Mass and Rapidity dependent Top Forward-Backward Asymmetry

Dong-Won JUNG

KIAS, Korea

Based on
Phys.Lett.B691 (2010) 238-242,
Phys.Lett.B708 (2012) 157-161,
and more works in progress

with P. Ko (KIAS), J. S. Lee (JNU) and S. Nam (KISTI)

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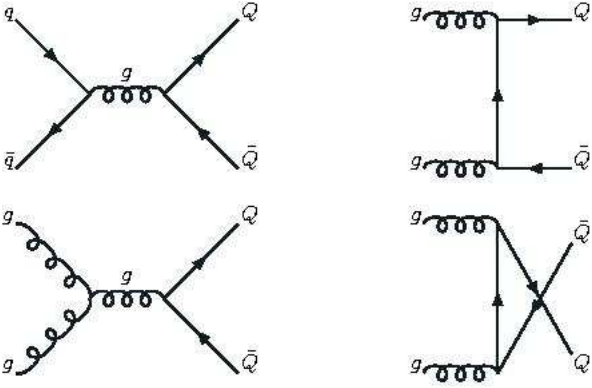
Tevatron with $\sqrt{S} = 1.96\ \mathrm{TeV}$,

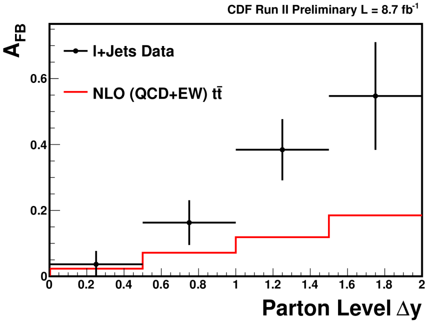
- $\sigma_{t\bar{t}} = 7.50 \pm 0.48\ \mathrm{pb}$
- $q\bar{q} \to t\bar{t} \sim 85\%$
- $gg \to t\bar{t} \sim 15\%$

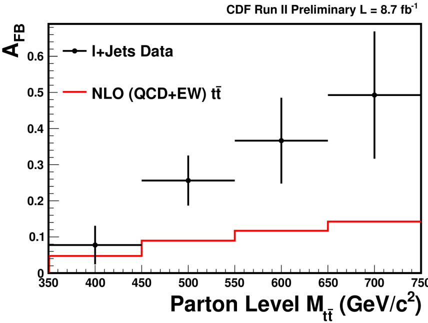


Recent Results @Tevatron [1]

- **CDF, l+jets:**
  $A_{\rm FB}^{t\bar{t}} = 0.158 \pm 0.074 \ \ [0.058 \pm 0.009]$
- **CDF, dileptons:**
  $A_{\rm FB}^{t\bar{t}} = 0.42 \pm 0.16$
- **Combinded:**
  $A_{\rm FB}^{t\bar{t}} = 0.201 \pm 0.067 \quad cf. \quad A_{\rm FB}^{t\bar{t}} = 0.196 \pm 0.065$ **@ D0**
- **CDF, l+jets:**
  $A_{\rm FB}^{t\bar{t}}(|\Delta y| < 1.0) = 0.088 \pm 0.042 \pm 0.022 \ \ [0.043]$
  $A_{\rm FB}^{t\bar{t}}(|\Delta y| \geq 1.0) = 0.433 \pm 0.097 \pm 0.050 \ \ [0.139]$
- **CDF, l+jets:**
  $A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} < 450 \ {\rm GeV}) = -0.078 \pm 0.048 \pm 0.024 \ \ [0.047]$
  $A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} \geq 450 \ {\rm GeV}) = 0.296 \pm 0.059 \pm 0.031 \ \ [0.100]$

[1] The values in the squared bracket are SM predictions.


CDF Run II Preliminary L = 8.7 fb-1
A_FB
l+Jets Data
NLO (QCD+EW) tt̄
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Parton Level Δy


CDF Run II Preliminary L = 8.7 fb-1
A_FB
l+Jets Data
NLO (QCD+EW) tt̄
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
Parton Level M_tt̄ (GeV/c2)

Effective Field Theory (EFT) approach

- **If the NP particles are heavy enough, we can adopt the veiwpoint of effective Lagragian.**
- **Assuming** $SU(2)_L \times U(1)_Y$ **and the custodial symmetry** $SU(2)_R$ **for the light quark sector,**

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

where $T^a = \lambda^a/2$, $\{A, B\} = \{L, R\}$, **and** $L, R \equiv (1 \mp \gamma_5)/2$ **with** $q = (u, d)^T, (s, c)^T$.

- **Cross section up to** $O(1/\Lambda^2)$ **is calculated, keeping only the INTERFERENCE between the SM and NP.**

Amplitude

- **The amplitude for** $q(p_1) + \bar{q}(p_2) \to t(p_3) + \bar{t}(p_4)$

$$\overline{|\mathcal{M}|^2} \simeq \frac{4\, g_s^4}{9\, \hat{s}^2} \left\{ 2 m_t^2 \hat{s} \left[1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_{\hat{\theta}}^2 + \frac{\hat{s}^2}{2} \left[\left(1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right) (1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_{\hat{\theta}} \right] \right\}$$

where $C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}$ **and** $C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$

- $\hat{s} = (p_1 + p_2)^2$, $\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}$, **and** $s_{\hat{\theta}} \equiv \sin\hat{\theta}$ **and** $c_{\hat{\theta}} \equiv \cos\hat{\theta}$, **with** $\hat{\theta}$ **being the polar angle between the incoming quark and the outgoing top quark in the** $t\bar{t}$ **rest frame.**

Result for Integrated A_{FB}

- **Convoluted with CTEQ6L and K factor 1.3.**
- A_{FB} **must be expanded with** $\sigma^{int}_{NLO}, \sigma^{int}_{NP}$,

$$A_{FB} \simeq A^{SM}_{FB} + \Delta\sigma^{int}_{NP}/\sigma^{SM}_{0}.$$

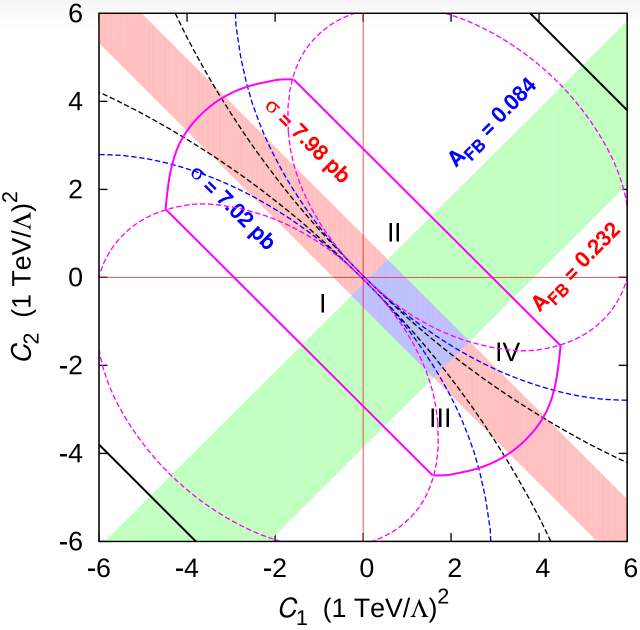
- **For validity check, we impose three criteria,**

$$\sigma = \sigma_{SM} + \sigma^{int}_{NP} + \sigma_{NP},$$

$$\begin{aligned} |\sigma^{int}_{NP}| &< r \times \sigma_{SM} \quad (straight) \\ \sigma_{NP} &< r \times |\sigma^{int}_{NP}| \quad (two\ ellipses\ adjacent\ at\ the\ origin) \\ \sigma_{NP} &< r^2 \times \sigma_{SM} \quad (ellipses\ centered\ at\ the\ origin) \end{aligned}$$

with $r = 0.3,\ 0.5\ 1.0.$

- $\Delta\sigma_{t\bar{t}} \equiv \sigma_{t\bar{t}} - \sigma^{\mathrm{SM}}_{t\bar{t}} \propto (C_1 + C_2)$,
  $\Delta A_{\mathrm{FB}} \equiv A_{\mathrm{FB}} - A^{\mathrm{SM}}_{\mathrm{FB}} \propto (C_1 - C_2)$.



σ = 7.98 pb
σ = 7.02 pb
AFB = 0.084
AFB = 0.232
I
II
III
IV
6
4
2
0
-2
-4
-6
C2 (1 TeV/Λ)2
C1 (1 TeV/Λ)2

- **General Lagrangian**

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

- **Integrating out heavy fields, the Wilson coefficients are,**

$$\frac{C_{8q}^{RR}}{\Lambda^2} = -\frac{g_{8q}^R g_{8t}^R}{m_{V_{8R}}^2} - \frac{2|\tilde{g}_{1q}^R|^2}{m_{\tilde{V}_{1R}}^2} + \frac{1}{N_C} \frac{|\tilde{g}_{8q}^R|^2}{m_{\tilde{V}_{8R}}^2},$$
$$\frac{C_{8q}^{LL}}{\Lambda^2} = -\frac{g_{8q}^L g_{8t}^L}{m_{V_{8L}}^2} - \frac{2|\tilde{g}_{1q}^L|^2}{m_{\tilde{V}_{1L}}^2} + \frac{1}{N_C} \frac{|\tilde{g}_{8q}^L|^2}{m_{\tilde{V}_{8L}}^2},$$
$$\frac{C_{8q}^{LR}}{\Lambda^2} = -\frac{g_{8q}^L g_{8t}^R}{m_{V_8}^2} - \frac{|\tilde{\eta}_{1q}^L|^2}{m_{\tilde{S}_{1L}}^2} + \frac{1}{2N_c} \frac{|\tilde{\eta}_{8q}^L|^2}{m_{\tilde{S}_{8L}}^2},$$
$$\frac{C_{8q}^{RL}}{\Lambda^2} = -\frac{g_{8q}^R g_{8t}^L}{m_{V_8}^2} - \frac{|\tilde{\eta}_{1q}^R|^2}{m_{\tilde{S}_{1R}}^2} + \frac{1}{2N_c} \frac{|\tilde{\eta}_{8q}^R|^2}{m_{\tilde{S}_{8R}}^2},$$

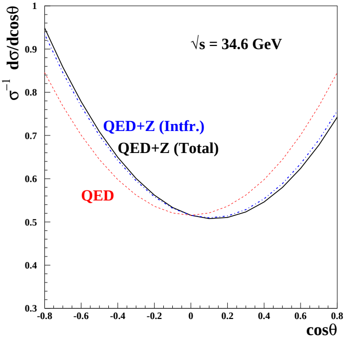
Summary Table

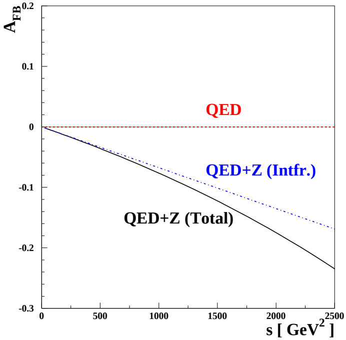
New particles	couplings	C_1	C_2	**1** σ **favor**
V_8 **(spin-1 FC octet)**	$g^{L,R}_{8q,8t}$	**indef.**	**indef.**	$\surd$
$\tilde{V}_1$ **(spin-1 FV singlet)**	$\tilde{g}^{L,R}_{1q}$	$-$	0	$\times$
$\tilde{V}_8$ **(spin-1 FV octet)**	$\tilde{g}^{L,R}_{8q}$	$+$	0	$\surd$
$\tilde{S}_1$ **(spin-0 FV singlet)**	$\tilde{\eta}^{L,R}_{1q}$	0	$-$	$\surd$
$\tilde{S}_8$ **(spin-0 FV octet)**	$\tilde{\eta}^{L,R}_{8q}$	0	$+$	$\times$
S_2^{α} **(spin-0 FV triplet)**	η_3	$-$	0	$\times$
$S_{13}^{\alpha\beta}$ **(spin-0 FV sextet)**	η_6	$+$	0	$\surd$

Mass and Rapidity dependent A_{FB}

- **Old Wisdom from Weak Interaction, RETRA :**
  Far below the Z pole mass,

$$A_{FB}(s) \simeq -\frac{3G_F}{\sqrt{2}}\,\frac{s}{4\pi\alpha}\,(g_L - g_R)^2 \equiv kG_F s \simeq -7.18 G_F s.$$





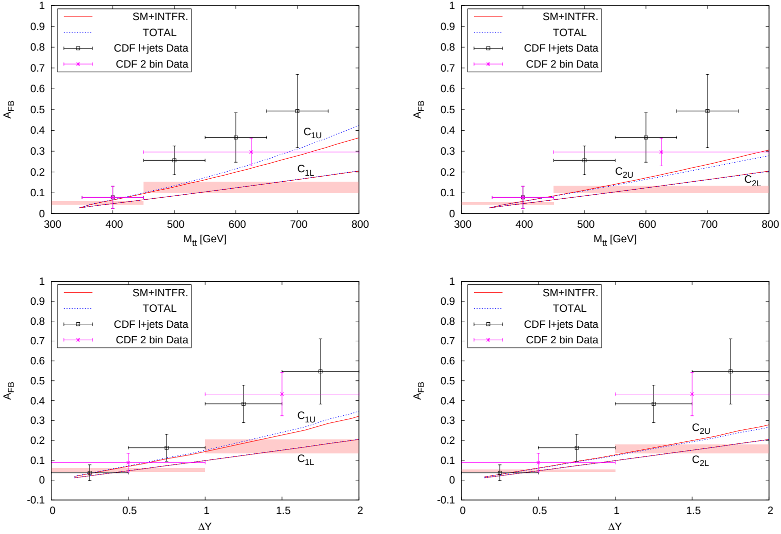
The case for $q\bar{q} \to t\bar{t}$

$$
\begin{aligned}
\widehat{A}_{\mathrm{FB}}(M_{t\bar{t}}) &= \frac{\hat{\beta}_t \frac{\hat{s}}{\Lambda^2}(C_1 - C_2)}{\frac{8}{3}\left[1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)\right] + \frac{16\hat{s}}{3m_t^2}\left[1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)\right]} \\
&\simeq \frac{3\hat{\beta}_t \frac{\hat{s}}{\Lambda^2}(C_1 - C_2)}{8 + 16\frac{m_t^2}{\hat{s}}}.
\end{aligned}
$$

- **FB asymmetry near the threshold is approximately linear in $\hat{s}$.**
- **Some nontrivial structure like wiggles or it changes the shape, one can say more about the underlying physics.**

- **Most models predict that only one of C_1 or C_2 nonzero.**

$$(C_1, C_2) = (0.15 \sim 0.97, 0) \quad \text{or} \quad (C_1, C_2) = (0, -0.67 \sim -0.15).$$



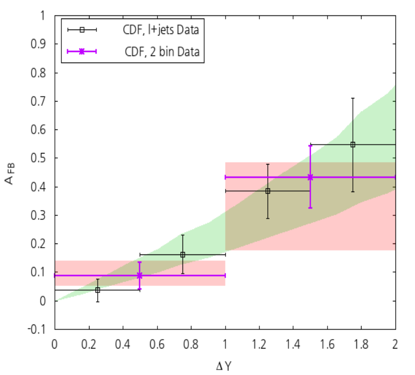
More general analysis

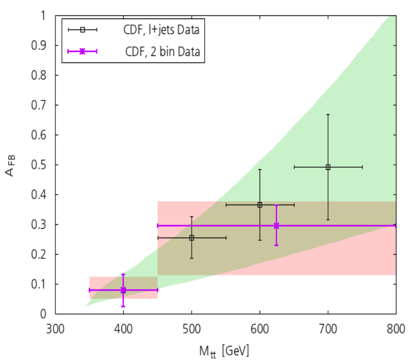
- **Through the region** $A_{\rm FB}^{t\bar{t}} = 0.158 \pm 0.074 \;\; [0.058 \pm 0.009]$**.**

- **Assuming that** $C_1 + C_2 = 0$**, which means no contribution to the cross section.**
  $\rightarrow$ **Reasonable assumption since variation of** σ **is smaller than** A_{FB}.

- **To minimize the** NP^2 **contribution, we take** $C_{8q}^{RR} = C_{8q}^{LL} = \frac{1}{2}C_1$ **and** $C_{8q}^{RL} = C_{8q}^{LR} = -\frac{1}{2}C_1$**. In this case there is no contribution to** $\hat{A}_{FB}$ **from** NP^2 **terms.**

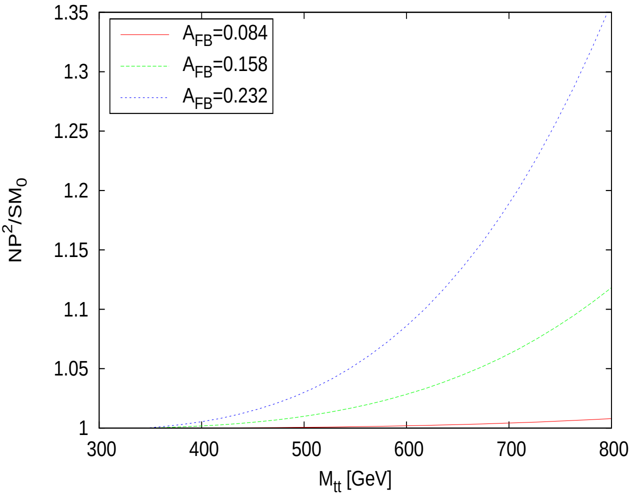
- NP^2 **increases as larger** M_{tt} **and** ΔY**.** $\rightarrow$ **Validity of EFT??**





- **Well fit!**
- **Central value of A_{FB} is favored.**
- **Validity issue : $NP^2/SM0$ goes upto $0.08\%, 12\%$ and 35% in the high M_{tt} and ΔY region.**

e.g.,



1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
300
400
500
600
700
800
NP^2/SM_0
M_{tt} [GeV]
A_{FB}=0.084
A_{FB}=0.158
A_{FB}=0.232

Summary and Prospect

- M_{tt} **and** ΔY **dependent** $\hat{A}_{FB}$ **can be well fit with EFT approach.**
- **Preferred region for the Wilson coefficients can be seleceted : Model discrimination?**
- **For large** M_{tt} **and** ΔY **region there is validity issue of EFT approach.**
- **LHC study and longitudinal observables etc. ..?**