Top FB asymmetry at the Tevatron

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High Energy Collider Physics Research

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.

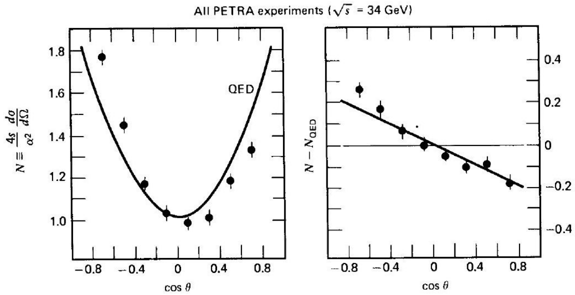
- Forward-backward asymmetry A_{FB} in $t\bar{t}$ production has been off the SM prediction ($\sim$ 0.078) by 2σ in the $t\bar{t}$ rest frame (CDF2008):

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

- 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_{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 γ or Z vector coupling and the axial vector Z coupling.

- 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

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

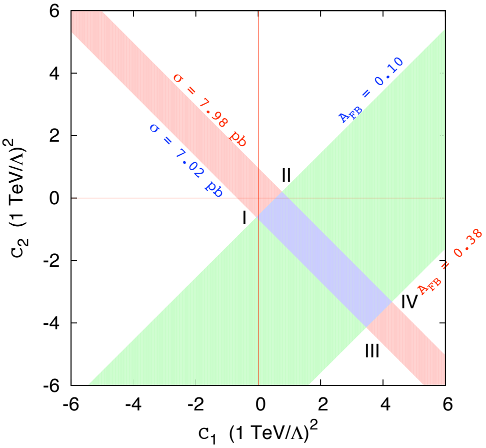
where

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

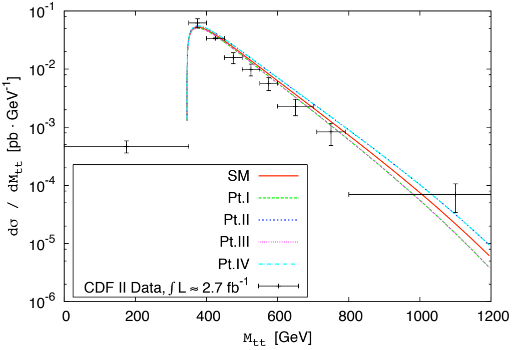
$$
\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}, \quad s_{\hat{\theta}} \equiv \sin\hat{\theta}, \quad c_{\hat{\theta}} \equiv \cos\hat{\theta}
$$

- 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

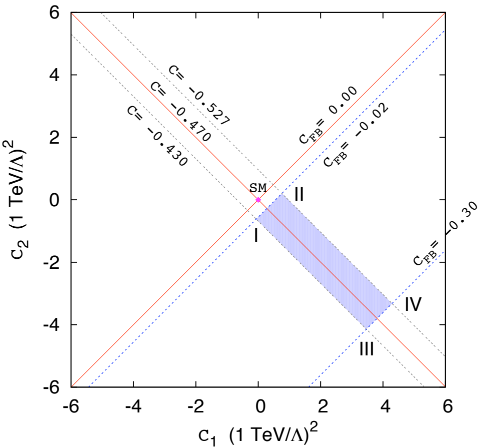
- chiral structure of new physics affecting $q\bar{q} \to t\bar{t}$ is also sensitive to the top quark spin-spin correlation:

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

- 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



- 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:

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

- 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^γ and color-sextet scalars $S_{ij}^{\alpha\beta}$ with minimal flavor violating interactions with the SM quarks:

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

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

$$\frac{C_{8q}^{LL}}{\Lambda^2} = -\frac{1}{m_V^2} g_{8q}^L g_{8t}^L - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^L|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^L|^2\right]$$

$$\frac{C_{8q}^{RR}}{\Lambda^2} = -\frac{1}{m_V^2} g_{8q}^R g_{8t}^R - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^R|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^R|^2\right] - \frac{|\eta_3|^2}{m_{S_3}^2} + \frac{2|\eta_6|^2}{m_{S_6}^2}$$

$$\frac{C_{8q}^{LR}}{\Lambda^2} = -\frac{1}{m_V^2} g_{8q}^L g_{8t}^R - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^L|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^L|^2\right]$$

$$\frac{C_{8q}^{RL}}{\Lambda^2} = -\frac{1}{m_V^2} g_{8q}^R g_{8t}^L - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^R|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^R|^2\right]$$

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Resonance States

- Earlier efforts to explain the current A_{FB}^{t} data with Resonances:
  - Axigluon model corresponding to flavor universal chiral couplings (Pati and Salam 1975):

$$g_{8q}^{L} = g_{8t}^{L} = -g_{8q}^{R} = -g_{8t}^{R} = 1$$

  - New gauge boson $Z^{'}$ with dominant coupling to $u - t$ (Jung, Murayama, Pierce, and Wells 2009):

$$V_1 = \tilde{V}_1 = Z^{'}, \quad g_s \tilde{g}_{1q}^{R} = g_X, \quad g_s g_{1q}^{R} = g_X \epsilon_U \quad (|\epsilon_U| \lesssim 1)$$

  - New charged gauge boson $W^{'\pm}$ contributions (Cheung, Keung, and Yuan 2009):

$$\tilde{V} = W^{'}, \quad g_s \tilde{g}_{1q}^{A} = g^{'} g_A$$

  - Some RS scenarios with large flavor mixing in the right-handed quark sector (Aquino et al 2007; Agashe et al 2008):

$$g_{8q}^{L} = g_{8q}^{R} = g_{8b}^{R} \simeq -0.2, \quad g_{8t}^{L} = g_{8b}^{L} \simeq (1 \sim 2.8)$$
$$g_{8t}^{R} \simeq (1.5 \sim 5), \quad \tilde{g}_{8q}^{L} \simeq V_{tq}, \quad \tilde{g}_{8q}^{R} \simeq 1$$

Resonance States

New particle	couplings	C_1	C_2	$1\ \sigma$ favor
V_8 (spin-1 FC octet)	$g_{8q,8t}^{L,R}$	indefinite	indefinite	$\surd$
$\tilde{V}_1$ (spin-1 FV singlet)	$\tilde{g}_{1q}^{L,R}$	$-$	0	$\times$
$\tilde{V}_8$ (spin-1 FV octet)	$\tilde{g}_{8q}^{L,R}$	$+$	0	$\surd$
$\tilde{S}_1$ (spin-0 FV singlet)	$\tilde{\eta}_{1q}^{L,R}$	0	$-$	$\surd$
$\tilde{S}_8$ (spin-0 FV octet)	$\tilde{\eta}_{8q}^{L,R}$	0	$+$	$\times$
S_3^{α} (spin-0 FV triplet)	η_3	$-$	0	$\times$
$S_6^{\alpha\beta}$ (spin-0 FV sextet)	η_6	$+$	0	$\surd$

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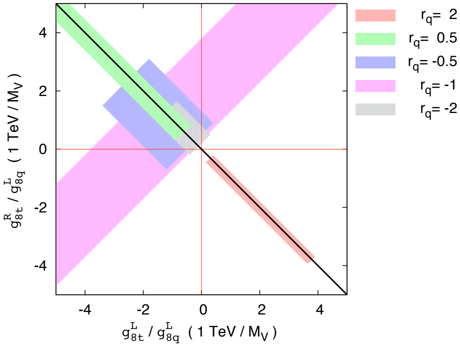
Resonance States

- 1-σ favored region for V_8:



Resonance States

- 1-σ 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 $A_{\rm FB}^{t}$.

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Appendix

- In this section, we show the full expression for the $t\bar{t}$ pair production including the squared terms of the NP amplitude (in the existence of vectors and scalars with arbitrary colors).

- $q(k_1)\bar{q}(k_2) \to t(p_1)\bar{t}(p_2)$ transition amplitude:

$$\mathcal{M}(q\bar{q} \to t\bar{t}) = \frac{g_s^2}{\hat{s}} \sum_{A,B} \Big[C_{S1}^{AB} \left(\overline{v_q(k_2)} A u_q(k_1)\right) \left(\overline{u_t(p_1)} B v_t(p_2)\right) + C_{S8}^{AB} \left(\overline{v_q(k_2)} A T^a u_q(k_1)\right) \left(\overline{u_t(p_1)} B T^a v_t(p_2)\right)$$
$$+ C_{V1}^{AB} \left(\overline{v_q(k_2)} \gamma_\mu A u_q(k_1)\right) \left(\overline{u_t(p_1)} \gamma^\mu B v_t(p_2)\right) + C_{V8}^{AB} \left(\overline{v_q(k_2)} \gamma_\mu A T^a u_q(k_1)\right) \left(\overline{u_t(p_1)} \gamma^\mu B T^a v_t(p_2)\right)$$
$$+ C_{T1}^{A} \left(\overline{v_q(k_2)} \sigma_{\mu\nu} A u_q(k_1)\right) \left(\overline{u_t(p_1)} \sigma^{\mu\nu} B v_t(p_2)\right) + C_{T8}^{A} \left(\overline{v_q(k_2)} \sigma_{\mu\nu} A T^a u_q(k_1)\right) \left(\overline{u_t(p_1)} \sigma^{\mu\nu} B T^a v_t(p_2)\right) \Big]$$

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Appendix

- In the helicity basis,

$$
\begin{aligned}
\overline{|\mathcal{M}(\lambda_t, \lambda_{\bar{t}})|^2} = \frac{g_s^4}{16\hat{s}^2} \Big\{ & \left(|C_s^{LL}|^2 + |C_s^{RL}|^2\right) \left[(1 + \lambda_t\lambda_{\bar{t}})(1 + \beta_t^2)/2 - (\lambda_t + \lambda_{\bar{t}})\beta_t\right] \hat{s}^2 \\
& + \left(|C_s^{LR}|^2 + |C_s^{RR}|^2\right) \left[(1 + \lambda_t\lambda_{\bar{t}})(1 + \beta_t^2)/2 + (\lambda_t + \lambda_{\bar{t}})\beta_t\right] \hat{s}^2 \\
& - 4\mathrm{Re}\left[C_S^{LL} C_S^{LR*} + C_s^{RR} C_s^{RL*}\right] \lambda_t\lambda_{\bar{t}} m_t^2 \hat{s} \\
& + |C_V^{LL}|^2 \left[(1 + \beta_t c_\theta)^2 - \lambda_t\lambda_{\bar{t}}(\beta_t + c_\theta)^2 + (\lambda_t - \lambda_{\bar{t}})(1 + \beta_t c_\theta)(\beta_t + c_\theta)\right] \hat{s}^2 \\
& + |C_V^{RR}|^2 \left[(1 + \beta_t c_\theta)^2 - \lambda_t\lambda_{\bar{t}}(\beta_t + c_\theta)^2 - (\lambda_t - \lambda_{\bar{t}})(1 + \beta_t c_\theta)(\beta_t + c_\theta)\right] \hat{s}^2 \\
& + |C_V^{LR}|^2 \left[(1 - \beta_t c_\theta)^2 - \lambda_t\lambda_{\bar{t}}(\beta_t - c_\theta)^2 - (\lambda_t - \lambda_{\bar{t}})(1 + \beta_t c_\theta)(\beta_t - c_\theta)\right] \hat{s}^2 \\
& + |C_V^{RL}|^2 \left[(1 - \beta_t c_\theta)^2 - \lambda_t\lambda_{\bar{t}}(\beta_t - c_\theta)^2 + (\lambda_t - \lambda_{\bar{t}})(1 + \beta_t c_\theta)(\beta_t - c_\theta)\right] \hat{s}^2 \\
& + 8\mathrm{Re}\left[C_V^{LL} C_V^{LR*}\right] \left[1 - \lambda_t\lambda_{\bar{t}} c_\theta^2 + (\lambda_t - \lambda_{\bar{t}}) c_\theta\right] m_t^2 \hat{s} \\
& + 8\mathrm{Re}\left[C_V^{RR} C_V^{RL*}\right] \left[1 - \lambda_t\lambda_{\bar{t}} c_\theta^2 - (\lambda_t - \lambda_{\bar{t}}) c_\theta\right] m_t^2 \hat{s} \\
& - 4\mathrm{Re}\left[C_S^{LL} C_T^{L*}\right] \left[2(1 + \lambda_t\lambda_{\bar{t}})\beta_t - (\lambda_t + \lambda_{\bar{t}})(1 + \beta_t^2)\right] c_\theta \hat{s}^2 \\
& - 4\mathrm{Re}\left[C_S^{RR} C_T^{R*}\right] \left[2(1 + \lambda_t\lambda_{\bar{t}})\beta_t + (\lambda_t + \lambda_{\bar{t}})(1 + \beta_t^2)\right] c_\theta \hat{s}^2 \\
& - 16\mathrm{Re}\left[C_S^{LR} C_T^{L*} - C_S^{RL} C_T^{R*}\right] (\lambda_t + \lambda_{\bar{t}}) c_\theta m_t^2 \hat{s} \\
& + 8|C_T^L|^2 \left[1 + \beta_t^2 c_{2\theta} + \lambda_t\lambda_{\bar{t}}(\beta_t^2 + c_{2\theta}) - 2(\lambda_t + \lambda_{\bar{t}})\beta_t c_\theta^2\right] \hat{s}^2 \\
& + 8|C_T^R|^2 \left[1 + \beta_t^2 c_{2\theta} + \lambda_t\lambda_{\bar{t}}(\beta_t^2 + c_{2\theta}) + 2(\lambda_t + \lambda_{\bar{t}})\beta_t c_\theta^2\right] \hat{s}^2 \Big\}
\end{aligned}
$$