Manifestations of Top Compositeness at Colliders

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Based on: Kunal Kumar, Tim Tait, Roberto Vega-Morales, JHEP 05(2009)022

Overview

- Motivation
- Approach
- Top Compositeness at the Tevatron
- Top Compositeness at the LHC
- Future Work/Conclusions

Motivation for right handed top quark compositeness

- Could be evidence of BSM physics
- Many models exist in which the top is composite to motivate its large mass relative to other quarks (172.6 GeV)

  A. Delgado and T. M. P. Tait, JHEP 0507, 023 (2005) M. Suzuki, Phys. Rev. D 44, 3628 (1991) K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, arXiv:hep-ph/0612015 K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP 0308, 050 (2003) etc.

- Only sector of the SM not currently strongly constrained by existing measurements such as LEP
- LHC will be sensitive to compositeness scales as high as 5 TeV
- Take advantage of large amounts of top pair data from the Tevatron

Approach - Effective Field Theory

- Model Independent-not limited to a specific theory of top compositeness
- Use Effective Field Theory as a framework to explore most important operators which can modify the top's interactions with itself and other SM particles.
- Parameterize the modifications of top interactions, through high scale physics, with higher dimensional operators in the following way:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\{\mathcal{O}_t + \mathcal{O}_1 + \mathcal{O}_2 + \mathcal{O}_3\} + O\left(\frac{1}{\Lambda^4}\right)$$

Where the $\mathcal{O}_i$ will be defined below and additional operators with mass dimension > 6 will have suppressed contributions to the processes we consider, which take place at energies $\lesssim \Lambda$

- For only t_R composite, NDA argues the most significant operator is given by (where i,j,k,l are contracted as color singlets or octets):

$$\mathcal{O}_t = g^2 \left[\bar{t}^i \gamma^\mu P_R t_j\right] \left[\bar{t}^k \gamma_\mu P_R t_l\right]$$

Georgi, Kaplan, Morin, Schenk PRD51, 3888 (1995)

- But when four real tops are difficult to produce, such as at the Tevatron, we turn to sub-leading operators which can contribute to observable processes, such as $t\bar{t}$ production.
- Dimension 6 operators which contribute to the top quark coupling to the gluon at tree level:

$$\begin{aligned}
\mathcal{O}_1 &= g_1 g_S \left[\left(H\bar{Q}_3\right) \sigma^{\mu\nu} \lambda^a P_R t\right] G^a_{\mu\nu} + H.c. \\
\mathcal{O}_2 &= g_2 g_S \left[\bar{t}\gamma^\mu \lambda^a D^\nu P_R t\right] G^a_{\mu\nu} + H.c. \\
\mathcal{O}_3 &= g_3 g_S \left[\bar{t}\gamma^\mu \lambda^a P_R t\right] \sum_q \left[\bar{q}\gamma_\mu \lambda^a q\right]
\end{aligned}$$

Buchmuller, Wyler NPB 268,621(1986) Atwood, Kagan, Rizzo PRD52, 6264(1995) Hill, Parke PRD49, 4454(1994)

- The equations of motion relate $\mathcal{O}_3$ to $\mathcal{O}_2 + \mathcal{O}_2^\dagger$ and thus take $g_3 = 0$

Top Compositeness Tevatron - Top Pair Production

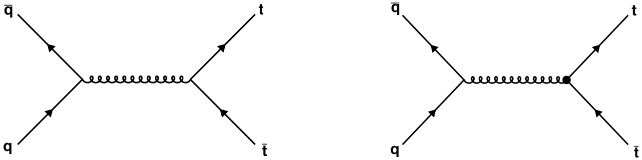
- For Tevatron the most promising measurements to constrain new physics come from $t\bar{t}$ production so we need only consider $\mathcal{O}_1$ and $\mathcal{O}_2$:

$$\mathcal{O}_1 = g_1 g_S \left[\left(H\bar{Q}_3\right)\sigma^{\mu\nu}\lambda^a P_R t\right] G^a_{\mu\nu} + H.c.$$
$$\mathcal{O}_2 = g_2 g_S \left[\bar{t}\gamma^\mu\lambda^a D^\nu P_R t\right] G^a_{\mu\nu} + H.c.$$

- Give the following Feynman rule for the induced g-t-$\bar{t}$ vertex:

$$\frac{\lambda^a}{\Lambda^2}\left[2v\left(\not{q}\gamma^\mu - q^\mu\right)\left(g_1 P_R + g_1^* P_L\right) - g_2\left(\not{q}p^\mu - \gamma^\mu(q\cdot p)\right)P_R - g_2^*\left(\not{q}k^\mu - \gamma^\mu(q\cdot k)\right)P_R\right]$$

- Neglecting gluon initiated graphs (roughly 10% error in our estimates) gives the following graphs for $t\bar{t}$ production



Obtaining constraints by looking at $t\bar{t}$ production rate

- Inclusive cross sections

$$\sigma(t\bar{t})_{CDF} = 7.0 \pm 0.3 \pm 0.4 \pm 0.4 \text{ pb}$$
$$\sigma(t\bar{t})_{D0} = 7.62 \pm 0.85 \text{ pb}$$
$$\sigma(t\bar{t})_{SM} = 6.6 \pm 0.8 \text{ pb}$$

Kidonakis, Vogt Eur Phys J C 33 S466(2004)
Mangano, Nason, Ridolfi JHEP0407, 033(2004)

- We take the stricter bounds provided by CDF and after combining errors in quadrature

$$\sigma(t\bar{t})_{exp} = 7.0 \pm 0.61 \text{ pb}$$

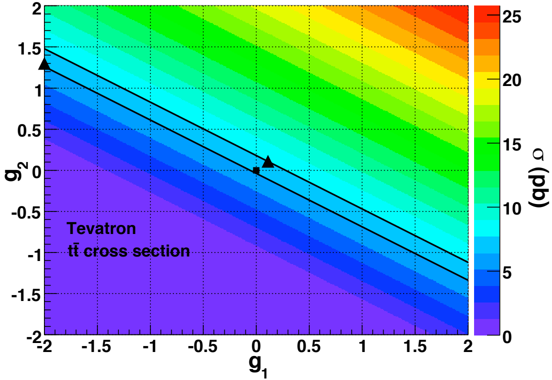
- Keeping terms to $O\left(\frac{1}{\Lambda^2}\right)$ we have:

$$\hat{\sigma} \propto |\mathcal{M}|^2 = |\mathcal{M}_{SM} + \mathcal{M}_{NP}|^2 = |\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\left[\mathcal{M}^*_{SM}\mathcal{M}_{NP}\right] + O\left(\frac{1}{\Lambda^4}\right)$$

- Leading new physics corrections arise from the interference term between SM and NP graphs shown previously
- Rewriting the new physics cross section as proportional to SM cross section

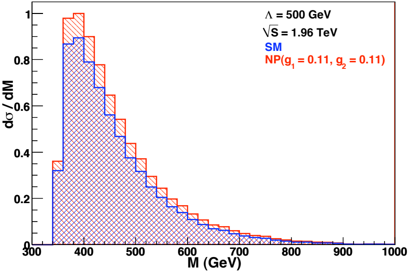
$$\hat{\sigma} = \sigma_{\hat{S}M}\left(1 + \ \mathrm{Re}\ \frac{g_1(16vms^2) + g_2(4m^2s^2 + s^3 + s(s + 2t - 2m^2)^2}{2\Lambda^2(2m^4 + s^2 - 4m^2t + 2st + 2t^2)}\right)$$

- SM cross section generated for $p\bar{p} \rightarrow t\bar{t}$ by Madevent reweighted event by event for Λ = 500 GeV
- At $O\left(\frac{1}{\Lambda^2}\right)$, only the real parts of g_1 and g_2 contribute so we only consider real values in our parameter space below

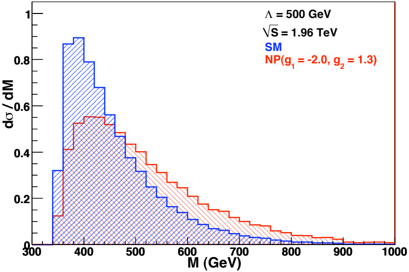


- Doesn't constrain New Physics very well because of potential cancellations between operators
- This serves as motivation to look at kinematic distributions for better constraints
- Choose two points leading to largest deviations from SM, but still within bounds, from which to compute kinematic distributions

Invariant mass distributions

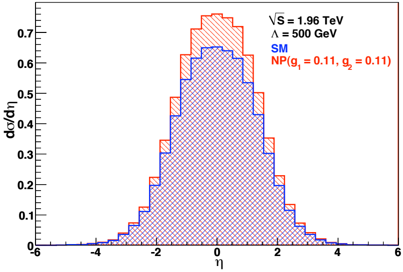


- PT1(0.11, 0.11) represents a case where both operators do not result in any cancellations in the inclusive rate.
- Leads to a slight deviation from the SM for the $t\bar{t}$ invariant mass distribution

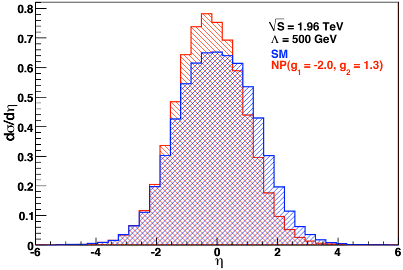


- PT2 (-2.0, 1.3) represents a case where moderate cancellations result in a $t\bar{t}$ cross section consistent with SM
- Leads to a noticeable deviation from the SM for the $t\bar{t}$ invariant mass distribution

Rapidity distributions



- PT1 leads to moderate effects on top rapidity distribution



- PT2 leads to an asymmetric top rapidity distribution

Tevatron Conclusion

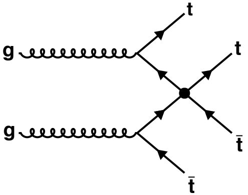
- Values of g $\sim$ 1 and $\Lambda \sim$ 500 GeV are consistent with Tevatron data
- Since cross section data provides weak constraints, perhaps more careful analysis of kinematic distributions could help to come up with better constraints on the New Physics
- Look to the LHC for more direct signs of top compositeness

Top Compositeness at the LHC - Four top production

- Sufficient energy to consider processes mediated by four top operator:

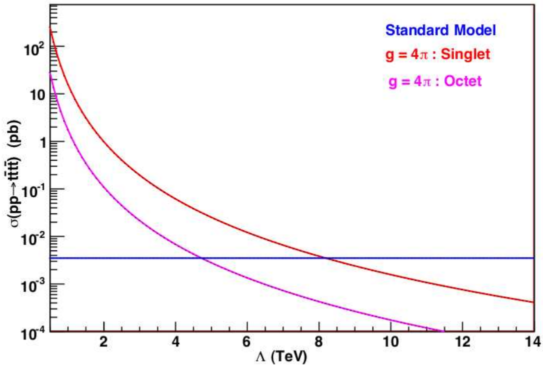
$$\mathcal{O}_t = g^2 \left[\bar{t}^i \gamma^\mu P_R t_j\right] \left[\bar{t}^k \gamma_\mu P_R t_l\right]$$

- Unlike the Tevatron, the gluon mediated process dominates
- Since the standard model cross section for four tops is small ($\sim$3 fb) we expect new physics amplitudes for $gg \to t\bar{t}t\bar{t}$ to be much larger than the sum of the Standard Model amplitudes
- So to $O\left(\frac{1}{\Lambda^4}\right)$ in the cross section we can neglect terms involving SM graphs and we are left only with terms which involve the 4-top operator. One representative term is the square of the following diagram:



- Need not consider dimension 8 operators because to $O\left(\frac{1}{\Lambda^4}\right)$ they do not contribute to the 4-top cross section when neglecting SM diagrams
- Implemented in Madevent by introducing an Auxillary field (singlet or octet) to model effects of the dimension 6 operator at low energies and plot the cross section as a function of Λ
- Similar work was done previously (for the octet case):

  Pomarol, Serra Phys. Rev. D 78, 074026 (2008)



- We see that new physics can lead to enhancements by many orders of magnitude over the SM.
- A previous study concluded that four tops are observable over backgrounds provided the raw four top production is greater than 45 fb B.Lillie, J.Shu and T.M.P.Tait, arXiv:0712.3057 [hep-ph]
- From the figure this occurs for $\Lambda \leq 5$ TeV

LHC Conclusion

- For sufficiently low composite scales the LHC should be sensitive enough to observe potential new physics effects in the production of 4-tops
- Many other theories give excess of the 4-top production rate:

C.R.Chen, W.Klemm, V.Rentala and K.Wang, arXiv:0811.2105 [hep-ph], Gerbush, Khoo, Phalen, Pierce, Tucker-Smith 0710.3133 [hep-ph], Dobrescu, Kong, Mahbubani 0709.2378, Kilic, Okui, Sundrum JHEP 0807, 038 (2008), Guchait, Mahmoudi, Sridhar Phys. Lett. B 666, 347 (2008), Mohopatra, Okada, Yu Phys. Rev. D 77, 011701 (2008)

Future Work/Conclusions

Tevatron

- Including effects of higher order terms and gluon initiated graphs
- Analysis of other distributions can lead to better constraints on the coefficients of dimension 6 operators

LHC

- A systematic study of four top signals
- Many aspects of the top quark are still a mystery and we should continue to explore it as a possible source for evidence of physics beyond the standard model.