Bottom Production in \( pp \) Collisions at Large Hadron Collider Energies using Parton Cascade Model

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We study the production of bottom quarks in \( pp \) collisions at Large Hadron Collider energies using previously developed parton cascade model to explore the impact of Landau Pomeranchuk Midgal (LPM) effect on their dynamics. In contrast to the case for charm quarks reported recently, we find only a marginal impact of the suppression of multiple scatterings of partons due to the LPM effect on their production. It is felt that this happens as they are only produced in very hard collisions.

I. INTRODUCTION

The study of bottom production in relativistic collisions of protons as well as heavy nuclei is quite important for a variety of reasons. Their production in \( pp \) collisions is expected to provide a stringent test of perturbative Quantum Chromo Dynamics as the \( Q^2 \) for their production (\( \geq 4m_b^2 \)) is of the order of 64–100 GeV\(^2\). Their decay provides an important contribution to charm and \( J/\Psi \) production. An accurate description of their production is an important prerequisite in a search for new physics. It is also expected that the angular correlation of \( b \) and \( \bar{b} \) may provide insight into the influences affecting their movements in the plasma as well as, into the mechanism of their production.

Their reasonably abundant production in \( AA \) collisions at higher energies, the recent and planned increase in the beam-luminosity and the detector systems for the experiments at Large Hadron Collider (LHC) elevate them to a unique position in the study of relativistic heavy ion collisions, which are being investigated in order to explore the dynamics of production of Quark Gluon Plasma (QGP) and its properties. The QGP is predicted to exist by lattice QCD calculations (see Refs. [1–3] and references therein). It is also believed that QGP filled the nascent Universe till about a few microseconds after the Big Bang.

As bottom quarks are produced very early in the collision (\( \tau \approx 1/2m_b \)), they, or rather the \( b\bar{b} \) duo, will be a witness to the evolution of the system of initial partons from a pre-equilibrium stage of energetic partons to a thermalized and possibly chemically equilibrated QGP due to a vehement multiplication of partons and their scatterings and then to a hadronised state, before undergoing freeze-out to a system of hadrons. In the mean time the \( b\bar{b} \) would have either formed an \( \Upsilon \) (or one of its excited states) or the bottom and anti-bottom quarks would have drifted apart, buffered by the energetic quarks and gluons and weakening of the colour force between them due to Debye screening, to be hadronized to form B-mesons.

Do bottom quarks thermalize in the plasma? Are they affected by the hydrodynamic flow which is believed to develop in the system? If yes, to what extent? Do they lose energy in the plasma (see e.g., [4–9], and references therein) due to collision with partons or radiation of gluons or both? Can they be developed as an effective tool to determine the flavour dependence of jet quenching? These and many other questions are expected to be answered in precise detail in near future. The usual first step in this direction is a comparison of their production in nucleus-nucleus collisions with those for appropriately normalized (by number of collisions) \( pp \) collisions.

This procedure has come under strain due to recent findings which found ”QGP like” features in \( pp \) collisions, especially in events having large multiplicities [11, 12].

A recent theoretical study of \( pp \) collisions at LHC energies [12] within Parton Cascade Model (PCM) suggested onset of a substantial multiple scattering, necessary for the formation of an interacting system. A further support for this was provided by the study of charm production which gave indications of deviations in results for calculations performed with and without multiple scatterings, already in minimum bias events for \( pp \) collisions at LHC energies [13]. The experimental data were found to indicate a preference for results of the calculations obtained with the inclusion of Landau Pomeranchuk Midgal (LPM) effect and multiple scatterings for low transverse momenta and central rapidities.

Does this happen for bottom production as well? Considering that bottom quark mass is much larger than the charm quark mass, we expect that they may be produced only in the initial hard scatterings and that the subsequent (multiple) scatterings may not entail a sufficiently large momentum transfer for their production. The same consideration would also affect the \( g \rightarrow b\bar{b} \) fragmentation, as it would involve a very large virtuality for the scattered gluon, in our description. Thus, even if there is an increased multiple scattering in (high multiplicity) \( pp \) collisions, the bottom production may differ only marginally for results of calculations with and without inclusion of multiple collisions, once the LPM effect is accounted for.

If confirmed, this would provide a justification to continue to use the so-called medium modification factor \( R_{AA} \) with confidence as an accurate measure of the medium modification of the bottom production due to the formation of QGP in \( AA \) systems. We put this to test in the following and find that it is indeed so.
We very briefly discuss the necessary formulation in the next section, followed by a section giving our results. Finally we give our conclusions.

II. FORMULATION

We shall use the Monte Carlo implementation VNI/BMS of the parton cascade model, discussed in detail by several authors including the implementation of the LPM effect and heavy quark production [14–19]. We obtain the time-evolution of the ensemble of quarks and gluons populating the nucleons (which populate the nuclei in the case of AA collisions) on the basis of the Boltzmann equation. The $2 \to 2$ scatterings between light quarks, heavy quarks and gluons, and the $2 \to 3$ reactions via time-like branchings of the final-state partons (see Ref. [15, 20]) are included following the procedure.
adopted in PYTHIA $^2$\textsuperscript{21}. We add that this procedure is known to account for higher order effects in the parton scattering within Leading Logarithmic Approximation.

The two body matrix elements are regularized by implementing a $p_T^{\text{cut-off}}$. The build up of soft gluons is regularized by implementing a virtuality cut-off $\mu_0$ for fragmentations. We shall use a value of 2 GeV for $p_T^{\text{cut-off}}$ and keep $\mu_0$ fixed at 1 GeV. The LPM $^2$\textsuperscript{22} effect is implemented using the procedure discussed in Ref. $^1$\textsuperscript{17} by assigning a formation time

$$\tau = \frac{\omega}{k_T},$$

where $k_T$ is its transverse momentum with respect to the emitter and $\omega$ is its energy. We further require that the radiated particle does not interact with other partons during the formation time. The radiating parton, however, is allowed to interact, and if that happens during the formation time, the radiated particle is removed.
from the list of partons forming the system. It has been reported \[13, 17\] that the dependence of the results obtained in the parton cascade model on \(\mu_0\) is rather modest once the LPM effect is accounted for.

The results for bottom production in pQCD depend on the mass for the bottom quark used in the matrix elements. Values ranging from 4 to 5 GeV have been used in the literature. We give our results for the two extremes as well as for the one used most often, 4.75 GeV \[23\].

The calculations are presented for pp collisions at \(\sqrt{s} = 7\) and 13 TeV.

Next we give results where only primary partons (the partons which initially populate the nucleons) interact and radiate after scattering and thus exclude multiple scatterings of partons. We emphasize that by multiple scattering we imply a scenario where a given parton undergoes several collisions.

Finally we give our results for calculations accounting for multiple scatterings as well as the LPM effect. If the results for the later two calculations differ significantly, it would indicate that the bottom quark production is affected by multiple scatterings in realistic situations after LPM effect is accounted for. We recall that there are indications \[13\] that the results for charm production are quite sensitive to these differing scenarios for lower transverse momenta and central rapidities.

In Fig. 1 we give our results for the transverse momentum distribution of bottom quarks for the three sets of calculations. We see that for all the cases the complete neglect of the LPM effect increases the production of bottom quarks considerably as compared to the case when the LPM effect is accounted for. This, we think happens as the formation time of the gluons delays their materialization, while the system continues to expand and dilute, thus reducing the chances of their undergoing multiple scatterings. In any case multiple scatterings which are hard enough to produce a pair of \(b\bar{b}\) quarks are rather rare.

We also see that once LPM effect is accounted for, the results for bottom production with and without inclusion of multiple scatterings are nearly identical for the more realistic values of \(m_b\), viz. 4.75 or 5.00 GeV. These aspects become even more clear when we look at the \(p_T\) integrated rapidity spectra (Fig. 2), where we see that for these masses the rapidity spectra for bottom quarks are quite close when the LPM effect is accounted for. This suggests that the inclusion of multiple scatterings does not lead to additional production of bottom quarks for reasonable values of \(m_b\). The deviations seen for \(m_b = 4.00\) GeV are similar in nature, though much smaller than that for the production of charm quarks reported earlier \[13\].

The corresponding results for pp collisions at 13 TeV are given in Figs. 3 and 4. We see that, while there is a larger production of bottom quarks as the energy rises, the relative trends of the productions for different masses and the three production scenarios remain similar to the case of collisions at 7 TeV earlier.

These results suggest that when LPM effect is accounted for the contribution of multiple scatterings of partons (where the same parton interacts repeatedly) to bottom production is rather marginal for reasonable values of \(m_b\).

Finally, we give the ratio of production of bottom quarks as a function of transverse momenta for \(y = 0\) and as a function of rapidity for \(p_T\) integrated results (Fig. 5). We see that the production of bottom quarks at 13 TeV is about 1.4 times larger than that at 7 TeV as a function of \(p_T\) at \(y = 0\), while the \(p_T\) integrated re-

\[VNI/BMS\]

\[\text{With LPM}\]

\[p_T\text{\,cut-off} = 2\text{ GeV}, \mu_0 = 1\text{ GeV}\]

\[m_b = 5.00\text{ GeV}\]

\[m_b = 4.75\text{ GeV}\]

\[m_b = 4.00\text{ GeV}\]

\[\sqrt{s} = 13\text{ and 7 TeV}\]

\[y = 0\]

\[p_T (\text{GeV})\]

\[y\]

\[R_{pp}(dN/dp_T(\text{pp} \to bX))\]

\[R_{pp}(dN/dy (\text{pp} \to bX))\]

\[\text{FIG. 5: (Color online) Ratios of the transverse momentum spectra at } y = 0\text{ (upper panel) and } p_T\text{ integrated rapidity spectra (lower panel) for bottom quarks at at } \sqrt{s} = 13\text{ and 7 TeV, for } m_b = 4.00, 4.75\text{ and } 5.00\text{ GeV.}\]

### III. RESULTS

We discuss our results for three sets of calculations. In the first case, we put the formation time of the gluons radiated off a final state parton in a hard scattering as zero, which corresponds to ignoring the consequences of the LPM effect. These results are given only as a reference as we do know that LPM effect definitely affects the dynamics of light partons at low transverse momenta rather substantially.
results for the rapidity spectra are close to a value of 1.5 at central rapidities and rise slowly to about 2 at more forward (backward) rapidities. We note that there is only a modest dependence of these ratios on the mass of the bottom quarks used in the calculations.

We add that these corresponding ratios for cross-sections can be obtained by multiplying these results with $\frac{\sigma_{in}(7 \text{ TeV})}{\sigma_{in}(13 \text{ TeV})} \approx 0.9$, and are similar to the results obtained from Fixed Order + Next to Leading Log (FONLL) calculations reported earlier [23].

IV. SUMMARY AND CONCLUSIONS

We have reported results of calculations for production of bottom quarks in $pp$ collisions at Large Hadron Collider energies using Parton Cascade Model.

We find that for reasonable values of the mass of bottom quark ($\approx 4.75 \text{ GeV}$ or more) multiple scattering of partons does not play any significant role for their production, once Landau Pomeranchuk Midgal effect is switched on. This, we feel, happens as multiple scatterings strongly affect the dynamics of partons at lower transverse momenta, which however may not be able to produce bottom quarks which have a large mass, in contrast to the case of charm quarks reported earlier.

This suggests that the usual nuclear modification factor $R_{AA}$ for bottom quarks can be used with relative confidence to obtain medium modification of bottom production in relativistic collision of heavy nuclei at Large Hadron Collider.

These results taken along with our earlier findings about charm quarks [13] elevate bottom quarks to a pre-eminent position to study medium modification of heavy quark production in $AA$ collisions by comparing the same to that for $pp$ collisions, while the charm quarks are elevated to a pre-eminent position for confirming the advent of an interacting medium in $pp$ collisions at LHC energies, where multiple semi-hard partonic collisions take place even when LPM effects are accounted for.

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