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

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based on arXiv:0912.1105

February 5, 2010

< France-Korea CDF Meeting >

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# Introduction

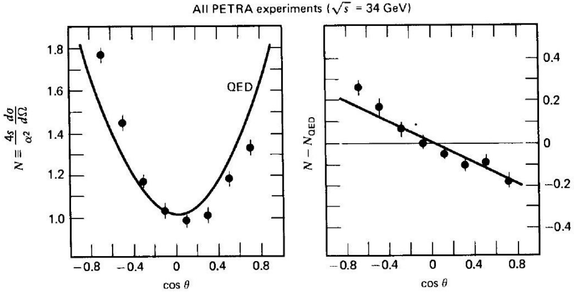
- Top physics has began to enter a new era after its first discovery, due to the high luminosity achieved at the Tevatron, and precision study will be possible at the LHC in the coming years.
- Forward-backward asymmetry $A_{\rm FB}$ in $t\bar{t}$ production has been off the SM prediction ($\sim$ 0.078)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

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

- This $\sim 2\sigma$ deviation stimulated some speculations on new physics scenarios, and we adopt a model independent approach using effective Lagrangian in order to accommodate the current measurement of $A^t_{\rm FB}$.

# Introduction

- The first evidence of asymmetry was found in angular distribution of muons from $e^+e^-$ collisions at PETRA in the 80's.




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

# Effective Lagrangian Approach

## Forward-Backward Asymmetry

- At the Tevatron, the $t\bar{t}$ production is dominated by $q\bar{q} \to t\bar{t}$, and it would sufficient to consider dimension-6 four-quark operators to describe the new physics effects if 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 by Fierz rearrangement back into the above basis (Hill and Parke 1994).
- We have not included the 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

- The squared helicity amplitude is given by

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

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

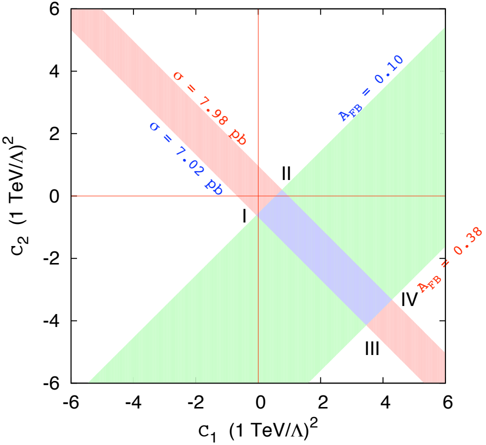
where

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

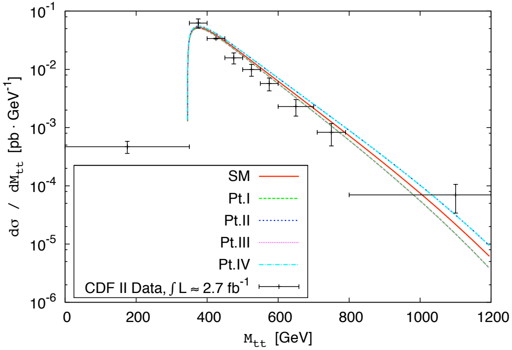
$$\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}, \quad s_{\hat{\theta}} \equiv \sin\hat{\theta}, \quad c_{\hat{\theta}} \equiv \cos\hat{\theta}$$

- 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



# Effective Lagrangian Approach



# Effective Lagrangian Approach

## Spin-Spin Correlation

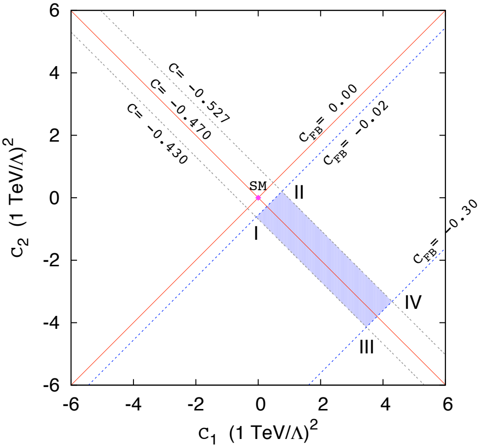
- chiral structure of new physics affecting $q\bar{q} \to t\bar{t}$ is also sensitive to the top quark spin-spin correlation:

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

- New physics should have chiral couplings both to light quarks and top quark, and so parity is necessarilry broken.

# Effective Lagrangian Approach

## Spin-Spin Correlation



# Resonance States

## 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 $A_{FB}^t$:

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

# Resonance States

## 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 $A_{FB}^t$:

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

- One can also consider color-triplet $S_k^\gamma$ and color-sextet scalars $S_{ij}^{\alpha\beta}$ with minimal flavor violating interactions with the SM quarks:

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

# Resonance States

## Wilson Coefficients from Resonances

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

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

# Resonance States

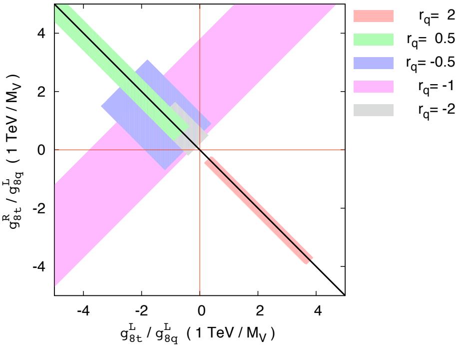
- Earlier efforts to explain the current $A^t_{FB}$ data with Resonances:
  - Axigluon model corresponding to flavor universal chiral couplings (Pati and Salam 1975):
    $$g^L_{8q} = g^L_{8t} = -g^R_{8q} = -g^R_{8t} = 1$$
  - New gauge boson $Z^{'}$ with dominant coupling to $u - t$ (Jung, Murayama, 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):
    $$g^L_{8q} = g^R_{8q} = g^R_{8b} \simeq -0.2, \quad g^L_{8t} = g^L_{8b} \simeq (1 \sim 2.8)$$
    $$g^R_{8t} \simeq (1.5 \sim 5), \quad \tilde{g}^L_{8q} \simeq V_{tq}, \quad \tilde{g}^R_{8q} \simeq 1$$

# Resonance States

| New particle | couplings | $C_1$ | $C_2$ | $1\ \sigma$ 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 | $+$ | $\times$ |
| $S_3^{\alpha}$ (spin-0 FV triplet) | $\eta_3$ | $-$ | 0 | $\times$ |
| $S_6^{\alpha\beta}$ (spin-0 FV sextet) | $\eta_6$ | $+$ | 0 | $\surd$ |

# Resonance States

- 1-$\sigma$ favored region for $V_8$:




preliminary

# Resonance States

- 1-$\sigma$ favored values of the couplings:

$$\tilde{V}_8 \quad : \quad \frac{1}{N_c}\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{V}}}\right)^2 \left(|\tilde{g}^L_{8q}|^2 + |\tilde{g}^R_{8q}|^2\right) \simeq 0.76\,,$$

$$\tilde{S}_1 \quad : \quad \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{S}}}\right)^2 \left(|\tilde{\eta}^L_{1q}|^2 + |\tilde{\eta}^R_{1q}|^2\right) \simeq 0.62\,,$$

$$S^{\alpha\beta}_{13} \quad : \quad 2\left(\frac{1\,\mathrm{TeV}}{m_{S_6}}\right)^2 |\eta_6|^2 \simeq 0.76$$

# 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, if $u(d) - t$ transitions are used in order to explain $A_{\rm FB}^t$.