The Top-Quark Forward-Backward Asymmetry

Susanne Westhoff

EPS 2011, July 23rd, 2011 – Grenoble, France
Top-quark pair production at the Tevatron

Proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV.

$q\bar{q} \rightarrow t\bar{t}$: 90%
$gg \rightarrow t\bar{t}$: 10%

Test Quantum Chromodynamics (QCD):
Universal quark-gluon vector coupling, in particular

$g_L = g_R \equiv g_s$
Top-quark forward-backward asymmetry

In a theory with CP-conserving couplings, the forward-backward asymmetry is equal to a top-quark charge asymmetry.

\[ A_{FB}^t = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)} = \frac{\sigma_a}{\sigma_s} \]

Charge-(a)symmetric cross section

\[ \sigma_{a(s)} = \int_0^1 \cos \hat{\theta} \left[ \frac{d\sigma(p\bar{p} \rightarrow ttX)}{d \cos \hat{\theta}} - (+) \frac{d\sigma(p\bar{p} \rightarrow \bar{t}tX)}{d \cos \hat{\theta}} \right] \]
Asymmetry in the Standard Model

In QCD, the charge asymmetry arises at next-to-leading order:

\[ q \bar{q} t \bar{t} \]

Small standard-model (SM) prediction

\[
(A_{FB}^t)_{\text{lab}} = 0 |_{\alpha_s^2} + \text{few } \% |_{\alpha_s^3} + \text{few } \%_0 |_{\alpha \alpha_s^2} = (4.8 \pm 0.5)\% + \mathcal{O}(\alpha) 
\]

- expected to be robust under higher-order QCD corrections.
  
  
- enhanced by electroweak corrections of about 20%.


  [Hollik & Pagani, arXiv:1107.2606]
Evidence for new physics in $t\bar{t}$ production


\[
(A^t_{FB})^\text{exp}_{\text{lab}} = (15.0 \pm 5.5)\%
\]
\[
(A^t_{FB})^{t\bar{t}}_{\text{exp}} = (15.8 \pm 7.4)\%
\]
\[
(A^t_{FB})^\triangleright_{\text{exp}} \equiv A^t_{FB}[M_{t\bar{t}} > 450 \text{ GeV}]
= (47.5 \pm 10.1_{\text{stat.}} \pm 4.9_{\text{syst.}})\%
\]

CDF dilepton channel [CDF note 10398, 2011]

\[
(A^t_{FB})^{t\bar{t}} = (42 \pm 15_{\text{stat.}} \pm 4_{\text{bkg.-shape}})\%
\]

D0 lepton + jets channel [D0 note 6062-CONF, 2010]

\[
(A^t_{FB})^\text{obs.}_{\text{exp}} = (8 \pm 4_{\text{stat.}} \pm 1_{\text{syst.}})\%
\]

Observables at the Tevatron

Standard-model predictions $O_{SM}$ versus measurements $O_{exp}$

Tension between charge-symmetric and -asymmetric observables.
New physics in top-antitop production

First approach: Effective theory for new physics (NP) at $\Lambda > M_{t\bar{t}}$.

- The dominant partonic process $u\bar{u} \rightarrow t\bar{t}$ is mediated by 8 vector, 8 scalar, and 2 tensor dimension-six operators of $\mathcal{O}(\Lambda^{-2})$.

[Delaunay et al., arXiv:1103.2297][Aguilar-Saavedra & Perez-Victoria, JHEP 1105:034, 2011]

- Operators interfering with the Standard Model,

  \[ \mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t), \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu \gamma_5 T^a u)(\bar{t}\gamma^\mu \gamma_5 T^a t), \]
  \[ \mathcal{O}_S^3 = (\bar{t} T_3 u)(\bar{u} T^3 t), \quad \mathcal{O}_P^3 = (\bar{t} T_3 \gamma_5 u)(\bar{u} T^3 \gamma_5 t), \quad T_3 = \epsilon_{abc}. \]

Hint towards $A_{FB}^t$ from SM-NP interference effect:

- The data on $(A_{FB}^t)^{>}$ $\sim \sigma_{tt\bar{t}}^F - \sigma_{tt\bar{t}}^B$ and $\sigma_{tt\bar{t}}^{>}$ $= \sigma_{tt\bar{t}}^F + \sigma_{tt\bar{t}}^B$ prefer $(\sigma_{tt\bar{t}}^F)_{NP} > 0$ and $(\sigma_{tt\bar{t}}^B)_{NP} < 0$ with a significance of 2$\sigma$.


Since a large asymmetry requires $\Lambda \lesssim \mathcal{O}(1 \text{ TeV})$, resonance and width effects of the new particle are important.
Candidates for a large asymmetry

A massive vector boson can generate a charge asymmetry at tree level from the interference with the standard gluon amplitude.

**s channel:** axial-vector couplings \( g_A = g_L - g_R \)

\[
\sigma_a \sim \frac{\alpha_s g_A^q g_A^t}{s - M_G^2}
\]

\( M_G = \mathcal{O}(1 \text{ TeV}) \)

**t and u channels:** flavor-changing couplings \( g^{ut} \)

\[
\sigma_a \sim \frac{\alpha_s (g^{ut})^2}{t - M_{Z'}^2}
\]

\( M_{Z'} = \mathcal{O}(\text{few 100 GeV}) \)
New physics in s channel: color-octet vectors (axigluons)

Axigluon contributions to $t\bar{t}$ production

$$\sigma_a^{\text{INT}} \sim g_A^q g_A^t \frac{1}{M_{t\bar{t}}^2 - M_G^2}, \quad \sigma_s^{\text{NP}} \sim (g_A^q)^2 (g_A^t)^2 \frac{M_{t\bar{t}}^2}{(M_{t\bar{t}}^2 - M_G^2)^2}.$$ 

A positive charge asymmetry $\sigma_a^{\text{NP}} > 0$ requires

- $M_G > M_{t\bar{t}}$: flavor non-universal axigluon couplings,
- $M_G < M_{t\bar{t}}$: flavor universal axigluon couplings.

Upper limit on $|g_A^q g_A^t|/M_G^2$: effect on total cross section $\sigma_{t\bar{t}} \sim \sigma_s^{\text{NP}}$ and resonance in spectrum $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$. 
Indirect constraints on axigluons

- Flavor-changing neutral currents at tree level

\[ D \text{ meson mixing: } M_G \gtrsim 200 \text{ GeV} \]

(flavor non-universal couplings)


- Electroweak precision observables

\[ Zb\bar{b}, \Gamma_Z, \sigma_{\text{had}} : M_G \gtrsim 500 \text{ GeV} \]


Oblique corrections \( S, T \):

\[ M_G \gtrsim \text{few} 100 \text{ GeV} \] (model-dependent)

[Haisch & SW, arXiv:1106.0529]

\( T \) constraints are important for large \( g_A^t \).
Direct constraints: dijet production at the LHC

Consider $pp \rightarrow G \rightarrow 2 \text{jets}$ at $\sqrt{s} = 7 \text{ TeV}$.

(\left| g_{L,R}^q \right| = 1, \Gamma_G/M_G = 10\%)

Resonance search in dijet invariant mass spectrum:
bounds on $\sigma(pp \rightarrow G) B(G \rightarrow q\bar{q})$

$\rightarrow M_G > 2.0 \text{ TeV}$

(only for narrow resonances, $\Gamma/M \lesssim 15\%$)


Angular distribution of jets: $M_G > 1.7 \text{ TeV}$

QCD:
forward scattering

Axigluon:
rather uniform distribution


Chiral color


Spontaneous breaking of an extended color gauge group,

\[ SU(3)_L \times SU(3)_R \rightarrow SU(3)_{QCD}, \]

gives rise to a massive axigluon \( G_\mu = \frac{1}{\sqrt{2}} (L_\mu - R_\mu). \)

Heavy axigluon


Flavor non-universal couplings \( g_A^q = -g_A^t = 1, M_G = 2 \text{ TeV}, \Gamma_G/M_G = 10\%. \)

- Effects limited by dijet production \((g_A^q).\) \((A^t_{FB})_{max} = 20\%\)

Light axigluon

[tavares & schmaltz, arxiv:1107.0978][see also barcelo et al., arxiv:1106.4054]

Flavor universal couplings \( g_A^q = g_A^t = 1/3, M_G = 400 \text{ GeV}, \Gamma_G/M_G \gtrsim 10\%. \)

- Evade bounds from dijet production \((g_A^q)\) and \( T \) parameter \((g_A^t).\)
- Need large width \( \Gamma_G \) to suppress resonance in \( M_{tt} \) spectrum
  \( \rightarrow \) additional matter in axigluon decay.

\((A^t_{FB})_{NP} \approx 30\%\)
Kaluza-Klein gluons in a warped extra dimension (ED) act as axigluons.

**Anarchic flavor structure**

Fermion masses and mixings determine their localization in the ED.

\[ g_A^q = g_L^q - g_R^q \]

- Strongly suppressed

\[ g_A^t = g_L^t - g_R^t \]

- Large

No enlarged forward-backward asymmetry.

**Relaxed flavor anarchy**

Light quarks are more IR-localized \( \rightarrow g_A^q \) increased.

But: need flavor protection to avoid strong flavor constraints.
New physics in $t$ channel: color-singlet vectors ($Z', W'$)

$Z'$ contributions to $t\bar{t}$ production

$$\sigma^\text{INT}_a \sim a \cdot \frac{(g^u_L)^2 + (g^u_R)^2}{t - M^2_{Z'}} , \quad \sigma^\text{INT}_s \sim b \cdot \frac{(g^u_L)^2 + (g^u_R)^2}{t - M^2_{Z'}} + c \cdot \frac{g^{\bar{u}u}_L g^{\bar{t}t}_L}{t - M^2_{Z'}} .$$

Rutherford enhancement at high $M_{t\bar{t}}$:

Excess of forward-scattered top quarks in both $A_{FB}^t \checkmark$ and $\sigma_{t\bar{t}}(M_{t\bar{t}}) \times$.


- $\sigma^\text{INT}_a < 0 \Rightarrow \sigma^\text{NP}_a \sim (g^u)^4 / M^4_{Z'}$, relevant, need $g^u = \mathcal{O}(1)$.
- $\sigma_{t\bar{t}}(M_{t\bar{t}})$ sets upper bound on $M_{Z'}$. 
Indirect constraints on $Z'$ bosons

Universal $Z'$ couplings to left-chiral quarks in $SU(2)_L$ doublets,

$$\mathcal{L} \supset g_L^{ut} (u, d)_L \gamma^\mu Z'_\mu (t)_L \Rightarrow g_L^{ut} \overline{d_L}(V^*_u d) V_{tb} \gamma^\mu Z'_\mu b_L.$$ 

- $g_L^{ut}$ constrained by $B_d - \overline{B}_d$ meson mixing: [Cao et al., Phys.Rev.D81:114004,2010]

$$g_L^{ut} < 3.5 \times 10^{-4} \left( \frac{M_{Z'}}{100 \text{ GeV}} \right)$$

Generically, coupling $g^{ut}$ implies $g^{uc}$ and $g^{ct}$.

- $g_L^{uc}$ constrained by $D - \overline{D}$ mixing: [Jung et al., Phys.Rev.D81:015004,2010]

$$\Rightarrow \text{impose } ut \text{ flavor symmetry}.$$ 

Natural motivation for large $g_R^{ut}$: top condensates. [Cui et al., arXiv:1106.3086]
Direct constraints: same-sign top production

**Tevatron**: $\sigma(tt + \bar{t}\bar{t}) \lesssim 0.7$ pb.  

Excludes part of the parameter space $(M_{Z'}, g^u_t R)$ that fits $t\bar{t}$ data.


**LHC**:  
[CMS, arXiv:1106.2142] $f_R = g^u_t R / g_W$

High abundance of $uu$ parton density $\rightarrow$ increased $tt$ production rate.

Search for $pp \rightarrow tt$ or $pp \rightarrow ttj$ in dilepton channel.

$Z'$ for $A^t_{FB}$ excluded at 95% CL.
Non-abelian flavor symmetry

Add (spont. broken) $SU(2)_{ut}$ gauge symmetry: [Jung et al., Phys.Rev.D83:114039,2011]

$$\mathcal{L} = \left( \overline{u}_R \gamma^\mu t_R \right) \frac{g}{\sqrt{2}} \gamma^\mu W^a_{\mu} \left( \overline{u}_R ight) t_R$$

$$= \frac{g}{\sqrt{2}} \left( \overline{u}_R \gamma^\mu t_R W^\prime_{\mu} + \overline{t}_R \gamma^\mu u_R W^\prime_{\mu} \right) + \frac{g}{2} \left( \overline{u}_R \gamma^\mu u_R - \overline{t}_R \gamma^\mu t_R \right) Z^\prime_{\mu}$$

- Same-sign top production suppressed by flavor isospin conservation.
- Dangerous: $Z'$ effects in dijet production $\rightarrow$ increase $M_{Z'}$.

\[(A^t_{FB})^\approx \approx 30\%\] with $M_{W'} = 200$ GeV, $M_{Z'} = 280$ GeV, $\alpha = g^2/4\pi = 0.06$.

Lost $W'$ events in forward direction due to selection cuts.
$\rightarrow$ Observed asymmetry reduced to \[(A^t_{FB})^\approx \approx 22\%\].
New physics in u channel: colored scalars

\[(SU(3)_C, SU(2)_L)_{U(1)_Y} : S_6 = (6, 1)_{4/3} \text{ or } S_\bar{3} = (\bar{3}, 1)_{4/3}\]

No Rutherford enhancement due to spin correlation (top backwards).

\[\rightarrow A_{FB}^t \text{ smaller than from } t\text{-channel NP.}\]

\[\rightarrow \text{stronger constraints from } \sigma_{t\bar{t}}(M_{t\bar{t}}) \text{ for fixed } A_{FB}^t.\]

Same-sign top production forbidden by electric charge conservation.

Color symmetry dictates flavor symmetry:

\[S_6: \quad g^{ij} = g^{ji} \quad \text{ruled out by dijet production, } uu \rightarrow S_6 \rightarrow uu.\]

\[S_\bar{3}: \quad g^{ij} = -g^{ji} \quad \text{moderate dijet bounds, } uc \rightarrow S_\bar{3} \rightarrow uc.\]

Light \(S_\bar{3}\) motivated by grand unification (45\(_H\)).
Top-quark charge asymmetry at the LHC

The process $pp \rightarrow t\bar{t}$ is symmetric $\Rightarrow$ no forward-backward asymmetry.

But: more boosted valence quarks $q$ than sea quarks $\bar{q}$ inside the proton.
$\Rightarrow$ Excess of boosted top quarks along the beam axis.

Charge-asymmetric contributions to $q\bar{q} \rightarrow t\bar{t}$ can be probed by an asymmetry in pseudo-rapidities $\eta = -\ln(\tan(\hat{\theta}/2))$,

$A_{\eta}^t = \frac{N(\Delta \eta > 0) - N(\Delta \eta < 0)}{N(\Delta \eta > 0) + N(\Delta \eta < 0)}$, \hspace{1cm} \Delta \eta = |\eta_t| - |\eta_{\bar{t}}|$, $A_{\eta}^{t,SM} = 0.0130(11)$

$= -0.016 \pm 0.030^{+0.010}_{-0.019} \text{stat} - 0.019 \text{syst}$

$= -0.023 \pm 0.015 \text{stat} \pm 0.021 \text{syst}$
Model distinction from top observables

Shape of $A_{FB}^{t}(M_{t\bar{t}}) \ [s, t, u]$ 

Resonances in $\sigma_{t\bar{t}}(M_{t\bar{t}}) \ [s]$ 
and enhanced tail at high $M_{t\bar{t}} \ [t, u]$

Top-quark polarization: departures from QCD vector coupling

High-$p_T$ observables: high sensitivity to TeV-scale new physics
Top asymmetry - to be taken home

Candidates
s channel: color-octet vector axigluons

\( t \) channel: color-singlet vector \( Z', W' \)

\( u \) channel: color-triplet scalar \( S_3 \)

Constraints
Dijet production
Same-sign top production
\( \sigma_{t\bar{t}}(M_{t\bar{t}}) \) tail

Tests
Resonances in \( t\bar{t} \) production
Top decay patterns
Direct production of new particles