Interference effects in vector-like quarks production

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Objectives

Vector-like quarks (VLQ) are a particular kind of quarks that are predicted by many models beyond the Standard Model (SM). If several VLQs with close masses exist, the contribution of interference effects in processes of pair production of VLQs can be relevant: bounds coming from current experimental studies should be rescaled. Our goal is to compute analytically the value of these interferences and check the obtained results with Monte-Carlo simulations for different parameters.

Introduction

A VLQ is a quark whose left- and right-handed chiralities belong to the same representation of the symmetry group G of the underlying theory. For the SM, $G = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$.
VLQs have never been observed but are predicted by many scenarios beyond the SM (extra dimensions, composite Higgs, SUSY...) in different numbers and types. Moreover, since a minimal SM extension with a 4th chiral generation is excluded with high confidence level, experimental searches for VLQs have acquired high priority.

Production, decay & interferences

We consider the production of a VLQ T. The probability of production is proportional to e^2 for the electromagnetic interaction, to g_S^2 for the strong interaction and to g_W^2 for the weak interaction, but since $|e| \ll g_S$ and $g_W \ll g_S$, we can consider that the production by electromagnetic and weak interaction is suppressed. **Therefore the pair production cross section only depends on the mass of the VLQ.**

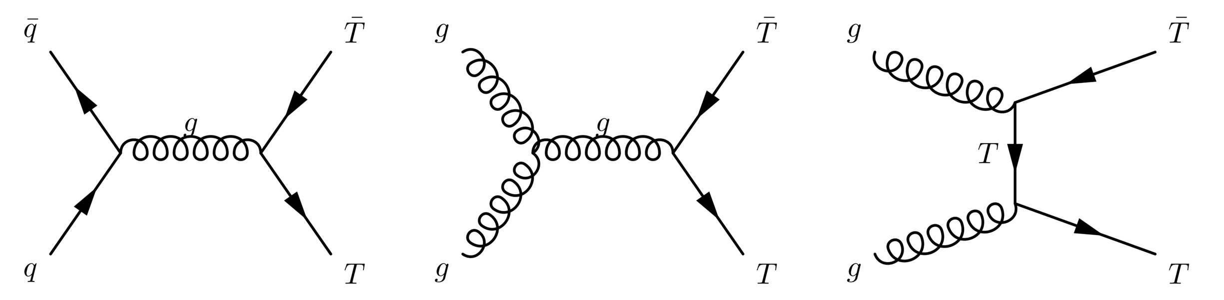


Figure 1: The three possibilities of production

We now consider a model with two VLQs T_1 and T_2. Let us consider the decay of a $T_1\bar{T}_1$ pair in a $W^+b\ W^-\bar{b}$. It is clear that the $T_2\bar{T}_2$ can decay in the same final state so if we detect a $W^+b\ W^-\bar{b}$ final state, we cannot know if these particles come from a $T_1\bar{T}_1$ or a $T_2\bar{T}_2$ pair. The amplitude for the production of a final state $W^+b\ W^-\bar{b}$ from a $T_i\bar{T}_i$ pair is

$$\mathcal{A}_{T_i} \propto (\kappa_W^{T_i})^2 V_{T_i t} V^*_{T_i t} = (\kappa_W^{T_i})^2\, |V_{T_i t}|^2$$

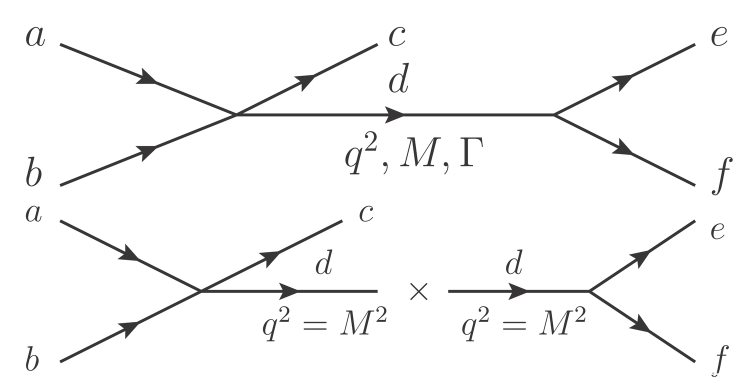
where $\kappa_W^{T_i}$ is the coupling strength, and $V_{T_i t}$ is the mixing between T_i and t. The cross section of this event will be

$$\sigma \propto (\mathcal{A}_{T_1} + \mathcal{A}_{T_2})^2 \propto \mathcal{A}_{T_1}^2 + \mathcal{A}_{T_2}^2 + \underbrace{2\,\mathrm{Re}(\mathcal{A}_{T_1}\mathcal{A}_{T_2}^*)}_{\textbf{interference term}}$$

$$\sigma = \sigma_1 + \sigma_2 + \sigma_{\text{int}}$$

Narrow-Width Approximation

The Narrow-Width Approximation (NWA) allows us to simplify the computation of complex processes by factorising the whole process into the on-shell production and the subsequent decay.



The matrix element of the full process is

$$\mathcal{M} = \mathcal{M}_P \frac{1}{q^2 - M^2 - iM\Gamma} \mathcal{M}_D$$

so the squared matrix element is

$$|\bar{\mathcal{M}}|^2 = |\mathcal{M}_P|^2 \frac{1}{(q^2 - M^2)^2 + (M\Gamma)^2} |\mathcal{M}_D|^2$$

and with the NWA $\Gamma \ll M$, we find $\boxed{\sigma \simeq \sigma_P \cdot BR}$ where $BR = \Gamma_D/\Gamma$.

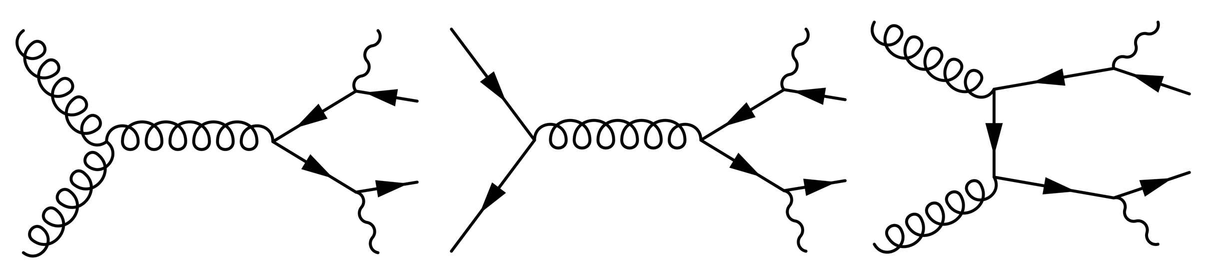


Figure 2: Diagrams 2 to 4 considered

In the case of the 2 to 4 processes that we consider (Fig. 2), the previous formula can be generalized in

$$\boxed{\sigma \simeq \sigma_P \cdot BR_+ \cdot BR_-}$$

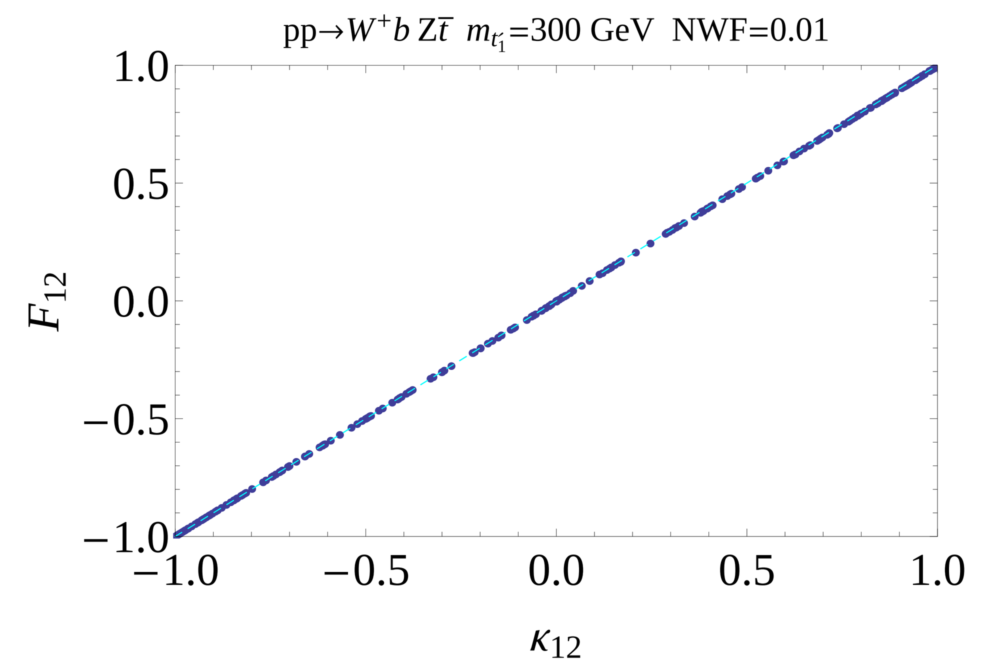
With this formula we can compute σ_1 and σ_2, but not σ_{int}.

Ansatz and Simulations

Ansatz We study $F_{12} = \frac{\sigma_{\text{int}}}{\sigma_1 + \sigma_2}$ (which we numerically compute using MadGraph) as a function of

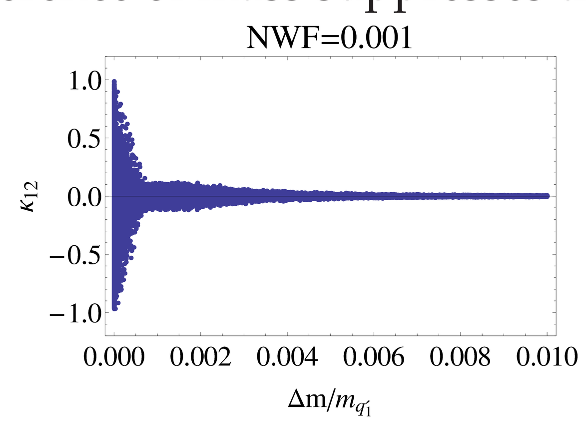
$$\kappa_{12} = \frac{2 g_{1+} g_{1-} g_{2+} g_{2-}\ \mathrm{Re}\left\{\left(\int \frac{\mathrm{d}q^2}{2\pi} \mathcal{P}_1^0 \mathcal{P}_2^{0*}\right)^2\right\}}{g_{1+}^2 g_{1-}^2 \left(\int \frac{\mathrm{d}q^2}{2\pi} \mathcal{P}_1^0 \mathcal{P}_1^{0*}\right)^2 + g_{2+}^2 g_{2-}^2 \left(\int \frac{\mathrm{d}q^2}{2\pi} \mathcal{P}_2^0 \mathcal{P}_2^{0*}\right)^2}$$

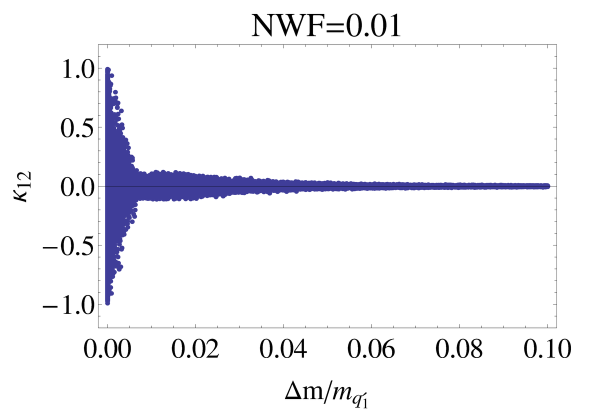
the normalized quotient of the product of the couplings times the integrals of the propagators which only depend on the masses M_i and on the couplings $g_{i\pm}$ of the VLQs. This ansatz is easily computable analytically.



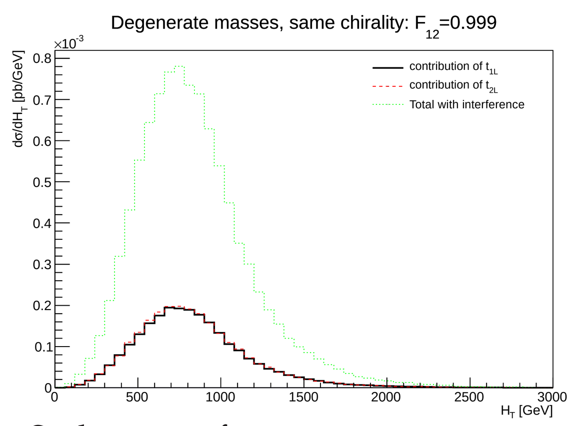
$\mathrm{NWF} = \Gamma/M$ $\boxed{F_{12} \simeq \kappa_{12}}$

Influence of the difference of mass We check that the difference of mass suppresses the interferences.

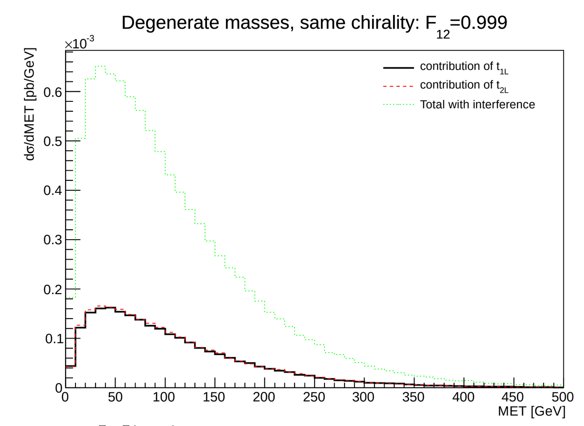




Differential distributions The scalar sum of transverse momentum and missing transverse energy including interference can be obtained by a rescaling of the differential distributions for production of the VLQs using $(1+\kappa_{12})$ for the rescaling factor.

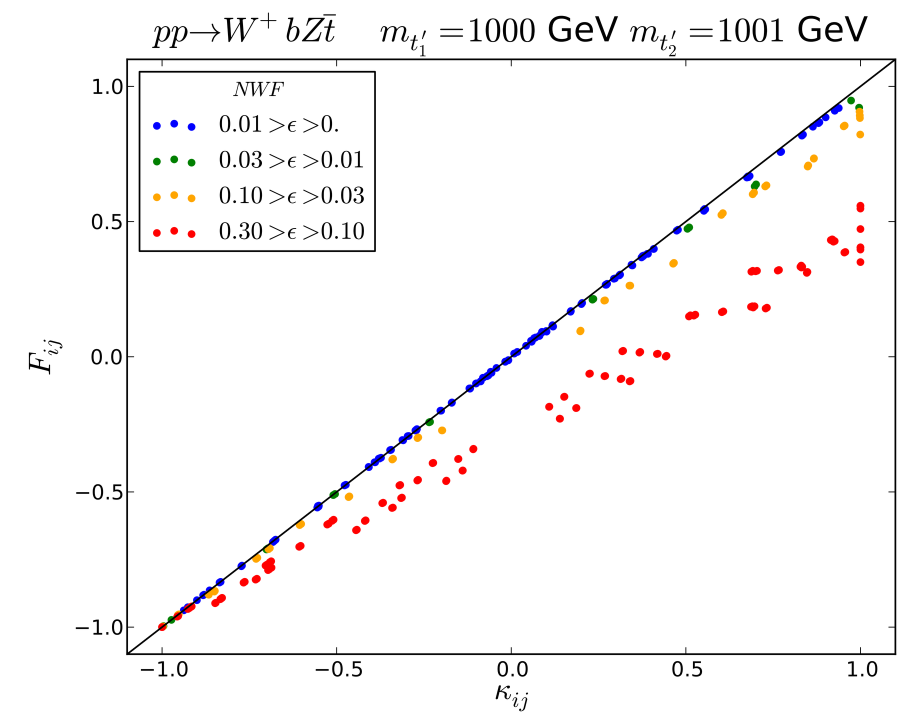


Scalar sum of transverse momentum



Missing transverse energy

Limits of our ansatz Since our ansatz is based on the NWA, the quotient Γ/M must not be too important so that our ansatz remains valid.



Remark The ansatz also only works when the mass and width eigenstates are not misaligned (i.e. when loop effects are not too strong).

Conclusion

Finally, we found a way to compute analytically the value of the interferences for the pair-production of VLQs, in a *model-independent way*. We observed through numerical simulation that the value of interferences rate is very well described by our ansatz:

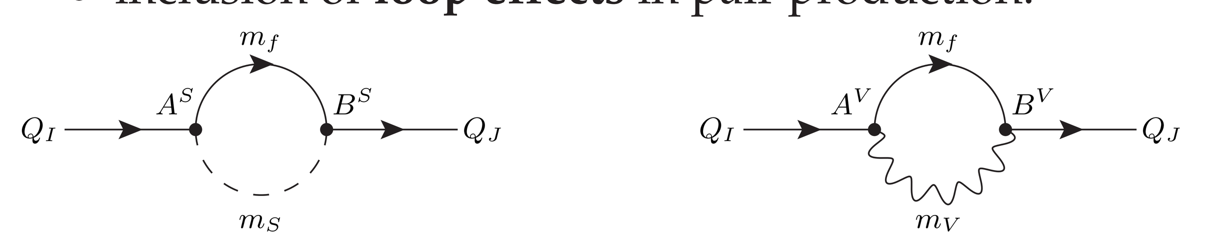
- it allows us to get the value of the total cross section for a specified process involving VLQs,
- it also allows us to obtain the differential distributions including the interferences by a simple rescaling.

Furthermore, we showed using numerical simulations that the value of the interferences only depend on the relative mass splitting and on the value of couplings of the VLQs considered. We also saw that our ansatz describe well the interference in the limit of the NWA.

Further Research

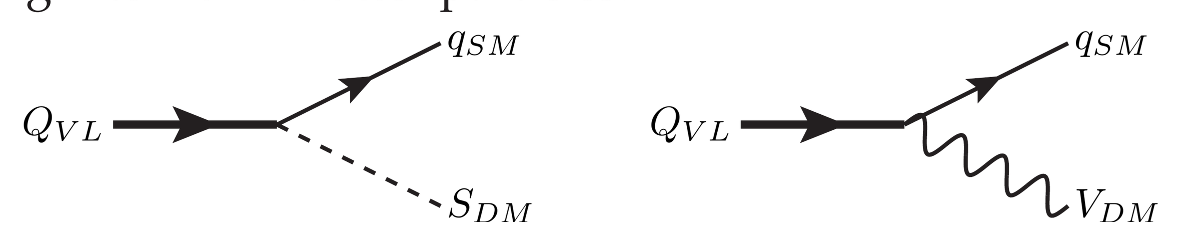
To improve the accuracy of our results, several subleading effects have to be taken in account, e.g.:

- inclusion of **loop effects** in pair production:



- inclusion of **chain decays** between VLQs: $T_1 \to Z\,T_2$.

Yet, those effects are *model-dependent* which make them more difficult to take in account.
We also want to study other possible phenomenologies of VLQs like **single production** processes and VLQs decaying into **Dark Matter** particles:



References and Contact

[1] Daniele Barducci, Alexander Belyaev, Jacob Blamey, Stefano Moretti, Luca Panizzi, and Hugo Prager. Towards model-independent approach to the analysis of interference effects in pair production of new heavy quarks. *JHEP*, 1407:142, 2014.

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