$t\bar{t}$ Forward-Backward Asymmetry from Loops of New Strongly Coupled Quarks

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The top quark

Vital statistics

- Spin: $\frac{1}{2}$
- Charge: $+\frac{2}{3}$
- Color: $\mathbf{3}$
- Height: Zero?
- Weight: $173\,\mathrm{GeV} \times g/c^2$
- Age: 17 years
- Sign: Pisces
- Birthplace: Batavia, Illinois
- Current residence: Geneva, Switzerland

The top quark

- The top quark is very heavy: $m_t \approx m_{\mathrm{W}}$ (W = tungsten)
- and very close to the EW scale: $m_t \approx v/\sqrt{2}$.
- This suggests that it may play a role in EWSB or be sensitive to other new physics.
- One observable where new physics may show up is the forward-backward asymmetry.

Forward-backward asymmetry

- Define $t\bar{t}$ events as F or B based on sign($\Delta y_{t\bar{t}}$)
- Asymmetry:

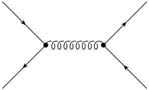
$$A \equiv \frac{N_F - N_B}{N_F + N_B}$$

- To see this asymmetry, one needs an asymmetric initial state:
  - $A = 0$ at a pp collider due to the symmetric initial state
  - Gluon and sea quark PDFs are the same in p as in $\bar{p}$.
  - Nonzero A requires $p\bar{p}$ collider and $u\bar{u}$ or $d\bar{d}$ initial state.
- The Tevatron is a good place to measure the asymmetry.
  - It's a $p\bar{p}$ collider.
    - Protons go clockwise ($\equiv$ Forward).
    - Antiprotons go anticlockwise ($\equiv$ Backward).
  - $t\bar{t}$ production is dominated by the $q\bar{q}$ channel.

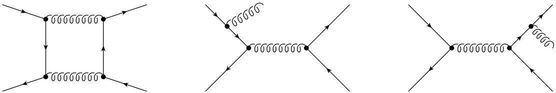
Forward-backward asymmetry

in the Standard Model

- At leading order, $A = 0$ due to charge-conjugation symmetry



- NLO QCD permits an asymmetry due to interference between C-even and C-odd amplitudes



  - Virtual corrections give a positive asymmetry
  - Real radiation gives a negative asymmetry
  - Net result: $A^{t\bar{t}} \approx 0.05$. [Kühn, Rodrigo 1998]

Tevatron results

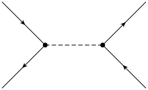
[CDF, Phys. Rev. **D83**, 112003 (2011); D0, arXiv:1107.4995]

- CDF measures $A^{t\bar{t}} = 0.158 \pm 0.075$ ...
  - ...with a significant dependence on invariant mass:
    - $A^{t\bar{t}}(M_{t\bar{t}} < 450\,\text{GeV}) = -0.116 \pm 0.153$
    - $A^{t\bar{t}}(M_{t\bar{t}} > 450\,\text{GeV}) = 0.475 \pm 0.114$
  - ...and on separation in rapidity:
    - $A^{t\bar{t}}(|\Delta y_{t\bar{t}}| < 1) = 0.026 \pm 0.118$
    - $A^{t\bar{t}}(|\Delta y_{t\bar{t}}| > 1) = 0.611 \pm 0.256$
- D0 measures $A^{t\bar{t}} = 0.196 \pm 0.065$ ...
  - ...without the strong enhancement at high $M_{t\bar{t}}$ and $|\Delta y_{t\bar{t}}|$.

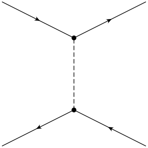
The theorists' challenge

How to explain the observed asymmetry without changing the total cross section or violating other constraints?

- Various ideas:
  - New particle in the s-channel (axigluons, ...)



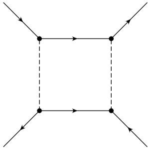
  - New particle in the t-channel (flavor-changing Z', new scalar, ...)



The theorists' challenge

How to explain the observed asymmetry without changing the total cross section or violating other constraints?

- A new idea: $A^{t\bar{t}}$ arises from loop diagrams involving new heavy quarks.



A model

- New heavy quarks $Q = t', b'$, with mass m_Q
- New scalars $\phi^0, \phi^\pm$, with mass m_ϕ
- Flavor-changing interactions $\phi \bar{q} Q$

$$\mathcal{L} \supset \lambda_{ut'} \phi^0 \bar{u} t' + \lambda_{ub'} \phi^+ \bar{u} b' + \lambda_{dt'} \phi^- \bar{d} t' + \lambda_{db'} \phi^0 \bar{d} b' + \lambda_{tt'} \phi^0 \bar{t} t' + \lambda_{tb'} \phi^+ \bar{t} b' + \mathrm{H.C.}$$

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- Flavor-changing interactions $\phi \bar{q} Q$

$$\mathcal{L} \supset \lambda_u(\phi^0 \bar{u} t' + \phi^+ \bar{u} b') + \lambda_d(\phi^- \bar{d} t' + \phi^0 \bar{d} b') + \lambda_t(\phi^0 \bar{t} t' + \phi^+ \bar{t} b') + \mathrm{H.C.}$$

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- Some of these Yukawa couplings will need to be strong.
- Couplings to s, c, b may exist, but are constrained by flavor physics.

A model

- New heavy quarks $Q = t', b'$, with mass m_Q
- New scalars $\phi^0, \phi^\pm$, with mass m_ϕ
- Flavor-changing interactions $\phi\bar{q}Q$

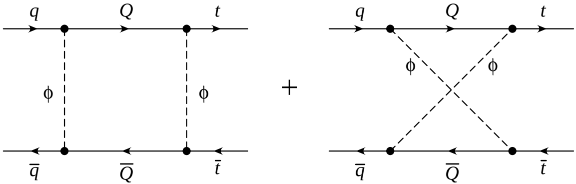
$$\begin{aligned}\mathcal{L} \supset & \lambda_u(\phi^0\bar{u}t' + \phi^+\bar{u}b') + \lambda_d(\phi^-\bar{d}t' + \phi^0\bar{d}b') \\ & + \lambda_t(\phi^0\bar{t}t' + \phi^+\bar{t}b') + \text{H.C.}\end{aligned}$$

- ϕ may have additional couplings to light quarks, leptons, ...
- Decay modes of ϕ are unspecified.

New diagrams

Boxes!

- The new particles appear in box diagrams . . .

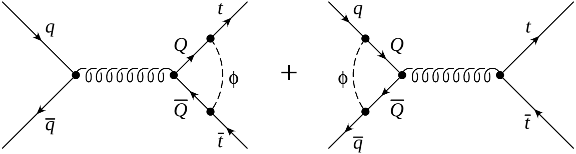


- . . . which interfere with the LO diagram and produce an asymmetry.

New diagrams

Triangles!

- We also have vertex corrections ...



- ...analogous to SM diagrams involving the Higgs.

[Stange, Willenbrock 1993]

- These diagrams do not produce an asymmetry, but do affect the total cross section.

Asymmetry

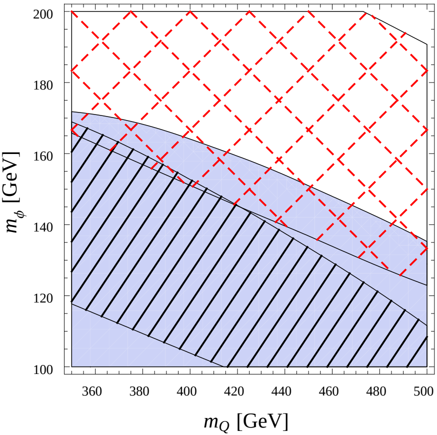
Can we match the CDF measurement?

For what values of $\lambda_u, \lambda_d, \lambda_t, m_Q, m_\phi$ do we pass these six criteria?

- Agreement with the CDF inclusive asymmetry, within 2σ
- and with the high and low $M_{t\bar{t}}$ bins, within 2σ
- and with the high and low $|\Delta y_{t\bar{t}}|$ bins, within 2σ
- and with the SM total cross section, within 30%

Asymmetry

Can we match the CDF measurement?



Cross-hatched: $\lambda_u = 1, \lambda_d = 3, \lambda_t = 5$

Shaded: $\lambda_u = 1, \lambda_d = 2, \lambda_t = 6$

Hatched: $\lambda_u = 0, \lambda_d = 3.5, \lambda_t = 4.5$

Asymmetry

Can we match the D0 measurement?

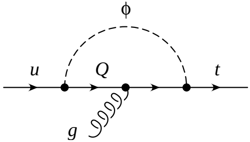
- Generally, the limiting factor in matching the CDF measurement is the high-$M_{t\bar{t}}$ bin.
- Therefore the D0 measurement can be accommodated more easily (i.e. with smaller couplings).

What about constraints?

- This model predicts new heavy quarks t' and b'.
  - Experimental searches rule out e.g. $t' \to Wb$ with $m_t' \lesssim 550\,\text{GeV}$. [CMS, arXiv:1203.5410]
  - These bounds do not directly apply to our model, since we expect decay modes such as . . .
    - $t' \to t\phi^0 \to Wbjj$
    - $t' \to d\phi^+ \to 3j$
    - etc.
- We can produce same-sign top pairs: $uu \to tt$.
  - We estimate that recent constraints [CMS, JHEP **1108**, 005 (2011)] do not exclude our model if $m_Q \gtrsim 400\,\text{GeV}$.
  - We can also evade the bounds by choosing couplings such that λ_u is small.

What about constraints?

- Our model allows exotic single-top production.



  - This can be suppressed by $\lambda_u \to 0$.
  - Or, if $\lambda_{ut'} \approx -\lambda_{ub'}$, the two diagrams cancel.

Conclusions

- Strongly coupled heavy quarks appearing in loops can produce an $A^{t\bar{t}}$ consistent with the CDF results.
- The D0 results can also be accommodated with smaller couplings.
- Various predictions and possibilities for the LHC:
  - Discovery of t', b'
  - Decay modes such as $t' \to t\phi$
  - Single t', b' production
  - Forward-backward asymmetry in $t'\bar{t}'$ and $b'\bar{b}'$ production