Analysis of reaction dynamics at RHIC in a combined parton/hadron transport approach

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Abstract

We introduce a transport approach which combines partonic and hadronic degrees of freedom on an equal footing and discuss the resulting reaction dynamics. The initial parton dynamics is modeled in the framework of the parton cascade model, hadronization is performed via a cluster hadronization model and configuration space coalescence, and the hadronic phase is described by a microscopic hadronic transport approach. The resulting reaction dynamics indicates a strong influence of hadronic rescattering on the space-time pattern of hadronic freeze-out and on the shape of transverse mass spectra. Freeze-out times and transverse radii increase by factors of $2-3$ depending on the hadron species.

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Ultra-relativistic heavy ion collisions offer the unique opportunity to probe highly excited dense nuclear matter under controlled laboratory conditions and probably recreate a Quark Gluon Plasma (QGP), the highly excited state of primordial matter which is believed to have existed shortly after the creation of the universe in the Big Bang (for recent reviews on the QGP, we refer to [1,2]).

While there is currently a strong debate whether deconfined matter may have been produced at the CERN/SPS, it is widely expected that in collisions of heavy nuclei at RHIC a QGP will be formed. However, the deconfined quanta of a QGP are not directly observable because of the fundamental confining property of the physical QCD vacuum. What is observable are hadronic and leptonic residues of the transient QGP state.

Transport theory has been among the most successful approaches applied to the theoretical investigation of relativistic heavy ion collisions. Microscopic transport models attempt to describe the full time-evolution from the initial state of the heavy ion reaction (i.e. the two colliding nuclei) up to the freeze-out of all initial and produced particles after the reaction. The consequence for the RHIC energy domain is that both, partonic and hadronic, degrees of freedom have to be treated explicitly.

In this letter we introduce a transport approach which combines partonic and hadronic degrees of freedom on an equal footing and discuss the resulting reaction dynamics. In terms of physics concepts the time evolution of the heavy ion collision can be subdivided into three reaction stages: partonic evolution, hadronization and hadronic evolution/freeze-out.

The initial partonic stage of the reaction is modeled according to the Parton Cascade Model (PCM) [3,4]: The nucleons of the colliding nuclei are resolved into their parton substructure according to the measured nucleon structure functions and yield the initial parton distributions. Parton interactions as described by perturbative QCD are used to model the evolution of the ensemble of partons during the high energy density phase of the collision.

To model hadronization, an effective QCD field theory [5] which fully describes the parton dynamics including the formation of *preconfined* clusters is introduced. Color singlet states are then formed via a configuration space coalescence and a cluster ansatz [6,7].

For the hadronic phase of the collision a microscopic transport approach is employed [8–11], containing string- and hadronic degrees of freedom. All hadronic states can be produced in string decays, t-channel excitations, s-channel collisions or resonance decays. Tabulated or parameterized experimental cross sections are used when available. Resonance absorption and scattering is handled via the principle of detailed balance.

Note that our approach does not include any parton-hadron interactions: partons first hadronize when they cease to interact on a partonic level. Therefore the newly formed hadronic states do not exert any pressure on the partons and hadronization occurs as a unidirectional non-equilibrium process.

The technical realization of our approach uses the framework of VNI [12][1], both for the parton cascade model, as well as for the hadronization scheme. The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [11,13] is employed for the hadronic transport, decays and rescattering. The UrQMD model has been extensively tested in the SIS, AGS and SPS energy domain [11], it provides a robust description of hadronic heavy-ion physics phenomenology.

Let us now turn to the reaction dynamics of central (impact parameter $b \leq 1$ fm) Au+Au collisions at RHIC energies ($\sqrt{s} = 200$ GeV per incident colliding nucleon-pair): The initial reaction stage in VNI is dominated by the formation of a dense partonic state. Rapid thermalization is caused in VNI by radiative energy degradation and spatial separation of partons with widely different rapidities due to free streaming – at RHIC, thermalization is predicted on a proper time scale of approximately 1 fm/c [14]. The thermalized QGP is initially gluon rich and depleted of quarks due to the larger cross section and higher branching ratios for gluons [15]. The expansion then of course triggers the onset of hadronization, leading to a phase in which partonic and hadronic degrees of freedom [16] coexist.

Starting point of our analysis is the time evolution (in c.m. time, $t_{c.m.}$) of the rapidity density dN/dy of partons (i.e. quarks and gluons) and on-shell hadron multiplicities at $|y_{c.m.}| \leq 0.5$, depicted in the upper frame of figure 1. Note that there are no distinctly separate time scales for the three reactions stages discussed earlier in this article: hadronic and partonic phases may evolve in parallel and both, parton-parton as well as hadron-hadron interactions occur in the same space-time volume. The overlap between the partonic and hadronic stages of the reaction stretches from $t_{c.m.} \approx 1$ fm/c up to $t_{c.m.} \approx 4$ fm/c for the midrapidity region. Our analysis shows that this overlap occurs not only in time but also in coordinate space – partonic and hadronic degrees of freedom occupy the same space-time volume during this reaction phase. Hadronic resonances like the $\Delta(1232)$ and the $\rho(770)$ (which are the most abundantly produced baryonic and mesonic resonance states) are formed and remain populated up to $t_{c.m.} \approx 15 - 20$ fm/c, indicating a considerable amount of hadronic rescattering. Hadron yields saturate at time-scales $t_{c.m.} \approx 25$ fm/c. Since resonance decays have not been factored into this estimate of the saturation time, this number should be viewed as an upper estimate for the time of chemical freeze-out.

Rates for hadron-hadron collisions per unit rapidity at $y_{c.m.}$ are shown in the lower frame of figure 1, i.e. all hadron-hadron collisions for hadrons with $|y_{c.m.}| \leq 0.5$ were taken into account. Meson-meson and meson-baryon interactions dominate the dynamics of the hadronic phase. Due to their larger cross sections baryon-antibaryon collisions occur more frequently than baryon-baryon interactions. However, both are suppressed as compared to

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[1]the current version of VNI, 4.12, contains an erroneous rescaling of partons in coordinate space to the light-cone located at the origin of the computational coordinate system instead of that defined by the respective production vertex of the parton. This erroneous rescaling has been removed for our calculations.

meson-meson and meson-baryon interactions. This is due to the large meson multiplicity, which creates a "mesonic medium" in which the baryons propagate.

A comparison of calculations with and without hadronic rescattering shows that e.g. the proton and antiproton multiplicities change by a factor of two due to hadronic rescattering, whereas the ratio of their yields remains roughly constant. Evidently chemical freeze-out of the system occurs well into the hadronic phase and not at the "phase-boundary". The collision rates indicate that interactions cease at $t_{c.m.} \approx 30 - 40$ fm/c at which point the system can be regarded as kinetically frozen out. Since the saturation of the hadron yields occurs earlier, there is a clear separation between chemical and kinetic freeze-out.

Figure 2 shows freeze-out time t_f and transverse radius r_t, $\mathrm{d}^2N/(r_t\mathrm{d}r_t\mathrm{d}t_f)$, for pions (left column) and protons (right column). The top row shows the result of parton cascading, hadronization and hadronic decays, but without hadronic reinteraction, whereas the lower row shows the same calculation with full hadronic dynamics. The contour lines have identical binning within each column, but differ between the two columns. Obviously hadronic interactions have an enormous effect on the freeze-out:

The average freeze-out time for protons increases tenfold from 3.2 fm/c without hadronic rescattering to 27.4 fm/c with hadronic rescattering. The average transverse proton freeze-out radius increases from 3.6 fm to 13 fm.

For pions t_f increases from 6.3 fm/c to 18.6 fm/c and r_t from 5.6 fm to 9.6 fm!

Also, the overall shape of the distributions varies drastically: without hadronic rescattering, the emission of pions and particularly protons is more strongly restricted to the light-cone than with rescattering. This may give rise to the speculation that HBT interferometry may indicate a surface-like emission pattern in the case of negligible hadronic reinteraction and a bulk-like emission pattern in the case of strong hadronic reinteraction. In the proton $\mathrm{d}^2N/(r_t\mathrm{d}r_t\mathrm{d}t_f)$ distribution hadronic rescattering effects also manifest themselves through a second maximum at $t_{c.m.} \approx 25$ fm/c. It should be noted, however, that even in the case of full hadronic rescattering, approximately 15% of protons and pions still freeze out directly after hadronization without any hadronic (re)interaction or decay at all.

In contrast to the physics at the SIS and AGS, where (vector-)mesons propagate in a dense baryonic environment (allowing e.g. for a search for the onset of chiral symmetry restoration), the situation at RHIC is reversed: here the baryons propagate in a mesonic medium. Therefore we shall now focus on the dynamics of baryons in the intermediate and late reaction stages: Figure 3 shows the collision number distribution for protons and hyperons around midrapidity. The collision number distribution shows a very slow decrease from $N_{coll} \approx 5$ to $N_{coll} \approx 17$, before falling off roughly exponentially. Approximately 15% of the protons and 6% of the hyperons do not rescatter at all. However, on average protons rescatter 14 and hyperons 15 times. Baryonic rescattering is dominated (to 99%) by meson-baryon interactions – roughly 1/3 of those are elastic scatterings, 1/3 lead to the excitation of a discrete baryon resonance state with a resonance-mass below 2.2 GeV and 1/3 lead to the excitation of a state in the high-mass resonance continuum with masses above 2.2 GeV. The rather small fraction of elastic scatterings serves as an indication that the system does

not fully thermalize in the course of the reaction.

This massive hadronic rescattering does *not only* lead to changes in the freeze-out space-time distribution, but it also influences the momentum distributions of the baryons: Figure 4 shows the $dN/m_t dm_t$-spectra for nucleons around midrapidity. The circles denote nucleons which have not rescattered after hadronization, whereas the squares refer to nucleons which have rescattered at least 4 times. The respective m_t slope decrease by roughly 25% from $T_{N_c=0} = 350$ MeV to $T_{N_c \geq 4} = 270$ MeV, thus indicating a softening of the protons in the mesonic medium via rescattering. This softening is quite surprising since other microscopic calculations at CERN/SPS and even RHIC energies in the framework UrQMD [18] and hybrid macro/microscopical [19] models find massive rescattering leading to an additional build-up of radial flow and a respective increase in the m_t slope.

The effects of hadronic reinteraction on the predictions of perturbative QCD based transport descriptions [12,17] have also been investigated in [16,20,21]. In [16,21] the analysis was focused strongly on the influence of hadronic rescattering on inclusive hadronic spectra, whereas in [20] the partonic phase was not implemented in a fully microscopic fashion. In contrast to [16,20,21], here we have carried out an in-depth analysis of the underlying reaction dynamics in the framework of a combined microscopic parton/hadron transport approach. Our results show that a radial flow analysis of hadrons and HBT correlation measurements may be best suited to experimentally estimate the importance of hadronic reinteractions at RHIC. A detailed analysis of these experimentally accessible phenomena is in preparation [22].

In summary, we have introduced a novel transport approach combining partonic and hadronic degrees of freedom and discussed the resulting reaction dynamics. At midrapidity partonic and hadronic degrees of freedom coexist between $t_{c.m.} \approx 1$ fm/c and $t_{c.m.} \approx 5$ fm/c in which numerous parton-parton and hadron-hadron interactions take place. There exists no spatial separation between the partonic and hadronic interaction regions. The space-time pattern of particle freeze-out is strongly modified by hadronic rescattering. Freeze-out times and transverse radii increase by factors of $2-3$ depending on the hadron species. Massive rescattering of baryons in a highly excited meson gas is observed, even though roughly 10% of the baryons do not rescatter at all and are directly emitted after hadronization. The rescattering also leads to a considerable softening in the baryon spectra.

REFERENCES

[1] J. Harris and B. Müller, Ann. Rev. Nucl. Part. Sci. **46** (1996) 71.

[2] S.A. Bass, M. Gyulassy, H. Stöcker and W. Greiner, J. Phys. **G25** (1999) R1, hep-ph/9810281.

[3] K. Geiger and B. Müller, Nucl. Phys. **B369** (1992) 600.

[4] K. Geiger, Phys. Rep. **258** (1995) 237.

[5] J. Ellis and K. Geiger, Phys. Rev. **D52** (1995) 1500.

[6] K. Geiger, Phys. Rev. **D47** (1993) 133.

[7] B. R. Webber, Nucl. Phys. **B238** (1994) 492.

[8] G. Peilert, A. Rosenhauer, H. Stöcker, W. Greiner, and J. Aichelin, Modern Physics Letters **A3** (1988) 459.

[9] J. Aichelin, Phys. Rep. **202** (1991) 233.

[10] H. Sorge, H. Stöcker, and W. Greiner, Annals of Physics **192** (1989) 266.

[11] S. A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann, J. Konopka, G. Mao, L. Neise, S. Soff, C. Spieles, H. Weber, L. A. Winckelmann, H. Stöcker, W. Greiner, C. Hartnack, J. Aichelin and N. Amelin, Progr. Part. Nucl. Physics Vol. **41** (1998) 225, nucl-th/9803035.

[12] K. Geiger, Comp. Phys. Com. **104** (1997) 70.

[13] M. Bleicher, E Zabrodin, C. Spieles, S. A. Bass, C. Ernst, S. Soff, L. Bravina, H. Weber, H. Stöcker and W. Greiner, submitted to J. Phys. **G**.

[14] K. Eskola and X. N. Wang, Phys. Rev. **D49** (1994) 1284.

[15] E. V. Shuryak, Phys. Rev. Lett. **68** (1992) 3270.

[16] K. Geiger and R. Longacre, Heavy Ion Phys. **8** (1998) 41.

[17] X. N. Wang and M. Gyulassy, Phys. Rev. **D44** (1991) 3501.

[18] M. Bleicher, C. Spieles, C. Ernst, L. Gerland, S. Soff, H. Stöcker, W. Greiner and S.A. Bass, Phys. Lett. **B** in print, hep-ph/9803346.

[19] A. Dumitru, S.A. Bass, M. Bleicher, H. Stöcker and W. Greiner, nucl-th/9901046

[20] G. Bertsch, M. Gong, L. McLerran, V. Ruuskanen and E. Sarkinnen, Phys. Rev. **D37** (1988) 1202.

[21] Y. Nara, Nucl. Phys. **A638** (1998) 555c.

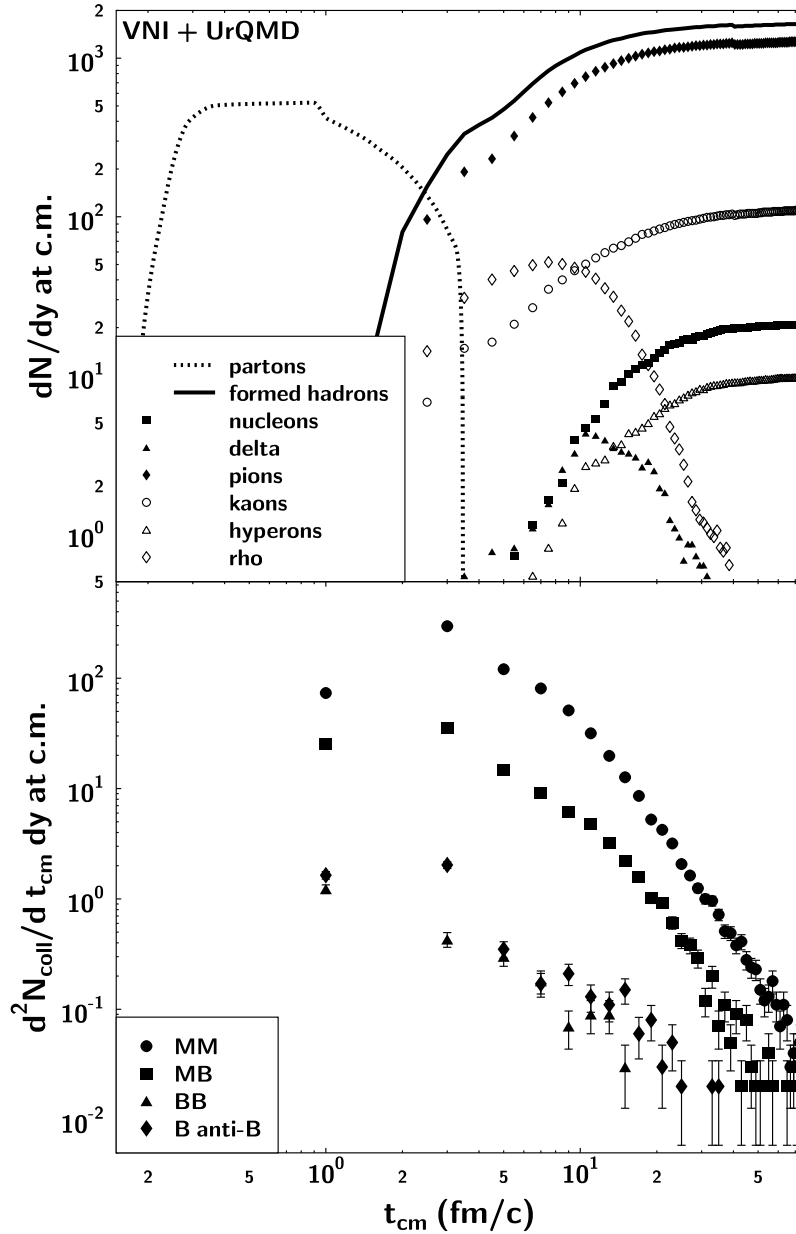[22] S.A. Bass et al., in preparation

FIG. 1.   Top: time evolution of the parton and on-shell hadron rapidity densities at c.m. for central ($b \leq 1$ fm) Au+Au collisions at RHIC. There exists a considerable overlap between the partonic and hadronic phases of the reaction. Hadronic resonances are formed and remain populated up to ≈ 20 fm/c indicating a large amount of hadronic interaction. Bottom: Rates for hadron-hadron collisions per rapidity at c.m.. Meson-meson and to a lesser extent meson-baryon interactions dominate the dynamics of the hadronic phase.
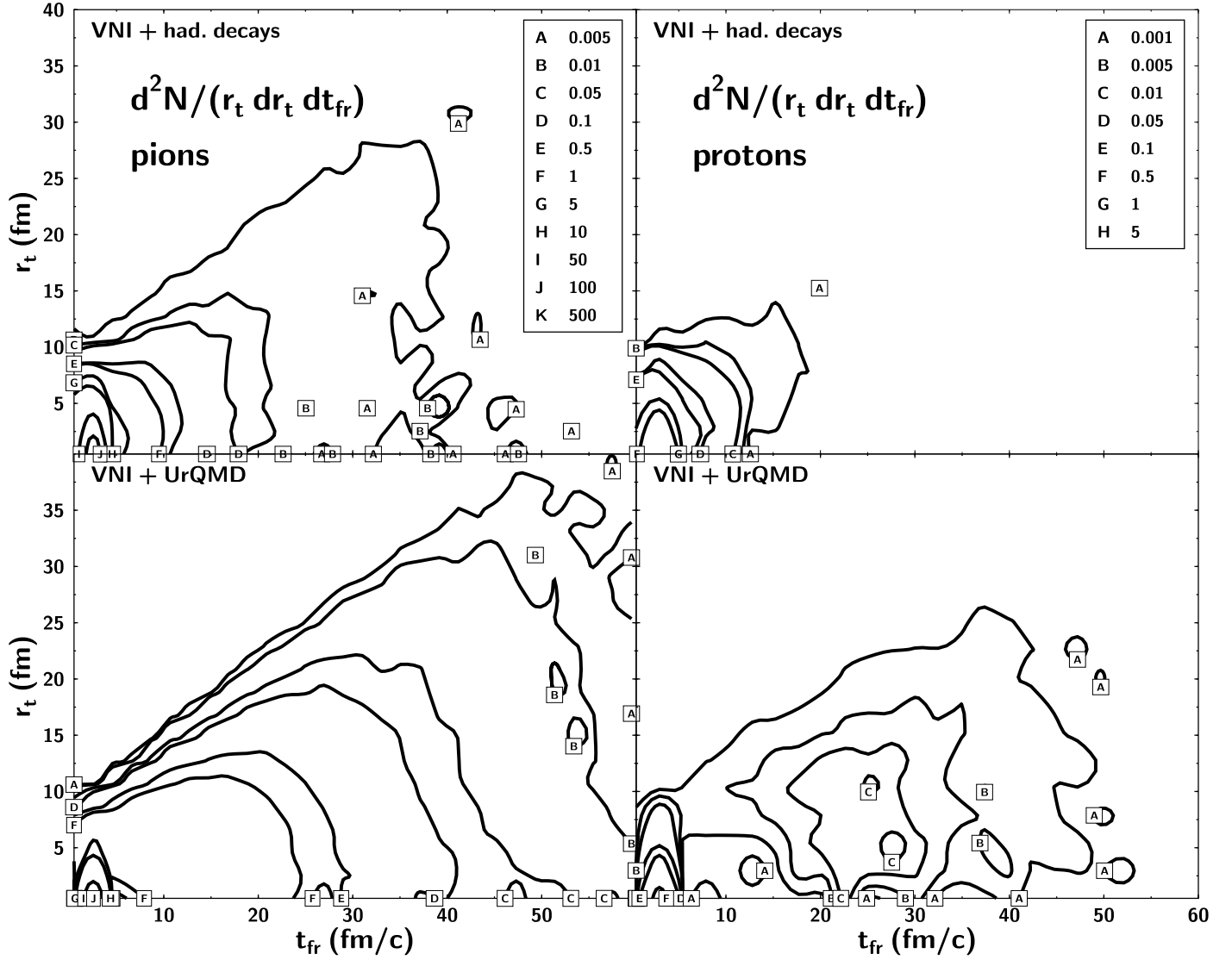
FIG. 2. Freeze-out time and transverse radius distribution $\mathrm{d}^2N/(r_t\mathrm{d}r_t\mathrm{d}t_f)$ for pions (left column) and protons (right column) around mid-rapidity ($-1 \le y_{c.m.} \le 1$). The top row shows the result of parton cascading, hadronization and hadronic decays but without hadronic reinteraction whereas the lower row shows the same calculation with full hadronic dynamics. The contour lines have identical binning within each column but differ between the two columns.
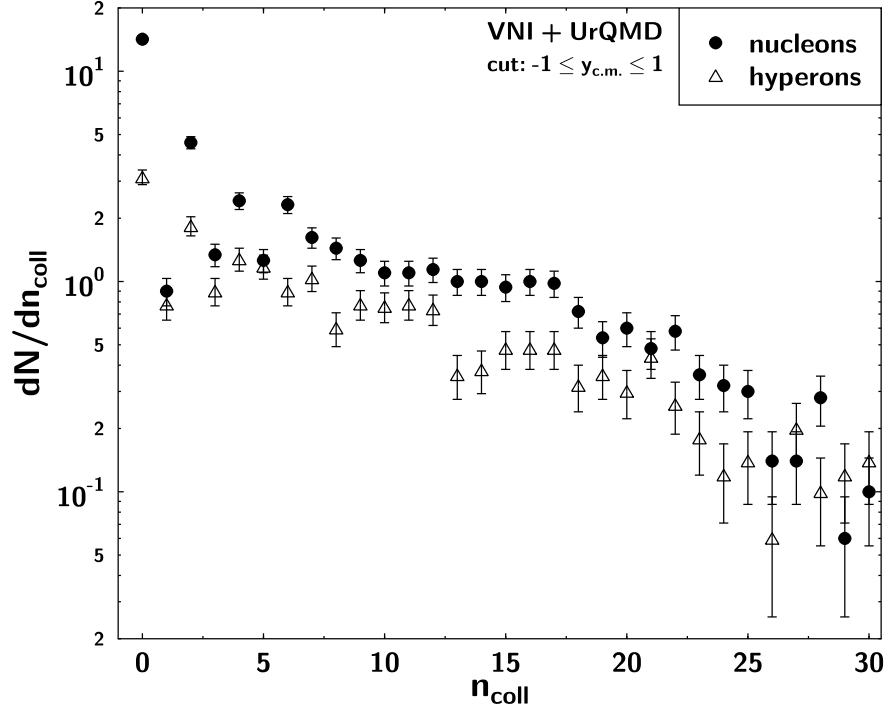
FIG. 3. Collision number distribution for nucleons and hyperons around midrapidity: approximately 15% of the protons and 6% of the hyperons do not rescatter at all. The distribution exhibits a slow decrease from $N_{coll} \approx 5$ to $N_{coll} \approx 17$ before falling roughly exponentially.
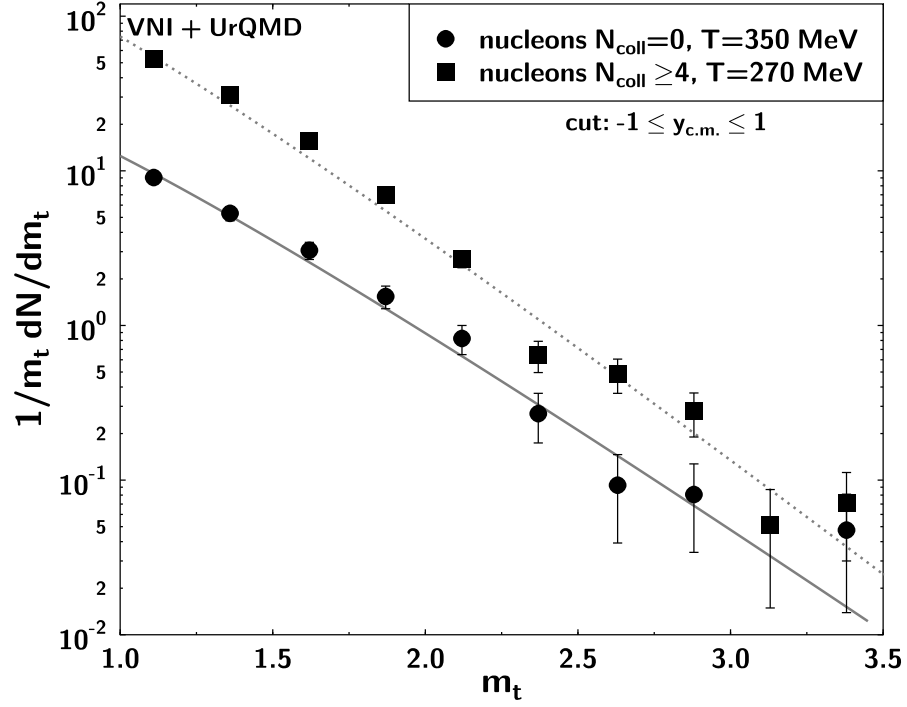
FIG. 4. $dN/m_t dm_t$ spectra for protons around midrapidity. The circles show protons which have not rescattered after hadronization whereas the squares refer to protons which have rescattered at least 4 times. The respective slope decreases by roughly 25% indicating a cooling of the protons via hadronic rescattering.