Implications of the Measurement of Ultra-Massive Boosted Jets at CDF

Yochay Eshel, Oram Gedalia, Gilad Perez and Yotam Soreq

Department of Particle Physics & Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel

The CDF collaboration recently reported an upper limit on boosted top pair production and noted a significant excess above the estimated background of events with two ultra-massive boosted jets. We discuss the interpretation of the measurement and its fundamental implications. In case new physics is involved, the most naive contribution is from a new particle produced with a cross section that is a few times higher than that of the top quark and a sizable hadronic branching ratio.

We quantify the resulting tension of a possible larger top pair cross section with the absence of excess found in events with one massive boosted jet and missing energy. The measured planar flow distribution shows deviation from CDF’s Pythia QCD prediction at high planarity, while we find a somewhat smaller deviation when comparing with other Monte Carlo tools. As a simple toy model, we analyze the case of a light gluino with R-parity violation and show that it can be made consistent with the data.

Introduction. New physics searches at colliders typically focus on signals with leptons and/or missing energy. Recently, there has been some interest in extending the hunt to include particles that decay only to quarks and gluons (see e.g. [1, 2] for some theoretical studies), as was done in an analysis by CDF [3]. In this analysis the focus was on supersymmetry (SUSY) with R-parity violation (RPV), where a light gluino decays to three quarks. However, this results in a multi-jet signal, which makes it challenging to distinguish from the QCD background. Indeed, it was found in [3] that the current sensitivity is far below the expected signal, thus it is not useful for obtaining a bound on the parameter space of SUSY (or any alternative theory which would produce this type of a signal).

Progress has been recently achieved in another CDF study by restricting the data sample to include only high transverse momentum ($p_T$) and high mass jets [4, 5], thus reducing the QCD background much more than the signal and increasing the sensitivity (as was anticipated in [2]). The idea is that the decay products of a highly boosted massive object would collimate to a single jet in the detector. While the data is still dominated by the QCD background, it has much larger discrimination power. Moreover, it is possible to use various jet substructure analysis techniques to further improve the efficiency. Applying this approach enabled to obtain the strongest existing bound on the cross section for the production of a (high-$p_T$) top pair, even without relying on substructure analysis.

The CDF study focused on events including two boosted jets ($p_T > 400$ GeV for the leading jet) with mass close to the top mass (130-210 GeV) and pseudorapidity $\eta < 0.7$ (to be precise, an $\eta$ cut was applied only for the leading jet, but it was found that the second jet admitted a similarly bounded $\eta$ value) [4, 5]. The jet algorithms used are Midpoint and anti-$k_T$ [6] with $R = 1.0$ ($R = 0.7$ was also checked), which were in excellent agreement. As discussed below, the estimation of the background depends on a parameter $R_{mass}$ (see Eq. (3)).

Using data sample of 5.95 fb$^{-1}$ and assuming $R_{mass} = 1$, the standard model (SM) expected number of events is

\[
QCD|_{R_{mass} = 1} : 13 \pm 2.4 \text{ (stat.)} \pm 3.9 \text{ (syst.)} \times 10^3, \quad t\bar{t} : 3.0 \pm 0.8.
\]

The number of observed events was 32 [5], which constitutes a deviation of 3.44 standard deviations ($\sigma$) from the above expectation. In order to translate this to cross section, we perform the following exercise. The SM NNLO cross section for $t\bar{t}$ production with $p_T > 400$ GeV is 4.5 fb [5, 7]. Multiplying this by a branching ratio of 4/9 for hadronic tops, we get 2 fb, which corresponds to the 3 events reported in Eq. (1). Thus the difference between the 32 observed events and the mean value of Eq. (1) is translated to a cross section of

\[
\sigma_{excess} \sim (11 \pm 3.2) \text{ fb}.
\]

This is the excess found in [5] in terms of hadronic top-equivalent cross section, under the assumption that the signal cannot be accounted for within the SM. The data can also be used to provide an upper bound on the all hadronic top pair production cross section, which is given by 20 fb at 95% confidence level [5].

The evaluation of the QCD background in Eq. (1) was done in the following way. The search was divided into four different regions in terms of the jet masses. Region A corresponds to events with two “light” jets, with masses in the range of 30-50 GeV. Regions B and C are for one massive jet (130-210 GeV) and one light jet, depending on which is the leading jet in terms of $p_T$. Finally, region D corresponds to two massive jets. There are three basic assumptions involved: i) all the events in regions A-C come only from QCD; ii) the actual cross section can be factorized into the partonic cross section, which only weakly depends on the masses of the final states, and the jet and soft functions [8]; iii) the masses of the leading and sub-leading jets are largely uncorrelated variables for QCD jet production, and the correlation cancels in the ratio $R_{mass}$ described below. Under these assumptions,
we have
\[ R_{\text{mass}} \equiv \frac{n_{BNC}}{n_{AD}} = 1, \quad (3) \]
where \( n_X \) is the number of events in region \( X \). One can therefore estimate the number of QCD events in region D by \( n_{BNC}/n_A \). The result of this calculation is the one given in Eq. (1) for QCD. Below we test this estimation in more detail.

The CDF study [5] used another search channel, including one jet (with \( p_T > 400 \) GeV and mass 130–210 GeV) plus missing energy (with missing \( E_T \) significance between 4 and 10 – see definition in [5]). In the context of \( t\bar{t} \) production, this corresponds to events with one top decaying hadronically and the other semileptonically. Note that this type of measurement suffers from a lower signal to background ratio, since there are large fluctuations in the jet energy scale, which make the estimation of the missing energy noisy (see Fig. 10 in [4], where there are long tails for both the \( t\bar{t} \) and QCD missing transverse energy significance distributions). The total number of events observed in both channels is 58, the estimated QCD background (for \( R_{\text{mass}} = 1 \)) is 44 ± 8.4 (stat.) ± 13 (syst.) and the \( t\bar{t} \) background is 4.9. This leads to an upper bound of 40 fb at 95% confidence level on the \( t\bar{t} \) production cross section for top quark \( p_T > 400 \) GeV.

Another result given in [4] is the planar flow (Pf) distribution [9–10] (see also [11]). This jet substructure variable distinguishes between a linear deposition of the energy inside the jet, favored by QCD processes (giving values close to 0 for Pf), and a planar one (that is, Pf close to 1), produced by the 3-body decay of a top quark. The plot given in [4] shows that in the data there are more events with high Pf values than predicted for QCD alone.

**Model Independent Interpretation.** The excess of events with two ultra-massive boosted jets hints for a contribution which is characterized by a mass scale around the top one. This new source of massive jets should be produced with a cross section bigger than that of the SM hadronic \( t\bar{t} \) by a factor of roughly 5 (about 11 fb in the signal region, as in Eq. (2), but not more than 20 fb) and a dominant branching ratio for a fully hadronic decay. In order to have significant acceptance under the search criteria, the production should be mostly central, that is with \( \eta \lesssim 0.7 \) for both jets. Furthermore, if it is due to the decay of a massive particle, the collimation rate, which is the fraction of decays where the daughter particles collimate into a single jet, must be high, e.g. similar to that of the top \((\sim 0.5 \text{[10]}).\)

The simplest explanation of this excess would be an underestimation of the QCD production strength (no massive particle involved). As described above, the existence of an excess was established based on an estimation of the QCD background in the signal region D, without relying on Monte Carlo (MC) simulations. In this estimation, it was assumed that the dependence of the partonic cross section on the outgoing particles’ virtuality (jet mass) is negligible\(^1\), as mentioned in assumption ii above. To estimate the significance of this effect, we calculated the leading order partonic cross section\(^2\) for each of the regions of jets masses A-D (denoted as \( \sigma_X \) for region X) with the virtuality of the particle representing each jet mass,

\[ \sigma_X = \int dp_Tdy2p_T \sum_{ij} \int_{x_{\min}}^1 dx_1 \frac{f_1(x_1,Q^2)f_2(x_2,Q^2)\sigma_{ij}}{x_1s + u - m^2}, \quad (4) \]

where \( m \) is the mass of the jet whose rapidity is \( y \), \( s \) and \( u \) are Mandelstam variable of the \( pp \) system, \( \sigma_{ij} \) is the underlying partonic cross section and \( f_i \) is the PDF at momentum fraction \( x \) and energy \( Q \). The relation between \( x_1 \) and \( x_2 \) and their integration range are determined by the kinematics (see e.g. [12]). Now the number of events \( n_X \) is proportional to \( \sigma_X \) times the jet mass functions (still neglecting any jet correlations, as mentioned in assumption iii above). Since only the latter part factorizes, the ratio of events \( n_{BNC}/n_A \) used to estimate \( n_D \) should be corrected as follows:

\[ n_D = \frac{n_{BNC}}{n_A} \times \frac{\sigma_A \sigma_D}{\sigma_B \sigma_C}. \quad (5) \]

We found that this correction raises the estimated QCD background by only about 5% in the given jet mass window\(^3\). This substantiates the reliability of the result of [4, 5].

One possible caveat in this argument is that assumption iii above could turn out to be wrong. If there is some mechanism in QCD which leads to bias towards two massive jets (relative to the evaluation used in [4, 5]), then it might be that the excess of events in region D is simply the consequence of underestimating the QCD contribution.

The relation in Eq. (3) is examined by MC simulations in [13]. The results from different MC tools are shown in Table I. From this we learn that: i) the deviations from \( R_{\text{mass}} = 1 \) are small (within the systematic uncertainties); ii) the matched MC results, which include \((jj+jjj+jjjj)\) and are expected to better estimate the QCD jet mass distribution at large masses, are in very good agreement with each other (even though they tend not to agree on the individual jet mass distribution [10]), giving \( R_{\text{mass}}^{\text{MC}} \simeq 0.87 \).

\(^1\) We are grateful to Steve Ellis who questioned this assumption.

\(^2\) For the parton distribution functions (PDF), we used the CTEQ5 Mathematica implementation from \url{http://www.phys.psu.edu/~cteq/}

\(^3\) We found no significant sensitivity to interchanging between CTEQ5M and CTEQ5L and to multiplying or dividing the energy scale by \( 2^{1/4} \).
TABLE I: The results for $R_{\text{mass}}$ (borrowed from [13]) from different MC tools: Sherpa (1.2-3) [14] with matching MadGraph/MadEvent 4.4.56 [15] with MLM matching [16] to the Pythia package 2.1.4 [17], MadGraph/MadEvent with no matching and Herwig 6.520 [18] with no matching. The PDF set used was CTEQ6M [19], and FastJet 2.4.2 [20] with anti-$k_t$ algorithm [21] ($\Delta R = 1$) was used for jet clustering. Quoted errors are statistical only.

| MC tool     | Matching | $R_{\text{mass}}$ |
|-------------|----------|-------------------|
| Sherpa      | Yes      | 0.88 ± 0.03       |
| MadGraph    | Yes      | 0.86 ± 0.04       |
| MadGraph    | No       | 0.76 ± 0.04       |
| Herwig      | No       | 0.86 ± 0.02       |

The other possible explanation would be that the excess is related to non-SM production of boosted top pairs. A relevant aspect of the CDF data is that no excess was found compared to the SM in the channel with one jet plus missing energy described above. However, this channel suffers from larger uncertainties, as already mentioned.

In the following exercise we estimate the tension in case the hadronic excess is completely accounted for by tops. Adding 16 hadronic top events, the expected semileptonic sample (since including $\tau$'s the ratio is the same) would be

$$31 + 1.9 + 16 \times (1.9/3) \approx 43,$$

where 31 is the expected number of QCD events (estimated as before using the ratio $n_B n_c/n_A$), 1.9 is the number of expected hadronic-semileptonic top events, and thus (1.9/3) is the ratio of acceptance of this sample to the fully hadronic one, based on the estimation in [5]. This constitutes an excess of 17 compared to the observed 26 events [5]. The statistical uncertainty involved is 8.1 events, while the systematics from the jet energy scale and jet mass measurements is 30% of the original 31 expected events. These are combined to a standard deviation of 12 events, which means that the tension with the semileptonic sample is at the level of $17/12 \approx 1.4\sigma$. Thus we conclude that while a pure top excess is not perfectly consistent with the data, it is far from being disfavored.

Further motivation for an excess of boosted tops originates from the possible relation with the measurement of forward-backward asymmetry in $tt$ production [21] and specifically the large deviation recently observed by CDF at high invariant masses [22]. This issue is investigated in detail in [13, 23].

Finally, it is possible that the data hints for a presence of new massive particles with a large production cross section and hadronic final states. Standard hadronic top searches include b-tagging as a necessary condition. Since these show good agreement with the SM prediction [24], the existence of a new particle which decays to a bottom is probably disfavored, unless this state would only be produced with a high boost, where these searches would fail [25].

Regarding the planar flow distribution, it is interesting to note that a sizable excess for Pf > 0.4, relative to the Pythia prediction, was found in [4]. This might motivate a search for particles with 3-body (or higher) decays effectively (for this purpose, the top’s decay is considered as 3-body).

In order to investigate this issue, we used different MC tools to estimate the QCD Pf distribution in the relevant search window. The first is Herwig 6.520 with the PDF set CTEQ6L. The second is Madgraph/MadEvent 4.4.51 with the Pythia 2.1.4 package and the same PDF set, with and without MLM matching. We also used Pythia 6.4 by itself. All MCs were interfaced to FASTJET 2.4.2 for jet clustering. The cuts used are the same as in the CDF study (excluding the $\eta$ cut, which was found to have a negligible effect). The result is shown in Fig. 1 together with the recent CDF data. It is evident that the three simulations that we use exhibit good agreement with each other, and furthermore that their resulting distributions are closer to the data than the Pythia one in [4]. Note also that reasonable agreement was found between the predictions of MadGraph/Pythia and Sherpa in [10].

![FIG. 1: QCD planar flow distribution (normalized to unit area) calculated by different MC tools compared to the CDF data with the anti-$k_T$ jet algorithm (R=1.0) [4]. The data is represented by orange circles with error bars, while the solid blue, dashed red and dotted green lines correspond to Herwig, Pythia and MadGraph with Pythia including MLM matching, respectively.](image)

We further demonstrate that a contribution from particles with 3-body decays favor higher Pf values, such that a proper combination with the QCD prediction can yield a better agreement with the data. In Fig. 2 we show the distribution generated by an RPV light gluino (see
FIG. 2: Planar flow distribution of an RPV gluino decay (normalized to unit area) calculated by different MC tools compared to the CDF data with the anti-$k_T$ jet algorithm ($R=1.0$) [4]. The data is represented by orange circles. The solid light blue (dashed red) and dashed-dotted purple (dotted blue) lines correspond to a particle level (partonic level) simulation using Herwig and MadGraph with Pythia, respectively. The short-dashed green line is for a hadronic top distribution, borrowed from [4].

below), separating between runs that include only a partonic decay to three quarks and runs with showering and hadronization (we do not combine the QCD contribution here). Additionally, the figure presents the Pf distribution of a hadronic top quark, borrowed from [4].

As an exercise, we calculated the Pf distribution of a toy model where a heavy scalar decays to three massless scalars. The decay was computed analytically, and the Pf distribution was obtained by random generation of events admitting the proper kinematics. It is interesting to mention that the resulting curve is in perfect agreement with the MG/Pythia partonic case, while if we add the proper matrix element of the decay to this “random” model, we find perfect agreement with the Herwig partonic curve.

We note that given the large uncertainties on the data, it does not seem instructive to make any quantitative comparisons of the Pf distributions in the two figures. At this stage, both QCD and 3-body decaying particles provide reasonable fits to the data. We expect that in the near future, when LHC data is available, it would be possible to make a distinction between the different cases [9] [11].

**Toy Model.** In order to demonstrate a toy model that can account for the observed excess, we consider an RPV gluino in the context of SUSY, where the rest of the sparticles are decoupled for simplicity (In principle, there could be interference effects in gluino production from squarks, but this is highly model dependent). The gluino decays to three quarks, hence in case its mass is inside the window used in the search, it would lead to an excess of events with boosted jets [2].

Such a scenario has already received attention in a recent CDF search [3], considering only a non-boosted region with conventional reconstruction. This study focused on signals of six jets, and employed sophisticated techniques for reducing the background, such as three-jet correlations and vertex position tracking. Yet it turned out to be practically insensitive to a possible gluino contribution.

Another interesting recent work [2] adopted a similar approach to that of [4, 5] in search of an RPV gluino at the Tevatron, though it was based only on MC simulations rather than real data. It required two boosted jets ($p_T > 350$ Gev) with masses close to each other and further applied a certain jet substructure cut. This approach was found to be quite sensitive to a gluino signal.

We estimate the gluino signal as a function of its mass using both Herwig and MadGraph/MadEvent with Pythia. The results are presented in Table II (note that there is some difference between the two MC tools, yet it is evident that the ratio of these cross sections to that of top pair production is constant). Also shown in the table is the acceptance, which is the percentage of events that pass all the cuts out of the overall sample of one boosted jet from the corresponding particle. It is evident that the cross section is indeed in the ballpark of the observed excess. Since we do not try to provide a precise fit of the signal, NLO corrections are not expected to change this statement (and in any case they should be small because of the strong $p_T$ cut – see e.g. Figure 9 in [27]). Moreover, it is interesting that the gluino contribution enhances the large Pf region of the distribution, as shown in Fig. 2.

As an outlook to the near future, we point that the LHC should be able to test whether indeed there is a deviation from the SM in this type of signal, possibly even with only $\mathcal{O}(1)$ fb$^{-1}$. It would thus be interesting to adapt the search of ultra-massive highly-boosted jets to the LHC.

**Acknowledgments.** We thank Johan Alwall, Jon Butterworth, Benjamin Fuks, Seung Lee, Fabrizio Maragoli, Pekka Sinervo and Jay Wacker for useful discussions. GP is the Shlomo and Michla Tomarin career development chair and supported by the Israel Science Foundation (grant #1087/09), EU-FP7 Marie Curie, IRG fellowship, Minerva and G.I.F., the German-Israeli Foundations, and the Peter & Patricia Gruber Award.

---

4 Very recently a new lower bound of 144 GeV for the gluino mass appeared [20], thus excluding the first line in Table II.
TABLE II: The gluino cross section and acceptance for masses of 130, 150 and 170 GeV, computed by both Herwig and MadGraph with Pythia. For the latter we also add a calculation including an extra jet with MLM matching. As a comparison, we present the hadronic top cross section and acceptance.

| Particle                  | Acceptance Herwig | Acceptance MG/Pythia no matching | Cross section [fb] | Cross section [fb] | Cross section [fb] |
|---------------------------|-------------------|---------------------------------|-------------------|-------------------|-------------------|
| Gluino $m_{\tilde{g}}$ = 130 GeV | 0.43              | 0.49                            | 15                | 17                | 18                |
| Gluino $m_{\tilde{g}}$ = 150 GeV | 0.52              | 0.50                            | 13                | 14                | 15                |
| Gluino $m_{\tilde{g}}$ = 170 GeV | 0.49              | 0.48                            | 11                | 12                | 12                |
| Hadronic top quark pair    | 0.47              | 0.46                            | 1.6               | 1.7               | 1.8                |

[1] C. Kilic, T. Okui and R. Sundrum, JHEP 0807, 038 (2008) [arXiv:0802.2568 [hep-ph]]; J. M. Butterworth, J. R. Ellis, A. R. Raklev and G. F. Salam, Phys. Rev. Lett. 103, 241803 (2009) [arXiv:0906.0728 [hep-ph]]; R. Essig PhD Thesis, Rutgers University, http://mass.libraries.rutgers.edu/dlr/showfed.php?id=rutgers-lib:24540.

[2] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 100, 142002 (2008) [arXiv:0712.0851 [hep-ex]]; T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 101, 202001 (2008) [arXiv:0806.2472 [hep-ex]].

[3] C. Kilic, T. Okui and R. Sundrum, JHEP 0807, 038 (2008) [arXiv:0802.2568 [hep-ph]]; J. M. Butterworth, J. R. Ellis, A. R. Raklev and G. F. Salam, Phys. Rev. Lett. 103, 241803 (2009) [arXiv:0906.0728 [hep-ph]]; R. Essig PhD Thesis, Rutgers University, http://mass.libraries.rutgers.edu/dlr/showfed.php?id=rutgers-lib:24540.

[4] CDF Collaboration, CDF note 10199, January 18, 2011. http://www-cdf.fnal.gov/physics/new/qcd/BoostedJets/.

[5] CDF Collaboration, CDF note 10234, January 5, 2011. http://www-cdf.fnal.gov/physics/new/top/2011/BoostedTops/.

[6] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008) [arXiv:0802.1189 [hep-ph]].

[7] N. Kidonakis and R. Vogt, Phys. Rev. D 68, 114014 (2003) [arXiv:hep-ph/0308222].

[8] J. C. Collins, D. E. Soper and G. F. Sterman, Adv. Ser. Direct. High Energy Phys. 5, 1 (1988) [arXiv:hep-ph/0409013]; N. Kidonakis, G. Oderda and G. F. Sterman, Nucl. Phys. B 531, 365 (1998) [arXiv:hep-ph/9803241]; N. Kidonakis, G. Oderda and G. F. Sterman, arXiv:hep-ph/9805279.

[9] L. G. Almeida, S. J. Lee, G. Perez, G. F. Sterman, I. Sung and J. Virzi, Phys. Rev. D 79, 074017 (2009) [arXiv:0807.0234 [hep-ph]].

[10] L. G. Almeida, S. J. Lee, G. Perez, I. Sung and J. Virzi, Phys. Rev. D 79, 074012 (2009) [arXiv:0810.0034 [hep-ph]].

[11] J. Thaler and L. T. Wang, JHEP 0807, 092 (2008) [arXiv:0806.0023 [hep-ph]].

[12] E. Eichten, I. Hinchliffe, K. D. Lane and C. Quigg, Rev. Mod. Phys. 56, 579 (1984) [Addendum-ibid. 58, 1065 (1986)].

[13] K. Blum et al., Phys. Lett. B 702, 364 (2011) [arXiv:1102.3133 [hep-ph]].

[14] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP 0902, 007 (2009) [arXiv:0811.4622 [hep-ph]].

[15] J. Alwall et al., JHEP 0709, 028 (2007) [arXiv:0706.2334 [hep-ph]].

[16] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006) [arXiv:hep-ph/0603175].

[17] G. Corcella et al., JHEP 0902, 012 (2009) [arXiv:0811.4622 [hep-ph]].

[18] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, JHEP 0207, 012 (2002) [arXiv:hep-ph/0201195].

[19] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 100, 142002 (2008) [arXiv:0712.0851 [hep-ex]]; T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 101, 202001 (2008) [arXiv:0806.2472 [hep-ex]].

[20] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. D 83, 112003 (2011) [arXiv:1101.0034 [hep-ex]].

[21] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D 82, 032002 (2010) [arXiv:0911.4286 [hep-ex]]; T. Aaltonen et al. [The CDF Collaboration], Phys. Rev. D 81, 052011 (2010) [arXiv:1002.0365 [hep-ex]]; W. Wagner [CDF and D0 Collaboration], Mod. Phys. Lett. A 25, 1297 (2010) [arXiv:1003.4359 [hep-ex]].

[22] K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D 77, 015003 (2008) [arXiv:hep-ph/0812.2297 [hep-ph]].

[23] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D 82, 032002 (2010) [arXiv:0911.4286 [hep-ex]]; T. Aaltonen et al. [The CDF Collaboration], Phys. Rev. D 81, 052011 (2010) [arXiv:1002.0365 [hep-ex]]; W. Wagner [CDF and D0 Collaboration], Mod. Phys. Lett. A 25, 1297 (2010) [arXiv:1003.4359 [hep-ex]].