Production of Different Flavor Heavy Quarks at LHC

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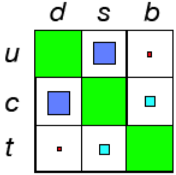
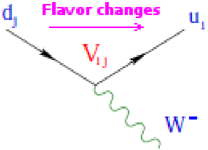
"Ankara YEF Gunleri", 27-30/12/2011

Outline

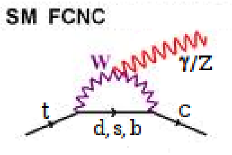
In particle physics, flavor is a quantum number of elementary particles. For three families of fermions, there are six different quark flavors (up, down, strange, charm, bottom, top), three different charged leptons (electron, muon, tau) and their corresponding neutrinos. The flavor is conserved by the strong and electromagnetic interactions. However, only the weak charged current interactions change flavor.

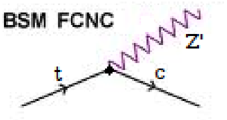




A weak doublet partner (d'_i) of the up-type quark (u_i) turns out to be a quantum superposition of down-type mass eigenstates (d_j), $d'_i = \sum_j V_{ij} d_j$. This flavor mixing generates a rich variety of observable phenomena including CP-violation effects.

In spite of its phenomenological success, the Standard Model (SM) of particle physics does not provide a full understanding of the flavor. In the SM, flavor changing neutral currents (FCNC) are absent in tree-level processes. However, one-loop level FCNC processes can be enhanced by orders of magnitude in some cases due to the presence of new physics.


SM FCNC


BSM FCNC

Due to its large mass it is expected that the top quark would be sensitive to the new physics at the TeV scale. An important aspect of the top quark physics can be the investigation of the possible FCNC couplings with the extra gauge boson Z' at the Large Hadron Collider (LHC).

The recent experimental searches for the Z' boson at **Tevatron** have put lower limits on the mass range 0.6 - 1.0 TeV at 95% C.L. depending on the specific Z' models [1]. This range is slightly changed by the **LHC** experiments such that the resulting mass limits at 95% C.L. are given as 1.83 TeV for the sequential Z' boson, 1.49 - 1.64 TeV for various E_6-motivated Z' bosons [2].

We investigate the associate production of different flavors $t\bar{c}$ through the Z' boson FCNC interactions implemented into the Monte Carlo framework. A parameter search for different Z' models is given for the LHC with $\sqrt{s}$=7 and 14 TeV.

A grand unified symmetry group E_6 breaks into $SO(10)$ and $U(1)_\psi$ groups, then $SO(10)$ breaks into $SU(5)$ and $U(1)_\chi$ groups, leading to new neutral gauge fields. The particles associated with the additional fields can mix in a linear combination to form the Z' candidate: $Z'(\theta) = Z'_\psi \cos\theta + Z'_\chi \sin\theta$, where θ is the mixing angle between the two states. The pattern of spontaneous symmetry breaking and the value of θ determine the Z' couplings to fermions.

In order to compare the predictions from different models, here we consider some special Z' models: the Z'_ψ, Z'_χ and Z'_η models corresponding to the specific values of the mixing angle θ (0, $\pi/2$ and -arctan $\sqrt{3/5}$, respectively) in the E_6 model, left-right symmetric Z'_{LR} model having the couplings as a combination of right-handed and B-L neutral currents, and sequential Z'_S model having the same couplings to fermions as the Z boson.

In a larger group beyond the standard model, additional or exotics quarks may have their $U(1)'$ charges different from the left-handed or right-handed quarks. In this case, the SM quarks will mix leading to the FCNC. Moreover, in some string models, the three generations of SM fermions are constructed differently, resulting in family non-universal Z' couplings to fermions.

In the interaction basis, the additional neutral current Lagrangian associated with the $U(1)'$ symmetry can be written as

$$\mathcal{L}' = -g' \sum_f \bar{f} \gamma^\mu \left[\epsilon_L^f P_L + \epsilon_R^f P_R \right] f Z'_\mu \tag{1}$$

where $\epsilon_{L,R}^f$ are the chiral couplings of Z' boson with fermions. The g' is the gauge coupling of the $U(1)'$, and $P_{R,L} = (1 \pm \gamma_5)/2$.

When the Z' couplings are flavor diagonal but family non-universal, FCNC couplings are emerged from fermion mixing.

We assume flavor diagonal and family universal Z' couplings to down-type quarks: $\epsilon^d_{L,R} = C^d_{L,R}\mathbf{1}$ where $\mathbf{1}$ is the 3×3 identity matrix in the family space and $C^d_{L,R}$ is the chiral charge for down-type quarks [3]. On the other hand, chiral couplings for the up-type quarks can be written as

$$\epsilon^u_L = C^u_L \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & x \end{pmatrix} \quad \text{and} \quad \epsilon^u_R = C^u_R \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (2)$$

Keeping only the left-handed couplings family non-universal, the magnitude of the FCNC is characterized by the parameter x [4]. The chiral charges for the up and down-type quarks are specified by the Z' model of interest.

When diagonalizing the mass matrix or Yukawa coupling matrix we rotate the left-handed and right-handed fields by unitary rotations $V^f_{L,R}$, such that $Y^f_D = V^f_R Y^f V^{f\dagger}_L$. The chiral couplings of Z' in the mass eigenstate basis are given by

$$B^f_L \equiv V^f_L \epsilon^f_L V^{f\dagger}_L \quad \text{and} \quad B^f_R \equiv V^f_R \epsilon^f_R V^{f\dagger}_R \tag{3}$$

here the CKM matrix can be written as $V_{CKM} = V^u_L V^{d\dagger}_L$. The flavor mixing in the left-handed quark fields is simply related to V_{CKM}, assuming the diagonalization of up sector and unitarity of CKM matrix we find the couplings

$$B^u_L \approx \begin{pmatrix} 1 & (x-1)V_{ub}V^*_{cb} & (x-1)V_{ub}V^*_{tb} \\ (x-1)V_{cb}V^*_{ub} & 1 & (x-1)V_{cb}V^*_{tb} \\ (x-1)V_{tb}V^*_{ub} & (x-1)V_{tb}V^*_{cb} & x \end{pmatrix} \tag{4}$$

Current measurements of CKM elements imply the following hierarchy: $|B^{tc}_L| > |B^{tu}_L| > |B^{cu}_L|$.

In numerical calculations, we take the coupling $g' \simeq 0.65$ for the sequential model, and $g' \simeq 0.40$ for other models. In the left-right symmetric model we use $g_L = g_R$ and the chiral charges $C_L^f = -\sqrt{3/5}(B-L)/2\alpha_{LR}$ and $C_R^f = \sqrt{3/5}(\alpha_{LR} I_{3R}^f) + C_L^f$ where $\alpha_{LR} \simeq 1.52$.

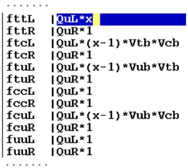
	Z'_S	Z'_{LR}	Z'_χ	Z'_ψ	Z'_η
C_L^u	0.3456	-0.08493	$-1/2\sqrt{10}$	$1/\sqrt{24}$	$-1/\sqrt{15}$
C_R^u	-0.1544	0.5038	$1/2\sqrt{10}$	$-1/\sqrt{24}$	$1/\sqrt{15}$
C_L^d	-0.4228	-0.08493	$-1/2\sqrt{10}$	$1/\sqrt{24}$	$-1/\sqrt{15}$
C_R^d	0.0772	-0.6736	$-3/2\sqrt{10}$	$-1/\sqrt{24}$	$-1/2\sqrt{15}$
C_L^e	-0.2684	0.2548	$3/2\sqrt{10}$	$1/\sqrt{24}$	$1/2\sqrt{15}$
C_R^e	0.2316	-0.3339	$1/2\sqrt{10}$	$-1/\sqrt{24}$	$1/\sqrt{15}$
C_L^ν	0.5	0.2548	$3/2\sqrt{10}$	$1/\sqrt{24}$	$1/2\sqrt{15}$

The standard CompHEP [5] package has five files for each model, here are some details about the implementation.

lgrng.mdl

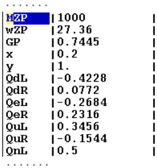
```
 .......
|T    |t    |ZP    |        |-GP/2                                         |fttL*G(m3)*(1-G5)+fttR*G(m3)*(1+G5)
|C    |c    |ZP    |        |-GP/2                                         |fccR*G(m3)*(1+G5)+fccL*G(m3)*(1-G5)
|U    |u    |ZP    |        |-GP/2                                         |fuuR*G(m3)*(1+G5)+fuuL*G(m3)*(1-G5)
|T    |c    |ZP    |        |-GP/2                                         |ftcL*G(m3)*(1-G5)+ftcR*G(m3)*(1+G5)
|C    |t    |ZP    |        |-GP/2                                         |ftcL*G(m3)*(1-G5)+ftcR*G(m3)*(1+G5)
|T    |u    |ZP    |        |-GP/2                                         |ftuL*G(m3)*(1-G5)+ftuR*G(m3)*(1+G5)
|U    |t    |ZP    |        |-GP/2                                         |ftuL*G(m3)*(1-G5)+ftuR*G(m3)*(1+G5)
|C    |u    |ZP    |        |-GP/2                                         |fcuL*G(m3)*(1-G5)+fcuR*G(m3)*(1+G5)
|U    |c    |ZP    |        |-GP/2                                         |fcuL*G(m3)*(1-G5)+fcuR*G(m3)*(1+G5)
|B    |b    |ZP    |        |-GP/2                                         |fbbR*G(m3)*(1+G5)+fbbL*G(m3)*(1-G5)
|S    |s    |ZP    |        |-GP/2                                         |fssR*G(m3)*(1+G5)+fssL*G(m3)*(1-G5)
|D    |d    |ZP    |        |-GP/2                                         |fddR*G(m3)*(1+G5)+fddL*G(m3)*(1-G5)
 .......
```

func.mdl



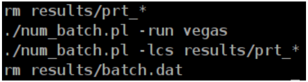
```
 .......
|fttL   |QuL*x
 fttR   |QuR*1
 ftcL   |QuL*(x-1)*Vtb*Vcb
 ftcR   |QuR*1
 ftuL   |QuL*(x-1)*Vub*Vtb
 ftuR   |QuR*1
 fccL   |QuL*1
 fccR   |QuR*1
 fcuL   |QuL*(x-1)*Vub*Vcb
 fcuR   |QuR*1
 fuuL   |QuL*1
 fuuR   |QuR*1
 .......
```

vars.mdl



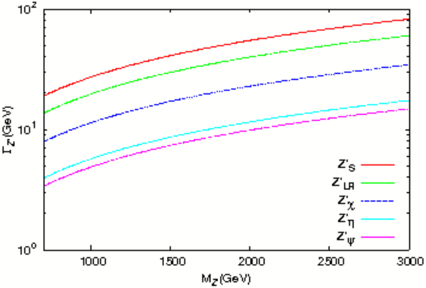
```
 .......
|MZP     |1000         |
 wZP     |27.36        |
 GP      |0.7445       |
 x       |0.2          |
 y       |1.           |
 QdL     |-0.4228      |
 QdR     |0.0772       |
 QeL     |-0.2684      |
 QeR     |0.2316       |
 QuL     |0.3456       |
 QuR     |-0.1544      |
 QnL     |0.5          |
 .......
```

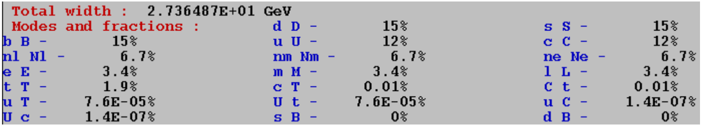
...and batch mode.



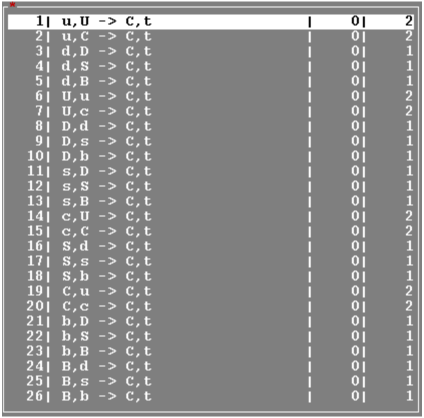
```
rm results/prt_*
./num_batch.pl -run vegas
./num_batch.pl -lcs results/prt_*
rm results/batch.dat
```

The total decay width, modes and fractions of Z' boson are calculated for the parameter $x = 0.2$.



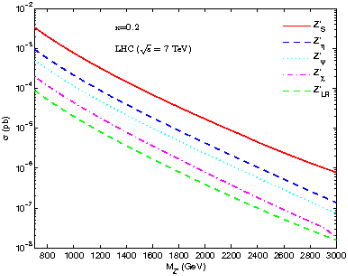

```
 Total width :   2.736487E+01 GeV
 Modes and fractions :               d D -         15%                     s S -         15%
b B -         15%                    u U -         12%                     c C -         12%
nl Nl -        6.7%                  nm Nm -        6.7%                   ne Ne -        6.7%
e E -        3.4%                    m M -        3.4%                     l L -        3.4%
t T -        1.9%                    c T -      0.01%                      C t -      0.01%
u T -    7.6E-05%                    U t -    7.6E-05%                     u C -    1.4E-07%
U c -    1.4E-07%                    s B -          0%                     d B -          0%
```

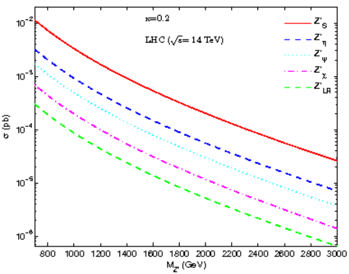
Contributing sub-processes to the production process $pp \to t\bar{c}X$



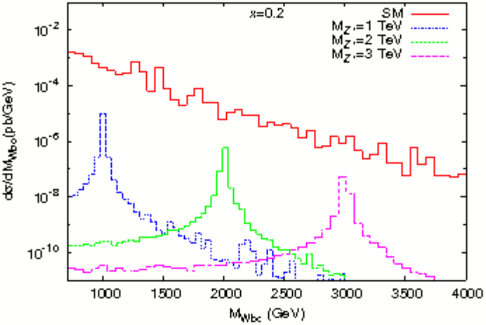
```
  1| u,U -> C,t           |    0|    2
  2| u,C -> C,t           |    0|    2
  3| d,D -> C,t           |    0|    1
  4| d,S -> C,t           |    0|    1
  5| d,B -> C,t           |    0|    1
  6| U,u -> C,t           |    0|    2
  7| U,c -> C,t           |    0|    2
  8| D,d -> C,t           |    0|    1
  9| D,s -> C,t           |    0|    1
 10| D,b -> C,t           |    0|    1
 11| s,D -> C,t           |    0|    1
 12| s,S -> C,t           |    0|    1
 13| s,B -> C,t           |    0|    1
 14| c,U -> C,t           |    0|    2
 15| c,C -> C,t           |    0|    2
 16| S,d -> C,t           |    0|    1
 17| S,s -> C,t           |    0|    1
 18| S,b -> C,t           |    0|    1
 19| C,u -> C,t           |    0|    2
 20| C,c -> C,t           |    0|    2
 21| b,D -> C,t           |    0|    1
 22| b,S -> C,t           |    0|    1
 23| b,B -> C,t           |    0|    1
 24| B,d -> C,t           |    0|    1
 25| B,s -> C,t           |    0|    1
 26| B,b -> C,t           |    0|    1
```

The cross section for the process $pp \to t\bar{c}X$ is calculated with CompHEP depending on the Z' boson mass at the LHC for the center of mass energy 7 TeV and 14 TeV [6].

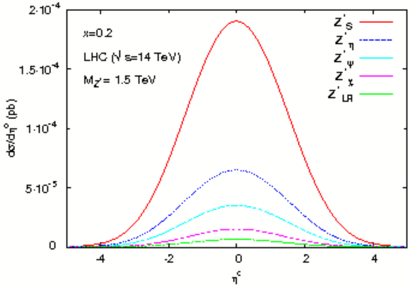


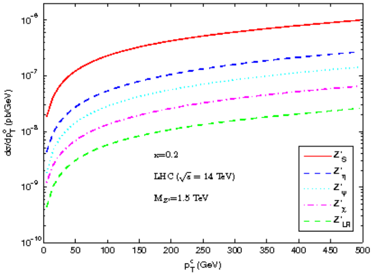


The invariant mass distribution of the $W^+b\bar{c}$ system is plotted for the signal and background at the LHC. We consider two types of background for the analysis: the same final state as for the signal process and the other background (single top associated with b quark) which contribute to the same final state assuming *b* quark might be taken as the charmed jet.



We apply some kinematical cuts to reduce the background significantly, $|\eta| < 2.5$ and $p_T > M_{Z'}/2 - 4\Gamma_{Z'}$, without affecting much the signal in the interested Z' mass range.





For the signal observability criteria we use

$$SS = \sqrt{2L_{int}\epsilon[(\sigma_S + \sigma_B)\ln(1+\sigma_S/\sigma_B) - \sigma_S]} \qquad (5)$$

Here, σ_S and σ_B are cross sections for signal and background calculated in the mass interval $M_{Z'} - 2\Gamma_{Z'} < M_{tc} < M_{Z'} + 2\Gamma_{Z'}$. Assuming the integrated luminosity $L_{int} = 10^5$ pb^{-1}, it is shown that the LHC ($\sqrt{s} = 14$ TeV) can measure the Z' boson up to the mass of 2 TeV for the FCNC mixing parameter $x = 0.2$.

$M_{Z'}$ (GeV)	Z'_S	Z'_{LR}	Z'_χ	Z'_η	Z'_ψ
700	13.4	18.4	20.3	20.4	20.3
1000	8.0	10.5	11.3	11.6	11.6
1500	4.1	5.2	5.4	5.4	5.4
2000	2.4	2.9	3.0	2.9	2.9
3000	1.4	1.7	1.8	1.8	1.8

Conclusions

Heavy quark flavor tagging is useful to analyze the final state event topology. A charmed jet has secondary vertex mass ranging from 0 to 2 GeV with a peak around 1 GeV, while bottom jet has larger secondary vertex mass with a tail up to 4 GeV. The MC samples can be used to determine the fractions of charm, bottom and other light quarks in the event. We find the discovery regions of the parameter space for the top-charm associate production via Z' exchanges. For a the mass of $m_{Z'} = 2$ TeV, the LHC can search for the FCNC mixing parameter up to $x = 0.2$. There are also constraints from the $D^0\bar{D}^0$ mixing. The current experimental bounds are satisfied as long as $(x-1)C_L^u < \mathcal{O}(1)$ in the Z' models.

References

[1] C. Amsler *et al.*, [Particle Data Group], Phys. Lett. B 667, 1 (2008).
[2] G. Aad *et al.*, [The ATLAS Collaboration], arXiv:1108.1582 [hep-ex].
[3] V. Barger *et al.*, Phys. Lett. B 598, 218 (2004).
[4] A. Arhrib *et al.*, Phys. Rev. D 73, 075015 (2006).
[5] E. Boos *et al.*, [CompHEP Collaboration], Nucl. Instrum. Meth. A 534, 250 (2004); arXiv:hep-ph/0403113.
[6] O. Cakir, I.T. Cakir, A. Senol and A.T. Tasci, Eur. Phys. J. C 70, 295 (2010); arXiv: 1003.3156 [hep-ph].