$R$–Parity Violating Supersymmetry Explanation for the Large $t\bar{t}$ Forward-Backward Asymmetry

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We examine a supersymmetric explanation for the anomalously high forward backward asymmetry in top pair production measured by CDF and D0. We suppose that it is due to the $t$–channel exchange of a right-handed sbottom which couples to $d_R$ and $t_R$, as is present in the $R$–parity violating minimal supersymmetric standard model. We show that all Tevatron and LHC experiments’ $t\bar{t}$ constraints may be respected for a sbottom mass between 300 and 1200 GeV, and a large Yukawa coupling $>2.2$, yielding $A_{FB}$ up to 0.18. The non standard model contribution to the LHC charge asymmetry parameter is $\Delta A_C = 0.017 - 0.045$, small enough to be consistent with current measurements but non-zero and positive, allowing for LHC confirmation in the future within 20fb$^{-1}$. A small additional contribution to the LHC $t\bar{t}$ production cross-section is also predicted, allowing a further test. We estimate that 10 fb$^{-1}$ of LHC luminosity would be sufficient to rule out the proposal to 95% confidence level, if the measurements of the $t\bar{t}$ cross-section turn out to be centred on the Standard Model prediction.

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In the 1.96 TeV centre of mass energy $p\bar{p}$ collisions at the Tevatron collider, measurements of the $t\bar{t}$ forward backward asymmetry $A_{FB}$ were made by the CDF and D0 experiments. A positive non-zero value indicates that, in $t\bar{t}$ production events, a higher number of events$^1$ $N(c > 0)$ had a $t$ travelling in a more forward direction than the $\bar{t}$ compared to the number $N(c < 0)$ of those events where the $t$ travelled in a more backward direction than the $\bar{t}$

$$A_{FB} = \frac{N(c > 0) - N(c < 0)}{N(c > 0) + N(c < 0)} \tag{1}$$

The Standard Model (SM) prediction of this quantity is $A_{FB}^{SM} = 0.066 \pm 0.020$ $^3$, and dominantly derives from the interference between tree-level and one-loop quantum chromodynamics (QCD) diagrams. CDF measured an unfolded value$^2$ $0.158 \pm 0.075$ $^4$, whereas D0 measured $0.196 \pm 0.065$ $^5$, each significantly higher than $A_{FB}$. We suppose here that the discrepancy between measurements and the SM prediction for $A_{FB}$ is due to a particular beyond the SM process, and examine other constraints to see if the explanation remains viable.

Since the LHC is a $pp$ collider and thus has an initial state which is symmetric under $c \leftrightarrow -c$, $A_{FB}^{LHC} = 0$. However, the LHC is able to measure a related but different charge asymmetry in the number of tops that are travelling at a smaller angle to the beam-line compared to the number of anti-tops that are travelling closer to the beam-line:

$$A_{C}^p = \frac{N(|y_i| > |y_i|) - N(|y_i| > |y_i|)}{N(|y_i| > |y_i|) + N(|y_i| > |y_i|)} \tag{2}$$

where $y_i = 1/2 \ln(E_i + p_{iz})/(E_i - p_{iz})$ is the rapidity of particle $i$. The SM prediction for 7 TeV collisions is $A_{C}^{SM} = 0.006 \pm 0.002$, which is consistent with the combined ATLAS and CMS measurements $A_{C}^p = -0.015 \pm 0.04$ $^6$. Any non-SM explanation for the high measured value of $A_{FB}$ must also therefore not predict too high a value for a non-SM contribution $\Delta A_C = A_C^p - A_C^{SM}$.

Many models have so far been proposed to explain $A_{FB}$ measurements and several have failed other constraints. Axigluons, $W'$ and $Z'$ vector bosons, as well as the $t$–channel exchange of various scalars $^8$ have all been proposed. Here, we show that the exchange of a particular scalar: a right-handed sbottom, can explain the apparent sizable enhancement to $A_{FB}$ while respecting other relevant constraints. Ref. $^9$ included this, among other possibilities, as an explanation for $A_{FB}$. However, the authors only considered couplings smaller than 1.25 because they required perturbativity up until the GUT scale, and found that the new physics contributions to $A_{FB}$ were too small to obtain it to within the 1σ measurement errors, although they were able to obtain it to just within 2σ measurement errors. We shall consider larger values of the coupling, which we show are necessary to explain the data. Our work also goes further than Ref. $^9$ in the sense that we consider the LHC charge asymmetry and top production constraints as well.

The $R$–parity violating (RPV) interactions of the min-

\footnotesize

$^1$ $c = \cos \theta$, where $\theta$ is defined to be the scattering angle between incoming proton beam and outgoing top in the centre of mass frame of $t\bar{t}$.

$^2$ Different shower models can produce different values when they are used in the unfolding because of the different treatments of QCD coherence $^2$, yielding effects on $A_{FB}$ of order several percent.
inal supersymmetric standard model (MSSM) include the superpotential term

\[ W = \frac{\lambda''_{313}}{2} \bar{T}_R D_R \bar{B}_R, \]

where gauge indices have been suppressed and \( \bar{T}_R, D_R, \bar{B}_R \) are chiral superfields containing the anti-right handed top \( \bar{T}_R \), anti-right handed down \( D_R \) and anti-right handed bottom quark \( \bar{B}_R \), respectively. \( W = \lambda''_{313} \bar{T}_R D_R \bar{B}_R \) could also explain \( A_{FB} \), although the constraints on \( m_{bR} \) are likely to be stronger than those on \( b_R \), since the strange PDFs are higher than the bottom PDFs, and so they will be predicted to be produced more readily at the LHC. The operator in Eq. 3 has an antisymmetric colour structure. It leads to an additional tree-level process that contributes to \( A_{FB} \), the Feynman diagram of which is shown in Fig. 10 Ref. 11 put an upper bound on \( \lambda''_{313} < 1.25 \) on the grounds of perturbativity up to the GUT scale. In the present paper, we shall not worry about a premature ultra-violet completion of our model: the coupling will reach a Landau pole around \( 10 - 100 \) TeV about a premature ultra-violet completion of our model: the coupling will reach a Landau pole around \( 10 - 100 \) TeV. It disagrees with the expression for \( \lambda'_{313} \), if it is only the non-negligible real RPV coupling, is not constrained to be small by indirect experimental data \[12\] \[17\] for \( b_R \) that are not too light\[3\]. The strongest constraints from \( R_t = \Gamma(Z^0 \to \text{hadrons})/\Gamma(Z^0 \to \ell \ell) \[19\] \[20\] are still too weak (for the right-handed bottom masses > 300 GeV that we shall be interested in) to be limiting. Eq. 3 has exactly the right properties to evade current stringent flavor constraints on di-quarks: it only couples to right-handed quarks and induces no tree-level flavour changing neutral currents \[20\]. Entertaining the possibility of other baryon-number-violating couplings \( \lambda''_{ijh} \), in the presence of a large coupling \( \lambda''_{313} \), there is a particularly strict bound on \( |\lambda''_{313} |^2 < 0.01 \[21\] coming from \( K^0 - \bar{K}^0 \) mixing constraints for particle mass input parameters less than 1 TeV. Thus, strong constraints upon \( |\lambda''_{323} | \) would apply, and some fermion mass model building would have to be performed to see if this were realistic. It has been argued that simple Higgsed abelian flavour symmetries and the Froggatt-Nielsen mechanism would naively predict that the order of magnitude of \( |\lambda''_{323} | \) would be larger than that of \( |\lambda''_{313} | \). However, this order of magnitude estimate is rather rough, and assumes that several couplings involved in the Froggatt-Nielsen mechanism are of order 1, an assumption that may be violated in more explicit constructions. Here, it seems premature to apply any such model building, since as we shall show, LHC...
We define an implementation of the RPV MSSM [30, 31]. We define an
CTEQ6L1 basis that...

TABLE I: 95% CL constraints on new physics contributions to observables that are brought to bear upon our model. The limits have been derived by using naive summation in quadrature of all errors.

| Parameter | Lower Limit | Upper Limit |
|-----------|-------------|-------------|
| $0.037 < \Delta A_{FB}$ | $< 0.205$ | $-0.079 < \Delta A_{FB}^c < 0.061$ |
| $-0.65 < \Delta \sigma_{TEV}^{H}/pb$ | $< 1.51$ | $-76 < \Delta \sigma_{T}^{H}(bin)/fb < 76$ |
| $-0.38 < \Delta A_{FB}$ | $< 0.23$ | $0.062 < \Delta A_{FB}^c < 0.33$ |
| $-19.2 < \Delta \sigma_{LHCT}^{H}/pb$ | $< 39.2$ | $< 313$ |

On the day of completion of this article, Ref. [32] appeared on the electronic archive. It considers the effect of the exchange of a charge $-1/3$ scalar triplet diquark, and the bounds on parameter space coming from $A_{FB}$, $A_c$, $\sigma_{T}^{H}$, and $\sigma_{LHCT}$ measurements agree with those shown here and aside from the fact that the paper also uses MadGraph to do the simulations, it provides an independent confirmation of some of our results.

All of the predictions above apply to a generic model containing a colour triplet scalar of charge $-1/3$ coupling to $d_{R}d_{R}$. Such models are extremely strongly constrained by atomic parity violation (APV) constraints [33]. The RPV MSSM, however, has many additional particles and interactions and the possibility for cancellations of different contributions to the APV is open. Indeed, a very recent paper [13] has shown that stop mixing contributions to APV can completely cancel the contribution from $\lambda''_{313} \neq 0$.

It was recently argued that baryon number violating couplings such as $\lambda''_{313}$ and a light stop could simultaneously explain the naturalness of SUSY and its evasion of 7 TeV LHC searches based on large missing transverse momentum [34]. SUSY implies additional interactions with identical coupling strengths: in particular, $\mathcal{L} = (\lambda''_{313})^* t_R d_R^c C^{1/2} d_R + H.c. + \ldots$, where $C$ is the charge conjugation matrix and $T$ denotes transpose. If $t_R$ is not too heavy, $t$–channel stop exchange should induce a $b\bar{b}$ forward backward asymmetry [35]. One may also expect resonant stop production to produce a bump in the $m_{jj}$ distribution in two jet events where one of the jets is a $b$. However, such a signal will be suppressed by small bottom PDFs and further study is required to establish the viability of detection.

In summary, we have shown that the RPV MSSM can explain the anomalously large $A_{FB}$ measured at the Tevatron experiments, provided that couplings are chosen in a region that may violate perturbativity below the GUT scale. The $t$–channel exchange of a right-handed sbottom of mass 300-1200 GeV which couples to $d_{R}d_{R}$...
FIG. 2: Predicted non-SM contributions to various constraining observables: (a) the non-SM $t\bar{t}$ forward backward asymmetry parameter, (b) the total $t\bar{t}$ Tevatron cross-section, (c) the total $t\bar{t}$ Tevatron cross-section in the bin $700 \text{ GeV} < m_{t\bar{t}} < 800 \text{ GeV}$, (d) the LHC charge asymmetry. Each individual constraint is respected below the broken contour, except for in (a), where it is respected above the contour. Inside the solid contour, all limits in Table I are respected. We have checked that the 8 TeV LHC has the same predictions for $A^p_C$ as those displayed in (d), to a very good approximation.

with an interaction strength bigger than 2.2 is required. There is parameter space which passes all relevant constraints from the Tevatron and the LHC. Future LHC signals are predicted to be: a small positive asymmetry parameter $0.017 < \Delta A^p_C < 0.045$ and a $t\bar{t}$ production cross-section that should be larger than the SM prediction by at least 8 (13) pb at 7 (8) TeV. Assuming that

\[
0.037 < \Delta A_{FB} < 0.11 \\
-0.1 < \Delta \sigma_{t\bar{t}}^{TEV}/\text{pb} < 1.8 \\
0.006 < \Delta A_{FB} < 0.07 \\
8 < \Delta \sigma_{LHC}/\text{pb} < 25
\]

TABLE II: Predicted values of new physics contribution to various observables for parameter space that passes all current experimental constraints.

the uncertainties $\propto 1/\sqrt{L}$ (where $L$ is the integrated luminosity), there should be enough information in 10 fb$^{-1}$ of 7 TeV LHC data to exclude such an enhancement of the production cross-section to the 95% confidence level. Further confirmation through the top charge asymmetry may take longer, but is within reach of 20 fb$^{-1}$. These predictions, along with the other predictions in Table II, provide targets for ongoing LHC tests of the model. Top spin observables also provide an interesting way to discriminate models of new physics that explain the Tevatron measurements $A_{FB}$ [36, 37], and it would be an interesting future project to investigate the predictions for them coming from $\lambda''_{333}$. If the sbottoms are not too heavy, then there is the possibility of confirming the mechanism through $b\bar{b}b\bar{b}$ production at the LHC, which would then decay to $t\bar{t}$ plus 2 jets, with an invariant mass bump in the combined $t$ and jet mass. A discovery such
as this would provide a definitive test of the model. We leave its investigation to future work.

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