Charm quark energy loss in proton-proton collisions at LHC energies

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Abstract. Heavy quarks, i.e. charm and bottom quarks are one of the crucial probes in the high energy nuclear collision program at current day accelerators. It has been shown at the Relativistic Heavy Ion Collider (RHIC) that heavy quarks show a remarkable medium suppression despite their high mass. In these proceedings we report on a study of heavy quark energy loss in high multiplicity proton-proton collisions at energies accessible to the Large Hadron Collider (LHC). Recent experimental results from the LHC collaborations have shown that the notion of creating an interacting system is not completely off limits. The higher energies in LHC proton-proton collisions lead to multiplicities comparable to Cu+Cu collisions at RHIC. Within this environment high-momentum heavy quarks experience a non-negligible energy loss.

1. Introduction

It is commonly assumed that high energy heavy ion collisions at the Relativistic Heavy Ion Collider create a new state of matter, the Quark Gluon Plasma (QGP). The transition from ordinary nuclear matter to this state of deconfined quarks and gluons is supposed to happen at high temperatures in heavy colliding systems. Usually the multiplicities of Au+Au collisions or to a certain extent Cu+Cu collisions are needed to create a system which undergoes this transition. Given the much higher energies at the Large Hadron Collider the multiplicities in 7-14 TeV proton-proton collisions are even comparable to Cu+Cu collisions at the Relativistic Heavy Ion Collider. Since one expects at least a partially deconfined state in Cu+Cu collisions at an center-of-mass energy of 200 AGeV [1, 2, 3, 4, 5, 6] it might be possible to reach a phase of deconfined matter in p+p collisions at the LHC as well. During the RHIC program it has been shown that even heavy quarks (despite their high mass) experience a remarkable energy loss in the created medium.

Assuming a strongly interacting medium is created in high multiplicity proton-proton collisions then heavy mesons would be an ideal probe to verify the existence of a QGP in proton-proton collisions. If a deconfined plasma is created and the heavy quarks pass this plasma, the same strong interaction between plasma constituents and heavy quarks is expected which one has observed in RHIC heavy ion data (see e.g. [7, 8]), albeit on shorter length scales. If no plasma is created and all hadrons are created as color-neutral particles in the vacuum no modification is expected.

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In this study we show that high multiplicity proton-proton collisions feature a small, however non-negligible energy loss of heavy quarks. For our studies we use the model proposed in [10, 11, 12] and adjust it to proton-proton collisions at LHC. The original publication can be found in [13]. Since the conference contribution was based on this publication, the content of these proceedings is very similar.

This article is organized as follows: In section 2 the models which are used to calculate the underlying medium properties from the proton-proton collisions are described. We will then present the selection of high multiplicity proton-proton event within our theoretical framework. After that, we briefly review the elementary reactions that are the basis of our energy loss calculation. In section 3 the energy loss of heavy quarks in proton-proton collisions is discussed, section 4 presents possible experimental observables. The article ends with conclusions.

2. Modelling
As previous analyses have shown [14] there are at least two major contributions to the modelling of heavy quark energy loss. The description of the medium the heavy quarks propagate through and the interaction of the heavy quark with that medium. For this analysis, we split the description of the medium from the description of the heavy quark interaction with that medium (i.e. the light quarks and the gluons). The models we use are well tested against experimental data in their respective reach of physics.

The simulation of the proton-proton collisions is done via the EPOS model, which is successfully used from RHIC to LHC energies. EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings [18], where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases (unlike other models where energy conservation is not considered for cross section calculations [19]). A special feature is the explicit treatment of projectile and target remnants, leading to a very good description of baryon and antibaryon production as measured in proton-proton collisions at 158 GeV at CERN [20]. Nuclear effects related to Cronin transverse momentum broadening, parton saturation, and screening have been introduced into EPOS [21]. In heavy ion collisions (and more recently also in proton-proton collisions) collective behavior is taken into account [22], in the following fashion: the initial scatterings, as described above, lead to the formation of strings, which break into segments, usually identified with hadrons. When it comes to heavy ion collisions, the procedure is modified: one considers the situation at an early proper time $\tau_0$, long before the hadrons are formed: one distinguishes between string segments in dense areas (more than some critical density $\rho_0$ segments per unit volume), from those in low density areas. The high density areas are referred to as core, the low density areas as corona [22]. It is important to note that initial conditions from EPOS are based on strings, providing a flux-tube like structure in case of individual events (a single flux tube in case of many overlaid events, for a schematic view of a fluxtube we refer to Fig. 1 (left)). Based on the four-momenta of the string segments which constitute the core, we compute the energy density $\epsilon(\tau_0, \vec{x})$ and the flow velocity $\vec{v}(\tau_0, \vec{x})$. Having fixed the initial conditions, the system evolves according to the equations of ideal hydrodynamics.

While the notion of a hydrodynamical phase sounds unusual in proton-proton collisions the concept was successful in former studies [23]. The next step of the process is to select high multiplicity collisions. Those are selected by triggering on the number of elementary parton-parton collisions in the proton-proton collision itself. This can also be seen as the number of color fluxtubes formed in the collision. By using a fixed number of elementary collisions or fluxtubes (labeled in these proceedings as $\nu$) one has to deal with a distribution in multiplicity and impact parameter. Both of those distributions have a certain width, which is not necessarily accessible in experiments. It is possible however to calculate the mean of the distribution and compare those values. Shown in Fig. 1 (right) is the impact parameter distribution for two values of $\nu$. 


For $\nu = 5$ the average multiplicity of charged particles at mid-rapidity $dN_{ch}/dy|_{(y=0)}$ is 16.05, for collisions with $\nu = 10$ it equals 29.00. We are calculating the energy loss for matter with an energy density larger than 1.5 GeV/fm$^3$. Between 1.5 GeV/fm$^3$ and 0.4 GeV/fm$^3$ we are treating the matter as a so called mixed phase, with a reduced rate for reactions of heavy quarks with the medium. These values are in accordance with former hydrodynamical calculations applied to Au+Au reaction at RHIC. The impact of the hadronic phase has been checked and can be safely neglected. The interesting, possibly deconfined, phase is then roughly 2-3 fm in diameter (see e.g. [23].) It has been cross-checked that for smaller values of the number of elementary interactions (i.e. smaller $\nu$, on the order of 1-2, which corresponds to multiplicities below 10) the medium modification of heavy quarks vanishes.

The second, equally important step in modelling heavy quark energy loss is the interaction of the heavy quarks with the medium (for more details, see [14]). This is calculated within the MC@sHQ approach, which has been successfully used against RHIC and LHC data [12, 24]. These proceedings will only cover a small portion of the model’s features. The two major improvements in comparison to conventional pQCD inspired models are the inclusion of a running coupling constant and a proper matching of the infrared regulator of the gluon propagator to HTL calculations. These changes allowed to describe data in heavy ion collisions at RHIC within reasonable K-factors (K-factors account for higher order corrections in perturbative QCD calculations, which can only be estimated by comparing the theoretical calculation up to a certain order with experimental data). For a recent comparison to experimental data, we refer to [12]. In addition to collisional energy loss a radiative component to the energy loss is implemented. This is calculated as incoherent gluon bremsstrahlung pushing to its limit the idea that the gluon formation time is strongly reduced when the gluon is radiated off heavy quarks. For more information we refer to [12]. The probability of collisional or radiative energy lost per unit length for a 10 GeV c-quark is shown in Fig. 2 (left) as a function of energy. Collisional energy loss (dashed line) mostly consists of a large number of collisions in which the incoming heavy quark loses a small part of its energy, hence the pronounced peak at around zero in Fig. 2 (left). For radiative losses (solid line) the probability to lose a larger fraction of the heavy quark energy in a single process is more important.

To combine the description of the medium and the energy loss, we generate an averaged medium, i.e. an energy density profile with EPOS. Within this medium heavy quarks are gener-
3. Energy Loss of Charm Quarks

One major problem when trying to define the energy loss in high multiplicity proton-proton collisions is the lack of a proper reference. This role has usually been filled by proton-proton collisions, which in this study is the probed system as well. Theoretically the difference is well defined, since one can distinguish between a scenario with and without interaction (medium vs. vacuum). By calculating those two spectra and dividing them one gets a theoretically well-defined medium modification factor, which is displayed in Fig. 2 (right) for charm quarks. This is shown for two scenarios, once for $\nu = 5$ and $\nu = 10$, which corresponds to average multiplicities of $dN_{ch}/dy|_{(y=0)} = 16.05$ and 29 respectively. Depicted is a small, non-negligible energy loss of charm quarks at high $p_T$. This manifests itself in a suppression of roughly 10% at $p_T > 7$ GeV.

One should note that the suppression for $\nu = 5$ and $\nu = 10$ seem very similar. This originates from the fact that the heavy quark undergoes few interactions due to the generally small interaction zone. Once the energy density reaches a certain threshold the suppression sets in and the particles with high transverse momentum escape the high energy density zone rapidly. Thus the low $p_T$ part of the spectrum is affected more, which is in line with the observation in Fig. 2 (left). Here, a word of caution is necessary - additional initial state effects might shift the data in the opposite direction, also path-length dependencies as described in [25] are not taken into account in our calculation.

4. Experimental Observables

When trying to define experimental observables one faces the aforementioned problem that the investigated system has to serve as a reference system as well. The ratio...
\[
R_{HM/LM} = \frac{\frac{dN}{dpT_{HM}}}{\frac{dN}{dpT_{LM}}} = \frac{N_{HM}}{N_{LM}},
\]

might serve here as a intuitive observable, where the index HM denotes the spectrum extracted from high multiplicity events and LM the spectrum obtained from low multiplicity collisions. By triggering on low multiplicity collisions one can minimise or completely take out any potential medium effects.

The prediction for this observable is shown in Fig. 2 (right) as well (black, full line). It was obtained by dividing the high multiplicity sample with \( \nu = 10 \) by a calculation with a low multiplicity sample \( \nu = 1 \). Both calculations are scaled by their respective average multiplicities to take out trivial scaling effects.

Instead of a low multiplicity sample one could choose minimum bias data as well, since it is dominated by collisions producing a small number of particles. Although this might be more accessible to experiments, we suggest that a clear cut between low and high multiplicity collisions enhances the viability of this observable.

This ratio also depends on centrality and multiplicity respectively. This can be shown quantitatively by considering the observable

\[
R(z) = \frac{\left. \frac{dN}{dpT(N_{ch})} \right|_{pT>10\text{ GeV}}}{\langle \frac{dN}{dpT(MB)} \rangle} \times \frac{N_{MB}}{N_{ch}},
\]

where \( z = N_{ch}/\langle N_{ch} \rangle \) and \( N_{ch} \) denotes the number of charged particles in a certain centrality class and \( \langle N_{ch} \rangle \) the mean value from minimum bias (MB) data.

This observable can be evaluated within different centrality classes, thus different multiplicities and different \( z \).

Shown in Fig. 3 is a calculation of \( R(z) \) within our approach. One observes a decrease of roughly 10-15% with increasing centrality/multiplicity of the collision, which is in line with the expectation from the previous arguments.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Suppression at high transverse momentum of charm quarks as a function of the scaling variable \( z = \frac{N_{ch}}{N_{MB}} \). Shown are the medium calculations divided by the vacuum calculations averaged at values larger than 10 GeV in \( p_T \). Error bars are statistical only.}
\end{figure}
Conclusions
We have shown that high multiplicity proton-proton collisions exhibit a non-negligible energy loss for heavy quarks which could be studied experimentally. Fast charm quarks lose energy due to the interaction with the medium and thus are quenched. This effect amounts to roughly 10% at large transverse momentum. This might be experimentally observed by LHC experiments. Another insightful measurement would be the multiplicity dependent study of this quenching, which could lead to a clear measurement of the onset of deconfinement in such proton-proton collisions.

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