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Pôvabné a krásne vône kvarkovo-gluónovej prapolievky

Charm and beauty flavors of quark-gluon soup

Summary:

In this habilitation lecture heavy flavor production in ultra-relativistic heavy ion collisions is discussed. The experiment STAR at the Relativistic Heavy Ion Collider in Brookhaven National Laboratory enabled to study the properties of nuclear matter under conditions of high temperature and energy density, where the phase transition to a new state of matter, quark-gluon plasma was theoretically predicted. There are several experimental tools to uncover the characteristics of this matter. Heavy charm and beauty quarks are ideal probe, hence they are produced in early phase of the collision and therefore are sensitive to all phases of system evolution. The measurement of heavy quark production in p+p collisions is an important test of perturbative Quantum Chromodynamics calculations and also a baseline for heavy ion measurements. The measurements of heavy quark production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV energy showed that energy loss of charm quarks in quark-gluon plasma might be unexpectedly similar to energy loss of light quarks. The installation of the heavy flavor tracker sub-detector enabled to study heavy flavor meson production in more complex way.

Zhrnutie:

Hlavnou témou tejto habilitačnej prednášky je fyzika ťažkých kvarkov vytvorených v ultra-relativistických jadro-jadrových zrážkach. Urýchľovač RHIC (Relativistic Heavy Ion Collider) v Brookhavenskom národnom laboratóriu umožnil experimentálne skúmať vlastnosti jadrovej hmoty v podmienkach vysokej teploty a energetickej hustoty, za ktorých sa teoreticky predpovedá fazový prechod do nového stavu hmoty, kvarkovo-gluónovej plazmy. Je niekoľko exprimentálnych pozorovateľných, ktoré na popis tejto hmoty môžeme využiť. Kvarky s pôvabnou a krásnou vôňou sú ideálnou sondou, pretože sa tvoria v skorých fázach jadro-jadrovej zrážky, a sú preto citlivé na jednotlivé fázy vývoja systému. Meranie tvorby ťažkých kvarkov v protón-protónových zrážkach je dôležitým testom výpočtov kvantovej chromodynamiky v poruchovom režime a taktiež ako referencia pre merania v jadro-jadrových zrážkach. Meranie výťažku ťažkých kvarkov v zrážkach Au+Au pri energii $\sqrt{s_{NN}} = 200$ GeV ukázalo, že straty energie pôvabných kvarkov sú podobnej velkosti ako pre ľahké partóny. Ostatné merania z experimentu STAR, ktoré využívajú signály z nového detektora Heavy Flavor Tracker umožnujú komplexnejšie merania produkcie ťažkých kvarkov.

Klúčové slová:
zrážky ťažkých iónov, urýchľovače, kvarkovo-gluónová plazma, ťažké kvarky, STAR

Keywords:
heavy-ion collisions, accelerators, quark-gluon plasma, heavy quarks, STAR

Contents

Chapter 1

Introduction to quark-gluon plasma

When we look up at the sky with bare eyes during a clear night we can see about 3000-4000 stars. The stars are sources of photons, that travel long distances before they make a signal in our biological detector of the visible light - eye. A fascinating event of particle detection from our daily life. Most of these photons from the visible stars have to travel several dozens up to hundreds of years before they end up in our eye and our brain reconstructs the signal. Hence we are looking back in time. Some objects that we can see are significantly older. The galaxy M31 in Andromeda is as far as 2.5 million light-years away. With the proper instruments we can observe the light from even older events. The NASA space telescope Neil Gehrels Swift Observatory detected on April 23, 2009 a gamma-ray burst (GRB 090423) in the direction of the constellation Leo that lasts 10 s and is understood as a result of an explosion related to the formation of a black hole. This event is the earliest ever detected for which a spectroscopic redshift has been measured. The Universe was only 630 million years old when the light from GRB 090423 was emitted and it took more than 13 milliards years to travel to be observed. Ultra-relativistic heavy ion collisions enable to mimic conditions that existed much sooner, the first microseconds after Big Bang. At normal conditions matter consists of nucleons (neutrons, protons) and electrons. The nucleons have inner sub-structure and quarks and gluons are confined inside of them by a strong force. It is likely that matter at first moments of the Universe existed in a form of Quark-Gluon Plasma (QGP), where quarks and gluons were deconfined and could travel over distances much larger than the size of the nucleon. After the matter expanded and cooled down, it went through a phase transition to a confined phase. One of the recent tasks in modern nuclear and particle physics is to identify the structure and phases of such strongly interacting matter at extreme conditions of high temperature and high density.

In the first half of the 20th century the cosmic rays measurements showed the existence of many new particles. Later, particle accelerators enabled to study these particles in a systematic way. The first accelerator with energy of protons above GeV (eV is the unit of energy used in particle physics, 1 eV $\approx 1,6 \times 10^{-19}$ J) was a proton synchrotron Cosmotron at the Brookhaven National Laboratory. In an electron accelerator at the Stanford Linear Accelerator Center (SLAC), electrons were scattered on protons and neutrons and it was discovered that nucleons have substructure and consist from three point-like partons. There are two types of particles with substructure: hadrons - consisting from 3 quarks and mesons - consisting from a quark and an antiquark. The ordinary matter can be described with two lightest quarks: u (up), $m_u = 2,2^{+0,6}_{-0,4}$ MeV a d (down, $m_d = 4,7^{+0,5}_{-0,4}$ MeV) [1] and electrons. The composition of the proton is uud and of the neutron is ddu. In addition, we know four more quarks: s (strange, $m_s = 96^{+8}_{-4}$ MeV), c (charm, $m_c = 1,28 \pm 0,03$ GeV), b (beauty or bottom, $m_b = 4,18^{+0,04}_{-0,03}$ GeV) and t (top or true, $m_t = 173,1 \pm 0,6$ GeV). Altogether we have six quark flavors, each flavor is one quark type. In heavy ion physics we consider the charm and beauty flavors as the heavy flavors. Recently, in 2015 the LHCb experiment at the Large Hadron Collider at CERN has discovered the existence of pentaquarks $P_c^+(4450)$ a $P_c^+(4380)$, hadrons consisting from four quarks and one antiquark. In addition to quarks there are six leptons: electrons, muons, tauons and electron, muon and tauon neutrinos. These quarks and leptons interact among themselves with electromagnetic, strong and weak interaction (gravitation is negligible in particle physics). These interactions are mediated by calibration bosons: γ, gluons and W^+, W^-, Z^0. The strong force has an unusual property of a color confinement. Quarks are confined in hadrons and when we increase the energy in order to free them, a new quark-antiquark pair is created. Experimentally we can observe only color neutral hadrons as free particles.

The calculations of perturbative Quantum Chromodynamics, the theory of strong interaction, on the lattice show that at a critical temperature of $T_c \approx 160$ MeV (at a baryon chemical potential μ_b= 0 GeV) a gas of hadrons makes a phase transition to the quark-gluon plasma. In Fig. 1.1 an artistic view of several important stages of evolution of the nuclear matter after a heavy-ion collision is shown. It includes a short preequilibrium stage, quark-gluon plasma, hadron gas and free streaming of particles into detectors. In experiments we directly record signals from hadrons and leptons from the final phase and try to understand how the matter evolves through the stages and what are its properties in different phases, such as temperature, energy density and interactions of quarks and gluons.

In Fig. 1.2 there is a schematic visualization of the space-time evolution of hot and dense nuclear matter created after the ultra-relativistic heavy ion collision. First, the kinetic energy of incoming nuclei transforms into production of matter, quarks and gluons. During the initial preequilibrium phase ($\tau_0 \approx$1 fm/c) real partons are formed from virtual quanta. These partons interact and equilibrate in the quark-gluon plasma. The QGP expands and cools down.

The extraction of QGP properties is the main focus of the heavy-ion program. The phase of QGP lasts about 10 fm/c ($\approx 3 \times 10^{-23}$s). From the measurements of direct photons we could extract the temperature of QGP to be more than 500 MeV at the energies accessible at the Relativistic Heavy Ion Collider (RHIC). When the

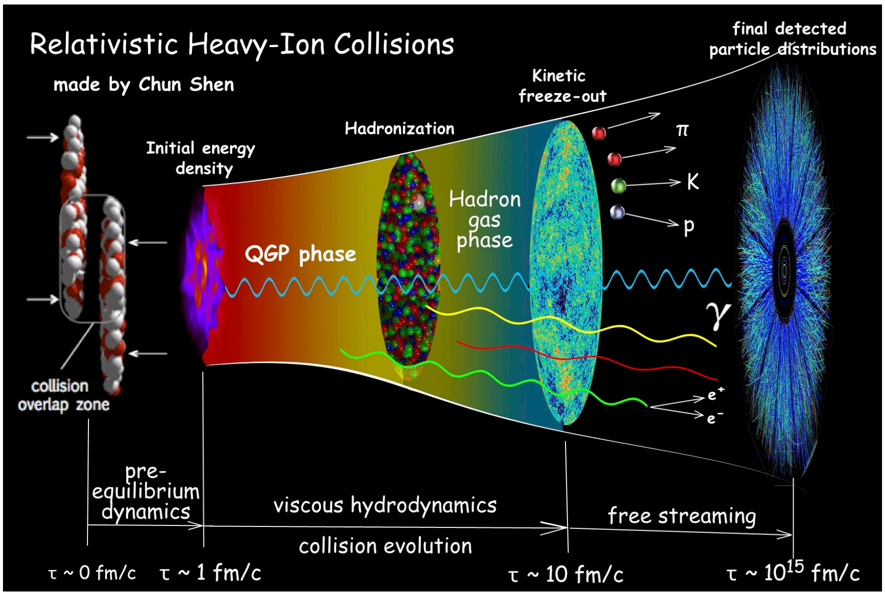

Figure 1.1: An artistic visualization of ultrarelativic heavy-ion collision. The evolution of the nuclear matter after the collision includes several stages: short pre-equilibrium, quark-gluon plasma, hadron gas, free streaming of particles into detectors.

temperature drops under T_c, the phase transition to hadron gas occurs. The quarks and gluons become confined in hadrons. In this phase hadrons further elastically and inelastically interact until the moment of a chemical freeze-out at T_{ch}. At this moment the hadron ratios are fixed and only elastic collisions take place afterwards, till the moment of a thermal freeze-out at T_{fo}. After this moment particles free stream to detectors. Particles with a short lifetime might decay before they reach the detectors and thus have to be reconstructed from their decay products. In the detectors we typically detect charged pions, kaons, protons, electrons, muons, and their antiparticles as well as γ.

The experimental studies of heavy-ion collisions started in the year 1986 at CERN at the SPS accelerator with ^{16}O + ^{208}Pb collisions and at Brookhaven National Laboratory at the AGS accelerator with ^{16}O + ^{197}Au collisions. Both laboratories are currently actively studying the QGP properties at their new facilities. In BNL, the STAR experiment at RHIC is the only active experiment still taking data. It is expected that STAR will collect data up to 2023. A next experiment, sPHENIX, is under construction at RHIC to take data in 2022-2023. At CERN, there are four experiments at the Large Hadron Collider (LHC) having heavy-ion program: ALICE, ATLAS, CMS and LHCb. Already the experimental program at the SPS showed a compelling evidence for the existence of QGP observing several phenomena in central collisions consistent with the existence of the QGP [2]. The central collisions are those with a small value of an impact parameter. Usually we quantify the number of percent of the most central collisions, e.g. 0-10% centrality. At the SPS it was observed

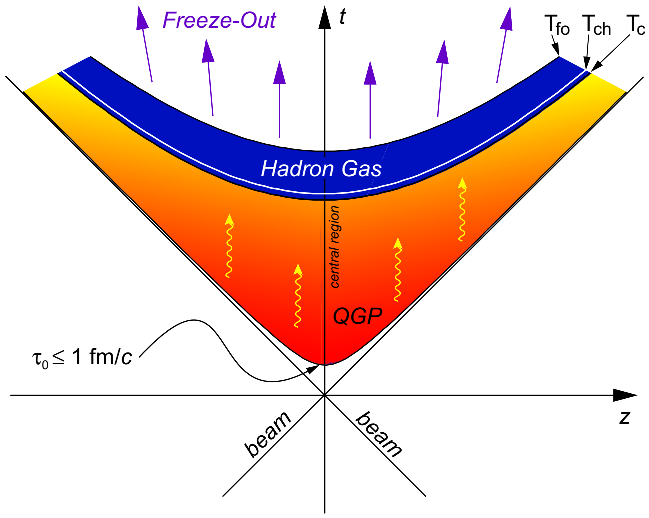

Figure 1.2: A schematic space-time evolution of a heavy-ion collision. After QGP formation the nuclear matter expands and cools down and undergos a phase transition to hadron gas at T_c. Hadrons further interact and system chemically and thermaly freezes-out at T_{ch} a T_{fo}.

that production of strange baryons is enhanced with respect to p + p collisions at the same energy due to quark and gluon interactions at high gluon density. Another observed signature was an anomalous suppression of J/ψ meson production beyond the cold nuclear matter effects, due to color screening of binding di-quark potential at high temperature and high energy density. The RHIC accelerator started to produce data in the year 2000 and the experiments STAR, PHENIX, PHOBOS and BRAHMS quickly discovered additional unexpected phenomena. It was found that the matter created in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV energy is opaque for high energetic partons, that are formed at early stages of the collisions in hard parton scatterings. This phenomenon is known as jet quenching and it is a consequence of parton energy loss due to interactions of quarks and gluons in QGP. Another surprise was the observation that the QGP has collective behavior and can be described by hydrodynamic models of an ideal liquid with a very low shear viscosity over entropy ratio $\frac{\eta}{s}$. One of the important quantities to evaluate the influence of nuclear matter in particle production is a nuclear modification factor R_{AA}. It is a ratio of the particle production in heavy-ion collisions and proton-proton collisions, scaled by an average number of individual binary nucleon-nucleon collisions ($\langle N_{bin} \rangle$) in heavy-ion collisions. If there would be no difference in particle production between Au+Au and proton-proton collisions, the value of the R_{AA} would be around one for particles with a high transverse momentum p_T. These high-p_T particles are from above mentioned hard processes. Majority of particles is produced with $p_T < 2$ GeV/c in soft processes during QGP evolution. In Fig. 1.3 a compilation of the measurements of R_{AA} for various particles as a function of p_T extracted from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV energy [3] by the PHENIX experiment is presented. For direct γ produced in the QGP is $R_{AA} \approx 1$. Photons do not interact strongly and their production is therefore not modified. However the production of other particles at high-p_T above 2 - 4 GeV/c is suppressed. For example the production of π^0 is suppressed by a factor of 5, $R_{AA} \approx 0.2$ as a consequence of jet quenching.

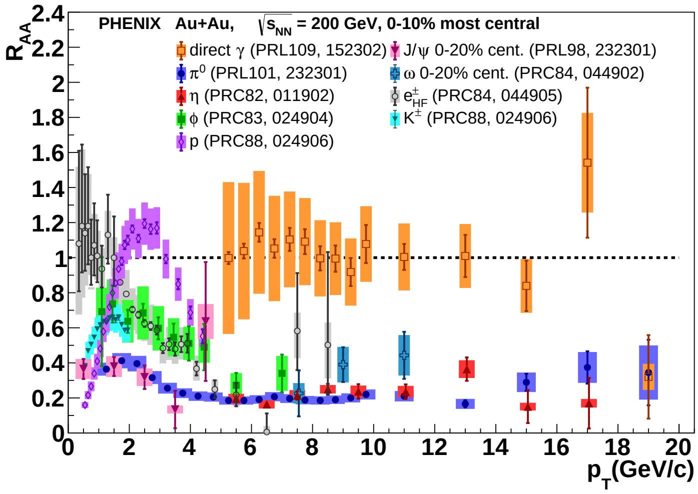

Figure 1.3: The measurements of R_{AA} for direct $\gamma, \pi^0, \eta, \phi, \omega, K^{\pm}, e^{\pm}$ from heavy flavor mesons decays, J/ψ and protons as a function of p_T measured by the PHENIX experiment for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Taken from Ref. [3].

The critical assessment of the first five years of the STAR measurements at RHIC was summarized in a white paper [4]. In addition to insightful studies of the QGP properties, STAR has contributed also with other unexpected discoveries of general interest. It was a first experimental measurement of anti-hypertriton [5] (Science 328 (2010) 58), the bound state of an anti-neutron, anti-proton and anti-lambda. In addition, it was a measurement of the heaviest so far produced anti-nuclei - anti-helium [6] (Nature 473 (2011) 353). We have also found out that the interaction between anti-protons is attractive [7] (Nature 527 (2015) 345). From the measurements of global polarization of Λ hyperon we have indirectly found out that the QGP has also an extreme value of vorticity $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$ in non-central collisions [8] (Nature 548 (2017) 62).

Recent studies at the LHC related to collective behavior of the QGP such as an elliptic flow and two-particle correlations revealed that even in those proton-proton collisions and p+Pb collisions that have a large multiplicity of produced particles we can observe collectivity [9]. This is an example that the properties of QGP are still not completely understood and has to be further studied. The experimental program at RHIC will focus to study the phenomena related to the onset of the QGP signatures.

Chapter 2

Open heavy flavor mesons in proton-proton collisions

In a typical central Au+Au collision at the RHIC colliding energy of $\sqrt{s_{NN}} = 200$ GeV there is up to about 4000 charged hadrons produced. Most of them are pions consisting from light u and d quarks. During the collision also a significant number of s quarks is created. However, the production of heavy quarks such as charm c and beauty b is rather rare due to their large mass. These heavy quarks are dominantly produced in the initial phase of the heavy-ion collision in hard gluon-gluon scatterings [10]. This makes them an interesting probe of the QGP, as they are sensitive to all later stages of the system evolution. Due to large masses of heavy quarks it is possible to calculate their production in a perturbative QCD and compare the calculations to the measurements of the heavy flavor production in proton-proton collisions. We can not observe the quarks directly therefore we have to rely on the measurements of hadrons that contain these quarks. From the LEP experiment measurements we know that the fragmentation fractions of the c quark into charm hadrons are $c \rightarrow D^0$ about 54%, $c \rightarrow D^{\pm}$ about 23%, $c \rightarrow D_s^{\pm}$ about 9% and $c \rightarrow \Lambda_c^{\pm}$ about 5%. These charm hadrons decay weakly, flavor of the quark has to be changed, and therefore they have a rather long lifetime of about $10^{-15} - 10^{-14}$ s and they decay outside of the interaction region at about 100 μm distance in a so-called secondary vertex. From the experimental point of view it is important to use this property as a selection criterion when looking for charm hadron candidates in data. There are two types of decays used to identify D mesons. One possibility is to identify all daughter particles from the hadron decay, e.g. K and π from $D^0(\overline{D^0}) \rightarrow K^{\mp} + \pi^{\pm}$ decay. This decay has a branching ratio of BR = 3,89 %. Here the most critical task is to reduce random K and π pairs with their invariant mass to be close to the D^0 mass. Another possibility is to reconstruct electrons from semi-leptonic decays, $D^0 \rightarrow K^- + e^+ + \nu_e$. Here the complication is that we do not reconstruct all decay products and we measure the continuum distribution of electrons and therefore the most critical part is to remove the electrons from other decays. The advantage of the semi-leptonic decay is that we can also measure the electrons from B meson decays.

The STAR detector at RHIC is an excellent instrument to explore heavy-ion collisions. It has a large geometrical acceptance to detect products of these collisions. The most relevant detector sub-systems for heavy flavor physics are the Time Projection Chamber (TPC), Time of Flight detector (TOF), Barrel Electromagnetic Calorimeter (BEMC) and Heavy Flavor Tracker (HFT). The role of the TPC is a particle track reconstruction, momentum determination and particle identification based on a specific energy loss of charged particles in active gas of the detector. In the TOF detector we can further identify K and π by measuring their time of flight from the collision vertex. The BEMC detector is important for the electron measurements, it can discriminate electrons from hadrons by measuring their deposited energy in the calorimeter. The HFT detector was installed in STAR for the measurements in years 2014 up to 2016. It is composed of three different silicon detectors arranged in four concentric cylinders close to the STAR interaction point. The two inner-most layers are based on CMOS monolithic active pixels, featured for the first time in a collider experiment, while the two outer layers are based on pads and strips. The HFT has excellent distance of closest approach (DCA) resolution for tracks found in the TPC. E.g. for kaons with p_T larger than 1.5 GeV/c , the DCA resolution is better than 30 μm. The schematic view of the STAR detector is shown in Fig. 2.1.

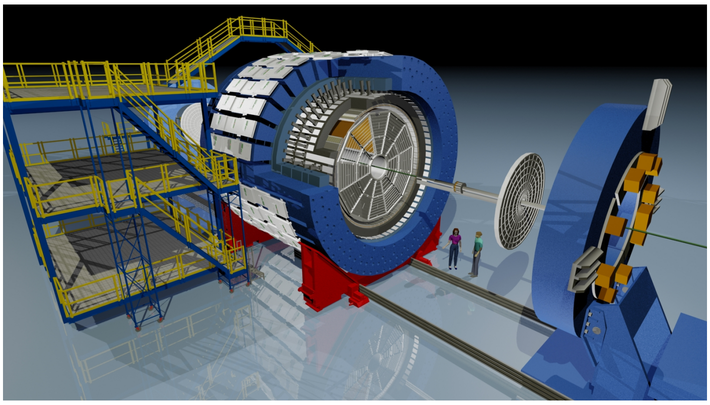

Figure 2.1: A schematic view of the STAR detector. STAR consists of several sub-detectors. The main one, the central time projection chamber is surrounded by the time of flight detector and electromagnetic calorimeter. These detectors are placed in magnetic field.

The first question in heavy flavor program in STAR we tried to address was whether the production of heavy flavors is well understood in proton-proton collisions at RHIC. We have studied electrons from semi-leptonic decays in Ref. [11]. We have measured electron spectra from D, B decays in a large p_T range $1, 2 \ < p_T < 10$ GeV/c . We compared them with the calculations from the Fixed Order Next-to-Leading Log (FONLL) pQCD [12]. In the year 2008 the STAR detector set up changed and more precise measurement of electrons was possible [13]. We have found out that pQCD calculations can describe the electrons from semi-leptonic heavy flavor decays well. The calculations from pQCD show that at $p_T \approx 5$ GeV/c the contribution of beauty decays starts to dominate over charm contribution. In Ref. [14] we could separate both contributions in the data and confirmed the pQCD predictions of relative B contribution $\frac{e_B}{e_B+e_D}$. Once the TOF was fully installed we could also reconstruct D mesons from hadron decays. We have analyzed p + p data at two energies, $\sqrt{s}$= 200 GeV and $\sqrt{s}$= 500 GeV. We could extract D^0 yield in p_T = 0,6 - 2 GeV/c and $D^{*\pm}$ in p_T = 2 - 6 GeV/c range for the 200 GeV collision energy.

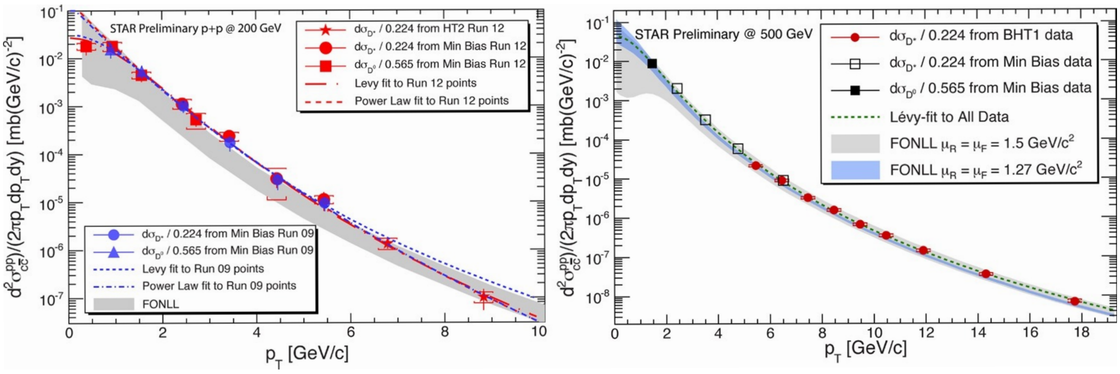

Figure 2.2: The dependence of the differential cross section of $c\bar{c}$ production on p_T for $D^{*\pm}$ a D^0 in p + p collisions at $\sqrt{s}$= 200 GeV (left) and $\sqrt{s}$= 500 GeV (right). The color regions are calculations from the FONLL pQCD [12].

In the 500 GeV p + p data set we could even extend the p_T reach up to 20 GeV/c due to improvements in the analysis methods that enabled us to include also data with a special trigger. From the data we could extract the total charm production cross section in p + p collisions at $\sqrt{s}$= 200 GeV. The value is $\sigma_{c\bar{c}} = 797 \pm 210$ (stat.)$^{+208}_{-295}$ (sys.) μb. In Fig. 2.2 the measured spectra are compared with the FONLL pQCD calculations [12]. The measured spectra and the calculations are consistent within the uncertainties.

With this we have answered the first question of the RHIC heavy flavor program and we found out that the production of charm mesons in proton-proton collisions is well understood and pp is a good reference for heavy-ion measurements.

Chapter 3

Open heavy flavor mesons in heavy-ion collisions

The jet quenching that was observed in central nucleus-nucleus collisions is a consequence of light parton energy loss while traversing through the quark-gluon plasma. The question that was raised in the beginning of the RHIC experimental program was about the energy loss of heavy quarks. The initial theoretical calculations of radiative energy loss of heavy quarks predicted that their energy loss will be smaller than that of light quarks and gluons [15]. The expected difference was attributed to a dead-cone effect, mass dependent suppression of gluon radiation off heavy quarks under small angles with respect to the direction of the movement of the heavy quark [16]. Experimentally this should lead to hierarchy in the suppression of high-p_T production of B, D and π mesons. The suppression of B mesons would be the smallest, the suppression of D mesons stronger and the suppression of π mesons the largest [17]. The measurement of heavy flavor production in heavy-ion collisions is another probe of the properties of the hot and dense nuclear matter. The successful model of the nuclear matter should be able to simultaneously describe the suppression of B, D and π mesons and their elliptic flow. One of the very fundamental parameters characterizing the QCD matter is a diffusion parameter of heavy quarks, D_s. The heavy flavor measurements at the LHC showed that the value of this parameter at LHC energies is less than $D_s(2\pi T) = 6$ [18]. The value of this parameter at RHIC energies might be different. In order to find answers to all these questions we performed the analysis of the data with an aim to study heavy flavor production in both hadron as well as in semi-leptonic decay channels in Au+Au collisions. In the semi-leptonic decay channel we were able to extract electrons from the decays of the heavy flavor mesons up to $p_T \approx 8$ GeV/c [11]. The yields of electrons from other sources were rather high, the value of the ratio of total number of electrons to background electrons was about 1.1 - 1.3. Therefore it was very important to properly subtract the background electrons. The method of subtraction used the fact that electron-positron pairs from γ conversions have close to zero invariant mass of the pair. We could reconstruct a part of the background from the data and determine efficiency of this reconstruction based on Monte-Carlo simulation. After the extraction of corrected yields of electrons from D, B decays we have constructed the nuclear modification factor and we found out that the lowest value of R_{AA} is $\approx$ 0,2 - 0,3 for $p_T >$ 0,3 GeV/c [11] in most central collisions. The level of this suppression is similar to the suppression of pions. From a comparison of our results with models we found out that models that include besides radiative energy loss, also collisional energy loss tend to describe the data better.

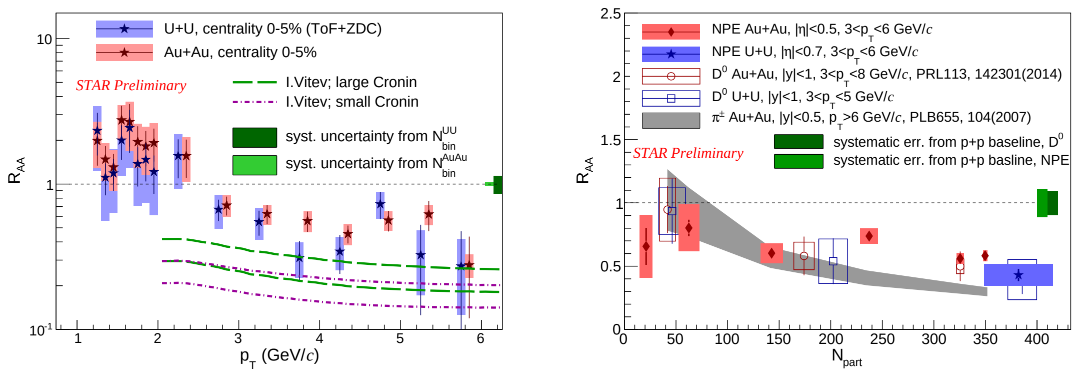

Figure 3.1: Left: A preliminary measurement of the nuclear modification factor of electrons from heavy flavor decays in 0-5% most central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV. Experimental data are compared with models from Ref. [19]. Right: A preliminary measurement of the nuclear modification factor as a function of the average number of collision participants for electrons from heavy flavor decays, D^0 a $\pi^{\pm}$ mesons.

At RHIC we also measured data in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV in order to reach higher energy density of nuclear matter. We have also in this data set extracted yield of electrons from heavy flavor meson decays. In Fig. 3.1 (left) we can see a comparison of the nuclear modification factor as a function of p_T for the most central U+U and Au+Au collisions. The level of suppression in both collision systems is similar. In more central collisions there are more participating nucleons in the collision. In Fig. 3.1 (right) the nuclear modification factor is shown as a function of the averaged number of participants in the collision for electrons, D^0 and $\pi^{\pm}$ mesons with $p_T >$ 3 GeV/c ($p_T >$ 6 GeV/c). It can be seen that the suppression increases for all particle species with increasing centrality. Although $\pi^{\pm}$ might be more suppressed than other particles in Fig. 3.1 within the uncertainties the suppression is overall the same.

As it was mentioned in the previous chapter the most direct way to study the charm quarks is to measure production of charm hadrons. We were able to reconstruct D^0 mesons also in Au+Au collisions without the HFT detector from the data taken in the years 2010/2011 [20]. With the help of the HFT detector signals we could apply the topological cuts to suppress the background of random combinations in the signal region. We obtained more precise measurements of D^0 and in addition we could also

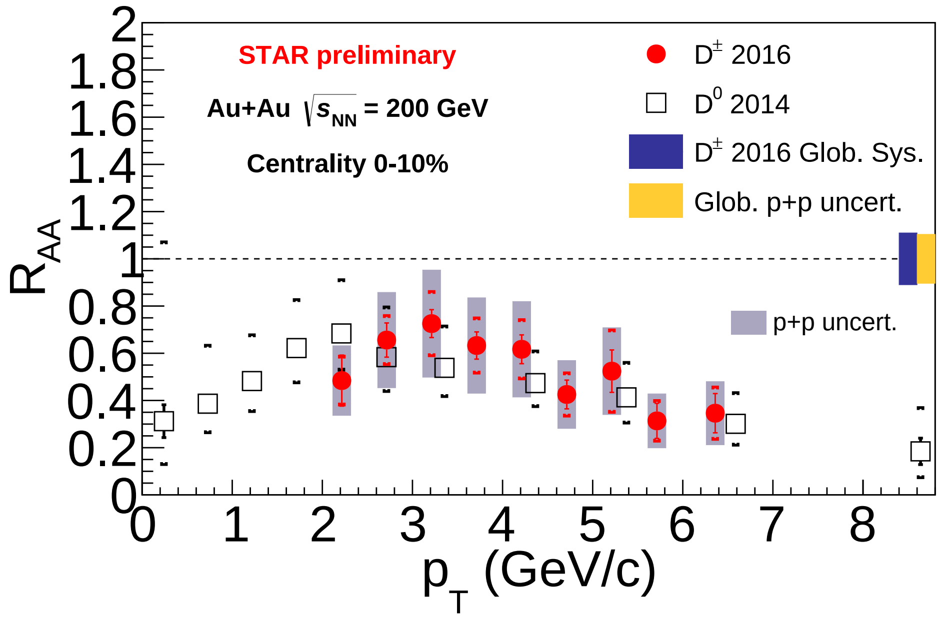

Figure 3.2: The nuclear modification factor of $D^{\pm}$ a D^0 measured in 0-10% most central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR experiment.

reconstruct $D^{\pm}$ meson. The nuclear modification factor from all these measurements is shown in Fig. 3.2. We can see that both D^0 as well as $D^{\pm}$ meson production is suppressed at high-p_T . The level of the suppression is similar to that of pions. Even more precise measurement will be possible when the results from the year 2014 and year 2016 data sets will be combined. In Ref. [21] we have shown that the current STAR results are consistent with the heavy quark diffusion parameter $D_s(2\pi T)$ = 2 - 12 [21].

The experiments at the LHC due to larger collision energy and therefore larger charm and beauty production could provide more precise measurement of flavor dependence of energy loss. In the experiment CMS at the LHC it was possible for the first time to reconstruct B mesons directly via hadron decay channel $B^{\pm} \rightarrow J/\psi\ + K^{\pm}$ in p + p and Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5,02 TeV energy [22]. The value of the nuclear modification factor was from 0.3 to 0.6 for the range of p_T from 7 to 50 GeV/c . When compared to D mesons, the suppression of B mesons is smaller. However, the precision of the data makes the conclusion ambiguous.

It has to be noted that phenomenological development is still ongoing. It is very challenging to provide complete description of both light and heavy flavor production at the LHC and at RHIC, not only for the R_{AA} observable but also for parameters of collectivity such as elliptic flow [23].

Chapter 4

Conclusions

In this habilitation lecture selected measurements of heavy flavor production in proton-proton and Au+Au collisions carried out by the STAR experiment at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory in the USA are discussed. The main motivation is to extract the properties of the new state of matter, created in the central ultra-relativistic heavy-ion collisions, the quark-gluon plasma. The heavy quarks are produced in the initial phase of the collision and they are sensitive to all stages of system evolution. It was found that the measurements of heavy flavor production in proton-proton collisions are consistent with perturbative QCD calculations. The measurements in central Au+Au collisions showed that the energy loss of heavy quarks in hot and dense nuclear matter might be unexpectedly of the similar level as in the case of light quarks at RHIC. The more precise measurements are possible with newly installed heavy flavor tracked detector. In near future the STAR experiment will study onset of various QGP signatures.

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Publications:
Web of Science: 388 publications, 2237 citations, h-index=52

Selected publications:

1. Adamczyk, L. et al., *Global Λ hyperon polarization in nuclear collisions*, Nature 548, 62 (2017)
2. Adamczyk, L. et al., *Measurement of interaction between antiprotons*, Nature 527(2015) 353
3. Agakishiev, H. et al., *Observation of the antimatter helium-4 nucleus*, Nature 473 (2011) 353
4. Adamczyk, L et al., *Observation of D^0 Meson Nuclear Modifications in Au+Au Collisions at 200 GeV*, Phys. Rev. Lett. 113, 142301 (2014)
5. Adamczyk, L et al., *Beam Energy Dependence of Moments of the Net-Charge Multiplicity Distributions in Au plus Au Collisions at RHIC*, Phys. Rev. Lett. 113, 092301 (2014)
6. Adamczyk, L et al., *Measurement of J/ψ Azimuthal Anisotropy in Au+Au Collisions at 200 GeV*, Phys. Rev. Lett. 111 052301 (2013)
7. Adamczyk, L. et al., *Measurements of D^0 and D^* production in p plus p collisions at 200 GeV*, Phys. Rev. D86, 072013 (2012)
8. Agakishiev, H. et al., *High p_T nonphotonic electron production in $p + p$ collisions at 200 GeV*, Phys. Rev. D 83, 052006 (2011)