Notes on single B production

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1 Sigmahats

The total cross section for the process of single production and decay of a B quark can be written as:

$$\sigma(C_1, C_2, m_{\rm B}, \Gamma_B) = C_1^2\; C_2^2\; \tilde{\sigma}_{FW}(m_{\rm B}, \Gamma_B), \tag{1}$$

where C_1 and C_2 are the couplings corresponding to the interactions through which B is produced and decays, and $\Gamma_B = \Gamma(C_i, m_{\rm B}, m_{\rm decays})$ is the total width of the B quark, which depends on its mass, the masses of all its decay products and the couplings through which the B interacts with all the particles it can decay to, including (but not exclusively) C_1 and C_2. The above relation is valid in the absence of interference contributions or if such contributions are negligible, as it is the case when producing the B VLQ via interactions with the Higgs boson. A large total width can be obtained in two ways: both by increasing the couplings of B with its decay products and by enlarging the number of decay channels. From a model-independent point of view, the mechanism by which the B VLQ achieves a large width will not be specified, and Γ_B will be considered as a free parameter.

Eq.1 is valid in all width regimes, from NWA to large width. However, as the Γ_X/M_X ratio approaches zero (NWA regime) it is possible, and simpler, to factorise production and decay and write the cross-section as:

$$\sigma(C_1, C_2, m_{\rm X}, \Gamma_X) = \sigma_P(C_1, m_{\rm X}) BR_{X\to \text{decay channel}} = C_1^2 \hat{\sigma}_{NWA}(m_{\rm X}) BR_{X\to \text{decay channel}}, \tag{2}$$

where C_1 is the coupling corresponding to the interaction through which the B is produced and all the information about C_2 and Γ_B are contained in the branching ratio $BR_{B\to \text{decay channel}}$. Of course, Eq. 1 reproduces Eq. 2 with better accuracy as Γ_X/M_X approaches zero, *i.e.* the NWA.

2 Interpretation in simplified models

2.1 The NWA regime

In a simple extension of the SM with just one VLQ representation containing the X, the couplings of X with SM bosons and quarks can be parametrised as:

$$c_Z^X = \frac{e}{2c_w s_w}\kappa_Z^X, \quad c_W^X = \frac{e}{\sqrt{2}s_w}\kappa_W^X \quad \text{and} \quad c_H^X = \frac{M_B}{v}\kappa_H^X \tag{3}$$

where $v = 246$ GeV is the Higgs VEV, c_w and s_w are the cosine and sine of the Weinberg angle θ_W and κ is a coupling strength which can be fixed to obtain the desired width. Numerically, and for further reference, $\frac{e}{2c_w s_w} = 0.370349$ and $\frac{e}{\sqrt{2}s_w} = 0.458486$. The advantage of this parametrisation is that fixing the representation of the B, the κ parameters determine with excellent approximation the width and the amount of mixing between X and the SM bottom quark (for a relation between couplings and mixing angles see, *e.g* Ref. [1, 2]).

In the different VLQ types and simplified models one can use relations between the couplings in order to define a unique order parameter, those relations are:

The decay rates in each decay mode can be generally written as:

Multiplet	relations	main coupling chirality
B singlet	$\kappa_{ZB} = \kappa_{HB} = \kappa_{WB} = \kappa$	L
T singlet	$\kappa_{ZT} = \kappa_{HT} = \kappa_{WT} = \kappa$	L
$X_{5/3}$ doublet	$\kappa_{ZX} = \kappa_{HX} = 0, \quad \kappa_{WX} = \kappa$	R
$Y_{4/3}$ doublet	$\kappa_{ZY} = \kappa_{HY} = 0, \quad \kappa_{WY} = \kappa$	R
TB doublet (1)	$\kappa_{ZB} = \kappa_{HB} = \kappa, \quad \kappa_{WB} = 0$	R
	$\kappa_{ZT} = \kappa_{HT} = 0, \quad \kappa_{WT} = \kappa$	R
TB doublet (2)	$\kappa_{ZB} = \kappa_{HB} = 0, \quad \kappa_{WB} = \kappa$	R
	$\kappa_{ZT} = \kappa_{HT} = \kappa, \quad \kappa_{WT} = 0$	R

Table 1: Relation between couplings to SM particles in simplified models in the NWA regime.

$$\Gamma_{X\to Hq}[\kappa_{H^{X_L}}, \kappa_{H^{X_R}}, M_X, m_q] = 3 * (\kappa^2_{H^{X_L}} + \kappa^2_{H^{X_R}}) \frac{\lambda(m_q, M_X, M_H)}{96\pi M_X^3}$$
$$(m_q^2 + M_X^2 - M_H^2 + 4\frac{\kappa^2_{H^{X_L}}\kappa^2_{H^{X_R}}}{\kappa^2_{H^{X_L}} + \kappa^2_{H^{X_R}}} m_q M_X) \qquad (4)$$

where m_q is the mass of the quark present on the decay, and
$\lambda(m_1, m_2, m_3) = \sqrt{m_1^4 - 2m_1^2m_2^2 + m_2^4 - 2m_1^2m_3^2 - 2m_2^2m_3^2 + m_3^4}$.

$$\Gamma_{X\to Vq}[\kappa_{V^{X_L}}, \kappa_{V^{X_R}}] = d_V \times (\kappa^2_{V^{X_L}} + \kappa^2_{V^{X_R}}) \frac{3e^2}{4s_w^2} \frac{\lambda(m_q, M_X, M_H)}{(96.\pi * M_X^3)}) \times$$
$$(m_q^2 + M_X^2 + \frac{m_q^4 - 2m_q^2M_X^2 + M_X^4}{m_V^2} - 2m_V^2$$
$$-12\frac{\kappa^2_{V^{X_L}}\kappa^2_{V^{X_R}}}{\kappa^2_{V^{X_L}} + \kappa^2_{V^{X_R}}} m_q M_X) \qquad (5)$$

where $V = Z, W$, and $d_W = 1$ and $d_Z = 1/c_w^2$.

2.2 The large width regime

Disclaimer: For future reference, I here want to stress that this interpretation is just to show an application of the $\tilde{\sigma}_{FW}$, but that since simplified models with large widths are already experimentally excluded, see *e.g.* Ref. [2]) the cross-sections obtained in the limit of large width in this section are useless from a theory point of view.

In the context of simplified models, where only one VLQ is the **only** new particle besides the SM, there is a limit to the maximum width it can obtain. This limit is due to the fact that the total width is entirely given by the partial widths of its decays into the SM gauge bosons, but all couplings are bounded from above by the fact that κ_Z, κ_W and κ_H are combination of sines and cosines of mixing angles, which cannot be therefore larger than 1, and for the coupling with the Z boson, of a factor which depends on the weak isospin of the VLQ which can be at most 2 [2]. Therefore, increasing the Yukawa coupling between B and SM quarks has both the effect of increasing the width and modifying the relations between BRs, but the partial widths are limited (for any given mass) by the upper limits on the couplings, *i.e.* the factors in front of the κ parameters in Eq. 3.

2.2.1 B with assumptions on κ values

Alternatively, one can **impose** the relations between κ_W, κ_Z and κ_H. This would allow to obtain large widths due to the freedom to choose values which reproduce the desired total width. The price to pay is that by doing this the assumption to be in a simplified model is relaxed: one must assume that new physics (in the form of mixings either in the quark or boson sectors due to further VLQs or new gauge bosons or scalar fields) enter into play and conjures to generate the needed couplings. This assumption, though legitimate *per se*, would bring unspecified new physics into the analysis, and with no further purpose than modifying couplings. Therefore, from a model-independent and simplified point of view, this approach is not very meaningful.

The price to pay when imposing the relations between κ_X is that the assumption to be in a simplified model is relaxed and new physics (*e.g.* in the form of mixings either in the quark or boson sectors due to further VLQs or new gauge bosons or scalar fields) must enter into play to generate the needed couplings. As we do not want to constrain the range of results to make sense only in the simplest scenarios we will not use it. See for example [3] for examples of less minimalistic scenarios.

References

[1] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Prez-Victoria. "Handbook of vectorlike quarks: Mixing and single production". In: *Phys. Rev.* D88.9 (2013), p. 094010. DOI: 10.1103/PhysRevD.88.094010. arXiv: 1306.0572 [hep-ph].

[2] C.-Y. Chen, S. Dawson, and E. Furlan. "Vector-like Fermions and Higgs Effective Field Theory Revisited". In: (2017). arXiv: 1703.06134 [hep-ph].

[3] G. Cacciapaglia, A. Deandrea, N. Gaur, D. Harada, Y. Okada, and L. Panizzi. "Interplay of vector-like top partner multiplets in a realistic mixing set-up". In: *JHEP* 09 (2015), p. 012. DOI: 10.1007/JHEP09(2015)012. arXiv: 1502.00370 [hep-ph].