Vector-like Quarks, a New Heavy Top

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Objectives

The aim is to examine the significance of the off-shellness effects with 2 to 4 processes involving the Vector Like Quarks (VLQ's). The model has a vector-like top T′ as singlet decaying into SM particles. The decays allowed are T′ to Wb, Zt and Ht, with 100% branching ratio's for each channel (not simultaneously). The on-shell and off-shell cross-sections are found with Madgraph5 with the diagrams containg VLQ's in the decay chain. The mass dependence is then analyzed for varying values of the mass of the VLQ's.

Introduction

VLQ's are of interest because they are needed for inducing symmetry breaking with the Higgs as a pseudo-Goldstone boson, a possible explanation for the Higgs being light. They are used in many theories, like composite Higgs, extra dimensions and little Higgs models, among many others. The top quark has a large Yukawa coupling enabling a significant mixing with the third family of quarks in the Standard Model (SM), this is the reason for studying the heavy top.
Vector-like quarks transform as the SM quarks do but with left as well as right handed charge currents.

OFF-SHELL

The following types of diagrams are the main contribution in the 2 to 4 processes for the VLQ production,

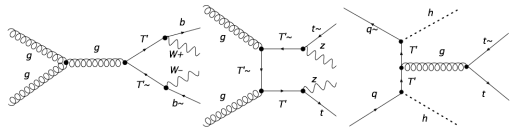

Figure 7: 2 to 4 Off-shell Production of VLQ's

The partial widths in the different channels are given by:

$$\Gamma(T' \to Wb, Zt, Ht) = \kappa^2_{W,Z,H} |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\Pi m^2_W} \times \Gamma_{W,Z,H}(M_{T'}, m_{W,Z,H}, m_{b,t,t})$$

for a mass M of the VLQ's and mixing matrices between VLQ's and SM quarks is $|V^{4i}_{L/R}|$ with the kinematic relations are given by:

$$\Gamma_{W,Z} = \frac{1}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_q^2}{M^2_{T'}}, \frac{m^2_{W,Z}}{M^2_{T'}}\right)\left[\left(1 - \frac{m_q^2}{M^2_{T'}}\right)^2 + \frac{m^2_{W,Z}}{M^2_{T'}} \times -2\frac{m^4_{W,Z}}{M^4_{T'}} + \frac{m_q^2 m^2_{W,Z}}{M^4_{T'}}\right]$$

and

$$\Gamma_H = \frac{1}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_q^2}{M^2_{T'}}, \frac{m^2_H}{M^2_{T'}}\right)\left[1 + \frac{m_q^2}{M^2_{T'}} - \frac{m^2_H}{M^2_{T'}}\right]$$

ON-SHELL

We define the two cross-sections for channels

- The off-shell process σ_P:
  p p > W+ b W- b , Z t Z t , H t H t / Excluding all particles propagation except the T′ and gluon.
- The on-shell σ_X:
  p p > T′ T′ QED=0

The cross-section σ_X of the on-shell production of the VLQ allows us to test the validity of the approximation made by XQCAT for high values of $\Gamma/M_{T'}$.
Only QCD couplings are involved. This means that resulting 2 to 2 cross-section will be proportional to the mass of the VLQ.

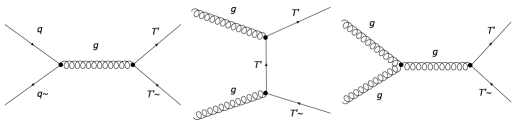

Figure 8: On-shell 2 to 2 Production

This is to be compared with the cross-section σ_P off-shell VLQ production of the 2 to 4 process. The observable examined is then defined as $\frac{\sigma_P - \sigma_X}{\sigma_X}$ which is plotted against $\frac{\Gamma_{W,Z,H}}{M_{T'}}$.

Results

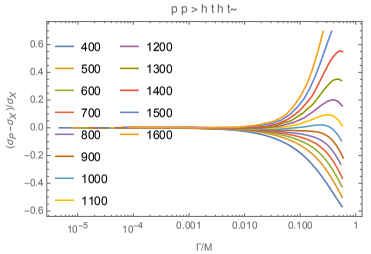

Figure 1: 2D plot: p p > H t H t

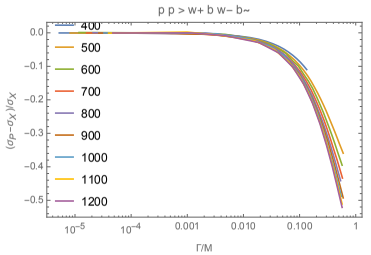

Figure 2: 2D plot: p p > W+ b W-b

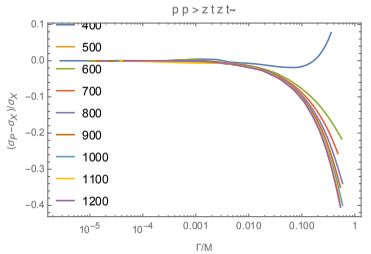

Figure 3: 2D plot: p p > Z t Z t

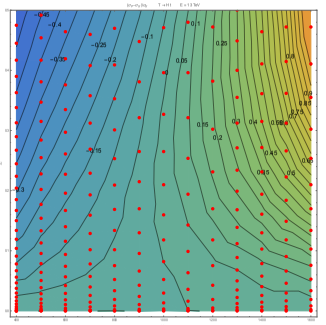

Figure 4: 3D contour plot: p p > H t H t

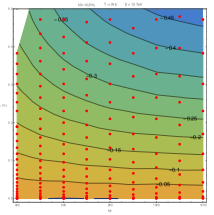

Figure 5: 3D contour plot: p p > W+ b W- b

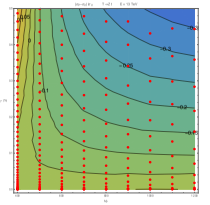

Figure 6: 3D contour plot: p p > Z t Z t

It is useful for seeing the dependence on the VLQ top mass to do a 3D of contour plot, $\Gamma/M_{T'}$ vs $M_{T'}$ with $\frac{\sigma_P - \sigma_X}{\sigma_X}$ as the contours. As well as the 2D plot of $\frac{\sigma_P - \sigma_X}{\sigma_X}$ vs $\Gamma/M_{T'}$.
It can be seen here that the Wb and Zt channels are stable for values of the width Γ. There is a very slight mass dependence for Wb, Zt having a more massive final state. The Ht channel however differs greatly from the previous channels as it involves a coupling which is proportional to $M_{T'}$. Further research is being done in these channels for other observables with similar plots not mentioned here as well as the off-diagonal terms, ZtWb, Ztht, WbHt. This study should be available shortly.

References

1 XQCAT: eXtra Quark Combined Analysis Tool. D. Barducci, A. Belyaev, M. Buchkremer, J. Marrouche, S. Moretti, L. Panizzi : arXiv:1409.3116 [hep-ph]

2 Nucl.Phys. B876 (2013) 376-417 ; M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi ; Model Independent Framework for Searches of Top Partners

3 In preparation. S. Moretti, D. O'Brien, L. Panizzi, H. Prager

Conclusion

It was seen that the Wb and Zt processes had the same behaviour, the off-shell effect becoming considerable when the width is large. The differences that do occur are due to the fact that Zt has a more massive final state, so has a stronger mass dependence. For the Ht process it was found to have a very strong mass dependence, this is due to the fact that the coupling structure has a mass, which is not the case for the Wb and Zt processes.

Future Research

Almost completed the off-diagonal elements of the matrix. With varying fractions of the branching ratio to each channel. We will then do a similar study of off-shell effects with additional heavy vector-like top partners.