Hunting for New Physics in Top Pair Production

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Outline

• Persistent hints of anomalous FBA in $t\bar{t}$ production at Tevatron
  • NP proposals (phenomenological approach)

• Impact of existing LHC measurements

• Possible future directions
  • Discriminating power of $t\bar{t}$ observables
FB & Charge asymmetries in $t\bar{t}$ production

- Charge (a)symmetric cross-section

\[
\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta, \quad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta.
\]

\[
A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]

\[
\Delta y = y_t - y_{\bar{t}}
\]
FB & Charge asymmetries in $t\bar{t}$ production

- Charge (a)symmetric cross-section

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\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos \theta} d\cos \theta, \quad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos \theta} d\cos \theta.
\]

\[
A_C = \text{sign}(Y) \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N(\Delta y^2 > 0) - N(\Delta y^2 < 0)}{N(\Delta y^2 > 0) + N(\Delta y^2 < 0)}
\]

\[
Y = y_t + y_{\bar{t}}, \quad \Delta y^2 = y_t^2 - y_{\bar{t}}^2
\]
FB & Charge asymmetries in $t\bar{t}$ production

- Non-zero $A_{FB,C}$ require $\hat{t}-\hat{u}$ odd contributions to $\sigma$

\[
\hat{t}, \hat{u} = m_t^2 - \frac{\hat{s}}{2} \left[ 1 \mp \beta_t \cos \theta \right]
\]

- In QCD induced at order $\alpha_s^3$

- Additional EW contributions

- SM predictions for Tevatron: $A_{FB}^{SM} \sim 7 - 9\%$ (qq̄ initial states dominate)

LHC: $A_C^{SM} \sim 1\%$ (gg initial state dominates)
Measurements of $t\bar{t}$ production at Tevatron & LHC

- Precisely measured inclusive observables

$\sigma = (7.50 \pm 0.48) \text{ pb}$ \hspace{1cm} $A_{FB} = 0.187 \pm 0.037^*$

$O/O^{\text{exp}}$

\begin{center}
\begin{tabular}{ccc}
\hline
\textbf{O} & \textbf{exp} & \\
\hline
\textbf{0.0} & \\
\textbf{0.5} & \\
\textbf{1.0} & \\
\textbf{1.5} & \\
\textbf{2.0} & \\
\hline
\end{tabular}
\end{center}

Tevatron

Kidonakis, 1009.4935
1105.3481

Beneke et al., 1109.1536
see also talks by
Mitov, Kidonakis, Yang

CDF, Public Notes
9913, 10398, 10807

D0, 1107.4995

$*\text{naive average of CDF & DO measurements}$
Measurements of $t\bar{t}$ production at Tevatron & LHC

- Precisely measured inclusive observables
- Sensitive $m_{t\bar{t}}$ exclusive observables

Figure 11: Distributions $d\sigma/d\beta_t$ at the Tevatron (left) and LHC (right).

Figure 12: Comparison of the RG-improved predictions for the invariant mass spectrum with CDF data [9]. The value $m_t = 173.1$ GeV used. Nottott ed data performed.

The resulting spectra for the Tevatron and LHC, obtained using RG-improved perturbation theory, are shown in Figure 11. As before, the distributions are normalized such that the area under the curves corresponds to the total cross section. Recall that the physical meaning of the variable $\beta_t$ is that of the 3-velocity of the top quarks in the $t\bar{t}$ rest frame. The distributions show that the dominant contributions to the cross section arise from the region of relativistic top quarks, with velocities of order 0.4–0.8 at the Tevatron and 0.5–0.9 at the LHC. We will come back to the significance of this observation in the next section.

In Figure 12, we compare our RG-improved prediction for the invariant mass spectrum with CDF data [9]. The value $m_t = 173.1$ GeV used. Nottott ed data performed.

Ahrens et al., 1003.5827
CDF, 0903.2850

$\sqrt{s} = 1.96$ TeV

CDF, Public Notes
9913, 10398, 10807

D0, 1107.4995

see talks by Soustruznik, Vellidis
Measurements of $t\bar{t}$ production at Tevatron & LHC

- Precisely measured inclusive observables

- Sensitive $m_{t\bar{t}}$ exclusive observables

\[
\sigma^h = \sigma(700\text{GeV} < m_{t\bar{t}} < 800\text{GeV}) \quad A_{FB}^h = A_{FB}(m_{t\bar{t}} > 450\text{GeV})
\]
Measurements of $t\bar{t}$ production at Tevatron & LHC

- Precisely measured inclusive observables

- Sensitive $m_{t\bar{t}}$ exclusive observables

\[
\sigma^h = \sigma(700\text{GeV} < m_{t\bar{t}} < 800\text{GeV}) \quad A_{FB}^h = A_{FB}(m_{t\bar{t}} > 450\text{GeV})
\]
Measurements of \( \bar{t}t \) production at Tevatron & LHC

- Confronting Tevatron \( A_{FB} \) & LHC \( A_C \) measurements

\[ A_C = 0.001 \pm 0.014 \]

\[ A_C^h = -0.008 \pm 0.047 \text{ (ATLAS)} \]

No deviations seen at the LHC!
New Physics Interpretation(s)

t(u)-channel resonances

- Z’, W’, H’, scalar color triplets, sextets,...
- asymmetries driven by kinematics (Rutherford scattering)

![Tree level t-antitop production diagram with mediator M exchange.](image.png)

Since the SM contribution is generated at NLO, if there is an additional LO tree-level contribution from new physics, it can easily dominate. Such LO diagrams are of the form of those in Fig. They can be either

- s-channel: $q\bar{q}$
- t-channel: $q\bar{t}$

mediators couple directly to light flavors and gluons, and therefore the mediator masses must be large enough to evade dijet resonance search constraints. To maximize the contribution to $A_{FB}$, such a model must have a big axial coupling. On the other hand, t-channel models should have large flavor violation between the light and the top generations, as can be seen in Fig. Large flavor violation is experimentally allowed even for low mass mediators, $M$, as long as new couplings between light generations and left-handed quarks is suppressed, then strong limits on flavor violation and from dijet interference between initial state gluon radiation and final state gluon radiation makes a very small negative contribution to the asymmetry.

C.f. Kamenik, Shu, Zupan, 1107.5257
New Physics Interpretation(s)

- **t(u)-channel resonances**
  - $Z'$, $W'$, $H'$, scalar color triplets, sextets, ...
  - asymmetries driven by kinematics (Rutherford scattering)
  - Present impact of LHC: $Z'$, $W'$ incompatible with combined $A_{FB}$ & $A_{C}$ values
New Physics Interpretation(s)

- **t(u)-channel resonances**
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- expect sizable $\sigma$ excess in the forward region: **top quarks at LHCb?**
  - Kagan, J.F.K., Perez & Stone, 1103.3747

- alternatively extend rapidity coverage of semileptonic $t\bar{t}$ events at ATLAS & CMS - **y dependent charge asymmetries**
  - Arguin et al., 1107.4090
  - Antunano et al., 0709.1652
  - Hewett et al., 1103.4618
New Physics Interpretation(s)

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  - $Z'$, $W'$, $H'$, scalar color triplets, sextets, ...
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  - predict flavor violating (**t-j**) resonances in t-associated production

**Table I: Contributions to systematic uncertainty on $t\bar{t}/\mu$**

| Process | Gluon radiation | $6\%$ | $5\%$ | $4\%$ |

**Figure 1:** Tree level production diagram with mediator $g$.

**Figure 2:** Self-conjugate events where $m=\tilde{q}$ is not the mediator, as in Fig. 1 is expected to be

**Figure 3:** Upper limits at 95% CL on the two main expected background processes and the total $t\bar{t}$ and single-top production cross-sections, respectively. Also see also talk by Peters.

**Figure 4:** Expected limit at 95% C.L. Upper limit on resonance mass $M$ as a function of the top quark mass $M_t$ and the mediator mass $M$.
New Physics Interpretation(s)

- \textit{t(u)-channel resonances}

  - Z', W', H', scalar color triplets, sextets, ...
  - asymmetries driven by kinematics (Rutherford scattering)
  - Present impact of LHC: Z', W' incompatible with combined \( A_{FB} \) & \( A_{C} \) values
  - predict flavor violating (t-j) \textit{resonances} in t-associated production

![Diagram of t(u)-channel resonances](image)

\[
\int L \, dt = 8.7 \text{ fb}^{-1}
\]

![Graph showing resonance mass vs. coupling](image)

CDF,1203.3894

Gresham et al., 1102.0018
New Physics Interpretation(s)

- **t(u)-channel resonances**
  - Z’, W’, H’, scalar color triplets, sextets, ...
  - asymmetries driven by kinematics (Rutherford scattering)
  - Present impact of LHC: Z’, W’ incompatible with combined $A_{FB}$ & $A_{C}$ values
  - predict flavor violating (t-j) resonances in t-associated production
  - same-sign top pair production can be a problem - model-dependent

Z’ of Berger et al., 1101.5625

1202.5520, see also talk by Calfayan

Aguilar-Saavedra & Perez-Victoria, 1104.1385
Degrande et al., 1104.1798
New Physics Interpretation(s)

- **s-channel resonances (KK or “Axigluon”, also EFT*)**
  - asymmetries driven by spin interference effects

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[c.f. Kamenik, Shu, Zupan, 1107.5257]

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*Interference between initial state gluon radiation and final state gluon radiation makes a very small negative contribution to the asymmetry.*

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*c.f. Delaunay et al., 1103.2297*
New Physics Interpretation(s)

- **s-channel resonances (KK or “Axigluon”, also EFT*)**
  - asymmetries driven by spin interference effects
  - top spins at threshold probe initial state chiralities
  - use **leptonic asymmetries** as probes

\[
A_{\ell}^{FB} = \frac{N_l(q_l \cos \theta_l > 0) - N_l(q_l \cos \theta_l < 0)}{N_l(q_l \cos \theta_l > 0) + N_l(q_l \cos \theta_l < 0)}
\]

First exp. result by D0, 1107.4995
see talk by Soustruznik

- at large \( m_{tt} \) interesting **spin correlations**

G. Mahlon and S. J. Parke  
hep-ph/9512264  
Bernreuther et al., hep-ph/0403035  
Hewett et al., 1103.4618  
Krohn et al., 1105.3743  
Bai et al., 1106.5071  
Berger et al., 1201.1790

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Falkowski, Perez & Schmaltz  
1110.3796

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G. Mahlon and S. J. Parke  
hep-ph/9512264  
Bernreuther et al., hep-ph/0403035  
Hewett et al., 1103.4618  
Krohn et al., 1105.3743  
Bai et al., 1106.5071  
Berger et al., 1201.1790
New Physics Interpretation(s)

• **s-channel resonances (KK or “Axigluon”, also EFT*)**
  - asymmetries driven by spin interference effects
  - need color octet axial vector contributions
    - \( m_{tt} \) differential \( A_{FB,C} \) change sign at resonance mass
  - Tevatron data suggest
    \[
    M \lesssim 400 \text{ GeV}
    \]
    or
    \[
    M \gtrsim 1 \text{ TeV}
    \]
New Physics Interpretation(s)

- *s-channel resonances (KK or “Axigluon”, also EFT*)*
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    - $m_{tt}$ differential $A_{FB,C}$ change sign at resonance mass
  - predict resonance in $m_{tt}$
    - may be very broad

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- **Figure 1:** Tree level diagram
  - $q$ (top quark) to $q$ (anti-top quark)
  - $t$ (top quark) to $t$ (anti-top quark)
  - Resonance exchange

- **Figure 2:** Events vs. $M_{tt}$ (GeV)
  - **SM NNLO**
  - **Data Prediction → RS + SM {smearing}**
  - **LHC 7 TeV**
  - **Luminosity 1 fb^{-1}**
New Physics Interpretation(s)

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  - asymmetries driven by spin interference effects
  - need color octet axial vector contributions
    - \( m_{tt} \) differential \( A_{FB,C} \) change sign at resonance mass
    - predict resonance in \( m_{tt} \)
      - may be very broad \([\text{Br}(t\bar{t})] \ll 1\]

  care needed when interpreting LHC bounds
New Physics Interpretation(s)

- **s-channel resonances (KK or “Axigluon”, also EFT*)**
  - asymmetries driven by spin interference effects
  - need color octet axial vector contributions
    - $m_{tt}$ differential $A_{FB,C}$ change sign at resonance mass
  - predict resonance in $m_{tt}$
    - may be very broad
  - also (resonant) 4-top production

\[ \text{Diagram with fermions and bosons interacting} \]

\[ \text{Graph showing cross section dependence on mass} \]

Zhou et al., 1203.5862
using ATLAS, 1202.5520
New Physics Interpretation(s)

- **s-channel resonances (KK or “Axigluon”, also EFT*)**
  - asymmetries driven by spin interference effects
  - need color octet axial vector contributions
    - $m_{tt}$ differential $A_{FB,C}$ change sign at resonance mass
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    - large widths can again upset the limits
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  - asymmetries driven by spin interference effects
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  - predict resonance in $m_{tt}$
    - may be very broad
  - also (resonant) 4-top production
    - large widths can again upset the limits

- however, complementary dijet resonance searches

Concrete models already very constrained
New Physics Interpretation(s)

- **Incoherent $t\bar{t}$ production**  
  Isidori & J.F.K. 1103.0016

  - Production of “top partners” decaying to $\text{top} + \text{invisible particles}$
  - Need to pass $t\bar{t}$ selection criteria and escape searches for $t\bar{t}+E_{\text{miss}}$
  - QCD production of scalars mostly p-wave, vanishes at threshold!
    
    - ‘4th gen’ exclusions do not apply!
    
    - In low mass region sizable $\sigma$ still allowed
      
      - $m_{t\bar{t}} \sim 190\text{GeV}$, $m_X \sim O(\text{GeV})$

![Diagram of $t\bar{t}$ production](image)
Conclusions

- **The most significant hints of BSM physics at the Tevatron in top sector**
  - Large measured $A_{FB}$ could still be due to $O(\text{TeV})$ (s-channel) resonances
    - at LHC expect excess in di-jet & $t\bar{t}$ spectra - already constrain such NP
  - Interesting possibilities of sub TeV contributions in u- or t-channel
    - predicted LHC signatures in $t\bar{t}+\text{jets}$ - *opportunity for ATLAS & CMS*
Conclusions

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  - Interesting possibilities of sub TeV contributions in $u$- or $t$-channel
    - predicted LHC signatures in $t\bar{t}$+jets - *opportunity for ATLAS & CMS*
  - At LHC, $A_{FB}$ manifestation as **rapidity dependent charge asymmetry**
    - Inclusive values consistent with SM - some tension in all NP proposals
    - Enhanced $\sigma_t$ in forward region - *opportunity for LHCb*
Conclusions

• The most significant hints of BSM physics at the Tevatron in top sector
  • Large measured $A_{FB}$ could still be due to $O(\text{TeV})$ (s-channel) resonances
    • at LHC expect excess in di-jet & $tt$ spectra - already constrain such NP
  • Interesting possibilities of sub TeV contributions in u- or t-channel
    • predicted LHC signatures in $t\bar{t}+$jets - opportunity for ATLAS & CMS
  • At LHC, $A_{FB}$ manifestation as rapidity dependent charge asymmetry
    • Inclusive values consistent with SM - some tension in all NP proposals
    • Enhanced $\sigma_t$ in forward region - opportunity for LHCb
  • Also top polarization, spin correlations affected by NP addressing $A_{FB}$
    • related leptonic angular asymmetries
  • For incoherent $A_{FB}$ contributions, expect $t\bar{t}+E_{\text{miss}}, jj+E_{\text{miss}}$

Looking forward to more exciting results from the LHC
Backup
New Physics Interpretation(s)

- **t(u)-channel resonances**
  - $Z'$, $W'$, $H'$, scalar color triplets, sextets, ...
  - Need large FC (u-t, d-t) couplings
  - potentially severe constraints from $\Delta F=2$ and dijet searches
    - first significant impact of LHC data with $>1\text{fb}^{-1}$
      - Tevatron still more sensitive if NP light!
    - important constraints from dijet angular distributions

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ATLAS, 1108.6311  
CMS, 1107.4771  
Grinstein et al., 1102.3374  
1108.4027
New Physics Interpretation(s)

- **t(u)-channel resonances**
  - Z', W', H', scalar color triplets, sextetets...
  - Need large FC (u-t, d-t) couplings

- Potentially severe constraints from ΔF=2 and dijet searches

- Requires non-trivial flavor structure of the underlying theory
  - **Gauge symmetries**
    $$ - \frac{\lambda_{ij}}{2} \epsilon^{abc} \phi_a \psi_{Rb}^i \gamma^j \psi_{Rc}^j $$

  - **Flavor symmetries**
    $$(\bar{U}_R T^A \gamma^\mu U_R) V^A_\mu = (V^4_\mu - i V^5_\mu) (\bar{t}_R \gamma^\mu u_R) + \cdots$$

References:
- Dorsner, S. Fajfer, J.F.K., N. Kosnik, 0912.0972, 1007.2604
- Giudice et al., 1105.3161
- Grinstein et al., 1102.3374
- Ligeti et al., 1103.2757
- Jung et al., 1103.4835
- See also
- J. Shelton & K. M. Zurek, 1101.5392
New Physics Interpretation(s)

- **$t(u)$-channel resonances**
  - $Z'$, $W'$, $H'$, scalar color triplets, sextets, ...
  - Need large FC (u-t, d-t) couplings
  - Generically predict slow rise in $m_{tt}$ spectrum

![Diagram showing scalar and vector models](image)

- Figure 8.0: Predictions for the ratio $\frac{\sigma}{\sigma_{\text{SM}}}$ with $m_{H} > 1$ TeV

- There is some evidence for NP contributions to the measurement of the $\tau$ channel models with $m_{H} > 1$ TeV as pointed out in Refs. [6, 7].

- In models with $m_{H} > 600$ GeV, $m_{H} > 800$ GeV, and $m_{H} > 1000$ GeV, the model with large FC (u-t, d-t) couplings displays virtually no deviation from the SM spectrum as pointed out in Refs. [6, 7].

- The leading order SM treellevel amplitude for $m_{H} > 450$ GeV is $\sigma_{\text{SM}}(t\bar{t})$, which only contributes in $t$-channel mediators couple directly to light $q$ and left lhanded quarks is suppressed, then strong limits on flavor violation and from dijet eventsk which has recently been discussed in a CDF note. Lastly, we produce a moderate tail at LHC. (Note that quadratic terms in the interference terms increase the asymmetry be-
• Top quarks at LHCb identified via single muon and b-tagged high-p_T jet

• Backgrounds for t\bar{t}:
  • Real muons, jets: W+b\bar{b}, W+jets
  • Fake muons, jets: b\bar{b}, jj

• Prospects for top charge asymmetry measurement
  • top rest-frame cannot be reconstructed
  • use \mu, b pseudorapidity distribution instead