m_{S_6}^2} \\
\frac{C_{8q}^{LR}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^L g_{8t}^R - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^L|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^L|^2\right] \\
\frac{C_{8q}^{RL}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^R g_{8t}^L - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^R|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^R|^2\right]
\end{aligned}
$$

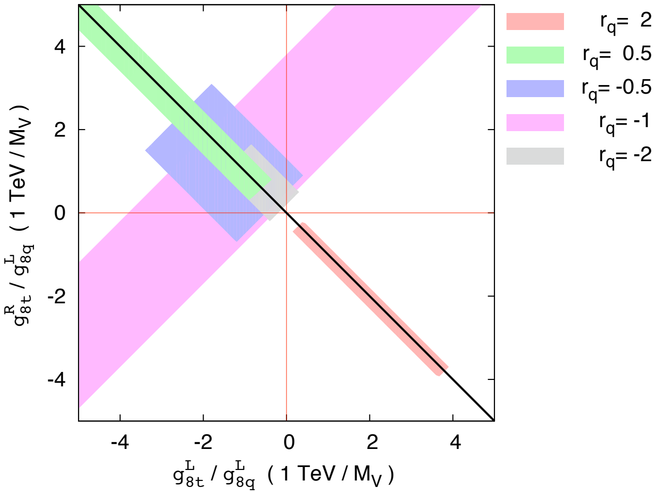
Examples of Resonances

- Axigluon model corresponding to flavor universal chiral couplings (Pati and Salam 1975): $g^L_{8q} = g^L_{8t} = -g^R_{8q} = -g^R_{8t} = 1$
- New gauge boson Z' with dominant coupling to $u - t$ (Jung, Murayama, Pierce, and Wells 2009):
  $V_1 = \tilde{V}_1 = Z', \quad g_s \tilde{g}^R_{1q} = g_X, \quad g_s g^R_{1q} = g_X \epsilon_U \quad (|\epsilon_U| \lesssim 1)$
- New charged gauge boson $W'^{\pm}$ contributions (Cheung, Keung, and Yuan 2009): $\tilde{V} = W', \quad g_s \tilde{g}^A_{1q} = g' g_A$
- Some RS scenarios with large flavor mixing in the right-handed quark sector (Aquino et al 2007; Agashe et al 2008):
  $g^L_{8q} = g^R_{8q} = g^R_{8b} \simeq -0.2, \quad g^L_{8t} = g^L_{8b} \simeq (1 \sim 2.8)$
  $g^R_{8t} \simeq (1.5 \sim 5), \quad \tilde{g}^L_{8q} \simeq V_{tq}, \quad \tilde{g}^R_{8q} \simeq 1$

Scores for each model

New particle	couplings	C_1	C_2	1 σ favor
V_8 (spin-1 FC octet)	$g^{L,R}_{8q,8t}$	indefinite	indefinite	$\surd$
$\tilde{V}_1$ (spin-1 FV singlet)	$\tilde{g}^{L,R}_{1q}$	$-$	0	$\times$
$\tilde{V}_8$ (spin-1 FV octet)	$\tilde{g}^{L,R}_{8q}$	$+$	0	$\surd$
$\tilde{S}_1$ (spin-0 FV singlet)	$\tilde{\eta}^{L,R}_{1q}$	0	$-$	$\surd$
$\tilde{S}_8$ (spin-0 FV octet)	$\tilde{\eta}^{L,R}_{8q}$	0	$+$	$\times$
S^{α}_3 (spin-0 FV triplet)	η_3	$-$	0	$\times$
$S^{\alpha\beta}_6$ (spin-0 FV sextet)	η_6	$+$	0	$\surd$

1-σ favored region for V_8



$r_q = g^R_{8q}/g^L_{8q}$ and $g^L_{8q} = 1$

Constraints on masses and couplings

- 1-σ favored values of the couplings:

$$
\begin{aligned}
\tilde{V}_8 &: \quad \frac{1}{N_c}\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{V}}}\right)^2 \left(|\tilde{g}^L_{8q}|^2 + |\tilde{g}^R_{8q}|^2\right) \simeq 0.76\,, \\
\tilde{S}_1 &: \quad \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{S}}}\right)^2 \left(|\tilde{\eta}^L_{1q}|^2 + |\tilde{\eta}^R_{1q}|^2\right) \simeq 0.62\,, \\
S^{\alpha\beta}_{13} &: \quad 2\left(\frac{1\,\mathrm{TeV}}{m_{S_6}}\right)^2 |\eta_6|^2 \simeq 0.76
\end{aligned}
$$

These could be discovered and tested at the LHC, by measuring the mass and the couplings

Summary

- We performed a model independent study of $t\bar{t}$ productions at the Tevatron using dimension-6 $q\bar{q}t\bar{t}$ contact interactions with all the possible Dirac and color structures.
- We considered the $s-$, $t-$ and $u-$channel exchanges of spin-0 and spin-1 particles whose color quantum number is either singlet, octet, triplet or sextet.
- Our results encode the necessary conditions for the underlying new physics in a compact and an effective way when those new particles are too heavy to be produced at the Tevatron.
- Those new particles might leave imprints on the low energy flavor physics such as K or B physics (mixing and CP violation), if $u(d) - t$ transitions are employed (future study)