Overview of Hard processes at RHIC: high-$p_T$ light hadron and charm production

M van Leeuwen
Lawrence Berkeley National Laboratory, Berkeley, California 94720
E-mail: mvanleeuwen@lbl.gov

Abstract. An overview of the experimental results on high-$p_T$ light hadron production and open charm production is presented. Data on particle production in elementary collisions are compared to next-to-leading order perturbative QCD calculations. Particle production in Au+Au collisions is then compared to this baseline.

PACS numbers: 13.85.Ni, 25.75.Dw

Submitted to: J. Phys. G: Nucl. Part. Phys.

1. Introduction

The goal of research in high-energy heavy-ion collisions is to study the properties of strongly interacting matter at extreme energy density, including the possible phase transition to a colour-deconfined state: the Quark Gluon Plasma (QGP). The matter produced in these collisions can be probed using hadrons produced in partonic processes with a large momentum transfer (‘hard scatterings’). These processes take place early in the collision and are only sensitive to short distance scales. In the absence of nuclear effects the hard production yields in nucleus-nucleus collisions are therefore expected to scale as if the collision were an independent superposition of nucleon-nucleon collisions. Measurements at SPS have shown that dilepton production in the Drell-Yan process indeed follows this expectation [1].

Among the first measurements at RHIC was the measurement of light hadron production at high transverse momentum $p_T$ in Au+Au collisions, which shows a suppression with respect to the scaled p+p results. Since these first observations, measurements in d+Au collisions have confirmed that the observed suppression is a final state effect. Recently there has also been an increased activity to verify that high-$p_T$ light-hadron production in proton-proton collisions can be understood in terms of perturbative QCD (pQCD) calculations, as expected for hard processes. Some of the relevant results will be reviewed in the next section.

While for light hadron production much of the groundwork has been done and analyses are clearly moving towards more advanced observables like identified hadron spectra and correlation measurements, first results on open charm production are becoming available. Like high-$p_T$ light hadrons, open charm is expected to be
dominantly produced in hard processes and can therefore serve as a calibrated probe of the medium. Due to their large mass, however, charm quarks and hadrons are expected to be affected differently by the medium than high-\(p_T\) light hadrons \(^{[2]}\).

In the second part of this paper an overview will be presented of the existing results on open charm production at RHIC. The present results are based on run-2 and run-3 data. First results from the large statistics Au+Au data sample from run-4 are to be expected soon. These will greatly improve the precision and \(p_T\)-coverage of the open charm measurements in Au+Au collisions at RHIC.

2. High-\(p_T\) light hadron production

High-\(p_T\) hadron production at RHIC is the most readily accessible observable for hard processes at RHIC. At sufficiently high \(p_T\), all hadrons are expected to be produced in jet fragmentation. The non-perturbative dynamics of jet-fragmentation can be characterised by a universal fragmentation function \(D(z)\) which is parametrised using data from \(e^+e^-\) collisions at different energies \(^{[3,4]}\). With these fragmentation functions and the parton densities from deep inelastic scattering experiments, the expected cross sections for high-\(p_T\) hadron production can be calculated in perturbative QCD (pQCD).

2.1. Neutral pions and charged hadrons in p+p collisions

Figure 1 shows \(p_T\)-spectra of \(\pi^0\) measured by PHENIX \(^{[5]}\) (left panel) and charged hadrons from STAR \(^{[6]}\) and BRAHMS \(^{[7]}\) (right panel) in p+p collisions at \(\sqrt{s} = 200\) GeV. The data are compared to a next-to-leading order (NLO) pQCD calculation \(^{[8]}\). The uncertainty in the theoretical calculation is estimated by varying the renormalisation and factorisation scales \(\mu_R\) and \(\mu_F\) to half and twice the nominal value of \(\mu_R = \mu_F = p_T\). These scale variations change the calculated cross-sections by about 20\% for \(p_T > 5\) GeV. To illustrate the uncertainty in the fragmentation functions, the calculation was performed with two different sets of fragmentation functions, from Kniehl, Kramer and Potter (KKP) \(^{[3]}\) and from Kretzer \(^{[4]}\). Both sets were independently determined from similar selections of \(e^+e^-\) data using slightly different assumptions about relations between the fragmentation functions for different partons. This turns out to be the dominant source of uncertainty for the \(\pi^0\) spectrum: variations of the order of 50\% are seen, mainly due to uncertainties in the gluon fragmentation function. Note, however, that these are partly normalisation uncertainties and do not change the shape of the spectra very much. The measurements have an overall normalisation uncertainty of about 10\%, which is not indicated in the figures. The systematic offset between the STAR and BRAHMS results in figure 1 can probably be attributed to this normalisation uncertainty.

Both for neutral pions and charged hadrons, data and theory agree over more than 5 orders of magnitude, which gives confidence that hadron production at high \(p_T\) (> 3 GeV) is indeed governed by hard point-like processes.

2.2. Strange hadron production in p+p collisions

The above comparisons can be extended to the strange hadrons \(K^0_S\) and \(\Lambda\). While the kaon fragmentation function is relatively well-constrained by the data from \(e^+e^-\) collisions, data on \(\Lambda\) production are scarce \(^{[9]}\).
Hard processes at RHIC

\[ a \cdot \frac{\text{mb}}{\text{GeV} \cdot \sigma} \]

\[ 10^{-5} \]

Figure 1. Measured \( p_T \)-distributions of \( \pi^0 \) (left) and charged hadrons (right) in p+p collision compared to NLO pQCD calculations (lines). The different lines indicate results using different parametrisations of the fragmentation functions (see text) and choice of the factorisation and renormalisation scales. The lower panels show the difference between data and calculations, divided by the calculated curves.

\[ b \\begin{array}{l}
\text{PHENIX Data} \\
\text{KKP NLO} \\
\text{Kretzer NLO}
\end{array}\]

\[ c \]

\[ d \]

Figure 2. Comparison of \( K^0_S \) and \( \Lambda \) spectra in p+p collisions as measured by STAR to NLO pQCD calculations [10]. The different lines indicate results for several settings of the factorisation and normalisation scales.
Hard processes at RHIC

Figure 3. Nuclear modification factor $R_{AA}$ for $\pi^0$ and charged hadron production in central and peripheral Au+Au collisions, as measured by PHENIX [12] and STAR [6].

A first comparison of $K_S^0$ and $\Lambda$ spectra in $\sqrt{s} = 200$ GeV p+p collisions to NLO calculations as presented at this conference is shown in figure 2 [10]. The agreement between the measured $K_S^0$ spectrum and the expectation from NLO pQCD is reasonable, although the shape of the calculated spectrum is slightly more concave than the measured one. This difference is mainly apparent at relatively low $p_T$ (1-2 GeV), where soft production processes may still contribute significantly.

For the $\Lambda$ on the other hand, the agreement between the data and the NLO calculations is far from satisfactory. This might be indicative of the breakdown of the massless formalism and the factorization ansatz for particles with mass that is significant compared to $p_T$ [11]. Before drawing this conclusion, however, the uncertainties in the $\Lambda$ fragmentation functions should be better quantified.

2.3. Suppression in Au+Au collisions

To compare measured the particle spectra in Au+Au collisions to the expected $N_{coll}$ scaling from p+p, the nuclear modification factor

$$R_{AA} = \frac{dN/dp_T|_{Au+Au}}{N_{coll} dN/dp_T|_{p+p}}$$

is generally used. In figure 3 these ratios are shown for peripheral and central Au+Au collisions at $\sqrt{s} = 200$ GeV, both for $\pi^0$ from PHENIX (left panel) [12] and charged hadrons from STAR (right panel) [6]. The suppression ratio $R_{AA}$ in peripheral collisions is close to unity, while for central collisions a suppression of up to a factor 5 is observed. This suppression was one of the first indications of a strong final state modification of particle production in Au+Au collisions that is now generally ascribed to energy loss of the fragmenting parton in the hot and dense medium.

3. Open charm production in d+Au and Au+Au collisions

While light hadron production is only expected to be calculable in perturbative QCD at higher $p_T$, the charm quark mass ($m_c \approx 1.35$ GeV) is large enough to expect pQCD
3.1. Charmed meson spectra in d+Au collisions

None of the RHIC experiments currently has a vertex detector with sufficient resolution to reconstruct secondary vertices of charm decays. Even without secondary vertex reconstruction, STAR has been able to statistically reconstruct decays to charged hadrons in d+Au collisions at $\sqrt{s} = 200$ GeV using an invariant mass method [13]. Different charmed mesons ($D^0$, $D^\pm$, and $D^{*\pm}$) can be reconstructed in different $p_T$ ranges, thus providing a charm measurement up to $p_T = 11$ GeV, as shown in the left hand panel of figure 4. The $D^\pm$ (triangles) and $D^{*\pm}$ (squares) spectra have been scaled to match the $D^0$ spectra (circles). Note that the $D^0$ has been measured at low $p_T$ and at high $p_T$ using different decay modes and thus provides a normalisation for the whole $p_T$ range.

Also shown in figure 4 (left) are NLO pQCD calculations of charm quark spectra [14]. To illustrate the sensitivity of those calculations to the charm quark mass $m_c$ and the choice of renormalisation scale, curves are drawn for $m_c = 1.2$ GeV and $m_c = 1.5$ GeV and with two choices for the renormalisation and factorisation scales: $\mu_R = \mu_F = m_T$ and $\mu_R = \mu_F = 2m_T$. Note that the shape of the spectra at low $p_T$ is most sensitive to both the charm quark mass and the choice of scales.

For a detailed comparison of the data to theory, the calculated charm quark spectrum should be convoluted with the charm fragmentation function. This would lead to a softening of the spectrum and a reduction of the yield, both of which may in principle depend on the meson species. Given the limited $p_T$ range of the spectra calculations to be valid for all $p_T$. Final state effects on charm quarks and hadrons are expected to be smaller than for the light hadrons due to the large charm mass [2].
Hard processes at RHIC

for the separate species and the relatively large uncertainties in their fragmentation functions, we have chosen to compare the shape of the combined meson spectrum directly to the charm quark spectra. For this purpose, the calculated spectra were scaled up by a factor of 4 to approximately match the data. The shapes of the calculated charm quark spectra and the measured meson spectra are surprisingly similar, leaving little room for softening due to fragmentation.

All in all, it is far from clear that the present data can be matched with a NLO pQCD calculation. Before drawing any conclusions about charm production in elementary collisions at RHIC, though, we should wait until the present data are finalised. Although it is expected that $N_{\text{coll}}$ scaling is valid for charm production in d+Au, it would be good to confirm this by similar measurements in p+p. There are also some open questions for theory. For example, a matched next-to-leading logarithm calculation is needed to describe beauty production at the Tevatron [15]. In addition, a new way of extracting fragmentation functions, by fitting the Mellin moments instead of a direct $z$-space fit is found to lead to an effectively harder fragmentation function [16]. Similar considerations may also affect calculations of charm production at RHIC.

3.2. Total charm cross section

The right-hand panel of figure 4 shows the measured energy dependence of the total charm quark cross section [17, 18], compared to NLO pQCD calculations [14]. Estimating the total charm quark cross section from experimental data involves substantial extrapolations to the unmeasured regions of momentum space and corrections to include unmeasured charmed hadron species. These corrections lead to sizeable systematic uncertainties on the data, as can be seen from the figure. The uncertainties on the NLO pQCD calculations due to higher order corrections and the choice of the charm mass are also significant. It is therefore preferable to directly compare data and calculations in the measured regions (see also [19]).

Note also that it seems that the charm cross section per nucleon-nucleon collision as measured by STAR in d+Au collisions from a combination of the electron measurements and the invariant mass method is somewhat higher than expected from the trend observed by other experiments and the pQCD calculations. The deviations are within the present uncertainties on the measurements.

3.3. Centrality dependence of charm production in Au+Au collisions

A first indication of the centrality dependence of charm production in Au+Au collisions can be taken from electron spectra. After subtraction of the contributions from light hadrons (mainly through photon conversions, but also from Dalitz decays of $\pi^0$, $\eta$, $\eta'$, $\rho$, $\omega$ and $\phi$) the electrons from heavy flavour decays remain (‘non-photonic’ electrons). In the left hand panel of figure 5 the electron spectra from heavy flavour decays as measured by PHENIX in centrality-selected Au+Au collisions [20] are shown. The lines show reference spectra obtained from a fit to the measured spectrum in p+p, scaled by the number of collisions. At each centrality, the spectra agree with the expected $N_{\text{coll}}$ scaling from p+p, albeit within large errors.

In the right-hand panel of figure 5 the yields of non-photonic electrons with $0.8 < p_T < 4.0$ GeV per nucleon-nucleon collision are shown as a function of centrality. There is no indication of a suppression as seen for light hadrons (see figure 3). One should keep in mind, however, that electrons with $p_T > 0.8$ GeV have contributions
Hard processes at RHIC

![Graph showing non-photonic electron spectra from Au+Au collisions compared to the expectation from p+p.](image)

**Figure 5.** (left) Non-photonic electron spectra from Au+Au collisions, compared to the expectation from p+p. (right) Nuclear modification factors $R_{AA}$ for non-photonic electrons with $p_T > 0.8$ GeV as measured by PHENIX [20].

![Graph showing elliptic flow $v_2$ of non-photonic electrons in Au+Au collisions measured by STAR and PHENIX [21].](image)

**Figure 6.** Elliptic flow $v_2$ of non-photonic electrons in Au+Au collisions as measured by STAR and PHENIX [21].

from semi-leptonic charm decays at all $p_T$. The presented results are therefore not very sensitive to a possible suppression of charm production at moderate or high $p_T$ (> 2 GeV).

### 3.4. Charm flow

A measurement of the elliptic flow $v_2$ of charmed mesons is an independent way of assessing the sensitivity of charmed mesons to final state interactions. Here again, we have to rely on measurements of decay electrons for the time being. In figure 6 the elliptic flow of non-photonic electrons is shown [21]. Both STAR and PHENIX observe non-zero electron flow, which is a strong indication that charmed mesons flow. This is an intriguing possibility, because it would show decisively that charm production is sensitive to the dense hadronic or even partonic environment in the collision. At
Hard processes at RHIC

the moment the statistical and systematic errors are still large, precluding a precise quantitative extraction of flow values. The situation is expected to dramatically improve with the larger Au+Au data samples which were recorded this year.

4. Summary and outlook

A comparison of neutral pion and charged hadron $p_T$-spectra measured in p+p collisions at $\sqrt{s} = 200$ GeV at RHIC to NLO pQCD calculations shows that high-$p_T$ light hadron production is well described by perturbative QCD, albeit within relatively large uncertainties, mainly from the fragmentation functions. This gives confidence that high-$p_T$ particle production is governed by hard, point-like processes, for which the cross section in Au+Au collisions is expected to scale with the number of nucleon-nucleon collisions. A suppression of light hadrons by approximately a factor of 5 compared to the expected scaling is observed in central Au+Au collisions, due to final state interactions of the fragmenting quarks and/or the produced hadrons.

For strange hadrons, $K_S^0$ and $\Lambda$, the agreement between data and NLO pQCD calculations is not as good, or even unsatisfactory (for $\Lambda$). In those cases, however, the data do not extend to very high $p_T$ and the fragmentation functions are not as well known as for the light hadrons. This needs more investigation before conclusions can be drawn about the applicability of pQCD.

The same is true for open charm production in d+Au collisions, where shape of the measured $D$ meson spectra is similar to the calculated charm quark spectra, leaving little room for softening due to fragmentation.

First results on electron production from PHENIX indicate that there is no or very little suppression of charm production in Au+Au collisions. Measurements of electron flow, on the other hand, indicate significant flow of the charmed mesons, which can only be due to significant final state interactions.

In the near future, a measurement of the $p_T$-dependence of nuclear modification factors for non-photonic electrons or maybe even open charm can be expected from the large statistics Au+Au data samples collected in run-4 at RHIC. This, together with a more accurate measurement of charm flow, will map out the interactions of charm quarks and hadrons with the medium and, through comparison with the light hadron results, may eventually shed more light on the nature of these interactions.

References

[1] Abreu M C et al. (NA50 Collaboration) Phys. Lett. B 410 327  
[2] Molnar D these proceedings  
[3] Kniehl B A, Kramer G and Potter B Nucl. Phys. B 582 514 arXiv:hep-ph/0010289  
[4] Kretzer S Phys. Rev. D 62 054001 arXiv:hep-ph/0003177  
[5] Adler S S et al. (PHENIX Collaboration) Phys. Rev. Lett. 91 241803 arXiv:hep-ex/0304038  
[6] Adams J et al. (STAR Collaboration) Phys. Rev. Lett. 91 172302 arXiv:nucl-ex/0305015  
[7] Arsene I et al. (BRAHMS Collaboration) Preprint arXiv:nucl-ex/0403026  
[8] Jager B, Schafer A, Stratmann M and Vogelsang W Phys. Rev. D 67 054005 arXiv:hep-ph/0211007 and private communication  
[9] de Florian D, Stratmann M and Vogelsang W Phys. Rev. D 57 5811 arXiv:hep-ph/9711387  
[10] Heinz M et al. (STAR collaboration) these proceedings  
[11] Kretzer S Preprint arXiv:hep-ph/0410219  
[12] Adler S et al. (PHENIX Collaboration) Phys. Rev. Lett. 91 072301 arXiv:nucl-ex/0304022  
[13] Tai A (STAR Collaboration) J. Phys. G 30 S809 arXiv:nucl-ex/0404029  
[14] Vogt R (Hard Probe Collaboration) Int. J. Mod. Phys. E 12 211 arXiv:hep-ph/0111271 and private communication
[15] Cacciari M, Frixione S, Mangano M L, Nason P and Ridolfi G JHEP 0407 033
  [arXiv:hep-ph/0312132]
[16] Cacciari M and Nason P Phys. Rev. Lett. 89 122003 [arXiv:hep-ph/0204025]
[17] Adams J et al. (STAR Collaboration) Preprint [arXiv:nucl-ex/0407006]
[18] Kelly S (PHENIX Collaboration) J. Phys. G 30 S1189 [arXiv:nucl-ex/0403057]
[19] Frixione S Preprint [arXiv:hep-ph/0408317]
[20] Adler S S et al. (PHENIX Collaboration) Preprint [arXiv:nucl-ex/0409028]
[21] Laue F et al. (STAR collaboration) these proceedings