Hints from Tevatron, a prelude to what?

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Abstract

We comment on the recent results from the Tevatron experiments in the W+jets channel and consider some models as the possible underlying physical theories. We also list some channels for further studies.

1 Introduction

The Standard Model (SM) is expected to be the low energy limit of a more fundamental theory [1]. The known candidates for such a theory have more fundamental particles than what is experimentally known today. Therefore, searches for new particles hence for the new model of elementary particles and their interactions, continue in both the precision physics and collider experiments. In a recent public note, CDF experiment at Tevatron excluded a standard model fourth-generation $t'$ quark with mass below 311 GeV at 95% CL using 2.8 fb⁻¹ of data (see figure 1) [2]. The shown theoretical model shows the tree-level cross section of a new quark with q=2/3 charge.

The same note also reports an excess of about 5 events in the W+ jets channel in the region between 375-500 GeV. Although this small number of excessive events can be explained by a detector over-efficiency or by some unknown SUSY process, in the following text we will consider some theoretical models where an additional heavy quark is predicted. Some of these models were also mentioned in the above mentioned note.

2 Recent CDF measurement on W+jet

The CDF result on the reconstructed invariant mass in the W+jet channel is presented in figure 2. The number of observed events in the range 375 - 500 GeV is 7 with an expected background of about 1.8 events. The Poisson probability of such a statistical deviation is 0.2%, which is rather low. Taking this excess at its face value, we calculate its significance, using the well known estimator \[ S = \sqrt{2 \times [(s + b) \ln(1 + s/b) - s]} \], to be about 2.9σ, perhaps a hint for a new quark decay. However the candidate underlying model has to be investigated in the light of the number of excess events. The model should produce enough cross section for an excess of 5 events with 2.8 fb⁻¹ integrated luminosity.

The efficiency of the CDF event selection can be estimated from the results in [2]. The 95% exclusion limit for $m_Q \approx 400$ GeV is given as 81 fb. The SM background at 400 GeV can be estimated using the average of the two adjacent bins, as 0.75 events. Using the above mentioned signal significance estimator and 0.75 events, to have 95% observation limit (i.e. 1.96σ) one needs 3 signal events which can be converted to a reconstruction efficiency of \( \epsilon = \frac{2.8 \times 3}{81} = 0.01 \). The efficiency value can be used to calculate the number of signal events predicted by the theoretical model shown in figure 1 to see whether it provides enough events to explain the observed excess. We find that the cross section given in figure 1 can only provide 18 × 2.8 × $e = 0.5$ events. The Poisson probability of having 2.3 (=0.5 + 1.8) expected events to oscillate statistically to 7 or more events is 0.9%. The cross section value can be increased about 10% with the QCD scale and PDF uncertainties. The LO to NLO conversion factor, $k$, for $t\bar{t}$ at the Tevatron is estimated as a number between 1.2 and 1.5 [4]. Folding in these changes, one can increase the expected number of signal events to a value of 0.8 events, still quite small to account for the 5 events in question.
Figure 1: Upper limit, at 95% CL, on the production rate for $t'$ as a function of $t'$ mass (red) using 2.8 fb$^{-1}$ of integrated luminosity. The purple curve is the theoretical cross section assuming SM like couplings of the new quarks. The dark blue band is the range of expected 95% CL upper limits within one standard deviation. The light blue band represents two standard deviations.

Figure 2: The measurement from CDF in the Wjet channel using 2.8 fb$^{-1}$ of integrated luminosity.
Figure 3: The expected cross section of the $p\bar{p} \rightarrow Q\bar{Q}$ as a function of the quark mass from Fourth Family, Little Higgs and E6 GUT models for $\sqrt{s} = 1.96$ TeV. In all cases, the PDF set CTEQ6L1 [12] is used and the QCD scale is set to the mass of the new quark.

2.1 Possible Explanations

As pointed out in the CDF public note [2], the fourth family predicted by the DMM [5, 6, 7, 8, 9] approach could be the underlying model providing such an excess of events. The additional quarks in the fourth family are denoted in the literature as $u_4$, $d_4$ or $t'$, $b'$ and they are expected to be quasi-degenerate, i.e. the mass difference between the up-type and down-type quark to be less than $m_W$, disabling the $u_4 \rightarrow Wd_4$ decay channel. Other often cited models with additional quarks are the E6-GUT [10] and the Little Higgs [11] models. The latter has only one additional up-type iso-singlet quark, $T$, whereas the former has one additional down-type iso-singlet quark per SM family denoted as $D$, $S$, and $B$. The case where the masses of these 3 quarks are close to each other can be considered as the ‘degenerate’ E6 model. The figure 3 gives the expected cross section of these models as a function of the (degenerate) quark mass at the Tevatron for QCD scale set to the mass of the new quark.

If the the forth family quark masses are indeed degenerate, and the $4 \times 4$ CKM matrix is such that the fourth family mixings to the first two families are favoured, the expected number of events can be calculated as $N = 2.8 \times \sigma \times k \times \epsilon$, where $\sigma$ is the tree-level pair production cross section and $k =1.5$ as given before. For quarks of mass $m_Q \approx 400$ GeV and with $M_Q$ as the QCD scale choice, the cross section is obtained as 35 fb and $N$ as 1.5 events, whereas for another possible choice of QCD scale as $2 \times m_W$, $\sigma$ is found as 57 fb, yielding $N=2.4$ events. In these two scenarios, the expected number of events become 3.3 and 4.2, respectively, bringing in better compatibility with the measurement of 7 events. The error on these event yields originating from the PDF choice is about 7%. A more favorable event yield might be obtained if the mass difference between the up-type and down-type quarks is assumed to be slightly larger but still smaller than $m_W$. For example, if $m_{t'}=375$ GeV and $m_{b'}=400$ GeV, the expected number of total events become 3.9 and 5.3 for the two considered QCD scales. In this case, the probability of measuring 7 events or more becomes 10% and 28% respectively.

Such an excess could also arise from the E6 GUT models when the additional iso-singlet object in the 27-plet, has quark-like properties. In the case of an E6 GUT with degenerate iso-singlet quark mass values of approximately 400 GeV, the pair production cross section at the tree level is 50.4 fb for QCD scale of $m_Q$ and 84.9 fb for QCD scale of $2 \times m_W$. The branching fraction of $D \rightarrow Wj$ is 67% and reduces the number of the expected heavy quark CC decay events to the level of the above discussed fourth family case: 1.5 and 2.5 signal events. However if two of the quarks have masses around 375 GeV and one around 400 GeV, one finds 5.6 expected events for the measurement of 7 events yielding an occurrence probability over 31%.

The Little Higgs model also predicts an additional quark whose the production cross section is one-third of the ‘degenerate’ E6 GUT model at the Tevatron. However, as this model has only one additional quark it is
unlikely to provide enough cross section in a trivial way.

2.2 A cross check with the Higgs searches in CDF and D0

Recently both CDF and D0 reported the results of their searches for $ZZ$ production in four-lepton channel [13]. The most recent D0 measurement is given in figure 4 for 1.7 fb$^{-1}$ integrated luminosity. The SM $p\bar{p} \rightarrow ZZ \rightarrow 4\ell$ cross section is experimentally measured as 7.9 fb. The D0 data is with 1.7 fb$^{-1}$ integrated luminosity, resulting in 13.4 expected events before event selection and reconstruction cuts. The integration of the shaded area in the same figure gives 2.4 events yielding a reconstruction efficiency $\epsilon$ of 17.9%. If the previously discussed excess is really coming from one or more new quarks, their influence on other processes, such as Higgs boson production, should be cross checked. The new quarks in the mass region 375 - 500 GeV will strongly influence the Higgs production at the Tevatron, thus possibly manifesting themselves in the $ZZ$ channel as well. For example, the fourth family quarks would lead to substantial enhancement of $ggH$ cross-section and thus would give a chance for Tevatron to observe the SM Higgs. For a Higgs of mass 200 GeV, the effective cross section of 4 lepton events was calculated to be 1.5 fb in the presence of a fourth SM generation[14]. In this case, the expected number of $H \rightarrow ZZ \rightarrow 4\ell$ events is $1.5 \times 1.7 \times 0.179 = 0.46$, making the agreement between the calculations and data even better: $2.4 + 0.46 \approx 2.9$ expected events versus 3 observed events.

The iso-singlet quarks might also boost the Higgs searches via their possible NC decays, i.e. using the $D \rightarrow H \text{jet}$ channel[15]. However even if the total luminosity is tripled, the Tevatron will not be able to benefit from this mode, one will have to wait for the LHC data.

In a recent Fermilab press-release, D0 results were announced as the “Prelude to the Higgs” keeping in mind the $ZH$ production [16]. However, in $ZH$ channel, with 2.3 fb$^{-1}$ integrated luminosity, the ratio of observed limit to the SM prediction still exceeds 10. Therefore, this channel is quite unlikely to be seen before 2010, even when CDF and D0 data are combined. As a second option one could consider “golden” mode keeping in mind the above-mentioned enhancement in four SM family case. The Higgs mass regions around 150 GeV and 200-240 GeV could be reached by the combined data at the end of 2009. Unfortunately, both opportunities seem to be rather pessimistic.

3 Some suggestions

In section 2.1 we estimated the same number events for both the fourth family and E6 GUT models. The method to distinguish between these two would be a search for the NC decays, namely the $t' \rightarrow Z + \text{jet}$ channel. Since there is no FCNC at the tree level in the models with fourth SM family, the presence of a signal in this channel would motivate preference of E6 GUT models over the fourth family models. However as the branching fraction of $D \rightarrow Z + \text{jet}$ is 33%, the expected excess at the same integrated luminosity of 2.8 fb$^{-1}$ would be 2-3 events depending on the QCD scale if the same event selection and reconstruction efficiency is assumed. A
suggested mode would be $p\bar{p} \rightarrow t\bar{t} \rightarrow WjZj$ where leptonic decays of the $W$ branch could be used for trigger and the $Z$ branch for the reconstruction purposes. In order to increase the statistics the combination of results between the two Tevatron experiments is obligatory.

If the four family SM is realized in Nature, then the Higgs boson could be searched in the so-called “silver” mode, where the Higgs decays to two heavy neutrinos [17]. If both the Higgs boson and the fourth family neutrino have appropriate masses, then the $p\bar{p} \rightarrow h \rightarrow \nu\bar{\nu} \rightarrow 2W2\mu$ chain would be the channel to look for the Higgs boson, especially if $\nu$ is of Majorana nature, thus providing same sign leptons in the final state. For example if $m_H=200$ GeV and $m_\nu=90$ GeV, the $\sigma(p\bar{p} \rightarrow h) = 1337$ fb and $BR(H \rightarrow \nu\bar{\nu})$ is about 6%, resulting in 80 fb effective cross section. Taking the 4x4 extension of MNS matrix compatible with the neutrino mixing measurements [15], the $BR(\nu \rightarrow W\mu)$ is found as 0.68. Using the 2.8 fb$^{-1}$ integrated luminosity reported in [2], this channel yields more than 100 $WW\mu\mu$ events out of which 50 would be with same sign leptons.

4 Conclusions

In the light of the recent data from the Tevatron, there might already be a hint for beyond the 3 family SM physics, yet to be discovered. We propose degenerate fourth family and E6-GUT models with quarks around 400 GeV to explain the observed excess of events. Clearly, more data from the Tevatron is needed to understand the situation completely, as well as the study of the channels suggested in section 3 by both collaborations together with the combination of their experimental results. On the other hand, we believe this “hint” is a prelude to the BSM physics to come from the LHC at the early stages of the data taking [19]. For example, degenerate fourth family quarks with mass 400 GeV would be discovered at $5\sigma$ level with 80pb$^{-1}$ integrated luminosity [20], i.e. during the first weeks. Similarly, an iso-singlet $D$ quark with 400 GeV mass would be discovered with 1fb$^{-1}$, i.e. during first year [21]. Or, 300 GeV mass Higgs boson which corresponds to quartic Higgs boson coupling constant equal to $g_w$ will be discovered with 200pb$^{-1}$ (4fb$^{-1}$) in 4 (3) SM family case [22]. Therefore, a rapid startup and commissioning of the LHC beams is needed to provide enough luminosity to both general-purpose detectors on this new energy frontier.

Finally, it seems that the next two years will be very competitive.

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References

[1] W.-M. Yao et al., *Review of Particle Physics, Data Group, Journal of Physics G* **33** (2006) 1.

[2] CDF public note, [http://www-cdf.fnal.gov/physics/new/top/2008/tprop/Tprime2.8/public.html](http://www-cdf.fnal.gov/physics/new/top/2008/tprop/Tprime2.8/public.html)

[3] CMS Collaboration, *CMS Physics, Technical Design Report*, CERN/LHCC 2006-001.

[4] N. Kidonakis and R. Vogt, *Next-to-next-to-leading order soft-gluon corrections in top quark hadroproduction*, Phys. Rev. D **68**, 114014, (2003).

[5] H. Fritzsch, *Light neutrinos, nonuniversality of the leptonic weak interaction and a fourth massive generation*, Phys. Lett. B **289** (1992) 92.

[6] A. Datta, *Flavor democracy calls for the fourth generation*, Pramana **40** (1993) L503 [hep-ph/9207248].

[7] A. Celikel, A Ciftci and S. Sultansoy, *A Search for fourth SM family*, Phys. Lett. B **342** (1995) 257.

[8] A. Datta and S. Raychaudhuri, *Quark masses and mixing angles in a four generation model with a naturally heavy neutrino*, Phys. Rev. D **49** (1994) 4762.

[9] S. Sultansoy, *Flavor Democracy in Particle Physics*, AIP conf. proc. **899** (2007) 49 [hep-ph/0610279].

[10] F. Gursey, P. Ramond and P. Sikivie, Phys. Lett. B **60**, 177 (1976); F. Gursey and M. Serdaroglu, Lett. Nuovo Cimento **21**, 28 (1978).

[11] T. Lari et al., *Collider aspects of flavour physics at high Q*, [arXiv:0801.1800](http://arxiv.org/abs/0801.1800) (January 2008).
[12] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **0207** (2002) 012 [hep-ph/0201195].

[13] CDF Collaboration (T. Aaltonen et al.), *First Measurement of ZZ Production in panti-p Collisions at $s^{**}(1/2) = 1.96$-TeV*, Phys. Rev. Lett. **100**: 201801, 2008. e-Print: [arXiv:0801.4806](http://arxiv.org/abs/0801.4806) [hep-ex]; D0 Collaboration, *Measurement of $p\bar{p} \rightarrow ZZ \rightarrow \ell\ell\ell$ production cross section using RunIIB data*, D0 note 5753-CONF (2008).

[14] O. Cakir and S. Sultansoy, *Fourth standard model family enhancement to the golden mode at the upgraded Fermilab Tevatron*, Phys. Rev. D **65**, 013009 (2001).

[15] S. Sultansoy and G. Unel, *The $E_6$ inspired isosinglet quark and the Higgs boson*, [hep-ex/0610064](http://arxiv.org/abs/hep-ex/0610064), Accepted for publication in Phys. Lett. B.

[16] Fermilab D0 Press Release, *Prelude for the Higgs: A work for two bosons in the key of Z*, [http://www.fnal.gov/pub/presspass/press_releases/Dzero_zzdboson.html](http://www.fnal.gov/pub/presspass/press_releases/Dzero_zzdboson.html) (2008).

[17] S. Sultansoy and G. Unel, *‘Silver’ mode for the heavy Higgs search in the presence of a fourth SM family*, Turk J. Phys. **31** (2007) 295 [arXiv:0707.3266]; T. Cuhadar-Donszelmann, M. Karagoz Unel, V. E. Özcan, S. Sultansoy and G. Unel, *Fourth Family Neutrinos and the Higgs Boson* [arXiv:0806.4003](http://arxiv.org/abs/0806.4003) (June 2008).

[18] A. K. Ciftci, R. Ciftci and S. Sultansoy, *The Fourth SM family neutrino at future linear colliders*, Phys. Rev. D **72** (2005) 053006.

[19] J.A Aguilar Saavedra, S. Sultansoy, G. Unel, *Early years of the LHC: opportunities for a new quark and the Higgs boson*, in preparation.

[20] V. E. Özcan, S. Sultansoy and G. Unel, *Search for 4th family quarks with the ATLAS detector*, ATLAS-Sci-note SN-ATLAS-2008-069 [arXiv:0802.2621](http://arxiv.org/abs/0802.2621), Accepted for publication in Euro. Phys. J. C.

[21] R. Mehdiyev et al., Eur. Phys. J. C. **49**, 13 (2007); R. Mehdiyev et al., *Down Type Isosinglet Quarks in ATLAS*, Eur. Phys. J. C. **54**, 507 (2008).

[22] E. Arik et al., *Consequences of the extra SM families on the Higgs boson production at Tevatron and LHC*, Phys. Rev. D **66** (2002) 033003 [hep-ph/0203257]; E. Arik et al., *With four standard model families, the LHC could discover the Higgs boson with a few fb$^{-1}$*, Eur. Phys. J. C **26** (2002) 9 [hep-ph/0109037]; E. Arik et al., *Observability of the Higgs boson and extra SM families at the Tevatron*, Acta Phys. Polon. B **37** (2006) 2839 [hep-ph/0502050].