$t \bar{t}$ charge asymmetry, family and friends

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Outline of the talk

- The Tevatron charge / FB asymmetry
- The younger sister: the LHC charge asymmetry
- The parents: the collider-independent asymmetries
- The friends: $t\bar{t}$ differential distribution, top polarisation
- Discussion

Not covered: the acquaintances (same-sign tops, four tops, tj resonances...)
The charge / FB asymmetry at Tevatron

$q\bar{q} \rightarrow t\bar{t}$ is not symmetric under interchange of $t$ and $\bar{t}$ momenta; the most commonly used observable at Tevatron is the FB asymmetry

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_t - y_{\bar{t}}$, exploiting that in $p\bar{p}$ collisions we know where $q$ and $\bar{q}$ come from. In the SM this asymmetry arises from interference between LO and NLO diagrams, e.g.

As it is well known, Tevatron measures a **positive** asymmetry exceeding the SM expectation...
Status of Tevatron measurements

inclusive measurements not converging to SM
avg $2.7\sigma$ from closest prediction

$SM = \begin{align*}
0.058 & \quad MCFM \\
0.0724 & \quad Ahrens et al. \\
0.087 & \quad Kuhn & Rodrigo \\
0.088 & \quad Bernreuther & Si \\
0.089 & \quad Hollik & Pagani
\end{align*}$
Status of Tevatron measurements

A high-mass measurement that triggered interest is closer to SM but still 2.5σ away.
These consistent discrepancies have motivated a plethora of papers proposing new physics explanations.

$A_{FB}$ is an effect competing with QCD

- most likely, new physics in $q\bar{q} \rightarrow t\bar{t}$
- and expected at tree level

What could this new physics be? Group theory helps here.

The Lagrangian must be singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$

type of bosons determined by quantum numbers of quarks.
**Colour**

\[ 3 \otimes \bar{3} = 8 \oplus 1 \]
\[ 3 \otimes 3 = 6 \oplus \bar{3} \]

**Isospin**

\[ 2 \otimes 2 = 3 \oplus 1 \]
\[ 2 \otimes 1 = 2 \]
\[ 1 \otimes 1 = 1 \]

**Hypercharge**

\[ \sum Y = 0 \]

| \( B \) | \((1,1)\) | \(0\) | \( \phi \) | \((1,2)\)-1/2 |
| \( W' \) | \((1,3)\) | \(0\) | \( \Phi \) | \((8,2)\)-1/2 |
| \( B^1 \) | \((1,1)\) | \(1\) | \( \omega^1 \) | \((6,1)\)-1/3 |
| \( G \) | \((8,1)\) | \(0\) | \( \Omega^l \) | \((6,1)\)-1/3 |
| \( H^l \) | \((8,3)\) | \(0\) | \( \omega^4 \) | \((3,1)\)-4/3 |
| \( G^l \) | \((8,1)\) | \(1\) | \( \Omega^4 \) | \((6,1)\)-4/3 |
| \( Q^l \) | \((3,2)\)1/6 | \(\sigma\) | \((3,3)\)-1/3 |
| \( Q^5 \) | \((3,2)\)-5/6 | \(\Sigma\) | \((6,3)\)-1/3 |
| \( Y^l \) | \((6,2)\)1/6 |  |  |  |
| \( Y^5 \) | \((6,2)\)-5/6 |  |  |  |
Most popular models

s channel
\( G \sim (8,1)_0 \)

0809.3354, 0906.0604, 0911.2955, 1007.0243, 1011.6380, 1011.6557, 1101.2902, 1101.5203, 1103.0956, 1104.1917, 1105.3158, 1105.3333, 1106.0529, 1106.4054, 1107.0978, 1107.1473, 1107.2120, 1107.5769, 1109.0648, 1205.4721, 1209.2741, 1209.3636, 1209.6375

0907.4112, 1101.4456, 1101.5625, 1102.0545, 1103.1266, 1103.4835, 1104.1385, 1104.3139, 1106.5982, 1108.0350, 1108.1802, 1205.0407, 1207.0643, 1209.4354, 1209.4872

1101.1445, 1101.5392, 1104.0083, 1105.4606, 1203.4489, 1205.3311

\( \omega^4 \sim (3,1)_{-4/3} \)

0911.3237, 0911.4875, 0912.0972, 1007.2604, 1102.3374, 1102.4736, 1103.2757, 1108.4027, 1205.5005

\( \Omega^4 \sim (6,1)_{-4/3} \)
These models are mostly “phenomenological”

(which means: do not ask for all bells & whistles)

but good to test:

1. can one enhance $A_{FB}$ without spoiling the good agreement of the total cross section?

2. can one reproduce the Tevatron inclusive and high-mass $A_{FB}$?

3. is this compatible with other measurements, in particular at LHC?

If all these conditions are met, one can go further and try to build a new physics theory explaining $A_{FB}$.
Can the asymmetry be generated keeping $\sigma_{\text{exp}} \sim \sigma_{\text{SM}}$ at Tevatron?

$\sigma_{\text{exp}} = 7.50 \pm 0.48 \text{ pb}$

$\sigma_{\text{SM}} = \begin{cases} 7.46^{+0.66}_{-0.80} \text{ pb} & \text{Langenfeld et al `09 and others} \\
6.30 \pm 0.19^{+0.31}_{-0.23} \text{ pb} & \text{Ahrens et al `10} \end{cases}$

$\sigma(t\bar{t}) = \sigma_{\text{SM}} + \delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim \sigma_{\text{SM}}$ implemented in two ways

$\begin{cases} \delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0 & \text{fine-tuned cancellation} \\
\delta\sigma_{\text{int}} \sim 0 & \delta\sigma_{\text{int}}^F = -\delta\sigma_{\text{int}}^B \text{ from symmetry} \end{cases}$

These possibilities are radically different:

- $\delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0$ occurs at a given CM energy for a given coupling
- $\delta\sigma_{\text{int}}^F = -\delta\sigma_{\text{int}}^B$ arises from vertex structure (axial), at all energies
Results of test #1

There are many models with new particles exchanged at tree level in s, t or u channel that can generate large $A_{FB}$ while keeping the total $\sigma$

Other more exotic models:
- one loop: effective $g_{tt}$ couplings 1106.4553, 1108.1173, 1112.5885
- spin-2 particles 1203.2183
- combinations of particles 1102.0279, 1208.4675
Test #2

Is the Tevatron picture consistent? (new CDF 9.4 fb\(^{-1}\))

![Graphs showing various decay channels and their AFB distributions for m_{t\bar{t}} > 450 GeV, with different decay modes such as Z', W', φ, and Ω. Each graph illustrates the AFB as a function of the AFB for different mass intervals and decay branching ratios.](image-url)
Results of test #2

Most models can reproduce the central values

\[ A_{FB} = 0.187 \pm 0.036 \quad \text{inclusive (naive world avg)} \]
\[ A_{FB} = 0.295 \pm 0.066 \quad \text{CDF high-mass (new)} \]

Only Z´fails the test

The picture is more consistent than in January 2011 when the $3.6\sigma$ discrepancy appeared. This is good news!
The younger sister: the LHC charge asymmetry

At the LHC, a suitable observable to test “asymmetric” $t\bar{t}$ production is

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$, that exploits the fact that we have $pp$ instead of $p\bar{p}$ collisions.

Clearly, this is not the same observable as at Tevatron, and a result consistent with the SM does not say anything about the Tevatron excess.

But comparing predictions for $A_{FB}$ and $A_C$ does say a lot about models addressing the Tevatron excess.
Status of LHC measurements

Good agreement with SM

SM =

0.006  MC@NLO
0.0115  Kuhn & Rodrigo
0.0123  Bernreuther & Si
Test #3

Is the Tevatron - LHC picture consistent?

$Z', W'$ disfavoured/excluded

(choose preferred wording)

for the rest of models the future is unclear
Results of test #3

The interest on AFB has decreased… or maybe not!
$A_{FB}$ strikes back!

Full CDF data set shows a smooth, convincing excess…

... that is hard to regard as a statistical fluctuation!

$p$-value of slope: $7.4 \times 10^{-3}$ (2.4$\sigma$)
But the rebel $A_C$ agrees with the SM!

<table>
<thead>
<tr>
<th>Kinematic variable</th>
<th>$A_C$ in bin 1</th>
<th>$A_C$ in bin 2</th>
<th>$A_C$ in bin 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{t\bar{t}}$</td>
<td>0.029$\pm$0.021</td>
<td>0.016$\pm$0.015</td>
<td>0.001</td>
</tr>
<tr>
<td>$p_{T,t\bar{t}}$</td>
<td>0.037$\pm$0.025</td>
<td>0.014</td>
<td>0.030$\pm$0.021</td>
</tr>
<tr>
<td>$m_{t\bar{t}}$</td>
<td>0.051$\pm$0.027</td>
<td>0.017</td>
<td>0.019$\pm$0.017</td>
</tr>
<tr>
<td>(SM pred.)</td>
<td>0.0030$\pm$0.0002</td>
<td>0.0086$\pm$0.0004</td>
<td>0.0235$\pm$0.0010</td>
</tr>
</tbody>
</table>

- is all this compatible?
- how to solve this puzzle?
- is there something we can measure at both colliders and compare?
The parents: the collider-independent asymmetries

The Tevatron $A_{FB}$ and LHC $A_C$ originate from the “intrinsic” partonic asymmetries $A_u$, $A_d$ in $u\bar{u} \rightarrow t\bar{t}$ and $d\bar{d} \rightarrow t\bar{t}$ respectively.

$A_{FB}$ and $A_C$ are different “combinations” of $A_u$, $A_d$

- Different sizes of $u\bar{u} \rightarrow t\bar{t}$ and $d\bar{d} \rightarrow t\bar{t}$ relative to total $t\bar{t}$ production
- Asymmetry “dilution” at LHC due to $q, \bar{q}$ coming from either $p$

but, for fixed $\hat{s}$, $A_u$ and $A_d$ are ($\sim$) the same at Tevatron and LHC (!!!)

Precisions:
- SM asymmetries in $gq \rightarrow t\bar{t}j$ irrelevant
- in practice, replacing fixed $\hat{s}$ by finite $m_{t\bar{t}}$ intervals introduces small deviations
- deviations smaller at low $p_T^{t\bar{t}}$

a possible solution to the asymmetry puzzle is to measure $A_u$, $A_d$ at Tevatron and LHC and compare
Measure \(A_u\) and \(A_d\)?

Exploiting the dependence of \(A_{FB}\) and \(A_C\) on the \(t\bar{t}\) velocity

\[
\beta = \frac{|p_{\tilde{t}} + p_{\tilde{\bar{t}}}|}{E_{\tilde{t}} + E_{\tilde{\bar{t}}}}
\]

\(A_u\) and \(A_d\) can be extracted from a fit to

\[
A_{FB}(\beta) = A_u F_u(\beta) + A_d F_d(\beta)
\]

\[
A_C(\beta) = A_u F_u(\beta) D_u(\beta) + A_d F_d(\beta) D_d(\beta)
\]

where \(F_q(\beta)\) (\(q\bar{q}\) fractions) and \(D_q(\beta)\) (dilution factors) are computed from MC in the SM.
$A_u$ and $A_d$ in the SM

\begin{align*}
\text{no cut on } p_T^{t\bar{t}} \\
\text{\quad } \text{Tevatron / LHC} \\
\text{differences much smaller than exp. uncertainty}
\end{align*}
Goal: to measure $A_u$ and $A_d$. What if?

That might tell us

- whether Tevatron and LHC results are compatible or not.

Possible results assuming SM, stat. unc. only.
Goal: to measure $A_u$ and $A_d$. What if?

That might tell us

- whether their combination is compatible with SM

`Expected` $1\sigma$ combined limits in axigluon model, $\Delta A_{FB} = 0.07$
Asymmetry friend #1: $t\bar{t}$ differential distribution

Enhancements expected in *almost all* models, especially those implementing $\delta\sigma_{\text{int}} + \delta\sigma_{\text{quad}} \sim 0$ to keep Tevatron cross section agreement...

... but nothing unusual seen as yet!
Tevatron asymmetries after LHC $t\bar{t}$ tail constraints

Disclaimer: additional constraints (tj resonances, top FCNC…) not included
Least disturbing model: s-channel coloured resonance $\mathcal{G}$

necessary that $\mathcal{G}$ couples to up/down and to top
coupling to light quarks small, otherwise dijet production
large coupling to top required (natural in extra dimensions)
Colour octet features

- Interference $\delta\sigma_{\text{int}}$ identically zero (at all energies) if either coupling to $q\bar{q}$ or $t\bar{t}$ axial.

- Asymmetry maximised respect to $\delta\sigma$ if both couplings axial (old friend axigluon).

- Distinctive signature: peak (bump) in the $m_{t\bar{t}}$ distribution from quadratic term $\delta\sigma_{\text{quad}}$ if the resonance is reached.

- Non-observation of peak $\xrightarrow{} G$ heavy, wide or below threshold.

- LHC limits more and more stringent: if $G$ heavy, it is “too heavy” and large (nonperturbative) couplings required to reproduce $A_{FB}$.

- Cool, fashionable, viable alternative: light gluons.
Light gluons below the TeV

- invisible at Tevatron if very wide or below threshold
- even more at LHC ($gg$ dominated)
- can satisfy flavour and dijet constraints
- diverse $A_{FB}$ profiles vs $m_{t\bar{t}}$ possible
$A_{FB}$ profiles: from flat to camel

Sustainable model

flat

rising

hill

dip-rising

dip-hill

camel

$G_\mu$ below $\tilde{t}$ threshold

$G_\mu$, $M = 1050$ GeV

$G_\mu$, $M = 870$ GeV

$G_\mu$, $M = 870$ GeV

$G_\mu$, $M = 1050$ GeV

$G_\mu$, $M = 870$ GeV

$G_\mu$, $M = 870$ GeV

$G_\mu$, $M = 450$, 1050 GeV

$G_\mu$, $M = 450$, 870 GeV

$G_\mu$, $M = 450$, 870 GeV

$G_\mu$, $M = 450$, 570, 870
Light gluons are LHC-friendly

Light gluons can accommodate small $A_C$… for the moment…

Average value of $A_C = 0.013 \pm 0.012$ has 90% uncertainty!

Borrowed from Gross et al. `12

![Graph showing LHC and Tevatron asymmetry](image)

Latest averages (this talk)

crucial to see what happens when the precision is improved and with 8 TeV data
Asymmetry friend #2: $t\bar{t}$ polarisation

The double angular distribution for a $t\bar{t}$ pair is

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_t d \cos \theta_{\bar{t}}} = \frac{1}{4} [1 + B_t \cos \theta_t + B_{\bar{t}} \cos \theta_{\bar{t}} - C \cos \theta_t \cos \theta_{\bar{t}}]$$

with $\theta_t, \theta_{\bar{t}}$ the angles of the top, antitop momenta w.r.t. chosen spin axes.

In the SM:

- $B_t, B_{\bar{t}} = 0$ (unpolarised tops) at tree level due to QCD vector coupling, and $B_t, B_{\bar{t}} \approx 0$ at higher orders
- $C \neq 0$ choosing suitable axes

Beyond the SM, these predictions can be significantly altered.
C at Tevatron, beamline basis

Borrowed from Fajfer et al. ’12

ΔC_{beam, (Tevatron)}

ΔA_{FB}

CDF dil 5.1 fb^{-1}
D0 dil 5.4 fb^{-1}
D0 l+j 5.3 fb^{-1}
D0 l+j / dil

naive world avg
C at LHC, helicity basis

Borrowed from Fajfer et al. ’12

The results for the relevant spin observables at the 7 TeV LHC are shown in Fig. 8. Among these, presently the most powerful probe of FBA inspired models is the helicity basis spin correlation as measured recently by ATLAS [41]. In particular it already represents a non-trivial constraint for the scalar isodoublet and heavy axigluon models. In the light scalar isodoublet scenario, the large negative deviation in $C_{\text{hel}}$ can be traced to sizable non-standard contributions. For example, at the Tevatron, spin correlation measurements at O(2%) precision would be required to probe such FBA explanations.

The results for $D_i$, $C_i$ and $B_i$ at the 7 TeV and 8 TeV LHC are almost identical and we do not show the later separately.
B at LHC, helicity basis

- CMS dil 5.0 fb\(^{-1}\)
- ATLAS \(l+j\) 4.7 fb\(^{-1}\)
- naive world avg

Borrowed from Fajfer et al. '12

\[ \Delta A_{FB} \]

\[ B_{\text{hel}}(\text{LHC7}) \]

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The results for \(D, C_i, B_i\) at the 7 TeV and 8 TeV LHC are almost identical and we do not show the later separately.
Discussion

After various measurements at the Tevatron and LHC
various updated SM asymmetry predictions
plenty of proposals for new physics explanations
at this point the question is:

Is this a hint of new physics? Or we will have another $3\sigma$ disappointment?

Typical answers are:

- it is new physics!
- it is a higher-order QCD effect
- it is an unknown systematic
Can the excess be new physics?

Using the equations for the collider-independent asymmetries

\[ A_{FB}(\beta) = A_u F_u(\beta) + A_d F_d(\beta) \]
\[ A_C(\beta) = A_u F_u(\beta) D_u(\beta) + A_d F_d(\beta) D_d(\beta) \]

one can revert the argument and obtain model-independent predictions for \( A_{FB} \), \( A_C \) by scanning over \( A_u \), \( A_d \)

\( A_{FB} \sim 0.2 \) compatible even with \( A_C \lesssim 0 \) if \( A_u \), \( A_d \) have opposite signs

model implementing this mechanism: Drobnak et al. ’12
other models with small \( A_C \): Alvarez et al. ’12, Drobnak et al. ’12
Can the excess be higher-order QCD?

One can estimate the effect of higher QCD (& EW) orders with the same procedure, but randomly varying $A_u$, $A_d$ around the SM NLO values to “predict” the relation $A_{FB}$ vs $A_C$…

… an explanation by QCD would not (likely) fit current data!
Can the excess be an unknown systematic?

Hard to think of, because it appears in two experiments. But unknown systematics are by definition unknown…
One-page summary

The $A_{FB}$ puzzle is far from being solved. There are some chances that there is new physics in the top sector.

This new physics might also be visible indirectly, in precision measurements of the $t\bar{t}$ differential distribution and in top polarisation measurements.

Or not.

And, in any case, the puzzle may be in its way to be solved.
Farewell

A day may come when the courage of men fails, when we forsake our models and break all bonds with $A_{FB}$. But it is not this day.

JAAS & the rest of $A_{FB}$ fans
ADDITIONAL SLIDES
$F_{u/d}$ and $D_{u/d}$: dependence on $\beta$
$A_{u,d}$: dependence on $\beta$?

As defined by

$$A_{FB}(\beta) = A_u(\beta)F_u(\beta) + A_d(\beta)F_d(\beta)$$


Fu: 3x variation
Du: 20x Dd: 30x

Tevatron $m_{t\bar{t}} < 450$ GeV

LHC7

$p_{T} < 30$ GeV

The dependence on $\beta$ is small
Prediction / constraint on light gluons: four tops

The parameter space for masses / couplings / widths can be probed at 7 TeV and the model may be excluded at 14 TeV.
flavour-changing $ut$ couplings required
this gives problems at low energy, for example atomic parity violation
but these models already have worse problems in $t\bar{t}$ production itself
Z’ features

• Negative interference with SM decreases $A_{FB}$

• A positive contribution to $A_{FB}$ and agreement with Tevatron $\sigma(t\bar{t})$ requires large coupling and cancellation $\delta \sigma_{int} + \delta \sigma_{quad} \sim 0$

• Cancellation cannot happen at LHC too: excess in $t\bar{t}$ tail (unobserved)

• The same comments apply to $W$ (also $t$-channel)
\( \Omega^4 / \omega^4 \) features

- The contribution to \( A_{FB} / A_C \) is negative for small \( \Omega^4 / \omega^4 \) masses
  - u-channel propagator prefers *backward* tops
- Numerator does not, and wins for large \( M \)
- Going to high \( m_{t\bar{t}} \) you finally `see´ the u-channel propagator:
  - good test for LHC