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Top quark forward-backward asymmetry at Tevatron and its implications at the LHC

Biplob Bhattacherjee,[1,*] Sudhansu S. Biswal,[1,†] and Diptimoy Ghosh[1,‡]

[1] *Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India*

The measurement of forward-backward asymmetry in the top and anti-top quark ($t\bar{t}$) production has been recently reconfirmed by the CDF Collaboration and shows a more than 3σ deviation from the Standard Model(SM) prediction in the large $t\bar{t}$ invariant mass region. Models with new W′ or Z′ bosons have been invoked to explain this deviation. In the context of these models we perform a χ^2 analysis with all the available experimental numbers in different ΔY and $M_{t\bar{t}}$ bins. We show that for the Z' model the region of parameter space which explain the Tevatron asymmetry can be probed in the same sign top production channel by Tevatron itself. Moreover, we consider a recently proposed observable, the one sided forward-backward asymmetry (A_{OFB}) at the LHC and conclude that both the W′ and Z′ models can lead to sizable A_{OFB} even at the LHC running at a center of mass energy of 7 TeV for the model parameters consistent with the Tevatron measurements.

I. INTRODUCTION

The top quark with its mass close to the electroweak symmetry breaking scale and being about 40 times heavier than the next heavy quark is expected to be crucially sensitive to the physics which underlie the mechanism of electroweak symmetry breaking. Many properties of top quark have been undergoing serious examination at the Fermilab Tevatron and LHC, being a top factory, will study the properties of top quark with unprecedented precision. The forward-backward(FB) asymmetry of top quark pairs $A^{t\bar{t}}_{FB}$ in $p\,\bar{p}$ collisions was measured by Tevatron with $\sqrt{s}$=1.96 TeV in 2008, which is defined as:

$$A^{t\bar{t}}_{FB} \equiv \frac{\sigma(\Delta Y > 0) - \sigma(\Delta Y < 0)}{\sigma(\Delta Y > 0) + \sigma(\Delta Y < 0)}\,, \tag{1}$$

where $\Delta Y \equiv Y_t - Y_{\bar{t}}$, the difference of rapidities of the top and anti-top quarks respectively in an event. The DØ collaboration[1] measured [12$\pm$8(stat)$\pm$1(sys)]% asymmetry with 0.9 fb^{-1} data for

* biplob@theory.tifr.res.in

† sudhansu@theory.tifr.res.in

‡ diptimoyghosh@theory.tifr.res.in

$t\bar{t}+X$ events with four or more jets while the CDF collaboration[2] reported [24±13(stat)±4(sys)]% parton level asymmetry with 1.9 fb^{-1} data.

In the SM the FB asymmetry arises at the order α_s^3 [3–5] in QCD from i) interference between the tree level amplitude and the box diagram, ii) initial and final state gluon bremsstrahlung, iii) gluon-quark annihilation and scattering into $t\bar{t}$ final state. The size of this asymmetry is predicted to be [6 ± 1]%[6] in the SM. Though the SM prediction is consistent with the experimental numbers within 2σ, the large central value of the asymmetry has provoked theorists to propose possible new physics scenarios[7–28] which can give rise to large forward-backward asymmetry. Recently the CDF collaboration has updated their result with much more data of 5.3 fb^{-1} to get the parton level total asymmetry $A_{FB}^{t\bar{t}} = 0.158 \pm 0.075$(stat+syst) [6] which reconfirmed their earlier measurement. More interestingly, the forward-backward asymmetry is observed to be more pronounced in the large $t\,\bar{t}$ invariant mass region and in the region where the rapidity difference ΔY is large. We quote their results in Table-I for better readability. From Table-I one should notice that the

Observable	$A_{FB}^{t\bar{t}}(\lvert\Delta Y\rvert < 1.0)$	$A_{FB}^{t\bar{t}}(\lvert\Delta Y\rvert > 1.0)$
CDF result	0.026 ± 0.118	0.611 ± 0.256
SM Prediction	0.039 ± 0.006	0.123 ± 0.008
Observable	$A_{FB}^{t\bar{t}}(M_{t\bar{t}} < 450\ GeV)$	$A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ GeV)$
CDF result	-0.116 ± 0.153	0.475 ± 0.114
SM Prediction	0.040 ± 0.006	0.088 ± 0.013

TABLE I. CDF measurements and SM predictions of the Forward-Backward Asymmetry in different ΔY and $M_{t\bar{t}}$ bins.

asymmetry at high invariant mass region is more than 3 standard deviations above the NLO SM prediction. It is intriguing that though the forward backward asymmetry shows a clear deviation from SM QCD prediction at least in the large $t\bar{t}$ invariant mass region, the measured parton level $t\bar{t}$ cross section $\sigma_{t\bar{t}}^{\rm Measured} = 7.70 \pm 0.52$ pb [29] and invariant mass distribution[30] are still consistent with SM prediction $\sigma_{t\bar{t}}^{\rm SM}$(MCFM) $= 7.45^{+0.72}_{-0.63}$ pb [31]. Hence, any model which will explain the invariant mass dependent asymmetry should also accommodate the observed consistency of the invariant mass distribution with SM. To this end, we consider the new physics scenarios with a t-channel vector boson exchange such as a new flavor changing Z'[7] or a new W'[8]. A s-channel vector boson mediated $q\bar{q} \to t\bar{t}$ process can also produce the required asymmetry, but also increases the $t\bar{t}$ production cross section which is measured to be consistent with SM [18, 32–36]. Unlike s-channel exchange, a t-channel diagram generally has the advantage of not changing the cross section appreciably. Apart from generating the forward-backward asymmetry the t-channel Z' scenario also contributes to same sign top production, single top production and FCNC top quark decays which make this model very interesting. On the other hand, the W' model has no same sign top signal and it is challenging to see how this model can be probed at Tevatron or LHC.

This paper is organized as follows. In the next section we briefly describe the Z′ and W′ models and perform a χ^2 analysis of their parameter spaces and study some of their collider signatures. In section III we consider a recently proposed observable called the one sided forward-backward asymmetry (A_{OFB}) [37, 38] and calculate it at 7 TeV LHC for both these models. We discuss our results and summarize in section IV.

II. SCENARIO WITH A NEW Z′/W′ BOSON

We parametrize the Lagrangian for the Z′ model as

$$\mathcal{L} \ni g_{_{Z'}} \bar{u}\gamma^\mu P_R t\, Z'_\mu + \epsilon_{_U} g_{_{Z'}} \bar{u}_i \gamma^\mu P_R u_i\, Z'_\mu + h.c.\ , \tag{2}$$

where $g_{_{Z'}}$, $\epsilon_{_U}$ are the new coupling constants and i is the generation index. In this analysis we do not consider new (V-A) couplings as they are highly restricted from the $B_d - \bar{B}_d$ mixing measurements[39].

Note that the new Z' contributes to both the single top production via $ug \to tZ'(\to u_i\bar{u}_i)$ as well as the same sign top production via t-channel $u(\bar{u})u(\bar{u}) \to t(\bar{t})t(\bar{t})$, $u(\bar{u})g \to t(\bar{t})Z'(\to t(\bar{t})\bar{u}(u))$ and $u\bar{u} \to Z'(\to \bar{u}t)Z'(\to \bar{u}t)$ processes. The term proportional to $\epsilon_{_U}$ give rise to the decay modes $Z' \to \bar{u}_i u_i$. If mass of Z' is greater than the top quark mass then this helps reducing the same sign top quark production via $u\bar{u} \to Z'(\to \bar{u}t)Z'(\to \bar{u}t)$ and $u(\bar{u})g \to t(\bar{t})Z'(\to t(\bar{t})\bar{u}(u))$.

We now consider the six measured observables $\sigma^{t\bar{t}}(\text{total}), A^{t\bar{t}}_{FB}(\text{total}), A^{t\bar{t}}_{FB}(M_{t\bar{t}} < 450\text{GeV})$, $A^{t\bar{t}}_{FB}(M_{t\bar{t}} > 450\text{GeV}), \mathrm{A^{t\bar{t}}_{FB}}(|\Delta\mathrm{Y}| < 1.0), \mathrm{A^{t\bar{t}}_{FB}}(|\Delta\mathrm{Y}| > 1.0)$ and try to find out the favoured parameter space of the $Z^{'}$ model. To do this we define the χ^2 function as:

$$\chi^2 = \sum_i \frac{(O_i^{\text{Theory}} - O_i^{\text{Measured}})^2}{\sigma_i^2}, \tag{3}$$

where O_i are the six observables. We add the experimental and Standard Model errors in quadrature to calculate σ_i.

For numerical studies we use $m_t = 172.5$ GeV. To get the correct SM $t\bar{t}$ production cross section at Tevatron we use the QCD K factor=1.3. We set both the renormalization and factorization scales to be m_t and convolute the parton level cross section with CTEQ6L parton distribution functions. We use CalcHEP [40] for parton level analysis. Note that our $O_i^{\rm Theory}$ includes both the new physics and the Standard Model contributions.

Fig.1 shows the χ^2 distribution in the $M_{Z'} - g_{Z'}$ plane for the Z' model. The region between the two dashed lines corresponds to 99% confidence level which is obtained by the frequentist approach assuming all errors to be Gaussian. Notice that large values of the Z' mass, consistent with the Tevatron data, are also possible if one allows for large coupling. Note that the uncoloured region in Fig. 1 has χ^2 more than 40, primarily because of very large $t\bar{t}$ production cross section. As

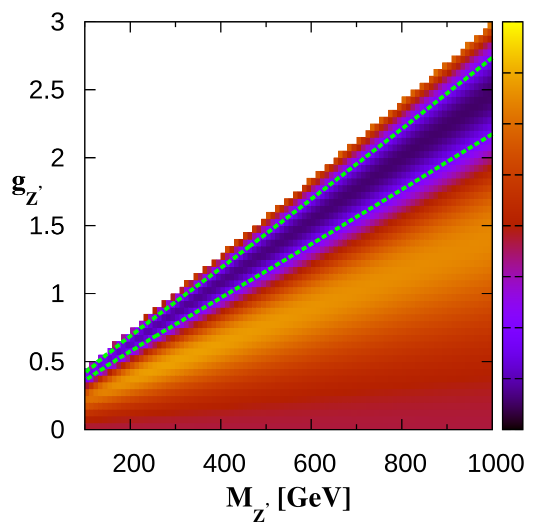

FIG. 1. χ^2 distribution in the $M_{Z'} - g_{Z'}$ plane for the Z' model. The area between the two dashed lines corresponds to the 99% CL region.

mentioned before, the existence of the Z' boson contributes to the same sign top pair production via $u(\bar{u})u(\bar{u}) \to t(\bar{t})t(\bar{t})$, $u(\bar{u})g \to t(\bar{t})Z'(\to t(\bar{t})\bar{u}(u))$ and $u\bar{u} \to Z'(\to \bar{u}t)Z'(\to \bar{u}t)$ channels. The second and the third channels contribute only if the mass of Z' is greater than the top quark mass. These two contributions can be decreased by increasing the coupling ϵ_U, though very large value of ϵ_U may contradict with the di-jet resonance search at both the Tevatron and LHC [41, 42]. On the other hand the first channel is independent of ϵ_U. We consider ϵ_U in the range $\sim 10^{-2} - 10^{-1}$ for the numerical analysis. All our results are practically independent of the value of ϵ_U for the above range. The leptonic branching ratio of top quark is about 0.22 (considering electron and muon only). Thus, about 5% of the same sign top quark pair decays through the same sign dilepton channel. In Fig.2 we show the number of same sign dilepton events from the same sign top pair decays expected at Tevatron with 10fb^{-1} data. As an example, for $M_{Z'} = 200$ GeV and $g_{Z'} = 0.6$

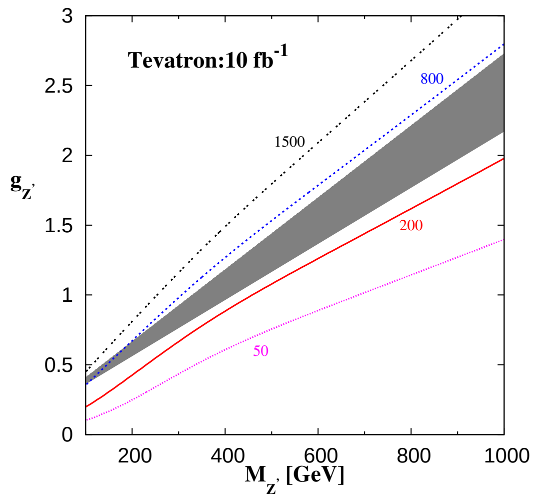

FIG. 2. Number of same sign dilepton events from the same sign top pair decays at Tevatron. The shaded area is the 99% CL allowed region of Fig.1.

the total same sign top production cross section in the three channels mentioned at Tevatron is about 1.1 pb giving rise to about 550 same sign dilepton events at 10 fb^{-1}. CDF has searched for like sign dilepton events plus b jet and missing transverse energy and found only 3 such events with 2fb^{-1} of data [43] which is consistent with the SM expectation. We see that the parameter values which explain the Tevatron asymmetry quite well also predict quite a few same sign top pairs at the Tevatron with $10fb^{-1}$ of data. Note that, in real experiment, the number will be much smaller than our numbers because of detector effects. Following the cuts mentioed in [43] we get roughly about 20% efficiency (including b tagging) in a PYTHIA [44] level simulation. Hence, out of the 550 same sign dilepton events mentioed above we expect about 100 events to survive the standard experimental cuts. A detailed study of all the backgrounds and detector effects is beyond the scope of this work. Nevertheless, we expect a large part of the parameter space in the $M_{Z'} - g_{Z'}$ plane can already be probed with the collected data at Tevatron. At the LHC the situation is much better than Tevatron [27, 39] as can be seen in the Fig.3. Fig.3 is similar to Fig.2, but with a smaller integrated luminosity of $1fb^{-1}$ at 7 TeV LHC and the numbers are only for the $u(\bar{u})u(\bar{u}) \to t(\bar{t})t(\bar{t})$ channel. To compare with Tevatron, for the same parameter point $M_{Z'} = 200$ GeV and $g_{Z'} = 0.6$ the same sign top production cross section at LHC (only for $u(\bar{u})u(\bar{u}) \to t(\bar{t})t(\bar{t})$ channel) is about 50pb which will lead to about 2500 same sign dilepton events at 1fb^{-1}. Note that the $t\,t$ production will be much more than the $\bar{t}\,\bar{t}$ production because of the difference in the valence and sea quark

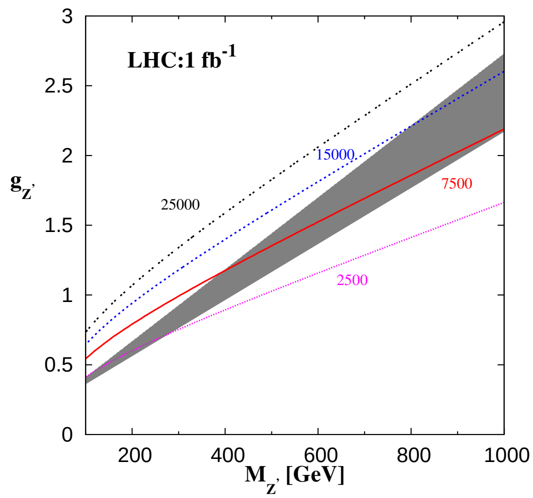

FIG. 3. Number of same sign dilepton events from the same sign top pair decays at 7 TeV LHC. The shaded area is the 99% CL allowed region of Fig.1.

fluxes in the initial state. Hence the same sign dilepton final state will contain more l^+l^+ events than l^-l^- events. New physics models like supersymmetry or universal extra dimension also have such same sign dilepton signals but generally with similar number of events in the l^+l^+ and l^-l^- final states.

If we do not see any excess in the production of same sign top pair at Tevatron as well as at LHC, then that will conclusively rule out the Z' explanation of the Tevatron asymmetry. Still, the t channel vector boson exchange as a possible explanation of the Tevatron Asymmetry cannot be ruled out by the non-observation of excess same sign top pair events. This is because instead of considering a new Z' if a new t channel W' exchange is considered then no such excess is expected. Such a model was proposed in [8, 45] with the Lagrangian

$$\mathcal{L} \ni -g_{_{W'}} \bar{t}\gamma^{\mu}(g_{_L} P_L + g_{_R} P_R) d\, W_{\mu}^{+\prime} + h.c. \ . \tag{4}$$

Here $g_{_{W'}}, g_{_L}, g_{_R}$ are the new coupling constants. It was observed in [8] that the results with only $g_{_L}$ or only $g_{_R}$ are similar but only $g_{_R}$ explains the data in a more consistent way[45]. We fix $g_{_L} = 0, g_{_R} = 1$ and take $g_{_{W'}}$, $M_{_{W'}}$ as free parameters.

In Fig.4 we show the χ^2 distribution in the $M_{_{W'}} - g_{_{W'}}$ plane for the W' model. The result is similar to the Z' case except that for the W' case slightly larger coupling is required for the same values of the vector boson masses as compared to the Z' model.

At colliders W's can be pair produced via $d\bar{d} \to W'W'$ or can be produced in association with a t quark via $d\,g \to W't(\bar{(t)})$(and also $d\bar{d}/gg \to W't(\bar{t})\bar{d}(d)$) channels[46]. In Fig.5 and Fig.6 we

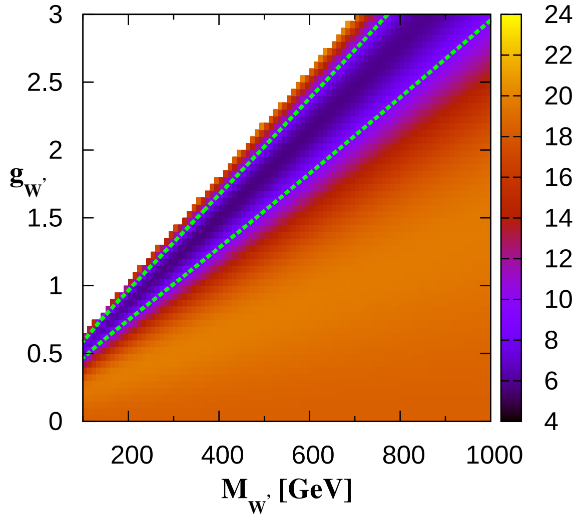

FIG. 4. χ^2 distribution in the $M_{W'} - g_{W'}$ plane for the W' model. The area between the two dashed lines corresponds to the 99% CL region.

show the production cross sections of W' in these two channels at the 7 TeV LHC. One can see that the dominant production mode for W' is the associated production channel. As an example, for $M_{W'} = 200$ GeV and $g_{W'} = 0.85$ the W^+W^- production cross section is about 10 pb while the production cross section in the $W't$ and $W't(\bar{t})\bar{d}(d)$ channels is about 90 pb. For larger W' masses the cross section decreases rapidly and will be difficult to discover with early LHC data.

If W' is heavier than top quark, it can decay to top quark and will contribute to the $t\bar{t}$ production. Unlike Z', the W' model does not give rise to new channels for the same sign top pair production. Hence non observation of excess number of same sign top events cannot rule out the W' explanation of the Tevatron asymmetry.

LHC, being a $p\,p$ machine, has no directional preference and hence, no forward-backward asymmetry can be formed. Thus, we focus on another observable called the One sided forward backward asymmetry at LHC and study the prediction of the W' model for this observable. This will be the content of the next section.

III. ONE SIDED FORWARD BACKWARD ASYMMETRY AT LHC

As mentioned before, unlike Tevatron LHC does not have any preferred direction to produce the FB asymmetry and hence the definition of $A^{t\bar{t}}_{FB}$(see Eq. 1) is not applicable for LHC [47, 48]. On

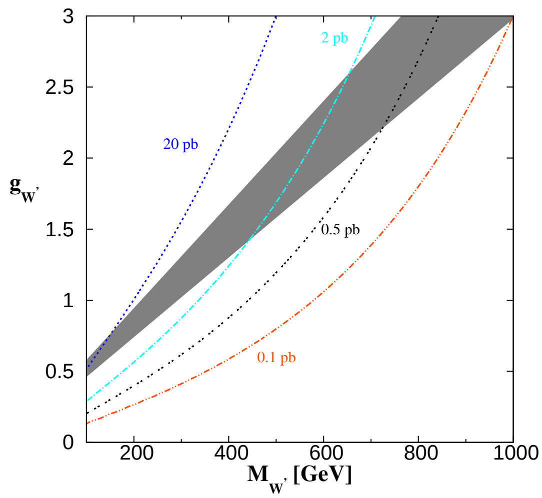

FIG. 5. W' W' production in the $d\bar{d} \to W'W'$ channel in the W' model at 7 TeV LHC. The lines are for constant crosssection contours. The shaded region is the 99% CL allowed region of Fig.4.

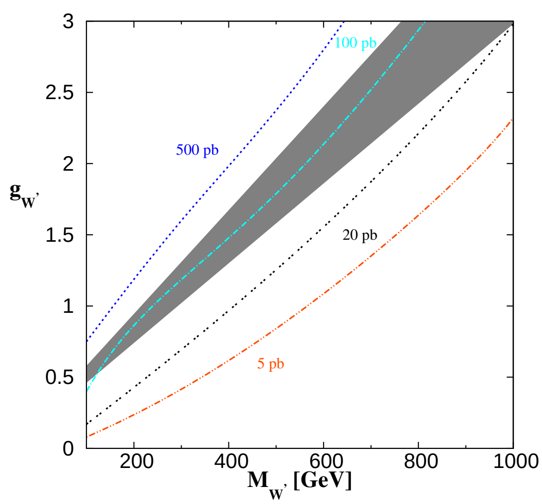

FIG. 6. The combined production cross section(fb) of $W't(\bar{t})$ and $W't(\bar{t})\bar{d}(d)$ at 7 TeV LHC. The shaded area is the 99% CL allowed region of Fig.4.

the other hand , the momentum distributions of the valence and sea quarks inside the proton are different. For example, for the subprocess $d\bar{d} \to t\bar{t}$ very often the d quark will have more velocity than the $\bar{d}$ quark which gives a non-zero and positive z component of $t\bar{t}$ total momentum in the lab frame(i.e., $P_z^{t\bar{t}} > 0$). Unfortunately, this asymmetry will be erased with the opposite $P_z^{t\bar{t}}$ for the subprocess $\bar{d}d \to t\bar{t}$. One way to observe such an asymmetry at the LHC is to put a cut on $P_z^{t\bar{t}}$. Note that the gluon contribution is completely symmetric and it is the dominant $t\bar{t}$ production channel at the LHC. In order to reduce the gluon contribution one can impose a lower cut on the

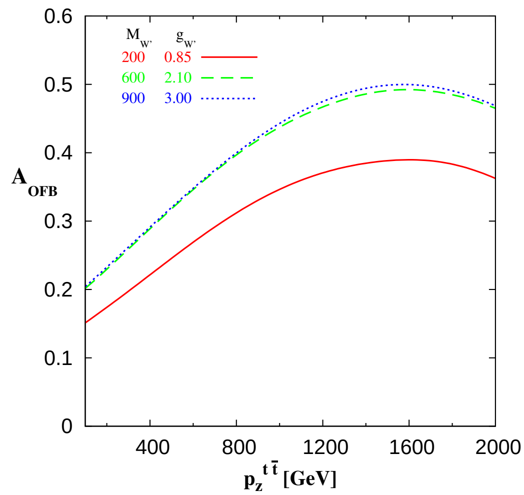

FIG. 7. One sided forward backward asymmetry at 7 TeV LHC for the W' model.

invariant mass $M^{t\bar{t}}$ of the $t\bar{t}$ system.

Keeping this fact in mind a quantity called one sided forward-backward asymmetry was constructed in ref. [37] which is defined as:

$$A_{OFB} \equiv \frac{\sigma(\Delta Y > 0) - \sigma(\Delta Y < 0)}{\sigma(\Delta Y > 0) + \sigma(\Delta Y < 0)}|_{P_z^{t\bar{t}} > P_z^{cut}, M^{t\bar{t}} > M^{cut}} \ .$$

Here $P_z^{t\bar{t}}$ is the z component of the total momentum of the $t\,\bar{t}$ system in the pp centre of mass frame.

Similar to A_{FB}, A_{OFB} also gets contribution at the order α_s^3 in the SM. For the SM prediction we refer the reader to Fig.5 and 6 of [37]. We consider three benchmark points (corresponding to low value of χ^2) for the W' model and calculate the one sided forward backward asymmetry at LHC for 7 TeV center of mass energy. We show the results in Fig. 7 as a function of P_z^{cut} for $M^{t\bar{t}} > 500$GeV. The size of the asymmetry increases when $M^{t\bar{t}}$ cut is increased. We observe that W' model predicts quite large A_{OFB} for a centre of mass energy of 7 TeV in pp collision and hence, LHC can verify this prediction by measuring A_{OFB}. Thus, if we do not see any excess same sign top events but observe large one sided forward backward asymmetry then that would motivate more detailed study of the W' model. Further, large values of the one sided forward backward asymmetry is also possible for the Z' model (shown in Fig. 8) and perhaps in many other new physics scenarios. The shape of the variation of A_{OFB} with P_z^{cut} may help to differentiate these models, though, distinguishing many different models conclusively will probably require more specific signatures and much more detailed studies. We have checked that even for $P_z^{t\bar{t}} > 1500$GeV most of the top quarks produced will have rapidity less than 3 and p_T less than 300 GeV. As a consequence, these top quarks can be detected

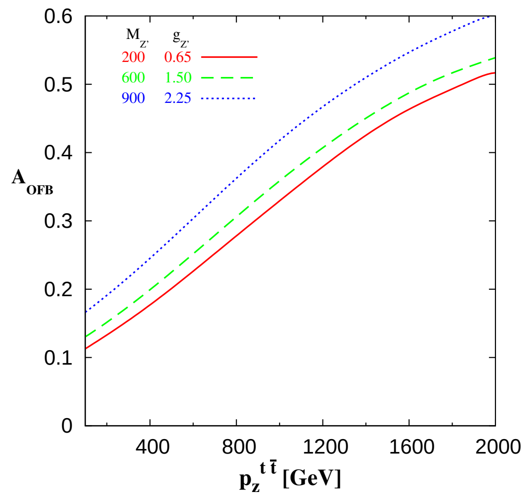

FIG. 8. One sided forward backward asymmetry at 7 TeV LHC for the Z' models.

using conventional techniques and more challenging techniques like boosted top algorithms are not required.

IV. DISCUSSION AND SUMMARY

We have investigated the possible explanation of the measured FB-asymmetry at Tevatron in the framework of Z' and W' models. We perform a χ^2 analysis using the FB-asymmetry measured in different rapidity (ΔY) and $t\bar{t}$ invariant mass ($M_{t\bar{t}}$) regions. We find that only a small region in the parameter space can accommodate the measured cross section and FB-asymmetry simultaneously.

The Z'-model predicts production of $t\bar{t}$, same sign top pairs and single tops whereas W'-model predicts only production of $t\bar{t}$ at the LHC. Though both these models can explain the recent Tevatron measurements, however, we argue that non observation of excess of same sign top events may exclude the Z'-model and Tevatron itself has the potential to do so with the current data.

LHC being a pp-machine one does not have the freedom to define the FB-asymmetry as defined in case of Tevatron. Thus we study the recently proposed one-sided FB-asymmetry that can be measured at the LHC. We choose a few benchmark points consistent with Tevatron measurements and calculate this asymmetry for both the Z' and W' models. We find the size of this asymmetry quite large and can be measured at the LHC even running at a center of mass energy of 7 TeV.

To summarize, we investigate the possibility of discriminating Z' from W' model by same sign top quark pair signals and measuring one sided forward-backward asymmetry at the LHC using the recent measurements of Tevatron as inputs. We conclude that non observation of excess of same sign top events and observation of large one sided forward-backward asymmetry at the LHC may exclude the Z' model and point towards a W' like scenario.

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[1] V. M. Abazov *et al.* (D0), Phys. Rev. Lett. **100**, 142002 (2008), arXiv:0712.0851 [hep-ex].

[2] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **101**, 202001 (2008), arXiv:0806.2472 [hep-ex].

[3] M. T. Bowen, S. D. Ellis, and D. Rainwater, Phys. Rev. **D73**, 014008 (2006), arXiv:hep-ph/0509267.

[4] O. Antunano, J. H. Kuhn, and G. Rodrigo, Phys. Rev. **D77**, 014003 (2008), arXiv:0709.1652 [hep-ph].

[5] L. G. Almeida, G. F. Sterman, and W. Vogelsang, Phys. Rev. **D78**, 014008 (2008), arXiv:0805.1885 [hep-ph].

[6] T. Aaltonen *et al.* (CDF)(2011), arXiv:1101.0034 [hep-ex].

[7] S. Jung, H. Murayama, A. Pierce, and J. D. Wells, Phys. Rev. **D81**, 015004 (2010), arXiv:0907.4112 [hep-ph].

[8] K. Cheung, W.-Y. Keung, and T.-C. Yuan, Phys. Lett. **B682**, 287 (2009), arXiv:0908.2589 [hep-ph].

[9] J. Shu, T. M. P. Tait, and K. Wang, Phys. Rev. **D81**, 034012 (2010), arXiv:0911.3237 [hep-ph].

[10] J. Cao, Z. Heng, L. Wu, and J. M. Yang, Phys. Rev. **D81**, 014016 (2010), arXiv:0912.1447 [hep-ph].

[11] P. Ferrario and G. Rodrigo, Phys. Rev. **D80**, 051701 (2009), arXiv:0906.5541 [hep-ph].

[12] A. Arhrib, R. Benbrik, and C.-H. Chen, Phys. Rev. **D82**, 034034 (2010), arXiv:0911.4875 [hep-ph].

[13] I. Dorsner, S. Fajfer, J. F. Kamenik, and N. Kosnik, Phys. Rev. **D81**, 055009 (2010), arXiv:0912.0972 [hep-ph].

[14] D.-W. Jung, P. Ko, J. S. Lee, and S.-h. Nam, Phys. Lett. **B691**, 238 (2010), arXiv:0912.1105 [hep-ph].

[15] Q.-H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, and C. E. M. Wagner, Phys. Rev. **D81**, 114004 (2010), arXiv:1003.3461 [hep-ph].

[16] B. Xiao, Y.-k. Wang, and S.-h. Zhu, Phys. Rev. **D82**, 034026 (2010), arXiv:1006.2510 [hep-ph].

[17] V. Barger, W.-Y. Keung, and C.-T. Yu, Phys. Rev. **D81**, 113009 (2010), arXiv:1002.1048 [hep-ph].

[18] M. Bauer, F. Goertz, U. Haisch, T. Pfoh, and S. Westhoff, JHEP **11**, 039 (2010), arXiv:1008.0742 [hep-ph].

[19] C.-H. Chen, G. Cvetic, and C. S. Kim, Phys. Lett. **B694**, 393 (2011), arXiv:1009.4165 [hep-ph].

[20] D. Choudhury, R. M. Godbole, S. D. Rindani, and P. Saha(2010), arXiv:1012.4750 [hep-ph].

[21] R. S. Chivukula, E. H. Simmons, and C. P. Yuan, Phys. Rev. **D82**, 094009 (2010), arXiv:1007.0260 [hep-ph].

[22] C. Degrande, J.-M. Gerard, C. Grojean, F. Maltoni, and G. Servant(2010), arXiv:1010.6304 [hep-ph].

[23] J. Cao, L. Wu, and J. M. Yang(2010), arXiv:1011.5564 [hep-ph].

[24] D.-W. Jung, P. Ko, and J. S. Lee(2010), arXiv:1011.5976 [hep-ph].

[25] E. Alvarez, L. Da Rold, and A. Szynkman(2010), arXiv:1011.6557 [hep-ph].

[26] C. Delaunay, O. Gedalia, S. J. Lee, G. Perez, and E. Ponton(2011), arXiv:1101.2902 [hep-ph].

[27] J. Cao, L. Wang, L. Wu, and J. M. Yang(2011), arXiv:1101.4456 [hep-ph].

[28] Y. Bai, J. L. Hewett, J. Kaplan, and T. G. Rizzo(2011), arXiv:1101.5203 [hep-ph].

[29] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **105**, 012001 (2010), arXiv:1004.3224 [hep-ex].

[30] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **102**, 222003 (2009), arXiv:0903.2850 [hep-ex].

[31] S. Moch and P. Uwer, Nucl. Phys. Proc. Suppl. **183**, 75 (2008), arXiv:0807.2794 [hep-ph].

[32] L. M. Sehgal and M. Wanninger, Phys. Lett. **B200**, 211 (1988).

[33] J. Bagger, C. Schmidt, and S. King, Phys. Rev. **D37**, 1188 (1988).

[34] D. Choudhury, R. M. Godbole, R. K. Singh, and K. Wagh, Phys. Lett. **B657**, 69 (2007), arXiv:0705.1499 [hep-ph].

[35] P. H. Frampton, J. Shu, and K. Wang, Phys. Lett. **B683**, 294 (2010), arXiv:0911.2955 [hep-ph].

[36] A. Djouadi, G. Moreau, F. Richard, and R. K. Singh, Phys. Rev. **D82**, 071702 (2010), arXiv:0906.0604 [hep-ph].

[37] Y.-k. Wang, B. Xiao, and S.-h. Zhu, Phys. Rev. **D82**, 094011 (2010), arXiv:1008.2685 [hep-ph].

[38] Y.-k. Wang, B. Xiao, and S.-h. Zhu, Phys. Rev. **D83**, 015002 (2011), arXiv:1011.1428 [hep-ph].

[39] E. L. Berger, Q.-H. Cao, C.-R. Chen, C. S. Li, and H. Zhang(2011), arXiv:1101.5625 [hep-ph].

[40] A. Pukhov(2004), arXiv:hep-ph/0412191.

[41] T. Aaltonen *et al.* (CDF), Phys. Rev. **D79**, 112002 (2009), arXiv:0812.4036 [hep-ex].

[42] V. Khachatryan *et al.* (CMS), Phys. Rev. Lett. **105**, 211801 (2010), arXiv:1010.0203 [hep-ex].

[43] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **102**, 041801 (2009), arXiv:0809.4903 [hep-ex].

[44] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP **05**, 026 (2006), arXiv:hep-ph/0603175.

[45] K. Cheung and T.-C. Yuan(2011), arXiv:1101.1445 [hep-ph].

[46] M. I. Gresham, I.-W. Kim, and K. M. Zurek(2011), arXiv:1102.0018 [hep-ph].

[47] P. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. **D30**, 1470 (1984).

[48] R. Diener, S. Godfrey, and T. A. W. Martin, Phys. Rev. **D80**, 075014 (2009), arXiv:0909.2022 [hep-ph].