Forward-Backward $t \bar{t}$ Asymmetry from Anomalous Stop Pair Production

based on
G. Isidori & J.F.K., 1103.0016

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Forward-backward asymmetry in $t\bar{t}$ production

- Charge (a)symmetric cross-section

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

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

$\Delta y = y_t - y_{\bar{t}}$
Forward-backward asymmetry in $t\bar{t}$ production

- Non-zero $A_{FB}$ requires u- or t-odd contributions to $\sigma_+$

$$\hat{t} = m_t^2 - \frac{s}{2} [1 - \beta_t \cos \theta]$$

$$\beta_t = \sqrt{1 - \frac{4m_t^2}{s}}$$

$$\hat{t} = (p_q - p_t)^2$$

$$\hat{s} = (p_t + p_{\bar{t}})^2$$

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

$$A_{FB}^{SM} = 0.058 \pm 0.009$$

Almeida et al., 0805.1885
Forward-backward asymmetry in $t\bar{t}$ production

- Measurements at the Tevatron vs. SM (QCD) predictions

\[
\begin{align*}
\sigma &= (7.50 \pm 0.48) \text{ pb} \\
A_{FB} &= 0.158 \pm 0.074
\end{align*}
\]
Forward-backward asymmetry in $t\bar{t}$ production

- Measurements at the Tevatron vs. SM (QCD) predictions

\[ A_{FB} = 0.158 \pm 0.074 \]

\[ \sigma = (7.50 \pm 0.48) \text{ pb} \]

CDF, 0903.2850

Schwanenberger [CDF], 1012.2319

Ahrens et al., 1003.5827

Kidonakis, 1009.4935, 1105.3481
Forward-backward asymmetry in $t\bar{t}$ production

- Measurements at the Tevatron vs. SM (QCD) predictions

\[ \sigma = (7.50 \pm 0.48) \text{ pb} \quad \quad A_{FB} = 0.158 \pm 0.074 \]

- High $m_{tt}$ region less sensitive to threshold effects

\[ m_{t\bar{t}} = \sqrt{s} = \sqrt{(p_t + p_{\bar{t}})^2} \]
Forward-backward asymmetry in $t\bar{t}$ production

- Measurements at the Tevatron vs. SM (QCD) predictions

\[
\begin{align*}
\sigma &= (7.50 \pm 0.48) \text{ pb} \\
\sigma^h &= (80 \pm 37) \text{ fb} \\
A_{FB} &= 0.158 \pm 0.074 \\
A_{FB}^h &= 0.475 \pm 0.114 \\
\sigma^h &= \sigma(700\text{GeV} < m_{t\bar{t}} < 800\text{GeV}) \\
A_{FB}^h &= A_{FB}(m_{t\bar{t}} > 450\text{GeV})
\end{align*}
\]
New Physics Interpretation(s)

• **NP interfering with the SM**
  
  • positive contributions to $A_{FB}$
    
    $$\sigma_B^{NP} < \sigma_F^{NP}$$
  
  • interference in $\sigma$ negative or vanishing
    
    $$\sigma_B^{NP} \lesssim 0$$

\[
A_{FB}^{tot} = \frac{\sigma_F^{SM} - \sigma_B^{SM} + \sigma_F^{NP} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_B^{SM} + \sigma_F^{NP} + \sigma_B^{NP}}
\]

Grinstein et al., 1102.3374
New Physics Interpretation(s)

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  *concrete models rarely satisfy this!*

• **NP not interfering with SM?**
  
  • saturate uncertainties in $\sigma$
  
  • need very asymmetric incoherent contribution

\[
A_{FB}^{tot} = \frac{\sigma_F^{SM} - \sigma_B^{SM} + \sigma_F^{NP} - \sigma_B^{NP}}{\sigma_F^{SM} + \sigma_B^{SM} + \sigma_F^{NP} + \sigma_B^{NP}}
\]
tt production from top partner decays

- Inclusive $\sigma$ measurements allow for 13% new incoherent contribution

- Large asymmetric contribution can reconcile the inclusive $A_{FB}$ measurement
  - Needs to overcome symmetric QCD production

- Production of “top partners” decaying to top + invisible particles
  - Need to pass $t\bar{t}$ selection criteria and escape searches for $t\bar{t}+E_{\text{miss}}$
$t\bar{t}$ production from top partner decays

- Fermionic top partners (4th gen, vectorlike $T$)
  - Large (symmetric) QCD cross-section
  - Excludes masses $m_T \sim m_t$

![Graph showing exclusion limits and production cross-sections](image-url)
tt̄ production from top partner decays

- Fermionic top partners (4th gen, vectorlike T) 

- Scalar top partner - “stop” (SUSY)

- QCD production mostly p-wave, vanishes at threshold!

- Low mass region still allowed with sizable cross-section

  - decay to $t + \chi^0$

  - $m_{t̄} \sim 190\text{GeV}$, $m_\chi \sim O(\text{GeV})$

  Could easily pass top reconstruction
tt̄ production from top partner decays

- Fermionic top partners (4th gen, vectorlike $T$) ✗
- Scalar top partner - “stop” (SUSY) ✓
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  - decay to $t + \chi^0$
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Beenakker et al., 1006.4771

CDF Public Note 10374

[Graph showing exclusion limits on $m_T$ vs $m_\chi$.]
tt̄ production from stop decays

- Asymmetric production mechanism

- Exchange of heavier states \(\Rightarrow\) Higher dim effective operators

\[
\bar{u}u \bar{t}^\dagger \bar{t}, \quad \bar{u} \gamma_5 u \bar{t}^\dagger \bar{t}, \quad \bar{u} \gamma_\mu u \bar{t}^\dagger \partial^\mu \bar{t}, \quad \bar{u} \gamma_\mu \gamma_5 u \bar{t}^\dagger \partial^\mu \bar{t}.
\]

- Up to dim 6 no asymmetry can be generated

- Exchange of light states in t- or u-channel \(\Rightarrow\) Need light SM singlet: \(\chi^0\)

- Minimal setup:
tt production from stop decays

- Simple(st) model: \[ \mathcal{L} = \mathcal{L}_{SM} + (D_\mu \tilde{t})^\dagger (D^\mu \tilde{t}) - m_t^2 \tilde{t}^\dagger \tilde{t} + \tilde{\chi}^0 (i \gamma_\mu D^\mu) \chi^0 - m_\chi \tilde{\chi}_c \chi^0 + \sum_{q=u,c,t} (\tilde{Y}_q \tilde{q}_R \tilde{t} \chi^0 + \text{h.c.}) , \]

- \( \tilde{t} \) can be identified with right-handed stop in MSSM

- Majorana or Dirac nature of \( \chi^0 \) irrelevant for collider phenomenology

- can \( \chi^0 \) be the MSSM bino?
\( \ttbar \) production from stop decays

- Simple(st) model:  
  \[
  \mathcal{L} = \mathcal{L}_{SM} + (D_\mu \tilde{t})^\dagger (D^\mu \tilde{t}) - m_{\tilde{t}}^2 \tilde{t}^\dagger \tilde{t} + \tilde{\chi}_0^0 (i \gamma_\mu D^\mu) \chi^0 \\
  - m_\chi \tilde{\chi}_c^0 \chi^0 + \sum_{q=u,c,t} (\tilde{Y}_q \tilde{q}_R \tilde{t} \chi^0 + \text{h.c.}) ,
  \]

- \( \tilde{t} \) can be identified with right-handed stop in MSSM

- Majorana or Dirac nature of \( \chi^0 \) irrelevant for collider phenomenology

- can \( \chi^0 \) be the MSSM bino?  No (bino couplings determined by symmetry)

  - singlino in NMSSM or similar
$t\bar{t}$ $A_{FB}$ from anomalous stop production

- Need large $Br(t \rightarrow t \chi^0)$ $\Rightarrow$ Fix $\tilde{Y}_t=4$

- Both $\sigma$ and $A_{FB}$ can be accommodated
ttbar $A_{FB}$ from anomalous stop production

- Need large $Br(t \to t \chi^0) \Rightarrow \text{Fix } \tilde{Y}_t=4$

  - Both $\sigma$ and $A_{FB}$ can be accommodated

  - $\sigma^h$ and $A_{FB}^h$ in some tension

  - Can both be made consistent at 90% C.L.
Collider constraints

- $t\bar{t}$ cross section at the LHC

\[ \sigma_{\text{LHC}} = (180 \pm 19) \text{ pb} \]

ATLAS-CONF-2011-040

\[ \sigma_{\text{SM}}^{\text{LHC}} = (158 \pm 24) \text{ pb} \]

Campbell & Ellis, 1007.3492

- QCD $gg$ fusion process dominates:

\[ \sigma(\tilde{t}\tilde{t}^\dagger)_{\text{LHC}} \simeq 10 \text{ pb} \]

✔

Beenakker et al., 1006.4771
Collider constraints

• $t\bar{t}$ cross section at the LHC

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ATLAS-CONF-2011-040

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Beenakker et al., 1006.4771

• SUSY searches at LHC, low mass region (35pb$^{-1}$)

ATLAS, 1102.5290

• ATLAS 2 jets+$E_{\text{miss}}$ search: $p_T > 140, 40 \text{ GeV}$ \hspace{1cm} $E_T^{\text{miss}} > 100 \text{ GeV}$

(+ additional selection cuts)

• background uncertainty of 42 events

• less than 1pb of signal pass kinematic cuts
Flavor constraints

- Model interactions consistent with conserved $Z_2$ symmetry ("$R$-parity")
  - No FCNCs at tree level

- At one loop contribution to $D\bar{D}$ mixing observables

\[
\mathcal{H}_{\text{eff}} = C_{ud}^R \left( \bar{c}_R \gamma_\mu u_R \right)^2 \\
C_{ud}^R = -\frac{1}{32\pi^2 m_t^2} (\tilde{Y}_c \tilde{Y}_u^*)^2
\]

using G. Isidori, Y. Nir & G. Perez, 1002.0900

\[
\left| \tilde{Y}_c / \tilde{Y}_u \right| < 0.06 ,
\]

Requires sizable flavor hierarchy (comparable to CKM)
Dark Matter Implications

- stable light fermions \( \chi^0 \)
- mass of a few GeV
- annihilating via effective interaction

\[
\mathcal{L}_{\text{annih.}} = \frac{|Y_u|^2}{4m_t^2} \bar{u}_R \gamma_\mu u_R \chi^0 \gamma^\mu (1 - \gamma_5) \chi^0
\]

fixed by \( A_{\text{FB}} \)

If Dirac, correct cosmological DM abundance can be reproduced!
Dark Matter Constraints

- stable light fermions $\chi^0$ as viable DM candidates?

- Tension with direct DM searches?
  (SI nucleon $\sigma \sim 10^{-37}$ cm$^2$)
  
  See also Hector et al., 1105.5644

- Cosmological (CMB) constraints on annihilation of light thermal relics
  
  Huetsi et al., 1103.2766
  
  - for masses below 5 GeV, in conflict with thermal annihilation
Dark Matter Constraints

• stable light fermions $\chi^0$ as viable DM candidates?

  • Alternative possibilities if $\chi^0$ Majorana

    • thermal annihilation cross-section velocity suppressed

    • nucleon cross-section spin-dependent

  • DM needs to be produced non-thermally (i.e. asymmetric DM)

D. E. Kaplan et al., 0901.4117
Prospects for LHC discovery

• Generic SUSY searches in 2 jets + $E_{\text{miss}}$, sensitive to low squark masses

  • Benefits of lower luminosity (trigger menu)!

  Best LHC sensitivity expected this year

• Can a scalar admixture be disentangled from top properties measurements?

  • Top Mass, Width measurements?

  • Spin (correlation) measurements?

  • QCD produced top quarks not polarized, $t\bar{t}$ spins correlated

  ATLAS, 1102.5290
  CMS, 1101.1628

  Mahlon & Parke, 1001.3422
  Godbole et al., 1010.1458
  Jung et al., 1011.5976
  Degrande et al., 1010.6304
Conclusions

- The most significant hints of BSM physics at the Tevatron in top sector
  - Large measured $A_{FB}$ could be due to $O$(few TeV) (s-channel) resonances or sub TeV contributions in $u$- or $t$-channel
  
  c.f. J.F.K @ FPCP 2011

- Even incoherent contributions to $\sigma(t\bar{t})$ still consistent with present data

  - Example: light stop + neutralino

    predicted LHC signatures in jets+$E_{\text{miss}}$

    possible implications for DM searches
    (or even CDF $Wjj$ anomaly)

    not vanilla SUSY

Hector et al.,1105.5644
G. Punzi @ Recontres de Blois 2011