SENSITIVITY STUDIES OF COLOR RE-CONNECTION IN TOP UNDERLYING EVENT MEASUREMENTS

ESTUDIOS DE LA SENSIBILIDAD A LA RECONEXIÓN DE COLOR EN EVENTOS SUBYACENTES DE PRODUCCIÓN DEL TOP QUARK

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Sensitivities studies of color re-connection (CR) effects in $t\bar{t}$ underlying events were performed for the fully leptonic and fully hadronic final states (FLFS and FHFS respectively) events. Effects of CR parameters were studied. Differences between predictions with and without CR were observed of $\sim 8-15\,\%$ for the investigated observables, charged particle multiplicity, charged particle average transverse momentum and transverse momentum sum. For different color re-connection models, effects around 5 % were observed. No differences for predictions with and without CR between FLFS and FHFS were found for all the observables. This study shows the sensitivity of the UE observables to CR effects and may help to decrease the uncertainties due to the UE simulation in top mass measurements.

Estudios de la sensibilidad a la reconexión de color (CR) en los eventos subyacentes (ES) que tienen lugar en los eventos de producción de una pareja de quarks *top* y *antitop* fueron desarrollados para los estados finales completamente hadrónicos (EFCH) y leptónicos (EFCL). Se observan diferencias en un rango de ∼ 8-15 % para las predicciones generadas con y sin reconexión de los observables investigados, multiplicidad de partículas cargadas, momento transversal de las partículas cargadas y suma del momento transversal. Para los diferentes modelos de reconexión de color se encontraron efectos alrededor de un 5 %. No se observaron diferencias entre los EFCH y EFCL para las predicciones con y sin reconexión de color de ninguno de los observables. El estudio muestra la sensibilidad a la reconexión de color de los observables estudiados, lo que podría contribuir a disminuir las incertidumbres debidas a la modelación de los UE en las mediciones de la masa del *top*.

PACS: Top quarks, 14.65.Ha; Standard model, 14.80.Bn; Gauge bosons, 14.70.-e

I. INTRODUCTION

The Standard Model (SM) of particle physics [1] is the gauge field theory which knits together all the known elementary particles. It relates the twelve fundamental fermions divided into three generations of quarks and leptons which are identical respect to all their quantum numbers except their masses. The SM also includes the gauge bosons, these are the mediators of interactions among the fundamental particles plus the Higgs boson which is responsible for giving the mass to the particles. The top quark, discovered by the Tevatron experiments in 1995, is the heaviest particle in the SM. It has a lifetime of about 10^{-25} s [2], which is shorter than the average time of hadronization. Because of this, it always decays into other fundamental particles, a W boson and a b quark (BR∼95 %) [2], which later on form space bound states, the hadron. With a mass of $m_t = 173.21 \pm 0.51\,(stat.) \pm 0.71\,(syst.)$ GeV [2], the top quark is expected to be one of the major loop corrections to the Higgs boson self-coupling evolution with energy scale. Additionally, the large top mass implies that the Higgs boson mass also gets large loop contributions that depend quadratically on the scale of new physics. The latter constitutes sufficient reasons for performing precision measurements of its mass, where the 0.5 % currently precision is not good enough.

At the LHC, the experimental measurement of the top mass relies on the interpretation of the observed final state in terms of the parton-level kinematics. However, this strategy has some issues, related to the decay of the b quark. The fragmentation of the b quark is expected to occur in a B hadron, plus other hadronic particles which form the so-called b-jet. This feature may compromise the reconstruction of the initial kinematics for two different reasons: the fact that the particles originating from the b-quark evolution may tend to escape the clustered jet, affecting the reconstructed final state; and the possibility of interaction and interference between the top-decay products during the hadronization, which impacts on the reconstruction of the initial kinematics. This occurrence is known as color re-connection (CR) and it is responsible for a decrease in the precision that can be achieved in the top mass measurements and moreover constitutes 20 to 40 % of total the uncertainty. Because of that, modeling top events constitutes well-grounded motivation to look for a better understanding of the "underlying events".

II. UNDERLYING EVENT (UE) AND COLOR RE-CONNECTION (CR)

In this paper, we define as UE any hadronic activity which can not be attributed to the particles arising from the hard scattering, i.e. the decay products of the $t\bar{t}$ system. The hadronization of initial- and final-state radiation (ISR/FSR) is also considered part of the UE as long as the particles are not clustered within the two reconstructed b-jet candidates. In the interaction process, other partonic constituents within the initial colliding hadrons can scatter. This can lead to multiparton interactions (MPI) which produce particles that contribute to the UE. In addition, particles from the hadronization of beam-beam remnants (BBR) are also considered part of the UE.

Color re-connection is an *ad hoc* mechanism mainly used to describe the interactions that can occur between colored fields during the hadronization process [3]. In the proton-proton collision at the LHC, the combination of MPI, BBR and parton showers increase the number of colored partons, hence CR is expected to occur at an important rate. CR is a significant ingredient of the UE contributions. However, there is no first-principles model that can bring a definite solution, reason why it is necessary to test different models and evaluate their effects on the final states.

III. EVENT SIMULATION AND EVENT SELECTION

The simulation process was performed with the PYTHIA 8 [4] event generator, CUETP8M1 tune, at the center of mass energy $\sqrt{s}$=8 TeV. To achieve a good statistic and accuracy generation of 1 million events was set for each simulated sample. PYTHIA 8.1 contains only one model (sometimes referred to as the MPI-based one) with two possibilities for resonance system, denoted as "default" and "default Early Resonance Decays (ERD)". Our simulation was performed using only the default possibility, which evaluated the probability of CR between the hard scattering and the UE according to the following equation:

$$P_{rec}\left(p_T\right) = \frac{\left(R_{rec} p_{T0}\right)^2}{\left(R_{rec} p_{T0}\right)^2 + p_T^2}, \tag{1}$$

where $0 \leq R_{rec} \leq 10$ (for $R = 10$, saturation effects take place) is a phenomenological parameter and p_{T0} is an energy dependent parameter used to damp the low-p_T divergence of the $2 \to 2$ QCD cross section. For a more detailed description of the CR models see [3].

Event selection was performed with Rivet 2.2.0 [5], based on the CMS-PAS-TOP-13-007 analysis. For the top selection two b-jets were required, selected with $p_T > 30$ GeV in a pseudorapidity range of $|\eta| \leq 2.5$. Two leptons were also required with $p_T > 20$ GeV in $|\eta| \leq 2.5$. The charged particle selection was made by applying a cut for $|\eta| \leq 2.1$ and $p_T > 0.5$ GeV. In our study three basic quantities were considered to describe the UE in $t\bar{t}$: the charged particle multiplicity resulting from the simple count of selected charged candidates (N_{ch}); the charged flux in the transverse plane resulting from the scalar sum of the transverse momentum of the selected candidates ($\sum p_T$); the average flux per charged particle, computed from the ratio of the two previous quantities $\bar{p}_T = \sum p_T / N_{ch}$. These three quantities were studied with respect to an axis defined event by event, after computing the reconstructed momentum of the $t\bar{t}$ system, as

$$\vec{p}_T(t\bar{t}) = \vec{p}_T(b_1) + \vec{p}_T(b_2) + \vec{p}_T(l) + \vec{p}_T(l') + \vec{p}_T^{miss}, \tag{2}$$

where $\vec{p}_T(b)$ and $\vec{p}_T(l)$ are the transverse momentum of the b-tagged jets and the charged leptons and $\vec{p}_T^{miss}$ is the imbalance in the transverse momentum of the event computed from the negative of the sum of the momenta of all reconstructed particles. It is expected that this axis be correlated with the direction of the $t\bar{t}$ system. The regions are constructed according to the distance in azimuthal angle with respect to the direction of the $t\bar{t}$ system.

IV. STUDY RESULTS

A first comparison of the default predictions and the predictions with CR switched off was performed for the three observables in the three regions of the transverse plane. In figure 1 the predictions with and without CR for the studied observable is shown for the transverse region. Significant differences, around 10 %, can be observed, between the default and CR off predictions. This behavior appeared for all the studied regions.

It can be observed that the most sensitive observables are N_{ch} and $\bar{p}_T$. For the three regions, it is possible to observe an increase in the charged particle multiplicity for the CR off predictions, which is due to the longer color strings. As a consequence, these strings are more energetic and produce more particles. The sum of the transverse momentum does not show noticeable changes. In this case, this behavior is related to the interplay of two processes, the length of the strings and the different momentum transferred from the hard scattering to the MPI products. This may explain the absence of significant difference between these two predictions.

The difference observed between both predictions indicates the possibility of using these two observables to constrain the CR in top UE, which would bring to a better constraint of the UE contribution and to an improvement in the top mass uncertainties.

The routine CMS-PAS-TOP-13-007 was modified to obtain a fully hadronic final state (FHFS) requiring the decay of the W boson in two more jets. For this final state, the influence of the CR was also studied. It is possible to note, (Figure 2), that the differences among the predictions are around 10 % again which are of the same order of the difference observed for the FLFS. Again this seems to indicate that the charged particle multiplicity and charged average p_T could be used for constraining color re-connection in top underlying events.

This behavior can be understood if we assume that in PYTHIA 8 there is no implementation of the color re-connection for the decay products of the W boson, which in principle, needs to be done to describe top UE data.

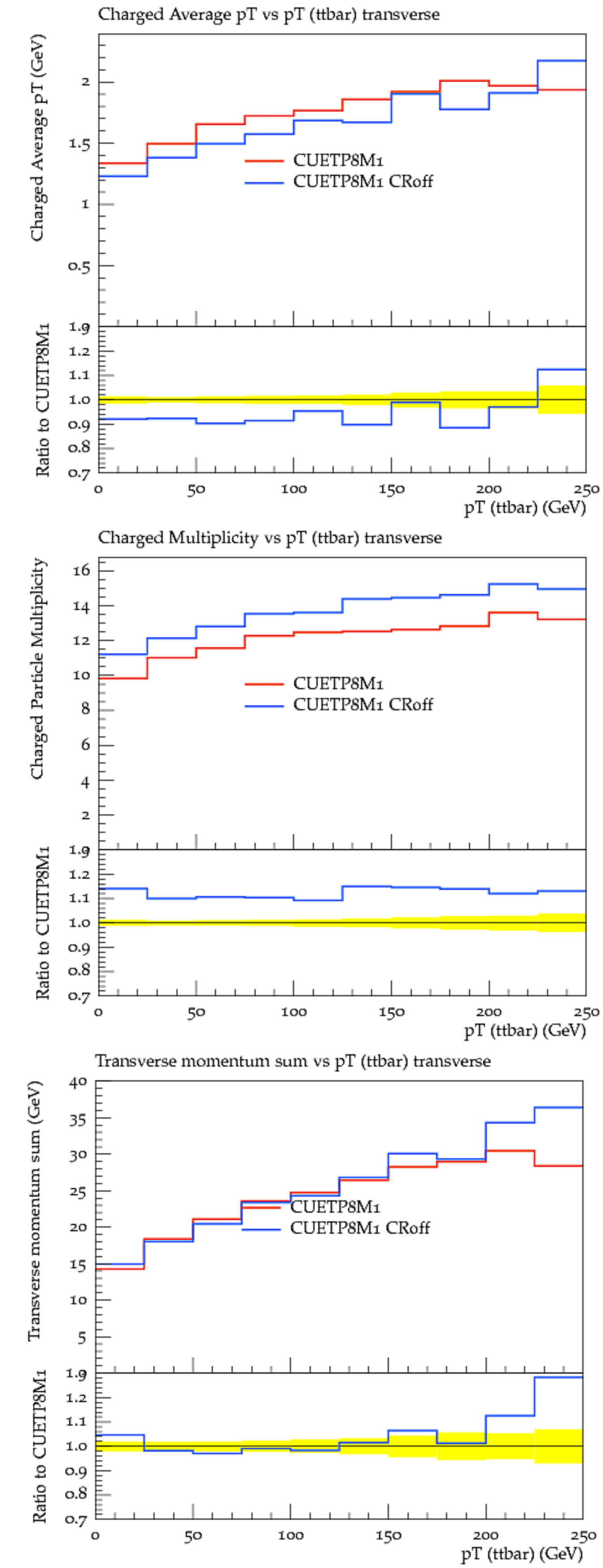

Figure 1. CR switched off effect on (from top to bottom) $\bar{p}_T = \sum p_T/N_{ch}$, N_{ch} and $\sum p_T$ for the transverse region (up) and the inclusive (down) total effect.

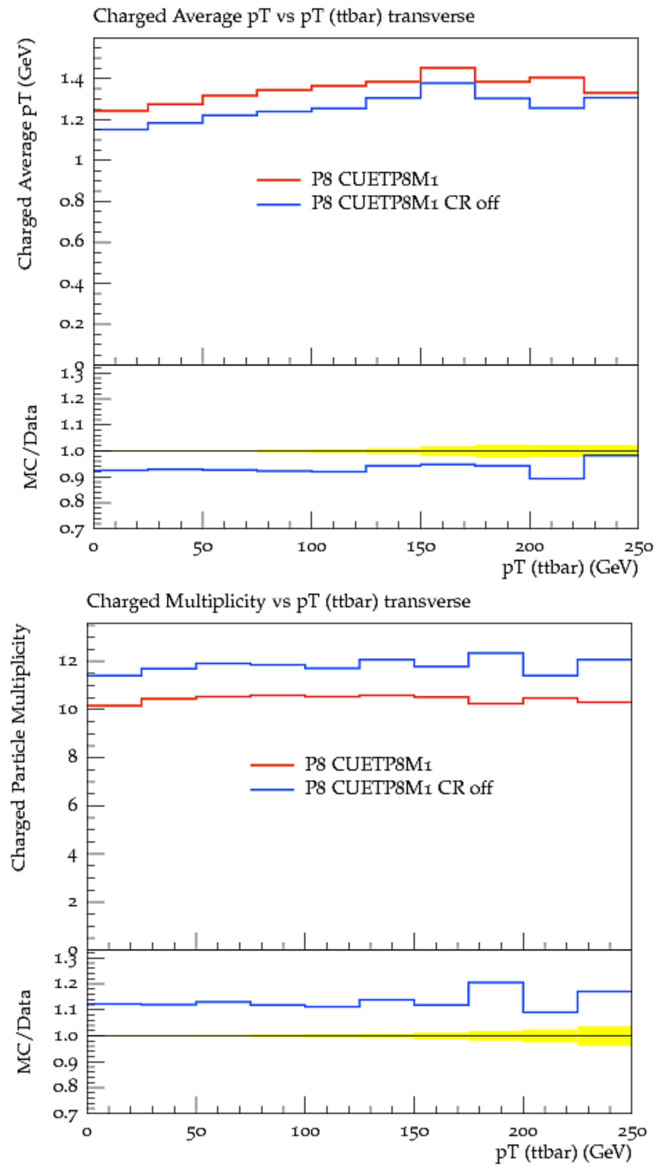

Figure 2. CR switched off in the FHFS for (top to bottom) charged average p_T and b) charged particle multiplicity in the transverse region

V. CONCLUSIONS

A study of the top UE was performed. The effects of the MPI and the hadronization level were studied. The large difference between the default predictions and the MPI-off and Hadronization-off option was observed, showing the need of these components to describe the data. Color re-connection effects in the fully leptonic and hadronic final state in $t\bar{t}$ have an impact of around 10 % for charged particle multiplicity and charged average p_T while for the sum of transverse momentum no noticeable changes were observed.

Due to all these facts, this study shows that the charged particle multiplicity and the charged average p_T might be two appropriate observables for constraining color re-connection in the top underlying event, and as a result would allow to lower top mass uncertainties due to color re-connection.

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