

# Top FB asymmetry at the hardron colliders

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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  $A_{\text{FB}}^t$  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):

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

(=  $0.158 \pm 0.072 \pm 0.017$ : CDF Run II Preliminary)

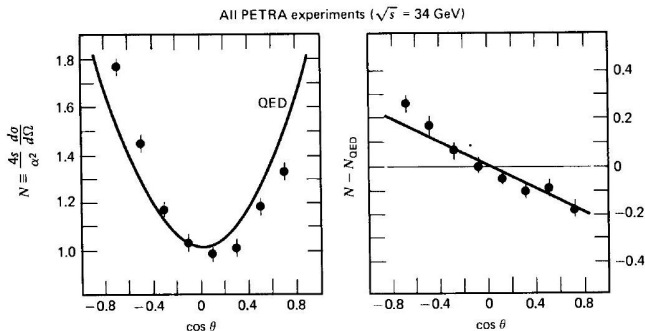
- This  $\sim 2\sigma$  deviation stimulated some speculations on new physics scenarios (about 30 related theory papers in last 2 years!).
- We adopt a model independent approach using effective Lagrangian in order to accommodate the current measurement of  $A_{\text{FB}}^t$ , since there is no clear evidence for any new particles coupling to the top quark.



# Introduction

## Lesson 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.



- 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  $q\bar{q} \rightarrow t\bar{t}$ , and it would be sufficient to consider dimension-6 four-quark operators to describe the new physics effects if the new physics scale is high enough:

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

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  $\bar{d}_R \gamma^\mu s_R \bar{t}_R \gamma_\mu t_R$  since those contributions to the  $t\bar{t}$  production cross section will be of an 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

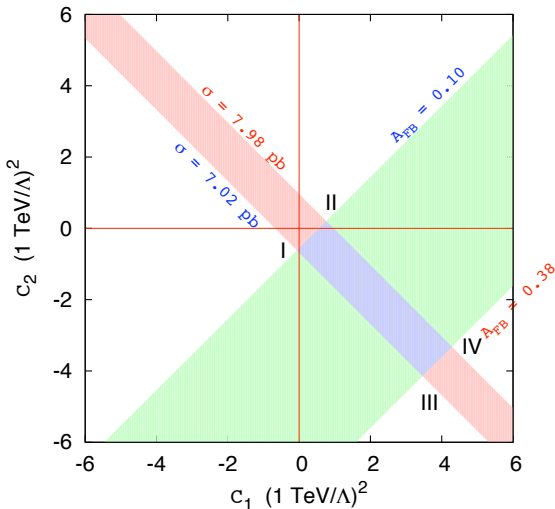
$$\begin{aligned}C_1 &\equiv C_{8q}^{LL} + C_{8q}^{RR}, & C_2 &\equiv C_{8q}^{LR} + C_{8q}^{RL} \\ \hat{\beta}_t^2 &= 1 - 4m_t^2/\hat{s}, & s_{\hat{\theta}} &\equiv \sin \hat{\theta}, & c_{\hat{\theta}} &\equiv \cos \hat{\theta}\end{aligned}$$

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



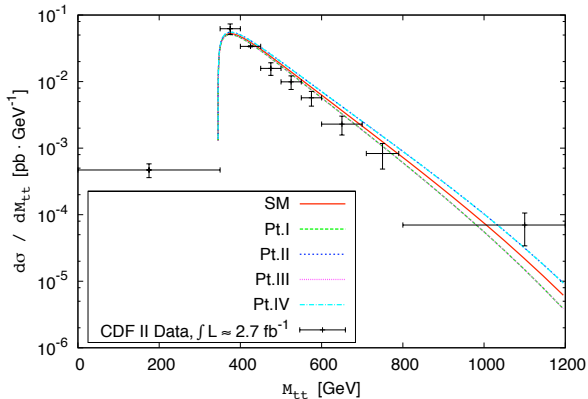
# Effective Lagrangian Approach

Allowed region in the  $(C_1, C_2)$  plane



# Effective Lagrangian Approach

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





# Effective Lagrangian Approach

## Spin-Spin Correlation

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

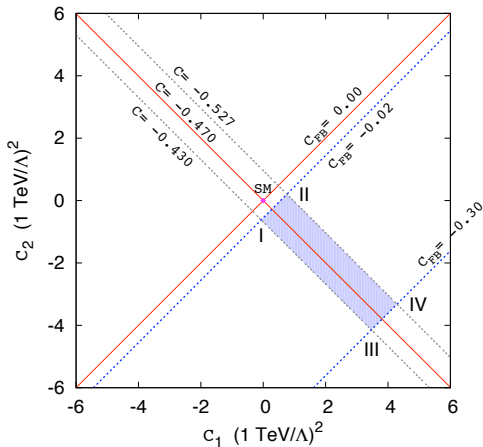
$$C = \frac{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) - \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) + \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}$$

- New physics should have chiral couplings both to light quarks and top quark, and so parity is necessarily 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  $A_{FB}^t$ :

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

# 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  $A_{FB}^t$ :

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

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

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



# Resonance States

## Wilson Coefficients from Resonances

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

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

# Resonance States

- Earlier efforts to explain the current  $A_{FB}^t$  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):

$$g_{8q}^L = g_{8q}^R = g_{8b}^R \simeq -0.2, \quad g_{8t}^L = g_{8b}^L \simeq (1 \sim 2.8)$$

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

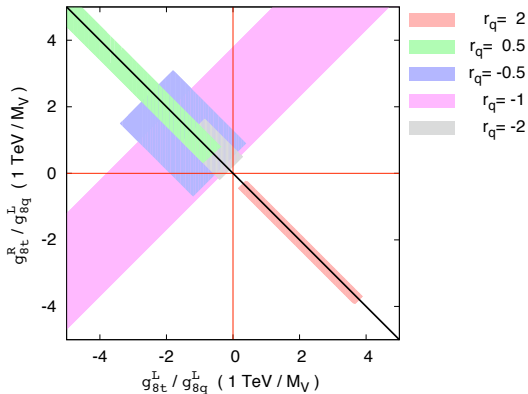


# Resonance States

New particle	couplings	$C_1$	$C_2$	1 $\sigma$ favor
$V_8$ (spin-1 FC octet)	$g_{8q,8t}^{L,R}$	indefinite	indefinite	✓
$\tilde{V}_1$ (spin-1 FV singlet)	$\tilde{g}_{1q}^{L,R}$	–	0	×
$\tilde{V}_8$ (spin-1 FV octet)	$\tilde{g}_{8q}^{L,R}$	+	0	✓
$\tilde{S}_1$ (spin-0 FV singlet)	$\tilde{\eta}_{1q}^{L,R}$	0	–	✓
$\tilde{S}_8$ (spin-0 FV octet)	$\tilde{\eta}_{8q}^{L,R}$	0	+	×
$S_3^\alpha$ (spin-0 FV triplet)	$\eta_3$	–	0	×
$S_6^{\alpha\beta}$ (spin-0 FV sextet)	$\eta_6$	+	0	✓

# Resonance States

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





# Resonance States

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

$$\tilde{V}_8 : \frac{1}{N_c} \left( \frac{1 \text{ TeV}}{m_{\tilde{V}}} \right)^2 (|\tilde{g}_{8q}^L|^2 + |\tilde{g}_{8q}^R|^2) \simeq 0.76 ,$$

$$\tilde{S}_1 : \left( \frac{1 \text{ TeV}}{m_{\tilde{S}}} \right)^2 (|\tilde{\eta}_{1q}^L|^2 + |\tilde{\eta}_{1q}^R|^2) \simeq 0.62 ,$$

$$S_{13}^{\alpha\beta} : 2 \left( \frac{1 \text{ TeV}}{m_{S_6}} \right)^2 |\eta_6|^2 \simeq 0.76$$

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



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

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

- In the helicity basis,

$$\begin{aligned}
 |\overline{\mathcal{M}(\lambda_t, \lambda_{\bar{t}})}|^2 = & \frac{g_s^4}{16\hat{s}^2} \left\{ (|C_S^{LL}|^2 + |C_S^{RL}|^2) \left[ (1 + \lambda_t \lambda_{\bar{t}})(1 + \beta_t^2)/2 - (\lambda_t + \lambda_{\bar{t}})\beta_t \right] \hat{s}^2 \right. \\
 & + (|C_S^{LR}|^2 + |C_S^{RR}|^2) \left[ (1 + \lambda_t \lambda_{\bar{t}})(1 + \beta_t^2)/2 + (\lambda_t + \lambda_{\bar{t}})\beta_t \right] \hat{s}^2 \\
 & - 4\text{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\text{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\text{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\text{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\text{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\text{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 \\
 & \left. + 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 \right\}
 \end{aligned}$$